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Aircraft Propeller Handbook

STANFORD UNIVERSITY
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MUNITIONS BOARD

Issued Jointly
by
DEPARTMENT OF THE AIR FORCE
DEPARTMENT OF THE NAVY
DEPARTMENT OF COMMERCE

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ANC-9 BULLETIN

STANFORD UNIVERSITY
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DEC 10 1956
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Aircraft Propeller Handbook

Issued by

DEPARTMENT OF THE AIR FORCE
AIR RESEARCH AND DEVELOPMENT COMMAND
DEPARTMENT OF THE NAVY
BUREAU OF AERONAUTICS
DEPARTMENT OF COMMERCE
CIVIL AERONAUTICS ADMINISTRATION

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PREFACE

This handbook was prepared under the auspices of the ANC–9 Panel on Propellers of the Subcommittee for Air Force-Navy-Civil Aircraft Design Criteria of the Aircraft Committee of the Munitions Board. While this agency has been dissolved, it is considered highly important that the results of its efforts in compiling the information contained herein should be made more generally available through suitable publication.

It would be unrealistic indeed to assume that this handbook presents the last word in the design and development of propellers. The staff members who have written the separate sections are fully cognizant of the rapid evolution which the propeller art is presently undergoing. They have been compelled through circumstances to record only the most pertinent portions of information available at this time in this highly specialized field of endeavor. In the minds of those versed in the art there is no reason to believe that developments of tomorrow in the field of propellers will be any less spectacular and far-reaching than those of the past. The development and utilization of supersonic propellers are envisioned. New and improved designs and methods of fabrication are expected to enhance the production of propellers in the quantity and of the quality required for advanced designs of aircraft.

In view of the circumstances under which it was necessary to compile the material of this handbook, no apologies are offered for its shortcomings or for errors which eluded observation during its preparation. In consideration of its intended purpose, it was adjudged more important to release it for publication in its present form than to withhold it for further refinement in the dubious future.

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Aircraft Propeller Handbook

CHAPTER I. INTRODUCTION

General Considerations

Objectives

(1) *Purpose.* This handbook has been prepared for use as a general guide in consideration of some of the most common problems associated with design, construction and use of both military and commercial aircraft propellers. Therefore, as an "ANC" document, it contains material which is acceptable to the Air Force, Navy, and Civil Aeronautics Administration (CAA) of the Department of Commerce. Specifically, it has been prepared for the following purposes:

- (*a*) To acquaint aeronautical newcomers with problems of design, manufacture, and use of propellers to meet objectives of the Air Force, Navy, and CAA.
- (*b*) To summarize and present propeller practices which have been found to be reasonably satisfactory.
- (*c*) To present, where possible, the reasons for current propeller practices so that sound procedures will not be ignored through lack of understanding, or employed needlessly and possibly even detrimentally, where inapplicable.
- (*d*) To stress the importance of airworthiness and safeness in propellers.

(2) *Use of the handbook.* It is not the purpose of this handbook to supplant propeller specifications. The handbook is an adjunct to specifications in that it is designed to furnish general background from which propeller specifications have emerged. In all cases, specifications applicable and made a part of particular contracts will take precedence. Those specifications cannot be subrogated by stipulations within this handbook. This handbook has not been designed to serve as a textbook.

Scope

It should be understood, of course, that methods, procedures, and techniques applicable to propeller design, development or testing, other than those outlined herein, may be acceptable provided those practices have been substantiated properly and adjudged, by the responsible governmental agency, to serve Government interests most adequately.

In a sense, this handbook is but a progress report of the state of propeller art. It is intended that basic findings will be presented for guidance, but that present practices, as presented herein, will not restrict in any manner development of new propeller designs and methods of fabrication or testing.

Airworthiness

(1) *Definition.* Airworthiness consists of two basic criteria; namely, structural safeness and functional achievement. Even though a propeller can deliver the required thrust with no more than the allowable drag or power consumption, it is of little value if it is not structurally sound and safe to use. This combination of safeness and capacity for functional accomplishment will determine airworthiness of a propeller.

(2) *Safeness.* The matter of safeness receives such an enormous amount of attention because propellers are a potential source of tremendous damage should they fail structurally. Like most aircraft items, propellers must be designed with minimum weight as a prime consideration; hence, propeller materials will be worked under highly stressed conditions.

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But, unlike many other aircraft components, an operating propeller has stored within itself a very large quantity of dynamic energy, the release of which can be catastrophic, if the propeller fails.

Consequently, severe tests for propellers have been formulated to eliminate serious risks to life and property which may accrue when a propeller is subjected to operational use. In the United States, large amounts of money have been devoted to providing facilities for accomplishment of testing programs. The policy of propeller testing was adopted early in World War I and has endured down through the years. That this policy has paid dividends is attested by the record of relatively few disasters primarily due to propeller failure, while simultaneously great strides have been made in propeller development. It has been possible to test advanced or radical ideas embodied in new propellers which never would have been risked in aircraft flight without such prior proof-testing.

(3) *Functional requirements.* The severe tests to which propellers are subjected encompass propeller effectiveness to accomplish a given function under certain limited conditions. Propeller tests must establish both safeness and functional achievement prior to general approval for release. However, it is neither wise nor sufficient that sole reliance be placed upon the results of a test of a complete propeller to determine its airworthiness. Prior to testing, full advantage must be taken of every item of knowledge or practice which has been found favorable to development of successful propellers so that the final design will be the best obtainable. By the time that a new complete propeller has been made ready for test, a considerable amount of time and money has been invested. In event of propeller failure during test, irrecoverable loss has been suffered. Therefore, it is quite important that realization of functional requirements and difficulties involved be recognized at the outset of a propeller development project so that adequate allowances may be made and precautions taken to produce a satisfactory propeller. In addition to good design, it is necessary to control the manufacturing processes closely, since lack of control may negate all of the advantages gained from good design. The pitfalls introduced by poor design and lack of control of manufacturing processes will be discussed in more detail in appropriate sections of the handbook.

Definitions and Symbols

Definitions

Definitions particularly related to propellers have been adopted for use throughout this handbook and are here listed.

Activity factor. A nondimensional function of propeller planform designed to express, in a relative way, the integrated capacity of a respective blade planform for absorbing horsepower.

$$AF=\frac{100,000}{16}\int_{r=0.2R}^{r=R}\frac{b}{D}\frac{r^3}{R}\,d\frac{r}{R}$$

Wherein D=propeller diameter
R=propeller tip radius $\left[\frac{D}{2}\right]$
r=radius of any blade element
b=blade width at radius r

Advance ratio. Advance ratio (J_A) of a propeller is the ratio of forward velocity, V (fit/sec.) to the product nD, where n is revolutions per second, and D is the propeller diameter (in feet).

Airfoil. An airfoil is the geometric shape of any cross-section taken normal to the longitudinal axis of any lifting surface, such as a wing or propeller blade.

Angle of attack. The acute angle between blade airfoil section chord line and relative air velocity measured in a plane perpendicular to the blade axis.

Anti-icing. A term applied to a method employed for prevention of ice formation on a propeller.

Aspect ratio. The aspect ratio of a propeller blade is the ratio of the square of the length or span of the surface, to the area of the surface (blade surface projecting beyond the spinner surface).

Blade angle. The acute angle between blade airfoil section chord line and plane of rotation.

Blade axis. The axis from blade tip to shank end about which the individual blade may rotate to change pitch.

Blade base. The extreme end of a detachable propeller blade which, when installed in a hub, is nearest the hub centerline.

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Blade, propeller. The thrust producing and major torque absorbing component of a propeller. It may be constructed integrally with a propeller hub or provided with a suitable shank section for assembly in a propeller hub.

Blade retention. The method or physical system by means of which a propeller blade is held in the hub.

Blade root. That portion of the blade shank involved in positioning and retaining the blade in a hub or hub boss.

Blade shank. That portion of a blade radially outward from the base or hub boss including that faired portion of the blade which contributes negligibly to thrust or engine cooling.

Blade tip. That end of a propeller blade which, when installed in a hub, is farthest from the propeller shaft centerline.

Blade width. The maximum linear dimension at any chosen station measured normal to the line of centers between the blade leading and trailing edges.

Camber. Camber is the degree of curvature of the mean line of an airfoil relative to the airfoil chord line. Generally, this may be defined in terms of design lift coefficient; or, that lift coefficient obtained when an airfoil operates at zero angle of attack.

Camber, face. That side of a propeller section having maximum curvature in relation to the chord.

Centrifugal twisting moment. A torque or moment in the plane of the blade element, generated by centrifugal force. In a normally forward-pitched blade, the moment tends to reduce the blade angle.

Chord. A propeller section chord is the length of a straight line equal to the diameter of a circle circumscribing the section.

Chord line. The chord line is a straight line passing through the center of the blade leading and trailing edge radii. Chord line is the reference base from which the mean camber line and the airfoil contour are established.

Cone. A sleeve with a conical outer surface, used for centering a propeller on a shaft.

Controls, propeller.

General. The complete system by means of which pitch, or blade angle, of an operating propeller can be changed.

Restricted. That particular portion of a complete propeller control system by means of which remote control of propeller pitch, or units which automatically adjust the pitch, is obtained.

Cuffs. Propeller blade components, attached to the exposed portions of blade shanks, forming favorable airfoil sections. Cuffs improve aerodynamic characteristics (by reducing drag) of the exposed portions of propeller blades and aid in engine cooling.

Deicing. A term applied to a method of removing ice after it has formed on a propeller.

Diameter, propeller. The diameter of the circle having its center coincident with the engine crank shaft center and circumscribing the propeller in its plane of rotation.

Disc area. The area of a circle having the same diameter as a given propeller.

Drag. Drag is that force acting on any body which resists movement of the body through any medium.

Dual rotation propeller. Two propeller hub-blade components coaxially mounted but turning in opposite directions. Normally, these propellers are separated only by sufficient distance to afford adequate mechanical clearance. Often, the term is abbreviated to "dual propeller."

Edge alignment. The distance, parallel to the chord of a propeller section, from blade centerline to the leading edge of the blade cross-section at any station. This dimension is shown on all blade drawings at specific stations. Trailing edge alignment is a corollary to leading edge alignment.

Efficiency, propulsive. The ratio of the product of effective thrust and flight speed, to actual power input to the propeller as mounted on an airplane.

Effective thrust. The net driving force developed by a propeller when mounted on an aircraft, i.e., the actual thrust exerted by a propeller as mounted on an airplane minus any increase in drag of the airplane due to propeller action.

Element, blade. A cross-section of the propeller blade between two parallel and infinitesimally close planes perpendicular to the propeller radius, at a specific station.

Face alignment. The distance, perpendicular to the section chord, measured from the blade

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centerline to the blade downstream face at any station. This dimension is shown on all blade drawings at specific stations.

Face, blade. The surface on either side of a propeller blade. The surface corresponding to the upper airfoil surface is the upstream face, sometimes called camber face, and the one corresponding to the lower airfoil surface is the downstream face, sometimes called thrust face.

Feathering. A term applied to the action of changing propeller blade pitch by rotation to such a position (usually about 90° to the plane of rotation) that the propeller will have minimum drag when not rotating.

Flutter. Blade vibration of sufficient severity to be unmistakably noticeable without the use of instruments.

Frequency. The rate of vibration usually expressed in cycles per minute (CPM).

Geared propeller. A propeller driven at other than engine speed by use of intermediate gear trains.

Governor, propeller. That part of a propeller control system which senses or anticipates departures of rotational speed from the preset reference value and which causes the pitch-changing mechanism to correct the departure through an appropriate change in blade angle.

Hub. That part of a propeller mounted upon an engine drive shaft and to which the blades are attached.

Hub barrel. That part of a hub in which the blade roots are fastened. Usually this part of the hub is a socket into which blade roots are inserted (with bearings) to be held in place by a spanner nut.

Induced flow. The increment of air quantity moving into a propeller in excess of the relative quantity moving past the propeller in movement through undisturbed air. The extra inflow quantity is "induced" by action of the propeller.

Inflow. The flow of air into a propeller disc area.

Leading edge. That part of a blade which leads the advance through air along a helical path.

Lift. That component of the total air force which is perpendicular to the relative wind.

Mach number. Mach Number is the ratio of velocity of flow of a fluid over a body to the local velocity of sound in the fluid.

Mode of vibration. Manner in which various parts of a vibrating propeller move relative to each other, ordinarily designated by specifying a mode shape and relative frequency of vibration (e. g., fundamental order flatwise bending; second order, edgewise bending; fundamental torsional, etc.). Mode shape is characterized by a series of propeller deflections at all points at successive instants.

Pitch, propeller

Effective pitch. The axial advance of a propeller with respect to the undisturbed air during each revolution of the propeller.

Experimental mean pitch. The relative axial distance of air-propeller movement for each turn of the propeller under conditions of zero thrust.

Geometric pitch. The axial advance for each propeller revolution which would result if a blade of uniform pitch moved along a helix with pitch angles equal to the blade angles at the respective radii.

Propeller. Any device for propelling a craft through a fluid, such as water or air, by the action of blades which, when mounted on a power-driven shaft, produce an axial force or a thrust on a fluid.

Propeller axis. The axis about which a propeller turns, or the centerline of a propeller shaft.

Propeller shaft. The shaft on which a propeller is mounted and by means of which power from an engine can be transmitted to the propeller.

Radius, propeller. The distance of the outermost point of a propeller blade (tip) from the axis of rotation.

Radius, station. The distance from the axis of rotation to a plane perpendicular to the blade centerline intersecting the blade at a given point or station.

Ram or ram pressure. Ram is used in aeronautics in the literal sense; it is the impact or dynamic pressure of air impinging on a surface.

Ram recovery. A term used, generally, in connection with engine air inlets. It is usually expressed as that percent of the ram pressure which is recoverable or available to do useful work at the entrance to the engine proper.

Reynolds number. Reynolds number is defined

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as the ratio of the product of fluid velocity and length, to kinematic viscosity; or algebraically:

$$R_e = \frac{V \times L}{\nu}$$

Wherein V = Velocity.
L = Representative length of the fluid under consideration.
ν = Kinematic viscosity or ratio of viscosity of the fluid to its density.

Shaft nut. A propeller retaining nut used to hold a propeller on the shaft.

Single rotation. A propeller having hub-blade components which rotate in the same direction.

Slinger ring. A circular U-shaped collector channel mounted on the rear of the propeller hub by means of which anti-icing fluid, emerging from the stationary supply nozzle, will be transferred to the blades by centrifugal action.

Slip. The air velocity, relative to undisturbed air, imparted by action of a propeller. Both axial and rotational slip exist but unless specifically qualified otherwise, the term slip will apply only to the axial component of total slip. Most frequently, slip is expressed in terms of a percentage of the velocity of an aircraft relative to undisturbed air.

Slip rings. Metallic rings, rotating with propeller hubs, with which stationary (carbon) brushes make contact for the purpose of completing electrical circuits between rotating and non-rotating parts.

Solidity. Solidity can be defined in the following ways:

(1) The ratio of the chord at some representative radius multiplied by the number of blades, divided by the circumference at that same radius.

(2) The ratio of total blade area of a propeller to the area of the propeller disc.

Sonic. Reference to the velocity of sound in a given fluid under particular flow conditions.

Spinner. A fairing, usually of conical or parabolical shape at the nose, which is mounted coaxially with a propeller (and revolves with it) and which encloses the hub and front end of the propeller.

Static thrust. The thrust developed by a propeller when rotating without translation or axial motion.

Station. Designation of a transverse blade section at a given radius.

Subsonic propeller. A propeller type, the design of which is predicated on substantially all airfoil portions of the blades operating under conditions of subsonic flow.

Supersonic propeller. A propeller type, the design of which is predicated on substantially all airfoil portions of the blades operating under conditions of supersonic flow.

Synchronizer. A device for controlling the speed of individual propellers so that all propellers of a multi-engine aircraft will operate at the same selected speed.

Tandem propellers. Two or more coaxial propellers, separated by a substantial axial distance, but still sufficiently close together to influence the flow of the air through the propellers. The propellers may rotate in either the same or opposite directions.

Test club. A propeller-like device used for absorbing torque during aircraft engine test which may or may not be designed to provide some cooling by forcing a blast of air over the engine.

Thickness ratio. The ratio of maximum thickness of an airfoil section to its chord.

Tip volocity (*Speed*). The circumferential velocity of the tip of a propeller, usually expressed in feet per second. It may be defined mathematically:

$$\text{Tip velocity} = \frac{\pi ND}{60}$$

wherein

D = Diameter in feet
$N = RPM$

Tip volocity (*Helical*). Helical tip velocity is the vectorial sum of tip velocity of propeller and velocity of forward advance. It may be expressed by the formula:

Helical tip velocity =

$$\left[\frac{(\pi ND)^2}{60} + \left(MPH \times \frac{88}{60}\right)^2\right]^{1/2}$$

Thrust. That component of the resultant of all air forces acting on a propeller, which is parallel to the axis of rotation. Positive thrust is in the direction of flight.

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Thrust face. The downstream face of a blade.

Track. The path described by a point in a blade of a propeller as the propeller rotates. When the paths of corresponding points of all blades of a propeller are in a single plane perpendicular to the axis of rotation, the propeller "tracks" perfectly.

Degree of track. Closeness with which the corresponding points of propeller blades rotate in the same plane as the respective points of a reference blade.

Trailing edge. The rearmost or downstream edge of a propeller blade.

Transonic propeller. A propeller type, the design of which is predicated on a major portion of the airfoil sections of the blades operating under conditions of transonic flow.

Twin propellers. A propeller arrangement similar to the usual twin-engine arrangement except that both propellers are driven by the same engine.

Twist. The angular difference between airfoil sections formed by cutting planes passing through a propeller at right angles to the blade axis.

Vibration orders. Frequency of vibration of a propeller blade, given in cycles of vibration, per propeller or engine revolution. Thus, $(1\times P)$ identifies one vibration cycle per propeller revolution; $(2\times P)$ indicates two cycles per propeller revolution; $(7\times E)$ indicates seven cycles per engine revolution, etc.

Windmilling. Forced rotation of a propeller by action of air flow through the disc area, which occurs when engine power is cut off suddenly.

Letter Symbols for Propeller Usage

Letter symbols indicated herein are those used for primary concepts. Wherever possible, the symbols and definitions used in this handbook are in accordance with American standard, "Letter Symbols for Aeronautical Sciences." However, some departures and additions have been necessary due to the specialized nature of propeller analysis. Such departures and additions are denoted by an asterisk (*). Dimensionless quantities are indicated by DLS in the column headed "Dimensions."

Principal Symbols

Symbol	*Concept and Definition*	*Dimensions*
a	Slope of lift curve	DLS

$$a=\frac{dC_L}{d\alpha}$$

Symbol	*Concept and Definition*	*Dimensions*
A	Area, cross-section, usually referring to propeller disc area or to cross-section perpendicular to blade longitudinal axis at a given radius, r.	L
AF	Activity factor*	DLS

$$AF=\frac{100{,}000}{16}\int_{0.2}^{1.0}\left(\frac{b}{D}\right)\left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right)$$

Symbol	*Concept and Definition*	*Dimensions*
AR	Aspect ratio	DLS
b_s	Span	L
b	Propeller blade width	L
B	Number of blades*	DLS
c	Chord of an airfoil	L
c_s	Coefficient, section	DLS
c_d	Section drag coefficient*	DLS
c_l	Section lift coefficient*	DLS
c_{l_i}	Section design lift coefficient*	DLS
c_m	Section moment coefficient*	DLS
c_n	Section normal force coefficient*	DLS
C	Coefficient	DLS
C_D	Drag coefficient*	DLS
C_L	Lift coefficient*	DLS

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Symbol	*Concept and Definition*	*Dimensions*
C_{L_i}	Integrated design lift coefficient*	DLS
	$C_{L_i}=4\int_{0.2}^{1.0} c_{l_i}\left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right)$	
C_M	Moment coefficient*	DLS
C_N	Normal force coefficient*	DLS
C_P	Power coefficient*	DLS
	$C_P=\frac{P}{\rho N^3D^5}, \left(\frac{5(10^{10})\,(SBHP)}{\sigma N^3D^5}\right)$	
C_Q	Torque coefficient*	DLS
	$C_Q=\frac{Q}{\rho n^2D^5}, \left(\frac{1.514(10^6)Q}{\sigma N^2D^5}\right)$	
C_S	Speed power coefficient*	DLS
	$C_S=5\sqrt{\rho\frac{V^5}{Pn^2}}$	
C_T	Thrust coefficient*	DLS
	$C_T=\frac{T}{\rho n^2D^4}, \left(\frac{1.514(10^6)T}{\sigma N^2D^4}\right)$	
d	Diameter	L
D_p	Diameter of propeller	L
D	Drag	ML/T^2
e	Span effectiveness	DLS
E_y	Modulus of elasticity; Young's modulus	M/LT^2
E	Energy	ML^2/T^2
f	Frequency	$1/T$
F	Force	ML/T^2
F_T	Thrust; Jet and rocket. Use T for propeller thrust	ML/T^2
g	Acceleration of gravity	L/T^2
G_S	Shear modulus	M/LT^2
G	Goldstein induced-velocity correction factor for finite number of blades;*	DLS
	$G=\frac{K(x)}{\cos^2\phi}$	
h	Altitude	L
I	Area moment of inertia*	L^4
I_{maj}	Major moment of inertia*	L^4
I_{min}	Minor moment of inertia*	L^4
I_P	Polar moment of inertia*	L^4
I_M	Mass moment of inertia	ML^2
J	Mass polar moment of inertia	ML^2
J_A	Advance ratio	DLS
	$J_A=\frac{V}{nD}$	
k	Spring constant, linear-force	M/T^2

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Symbol	*Concept and Definition*	*Dimensions*
$K\theta$	Spring constant, angular-moment	ML^2/T^2
k_r	Radius of gyration	L
K_m	Mass coefficient*	DLS

$$k_m=2\int_0^{1.0} K(u)\times dx$$

K	Factor for comparison purposes	DLS
K_R	Retention flexibility*	DLS
$K_{(x)}$	Circulation function	DLS

$$K_{(x)}=\frac{B\Gamma n}{V_W} \text{ (for lightly loaded propellers*)}$$

$K_{(x)}$	Circulation function	DLS

$$K_{(x)}=\frac{\Gamma Bn}{(V+w)_w} \text{ (for moderately heavy loadings.*)}$$

l	Length, distance	L
L	Lift, total	ML/T^2
m	Mass	M
M	Moment	ML^2/T^2
M_a	Free air stream Mach number (forward Mach number)	DLS
M_t	Helical tip Mach number*	DLS

$$M_t=M\sqrt{1+\left(\frac{\pi}{J}\right)^2}$$

M_x	Apparent or geometric helical Mach number at station x*	DLS

$$M_x=M\sqrt{1+\left(\frac{\pi X}{J}\right)^2}$$

n	Revolutions per second, usually of propeller	$1/T$
N	Revolutions per minute, usually of propeller	$1/T$
N_F	Normal force	ML/T^2
N_g	Number, in general	DLS
p	Pressure; static pressure	M/LT^2
p_g	Geometric pitch of propeller; distance propeller would advance in one revolution with no slip.	L
P	Power	ML^2/T^3
P_L	Load	ML/T^2
q	Dynamic pressure	M/LT^2

$$q=\rho\frac{V^2}{2}$$

Q	Twisting moment	ML^2/T^2
Q_P	Torque, usually of propeller	ML^2/T^2
Q_f	Torque force acting at some radius or lever arm	ML^2/T^2
Q_c	Coefficient of torque*	DLS

$$Q_c=\frac{Q}{\rho V^2D^3}$$

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Symbol	*Concept and Definition*	*Dimensions*
r	Radius, usually at a blade element	L
R	Radius, usually to propeller tip	L
R_e	Reynolds Number	DLS
s	Stress	M/LT²*
S	Shear	ML/T²
$SBHP$	Shaft brake horsepower	ML²/T³*

$$SBHP=\frac{P}{550}$$

t_b	Thickness, usually maximum thickness of blade section	L
t	Time	T
T_n	Thrust, usually net propeller thrust	ML/T²
T	Temperature, absolute, usually Rankine	
u	Velocity, longitudinal, component of	L/T
u_e	Deflection, displacement*	L
U	Velocity, alternate	L/T
v_l	Velocity, lateral component	L/T
v	Volume, specific volume; per unit mass,	L³/M
	or per unit weight	L²T²/M
V	Velocity, usually forward velocity	L/T
V_R	Actual resultant velocity at blade section, often denoted by W	L/T
V_{R_0}	Apparent or geometrical resultant velocity at blade section	L/T

$$V_{R_0}=V\sqrt{1+\left(\frac{\pi X}{J}\right)^2}$$

often denoted by W_o.

V_{S_0}	Velocity of sound	L/T

$$V_{S_0}=49.1\sqrt{T}$$

V_t	Resultant tip velocity	L/T

$$V_t=V\sqrt{1+\left(\frac{\pi}{J}\right)^2},\ \text{Since } X^2=1$$

V_m	Volume	L³
w_N	Velocity, normal component	L/T
w	Specific weight*	M/L²T²
w_a	Apparent axial velocity of helicoidal vortex sheets, at station (x)*	L/T

$$w_a=\frac{w_1}{\cos\phi}$$

w_N	Induced velocity, normal to the helicoidal surface generated by the propeller blades	L/T

$$w_N=\frac{B\Gamma}{4\pi G\,\mathrm{Sin}\phi}$$

W	Weight	ML/T²

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Symbol	*Concept and Definition*	*Dimensions*
x	Fraction of propeller tip radius*	DLS
	$x=\frac{r}{R}$	
x,y,z	Coordinate system; earthbound axes	DLS
X,Y,Z	Coordinate system; propeller axes*	DLS
α	Angle of attack	L
α_i	Blade section induced angle of attack*	L
	$\alpha_i=\text{arctan}\left(\frac{w_1}{w}\right)$	
α_o	Basic or two-dimensional section angle of attack*	L
α_A	Propeller axis angle with free-stream velocity*	L
α_a	Angular acceleration	1/T²
β_S	Angle of sideslip	L
β	Propeller blade angle	L
γ_R	Ratio of specific heats	DLS
γ	Section drag-lift ratio	DLS
	$\gamma=\frac{c_d}{c_l}$	
γ_S	Strain, shear	M/L²
Γ	Circulation; strength of a single vortex	L/T
δ	Density of solids	M/L²T²
ϵ_N	Strain, normal	L
ϵ	Angle of downwash	L
π	Efficiency, usually net propeller efficiency	DLS
	$\pi=J_A\left(\frac{C_T}{C_P}\right)$	
π_i	Propeller induced or ideal efficiency; efficiency when no drag loss is assumed.*	DLS
$\Delta\pi_i$	Theoretical efficiency loss due to unavailable energy in propeller wake*	DLS
$\Delta\pi_p$	Efficiency loss due to blade section profile drag.*	DLS
$\Delta\pi_{in}$	Efficiency loss due to propeller installation (blade shank drag, hub and spinner drag, etc.)*	DLS
$\Delta\pi_s$	Efficiency loss due to increase in airplane drag because of propeller slipstream.*	DLS
λ	Taper ratio	DLS
	Sweep back, angle	L
μ	Poisson's ratio	DLS
μ_{M_a}	Mach angle	L
μ_c	Absolute viscosity; coefficient of viscosity	M/LT
ν	Kinematic viscosity	L²/T
ρ	Density, usually of air	M/L³
σ	Density ratio	DLS
	$\sigma=\frac{\rho}{r_0}$	

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Symbol	*Concept and Definition*	*Dimensions*
σ_N	Normal stress	M/LT^2
σ	Propeller solidity	DLS

$$\sigma=\frac{bB}{2\pi r}$$

Symbol	*Concept and Definition*	*Dimensions*
τ	Angle of blade tilt with respect to plane of station*	L
ϕ	Angle of actual resultant velocity W (or V_R) with plane of rotation*	L
ϕ_o	Angle of geometric resultant velocity (W_o or V_R) with plane of rotation*	L

$$\theta=\text{Arctan}\left(\frac{V}{2\pi rn}\right)$$

Symbol	*Concept and Definition*	*Dimensions*
ϕ	Potential function	DLS
ψ_s	Stream function	DLS
ψ	Angle of inflow to propeller*	L
ω	Angular velocity, circular frequency	1/T
Ω	Angular velocity, alternate	1/T

Subscript Symbols

Symbol	*Concept*
A	Advance
a	Absolute
	Added, additional
	Air, relative to air
	Allowable
	Ambient
	Angular
	Available
	Axial
av	Average
b	Blade
B	Bending
	Basic
c	Chord
	Coefficient
	Compressibility, compressible, compression, compressor
	Critical
	Camber (surface)*
$corr$	Corrected
$calc$	Calculated
cg	Center of gravity
cr	Critical
d	Section drag
D	Total drag

Symbol	*Concept*
e	Equivalent
	Effective
	Engine
f	Friction
	Flatwise*
	Frequency*
F	Force
g	General
G	Gyroscopic*
	Geometric*
h	Hub
	Hinge
i	Design Camber*
	Ideal
	Induced
	Interference
j	Jet
l	Lower surface
	Section lift*
	Lateral
L	Total lift
	Load
m	Mean
m	Section moment*
	Mass
max	Maximum

Symbol	*Concept*
maj	Major*
min	Minimum
	Minor
M	Moment, in general*
n	Net
	Section normal force*
	Nozzle
	Any preferred element at radius r*
N	Normal
	Total normal force
o	Profile (drag)
	Standard or reference condition
	Standard sea level conditions
	Outer
	Root*
p	Pressure
	Profile
	Plate*
	Polar*
	Propeller
P	Power
Q	Torque*
	Twisting moment

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Symbol	*Concept*	*Symbol*	*Concept*	*Symbol*	*Concept*
r	Radial		Static*	x	At station x*
	Ram		Section	x, y, z	With reference to coordinate axes*
	Preferred radius*	t	Tip		
R	Resultant		Turbine	0, 1, 2	Station subscripts*
	Restoring*		Thrust (surface)*		Iteration subscripts in strip analysis
	Retention		Tensile tension		
	Ratio		Total	∞	Undisturbed; free-stream
s	Slipstream, span	T	Thrust		
	Speed-power	u	Upper surface	so	Sound
	Shear		Ultimate		

Types or Classes of Propellers

General

There are various types or classes of propellers, the simplest of which are fixed pitch and ground adjustable propellers. The complexity of propeller systems increases in passing from these simpler forms to controllable and complex automatic types. Various outstanding characteristic features of important propeller types are discussed in the following paragraphs, but no attempt is made to encompass all possible types or classifications of propellers. For instance, to mention two fields in which division could be extended, discussion of material or structural classifications are not undertaken.

Fixed Pitch Propeller

As the name implies, a fixed pitch propeller has the blade pitch, or blade angle, built into the propeller. The blade angle cannot be changed after the propeller has been built. Generally, this type of propeller is of wood or aluminum, one piece construction. Necessarily, a fixed pitch propeller has been designed for one specific operating condition and, because of its construction, no change in pitch angle can be made to meet other operating conditions. Obviously, low weight and cost make this propeller attractive for use on airplanes of low power, speed, range and altitude. A fixed pitch propeller is illustrated in figure 1.1.

Ground Adjustable Propeller

The ground adjustable propeller must operate at fixed pitch in flight. The pitch or blade angle can be altered only when the propeller is at rest, usually, by loosening the clamping mechanism which holds the blade in place. After the clamping mechanism has been tightened, pitch of the blades will be fixed; hence, blades cannot be adjusted in flight to meet variable flight condition requirements. This propeller has a desirable characteristic in that blade pitch can be preset for any one of a number of different operating conditions. Furthermore, if one blade has been damaged, it can be replaced without discarding the entire propeller. Like the fixed pitch propeller, the ground adjustable propeller has been used chiefly on airplanes of low power, speed, range and altitude. A typical example of a ground adjustable propeller is shown in figure 1.2.

Controllable Pitch Propeller

The controllable propeller has been designed to permit change of blade pitch, while the propeller is rotating, making it possible for the propeller to assume a pitch which will give better performance for particular flight conditions.

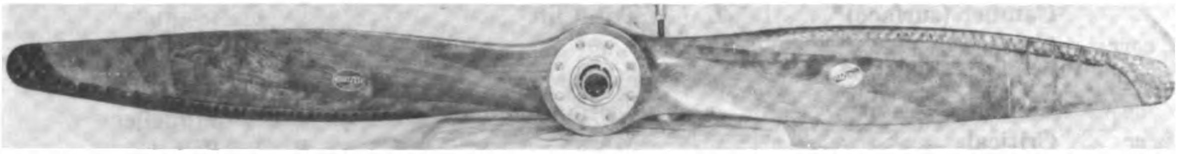

Figure 1.1.—Fixed pitch propeller.

Figure 1.2.—Ground adjustable pitch propeller.

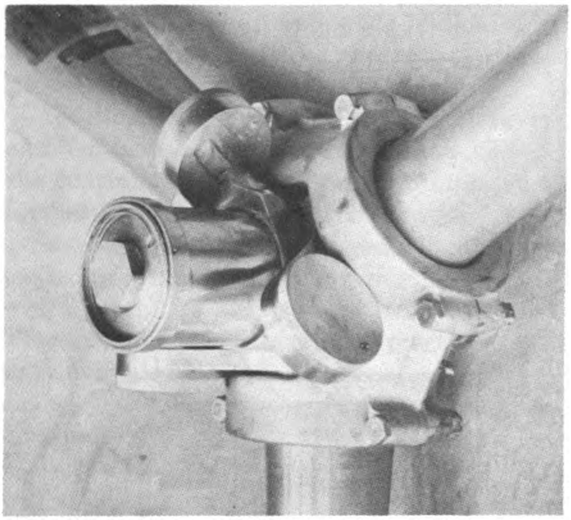

Figure 1.3.—Two-position controllable pitch propeller.

The number of pitch positions may be limited, as in the two-position controllable propeller; or the pitch may be adjusted to any value between minimum and maximum pitch setting of the given propeller. Pitch control may be effected either manually or automatically. The mechanical pitch control mechanism, the simplest and most direct means of changing propeller blade angle, was the first blade angle control system used. This type of control was used only in aircraft having small engines, since the operator must supply nearly all of the force necessary to overcome friction and twisting moment involved in a change of propeller pitch.

More recently, engine power has been utilized to change blade angles through clutch arrangements. This class of pitch changing equipment may be considered as mechanically actuated pitch control mechanism.

Of limited pitch position propellers, the two-position controllable propeller has been used most extensively. In a two-position controllable propeller, one position will be selected to provide most desirable blade pitch for takeoff, while the other position will be selected for optimum cruising operation. For use with airplanes of low power, low altitude and low speed range, two-position propellers serve quite well and are less expensive than fully automatic variable pitch propellers. A typical example of a two-position controllable pitch propeller is shown in figure 1.3.

Controllable or automatic propellers, which can be adjusted to any pitch setting between maximum and minimum values, are adjusted automatically by means of governors, usually. In some propeller systems, the control can be switched from automatic to manual. When the automatic control can be adjusted to maintain rotational speed at a preset value, the propeller system is spoken of as a constant speed system. Automatic propellers are necessary for aircraft of high power and wide ranges of speed and altitude, a classification which encompasses all multi-engine aircraft.

Automatic Propellers

(1) *General characteristics.* In automatic propeller systems, the controls will function to adjust pitch, without attention of the operator, to maintain preset specific engine speed. For example, if engine speed should increase, the controls automatically increase the blade angle until desired speed has been reestablished. A good automatic control system will respond to such small departures of speed that, for all practical purposes, speed will be maintained at a given speed setting. For this reason, automatic propellers which govern the speed requirements are often termed constant speed propellers. A propeller of this type is exemplified in figure 1.4,

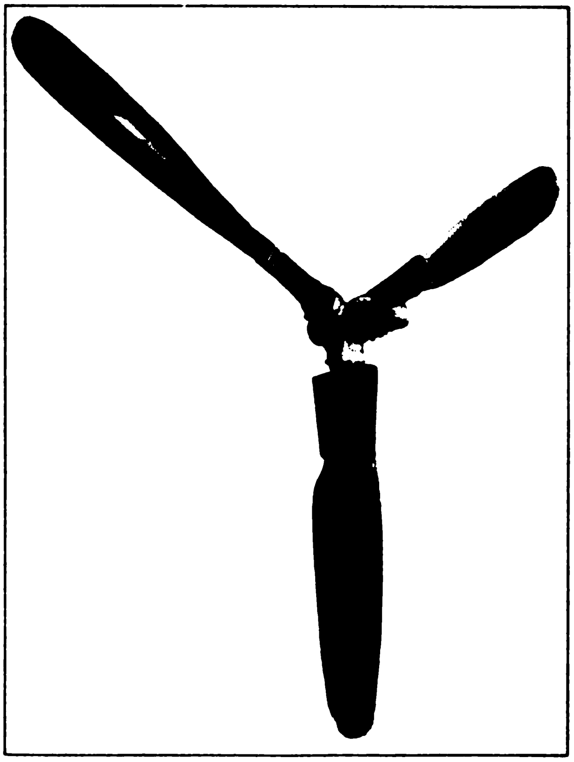

Figure 1.4.—Electric constant speed propeller.

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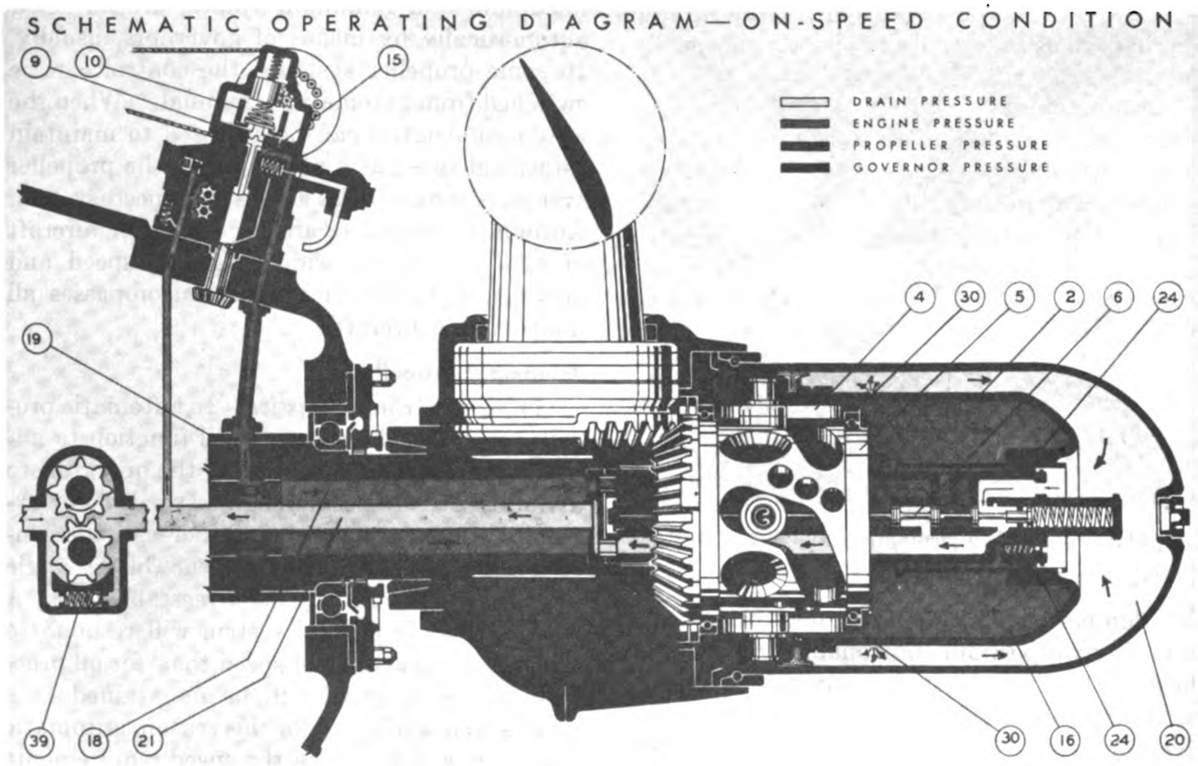

No.	NAME	No.	NAME	No.	NAME
2	Double Acting Piston	10	Governor Fly-Weights	20	Outboard Piston End
4	Fixed Cam	15	Propeller-Governor Metering Port	21	Propeller Shaft Engine Oil Passage
5	Rotating Cam	16	Inboard Piston End	24	Distributor Valve Oil Seal Rings
6	Distributor Valve	18	Propeller Shaft Governor Oil Passage	30	Piston Bleed Hole
9	Governor Pilot Valve	19	Propeller Shaft Oil Transfer Rings	39	Engine Oil Pump

Figure 1.5.—Hydraulic controllable pitch propeller.

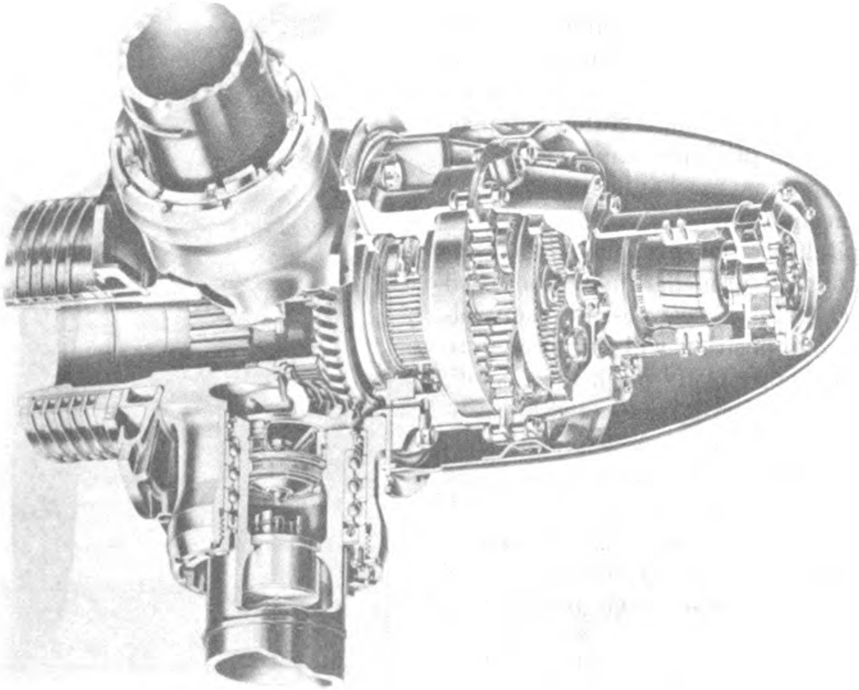

Figure 1.6.—Electric controllable pitch propeller.

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which shows the hub and some of the internal mechanism of an electrically operated automatic propeller.

Additional refinements, such as pitch reversal and feathering features, have been added to the controllable pitch propeller to improve still further its operational characteristics.

Some forms of automatic propellers have the control mechanism built into the propeller, which prohibits adjustment while in flight. The controlling and operating mechanisms are so constructed as to function in response to a change in flight conditions without attention or manipulation on the part of the operator. Because these propellers do not lend themselves to willful adjustment by the operator while rotating, they are classified as variable pitch propellers. In modern airplanes operating under wide ranges of flight conditions, it is very important that the pilot be able to set, at will, the conditions to which an automatic system will govern. Therefore, variable pitch propellers have had but very limited use. Performance-wise, variable pitch propellers occupy a position between fixed pitch, or ground adjustable, and controllable propellers.

(2) *Hydraulic controllable propeller.* The hydraulic controllable propeller was developed early in the art and has been used successfully for years. The hydraulic controllable propeller depends on hydraulic force to actuate the pitch changing mechanism. This hydraulic force may be developed by utilizing engine oil under pressure, with or without booster pumps, or may be developed by utilizing energy stored in oil under pressure within the propeller hub or other parts of the propeller system. Use of engine oil pressure alone usually will be inadequate to change pitch of propellers having large blade twisting moments so that booster pumps must be used. Since this type of propeller uses heavy engine oil, precautions must be taken to prevent the oil from congealing and causing sluggish operation during low temperature conditions. Furthermore, when benefits of higher oil pressure are utilized, it becomes more difficult to contain the oil and excessive leakage occurs. Figure 1.5 schematically shows the principle of operation.

(3) *Electric controllable propeller.* The electric controllable propeller is one on which the mechanism for changing blade pitch is actuated electrically. Usually, the turning force is derived from an electrical motor or motors operating through planetary gear systems. The high ratio reduction gearing is necessary to convert low torque of the motor at high speed into high torque required to rotate the propeller blades at low speed. Figure 1.6 shows the hub and some of the electrical connections of an electrical controllable propeller.

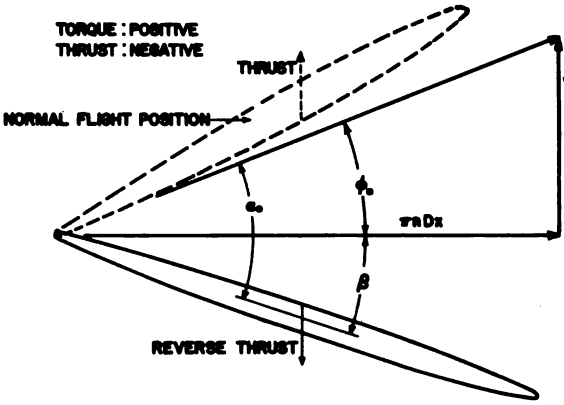

Figure 1.7.—Typical blade section—reverse pitch propeller.

Reverse Pitch Propellers

A reverse pitch propeller is a controllable propeller in which the blade angle can be changed during operation to a negative value. The primary purpose of the reversible pitch feature is to produce a high negative thrust at low speed by use of engine power. While reverse pitch may be used in flight for steep descents, it is used principally as an aerodynamic brake to reduce ground roll after landing of heavy airplanes. The vector diagram shown in figure 1.7 indicates the blade position of a reverse pitch propeller and the reverse thrust obtained from a negative blade angle.

Figure 1.8 depicts graphically the advantages to be obtained by use of reverse pitch during landing operations. It is significant that reverse pitch is now considered a necessity for airplanes having a gross weight in excess of 70,000 pounds.

Feathering Propellers

A feathering propeller is a controllable propeller having a mechanism to change the pitch within a suitable range during operation so that forward airplane motion will produce a minimum windmilling effect on a "power off" propeller. Feathering propellers must be used on multi-engine aircraft, to reduce propeller drag to a minimum under emergency engine

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Figure 1.8.

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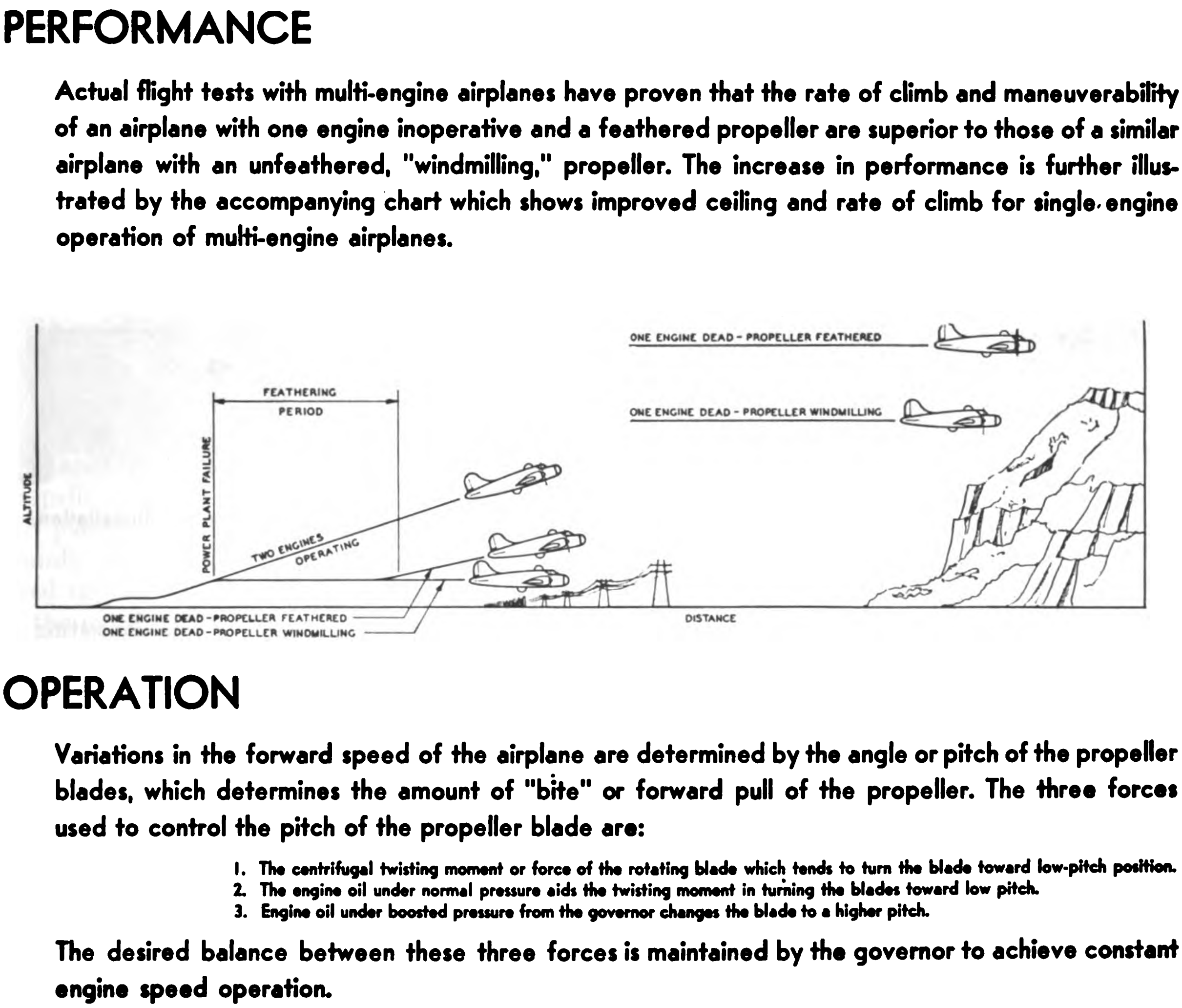

PERFORMANCE

Actual flight tests with multi-engine airplanes have proven that the rate of climb and maneuverability of an airplane with one engine inoperative and a feathered propeller are superior to those of a similar airplane with an unfeathered, "windmilling," propeller. The increase in performance is further illustrated by the accompanying chart which shows improved ceiling and rate of climb for single engine operation of multi-engine airplanes.

OPERATION

Variations in the forward speed of the airplane are determined by the angle or pitch of the propeller blades, which determines the amount of "bite" or forward pull of the propeller. The three forces used to control the pitch of the propeller blade are:

1. The centrifugal twisting moment or force of the rotating blade which tends to turn the blade toward low-pitch position.
2. The engine oil under normal pressure aids the twisting moment in turning the blades toward low pitch.
3. Engine oil under boosted pressure from the governor changes the blade to a higher pitch.

The desired balance between these three forces is maintained by the governor to achieve constant engine speed operation.

Figure 1.9.—Performance of feathering propellers.

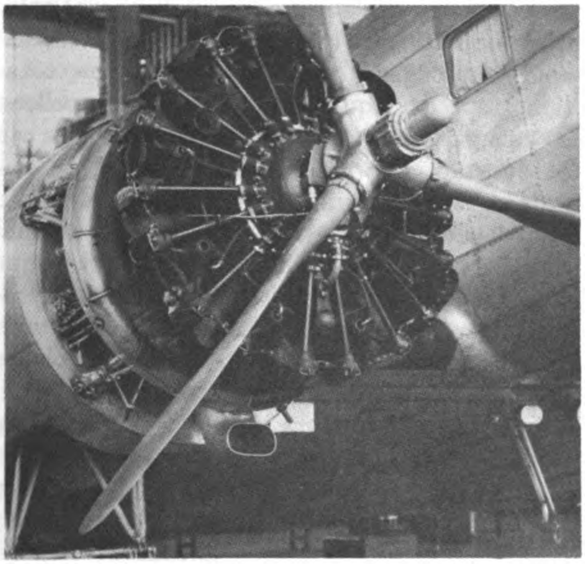

Figure 1.10.—Full feathering reverse pitch propeller.

failure conditions. The advantages of the use of feathering propellers are portrayed graphically in figure 1.9.

Some propellers have both feathering and pitch reversing features; a propeller of this type is shown in figure 1.10.

Classification of Propellers by Type of Thrust

(1) *Tractor propellers.* Tractor propellers are those mounted on the upstream end of a propeller drive shaft in front of the supporting structure. Most of the airplanes now being used are equipped with this type of propeller. A major advantage accrues to a tractor propeller since lower stresses are induced in the propeller as it rotates in relatively undisturbed air. However, the air disturbed by a tractor propeller causes increased wing drag. Tractor propellers encompass all types of fixed or variable pitch propellers.

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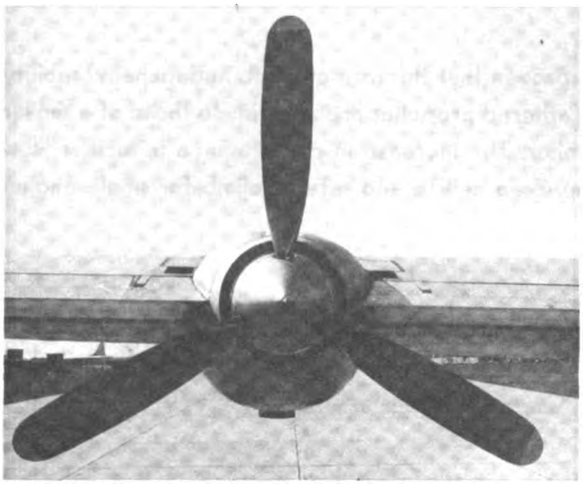

Figure 1.11.—Pusher type propeller.

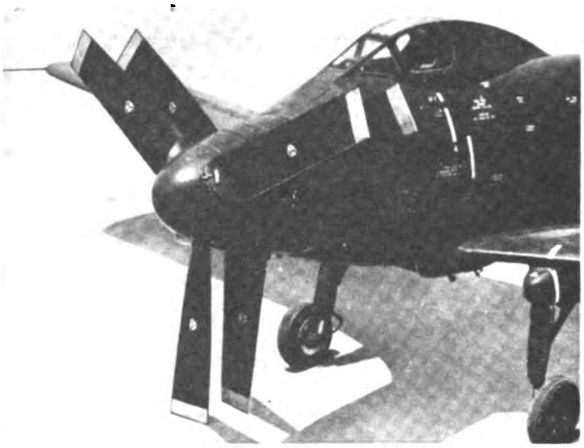

Figure 1.12.—Dual rotation propeller installation.

(2) *Pusher propellers.* Pusher propellers are those mounted on the downstream end of a propeller drive shaft, behind the supporting structure. Pusher propellers may be constructed as fixed or variable pitch propellers, with any or all of the control features previously discussed. Seaplanes and amphibious aircraft as a class, have employed a greater percentage of pusher propellers than other kinds of aircraft. On land planes, where propeller-to-ground clearance usually is less than propeller-to-water clearance of water craft, pusher propellers are subject to more damage than tractor propellers. Rocks, gravel and small objects, dislodged by the wheels, quite often may be thrown or drawn into the propeller in this type of installation. Similarly, planes equipped with pusher type propellers are apt to encounter propeller damage from water spray thrown up by the hull during landing and takeoff from water. Consequently, the pusher type propeller quite often has been mounted above and behind the wings to prevent such damage. Figure 1.11 shows a pusher type installation.

Single Rotation Propellers

A single rotation propeller is one in which all blades are mounted in a single component so that they rotate in the same direction. Single rotation propellers consist chiefly of 2, 3, and 4 blades (some have been tried with 1, 5, and 6 blades) and comprise a major portion of the propellers presently in use.

Dual Rotation Propellers

A dual rotation propeller is one consisting of two or more blade-carrying components, part of which rotate in one direction and part in the opposite direction. The dual rotation propeller has a front and a rear section, closely mounted coaxially, with the sections rotating in opposite directions. Usually, though not necessarily, the front and rear components contain an equal number of blades. This type of propeller was developed to meet a need to absorb more power than certain limiting propeller diameters and tip speeds would permit with a given number and width of blades. Increasing the number or width of blades results in higher rotational slip losses in a single rotation propeller, especially when operating at the high pitch angles associated with high forward speeds and low rotational speeds required in subsonic propellers. By using dual rotation, rotational slip losses can be substantially reduced and the thrust improved with corresponding improvement in propeller efficiency. In addition, use of dual rotation propellers eliminates both power torque reaction and gyroscopic couples between propeller and airplane. Hence, more blades with dual rotation instead of more and wider blades in single rotation propellers offer strong appeal. Principal disadvantages in use of dual rotation propellers include: greater complications in engine-propeller power gearing and shafting, complexity of propeller controls and pitch change mechanism, and increased weight. Figure 1.12 shows a dual rotation propeller installation.

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CHAPTER II. AERODYNAMIC DESIGN AND PROPELLER PERFORMANCE

Introduction to Aerodynamics of Propellers

General Considerations

All aircraft propulsion systems produce thrust through reaction of a fluid jet. Thrust produced by a propeller is no exception. A propeller imparts an acceleration to the mass of air passing through it. The acceleration is mainly in a direction opposite to that of desired thrust. Thrust produced is proportional to the increase in momentum of the air passing through the propeller disc.

No attempt will be made in this discussion to delve deeply into the ramifications of propeller theory. In the development of aerodynamic design and performance of propellers, occasional reference will be made to that part of propeller theory which contributes most to propeller development and design. Rigorous mathematical treatment of propeller theory (single rotation propellers operating in an incompressible nonviscous fluid) can be found in the classical literature dealing with propeller aerodynamics. Presentation of that phase of propeller analysis is outside the scope of this handbook.

Propeller theory serves three useful purposes, namely:

(1) Enlightenment of the propeller analyst by introducing a physical concept of how it works.
(2) Identification and direction of attention to limitations of propeller performance under various operating conditions.
(3) Establishment of useful quantitative data to supplement recorded test data.

It is evident that rational development of design procedures which will include such manufacturing and service problems as exact angle settings, airfoil dimension tolerances, surface roughness and material composition is impossible. Appropriate compensation for such variables can be made only upon the basis of experience and adequate performance testing.

In addition to propeller blade design, difficult problems arise involving blade aerodynamic characteristics, propeller spinner design, blade cuff design and deicing boot design. The requirements of these auxiliaries are well covered in various specifications and need not be discussed here. However, some of the design considerations and service experiences will be presented as a part of the aerodynamic design problem.

Propeller Efficiency

Efficiency can be defined as the final thrust horsepower produced divided by the brake horsepower input to the propeller shaft.

$$\eta=\frac{T_n \times V}{SBHP}$$

The increased velocity imparted to air passing through the propeller can be looked upon as slip and, from a momentum standpoint, highest efficiency will be obtained when slip is a minimum. Since slip can be kept low in propeller practice, propeller efficiency usually is very high. To produce a given amount of thrust, a relatively large propeller diameter is utilized, generally; hence, mass flow through the propeller is large. Therefore, for a given amount of thrust, acceleration imparted to this mass of air is low. As a result, slip is low, giving high propeller efficiency.

There are several references upon which to base efficiency, but the only one of real significance in determining performance of an aircraft is that which reveals the final net propulsive efficiency experienced; i. e., efficiency indicating net thrust experienced by the airplane as a whole as compared to applied brake power input to the propeller. This point is raised, at this time, because thrust upon the propeller shaft is not equal, generally, to thrust upon the aircraft as a whole. Thrust upon the propeller shaft is higher and in fact can be high enough to result in shaft thrust efficiencies in excess of 100 per-

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cent. The major sources of difference between shaft thrust and net airplane thrust are as follows:

(1) If the propeller operates in front of a blunt cowling, there will be a pressure built up between propeller, spinner and engine nose. This pressure differential exerts a thrust on the propeller shaft but at the same time exerts an equal and opposite reaction on the engine nose. It is evident that the aircraft experiences no additional thrust equivalent to this thrust upon the propeller shaft. Efficiency measurements based on shaft thrust measurements must be corrected for this inactive thrust.

(2) Momentum increases given to the slipstream reacts upon the propeller shaft as a thrust; but increased slipstream velocity creates a drag on the wing in excess of that which would exist if the slipstream were non-existent. Hence, the net aircraft thrust is less, by this drag increment, than that experienced by the shaft.

(3) Also, impingement of the slipstream upon tail surfaces results in a loss of aircraft thrust, which is not effective upon propeller shaft.

Propeller Theory

The Momentum Theory

The simplest propeller theory is the Slipstream Momentum Theory, originally developed by Rankine in 1865. Rankine, and other early investigators, were interested in water propellers, primarily; but the broad assumptions necessary to development of this theory make the momentum theory applicable to propellers operating in any fluid.

Briefly, the momentum theory and the mathematical expressions associated with it are based upon the assumption that a propeller is an actuator disc having an infinite number of blades. Further, in application of the theory to airplane propellers, it is assumed that air is a perfect, incompressible, non-viscid fluid which flows through the actuator disc in an axial direction. It is assumed that the propeller creates a rigid helicoidal wake system of infinite length.

Flow conditions in accord with this theory are graphically represented in figure 2.1.

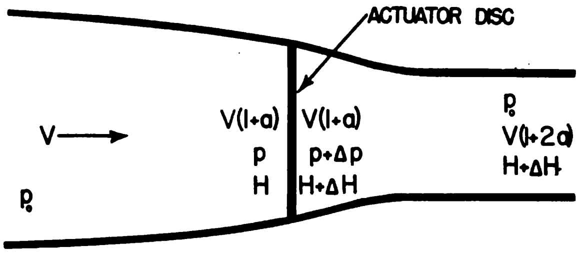

Figure 2.1.—Rankine's momentum theory—propellers.

Based upon the assumption given, it is possible to express propeller efficiency in terms of the increment of increase in air velocity passing through the disc. In algebraic form, this statement is:

$$\eta=\frac{1}{1-\alpha}$$

where

η = propeller efficiency
α = incremental factor of air velocity increase ahead of the propeller.

Using fundamental relationships for conservation of mass, momentum and energy, an expression for ceofficient of power can be written as:

$$C_P=\frac{\eta J_A^3(1-\eta)}{2\eta^3}$$

in which

C_P = power coefficient
η = maximum theoretical propeller efficiency
J_A = advance ratio

This relationship indicates the maximum propeller efficiency obtainable for any given set of power and speed conditions.

Froude, a contemporary of Rankine, made notable contributions to the development of the momentum theory, in 1865. A. Betz, in 1920, extended the theory to encompass rotational effects of the propeller. In 1950, A. Vogeley of the NACA modified the theory to include fluid compressibility effects.

The simple momentum theory is of little use in design of a propeller, since it does not include the effect of friction losses, nor does the theory consider geometrical aspects of a real propeller. Further, the theory evolved disregards the practical aspects of propeller design and selection, involving diameter, rotational speed, and number of blades. Therefore, propeller aerodynamics is usually not treated analytically from a momentum standpoint.

The Vortex Theory

Treatment of a propeller as a finite body, whose characteristics are defined or are being sought, is analogous to a wing problem, since

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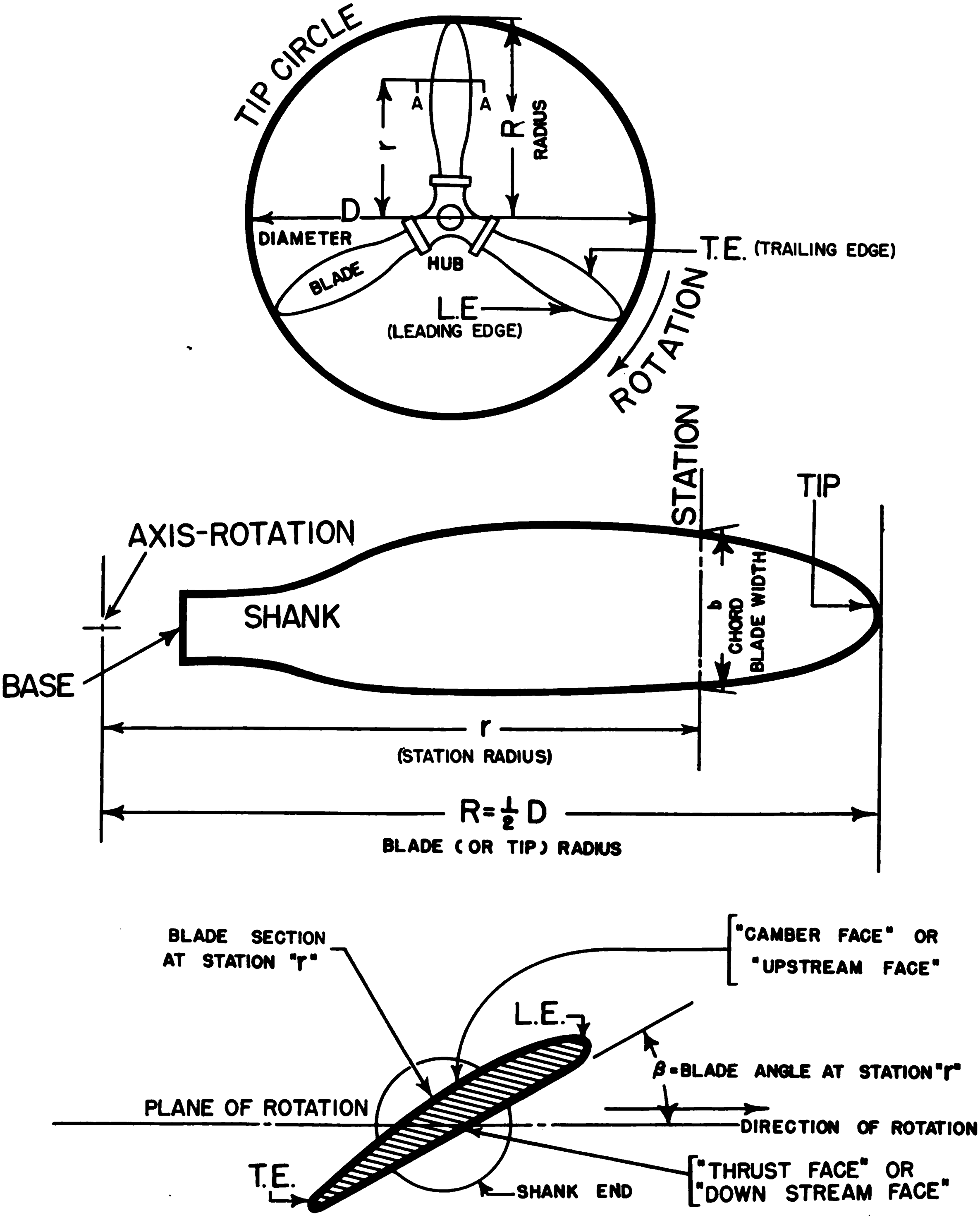

SECTION A-A

Figure 2.2.—Graphical representation of a propeller with nomenclature.

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a propeller and wing are made up of similar airfoils and have many common features. The general theories, as originally developed by Kutta, Joukowski, Lanchester and Prandtl, are applicable to propeller design. The propeller is, of course, a special case in that the relative path it follows through the atmosphere is helical rather than pure translation. Theoretical treatment of a propeller in this fashion is known as the vortex or strip theory, which has been developed by Froude, Lanchester, Lock, Goldstein, Glauert, Theodorsen, Prandtl, and Betz. The mathematics involved in development of the theory is quite complex, but in application, the procedures have been simplified. The procedures used in analyzing propellers by this method are treated in a later section of this handbook.

Physical Concept of a Propeller

As a foundation on which to base other considerations, which are to be discussed, it is well, at this point, to present a simple physical concept of a propeller blade and illustrate the method by means of which a propeller produces thrust.

The diagrams shown in figures 2.2 and 2.3 have been designed to relate abstract ideas presented in definitions with physical representation of a propeller.

If a propeller blade were sliced along a chord A—A and viewed from a position looking along the blade axis, an airfoil section such as that shown in figure 2.2 and figure 2.3 would be seen. This airfoil would form some angle, β, with the plane of rotation. In flight, airfoil section is rotating with a velocity equal to $2\pi rn$ and is advancing along a flight path at right angles to the plane of rotation with a velocity equal to V.

The angle ϕ formed by these two vectors is shown as the angle of advance. The parameter $J_A = V/nD$ is one of the primary factors in propeller performance. The vector V_R is the resultant of velocity vectors V and $2\pi rn$. The direction and sense of this vector are the same as that of the helical path along which the section moves. The blade section actually will be oriented with respect to the air at some angle with the velocity vector V_R, which has been designated as *angle of attack* (α). As a result of movement through the air with a velocity (V_R) at an angle of attack (α), the airfoil experiences a resultant force (R) which may be resolved into components referred to either one of two sets of axes. Characteristics of the airfoil being of principal interest; the resultant force is resolved, usually into components perpendicular and parallel to the initial (undisturbed) direction of air flow (V_R). These components of the total force are designated lift (L) and drag (D) forces, respectively. If the chief concern is propeller performance, the resultant force (R) is resolved, usually, into components parallel to the *axis* of rotation and parallel to the *plane* of rotation of the propeller. These components are called thrust force (T) and torque force (Q_f), respectively. The angle between the lift vector (L) and the resultant force vector (R) is designated γ.

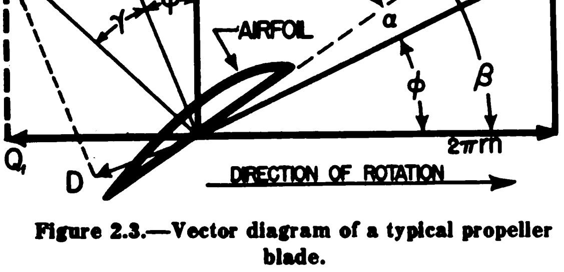

Figure 2.3.—Vector diagram of a typical propeller blade.

Propeller Section Efficiency

Overall efficiency of a propeller is, of course, the ratio of useful work produced, or the product of thrust and forward velocity to work expended or brake horsepower input to the propeller. Expressed algebraically, where C is some constant:

$$\eta = C_B T_{HP} V$$

A particular airfoil, such as the one previously discussed, produces an elemental thrust (dT) at the expense of an elemental torque (dQ). Efficiency of the section, therefore, may be defined as:

$$\eta = \frac{dT \cdot V}{dQ \cdot 2\pi n} = \frac{dR \cdot \text{Cos}\,(\phi+\gamma) \cdot V}{dR \cdot \text{Sin}\,(\phi+\gamma) \cdot 2\pi rn}$$

As shown in the diagram of figure 2.2, propeller efficiency may be reduced to the form:

$$\eta = \frac{\text{Tan}\,\phi}{\text{Tan}\,(\phi+\gamma)}$$

It can be seen from the preceding mathematical

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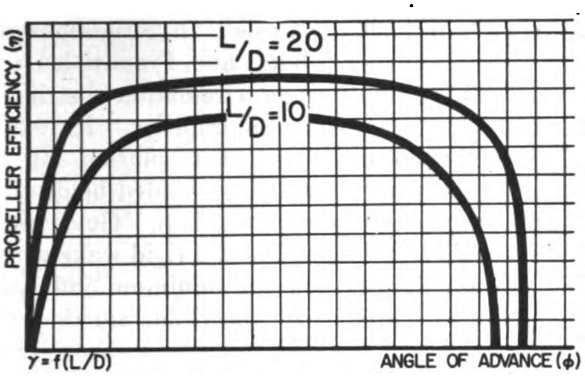

Figure 2.4.—Propeller efficiency vs. angle of advance.

relationships that the two major elements which define efficiency are: lift/drag ratio of the airfoil, which determines γ, and the angle of advance ϕ. Figure 2.4 shows the variation of propeller efficiency with L/D ratio and angle of advance.

Induced Effects

An ordinary airfoil of an airplane wing produces lift by accelerating the air which passes over it in a downward direction. The force required to accomplish air acceleration reappears as a lift reaction on the wing. With a propeller airfoil in motion, air is accelerated to the rear; and, as a result of propeller rotation, in a circumferential direction, also. Generation of lift by a wing at any positive geometric angle of attack induces an upwash ahead of the wing and a downwash behind it. Therefore, the real aerodynamic angle of attack is not the same as the geometric angle of attack for a wing; and therefore, lift and drag are altered, accordingly. The changes from geometric angle, lift and drag are called induced effects. Induced drag of a wing, for example, is a very real loss associated with production of lift, and is quite apart from and in addition to friction and profile drag of the wing. Similarly, in a propeller performance, there are induced effects which are of first order importance in design of propeller blades. The simple vector diagram of figure 2.3 must be changed to that shown in figure 2.5 to adjust for induced effects.

Consider an airfoil of a propeller advancing in flight at a geometric angle of advance determined by the ratio of flight velocity (V) to rotational velocity ($2\pi nr$). The pressure or potential field around the propeller airfoil caused by airfoil movement creates an upwash ahead of the section in much the same manner as the phenomena occur during airflow over a conventional wing. This upwash is, in reality, an added component of velocity (W_t) as indicated in figure 2.5 which can be broken down into components perpendicular and parallel to the plane of rotation. The component perpendicular to the plane of rotation, in effect, increases relative axial velocity by an increment equal to the vector, (V_t). The component parallel to the plane of rotation reduces rotational speed from a value of $2\pi rn$ by a decrement equal to the vector (V_r). The induced angle changes are more important than the velocity changes. The angle of advance (ϕ) is increased to a larger angle (ϕ_1) and the angle of attack (α) is reduced. Reduction of the angle of attack results in a change in lift and drag coefficients of an operating airfoil. Determination of induced effects can be made through use of modern airfoil (vortex) theory involving concepts of circulation, and systems of bound and trailing vortices.

The Blade Element Theory

The next significant step in propeller development, after introduction of the momentum theory, was promulgation of the simple blade element theory by Froude. In reality, this theory is the same as that of the helical mechanical screw. The blade element efficiency is a function of lift and drag forces acting on each propeller blade section. The blade element efficiency may be expressed as:

$$\eta=\frac{\text{Tan }\phi}{\text{Tan }(\phi+\gamma)}$$

ϕ=Angle of advance

$\gamma=\text{Tan}^{-1}(D/L)$

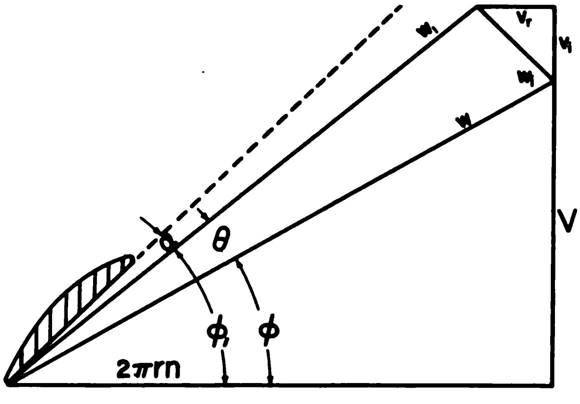

Figure 2.5.—Modified vector diagram of typical propeller blade.

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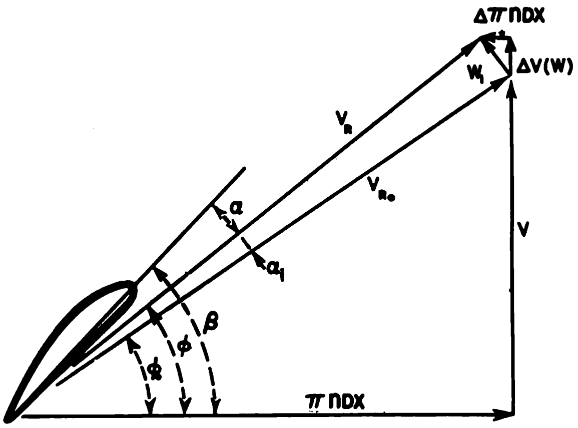

Figure 2.6.—Vector diagram for a propeller section showing induced effects.

The overall propeller efficiency can be determined by integration of elemental efficiencies along a blade radius.

The blade element theory indicates that best efficiency will obtain with maximum lift-drag ratios, optimum values of J_A and a section angle of advance at or near 45°.

Limitations of the Momentum and Blade Element Theories

The momentum theory indicates high propeller efficiency will obtain with a large propeller diameter and high value of advance ratio (J_A). The requirement for a large diameter is sometimes in conflict with the requirement for section maximum lift-drag ratio, unless the number of blades is adjusted to permit section C_L near that for L/D maximum. Also, while the momentum theory indicates that efficiency improves continuously with J_A, the blade element theory indicates that there is an optimum value of J_A. The momentum theory does not account for rotational or tip losses. The blade element theory ignores all induced losses. Neither theory considers the effect of numbers of blades. The blade element theory cannot be applied without knowledge of section lift and drag, usually obtained from experimental wing data rather than propeller section data. A combination of the blade element and simple momentum theories would be more accurate than either one alone and would be a step towards the modern strip analysis.

Propeller Analysis

(1) *Evolution of analysis method.* It was natural that the concept of circulation, and later the concept of vortex formation, would be applied to propeller analysis. Investigations of Joukowski, Glauert, Betz, and Prandtl led to approximate solutions of circulation distribution and vortex system of a propeller. In 1929, Goldstein published his exact solution for a propeller having a few lightly loaded blades in an incompressible nonviscous fluid. Goldstein, in his exact solution, assumed a rigid wake with circulation distribution for minimum induced losses. Since advent of the Goldstein theory, work has been directed towards a theoretical solution for dual-rotation and heavily loaded propellers. However, the purely theoretical approach has not yielded a satisfactory solution to these problems, as yet. But, Theodorsen, using an electrical analogy, has determined ideal performance and circulation distribution for heavily loaded and dual rotation propellers. Application of Theodorsen's work has not been made, as yet.

(2) *Effect of assumptions.* The assumptions necessary to arrive at a workable and rigorous propeller theory are many, as indicated previously. Two important assumptions pertaining to the nature of the fluid, i. e., nonviscous and

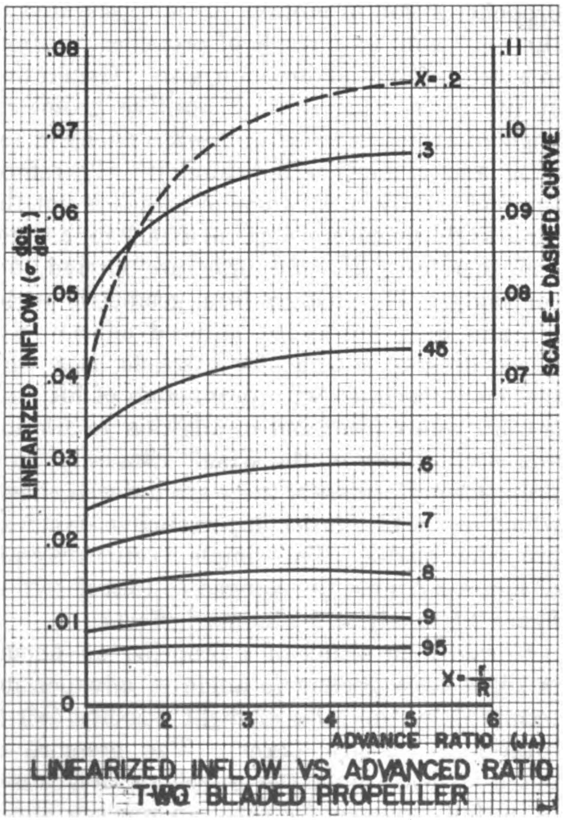

Figure 2.7.

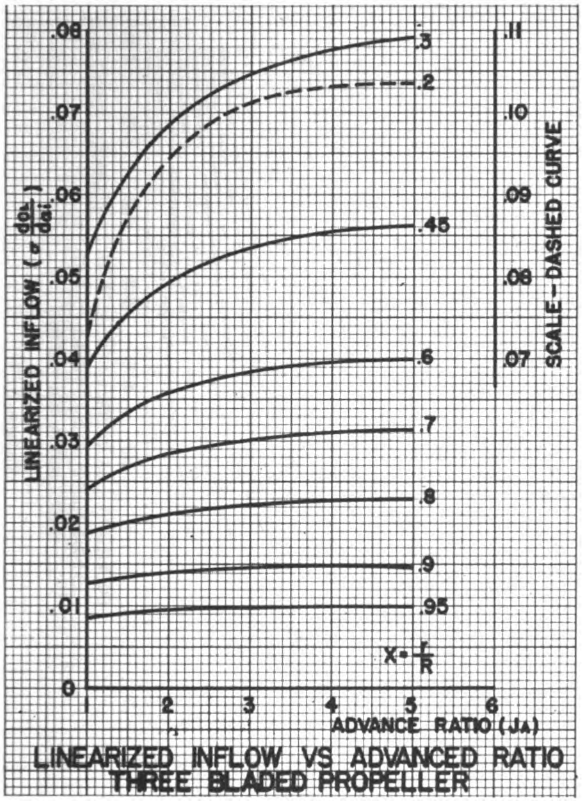

Figure 2.8.

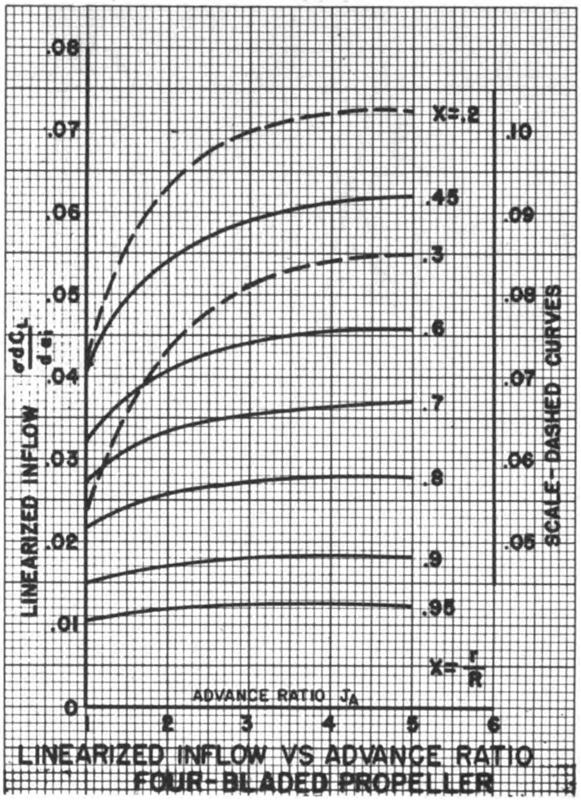

Figure 2.9.

incompressible, are obviously incorrect for a real case. It will be seen, however, that actual methods evolved from the basic theory reduce greatly the effect of assuming a nonviscous fluid. Correction for losses due to fluid viscosity and compressibility can be made separately, using empirical data wherever necessary. This procedure is followed in application of the strip analysis and summation of losses methods.

The validity of assuming a circulation distribution for minimum induced loss is dependent on the degree of blade profile drag loss. When the blade profile drag loss is small, a propeller of proper pitch arrangement will have a distribution of air load along the blade closely approximating that of the ideal case. When profile losses are large, however, air load distribution may be far from the idealized case. High profile drag at a given section results in a reduction in momentum and hence a decrease in the induced angle with lower lift coefficients at that section. The effects of high profile losses are favorable to actual performance of a propeller in that a propeller tends to load itself to a radial distribution of air load which approaches that for minimum total losses. Probably, the effect on the accuracy of calculations by the assumption of an ideal air load distribution is small, except in those cases where the ideal load distribution requires blade section lift coefficients that result in large drag coefficients. In the latter case, the error is one of disregarding the blade air loading at other sections. The existence of this kind of an error suggests that an iterative strip analysis is desirable, recalculating circulation at those sections having large momentum loss due to drag.

The assumption that a rigid wake exists does not appear to be particularly troublesome provided that the inevitable wake distortion, found in all practical propeller installations, occurs sufficiently far downstream that the induced flow field at the propeller disc is not materially affected. It should be noted here that not all changes in wake, caused by obstructions, are harmful. Wings or struts may increase the ideal efficiency of a single rotation propeller by acting as straightener vanes to assist in recovery of some rotational energy appearing in the wake. This increase in efficiency is effected by a decrease in rotational components of induced velocities at the propeller disc.

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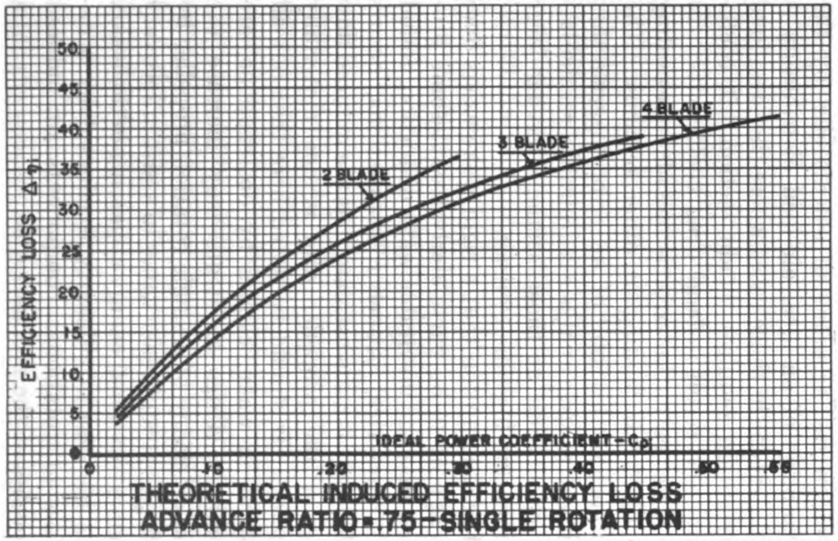

Figure 2.10.

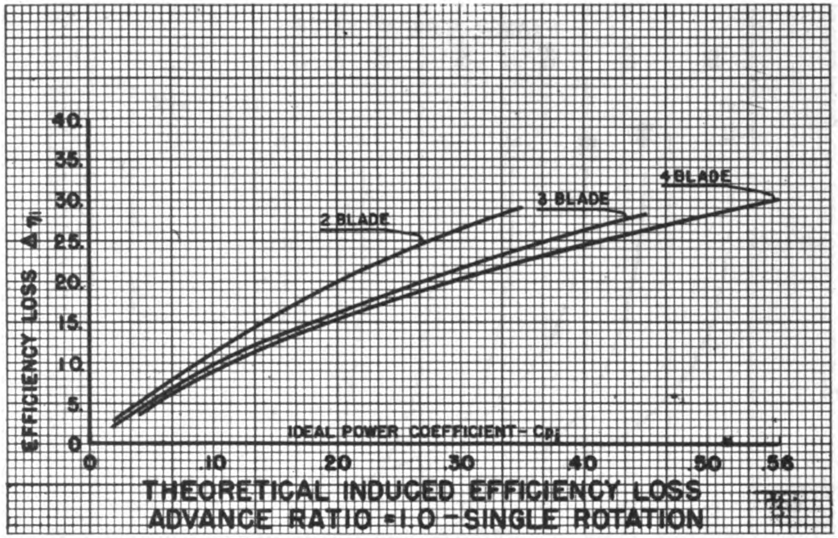

Figure 2.11.

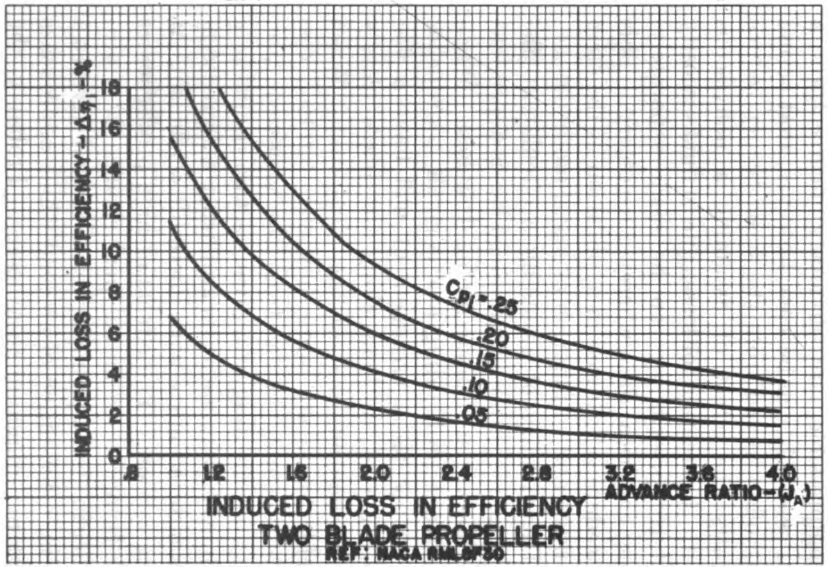

Figure 2.12.

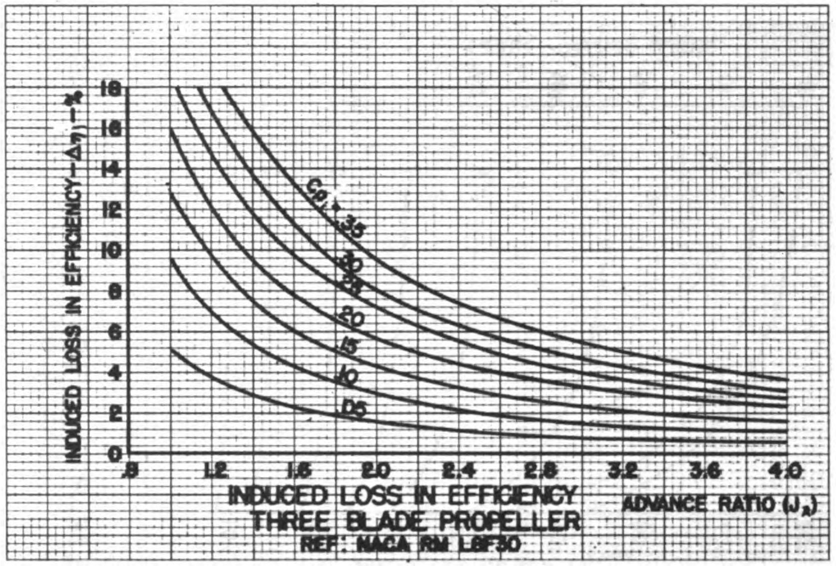

Figure 2.13.

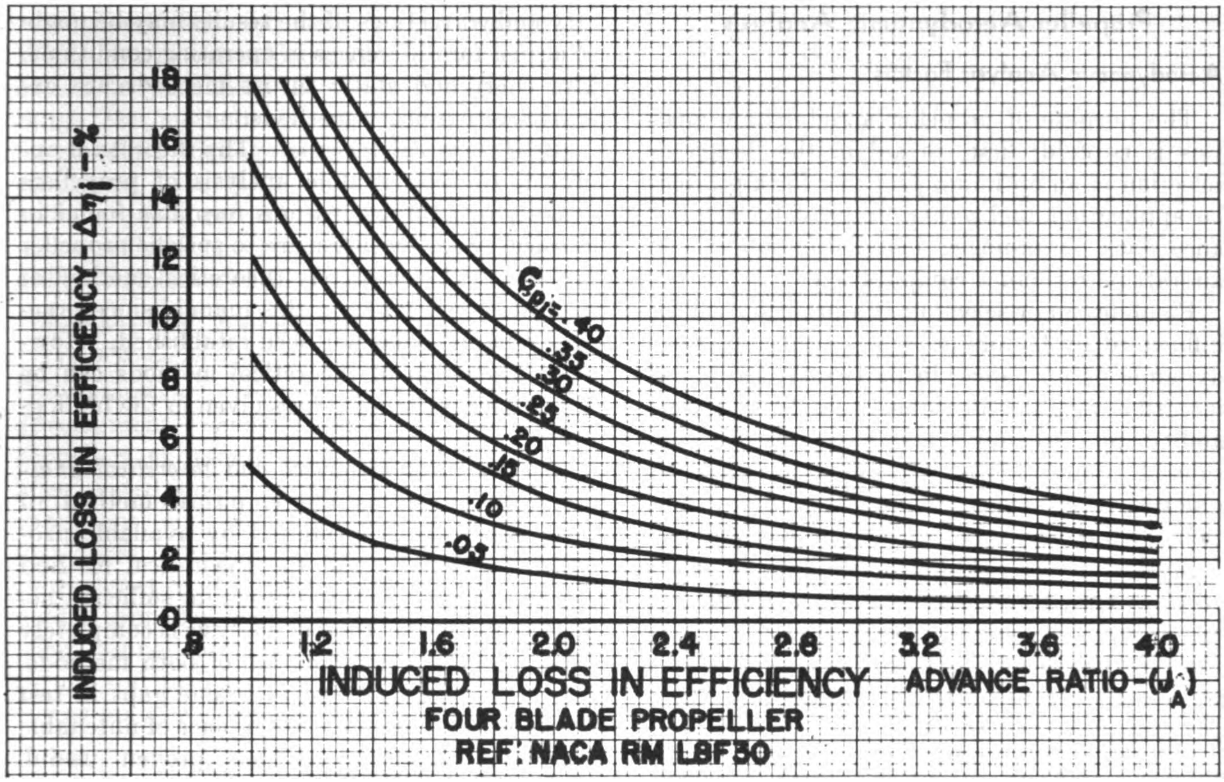

Figure 2.14.

(3) *Current design parameters.* The current theory serves all three purposes presented in the first paragraph of this chapter. The only means, at present, of determining the flow field about a propeller is based upon current propeller theory. Strip analysis, usually the most accurate and informative method of analyzing propellers, is based upon a known or assumed flow field. The flow field usually is defined in terms of an induced angle (α_i) at a given station, advance ratio, and circulation (defined in terms of total propeller power coefficient or the product of the section chord and lift coefficient (bC_L), for various numbers of blades. The induced angle (α_i) is indicated in figure 2.6.

The theoretical development by Goldstein defined induced angle (α_i) as a complex function of x, J_A, C_P and B. These relationships have been evaluated and, in order to reduce space and simplify the strip analysis, are given in graphical form only (figures 2.7, 2.8, 2.9).

It is emphasized that the induced angles (α_i) presented by these charts are not those of Goldstein or Theodorsen but approximations believed accurate enough for strip analysis calculations. The use of such an induced angle in the strip analysis will be shown later.

As a guide to ultimate performance of a propeller, the ideal efficiency is most useful. The same theory (Goldstein or Theodorsen's additional work) used to obtain section induced angles, is used to determine the ideal efficiency of a propeller operating in an incompressible, nonviscous fluid and having radial distribution of loading required for minimum induced losses. The ideal efficiency calculation for a complete propeller represents essentially the difference between 100 percent and proper summation of minimum losses at various blade sections resulting from change in momentum of the fluid.

Experimental data has been used to obtain values of induced efficiency loss (100 less the percent ideal efficiency) for various classes of propellers, which have been plotted with the ideal power coefficient as the other variable. The resulting curves for various advance ratios of two-blade, three-blade, and four-blade propellers are shown in figures 2.10 and 2.11.

The induced efficiency loss vs. advance ratio curves for low values of induced power coefficient of two, three and four blade propellers are shown in figures 2.12, 2.13, and 2.14.

Propeller Aerodynamic Analysis

Aerodynamic Analysis Factors

The purpose of propeller aerodynamic analysis is twofold; first, to aid in the design or selection of an optimum propeller for a particular application, and second, to provide performance data on propeller installation for use in aircraft performance computation.

Final design or selection of a propeller will be influenced by factors other than those of aerodynamic performance; in particular, structural integrity, weight, functional reliability, serviceability, produceability and cost must be considered. Some of these items must be evaluated qualitatively; hence, the final design or selection of a propeller is not, at present, a completely analytical process. Other items, notably structural integrity and aerodynamic performance, are subject to quantitative analysis. Therefore, significant numbers can be made available to a propeller designer with respect to these two important factors.

Procedure of Analysis

The procedure used in propeller aerodynamic analysis is essentially one of determining aerodynamic loads imposed upon a propeller and using those loads to determine thrust and torque required. Efficiency and power absorption, the two most significant aerodynamic characteristics of a propeller, are determined from knowledge of thrust and torque required. Since these loads must be determined with accuracy and rapidity for various propeller operating conditions, the method of analysis is of prime importance. Therefore, a discussion of methods of propeller aerodynamic analysis which are aimed at predicting efficiency or thrust under various propeller operating conditions is highly desirable. An approach to propeller aerodynamic analysis might be made on either an empirical or a theoretical basis, or a combination of empirical and theoretical analyses.

(1) *Empirical methods.* The empirical approach to aerodynamic analysis of propellers consists essentially of reducing complete propeller test data to dimensionless parameters involving significant performance variables, after which this information may be applied to all other propellers of the same geometry, regardless of size. Corrections of the parameters may be made to account for differences in geometry and corrections of the results may be made to adjust for differences in operating conditions. The chart and static thrust methods are examples of empirical methods.

(2) *Theoretical analysis.* The theoretical approach to aerodynamic analysis of propellers consists of applying various formulae found in classical propeller literature to specific propeller problems. A completely theoretical method of analysis is not given in this manual since practical reliability has not been established. However, discussion of theoretical methods can be found within the references given in the bibliography.

(3) *Combined empirical and theoretical analysis.* Inasmuch as the empirical method of propeller analysis is limited by available propeller test results and the theoretical method requires assumptions too broad for sufficient accuracy, neither method of analysis is completely satisfactory. A combination of both methods, in which theory is used to bridge gaps in test data and test data are used in place of untenable theoretical assumptions, has proven useful. The strip analysis and summation of losses methods are typical examples of this approach to the propeller analysis problem.

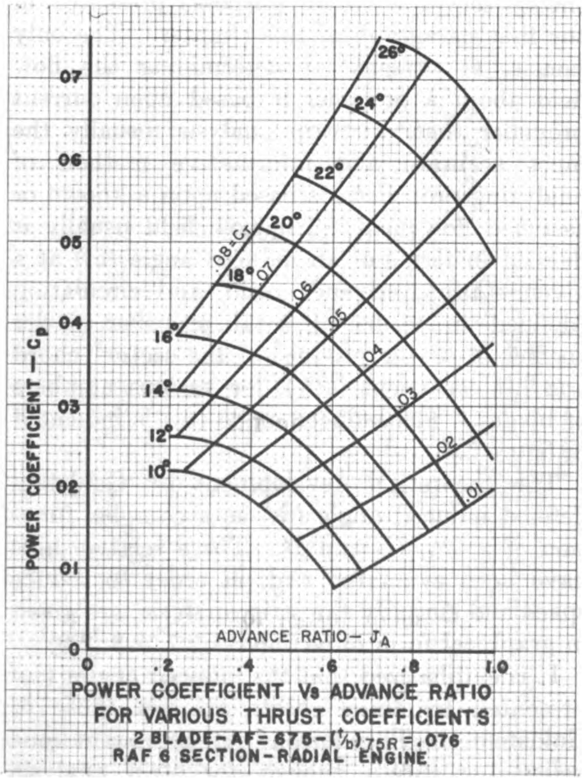

Figure 2.15.

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(4) *Limitation of methods in application.* While data presented herein are limited in application to propellers in the subcritical speed range, the methods of analysis are applicable to so-called high-speed propellers. Sufficient additional data for complete high-speed propeller analysis can be made available to those whose activities in this field are adjudged essential to the mission of the Department of Defense.

"Chart Method" Aerodynamic Analysis

(1) *Efficiency Computations.* (*a*). Efficiency Determination. During the course of propeller development, several reduced scale model propellers and some full scale propellers have been tested under simulated or actual flight conditions and respective aerodynamic performances measured. Given performance characteristics of a full scale or a reduced scale model propeller, as measured by means of a wind tunnel propeller dynamometer, or by thrust and torque meters in flight, the efficiency may be calculated from the equation:

$$\eta=\frac{TVC}{BPH}$$

in which C is some constant, experimentally determined.

(*b*) Application of Computed Efficiency to Similar Propellers. Since efficiency is a dimensionless number, it should apply to all propellers of similar geometry, regardless of size. This assumption is valid if Reynolds number effects are ignored. Being a function of airplane velocity, BHP, brake horsepower and thrust ($\eta=f(V, BHP, T)$), efficiency will vary considerably with operating conditions. The operating conditions are known usually, while efficiency is unknown in a practical case. Hence, it is necessary to reduce operating conditions to dimensionless parameters before test efficiency may be applied to another propeller of the same geometry but different size. Several systems of coefficients have been developed, by dimensional analysis, for propeller applications. The most useful appear to be power coefficient, (C_P), thrust coefficient, (C_T), and advance ratio, (J_A). In most practical propeller analysis problems, J_A and C_P can be readily calculated from given or observed data. C_T may be found from a performance chart prepared from test results on a propeller of similar geometry. Figures 2.15, 2.16, and 2.17 are examples of such charts.

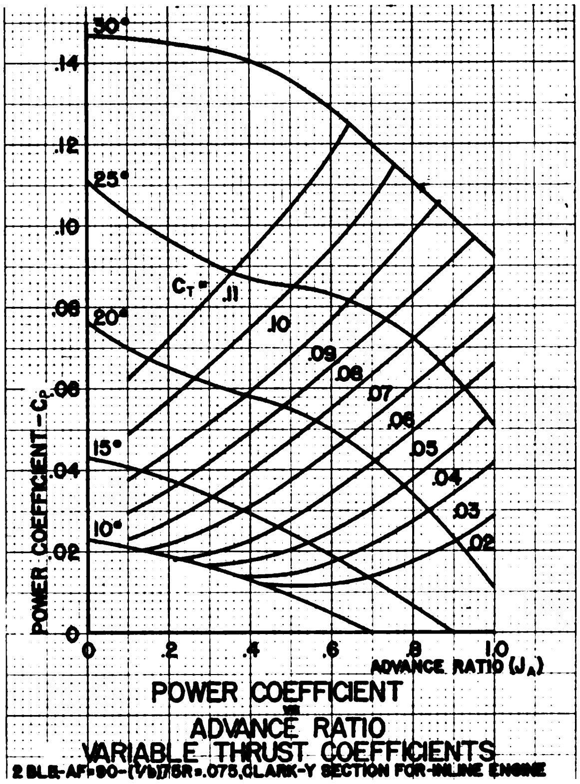
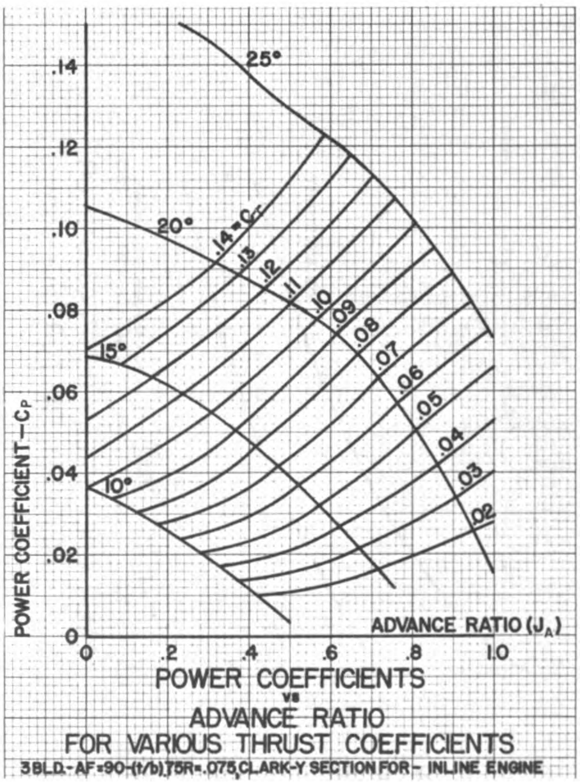


Figure 2.16.



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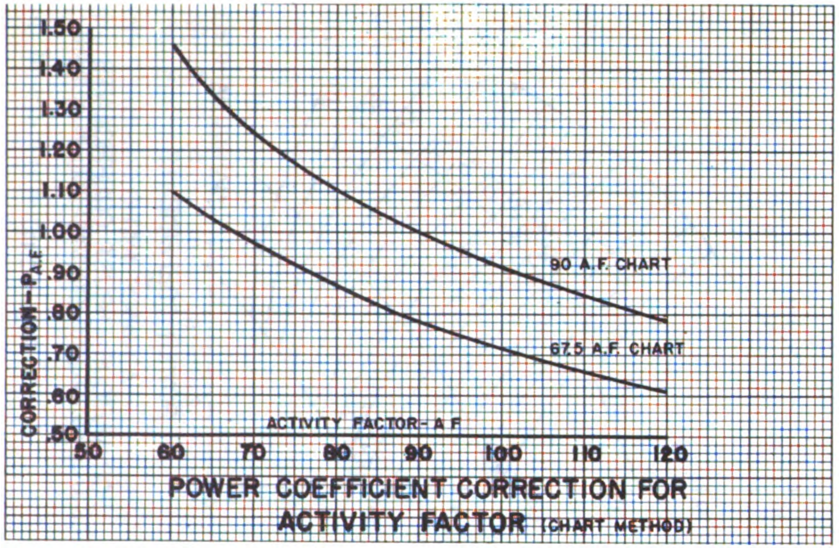
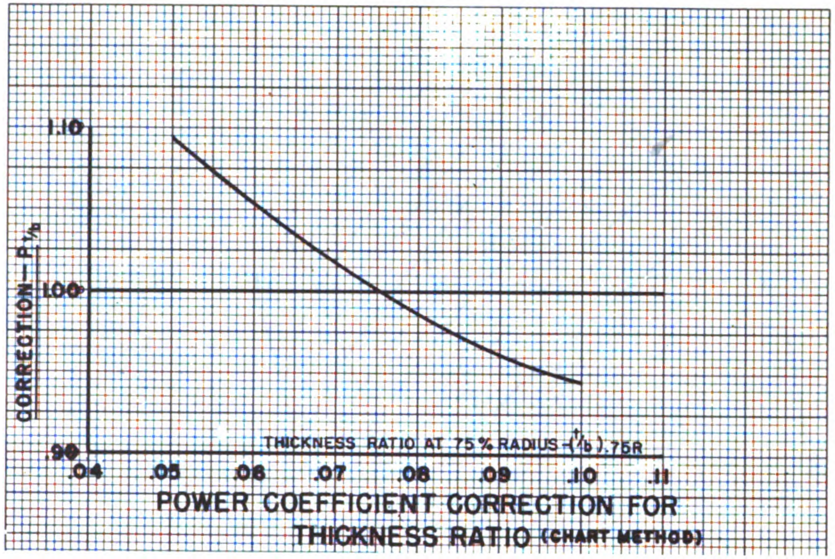


Figure 2.18



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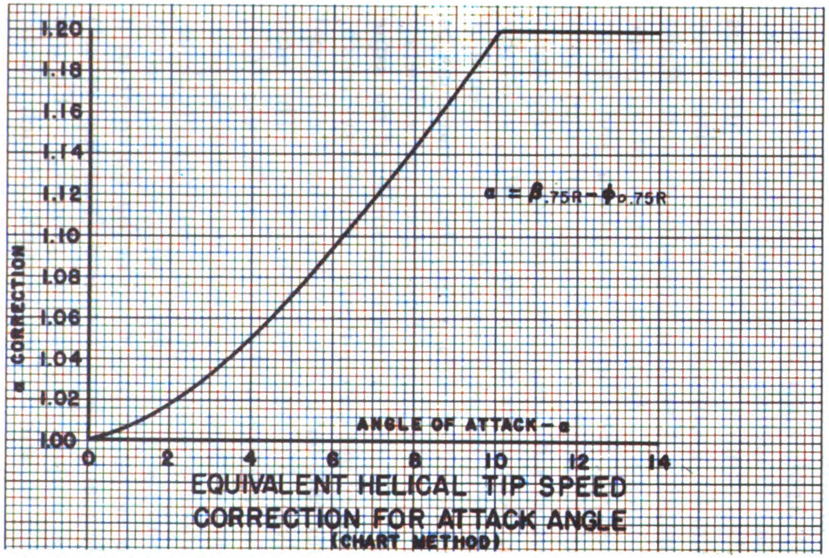

Figure 2.20.

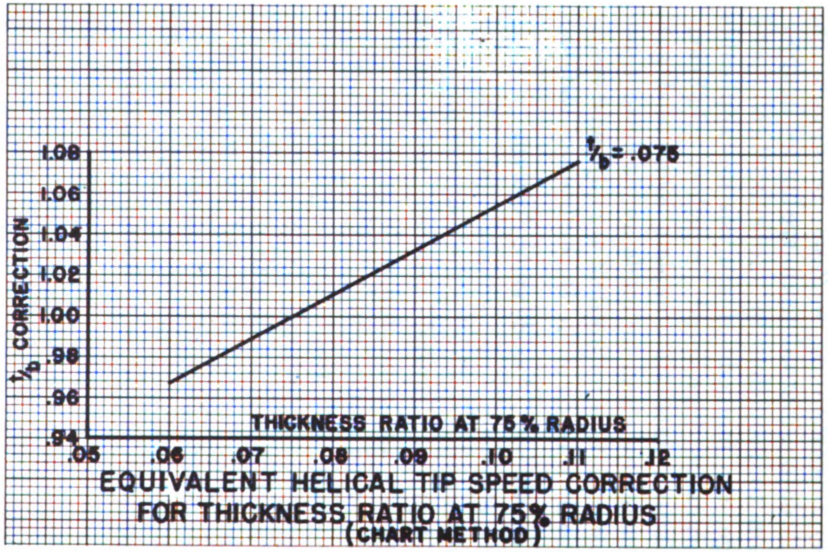

Figure 2.21.

With the coefficients C_P, C_T, and the advance ratio J_A known, propeller efficiency may be calculated by using the equation:

$$\eta = \frac{C_T J_A}{C_P}$$

(c) Propeller Efficiency Correlation Factors. It is emphasized again that application of efficiency, determined on the basis outlined in the preceding paragraph, ignores Reynolds number and Mach number effects, usually. If a test propeller and the propeller being studied differ in geometry (that is, one propeller is not an exact scale model of the other), further errors may be introduced. In an attempt to overcome these faults of the chart method, correction factors have been developed to make approriate adjustments for difference in shape and Mach number of test propeller and the propeller under consideration.

(2) *Propeller blade variation—Effect on performance.* Planform and thickness ratio are the principal variables of propeller blades. Planform differences may introduce considerable variation in performance. For the same diamter, a propeller application may use either a narrow or wide blade. The ratio of blade widths (larger to smaller) may vary, in extreme cases, by as much as two to one. Likewise, large variations in thickness ratio are common. These variations result in large differences in section drag at high speeds. Whereas wing aerodynamic performance is a function of aspect ratio, propeller performance is influenced by its activity factor or solidity.

(3) *Effect of blade solidity and activity factor upon propeller performance.* Solidity may be defined either, as the ratio of total blade chord lengths to propeller disc circumference at some particular blade radius (usually *.70R*), or, as the ratio of total blade area to total disc area.

Activity factor is a measure of the amount of power (in terms of C_P) that a blade may absorb for a given performance level, without considering changes in ideal efficiency. It can be shown that:

$$dC_P \approx \frac{b}{D}\left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right)$$

from which the activity Factor may be developed, and expressed mathematically in the form:

$$AF = \frac{100{,}000}{16}\int_{2.0}^{1.0} \frac{b}{D}\left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right)$$

However, this relationship is exact only when the advance ratio, $J_A = O$. In this handbook, activity factor (AF) is used to define propeller planform for advance ratios equal to or less than one ($J_A \leqq 1.0$); and solidity (σ) at $.7(r/R)$ for values of J_A above one. A comparison of activity factors or solidities of propellers having the same diameter and number of blades is, therefore, a rough measure of relative power absorptions of the blades. Utilizing the curves shown in figure 2.18, blade power coefficients can be corrected for variations of computed propeller activity factor by use of chart values of blade activity factor.

(4) *Correction factors for variation in thickness ratios and tip speeds.* Deviation of thickness ratio of a propeller at the .75 (r/R) station will affect the power coefficient. Suitable corrections for (t/b) ratios can be obtained from the chart, figure 2.19.

Since basic test data for the power coefficient curves shown in figures 2.15, 2.16, and 2.17 were obtained at very low blade speeds, a correction of the power coefficient is necessary to adjust the coefficient for higher tip speeds. The methods to be used for correction of the power coefficient for tip speed is as follows:

(a) Calculate the helical tip speed using the equation:

$$V_T = \sqrt{V^2 + (\eta n D)^2}$$

(b) Correct (V_T) for the effect of temperature by multiplying helical tip speed by the square root of the ratio of standard sea level absolute temperature to absolute temperature at propeller performance altitude, i. e.

$$V_{t_t} = \sqrt{V^2 + (\eta n D)^2}\sqrt{\frac{T_0}{T}}$$

(c) Adjust the temperature corrected tip speed (V_{t_t}) for the effect of variations in blade section angle of attack and section thickness ratio by multiplying (V_{t_t}) by chart values obtained from the curves in figures 2.20 and 2.21.

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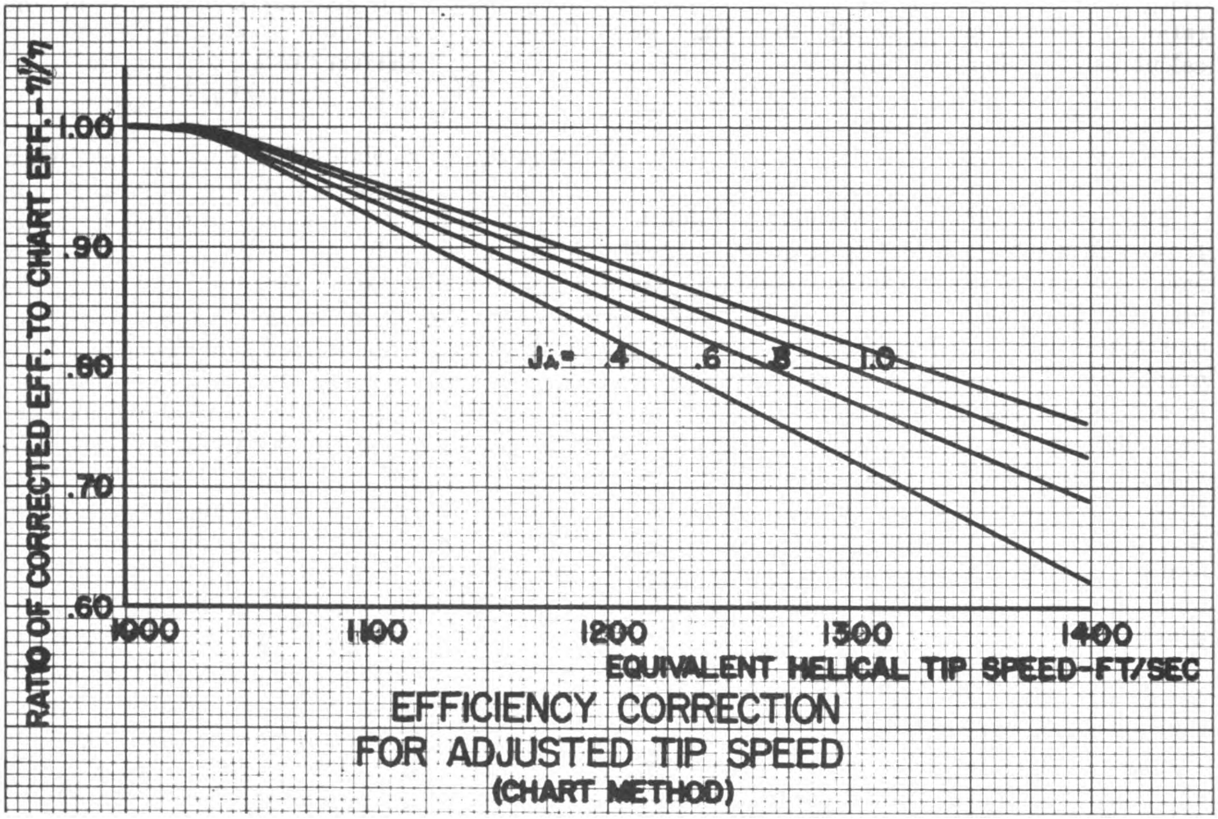

Figure 2.22.

NOTE: The result of these operations is to establish a fictitious tip speed, but a speed at which a blade of .075 thickness ratio, operating at sea level, and zero angle of attack would have the same efficiency loss as the given blade.

(*d*) Obtain the ratio of corrected propeller efficiency (η') to chart propeller efficiency (η) from the curves shown in figure 2.22.

(5) *Constant speed propeller performance—Chart method.* The procedure for determination of constant speed propeller performance by the chart method may be summarized as follows:

(*a*) Calculate the advance ratio;

$$J_A = V/ND$$

(*b*) Compute the power coefficient;

$$C_P = \frac{5\times10^{10}\times BHP}{\sigma\times N^3D^5}$$

Correct C_P as necessary for activity factor and blade thickness to width ratio variations.

(*c*) Obtain value of torque coefficient (C_T) from charts: (figures 2.15, 2.16, and 2.17).

(*d*) Obtain propeller blade angle (β) from the same set of charts.

(*e*) Calculate propeller efficiency:

$$\eta = J_A \frac{C_T}{C_P}$$

(*f*) Determine the value of ϕ_o:

$$\phi_o = \text{Tan}^{-1}\left(\frac{J_A}{.75\eta}\right)$$

(*g*) Determine the angle of attack, α:

$$\alpha = (\beta - \phi_o)$$

(*h*) Find the helical tip speed, V_t:*

$$V_t = \sqrt{V^2 + (\pi nD)^2}$$

(*i*) Obtain corrections for V_T from charts 2.20 and 2.21.

(*j*) Apply chart corrections found in (9) to V_t (as found in (8)).

(*k*) Determine the ratio $\left(\frac{\eta'}{\eta}\right)$ from the chart (figure 2.22).

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*NOTE: n=engine r. p. m.×gear ratio÷60
V=forward velocity (ft/sec.)

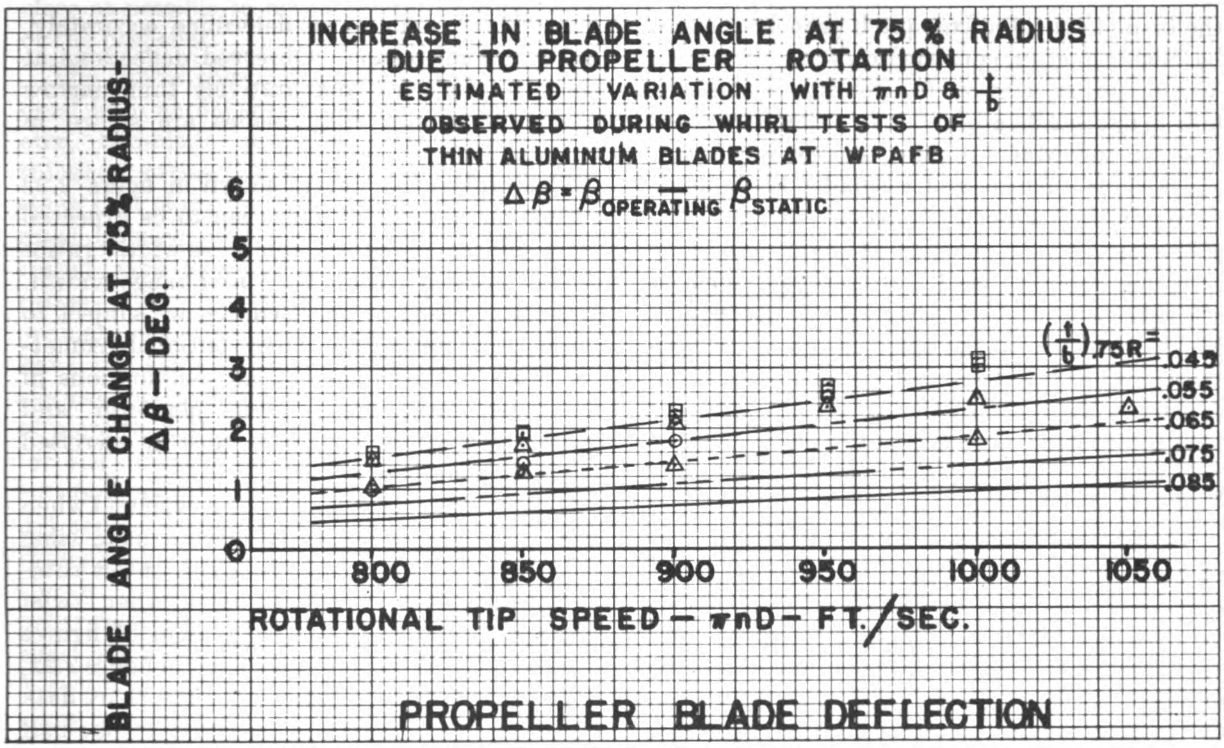

Figure 2.23.

(l) Compute the final propeller efficiency:

$$\eta' = \eta \left(\frac{\eta'}{\eta} \right)$$

(6) *Fixed pitch propeller analysis.* (*a*) General Procedure. In case of fixed pitch propellers, in which blade angle will be the only known quantity, it is necessary to obtain the variation of engine power with engine speed (usually, full throttle curve will be used) for the flight altitude under consideration. Using engine speed versus horsepower data, the power coefficient may be calculated for several power requirements and speeds ranging from minimum to maximum. For each value of power coefficient at the known fixed pitch blade angle (referred to .75 radius) the advance ratio may be read from the chart (i. e., figure 2.15, 2.16 or 2.17). Since rotational velocity (n) and propeller diameter (D) are known, forward velocity (V) can be found using the chart value of advance ratio (J_A) and the equation:

$$J_A = \frac{V}{nD}$$

This calculated value of V is the velocity at which the propeller will operate under selected power and speed conditions. The propeller efficiency can be found for these conditions, also, by reading C_T from the chart and calculating:

$$\eta = \frac{C_T J_A}{C_P}$$

Corrections to the efficiency should be made in the same way as was indicated for constant speed propellers. However, it should be noted that an indicated tip speed correction of more than five percent implies that the torque actually required is much different from that predicted by the charts, and the results obtained are in error to a considerable degree.

(*b*) Effect of Propeller Tip Speed Variation. The fact that the charts are based on a propeller tip speed other than selected operating tip speed usually results in greater errors in projecting propeller performance of fixed pitch propellers than constant speed propellers. In the latter case, the propeller adjusts itself to the blade angle required for a given power input and the efficiency change resulting from this small blade angle change is negligible. In the former case, the nonadjustable blade angle feature of fixed pitch propellers will cause considerable variation in power, speed, and often efficiency, for small differences in predicted and actual required torque. Bearing in mind that

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the blade angle of a fixed pitch propeller cannot be changed after construction, the lift versus Mach number, as given for two dimensional airfoils in figure 2.35 is of interest. It will be noted that as the Mach number increases, the lift curve slope changes and a smaller blade angle is required to absorb the same power. The efficiency contour remains at about the same level for given C_P and J_A, however, until an effective part of the blade is above the critical Mach number. Using the analogy of two dimensional airfoil data, this phenomena can be explained by the fact that peak L/D remains about the same over the range in which the ratio $\frac{dC_L}{d\alpha_0}$ is increasing.

(*c*) Effect of Blade Deflection in Performance of Fixed Pitch Propellers. Most blades deflect to some extent from their static pitch distribution when rotated, which must be given consideration in fixed pitch propeller analysis. The amount of deflection, usually observed as an increase in blade angle outboard (blade untwisting), is a function of rotational speed, blade geometry, and material. Propeller twist is determined, usually, by consideration of the algebraic sum of aerodynamic, external and internal centrifugal moments, together with the contribution of longitudinal tension and compression in the blade. Since rigid mathematical treatment of propeller twist is not feasible, blade deflection is difficult to determine accurately, by analytical means. Observed deflections at specific speeds for comparatively thin, narrow chord, aluminum alloy blades are shown in figure 2.23.

The broken line curves shown in figure 2.23 reflect the amount of deflection to be expected from blades of given thickness-width ratios when operated within the speed range shown. Estimates based on these curves are subject to large errors for certain unconventional geometric blade patterns (particular combinations of thickness ratio distribution, planform and twist). Therefore, judgment must be exercised in using such data.

The blade deflection must be considered when fixed pitch propeller calculations are made using chart data obtained from tests run at low rotational speeds. It is estimated that twist necessary to correct the chart data of figures 2.16 and 2.17 is the amount shown in figure 2.22. A reasonable twist correction for the chart data of figure 2.15 appears to be equal to one-half that shown in figure 2.23.

(7) *Limitations of the chart method of propeller analysis.* It is emphasized, again, that accuracy of the chart method is largely dependent on the degree to which chart, or test, data matches operating conditions of the propeller under consideration. For this reason, every effort should be made to secure test data as

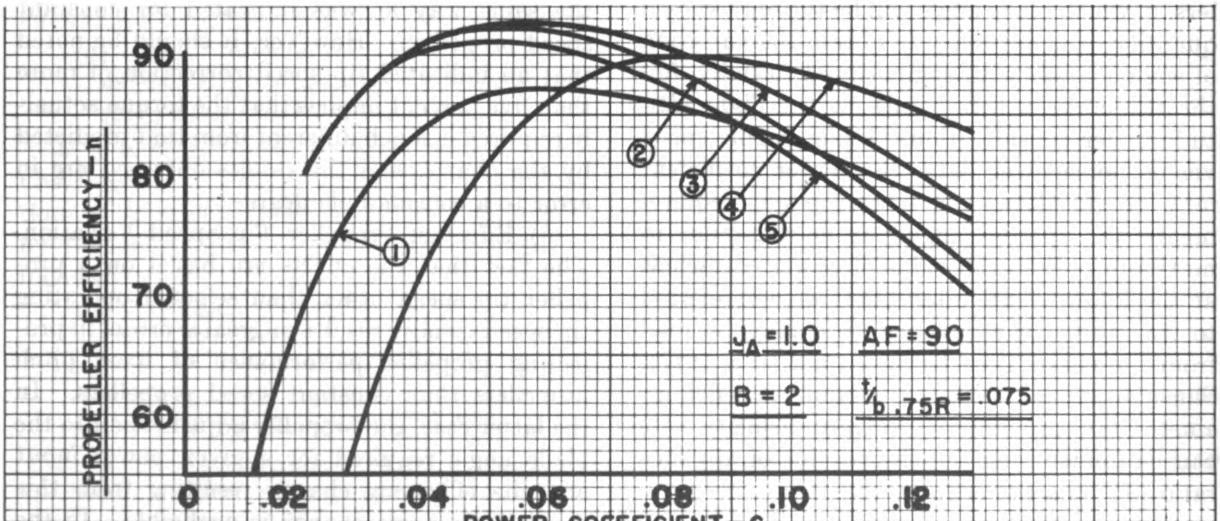

Figure 2.24.

close as possible to actual operating conditions of the propeller.

The curves shown in figure 2.24 were developed from actual test results of ten foot diameter, two-blade propellers having identical thickness ratios. A study of this diagram will show that chart methods of propeller analysis must be used with discretion. The propellers tested were operated with identical advance ratios and activity factors. Therefore, by ordinary chart methods, these propellers should have the same efficiency curve when plotted against power coefficient. However, differences of more than 10 percent in efficiency are shown for the different propellers when operating at constant power coefficient. Reasons for the differences involve design of shanks and section type along with variations in Reynolds number. Curve Number 1 is representative of the propeller most used as a basis for development of chart methods. This type propeller has Clark–Y sections with a round shank; it was tested at a low rotative speed which results in low section Reynolds numbers. The curves identified as 2, 3, and 4 were developed from tests of propellers having airfoil shanks with NACA–16 series sections; and were tested at higher rotative speeds (1600 r. p. m.). The only difference in the latter three blades involves section camber.

The propeller for curve 3 has greater camber than the propeller represented by curve 2, and the propeller for curve 4 has much greater camber than that of curve 3. The propeller from which curve 5 was derived differs from that of curve 2 only in that it has round shanks similar to those of the basic propeller type (curve 1).

At high power coefficients, effects of Mach number may be a dominant factor in the large decrease of efficiency shown in the diagram.

Consideration of the information shown in figure 2.24 further emphasizes limitations of the chart method. Since the data is not general, use of the chart method should be confined to two- and three-blade propeller applications for advance ratios up to and including one (1.0). Airfoil sections represented in the charts are the Clark–Y type, which is obsolete, and the RAF 6 type, which is obsolete for use in high speed propellers. Therefore, the charts are most useful for analyzing propellers designed for use on slow airplanes such as liaison, trainer and light transport types.

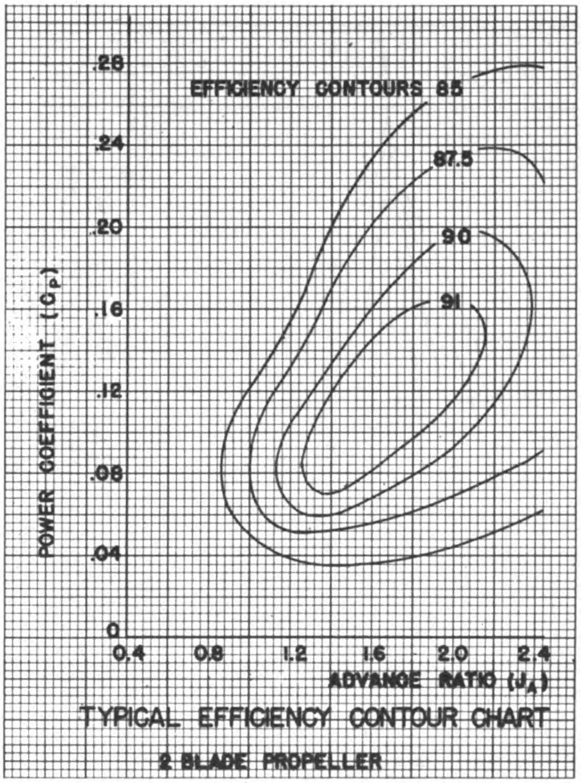

Figure 2.25.

Plots of propeller operating characteristics which are required for the chart method (shown in figures 2.15, 2.16, and 2.17) are of qualitative educational value. Careful study of these and similar charts will reveal relationships that exist between flight velocity, power, rotative speed, and blade angle. For example, the velocities for zero thrust and zero power at a given rotative speed and propeller blade angle(β) may be estimated from the charts with reasonable accuracy. Also, maximum power that can be used at any given air velocity and propeller speed without stalling the blades, may be estimated. Since each point on the chart represents specific values of J_A, C_P and C_T, each point also represents a specific value of propeller efficiency.

(8) *Construction and use of efficiency contour charts.* A propeller efficiency contour chart can be constructed by plotting constant efficiency values for various combinations of advance ratio and power coefficient. A typical efficiency contour chart is illustrated in figure 2.25. Examination of such efficiency charts reveals the range of parameters which are required for any desired efficiency or range of efficiency.

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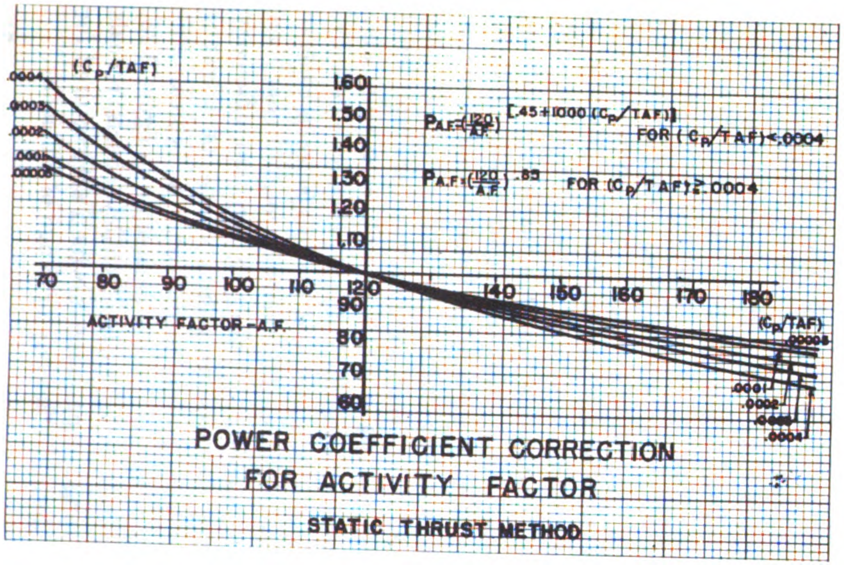

Figure 2.26.

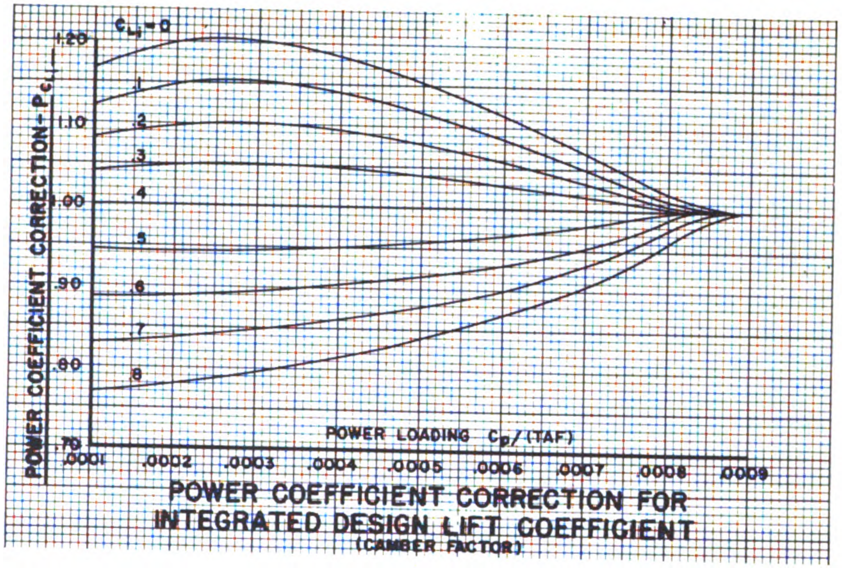

Figure 2.27.

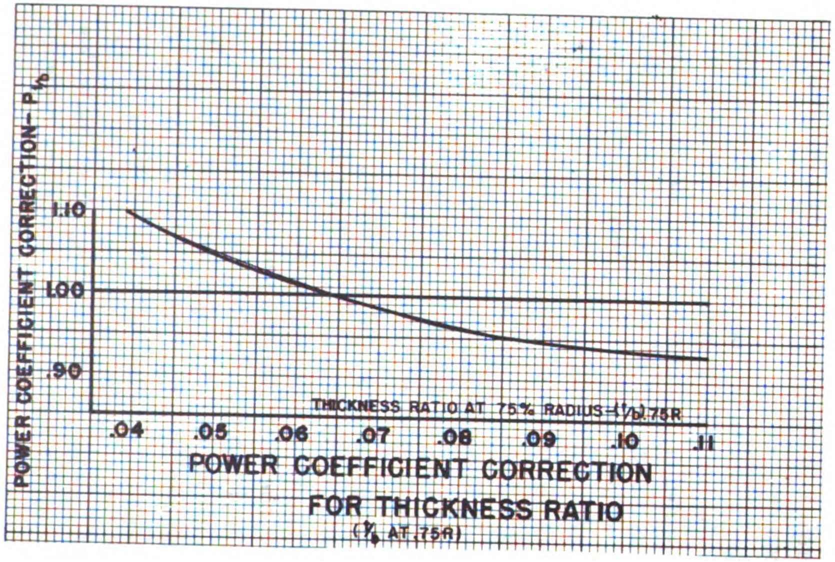

Figure 2.28.

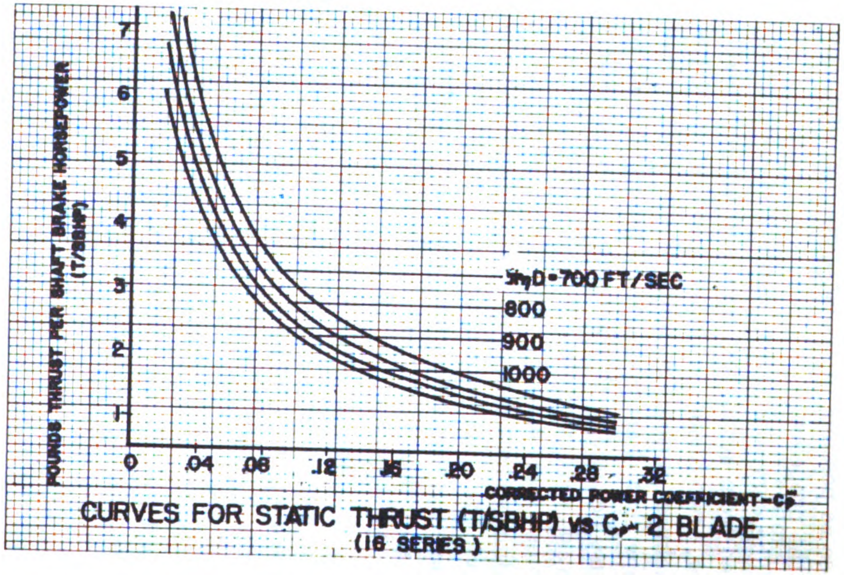

Figure 2.29.

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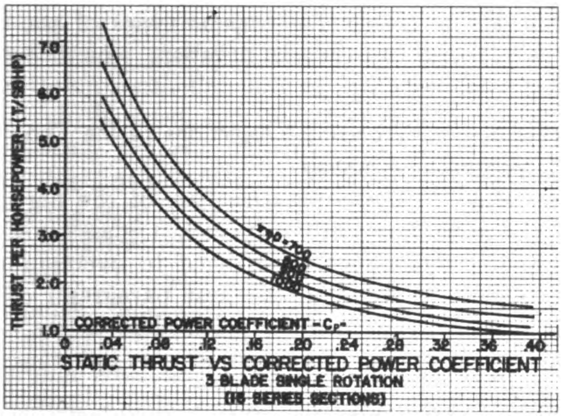

Figure 2.30.

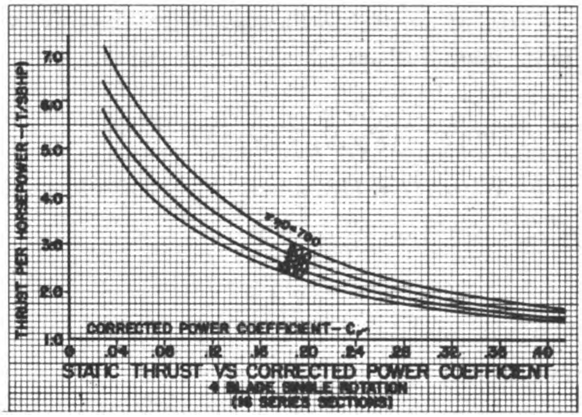

Figure 2.31.

Static Thrust Calculations

Static Thrust Definitions

The following method has been developed by the Propeller Laboratory of Wright Air Development Center for calculating static shaft thrust of a propeller. The curves of thrust per shaft brake horsepower versus corrected power coefficient were derived from numerous static whirl tests conducted at Wright-Patterson Air Force Base and results published by the National Advisory Committee for Aeronautics. Power coefficient correction factors were derived mainly from test results published by the National Advisory Committee for Aeronautics.

This method applies only to propellers composed of 16-series sections. Further, this method will give shaft thrust and not propulsive, or net thrust.

The following are some special symbols and definitions used in this method of static thrust calculation:

C_P=Power coefficient corrected for activity factor, camber factor, and thickness ratio.

P_{AF}=Power coefficient correction for activity factor.

$P_{t/b}$=Power coefficient correction for thickness ratio.

P_{CF}=Power coefficient correction for camber factor.

TAF=Total activity factor=AF x number of blades.

Procedure—Static Thrust Determination

The procedure in determining the static shaft thrust of a given propeller for a given power and angular speed is as follows:

(1) Calculate C_P, ηnD, and (C_P/TAF) for the propeller.

(2) Using activity factor and (C_P/TAF), find P_{AF} from figure 2.26.

(3) With camber factor and (C_P/TAF), find P_{CF} from figure 2.27.

(4) Using the thickness ratio at $.75R$, find $P_{t/b}$ from figure 2.28.

(5) Calculate: $C_P''''=C_P \text{ x } P_{AF} \text{ x } P_{CF} \text{ x } P_{t/b}$.

(6) From the appropriate curve of $(T/SBHP)$ vs. C_P'''' (figure 2.29, 2.30 or 2.31) read $T/SBHP$ at calculated C_P'''' and ηnD.

(7) Multiply $(T/SBHP)$ by $(SBHP)$ to obtain the propeller shaft static thrust.

Example of Static Thrust Determination

(1) *Propeller data:*

Blade sections: 16-Series
Diameter=16 ft. 6 in., four blades, CF=.379
Activity factor (AF)=113
Camber factor (CF)=.379
Thickness ratio (t/b) at .75R=.073
Engine speed=2700 r. p. m.
SBHP=3500
Gear ratio=.375
Propeller speed=.375·2700=1012=N=60n (RPS)

(2) *Static thrust determination.*

$$(a)\ C_P=\frac{5\times10^{10}\times(\text{SBHP})}{\text{N}^3\text{D}^5}=\frac{5\times10^{10}\times3500}{(1012)^3\times(16.5)^5}=.138$$

Tip speed calculation

$$\pi nD=\pi\frac{(1012)}{60}\times16.5=874 \text{ ft/sec.}$$

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Ratio of power coefficient to total activity factor computation

$$\frac{C_P}{TAF}=\frac{C_P}{AF\times N_b}=\frac{.138}{4\times 113}=.000305$$

(*b*) With $AF=113$, and $\frac{C_P}{TAF}=.000305$, read $P_{AF}=1.045$ from figure 2.26.

(*c*) Using the values $\frac{C_P}{TAF}=.000305$ and $CF=.379$, the correction factor, $P_{CF}=1.010$ can be read from the chart, figure 2.27.

(*d*) The power coefficient correction factor $P_{t,b}=.977$ can be obtained from the chart (figure 2.28) for t/b value (at $.75R$)$=.073$.

(*e*) By computation, $C_P=C_P\times P_{AF}\times P_{CF}\times P_{t/b}=.138\times 1.045\times 1.010\times .977=.142$.

(*f*) For $C_P''''=.142$ of a four-blade propeller, the unit torque $(T/SBHP)=3.21$ can be obtained from figure 2.31.

(*g*) Therefore, shaft thrust$=3.21\cdot 3500=$ 11,230 lb.

Summation of Losses Method of Analysis

Review of Limitations of the Chart Method of Analysis

It has been explained that several fundamental limitations restrict use of the chart method of propeller aerodynamic analysis. Some objections to the chart method of analysis have been overcome in recent years by testing (principally, by the National Advisory Committee for Aeronautics) model propellers at moderate and high speeds. The propellers tested represent a significant range of blade planforms and blade section cambers and thicknesses.

Data recently obtained could be used in the chart method except for the following reasons:

(1) Most of the high speed testing has been done using two-blade propellers because the power required per blade to obtain high speed data for even small (four foot) four-blade propellers exceeded available power.

(2) In these tests, most blade-to-spinner junctures were idealized; that is working gaps were not included and round shanks, radial engine cowlings, and other practical mechanical considerations were omitted from test propeller configurations.

(3) Excessive interpolation and cross plotting of data obtained from a large number of charts for various types of propellers and Mach numbers would be required.

Methods of Overcoming Objections to the Chart Method of Analysis

In order to make practical use of the high speed test data recently acquired, it is essential that some system be established to overcome the objections listed in the first paragraph of this section. The devices established to meet the objections are discussed in the following paragraphs.

(1) *Adjustment of two-blade performance data for four-blade use.* Propeller induced and parasite losses are functions of the advance ratio (J_A). However, induced losses are functions of the numbers of blades and section blade widths multiplied by section lift coefficients; while parasite losses are functions of blade geometry, section lift coefficient and Mach number.

Assuming the profile loss per blade of a two-blade propeller to be the same as the profile loss per blade of a four-blade propeller having identical blade shape, the actual performance of a four-blade propeller could be determined by two steps, namely:

(*a*) Obtain unit blade profile loss from two-blade propeller tests by finding the difference between actual and ideal efficiencies (calculated).

(*b*) Add the quantity found in (1) to the theoretical induced loss of the four-blade propeller.

(2) *Special Considerations—Proposed Method of Analysis.* (*a*) Effect of Inflow. The procedure outlined for adjustment of two-blade performance data for four-blade use may be followed using a constant ratio of power coefficient to density ratio (C_P/σ_P) to obtain equivalent section lift coefficients. Actually, of course, the distribution of inflow along the blade is different for propellers having different numbers of blades even though the ratio (C_P/σ_P), advance ratio and Mach number are held constant. However, this distribution varies most at low advance ratios and over inboard sections of the propeller. Therefore, significant errors have not been found (based on limited test data) in applying the method to moderate and high speed propellers having more than two blades. Because of large differences of inboard inflow between

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single and dual rotation propellers, the latter must be treated separately, applying the same principles. For example, performance of a dual rotation propeller having eight wide blades should be predicted from test results of a dual rotation propeller having four or six narrow blades, but not from a single rotation propeller having eight wide blades.

(*b*) Effect of Non-Ideal Blade-Spinner Junctures. To account for non-ideal blade-to-spinner junctures, an increment of efficiency loss must be added to the above determined profile efficiency loss; the magnitude of correction will be dependent upon the particular configuration and operating conditions of the propeller.

(*c*) Reduction of Number of Charts Required. To cut down the number of charts required, profile loss may be generalized; that is, the loss may be made a combined function of thickness ratio, camber factor, Mach number, planform and other variables. A generalized expression for profile loss could be obtained from an equation only, a set of experimental data curves, or a combination of both.

Summation of Losses

(1) *Method application.* The summation of losses method of propeller performance analysis, different procedures should be used for advance ratio regions of $J_A < 1.0$, and $J_A > 1.0$. Distinctly different procedures for these two advance ratio regions are desirable for the following reasons:

- (*a*) Special care must be taken in determination of profile efficiency loss at low advance ratios, since the effect of section lift/drag upon propeller efficiency is most pronounced at low advance ratios.
- (*b*) Test data for propellers operating at advance ratios of less than one is limted. Acquisition of reliable data for propellers operating on wind tunnel dynamometers, or on aircraft in flight, at low speeds and high power inputs becomes extremely difficult because of the velocity increasing characteristic of increased power, which results in unstable test runs.
- (*c*) The simplest descriptions of blade size (namely, activity factor and solidity) are not equally accurate for the same value of advance ratio. Activity factor is accurate only when $J_A = 0$; activity factor decreases in reliability as advance ratio increases. Solidity factor increases in reliability as advance ratio increases. Hence, at some value of advance ratio it is advantageous to describe blade size by solidity factor rather than by activity factor.

(2) *Prediction of low speed performance.* Low speed performance of modern propellers may be predicted as follows:

- (*a*) Static thrust of a propeller may be found by the method outlined on page 37, Static Thrust Definitions, Procedure—Static Thrust Determination.
- (*b*) Propeller efficiency and thrust can be calculated for advance ratios of 0.75 and 1.00.
- (*c*) A thrust vs. velocity curve may be plotted for the three points just established. These curves may be used for several operating conditions if the curves have been determined for proper engine ratings, since moderate and low speed aircraft normally take off, climb and cruise at $J_A < 1.0$.
- (*d*) Thrust at any desired velocity may be obtained from the plotted thrust versus velocity curves.

(3) *Efficiency and thrust calculations*—($J_A = 0.75$ *and* $J_A = 1.00$). Calculation of efficiency and thrust at advance ratios of 0.75 and 1.00 for single rotation propellers may be accomplished as follows:

(*a*) Calculate coefficient of performance from the relationship:

$$C_P = \frac{5 \times 10^{10} \times BHP}{\sigma N^3 D^5}$$

(*b*) Determine total activity factor:

$TAF =$ (AF of single propeller blade) $\times$ (number of blades).

(*c*) Determine the value of the ratio C_p/TAF.

(*d*) From figures 2.32 and 2.33, read values of $\Delta\eta_p$ (blade profile loss) at $J_A = 0.75$ and $J_A = 1.00$ for CF (or C_{L_i}), (camber factor), of the blade under consideration.

(*e*) Add an additional increment of loss for round shank blades:

($\Delta\eta_s = 1$ per cent for radial type installations
$\Delta\eta_s = 2$ per cent for inline installations.

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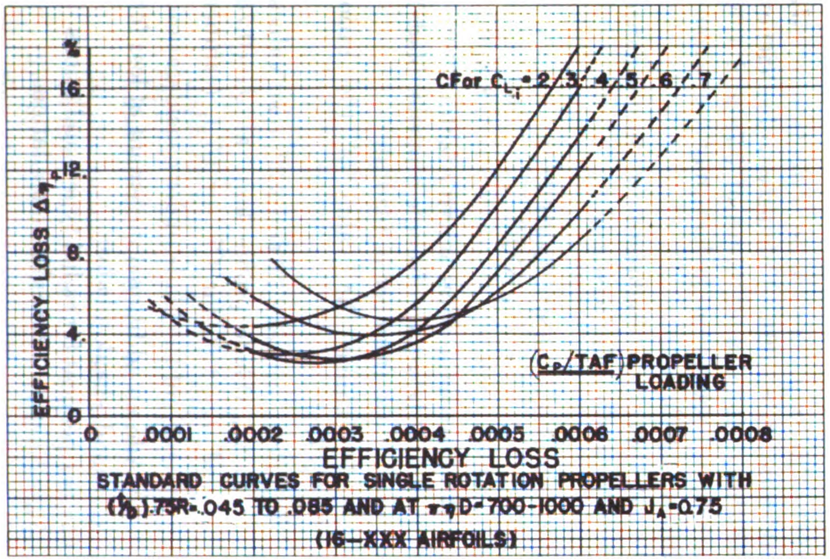

Figure 2.32.

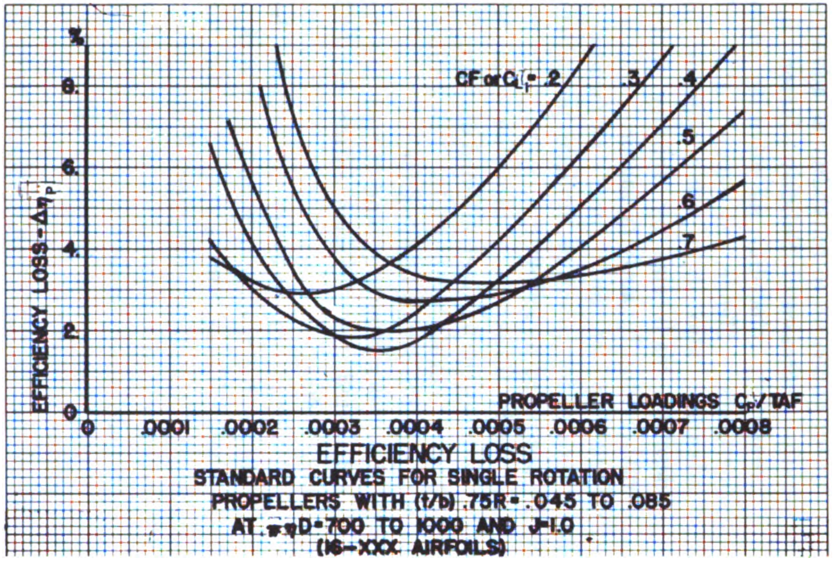

Figure 2.33.

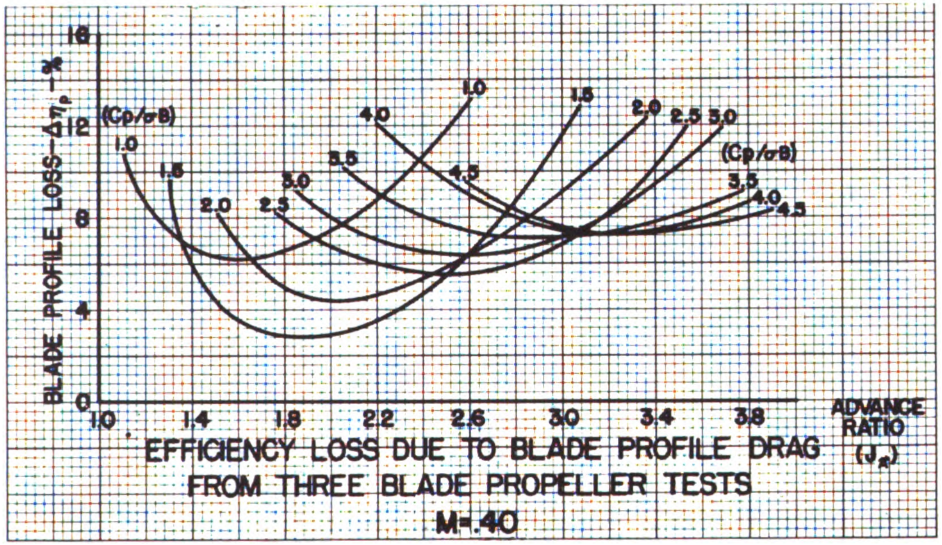

Figure 2.34.

(*f*) Calculate the ideal power coefficient, $\left(C_{P_i}\right)$ from the relationship:

$$C_{P_i}=C_P.(1.00-\Delta\eta_p-\Delta\eta_s)$$

(*g*) At the proper value, C_{P_i} and B, read $\Delta\eta_i$ from figures 2.10 and 2.11.

(*h*) Determine propeller efficiency from the equation:

$$\eta=1.00-(\Delta\eta_p+\Delta\eta_s+\Delta\eta_i)$$

(*i*) Calculate the forward velocity (in feet per second) from:

$$V=J_A\ nD$$

(*j*) Determine propeller thrust from the equation:

$$T=\frac{\eta\times BHP\times 550}{V}$$

(*k*) Plot a chart of thrust vs. velocity (V)

(4) *Thrust vs. velocity chart utilization and limitations.* The curve thrust vs. velocity may be used to find thrust at any designated velocity in the takeoff region, and quite often may be used to find thrust at some cruise or climb condition if those conditions occur at advance ratios less than 1.00.

(*a*) Fitting a curve to experimental data consisting of only three points introduces a large probability of error and is an expedient justified only by virtue of the fact that additional data at low values of advance ratio is unavailable. Actually, the resulting curve would be more complex than an average curve through three points indicates. Under high loading conditions ($C_P/TAF>.00035$), the propeller produces higher thrust in the region of advance angles $J_A=0$ to $J_A=0.5$ than the three point curve would indicate.

(*b*) In some cases, if loading is sufficiently high, the peak thrust will be obtained at some low forward speed rather than at zero speed. A less definite trend will be indicated toward smaller-than-predicted thrust at $J_A\approx.5$ if loading is very small.

(5) *Chart assumptions.* Study of test data, on which the curves shown in figures 2.32 and 2.33 are based, indicated that profile drag loss was affected by camber factor much more than by thickness ratio and rotational speed (within the limits indicated on the curves). Therefore, the procedure was simplified by making profile loss a function of camber factor and loading factor (C_P/TAF) only, and ignoring the minor effects of other variables.

(6) *Determination of propeller performance when $J_AM>1.0$.* Calculation of propeller performance for advance ratios greater than unity requires development of profile loss curves for a specific blade (or a similar blade). A sample set of curves for one Mach number is shown in figure 2.34.

When such curves are used, it is necessary to extrapolate to the desired Mach number if that number varies from the Mach number used in development of the curves. The profile loss may be approximated also by a general formula of the form:

$$\Delta\eta_p=2+\left(\frac{C_p\times CF\times J_A\times K_1}{\sigma_p}\right)+$$
$$M\left(\left(\frac{t}{b}\right)_{0.25R}\right)K_2+\frac{M}{J_A}\left(\left(\frac{t}{b}\right)_{0.75R}\right)K_3$$

where the K's are experimental constants. In the expression given for profile loss, the first term represents skin friction loss, the second term represents pressure drag loss, and the third and fourth terms account for compressibility loss. In addition to blade profile loss (regardless of whether it is determined by generalized formula or test results), it is necessary to include shank drag loss, as in the case of low speed calculations.

Strip Analysis Method

Basic Theory of the Strip Analysis Method

In the strip analysis method, a propeller blade is considered to be composed of sections. For any given flight conditions, lift and drag of each section may be determined; the resultant forces can be resolved into section thrust and torque components the summation of which will furnish total thrust and torque of the blade. Performance of the propeller can be determined from the total thrust produced and torque required. The strip analysis method is confronted with two problems, namely:

(1) Determination of the induced flow field.

(2) Determination of the lift and drag forces on a given airfoil section operating

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in such an induced flow field. The method used to determine the flow field was discussed previously in consideration of propeller theory.

Limitations of Strip Analysis Methods

The first serious attempt to determine characteristics of propeller blade sections directly, by means of pressure distribution measurements on operating propeller blades, is under way. However, until the results of pressure distribution measurements have been analyzed and proven to be reliable, it will be necessary, as in the past, to depend on tests and calculations of the properties of two dimensional airfoil sections for prediction of propeller performance. The latter basis of analyzing propeller blades assumes that such test data is representative of that for operating propeller blade sections. The effect of flow over one section on that of an adjacent section is assumed to be secondary, despite the fact that the sections are operating at different velocities and probably have different thicknesses, camber, and angle of attack, with section boundary layers subject to varying amounts of centrifugal force. Despite these differences, the assumption that two dimensional airfoil section data may be used for propeller blade section data appears reasonable, provided the lift curve slope is corrected (especially at moderate lift coefficients and subcritical section Mach numbers). The total profile drag loss of a propeller blade under such circumstances is very small (ranging from 2 percent to 4 percent) and a large error made in computation of profile drag loss may still result in an acceptably small error in final efficiency computation. Greater errors will result in calculation of power absorbed, however.

Source of Pertinent Data

(1) *Subsonic data.* Data on a particular airfoil section, operating at given fixed values of subsonic Mach and Reynolds numbers has been obtained by test, usually, since a satisfactory theory for determination of subsonic drag has not been established and calculation of the theoretical lift coefficient was laborious, and not completely accurate. NACA has accumulated considerable data for airfoils operating at subsonic speed. NACA publications include descriptions of families of airfoils, along with notes on drag and compressibility, in addition to the basic test data.

(2) *Transonic flow region data.* Data in the transonic region is very difficult to obtain, largely because of "choking" in the conventional wind tunnel. Tunnel choking usually occurs at a slight increment of Mach number above the critical ($M=1$). Two dimensional section data in the supersonic regime (attached shocks) may be computed by one of several theoretical methods. Good accuracy will be obtained for wedge, circular arc, and similar sections, provided the angle of attack is small, thickness ratio is low, and a skin friction drag coefficient is added to the theoretically computed drag coefficient. Usually more complex methods of computation will give better accuracy. For sections having a thickness ratio of five percent or less, the linear theory has been found to give results very similar to more complex theories. Transonic section data has been obtained by the Department of Defense and is available to those authorized access to such information.

(3) *Empirical data for airfoil sections.* Airfoil section data normally is given in the form of curves of c_l, c_m and c_d versus angle of attack for an airfoil section of a given series, camber, and thickness ratio.[1] Data in this form has been derived from flow conditions at a specific Reynolds number. Therefore, subsonic and transonic propeller section data for only one family of airfoils would require similar curves for at least 25 different cambers and thicknesses with flow conditions for a minimum of 25 different Mach numbers. Hence, a minimum of 625 sets of curves would be required, and difficult interpolation would be required for intermediate sets of parameters. A set of airfoil section characteristics has been developed to reduce the number of charts and to simplify interpolation within those charts. The airfoil characteristics were obtained by replacement of conventional curves by empirical formulae, wherever possible. The formulae are given as functions of Mach number and thickness ratio, usually. Reynolds number effects are introduced by using a separate skin friction drag coefficient appropriate to the Reynolds number and turbulence.

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[1] In the discussion of strip analysis, c_l and c_d are usually denoted by C_L and C_D, due to the fact that the resultant section coefficients are dependent upon the induced flow field in addition to the variables mentioned and hence are not section coefficients in the pure sense.

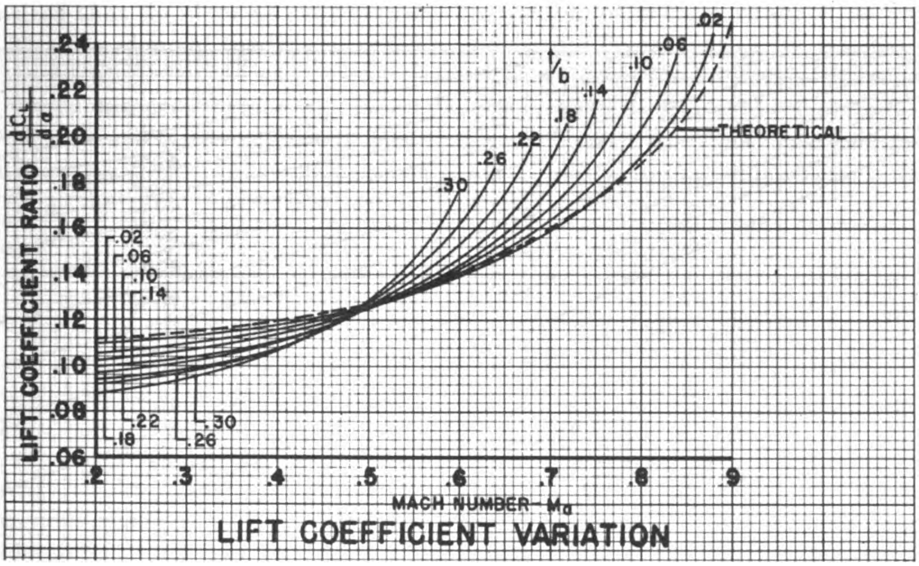


Figure 2.35.

Applications and Limitations of Airfoil Data Presented

The airfoil data discussed herein (and presented in the form of curves) apply to the NACA 16, NACA 64, and NACA 65 series airfoils. The 16 series airfoils were developed to have high critical Mach numbers, while the 64 and 65 series airfoils were developed for low profile drag. The 16 series sections have been used for most moderate and high power propeller installations since the start of World War II. There is a growing tendency towards use of the 64 and 65 series airfoils for moderate speed propeller sections, particularly in the thicker inboard part of the blade where these airfoils have a lower profile drag loss. A higher percentage of laminar flow should be used when calculating skin friction drag for the 64 and 65 series airfoils.

Variations of Airfoil Section Lift Coefficients

(1) *Two dimensional airfoils.* The curve of lift coefficient versus angle of attack closely approaches a straight line over the usual range of lift coefficients. The slope of this lift coefficient curve is a function of Mach number and thickness ratio. Rather than plot a series of lift coefficient curves, the slope of the lift curve as a function of Mach number and thickness ratio has been plotted as shown in figure 2.35.

Lift coefficient may be determined by multiplying the slope of the lift coefficient curve ($dC_L/d\alpha$) by the angle of attack (α), the latter quantity being determined in accordance with strip analysis procedure. Symmetrical sections have zero lift at zero angle of attack. Nonsymmetrical (cambered) sections have zero lift at some angle other than zero, usually negative. It is assumed that the lift curve slope is the same for cambered sections as for symmetrical sections of the same geometric family and thickness ratio, operating under identical Mach number conditions.

However, to find the proper lift coefficient, the slope must be multiplied by an angle equivalent to the sum of the actual angle of attack and the zero lift angle. (It is assumed that all practical combined sections have negative zero lift angle α_D. This angle of attack adjustment will account for the shift of the lift curve with camber change. The correction angle α_D may be obtained from curves such as those shown in figure 2.36 wherein α_D is plotted as a function of C_L and M_X.

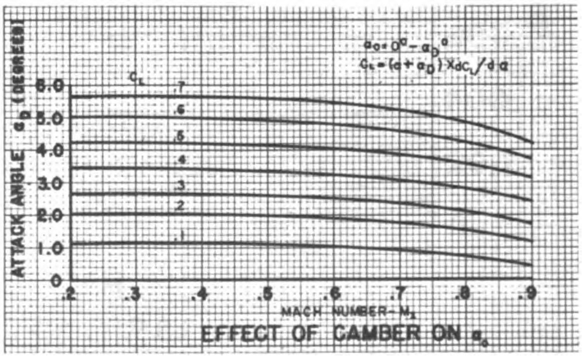
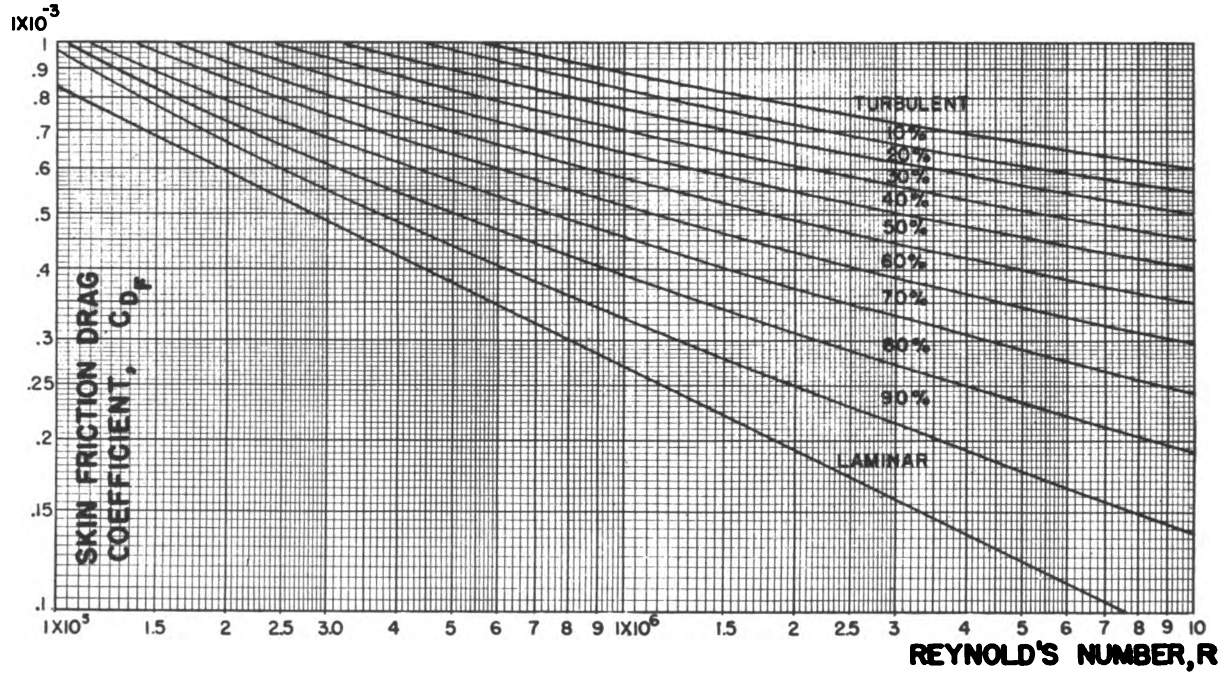


Figure 2.36.



VARIATION OF SKIN FRICTION DRAG COEFFICIENT WITH REYNOLD'S NUMBER

Figure 2.37.

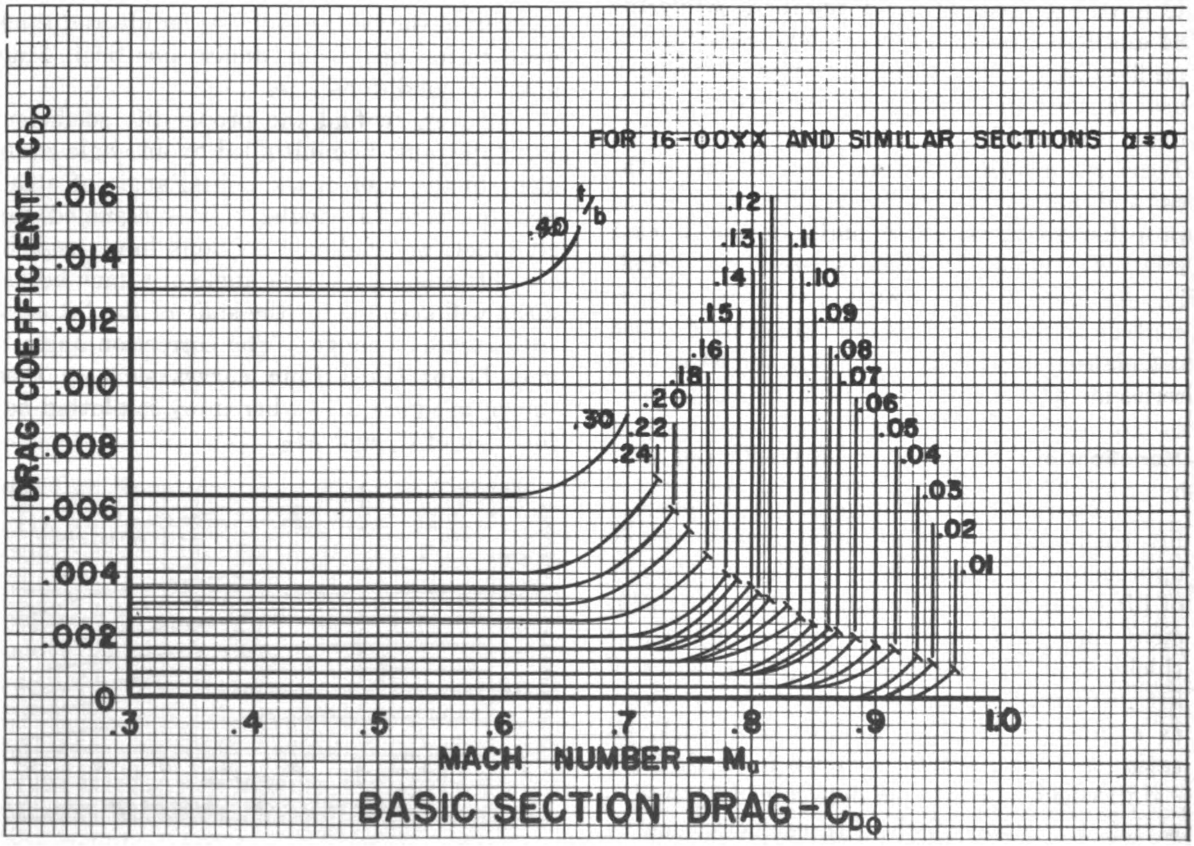


Figure 2.38.

It is emphasized that the slope as determined from figure 2.35 is the slope of the lift curve for a two dimensional airfoil.

(2) *Three dimensional airfoils.* Three dimensional airfoils (or propeller blades) will have a lift curve whose gradient or slope is smaller than a corresponding two dimensional airfoil. Consequently, for a given angle of attack, data obtained from figure 2.35 will result in a lift coefficient that is too high for three dimensional airfoils. To obtain representative lift coefficients for three dimensional airfoils using lift and slope data from figure 2.35, correction factors as outlined in the following table must be applied to the slope.

TABLE II–1. *Lift Curve Slope Correction Factors for Three Dimensional Airfoils*

Radial Station (Ratio $=r/R$)	Correction factor
(.2), (.3), (.45), (.6), (.7)	.85
(.8)	.80
(.9)	.70
(.95)	.65

The linear portion of the lift curve varies with (t/b) and (M_a). However, a maximum lift coefficient of (0.7) may be assumed as a point of curve flexure beyond which the lift curve of all sections no longer will be linear. In view of the last statement, data and procedures just outlined are not applicable for airfoils having $C_L > 0.7$.

Airfoil Section Drag

(1) *General considerations.* Total airfoil section drag may be obtained by a summation of three increments of section drag; namely, thin section skin friction drag, basic section drag and lift coefficient component of section drag. Methods for determination of the increments of airfoil section drag are discussed in the following paragraphs.

(2) *Skin friction drag.* Skin friction drag is a function of type of flow (laminar, turbulent, or a combination of both) and Reynolds number under which the section is working. Usually, outboard propeller sections are assumed to be at 50 to 90 percent laminar flow because of the effect of centrifugal force on the boundary layer. The effect of centrifugal force is favorable to reduction of section drag; it is analogous to boundary layer control by suction which has been shown to have reduced drag characteristics. While actual tests have not been made to confirm this effect directly, the high efficiencies obtained in certain propeller tests on wind tunnel dynamometers tend to confirm the effect. The small differences between efficiencies based upon ideal and test considerations can be explained only by assuming a minimum section drag. No attempt has been made to account for interactions between boundary layer and compressibility phenomena.

The skin friction drag coefficient is shown in figure 2.37 as a function of Reynolds number and percent laminar flow.

While 50 to 90 percent laminar flow is representative of the outer blade sections, thick inboard sections, sections ahead of radial engines, and sections having protuberances (such as deicing elements and cuff attachments) probably have 25 to 50 percent laminar flow. Since the actual surface area of a function of its thickness ratio, and since the skin friction drag will increase with thickness, the curves of figure 2.37 should be considered as applying only to thin airfoil sections. Additional skin friction drag penalty for thicker sections will be included in basic section drag.

(3) *Basic section drag.* Basic section drag consists, essentially, of all drag experienced by an airfoil section at zero lift other than skin friction drag of a thin section. Basic section drag (C_{D_O}) is made up of incremental skin friction drag, pressure drag, and compressibility drag. The magnitude of basic section drag is shown in coefficient form in figure 2.38 as a function of thickness ratio and Mach number.

A cambered section will not have as high a basic critical Mach number as does a symmetrical section. Compensation for variation of critical Mach number between different airfoil sections may be obtained by adding a Mach number increment to the actual section Mach number before interpolating from figure 2.38. The approximate increment to be added is equal to .01 M_a for each 0.1 C_{l_i}. Therefore, the equivalent Mach number to be used with figure 2.38 is the sum of the actual section Mach number and the increment due to camber.

(4) *Lift coefficient component of section drag.* An airfoil section operating under conditions to

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produce a finite lift coefficient has an additional drag induced upon it. This increase in airfoil drag is a function of the lift coefficient and is produced by two factors, namely:

(*a*) Increased skin friction associated with increased local velocities.

(*b*) Increased pressure drag of airfoil sections operating at lift coefficients other than those for which the camber was designed. The cambered sections, operating at design lift coefficient, should experience only an increased skin friction drag; this effect may be neglected as a first approximation.

The curves of figure 2.39 show drag due to lift as a function of the quantity

$$\left(\frac{\Delta C_D}{(C_L-C_{l_i})^2}\right)$$

versus Mach number corrected for thickness,

$$\left(\frac{M}{.9-(t/b)}\right)$$

For a section with zero camber ($C_{l_i}=0$), the lift coefficient (C_L) previously determined must be squared and multiplied by the chart quantity:

$$\left(\frac{\Delta C_D}{(C_L-C_{l_i})^2}\right)$$

to obtain drag due to lift, ΔC_D. It will be noted that the relationships given, reveal the parabolic shape of the drag versus lift coefficient curve at a given Mach number and thickness ratio.

For cambered sections involving a difference between working and design lift coefficient, the quantity ($C_L-C_{l_i}$) may be determined, then squared and multiplied by the quantity:

$$\left(\frac{\Delta C_D}{(C_L-C_{l_i})^2}\right)$$

to obtain the change in drag coefficient, (ΔC_D). This procedure has been established to credit the airfoil for favorable pressure drag of a cambered section at, or near, the design lift coefficient.

Strip Analysis Procedure

(1) *General instructions.* The actual strip analysis of a propeller may be accomplished using a form similar to that shown in figure 2.40.

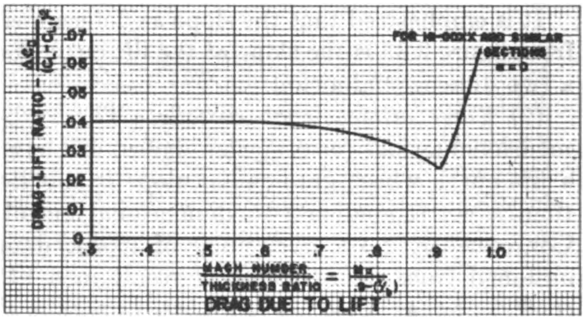

Figure 2.39.

The form shown has been prepared to make it self-explanatory. Complete data of a given propeller flight condition will be required. Engine power, speed, and reduction gear ratio along with airplane speed and altitude are necessary to complete the analysis. Furthermore, a complete description of the external shape of the propeller blade will be required. This data can be obtained from the blade drawing except for C_{l_i}, not usually given on drawings. (C_{l_i} may be determined by the methods outlined).

The sample form has appropriate spaces at the top of the page (along with the first four item number spaces) to record all data pertinent to the propeller analysis. The recorded information will define the operating conditions and physical characteristics of the propeller.

(2) *Blade angle setting* (*item 5*). Since the blade angle setting shown on the drawing of a variable blade angle propeller blade is an arbitrary value, an increment of angle is added or subtracted at each station to establish the blade in the setting required for a particular flight condition. This increment is included in line 5. The blade angle increment will be known for two position propellers, but in the case of a constant speed propeller, the exact blade angle setting normally is an unknown. (The purpose of a propeller control system and pitch change mechanism is to vary the blade angle, as required, to hold a constant propeller speed.) Normally, no indication of the exact blade angle setting can be given. Therefore, it will be necessary to assume a suitable blade angle setting based upon test results or previous strip analysis results of similar propellers.

(3) *Blade geometry and operating condition items.* Solidity (item 6) may be obtained from knowledge of the propeller geometry. The factors contained in items 7 and 8 are to be

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used to obtain the geometric angle of advance, item 9. The ideal geometric velocity (item 10) and the local Math number (item 11) can be obtained by direct calculation. Reynolds number (item 12) must be calculated for each section. The section geometric angle of attack (item 13) will be the next item to be calculated. The absolute value of zero lift angle must be obtained and added to the geometric angle to obtain item 15.

(4) *Determination of induced angle.* Calculation of the induced angle is dependent on knowledge of the lift coefficient which, in turn, requires knowledge of the airfoil section dimensional angle of attack, (α_0). However, the airfoil section dimensional angle of attack can be found only after the induced angle has been found. Therefore, determination of the induced angle must be an iterative process or a parallel determination with evaluation of the two dimensional angle of attack of the section. The latter approach is the shortest and may be accomplished geometrically by an intercept method. In this method, variation of induced

Figure 2.40.—Propeller Strip Analysis

(Sample Form)

Airplane........ Eng........ G. R........ Condition........ $\beta_{.75R}$........ SBHP........ Eng. r. p. m........
Prop. r. p. m...... Alt...... V_{MPH}...... V_{FPS}...... a_{FPS}...... M_a...... M_T...... Dia...... No. Blds........
Rot.......... J_A........ C_P.......... d/D.......... Blade.......... Hub.......... Section data............

Item No.	Blade stations: $x=r/R$							
	.2	.3	.45	.6	.7	.8	.9	.95
	Basis of Item Evaluation*							
1.......	b/D from blade characteristic							
2.......	t/B from blade characteristic							
3.......	c_{l_i} from blade characteritsic							
4.......	β CHAR from blade characteristic							
5.......	$\beta=④+a$ constant angle							
6.......	$\sigma_p=\frac{B①}{\pi x}$ =a constant $\left[\frac{\boxed{1}}{x}\right]$							
7.......	x/J_A							
8.......	$J_A/\pi x=\frac{.3183}{⑦}$							
9.......	$\phi_o=\tan^{-1}⑧$							
10......	W or $V_R=V/\sin ⑨$ (V in FPS)							
11......	$M=10/⊡$							
12......	$R_N=⑩\cdot①D\rho/\mu$							
13......	$\alpha=⑤-⑨$							
14......	α_D from airfoil data, Fig. 2.36							
15......	$\alpha_D+\alpha=⑬+⑭$							
16......	$(dC_L/d\alpha$ from airfoil data, Fig. 2.35							
17......	$[\sigma_p(dC_L/d\alpha_1)]$ from chart Figs. 2.7, 2.8, and 2.9							
18......	$(dC_L/d\alpha_1)=⑰/⑥$							
19......	$(dC_L/d\alpha)/(dC_L/d\alpha_i)=⑯/⑱$							
20......	$1+[(dC_L/d\alpha)/(dC_L/d\alpha_i)]=(1+⑲)$							
21......	$\alpha_o=⑮/⑳$							
22......	$\alpha_i=⑮-㉑$							
23......	$C_L=⑯\cdot㉑$							

Item No.	Blade stations: $x=r/R$							
	.2	.3	.45	.6	.7	.8	.9	.95
	Basis of Item Evaluation*							
24......	$\sigma_p C_L=⑥\cdot㉓$							
25......	$(C_L-c_{l_i})=㉓-③$							
26......	$M+.1_{c_i}=⑪+[.1③]$							
27......	$\Delta\ C_{D_o}$ from airfoil data Fig. 2.39							
28......	These items ore sometimes used to modify							
29......	drag at high speeds, etc.							
30......	$\Delta\ C_D/(C_L-c_{l_i})^2$ from airfoil data, Fig. 2.39							
31......	C_D lift$=㉚\ [㉕]^2$							
32......	C_{D_j} from skin friction chart, Fig. 2.37							
33......	C_D total$=㉖+㉗+㉛+㉜$							
34......	$\tan\gamma=㉝/㉔$							
35......	$\phi=⑨+㉒$							
36......	$\cot\phi=\cot ㉟$							
37......	$\cot\phi-\tan\gamma=[㊱-㉞]$							
38......	$\sin\phi=\sin ㉟$							
39......	$\alpha_i/57.3=㉒/57.3$							
40......	$\cot\phi+(\alpha_i/57.3)=㊱+㊴$							
41......	$[\cot\phi+(\alpha_i/57.3)]^2=[40]^2$							
42......	$dC_T(/dx=\frac{\pi^3x^3}{4}\ \frac{㉑㊲}{㊳㊶}$							
43......	$\cot\phi\ \tan\gamma=㉞\ ㊱$							
44......	$1+\cot\phi\ \tan\gamma=1+㊸$							
45......	$dc_Q(/dx=\left[\frac{x}{2}\right]\frac{㊹㊷}{㊲}$							

*Numerical values of the item number circled, as previously determined, are to be used to complete the operations indicated for a given item.

C_T.................... T.................. η.................. η Net...............
C_Q.................... C_P.................. SBHP..............
By.................. Date:...............

angle with the product of lift coefficient and station solidity (for any particular station, advance ratio and number of blades) must be plotted on the same graph as the curve of variation of blade section lift coefficient with section angle of attack. The point of intersection of the two curves will identify the induced angle.

The section angle of attack used in plotting the latter curve is the sum of the geometrical and zero lift angles minus the particular induced angle. Then, the section lift coefficient may be plotted as a function of that particular induced angle. The lift coefficient must be multiplied by station solidity in order to use the same scale as the induced angle versus solidity lift curve. Since both the section lift coefficient and induced flow field have been made linear functions of angle, the induced angle may be determined by comparing numerical values of curve slopes rather than plotting the variations of the product of solidity and lift with angle of attack and induced angle of attack. The numerical comparison will be accomplished and recorded in items 17, 18, 19, and 20 of the analysis form, figure 2.40. Proper evaluation of the preceding items will produce the angle of attack (α) item 21 and the section induced angle (α_i) item 22.

(5) *Lift and drag coefficients and resultant force on the section.* Evaluation of section angle of attack will permit determination of the section lift coefficient (item 23), and total section lift force coefficient (item 24). Completion of items 25 through 32 will permit determination of the section drag coefficient. The ratio of section drag over lift in terms of Tan γ' (item 34), can be found readily. The angle that the actual resultant velocity makes with the plane of rotation should be determined, next: which will complete the data necessary to evaluate the section resultant force numerically and to orientate that force with respect to the propeller disc.

(6) *Summation of propeller thrust and torque coefficients.* To complete the strip analysis and obtain total propeller thrust and torque, the section resultant force should be resolved into thrust and torque components which are added algebraically and vectorially composed into resultant forces. Coefficients may be used in the calculations to simplify the terms. Integration of section thrust and torque coefficients along the blade radius may be done graphically or by numerical methods.

(7) *Strip analysis method summary.* Propeller analysis by the strip method consists of a process of determining section lift and drag coefficients referred to a theoretically determined section velocity vector, changing those coefficients to another coordinate system, and summing up section thrust and torque forces to obtain total propeller thrust and torque. The assumptions necessary to strip analysis methods have been indicated in previous discussions, but may be restated as follows:

- (*a*) The section induced velocity may be determined by the incompressible fluid theory.
- (*b*) Lift and drag forces, along with forces which introduce an effective induced angle for a given section are independent of the forces acting upon adjacent sections. These quantities are fixed only by propeller geometry and operating conditions. This assumption implies that the slopes of the inflow curves, as given in figures 2.7, 2.8 and 2.9 are not affected by inflow at other stations.
- (*c*) The theory has been developed for a case of optimum load distribution along the blade radius; however, the strip analysis method need not be limited to this case. In plotting curves of incremental thrust and torque against blade radius, the curves should be terminated at that radius corresponding to propeller hub or spinner, before being integrated.

Accuracy of the Strip Analysis Method

Accuracy of the strip analysis method is quite good at low and moderate speeds. Table II-2 shows a comparison of calculated and actual performance of model propeller blades tested in a wind tunnel.

Steady Stress Calculations

By an extension of the strip analysis method to zero speed, the aerodynamic loads for use in steady stress structural calculations can be obtained. Strip analysis results in the form of lift and drag coefficients and induced angles can be expressed readily as normal and chordwise forces, or as a total resultant force. Details of this procedure are not shown here because, as

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stated in the stress analysis section, aerodynamic loads are not critical, usually, in steady stress analysis. The flatwise bending load, customarily, has been approximated by distributing known total thrust along the blade so that loading is proportional to the quantity (br^2). A typical graph of the resultant force (R) and resultant force direction with respect to a line perpendicular to the blade section expressed as an angle (a–r) is shown in figure 2.41.

TABLE II–2. *Accuracy of Strip Analysis Method*

M_a	J_A	β (.75R)	Tests		Calculated		Percent Error	
			C_P	η	C_P	η	C_P	η
0.366	2.20	45°	0.102	92.3	0.100	93.0	−2	0.7
.435	2.20	45°	.109	92.6	.107	92.7	2	.1
.370	2.20	45°	.134	94.1	.127	92.6	−5	−1.5
.530	2.50	50°	.122	91.0	.130	89.9	6	1.1
.516	2.20	45°	.126	91.9	.120	91.5	−5	−.4
.570	2.20	45°	.117	86.4	.115	87.7	−2	1.3
.530	2.30	45°	.129	91.2	.127	90.2	−2	−1.0
.300	2.00	45°	.282	86.5	.286	88.2	1	1.7
.400	2.10	45°	.272	87.4	.276	88.9	1	1.5
.500	2.20	45°	.249	86.3	.266	86.9	7	.6

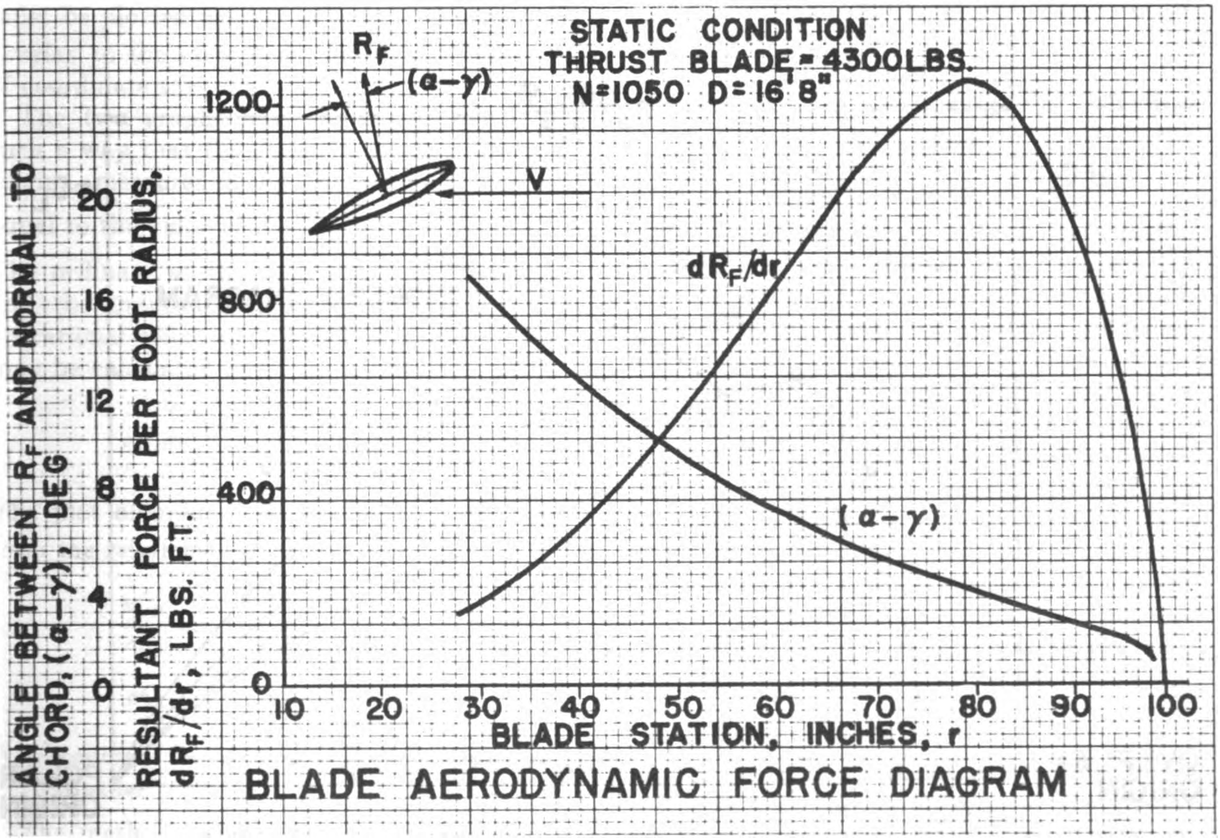

Figure 2.41.

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Simplified Performance Method

General Characteristics of the Method

An intermediate method between the chart method and the strip analysis method has been found useful. This simplified performance method has many advantages over the pure chart method and involves fewer calculations than the strip analysis method. This method may be considered as a one strip method in which the lift and drag polar will be obtained from propeller tests, instead of from two-dimensional airfoil tests. The method admits corrections for solidity, camber, thickness, number of blades, dual rotation and Mach number. The principal weakness of the method is that effects of radial distribution of the first three of these factors cannot be shown. The simplified performance method has some advantages over the strip analysis since the drag polars contain three dimensional flow effects which are not included in the strip method of analysis.

Outline of the Simplified Performance Method

This method consists of obtaining the total thrust and drag coefficient, as if the total effect were concentrated at the seven-tenths radius, from test measurements. The induced drag may be computed by means of Goldstein theory and subtracted from the total drag; thus, yielding data for a drag polar; viz., a plot of the drag coefficient (C_{D_x}) resulting from all effects other than lift, versus the lift coefficient. There will be one curve for each value of test rotational speed, which may be labeled *ND*. Because of the similarity of flow, this chart can be plotted as (σC_l) versus (σC_{D_x}) which holds for all solidities, regardless of whether the solidity results from dimensional changes in blade chords or in the number of blades. This fact permits extrapolation for solidity, provided the proper Goldstein correction factor for a finite number of blades is employed when the new induced drag is added and the corresponding thrust and torque coefficients determined.

Corrections and Extrapolation of Plotted Curves

The polar can be corrected for camber by shifting the curve parallel to the σC_L axis until design camber of the test blade coincides with the new required camber and by extrapolating

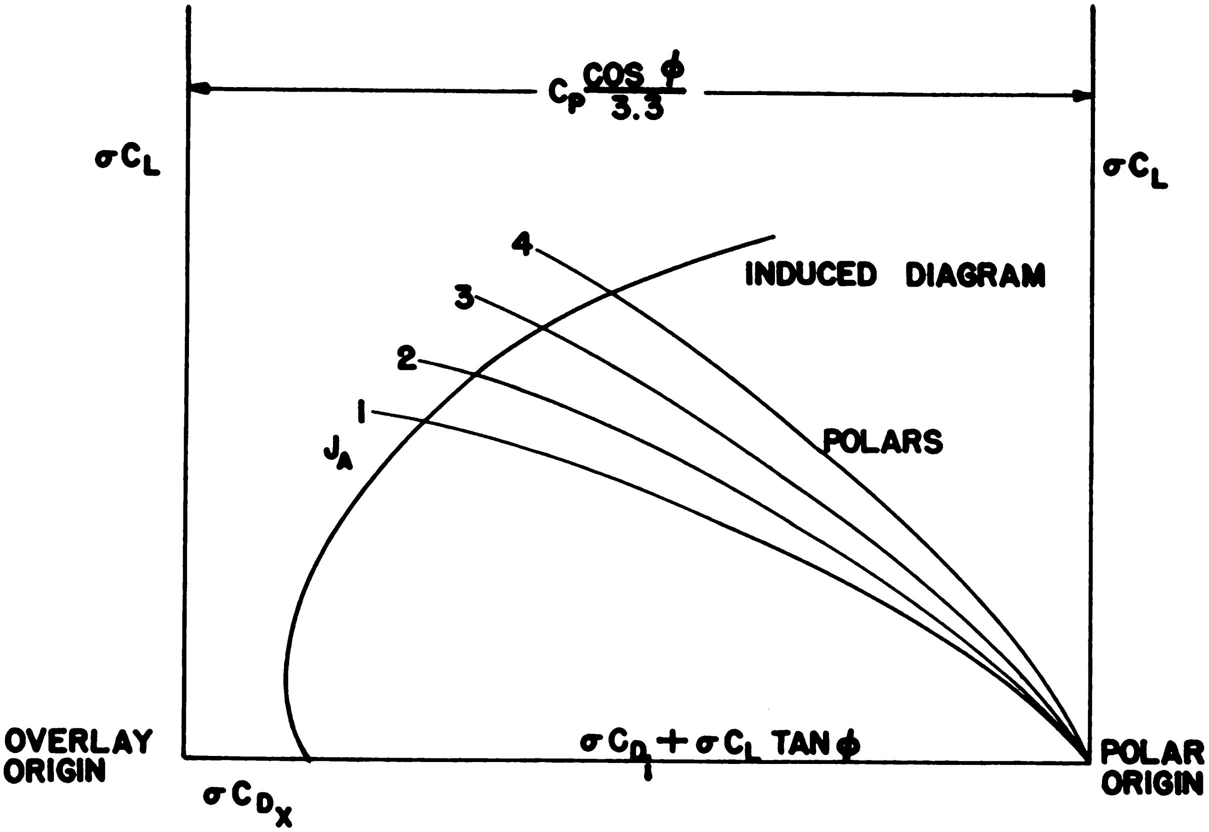

Figure 2.42.—Polar-induced diagram curves.

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the polar below the test points in a manner similar to that for test results of two dimensional airfoil sections.

Plots of various values of the quantity *ND* may be used in making extrapolations for diameter and speed changes. Each curve represents, in a way, a constant Mach number and speed condition.

The polar can be corrected for thickness by shifting points of the curve, parallel to the σC_{D_x} axis, an increment equal to the corresponding increments obtained from two dimensional airfoil test data.

Propeller Performance by the Simplified Performance Method

The performance of the propeller at any operating condition may be determined by the method outlined by Mr. Driggs.[2] The curve, σC_L, versus $(\sigma C_{D_i}+\sigma C_L \tan\phi)$ should be plotted for various advance ratios on a left hand set of coordinate axes. From the polar curve (corrected for proper solidity), of the advance ratio, J_A, and velocity involved, values of σC_L must be plotted against σC_{D_x} in a transparent overlay to the same scale, on a right hand set of coordinate axes.

The two graphs must be superimposed in such a way that the distance between the two origins, measured along the abscissa, will be equal to the value of: $C_P\frac{\cos\phi}{3.3}$.

The ordinate at the intersection of the polar and the induced diagram curve will be the operational value of σC_L. The value of σC_D may be calculated from the relation:

$$\sigma C_D=\frac{C_P\cos\phi}{3.3}-\sigma C_L\tan\phi$$

The plot of induced drag σC_{D_i} may be made from the relationship:

$$\frac{\sigma C_{D_i}}{\sigma C_L}=\sin\alpha_i$$

$$\sigma C_L= 4\,K\tan\alpha_i\sin(\phi+\alpha_i)$$

Application of the Method to Dual Rotation Propeller

The method has been extended to apply to determination of the performance of a dual rotating propeller based upon the tests of a single rotating propeller. The procedure is exactly the same, except for calculation of the induced drag, in which it is assumed that 60 percent of the rotational velocity will be recovered by the second blades. The Goldstein factor is the one corresponding to the total number of blades in the propeller. Precisely, it is assumed that:

$$\frac{\sigma C_{D_i}}{\sigma C_L}=\sin\alpha_i\sqrt{\cos^2(\phi+\alpha_i)+(1-P)^2\sin^2(\phi+\alpha_i)}$$

where *P* is the percentage of swirl recovery and *K* is the Goldstein factor for the total number of blades, σC_L being the same as defined in Propeller Performance by the Simplified Performance Method on page 50.

Static Thrust Determination by the Simplified Performance Method

In case the propeller has not been tested statically, the polars may be plotted versus test Mach number and extrapolated to zero, thereby yielding results for the static thrust determination.

Aerodynamic Factors in Propeller Selection and Design

Comparison—Propeller Selection vs. Design

The procedures to be used in selecting a propeller are quite similar to those used in designing a propeller. In selecting a propeller, the performance of several available propellers should be studied over the full range of airplane operating conditions; in the design of a propeller, identical procedures are followed, using several paper designs of propellers which might be built. The essential difference in procedure is that close examination of performance calculations may reveal possible modifications to proposed design which would improve performance; whereas selection involves choosing the best available propeller to serve a given purpose.

Basis of Propeller Design

At the present time, no adequate method exists whereby the optimum propeller design may be found by solving a single expression. A practical propeller must be designed for an operating condition that is a compromise of

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[2] Driggs, I. H., "Simplified Propeller Calculations," Journal of Aeronautical Sciences, Vol. 5, page 337, July 1938.

specific requirements for several different operating conditions (i. e., takeoff, climb, cruise, and partial engines climb for transport aircraft). Parasite losses of a propeller installation are not subject to theoretical analysis with any degree of accuracy, which adds to the complexity of design. A theoretical method does exist whereby a propeller may be designed for minimum induced loss for a single operating condition. However, since a propeller designed for minimum total loss is desired, practical propeller design remains a trial and error process.

Selection of an Appropriate Method of Analysis

It has been shown that two methods of propeller performance calculations are available for $J_A > 1.0$. These two methods, strip analysis and summation of losses, differ widely in time required and complexity. Therefore, it is advisable to use the shortest method, i. e., summation of losses, to determine propeller size (diameter, number of blades, and approximade blade width) and use the more accurate strip analysis to select or determine the final details of blade shape (thickness ratio, blade angle, section camber and chord distributions).

Preliminary Considerations in Propeller Design

Before a propeller design or selection study can be started, it is necessary to have complete knowledge of the airplane performance. Definite minimum figures serve to simplify the inevitable problem of compromise of various performance factors involved in the final selection of a propeller. Important factors involved in propeller selection or design include:

(1) Location of the propeller relative to airplane structure.

(2) Available clearances for the propeller.

(3) Airplane mission.

(4) Relative importance of various operating conditions and performance minimums (such as maximum runway roll required to obtain speed and lift to clear a 50-foot obstacle at design gross weight).

(5) Engine data, speed and gear reduction ratio for various flight conditions.

(6) Engine specific fuel consumption—Best cruise-propeller speed combination involves the maximum value of the quantity, efficiency divided by specific fuel consumption.

Propeller Selection

The background data enumerated provides a basis for selection of a series of propeller diameters with various combinations of numbers of blades for preliminary evaluation. The selection will be predicated upon previous experience with several obvious options. The selection will be influenced by engine gear ratio.

(1) *Variable engine gear ratios.* If the airplane clearances are fixed, with engine gear ratio variable, the maximum propeller diameter that can be cleared should be selected, along with several smaller diameters, for investigation of suitability.

(2) *Fixed engine gear ratios—Reciprocating engines.* If the engine gear ratio is fixed, the maximum value of the quantity (πND) should be 900 feet per second. Usually, the relationship $\pi ND = 900$ will furnish an optimum value of propeller diameter for subsonic applications. However, propellers having diameters both larger and smaller than that indicated by $\pi ND = 900$ should receive attention, also. Propeller diameter will vary widely for given takeoff horsepower of reciprocating engine aircraft, depending upon type of supercharging and importance attached to takeoff performance.

(3) *Turbine engine propellers.* Estimation of turbine engine propeller diameter may be made using the equation:

$$D = K\sqrt{SBHP/\sigma}$$

where $SBHP$ and σ are determined by design or most important flight conditions. $K = .170$ for four blade subsonic, single rotation propellers or $K = .135$ for eight blade, subsonic, dual propellers. Turbine engine characteristics match efficient power absorption potential of propellers much closer than characteristics of other engine types.

As in the case of propellers for reciprocating engines, the determination of a probable optimum diameter of a turbine propeller from the relationship given:

$$D = K\sqrt{SBHP/\sigma}$$

should not preclude study of propellers of both larger and smaller diameters.

(4) *Propellers for aircraft in design stage.* Aircraft still in the design stage with clearances not established permit study of a wider range

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of propeller diameters for possible application. The effect of propeller diameter on the weight of airplane components must be considered in selecting an appropriate propeller size. Some reduction in diameter can be achieved for a given power and efficiency, by increasing propeller solidity, which can be done either by using wider blades or more blades. However, the increase in weight and cost must be considered as a part of the increase in solidity study.

(5) *Propeller size determination.* The important factors in propeller size determination are illustrated in figure 2.42. The first chart shows a typical comparison of performance at two flight conditions, with fixed powers and speed as functions of diameter and number of blades. Usually, the two flight conditions shown are considered to be most important. Additional comparisons may be added at a risk of complicating the evaluation. Both takeoff thrust and cruise efficiency increase with increasing diameter: takeoff thrust has a rising characteristic but with the slope of the curve decreasing with increasing diameter, whereas the cruise efficiency increases to a maximum value at some fixed diameter, beyond which efficiency decreases. These curves are characteristic of propellers and analogous to the concept of *L/D* ratio changing with lift coefficient, in the case of the two dimensional airfoil. A propeller of very large diameter would be required to obtain peak thrust values at takeoff, which at cruise and high speed conditions probably would be underloaded. The result would be that the propeller airfoil sections would operate below C_L for *L/D* maximum and propeller efficiency would fall off rapidly. Dependent on the values of blade section thickness and Mach number, fluid compressibility will have the effect of decreasing propeller efficiency with increasing size, when operated at constant speed.

(6) *Effect of propeller weight.* (*a*) Propeller Weight vs. Performance—General. The variation of propeller weight with diameter and numbers of blades must be obtained from structural studies. Propeller diameters above a certain value require stronger supporting structures which mean increased airplane weight. This increased weight must be used in calculating the percent of the airplane weight, chargeable to the propeller. These statements are represented graphically in figure 2.42. The problem of compromising propeller weight and performance must be solved individually for each airplane application; however, a few general observations are applicable to all cases. Airplane performance will be improved by an increased propeller performance and decreased

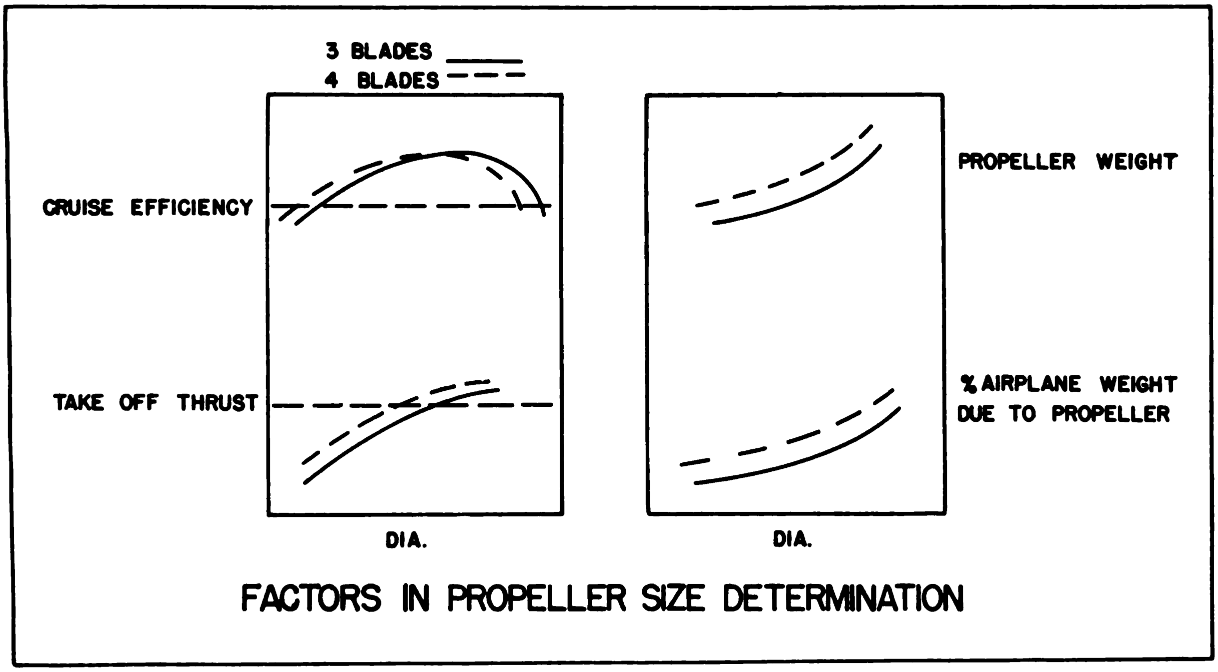

Figure 2.43.

by increased propeller weight, but the relative effects of these two factors vary with different performance conditions. The relative propeller effects on airplane performance also depend on governing factors of the airplane's gross weight which may be established by performance requirements, airplane capacity or structural requirements. If performance or capacity govern gross airplane weight, a much larger increase in propeller weight will be justified than would be justified by structural limitation wherein any increase in propeller weight means a corresponding loss in fuel weight.

(*b*) Magnitude of propeller weight. Total propeller weight, exclusive of additional airplane structure required for larger sizes, normally should be within the range of one and one-half to three percent of airplane gross weight. In light high powered aircraft, the propeller weight may be equivalent to as much as six percent of the gross weight. The extremes of variation in weight from the average weight of propellers available for a particular installation will not exceed ±25 percent. Propeller performance variations are represented in table II–3.

The tabular values of propeller performance variations seem to indicate that performance is the prime consideration in selection of propellers, which is not necessarily true even though percentage figure variations are greater for performance than weight factors. The relative effects of both performance and weight at each of the four significant operating conditions must be examined before the overall or relative value of each factor can be established.

(*c*) Propeller Weight vs. Performance (Takeoff and Climb). During takeoff, the problem is to accelerate the airplane to flying speed in the shortest possible distance. This objective will be achieved whenever the PW factor is

$$PW=\frac{(T-D)}{(W_A+W_P)}$$

in which

T=total propeller thrust
D=total airplane drag
W=weight of airplane less propeller
W_P=weight of propeller

This expression indicates that any propeller weight increase is allowable which causes PW to increase. The negligible effect of a change in W_P on airplane drag has been neglected. Since D is much larger with respect to T than W_P is with respect to W_A and because of the minus sign in the numerator, it is apparent that a considerable percentage increase in propeller weight may be tolerated in order to obtain a small increase in propeller thrust, takeoff performance being the criterion. The use of assist takeoff devices is an example of this principle.

TABLE II–3. *Variations in Propeller Performance*

Performance condition	Percentage performance variations	
	Minimum	Maximum
Takeoff thrust	6	25
Climb	4	15
Cruise	2	10
High speed	5	20

The performance-weight problem in climb is essentially the same as during takeoff, the only difference being that excess thrust can be used to raise the airplane vertically rather than accelerate it. The same principle of a large percentage propeller weight increase being justified for a moderate increase in efficiency applies to climbing conditions.

(*d*) Propeller Weight vs. Performance (cruise). During cruise condition, the problem is to obtain maximum range for a fixed quantity fuel weight plus weight chargeable to the propeller (W_F+W_P); or to obtain maximum payload (W_c) for a given range; or to carry a given load (W_c) over a given range for a minimum weight of fuel (W_F). Speed and altitude are not considered independent variables during cruise conditions. For the pruposes of this analysis, it has been assumed that the cruise flight plan has been chosed to achieve maximum performance ratios [airplane (L/D) and power plant (η/C); where C is the engine specific fuel consumption, pounds of fuel per brake horsepower per hour], and to give acceptable speed-altitude variations.

The classic Breguet formula for airplane

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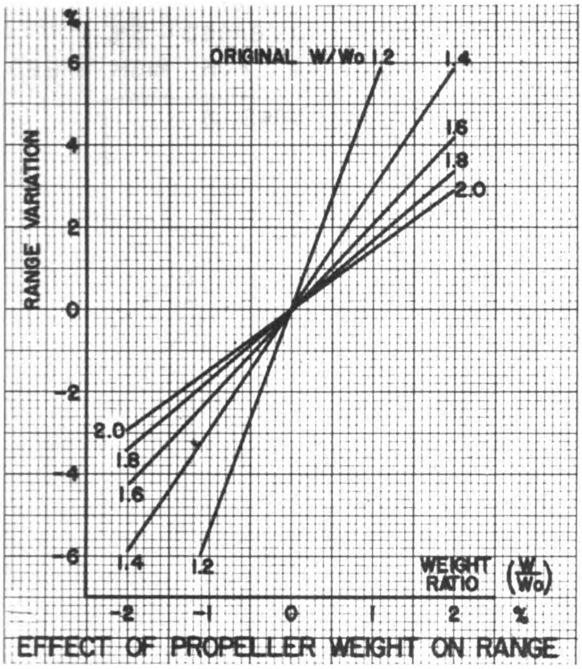

Figure 2.44.

range is useful in clarifying the propeller performance-weight relationship during cruise. The Breguet formula is:

$$R=K\left(\frac{L}{D}\right)\left(\frac{\eta}{C}\right)\log_{10}\left(\frac{W}{W_o}\right)$$

where

R=Range
W=Airplane weight loaded
W_o=Airplane weight at tend of cruise
K=863.5 (range in statute miles)
=749.5 (range in nautical miles)

whence

$W_f=(W-W_o)$

The range is directly proportional to propeller efficiency, and directly proportional to the logarithm of a weight ratio, of which propeller weight is a very small increment appearing in both numerator and denominator of the ratio. The curves of figure 2.44 illustrate the effect of propeller weight on range; Breguet's formula was used to obtain range values with L/D and η/C being held constant.

As the original value of W/W_o increases, the effect of a small change in propeller weight becomes less pronounced. This is to be expected, of course, since the percentage change in fuel available, for a given change in W/W_o, is smaller as W/W_o increases. As the logarithmic term implies, however, the change in range is not directly proportional to the change in fuel load.

Figure 2.44 indicates that propeller weight changes are most important for airplanes having small fuel capacity.

Figure 2.45, which is a typical plot of result of a detailed study of an airplane's range, illustrates the interaction between performance and weight variation.

The mileage $\left(\frac{\text{miles}}{\text{lb. fuel}}\right)$ plus oil at a given flight condition (usually L/D maximum) has been calculated for a range of airplane gross weights throughout the flight weight variation, and the results plotted giving a curve AB. The area under this curve (W_oABW) is directly proportional to the distance that can be flown. The miles per pound of fuel obtained is directly proportional to propeller efficiency; and propeller weight, of course, detracts from "payload" weight.

It should be noted that curve $A''B''$ can replace the original curve (AB) giving the same range if the areas $W_oAA'W_o'$ and $A'A''B''B$ are equal. If a propeller weight increase should be necessary without improvement in propeller efficiency, a much greater increase in fuel weight will be required to obtain the same range since loss of area $W_oAA'W_o'$ (range) must be compensated for by the addition of new range area $WBB'W'$. Since more power is required to fly a heavily loaded airplane than a lightly loaded airplane, fewer miles per pound of fuel are obtainable; and therefore, more fuel is required to obtain the same range. Similarly, a reduction in efficiency would require increased fuel to obtain necessary range (area under the curve).

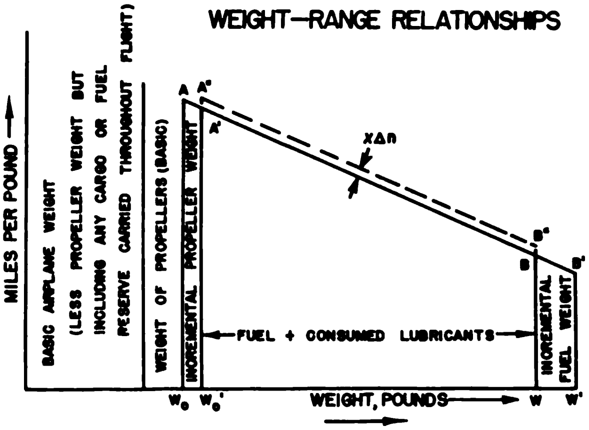

Figure 2.45.

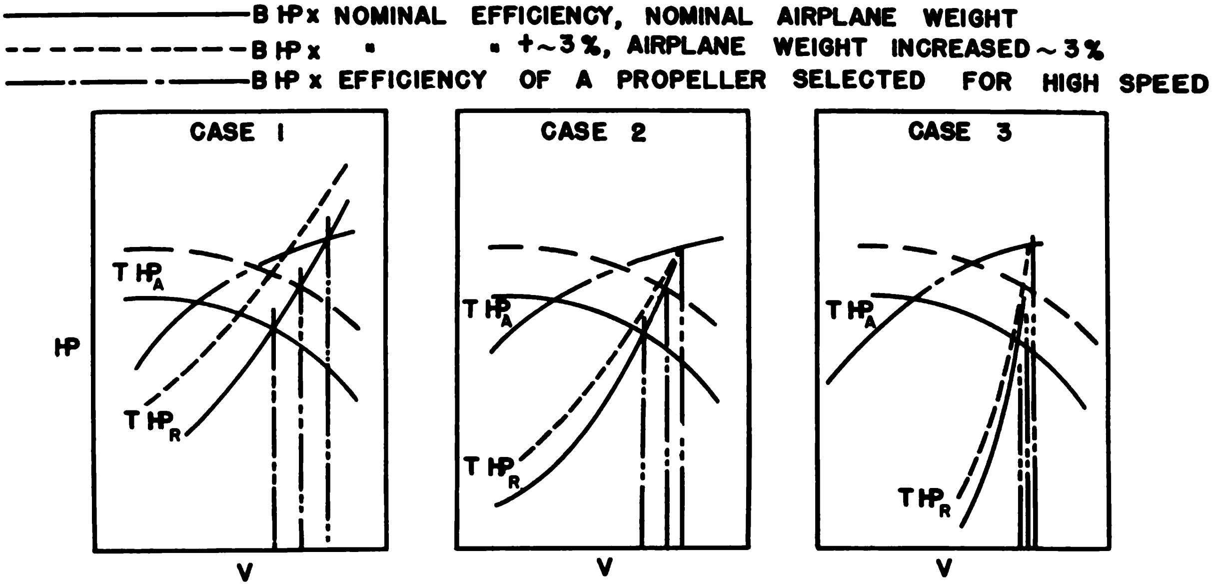

Figure 2.46.—Effect of propeller efficiency on high speed aircraft performance.

(7) *Effect of propeller efficiency on high speed airplanes.* Airplane speed is determined by thrust horsepower available and the required horsepower of a particular airplane. Thrust horsepower available is directly proportional to propeller efficiency, but the other quantity, total horsepower required (THP_R) is almost completely independent of propeller weight at high speeds. Considering THP_R independent of propeller weight is justified by the fact that induced power required, which is a function of airplane weight, is a very small part of the total airplane power required. Subject to variations imposed by required airplane power, moderate changes in propeller efficiency will produce insignificant or small changes in airplane performance, usually.

The charts of figure 2.46 illustrates the effect of propeller efficiency upon airplane performance at high speeds.

For plotting the curves, the power available (THP_R) was determined by multiplying engine propeller shaft brake horsepower by propeller efficiency. Power required (THP_R) was determined, utilizing knowledge of the airplane geometry, weight and drag characteristics in evaluation of the equation:[3]

$$THP_R=\frac{V^3 f\alpha}{146,600}+\frac{.332W^2}{eb^2\sigma V}$$

The first term on the right hand side of the equation represents the power required to overcome parasite drag, which increases at a rate proportional to the cube of the velocity. The second term on the right hand side of the equation represents the power required to overcome induced drag, which decreases with an increase in velocity. Study of the effects of propeller efficiency upon high speed aircraft performance is enhanced by subdivision of aircraft considered in three general groups: *Underpowered Aircraft*, *Moderate Speed Aircraft*, and *High Subsonic Speed Aircraft.*

Case I—Underpowered Aircraft. In this case, aircraft included are those having extremely light wing loading. The shape of the THP_R curve depicted in figure 2.45 is greatly influenced by the second term of the equation.

Case II—Moderate Speed Aircraft. This classification includes transport or bomber category of airplanes. The THP_R curve, in this case, very closely approaches a cubic inasmuch as the second term of the equation is very small at or near high speed operation.

Case III—High Subsonic Speed Aircraft. Included in this category are such aircraft as fighters where the airplane equivalent flat plate area (f) increases rapidly because of fluid compressibility effects. In this case, as in Case II, the induced power requirement is negligible and therefore the THP_R curve reflects high power requirements at higher speeds.

The effect of a weight change likewise depends on the value of induced power required with respect to parasite power required. In case I, a noticeable power increase occurs at high speed

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[3] *Elements of Practical Aerodynamics*, Bradley Jones, 1942.

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for a small weight change, whereas the increase is negligible for similar speed-weight conditions in cases II and III. The resulting change in airplane high speed performance for a given change in propeller efficiency or weight is greatest in case I and least in case III. Only in the first case is the actual velocity change likely to be significant. Further, selection of a propeller only on the basis of high speed performance will greatly penalize low speed performance, with little chance of obtaining the desired increase in velocity. However, this basis of selection will give small, lightweight propellers.

(8) *Effect of thickness ratio upon propeller selection.* While the previous discussion has referred to weight as a function of size, it should be noted that, with hollow blade construction, weight is also a function of thickness ratio; blade weight and consequently hub weight increasing as blade thickness ratio is reduced. The same relationships between performance and weight apply to evaluation of thickness ratio. Provided detailed information is available, the optimum blade thickness ratio distribution may be determined in the same manner as was done in the propeller weight case. As size is increased and thickness ratio decreased, a point of limited manufacturing experience may be reached; when this point is reached, chances of success with the first propeller become small.

(9) *Propeller blade design.* In a propeller design problem, determination of a propeller size will permit completion of details of the blade geometry. Assuming that an approximate thickness ratio has been found (a suitable compromise with weight), the principal remaining variables are: blade chord, blade twist, blade section type, and camber. The blade characteristics enumerated are interrelated; hence, a simultaneous solution by trial and error must be accomplished.

Twist may be approximated first, by assuming a distribution equal to that of the resultant velocity angle (θ_O) at each section along the blade for the advance ratio established as one of the design conditions. Next, this first approximation should be corrected for the change in velocity across the propeller disc which may be caused by the presence of some object near the propeller, for example, blockage of airflow by a radial engine nacelle. (An estimate of velocity reduction due to a common radial engine nacelle may be obtained from NACA data.) With the free stream velocity reduction thus obtained, a new resultant velocity angle (θ_O) must be calculated and the inboard blade angle reduced. In the same manner, inboard blade twist for a pusher propeller may be approximated by calculation of momentum loss due to wing drag.

Using the blade twist found, and a rectangular planform of the same width as indicated to be optimum by the summation of losses method or similar study, a strip analysis must be made at the most important or design condition of flight. The airfoil section type and camber used should be the 16 or 64 series, of moderate camber (about .3). Choice of 16 or 64 series depends on speed range and method of blade fabrication. If sections are to be operated below the critical Mach number, the 64 series is preferable. However, the thinner trailing edge may present a fabrication or maintenance problem (wrap around construction appears to be most adaptable to this type section). Usually, actual section concavities at the trailing edge are faired out by straight lines.

The preliminary strip analysis is merely a check to establish adequacy of the assumptions used. After the analysis is finished, the lift coefficient at each section should be tabulated and compared with that of maximum lift drag ratio for the section. Further, section drag coefficients should be tabulated and unusually high drag coefficients noted.

A second strip analysis must be made to redistribute blade loading by small alterations in pitch distribution to achieve, as nearly as possible, the lift coefficient for optimum lift drag ratio at each section. At those sections having high drag coefficients, the blade angle should be reduced slightly to minimize the effect of high drag coefficient. Furthermore, those sections operating at lift coefficients consistently below that for maximum lift drag ratio should have the blade chord reduced; conversely, if section lift coefficients are above those for L/D maximum, the chord should be increased.

For ease in fabrication plus adaptability to various sizes, it is well to retain a rectangular planform unless special considerations prevail. The planform, of itself, has no direct effect on propeller efficiency. The classical elliptical planform is not required for a propeller blade in which radial distribution of aerodynamic load may be readily controlled by alteration of blade

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pitch distribution. Propeller theory indicates desirability of optimum radial distribution of the product of chord length and lift coefficient (bC_L), rather than optimum value of lift coefficient distribution, as in wing theory. In a practical case, as was pointed out in the discussion of propeller theory, the designer seeks a planform that is easy to handle, in which the section lift drag ratio is near maximum.

Sometimes, inversely tapered planforms may be used where high activity factor is sought for takeoff, but low solidity is required to obtain high lift drag ratio for cruise conditions. This type of planform may be used because of its adaptability to a particular type of fabrication process. Probably, square tipped blades are slightly less efficient than those with rounded tips because, since the lift is comparatively low near the tip, a large chord results in section lift drag ratio below the optimum. However, no measurable difference in performance between square and rounded tip propellers has been noted in testing, and square tips are usually acceptable because of resulting simplifications in tooling for production.

Completion of the second strip analysis will permit a recheck of the propeller for high lift drag ratio and low loading at the high drag sections. Upon completion of a blade design, the propeller should be checked, preferably by the strip analysis method, at other important flight conditions. Assuming a cruise condition to be the basis of design, the other conditions to be checked include takeoff, climb, additional cruise points, and high speed operation. The results of this analysis must be examined carefully, section by section, in an attempt to discover those places where a slight change in pitch, camber, or thickness ratio would reduce high section drag. Changes in pitch, camber or thickness ratio resulting from this study will require another complete strip analysis.

Special attention should be paid to obtaining the smallest chord for good performance, which can be done by increasing section camber and reducing section chord until takeoff performance begins to drop. If the sections are operating at moderate Mach numbers, increase in camber and reduction in chord will usually have no significant effect on performance at other flight conditions.

Next, propeller structural design should be considered carefully to make propeller shape detail compromises that might be required. The final design is checked again by a strip analysis for all important flight conditions.

In addition to the proper compromise between weight and performance, there are several other factors in propeller aerodynamics which are of mutual concern to airplane and propeller designers. These factors affect airplane performance, stability and control. Conversely, there are airplane factors which will greatly affect air loads imposed on a propeller.

(10) *Airplane-propeller interactions and effect upon propeller design.* (*a*) Negative Thrust, or Increased Drag Caused by Propeller Slipstream. Since most propeller wind tunnel testing is done with stream-lined dynamometers and the force measured is usually shaft thrust, the efficiency obtained from test data is not propulsive efficiency, but essentially the efficiency of an isolated propeller. An increase in stream momentum will produce thrust, but simultaneously will act on any body in the propeller strip stream to cause an increased drag, which, usually, is not measured on the dynamometer. There is very little data available to indicate the amount of thrust that should be subtracted from the test or calculated value of thrust to account for the increase in airplane drag caused by the propeller slipstream. Measurement of this decrease in net thrust (or increase in drag) is dependent upon precise knowledge of engine power, propeller efficiency, and total drag of the airplane without the propeller. It is difficult to determine each of these quantities separately, and to date these items have not been obtained on the same high performance aircraft. The increase in drag may be estimated by expressing the momentum increase as an average velocity increment (calculated from the simple momentum theory) which is applied to an average skin friction drag coefficient of the airplane over that portion of the wetted area affected by propeller slipstream. Then the increase in drag may be calculated from the equation:

$$D = 1/2\rho S_s(\Delta V)^2$$

Wherein S_s = area affected by propeller slipstream.

A more precise determination of the drag increase, customarily, has been left to the airplane manufacturer who has necessary experience in correlating performance estimates with flight test data. Considerable large scale wind

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tunnel or flight testing of the particular airplane configuration would be required for a precise determination.

(*b*) Torque Reactions and Fin Effects. The propeller, besides creating a thrust force which usually does not act on the drag axis but which must be considered in stability calculations, introduces two other potentially destabilizing forces. These forces are torque reaction caused by single rotation propellers and propeller side force or fin effect which is proportional to the projected area of the propeller blades in the longitudinal plane. The forces acting on a propeller may be determined analytically and utilized in stability calculations for a given airplane. Thrust and torque forces are determined by the standard performance analyses previously described. Side force may be found by methods outlined in the references.[4] The importance of these items in propeller selection is reflected by the alterations necessary in an airplane design to counteract them. For example, primarily, the choice of a dual rotation propeller is dictated by clearance or stability considerations, the slight performance advantage usually being counteracted by additional weight and complexity of the dual propeller. In addition to torque and propeller side forces, stability effects may arise from components of vibratory propeller force [once per revolution, (1×P)], although usually this effect is not large enough to be significant. Normally, propeller mass and aerodynamic types of unbalance do not affect airplane stability.

(*c*) Effects of Inflow Deviations. As a rule, propeller aerodynamic calculations are based on the assumption that inflow into the propeller disc will be uniform in magnitude and parallel to the axis of rotation, and that any deviations from these flow conditions will be caused by the propeller. Flow deviation caused by a propeller is assumed symmetrical about the axis of rotation and may be determined by the methods discussed under propeller theory. Any aerodynamic body will cause a deviation in magnitude and direction of local fluid flow about that body. Mounting a propeller near a nacelle, fuselage, or wing, causes a flow deviation which is effective at the propeller disc.

The effect of small flow deviations on propeller efficiency has been shown to be negligible. Even rather large flow deviations, such as those resulting from pusher propeller installations, often cause but insignificant efficiency changes when compared with isolated propeller performance. This small efficiency variation is due to the local nature of fluid flow deviations, as well as the fact that both thrust and torque are affected by flow deviations. Small changes in both thrust and torque will produce little effect on efficiency, as long as the changes are in the same direction.

The propeller blade aerodynamic force changes, caused by fluid flow deviation, in turn, produce changes in total loads which the propeller structure must carry. Usually, the structural effect of load changes is much greater than the aerodynamic effect, because force changes which affect propeller structure are absolute whereas propeller performance is based upon a ratio of the changing forces. Further, propeller forces act at radii where even a small force change can cause a significant change in bending moment at the blade root. Also, force changes, being periodic in nature, aggravate fatigue problems.

To insure structural sufficiency, with improved propeller performance being additive, it is prudent to determine the extent of non-uniform and non-parallel fluid flow at the propeller disc for each particular airplane installation. Determination of airflow conditions at the propeller disc is desirable for any of the following situations:

(*i*) Propellers of diameter greater than fifteen feet.

(*ii*) Propeller installations on airplanes having speeds in excess of 300 m.p.h.

(*iii*) Propeller installations on airplanes having wing loadings in excess of 80 p. s. i.

(*iv*) Propeller installations on airplanes having thrust axes offset for stability reasons.

Based upon non-uniform flow field information, airload changes must be calculated for use in structural design of the propeller.

(*d*) Example of Non-Uniform Flow Field—Inclination of Thrust Axis. The most obvious example of a non-uniform flow field is that resulting from inclination of the propeller thrust axis with respect to the line of flight. Rotation of a propeller through one revolution produces

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[4] *Aerodynamics of the Propeller*, F. Weinig.

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changes in blade section angles of attack by amounts proportional to (but not equal to) the angle between the thrust axis and direction of flight. Reference is made to figure 2.47 for clarification of the effect of thrust axis inclination. In the diagram are shown velocity vectors for a typical section of a propeller having the thrust axis inclined at some angle with respect to the line of flight. As a result of inclination of the thrust axis with respect to direction of flight, the forward velocity vector (V) is not continuously normal to the rotational velocity vector (πnDx), as in the simple case, but varies in such a manner that the angle is $90° \pm \psi$. The value of ψ, in turn, varies between O and A, the angle of inclination of the thrust axis with respect to the direction of flight. The angle change, from the maximum positive value of ψ, through 0, to the maximum negative value, occurs once per revolution. When the propeller blades are in a plane normal to the plane of the angle of inclination, the value of ψ is zero. Rotation of the propeller blade causes the angle, ψ, to increase until after a 90° turn, ψ becomes a maximum and equal to A. Continuation of propeller rotation causes the angle ψ to decrease to zero degrees after another 90° turn. Further rotation of the propeller in the same direction causes the angle ψ to increase negatively to the maximum negative value at the end of the third 90 degrees (again the value of A). Finally, rotation through the last quarter turn causes ψ to become zero.

This oscillation of the forward velocity vector causes both a change in section angle of attack and resultant velocity. The change in section angle of attack and resultant velocity act to increase or decrease aerodynamic forces acting on the propeller blade, which in turn tend to produce significant effects on blade structure. It should be noted, however, from the geometry, that the change in section angle of attack is less than the change in ψ except when section blade angle exceeds 45°. In application, propeller inflow change is more complex than that caused by thrust axis inclination alone. In addition to aerodynamic force changes caused by propeller inflow variations, changes in airflow direction and magnitude caused by the wing, fuselage and nacelle must be taken into account. The effects of all these variables may be calculated, but accuracy of the result is questionable, especially in view of the methods which have been employed to obtain a total resultant effect.

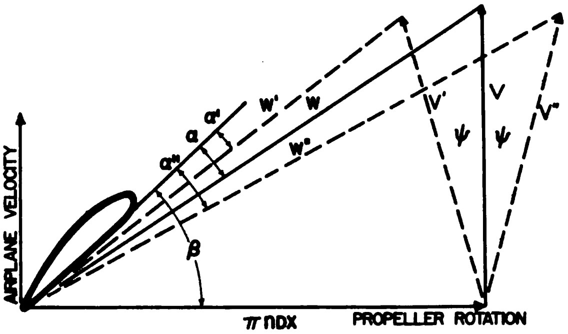

Figure 2.47.—Effects of thrust axis inclination.

(*e*) Wind Tunnel Surveys of Inflow Variations—Propeller Axis. In view of the doubtful authenticity of resultant forces, it is considered best that wind tunnel surveys be conducted to ascertain air flow through the propeller disc, using scale models of the complete airplane, operating through a complete range of pitch and yaw angles that the airplane will encounter in flight. Preferably, the surveys should be made at stations located 45° about the axis of rotation in the plane of the propeller. Four separate yaw heads and four static heads are recommended along each radius of the rake. The rake should extend somewhat beyond the propeller tip. Full scale Mach numbers are desirable; however, the Prandtl-Glauert correction to low speed data may be used.

The data obtained in the wind tunnel survey may be used directly in strip analysis calculation; or an equivalent inflow angle may be estimated. This equivalent inflow angle would be the thrust axis inclination which would give the same overall excitation, and would correspond to a root mean square of all local inflow angles determined in the wind tunnel tests. Effects of structural deflections due to flight loads (including 1xP bending moment acting on the propeller shaft) should be included in the inflow angle, as well as the build-up of all tolerances associated with orientation of the thrust axis. These increments do not necessarily increase the equivalent inflow angle.

Having established an equivalent inflow angle, A, the new local attack angle (α) and resultant forces (W) are calculated from the geometry of the velocity vectors as illustrated in figure 2.47. Before this derived data can be utilized in a strip analysis, a zero inflow strip analysis should be made to determine the proper value of propeller blade angle (β). Using the

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blade angle (β) found, two other analyses are run; one at minimum thrust loading, when (α) and (W) are minimum, and the second at maximum thrust loading, when (α) and (W) are maximum. The difference between maximum and minimum thrust loading represents the alternating load which the blade structure must sustain. The maximum-minimum load alternation occurs once each revolution.

(*f*) Design Adjustment Short Cuts for Propeller Inflow Variations. Rather than calculate several strip analyses to compensate for $1 \times P$ excitation, only one analysis need be run, in which case the values of lift coefficient would be adjusted in proportion to changes in slope of the lift curve, change in section angle of attack, and velocity. Furthermore, a representative station might be used rather than making multi-station analysis of the blades. A useful term to indicate the magnitude of $1 \times P$ excitation that is present in a particular airplane installation, is the factor Aq which is the product of the equivalent inflow angle (A) and the dynamic pressure (q) at which the airplane is operating. For a given advance ratio, blade station radius, blade chord and lift curve slope, excitation will be directly proportional to the quantity (Aq). Therefore, as long as the advance ratio, blade station radius, chord and lift curve slopes are held constant, or vary only a small amount, the periodic air load produced bending moment will be proportional to Aq. A typical variation of Aq with indicated air speed (*IAS*) and airplane weight is shown in figure 2.48. (The use of indicated air speed is convenient because it eliminates altitude as a variable.)

At airplane maximum weight, minimum flying speed, with flaps up, produces maximum excitation because the value of A is a maximum and sufficiently large so that, despite the moderate value of q, the product Aq is large. As airspeed increases, the airplane angle of attack decreases and, since this is usually the largest single factor in determining Aq, the value of A decreases sufficiently fast that, despite the increasing q, the product Aq decreases. Since q increases with the square of the velocity, the product again rises rapidly to a second peak at the airplane limiting IAS.

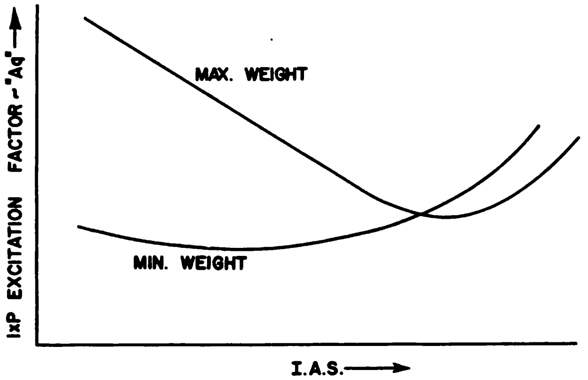

Figure 2.48.—Typical variation of "Aq" with IAS and weight.

If airplane angle of attack were the sole factor in A, the curve could eventually cross zero and become negative. However, as the angle of attack becomes small, the effects of other flow divergences resulting from fuselage, nacelle, and wing become the determining factor in Aq. At minimum weight, the same maximum angle of attack can be reached but at a lower q; hence, the product Aq is smaller. High speed at minimum weight usually results in a peak Aq higher than that of the heavy weight case because the thrust axis angle may be larger and negative, and the placard indicated air speed may be higher. Peak values of Aq can be controlled by proper orientation of the nacelle axis, an important factor to be considered in airplane design. Nacelle orientation which results in a slight down tilt is preferred, usually, which tends to equalize the two peak values of Aq. However, it is desirable to keep the value Aq at high speed somewhat lower than that at minimum speed because of the much greater effect of small dislocation of the nacelle when the airplane is operated at high indicated air speed.

Aerodynamics of Propeller Auxiliaries

Propeller Blade Ice Control Boots

To eliminate propeller icing, it is common practice to utilize external ice control boots on and around the leading edge of the propeller blade. Assuming that the basic blade section of a propeller has the required airfoil configuration, application of an external boot (or partial blade envelope) will change the blade section shape to an undesirable configuration. The amount of blade section deformation will be dependent upon the thickness and shape of boot applied.

Generally, the aerodynamic effect of a de-icing boot is unfavorable; the extent of the effect is dependent upon blade type, form of boot, and operating conditions. Regardless of detrimental effects introduced by the best possible installation, deicing boots are necessary to avoid excessive aerodynamic loss introduced by ice accretions which may form on the blades. Therefore, it is essential that every effort be made to produce ice control boots which will minimize detrimental aerodynamic effects on propeller blades. Serious consideration has been given to design of the basic blade structure so that addition of a boot is necessary to complete the desired airfoil section. Removal or deformation of blade material to provide deicing boot space introduces serious blade structure and fabrication problems. An attractive method of deicing, under development, has interior heating of the blade leading edge. Internal blade heating would circumvent the use of deicing boots, which would permit much better control of propeller blade aerodynamics.

Propeller Blade Cuffs

The magnitude and character of propeller blade loading, along with the necessity of working blade materials at highest possible stresses to minimize weight, require gradual transition from an aerodynamic blade form to a circular propeller shank section. The gradual transition from blade to shank represents a significant proportion of the blade that has very poor aerodynamic qualities. Reduction of effective working surface of a propeller blade is especially critical in those high speed aircraft having very clean nacelle nose design, and in applications wherein the propeller is in front of a turbine engine inlet.

A practical method of recovery of some of the propeller performance lost through reduction of effective working surface by transformation of aerodynamic blade form to round shank, involves fitting the propeller blade with a cuff. A propeller cuff is a structure, having a contour similar to that of the blade, surrounding the transition and shank end of the propeller and extending towards the point of juncture of hub and shank. Aerodynamically, the function of a cuff is to reduce drag and associated losses in ram pressure ahead of the engine. Torque-thrust conversion at a propeller radius requiring cuff application is not of dominating importance in subsonic propellers. Since development of adequate cuff structure and attachment to the blade present difficult problems, and in view of the lack of critical requirements insofar as aerodynamic form is concerned, compromise of the ideal aerodynamic shape is justified.

Propeller Hub Spinners

(1) *Aerodynamic requirements for spinners.* Important aerodynamic losses may develop from air flow over and around a propeller hub. Two significant effects are:

(*a*) Drag of the hub.

(*b*) Restriction of cooling or ram air flow to the engine.

To minimize the effects of air flow over propeller hubs, spinners have been developed. Spinners are structural envelopes that encompass the hub, having profile shapes and passages conducive to reduction of drag and increasing air flow to the engine.

There is small aerodynamic gain from use of spinners on low speed airplane (roughly 300 m. p. h.) propeller installations. Proper design of propeller shanks and engine cooling will insure adequate engine (reciprocating) cooling. Since compensation for development, additional weight, and maintenance is not fully obtained, use of hub spinners is avoided unless proven necessary.

(2) *Turbine engine-propelled spinner requirements.* The turbine engine, with annular air intakes, presents a different kind of problem; engine cooling is not involved, but ram recovery is essential. If full power of the engine is to be obtained, the pressure recovery due to ram must be substantial. Anything less than 90 percent ram recovery would be unacceptable; 100 percent recovery is desirable. Furthermore, distribution of ram pressure over the face of the compressor entrance must be uniform within close limits, if serious compressor vibration is to be avoided. In view of the foregoing, it is evident that turbine engines should be equipped with spinners.

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CHAPTER III. STRUCTURAL DESIGN OF PROPELLERS

Design Considerations

Basis of Propeller Loading Conditions

Aerodynamic characteristics of a body are solely a consequence of surface configuration and orientation of the body with respect to airflow over the body, and not a matter of how, or to what extent, the space within the boundary surfaces is filled. Therefore, aerodynamic surface having been defined, the problem of creating and maintaining this surface becomes a structural problem. Since a propeller is an aerodynamic device, aerodynamic requirements of the propeller establish the first conditions of loading.

Requirements of Propeller Physical Structure

The propeller structure must have sufficient strength to withstand not only aerodynamic loads generated on the propeller surface, but also inertia loads arising from centrifugal, gyroscopic, and vibratory effects produced by propeller movement. The propeller must have enough stiffness to prevent deformation of its surface configuration and orientation to extents aerodynamically intolerable. These structural requirements must be met with a minimum amount of material. In a propeller blade, weight inflicts a double penalty. In addition to adding to the weight which aircraft must transport, propeller weight is a source of a large component of the total force which propeller structure must withstand; namely, centrifugal force. Weight reduction may be effected by acceptance of higher stresses, but higher stresses bring higher unit deformations, often with introduction of objectionably high secondary stresses. It is obvious that demands for reduction in weight and those for increase in rigidity are antagonistic. An acceptable solution must be evolved utilizing only the space within the surface boundaries dictated by aerodynamic needs.

Special Functional Requirements

Structural design of propellers must, of necessity, encompass functional problems of pitch change mechanism, automatic control systems, anti-icing, and deicing equipment, as well as meet the basic requirement of converting rotative energy into propulsion. Incorporating these functional requirements often imposes more severe problems upon structural design than basic requirements.

Effect of Low Safety Factors

Involved in the effort of keeping weight to a minimum is the necessity of working materials at stresses much higher than those usually used in other design applications. Hence, in propeller design the margin for safety is reduced materially. Since the factor of safety is low, accurate information regarding structural loading is required. More precise analysis of the nature, patterns, and magnitudes of the stresses must be employed than is practiced in many other engineering design problems. These demands for advanced design are followed by equally exacting demands in the inspection of materials and workmanship that are blended into finished propellers. Extensive tests to reveal final verification of design adequacy and to acquire additional design information are continuing requirements.

Propeller Blade Forces

Design of a propeller starts with design of the blade. For the purpose of design analysis, forces acting upon a propeller blade are designated as *steady*, *fluctuating*, or *alternating*. None of these forces are ideally steady; centrifugal forces are the most nearly steady. It should be noted that those forces considered as steady forces are recognized as variable forces in reality, and due allowance is made by using maximum values of the steady forces in design calculations.

(1) *Steady applied forces.* (*a*) Centrifugal Forces. Among the steady forces acting upon rotating propellers are the following:

(*i*) Radial tension tending to pull the blade apart.

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(*ii*) Torsional action in which centrifugal force tends to untwist the blade, thereby eliminating built in pitch distribution.

(*iii*) Centrifugal twisting forces and moments which tend to rotate the blade about some longitudinal axis (usually the axis about which adjustable pitch blades rotate in the hub).

(*b*) Aerodynamic Forces. Aerodynamic forces acting upon a propeller blade include the following:

(*i*) Resultant air force (thrust and shaft torque).

(*ii*) Aerodynamic moment (which tends to change blade section angles, also).

(2) *Fluctuating or alternating forces.* Fluctuation of forces or stresses implies variation in magnitude, direction, sense, or combinations of the three characteristics. Alternation of forces or stresses implies variation in direction or sense, with or without variation in magnitude.

Fluctuating or alternating forces applied to a structure produce stresses of like nature in structural members. Alternating stresses superimposed upon steady stresses may result in a stress that is not alternating but fluctuating. In this case, then, alternating stresses are alternating components of fluctuating stresses.

Propeller Blade Stresses

The principal fluctuating stresses in a propeller are caused by variations in aerodynamic loads on the blade, engine shaft torque applied to the blade, or gyroscopic action of the propeller. The stresses will be in direct proportion to the magnitude of the applied force and may be computed directly by considering the force as a steady instantaneous force. However, force variation can be of such nature with respect to natural vibration characteristics of the propeller system that the ensuing stresses will be very much greater than if the applied force causing vibration were a steady force.

The ratio of stress obtained in vibration with a certain applied force, usually designated *exciting force*, to the stress which would obtain were the same magnitudes of force applied steadily has been designated *magnification factor*. Determination of this magnification factor is a deeply involved process requiring information which is very difficult to deduce during the early stages of propeller design. Movements of a propeller installation caused by forces originating outside of the propeller may cause stress variations, but will not be considered further here.

Accuracy Desired and Obtainable in Propeller Design

Exactness is a prerequisite in propeller design and analysis. However, the degree of exactness is limited by factual information available, analytical methods which can be used effectively, and the practical cut-off point beyond which returns in exactness, hence propeller performance, do not compensate for the extra effort required to achieve greater accuracy. Usually, the cut-off point will be established by limitations in knowledge of true operating conditions under which a given propeller must perform. This limitation of knowledge is quite evident for the extremely involved relationships existing for complex vibration loading superimposed on none too simple steady loads of a propeller blade.

Basic Propeller Structural Design Data

The following basic information, essential for structural design of a propeller, must be obtained from aerodynamic design studies: (Some of these characteristics are shown plotted against blade station radius in figure 3.13).

(1) Propeller diameter or radius.
(2) Blade planform (width distribution).
(3) Blade thickness distribution.
(4) Blade angle (pitch) distribution.
(5) Number of blades.
(6) Rotational speed.
(7) Airfoil section type and section design lift coefficient.
(8) Aerodynamic load distribution, both forces and moments.
(9) Aerodynamic load fluctuations in magnitude, frequency, and duration.
(10) Rates of change of angular orientation of the aircraft (rates of precession).
(11) Rates and extent of blade pitch change required.
(12) Type of engine on which the propeller is to be used.

Material and Manufacturing Process Considerations

Design considerations, of course, will be influenced greatly in many ways by available blade materials, techniques of fabrication, and type of construction, i. e., hollow or solid. In consideration of propeller blade material, the

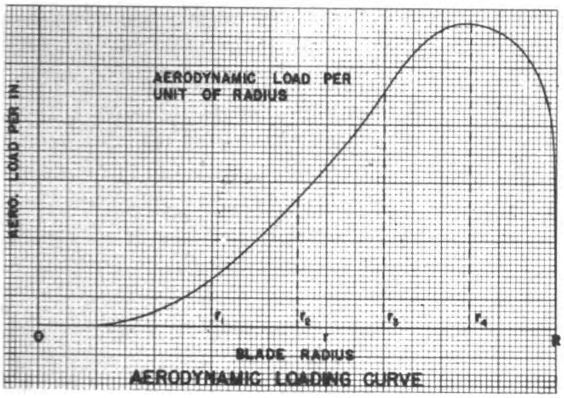

Figure 3.1.

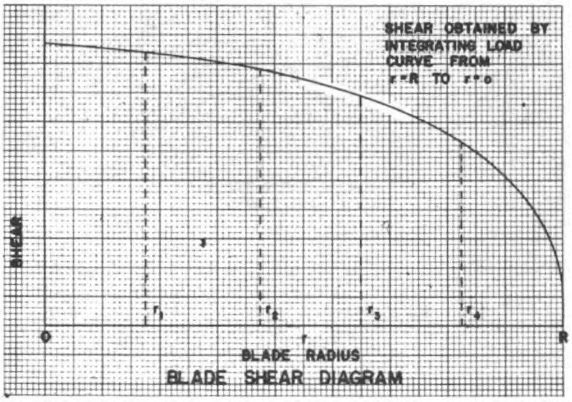

Figure 3.2.

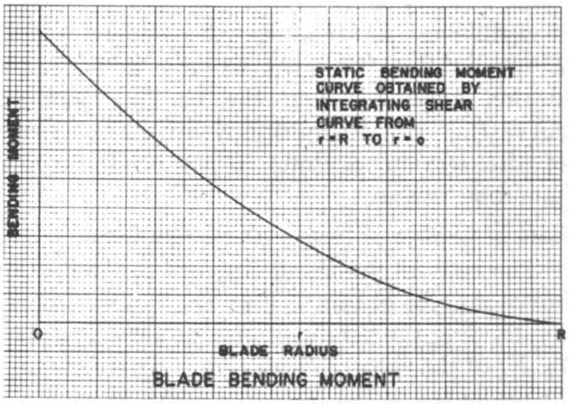

Figure 3.3.

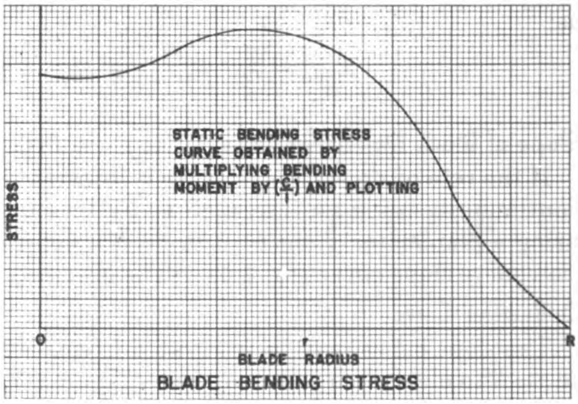

Figure 3.4.

influence upon design of such properties as strength, density, and elasticity are self-evident, but other properties such as corrosiveness, susceptibility to moisture effects, aging deterioration, responsiveness to heat removal or addition, and magnetic and radiographic characteristics (for inspection purposes) cannot be overlooked. The blade design must lend itself to practical and refined techniques of manufacture. Peculiarities of production processes which may affect structural characteristics or structural integrity of the propeller must be taken into account. Allowances must be made for specification tolerances on dimensions, material and workmanship.

Graphical Methods—Structural Analysis and Design

Aerodynamic Loading

Aerodynamic loading derived from the aerodynamic analysis may be available in either graphic or tabular form. Solution of blade structural problem may be accomplished by either graphical or tabular methods. In graphical form the aerodynamic load per unit of radius should be shown as indicated in figure 3.1.

Using the aerodynamic load curve, shear at various stations can be obtained.

The Shear Diagram

Blade shear quantities are derived by continuous integration of the load curve using an integraph, or integrating by sections using a planimeter to obtain areas under the curve from R to r_4 to get the shear value at r_4; from R to r_3 to get the shear at r_3; and so on for as many radial stations as desired. Shear quantities having been obtained at the desired number of stations, a shear diagram may be drawn as shown in figure 3.2.

Bending Moment Diagram

In a manner similar to load curve integration the shear curve may be integrated from blade radius $r=R$ to $r=0$ to get bending moment curve, figure 3.3.

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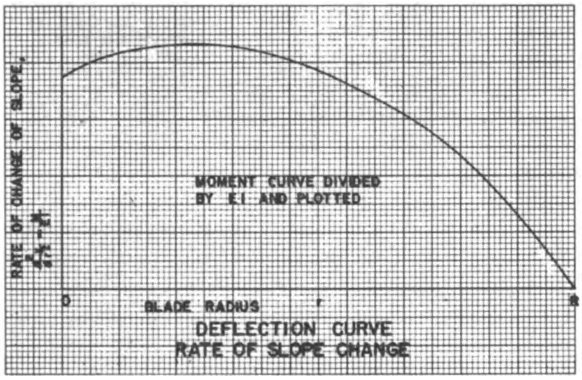

Figure 3.5.

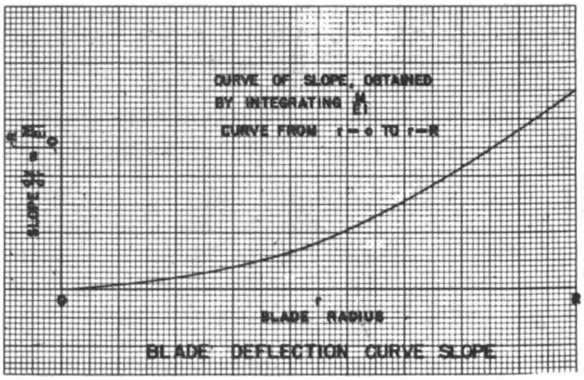

Figure 3.6.

Blade Bending Stress

Blade bending stress may be obtained readily if the bending moment at any given radial station obtained from the bending moment curve (fig. 3.3) is multiplied by the reciprocal of the section modulus (C/I) at the corresponding radius.

Rate of Change of Slope—Deflection Curve

The rate of change of slope of the deflection curve may be obtained from the moment curve by dividing the bending moment at each station by EI of the respective station. This data may be presented in the form of a curve as shown in figure 3.5.

The rate of change of slope may be expressed as:

$$\frac{d^2y}{dr^2}=\frac{M}{EI}$$

Slope of Blade Deflection Curve

If the rate of slope change curve is integrated continuously using an integraph or by sections using a planimeter, from $r=0$ to $r=R$ a deflection curve slope curve (fig. 3.6) will be obtained.

Deflection Curve

The slope curve may be integrated from $r=0$ to $r=R$ to obtain the deflection curve, figure 3.7. This deflection curve is the second integral of the M/EI curve.

Limitations of Graphical Analysis

For simplicity, the preceding considerations were limited to bending under conditions such as would be obtained were the blade not rotating (i. e., static) and subject to loading of magnitude, distribution, and direction similar to the aerodynamic load. If the blade were very rigid, bending but little under static loading, the bending stresses and deflections computed would be closely representative of those extant for a whirling blade. However, if blade deflection is substantial under static loading conditions, then centrifugal force will act to limit the deflection; and hence, the bending stresses from the combined loading must be determined by other methods. Centrifugal stresses will be determined and combined with bending stresses in another section of the handbook. This method of analyzing propeller blades is time consuming.

Tabular Method—Propeller Stress Distribution

The method of plotting and integrating curves described in the preceding paragraphs is a good, and fairly accurate, way of determining the static bending moment of a propeller blade. However, determination of the final bending moment (of which the static bending moment is a component) and final stress distribution can be made less time-consuming if the method can be adapted to permit use of calculating machines, thereby eliminating the necessity of using an integraph or planimeter. This adaptation may be accomplished by dividing the blade into radial increments (chosen small enough that accuracy will be retained) and setting up the problem in tabular form, for convenience in using a calculating machine. A tabular *finite increment* method has been derived using differential notation. This method has been used in an example of stress analysis of propeller blades to be presented in a later section of the handbook.

Steady Stress Analyses

Variable Factors Affecting Propeller Stress Analysis

From a structural viewpoint, a propeller blade is a tapered, twisted, rotating cantilever beam,

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subjected to rotational and translatory motion. It must be retained in a hub strong enough to withstand high centrifugal loading, generally, with provisions for changing blade pitch during operation. The blade must be designed to operate in a comparatively high stress range (weight saving feature) and yet be structurally sound to the extent that failures will not occur during the propeller service life.

An exact method of computing stresses and deformations of a propeller blade has not been developed, as yet, because of the complexity of the loading and variability of the geometric form which must be employed. Throughout propeller development, basic assumptions have been made to resolve the problem into a single degree of freedom system problem for the purpose of simplification. Experimental testing of conventional blade designs has verified the premise that only small deviations in accuracy result from these simplifying assumptions.

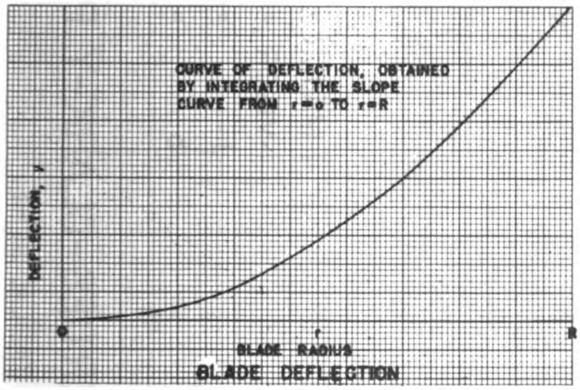

Figure 3.7.

Propeller Blade Nomenclature

(1) *Blade section.* A typical propeller blade cross-section illustrating section nomenclature is shown in figure 3.8.

The outer contour of the blade is defined by the surfaces: camber face, leading edge, thrust face and trailing edge. Similarity to wing section nomenclature is apparent. It would be well to observe the variation that exists between *through chord* and *face chord*, as well as make mental note of the major and minor axes of inertia.

(2) *Blade hub section and assembly.* The general nomenclature associated with propeller-hub combinations is shown in figure 3.9.

The figures shown have been made basic in nature to preserve simplicity.

Determination of Propeller Blade Contour

It has been stated previously that the outside contour of a propeller blade section is fixed by aerodynamic considerations. Determination of the blade contour is dependent upon availability of the basic design data listed under

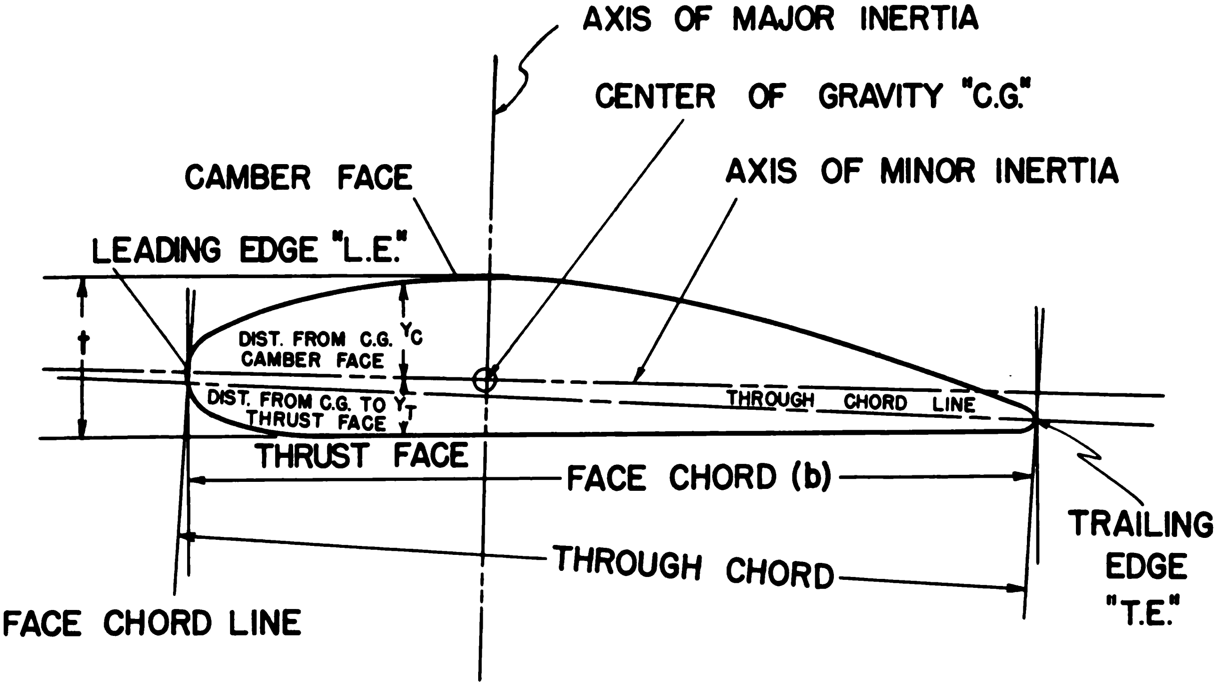

Figure 3.8.—Blade section nomenclature.

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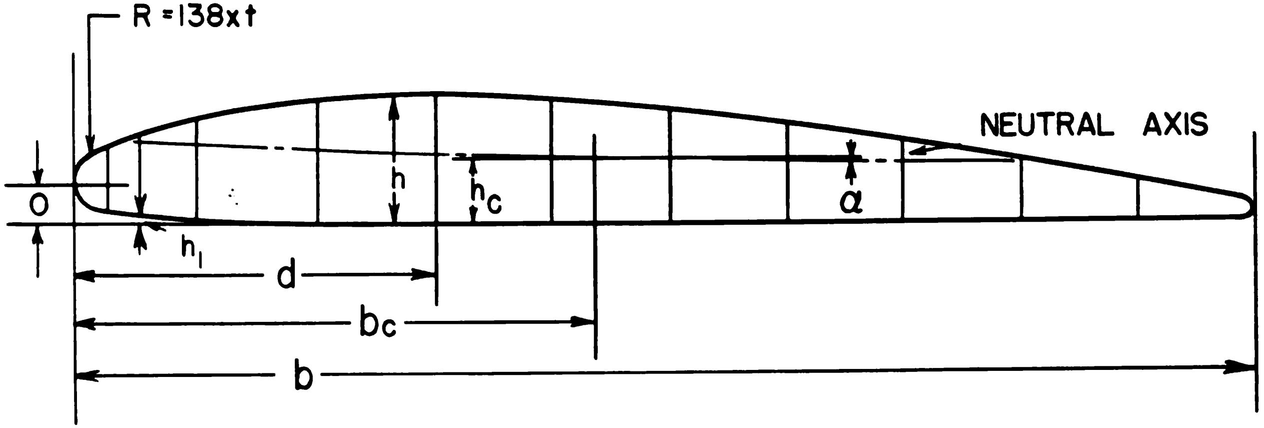
d/b	0	.025	.05	.1	.2	.3	.4	.5	.6	.7	.8	.9	[illegible]
h/t	.294	.550	.665	.808	.959	1.000	.985	.930	.830	.685	.523	.338	.086
h_1/t		.131	.0824	.0380	.0067								

DIMENSIONS AND SECTION PROPERTIES FOR THE FLAT FACED CLARK-Y PROPELLER SECTION.

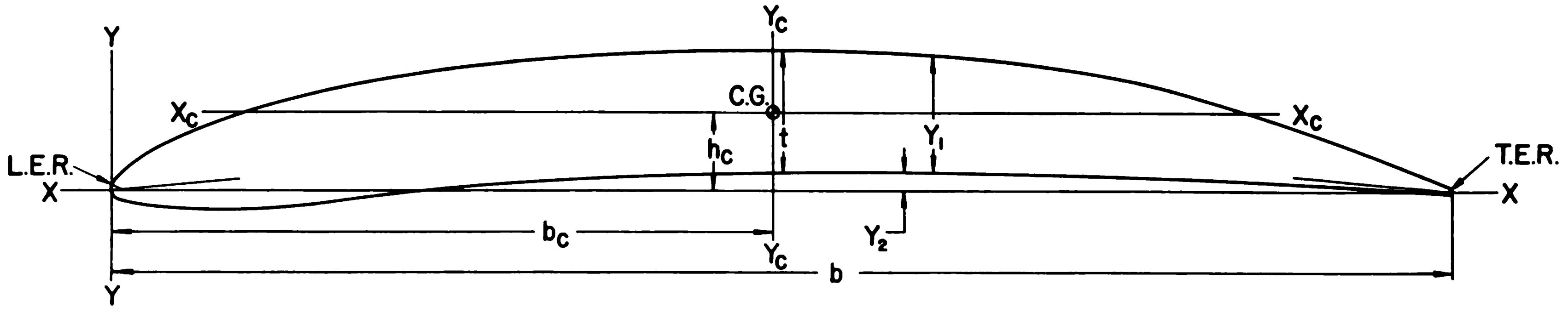


AREA = .7245 bxt
bc = .442b
hc = .416t
α(DEG) = 15.20 x t/b

I-MAJOR = .0418 b^3t
I-MINOR = .0454 bt^3
t = MAXIMUM THICKNESS
b = BLADE WIDTH

DIMENSIONS AND SECTION PROPERTIES—CLARK—Y PROPELLER SECTION

TABLE III-1



ABSCISSA	.025b	.050b	.10b	.20b	.30b	.40b	.50b	.60b	.70b	.80b	.90b	.95b
C_1	.00930	.01580	.02587	.03982	.04861	.05356	.05516	.05356	.04861	.03982	.02587	.01580
C_2	.12720	.09653	.06600	.03473	.01461	.00394	0	.00447	.01895	.04400	.05961	.05469
C_3	.15044	.20911	.28811	.38867	.45144	.48789	.50000	.48622	.43911	.34989	.20978	.11789
C_4	.00639	.00574	.00440	.00237	.00103	.00025	0	.00025	.00100	.00213	.00321	.00324

LEADING EDGE RADIUS = .489 (t/b) × t
TRAILING EDGE RADIUS = .01 t

SLOPE OF L.E.R. THRU CHORD = $.62234\,C_{l_i}$
SLOPE OF T.E.R. THRU CHORD = $.62234\,C_{l_i}$

(ALL L.E.R. AND T.E.R. LESS THAN .015" WILL BE STONED.)

$A = .7396\,(1+.00544\,C_{l_i}^2)\,t \times b$

$M_y = .3569\,(1+.00458\,C_{l_i}^2)\,t \times b^2$

$M_x = .03335\,(1+.00196\,C_{l_i}^2)\,C_{l_i}\,t \times b^2 + .01775\,(1+.1332\,C_{l_i}^2)\,C_L t^3$

$b_c \approx .4826\,b$

$h_c \approx .04509\,C_{l_i} \times b + .024\,\frac{C_{l_i} \times t^2}{b}$

$I_{y_c} = .04221\,(1+.01287\,C_{l_i}^2)\,t \times b^3$

$I_{x_c} = .04476\,(1-.00182\,C_{l_i}^2)\,t^3 \times b + .00009358\,(1+.02013\,C_{l_i}^2)\,C_{l_i}^2\,t \times b^3$

$Y_1 = C_1 \times C_{l_i} b + C_2 \times \frac{C_{l_i} t^2}{b} + C_3 \times t + C_4 \times C_{l_i}^2\,t$

$Y_2 = C_1 \times C_{l_i} b + C_2 \times \frac{C_{l_i} t^2}{b} - C_3 \times t - C_4 \times C_{l_i}^2\,t$

$I_{y_c} \approx I_{MAJOR}$ $\qquad I_{x_c} \approx I_{MINOR}$

A = AREA $\qquad$ b = CHORD LENGTH

t = MAXIMUM THICKNESS

C_{l_i} = DESIGN LIFT COEFFICIENT

C_1, C_2, C_3, C_4 = CONSTANTS FOR DETERMINING SECTION ORDINATES.

M = MOMENT OF SECTION AREA

b_c = DISTANCE FROM L.E. TO C.G.

h_c = DISTANCE FROM CHORD TO C.G.

I = MOMENT OF INERTIA OF SECTION

Y_1, Y_2 = SECTION ORDINATES

LAYOUT DATA FOR NACA 16-SERIES

(SOLID SECTIONS)

TABLE III-2

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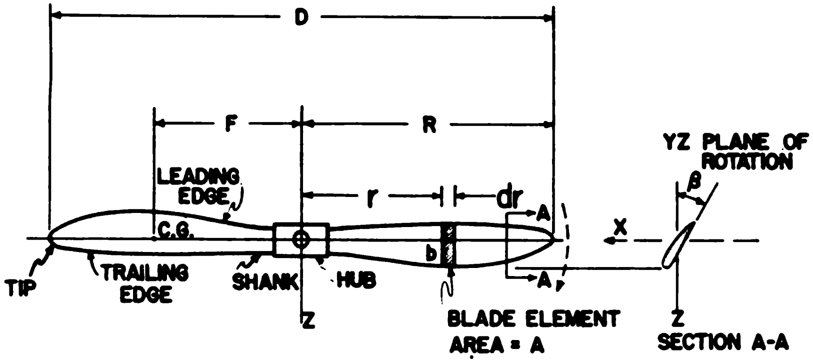

Figure 3.9.—Propeller-hub nomenclature.

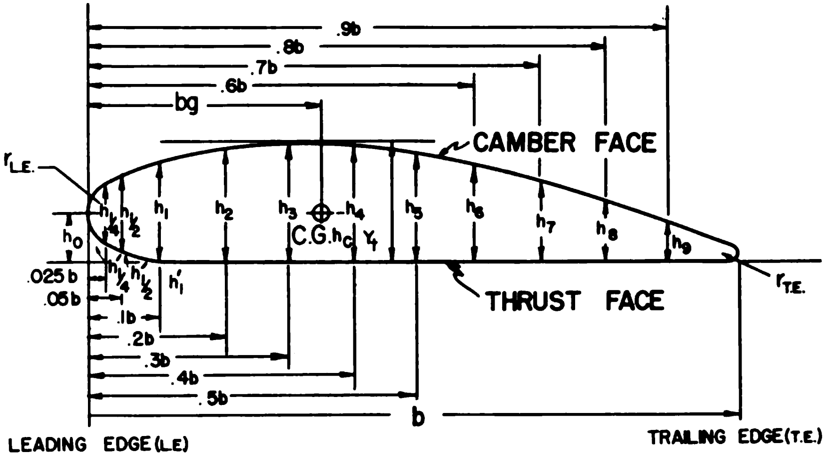

Figure 3.10.—Flat faced Clark-Y section.

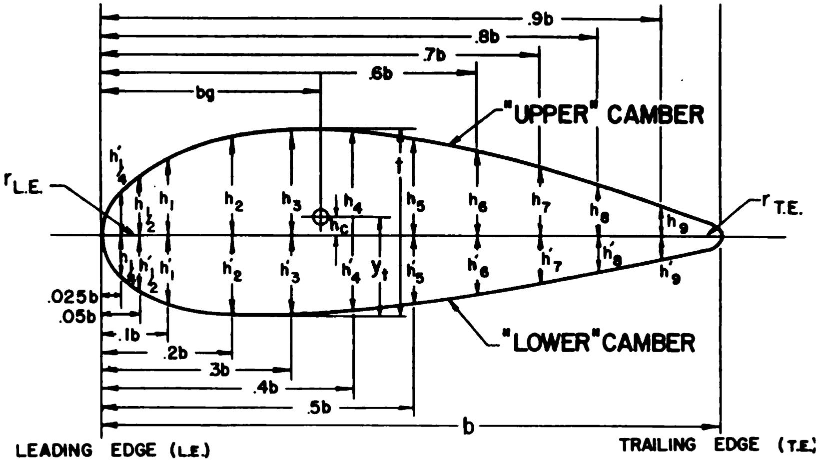

Figure 3.11.—Double cambered Clark-Y section.

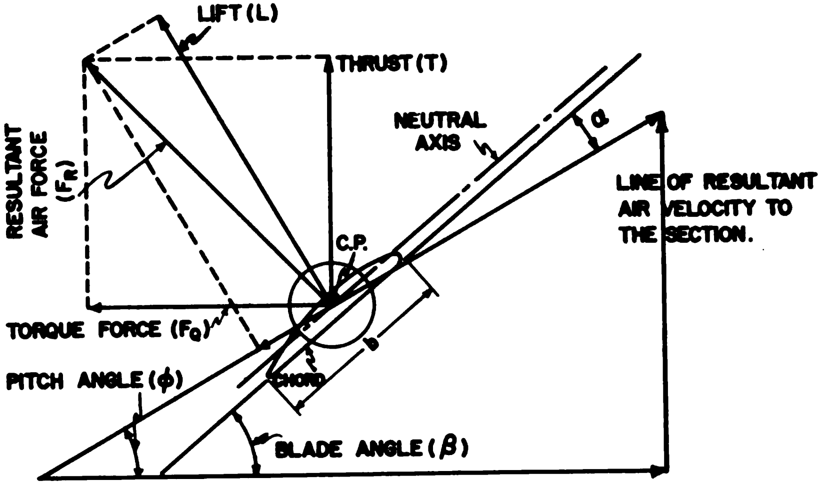

Figure 3.12.—Blade force-velocity diagram.

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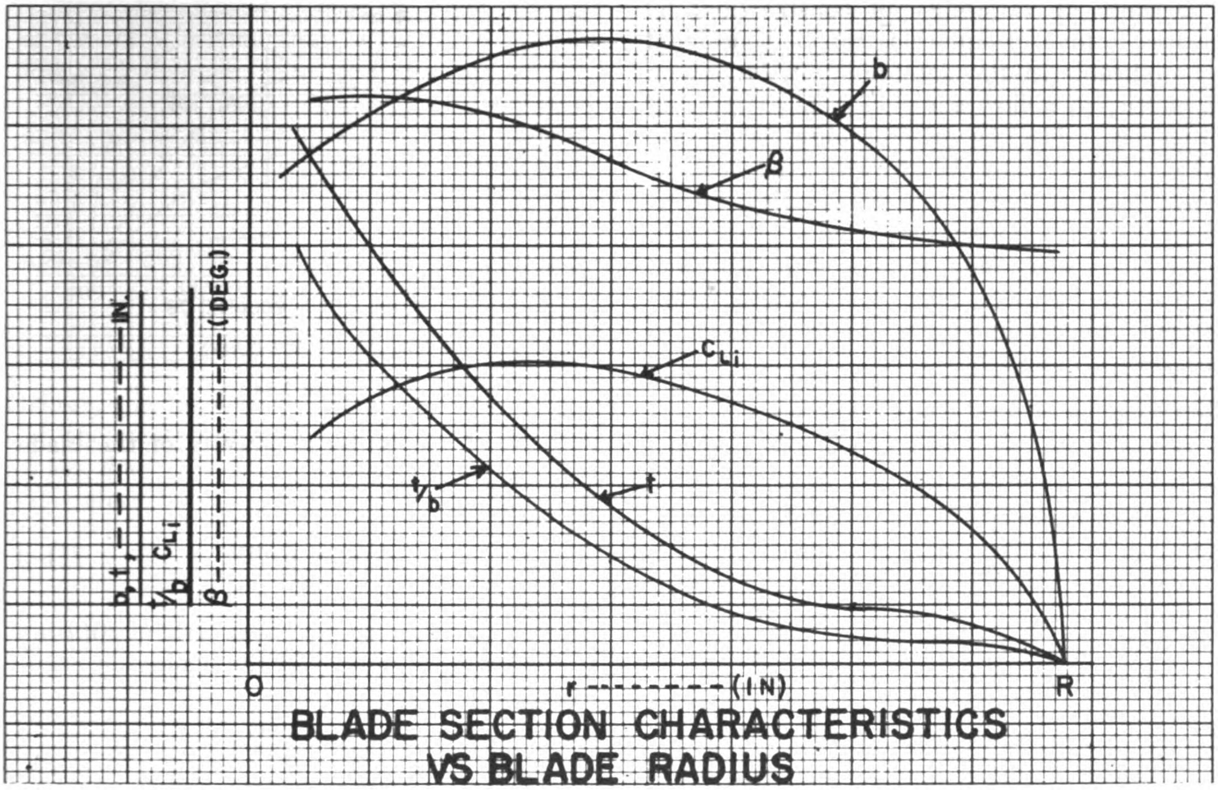

Figure 3.13.

Basic Propeller Structural Design Data on page 64. In addition to this data, dimensional relationships of the airfoil sections as shown in figure 3.10 and figure 3.11 must be known to establish numerical values of section dimensions (ordinates, leading and trailing edge radii, etc.)

The additional data necessary to complete blade section profile may be obtained from tabular data usch as that presented in table III-1 and table III-2 (or, the data may be abstracted from NACA reports, such as ACR No. L5C05).

The numerical value of ordinates for appropriate station points measured from the leading edge may be laid off to scale from a base reference line. A smooth curve dreawn through the points established as indicated, and faired into leading and trailing edge radii will define the contour of the propeller blade section.

Structural properties required to make a stress analysis can be obtained from these basic aerodynamic specifications for blade design.

Propeller Blade Force—Velocity Diagram

The force-velocity relationships are shown vectorially in figure 3.12.

A diagram of this nature defines the forces applied to a section in magnitude, direction, and sense; and indicates section loading so necessary to stress analysis.

Required Blade Structural Properties of Specified Sections

To conduct a stress analysis, the following structural properties of blade cross-sections must be determined:

(1) Area (A), structural material.
(2) Minor moment of inertia (I_{min}).
(3) Major moment of inertia (I_{maj}).
(4) Center of gravity location.
(5) Distance from center of gravity to outermost fiber of thrust face (y_t).
(6) Distance from center of gravity to outermost fiber of camber face (y_c).

Empirical formulae have been established for obtaining the required section properties for solid, homogeneous blade construction of certain airfoil types. Table III-1 includes ordinates and section properties data for the flat-faced solid Clark-Y sections, while Table III-2 includes similar data for NACA 16-series solid sections. Blade section characteristics are shown plotted against blade station radius in figure 3.13.

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Because of variability of construction, no general system of equations can be considered as applicable in the determination of section properties of hollow and hollow filled types of propellers. The general procedure used in the latter case consists of drawing the sections (twice size or larger), including plate thicknesses (t_p), rib thicknesses, effective filler material, etc., and using a mechanical first and second moment integrator to obtain the properties. Other methods may be used as long as accuracy is maintained.

Determination of Total Blade Properties

(1) *Blade weight.* Blade weight may be derived from a differential equation involving weight, area, radius, and material density relationship, as follows:

$$dW = \delta A dr$$

in which

δ = material density (lb/unit vol.)
dW = weight of an infinitesimal strip (lb.)
A = cross-sectional area of infinitesimal strip (units of length)^2
dr = thickness of infinitesimal strip (units of length) III–1

$$W = \int_{r=0}^{r=R} dW$$

$$= \int_{0}^{R} A dr$$

Therefore,

$$W = \delta \int_{0}^{R} A dr \qquad \text{III–2}$$

If the values of A at small intervals of r (say every six inches) are plotted against r, an area curve (A) will be obtained as shown in figure 3.14. Summation of the area under the A curve multiplied by the corresponding value of radius (r) will give the total propeller volume (Ar) at any specified section station, radius $= r$. Plotting the product Ar against blade radius will give the Ar curve.

The total weight of the blade will be equal to the area under the Ar curve (from $r = o$ to $r = R$, since this area represents the volume of the blade) multiplied by the material density (δ). Inasmuch as the mathematical relation between A and r cannot be ascertained readily, the area under the Ar curve may be determined graphically.

(2) *Center of gravity of blade.* The radial location of the center of gravity of the blade may be found as follows:

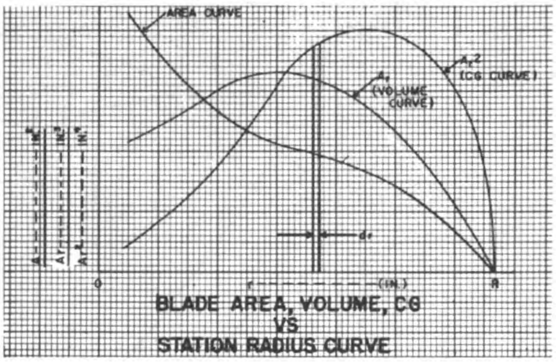

Figure 3.14.

By definition

$$W r_{cg} = \int r dW \qquad \text{III–3}$$

where r_{cg} is the distance from axis of rotation to the center of gravity of the blade.
Therefore,

$$r_{cg} = \frac{\int r dW}{W}$$

Substituting for W, its equivalent (δ Adr),

$$r_{cg} = \frac{\int r \, \delta \, A dr}{\int \delta \, A dr}$$

which reduces to the form:

$$r_{cg} = \frac{\int_{o}^{R} A r dr}{\int_{o}^{R} A dr} \qquad \text{III–4}$$

The center of gravity (cg), as indicated in the preceding equation, may be determined by obtaining the ratio of graphical integrations of the Ar^2 curve, figure 3.14.

The center of gravity (which is coincident with the center of mass, since g is assumed constant) may be found, also, from simple dynamic relationships. The value of r_{cg} may be found if the values of the angular velocity (ω), the mass of the blade (m) and the total centrifugal force ($c. f.$) acting on the blade are known:

$$CF = m r_{cg} \omega^2 \text{ Therefore, } r_{cg} = \frac{CF}{m \, \omega^2} \qquad \text{III–5}$$

A discussion of centrifugal force will be presented in another section of this handbook.

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(3) *Polar moment of inertia.* Polar moment of inertia of a blade may be determined in the following manner:

Mass of the blade element may be expressed algebraically as:

$$dm=\frac{dW}{g} \qquad \text{III–6}$$

and, by definition, the polar moment of inertia, I_P, may be expressed in the following manner:

$$I_P=\int r^2\,dm \qquad \text{III–7}$$

where, r is the distance from the reference axis to the center or gravity of the incremental mass, dm.

Therefore,

$$I_P=\int_{r=0}^{r=R} r^2\,\frac{dW}{g}$$

$$=\int_0^R r^2\,\frac{\delta A\,dr}{g}$$

which may be rewritten as:

$$I_P=\frac{\delta}{g}\int_0^R A\,r^2\,dr \qquad \text{III–8}$$

where

I_P = Polar moment of inertia, pounds-feet-second
δ = Material density, pounds per cubic foot
A = Area, square feet
r = Radius, feet.

Other sets of units may be employed provided the units used are consistent dimensionally, for example:

r may be expressed in inches
with A expressed in square inches
and δ expressed in pounds per cubic inch.

But, if the polar moment of inertia, I_P is to be expressed in lb-ft. sec.^{2} units, the equation would have to be written as follows:

$$I_p=\frac{\delta}{144g}\int_0^R A\,r^2\,dr \qquad \text{III–9}$$

The polar moment of inertia is equal to the ratio:

$$\frac{\delta}{144g}$$

multiplied by the area under the Ar^2 curve, from $r=0$ to $r=R$. This area may be obtained by graphical integration. See figure 3.14.

(4) *Activity factor.* A discussion of activity factor (*AF*) may be found in the Aerodynamics section of this handbook. As defined, "Activity factor is a non-dimensional function of the planform, designed to express the integrated capacity of the blade elements for absorbing power."

Or by definition:

$$AF=\frac{10^5}{16}\int_{0.2}^{1.0}\frac{b}{D}\left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right) \qquad \text{III–10}$$

Activity factor for propeller blade equals a constant, $\frac{10^5}{16}$, multiplied by the area under the planform characteristic curve,

$$\left[\frac{b}{D}\left(\frac{r}{R}\right)^3\right]$$

from

$$\left(\frac{r}{R}\right)=0.2 \text{ to } \left(\frac{r}{R}\right)=1.0$$

This area may be obtained by graphical integration. See figure 3.15.

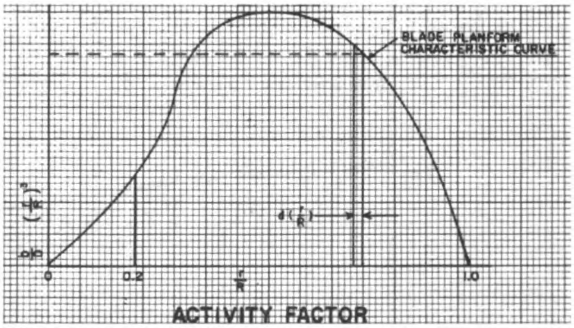

Figure 3.15.

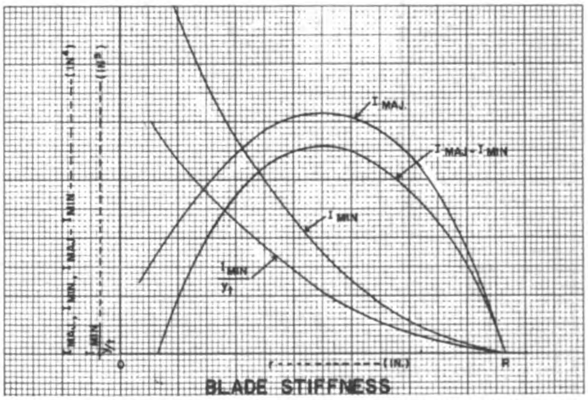

Figure 3.16.

(5) *Blade stiffness.* Blade stiffness at various stations is a function of the moment of inertia of the respective sections. Moments of inertia and section modulae are computed from the airfoil section characteristics previously discussed. Figure 3.16 illustrates stiffness distribution along a blade.

(6) *Integration by finite area method—Simpson's rule.* A numerical step integration principle may be employed to advantage in place of using an integraph or planimeter, especially if a good calculating machine is available. The principle shown here is called the trapezoidal or Simpson's rule, which may be developed as follows:

The area under the curve, $y=f(r)$, shown in figure 3.17, can be expressed mathematically:

$$A=\int_{r_0}^{r_n} f(r)dr$$

The area under the curve may be obtained by dividing the distance (r_n-r_o), into finite increments, Δr in width and of height (y). Each incremental area $(\Delta A=\Delta r\times h)$ can be found. Numerical summation of the incremental areas will give the total area, A. Let the ordinates of points on the curve $y=f(x)$ be represented by y_0, y_1, y_2—y_n for radial points designated r_0, r_1, r_2, r_3,—r_n, respectively.

Since,

$$A=\sum_{r=0}^{r=n}\Delta A \qquad \text{III-11}$$

$$A=\left(\frac{y_0+y_1}{2}\right)\Delta r+\left(\frac{y_1+y_2}{2}\right)\Delta r+\text{----}+$$

$$\left(\frac{y_{n-2}+y_{n-1}}{2}\right)\Delta r+\left(\frac{y_{n-1}+y_n}{2}\right)\Delta r$$

in which the quantities:

$$\left(\frac{y_0+y_1}{2}\right),\left(\frac{y_1+y_2}{2}\right)\text{----}\left(\frac{y_{n-1}+y_n}{2}\right)$$

represent mean values of the ordinates bounding

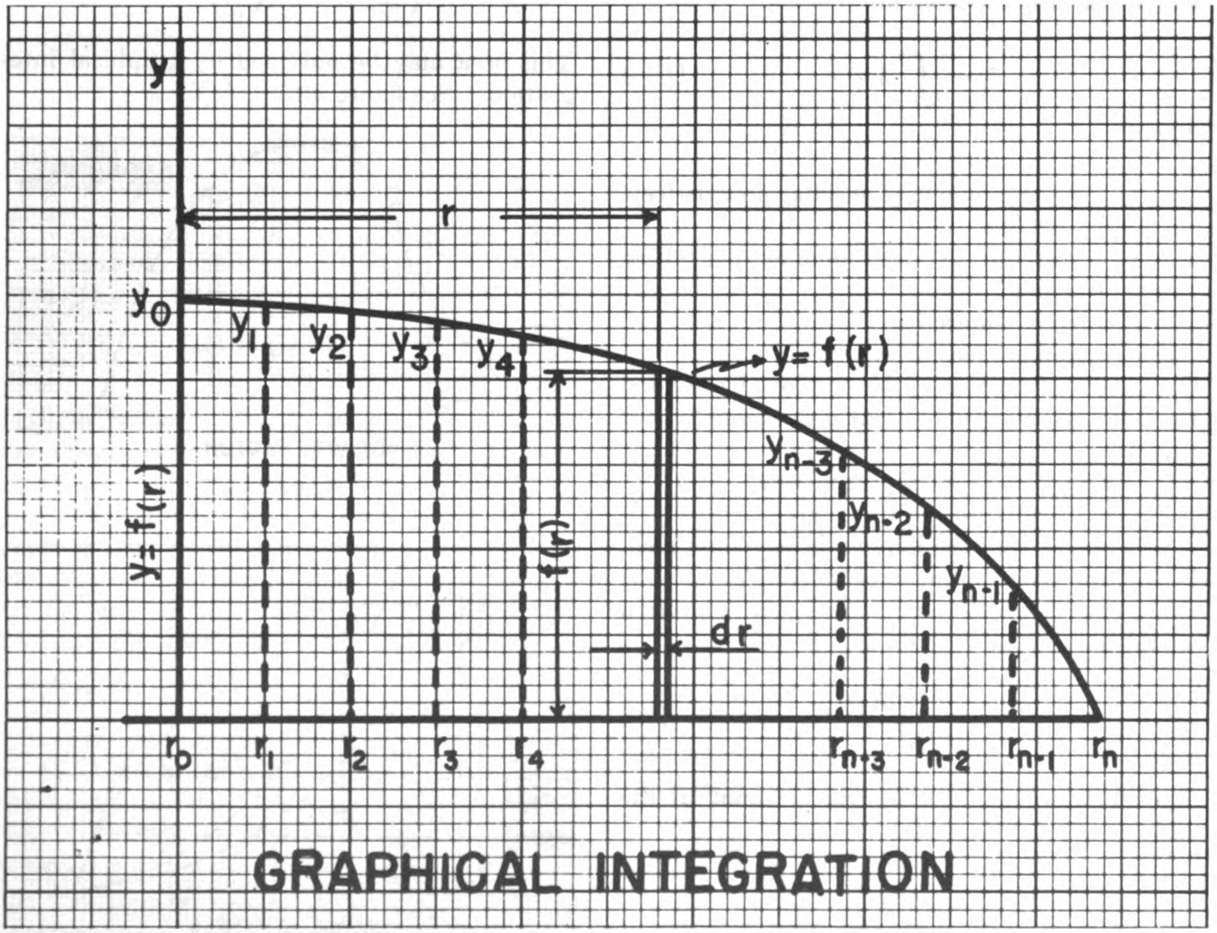

Figure 3.17.

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incremental areas. For a constant increment, Δr,

$$A=\Delta r\left[\left(\frac{y_0+y_1}{2}\right)+\left(\frac{y_1+y_2}{2}\right)+\ldots\ldots+\left(\frac{y_{n-2}+y_{n-1}}{2}\right)+\left(\frac{y_{n-1}+y_n}{2}\right)\right]$$

which in simplified form becomes:

$$A=\Delta r\left(\frac{y_0}{2}+y_1+y_2+y_3+\ldots\ldots+y_{n-2}+y_{n-1}+\frac{y_n}{2}\right) \qquad \text{III–12}$$

An acceptable degree of accuracy is contingent upon making Δr sufficiently small to maintain a constant rate of change of slope of the curve between adjacent ordinates. Appropriate corrections must be made, if necessary, when using the trapezoidal rule.

(7) *Mass-dynamic forces.* Having obtained, as a preliminary step, dimensions of blade sections necessary to carry the aerodynamic loads, it is necessary to investigate the forces and consequent stresses to which the blade structure will be subjected. Since the propeller blade does possess mass, and is subjected to accelerations, inertia forces will be set up in the system. These forces are often spoken of as mass-dynamic forces in distinction to aerodynamic forces.

Radial Distribution of Centrifugal Forces and Stresses in Propeller Blades

Increment of Centrifugal Force at Any Radial Station

Centrifugal force arising from blade rotation is the most dominant, important, and ever-present of the inertia forces. A method has been developed for determining the centrifugal force at the hub, viz., the product of the radius of the center of gravity of the blade, blade mass, and square of rotational speed.

However, centrifugal force distribution along the radius of the blade is desired for the purpose of obtaining centrifugal stress (CF/A) distribution. From the general equation for centrifugal force, (III–5)

$$CF=mr_{cg}\omega^2$$

An incremental centrifugal force equation in terms of an increment of mass Δm may be deduced; i.e.

$$\Delta CF=r_{cg}\omega^2\Delta m$$

But, $\Delta m=\frac{\delta A\Delta r}{g}$; when this equivalent is substituted, the increment of centrifugal force becomes:

$$\Delta CF=\frac{r_{cg}\omega^2}{12}\left(\frac{\delta}{g}\right)A\Delta r$$

Since $\omega=2\pi N$, centrifugal force equation may be expressed

$$\Delta CF=\left(\frac{r_{cg}}{12}\right)\left(\frac{2\pi N}{60}\right)^2\left(\frac{\delta}{g}A\Delta r\right)$$

Rearranging terms:

$$\Delta CF=\left(\frac{2\pi N}{60}\right)^2\left(\frac{\delta A r_{cg}\Delta r}{12g}\right) \qquad \text{III–13}$$

wherein

ω=rotational speed, radians per second
N=rotational speed, revolutions per minute
A=section area for the incremental distance Δr, square inches
r_{cg}=distance of center of gravity of increment from axis of rotation, inches
Δr=radial length of increment, inches
δ=material density, pounds per cubic inch
g=gravitational acceleration, feet per second, per second

Stress at Radial Station (r)

Summation of these incremental centrifugal forces from the tip towards the axis of rotation to some station (r) will give the total centrifugal force at that station. The centrifugal force divided by the cross sectional area (A_r) at the station of force computation will give the stress at station (r) due to centrifugal force, algebraically,

$$(S_{CF})_r=\frac{(CF)_r}{A_r} \qquad \text{III–14}$$

Air Load Bending Moment

Aerodynamic Load Determination Method

Distribution and magnitude of lift and drag loading along a blade are determined from aerodynamic characteristics of the blade. This loading distribution is generally supplied in

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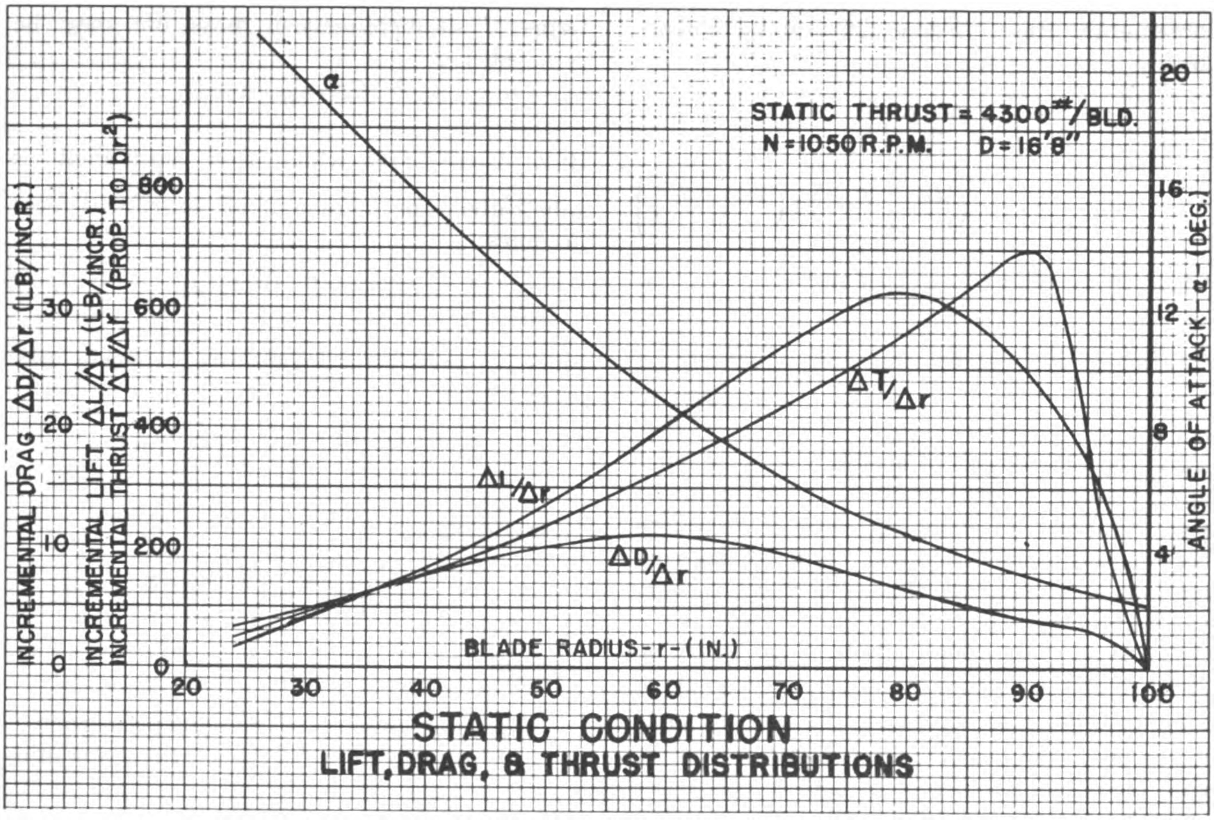

Figure 3.18.

the form of incremental lift and drag curves as shown in figure 3.18.

The vector sum of the forces acting upon radial station sections as shown provide a curve similar to the unit loading curve discussed in Graphical Methods—Structural Analysis and Design, pages 65 to 66, which, when integrated, gives shear distribution along the blade. However, the vector sum of lift and drag, i.e., the air resultant force may not be coincident with the normal force N' which is applied normal to the axis of least inertia of the blade sections.

In terms of increment lift $\left(\frac{\Delta L}{\Delta r}\right)$ drag $\left(\frac{\Delta D}{\Delta r}\right)$ and section angle of attack (α), the incremental normal force $\left(\frac{\Delta N'}{\Delta r}\right)$ may be written as:

$$\frac{\Delta N'}{\Delta r}=\frac{\Delta L}{\Delta r}\cos\alpha+\frac{\Delta D}{\Delta r}\sin\alpha \qquad \text{III–15}$$

From mid-blade to tip region, where the significant blade loading takes place, the ratio of lift to drag attains comparatively high values (in the order of 100 to 1). Hence, only small error is introduced by eliminating the drag component in the incremental normal force equation. With the drag component eliminated, the preceding equation becomes:

$$\frac{\Delta N'}{\Delta r}=\frac{\Delta L}{\Delta r}\cos\alpha \qquad \text{III–16}$$

Substitution of appropriate values in this equation will yield data from which an incremental loading vs. radius curve may be plotted.

Integration of the loading curve from the tip to any blade radius station will give the shear at that station. Mathematically, this statement may be expressed:

$$N'_r=\sum_R^r\left(\frac{\Delta L}{\Delta r}\cos\alpha\right)\Delta r \qquad \text{III–17}$$

Plotting shear values for each station radius, the shear vs. radius curve may be obtained.

Integrating the shear vs. radius curve from blade tip to any given station radius will yield a bending moment at that station. Hence, the area under the shear curve represents the total bending moment. Therefore, the incremental

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air load bending moment between (r) and ($r+\Delta r$) would be:

$$\Delta M=\left(\frac{N_{(r+\Delta r)}+N_r}{2}\right)\Delta r \qquad \text{III–18}$$

Then the air load bending moment (M_r) at any station of radius (r) may be expressed:

$$M_r\sum_{R}^{r}\Delta M \qquad \text{III–19}$$

The problem can be simplified further by neglecting bending moment due to chordwise loading, which may be assumed to be negligible.

Second Air Load Determination Method

Another method of determining the air load distribution, which is slightly more conservative than the direct aerodynamic method is based upon the assumption that air load distribution is proportional to the product of blade airfoil section chord (b) and the square of the section radius (r). This assumption is derived from the general relationship of aerodynamic load proportionality to lifting surface (in this case, $b\Delta r$) and to the square of the relative air velocity (ωr^2) of the lifting surface at radius (r). Then the load per increment of radius ($LOAD/\Delta r$) is proportional to br^2.

The total static thrust, T_S, must be known when using this method, so that the proportionality constant, K_T, can be determined. Using both differential and finite increment notations, the relationship between K_T and K_S are set forth in the following table:

Comparison of Air Loading Calculation Methods

A comparison of the loading curves is presented in figure 3.18. The ($\Delta T/\Delta r$) curve, or the curve that is proportional to br^2, is shown to be shifted *outboard* of the calculated ($\Delta L/\Delta r$) curve. The area under the two curves is approximately the same and is equal to the static lift and thrust of the blade, respectively, for the given static takeoff condition. However, the center of gravity of area under the ($\Delta T/\Delta r$) curve being farther outboard yields somewhat higher bending moments on the blade sections which results in a more conservative blade design.

In the sample calculation given later, provision is made for calculation of the air load bending moment by using either of the methods outlined (table III–8 using lift curve and table III–9 using (br^2) curve). However, the curve of normal force distribution is more precise in that it more nearly represents true aerodynamic loading along the blade. The curve of normal force distribution is used later in determination of the net bending moment.

Net Bending Moment

(1) *Centrifugal restoring moments.* Consideration must be given to a propeller blade having the centers of gravity of transverse sections located on a line extending radially and in the plane of rotation of the hub-tip blade center line. The plane of rotation may be used as a reference plane. Application of a load (equivalent to normal operating air loads in

Table III–3. K_T, K_S Relationships

Differential Notation		*Tabular Finite Increment Notation*	
$dT=K_Tbr^2dr$	III–20	$(\Delta T)_{r+\Delta r}^{r}=K_T\left(\frac{(br^2)_r+(br^2)_{(r+r)}}{2}\right)\Delta r$	III–20a
$T_r=K_T\int_R^r br^2dr$	III–21	$T_r=\sum_{R-\Delta r}^{r}\Delta T_r$	III–21a
$dM_{T_r}=T_rdr$	III–22	$\Delta M_{T_r}=\left(\frac{T_r+T_{(r+r\Delta)}}{2}\right)\Delta r$	III–22a
$M_{T_r}=\int_R^r T_rdr$	III–23	$M_{T_r}\sum_{R-\Delta r}^{r}\Delta M_{T_r}$	III–23a
$K_T=\frac{T_S}{\int_R^{r=0} br^2dr}$	III–24	$K_T=\sum_{R-\Delta r}^{r_0}\frac{T_S}{\left(\frac{(br^2)_r+(br^2)_{r+\Delta r}}{2}\right)\Delta r}$	III–24a

magnitude, direction and distribution) to a stationary propeller blade will cause blade deflection such that section centers of gravity are displaced from the reference plane. Under normal operating conditions, the offset blade sections are subjected to centrifugal forces acting along a line parallel to the reference plane and at a distance from the reference plane equal to the amount of deflection. The centrifugal force multiplied by the deflection produces a moment which tends to bend the blade back into the reference plane of rotation. This effect is called the centrifugal restoring effect and moments characterizing the effect are called centrifugal restoring moments. The adjective, restoring, is somewhat misleading. The centrifugal restoring effect always tends to move the blade into the reference plane of rotation, but this action is not necessarily a restoring action in all cases.

(2) *Blade deflections and deflection curves.* The distribution of centrifugal bending moments along the blade, in additional to being proportional to the centrifugal force of elemental masses of the blade, is proportional to displacements of the elemental masses from the reference plane. Hence, centrifugal bending moments, and ultimately, net bending moments, cannot be determined until the flexure curve of the blade is known. Since the true flexure curve (a key piece of information for determination of the net bending moment distribution) is unknown, a flexure curve must be assumed for a first trial with subsequent corrections to the curve being made by iterative trials.

The assumed blade deflection curve would appear as illustrated in figure 3.19 wherein only the flexure line of the centers of gravity of blade transverse sections is shown.

Also, the direction and distribution of the differential centrifugal force with respect to deflection (x) is shown relative to the blade flexure curve.

(3) *Differential centrifugal forces acting upon blade sections.* The differential centrifugal force with respect to the deflection (x) may be obtained in the following manner:
The incremental centrifugal force with respect to radius (r) may be expressed:

$$d(CF)=\frac{\delta}{g}A\omega^2 r\,dr \qquad \text{III-25}$$

The rate of change of centrifugal force with radius is represented by the following expression:

$$\frac{d(CF)}{dr}=\frac{\delta}{g}A\omega^2 r \qquad \text{III-26}$$

It is apparent that integration of the preceding equation with respect to the radius will yield a centrifugal force relationship. Figure 3.20 contains a plot of $d(CF)_r$ along with the blade flexure curve.

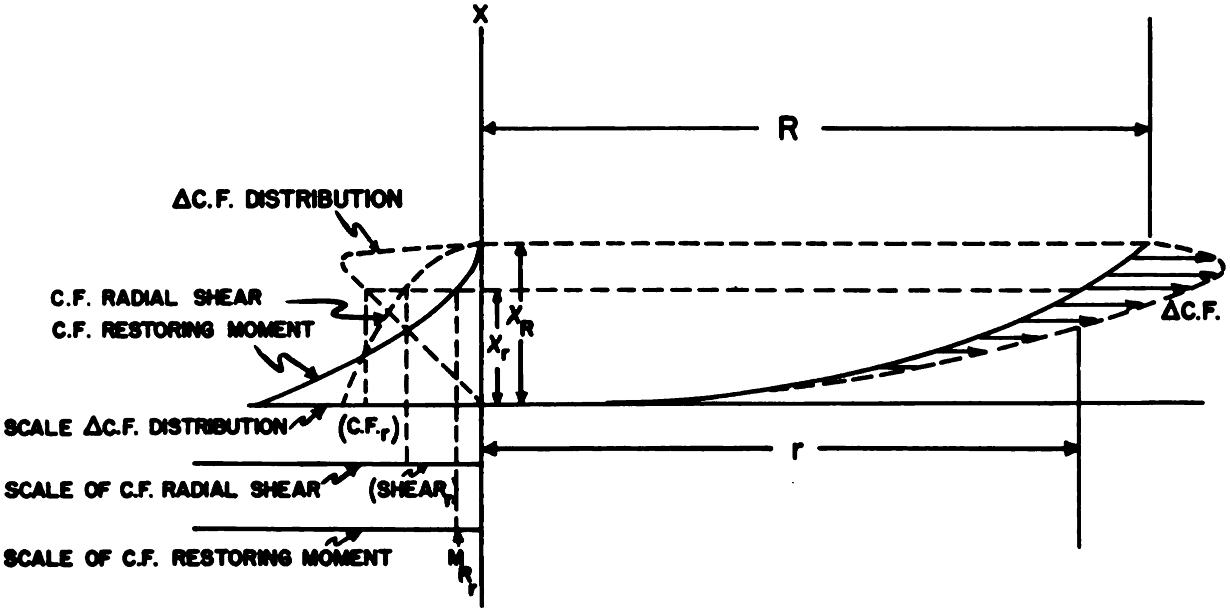

Figure 3.19.—Assumed deflection curve—net bending moment.

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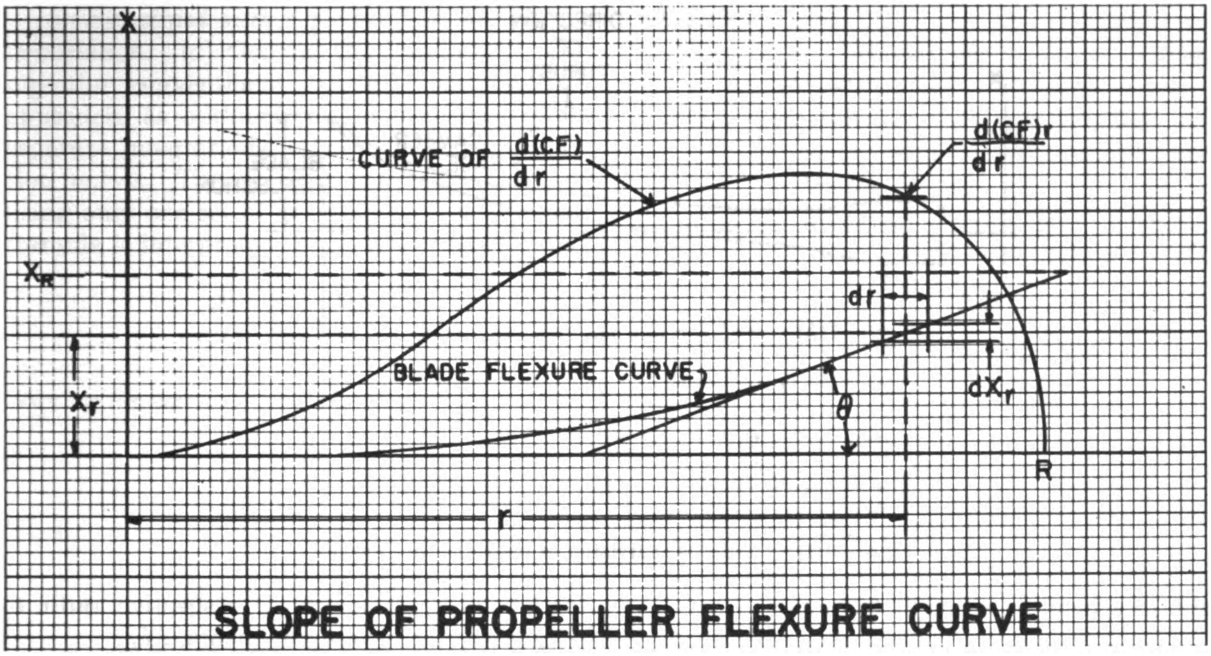

Figure 3.20.

Since centrifugal force acting on sections distributed along the blade radius (from $r=0$ to $r=R$) also must be distributed transversely (from $x=0$ to $x=x$), the force distribution along x will be determined from the blade flexure curve, inasmuch as blade mass is distributed in a radial direction with displacements in planes parallel to $(x-0)$. For all practical purposes, the radial centrifugal force distribution along a blade in deflected position is no different from the centrifugal force distribution along the blade rotating in the reference plane.

Thus,

$$\frac{d(CF)_x}{dx_r}=\frac{d(CF)_r}{dr}\cdot\frac{dr}{dx_r}$$

But,

$$\frac{dr}{dx_r}=\frac{1}{\tan\theta}$$

Where $\tan\theta_r$ is the slope of the flexure curve at radius, r, with respect to the radial line.

Therefore,

$$\frac{d(CF)_x}{dx_r}=\frac{d(CF)_r}{dr}\cdot\frac{1}{\tan\theta_r} \qquad \text{III–27}$$

(4) *Shearing forces acting on blade sections.* A curve of

$$\frac{d(CF)_x}{dx_r}$$

may be plotted against x, and then integrated to get the shearing force across the x-axis at any given value of x. That is,

$$(\text{Shear})_{x_r}=\int_{x=x_R}^{x=x_r}\left(\frac{d(CF)_x}{dx_r}\right)dx$$

$$=\int_{x=x_R}^{x=x_r}\left(\frac{d(CF)r}{dr}\cdot\frac{1}{\tan\theta_r}\right)dx$$

$$=\int_{x=x_R}^{x=x_r}\left(\frac{\delta}{g}A\omega^2r\cdot\frac{1}{\tan\theta_r}\right)dx \qquad \text{III–28}$$

(5) *Centrifugal bending moment.* Let $M_{(CF)_x}$=the centrifugal moment at any value of x.

$$\frac{dM_{CF_{x_r}}}{dx}=(\text{Shear})_{x_r}$$

So that

$$dM_{CF_{x_r}}=(\text{Shear})_{x_r}\cdot dx$$

And

$$M_{CF_q}=\int_{x=x_R}^{x=x_r}\int_{x=x_R}^{x=x_r}\left(\frac{\delta}{g}A\,\omega^2\,r\cdot\frac{1}{\tan\theta_r}\right)\cdot dx\cdot dx$$

III–29

In figure 3.19, a curve

$$\frac{d(CF)_x}{dx_r}\text{ vs }X$$

is plotted to the left of the ordinate axis. To

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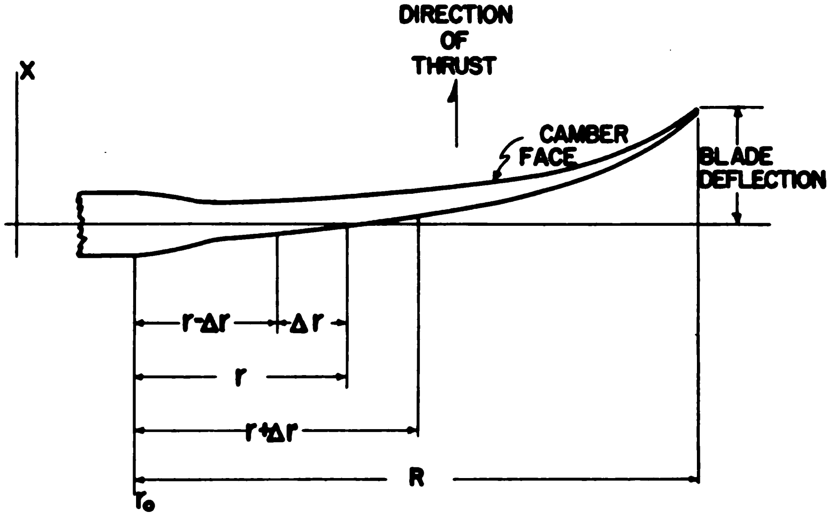

Figure 3.21.—Radial subdivision of blade flexure curve.

obtain a bending moment from the

$$\frac{d(CF)_x}{dx_r}$$

curve, the usual integrations must be performed. The first integration of

$$\frac{d(CF)_x}{dx_r}$$

(from x_R to x_r) yields transverse shear along the x-axis at x_r. Plotting successive values will produce a shear curve. Then, centrifugal bending moment may be obtained for any value of x by integrating the shear curve and evaluating for successive values of x (from x_R to x_r). The centrifugal bending moment at each radius, r, is the same as the centrifugal bending moment at corresponding value of x_r. Therefore, these bending moments may be transferred to radial stations of the blade in accordance with the relation of x_r to r, as established by the flexure curve. If the relation between x and r could be expressed mathematically in an integral form, the equation (III–30) could be integrated to furnish a simple expression for centrifugal bending moment.

$$M_{(CF)_x} = \int\int_{x_r}^{x_r} \left(\frac{\delta}{g} A_r\, \omega^2\, r \cdot \frac{1}{\tan \theta_r}\right) \cdot dx \cdot dx \qquad \text{III–30}$$

In lieu of that procedure, a graphical solution could be accomplished. Centrifugal bending moments along the blade radius must be combined algebraically with previously obtained air load bending moments at respective radii to obtain the net bending moments, M_{n_r}.

For the purpose of this discussion, air load bending moments will be considered as unchanged by blade deflection. A blade flexure curve representing net moments should be established in the usual manner. If the newly found curve is coincident with the assumed flexure curve, moments used in the calculations are true moments. If the new flexure curve does not correspond to the assumed blade flexure curve, a new curve must be assured and the entire process repeated.

The new assumption will be selected, of course, with due consideration for the relation of the previously assumed curve to the resulting calculated curve. In this trial-and-error or iterative process, the number of trial calculations required depends upon the accuracy of predicting the flexure curve in true profile. With experience, blade deflection curves can be predicted with accuracy, so that not more than two or three trials will be required, usually. If the blade is initially untilted, it has been shown that deflection, due to net moment, will be less than would obtain under action of the air load moment alone.

These integrations can be performed by either graphical or tabular methods. For tabular methods, elements of blade radius (Δr) are chosen so that chords of the flexure curve of the span, Δr, are practically coincident with the flexure curve of the given spans. A typical radial subdivision of a blade flexure curve is shown in figure 3.21.

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(1) *Simplified method for bending moment determination.* (*a*) General Considerations. Using the conventional strength of materials approach, as outlined, would necessitate four separate integrations for each assumed deflection curve. The problem may be solved by using only one set of calculations if the flexure formula is interpreted in the following manner:

$$\frac{d^2x}{dr^2}=\frac{M_n}{EI}\cong\frac{\Delta(\Delta x)}{(\Delta r)^2}$$

Solving for Δx:

$$\Delta(\Delta x)\cong\frac{M}{EI}(\Delta r)^2$$

Then,

$$(\Delta x)_r\cong\sum_{r_0}^{r}\frac{M_{n_r}}{EI_r}(\Delta r)^2 \qquad \text{III–31}$$

This relationship is justified when the rate of change in deflection is small.

Testing experience with conventional blades has proven that under conditions of small rate of change of deflection, the resulting accuracy obtained in using the preceding equation is sufficient. A method of determining net bending moment can be derived by using the preceding expression for deflection, with the problem being set up in tabular form so that calculating machines may be used in place of integrating devices.

(*b*) Development of general equation for net bending moment—Untilted blade. To simplify calculation of net bending moment, the following assumptions will be made:

(*i*) Air loads on a blade, calculated for operating conditions, are not appreciably affected by normal amounts of blade transverse deflection. Hence, the air load bending moment distribution will remain unchanged with blade deflection.

(*ii*) The blade is treated as an untwisted, rotating cantilever beam with minor axes of inertia of all transverse sections parallel to the plane of rotation. With a propeller blade divided into radial increments Δr in length, as shown in figure 3.21, the net bending moment at any station (*r*) may be written as:

$$M_{n_r}=M_{n_{r+\Delta r}}+\Delta M_{T_r}-\Delta M_{CF_r} \qquad \text{III–32}$$

wherein

$M_{n_{r+\Delta r}}$=net bending moment at station $(r+\Delta r)$.

M_{T_r}=incremental air load bending moment between station (*r*) and station $(r+\Delta r)$.

M_{CF_r}=incremental centrifugal bending moment between station (*r*) and station $(r+\Delta r)$.

The centrifugal force radial shear curve shown in figure 3.19 represents integration of the

$$\frac{\Delta CF}{\Delta x}$$

curve with respect to the deflection (*x*). It will be noted that distribution of

$$\frac{\Delta CF}{\Delta x}$$

may be derived from the relation between the quantity

$$\frac{\Delta CF}{\Delta r}$$

and the deflection curve, as previously shown. This transformation is shown, graphically, in figure 3.19. Further, centrifugal bending moment at any station (*r*) may be written as:

$$M_{CF_r}=\int_{x_R}^{x_r}\int_{R}^{r}\frac{d(CF)}{dr}\,dr\,dx \qquad \text{III–33}$$

wherein

$$\frac{d(CF)}{dr}=\frac{\delta}{g}A\omega^2r$$

which, in turn, may be rewritten as:

$$M_{CF_r}=\int_{x_R}^{x_r}(CF)_r dx \qquad \text{III–34}$$

Writing equation III–34 in incremental form:

$$\Delta M_{CF_r}=\left(\frac{(CF)_r+(CF)_{r+\Delta r}}{2}\right)\Delta x_r=(CF)_{r+.5\Delta r}\cdot\Delta x_r \qquad \text{III–35}$$

Substituting equation III–35 into equation III–32, net bending moment at any station (*r*) may be expressed as follows:

$$M_{n_r}=M_{n_{r+\Delta r}}+\Delta M_{T_r}-\left((CF)_{r+.5\Delta\cdot r}\right)\Delta x_r \qquad \text{III–36}$$

Further, substituting equation III–31 into equation III–36, the following form of the net bending moment equation can be obtained:

$$M_{n_r}=M_{n_{r+\Delta r}}+\Delta M_{T_r}-(CF)_{r+.5\Delta r}\left(\sum_{r_o}^{r}\frac{M_{n_r}}{EI_r}(\Delta r)^2\right) \qquad \text{III–37}$$

It should be noted that equation III–37 expresses the net bending moment for an untilted blade. Whenever displacements other than blade deflections due to air load are present (i. e., blade tilt, curvature, etc.) the restoring moment expression must be corrected, accordingly. To preserve simplicity throughout the derivation, displacements other than blade deflections due to air loads are not included.

Transposing equation III–37

$$M_{n_{r+\Delta r}}=M_{n_r}-\Delta M_{T_r}+(CF)_{r+.5\Delta r}\left(\sum_{r_o}^{r}\frac{M_{n_r}}{EI_r}(\Delta r)^2\right)$$

and considering the moment at a station $(r=r_1)$, (for simplicity of notation, let $r=1$), the moment equation becomes:

$$M_{n_1}=M_{n_0}-\Delta M_{T_0}+(CF)_{.5}\left(\frac{M_{n_0}}{EI_0}(\Delta r)^2\right)$$

$$=M_{n_0}\left(1+(CF)_{.5}\frac{(\Delta r)^2}{EI_0}\right)-\Delta M_{T_0} \qquad \text{III–38}$$

where $(r=r_0)$ is assumed to be that inboard station at which blade deflection is negligible $(x_0\approx 0)$. The subscripts 1, 2, 3, etc. represent the chronological sequence of stations, in outboard direction which are separated by the increment of radius (Δr).

At the station $(r=r_2)$ the moment equation becomes:

$$M_{n_2}=M_{n_1}-\Delta M_{T_1}+(CF)_{1.5}\left(\frac{M_{n_1}}{EI_1}(\Delta r)^2+\frac{M_{n_0}}{EI_0}(\Delta r)^2\right)$$

but, replacing M_{n_1} by equation III–38:

For convenience, let the coefficient of M_{n_0} in equation III–40 be equal to (F_2) and the remainder of the right hand side of this equation be equal to (G_2), then equation III–40 may be written:

$$M_{n_2}=F_2M_{n_0}+G_2$$

In more general terms,

$$M_{n_r}=F_rM_{n_0}+G_r \qquad \text{III–41}$$

Net moment at the blade tip is given in the relationship:

$$M_{n_R}=F_RM_{n_0}+G_R=0 \qquad \text{III–42}$$

from which

$$M_{n_0}=\frac{G_R}{F_R} \qquad \text{III–42a}$$

Net moment at the blade root is:

$$M_{n_0}=F_0M_{n_0}-G_0 \qquad \text{III–43}$$

Requirements of equation III–43 will be satisfied if the following conditions exist:

$$G_0=0,\ F_0=1 \qquad \text{III–43a}$$

Inspection of the (F_r) and (G_r) terms, of moment equations previously derived, reveals the following:

$$F_1=\left(1+(CF)_{.5}\frac{(\Delta r)^2}{EI_0}\right) \quad \text{(From equation III–38)}$$

$$F_2=\left(1+(CF)_{1.5}\frac{(\Delta r)^2}{EI_1}\right)F_1+(CF)_{1.5}\frac{(\Delta r)^2}{EI_0}$$

(From equation III–40)

which may be rewritten in the following form,

$$M_{n_2}=M_{n_0}\left(1+(CF)_{.5}\frac{(\Delta r)^2}{EI_0}\right)-\Delta M_{T_0}-\Delta M_{T_1}+(CF)_{1.5}\left(\left(\frac{M_{n_0}\left(1+(CF)_{.5}\frac{(\Delta r)^2}{EI_0}\right)-\Delta M_{T_0}}{EI_1}\right)(\Delta r)^2+\frac{M_{n_0}}{EI_0}(\Delta r)^2\right)$$

$$=M_{n_0}\left(1+(CF)_{.5}\frac{(\Delta r)^2}{EI_0}+(CF)_{1.5}\left(1+(CF)_{.5}\frac{(\Delta r)^2}{EI_0}\right)\frac{(\Delta r)^2}{EI_1}+(CF)_{1.5}\frac{(\Delta r)^2}{EI_0}\right)-$$

$$\Delta M_{T_0}\left(1+(CF)_{1.5}\frac{(\Delta r)^2}{EI_1}\right)-\Delta M_{T_1} \qquad \text{III–39}$$

The coefficient of M_{n_0} in the above equation may be factored, giving the following expression:

$$M_{n_2}=M_{n_0}\left(\left(1+(CF)_{.5}\frac{(\Delta r)^2}{EI_0}\right)\left(1+(CF)_{1.5}\frac{(\Delta r)^2}{EI_1}\right)+(CF)_{1.5}\frac{(\Delta r)^2}{EI_0}\right)-\Delta M_{T_0}\left(1+(CF)_{1.5}\frac{(\Delta r)^2}{EI_1}\right)-\Delta M_{T_1} \qquad \text{III 40}$$

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since $F_0=1$

$$F_2=F_1+CF_{1.5}\left(\frac{(\Delta r)^2}{EI_0}F_0+\frac{(\Delta r)^2}{EI_1}F_1\right)$$

Therefore the expression for the general term $(F_r+\Delta r)$ becomes:

$$F_{(r+\Delta r)}=F_r+(CF)_{r+.5\Delta r}\sum_{r_0}^{r}(\Delta r)^2\frac{F_r}{EI_r} \qquad \text{III–44}$$

Considering the expressions for (G_r)

$G_0=0$ (From equation III–43a)

$G_1=-\Delta M_{T_0}$ (From equation III–38)

$$G_2=-\Delta M_{T_0}\left(1+(CF)_{1.5}\frac{(\Delta r)^2}{EI_1}\right)-\Delta M_{T_1}$$

(From equation III–40)

The expression for (G_2) may be written as (recalling that $C_0=0$):

$$G_2=G_1+(CF)_{1.5}\left(\frac{(\Delta r)^2}{EI_0}G_0+\frac{(\Delta r)^2}{EI_1}G_1\right)-\Delta M_{T_1}$$

The expression for the general term $G_{(r+\Delta r)}$ becomes:

$$G_{(r+\Delta r)}=G_r+(CF)_{r+5\Delta r}\sum_{r_0}^{r}(\Delta r)^2\frac{G_r}{EI_r}-\Delta M_{T_r} \qquad \text{III–45}$$

Hence, a general equation has been established for an integrated tabular method of calculating net bending moment distribution along an initially untilted blade. The equation is:

$$M_{n_{r+\Delta r}}=M_{n_r}-\Delta M_{T_r}+(CF)_{r+.5\Delta r}\left(\sum_{r_0}^{r}\frac{M_{n_r}}{EI_r}(\Delta r)^2\right)$$
$$=F_{(r+\Delta r)}M_{n_0}+G_{(r+\Delta r)} \qquad \text{III–46}$$

in which $F_{(r+\Delta r)}$ and $G_{(r+\Delta r)}$ have equivalence as defined in equations III–44 and III–45, respectively.

Centrifugal Twisting Moment—Propeller Blade

(1) *Effect of centrifugal twisting moment upon a propeller.* Whenever the minor axis of inertia of a section of a rotating propeller blade is set at some angle with the plane of rotation, the action of centrifugal force on that section tends to rotate it so that its minor axis would be in the plane of rotation. This twisting effect of centrifugal force is designated centrifugal twisting moment.

Centrifugal twisting moment creates stresses in a propeller blade and tends to change pitch distribution within the blade. One of the most important effects of twisting moment, especially in relatively stiff blades, is that of the load imposed upon pitch changing mechanisms of controllable propellers. Determination of centrifugal twisting moments is, therefore, a very important phase of propeller design.

(2) *Centrifugal twisting moment acting upon an elemental blade mass* (*dm*). (*a*) Physical concept of twisting forces. Figure 3.22 represents a propeller blade section subjected to centrifugal forces. The action of centrifugal force on an infinitesimally small increment of volume, *dV*, cut from a blade cross-section having a thickness, *dr*, located at radius, *r*, is shown. Figure 3.23 shows the blade enlarged, with its center of gravity on the *Z-Z* axis. The blade section makes an angle β with the plane of rotation (*Y-Z* plane). The axis of propeller rotation is *X-X*. Axes *X′-X′* and *Y′-Y′* represent projections of the *X-X* and *Y-Y* axes, respectively, into the plane of the blade section which is perpendicular to the *Z-Z* axis. The elemental volume is at a radius *K* from the axis of propeller rotation.

The centrifugal force, *dF*, produced by rotation of this elemental volume of blade, is directed *ALONG THE RADIAL LINE K.* The centrifugal force (*dF*) may be resolved into components, one component being parallel to the *Z-Z* axis (which is the axis about which the blade would rotate in the hub to change pitch) and the other component being parallel to the *Y′-Y′* axis. It can be seen from figure 3.22 that the component of centrifugal force parallel to the *Z-Z* axis contributes to the axial tension in the blade, but does not tend to produce rotation of the section about the *Z-Z* axis. However, the component of centrifugal force, $dF'_{Y'}$ DOES TEND to produce rotation of the section about the *Z-Z* axis.

(*b*) Development of centrifugal twisting moment equation. The differential volume, as shown in figure 3.22 is:

$$dV=dx_0dy_0dr$$

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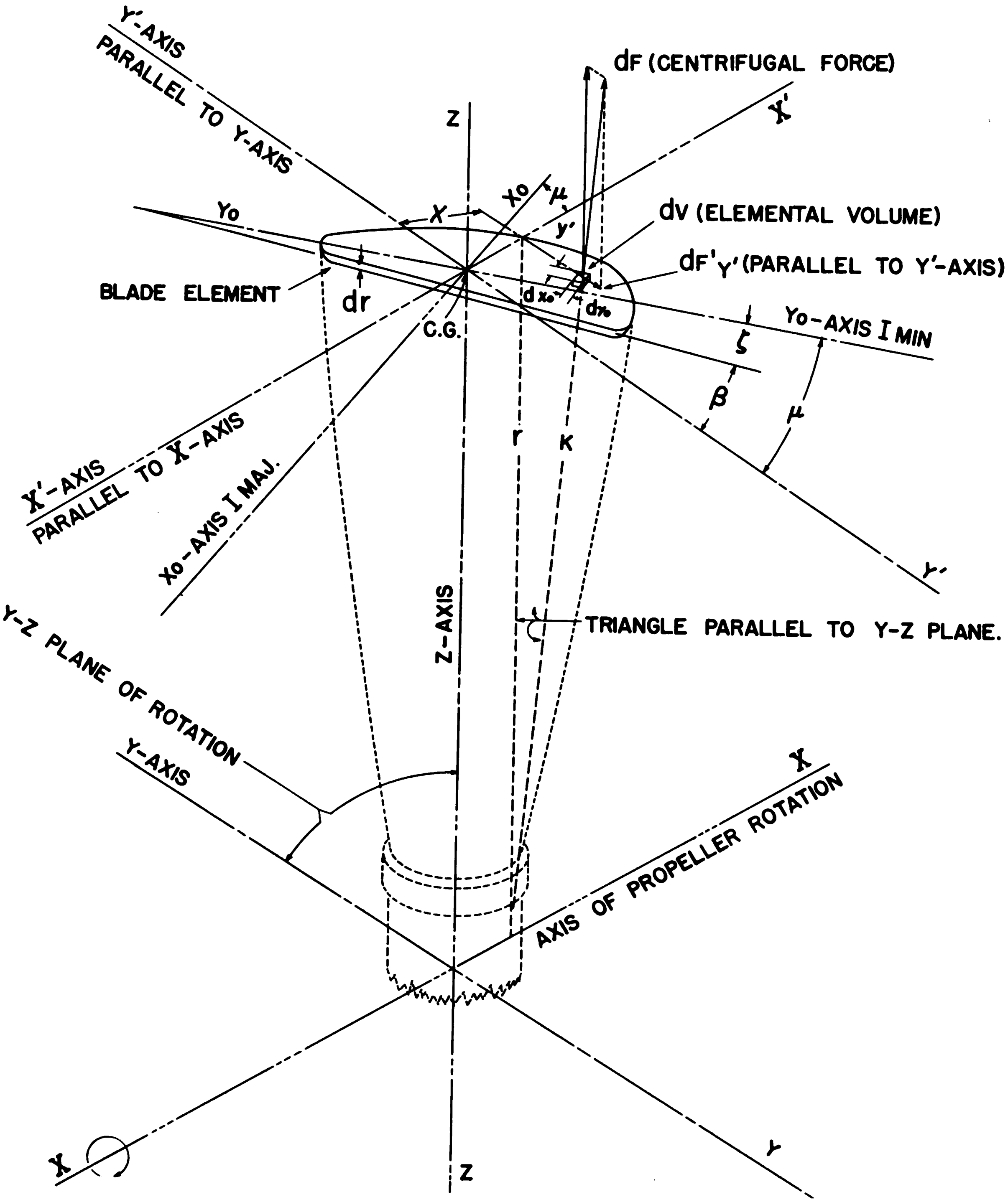

Figure 3.22.—Propeller blade centrifugal twisting forces.

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and differential mass is:

$$dm=\frac{\delta}{g}\,dV=\frac{\delta}{g}\,dx_o\,dy_o\,dr$$

Centrifugal force acting on the differential mass, *dm*, is:

$$dF=K\,\omega^2\,dm=\frac{\delta}{g}\,K\,\omega^2\,dx_o\,dy_o\,dr \qquad \text{III–47}$$

This force lies in a plane parallel to the *YZ* plane and has the components $dF_{Y'}$ and dF_Z. From figure 3.22:

$$\frac{dF_{y'}}{dF}=\frac{y'}{K}$$

therefore

$$dF_{y'}=dF\,\frac{y'}{K}=\frac{\delta}{g}\,y'\,\omega^2\,dx_o\,dy_o\,dr \qquad \text{III–48}$$

From figure 3.23:

$$x'=(e+x_o)\cos\mu=(y_o\tan\mu+x_o)\cos\mu$$

Hence,

$$x'=x_o\cos\mu+y_o\sin\mu$$

Also

$$y'=b\cos\mu=(y_o-c)\cos\mu=(y_o-x_o\tan\mu)\cos\mu$$

From which

$$y'=-x_o\sin\mu+y_o\cos\mu$$

Then, equation III–48 may be rewritten, substituting for y' its equivalent:

$$dF_{y'}=\frac{\delta}{g}\,\omega^2(-x_o\sin\mu+y_o\cos\mu)\,dx_o\,dy_o\,dr$$

The moment *dQ* of the force $dF_{y'}$ about the *Z* axis is (see fig. 3.23):

$$dQ_{CF}=dF_{y'}\,(x')=dF_{y'}\,(x_o\cos\mu+y_o\sin\mu \text{ or}$$

$$dQ_{CF}=\frac{\delta\omega^2}{g}\,(-x_o\sin\mu+y_o\cos\mu)\,dx_o\,dy_o\,dr\,(x_o\cos\mu+y_o\sin\mu)$$

$$dQ_{CF}=\frac{\delta\omega^2}{g}\,[(y_o^2-x_o^2)\sin\mu\cos\mu+x_o y_o(\cos^2\mu-\sin^2\mu)]\,dx_o\,dy_o\,dr \qquad \text{III–49}$$

(3) *Centrifugal twisting moment for the entire blade element*

$$dQ_{CF}=\frac{\delta\omega^2}{g}dr\iint[(y_o^2dx_ody_o-x_o^2dx_ody_o)\sin\mu\cos\mu+(x_oy_odx_ody_o)(\cos^2\mu-\sin^2\mu)]$$

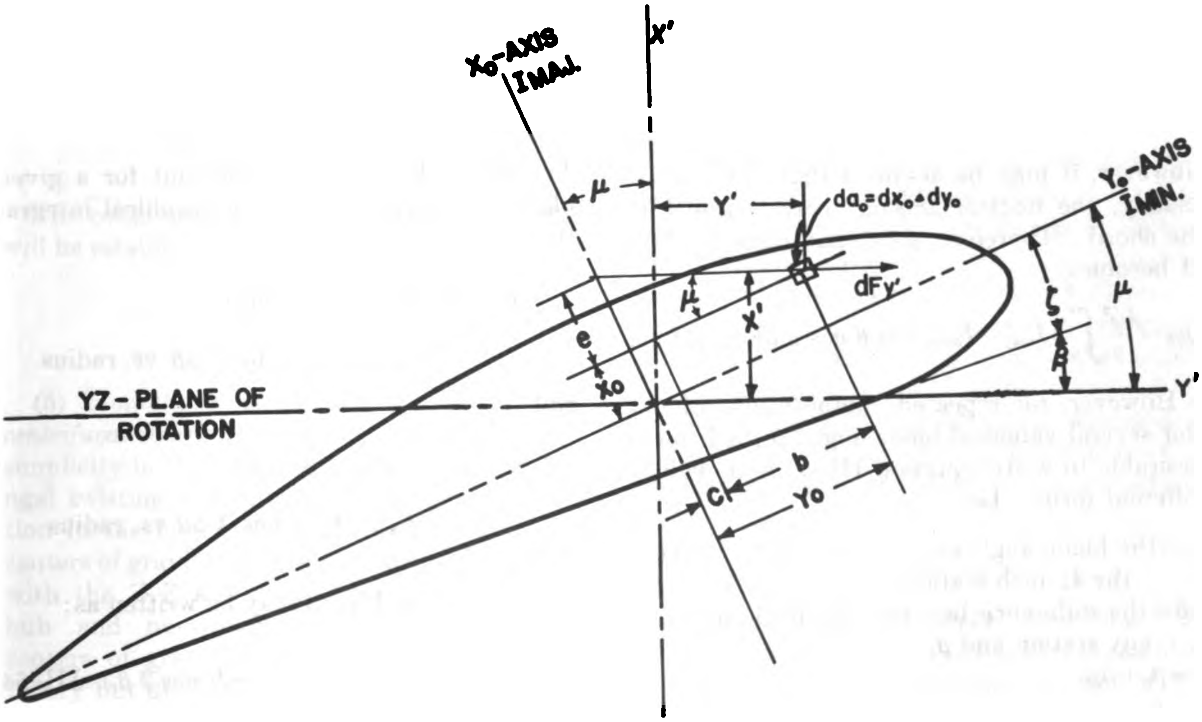

Figure 3.23.—Propeller blade section subject to twisting forces.

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But, for the entire blade element:

$$\iint y_o^2\,dx_o\,dy_o=\int y_o^2\,da=I_{x_o}=I_{\mathrm{major}}$$

and

$$\iint x_o^2\,dx_o\,dy_o=\int d_o^2\,da=I_{y_o}=I_{\mathrm{minor}}$$

$$\iint x_oy_o\,dx_o\,dy_o=\int x_oy_o\,da=0,$$

since the x_o and y_o axes are principal axes of inertia. Therefore,

$$dQ_{CF}=\frac{\delta\omega^2}{g}\,dr(I_{\mathrm{maj}}-I_{\mathrm{min}})\sin\mu\cos\mu \qquad \text{III–50}$$

(4) *Centrifugal twisting moment of a complete propeller blade.* Centrifugal twisting moment of a blade section of given thickness (dr) is entirely independent of the section radius (r). Centrifugal twisting moment of a particular section is dependent only upon rotational speed (ω) and angular orientation of the section (μ) with respect to the plane of rotation. For fixed values for ω and μ, the twisting moment would be the same for a given blade section at ANY radius, even at zero radius, if the section could be placed there.

Twisting moment, Q_{CF}, for the entire blade is:

$$Q_{CF}=\int dQ_{CF}=\frac{\delta\omega^2}{g}\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\sin\mu\cos\mu \qquad \text{III–51}$$

$$\mu=\beta+\zeta$$

However, it may be assumed that $\zeta=0$, since, usually, the neutral axis is nearly parallel to the chord. Therefore, $\mu=\beta$, and equation III–51 becomes:

$$Q_{CF}=\frac{\delta\omega^2}{g}\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\sin\beta\cos\beta\,dr \qquad \text{III–52}$$

However, for repeated computations of Q_{CF} (for several values of blade angle, β,) it is more desirable to write equation III–52 in a slightly different form. Let:

β_r = the blade angle at a particular station (say the 42-inch station)

$\Delta\beta$ = the difference between the blade angle at any station and β_r

$\beta=\beta_r+\Delta\beta$

Since

$$\sin 2\beta=2\sin\beta\cos\beta$$

and

$$\beta=\beta_r+\Delta\beta$$

$$\sin\beta\cos\beta=\frac{1}{2}\sin 2\beta=\frac{1}{2}\sin 2\,(\beta_r+\Delta\beta)$$

$$=\frac{1}{2}(\sin 2\,\beta_r\cos 2\,\Delta\beta+\cos 2\,\beta_r\sin 2\Delta\beta) \qquad \text{III–52a}$$

The anole β_r may be chosen at will. For a given value, β_r, the terms $\sin 2\,\beta_r$ and $\cos 2\,\beta_r$ are constant. For a given conventional blade, the value of $\Delta\beta$ between any two stations is fixed and independent of β_r.

Combining equations:

$$Q_{CF}=\frac{\delta\omega^2}{g}\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\,\frac{1}{2}(\sin 2\,\beta_r\cos 2\Delta\beta+\cos 2\,\beta_r\sin 2\Delta\beta)dr$$

Factoring,

$$Q_{CF}=\frac{\delta\omega^2}{g}\left(\sin 2\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\cos 2\,\Delta\beta\,\mathrm{dr}+\cos 2\,\beta_r\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\sin 2\,\Delta\beta\,\mathrm{dr}\right) \text{III–53}$$

For convenience, let:

$$C=\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\cos 2\,\Delta\beta\,dr$$

$$B=\int_R^{r_o}(\mathrm{I}_{\mathrm{maj}}-I_{\mathrm{min}})\sin 2\,\Delta\beta\,dr$$

The terms B and C are constant for a given blade and may be found by graphical integration, in which:

B = area under the curve,

$$\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\sin 2\,\Delta\beta \text{ vs. radius}$$

and

C = area under the curve,

$$\int_R^{r_o}(I_{\mathrm{maj}}-I_{\mathrm{min}})\cos 2\,\Delta\beta \text{ vs. radius}$$

Then, equation III–53 may be written as:

$$Q_{CF}=\frac{\delta\omega^2}{g}(C\sin 2\,\beta_r+B\cos 2\,\beta_r) \qquad \text{III–54}$$

(5) *Maximum centrifugal twisting moment—*

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Propeller blade. Generally, however, maximum centrifugal twisting moment is the only quantity desired. To arrive at maximum centrifugal twisting moment, equation III–54 may be modified as follows:

Let

$$\frac{C}{B}=\tan 2\lambda$$

then

$$\sin 2\lambda=\frac{C}{\sqrt{B^2+C^2}}$$

and

$$\cos 2\lambda=\frac{B}{\sqrt{B^2+C^2}}$$

then equation III–54 may be written as:

$$Q_{CF}=\frac{\delta\,\omega^2}{g}\sqrt{B^2+C^2}\left(\frac{C\sin 2\beta_r}{\sqrt{B^2+C^2}}+\frac{B\cos 2\beta_r}{\sqrt{B^2+C^2}}\right)$$

$$=\frac{\delta\,\omega^2}{g}\sqrt{B^2+C^2}\,(\sin 2\lambda \sin 2\beta_r+$$

$$\cos 2\lambda \cos 2\beta_r)$$

$$=\frac{\delta\,\omega^2}{g}\sqrt{B^2+C^2}\cos 2(\lambda-\beta_r) \qquad \text{III–55}$$

Q_{CF} will be a maximum when $\cos 2(\lambda-\beta_r=1$. Cosine of the angle, $2(\lambda-\beta_r)$ will be unity when the angle, $2(\lambda-\beta_r)=0$, or, when $\lambda=\beta_r$. Therefore,

$$Q_{CF\,\max}=\frac{\delta\,\omega^2}{g}\sqrt{B^2+C^2} \qquad \text{III–56}$$

The condition of maximum twisting moment will be established when,

$$\beta_r=\frac{1}{2}\arctan\frac{C}{B}$$

(6) *Limitations of derived expressions for centrifugal twisting moments.* For the sake of simplicity in the foregoing discussion of centrifugal twisting moments, the axis of blade rotation in the hub and the axis of blade section centers of gravity have been taken as coincident with the *Z–Z* axis. Tilt of the blade in the hub and non-coincidence of blade section centers of gravity would not alter the basic theory but due consideration would have to be given to the departures from conditions assumed in development of the preceding equations.

Steady Stress Analysis—Propeller Blade

Combined Stresses

Steady stress distribution, which provides a basis for blade design and a criterion for structural integrity of the blade, may be obtained by combining axial stress due to centrifugal force and axial stress due to net bending moment. The stress due to centrifugal force may be calculated from the equation:

$$S_{CF_r}=\frac{CF_r}{A_r} \qquad \text{III–57}$$

Determination of axial stress due to bending moment on thrust and camber faces can be obtained from the following relationships:

$$\text{Thrust Face, } (S_{BT})_r=\left(\frac{M_R Y_t}{I_{\min}}\right)_r \qquad \text{III–58}$$

$$\text{Camber Face, } (S_{BC})_r=\left(\frac{M_R Y_c}{I_{\min}}\right)_r \qquad \text{III–59}$$

Designating tensile stress as positive and compressive stress as negative, the combined (total) thrust face stress may be found from equation III–60.

$$S_{T_r}=S_{FC_r}+S_{BT_r} \qquad \text{III–60}$$

The combined camber face stress can be determined from the following equation:

$$S_{C_r}=S_{CF_r}-S_{BC_r} \qquad \text{III–61}$$

A complete steady stress calculation has been prepared to illustrate application of the concepts of steady blade loading that have been derived and a tabular method which may be used to obtain the combined stress distributions. A step-by-step method of procedure is presented in the following paragraphs, wherein the method of determination of the items indicated as column headings in the tables is explained in detail. A set of curves, which are plotted in conjunction with preparation of the analysis, is shown in figures 3.24–3.30, inclusive.

Steady Stress Analysis—Procedure

(1) *Assumed or given data—Recording.* To initiate a propeller stress analysis, it is essential that certain data be at hand. Some of the necessary information will be forthcoming from known requirements of the airplane, while other

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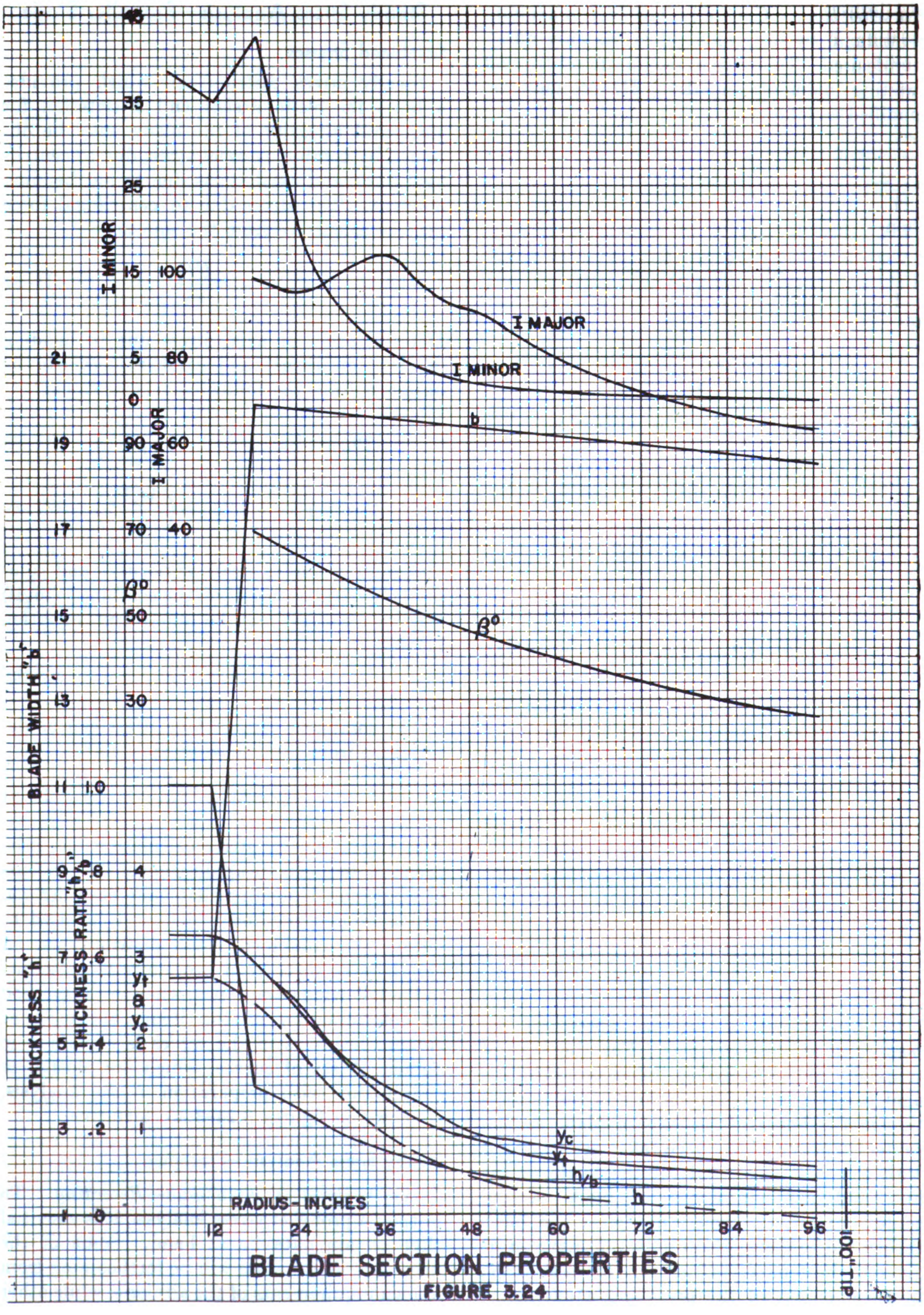
I MINOR
45
35
25
15
5
0
100
80
I MAJOR
60
40
21
19
17
15
13
11
9
7
5
3
1
90
70
β°
50
30
1.0
.8
.6
.4
.2
0
4
3
2
1
y_t
θ
y_c
BLADE WIDTH "b"
THICKNESS "h"
THICKNESS RATIO "h/b"
I MAJOR
I MINOR
b
β°
y_c
y_t
h/b
h
RADIUS - INCHES
12
24
36
48
60
72
84
96
100" TIP
BLADE SECTION PROPERTIES
FIGURE 3.24

Figure 3.24.

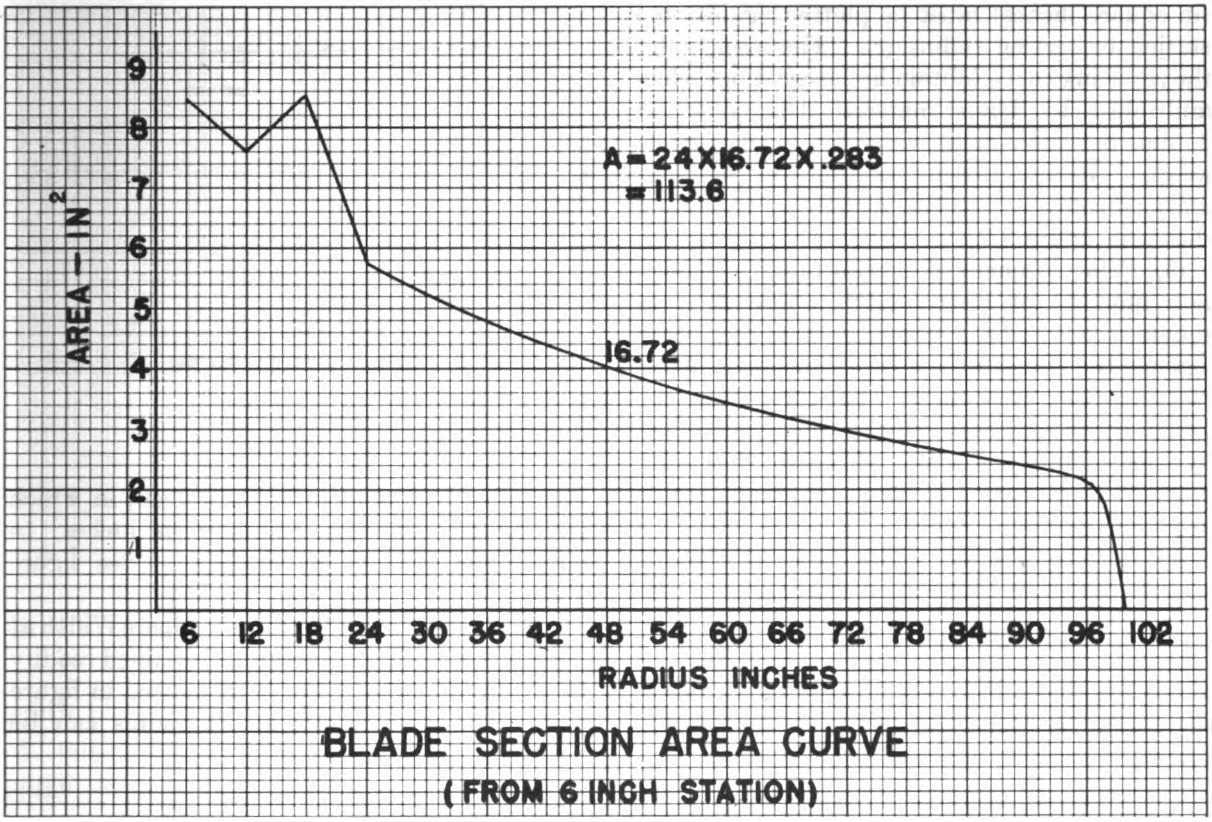

Figure 3.25.

equally pertinent information will have to be assumed. The following items are required for a propeller stress analysis:

- (*a*) Blade design identification number and airfoil section type.
- (*b*) Airplane type for application.
- (*c*) Engine BHP.
- (*d*) Engine speed; propeller gear ratio.
- (*e*) Propeller material and blade construction.
- (*f*) Number of blades.
- (*g*) Blade diameter.
- (*h*) Angle of tilt of the propeller blade (τ).

If, as is the case for a new design, some required data is not available, judgment must be exercised to select reasonable values that will most nearly meet the given design situation. As a matter of convenience, assumed or selected design data may be recorded upon the Summary Sheet (table III–11), the preparation of which is described in further detail in paragraph (10) of this section. Blade section properties for a given blade have been plotted against the blade radius in figure 3.24.

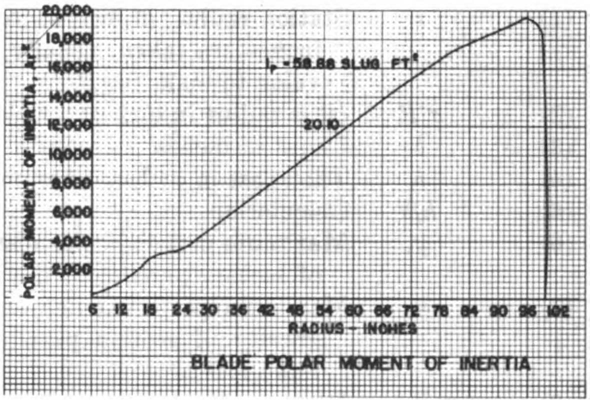

Figure 3.26.

(2) *Preparation of summary sheet.* While complete description of the propeller stress analysis sheet (table III–11) has been deferred to paragraph (10), it is highly desirable that the form be prepared before any computations are started. If the form is available, information assumed, or calculated, may be entered thereon just as soon as the calculations are complete. Before the forces, bending moments and stresses can be computed, certain physical quantities must be calculated from the assumed or given data of paragraph (1). Preliminary calculations will include the following:

(*a*) Blade Weight (W). Blade section area

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(in square inches) must be plotted against the station or section radius (r). The area under the resulting curve (obtain by integration) when multiplied by blade material density (δ, in pounds per cubic inch) will give propeller blade weight. Record this information on the summary sheet. A typical section area plot is shown in figure 3.25.

(b) Polar Moment of Inertia (I_P). The section moment of inertia (Ar^2, where A is in square inches and r is in inches) must be plotted against the blade radius (r, in inches). After plotting, the area under the curve may be found by integration, which, when multiplied by the quantity $\delta/4637$, will give the polar moment of inertia; δ is blade material density in pounds per cubic inch.

(c) Activity Factor. The ratio, station or section radius (r) divided by blade radius (R) raised to the fourth power, i. e. $\left(\frac{r}{R}\right)^4$, must be plotted against blade section chord (b). After the curve has been established, the area under the curve may be obtained by integration and multiplied by the quantity $(10)^5/64D$, in which (D) is the propeller diameter in inches, to obtain the activity factor (AF). See figure 3.27.

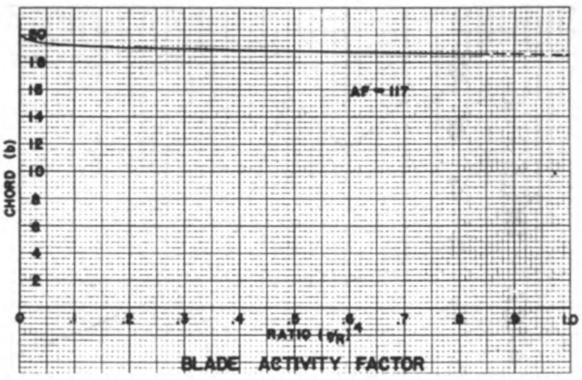

Figure 3.27.

(d). Ratio Blade Thickness to Blade Width at .75 Radius. This ratio can be obtained readily from the (h/b) vs. (r) curve as plotted in figure 3.24. The ratio of h/b at .75 radius can be read from the graph.

(3) *Determination of Section and Blade Properties—Table III-4*

Column Number	*Quantity*	*Basis of Determination*
(1)	r	Station radius, in inches, from innermost station to tip. Increments of 3 or 6 inches are taken, usually, with the last increment being of the appropriate value to make $r=R$.
(2)	r/R	(R is radius in inches) Calculate.
(3)	b	Chord in inches. Assumed or obtained from blade drawing.
(4)	h	Thickness in inches. Assumed or obtained from blade drawing.
(5)	h/b	Calculation.
(6)	y_t	Maximum perpendicular distance from a line passing through center of gravity of section parallel to the chord, to thrust face, in inches. See table III-2.
(7)	y_c	Maximum perpendicular distance from a line passing through the center of gravity of section parallel to the chord, to camber face, in inches. See table III-2.
(8)	Z_s	Distance from blade axis to section center of gravity measured perpendicular to chord. (+ sign means c. g. is located on camber side.) This column may be neglected when no static offsets of blade centers of gravity are present (i.e., no tilt, curvature, etc.)
(9)	β	Blade angle in degrees. Assumed or obtained from propeller blade drawing.
(10)	A.	Area of blade section in square inches.
(11)	$I_{maj.}$	Major moment of inertia of section, in (inches)^4.
(12)	$I_{min.}$	Minor moment of inertia of section, in (inches)^4.
(13)	Ar.	Column (1) entry multiplied by column (10) entry.
(14)	Ar^2.	Column (1)^2 entry multiplied by column (10) entry.

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TABLE III–4. *Propeller Section and Blade Properties*

1	2	3	4	5	6	7	7	9	10	11	12	13	14
r (*Inches*)	r/R (*Inches*)	b (*Inches*)	h (*Inches*)	h/b (*Inches*)	y_t (*Inches*)	y_c (*Inches*)	x_S (*Inches*)	β (*Degrees*)	A (*Inches*^{2})	I_{MAJ} (*Inches*^{4})	I_{MIN} (*Inches*^{4})	Ar (*Inches*^{3})	Ar^2 (*Inches*^{4})
6	0.060	6.485	6.485	1.000	3.242	3.242	0	----------	8.48	38.38	38.38	50.88	305
12	.120	6.485	6.485	1.000	3.242	3.242	0	----------	7.60	34.96	34.96	91.20	1,094
18	.180	19.900	5.855	.294	2.930	2.930	0	69.7	8.51	98.25	42.47	153.18	2,757
24	.240	19.800	4.790	.242	2.368	2.422	0	64.1	5.73	95.10	20.79	137.52	3,300
30	.300	19.690	3.610	.183	1.779	1.831	0	58.7	5.19	100.00	10.80	155.70	4,671
36	.360	19.590	2.840	.145	1.349	1.491	0	54.0	4.80	104.20	5.99	172.80	6,221
42	.420	19.490	2.240	.115	1.034	1.206	0	49.7	4.39	95.90	3.40	184.38	7,744
48	.480	19.390	1.804	.093	.872	.932	0	46.1	4.00	91.20	2.18	192.00	9,216
54	.540	19.280	1.543	.080	.696	.847	0	42.7	3.68	85.80	1.44	198.72	10,731
60	.600	19.180	1.380	.0719	.626	.754	0	39.6	3.42	80.00	.95	205.2	12,312
66	.660	19.080	1.280	.0671	.577	.703	0	36.6	3.16	75.60	.66	208.56	13,765
72	.720	18.980	1.195	.0630	.533	.662	0	34.0	2.93	71.90	.49	210.96	15,189
78	.780	18.880	1.115	.0591	.485	.630	0	31.7	2.75	68.90	.39	214.5	16,731
84	.840	18.770	1.033	.0550	.444	.589	0	29.7	2.51	66.50	.33	210.84	17,711
90	.900	18.670	.952	.0510	.403	.549	0	27.8	2.30	64.80	.28	207.0	18,630
96	.960	18.570	.892	.0480	.368	.524	0	26.0	2.11	63.70	.22	202.56	19,446
100	1.000												

(4) *Blade Loading Using $\Delta L/\Delta r$ Curve—Table III–5*

Column Number	*Quantity*	*Basis of Determination*
(1)	r	As selected in table III–4
(15)	$\Delta\ CF$	To be computed as follows: All radial stations except the one inboard from the tip: $\Delta\ CF=28.38\ \delta \left(\frac{N}{1000}\right)^2 \Delta r\ Ar_{(r+\Delta r)}$ For last station before blade tip: $\Delta\ CF=28.38\ \delta \left(\frac{N}{1000}\right)^2 \frac{\overline{\Delta r}}{r} \frac{2}{3} Ar_{(R-\overline{\Delta r})}$ Where: δ=Specific weight of material (lb. per in.^{3}) N=r. p. m Δr=Increment of blade between stations $\overline{\Delta r}$=Increment of blade between tip and first inboard station from the blade tip. $Ar_{(r+\Delta r)}=Ar$ at the next station beyond r.
(16)	CF	$CF=\sum_R^r \Delta\ CF$, CF at tip=0 CF may be plotted as shown in figure 3.28.
(17)	α	Angle of attack distribution along the blade radius, in degrees.
(18)	$\Delta L/\Delta r$	Incremental lift distribution to be obtained for stations along the blade radius, in lb. per blade increment, from figure 3.18.
(19)	$\Delta L/\Delta r$ *Cos* α	(Entry column 18) *Cos* α
(20)	N'	Normal force acting along the blade radius: $N'_r=\sum_R^r \left(\frac{\Delta L}{\Delta r} \text{Cos}\ \alpha\right) \Delta r$ loading is determined from aerodynamic considerations; sometimes taken as static thrust (T_s) for static conditions. See figure 3.18.
(21)	ΔM	$\Delta M=\left(\frac{N'_r N'_{(r+\Delta r)}}{2}\right) \Delta r$

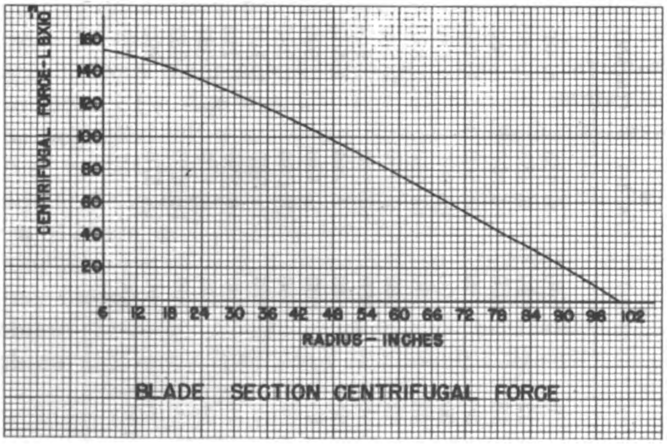

Figure 3.28.

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TABLE III-5. *Blade Loading, Using $\Delta L/\Delta r$ Curve*

1	15	16	17	18	19	20	21
r (Inches)	Δ *CF* (Pounds)	*CF* (Pounds)	α (Degrees)	$\Delta L/\Delta r$ (Pounds-Inches^{-1})	$\frac{\Delta L \cos A}{\Delta r}$ (Pound-Inches^{-1})	N' (Pounds)	ΔM_T (Inch-Pounds
6	4, 845	150, 635	----------	----------	----------	----------	25, 494
12	8, 138	145, 790	----------	----------	----------	----------	25, 494
18	7, 306	137, 652	----------	----------	----------	----------	25, 494
24	8, 272	130, 346	----------	----------	----------	----------	25, 494
30	9, 181	122, 074	19. 4	84. 0	79. 23	4, 289	25, 494
36	9, 796	112, 893	17. 0	126. 5	120. 972	4, 209	24, 891
42	10, 201	103, 097	14. 8	182. 0	176. 003	4, 088	24, 000
48	10, 558	92, 896	12. 6	247. 5	241. 540	3, 912	22, 749
54	10, 902	82, 338	10. 6	323. 0	317. 490	3, 671	21, 072
60	11, 081	71, 436	8. 8	404. 5	399. 739	3, 353	18, 921
66	11, 208	60, 355	7. 2	489. 5	485. 638	2, 954	16, 266
72	11, 396	49, 147	5. 8	567. 0	564. 046	2, 468	13, 116
78	11, 202	37, 751	4. 8	624. 5	622. 308	1, 904	9, 558
84	10, 998	26, 549	3. 9	594. 0	592. 622	1, 282	5, 913
90	10, 762	15, 551	3. 2	490. 0	489. 260	689	2, 667
96	4, 789	4, 789	2. 5	200. 0	199. 818	200	400
100	----------	----------	----------	----------	----------	----------	----------

(5) *Blade Loading Using $\Delta T/\Delta r$ Curve—Table III–6*

Column Number	*Quantity*	*Basis of Determination*
(1)	r	To be obtained from table III–4.
(15)	Δ *CF*	Δ *CF* can be calculated as outlined in table III–5.
(16)	*CF*	From table III–5.
(17)	br^2	Entry of column (1) squared, multiplied by blade chord (table III–4).
(18)	$\Delta T/K$	This quantity can be determined as follows: (a) For any station except the one next to blade tip $(\Delta T/K)_r = \left(\frac{(br^2)_r + (br^2)_{(r+\Delta r)}}{2}\right)\Delta r$ (b) First station inboard from blade tip $(\Delta T/K) = \left(\frac{(br^2)_{(R-\Delta r)} + (br^2)_R}{2}\right)\Delta r$
(19)	ΔT	To find ΔT, summation of entries in Column (18) must be obtained. Then $K = T_s$ * (or N' from summary sheet) divided by Σ ⑱ This value (K) should be recorded as shown in table III–6 $\Delta T = K$ (Entry column 18)
(20)	T	$T = \sum_R^r \Delta T$
(21)	ΔM_T	$\Delta M_T = \left(\frac{T_r + T_{(r+\Delta r)}}{2}\right)\Delta r$

*Recorded in table III–3 (see fig. 3.18)

NOTE: If an effective area is given in the data supplied (table III–1), that value should be used to find blade loading.

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TABLE III–6. *Blade Loading, Using $\Delta T/\Delta r$ Curve*

1	15	16	17	18	19	20	21
r (Inches)	ΔCF (Pounds)	CF (Pounds)	br^3 (Inches ^{3})	$\left(\frac{\Delta T}{K}\right)$ (Inches ^{4})	ΔT (Pounds)	T (Pounds)	ΔM_T (Inch-Pounds)
6	4, 845	150, 635	233	3, 501	2. 54	4, 300	25, 791
12	8, 138	145, 790	934	22, 146	16. 05	4, 297	25, 734
18	7, 306	137, 652	6, 448	53, 559	38. 81	4, 281	25, 572
24	8, 272	130, 346	11, 405	87, 378	63. 32	4, 243	25, 266
30	9, 181	122, 074	17, 721	129, 330	93. 72	4, 179	24, 795
36	9, 796	112, 893	25, 389	179, 307	129. 93	4, 086	24, 126
42	10, 201	103, 097	34, 380	237, 165	171. 86	3, 956	23, 220
48	10, 558	92, 896	44, 675	302, 685	219. 34	3, 784	22, 044
54	10, 902	82, 338	56, 220	375, 804	272. 32	3, 564	20, 568
60	11, 081	71, 436	69, 048	456, 480	330. 79	3, 292	18, 759
66	11, 208	60, 355	83, 112	544, 512	394. 58	2, 961	16, 584
72	11, 396	49, 147	98, 392	639, 774	463. 61	2, 567	14, 010
78	11, 202	37, 751	114, 866	741, 921	537. 63	2, 103	11, 007
84	10, 998	26, 549	132, 441	851, 004	616. 67	1, 566	7, 545
90	10, 762	15, 551	151, 227	967, 104	700. 81	949	3, 591
96	4, 789	4, 789	171, 141	342, 282	248. 03	248	496
100	0	0	0	0	0	0	0

(6) *Net Bending Moment—Table III–7.* (See Table III–7 on insert following page 96.)

Column Number	*Quantity*	*Basis of Determination*
(1)	r	Selected stations as in table III–4.
(22)	$EI/(\Delta r)^2$	To be calculated: E=Modulus elasticity, $I=I_{min}$, table III–4.
(23)	F	$F_{(r+\Delta r)}=F_r+CF_{\left(r+\frac{\Delta r}{2}\right)}\sum_{r_0}^{r}(\Delta r)^2F_r/EI,$ F=1.0 at first station.
(24)	$F\frac{(\Delta r)^2}{EI}$	$F(\Delta r)^2/EI$=Entry column (23)/entry column (22).
(25)	$\sum\frac{F(\Delta r)^2}{EI}$	$\sum F(\Delta r)^2/EI$=Summation entries column (24) to station radius (r).
(16)	$CF\sum\frac{F(\Delta r)^2}{EI}$	Obtain CF from table III–5 (or fig. 3.28); record in this table.
(26)	$CF\sum\frac{F(\Delta r)^2}{EI}$	$CF\sum F(\Delta r)^2/EI$=Product entries columns (16) and (25).

Procedural notes for the above section of Table III–7

Enter all radial stations (r values leaving a horizontal line space ($r+.5\Delta r$) between adjacent values of (r), for subsequent entries.

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Calculate the value of $EI/(\Delta r)^2$ at each radial station and enter the result in column (22) on the same horizontal line upon which r is shown.

Since $F=1.0$ at the first radial station, record this value (1.0) in column (23) opposite $r=6.0$ inches (on the same line).

Calculate the first entry for column (24), $F(\Delta r)^2/EI$, and record the result on the same horizontal line as radial station r.

Record the first entry of column (24) in column (25) on the horizontal space line $(r+.5\Delta r)$ between $r=6.0$ and $r=12.0$.

Record value of CF, from table III–5, in column (16) on horizontal line $(r+.5\Delta r)$.

The product of entries in columns (16) and (25) should be entered in column (26) on horizontal line $(r+.5\Delta r)$. This product should be carried out to nine significant places.

Upon completion of the foregoing operations, the horizontal lines $(r=6.0)$ and (space between $r=6.0$ and $r=12.0$) will have been filled in for all columns (1) through (26).

Returning to column (23) and to the horizontal line of the next radial station $(r=12)$ and space between $(r=12$ and $r=18)$, add the tabular value of column (26) line $(r+.5\Delta r)$ to the immediate preceding line (station r) entry of column (23) and record the sum in column (23) on the horizontal line at $(r+\Delta r)$ or $r=12$, in this case.

Divide the new value of F (column 23 at $r=12$) by the corresponding new value in column (22) (at $r=12$) and enter the quotient in column (24) (horizontal line, $r=12$).

The cumulative sum of entries in column (24) (in this case for horizontal lines $r=6$ and $r=12$) should be recorded in column (25) on the new horizontal line $(r+.5\Delta r)$.

Again, the product of new entries in columns (16) and (25) are entered in column (26) at the new $(r+.5\Delta r)$ station.

This step-by-step procedure is continued until all columns (1) through (26) are filled down to the radial station $r=R$, propeller blade radius.

Column Number	*Quantity*	*Basis of Determination*
(27)	G	$G=0$, at the first station (see equations III–43a and III–45).
(28)	$G(\Delta r)^2/EI$	Column (27) entry/entry column (22).
(29)	$G(\Delta r)^2/EI+\Delta r\tan\tau$	Self-evident, when $r=0$, column (29)=column (28).
(30)	ΔZ_s	$\Delta Z_s=Z_{s_{(r+\Delta r)}}$ at first station (table III–1). $\Delta Z_{s_r}=Z_{s_{(r+\Delta r)}}-Z_{s_r}$: Factor not often used. No entries in column (30).
(31)	$\sum G\frac{(\Delta r)^2}{EI}$	Horizontal summation of entries column (29) and column (30). When $r=0$ and $\Delta Z_s=0$, this column entry is the same as that in column (29).
(32)	$CF_{(r+.5\Delta r)}$	Product of entries in columns (31) and (16).
(21)	ΔM_T	Transcribe from table III–5.
(33)	$F_{M_{n_{r_0}}}$	M_n at root$=-\frac{G\ Tip}{F\ Tip}=M_n$ at first station $(r=6)$.
		$F_{M_{n_{r_0}}}=(M_n$ at root) (entry column 23).
(34)	M_n	Horizontal summation of entries in columns (27) and (33).

Procedural note

In completing table III–7, columns (27) through (34) are completed for each radial station r

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and line $(r+.5\Delta r)$ before passing on to the next succeeding radial station r_n. This procedure is similar to that employed in completing columns (1) through (26).

Column (28): $G(\Delta r)^2/EI$=Column (27)/column (22); enter the quotient on the horizontal line of radial station, r.

Add Δr tan τ to entry in column (28) and record the sum in column (29) on line $(r+.5\Delta r)$.

Z_s (if any) should be added to the entry of column (29) on line $(r+.5\Delta r)$ and recorded in column 30 on line $(r+.5\Delta r)$.

Column (31) entry on line $(r+.5\Delta r)$ is sum of entries in columns (29) and (30). In this example column (31) is same as column (29).

For column (32), obtain product of entries in column (16) and (32) and enter the result on line $(r+.5\Delta r)$.

Transcribe column (21) from table III–5 placing entries in table III–7, column 21 on line $(r+.5\Delta r)$.

Column (27): For entries at radial stations other than the first, G=entry in column (27) [on line $(r+.5\Delta r)$ preceding the radial station under consideration]+entry in column (32) [line $(r+.5\Delta r)$ preceding (r) under consideration]−entry in column (21) [same line as previous entries columns (27) and (32)]; G value obtained should be entered in column (27) on the horizontal line of new value of (r).

Example: at $r=60$.................. $G=-292093$

at $(r+.5\Delta r)$ or 65, column (32)= − 55415

at $(r+.5\Delta r)$ or 65, column (21)= − 18921

at $r=66$.................. $G=-366429$

This process can be continued until $r=R$.

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31	32	21	33	34
$\Sigma \frac{G(\Delta r)^2}{EI}$ $+\Delta r \tan \tau$ $+\Delta x_S$ (Inches)	$CF_{\tau+.5\Delta\tau}$ (Inch-Pounds)	ΔM_T (Inch-Pounds)	$FM_{n_{\tau_o}}$ (Inch-Pounds)	M_n (Inch-Pounds)
Same as column 29			196, 148	196, 148
		25, 494		
			197, 064	171, 570
	−128	25, 494		
			198, 923	147, 807
	−319	25, 494		
			[illegible]	124, 532
	−881	25, 494		
			[illegible]	[illegible] 068
	−2, 226	[illegible]		
				[illegible]90
	−5, 022	[illegible]		
			[illegible]	[illegible]16
	−10, 442	[illegible]		
			[illegible]	[illegible]71
	−19, 400	[illegible]		
			[illegible]	[illegible]47
	−33, 493	[illegible]		
			[illegible]	[illegible]21
	−55, 415	[illegible]		
			[illegible]	[illegible]51
	[illegible]39	[illegible]		
			[illegible]	[illegible]215
	[illegible]	[illegible]		
			[illegible]	[illegible]256

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Column (33): For the entry at radial station $v=6$

$F_{M_{n_{r_0}}}$ = (entry column 23) (M_n at root $= M_n$ at first station)

$$= (\text{entry column 23}) \left(-\frac{G \text{ at Tip}}{F \text{ at Tip}}\right)$$

$$= (1.0)\left(-\frac{-1,241,419}{6,328991928}\right) = 196,148 \text{ for this example.}$$

Subsequent entries (example)

$F_{M_{n_{r_0}}}$ = (entry column 23) (M_n first station)

= (1.593?55153) (196148) = 312,514 for column (33) entry at $r=60$ inches

Column (34): Example

M_n = (entry column 27) (entry column 33)

= (−292093) (312,514) = 20,421 at station, $r=60$ inches

If effective I_{min} is available, it should be used to find the bending moment.

(7) *Net Bending Moment Check—Table III–8*

Column Number	*Quantity*	*Basis of Determination*
(1)	r	Radial stations as previously determined, table III–4.
(35)	M_n	Entry for first radial station will be the same as that in column (34), table III–7 for the same radial station ($r=6.0$ in.). Subsequent entries will be calculated as explained in the notes.
(22)	$EI/(\Delta r)^2$	This column in table III–8 is reconstructed column (22) from table III–7.
(36)	$\frac{M_n(\Delta r)^2}{EI}$	To be calculated column (35)/column (22).
(37)	$\sum \frac{M_n(\Delta r)^2}{EI} + \Delta r \tan \tau$	Cumulative total column (36) entries $+\Delta r \tan \tau$ (0 this case).
(30)	ΔZ_s	Column (30), table III–7 reproduced in this table.
(38)	ΔZ	Column (37) + column (30)
(16)	CF	As calculated in table III–5, column (16) reproduced in this table.
(39)	ΔM_r	Product column (38) and column (16).
(21)	ΔM_T	As computed for table III–5, reproduce column (21) in this table.
(40)	ΔM_n	Entry column (21) − entry column (39).

Procedural notes

The same general procedure used in preparation of table III–7 can be used to complete this table.

Column (1) can be completed vertically from $r=6.0$ to $r=R$, leaving a line space designated $(r+.5\Delta r)$ between each radial station entry, at this time.

Progressing horizontally from left to right on lines of (r) and $(r+.5\Delta r)$ entries for all columns can be completed as follows:

For $r=6.0$ (first radial station), column (35) (M_n) will be the same value shown in column (34), table III–7.

Column (22) entry will be transcribed from table III–7.

TABLE III-8. *Bending Moment Check*

1	35	22	36	37	30	38	16	39	21	40
r (Inches)	M_n (Inch-Pounds)	$\frac{EI}{(\Delta r)^2}$ (Pounds)	$\frac{M_n(\Delta r)^2}{EI}$ (Inches)	$\Sigma \frac{M_n(\Delta r)^2}{EI}$ $+\Delta r \tan \tau$ (Inches)	ΔZ_S (Inches)	ΔZ (Inches)	CF (Pounds)	ΔM_{CF} (Inch-Pounds)	ΔM (Inch-Pounds)	ΔM_n (Inch-Pounds)
6	196, 148	31, 983, 333	.006 132 819		0	0				
				.006 132 819	0	0	150, 635	924	25, 494	24, 570
12	171, 578	29, 133, 333	.005 889 405		0	0				
				.012 022 224	0	0	145, 790	1, 753	25, 494	23, 741
18	147, 837	35, 391, 667	.004 177 169		0	0				
				.016 199 393	0	0	137, 652	2, 230	25, 494	23, 264
24	124, 573	17, 325, 000	.007 190 360		0	0				
				.023 389 753	0	0	130, 346	3, 049	25, 494	22, 445
30	102, 128	9, 000, 000	.011 347 555		0	0				
				.034 737 308			122, 074	4, 241	25, 494	21, 253
36	80, 875	4, 991, 667	.016 202 002		0	0				
				.050 939 310			112, 893	5, 751	24, 891	19, 140
42	61, 735	2, 833, 333	.021 788 826		0	0				
				.072 728 136			103, 097	7, 498	24, 000	16, 502
48	45, 233	1, 816, 667	.024 898 894		0	0				
				.097 627 030			92, 896	9, 069	22, 749	13, 680
54	31, 553	1, 200, 000	.026 294 166		0	0				
				.123 921 196			82, 338	10, 203	21, 072	10, 869
60	20, 684	791, 667	.026 127 146		0	0				
				.150 048 342			71, 436	10, 719	18, 921	8, 202
66	12, 482	550, 000	.022 694 545		0	0				
				.172 742 887			60, 355	10, 426	16, 266	5, 840
72	6, 642	408, 333	.016 266 135		0	0				
				.189 009 022			49, 147	9, 289	13, 116	3, 827
78	2, 815	325, 000	.008 661 538		0	0				
				.197 670 560			37, 751	7, 462	9, 558	2, 096
84	719	275, 000	.002 614 545		0	0				
				.200 285 105			26, 549	5, 317	5, 913	596
90	123	233, 333	.000 527 143		0	0				
				.200 812 248			15, 551	3, 123	2, 667	−456
96	579	412, 500	.001 403 636		0	0				
				.202 215 884			4, 789	968	400	−568
100	1, 147	0	0	0	0	0	0	0	0	0

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Column (36) entry (=entry column 35/entry column 22) to be recorded on the horizontal line $(r+.5\Delta r)$.

Column (30) to be reproduced from table III–7 and entered on line $(r+.5\Delta r)$. In this case $Z_s=0$.

Column (38) (summation of horizontal line entries in columns 37 and 30) to be entered upon line $(r+.5\Delta r)$. In this case $\Delta Z=$entry column (37).

Column (16): Reproduction of column (16), table III–5 to be entered upon line $(r+.5\Delta r)$.

Column (39): Horizontal line product of entries in columns (38) and (16) to be entered on line $(r+.5\Delta r)$.

Column (21): Reconstructed from table III–5. Make entries on line $(r+.5\Delta r)$.

Column (40): Horizontal line entries column (21)–column (39) to be entered in this table on line $(r+.5\Delta r)$.

Completion of the preceding step-by-step procedure will have provided entries in all columns for the line $r=6$ and the line between $r=6$ and $r=12$.

Starting again on lines $r=12$ and $(r+.5\Delta r)$, column (35) entry will be: $M_n=$previous $M_n-\Delta M_n$. In this case $M_n=196{,}148-24{,}570=171{,}758$. Enter on line $r=12$. Complete these two lines before going on to the line $r=18$ and the line between $r=18$ and $r=24$.

Values of M_n should check closely those found by the method outlined for table III–7. Calculations should be carried out to as many decimal places as necessary to give accuracy consistent with the basic data.

(8) *Blade Stresses—Table III–9.*

Column Number	*Quantity*	*Basis of Determination*
(1)	r	Same as table III–4.
(16a)	CF_r	To be obtained from plotted CF, (CF table III–5 at $(r+.5\Delta r)$ stations) curve. See figure 3.28. CF_r may be read from the curve at station r and recorded.
(10)	A	From table III–4, section area.
(41)	S_{CF}	$S_{CF}=CF_r/A=$entry column (16a)/entry column (10).
(34)	M_n	Repeat of same column, table III–7.
(42)	I_{min}/y_t	$I_{min}/y_t=$entry column (12)/entry column (6), table III–4.
(43)	I_{min}/y_C	$I_{min}/y_C=$entry column (12)/entry column (7), table III–4.
(44)	S_{B_T}	$S_{B_T}=$entry column (34)/entry column (42).
(45)	S_{B_C}	$S_{B_C}=$entry column (34)/entry column (43).
(46)	S_T**	$S_T=S_{CF}+S_{B_T}=$entry column (41)+entry column (44).
(47)	S_C**	$S_C=S_{CF}-S_{B_C}=$entry column (41)−entry column (45).

Actual values of area and effective I_{min} should be used.

**See figure 3.29.

TABLE III–9. *Stresses*

1	16a	10	41	34	42	43	44	45	46	47
r	CF	A	s_{CF}	M_n	$\frac{I_{min}}{y_t}$	$\frac{I_{min}}{y_C}$	s_{B_T}	s_{B_C}	s_T	s_C
(In.)	(Lb.)	(In.^{2})	(Lb.-in.$^{-2}$)	(In.-lb.)	(In.^{3})	(In.^{3})	(Lb.-in.$^{-2}$)	(Lb.-in.$^{-2}$)	(Lb.-in.$^{-2}$)	(Lb.-in.$^{-2}$)
6	153,000	8.48	18,042	196,148	11.838	11.838	16,569	16,569	34,611	1,473
12	148,500	7.60	19,539	171,570	10.783	10.783	15,911	15,911	35,450	3,628
18	142,000	8.51	16,686	147,807	14.495	14.495	10,197	10,197	26,883	6,489
24	134,500	5.73	23,473	124,532	8.780	8.584	14,184	14,507	37,657	8,966
30	126,000	5.19	24,277	102,068	6.071	5.898	16,812	17,306	41,089	6,971
36	118,000	4.80	24,583	80,790	4.440	4.017	18,196	20,112	42,779	4,471
42	108,000	4.39	24,601	61,616	3.288	2.819	18,740	21,857	43,341	2,744
48	98,000	4.00	24,500	45,071	2.500	2.339	18,028	19,269	42,528	5,231
54	88,000	3.68	23,913	31,347	2.069	1.700	15,151	18,439	39,064	5,474
60	77,000	3.42	22,515	20,421	1.518	1.260	13,453	16,207	35,968	6,308
66	66,000	3.16	20,886	12,151	1.144	.939	10,622	12,940	31,508	7,946
72	54,000	2.93	18,430	6,215	.919	.740	6,763	8,399	25,193	10,031
78	43,000	2.75	15,636	2,256	.804	.619	2,806	3,645	18,442	11,991
84	32,500	2.51	12,948	−8	.743	.560	−11	−14	12,937	12,959
90	21,500	2.30	9,348	−790	.695	.510	−1,137	−1,549	8,211	10,897
96	10,000	2.11	4,739	−504	.598	.420	−843	−1,200	3,896	5,939
100	0	0	0	0	0	0	0	0	0	0

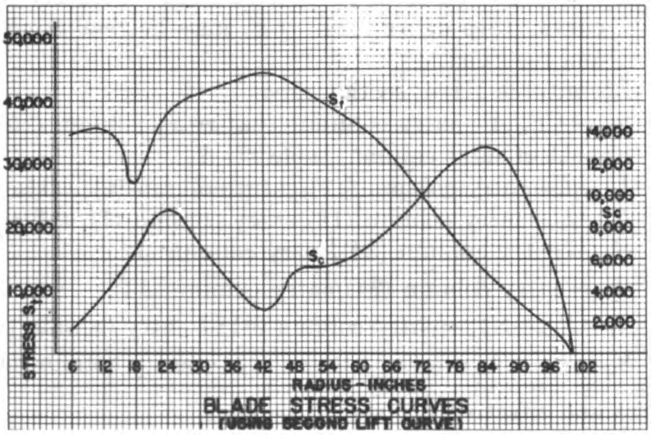

Figure 3.29.

(9) *Centrifugal twisting moment—Table III–10*

Column Number	*Quantity*	*Basis of Determination*
(1)	r	Same as table III–4.
(9)	β	Same as table III–4.
(48)	$\Delta\beta$	β_{rs}=angular value of arbitrarily chosen reference station. $\Delta\beta$=entry column (9)$-\beta_{rs}$
(49)	2 $\Delta\beta$	Twice the angle $\Delta\beta$
(50)	Sin 2 $\Delta\beta$	Trig. tables, Note: Sin negative angle is negative.
(51)	Cos 2 $\Delta\beta$	Trig. tables, Note: Cos negative angle is positive.
(52)	$I_{maj}-I_{min}$	$I_{maj}-I_{min}$=entry column (11)−entry column (12), table III–4.
(53)	dB	dB=(entry column 50) (entry column 52)
(54)	dC	dC=(entry column 51) (entry column 52)

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dB and *dC* plotted against radial stations (*r*) will give a set of curves such as those depicted in figure 3.30.

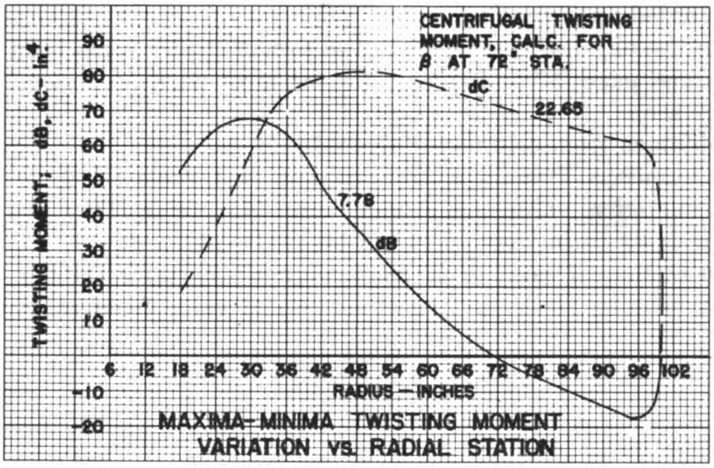

Figure 3.30.

Integration of these curves will give values for *B* and *C*, which may be used to find centrifugal twisting moment, Q_{CF}.

$$Q_{CF}=14.19\left(\frac{N}{1000}\right)^2\delta\sqrt{B^2+C^2}$$

$$\beta_r\ \text{Max}=\frac{1}{2}\ \text{arc tan}\ C/B$$

TABLE III–10. *Centrifugal Twisting Moment*

1	9	48	49	50	51	52	53	54
r (Inches)	β (Degrees)	$\Delta\beta$ (Degrees)	$2\Delta\beta$ (Degrees)	sin $2\Delta\beta$	cos $2\Delta\beta$	$I_{maj}-I_{min}$ (Inches ^{4})	dB (Inches ^{4})	dC (Inches ^{4})
6								
12								
18	69.7	35.7	71.4	.94 777	.31 896	55.78	52.867	17.792
24	64.1	30.1	60.2	.86 777	.49 697	74.31	64.484	36.930
30	58.7	24.7	49.4	.75 927	.65 077	89.20	67.727	58.049
36	54.0	20.0	40.0	.64 279	.76 604	98.21	63.128	75.233
42	49.7	15.7	31.4	.52 101	.85 355	92.50	48.193	78.953
48	46.1	12.1	24.2	.40 992	.91 212	89.02	36.491	81.197
54	42.7	8.7	17.4	.29 904	.95 424	84.36	25.227	80.500
60	39.6	5.6	11.2	.19 423	.98 096	79.05	15.354	77.545
66	36.6	2.6	5.2	.09 063	.99 588	74.94	6.792	74.631
72	34.0				1.0	71.41		71.410
78	31.7	−2.3	−4.6	−.08 020	.99 678	68.51	−5.495	68.289
84	29.7	−4.3	−8.6	−.14 954	.98 876	66.17	−9.895	65.426
90	27.8	−6.2	−12.4	−.21 474	.97 667	64.52	−13.855	63.015
96	26.0	−8.0	−16.0	−.27 564	.96 126	63.48	−17.498	61.021
100								

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(10) *Stress analysis summary—Table III-11.* Preparation of a summary of the propeller stress analysis should include all essential data pertaining to physical characteristics of the propeller under consideration, as well as a tabulation of test results. Accordingly, a sample form has been suggested and is represented in table III-11. The results obtained in the sample problem analysis have been recorded upon the form.

The fill in data for the physical characteristics section of the form has been discussed in Steady Stress Analysis-Procedure, pages 87 to 104, and, for the most part, is obvious. Source of data to complete the summary are:

CF total, to be obtained from column (16a), table III-9.
s_T (Max), largest numerical value of s_T from column (46), table III-9.
s_C (Max), largest numerical value of s_C from column (45), table III-9.
Q_{CF} (Max), centrifugal twisting moment from table III-10.
s_{CF} (Max), largest numerical value of s_{CF} from column (41), table III-9.
s_B (Max), largest bending stress or largest numerical value from columns (44), (45), table III-9.

TABLE III-11

Summary—Propeller Steady Stress Analysis

(Sample)

Blade Design No.: ; Date:
Propeller Manufacturer:
Proposed Installation:
For Airplane Designated as:
Engine Designation:
T. O. BHP: ; T. O. RPM: 2800 G. R.: .375/1

Propeller Physical Data:
Material: Steel; Construction: Hollow; Diameter: 16 ft. 8 in.
Basic Diameter: ; Airfoil Section: NACA 16 Series
RPM: 1050; Tilt Angle: 0°
Shank Size: ;
Hub Model: ; Number Blades: 4
W: 113.6 lb. (from 6.0″ sta.); I_p: 58.88 slug ft.^{2}; AF: 117
r_{CG}: 43.04 in.; h/b at .75R: .060

Calculated data:
N′ (or T_s): 4300 lb. for $\beta=32.8°$ at .75R;
CF Total: 153,000 lb. at 6 inch station;
s_T (Max): 43,341 psi at 42″ station; s_C (Max); 12,959 psi at 84 in. sta.
Q_{CF} 25,447 inch pounds for $\beta=35.5°$ at 72 in. sta.
s_{CF} (Max): 24,601 psi at 42 in. sta.
s_B (Max): 21,857 psi at 42 in. sta.

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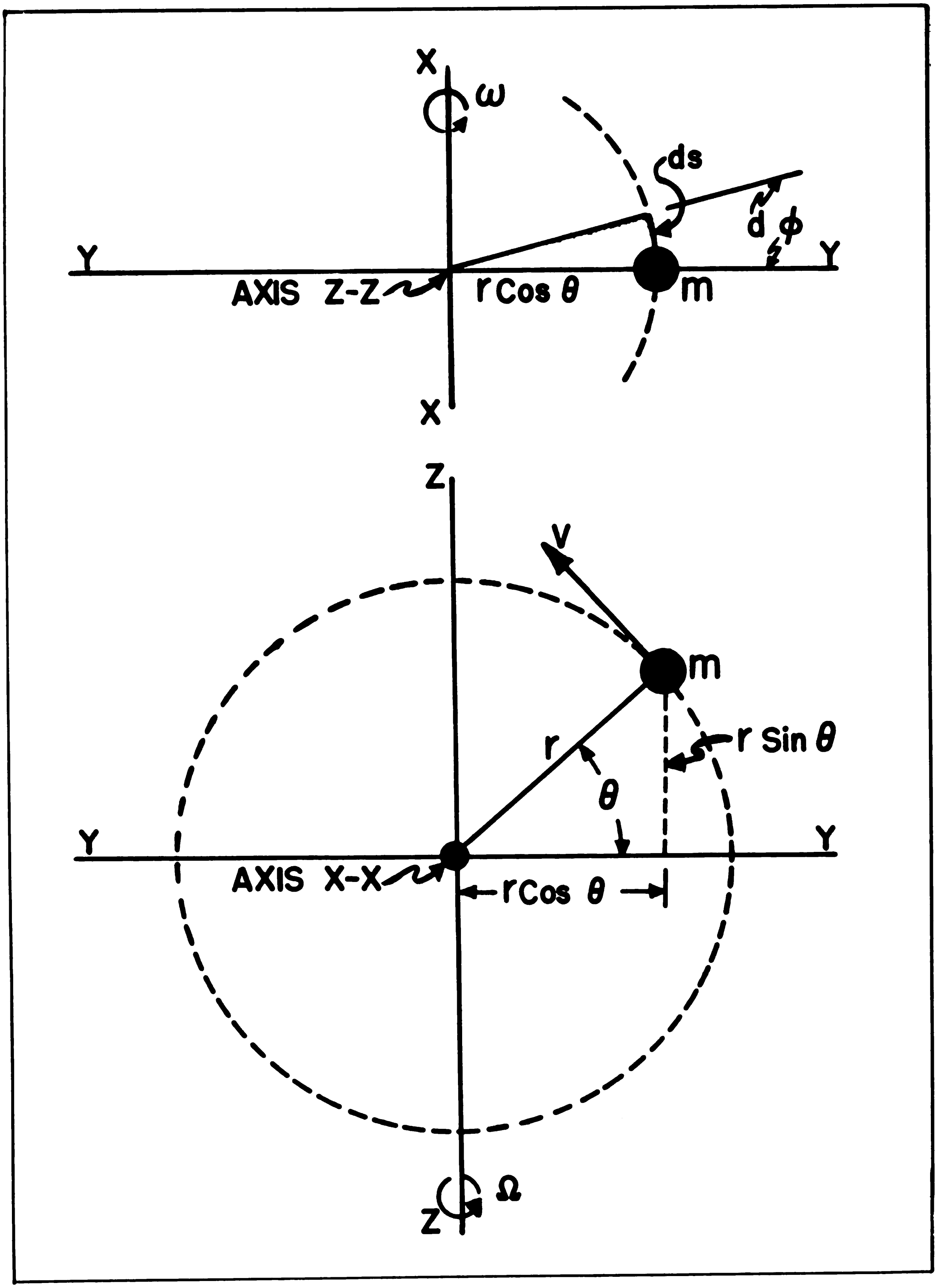

Figure 3.31.—Gyroscopic forces and movements.

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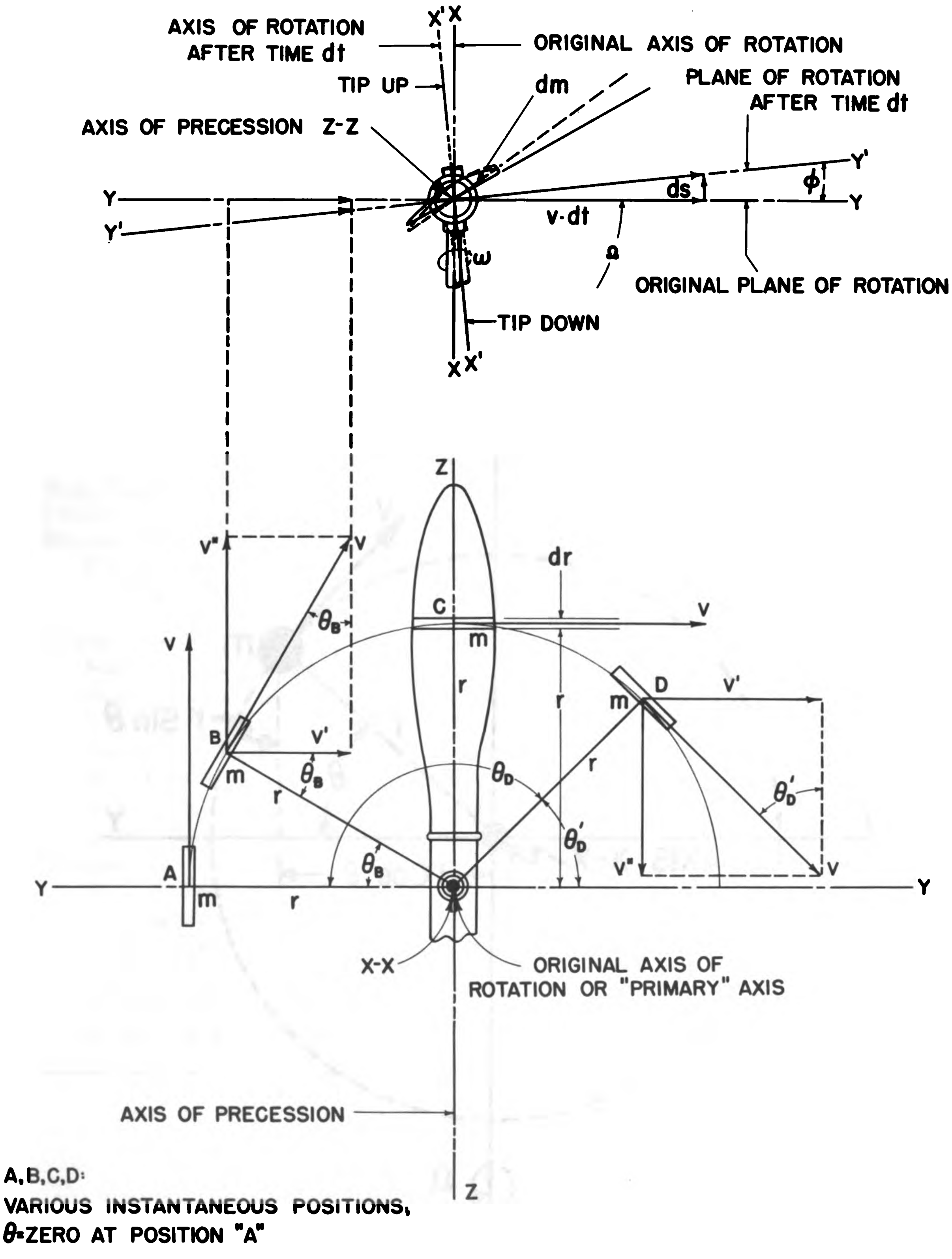

Figure 3.32.—Propeller gyroscopic moments.

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Gyroscopic Forces and Moments

Fundamental Relationships

The diagrams of figure 3.31 illustrate the conditions existing at any given instant for a mass (m) of radius (r) rotating about an axis (x–x) at a uniform angular speed (ω) while simultaneously being processed at a uniform angular speed (Ω) about an axis (z–z) at right angles to the (x–x) axis.

At the instant when the radius (r) makes an angle (θ) with the X–Y plane.

$$\omega=\frac{d\theta}{dt} \qquad \text{III–62}$$

$$\Omega=\frac{d\phi}{dt} \qquad \text{III–63}$$

and

$$v=\omega r \qquad \text{III–64}$$

In a very short increment of time (dt) the mass (m) is diverted from its rotational path in the Y–Z plane by a certain amount (ds). It is evident from the diagrams that:

$$ds=r \text{ Cos } \theta \, d\phi$$

and

$$\frac{ds}{dt}=r \text{ Cos } \theta \frac{d\phi}{dt}$$

Since acceleration (a) is the second derivative of the distance-time relationship, or algebraically,

$$a=\frac{d^2s}{dt^2},$$

acceleration of the mass (m) may be written:

$$a=\frac{d}{dt}\left(r \text{ Cos } \theta \frac{d\phi}{dt}\right)$$

$$=r \text{ Cos } \theta \frac{d^2\phi}{dt^2}-r \text{ Sin } \theta \frac{d\theta}{dt}\cdot\frac{d\phi}{dt}$$

$$=r \text{ Cos } \theta \frac{d^2\Omega}{dt^2}-r \text{ Sin } \theta\cdot\omega\Omega \qquad \text{III–65}$$

If Ω is constant, as assumed, then:

$$\frac{d^2\Omega}{dt^2}=0$$

and

$$r \cos \theta \frac{d^2\Omega}{dt^2}=0$$

hence,

$$a=-r \text{ Sin } \phi\omega\Omega \qquad \text{III–66}$$

The negative sign indicates that acceleration is opposite in direction to the assumed motion.

The force acting upon the mass (m) is equal to the product of mass and acceleration, or:

$$f=ma \qquad \text{III–67}$$

Substituting from equation III–66

$$f=2-mr \text{ Sin } \theta\omega\Omega \qquad \text{III–67}$$

Gyroscopic Action of a Propeller Blade

(1) *General considerations.* To properly develop fundamental relationships involved in gyroscopic action of propeller blades, it will be necessary to reach an understanding of the inertia forces evolved in blade rotation. The approach used herein to present the phenomena of inertia forces of rotating propeller blades is first, to consider two special cases wherein an elemental mass (dm) may be arbitrarily placed in specific locations, and then develop a general expression for inertia force of the elemental mass of a rotating propeller blade.

The diagram in figure 3.32 will aid considerably in development of the general theory of gyroscopic action. The upper sketch represents a view of the mass (dm) from a position looking down upon the propeller when the mass is in the X–Z plane (position C).

In this diagram the elemental mass (dm) is shown in four instantaneous positions identified as A, B, C, and D. To further illustrate and clarify the discussion of gyroscopic action, an isometric drawing of a propeller blade, with identical points and symbols indicated in figure 3.32, is shown in figure 3.33. It should be noted that point D has been omitted from figure 3.33 to eliminate complexity of the sketch.

From a study of the diagrams it is evident that a rotating mass of the propeller will produce inertia forces perpendicular to the plane of rotation. These lateral inertia forces will produce shearing forces and bending moments in the propeller blades. Blade bending moments are alternating, being a maximum at the instant that the blade is passing through the X–Z plane (position C) and zero when the blade passes through the X–Y plane (position A).

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Gyroscopic forces produced by the blade in various positions above the X–Y plane are opposite in direction to those produced by the blade in corresponding positions below the X–Y plane. Hence, opposing gyroscopic forces, above and below the X-Y plane, produce additive couples about the Y–Y axis. In single rotation propellers, the resultant of the couples is a torque or twisting, force carried into the propeller shaft, thence through shaft bearings and engine case to the aircraft frame.

In gyroscopically balanced dual-rotation propellers, gyroscopic couples are balanced out between the coaxial shafts and therefore never reach the aircraft frame. However, if the couples of the two rotating blades of a dual propeller are unequal, a twisting force will be transmitted to the aircraft frame.

Throughout the following discussion of gyroscopic action, the developments are founded upon consideration of an infinitesimal propeller blade transverse section of thickness (dr) rotating at a general radius (r). The area (A) of the transverse section at radius (r) is called the section area.

Therefore, volume of the blade element may be expressed as:

$$\text{volume} = Adr$$

and weight of the blade element must be:

$$W = \delta\ Adr$$

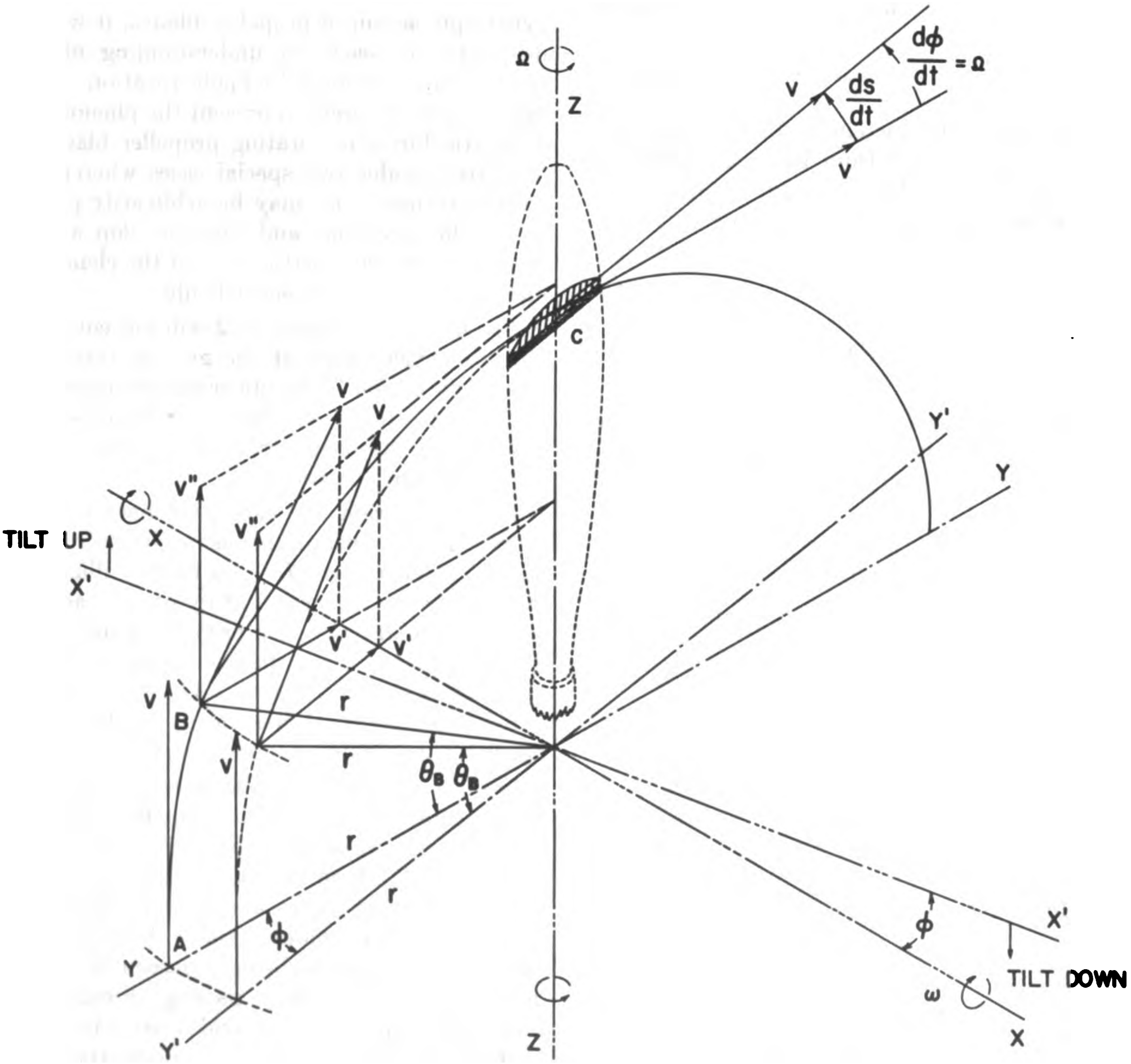

Figure 3.33.—Propeller gyroscopic moments.

Mass of the element, dm, is: $dm=\frac{\delta}{g}$

wherein:

δ=weight density of blade material (lb/ft.^{3})
A=section area (ft.^{2})
r=section radius (ft.)
g=gravitational acceleration (ft/sec.^{2})

The mass (dm) is assumed to be rotating about an axis, X–X, at a constant angular speed (ω), while simultaneously, the axis X–X is being precessed about an axis Z–Z at constant speed (Ω). The resultant moment about an axis perpendicular to the radius (r) is:

$$\begin{aligned} M&=fr \\ &=-mr^2 \operatorname{Sin} \theta\omega\Omega \end{aligned} \qquad \text{III–68}$$

And the resultant moment about the Y axis is:

$$\begin{aligned} M&=fr \operatorname{Sin} \theta \\ &=-mr^2 \operatorname{Sin}^2 \theta\omega\Omega \end{aligned} \qquad \text{III–69}$$

The inertia force is opposite in direction to the motion of precession.

(2) *Inertia forces of an elemental mass located upon the precession axis, Z–Z.* At the instant when the mass (dm) is exactly positioned upon the axis of precession (Z–Z Position C of figure 3.32), the mass will have a velocity, Y, in a direction outward along the Y–Y axis (upper view, fig. 3.32, marked *original plane of rotation*).

However, the plane of rotation will be turning simultaneously at a constant speed (Ω) about the axis of precession. Therefore, after an infinitesimally short period of time (dt), the mass (dm) will be moving in an outward direction along the axis Y–Y' (or as marked in the upper sketch of figure 3.32, *Plane of Rotation After Time dt*) at an angle (ϕ) to the original plane of motion. The velocity (v) is the peripheral velocity of the mass, and may be expressed:

$$v=r\omega$$

If the direction of motion of the mass were *not* changed from the Original Plane of rotation, the mass would have traveled a distance ($v\ dt$) in the original plane. But the actual displacement is some distance (ds) from the position which the mass would have occupied. Since a length of circular arc is equal to the product of the circular radius and the included angle, the distance (ds) may be written as:

$$ds=v\ dt\cdot\phi$$

or transposing dt,

$$\frac{ds}{dt}=v\phi \qquad \text{III–70}$$

It is obvious that, if motion of the mass (dm) were unrestrained with an initial velocity (v), the mass would continue to move in a path tangential to the circle of rotation, and *IN* the Original Plane. However, by the rigidity of the structure of which it is a part, the mass is forced to move in a circular path about the axis X–X and to remain in a plane of rotation at right angles to the axis, X–X. These restraints are effected by overpowering the centrifugal force and overcoming the gyroscopic force. This discussion is concerned with the gyroscopic force.

The gyroscopic force is equal to the product of mass and gyroscopic acceleration (a). In the case under consideration, acceleration of the mass can be written in algebraic form as:

$$a=\frac{d^2s}{dt^2}$$

$$a=\frac{d}{dt}\left(\frac{ds}{dt}\right)$$

Substituting from equation III–70,

$$a=v\frac{d\phi}{dt} \qquad \text{III–71}$$

It is to be noted that mass acceleration, in this case, is a function of the instantaneous peripheral velocity of the rotating mass and the rate of change of the precessing angle (ϕ).

Since $v=r\omega$

and $\frac{d\phi}{dt}=\Omega$

The acceleration of the mass can be written in the form:

$$a=r\omega\Omega \qquad \text{III–72}$$

The gyroscopic force on the element is:

$$\begin{aligned} df&=a\ dm \\ &=r\omega\Omega\ dm \end{aligned} \qquad \text{III–73}$$

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At the instant under consideration (Position C in fig. 3.32) the gyroscopic inertia force acting upon the mass is in a direction which tends to tip the axis of primary rotation (X–X) with respect to an axis (Y–Y) which is perpendicular to both the axis of primary rotation and the axis of precession (Z–Z). The direction of this tilt is indicated in the upper view of figure 3.32 as TIP UP and TIP DOWN. The moment of this force about the axis of tilt is:

$$dM = df \cdot r$$

$$= dm\, r^2 \omega \Omega \qquad \text{III–74}$$

Since $dm\, r^2$ is the moment of inertia, dI, about the axis of tilt, the expression may be rewritten in the more familiar form:

$$M_g = I\omega\Omega \qquad \text{III–75}$$

In which:

M_g = the total integrated moment of the rotating body.

I = total moment of inertia of the mass about the axis of rotation.

The process of obtaining M_g for a propeller will be discussed later.

(3) *Inertia forces of a mass located in a plane perpendicular to the precession axis.* At the instant in which the mass (dm) is in the X–Y plane (position A, fig. 3.32), velocity of the mass is perpendicular to the plane of precession. Any movement of the mass about the axis of precession does not change the direction of primary rotative velocity of the mass. The only forces acting on the mass are those which would occur in moving the mass were it not rotating about the primary axis. The latter forces would not be gyroscopic forces.

Inertia forces acting upon an elemental mass in two specific positions have been examined; the first case being that of an elemental mass at the instant of coincidence with the Z–Z axis, and the second being that of mass coincidence with the Y–Y axis. General conditions will be examined next, i. e., when an elemental mass is in some intermediate position between the Y–Y and Z–Z axes (such as positions B and D of fig. 3.32 and fig. 3.33).

(4) *Gyroscopic inertia forces acting upon a mass—general case.* In a more general case, with an elemental mass in any position, such as position B in figures 3.32 and 3.33, the radius of mass rotation about the X–X axis will make some angle, θ_B, with the Y–Y axis. The mass will have a velocity (v) which will be inclined at some angle (θ_B) to the plane of precession. Therefore, the mass will have a projected component of velocity (v') in the plane of precession which will experience a change in direction as the mass is rotated about the axis of precession. The vertical component (v'') of mass velocity will undergo no change in direction with precession of the mass axis of rotation. Hence, the lateral gyroscopic force developed at any position can be represented by the same expression as that representing the force at a position on the axis of precession, except that a component of mass velocity (v') must be substituted for velocity of the mass (v).

Since

$$v' = v \operatorname{Sin} \theta_B,$$

$$df_B = dm\, r \operatorname{Sin} \theta_B\, \omega\Omega \qquad \text{III–76}$$

If the mass were in some other position such as D, the instantaneous velocity of the mass would be inclined so that the projected component (v') would experience a change in direction during rotation of the mass about the axis of precession. Again the component of velocity of the mass parallel to the axis of precession would remain unchanged in direction. Hence, the component would not produce a gyroscopic force. In this case, then:

$$v' = v \operatorname{Sin} \theta_D'$$

Since $\operatorname{Sin} \theta_D' = \operatorname{Sin} \theta_D$

$$v' = v \operatorname{Sin} \theta_D \qquad \text{III–77}$$

The forces acting upon a rotating mass at the instant that the mass is located in position D are similar to those of the mass in position B. Therefore, the expressions for the gyroscopic force will be satisfied by the substitution of θ_D for θ_D in equation III–76:

$$df_D = dm\, r \operatorname{Sin} \theta_D \cdot \omega\Omega$$

Now a more general expression for gyroscopic force acting upon an element of mass may be written:

$$df = dm\, r \operatorname{Sin} \theta \cdot \omega\Omega \qquad \text{III–78}$$

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where θ represents any angular position of the rotating mass with respect to the $Y-Y$ axis.

From equation III–78, it is evident that the gyroscopic force of an elemental mass varies sinusoidally from zero when $\theta=0°$ (at the $Y-Y$ axis) to a maximum when $\theta=90°$ (at the $Z-Z$ axis). When $\theta=180°$ gyroscopic force is zero, again. When $\theta>180°$ the algebraic sign of Sin θ is negative, indicating that direction of the force is reversed. However, as a result of the mass being below the $Y-Y$ axis, the reversed direction of the force will yield a gyroscopic moment about the $Y-Y$ axis in the same direction as when the mass was above the axis.

(5) *Gyroscopic moment of a rotating mass relative to an axis* ($Y-Y$) *other than axis of primary rotation.* With respect to the $Y-Y$ axis, the moment arm of the gyroscopic force of a rotating mass is r Sin θ. Hence, the general expression for gyroscopic moment of the mass (dm) about the $Y-Y$ axis may be written as follows:

$$\begin{aligned} dM_{Y-Y} &= dm\ (r \text{ Sin } \theta)^2\ \omega\Omega \\ &= dm\ r^2 \text{ Sin}^2\ \theta \cdot \omega\Omega \qquad \text{III–79} \end{aligned}$$

In terms of polar moment of inertia of the mass about the axis of primary rotation, the expression takes the more familiar form:

$$dM_{Y-Y}=dI\ \omega\Omega \text{ Sin}^2\ \theta \qquad \text{III–80}$$

Equation III–80 may be used to obtain gyroscopic moments only about the $Y-Y$ axis. The effects of gyroscopic forces on a propeller structure are a matter of primary concern in propeller design. Suppose, for instance, the contribution of gyroscopic force; generated by a mass (dm), at some radius (r) to the bending moment on a blade section at some radius (r_s) less than r, is desired. Moment contribution could be found by substitution of $(r-r_s)$ for r in the moment equation as follows:

$$\begin{aligned} dM_s &= df\ (r-r_s) \\ &= dm\ r \text{ Sin } \theta \cdot \omega\Omega\ (r-r_s) \qquad \text{III–81} \end{aligned}$$

Since

$$dm=\frac{\delta}{g} \text{ Adr}$$

$$dM_s=\frac{\delta}{g}\ \omega\Omega \text{ Sin } \theta \cdot A\ (r-r_s)r\ dr \qquad \text{III–82}$$

(6) *Total gyroscopic moment.* The total gyroscopic moment on a blade section at some radius (r_s) is equal to the sum of the effects of all blade sections outboard of the given section, i. e., from radius, r_s, to radius, R, of the blade tip:

$$M_s=\frac{\delta}{g}\ \omega\Omega \text{ Sin } \theta \int_{r=r_s}^{r=R} A\ (r-r_s)r\ dr \qquad \text{III–83}$$

The equation for total gyroscopic moment about an axis through the center of rotation and perpendicular to the blade radius in the plane of rotation is identical to equation III–83, but the limits of integration will be changed to $r=0$ and $r=R$, or:

$$M=\frac{\delta}{g}\ \omega\Omega \text{ Sin } \theta \int_{r=0}^{r=R} A\ (r-r_s)r\ dr \qquad \text{III–84}$$

In the preceding moment equations, it was assumed that area of the section (A) will vary at different radii. Hence, the area cannot be considered as a constant in the differential equation. The area considered is the sectional area of the material having density δ, and is not necessarily equal to the area encompassed by the perimeter of the airfoil section. Due allowance must be made for blade construction involving composition of materials in the section by using appropriate material areas and densities.

Integration of gyroscopic forces and moments may be accomplished in the same manner as integration of aerodynamic forces and moments, which has been explained previously. Stations for which values of $A\ (r-r_s)r\ dr$ are computed must be close enough together to insure that physical changes from station to station will reflect section changes between stations.

(7) *Gyroscopic moment—Single blade.* In considering gyroscopic couples produced by rotating propellers and the resultant action upon engine and aircraft structures, the effects of variation in the number of blades must be examined. It may be assumed that the propeller blades will be equally spaced, which is a limiting condition in the following discussion.

It has been shown already that:

$$dM_{Y-Y}=d\ I\ \omega\Omega \text{ Sin}^2\ \theta$$

Therefore, moment about the $Y-Y$ axis may be expressed:

$$\begin{aligned} M_{Y-Y} &= \int dM_{Y-Y} \\ &= \omega\Omega \text{ Sin}^2\ \theta \int_{r=0}^{r=R} dI \\ &= I_P\ \omega\Omega \text{ Sin}^2\ \theta \qquad \text{III=85} \end{aligned}$$

where, I_P=the polar moment of inertia of the complete blade about the axis of rotation X–X.

In the following development, I_P will represent the polar moment of mass inertia of EACH blade, regardless of the number of blades in a propeller under consideration. As previously indicated, ω and Ω may be assumed to be constant. Let

$$K = I_P\,\omega\Omega \qquad \text{III–86}$$

Then, by substitution in equation III=85:

$$M_{Y-Y} = K \text{ Sin}^2\,\theta \qquad \text{III–87}$$

Equation III–87 is an expression for gyroscopic moment of a single blade, with respect to the Y–Y axis.

When the position of the center of gyration of the blade is on the axis of precession (Z–Z) as represented in figure 3.32 (position C), the angle $\theta=90°$. Therefore:

$$\text{Sin }\theta = 1$$

Also,

$$\text{Sin}^2\,\theta = 1$$

and equation III–87 reduces to the form:

$$M_{Y-Y} = K \qquad \text{III–88}$$

Examination of equation III–88 will show that K will be the maximum value of the gyroscopic moment of ONE blade at any instant throughout a complete revolution of the blade. That is equivalent to saying that $\text{Sin}^2\,\theta$ will not exceed a value of one as θ varies from 0 to $2\,\pi$ radians.

It has been pointed out that gyroscopic forces acting on a propeller blade are such that the resulting gyroscopic moment about the Y–Y axis will be in the same direction, regardless of blade position above or below the Y–Y axis. Consequently, regardless of the number of blades in a single rotation propeller, the instantaneous gyroscopic moments about the Y–Y axis of the individual blades are directly additive.

(8) *Gyroscopic moment—Two-blade propeller.* In considering multi-blade propellers, the angle θ will be the angular position relative to the Y–Y axis of one particular blade which has been selected as the REFERENCE BLADE. Also, the gyroscopic couple of a complete propeller about the Y–Y axis will be designated: ${}_BM_{Y-Y}$ in which the subscript B indicates the number of blades in the propeller.

Since the blades of a two-blade propeller are 180° apart, instantaneous values of gyroscopic forces acting on the two blades will be equal in magnitude for any value of θ. But the gyroscopic forces always will be in opposite directions with respect to any diametral axis. Further, these forces will produce a gyroscopic couple about such an axis, which will be double the moment of one of the blades at any instant. In equation form, the moment of a two blade propeller may be written:

$${}_2M_{Y-Y} = 2\ K \text{ Sin}^2\,\theta \qquad \text{III–89}$$

Two points involved in the moment equation of a two-blade propeller are of particular interest.

(*a*) Although θ and Sin θ may be either positive or negative, $\text{Sin}^2\,\theta$ is ALWAYS positive. Hence, moments of the blades ABOUT THE Y–Y AXIS will never reverse.

(Note: This statement is not true for moments with respect to the axis of a particular section of a blade, which rotates with the blade.)

(*b*) The $\text{Sin}^2\,\theta$ curve is a sinusoidal curve which is completely on the positive side of the zero axis (Y–Y), having TWO CYCLES for EACH REVOLUTION of the propeller. Therefore, the gyroscopic couple of a two-blade propeller tends to shake the airplane at a frequency equal to twice the rotational speed of the propeller, while applying a MEAN couple in one direction about the Y–Y axis.

(9) *Gyroscopic moment—Three-blade propeller.* In a three-blade propeller, the blades are spaced 120° $\left(\text{or } \frac{2}{3}\,\pi \text{ radians}\right)$ apart. When the reference blade is on the Y–Y axis at an angle, $\theta=0$, the other two blades will be positioned at $\frac{2}{3}\,\pi$ radians and $\frac{4}{3}\,\pi$ radians. If the reference blade is at any other position, θ, the other two blades will be positioned at $\left(\theta+\frac{2}{3}\,\pi\right)$ and $\left(\theta+\frac{4}{3}\,\pi\right)$

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radians, respectively. If the blades are designated as "*a*", "*b*", and "*c*", "*a*" being the reference blade, moment equations for the three blades may be written as follows:

$$(a)\quad {}_aM_{Y-Y}=K\,\text{Sin}^2\,\theta$$

$$(b)\quad {}_bM_{Y-Y}=K\,\text{Sin}^2\left(\theta+\frac{2}{3}\pi\right)$$

$$(c)\quad {}_cM_{Y-Y}=K\,\text{Sin}^2\left(\theta+\frac{4}{3}\pi\right)$$

Combining equations, the moment of a three-blade propeller will become:

$$(d)\quad {}_3M_{Y-Y}={}_aM_{Y-Y}+{}_bM_{Y-Y}+{}_cM_{Y-Y}$$

$$=K\left[\sin^2\theta+\text{Sin}^2\left(\theta+\frac{2}{3}\pi\right)+\text{Sin}^2\left(\theta+\frac{4}{3}\pi\right)\right]$$

III–90

This expression can be simplified still further by substitution of trigonometric identities, as follows:

From trigonometric relations

$$(e)\quad \text{Sin}^2\,\theta=\frac{1}{2}\,[1-\cos 2\theta]$$

also,

$$(f)\quad \text{Sin}^2\left(\theta+\frac{2}{3}\pi\right)=\frac{1}{2}\left[1-\text{Cos}\left(2\theta+\frac{4}{3}\pi\right)\right]$$

$$=\frac{1}{2}\left[1-\left(\text{Cos}\,2\theta\,\text{Cos}\,\frac{4}{3}\pi-\text{Sin}\,2\theta\,\text{Sin}\,\frac{4}{3}\pi\right)\right]$$

and,

$$(g)\quad \text{Sin}^2\left(\theta+\frac{4}{3}\pi\right)$$

$$=\frac{1}{2}\left[1+\text{Cos}\left(2\theta+\frac{8}{3}\pi\right)\right]$$

$$=\frac{1}{2}\left[1-\left(\text{Cos}\,2\theta\,\text{Cos}\,\frac{8}{3}\pi-\text{Sin}\,2\theta\,\text{Sin}\,\frac{8}{3}\pi\right)\right]$$

$$\frac{4}{3}\pi\ \text{radians}=240^\circ$$

hence,

$$(h)\quad \text{Sin}\,\frac{4}{3}\pi=\text{Sin}\,240^\circ$$

$$=-\text{Sin}\,60^\circ$$

$$=-\frac{\sqrt{3}}{2}$$

and,

$$(i)\quad \text{Cos}\,\frac{4}{3}\pi=\text{Cos}\,240^\circ$$

$$=-\text{Cos}\,60^\circ$$

$$=-\frac{1}{2}$$

also,

$$(j)\quad \text{Sin}\,\frac{8}{3}\pi=\text{Sin}\,480^\circ$$

$$=+\text{Sin}\,60^\circ$$

$$=\frac{\sqrt{3}}{2}$$

and,

$$(k)\quad \text{Cos}\,\frac{8}{3}\pi=\text{Cos}\,480^\circ$$

$$=-\text{Cos}\,60^\circ$$

$$=-\frac{1}{2}$$

Then, by substitution of equations *h* and *i* back into equation *f*:

$$(l)\quad \text{Sin}^2\left(\theta+\frac{2}{3}\pi\right)=\frac{1}{2}\left[1-\left(-\frac{1}{2}\,\text{Cos}\,2\theta-\left(-\frac{\sqrt{3}}{2}\,\text{Sin}\,2\theta\right)\right)\right]$$

$$=\frac{1}{2}\left(1+\frac{1}{2}\,\text{Cos}\,2\theta-\frac{\sqrt{3}}{2}\,\text{Sin}\,2\theta\right)$$

and similarly, equation *g* will become:

$$\text{Sin}^2\left(\theta+\frac{4}{3}\pi\right)=\frac{1}{2}\left[1-\left(-\frac{1}{2}\,\text{Cos}\,2\theta-\left(+\frac{\sqrt{3}}{2}\,\text{Sin}\,2\theta\right)\right)\right]$$

$$(m)\quad \text{Sin}^2\left(\theta+\frac{4}{3}\pi\right)=\frac{1}{2}\left(1+\frac{1}{2}\,\text{Cos}\,2\theta+\frac{\sqrt{3}}{2}\,\text{Sin}\,2\theta\right)$$

Making appropriate substitutions in equation III–90, the following equation will be obtained:

$${}_3M_{Y-Y}=\frac{1}{2}\,K\left[(1-\text{Cos}\,2\theta)+\left(1+\frac{1}{2}\,\text{Cos}\,2\theta-\frac{\sqrt{3}}{2}\,\text{Sin}\,2\theta\right)+\left(1+\frac{1}{2}\,\text{Cos}\,2\theta+\frac{\sqrt{3}}{2}\,\text{Sin}\,2\theta\right)\right]$$

$$=\frac{1}{2}\,K\left(1-\text{Cos}\,2\theta+1+\frac{1}{2}\,\text{Cos}\,2\theta+1+\frac{1}{2}\,\text{Cos}\,2\theta\right)$$

$$=\frac{1}{2}\,K(3-\text{Cos}\,2\theta+\text{Cos}\,2\theta)\qquad\text{III–91}$$

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Therefore,

$$(n)\quad {}_3M_{Y-Y}=1.5K$$

It is interesting and important to note from the preceding development that, for a three-blade propeller:

(*i*) The gyroscopic couple is independent of the position of the reference blade.

(*ii*) Magnitude of the couple is one and one-half (1.5) times the gyroscopic moment of a single blade. Substituting for K in equation n, the gyroscopic moment of a three blade propeller becomes:

$${}_3M_{Y-Y}=1.5I_P\omega\Omega$$

(10) *Gyroscopic moment—Propeller with any number* (*n*) *of blades.* Proceeding along a similar line of development, equations for gyroscopic couples (about the $Y-Y$ axis) can be evolved for propellers having various numbers of equally spaced blades, revolving in the same direction. The gyroscopic moment equations for propellers having one to eight blades are:

$${}_1M_{Y-Y}=I_P\ \omega\Omega\ \mathrm{Sin}^2\ \theta \qquad \text{III–92}$$

$${}_2M_{Y-Y}=2\ I_P\ \omega\Omega\ \mathrm{Sin}^2\ \theta \qquad \text{III–93}$$

$${}_3M_{Y-Y}=1.5\ I_P\ \omega\Omega \qquad \text{III–94}$$

$${}_4M_{Y-Y}=2\ I_P\ \omega\Omega \qquad \text{III–95}$$

$${}_5M_{Y-Y}=2.5\ I_P\ \omega\Omega \qquad \text{III–96}$$

$${}_6M_{Y-Y}=3\ I_P\ \omega\Omega \qquad \text{III–97}$$

$${}_7M_{Y-Y}=3.5\ I_P\ \omega\Omega \qquad \text{III–98}$$

$${}_8M_{Y-Y}=4\ I_P\ \omega\Omega \qquad \text{III–99}$$

From the derived equations, it is apparent that for MORE THAN TWO equally spaced blades, the general formula can be written as:

$${}_BM_{Y-Y}=\frac{B}{2}\ I_P\omega\Omega \qquad \text{III–100}$$

It should be noted further that, in this general case, the gyroscopic couple about the $Y-Y$ axis is independent of the position of the reference blade. For steady rates of precession and rotation, the moment is steady with respect to nonrotating parts, such as bearing housings, engine nose, and aircraft frame. The engine shaft, however, is subjected to complete cycles of alternating rotative bending. The action is similar to that of a fatigue specimen rotating in a steady moment field of a rotating beam test-

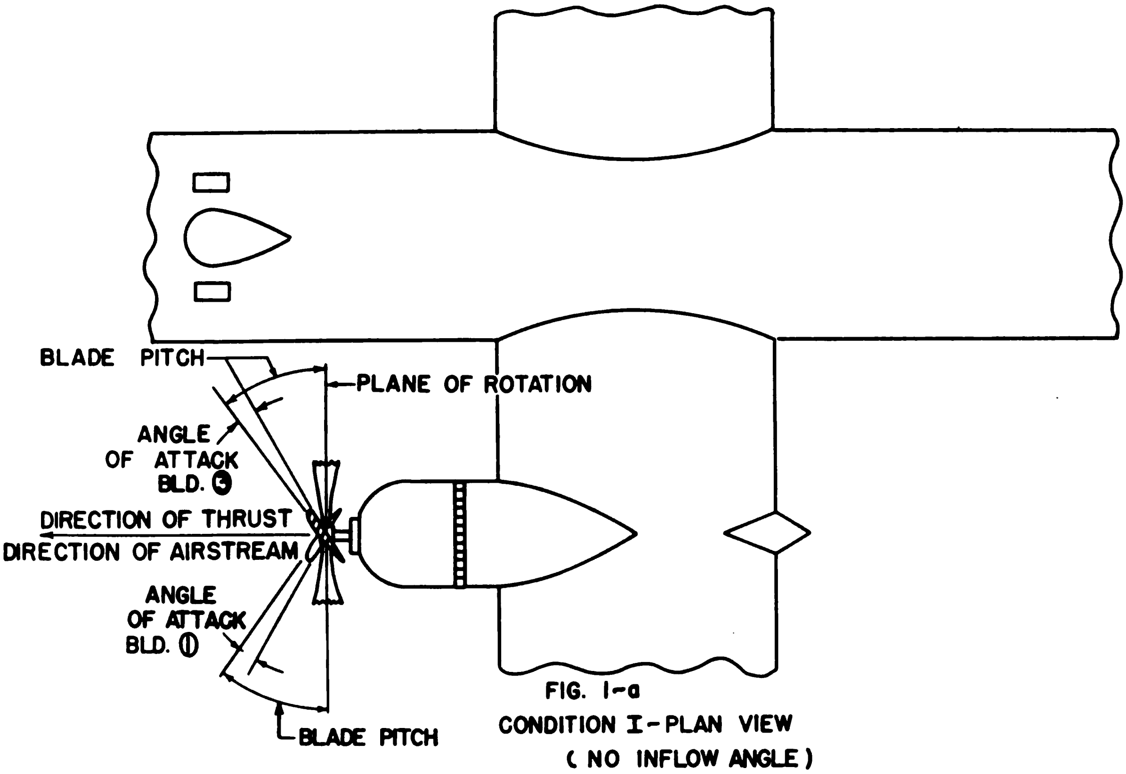

Figure 3.34.—Propeller constant attack angle, condition I.

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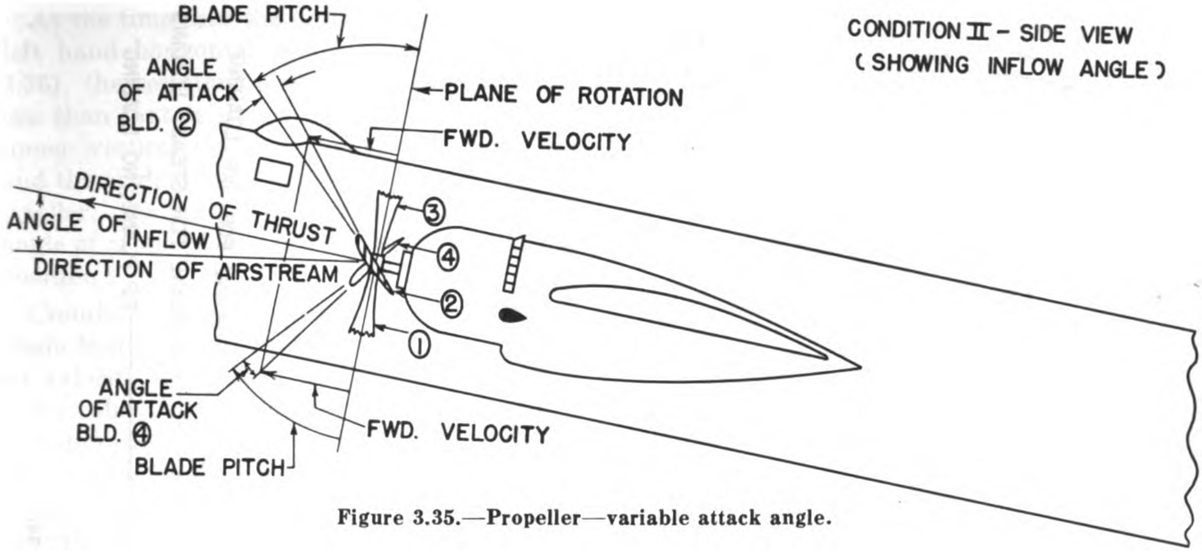

Figure 3.35.—Propeller—variable attack angle.

ing machine in which the specimen is subjected to alternating bending cycles. Frequency of the shaft bending moment cycle is once per revolution of the shaft.

Vibratory Stress Analysis

Basic Concept of Causes and Effects of Propeller Vibration

(1) *Effects of air flow and attack angle variations.* In steady stress analysis, it was implied that the propeller blades were subjected to a constant thrust during blade rotation or that the blades were operating at a constant angle of attack. The sketch shown in figure 3.34 illustrates this condition of zero inflow angle.

When a propeller is operating in a uniform airstream with no inflow angularity, the apparent resultant wind velocity to which the propeller section is subjected is equal to the vector sum of instantaneous tangential linear velocity of a particle in the rotating section and airplane velocity which is at right angles to the former component.

However, air, instead of entering the propeller disc along lines parallel to a normal line, may enter the disc along a path that makes some angle with the normal to the plane of rotation as shown in figure 3.35. This variation from normal inflow may be caused by yawing in flight or nose up or down attitude of the airplane.

Angularity of air flow into a propeller disc will alter the angular relationship between air flow and airplane movement. The air velocity will not be at right angles to propeller rotative velocity. For each complete revolution, a propeller blade receives a decreasing lift variation in one-half turn and an increasing lift variation in the other half turn. Lift variation is maximum when the blades are in a horizontal position and minimum when the blades are in a vertical position. In this case in which attack angle varies, the propeller blades are subjected to vibratory or cyclic forces which occur once per revolution designated *1 x P* vibration.

The sketches shown in figure 3.36 illustrate application of a cyclic force, or periodic lift to propeller blades. The left side sketch shows air on a line of entry to a propeller disc at some angle (A) with the thrust line. The center sketch depicts variation of velocity components effective upon a blade profile at each quarter turn position compared to velocity components resulting from air flow normal to the plane of rotation. The right side and lower sketches reflect displacement of the plane of the blade tip path from that of steady loading.

With propeller blade in a vertical (upward, position 1, or downward, position 3, fig. 3.36) position, the blade profile angle of attack variation will be insignificant. Considering angle of attack variation to be insignificant in these blade positions is justified, since radial or spanwise components of inflow air velocity have little effect upon aerodynamic forces acting on blade profiles, and axial velocity components of air flow are practically equal to the airplane velocity. (At small angles, $\cos\theta \approx 1.0$).

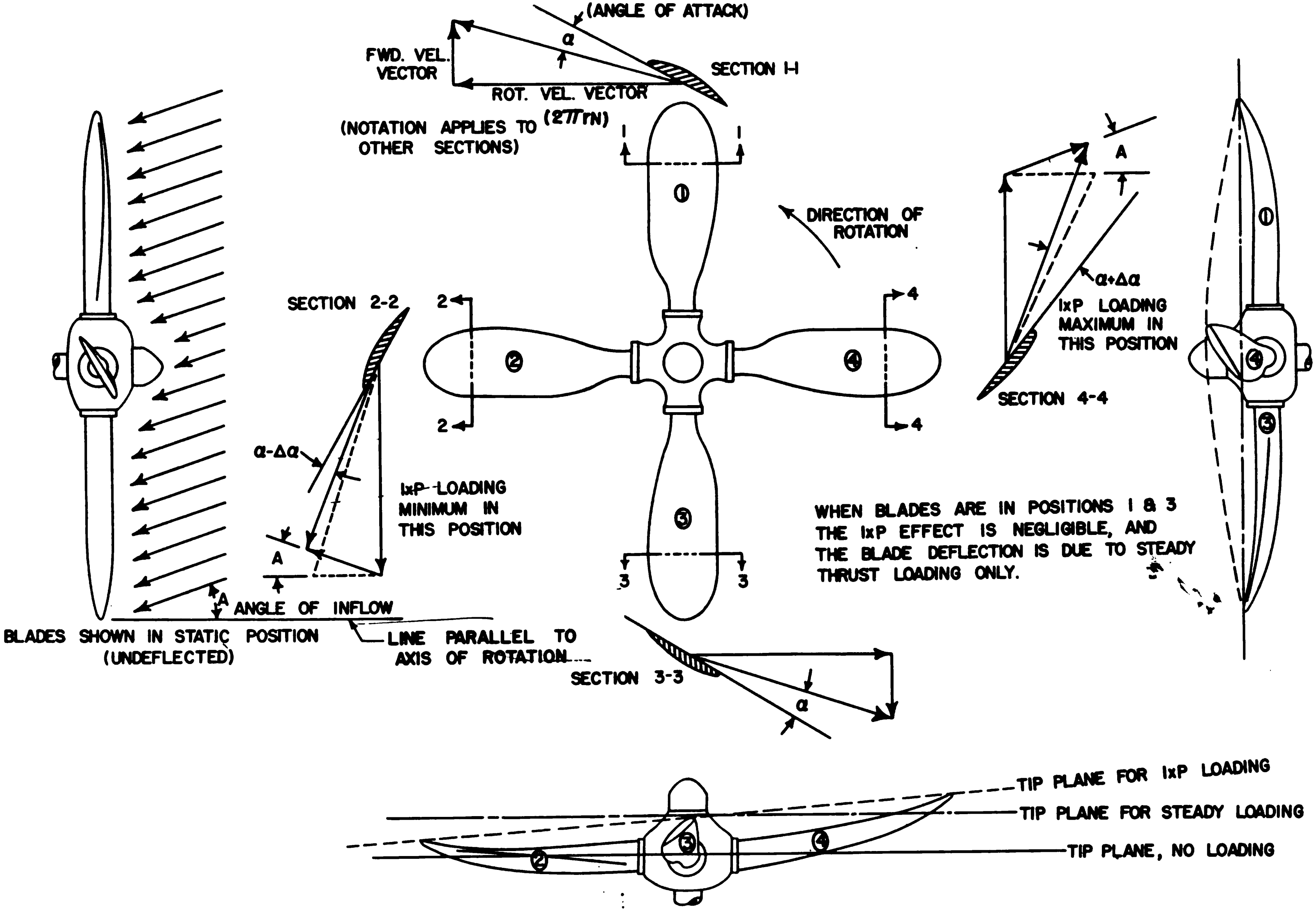

Figure 3.36.—Propeller blade movement during $1 \times P$ loading.

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At the time that the propeller blade is in the left hand horizontal position (position 2, fig. 3.36), the resultant airstream velocity will be less than that existing when the blade is in the upper vertical position (position 1, fig. 3.36) and the angle of attack of blade sections will be smaller. As a result of decreased velocity and angle of attack, blade lift will be a minimum in position 2.

Counterclockwise rotation of the propeller blade from position 2 towards position 3, causes air velocity and attack angle to increase (to a mean value) which results in blade lift reaching a mean or average value with the blade in position 3. Further rotation of the blade, towards position 4, causes an increase of resultant air velocity and angle of attack from the average value until a maximum section lift is produced with the blade in the right-hand position (position 4). Return of the propeller blade from position 4 to position 1 will result in a decrease in section lift to the mean value at position 1.

The variation in blade section lift (ΔL) is shown in figure 3.37.

Variation in blade lift induces blade bending vibration having a frequency equal to propeller rotational speed. The type of vibration discussed, $1 \times P$ (once per revolution), is some times referred to as first order vibration. Angularity of air flow into the propeller disc is a major but not exclusive source of $1 \times P$ vibration. It can be shown that $1 \times P$ vibration may be caused by blade tip interference effects.

(2) *General method of solution of $1 \times P$ vibration problem.* A solution to the $1 \times P$ vibration problem is a complex and laborious process inasmuch as inertia loading is a function of alternating deflections of the propeller blade. Displacements of a blade due to vibratory forces have a definite effect on force components of the steady stress field. Methods have been developed for analyzing the problem in which effects of edgewise and torsional vibrations have been included. However, discussion of methods that include these items is beyond the scope of this manual. The method for $1 \times P$ stress analysis presented herein is fundamental and considered acceptable for conventional blade design.

(3) *Aerodynamic blade loading.* Computation of aerodynamic forces acting on a propeller blade has been presented in another section of this manual. However, from aerodynamic theory, it can be shown that the maximum value of an alternating aerodynamic force on a blade section is:

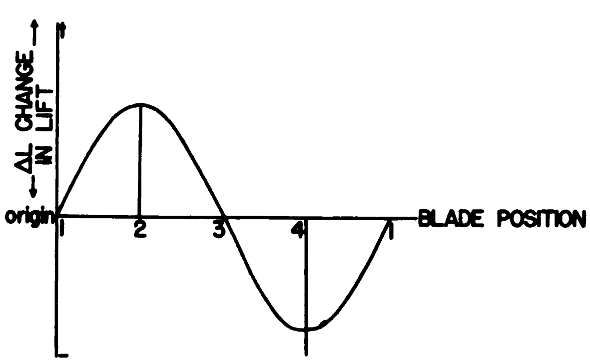

Figure 3.37.—Propeller blade lift variation per revolution.

$$\Delta L = \tfrac{1}{2}\, \rho V_{R_0}^2\, a \operatorname{Sin}^2 \phi_0\, b\, \Delta r \text{ (Approx.)} \qquad \text{III-101}$$

wherein,

ρ = mass density of the air.

V_{R_0} = apparent resultant air velocity.

a = slope of lift curve versus apparent angle of attack.

A = angle of inflow to the propeller disc.

ϕ_0 = angle of apparent resultant air velocity with the plane of rotation.

b = blade section cord.

Δr = radial increment of blade.

The maximum values and distribution of alternating loading can be determined by means of a blade strip analysis similar to that used in normal propeller blade load analysis.

Propeller Blade Bending Moment for First Order Vibration Conditions

(1) *Assumptions.* Calculation of propeller blade stresses under steady load conditions requires the use of some form of an approximate solution to the bending moment equation. The equation for a bending moment of first order vibration conditions will be solved here by means of a finite difference method. In this method, a deflection curve must be assumed in order to get a first approximation to inertia loading. The analysis may be simplified by making the following assumptions:

(*a*) Vibratory inertia loading and external force loading are in phase, i. e., no damping occurs and vibration frequency is below blade resonant frequency.

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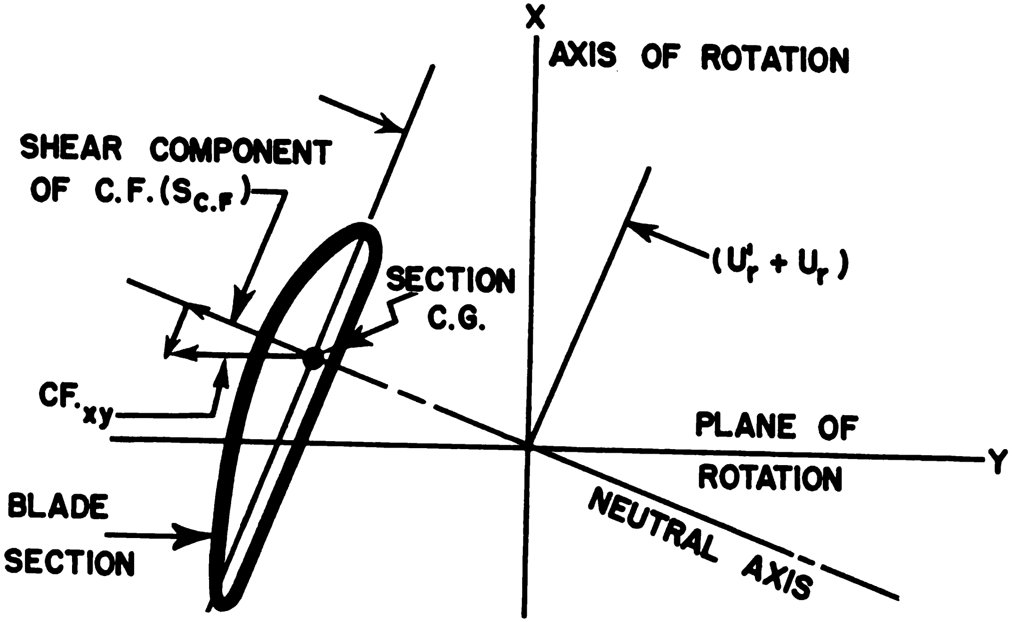

Figure 3.38.—Shear component of centrifugal force.

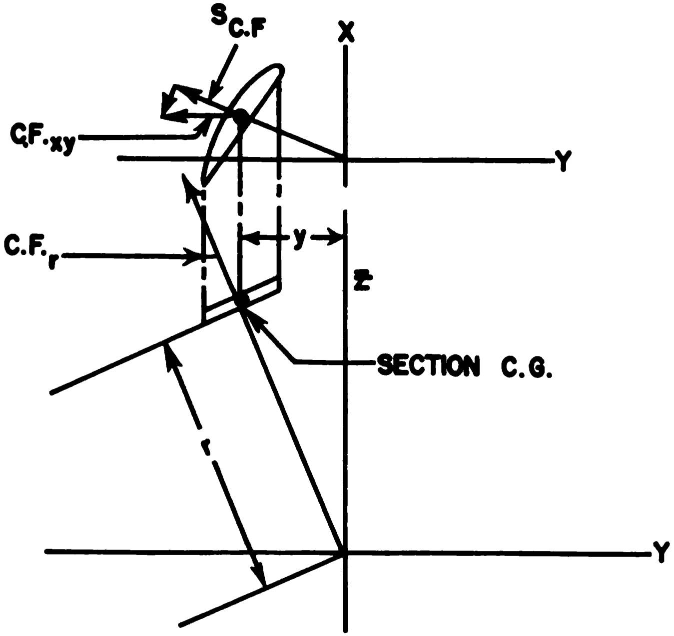

Figure 3.39.—Projection of CF vectors into plane of rotation.

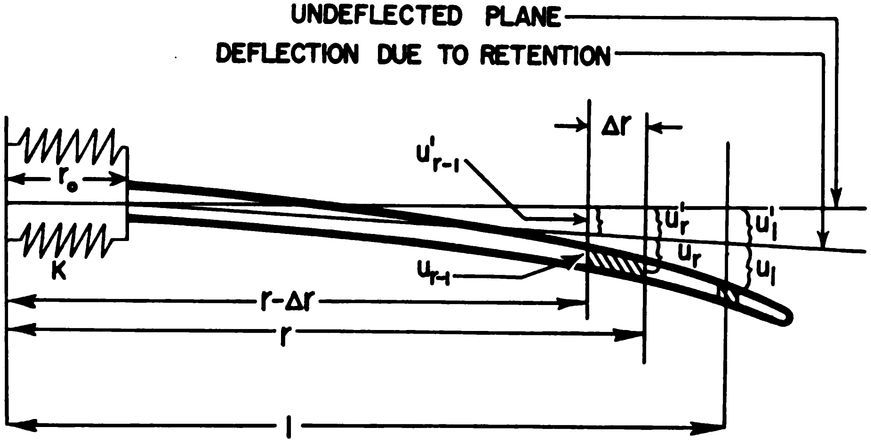

Figure 3.40.—Schematic—blade and retention in plane of bending.

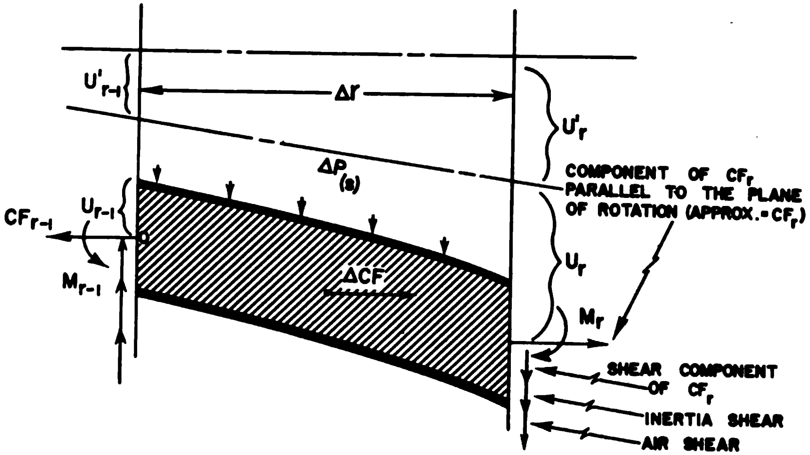

Figure 3.41.—Blade element, Δ*r*, as a free body.

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- (*b*) The blade is untwisted and the deflection curve lies in a plane making an angle (90° − β) with the plane of rotation.
- (*c*) Non-existent edgewise and torsional forces.
- (*d*) The alternating component of external loading is the only component of real significance.
- (*e*) Elastic limit of blade material will not be exceeded.
- (*f*) Other less basic assumptions will be introduced in the development.

(2) *Shear component of centrifugal force.* Figure 3.38 illustrates a propeller blade section subjected to load as viewed from blade tip toward hub. The section is shown displaced from its neutral position by the distance $(U'_r + U_r)$.

In displaced position, as indicated in figure 3.38, the centrifugal force has a shear component normal to the longitudinal axis of the blade, in the plane of bending. The projection of centrifugal force on the $X-Y$ plane is shown as CF_{XY}. From similar triangles, the $X-Y$ plane component of centrifugal force is:

$$(a)\quad CF_{XY}=\frac{Y}{r}CF_r$$

and the shear component may be expressed as:

$$(b)\quad S_{CF}=CF_{XY}\ \mathrm{Sin}\ \beta$$

$$(c)\quad Y=(U'_r+U_r)\ \mathrm{Sin}\ \beta$$

By substitution of equations (a) and (c), equation (b) may be rewritten in the form:

$$S_{CF}=\left(\frac{U'_r+U_r}{r}\right)CF_r\ \mathrm{Sin}^2\ \beta \qquad \text{III–102}$$

Projection of a blade section into the plane of propeller rotation is shown in figure 3.39.

Since centrifugal force acting upon a propeller blade section is a radial force, the centrifugal force shown in figure 3.39 is a true length vector.

A schematic representation of a propeller blade and blade retention projected into the plane of bending is shown in figure 3.40. The blade may be considered to be anchored so that it will pivot at a radius (r_o); retention is represented by a spring constant K.

The beam displacement due to retention alone is represented by U^1 while the deflection due to beam curvature is indicated by U. An enlarged view of the blade element (Δr) considered as a free body has been illustrated in figure 3.41.

The centrifugal force at some radius (r):

$$CF_r=\delta\omega^2\int_{1=r}^{1=R} Aldl \qquad \text{III–103}$$

wherein,

δ = mass density of blade material (slugs/ft.^{3})
ω = angular velocity (rad/sec.)
A = blade cross-sectional area at a radius, 1, (in.^{2})
l = radius between r and R.

Then, by substitution for CF_r in equation III–102, the shear component of centrifugal force can be obtained:

$$S_{CF}=\left(\frac{U'_r+U_r}{r}\right)\delta\omega^2\ \mathrm{Sin}^2\ \beta\int_{1=r}^{1=R} Aldl \qquad \text{III–104}$$

The shear component of inertia force may be expressed in a similar manner as:

$$S_I=\delta\omega^2\int_r^R A\,(U'_l+U_l)\,dl \qquad \text{III–105}$$

Finally, air shearing force can be written:

$$S_a=\int_r^R f(l)\,dl \qquad \text{III–106}$$

In which $f(l)$ = function of blade radius (based on aerodynamic considerations).

(3) *Blade section bending moments.* The moment equation (about Point O of figure 3.41) may be written to include equations III–104, III–105 and III–106. Since:

$$\sum M=0$$

$$\begin{aligned}\sum M=0=&(M_r-M_{r-1})+\Delta r\int_r^R f(1)\,dl+\\ &\Delta r\delta\omega^2\int_r^R A\,(U'_l+U_l)\,dl+\\ &\Delta r\left(\frac{U'_r+U_r}{r}\right)\delta\omega^2\ \mathrm{Sin}^2\ \beta\int_r^R Aldl-\\ &\Big((U'_r+U_r)-(U'_{r-1}+U_{r-1})\Big)\,\delta\omega^2\int_r^R Aldl\end{aligned} \qquad \text{III–107}$$

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Then, if

$$\Delta M=M_r-M_{r-1}$$

The incremental moment change may be written as follows:

$$\Delta M=-\Delta r\int_r^R f(1)\,dl-\Delta r\,\delta\omega^2\int_r^R AU_l'\,dl-$$

$$\Delta r\,\delta\omega^2\int_r^R AU_l\,dl-\frac{\Delta r}{r}U_r'\,\delta\omega^2\,\mathrm{Sin}^2\beta\int_r^R Aldl-$$

$$\frac{\Delta r}{r}U_r\,\delta\omega^2\,\mathrm{Sin}^2\beta\int_r^R Aldl+$$

$$(U_r'-U'_{r-1})\,\delta\omega^2\int_r^R Aldl+U_r\,\delta\omega^2\int_r^R Aldl-$$

$$U_{r-1}\,\delta\omega^2\int_r^R Aldl \qquad \text{III–108}$$

The blade retention spring constant (K) can be expressed in terms of M_o (bending moment at a point where $r=r_o$). One approach to this evaluation would be to use an infinitely stiff blade having a known deflection. An equivalent blade retention wherein a load K' placed at .75 R has produced a one inch deflection in an infinitely stiff blade is illustrated in figure 3.42.

In the case illustrated, the load K' will produce a moment, M_o:

(*a*) $M_o'=K'\left(\frac{3}{4}R-r_o\right)$

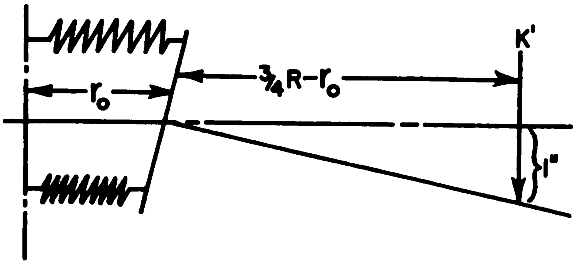

Figure 3.42.—Deflection of an infinitely stiff blade.

Furthermore, slope of the infinitely stiff blade may be expressed:

(*b*) $$\text{Slope}=S_o'=\frac{1}{\frac{3}{4}R-r_o}$$

Then, for any moment (M_o), the slope (S_o) can be written in the form:

(*c*) $$S_o=\frac{M_o}{M_o'}\left(\frac{1}{\frac{3}{4}R-r_o}\right)$$

where $\frac{M_o}{M_o'}$ is a deflection ratio. Substituting M_o' from equation (*a*), into equation (c).

$$S_o\ (\text{Slope at } r_o)=\frac{M_o}{K'\left(\frac{3}{4}R-r_o\right)^2} \qquad \text{III–109}$$

In which

$$K=\frac{1}{K'\left(\frac{3}{4}R-r_o\right)^2}$$

From figure 3.40, representing a blade which is not an infinitely stiff blade, the slope at r_o is:

(*d*) $$S_o=\frac{U_r'}{r-r_o}$$

Then, equation III–109 becomes:

(*e*) $$KM_o=\frac{U_r'}{r-r_o}$$

Solving equation (e) for the quantity U_r']:

(*f*) $$U_r'=KM_o\,(r-r_o)$$

Further, at station 1, blade deflection is:

(*g*) $$U_l'=KM_o\,(1-r_o)$$

and, the variation in blade deflection between stations r and r-l is:

(*h*) $$U_r'-U_{r-1}'=KM_o\,\Delta r$$

Substituting deflection equivalents found in equations (*f*), (*g*), and (*h*), into equation III–108 the change in moment becomes:

$$\Delta M=-\Delta r\int_r^R f(l)\,dl-\Delta r\,\delta\omega^2\,KM_o\int_r^R A\,(l-r_o)\,dl-\Delta r\,\delta\omega^2\int_r^R AU_1dl$$

$$-\Delta r\,\mathrm{Sin}^2\beta\left(\frac{r-r_o}{r}\right)\delta\omega^2\,KM_o\int_r^R \mathrm{Aldl}-\frac{\Delta r}{r}U_r\,\delta\omega^2\,\mathrm{Sin}^2\beta\int_r^R \mathrm{Aldl}$$

$$+\Delta r\,\delta\omega^2\,KM_o\int_r^R Aldl+U_r\,\delta\omega^2\int_r^R Aldl-U_{r-1}\,\delta\omega^2\int_r^R Aldl \qquad \text{III–110}$$

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Collecting similar terms and rewriting equation III-110, the increment of bending moment acting on a blade increment is:

$$\Delta M=-\left(\Delta r\int_r^R f(l)\,dl+\Delta r\,\delta\omega^2\int_r^R AU_1\,dl\right)$$
$$+M_o\left(-\Delta r\,r_o\,\delta\omega^2 K\int_r^R Adl-\Delta r\,\delta\omega^2 K \operatorname{Sin}^2\beta\int_r^R Aldl+\Delta r\frac{r_o}{r}\,\delta\omega^2 K\operatorname{Sin}^2\beta\int_r^R Aldl\right)$$
$$+U_r\left(1-\frac{\Delta r}{r}\operatorname{Sin}^2\beta\right)\delta\omega^2\int_r^R Aldl-U_{r-1}\left(\delta\omega^2\int_r^R Aldl\right) \qquad \text{III-111}$$

Equation III-111 may be written in the form:

$$\Delta M=-Y_r+X_rM_o+Z_rU_r-CF_rU_{r-1} \qquad \text{III-112}$$

In which X_r, Y_r and Z_r are purely arbitrary coefficients and bear no specific relation to any coordinate system. The coefficients, Y_r, X_r and Z_r may be evaluated from the following:

$$Y_r=\Delta r\int_r^R f(l)\,dl+\Delta r\,\delta\omega^2\int_r^R AU_1\,dl \qquad \text{III-113}$$

$$X_r=\Delta r\,\delta\omega^2 K\operatorname{Sin}^2\beta\left(\frac{r_o}{r}-1\right)\int_r^R Aldl+\Delta r\,r_o\,\delta\omega^2 K\int_r^R Adl \qquad \text{III-114}$$

$$Z_r=\left(1-\frac{\Delta r}{r}\operatorname{Sin}^2\beta\right)\delta\omega^2\int_r^R Aldl \text{ and} \qquad \text{III-115}$$

$$CF_r=\delta\omega^2\int_r^R Aldl \qquad \text{III-116}$$

$$Z_r=\left(1-\frac{\Delta r}{r}\operatorname{Sin}^2\beta\right)\varrho\omega^2\int_r^R Aldl \qquad \text{III-115}$$

and

$$CF_r=\delta\omega^2\int_r^R Aldl \qquad \text{III-116}$$

The quantity Y_r (equation III-113) can be determined if a value of U_1 is assumed. The quantities X_r, Z_r, and CF_r can be evaluated directly from known data. The moment equation is:

$$M_n=M_{n-1}+\Delta M_n \qquad \text{III-117}$$

In which n designates a particular station along the blade radius, and $(n-1)$ is an inboard station a distance Δr from station n. ΔM_n is the increment of moment (defined by equation III-112) for a limit of integration r which corresponds to the *nth* station along the propeller blade.

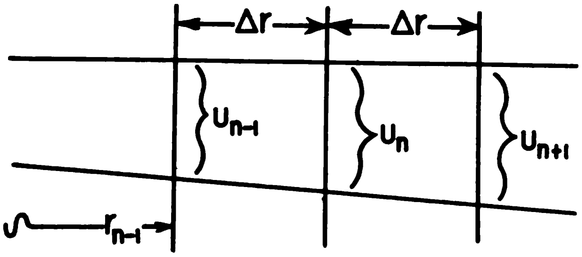

Figure 3.43.—Blade increment deflections.

(4) *Blade station deflections and bending moments.* (a) Development of general deflection formulas. In order to solve equation III-117, a beam deflection curve will be assumed, of the form:

$$U=C_1+C_2r+C_3r^2 \qquad \text{III-118}$$

In which C_1, C_2 and C_3 are constants. Figure 3.43 indicates the relation between U and r. The developed equations for deflection are found to be:

$$U_{n-1}=C_1+C_2\,(r_{n-1})+C_3\,(r_{n-1})^2 \qquad \text{III-119}$$

$$U_n\;=C_1+C_2\,(r_{n-1}+\Delta r)+C_3\,(r_{n-1}+\Delta r)^2 \qquad \text{III-120}$$

$$U_{n+1}=C_1+C_2\,(r_{n-1}+2\Delta r)+C_3\,(r_{n-1}+2\Delta r)^2 \qquad \text{III-121}$$

From which a solution for C_3 is found to be

$$C_3=\frac{U_{n+1}-2U_n+U_{n-1}}{2(\Delta r)^2} \qquad \text{III-122}$$

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The second derivative of U with respect to r, from equation III–118.

$$\frac{d^2U}{dr^2}=2\,C_3 \qquad \text{III–123}$$

From beam theory (the flexure formula)

$$\frac{d^2U}{dr^2}=\frac{M_n}{EI_n} \qquad \text{III–124}$$

Therefore:

$$\frac{M_n}{EI_n}=2\,C_3\;.$$

or, substituting in equation III–122.

$$\frac{M_n}{EI_n}=\frac{U_{n+1}-2U_n\,U_{n-1}}{(\Delta r)^2} \qquad \text{III–125}$$

Rewriting equation III–125:

$$U_{n+1}=\frac{M_n}{EI_n}(\Delta r)^2+2U_n-U_{n-1} \qquad \text{III–126}$$

To simplify the equation, let:

$$G_n=\frac{(\Delta r)^2}{EI_n}$$

Then

$$U_n=G_{n-1}\,M_{n-1}+2U_{n-1}-U_{n-2} \qquad \text{III–127}$$

(b) Development of General Bending Moment and Deflection Equations in Terms of Constants. It should be noted that determination of blade bending moment, M_n, is dependent upon previous determination of blade bending moment at an adjacent inboard station (M_{n-1}) and calculation of incremental moment change between adjacent stations, i. e.

$$M_n=M_{n-1}+\Delta M_n \qquad \text{III–117}$$

However evaluation ΔM_n requires solution of equation III–112

$$(\Delta M_r=-Y_r+X_rM_o+Z_rU_r-CF_rU_{r-1}).$$

Solution equation III–112 is, in turn, dependent upon evaluation of deflection at the given and adjacent inboard station, as reflected by equation III–127 ($U_n=G_{n-1}\;M_{n-1}+2U_{n-1}-U_{n-2}$). It is apparent, then, that an iterated solution to the bending moment problem must be made.

In order to establish an end condition and to facilitate solution of equation III–127, it will be assumed that the moment at the radial station r_o is equal to M_o. As shown in figure 3.40 the deflection U at station r_o will be assumed to be zero. Further, the reference plane will be established at radial station r_o so that $n=o$ at r_o. The cantilever beam representation shown in figure 3.40 will have a beam condition at r_o equivalent to that at the fixed midpoint ($U_o=0$) of the double free end beam shown in figure 3.44.

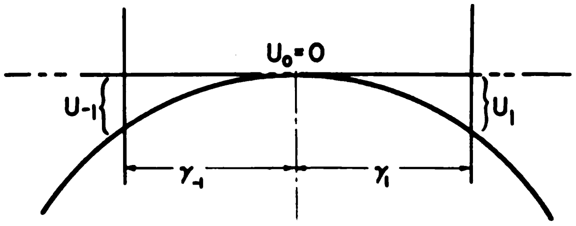

Figure 3.44.—Double free end beam—fixed center.

As shown in figure 3.44, deflections at stations $r=1$ and $r=-1$ will be equal.

Therefore,

$$U_1=U_{-1}\text{ and }U_o=0$$

Then from equation III–127,

$$U_1=G_oM_o+2U_o-U_{-1}$$

$$=G_oM_o+0-U_1$$

Hence

$$U_1=\frac{G_oM_o}{2}$$

which may be written in a more general form as:

$$U_1=A_1M_o+C_1 \qquad \text{III–128}$$

in which

$$A_1=\frac{G_o}{2},\text{ and }C_1+0$$

From the general moment equation, III–117, and the incremental moment change reflected by equation III–112, bending moment at station 1 may be expressed as follows:

$$M_1=M_o-Y_1+X_1M_o+Z_1U_1-CF_1U_o$$

and, since:

$$U_o=0$$

and

$$U_1=\frac{G_oM_o}{2}$$

$$M_1=M_o\left(1+X_1+\frac{Z_1G_o}{2}\right)-Y_1 \qquad \text{III–129a}$$

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To simplify equation writing, let:

$c_1 = -Y_1$ and

and

$$a_1 = \left(1 + X_1 + \frac{Z_1G_o}{2}\right)$$

Then equation III–129a may be written:

$$M_1 = a_1M_o + c_1 \qquad \text{III–129}$$

At another station (τ) where $n=2$, the deflection, from the general equation III–127, is:

$$U_2 = G_{(2-1)}M_{(2-1)} + 2\ U_{(2-1)} - U_{(2-2)}$$
$$= G_1M_1 + 2\ U_1 - U_o$$

since

$$U_1 = \frac{G_oM_o}{2}$$

and

$$U_o = 0$$
$$U_2 = G_1M_1 + G_oM_o$$

and substituting for M_1

$$U_2 = G_1(a_1M_o + c_1) + G_oM_o$$
$$= M_o(G_1a_1 + G_o) + c_1G_1$$

which may be simplified as:

$$U_2 = A_2M_o + C_2 \qquad \text{III–130}$$

wherein

$$A_2 = G_1a_1 + G_o \text{ and } C_2 = c_1G_1$$

Now, as before, the moment equation may be written for conditions when $n=2$:

$$M_2 = M_1 + \Delta M_2$$

in which

$$\Delta M_2 = X_2M_o - Y_2 + Z_2U_2 - CF_2U_1$$

Substituting for M_1 and ΔM_2, the bending moment at station 2 will be:

$$M_2 = (a_1M_o + c_1) + X_2M_o - Y_2 + Z_2U_2 - CF_2U_1$$

and by substituting for U_1 and U_2:

$$M_2 = (a_1M_o + c_1) + X_2M_o - Y_2 +$$
$$Z_2(A_2M_o + C_2) - CF_2(A_1M_o + C_1)$$
$$= (a_1 + X_2 + A_2Z_2 - CF_2A_1)M_o +$$
$$(c_1 - Y_2 + Z_2C_2 - CF_2C_1) \qquad \text{III–131}$$

or

$$M_2 = a_2M_o + c_2$$

wherein

$$c_2 = (c_1 - Y_2 + Z_2C_2 - CF_2c_1)$$

Similarly, deflection of the blade at station $n=3$ may be written:

$$U_3 = G_2M_2 + 2U_2 - U_1 \text{ (from equation III–127)}$$
$$= G_2(a_2M_o + c_2) + 2(A_2M_o + C_2) - (A_1M_o + C_1)$$
$$= M_o(a_2G_2 + 2A_2 - A_1) + (G_2c_2 + 2C_2 - C_1)$$
$$= A_3M_o + C_3 \qquad \text{III–132}$$

The foregoing developments permit writing general equations in terms of previously established constants, which can be used in evaluation of bending moments and deflections in a step-by-step method of analysis. These general equations are:

$$M_n = a_nM_o + cn \qquad \text{III–133}$$

$$U_n = A_nM_o + C_n \qquad \text{III–134}$$

In which

$$a_n = a_{n-1} + X_n + Z_nA_n - A_{n-1}CF_n$$

$$c_n = c_{n-1} - Y_n + Z_nC_n - C_{n-1}CF_n$$

$$A_n = 2A_{n-1} - A_{n-2} + A_{n-1}G_{n-1}$$

$$C_n = 2C_{n-1} + G_{n-1}c_{n-1} - C_{n-2}$$

These end conditions are sufficient to permit evaluation of the moment equations, by sequence procedure. At blade tip, the moment $(M_{t_p}) = 0$:

Hence, equation III–133 becomes:

$$M_{tip} = a_{tip}M_o + c_{tip} \qquad \text{III–135}$$

Solving equation III–135 for the moment at the root M:

$$M_o = -\frac{c_{tip}}{a_{tip}} \qquad \text{III–136}$$

The value of M_o as obtained in equation III–136 can be put into equation III–133 to obtain moment distribution along the blade.

Application of Equations

(1) *Vibratory stress analysis of a hollow steel blade.* (*a*) Propeller Data. In order to illustrate the equations that have been derived for 1×P vibratory stress analysis, the solution of a typical problem in determination of vibratory stress in a hollow steel propeller will be presented. This will be followed by a general discussion of the method, of computations and comparisons to flight test data. The following general data were known or assumed:

Propeller rotational speed	1,050 r. p. m.
Propeller diameter	16 ft. 8 in.
Blade angle at 50% radius	45°
Blade retention spring constant (k').	11,000 lb. per inch deflection.

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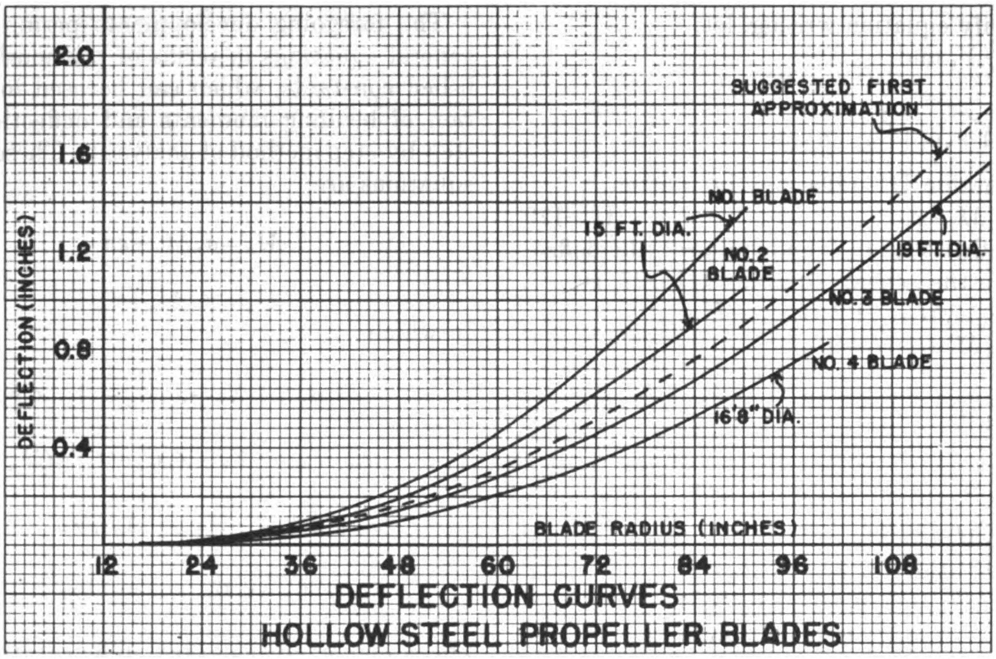

Figure 3.45.

The value of k' was determined from laboratory measurements. Cross-sectional area and moment of inertia of blade sections at given stations were determined previously in design development. The air shear (45° component of total alternating air shear) distribution was obtained from previous aerodynamic studies.

(*b*) Symbols Defined with Units Used

r=radius of blade section (inches).

A=cross-sectional area of the blade section (in.^{2}).

δ=mass density of blade material (slugs per in.^{3})

r_o=radius of the point about which the blade is assumed to pivot due to retention flexibility (in.).

CF=centrifugal force (lb.).

u=beam deflection (in.).

I_{min}=minor moment of inertia of area of blade section (in.^{4}).

Δr=increment of radius (6 in.).

$G=\frac{(\Delta r)^2}{EI_{min}}$, where E is the modulus of elasticity of the blade material.

K=blade retention flexibility constant.

Subscript n has been used to designate blade section under consideration. In this analysis, $n=o$ at blade radius, $r_o=6$ in. The other designations a_n, c_n, A_n, C_n, X_n, Y_n and Z have been defined in derivation of the equations used.

(*c*) Tabulation of Data and Computations. The vibratory stress analysis has been prepared in tabular form to facilitate computations and is shown in tables III–12A through III–12I, inclusive. Appropriate instructions accompany each table to explain the basis of computation, where necessary. Table III–12I, in addition to showing completion of the initial set of data (trial I), shows the final results (only) of trial II.

It should be remembered that all columns (1 through 50) of all tables are necessary to complete one set of vibratory stress analysis. Repeating the process, using refined data obtained from the first trial, improves accuracy of the analysis.

(2) *Selection of appropriate deflection curves.* To obtain a reasonable value of assumed deflection U for entry in column 7 of table III–12A, a set of curves of blade deflections for various diameters of a given type of propeller blade should be used. It is possible to construct on such a graph, a mean or average deflection curve that can be used to predict deflection for a first approximation. The suggested *first approximation curve* illustrated in figure 3.45 represents a case of maximum vibratory shank stress of 8000 p. s. i. for conventional blades.

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TABLE III-12A. *Vibratory Stress Analysis—Trial I*

1	2	3	4	5	6	7
r (Inches)	A Area (Inches^2)	Ar (Inches^3)	MEAN Ar (Inches^3)	ΣAr Begin at Blade Tip (Inches^3)	CF (53.0 × Col. 5) (Pounds)	Assumed u (Inches)
6	8.48	50.9		2834.3	150590	0.000
			71.0			
12	7.60	91.2		2763.3	146828	0.004
			122.2			
18	8.51	153.2		2641.1	140320	0.022
			145.4			
24	5.73	139.6		2695.7	132600	0.045
			146.8			
30	5.19	135.9		2348.9	124300	0.076
			164.5			
36	4.80	173.0		2184.4	116060	0.120
			178.7			
42	4.39	184.4		2005.7	106560	0.189
			188.2			
48	4.00	192.0		1817.5	96570	0.255
			195.3			
54	3.68	198.7		1622.2	86190	0.334
			201.9			
60	3.42	205.1		1420.3	75460	0.429
			206.8			
66	3.16	206.6		1213.5	64460	0.540
			209.7			
72	2.93	210.9		1003.8	53330	0.679
			211.8			
78	2.75	212.5		792.0	42080	0.847
			211.7			
84	2.51	210.8		580.3	30830	1.035
			209.1			
90	2.30	207.4		371.2	19720	1.233
			205.0			
96	2.11	202.5		166.2	8830	1.440
			166.2			
100	1.30	130.0		0.0	0	1.579

Entries in Column 4 are average values of successive pairs of values in Column 3.
To get entry for Column 6, multiply Column entry of 5 by 53.0 $(\Delta r \delta \omega^2 = 53.0)$.
Entries of Column 7 may be obtained from an average deflection curve such as that shown in Figure 3.45.

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Table III–12B. *Vibratory Stress Analysis—Trial I*

1 r (Inches))	8 Au (Inches)	9 MEAN (Inches)	10 $\Sigma\ Au$ From Tip (Inches)	11 Inertia Shear (Pounds)	12 I Min. (Inches ^{4})	13 $\frac{G\ (\Delta r)^2}{EI}$ (Pounds^{-1})
6	0. 0		21, 498	1143	38. 38	0.031×10^{-6}
		0. 017				
12	0. 034		21, 481	1142	34. 96	0.035×10^{-6}
		0. 113				
18	0. 192		21, 368	1136	42. 47	0.028×10^{-6}
		0. 225				
24	0. 258		21, 143	1124	20. 79	0.058×10^{-6}
		0. 328				
30	0. 398		20, 815	1107	10. 80	0.111×10^{-6}
		0. 487				
36	0. 577		20, 328	1081	5. 99	0.200×10^{-6}
		0. 703				
42	0. 830		19, 625	1044	3. 40	0.353×10^{-6}
		0. 925				
48	1. 020		18, 700	995	2. 18	0.550×10^{-6}
		1. 125				
54	1. 231		17, 575	935	1. 44	0.833×10^{-6}
		1. 349				
60	1. 466		16, 226	863	0. 95	1.257×10^{-6}
		1. 586				
66	1. 706		14, 640	779	0. 66	1.804×10^{-6}
		1. 849				
72	1. 991		12, 791	681	0. 49	2.424×10^{-6}
		2. 150				
78	2. 309		10, 641	566	0. 39	3.038×10^{-6}
		2. 444				
84	2. 579		8, 197	436	0. 33	3.636×10^{-6}
		2. 711				
90	2. 842		5, 486	291	0. 23	4.225×10^{-6}
		2. 940				
96	3. 038		2, 546	135	0. 22	5.455×10^{-6}
		2. 546				
100	2. 053		0	0	0. 0	0. 0

Entries in Column 9 are obtained by averaging successive pairs of entries in Column 8.
To get entry for Column 11, multiply entry in Column 10 by 53.0 ($\Delta r \delta \omega^2 = 53.0$).

TABLE III–12C. *Vibratory Stress Analysis—Trial I*

1	14	15	16	17	18	19	20
r Sta Inches	Air Shear Pounds	Total Shear (11)+(14) Pounds	MEAN Area A_m Inches²	ΣA_m Inches²	$\Delta r\ \delta\omega^2 r_0 \Sigma A_m$ $\Delta r\ \delta\omega^2 r_0 = 318$ Pounds	r_0/r	$(r_0/r)-1$
6	1460	2603		68. 48	21775	1. 00	0. 0
			8. 04				
12	1460	2602		60. 44	19220	0. 50	−0. 500
			8. 05				
18	1448	2584		52. 39	16660	0. 33	−0. 667
			7. 12				
24	1418	2542		45. 27	14396	0. 25	−0. 750
			5. 46				
30	1373	2480		39. 81	12660	0. 20	−0. 800
			5. 00				
36	1313	2394		34. 81	11070	0. 17	−0. 833
			4. 60				
42	1237	2281		30. 21	9607	0. 14	−0. 857
			4. 20				
48	1141	2136		26. 01	8271	0. 13	−0. 875
			3. 84				
54	1025	1960		22. 17	7050	0. 11	−0. 889
			3. 55				
60	888	1751		18. 62	5921	0. 10	−0. 900
			3. 29				
66	736	1515		15. 33	4875	0. 09	−0. 909
			3. 04				
72	577	1258		12. 29	3908	0. 08	−0. 917
			2. 84				
78	417	983		9. 45	3005	0. 07	−0. 923
			2. 63				
84	260	696		6. 82	2172	0. 07	−0. 929
			2. 91				
90	117	408		3. 91	1243	0. 06	−0. 933
			2. 21				
96	26	161		1. 70	541	0. 06	−0. 937
			1. 70				
100	0	0		0. 0	0	0. 06	−0. 940

Entries for Column 14 were obtained from blade aerodynamic data (basis of determination not given in this analysis).

To get any given entry in Column 15 add entries of Columns 11 and 14 at the same radial station.

Each entry in Column 16 is the average value between each pair of successive values in Column 2.

Entry in Column 18 is product of entry Column 17 and 318. ($\Delta r\ \delta\omega^2 r_0 = 53{\cdot}6 = 318$)

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TABLE III–12D. *Vibratory Stress Analysis—Trial I*

1	21	22	23	24	25	26
r (Inches)	(20) (6) $\text{Sin}^2\beta$ (Pounds)	X $[(21)+(18)]$ $\cdot\ (\Delta r)K$	$\frac{\Delta r\ \text{Sin}^2\ \beta}{r}$	Col. 1 Col. 23	Z Product Columns (24)(6) (Pounds)	Y Product of Δr Col. (15) (Pounds-Inches)
6	0	$+2460\times10^{-6}$	0. 500	0. 500	75295	15618
12	−37648	-2118×10^{-6}	0. 250	0. 750	110114	15612
18	−48964	-3700×10^{-6}	0. 167	0. 833	116891	15504
24	−49724	-4050×10^{-6}	0. 125	0. 875	116023	15252
30	−49920	-4270×10^{-6}	0. 100	0. 900	112870	14880
36	−48340	-4270×10^{-6}	0. 083	0. 917	106428	14364
42	−45664	-4140×10^{-6}	0. 071	0. 929	99001	13686
48	−42249	-3890×10^{-6}	0. 063	0. 937	90485	12816
54	−38311	-3580×10^{-6}	0. 056	0. 944	81363	11760
60	−33959	-3219×10^{-6}	0. 050	0. 950	71690	10506
66	−29304	-2800×10^{-6}	0. 045	0. 955	61574	9096
72	−24453	-2355×10^{-6}	0. 042	0. 958	51091	7548
78	−19420	-1885×10^{-6}	0. 038	0. 962	40482	5898
84	−14322	-1392×10^{-6}	0. 036	0. 964	29723	4176
90	−9200	-913×10^{-6}	0. 033	0. 967	19071	2448
96	−4137	-412×10^{-6}	0. 031	0. 969	8556	966
100	0	0	0. 030	0. 970	0	0

(*a*) Basis for obtaining entries in various columns is indicated at the top of each column. For example: Entries for Column 21 are obtained by multiplying entries of Columns 6 and 20 by $\text{Sin}^2\ \beta$.

(*b*) The sum of Columns 21 and 18 multiplied by $[(\Delta r)K]$ will give entry for Column 22 in which:

$$K=\frac{1}{11{,}000(3/4R-r_0)^2}$$

TABLE III-12E. *Vibratory Stress Analysis—Trial I*

	1	27	28	29	30	31
		$c_n=c_{n-1}-Y_n+Z_nC_n-CF_nC_{n-1}$				
n	r (Inches)	c_n	Y_n	Z_nC_n	CF_nC_{n-1}	Z_n
0	6	0	15618	0	0	75296
1	12	−15612	15612	0	0	110114
2	18	−31179	15504	−63	0	116891
3	24	−46587	15353	−228	−72	116023
4	30	−61904	14880	−683	−246	112870
5	36	−77379	14364	−1817	−706	106428
6	42	−93559	13686	−4313	−1819	99001
7	48	−111495	12816	−9328	−4208	90485
8	54	−132594	11760	−18224	−8885	81363
9	60	−158843	10506	−32645	−16920	71690
10	66	−193156	9090	−54582	−29359	61574
11	72	−238550	7584	−85122	−47275	51091
12	78	−296755	5898	−122417	−70110	40482
13	84	−364732	4176	−157040	−93239	29723
14	90	−432125	2448	−169145	−104200	19071
15	96	−476964	966	−122188	−78351	8556
16	100	−476964	0	0	0	0

As indicated in paragraph 2D of this section, $c_0=O$(at $r=6$)
Since $C_0=C_1$, $C_1=O$
Hence $c_1=-Y_1$
Line by line computation for "n" using the equation at the top of the page can be accomplished by completing Columns 27 through 35 of Tables XIV-E and XIV-F.

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TABLE III-12F. *Vibratory Stress Analysis—Trial I*

1	32	33	34	35	36
	$C_n=2C_{n-1}+c_{n-1}\,G_{n-1}-C_{n-2}$				Column 13 Reproduced
r (Inches)	CF_n (Pounds)	C_n	$2C_n$	c_nG_n	G_n
6	150590	0	0	0	0.0313×10^{-6}
12	146828	0	0	−0.00054	0.0348×10^{-6}
18	140320	−0.00054	−0.00108	−0.00088	0.0283×10^{-6}
24	132600	−0.00196	−0.00393	−0.00268	0.0577×10^{-6}
30	124300	−0.00608	−0.01216	−0.00687	0.1111×10^{-6}
36	116060	−0.01707	−0.03414	−0.01550	0.2004×10^{-6}
42	106560	−0.4357	−0.08714	−0.03301	0.3529×10^{-6}
48	96570	−0.10308	−0.20617	−0.06137	0.5505×10^{-6}
54	86190	−0.22397	−0.44795	−0.11049	0.8333×10^{-6}
60	75460	−0.45536	−0.91072	−0.19969	1.2572×10^{-6}
66	64460	−0.88644	−1.77288	−0.34855	1.8045×10^{-6}
72	53330	−1.66607	−3.33215	−0.57829	2.4242×10^{-6}
78	42080	−3.02399	−6.04799	−0.90154	3.0380×10^{-6}
84	30830	−5.28346	−10.5669	−1.32631	3.6364×10^{-6}
90	19720	−8.86924	−17.7384	−1.82590	4.2254×10^{-6}
96	8830	−14.2809	−28.5618	−2.60160	5.4545×10^{-6}
100	-------------	−22.2941	-------------	-------------	-------------

$C_0=C_1=O$ hence $C_2=c_1G_1$, which can be obtained from Column 35.

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TABLE III–12G. *Vibratory Stress Analysis—Trial I*

1	37	38	39	40	41
r	$a_n=a_{n-1}+X_n+Z_nA_n-CF_nA_{n-1}$				Recap. of Col. 31
(Inches)	a_n	X_n	X_nA_n	CF_nA_{n-1}	Z_n
6	1.00000	−0.00246	0.0	0	75296
12	1.00130	−0.00214	0.00345	0	110114
18	1.00308	−0.00373	0.00773	0.00220	116891
24	1.00705	−0.00408	0.01681	0.00876	116023
30	1.01631	−0.00430	0.03165	0.01876	112870
36	1.03587	−0.00430	0.05657	0.03270	106428
42	1.07296	−0.00417	0.09791	0.05665	99001
48	1.13867	−0.00393	0.16514	0.09550	90485
54	1.24527	−0.00362	0.26752	0.15730	81363
60	1.40888	−0.00325	0.41498	0.24812	71690
66	1.65228	−0.00284	0.61945	0.37322	61574
72	1.99793	−0.00239	0.88457	0.53653	51091
78	2.45802	−0.00192	1.10059	0.72857	40482
84	3.00545	−0.00143	1.45567	0.90681	29723
90	3.55416	−0.00093	1.51553	0.96587	19071
96	3.92135	−0.00043	1.06932	0.70170	8556
100	3.92135	0	0	0	0

According to end conditions previously established, $a_0=1$.

Then, using CF_n, X_n and Z_n, data previously computed in conjunction with appropriate values of "A" from Table III–12H, entries for Column 37 (a_n) can be calculated.

TABLE III–12H. *Vibratory Stress Analysis—Trial I*

1	42	43	44	45
r	$A_n=2A_{n-1}+a_{n-1}G_{n-1}-A_{n-2}$			
(Inches)	CF_n	A_n	$2A_n$	a_nG_n
6	150592	0	0	0.0313×10^{-6}
12	146818	0.0157×10^{-6}	0.0313×10^{-6}	0.0348×10^{-6}
18	140325	0.0661×10^{-6}	0.1322×10^{-6}	0.0284×10^{-6}
24	132598	0.1449×10^{-6}	0.2898×10^{-6}	0.0581×10^{-6}
30	124799	0.2818×10^{-6}	0.5636×10^{-6}	0.1129×10^{-6}
36	116061	0.5316×10^{-6}	1.0632×10^{-6}	0.2076×10^{-6}
42	106567	0.9890×10^{-6}	1.9780×10^{-6}	0.3787×10^{-6}
48	96596	1.8251×10^{-6}	3.6502×10^{-6}	0.6268×10^{-6}
54	86190	3.2880×10^{-6}	6.5760×10^{-6}	1.0377×10^{-6}
60	75463	5.7886×10^{-6}	11.576×10^{-6}	1.7712×10^{-6}
66	64475	10.060×10^{-6}	20.577×10^{-6}	2.9815×10^{-6}
72	53331	17.313×10^{-6}	34.627×10^{-6}	4.8434×10^{-6}
78	42082	20.410×10^{-6}	58.820×10^{-6}	7.4675×10^{-6}
84	30833	48.974×10^{-6}	97.949×10^{-6}	10.929×10^{-6}
90	19722	79.467×10^{-6}	158.93×10^{-6}	15.017×10^{-6}
96	8830	124.97×10^{-6}	349.05×10^{-6}	21.389×10^{-6}
100	0	191.87×10^{-6}	0	0

End conditions establish: $A_0=O$ and $A_1=\frac{G_0}{2}$; then, A_2 can be obtained by computation using the formula, since a_1 is available from Column 37.

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TABLE III–121. *Vibratory Stress Analysis—Results*

TRIAL I | TRIAL II (RESULTS ONLY)

1	46	47	1	47	48	49	50
r	A_nM_o	u_{cal}	r	u_{cal}	$a_nM_o+c_n$ (Inch-Pounds)	I/c (Inches)	Stress (PSI)
(Inches)	(Inches)	$A_nM_o+C_n$ (Inches)	(Inches)	(Inches)			
6	0	0	6	0	98400	11.90	8250
12	0.0019	0.0019	12	0.0016	85700	10.83	7900
18	0.0080	0.0075	18	0.0065	73300	14.49	5070
24	0.0176	0.0156	24	0.0139	61300	8.58	7150
30	0.0342	0.0282	30	0.0226	49800	5.90	8400
36	0.0646	0.0476	36	0.0385	39300	4.02	9600
42	0.1203	0.0767	42	0.0621	29600	2.82	10500
48	0.2220	0.1189	48	0.0961	21200	2.34	9000
54	0.3999	0.1759	54	0.1421	14600	1.70	8500
60	0.7040	0.2487	60	0.2007	9400	1.26	7450
66	1.2236	0.3372	66	0.2717	5600	0.94	5920
72	2.1059	0.4398	72	0.3538	3000	0.74	4050
78	3.5772	0.5532	78	0.4440	1200	0.62	2000
84	5.9569	0.6734	84	0.5391	600	0.56	1100
90	9.6658	0.7966	90	0.6358	140	0.51	300
96	15.201	0.9205	96	0.7330	0	0.42	0
100	23.338	1.0445	100	0.8290	0	0	0

$M_o=\frac{c_{16}}{a_{16}}=\frac{476964}{3.9213}=12163$ lb-in. $M_o=\frac{c_n\ (\text{tip})}{a_n\ (\text{tip})}=\frac{476964}{3.9213}=12163$

However, selection of the No. 2, 15 ft. hollow steel blade (figure 3.45) as basis for making an arbitrary first estimate of blade deflection, would permit illustration of rapidity of convergence of deflection curves by iterative calculations. The deflection curve actually used in the sample problem is illustrated in figure 3.46. It is evident that deflections are a function of blade station radius, independent of propeller diameter for all practical purposes.

Discussion of Method of Vibratory Stress Computation

(1) *Accuracy and time requirements.* The time required for an analyst to make a complete *1xP* calculation, after becoming accustomed to the method, is approximately five hours. Use of an automatic calculating machine is recommended, since some computations must be carried to a minimum of five significant figures. The importance of accurate calculations is illustrated by computation necessary to obtain the entry for column 47. The deflection (column 47) was obtained by subtracting the entry in column 33 from the entry in column 46, each of which had been carried to five significant figures. The resulting deflection was accurate to three significant figures. In the sample calculation, all computations were carried to a minimum of six significant figures, even though not more than five are recorded in the tables.

(2) *Computation procedures.* A second computation must be made whenever the difference in assumed and first trial calculated deflection curves is very large. Only a few of the data columns need be changed to complete the second calculation. Calculated deflections, as determined in the first trial, should be used in the next approximation which will prevent oscillation and effect accurate convergence, when the method is applied to the conventional stiff subsonic blade.

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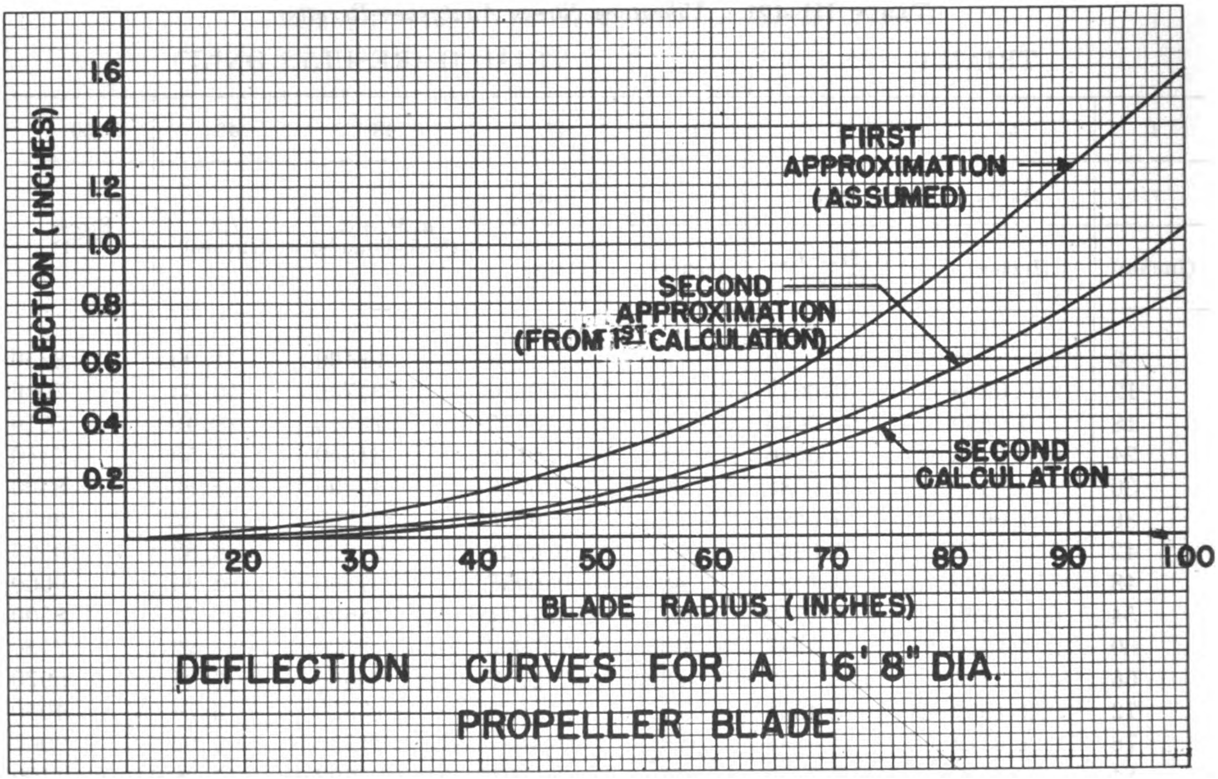

Figure 3.46.

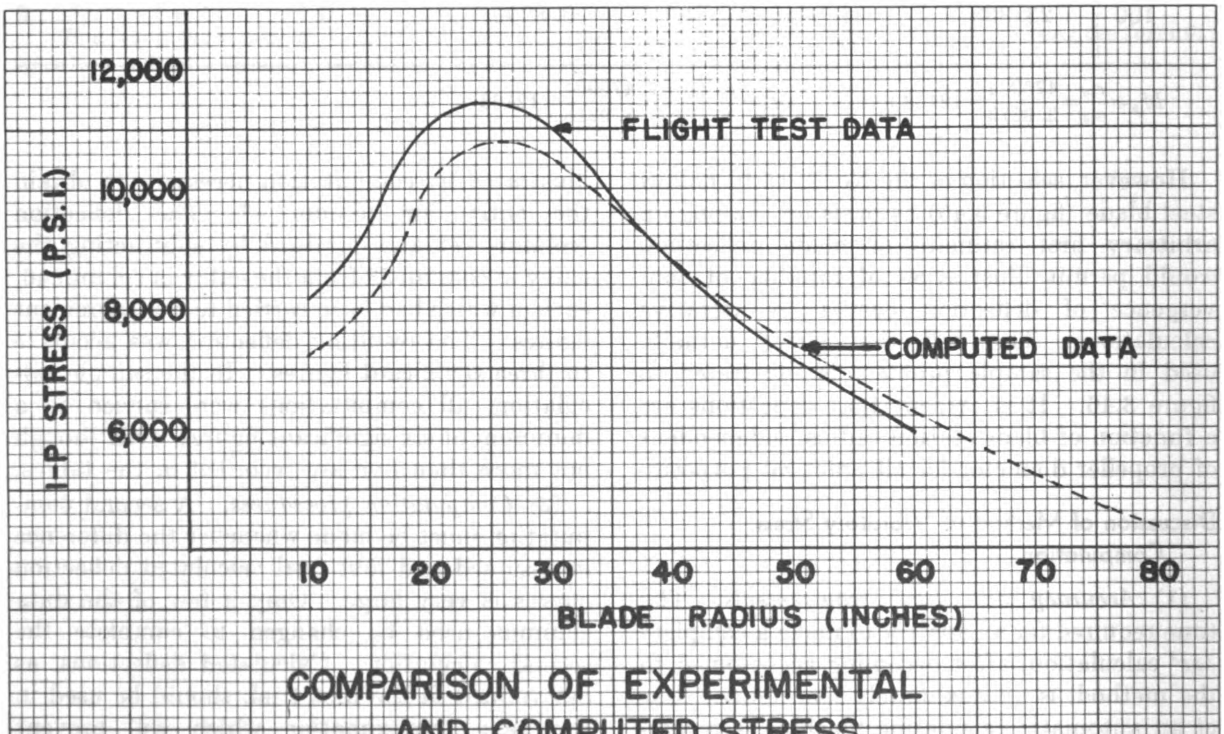

Figure 3.47.

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The second computation can be expedited by superimposing new cut-out data sheets upon the data sheets of the first trial. The cut-out sections should reveal data existing on the first computation sheets that is required in the next computation. For convenience in computation of the step-by-step data, columns numbered 27 through 36 should be on a single data sheet. Similarly, columns numbered 37 through 45 along with a G_n column should be included on a second sheet.

(3) *Deflection curve requirements.* The method of computation does not require graphical integration or curve plotting other than that shown in figure 3.46, which includes the assumed deflection curve for first approximation and resulting computed deflection curves.

The first computed curve was used as the second approximation in the sample problems. The difference in deflection of the two computed curves is less than the deflection difference between the first assumed curve and the first computed curve, which implies that the method is convergent. An examination of the basic equations indicates fairly rapid convergence, since the assumed deflection is only the beam deflection (it does not include deflections caused by retention flexibility) and the assumption relates only to inertia loading which is approximately one-half of the total alternating load for conventional blades.

(4) *Comparison of flight test and calculated data.* Measurement of propeller blade vibratory stresses in flight is quite common; however, to obtain sufficient data for a determination of loading associated with these stresses is quite difficult. Several tests have been made and some flight loading data have been obtained. The curves of figure 3.47 reflect average values of first order stresses in a 15 foot diameter propeller, obtained from a series of tests.

Aerodynamic loading was determined accurately and used to calculate stress using this method of analysis. It will be noted that experimental stress distribution was the same as computed distribution. However, maximum stress from flight test was slightly higher than computed maximum stress. This same deviation has been noted in several completely independent tests. Apparently the variation is caused by secondary effects which are disregarded in the computations.

(5) *Empirical determination of retention flexibility constant.* Computation of propeller blade stresses before accurate data pertaining to blade retention is known, will require employment of some empirical relationship to determine retention flexibility. Good design indicates fixed relation (approximately) between retention flexibility and blade flexibility. A retention flexibility constant K can be determined from the following empirical relation:

$$K=\frac{8.2\times10^{-6}}{D}$$

in which:

D= blade shank diameter (inches).

This relationship was derived from a known retention flexibility and was based upon an assumption that the retention rigidity will vary as the cube of blade shank diameter. Hollow steel blade shanks have approximately the same wall thickness regardless of shank diameter. Hence, the moment of inertia of the shank is very nearly proportional to the cube of the diameter.

(6) *Selection of blade angle station for determining the plane of bending.* The selection of a blade angle, at the station $\frac{r}{R}=0.5$, to be used in determining the plane of bending, is arbitrary. The total twist in some blades may be as high as 45 degrees. The maximum stress in conventional blades is generally near the blade station, $\frac{r}{R}=0.4$. The difference in resolving the loads into a plane normal to the station at $\frac{r}{R}=0.4$ or $\frac{r}{R}=0.5$ will not be appreciable, since angular difference is small. The plane normal to the chord of station $\frac{r}{R}=0.5$, is more representative of a three dimensional deflection curve and will give a better approximation of the loading associated with deflection relative to the plane of rotation.

(7) *Restriction of Method.* This method of analysis is applicable only to relatively stiff blades, such as those currently being used on subsonic propellers, that possess natural $1\times P$ frequencies which are outside of the normal range of operating speeds. When applied to high speed, thinner propeller blades, this method

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of analysis produces results that are divergent and, consequently, reliable indications of stresses cannot be obtained.

Blade Retention and Shank Fairing Design

Requirements of Blade Retention Systems

(1) *Basic considerations*. For obvious reasons, emphasis has been placed upon consideration of the aerodynamic portion of a propeller blade. However, in addition to blade form and structure, an adequate method of attaching the blade to the hub must be devised. The method of attachment of blade to hub has been identified and designated *blade retention*. The term, *blade retention*, has been shortened to *retention* by common usage. Since large forces are transmitted from blade to hub, the retention system design must incorporate a hub structure adequate for heavy loads as well as functional requirements. Production of acceptable propeller hubs requires workmanship of extremely high calibre. Dimensional tolerances must be held to low values and proper allowance for dimensional changes under stress conditions must be included in design, fabrication and assembly of propeller blade and hub.

Sources of stress concentration, such as sharp corners and tool marks in heavily loaded regions of the retention system, must be avoided by use of large radii fillets and close tolerance grinding. Shot peening or rolling may be used to increase fatigue strength.

(2) *Specific requirements*. An adequate propeller blade retention system must encompass either wholly, or in part depending upon particular applications, the following characteristics:

- (*a*) Blade must be free to turn in the hub, about the blade centerline for pitch changing requirements.
- (*b*) Provision must be made for torque application to the propeller blade to change pitch while blade is retained in the hub.
- (*c*) Angular positioning of the blade about the axis of rotation in the hub barrel must be adjustable in small increments relative to some fixed position of adjacent parts of the pitch control mechanism.
- (*d*) Design for incremental pitch change of the propeller while in flight.
- (*e*) Ease of servicing with minimum number of special tools.
- (*f*) Provision for adequate lubrication of all bearing surfaces.

Typical Blade Retention Systems

In a controllable pitch propeller, the portion of the blade involved in the retention system is also a part of the pitch-changing mechanism. To meet these requirements, the blade shank must be cylindrical and supported in some form of anti-friction bearings. Indicative of the extreme loading conditions involved, larger propeller blade retention systems are often subjected to loads of 25 to 100 tons in addition to large bending moments.

One retention system for controllable pitch propeller blades, employs a stack of ball bearings (two to five in number, usually) so placed that, theoretically, each ball bearing takes an equal proportion of the total load. By *race* contact, each ball bearing transmits the load it carries to a mating part of the hub along a centerline which makes an angle of 45 degrees, approximately, with the blade shank axis. The ball size must be adequate for high bearing loads, yet require minimum space consistent with functional characteristics. Resistance to race *Brinelling* must be incorporated. This type of retention is illustrated in figure 3.48.

In addition to illustration of the use of ball bearings in blade retention, the photograph shows the gear sector attachment to blade shank for pitch changing. A flange may be formed on the shank end as an integral part of the blade, if split inner race bearings are used, or if the inner bearing races are placed on the shank before upsetting. The shank may be threaded to receive a member with a proper flange in lieu of the integrally formed upset shank. Recent developments employ ground, hardened races formed integrally on shank and hub with special passages for ball insertion.

Inner ball bearing races formed on the blade shank must be ground to a close tolerance. The race requirements demand very high carbon steel suitable for induction hardening, as a shank material. Since reworking of blade shank races is impractical, races must be formed of material with surface characteristics to insure that the races will outlive the blade. These requirements have been met in current designs that have withstood thousands of hours of service. This development is an outstanding illustration

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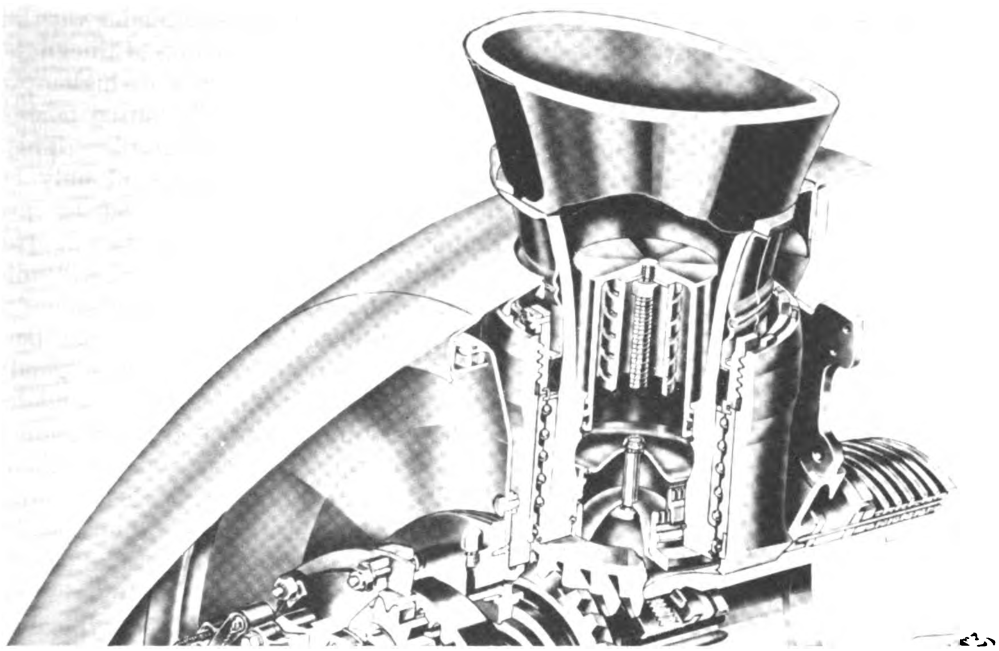

Figure 3.48.—Ball bearing retention system.

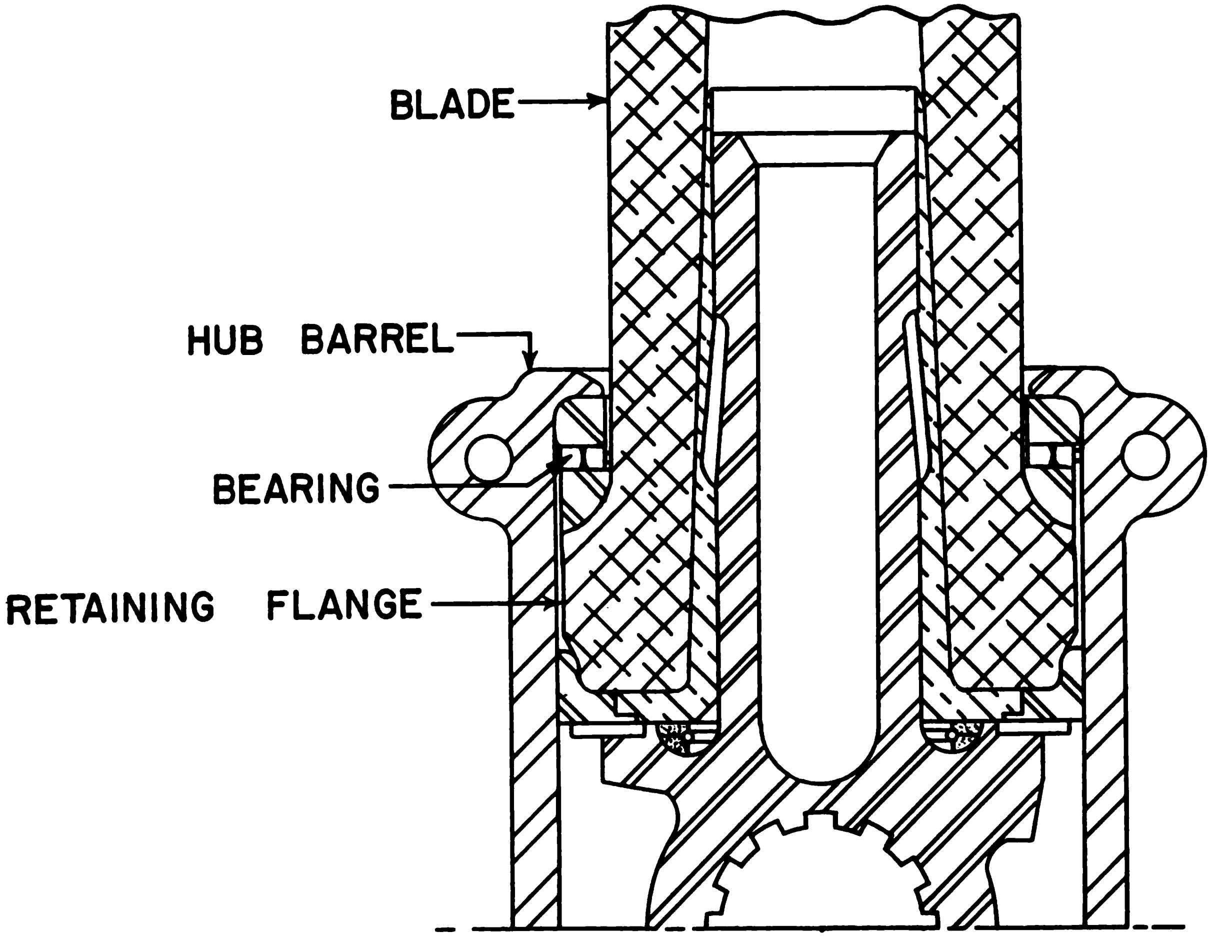

Figure 3.49.—Roller bearing retention system.

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of propeller development aimed at weight reduction.

Another system of retention employs a roller bearing to carry the centrifugal load and a portion of the bending moment. The balance of the bending moment is carried by a spider arm inserted into the blade shank as illustrated in figure 3.49.

Both ball and roller bearing retentions require accurately machined bearing surfaces.

Pitch Angle Control

Angular positioning of the propeller blade about the blade axis of rotation may be accomplished by means of mating splines milled or cut into blade shank, transfer ring (interposed between blade shank and pitch control turning spline) and pitch control turning spline. The splines on the blade shank are short length, usually cut into the inner surface of the blade shank in sufficient numbers to limit each spline to a portion of the shank circle equivalent to a small number of degrees.

If a propeller blade pitch is to be controlled by use of a blade end gear, driving mating splines on the blade directly, the smallest angular adjustment of the blade relative to the gear is the degree equivalent of the pitch of one spline. However, a transfer ring splined both internally and externally may be inserted so that the drive gear meshes on one side of the transfer ring while the propeller blade gear sector meshes with the other side of the transfer ring. In this case, pitches of the internal and external splines may be designed so that angular displacement of both gear and blade relative to the transfer ring will produce very small angular movement of the blade relative to the gear. This type of pitch angle control utilizes differential splines.

Other special shank end details may be required to accommodate pitch control mechanisms designed for particular hub-blade applications.

Propeller Shank Fairing

The section of a propeller blade from the inner shank end at point of juncture with hub to the point where desired airfoil section has been achieved is designated shank fairing. This section must be given utmost attention in development of a propeller blade because it is the portion of the blade in which aerodynamic and structural requirements are in greatest conflict. The tendency in propeller blade development is toward the use of wider blades with reduced thickness ratios. Reduction of thickness ratios are particularly important since higher propeller tip speeds require that the faired portion of a blade be clean aerodynamically. This additional aerodynamic requirement only adds to the difficulty of the shank fairing problem. Emphasis must be placed on the importance of using those shank fairings which will not result in intolerable stress concentrations.

The inner end of a blade must be round while the outer portion must have good airfoil shape. It is desirable to achieve a blade cross-section having optimum airfoil section at the smallest practical radius, which would require abrupt fairing and very sharp contouring. However, structural considerations prevent this construction. Steady blade loading is accumulative from blade tip to the shank. The fundamental vibratory loads are typical bending moment loads which increase from tip to shank. Consequently, maximum loads, which are composed of combination of vibratory and steady loads, must be transferred through the faired portion of the blade. Such a transition region is one in which many well-known and desirable features, representing stress concentrations of no small magnitude, could be incorporated. Sharp corners resulting from abrupt fairing and fabrication processes which result in lower strength than that of the basic blade material must be avoided.

The conception of smooth flow lines for blade to shank transition must be recognized as a law to follow. Many blade failures have resulted from yielding to the temptation to employ high fairing angles with resultant sharp corners. Contouring of present-day successful blades just about represents the ultimate limit and may be considered as a guide to permissible limits of abruptness in section transition. Susceptibility of the faired shank region to stress concentration is shown by the general shape of the radial steady stress curve of a blade in figure 3.29. Maximum stress occurs at a point located at 45 percent of blade radius very nearly. Further, the stress is much below the maximum value at that blade station where fairing approaches a round section; this stress reduction can be controlled by proper design. Yet, this faired region of the blade is one in which many failures have been encountered, necessitating redesign,

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usually. Susceptibility to failure must be due to stress concentration factors.

Generally, fatigue strength is the controlling factor for all parts of a propeller blade. If adequate fatigue strength is incorporated (i. e., vibratory stresses are below maximum allowable stresses) a satisfactory margin of safety prevails usually to accommodate steady stress loading. Of course, combined steady and vibratory stresses establish final strength requirements of a blade and use of either one alone would not represent actual blade loading conditions.

External dimensioning of solid blades can be examined visually and locations of excessive stress concentration established. Existence of unsatisfactory or marginal conditions can be recognized readily, but internal conditions of hollow blades become major design problems not so easily observed. Manufacturing variations from a desired internal blade form must be given careful attention during blade development. In particular, juncture of component parts of hollow blades in the critical faired sections must be carefully controlled. Smooth internal fairing is as important as proper external fairing.

Fatigue Phenomena in Propellers

General Characteristics and Causes of Propeller Fatigue

The combination of repeated and steady stresses, normally encountered in service and resulting in fatigue of some component, causes the most common type of propeller structural failure. Consequently, fatigue considerations constitute a major portion of evaluation of a propeller from a structural standpoint.

Fatigue failure of a propeller component will occur whenever operating stresses in the component produce a combined stress loading (vibratory or repeated stresses plus steady stresses) which is greater than the loading which component material with its existing surface condition, internal defects, etc., is able to withstand. Determination of the causes of fatigue failures can be resolved into two general phases:

(1) Determination of propeller loading and stresses for comparison with stress limits of component material.

(2) Evaluation of effects of corrosion, tool marks, sharp cuts or gouges, erosion and friction oxidation upon load-carrying capacity of the structure.

Excessive propeller loads can be introduced by any one or a combination of the following conditions:

(*a*) Abnormally rough operating engines (producing large vibration excitations which may be transmitted to the propeller).

(*b*) Unfavorable angles of air inflow to the propeller, which result in high cyclic aerodynamic loads on the propeller.

(*c*) Insufficient clearance between blade tip and fuselage or between adjacent propeller discs of rotation.

(*d*) Engine overspeeding.

(*e*) Unequal air flow distribution through propeller disc, which occurs in pusher type aircraft.

(*f*) Propeller operating speed at or near structural resonant frequency.

Fatigue studies of propeller structures can be divided into two general categories:

(*i*) Developmental research to arrive at satisfactory propeller designs.

(*ii*) Fatigue studies on specific propeller designs to establish safe operating stress limits for service usage of the propeller.

Influence of Material Properties Upon Fatigue

(1) *Material properties required for propeller use.* Properties of the materials used in propeller construction greatly affect fatigue properties of a propeller in service. Material properties which are important in determining fatigue strength of a propeller include:

(*a*) Fatigue limits for various types of repeated loading.

(*b*) Notch sensitivity.

(*c*) Resistance to mechanical abrasion.

(*d*) Resistance to attacks of corrosive chemical agents.

(*e*) Toughness, ductility and heat treatment required for industrial production of blades.

In propeller design, ultimate static strength is not a primary consideration in selecting materials. A much more important material property is capacity to withstand vibratory or repeated stresses in combination with steady stresses that are expected in service. Propeller materials should have a low variability or scatter of endurance limit under repeated stress loads. From a strength standpoint, therefore, a good propeller material has high fatigue

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strength reliability for large quantities of material, plus resistance to mechanical abrasion and chemical attacks.

(2) *Blade protective coatings.* Detrimental effects of chemical attacks can be mitigated or eliminated in some cases, by the use of protective coatings on the propeller. Reliance upon such protection may be dangerous because subsequent mechanical erosion may partially remove the protective coating. However, coatings used to give galvanic protection, such as zinc plating, are effective in protecting the blade material even though microscopic areas of the plating are missing. Good maintenance is necessary to insure continuous protection.

In general, protective coatings are ineffective for increasing resistance to mechanical abrasion, particularly if the abrading particles are relatively hard, sharp and large. Resistance to mechanical abrasion must be considered in relation to the notch sensitivity. A material which is easily eroded may be less sensitive to erosion damage so that usable fatigue strength actually may be equal to or higher than that of a material with greater resistance to erosion but more notch sensitive. For instance, polished X76ST aluminum alloy has a nominal endurance limit (for 10^9 cycles) of 16,000 p. s. i.. while polished 25ST has a limit of 13,500 p. s. i. However, under severe conditions of mechanical erosion, 25ST alloy (the softer alloy) appears to be more severely damaged but actually both alloys exhibit about the same endurance limit (approximately 4,000 p. s. i.) when tested in fatigue.

Influence of Steady Stresses Upon Fatigue

The steady stresses which exist in a propeller blade under operating conditions will influence the magnitude of repeated stress loadings that the structure can withstand. Large steady tensile stresses in a given section reduce capacity to absorb vibratory stress. Therefore, distribution of steady stresses in a blade or hub must be considered in relationship to expected vibratory stress distributions for a propeller blade or component. Steady stresses or pre-stresses may be caused by dynamic operating conditions (such as centrifugal loading) or some phase of heat treating or manufacturing operations. It is common practice in testing propeller structures, under operating conditions or simulated operating conditions, to measure only the vibratory stresses existing in various sections of the structure with steady stresses being obtained by calculation. Hence, actual observed fatigue strength may differ somewhat from the expected stress level because of the difference between calculated steady stress and actual stress existing in the structure.

Effect of Surface Finishes and Treatments Upon Fatigue

Since propeller parts and in particular propeller blades are primarily fatigue specimens when considered from a structural viewpoint, it is highly important that smooth finishes be obtained. Also, great care must be exercised to insure that workmen do not make punch marks, indexing marks or otherwise scar working surfaces.

In general, cold-working of material surfaces, to induce a layer of compressive prestress, has been found to be quite beneficial in improving fatigue strength. Methods of cold-working generally used are rolling, shot peening, and local hand peening. Rolling is particularly well adapted to cold-working those regions having circular cross-sections, but is not suitable for cold-working outboard sections of a propeller blade. A practical solution to the problem of cold-working propeller blades consists of rolling the heavy circular inboard sections and shot peening the outboard portions of the blade with an overlap of the two methods of surface treatment. Any proposed cold-working treatment must be evaluated by actual fatigue testing.

Cold rolling has been found to be a particularly effective method of working aluminum blade shanks. Laboratory fatigue tests have indicated that cold rolling of X76ST blade shanks has increased fatigue strength of polished shanks from 4,000 p. s. i. to 10,000 p. s. i. This increase in fatigue strength is significant, particularly, since the inboard shank sections are not likely to encounter mechanical erosion severe enough to affect fatigue strength.

Effect of Service Erosion and Friction Oxidation Upon Propeller Structures

(1) *Mechanical erosion damage.* One of the most common types of damage to which propeller blades are subjected during service is mechanical surface damage, which results from impact of the blade with stones, cinders, dust or rain. This surface damage involves both a

local stress raiser effect and a certain amount of plastic flow of metal which has been called *bruise effect*. It has been found very difficult to measure erosion damage quantitatively. Consequently, it is almost impossible to simulate closely this type of damage for laboratory testing of fatigue specimens.

Aluminum alloy and wooden blades are most subject to mechanical erosion damage. It is a common practice to reduce erosion effect on wood blades by armoring the blades with metal, especially on the leading edges. Shot-peening has been found to be most effective in mitigating the effect of surface damage to aluminum alloy blades, particularly X76ST alloy. However, prior shot-blasting does not remove the detrimental effects of severe bruises which subsequently have caused appreciable plastic flow of a shot-blasted surface.

(2) *Repair of eroded blades.* Laboratory test data of the effectiveness of prior surface treatment in mitigating effects of erosion of aluminum alloy blades has been obtained under simulated service erosion conditions by blasting the blade with granulated quartz particles fired from a shotgun. This method of inducing erosion for laboratory testing was found to be useful in arriving at a relative evaluation of various methods of prior surface treatment and subsequent repair treatment of damaged aluminum alloy blades. Some laboratory tests have indicated that re-shot-blasting of blades, previously shot-peened and then damaged by erosion, has no appreciable effect on blade strength. The type of erosion studied did not appreciably lower the strength of shot-blasted material (X76ST) and consequently repair treatment could not be judged to be ineffective. Subsequent tests have indicated that treatment of severe bruises may be accomplished by clean-up, followed by local hammer peening.

(3) *Cold bending damage to propeller blades.* Another type of damage sometimes encountered by blades in service is cold-bending. Not much is known quantitatively about the effect of this type of damage, but preliminary testing has indicated that annealing and straightening followed by heat-treating and shot-blasting is a satisfactory repair procedure for aluminum alloy blades.

(4) *Friction oxidation damage—Repair procedures.* Friction oxidation has been encountered frequently in bearing stacks used in blade retention assemblies. Surface damage due to friction oxidation may be encountered also in other parts of a propeller assembly in which mating surfaces under high normal loads have small relative motion. Friction oxidation is particularly damaging if allowed to progress over extended periods of running time. Shot-peening and cold-rolling of damaged surfaces have been found to be effective in repairing damage caused by friction oxidation.

Effect of Fabrication Upon Fatigue Strength

The method of joining component parts to form a completed propeller or subunit must be such that overall strength is not impaired. It is particularly important to consider variability of overall strength resulting from manufacturing processes used in any given fabrication. For instance, a certain welding process may exhibit an average strength comparable to the strength of the parent metal when just a few samples are tested in fatigue but test of a larger sample might indicate a definite probability of failure at a very low stress level. In another process, a lower overall average fatigue strength may be indicated by a limited number of tests of a joint but at the same time lower variability is shown. Hence, in this comparison of two types of welded joints, if failures are not to be tolerated and considering production quantities, fatigue strength of the second type must be considered higher than that of the first type joint (high average strength with high variability). The stress curves illustrated in figure 3.50 portray the effects of variability of two types of welding processes.

In considering selection of one of the two types of joints shown in figure 3.50, if the possibility of stress level falling below 30,000 lb. must be held to a half of one percent, or less, of the total number of joints, it is evident that a *Type B* joint must be specified.

Methods of fabrication used may dictate that certain equivalent notches be introduced into a stress analysis of propeller component structures. A simple, well-formed solid metal blade may have stress endurance limits close to those of the metal itself, while a blade of intricate structure must have an equivalent notch factor introduced to compensate for stress concentration produced by the complicated configuration with its attendant ribs, holes, fillets, and localized attachments. These features contrib-

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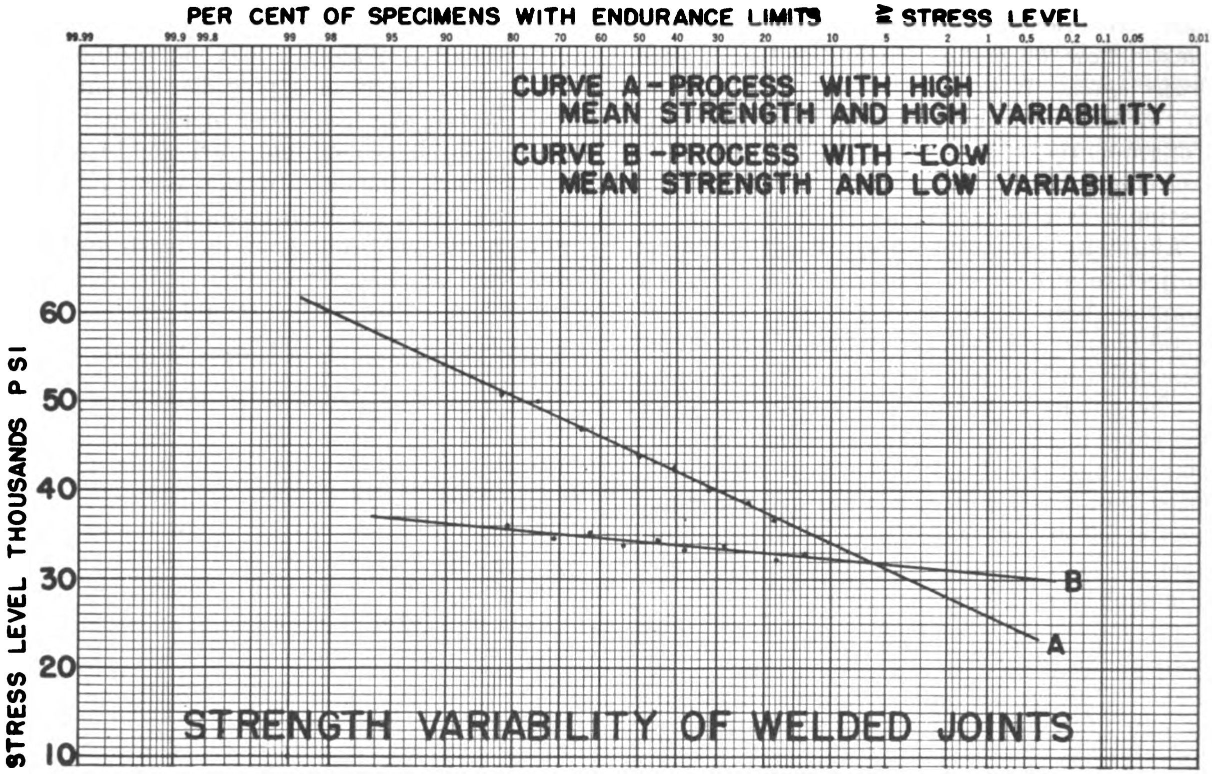

Figure 3.50.

ute heavily to lowering the allowable stress limit below that of the basic material used. It has been found that even small details of construction play a very prominent role in determining the strength of a finished hollow blade, probably because hollow blades are so much more intricate. For instance, in a fabrication process employing a brazed joint, fillets must be properly designed in order to achieve a usable blade strength under the repetitive loads encountered in normal service. The effect of holes in a blade structure, which are proposed to facilitate accomplishment of certain functions, upon fatigue strength of the finished blade structure must be carefully evaluated. Sometimes, such structural details may not reduce fatigue strength directly, but may produce galvanic action, friction oxidation or other effects which lower fatigue strength, materially.

Allowable Stress Limits vs. Quality of Inspection—Influence Upon Fatigue

(1) *Fatigue stress limits.* In defining fatigue strength of propeller blades or components, it is common practice to divide the component parts into sections and to specify allowable stress limits for those sections. For example, a propeller blade is divided, normally, into three sections designated shank, mid-blade, and tip sections. The repeated stress limits specified for blade section would be the highest repeated stress loading that could be allowed at some stress reference point in the given section, before failure would occur at any point in the section. A stress reference point is an accessible point at which a representative stress can be measured. A failing stress level at some point in a blade section other than the stress reference point may be reflected as a low allowable stress level when measured at the stress reference point.

(2) *Effect of quality control upon fatigue stress limits.* Inspection is relied upon to eliminate faulty blades having unacceptable fatigue strengths. Quality of inspection strongly influences the allowable strength limits which must be established for propeller blades or other propeller components. A blade structure possessing considerable strength variability that is not easily inspected can introduce considerable variation of the section stress limit when observed at the stress reference location. Internal welds, partial cavities, fillets and plating are typical details of construction which make

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proper inspection difficult or impossible. On planning methods of blade fabrication, it is very important that proper consideration be given to methods and order of fabrication of the propeller structure so that careful inspection may be accomplished readily.

(3) *Inspection methods.* Nondestructive methods of inspection in common usage include simple visual, magnaflux, x-ray, boroscopes, anodizing, caustic etching, fluorescent and dye penetrants methods. Of these inspection methods, all but x-ray and supersonic reflectoscope are primarily limited to detection of surface defects or microscopic cracks. In considering specification of inspection methods, it should be remembered that gouges and scratches on blade surfaces which would be unmeasurable in terms of change in overall section modulus, may have sufficient localized effect in conjunction with peaking internal stresses in adjacent fibers to cause serious reduction of fatigue strength. For instance, a hollow steel blade failure has been traced to a stone bruise measuring hardly .010 in. in depth. X-rays have been found to be most useful for detecting internal flaws or discontinuities.

It is common practice for propeller manufacturers to sample production at frequent intervals and to conduct such destructive fatigue testing as necessary to insure quality of production. This method of quality control is very important especially where changes in method of fabrication or heat treatment are involved.

Quality vs. Economics in Propeller Design

Structurally, the final propeller design must be a compromise of such factors as aerodynamic performance, weight, production feasibility, maintenance requirements, safety and cost. Aerodynamic performance with minimum weight and extremely low probability of failure are prime objectives in all propeller design. Selection of three prime objectives is not to be construed as an indication that cost of production and maintenance is of no consequence. Rather, these prime objectives must be attained at the lowest possible cost.

The combination of variation in manufacturing processes, insufficient or incomplete propeller structural inspection, improper maintenance and non-homogeneity of the material, insures that a definite probability of propeller failure will be ever present. That this possibility of failure must exist is chargeable directly to the requirement for weight reduction along with the incompatibility of weight reduction and increased strength for any given material, but every effort must be made to surmount this obstacle.

Fatigue Strength Evaluation of Propellers

(1) *Test data.* Whereas the primary purpose of fatigue research is to produce a blade design which will be safe in service, fatigue testing is to establish allowable endurance stress limits of specific propeller designs for service condition operation. The usual method of establishing such limits involves use of data obtained from propeller endurance tests (engine mounted) or data from laboratory fatigue tests of full scale propeller components. Engine testing of propellers approaches simulation of conditions under which stress distribution in the propeller will be obtained in service. Therefore, engine propeller testing will give proper relative loading of various parts of the structure. Full scale propeller components which are commonly tested in a fatigue laboratory are hubs, blades, spinners and other smaller units. Fatigue machines have been developed to produce high static and cyclic loading on barrels. Full scale propeller blades have been tested in bending as free-free beams (i. e. with unrestrained tip and shank root), or as cantilever beams with fixed root.

(2) *Modified Goodman diagram for a propeller blade.* Usually there is considerable difference between the stress endurance limit of a full scale component obtained in a fatigue laboratory and the limit obtained under more closely simulated service conditions (i. e., engine testing). A commonly used method of predicting allowable stress limit for a blade is to use a modified Goodman diagram, as shown in figure 3.51.

For illustrative purposes, the diagram of the basic material (steel in this case) is shown in the same figure. The diagram is for the blade shank. For either basic material or blade, the failure region (i. e. region of the diagram for which all load combinations in the region will cause failure) is above the respective failure line and included between the two stress axes.

Note that the vibratory stress endurance limit of the finished blade is considerably

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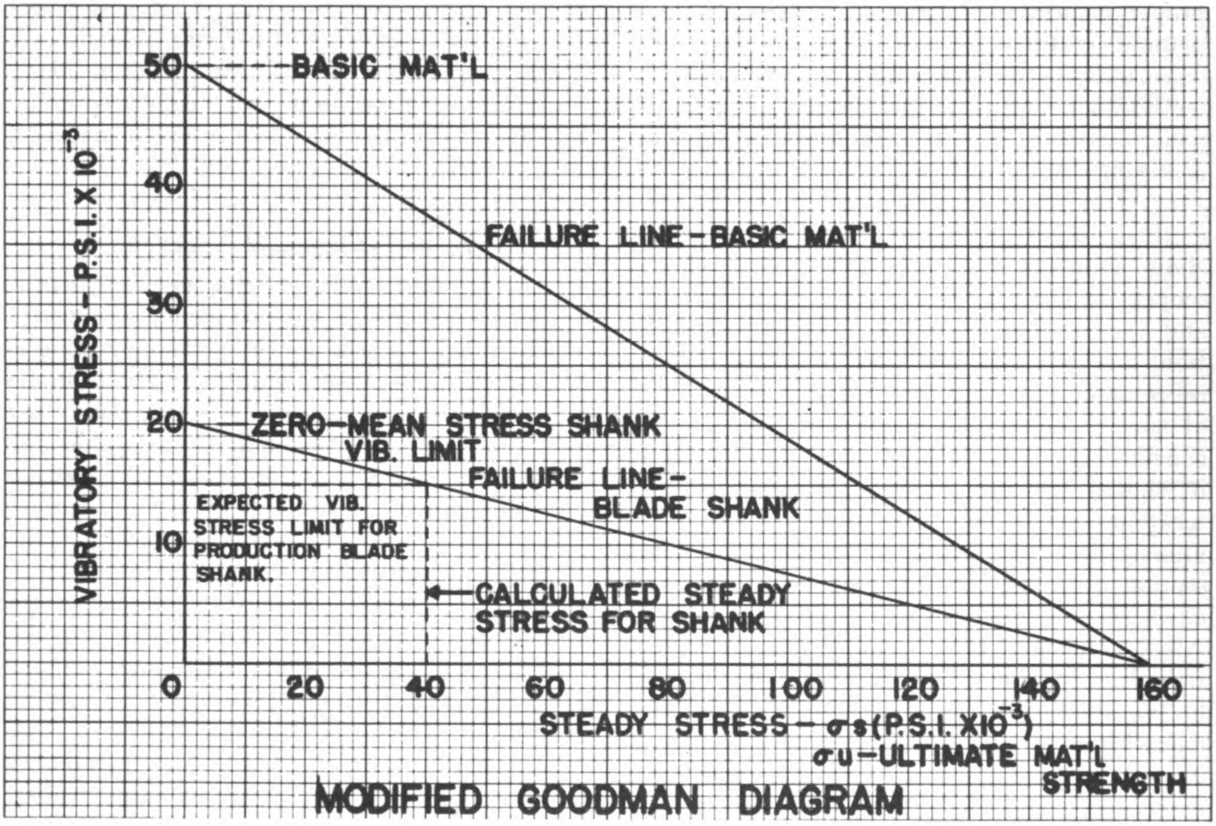

Figure 3.51.

lower than that of the basic material. The finished blade notch effects, fabrication variables, internal stresses, surface condition, statistical effect of size and amount of material in blade as compared to small fatigue specimens, are all reflected in a lower measured strength,in terms of stresses measured at some convenient reference location such as shank or blade centerline.

Of course, the operating stress levels allowed in service must be still lower than the expected strength of a blade or component just off the production line, because of detrimental effects of corrosion, erosion, and bruising encountered in service. No correction has been applied to the ultimate strength of the basic material to establish the full-scale blade diagram. Experimental justification for this procedure is given in University of Illinois Engineering Experiment Station Bulletin No. 26, dated 17 February 1952, *The Effect of Range of Stress on the Fatigue Strength of Metals*, by J. O. Smith. The vibratory stress limit with calculated steady stress included might be set at about 10,000 p. s. i. for the example illustrated in the diagram.

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CHAPTER IV. PROPELLER CONSTRUCTION

Wood Propellers

Advantages and Limitations of Wood

The first airplanes built were equipped with wood propellers. Wood propellers were selected because that material was readily obtainable, light in weight, and could be shaped readily with tools that were universally obtainable. Continued use of wood propellers in light, inexpensive airplanes is due to these factors along with relative cheapness. Development of metal propellers was encouraged by limitations of wood as a propeller material. These limitations are: inherent lack of moisture stability which is influenced by atmospheric humidity changes, low strength, lack of abrasion resistance, splitting tendency and lack of homogeneity and uniformity in physical properties. Scarcity of good propeller wood is also a limitation to wartime production of wood propellers.

Species of Wood Used for Propellers

Formerly both walnut and mahogany were used extensively for propellers. More recently, as a result of imposition of higher blade loadings, fixed pitch wood propellers have been made almost exclusively from sweet and yellow birch; or in a few cases, hard maple and white oak have been used as alternatives. Many species of wood, such as hickory, elm, black cherry and beech have been tried for propeller construction suitability. However, from a strength-weight-toughness consideration, birch is the most desirable wood. Physical properties of various species of wood may be obtained from Forest Products Laboratory Technical Bulletin No. 479.

Lumber Specifications for Propellers

The quality of lumber to be used in propeller construction is given in Specification No. MIL-L-6061. Certain defects such as shakes, checks, rot and knots, are unacceptable in wood to be used for propellers. The paragraph on "Defects and Blemishes" of ANC-19 gives a complete description of wood defects and distinguishing characteristics. Fixed pitch or single piece propellers are usually made from wood blanks that are made by gluing boards that range from ½ to 1 inch in thickness. The quality specifications concern this type of construction principally.

Wood Veneer Propellers

A more recent development is the use of wood propeller blanks made by gluing sheets or layers of wood veneer together. In principle, there is no difference between veneer and boards, except in thickness. Usually, any lumber ⅛ inch or less in thickness is regarded as veneer. The thickness of veneer most commonly employed in propellers is 1/28 inch, although other thicknesses have been used. Veneer may be sawed, sliced or rotary cut, with the latter type being employed almost exclusively. In general, the same qualities are desirable to selection of wood veneer as for lumber selection, except that not quite as much emphasis need be placed on grain straightness. A thorough discussion of defects and blemishes in wood veneer is given in a section of ANC-19. Specification MIL-P-5444 lists allowable defects permitted in veneer intended for use in propeller blades. The advantage of using laminated veneer for propeller blades is that greater uniformity of mechanical properties can be obtained and dimensional stability will be increased.

Compreg Propeller Blades

Compreg is a term applied to resin-impregnated and compressed wood. It was used extensively for propeller blades at one time but its use has been discontinued. The improvement that could be obtained by use of compreg instead of natural wood does not justify the much higher cost involved. A description of the process used for making this material is contained in ANC-19; also, some advantages and disadvantages of compreg as a propeller material are outlined. The most important advantages accruing from use of compreg as

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propeller blade material are increase in dimensional stability and compressive strength. It may be noted that compreg has been used only for detachable blades.

Kiln Drying of Propeller Lumber

The first step in preparation of lumber for propeller use, as it comes from the mill, is kiln drying. This treatment is necessary in order to lower the moisture content to an acceptable value, i. e., between 5 and 7 percent. Specification MIL–W–6109 and ANC–19 outline and describe in detail, kiln drying of lumber. Kiln drying of veneer is unnecessary because the material is thin enough that excess moisture can be evaporated in an ordinary drying room without adversely affecting the veneer. Ordinarily, veneer should be dried to about 3 percent moisture content. Low moisture content (5 to 7 percent for lumber and 3 percent for veneer) has been a propeller wood requirement to provide for an increase in moisture content of propeller blades in service, which is less harmful than a decrease in moisture content. In the eastern part of the United States, wood will eventually stabilize with 12 percent moisture, approximately. In the southwest, wood will stabilize at a point within a range of 4 to 5 percent moisture. Most glues add moisture to the wood at the time of application. There are so many glue lines in a laminated veneer block that it is necessary to keep the initial moisture content of veneer much lower than that of lumber for blade blanks.

Wood Propellers—Blade Design

Certain critical material factors must be taken into consideration in design of wood propellers. Wood, characteristically, has a shear strength approximately one-tenth of its ultimate tensile strength. This large tensile-to-shear strength ratio makes it extremely difficult to take full advantage of the tensile strength of wood. For instance, in certain designs of fixed pitch wood propellers, cases have been found in which all of the through fibers were cut off either by a large hub bore or by bolt holes. A number of these propellers failed in flight because the remaining wood could not withstand applied shearing loads. An example of this type of failure of a wooden propeller is shown in figure 4.1.

Compressive strength of wood is low, also, as compared to tensile strength. Strength data given in charts such as those of the Forest Products Laboratory Technical Bulletin No. 479 represent average strength of a great many selected pieces. Allowance must be made for some defects and for strength variation of samples of a given species. Wood strength varies almost directly with specific gravity which, for yellow birch, has been found to range from .58 to .76.

Wood Propeller Blade Retention

Because of the low compressive and shear strength of wood, it has been difficult to retain blades in ferrules. Also, lack of dimensional stability has been a contributing factor to the difficulty of blade retention. Some of the earlier detachable wood blades employed a compreg shank scarfed on a natural wood blade, with the shank end threaded to receive a ferrule. The compreg section increased compressive strength and dimensional stability, which eliminated some of the difficulty of wood blade retention. However, the low shear strength was not improved materially in this construction and

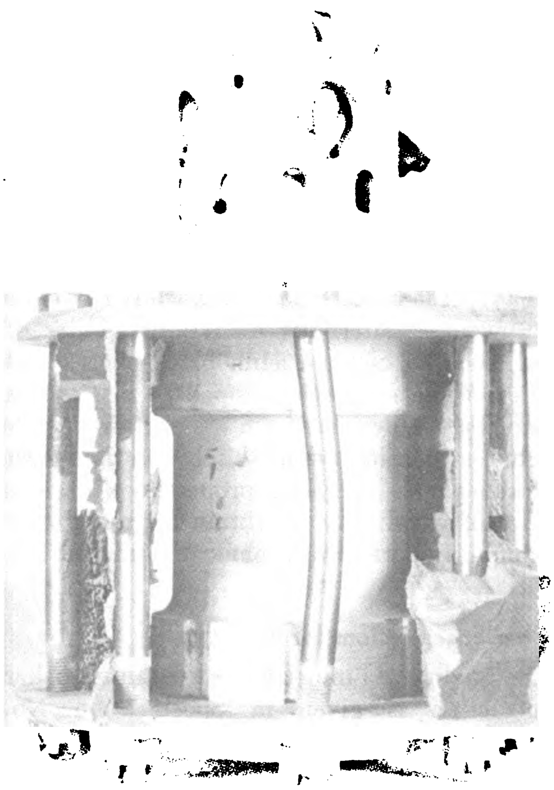

Figure 4.1.—Wood blade retention failure.

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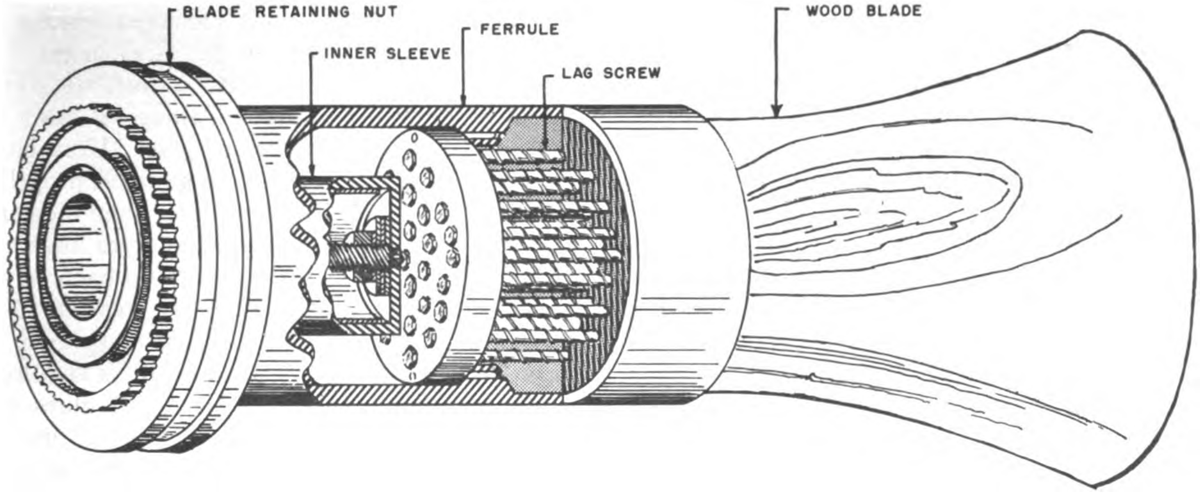

Figure 4.2.—Wood blade retention lag screw type.

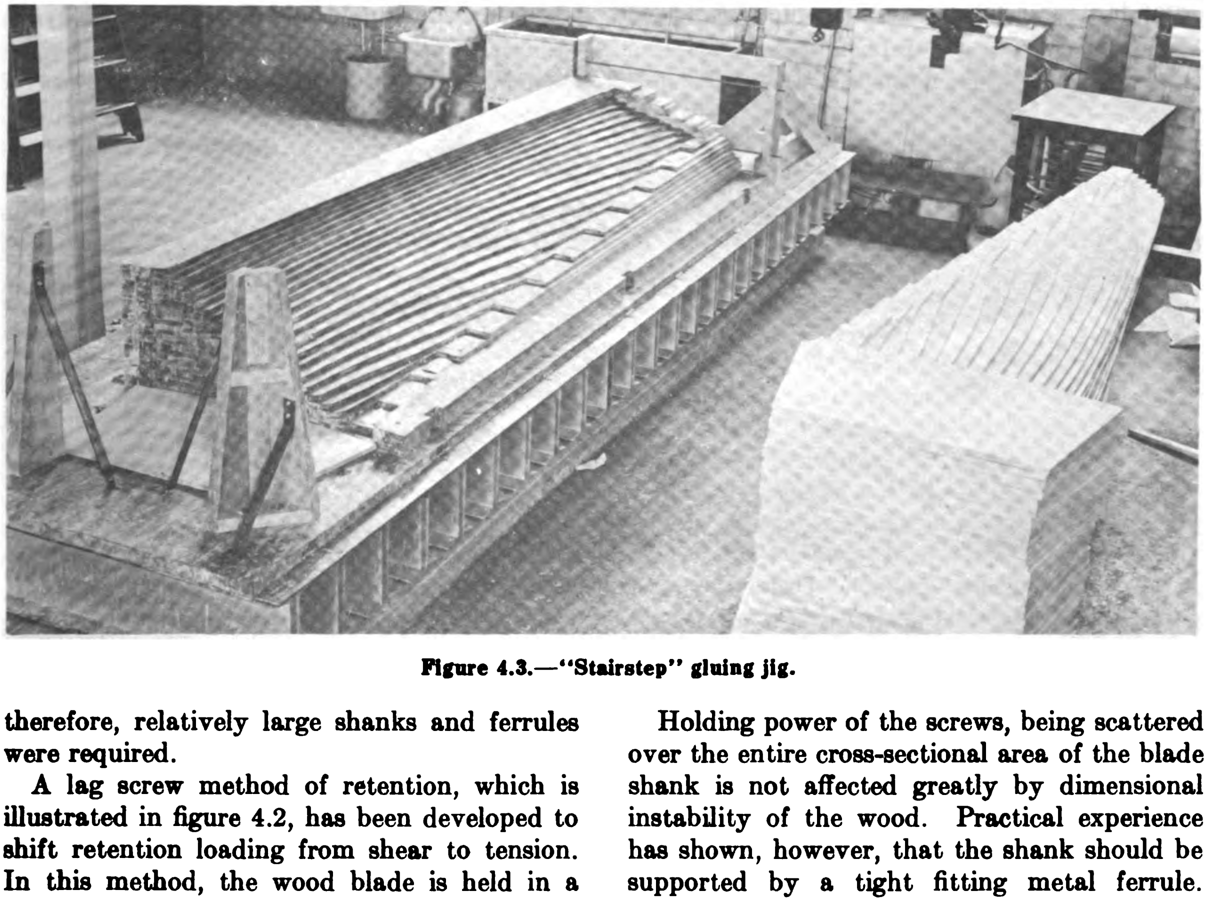

Figure 4.3.—"Stairstep" gluing jig.

therefore, relatively large shanks and ferrules were required.

A lag screw method of retention, which is illustrated in figure 4.2, has been developed to shift retention loading from shear to tension. In this method, the wood blade is held in a ferrule by a multiplicity of lag screws. Theoretically, each wood fiber could be gripped by a screw and thereby attached to the hub. Full advantage could be taken of the high tensile strength of wood, in this type retention. From a practical consideration, the number of screws must be limited to a number considerably less than one per fiber.

Holding power of the screws, being scattered over the entire cross-sectional area of the blade shank is not affected greatly by dimensional instability of the wood. Practical experience has shown, however, that the shank should be supported by a tight fitting metal ferrule. This type of retention has been used principally with blades made of laminated veneer. Specific design criteria may be found in Specification MIL–P–5444.

Machining Wood for Propeller Blades

Propeller blade lumber should be kiln-dried as received, rough sawn. The boards must be

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planed to final thickness, with edges jointed just prior to gluing. If a stairstep type gluing jig is to be used, board thickness must be held to a very close tolerance. This type of jig is illustrated in figure 4.3.

Planer knives must be kept sharp and the machine maintained in good working order to reduce additional labor or grooving, serrating, or sanding. Narrow boards may be edge-glued together before planing to final thickness. Veneer sheets need no further processing; however, tightness and smoothness of cut are mandatory. Thin veneers, being tighter cut, should be specified for propeller blades, usually.

Glue Requirements for Forming Wooden Blades

For many years, hide or hot glue was the standard glue for use in construction of wood propellers. Usually, this glue was lacking in moisture and fungi resistance. Casein glue has been used to a certain extent, but being susceptible to water and fungi damage, it has been displaced by other types of glue. Urea glues have been tested extensively as wood propeller adhesives but even though better than hide and casein glues, open glue joint troubles have not been eliminated. Resorcinol glues conforming to Specification MIL–A–397 have proven to be satisfactory. Since phenolic glues are thermosetting, special heating equipment is required, whereas both urea and MIL–A–397 glues will set at room temperature. However, use of urea and MIL–A–397 glue for setting at temperatures less than 70° F. is not recommended. In all cases, the manufacturer's glue-use specification should be followed.

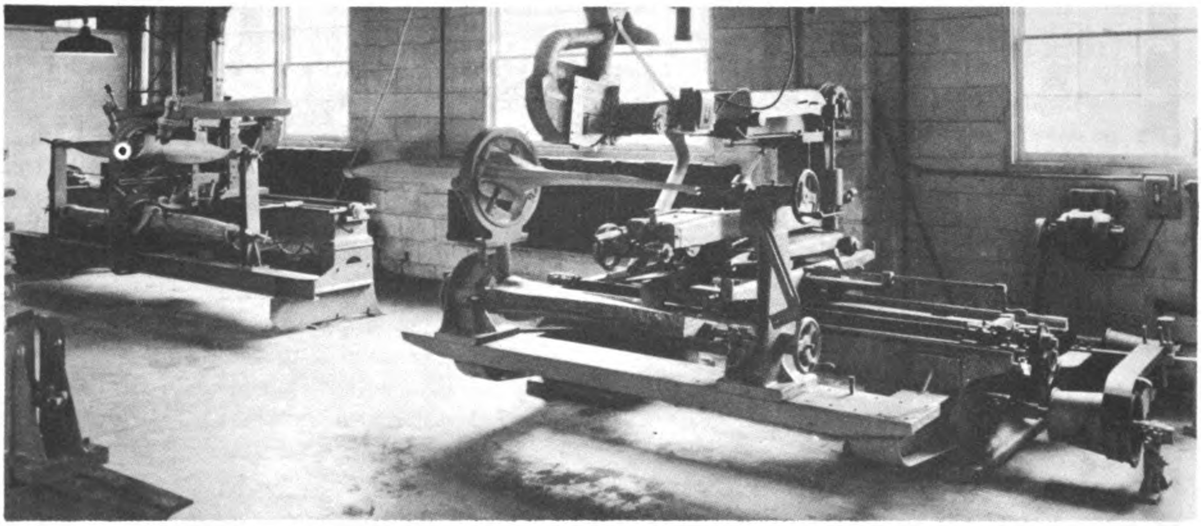

Figure 4.4.—Wood blade carving machines.

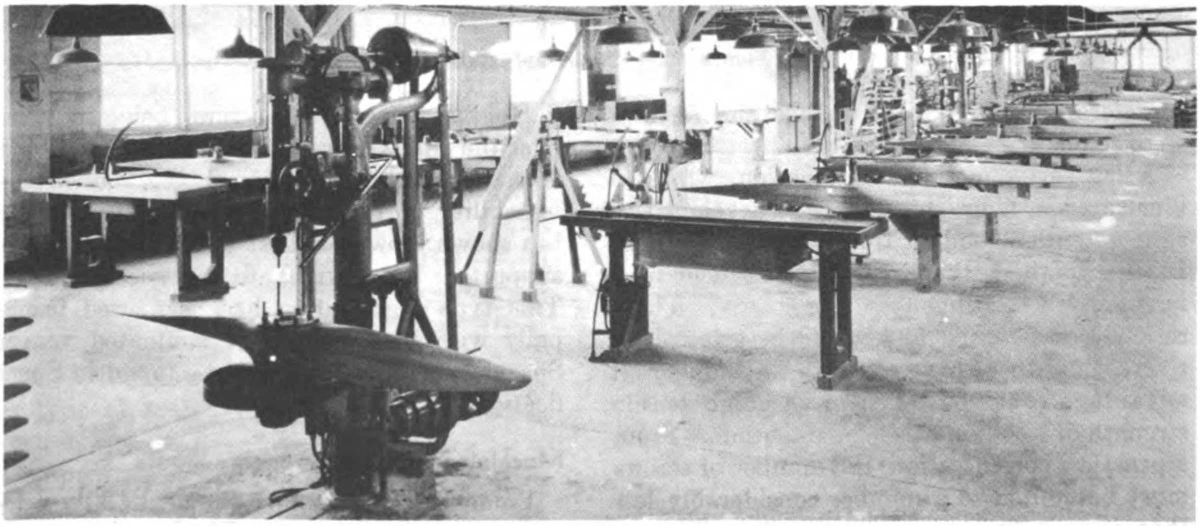

Figure 4.5.—Finish production line—wood propeller.

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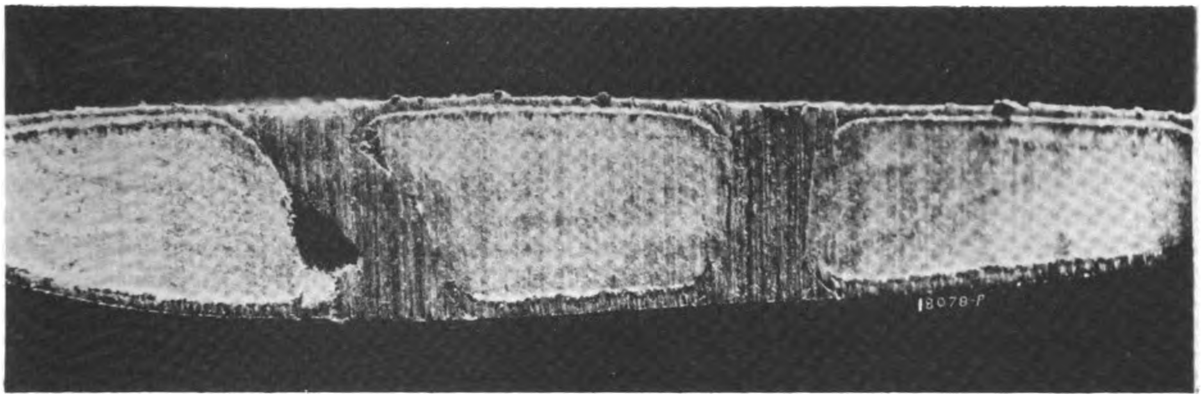

Figure 4.6.—Wood blade tip failure by rivet buckling.

Layup of Propeller Blanks

The layup of propeller blanks from boards is fully described in Specification No. MIL–P–5451. Only jack presses and "c" clamps are recommended for application of adequate pressure. A conditioning period, after removal of propeller blank from the press, is essential since most glues add a certain amount of moisture to the wood. This conditioning period allows the moisture to diffuse and become evenly distributed throughout the blank. Laminated veneer blanks are laid up with the grain direction of alternate plies splayed 15 degrees in alternate directions from the centerline of the blade blank. This arrangement will provide for an included angle of 30 degrees between grain slope of adjacent plies. The objective in arranging alternate plies in this manner is to obtain maximum increase in torsional rigidity with the least reduction in other properties. Furthermore, wood grain direction angularity of adjacent plies tends to prevent splitting and propagation of cracks. Where feasible, it has been found advantageous to use a form for veneer gluing that will impart an angular twist to the blank, representative of the desired blade twist. Specification MIL–P–5444 establishes requirements for laying up laminated veneer blanks.

Rough Carving of Wood Propeller Blanks

Propeller blanks should be rough-carved to within approximately ⅛ inch of final dimensions, after conditioning. For mass production, rough carving may be accomplished by use of a profiling or duplicating machine. There are many types of profile carving machines which can carve from one to four blades simultaneously. All types use a master or pattern for controlling the final carved shape. An illustration of two types of carving machines is shown in figure 4.4.

Laminated veneer blanks for detachable blades should have the shanks turned on a lathe and ferrules installed prior to carving. Installation of the ferrules prior to carving facilitates blade indexing, if that is required. Rough carving of laminated veneer blanks is similar to the process used in carving blanks built up from boards. After rough carving, a final conditioning period must be allowed in order to permit shrinkage or warpage.

Finish Carving of Wood Propeller Blades

Finish carving may be accomplished by use of templates and protractors to obtain correct dimensions. Figure 4.5 shows a typical factory production line for finish carving.

Balance stands are shown for checking balance as blade carving progresses. Tolerance spread may be utilized in order to obtain balance without adding additional material. The final finishing operation will consist of sanding the propeller blade to provide a smooth surface. Specifications MIL–P–5451 and MIL–P–5444 describe finish requirements in detail and list applicable tolerances. In addition, the two specifications cited furnish details of construction of blade finishing templates. Finish requirements of laminated veneer blades are the same as those of fixed pitch wood blade propellers.

"Tipping" Blades

It is common practice to cover the outboard portion of a wood blade, for a distance of approximately 15 inches, with airplane fabric to provide resistance to abrasion and splitting. The tip covering is glued to the blade using a

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suitable adhesive, with the lap joint located on the leading edge of the propeller so that the joint will be covered by the metal leading edge strip. Urea glues are not suitable for tip covering attachment since these glues destroy cloth effectiveness by embrittlement. Hide glue, later superseded by casein glue, has been used extensively for this purpose. Specifications MIL–P–5451 and MIL–P–5444 describe blade covering procedures and installation of the metal leading edge strip. If the final finish is to be a plastic covering, cloth sheathing may be omitted. Special care must be taken in installing tipping to avoid splitting the wood blade by rivet buckling. Figure 4.6 illustrates the effect of rivet buckling by rivets on the tip of one blade.

The military services have developed a fastener to use in place of rivets which has eliminated this type of failure. The fastener consists of a sleeve type nut (Air Force Drawing No. 49B10326) to be used with a standard screw (AN507B640). A sketch of the special nut with screw appears in figure 4.7.

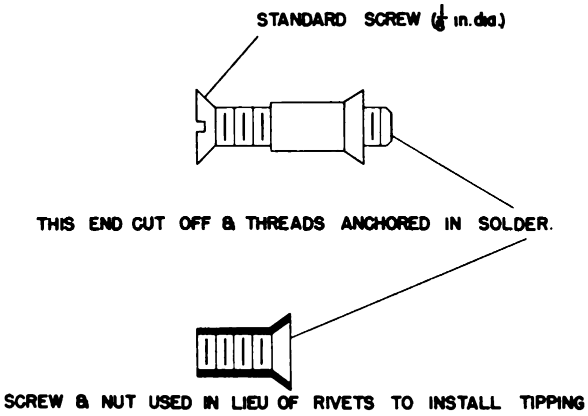

Figure 4.7.—Air force sleeve type nut and bolt.

Finishing Wood Propellers

A section of ANC–19 has complete information for finishing wood propellers along with specific requirements for CAA approval. Specifications MIL–P–5451 and MIL–P–5444 give specific requirements of finished military propellers.

In general, these specifications stipulate that fixed pitch wood propellers be dipped in a spar varnish, in order to adequately seal the hub and bolt holes. Detachable wood blades may be either sprayed or dipped. Plastic coverings for wood blades have proven superior to varnish or paint coatings. To obtain final balance, where unbalance is small, an extra coat or two of finish varnish may be added to that blade which is too light. Figure 4.8 shows an assembled propeller with detachable, laminated veneer blades.

Metal Propellers

Metal Blade Construction

(1) *Categories and types of blade structures.* (*a*) Solid Blades. Solid metal propeller blades are fabricated from light metals such as aluminum alloy. The structural features of this type of blade are self-evident. Economic considerations have dictated continued use of solid propellers for light and medium weight aircraft. In general, solid blades are used with low powered aircraft and are usually relatively small diameter propellers.

(*b*) Hollow Blades. Hollow structure metal blades are manufactured from high strength steel alloy as a rule. While appearing on the scene extensively only since the beginning of World War II (limited use in the early 1930's), hollow steel blades now are considered essential for large diameter propeller applications, in this country. It is apparent that first cost, maintenance and repair of hollow blades will exceed that of solid blades. A hollow blade should be considered as a single integral stress member. Manufacturing variations and required section changes, which are dependent upon aerodynamic and structural characteristics, present difficult design problems.

(*c*) "Core and shell" Blades. The core and shell type of blade construction was introduced

Figure 4.8.—Detachable, laminated veneer blade propeller.

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in an attempt to overcome section variation problems of the hollow blade. In reality, this type of construction is a form of hollow blade construction, but, in the core and shell blade, a tapered steel tube, round at the shank and flattened outboard, is employed as the load-carrying member. The correct aerodynamic span and contour are provided by comparatively thin steel sheets brazed to the tapered tube. Prevention of vibration and local distortion of the light sheet is accomplished by filling the blade interior with some type of foam compound.

This construction has not eliminated, completely, the abrupt change in section design problems. Blade failures caused by high stress concentration at the inboard end of the shell have been overcome by ingenious design. At this time, core and shell propeller design may be considered successful from a functional viewpoint.

(2) *Thickness distribution evaluation of blade structures.* Aerodynamically, it would be considered desirable to maintain a low blade thickness ratio inboard to the retention system. However, high steady and alternating stresses, along with requirements for stiffness in this region of the blade, thwart attainment of such a structure. Stress and stiffness considerations dictate that approximately one-third of the blade radius be utilized in fairing from round shank to airfoil sections having best aerodynamic efficiency. In the shank region, aluminum alloy blades compare unfavorably with hollow steel structures. Large values of steady and alternating bending moment, along with lower strength of aluminum alloy, require that solid aluminum alloy blades be designed with a larger shank outside diameter than those of hollow steel, for any given application. The difference in shank size becomes more marked in blades designed to absorb high horsepower. Furthermore, an increase in shank diameter increases drag, which in turn effects engine cooling and propeller efficiency at high speed.

In the outboard portion of a propeller blade, especially the outer third, bending moments are low, generally. Hence in the blade tip region, thickness ratios of solid aluminum and hollow steel blades are equivalent, approximately, for normal installations. For high speed applications, extremely thin blades are required. In thin blade applications even solid aluminum alloy blades have been found to be too flexible in bending and torsion, to be used successfully. However, with decreased blade thickness ratio, a solid steel blade design achieves greater feasibility from a weight standpoint. But a comparison of required torsional rigidity versus overall allowable stresses will indicate that hollow blade design and construction is more desirable.

(3) *Blade section distortion comparisons.* Section distortion presents a serious problem in design of hollow blade structures. Several types of distortion are possible, resulting from uneven distribution of steady or alternating loads over the blade surface or from vibration, at resonant frequency, of the blade surface. Generally, the latter phenomena may be termed *plate vibration.* Alternating stresses resulting from plate vibration as high as 40,000 p. s. i. have been measured. Distortions produced by both alternating and steady air loads can affect blade efficiency appreciably.

As a rule, the magnitude of distortions produced in blades of small size is not as great as that produced in blades of larger size, but the actual stress levels produced by distortions in small size blades can cause failure in the vicinity of stress raisers. Some form of internal stiffener is desirable in many designs of hollow steel blades in order to reduce plate vibration and other distortion effects. This stiffener may take the form of a steel rib incorporated as an integral part of the structure.

Use of transverse ribs, although feasible in wing design to prevent local distortions, has not proven desirable in propeller blade structures because of fabrication difficulties. Hence, propeller blade rib structures have been placed longitudinally with respect to the blade centerline, generally. An alternative to an integral steel rib structure involves use of a nonmetallic rib, bonded to thrust and camber plates. Rubber has been used successfully for this application. Ease of fabrication and elimination of high stress concentration are major advantages of this type of structure.

Selection of Propeller Blade Materials

(1) *General considerations.* Generally speaking, an extensive group of structural materials is available for construction of propeller blades and components. Metal, wood, rubber, plastic, glass and metallic foil and plating have been

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used with varying degrees of success in construction of principal structural parts, supporting members or components of complete propellers. Practically, however, propeller design requirements eliminate many of these materials or restrict their use to special applications or forms. For instance, rubber has been adopted for use in supporting members (ribs) of propeller blades, but, so far, has not proven adaptable for use as a principal load carrying member of the blade. As another example, metal foil can be used in "sandwich" or laminated form, or as filler material, but is inadequate for principal load support.

Organic materials, as a rule, are not nearly as suitable for the basic propeller structure as metals. This generalization is justified in consideration of the inherent characteristics of organic materials, namely: low moduli of rigidity and elasticity, low strength and low abrasive resistance. However, this class of materials is attractive, as propeller material, when weight, corrosive characteristics and ultimate cost (in some applications) are considered.

It is not to be assumed that the general statements of the two preceding paragraphs represent a complete summary of all important considerations involved in a comparison of organic materials and metals for propeller use. Specifically, low cost of organic materials may be completely offset by production cost of acceptable blades, which must include the cost of involved quality control measures. In brief, involved design problems must be solved prior to substitution of organic materials for metals. Specifications of some structural materials which have been used successfully in propeller construction are shown in table IV–1.

TABLE IV–1. *Propeller Blade Materials*

Material	Specification
Steel	Chrome molybdenum (X4130)
Steel	Chrome nickel molybdenum (X4340)
Aluminum alloy	25ST Forging
Aluminum alloy	75ST Forging
Wood	Birch—Propeller grade
Veneer	Birch or maple, aircraft quality

Young's Modulus, with the related shear modulus, is the most significant single property of a propeller structural material, as, in fact, it is in most any structural application in which deflection of the structure is important, functionally. Occasionally, since aerodynamic design of solid blades establishes an upper limit of volume and thickness ratio, modulus may be sufficient, as a criterion, to select a material, inasmuch as torsional stiffness must be maintained. However, in general, modulus or any other single property alone cannot be the basis for making the optimum propeller material selection. The propeller centrifugal force field tends to distort the effect of apparent weight and to limit deflection of the blade. Aerodynamic loading and natural blade vibration frequencies may emphasize torsional property requirements in an installation in which pure bending considerations are not exceptionally severe.

Therefore, choice of appropriate propeller material must be based upon all phases of analytical design, including blade deflection and stressing, shank loading and bearing design. In addition to analytical design criteria for material selection, careful consideration must be given to "reproducibility", i. e., ease of fabrication and adaptability to mass production, and cost of production. Included in the term reproducibility are such items as material adaptability to welding, forging, extruding and other machine tool operations which in the aggregate determine usefulness of a production process. Further discussion of these features appears in the handbook section pertaining to blade fabrication.

Finally, in selection of a propeller material, known properties and characteristics of all available materials must be balanced against the particular and peculiar requirements of a given installation. Major influence upon final utility and serviceability of propellers may be exerted by such properties as: ultimate strength, endurance limit in fatigue, impact strength, notch sensitivity, erosion, corrosion and galling. The effects of some of the most important properties are presented in the following paragraphs.

(2) *Influence of ultimate strength upon material selection.* While ultimate strength (or yield strength) of itself is not generally of prime concern, it must be considered in the light of anticipated stress concentrations, such as might exist in shank fillets for example. In the past, it has been accepted propeller practice to use

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maximum computed steady stresses equivalent to one-third to one-fourth of the ultimate strength of the material for conventional blades. Apart from this consideration, ultimate strength is important in its relationship to endurance limit, in view of the fact that a propeller must operate under combined steady and alternating loading. Normally, it will be found that the amount and distribution of material in a propeller is dictated by considerations other than those involving steady stresses alone. An important consideration other than steady stress includes establishment of blade natural frequencies well above the running range, if possible, to minimize resonance vibration problems. Other factors include limitation of alternating stresses to acceptable levels (generally determined by test), and weight reduction. However, high speed installations often develop such high centrifugal loads that the critical stress becomes a shear stress in the shank fillet.

(3) *Impact resistance--Propeller blade requirements.* Impact strength requirements of propeller materials must be considered, qualitatively. It is quite apparent that very brittle materials would be unsatisfactory for use in a propeller blade which might be struck during rotation by flying particles of appreciable size. Also, some degree of ductility is desirable, but some doubt exists of the exact location of the lowest acceptable impact strength. Blade failures have occurred in service as a result of propeller contact with semi-elastic objects, such as sea water and snow banks. In practice, propeller design must allow for these hazards which are out of line of normal service. Exercise of judgment based upon adequate blade testing is necessary to assign a minimum value to impact resistance of the material to be used.

(4) *Effect of notch sensitivity upon material selection.* Notch sensitivity is an elusive property of materials which cannot be specified in quantitative terms. Evaluation of notch sensitivity involves consideration of the conditions under which a propeller must operate, namely, runway, meteorological and atmospheric conditions (which incorporate possible dust, rain or hail damage). Notch-sensitivity of high strength material may be such that a presumed advantage of high strength will be eliminated under actual operating conditions. As an example, 76S aluminum alloy in polished form exhibits an endurance limit in fatigue of 20,000 to 21,000 p. s. i. (handbook value) while slightly lower strength 25S aluminum alloy shows an endurance limit of 17,000 p. s. i. Yet, under laboratory testing of erosion and brinelling, which was intended to approach service erosion, both alloys showed an endurance limit of 5,000 p. s. i.

(5) *Stress corrosion resistance.* Stress corrosion, more than any of the foregoing material properties, is not affected by particular applications, since stress corrosion is a characteristic of the material rather than of an installation. Often, however, materials having tendencies toward stress corrosion have sufficient promise in other respects to warrant development work in processing methods which will eliminate or reduce the hazard of corrosion failure in service. For example, stress corrosion of 75S aluminum alloy was reduced by re-alloying (to 76S) and use of a hot water quench.

(6) *Galling or friction oxidation.* Galling or friction oxidation must be considered, usually, as a characteristic of a specific retention system, involving the exact shank size along with the allowable stress levels. Experience with small sample testing has proven sample testing to be inadequate for predicting extent of galling in service. Galling of one type of aluminum alloy blade shank was reduced to an acceptable level by use of fabric impregnated phenolic chafing rings between blade shank and steel thrust ring, as shown in figure 4.9.

A later innovation, shot-peening or cold-rolling with a knurled-surface roller, has been applied, successfully, to both aluminum alloy and steel blades. Shot-peening or cold-rolling

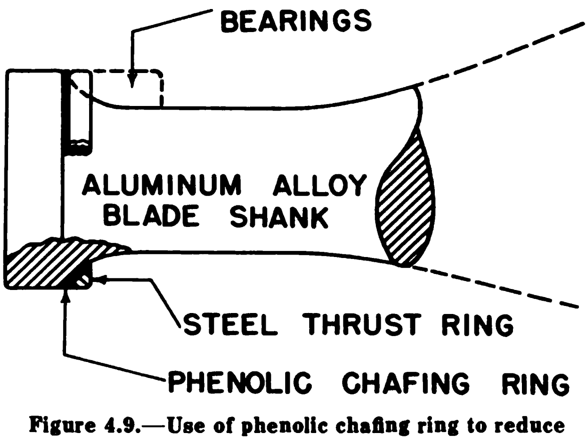

Figure 4.9.—Use of phenolic chafing ring to reduce calling.

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with a knurled surface does not eliminate galling completely; but, as a result of the process, the load will be carried on a compressive layer which has acceptable fatigue strength. In tests of eroded 76S–T blade shanks of a conventional type, shot-peening was found to increase the strength of the shanks from 6,500 to 8,000 p. s. i. In this test 1/16 inch diameter hard iron shot was used at an approximate intensity of 0.010C2. (This intensity factor is that used on standard shot-peening practice; namely, the number, .010, is the inch deflection of a standard "C" specimen, as measured by a No. 2 Almen gage.)

Cold-rolling with plain rolls, while ineffective for retardation of galling, has been used with some success in the formation of a compressive layer, similar to that of a knurled roller. (Cold-rolling the shank fillet area of aluminum alloy blades increased fillet strength from 4000 to 10,000 p. s. i., when the rolling load was adjusted for contact stresses of approximately 350,000 p. s. i. or slightly less than the stress which would produce surface flaking.) Galling is a known service problem which must be considered in design of all propeller mating parts.

(7) *Effects of surface treatments—Alloying, plating and heat treatments.* Hollow steel blades having integral races ground into the shanks are produced, usually, with slightly higher carbon steel in the shank (either SAE4350 or 52100 steel). Such surface treatment as nitriding, cyaniding, carburizing, and chromium plating may be used to improve fatigue strength, in some cases, although limited experience indicates small effect except in case of chromium plating. Surface alloying (nitriding, cyaniding or carburizing) produces distortion of the shank which must be prevented or minimized. Furthermore, cyaniding and nitriding apparently produce a skin too thin to stand up under high shank bearing loads. Use of chromium plating must be controlled carefully because of the adverse effect of the process upon fatigue strength.

Materials heat treated to produce very high levels of (above 200,000 p. s. i.) ultimate strength, frequently cannot develop that full strength in application and heat treatment to lower strength levels actually will be beneficial to propeller structures fabricated from those materials. An outstanding example of this effect was illustrated during design and development of a highly stressed landing gear part for the B–36 airplane. When the part was heat treated to produce ultimate strength of 205,000 to 220,000 p. s. i., repeated failures occurred. With some redesign and subsequent heat treatment to give an ultimate strength of 185,000 p. s. i., the failures were eliminated. Apparently, very hard materials do not yield locally to the degree necessary for optimum load-carrying capacity. Considerations such as this have established desirability of heat treatment of steel propeller blades to produce ultimate strength levels between 135,000 to 180,000 p. s. i.

(8) *Abrasive resistance requirements.* Abrasion of all blade materials, except very hard metals, by water spray and small solid particles has shown the existence of an absolute requirement for abrasive resistance of propeller blades. Unprotected aluminum alloy blades will be eroded under severe operational conditions encountered such as water spray, mud, cinders, ice, and gravel. Even steel blades may be damaged by small stones and gravel.

The degree of abrasive resistance required may depend upon specific design features and method of blade processing. For example, softer materials, such as wood, magnesium and aluminum to some extent, although easily damaged by abrasion, may be utilized in propeller blades if protective sheaths are placed at the leading edge or over the entire blade surface.

Protection of steel blades is necessary to prevent dents in blade edges formed of thin sheets .050 inch, or less, in thickness. In some types of construction, leading edge protection can be obtained by using a fillet of copper base alloy within the small radius interior of the leading edge.

The requirement for greater protection against blade failure by abrasion demands use of materials which possess a high degree of abrasive resistance as an inherent characteristic. This requirement has assumed greater importance since adoption of propeller blade reversal during aircraft landing operations. Economy of fabrication and processing convenience suggest use of materials which can be worked soft and hardened in a final major operation.

Soft working with subsequent surface hardening can be accomplished, generally, in three classes of materials, namely: materials adapt-

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able to heat treatment, materials which can be hardened by aging, and materials which can be cold-worked. Hence, it was not coincidence that aluminum alloys and steels, in turn, inherited the "front runner" position of propeller blade material, originally held by wood. However, abrasive resistance was not the only consideration involved in a choice of optimum propeller blade material.

(9) *Material processing properties.* In choosing particular types of alloy for propeller use, qualitative processing properties became the final selection criterion. In the early stages of detachable aluminum alloy blade fabrication, 25S was chosen because this alloy possessed good forging properties, reasonable hardness characteristics and an acceptable endurance limit. Subsequent evolution of aluminum alloys introduced the so-called hard alloy 76S, with attendant stress-corrosion problems to be solved. This choice was made because of the higher hardenability of 76S alloy which reduced erosion in service.

In the early stages of steel blade development, comparatively low alloy steels were used (such as SAE 6130) which were easily hardened by oil quenching and reasonably amenable to welding. It was found, however, that oil quenching produced severe distortion, resulting in high scrap loss caused by subsequent cold straightening. A solution to the scrap loss problem was obtained by conversion to the 4300 steel series (4330 for arc welded blades, and 4340 for non-welded blades). The 4300 series with its deeper hardening properties allowed use of die-quenching, even in thick sections required for large diameter blade shanks.

Hence, the general use of steel and aluminum alloys resulted from consideration of a combination of forming, machining, hardening, and bearing properties of blade materials. The weight of aluminum which allowed the use of solid blades, resulting in extreme simplicity of fabrication, was an important factor in adoption of this material. It is interesting to note that several early attempts to fabricate hollow aluminum alloy blades encountered difficulties which caused temporary abandonment.

Attempts to form hollow blades from laminated Fiberglas sheets have introduced many new fabrication problems, proving that a blade structure must be especially designed to use this material. Obviously, this special design requirement applies to the use of so-called sandwich materials, also.

Cold-worked materials have had but little application in production of propeller blades because of the difficulties encountered in cold-working the complex blade shape, after assembly, while maintaining close tolerances to final dimensions. Some effort has been expended in development of rocker rolling equipment for cold-working propeller blades fabricated from certain non-heat-treated alloys.

(10) *Raw materials.* (*a*) Availability. In considering large scale production of propeller blades, availability of the proposed material in time of emergency becomes a dominant factor. Availability of strategic materials has been documented in other publications of the U. S. Government. In addition, there is an ever-present factor of establishment of suitable propeller production rates using a given material processed to desired blade form with acceptable quality standards.

(b) Materials for Propellers of the Future. During and since World War II, the industrial material field has expanded to include a great many natural and synthetic substances that were unknown or undeveloped, previously. Many of these new materials may have propeller applications but remain in a state of suspended animation while studies are being made to determine the properties of the materials and the exact form of propeller application to exploit those properties. Limitation of time and money has delayed development of some materials.

Titanium is one of the most significant and promising new materials for propeller application. At the present time, titanium is being used to fabricate both solid and hollow blades which will be subjected to close scrutiny to establish the relative importance of this material in propeller applications. Titanium has a favorable strength-weight ratio but possesses a lower modulus than steel.

Magnesium is another material that may have future value as a propeller material, although it has been used to a limited extent so far. In fact, this material was one of the first metals to be used in propeller blade development. Because of the unfavorable fatigue properties, low modulus and softness of magnesium, propeller applications of the material have been

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limited to those in which weight must be a minimum and stress concentrations will not be high. It has been a suitable substitute for wood in the low power absorbing class of propellers. Further, development and improvement of physical properties of magnesium alloys, in time, may establish this material as a major structural material for propeller use.

Propeller Filler and Vibration Dampening Materials

(1) *General requirements.* A general discussion of organic materials has been given previously with respect to primary structures. In secondary structures, such as cuffs, vibration dampeners and deicing baffles, organic materials as a whole, have many desirable features. Phenolic rubber and diisocyanate alkyd cellular (blown) substances offer promise as vibration dampening materials. Problems encountered in the use of these materials include handling during processing and delamination under stress. Solution of the handling problem appears to be available through recompounding. Delamination under stress may be overcome by recompounding and introduction of reinforcing agents, such as threads or fibers. Exact specifications for required properties of a vibration dampener are difficult to define but general requirements may be established as indicated in Table IV–2.

(2) *Cellular and sandwich materials.* Cellular materials used as vibration dampeners must be adaptable to methods of excluding moisture. Since excessive moisture absorption may unbalance a propeller, the filled portion of a blade must be thoroughly sealed. Also, danger of corrosion from oxidation reactions in the blade makes blade sealing an absolute necessity. Careful and thorough tests throughout the complete range of humidity and temperature in which a blade may operate should be made for proposed blade sealing techniques.

Sandwich materials as a class are receiving serious consideration for various aircraft applications. The exact application of sandwich materials to the field of propeller blade design has not been explored, fully. Given proper quality control, structures can be conceived in which advantage is taken of the low density modulus ratio of sandwich materials. The problems of quality control for these materials are related to those of plastics already discussed.

Metal Blade Fabrication

General Basic Requirements

It is not the purpose of this section of the handbook to provide reference tables of machine tool cutting speeds, forging pressures and tooling design data for various materials used in propeller fabrication. Such data can be obtained from any one of several machine tool handbooks already in print. Propeller blade fabrication problems are peculiar to the nature and use of the finished product and not characterized by the machine tool operations involved.

The particular processes discussed herein are presented to illustrate production line techniques that, for the most part, have been introduced to eliminate scrap loss or unwieldy handling methods. Such objectives achieve paramount importance in periods of emergency.

But, important though scrap loss and time reduction may be, the basic requirement of quality control necessitated by the ever-present fatigue loading of propeller blades, must be fully met. Disastrous consequences of propeller failure establish for all time and in all processes, the importance of safety in performance. Certain known hazards exist which have been reduced or eliminated by sound fabrication

TABLE IV–2. *General Requirements for Propeller Blade Filler Materials*

(1) Throughout service temperature range, the ultimate tensile and compressive stress shall be 150 p. s. i. minimum.
(2) Initial modulus of elasticity shall be at least 3000 p. s. i.
(3) Fatigue strength to withstand a stress level of ±30,000 p. s. i. in the blade outboard of the shank.
(4) Adaptable to use with available bonding agents that will develop tensile and shear strengths in excess of those of the filler material.
(5) No deterioration of material properties with age.
(6) Noncorrosiveness either with or without bonding agent.
(7) Insoluble in water.

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methods. Some of these processes of fabrication will be presented to illustrate the requirements of aerodynamic design and to stimulate thought processes which may induce departures from old established practice, preserving advantages gained while achieving greater propeller performance and safety.

There is no single perfect process of fabrication of propeller blades. For any given installation, there exists a wide latitude of selection of blade structure type and fabrication process. Certain processing operations, which vary with type of structure, are representative of propeller blade fabrication. Many operations employed in blade fabrication are essentially those employed in production of many other manufactured items. For instance, shank machining and grinding operations, electrolytic plating, cleaning and painting processes and heat treating operations are performed during propeller fabrication in a manner normal to most manufacturing procedures.

Other processes, such as welding, brazing, finishing and inspecting, are peculiar to blade fabrication by the care exercised in execution and the special techniques employed. These operations along with special shaping and die quenching operations will be discussed in some detail as a part of fabricating procedures used in producing solid, hollow, tapered beam and monocoque blade structures.

Propeller Blade Finish

(1) *External surface finish.* Severe erosion encountered by propeller blades during operation has required the use of a metallic plating for protection of any surface subject to corrosion. Organic coatings and chemical treatments such as oxide, chromate, and sulphate treatments were used considerably during the war. However, recent trends toward the use of zinc plating on steel blades are preferred because of galvanic protection given to the steel. Zinc plating (in accordance with Specification No. QQ–Z–325) has been used by all propeller blade manufacturers. The quoted specification requires further processing of a plated surface by chemical treatment such as anodizing; or conversion to chromate to prevent oxidation while the blade is in storage. Finally, the blade surface must be either sealed or painted. Enamel (in accordance with Specification No. MIL–E–5556) may be used to seal the blade. Hydrogen embrittlement which may occur during plating operations either from action of the plating bath or from cleaning operations, must be avoided because of the detrimental effect of embrittlement on fatigue strength.

Methods of surface finishing propeller blades and component parts must be reviewed frequently in order to take full advantage of technological advances in treatment methods and processes. Recent studies have shown that comparatively stress-free coatings can be obtained by use of special plating baths. Hence, advantage may be taken of high surface hardness of nickel and chromium plating, provided absence of stress eliminates microcracking prevalent in the so-called "hard" chromium plate. Nickel plating of aluminum alloys has been accomplished, successfully, which may allow re-evaluation of the use of aluminum alloy in certain propeller applications.

(2) *Safety painting.* Propellers may be finished with safety painting; that is, bright strips may be painted around blade tips to make whirling tips more visible. Yellow lacquer is used, commonly, for these strips in accordance with Specification No. MIL–L–6805. Requirements for certain airplanes may specify that the entire blade be painted with a dark non-glare enamel, or lacquer.

(3) *Internal surface treatment.* Protection of internal surfaces of hollow blades against corrosion, both in storage and service, is of utmost importance. General specifications cannot be given for internal surface treatments because of the great variety of acceptable process specifications. Phenolic base resins, introduced as a liquid and cured at low temperature (200° to 400° F.) are the most widely used materials for internal surface treatment. Some experience has been obtained in the use of aluminum paints developed for high temperature applications in other fields. Although the blade interior coating operation is not complicated, care must be taken to insure that cleaning solvent pockets are not left to become sources of corrosion. The illustration in figure 4.10 shows a type of irregularity caused by coating an improperly cleaned surface. The corrosion pocket was judged to be contributing to the cause of blade failure. Corrosion under each *bubble* was attributed to the action of soldering flux used in installing the balance cup.

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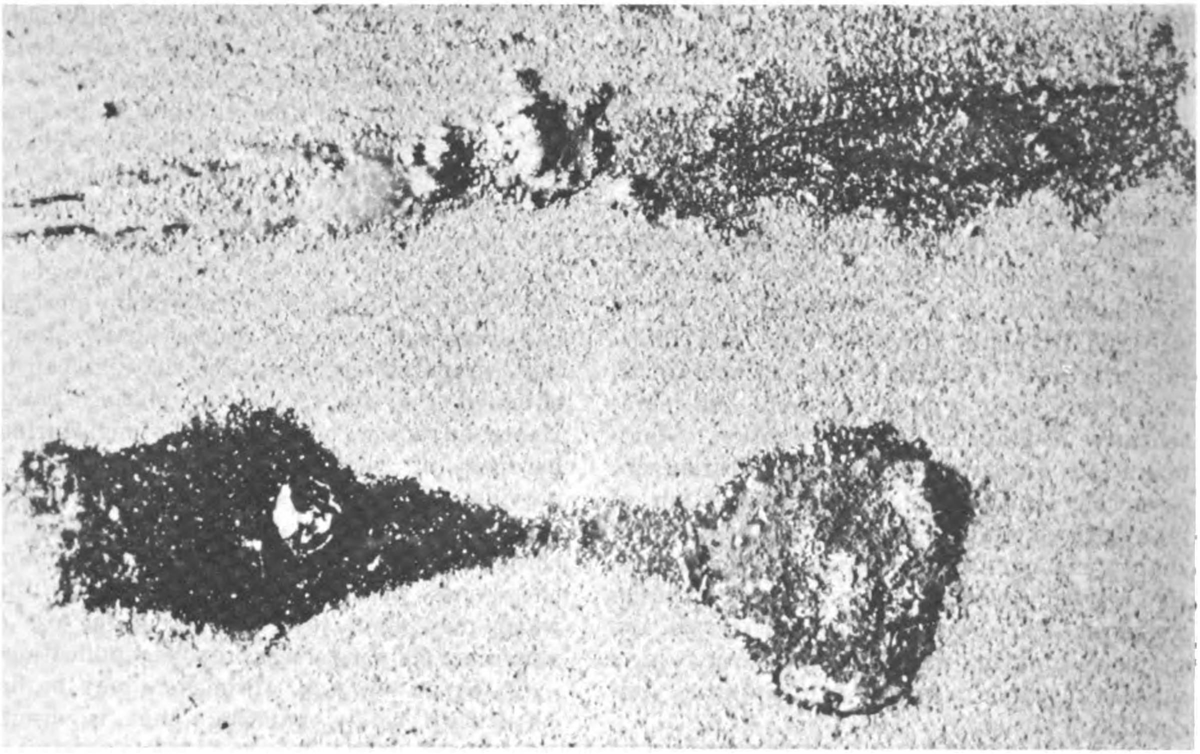

Figure 4.10.—Internal blade corrosion pocket.

This illustration directs attention forceably to the importance of choosing proper fabricating materials even including those which play a minor role in blade fabrication.

Solid Metal Blade Fabrication

(1) *Blade forming and machining operations.* Fabrication of solid metal blades, regardless of material, is relatively simple compared to fabrication of hollow sections. One-piece solid construction requires no joining processes, which eliminates much of the inspection and handling necessary to hollow structure fabrication. Procedures for forming solid blades, regardless of section thickness, require little elaboration since the necessary steps are obvious. Rough forming solid blades has been done by hammering or roll forging from billets carefully chosen for quality. Normal processing of an aluminum alloy billet includes proper slagging with direct chilling into ingots scalped ⅜ inch before or after blooming. As much metal as necessary (usually not in excess of 5 percent) should be removed from the ingot end after blooming to assure inclusion of only sound material in the blade structure. An additional 2 to 3 percent of the material must be removed after rolling with almost 75 percent reduction in cross-section being obtained. The weight ratio, rough forging to final blade weight, normally will be in the range of (1.5 to 2.0)/1.0 for conventional blades. However, certain types of aluminum alloy blades have been made with a weight ratio as low as 1.3 to 1. Most of the material can be removed by contour machining in single-stage milling machines or duplicators. Blades may be finished to final dimension by hand controlled belt or circular grinders which are illustrated in figures 4.11 and 4.12.

(2) *Blade inspections.* Semi-destructive inspection, such as caustic etching on aluminum alloy blades, must be performed prior to final surfacing so that the etched layer will be moved completely. Final inspection for irregularities may be visual, followed (in case of aluminum alloys) by anodizing in a chromic acid bath. The area adjacent to fissures will be stained by penetration and exudation (after washing) of the chromic acid and its reaction products. Although light etching may occur during anodizing, the effect has not been found to be detrimental if the process is controlled carefully.

(3) *Blade shank machining.* The propeller blade shank may be finished by conventional

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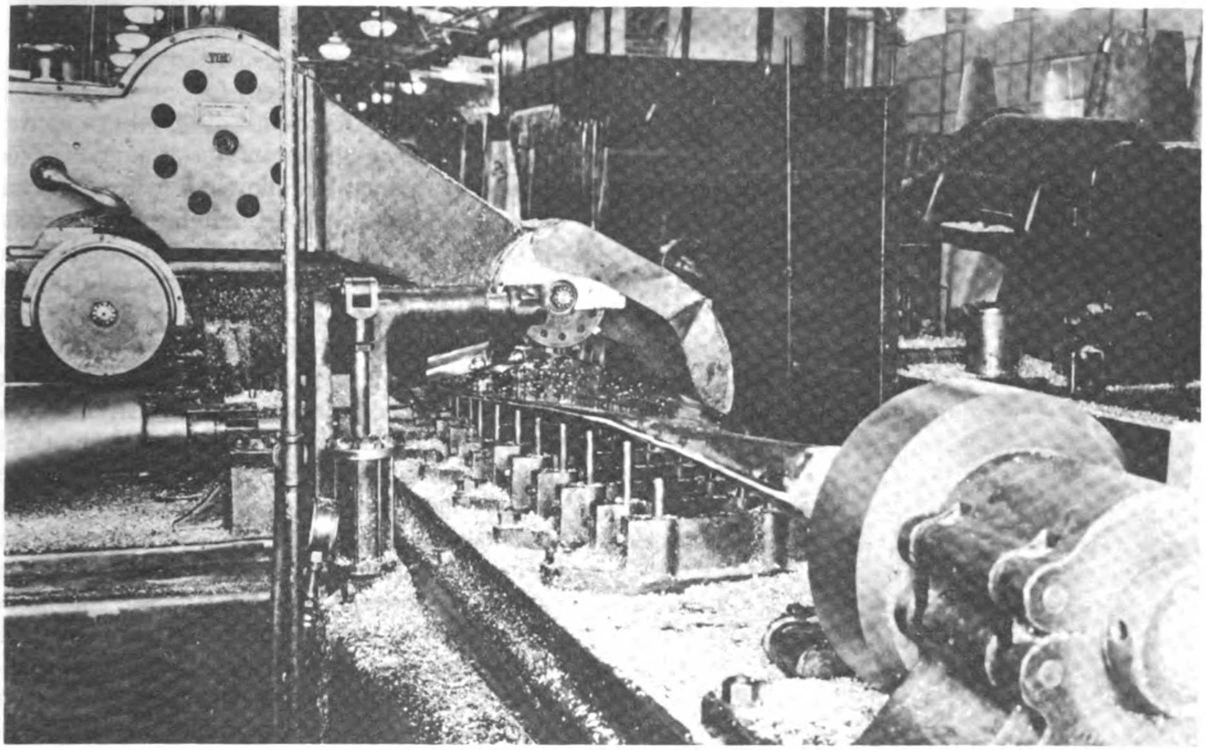

Figure 4.11.—Propeller blade contour machining operation.

Figure 4.12.—Propeller blade finish grinding

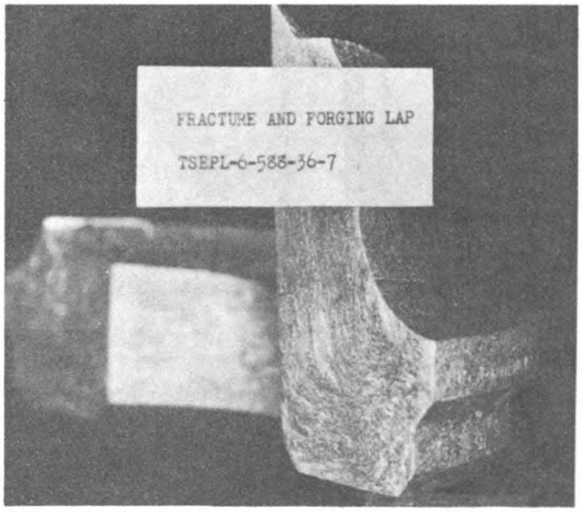

Figure 4.13.—Blade shank forging lap.

lathe turning and grinding to tolerances required by the particular retention system. When blade processing requires up-setting of the shank (for example, to provide a flange), careful inspection must be given the upset region. Use of a positive process, such as caustic etching, will reveal laps which have been formed during the up-setting operation. An illustration of a lap caused by improper temperature control during up-setting is shown in figure 4.13.

The shank size for a given blade design may be dictated by blade stresses, bearing area required for retention, blade stiffness, or other special considerations. Generally, shank requirements allow some possibility for weight reduction by boring at least a portion of the shank, which will provide a convenient space for balance weights. Depending upon heat treatment, which establishes residual stresses, inspection of the shank bore for cracking may become a prime necessity. It has been found

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necessary to quench X76S aluminum alloy in hot water to eliminate cracking, after the boring operation. The fluorescent penetrant method of inspection has been found useful for hub bore inspections.

(4) *Other solid blade forming processes.* In summary, fabrication of solid metal blades by rough forging, contouring and turning has been proven to be an economical, feasible and relatively simple process of manufacture. However, the relative simplicity of solid metal blade production must not be allowed to undermine the always present need for proper quality control. Exact methods of quality control specified for a given material and service environment must be followed. The preceding methods of fabrication (hammering and forging), although widely used, should not be considered exclusive possibilities for solid metal blade processing.

Press forging, contour rolling and extrusion show promise of future development by virtue of allowing blade forming closer to final dimensions. Experience in the use of these methods is not very extensive, in this country, in terms of the number of blades actually produced. Press tonage has been one limitation which has become less serious with increased press capacities of modern blade forming machines. Design factors such as thickness ratio, ratio of blade thickness to shank diameter and shank blade fairing will establish the optimum process for solid metal blade fabrication.

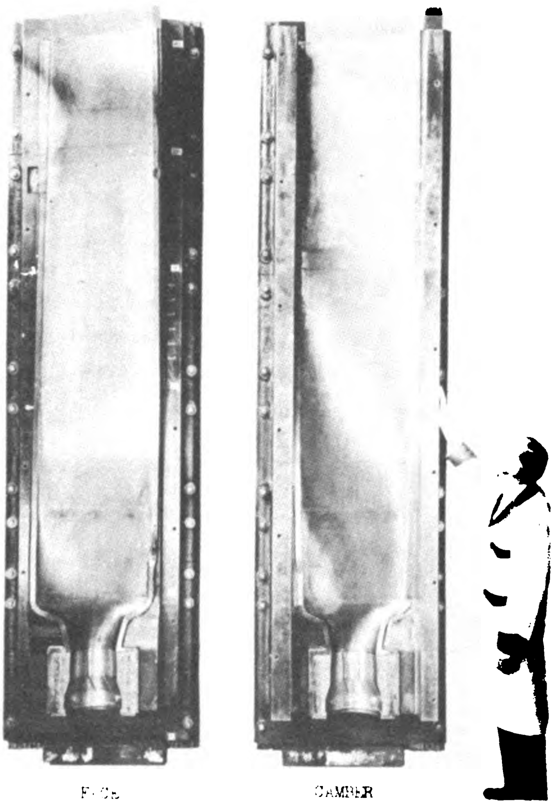

Figure 4.14.—Typical hollow blade quench dies.

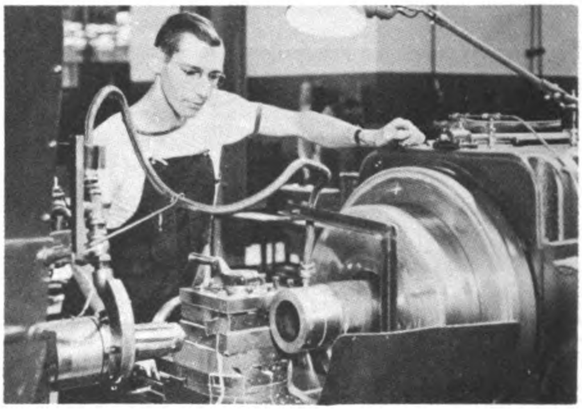

Figure 4.15.—Machining hollow metal blade shank.

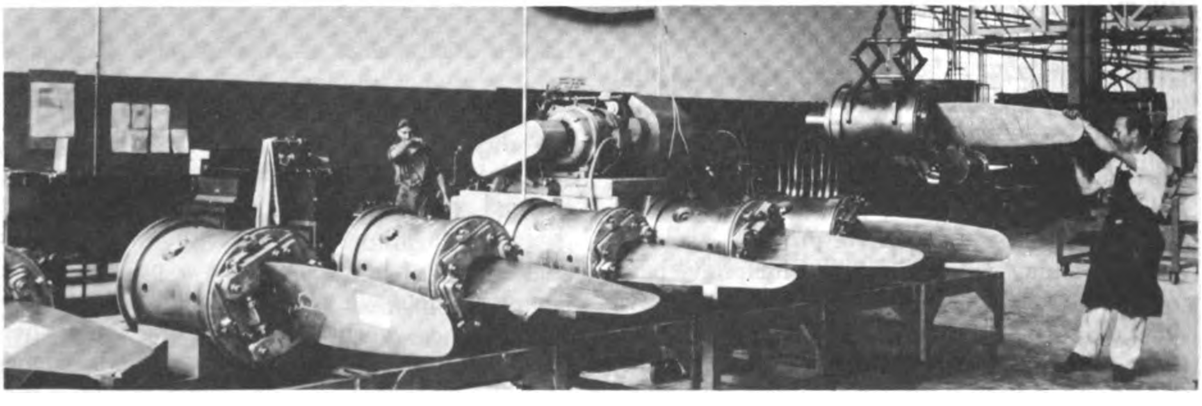

Figure 4.16.—Hollow blade jigs.

Fabrication of Hollow Metal Blades

(1) *General consideration.* Certain machining operations, along with design and production requirements, are common to fabrication of most metal hollow blades, which can be discussed most easily from a general viewpoint. Minor variations, in production of any given section from general processing procedures, are related to tooling design or usage rather than basic concepts. Therefore, the general requirements and procedures will be discussed first to prepare a background upon which special requirements of particular section types may be projected.

Other subdivisions of this chapter will present specific major operations involved in fabrication of production and experimental types of metal hollow blades.

(2) *Die forming hollow metal blades.* Die forming may be considered the climaxing operation in all hollow metal blade manufacture, particularly in those cases in which pitch distribution along the blade has been incorporated into the die-forming operation. The quenching die is the largest, most complicated in design, and specialized single tool required in hollow blade fabrication. In this operation, the assembled blade of general design dimension, except for cleaning allowances in plate thickness as locally distorted by joining, filleting or flattening operations, may be blown to proper airfoil contour by use of internal gas (normally nitrogen) under pressure. The gas pressure used in forming steel blades has been of the order of 600 to 800 p. s. i. in the final forming stages and may be controlled variably throughout the blowing cycle. The die operation must be followed by complete magnaflux and complete X-ray inspection. Types of hollow blade die equipment are illustrated in figure 4.14.

For fabrication of hollow steel blades, the die may be designed with an integral heating furnace, to reduce handling time between furnace and die; the blow-up operation will be performed simultaneously with quenching. In general, use of SAE 4300 series steel and certain titanium alloys makes this operational sequence feasible by virtue of the favorable heat treatment characteristics of this group of materials. Using air-hardening steels, blade shank sections, having greater than optimum wall thickness, normally will be formed in water-cooled dies.

If the blade has been assembled in untwisted form, with desired pitch distribution to be obtained in the die, it has been common practice to break the operation into two steps: First, a brief preforming operation of a few seconds duration will be made; second, following intermediate heating or soaking, a full quench will be performed to obtain proper grain structure. Exact specifications for blade forming sequence depend upon specific interrelation of multiple variables, such as design properties of material, loading time, plate thickness distribution and shank fairing design. Specification content must be established by test runs using the particular blade design proposed.

The die pressure system may be designed to automatically apply a low internal pressure prior to, or just at, closing of the die segments. Normally, the quenching blow-up operation should be followed by stress relieving before tempering. Use of a blow-up die will eliminate much of the scrap resulting from local distortion produced in previous forming operations and quenching, which justifies complexity of the equipment. Die-press complexity, which requires large capital expenditure, has made it necessary to design dies to accommodate blades of various models and sizes, by use of inserts. The inserts usually are split at the blade leading and trailing edges and are segmented radially to permit change in blade diameter of a given blade family, or change in tip shape to vary activity factor.

(3) *Forming hollow blade shanks.* In processing blade shank sections to final dimension, hollow metal blade practice differs little from that used in production of solid metal blades. Figures 4.15 and 4.16 illustrate typical turning and grinding operations.

A particular retention system selected may require use of specialized lathes and grinders but the requirement will be based upon equipment availability more than upon basic differences. Inspection requirements of hot or cold worked sections (e. g., flanges formed by up-setting or swaging) vary for hollow metal blade shanks only by virtue of the added internal surface area introduced. Welded shanks require very careful inspection because joining operations may establish high stress concentration areas.

(4) *Hollow blade finishing operations.* Certain finishing operations of outboard hollow blade sections differ from those used in produc-

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tion of solid sections, as might be expected. Turning or milling operations should not be performed on formed sections. Rather, forming operations should be done on unassembled blade components, as specifically noted for various blade section types in other sections of the handbook. Turning of a blade component is illustrated in figure 4.17.

In normal practice, skin allowances, ranging from .0015 inch to .015 inch, depending upon fabricating process, should be left at the time of blade blow-up. These allowances should be sufficient to permit cleaning, reduce scrappage due to mild local distortion, remove decarburized film and provide enough material the removal of which will aid in obtaining final balance. Extra material may be removed by hand or belt grinding (as shown in fig. 4.18 and fig. 4.19), grit-blasting, buffing and similar operations.

However, it is most desirable to avoid removal of material from hollow blades after blow-up. Since skin allowances are small, process design must incorporate enough material to permit cleaning, grinding or grit-blasting, in order to prevent local thinning below permissible tolerance. Final plate thickness inspection of hollow sections must be accomplished; the design must lend itself to reasonable inspection accuracy. General statements cannot be made with regard to acceptable deviations in plate thickness since skin thickness may vary with blade design. The sonigauge, as discussed elsewhere in this handbook, is a convenient

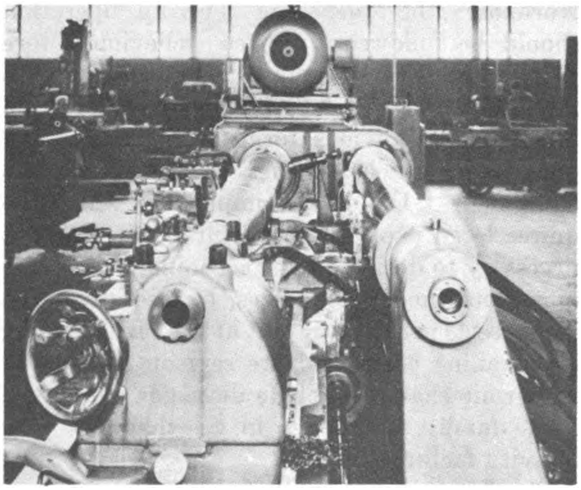

Figure 4.17.—Blade component turning operations.

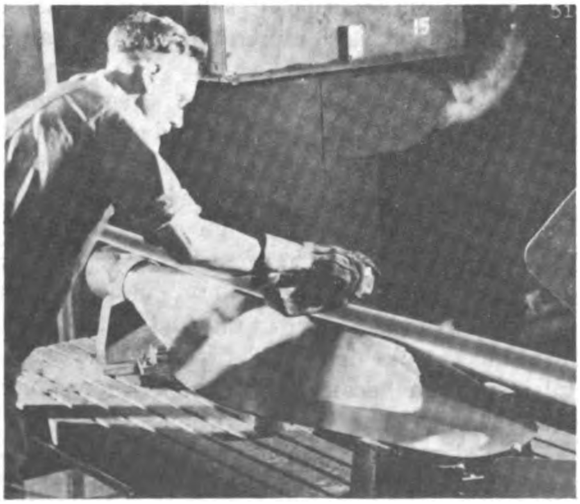

Figure 4.19.—Belt grinding hollow blades.

Figure 4.18.—Hand grinding of blades.

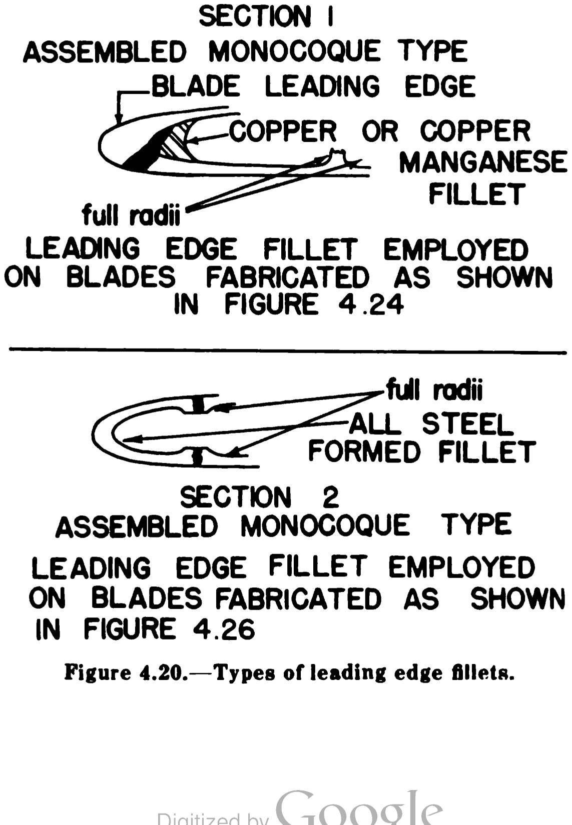

Figure 4.20.—Types of leading edge fillets.

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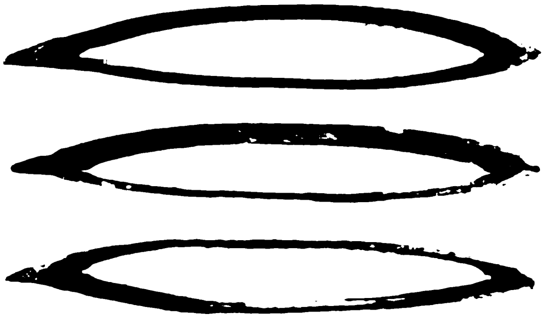

Figure 4.21.—Fillets formed by plate crushing.

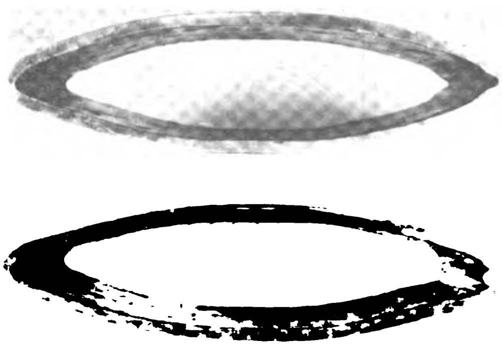

Figure 4.22.—Blade fillet formed by lapping.

instrument for revealing plate variations of certain magnitudes. Tolerances and balance of hollow blade sections are discussed more fully under a separate division of this handbook.

(5) *Hollow blade internal fillets.* Hollow blade experience has proven that true fillet outline is necessary whenever a change in section occurs. Fillets must be used along internal ribs and particularly along plate junctures at the leading and trailing edges, as shown in figure 4.20.

Formation of internal fillets along the plate edges is one of the most critical design features of a hollow blade. Prior to formation of a true fillet in the arc-welded section of a blade, failures occurred which were traceable to abruptness of change in section and roughness of the internal weld surface. It was not until a fillet was inserted that this type of blade section became a fully satisfactory design. It was found that introduction of a copper or copper-base alloy fillet, which could be placed subsequent to welding and weld cleaning, reduced local stresses to an acceptable level. Fillet formation subsequent to thrust and camber plate welding introduced problems of localized heating of the edges with subsequent distortion and, at least, temporarily induced residual stress in air-hardening steels. The solutions of these problems introduced development of butt welded sections wherein the fillets could be formed in the steel plate during the forming operation.

After proper design has been obtained, elimination of unserviceable blades will be secured by adequate inspection. Inspection of internal fillet radii must be considered imperative in view of the stresses which may be induced by plate vibration or section distortion caused by centrifugal loading. Inasmuch as blade internal fillet inspection is most difficult, acceptance specifications must be evolved after consideration of particular blade designs and processing methods. Adequate inspection of internal blade fillets may be obtained by use of the boroscope or by reproductive methods using such materials as Plastiflex.

Calculated fillet stresses, particularly in the faired region between shank and airfoil section, may reach appreciable magnitude. Fillet stresses which by calculation have been shown to be low will not insure production of serviceable propeller blades. Methods devised to reflect the presence of irregular fillet contours and inadequate fillets are fundamental to sound quality control.

That proper fillets are related to hollow sections as such and not merely to methods of fabrication has been proven by study of solid blade failures traceable to the use of improper fillets. Typical improper fillets, which may be obtained in hollow sections by crushing or lapping in the blow-up die, are shown in figures 4.21 and 4.22.

(6) *Design of hollow blade rib terminations.* Stress concentration caused by change in section, is a major design problem in thrust member

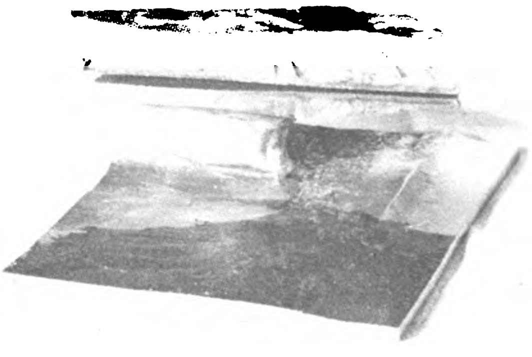

Figure 4.23.—Rib termination fillet failure.

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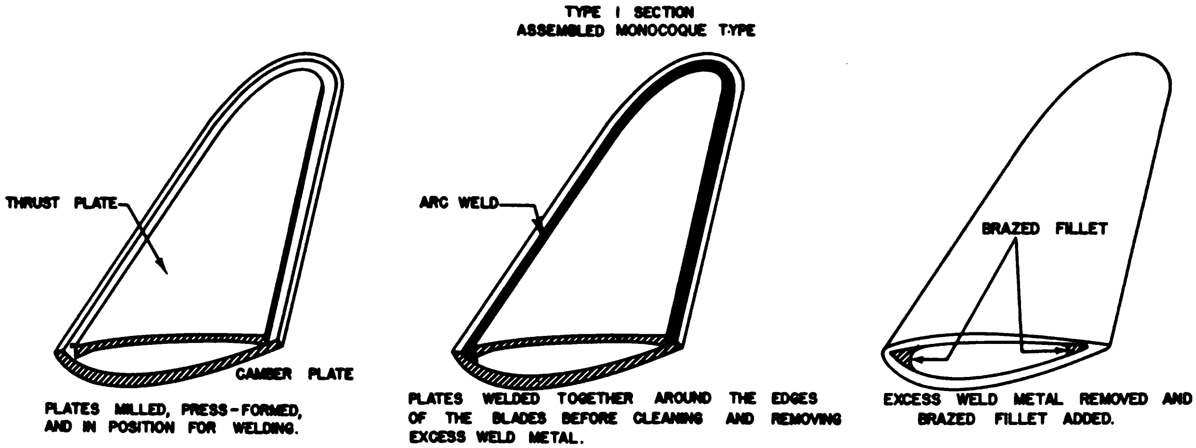

Figure 4.24.—Welded hollow blade fabrication—type I.

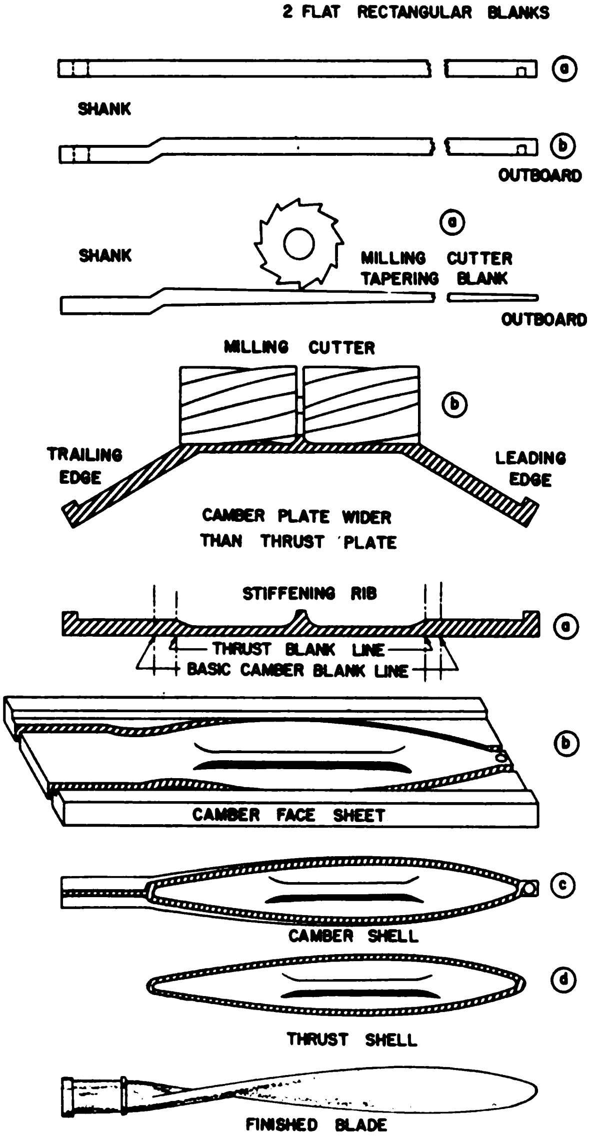

Figure 4.25.—Welded hollow blades—type I—forming operations.

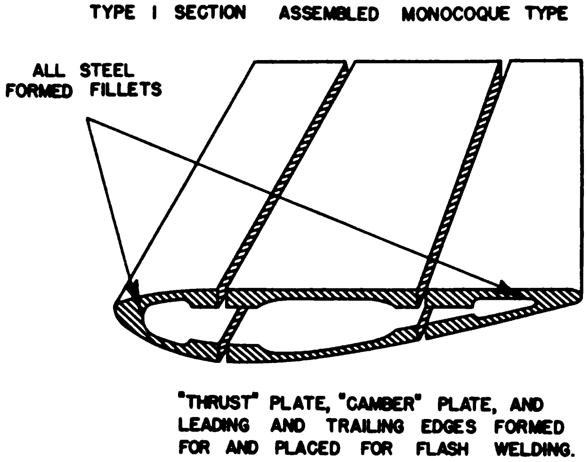

Figure 4.26.—Welded hollow blade fabrication—type II.

type blades in which proper rib terminations must be made. Proper rib termination fillet design is most difficult to obtain by analytical methods alone; therefore, extensive testing must be done to establish a basis for final approval. Figure 4.23 illustrates a blade failure caused by marginal contours in fillets leading into a rib termination. Such failures emphasize the need for careful design and processing.

Monocoque Section Fabrication

(1) *Design limitations.* Monocoque sections are adaptable to a variety of processing methods. For the purpose of discussion of propeller blades, arbitrary differentiation will be made between fabrication of blades composed of assembled sections and blades formed without joint sections, since the former encompasses joining, as well as basic forming operations. Joining operations will be discussed in a general way in another division of this section.

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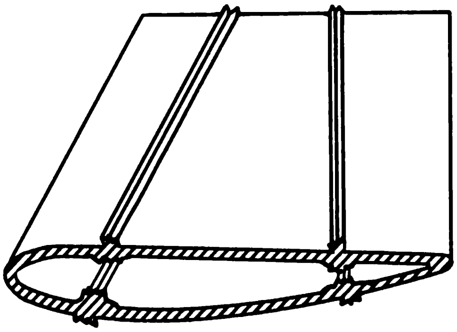
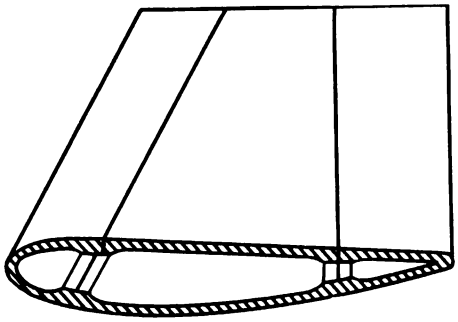
Blades composed of assembled sections must be considered, during design stage, from the standpoint of design of section joints, as well as from structural and functional requirements. It has been demonstrated, repeatedly, that the strength of blade joints could be the limiting strength of the assembled blade. However, such demonstrations do not imply, necessarily, that suitable joints cannot be made. But, the joint must be designed carefully and fabrication processes controlled thoroughly in blades of this type, if blade materials are to be worked to the optimum limit.

(2) *Types of welded joints—"Monocoque" sections.* Figures 4.24, 4.25, 4.26, 4.27 and 4.28 illustrate major operations necessary in producing assembled section propeller blades of two different designs. Each design utilizes a different method of welding which requires particular joint locations that are related to the welding method. The sequence of operations required to fabricate an arc-welded monocoque section (Type I) blade has been shown in table IV–3.

In the first design, designated Type I, the joint is a typical butt welded type. The second



AFTER FLASH WELDING, BEFORE FLASH HAS BEEN REMOVED



AFTER FLASH REMOVAL

Figure 4.27.—Welding operations—type II—hollow blade.

TABLE IV–3. *Arc Welded Blade Fabrication Sequence*

(Fabrication of Blade by Arc Welding Assembled Monocoque Section—Type I)

Reference Figure 4.25

1. *Preliminary machining*
   - (*a*) Two rectangular blanks have faces ground and locating holes drilled.
   - (*b*) Shank end pressed to provide clearance for milling.
2. *Milling*
   - (*a*) Plate milled, using straddle cutter, leaving stiffening rib along center line of plate. Entire plate must be milled to specified edge thickness.
   - (*b*) Plate edges have been bent to allow center plates to be milled to specified thickness.
3. *Blanking, forming, and welding*
   - (*a*) Plates straightened, as shown.
   - (*b*) Plates stamped, by blanking dies, to required planform.
   - (*c*) Plates formed into shells; each shell being one-half of airfoil section, but with no twist or pitch distribution.
   - (*d*) Thrust shell and camber shell joined together with atomic hydrogen arc weld.
4. *Finishing operations*
   - (*a*) Weld grinding.
   - (*b*) Proper twist given to blade.
     - (1) Blade placed in die press.
     - (2) Nitrogen gas blown into blade envelope simultaneously with die closing.
   - (*c*) Shank machined to specified dimensions.
   - (*d*) Blade given proper heat treatment.
   - (*e*) Copper alloy brazed into leading and trailing edges to form smoothly faired edge fillet.
   - (*f*) Protective zinc plating applied to entire blade surface.

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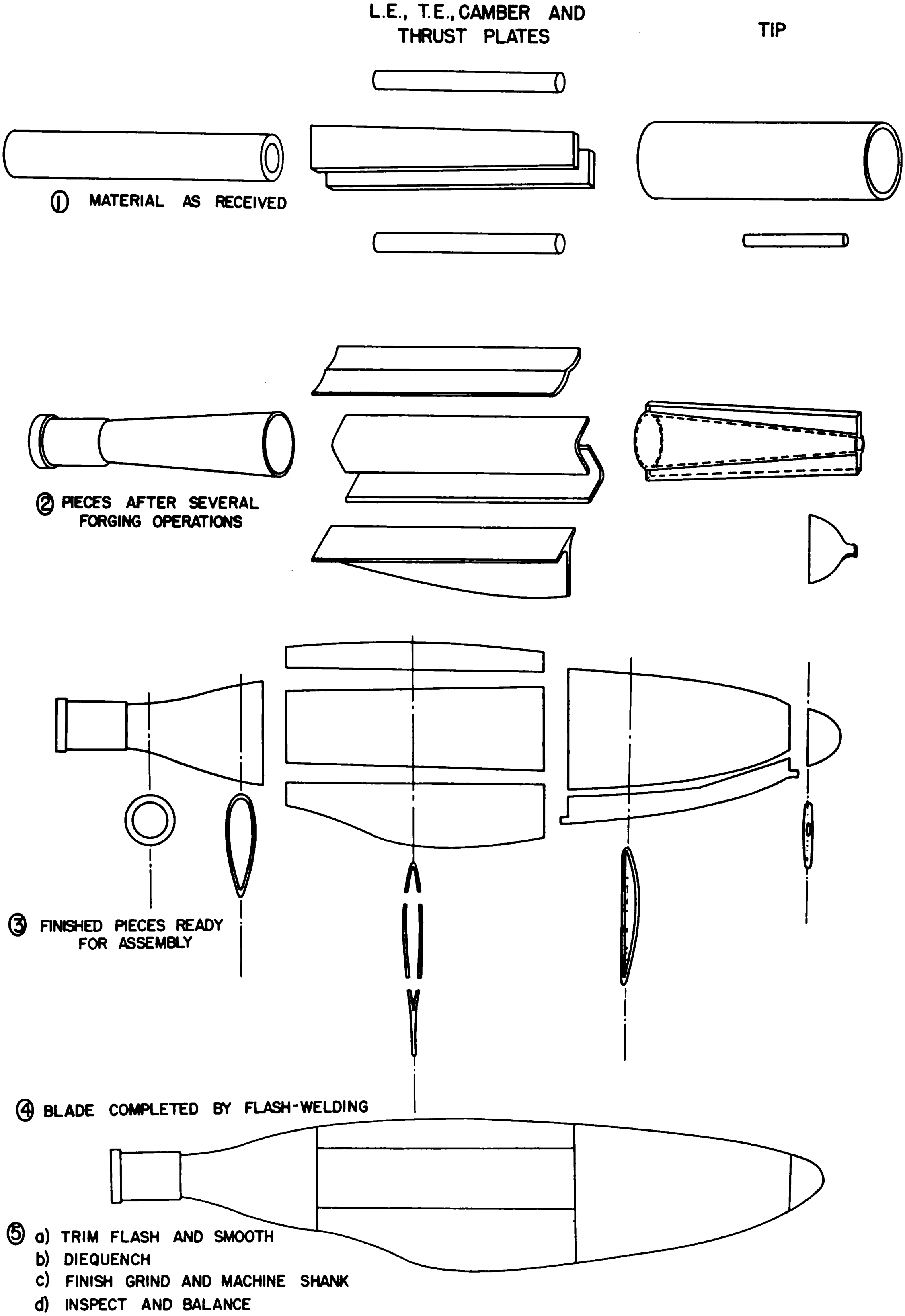

Figure 4.28.—Hollow blade forming operations—type II.

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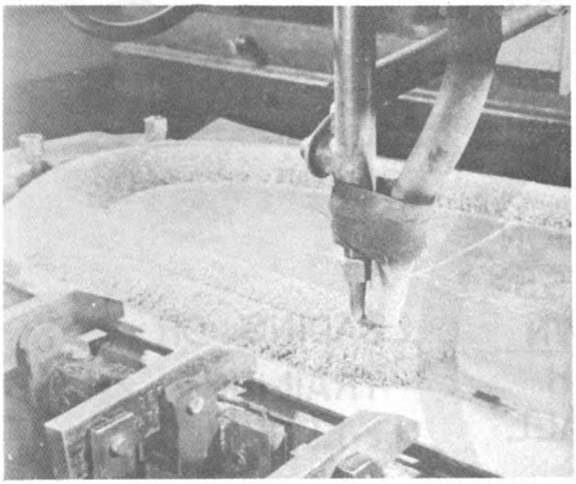

Figure 4.29.—Submerged-melt welding machine.

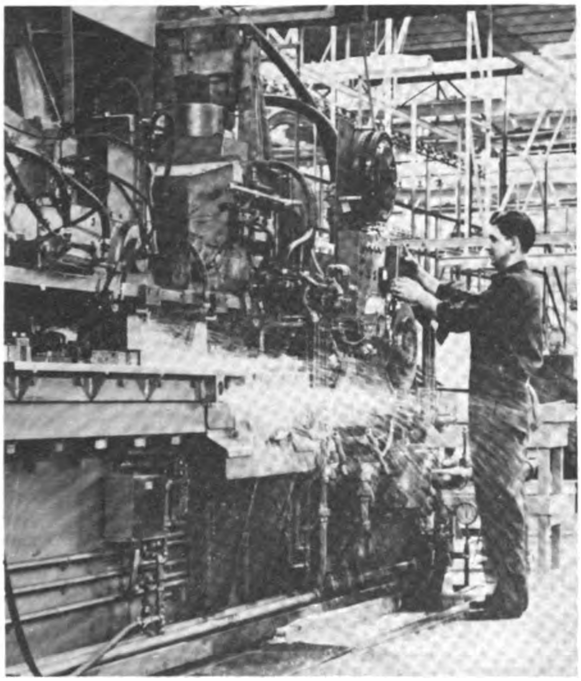

Figure 4.30.—Flash-welding machine.

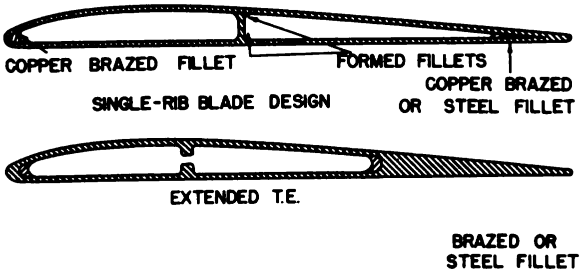

Figure 4.31.—Hollow blade design variations.

design, designated Type II, is essentially a full open corner type joint which can utilize one of several types of arc welding. Both section types have been used successfully in propeller blade fabrication; Type I utilizing flash-welding and Type II utilizing atomic-hydrogen or submerged-melt welding. Typical submerged-melt and flash-weld machines are shown in figures 4.29 and 4.30.

Experience with both Types I and II blade sections has served to emphasize that processing details such as hardness of welding rod, preheating and post-heating techniques, welding machine speed setting and weld material selection may individually or collectively so control the prevalence of micro-cracks, gas bursts, slag inclusions and other discontinuities as to directly establish the endurance limit of the blade in bending fatigue, with or without combined steady stress.

(3) *Inspection and control of joining methods—Monocoque sections.* The effects of the variables enumerated have been demonstrated by failure in the weld of a great many hollow blades of the monocoque type. Therefore, in designing assembled sections, exact specifications must be written for weld (or braze) processing and for assessing the size and nature of acceptable discontinuities. These specifications can be established only by careful research and test studies of the particular section design under consideration, since design differences preclude general statements of acceptable imperfections. A large variety of assembled sections other than Type I or Type II can be conceived, involving other weld and rib locations, and involving methods of joining other than welding. Use of brazing, organic adhesives or other continuous bond techniques, with proper consideration of limitations of properties of materials, present quite a variety of possibilities for forming blade components. The sketches shown in figure 4.31 indicate some possibilities of blade design variations.

(4) *Seamless tube monocoque blade sections.* Monocoque sections without joints can be produced as easily as those with welded joint. Two seamless sections which have been fabricated successfully, are illustrated in figure 4.32.

A seamless blade section (Type III) has been produced from a cold drawn tube, contour machined, to provide proper radial and chord-

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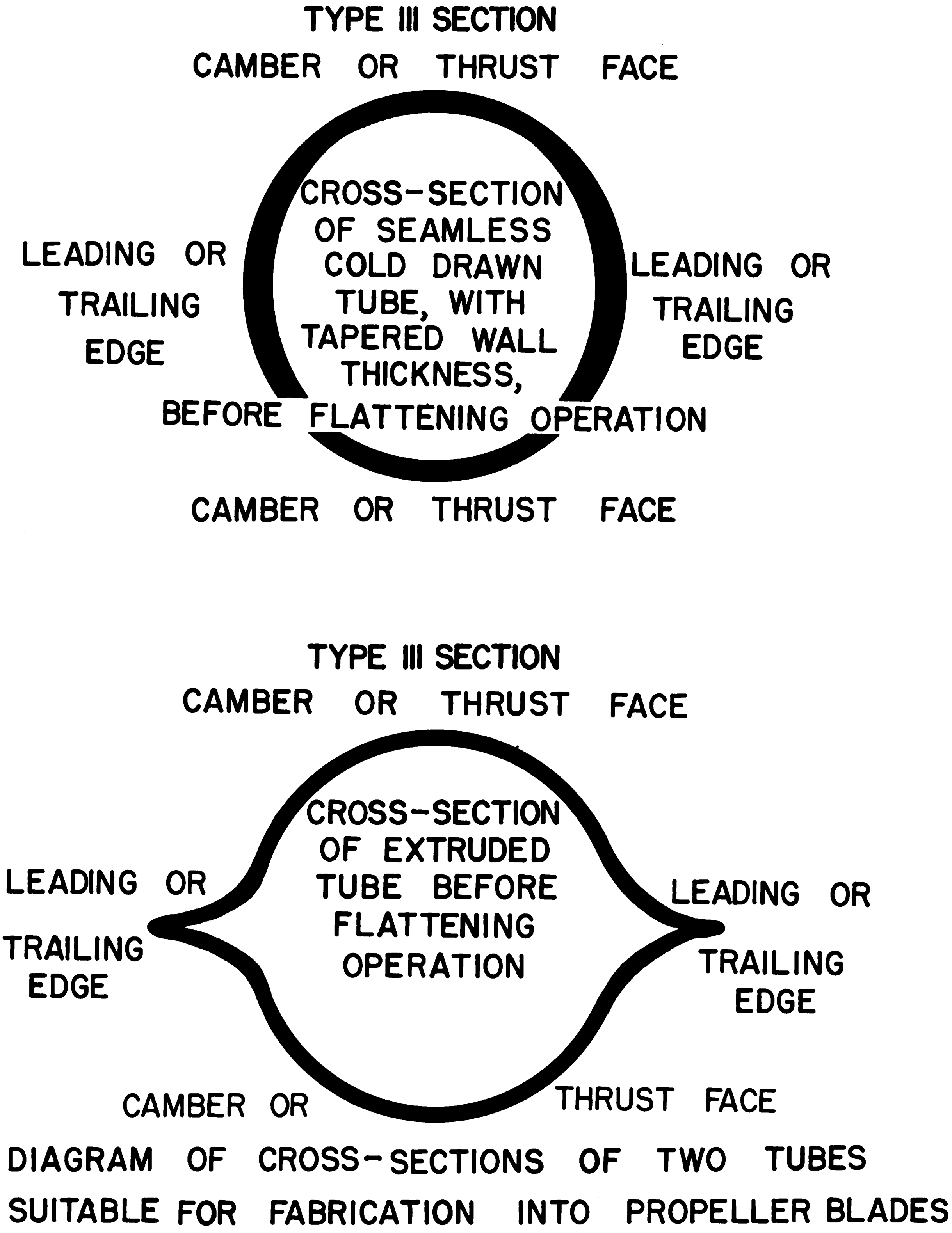

Figure 4.32.—Seamless blade sections.

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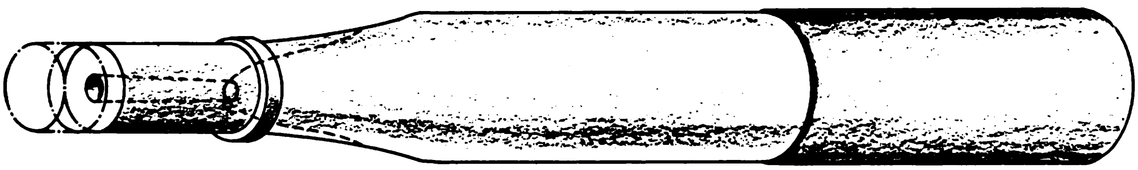
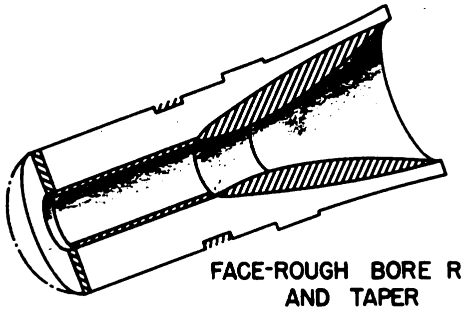
TUBE DRILLED, HONED I.D. AND TURNED O.D.

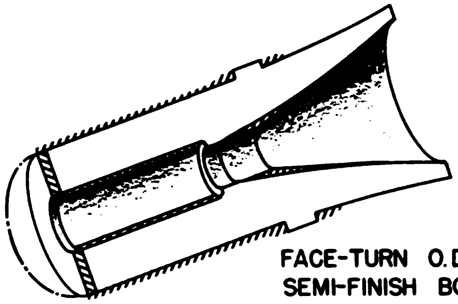
TUBE SWAGED AND CUT TO LENGTH



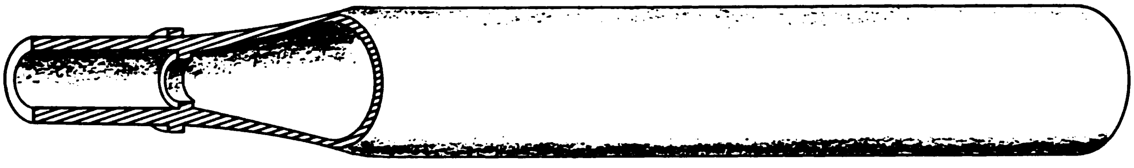
END OF TUBE UPSET



FACE-ROUGH BORE RADIUS
AND TAPER



FACE-TURN O.D.
SEMI-FINISH BORE
TAPER AND RADIUS



TUBE CAM TURNED AND POLISHED O.D.
POLISHED I.D.

Figure 4.33.—Hollow steel blade process—type III section.

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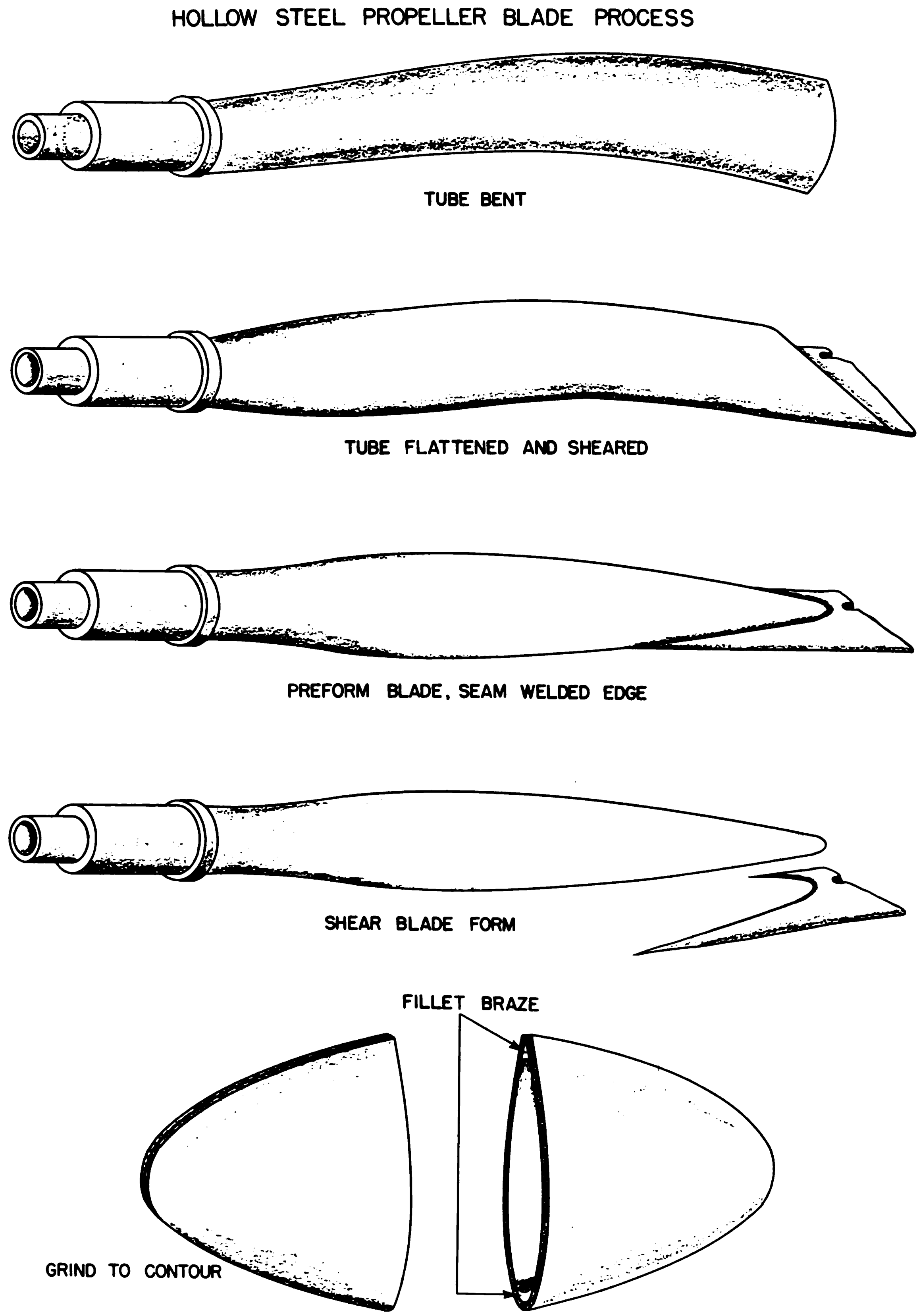

Figure 4.34.—Hollow steel blade process (cont'd)—type III section.

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wise thickness distribution along the blade. After the contour machining operation and after the shank section had been formed (by swaging) to obtain desired diameter and wall thickness, the tube was flattened hot. The sequence of machining operations is shown in figures 4.33 and 4.34.

Final uniform blade wall thickness may be obtained by contour milling wherein the cutters are controlled by means of profile followers. The sketches of figures 4.33 and 4.34 should be sufficient to outline the principal machining operations required to produce this type of blade section. Final blade forming to required dimensions may be accomplished in accordance with common practice of blade processing as outlined elsewhere in this handbook.

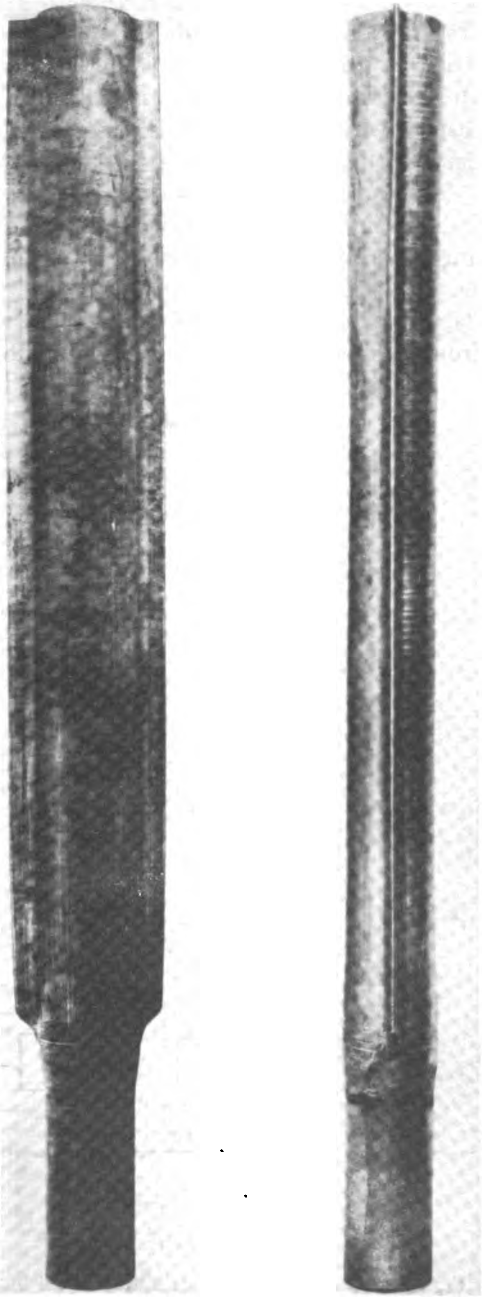

Figure 4.35.—Extruded hollow steel blade.

However, a discussion of the seamless tube type blade section would not be complete if emphasis were not placed upon the importance of proper internal fillets. In this section type, as well as the Type IV section, a discussion of which follows, the need for proper internal fillets is so urgent that supplemental alloys must be introduced to produce fillets if proper fillet contours cannot be maintained during the tube forming operations. As previously shown in figure 4.20, copper fillets may be placed in the outboard blade sections crushed during the forming operation. Experience with this type of fillet formation indicates that fillet radii may be determined in accordance with the following relationship:

$$R_f \geqq t/2$$

in which

R_f=fillet radius

t=plate thickness

For production of this type of blade section, forging presses must be designed to exert pressures required for forming and swaging particular blades. The machine pressures are not unreasonable, however, as indicated by the size of presses (4000 ton) used to form the blade.

(5) *Extruded monocoque blade sections* (*Type IV*). The Type IV blade section (fig. 4.32) may be formed by extrusion to blade contours adaptable to profile shaping and flattening. Detailed discussion of extruded blade sections is warranted since extrusion of complicated shapes formed from high alloy steels, such as SAE 4300 series, has shown considerable promise in propeller development. Illustration of a typical extruded hollow steel blade is shown in figure 4.35.

The extruded section shown is not necessarily of optimum design but does indicate a general type of extruded propeller blade section. The basic operations involved in fabrication of a hollow steel blade from extruded tubing are illustrated in figure 4.36.

The sequence of operations, required in extrusion of the blade section shown, has been set up in table IV–4. In general, the fabricating operations of the extruded type blade differ from those of the seamless tube only in minor details. Shank and outboard sections are finished by conventional propeller blade machining and grinding. Grinding operations are performed after a spot milling process designed to establish plate thickness. Of course, variations of the procedures outlined may be made to fit particular manufacturing requirements.

TABLE IV–4. *Extrusion Operation Sequence for Single-Piece Monocoque Section—Type IV.*

1. Extrusion of tube suitable for fabrication into propeller blade. Extruded tube has tapered wall thickness throughout to meet design conditions. Protruding ears will form leading and trailing edges.
2. Preparation for flattening
   (*a*) Grit blast all surfaces.
   (*b*) Bore inside diameter of shank.
   (*c*) Machine outside diameter of shank.
   (*d*) Spot mill and grind to specifications.
3. Insert hinged mandrels and flatten tube (cold process) in press.
4. Preparation for final forming and quench
   (*a*) Weld tip.
   (*b*) Perform hot forming operation to give final blade profile shape and twist. Heated hollow blade in die receives gaseous nitrogen under pressure which expands and forms blade metal to the die cavity.
5. Final operations
   (*a*) Die quench.
   (*b*) Draw.
   (*c*) Inspect and grind fillets.
   (*d*) Cut off welded tip.
   (*e*) Plate surface with zinc.
   (*f*) Insert rubber tip and rib.
   (*g*) Finish blade.

There are three particular sections of extruded blades which must receive careful attention, namely:

(*a*) Fairing between shank and extruded blade.
(*b*) Internal leading and trailing edge radii.
(*c*) Plate thickness adjacent to leading and trailing edge.

Shank-blade fairing will establish the position of the first outboard airfoil section relative to the hub. This indexing operation will determine the proper radial distribution of plate thickness. Furthermore, in this region (faired hub end of the blade) a sufficiently high extrusion ratio must be obtained to insure that necessary physical properties will be retained after heat treatment. The ultimate physical properties of the blade material will be greatly influenced by material working as well as by extrusion ratio. (Extrusion ratio has been defined as the ratio of cross sectional area of the original material billet to the cross sectional area of the extruded tube at any given point A/a.) Typical extrusion ratios of shank end and outboard sections are: 8/1 and 25/1, respectively. The outboard section material possess the best physical properties, usually.

The problem of obtaining proper internal leading and trailing edge radii can be considered only in conjunction with die and mandrel wear, scoring of fillets and internal contours after flattening. Exact insert wear to be expected from a given extrusion design cannot be estab-

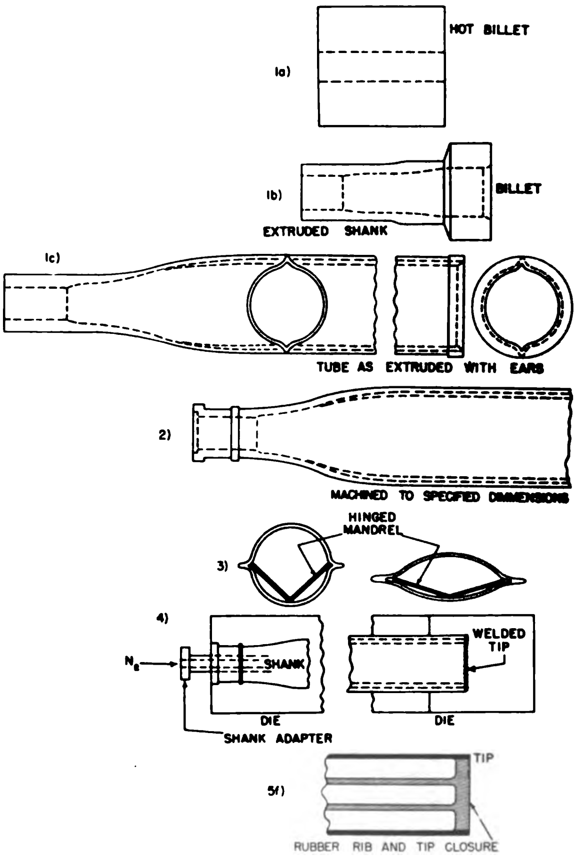

Figure 4.36.—Fabrication of hollow steel blade from extruded tubing.

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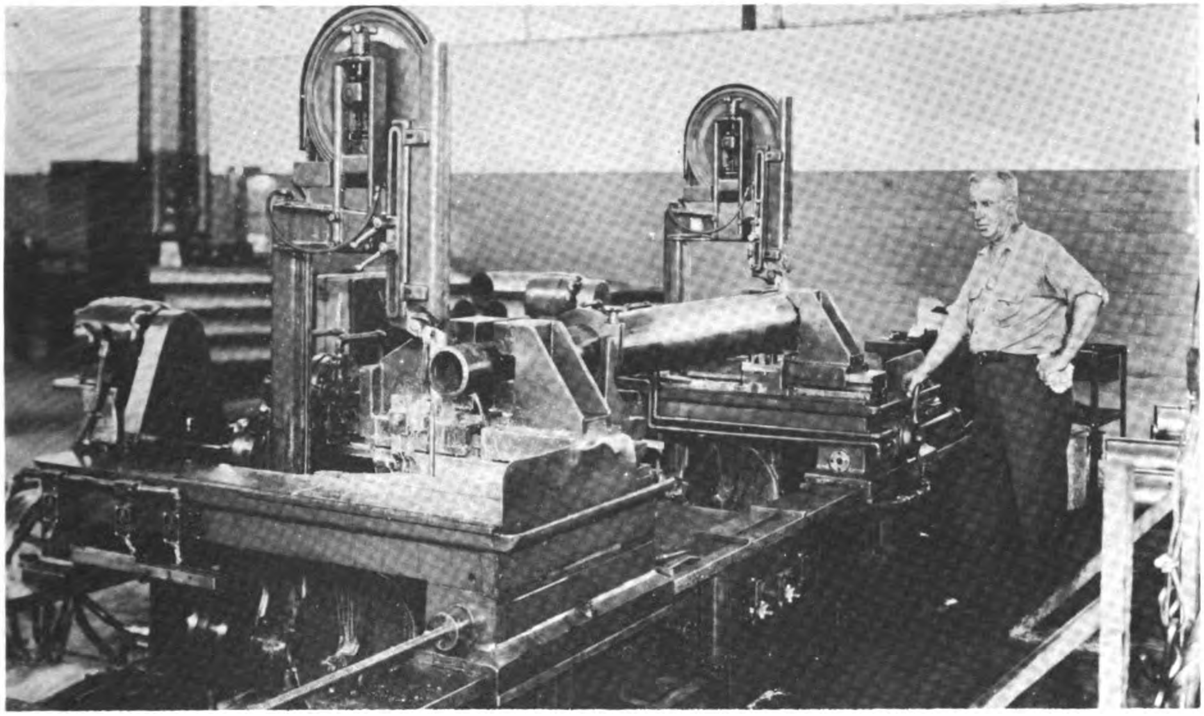

Figure 4.37.—Machining extruded tube for type IV blade section.

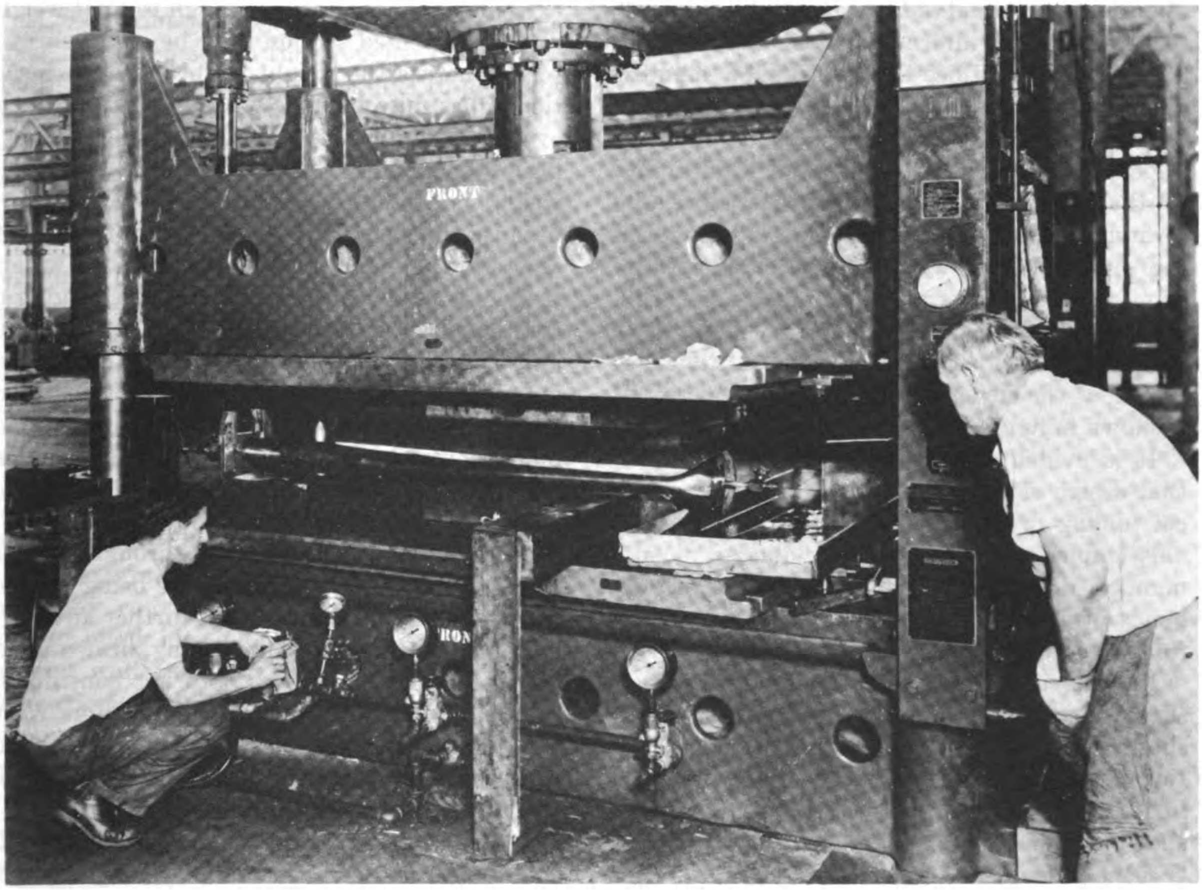

Figure 4.38.—Blade forming press.

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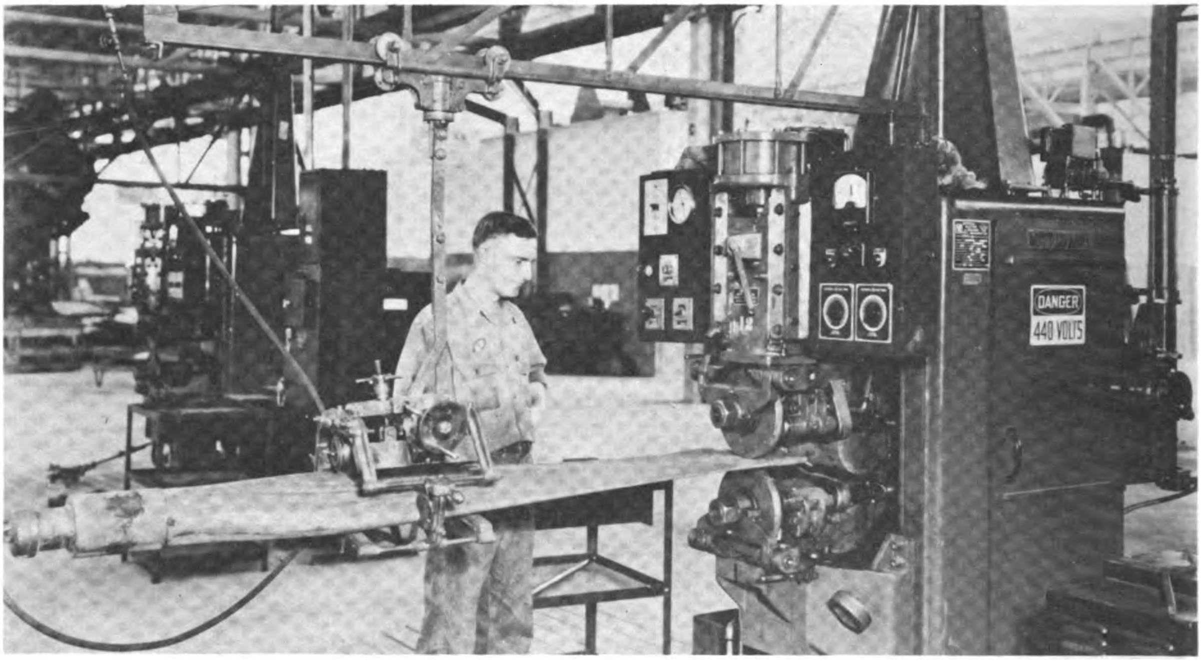

Figure 4.39.—Blade welding machine.

lished prior to actual trial. Therefore, no quantitative statement can be made relative to optimum internal radii design, but, in general, the smaller the internal radius of curvature, the greater will be the danger of mandrel chipping.

Plate thickness adjacent to leading and trailing edges of the section will establish suitability of the section for subsequent flattening and forming. Both hot and cold methods of forming appear feasible with proper control. Improper ratios of internal radii of leading or trailing edge mass to plate thickness will result in channelling. Illustration of the effects of channelling at the edges during flattening operations is shown in figure 4.22.

It is evident from the preceding discussion that design of die and mandrel is the most critical tooling problem. As with forging presses, only empirical methods are available for die and mandrel design. Therefore, assurance of adequacy of designs will emerge only after successful extrusion trials.

Indicative of the size of machine tools necessary to successful blade extrusion, the blade shown in figure 4.35 was obtained from a 5,500 ton extrusion press. Typical equipment used in forming propeller blades after extrusion is shown in figures 4.37, 4.38, and 4.39.

(6) *Comparison of seamless and welded sections.* From the standpoint of rough to final weight, either non-welded section offers advantages over a milled plate arc-welded section. In extreme cases, the ratio of rough to final weight of an arc-welded section may be as much as 7 to 1; whereas the weight ratio of seamless section types may be as low as 1.5 to 1.0. However, this comparison should not be taken as a basis to assume that high rough-to-finished weight is a requirement of assembled sections, because the weights involved are not attributable to the joining processes. The weight ratio of a flashwelded section, if press forging of components to close tolerances were used would approach the smaller ratio. This ratio could be approached, also, with arc-welded sections, were the plates taper-rolled to contour. In a like manner, waste material accompanying seamless tube section fabrication could be reduced by achieving wall thickness through hot or cold contour rolling, or by drawing through contour dies. Some of these methods are being applied to propeller blades now. But further advances in the arts of press forging, rolling, drawing and extruding may be expected to act continually toward waste material reduction. Some wastage always must be tolerated to accommodate thickness allowances desirable for balancing and other design considerations.

In all cases involving production of monocoque type blades, inspection by magnaflux or X-ray is necessary after each operation that

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might create faults or irregularities, or each operation that might develop faults or irregularities from existing sub-surface discontinuities. For example, magnaflux inspection of a Type I section, following intermediate and final grinding to design blade thickness, revealed bond line faults that developed, undoubtedly, during the welding operation. These faults were not visible during inspection which followed welding.

It is apparent that a large number of methods exist for fabricating monocoque blades. The advantages and disadvantages of a given method are, inherently, a part of particular techniques developed to meet manufacturing peculiarities, such as availability of certain equipment (for instance, sheet mills adaptable to rolling tapered plates) and capacity of machine tools. Unforeseen difficulties may arise, in any process. Arc-welding procedures have caused scrap loss as high as 60 to 80 percent, in unusual cases. Such difficulties cannot be particularized, and can be solved only by applied research and development.

Tapered Hollow Beam Blade Fabrication

(1) *Type classification and general considerations.* As discussed in the propeller design section of this handbook, it is possible to design a blade, theoretically, in which most of the propeller load would be carried by a central hollow beam. Aerodynamic requirements would be met by use of an airfoil section, formed as a separate shell, attached to the hollow beam by welding or brazing. Several methods have been developed and are available for fabrication of this type of blade. Undoubtedly, other methods, as yet untried, could be developed. The general methods of forming the hollow beam are:

(*a*) Single piece or integral unit (Type V).
(*b*) Multiple Piece Assembly (Type VI).

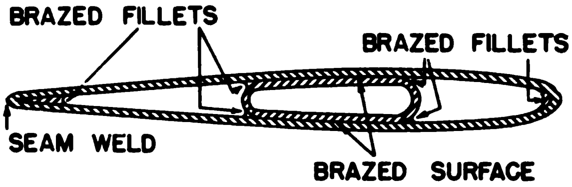
Sketches of typical hollow beam blade sections are shown in figure 4.40.

The integral unit hollow beam has been produced by cold rolling and pressing a hollow circular blank into a long, elliptical tube having tapered wall thickness of proper distribution. Formation of elliptical tube sections can be accomplished, readily, by extrusion or push bench forming.

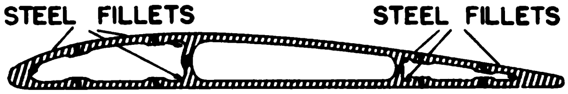
The Type VI blade section may be assembled by welding (flashwelding has been used) or brazing depending upon joint design. Considerable variation in design features of the Type VI blade can be obtained; for instance, the beam may have overhanging projections to simplify attachment of sheets that form the airfoil contour.

CORE-SHELL TYPE

a) TYPE V BRAZED ASSEMBLY



(b) TYPE VI FLASH WELDED ASSEMBLY



TWO-RIBBED DESIGN WITH HEAVY BACKBONE (EXPERIMENTAL)

Figure 4.40.—Hollow beam blade sections.

Generally, the major difficulty encountered in development of a tapered beam type of blade has been design of the joint attaching the airfoil envelope, or shell, to the beam. Use of a complete wrap-around sheet will introduce shear as the major joint stress developed by the blade during operation. This type of loading favors shell attachment to the beam by brazing if joint edges can be protected against tearing action caused by plate vibration.

One advantage of a tapered hollow beam is the reduction of material waste, incidental to blade fabrication, to a negligible quantity. Brazed sections can be produced by cold rolling the core to final dimension without loss of material; the sheet shell should be rolled to finish thickness. Flashwelded, Type VI, assembly will permit component formation with only forging flash material loss. In the latter case, skin allowance of only .0015 inch need be made for cleaning.

(2) "*Core-shell*" *section hollow beam blade* (*Type V*). The sequence of principal operations involved in development of a Type V hollow beam blade has been portrayed in figure 4.41.

In some cases, with proper choice of alloy, brazing, tempering, and final contouring of Type V blades have been accomplished in one operation. Design of the cut-off region (operation step 4, fig. 4.41) at the shank must include

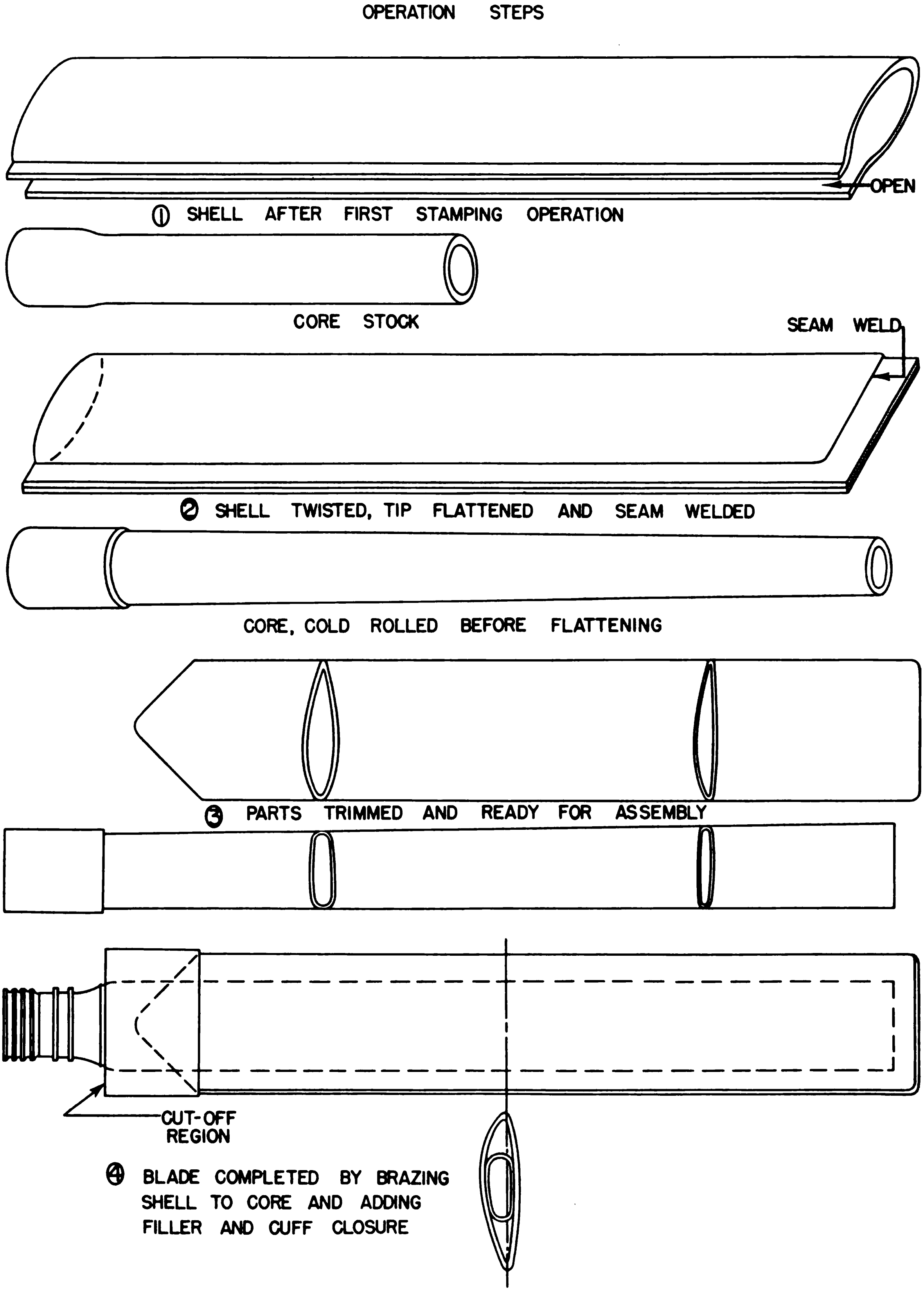


Figure 4.41.—Type V—hollow beam blade.

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consideration of the effects of modes of blade vibration as well as effective contribution of the shell to section modulus. Accurate analytical computations of stresses in shell structures in the cutoff region of hollow beam blades is most difficult. However, it can be shown that localized peak stress would be highest for a 90° cut-off section with optimum stress distribution occurring in a 45° cut-off section. These two cut-off sections for a Type V blade are shown in figure 4.42.

Since stress induced in the blade will be caused by primary bending rather than secondary plate vibration, optimum stress relationship exists at the 45° cut-off regardless of stiffening employed at the section. Attachment of stiffening bulkheads, in filled blades, by riveting has been found to be acceptable if primary stresses are not transmitted from the beam to the shell. Transmission of primary stresses from beam to shell will occur only if the bulkhead is rigidly attached to the primary beam. The cut-off region being a critical stress region, will require rigid inspection to insure procurement of a sound structure.

Tearing of brazed joint edges can be curtailed by filling the shell cavity at blade leading and trailing edges with a light cellular material of some kind. Filled blade sealing must be carefully controlled to insure elimination of voids in the braze. Inspection of blade filler and seals may be accomplished by pressure application and shell sounding by tapping. The latter method (using light hammer or metal rod) will disclose hollow spaces or delamination through tone change.

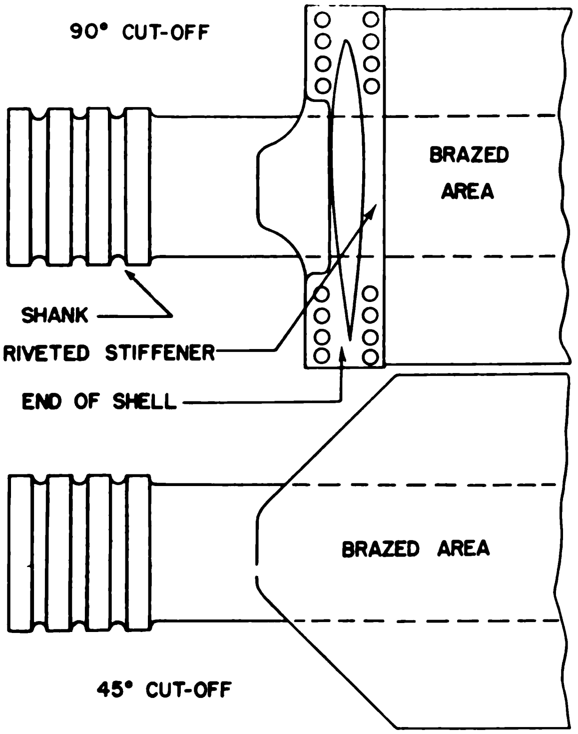

Figure 4.42.—"Cut-off" regions for hollow beam blade.

The Type V section lends itself to X-ray inspection since the braze is quite thick and fully exposed (to X-ray) under a comparatively thin shell. Inasmuch as the critical region for stress concentration and tearing exists along the brazed joint, X-ray inspection will reveal existing voids and permit rejection of unserviceable blades. Grit blasting braze edges will insure removal of ragged, overhanging drops of alloy which might form a nucleous from which fatigue failure could develop.

(3) *Jointed hollow beam blade—Type VI.* A typical jointed hollow beam blade is illustrated in figure 4.43. Fabrication of the required components of this type of blade presents serious problems which should not be considered insurmountable.

The integral projections of the flat core have been tapered in thickness from the beam to the edge of the brazed joint to aid in stress reduction. Hence, by design and control of beam rigidity, high stress concentration and tearing action in the brazed joint are prevented. Final blade contour and pitch distribution may be obtained in a blow-up die in much the same manner as that used in production of monocoque type blades.

An illustration of a Type VI propeller blade, exploded to depict the various components is shown in figure 4.44.

Since this blade is, in reality, a Type II, flash-welded blade, it may be fabricated in the general manner described for Type II blades.

Hollow Blade With Principal Load-Carrying Member (Type VII)

Blades can be designed so that one side, usu-

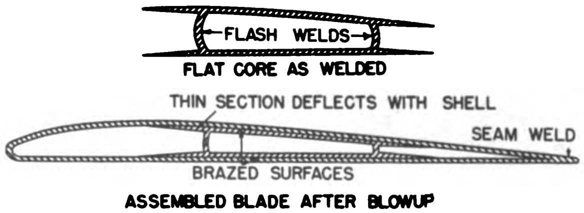

Figure 4.43.—Type VI—hollow beam blade.

EXPLODED VIEW OF PRODUCTION SP-36 BLADE - EXCLUDING BALANCE CUP AND DEICING HOT AIR BULKHEAD

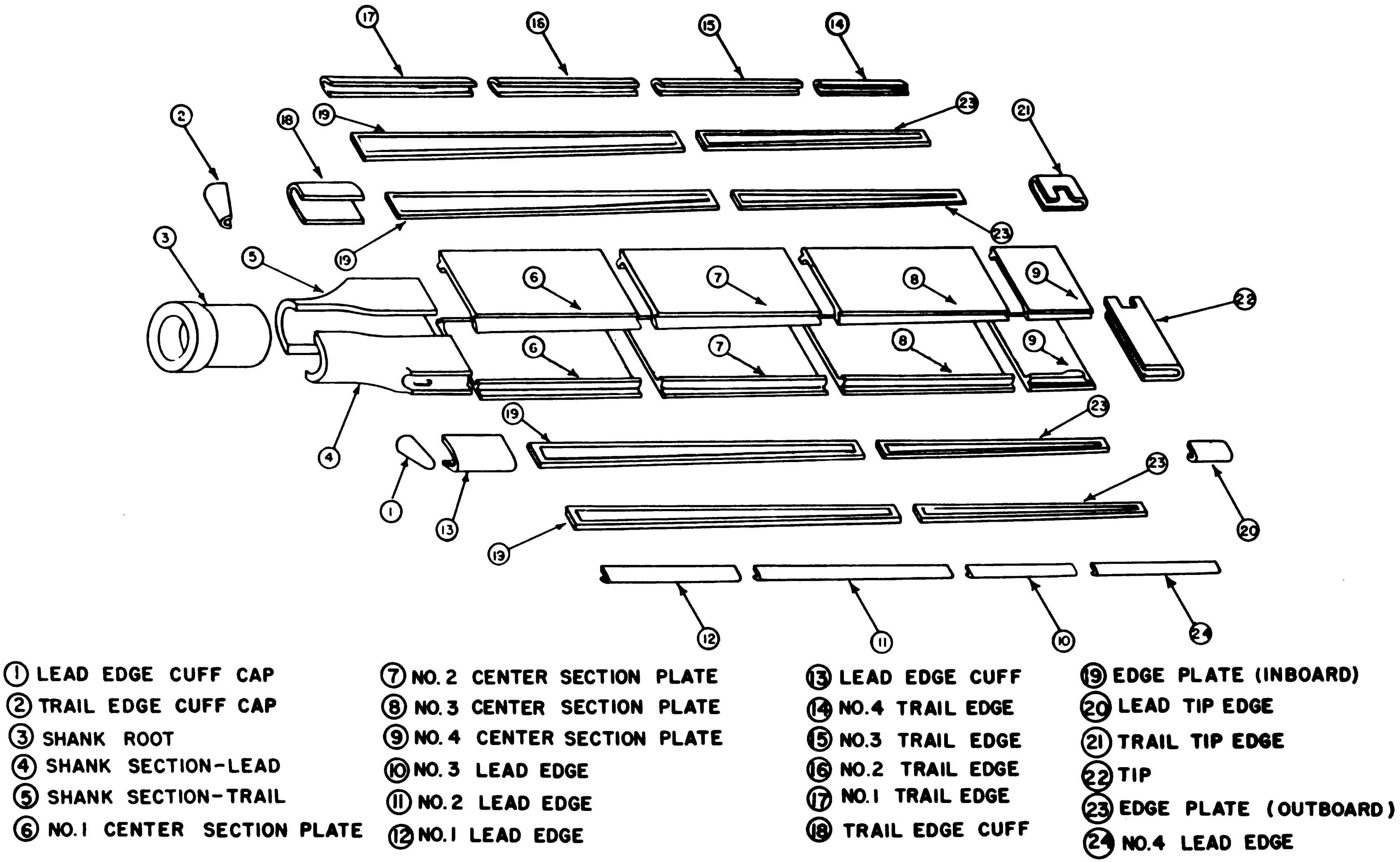

Figure 4.44.—Exploded view of production SP–36 blade.

ally the thrust face, will carry most of the load, with the camber face contributing mainly to formation of airfoil contour. A thrust face loaded blade, Type VII section, is shown in figure 4.45. Hereinafter, this main load-carrying member will be referred to as the principal member. Principal member-type blades may be designed with a shear loaded joint between thrust and camber faces which will permit use of brazed joints.

The principal member may be forged, machined, or formed in any manner consistent with existing equipment. Furthermore, as with the tapered hollow beam, it is possible to assemble the principal member from several smaller pieces.

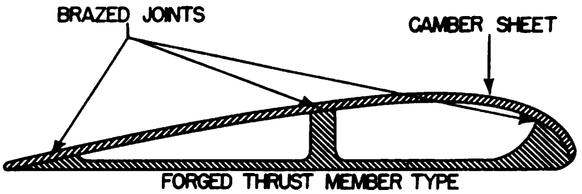

Figure 4.45.—Principal member blade—type VII section.

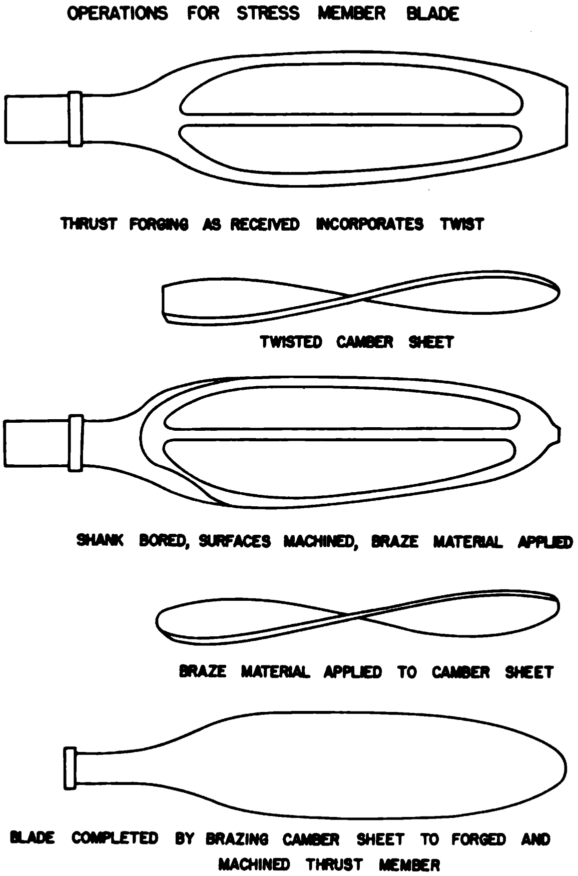

Figure 4.46.—Principal stress member blade fabrication.

Generally, in this process, pitch distribution may be obtained during formation of the principal member, with final contour being obtained in the *blow-up* die. Operational sequence of blade production is illustrated in figure 4.46. In wide blades of this type having thin cover sheets, generally one or more ribs will be required to obtain needed section moduli.

Rib termination, as with any ribbed blade, may be a critical design and inspection feature. Figure 4.47 illustrates a blade failure traced to the use of abrupt radii in the rib termination region. Any termination near or at the braze bond line must be carefully designed to prevent stress concentration in the braze.

The simplicity of this design permits adaptation to conventional tooling, such as contour millers or duplicators. Principal stress members when formed from hammer forged thrust members, may have a rough-to-final weight ratio of four to one. This weight ratio may be reduced by press-forming or contour rolling the member to final dimension.

One advantage of a brazed cover sheet type of fabrication is that full inspection can be given to the principal member before final blade assembly. Hence, final inspection may be aimed primarily at the cover sheet joint, which

Figure 4.47.—Rib termination fillet failure.

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offers the same advantages to X-ray inspection as a tapered beam section.

Joint Processing

(1) *General considerations.* It is apparent from the foregoing descriptions of blade section fabrication that proper welding and brazing technique is essential to modern propeller blade fabrication. Certain characteristics of welding and brazing processes have been established and the solutions to many general problems have been found. The general developments of joining processes deserve special consideration since the strength of joints may define overall blade strength.

(2) *Welded propeller blades.* It has been found that the quality of steel to be welded is an item of primary importance in welding processes. Routine chemical analyses are insufficient to properly define material properties essential for satisfactory welding operations. Sulfide composition and distribution in the weld material apparently are prime factors of "weldability" in arc welding processes. So-called penetrators, inherent in flash-welded processes, are believed to be related to the presence of oxygen, but the present state of knowledge precludes dogmatic statement. Efforts to obtain high quality steels suitable for arc welding have met with some success, but unceasing quality control is necessary to procure even a minimum level of acceptable metal.

Use of weld rod compositions lower in sensitivity to cracking than plate material and careful control of carbon content in weld rod and weld metal have reduced *grind-out*, blade scrap and weld deposit rework. Multiple magnetic inspection has aided maintenance of final joint quality at a level usable in blades but at the

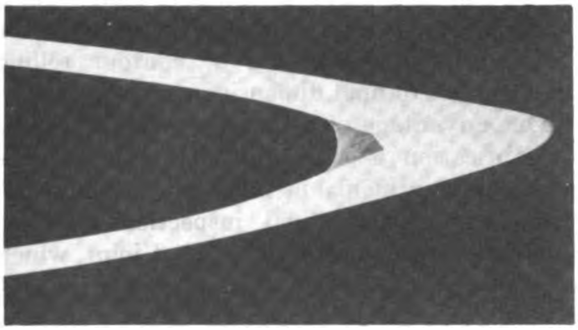

Figure 4.48.—Finished blade fillet.

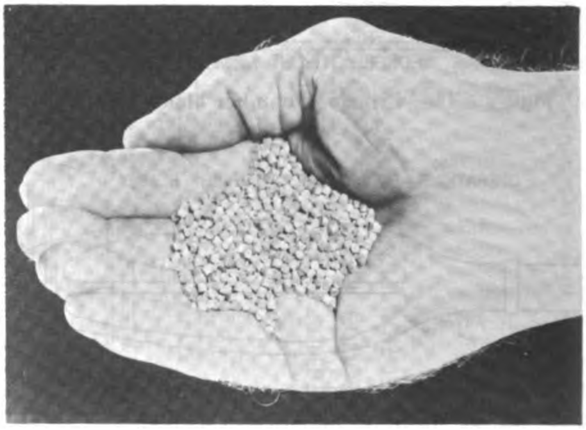

Figure 4.49.—Alloy pellets for brazing.

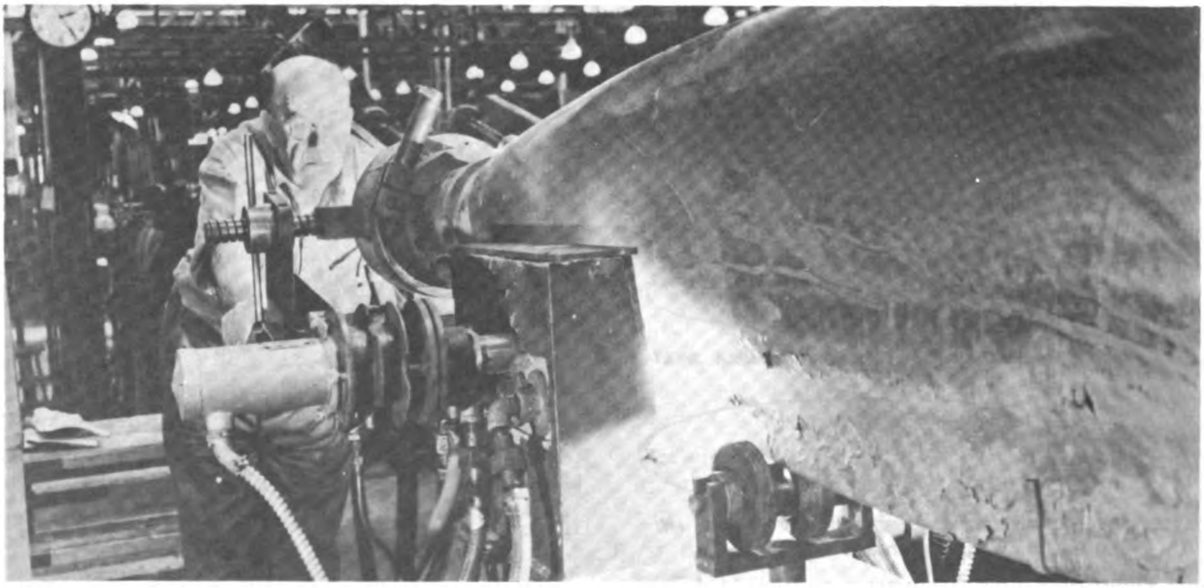

Figure 4.50.—Fillet forming machine.

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expense of economy of manufacture. Apparently, greater use of welding in blade fabrication, with low scrap rate and reasonable economy, will be more dependent upon improved joint design and weld accessibility than upon improved welding processes. With proper joint design, it appears that use of machine-controlled welds may reduce the amount of repair. Seam welding, flash-welding, argon (or Heli-arc) and submerged-arc welding show considerable promise of future development to meet blade fabrication requirements.

(3) *Brazed joints in propeller blade.* Development of brazing processes for use in blade fabrication has introduced a continuing design study of brazing alloys with attendant requirements for proper surface wetting and minimum occurrence of voids. Since the edge of a brazed joint is, almost invariably, the critical area, it is difficult to establish an acceptable percentage of voids within a braze. The braze area nearly always has been made much larger than necessary for an adequate brazed joint, with allowances as high as 25 percent being made for voids. Arbitrary allowances of this nature must be used with caution, since distribution of the voids relative to the joint edge has as much importance as the extent of void area.

Both copper and silver solders have been used successfully in blade fabrication. Techniques in using silver solders have been improved to such an extent that it is now possible to braze during heat treatment at approximately 1200° F. Optimum strength will be obtained with a silver solder braze, thickness of approximately three-thousandths of an inch, while optimum strength of copper braze will be obtained with practically zero thickness bond. These braze characteristics must be considered in both tooling and process design. The brazing alloy may range in form from metallic spray to foil, depending upon blade design. Evidence has not been found, as yet, to indicate applicable variation in bond strength caused by original alloy form.

(4) *Brazed fillets.* Difficulty has been encountered in the use of brazing alloys as fillet material because copper will penetrate steel at alloy melting temperature. Experimentation with copper-manganese brazing alloys has shown that the ratio of steel penetration by this class of alloys to that of copper is about one to seven. Low penetration factor has led to adoption of copper-manganese as a filleting alloy for propeller blades. Temperatures required for filleting copper-manganese alloys introduce dangers of local distortion; hence, the joints must be designed to form fillets in the steel blade rather than in the braze material. The method of forming copper alloy fillets used in the propeller industry is unique. A finished blade fillet of copper is shown in figure 4.48.

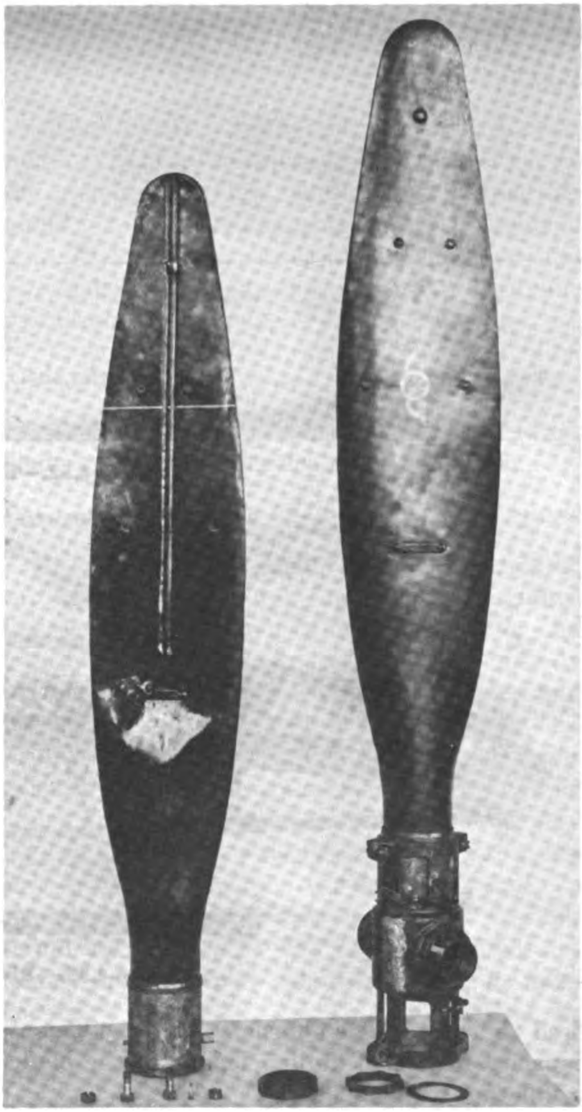

Figure 4.51.—Propeller blade riveted joints.

Salient features of the fillet forming process are illustrated in figures 4.49 and 4.50. Alloy, in the form of a measured quantity of shot, as shown in figure 4.49, must be placed in one edge of the blade.

Then, the blade may be placed on a cam-leveled carriage to move the edge between gas

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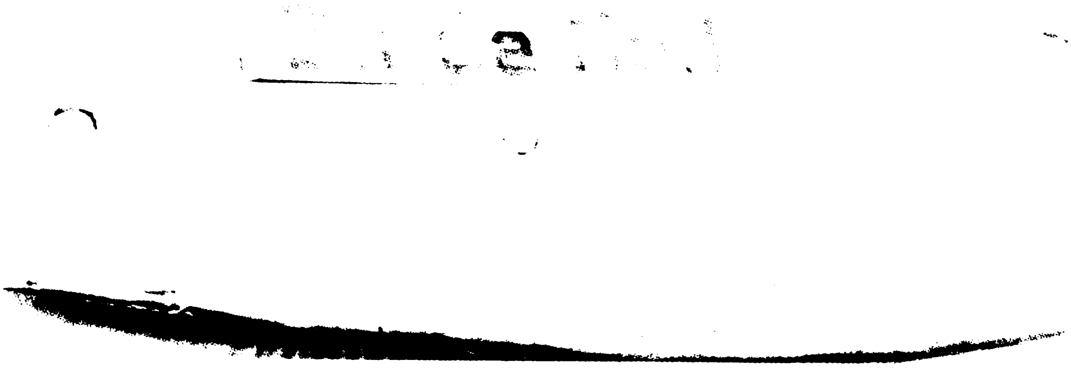

Figure 4.52.—Riveted joint failure.

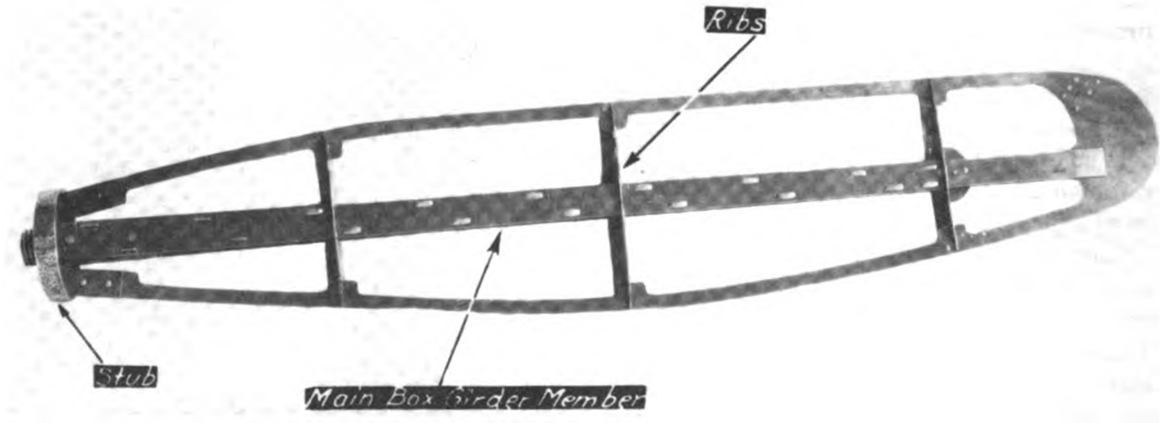

Figure 4.53.—Riveted blade structure.

fired burners. The burners have sufficient capacity to heat a limited length of the blade to filleting temperature.

The cam carriage of the fillet forming machine (fig. 4.50) has been designed to level and tilt the blade while heat is applied, thereby insuring placement of molten alloy in proper fillet forming position. After the fillet has been formed in one edge, the blade must be reversed and the process repeated to braze a fillet in the opposite edge. Local distortion may occur as a result of air quenching the blade from temperature (1800° to 2000° F.) with subsequent fillet cracking. Such cracking was common with the use of oxygen-free high conductivity copper as a filleting agent but has been less prevalent with the use of copper-manganese alloy.

(5) *Bonding processes.* In the field of continuous-type bonding processes, it has been found that only metallic type bonds have displayed properties necessary to withstand combinations of shearing, bending and stripping loads. Intermittent bond joints may be made using spot welds, rivets or bolts. However, intermittent bond assemblies have not proven suitable for use in primary structures of propeller blades under combined stress fatigue loading. Attractiveness of processing simplicity of riveted joints has induced many attempts to adopt riveted joints for propeller blade fabrication. However, high stress concentration at the rivet juncture has limited propeller application of riveted joints. Illustrations of figures 4.51 and 4.52 show riveted joints with rivet heads appearing in the blade skin surface, and subsequent failure under test.

Figure 4.53 shows an application of riveted joints to an internal blade structure.

Figure 4.54 illustrates a bolted propeller blade structure.

The use of local fastenings to reduce plate vibration (as illustrated in fig. 4.55) has encountered the same obstacle, high stress

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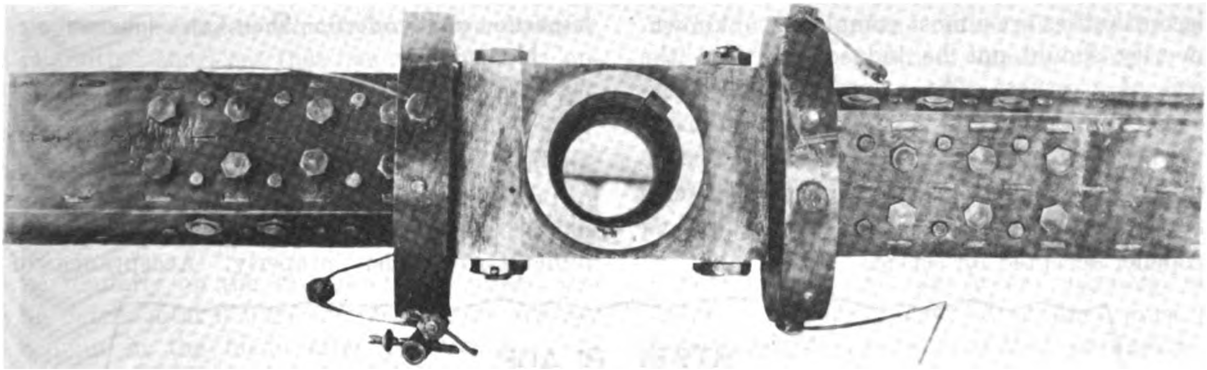

Figure 4.54.—Bolted blade structure.

concentration, that has plagued riveted and bolted joints. In view of past experience, considerable doubt exists that intermittent type bonds or joints ever can be applied safely to propeller fabrication.

Quality Control of Blade Manufacturing Processes and Materials

Quality of Workmanship

As discussed elsewhere in this handbook, a rotating propeller, subjected to high alternating loading, induces in the blade combined alternating-steady stress. This blade condition is somewhat analogous to that applied, in common practice, to small test specimens in combined tension and bending fatigue. The true stress condition in a blade is many times more complicated than any which can be applied by existing small specimen machines. The principles of fatigue must underlie and, in fact, determine the quality of workmanship required in propeller blades to the same extent that those principles influence quality of blade material.

Propeller blade manufacturing practices are directed towards reduction of blade processing irregularities to a minimum. Every effort must be made to reduce irregularities not only in the final cleanup operations, but also throughout each step of the manufacturing process. Carelessness in any stage of propeller production will be almost equally intolerable, since failure directly endangers life, costly equipment and, in case of military aircraft, success of a mission. Processing irregularities may be internal and most difficult to detect. Improper tooling or procedures are as likely to produce blade faults as careless workmanship. In every significant detail, the quality of every blade accepted for service must be known.

Common Blade Irregularities

It is common knowledge, accumulated through long experience, that surface irregularities—such as tool marks, scratches, cuts, and improper fillet radii—contribute most directly to fatigue failure. However, sub-surface and internal irregularities cannot be ignored, safely. Minute irregularities, such as microscopic blow holes in a weld or overhanging blobs of brazing alloys along the edge of a brazed joint in very high stress regions, are sufficient to create stress concentrations severe enough to result in structural failures. Very tight laps and internal surface checks will cause blade failures under proper stress conditions. It is most necessary that all propeller irregularities be eliminated, insofar as possible; particular care must be taken to reject those propeller components having irregularities which are most likely to produce propeller failure in service.

As a general rule, recognition of irregularities can be obtained only after a considerable amount of component testing before or during processing. Open discontinuities in external or internal surfaces of a propeller component will produce failure under proper conditions of stress. A realistic estimate must be made of the probability that stress conditions conducive to propagation of blade defects to failure will be encountered for finite periods during the airplane life. Furthermore, as discussed under the fatigue section of this handbook, it would be a mistake to assume that actual stress will be fixed by the calculated load acting on the cross sectional area of good material, since the internal stress conditions adjacent to open

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discontinuities are almost completely unknown. Severity should not be judged solely on the basis of grossness. As a matter of fact, experience in the field of propeller blade fabrication has shown that gross defects rarely cause failure, for the simple reason that gross defects usually have been eliminated from a finished propeller accepted for service.

Inspection and Production Short Cuts—Inherent Hazards

Certain practices which may be termed short cuts for lack of a better definition, are available and have been used in production and inspection of propeller blades. For example, shot-peening has been used, without excessive cost, in areas difficult to polish properly. Acceptance of

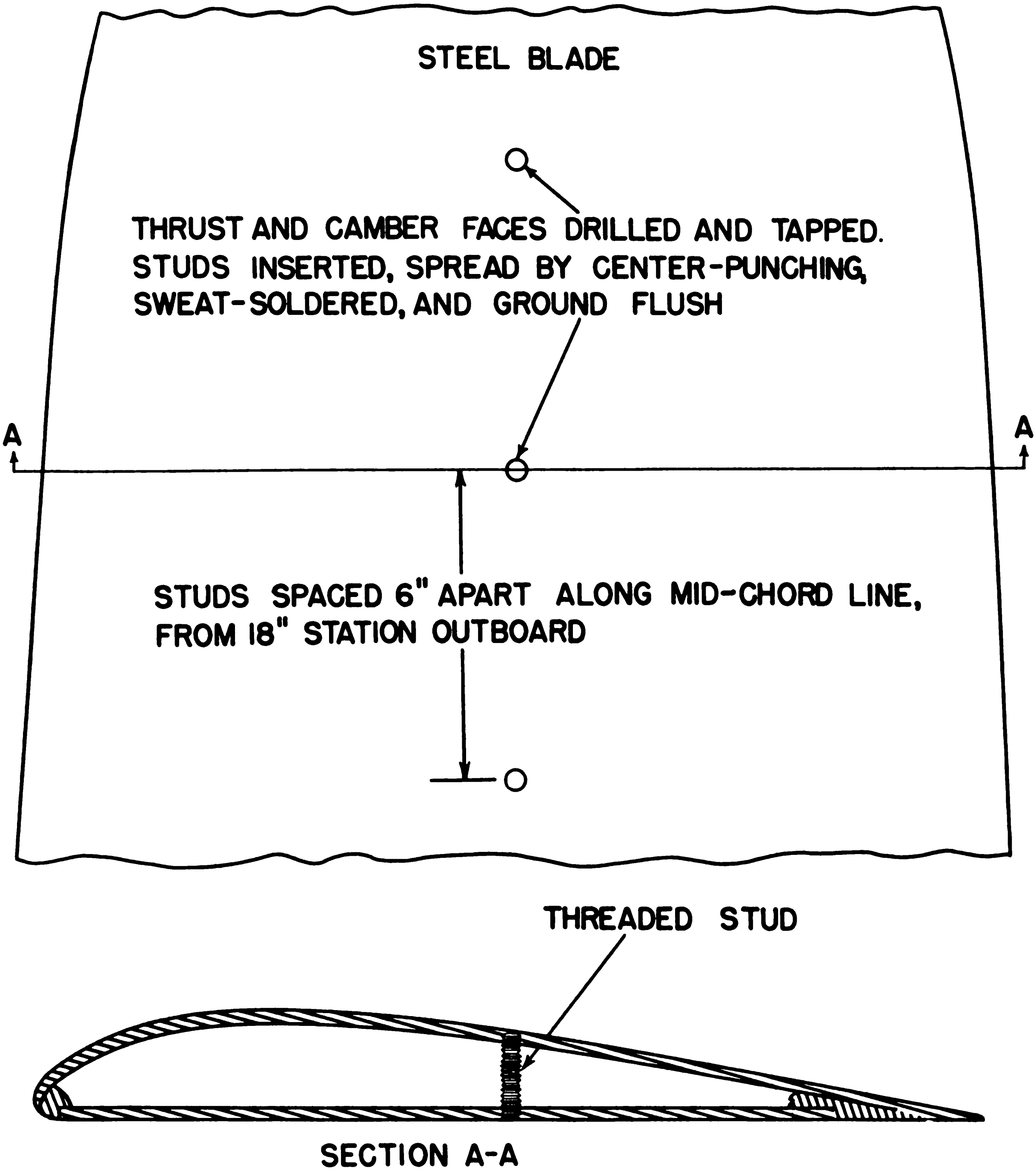

Figure 4.55.—Spool type stiffener.

unground surfaces, where the design permits, is another short cut that has been used. Considerable caution must be exercised, however, in the use of such short cuts. Short cut methods should be adopted for production economy only after the effects of the short cut methods have been evaluated by testing. As generally recognized, even the use of shot-peening, particularly on the surface of thin plates, can be detrimental if high residual tension stresses remain in the blade after processing. Cold straightening propeller blades, for alignment, should not be undertaken unless proper safeguards for subsequent stress relief have been incorporated into the process.

Final Blade Finish

Aerodynamically, the final blade surface has significance only beyond certain limits of roughness. These limits are not well defined and may vary with types of installations. The upper limit of roughness may be considered to be in the order of one hundred micro-inches, root-mean-square value. However, for structural as well as aerodynamic reasons, the surface finish quality should be as high as practically possible, even for internal, unexposed surfaces.

For national defense purposes, it has become a matter of urgency in propeller fabrication to replace skilled manpower with automatically controlled machines that can meet the quality requisites of blade finish. Hand welding certain types of blade structure has been replaced largely by automatic methods such as submerged-arc and flash-welding. Formation of long, continuous welds may have irregularities caused by variations of human performance resulting from fatigue. The influence of human fatigue factor in blade processing has been recognized as an element of statistical quality control. The effect of this human fatigue factor has become apparent not only in blade processing but also in final grinding to blade thickness and surface contour. Misuse of hand grinders by careless or fatigued workers has produced far too many instances of blade thin spots. Hence, the use of forging, rolling, or extruding to final dimension and grit blasting to clean the surfaces after hot operations, as well as for final balance, has replaced much of the hand work.

Quality Control

In a broad sense, quality control is imperative to blade fabrication. In application to propeller blades, statistical quality control has not been accepted widely. It is economical and sensible to produce many items with expectation of a certain percentage of marginal or sub-marginal assemblies. However, there is, actually, no acceptable percentage of submarginal propeller blades because of the costliness of failure. All that human ingenuity can devise to assure quality of product must be introduced; it is recognized that possibility of occasional oversight exists. Consequently, the practice of magnaflux and, in some cases, X-ray inspection has been adopted, not only of the finished article, but also of the article after every process in which irregularities may be introduced. In addition, direct visual inspection of every blade and component has become standard procedure.

Blade Balance Control

(1) *Significance of weight distribution variation.* The blade is the most significant component of a propeller with respect to balance. Blade center of gravity and weight distribution must be controlled, closely. Obviously, with such an irregularly shaped object, close control over manufacturing processes must be maintained to assure satisfactory distribution of metal. Metal distribution in solid blades is more easily controlled than in those of hollow constructions, since adjustments can be made, usually, by judicious removal of metal from solid blades unless metal thickness is approaching the minimum value. Alertness to the balance problem must be maintained throughout hollow blade processing because removal of metal to obtain proper distribution is not always feasible. To illustrate the importance of holding dimensions to close tolerances, the following example has been set up:

Assume a hollow shell blade having uniform width of 17 inches between the 12 inch radial station and the blade tip at 72 inch radius. Further, assume that the plate thickness of the blade shell (both faces) has a variation of only .001 inch from the value specified. This small variation introduces a wieght difference of about 0.6 pound. With its center of gravity at the 42 inch radius, the moment variation will be about 25 pound-inches.

An overweight blade would require material removal which must be accomplished with

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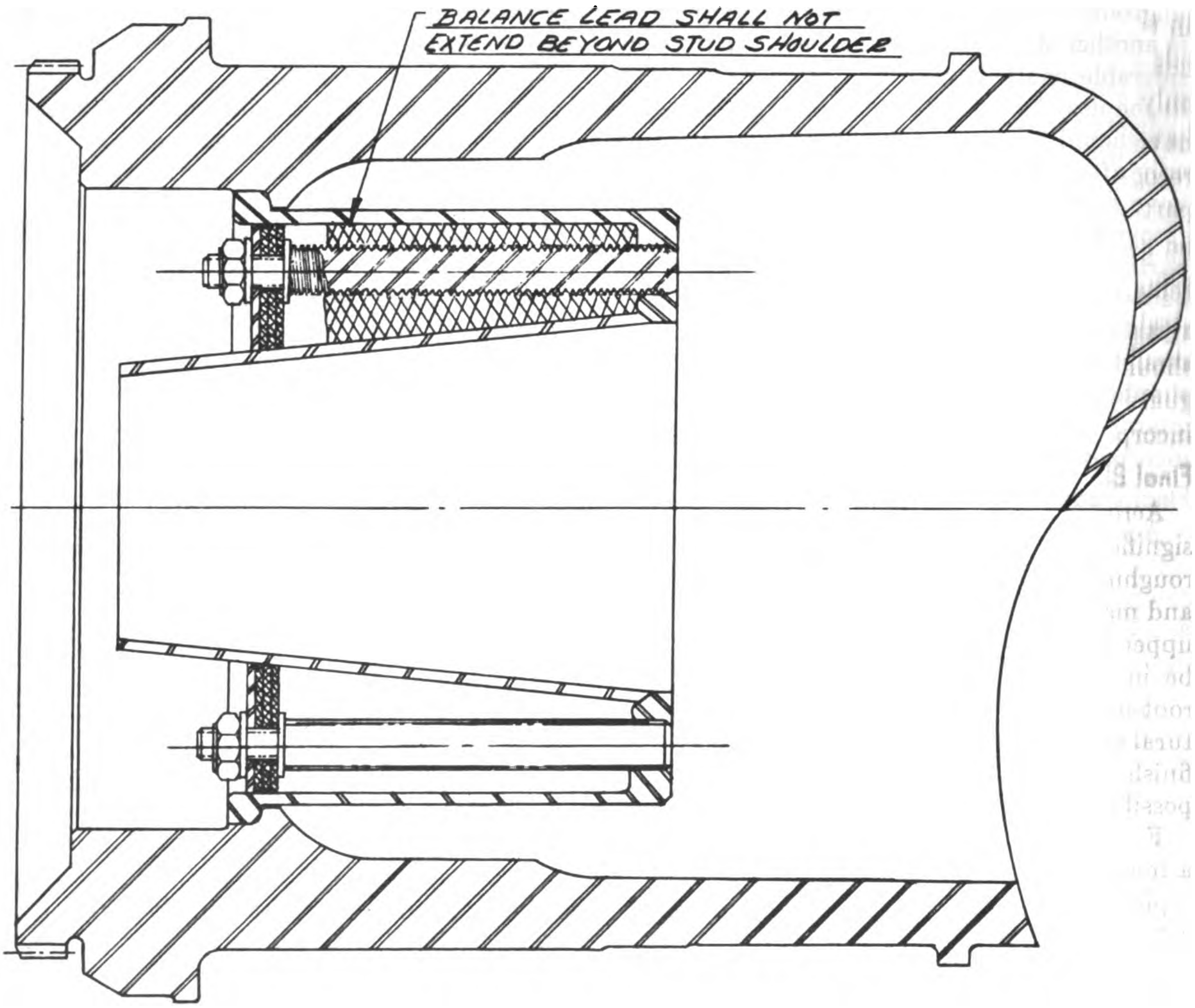

Figure 4.56.—Typical propeller blade balancing features.

great care in order to preserve required thickness. A blade with insufficient weight and thickness would require that a balance correction weight of 2.5 to 3.0 pounds be added in the blade root.

(2) *Balance control of articulated blade components.* The component parts of an articulated blade should be given preliminary balance checks before being incorporated into the blade. Generally, balance standards have been set up for blade components which establish certain limitations to be met before further processing. In early stages, metal can be removed from components to adjust weight distribution. After completion of hollow blade fabrication, removal of metal is exceedingly dangerous because the process may create thin plate in the blade. Removal of even small amounts of metal can affect blade balance, materially, magnitude of the effect being dependent upon the average radius of mass deficiency, of course. It is evident that dimensional control is essential to blade balance.

(3) *Blade interchangeability requirements.* Control of blade master moment, within certain tolerances, must be established to permit blade interchangeability in a propeller and to assure that propeller balance correction can be made within the range of hub balancing features. Propeller blades must be balanced individually in both vertical and horizontal positions. Balancing provisions are incorporated in each blade in the form of a balance cup arrangement which furnishes a small space for insertion of lead. A typical balance provision is shown in figure 4.56. The studs can receive weights which may be necessary to balance the finished propeller.

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(4) *Aerodynamic balance.* Complete propeller balance involves aerodynamic, as well as mass, balance. If equal thrust is not obtained from each blade of a propeller, the equivalent of an unbalanced rotating force acting along a line parallel to the axis of rotation will be produced. This unbalanced force acting along a line located at some radial distance from the axis of rotation will produce a moment of roughness that will be dependent upon the sensitivity of the power plant installation. Pitch angle variations radially along a blade, from specified pitch angle distribution require integration of pitch angle variations in some manner to determine the effective blade angle at a selected reference station. A method for production use has not been evolved although the problem has been considered. Some means for adjusting the angular position of a blade in the hub by small increments must be incorporated in the design of large propellers, to permit adjustment of aerodynamic unbalance.

Some airplanes are very sensitive to the effects of even small amounts of propeller unbalance. Adverse effects are represented by instrument panel vibration and associated vibration of instruments. In addition, propeller unbalance may cause vibration of airplane structure, engines, nacelles, pilot seats, controls, fuel and oil lines. Design of the engine mount has great influence on the extent to which propeller unbalance may affect an airplane.

(5) *Composite effect of component unbalance.* Obviously, plate thickness, edge metal distribution, edge alignment, face alignment, width, or length, individually, can have quite an effect on blade balance. But in the final analysis, overall propeller balance will be determined by the combined effect of separate unbalanced components.

Therefore, if adjustment of any component has been extended to the limit to correct unbalance without achieving balance, then adjustment of other components may be employed to obtain overall balance The cumulative effect of a large number of dimensional tolerances will influence final blade balance. Fortunately, the number of variables is large; hence, normal variation will insure introduction of counteracting effects that prevent unbalance from exceeding correctable amounts. Consideration of the desirability of variation of any detail blade feature to facilitate fabrication, must encompass the effect of the proposed change upon final overall propeller balance.

Required Quality of Blade Materials

(1) *Aircraft quality materials.* A general class of materials, specified as aircraft quality has been produced under conditions of greater quality control than usually employed in mill run production of materials. The exact effect of this manufacturing refinement, in terms of improved fatigue properties, cannot be defined. It is natural to expect that indigenous inclusions would influence fatigue endurance properties of steel as pointed out by the ASM Sub-Committee on Non-Metallic Inclusions in Steel, in the ASM Handbook, page 445, 1948 Edition. Yet, as indicated in the ASM Handbook, experimental evidence does not show that important variation in endurance properties has been caused by the presence of such inclusions. The lack of internal notches or cavities around the inclusions might account for the relatively small effect. In formation, the inclusion is wetted, apparently, by the steel which produces a bond between the steel and inclusion. Hence, even though the modulus of elasticity is undoubtedly different, inclusions do support a portion of the structural load. No logical reason exists for the greater effects of oxide or sulfide inclusions on endurance limit than those of carbide inclusions.

(2) *Effects of exogenous inclusions in blade material.* Gross exogenous inclusions, particularly those occurring near the surface of a finished article in regions of high stress, will limit allowable stress of the finished article. In fact, such inclusions have been known to cause welded blade failure. The illustration in figure 4.57 shows such a failure and the flaw from which failure propagated.

It is evident that the quality of blade materials cannot be judged merely by considera-

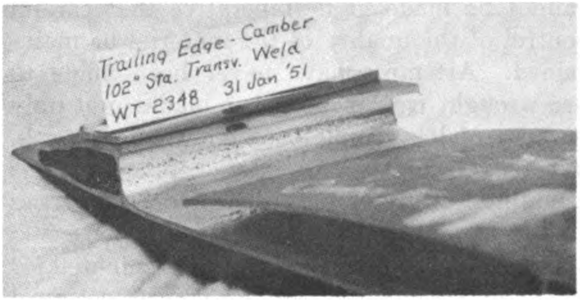

Figure 4.57.—Exogenous inclusions—blade failure.

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tion of extraneous material inclusion count. Repeated magnetic particle inspections must be made throughout blade material processing in a continuous effort to reveal exogenous inclusions which may be present.

(3) *Practical blade endurance limits.* The matter of quality of propeller materials must be considered in the light of actual operating conditions. A propeller blade may be considered as a fatigue specimen subject to uncontrolled failure. Normally, aircraft propellers operate not under controlled laboratory conditions but in the air and on open runways. Military aircraft must operate from runways upon which sand, grit, and stones are found; hence, propeller operating surfaces inevitably contain scratches and often gouges, cuts, or stone bruises. Certainly, such an eroded specimen cannot approach the theoretical combined loading endurance limit specified for a given material. A hollow blade cannot reach this limit even as a new unused blade. Consequently, a propeller blade, inevitably scarred under operating conditions, must be produced with other irregularities that contribute to further reduction in endurance limit, reduced to a minimum. The illustration of a modified Goodman diagram in another portion of this handbook shows endurance limits to be expected, based upon ideal material tests, along with limits obtained in test of production line and service operated propeller blades.

(4) *Effects of processing certain classes of materials.* Selection of propeller materials of high quality must be paramount, always, but materials particularly subject to notch-sensitivity or exaggerated defects of processing irregularities must be selected critically. For example, in selection of welding materials in which certain forms of sulfides are known to be harmful, or in selection of materials for rolling or forging after which complete inspection of the surface cannot be made, it is imperative that careful control of the quality of the material be maintained. Attempts have never been made to use wrought iron in propeller blades, not only because of low ultimate and fatigue strength, but also because the production process yields a material of pronounced directional properties caused by numerous exogenous inclusions.

Certain types of casting can be eliminated for the same reasons. However, use of cast steel has been limited more by an unfavorable weight-to-strength ratio than by lack of quality. In theory, at least, castings could be used in certain parts of propeller blades, if material quality were controlled. Wood and organic plastic applications of particular interest have limitations for use in propeller blades, which range from physical properties to methods of inspection.

(5) *Limitations of physical properties and quality control of nonmetallic material.* The low moduli of organic materials limits use of such materials in the primary propeller structure. Modulus of elasticity for phenolic bound vegetable fibers ranges from 400,000 to 1,200,000 p. s. i. and for cast phenolic resins ranges up to 2,600,000 p. s. i. While the figures quoted do not define total range for all plastic materials, it may be assumed that the ranges do indicate general levels.

Similarly, the ultimate strength of organic plastic materials, in the order of 6,000 to 20,000 p. s. i., is low enough to limit utilization of such materials. In addition, lack of practical ductility, low endurance limit and low abrasive resistance restrict use of non-metallic materials. Only in notch sensitivity and corrosion resistance do these materials, as a class, offer attractions. Some efforts have been directed towards development of solid and hollow plastic propeller blade sections, but there are very great property disadvantages which, so far, have blocked extensive use, particularly in high speed blades of thin cross-section and high level stresses.

Apart from physical property limitations there are further disadvantages in processing and inspection. Inspection of non-metallic propellers presents peculiar problems that must be solved prior to extensive production of plastic propellers.

Inspection of wood or plastic propellers cannot be accomplished by use of the magnetic particle inspection process; etching and X-ray applications have but limited use. Hence, process quality control has been the only practical method by which structural quality and uniformity could be obtained. But, even control of the process has not proven to be adequate enough to justify risk of propeller failure in service. Furthermore, acceptable propeller woods and plastics are difficult to obtain in production quantity during periods of national emergency.

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CHAPTER V PROPELLER HUBS

Fixed Pitch, Wood Blade Propeller Hubs

Basis of Design

Design of hubs for use in fixed pitch wood propellers has been established on an empirical basis, largely. However, the basis of design has been established after careful investigation of a large number of successful propeller hub installations. In considering hub design, critical sections of the loaded hub must be recognized and appropriate allowance made to accommodate anticipated loading. Retention of wood blades presents a major problem as discussed in chapter IV.

Wood Propeller Hub Loading

The principal loads which act upon the boss of a wood propeller hub consist of:

(1) Steady air load
(2) Centrifugal loads (hub and blade masses).
(3) Engine torque (intermittently applied)

Engine applied torque is the most severe load applied to the hub; evidence in the form of burned and elongated bolt holes substantiate this dogmatic statement insofar as fixed pitch wood propellers are concerned. Ultimate hub failure can be expected shortly after the hub bolt holes have become elongated. The type of failure usually will be bolt head shear caused by eccentric loading of the bolts produced by the propeller rocking in the hub. Visually, the greatest local bearing stress in the wood shank will occur at the point of minimum load deflection; namely, the rear hub flange and hub bolt juncture.

Design of Wood Propeller Hubs

Most wood propeller hubs are designed and constructed of steel with an integral rear flange-splined hub, to fit on the engine crankshaft. The front flange of the hub may be either splined to the crankshaft or of a floating collar type.

Propeller shank resisting torque may be computed for a particular design engine torque if it is assumed that:

(1) Bearing area of hub bolts will take all of the engine torque.
(2) Effect of friction between wood shank and hub metal surfaces is negligible.

If the front flange is splined to the crankshaft, the *resisting torque* will be increased. In theory, splining the front flange should permit equal division of loading, since hub bolts would be rigidly supported at each end. To allow for non-rigid support at the front splined flange, it has been the practice to use a front flange factor of 1.25.

Propeller shank resisting torque may be expressed mathematically as follows:

$$T_p = F_b \, ARF \qquad \text{V–1}$$

In which,

T_p=propeller resisting torque (ft-lb.)
F_b=allowable bearing stress (crushing lb. per sq. in.).
A=total hub bolt shearing area (sq. in.).
R=bolt circle radius (feet)
f=front flange factor (1.25 for front splined flange, or 1.00 for front floating flange).

The flange factor of 2.00 may be used for bushed bearing areas of rear flange driving bushings.

The allowable bearing stress for selected propeller woods may be obtained from *Properties of Materials* handbooks. A range of a stress from 750 p. s. i. to 800 p. s. i. for birch wood has been used in the past.

Determination of propeller resisting torque has been determined in the past from a straight line relationship as shown by the equation:

$$T_p = 1.4(T_E B) - 110 \qquad \text{V–2}$$

In which:

T_E=rated engine torque (ft-lb.).
B=cylinder bore (inches)

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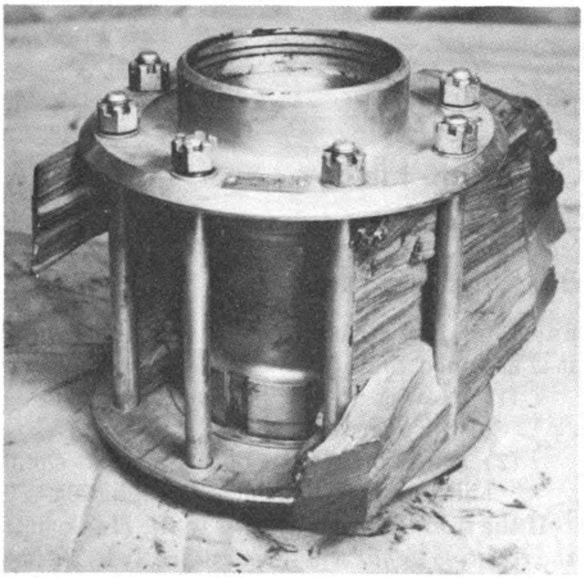

Figure 5.0.—Propeller failure in shear.

It is believed that use of propeller resisting torque defined by this equation will give safe minimum values to be used for conventional steel hub-wood propeller design. Use of the two preceding equations involving propeller resisting torque should permit determination of number, size and placement of bolts in the hub.

Determination of boss dimensions should encompass the following minimums, as well:

(1) Hub bolt length/diameter ratio=11. (max).

(2) Distance from bolt center to outer boss surface=2.5·bolt diameter.

(3) Center-to-center bolt spacing on bolt circle=5⅛·bolt diameter.

(4) Hub bolt center to hub bore center distance=3·bolt diameter.

Care must be taken in the application of the above formulas to avoid cutting away too much wood. It should be realized that wood is not a homogenous material. Roughly, wood is 10 times as strong in tension parallel to the grain as it is in shear or tension perpendicular to the grain. Some continuous uncut fibers should be left, as is shown in figure 5.1, to tie the blades together through the boss.

Formerly wood propellers turned at relatively slow speeds, 1400 to 1700 r. p. m. For these speeds the amount of tension fibers left uncut is not very critical. However, many present day wood propellers are being used in the 2500 to 3000 r. p. m. range. Figure 5.0 is representative of approximately 50 failures due to propellers disintegrating in the air. It was found that so arranging the hub bolts, sometimes in an asymmetric pattern, with relation to the hub bore so that a maximum of uncut tension fiber ran completely through the boss, as is shown in figure 4.1 and figure 5.1, these failures could be avoided.

Limitation of Applications

Design criteria presented in this section pertains to a type of blade retention system that, at best, can only be utilized by low powered aircraft propellers. Even in this field of application, the *lag screw* method of retention has the advantage of placing the wood fibers in tension rather than shear, with resulting increase in airworthiness. Shear failure has been illustrated in figure 4.1.

Ground Adjustable Propeller Hubs

Design Factors

Propeller hub design must be predicated upon imposition of forces and moments evolved in an analysis of propeller blades, as previously discussed (see strip analysis-propeller blades). It has been shown that strip analysis calculations agree reasonably well with actual stress determinations obtained during flight and whirl tests. The centrifugal forces and twisting moments acting upon a propeller blade are transmitted to the hub structure. In addition to blade reactions, the hub must withstand centrifugal forces promulgated by the hub mass during rotation.

Hub Nomenclature—Ground Adjustable Propellers

At this time, it is most desirable to introduce some standard hub nomenclature commonly

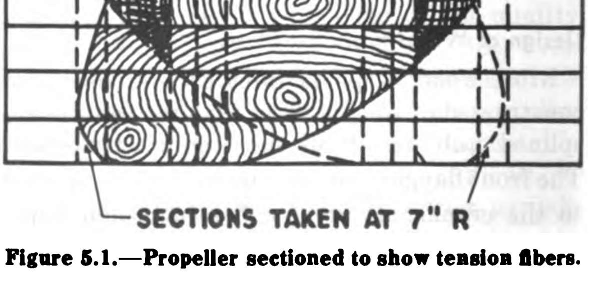

Figure 5.1.—Propeller sectioned to show tension fibers.

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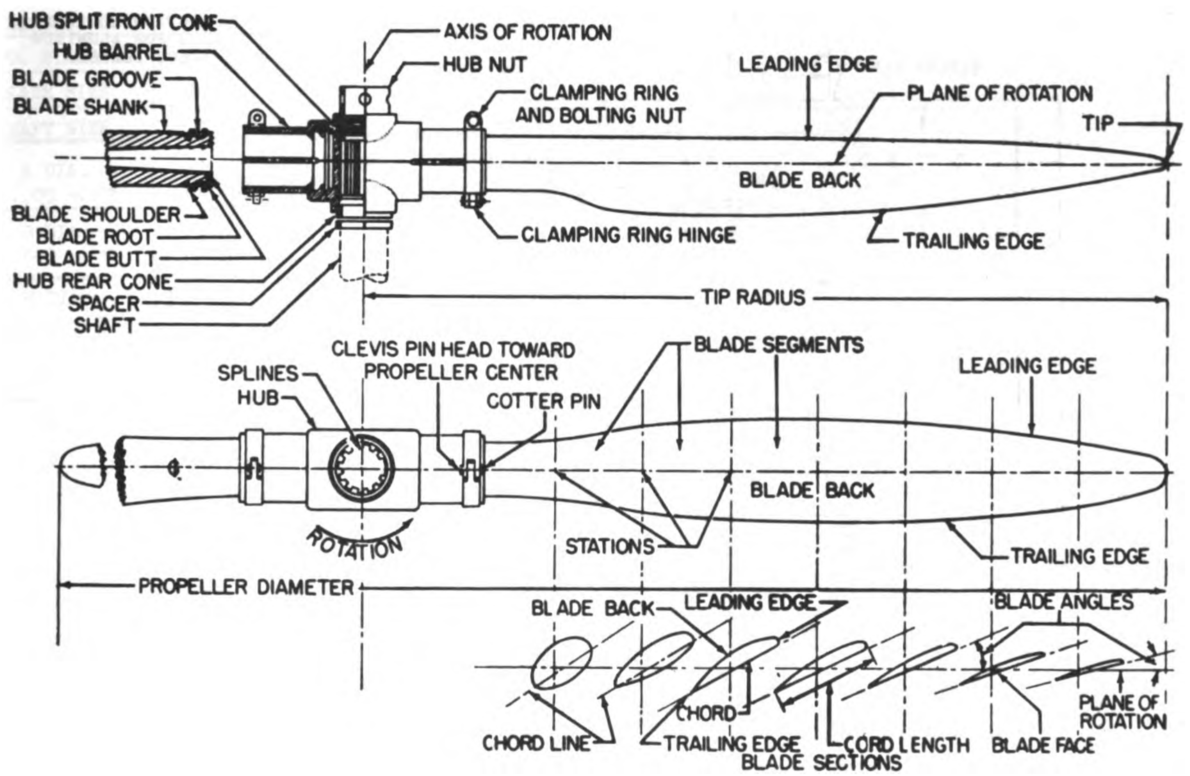

Figure 5.2.—Hub nomenclature—ground adjustable propeller.

used by propeller designers. Elements of a ground adjustable propeller are shown in figure 5.2.

As can be seen in the illustration, the barrel of the hub (split or one piece construction) is that part of the structure surrounding and retaining the blade shank. Hub splines which mate with those of the propeller shaft are shown in the bottom sketch. The hub proper with which this section of the handbook is concerned is shown in figure 5.3.

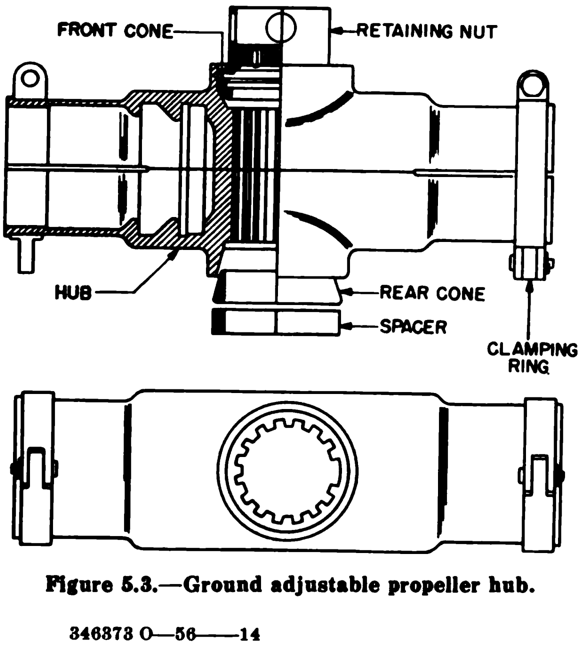

Figure 5.3.—Ground adjustable propeller hub.

Fabrication—Ground Adjustable Hubs

The ground adjustable hub (propeller) used on light aircraft (training, observation, private airplanes) usually is constructed of two alloy steel forgings each machined and finished to form a half of the final hub assembly. The hub contains machined shoulder recesses into which the blade shoulders will fit, in surface contact. Surface contact is assured by a ⅛ inch milled separation between hub halves at the outer end of the hub barrel which permit barrel deflection when clamping rings are tightened.

In processing, shoulder recess, spline and cone seat fabrication operations are performed on the hub halves assembled and clamped. This method is essential to procurement of close manufacturing tolerances required for hub splines and cone seats. Clamping rings of alloy steel (hinged type shown in fig. 5.2) are machined to fit into grooves at the outer end of the hub barrel with a nut-bolt locking or tightening device.

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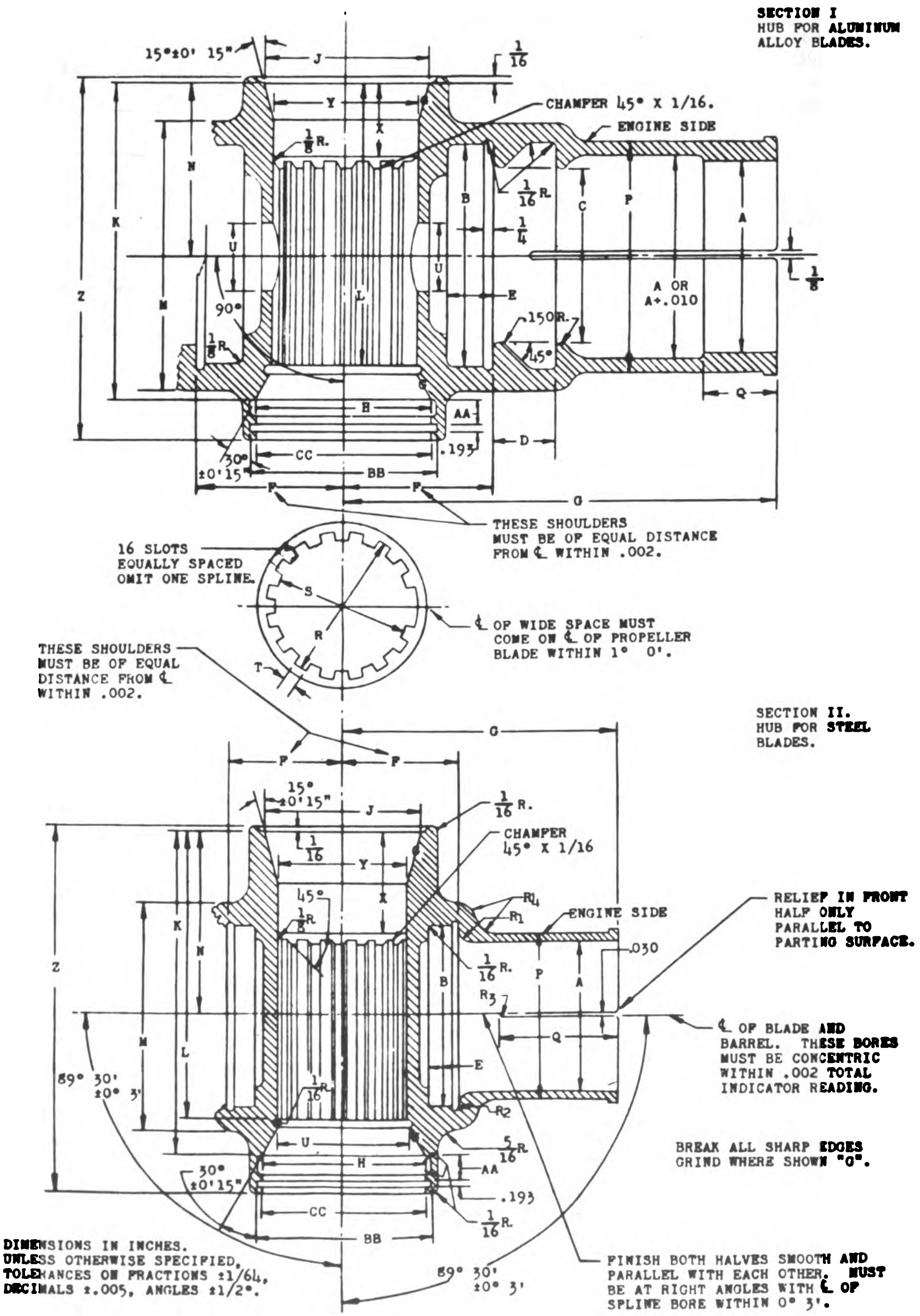

THESE SHOULDERS MUST BE OF EQUAL DISTANCE FROM ℄ WITHIN .002.

16 SLOTS EQUALLY SPACED OMIT ONE SPLINE.

℄ OF WIDE SPACE MUST COME ON ℄ OF PROPELLER BLADE WITHIN 1° 0'.

THESE SHOULDERS MUST BE OF EQUAL DISTANCE FROM ℄ WITHIN .002.

RELIEF IN FRONT HALF ONLY PARALLEL TO PARTING SURFACE.

℄ OF BLADE AND BARREL. THESE BORES MUST BE CONCENTRIC WITHIN .002 TOTAL INDICATOR READING.

BREAK ALL SHARP EDGES GRIND WHERE SHOWN "G".

DIMENSIONS IN INCHES. UNLESS OTHERWISE SPECIFIED, TOLERANCES ON FRACTIONS ±1/64, DECIMALS ±.005, ANGLES ±1/2°.

FINISH BOTH HALVES SMOOTH AND PARALLEL WITH EACH OTHER. MUST BE AT RIGHT ANGLES WITH ℄ OF SPLINE BORE WITHIN 0° 3'.

Figure 5.4.—Typical ground adjustable propeller hub.

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SEE SECTION	II	II	II	I	I	I	I	I	I	I
NO. BLADES	2	2	2	2	2	2	3	4	2	3
BLADE SIZE	00	00-1/2	0	1	2	1	1	1	1-1/2	1-1/2
SHAFT SIZE	10	10	20	20	20	30	30	30	30	30
A DIA. +.003 -.000	2.250	2.563	2.956	3.878	--	3.878	3.878	3.878	4.190	4.190
B DIA. +.002 -.000	2.750	3.250	3.747	4.247	--	4.247	4.247	4.247	4.622	4.622
C DIA. +.010 -.000	--	--	--	3.437	--	3.437	3.437	3.437	3.750	3.750
D +.002 -.000	--	--	--	.875	--	.875	.875	.875	1.062	1.062
E	1/2	17/32	37/64	13/16	--	13/16	13/16	13/16	15/16	15/16
F ±.010	1.937	1.9687	2.0937	2.375	--	2.375	2.375	3.125	2.500	2.500
G ±.005	4.750	4.750	5.125	7.000	--	7.000	7.000	7.750	7.750	7.750
H DIA. +.000 -.005	2.750	2.750	3.125	3.125	--	3.187	3.187	3.187	3.187	3.187
J DIA. +.000 -.005	2.625	2.625	2.875	2.875	--	3.187	3.187	3.187	3.187	3.187
K	5-3/16	5-3/16	6-1/4	6-1/4	--	6-21/32	6-21/32	6-21/32	6-21/32	6-21/32
L	4-1/4	4-1/4	5-17/32	5-17/32	--	6-3/32	6-3/32	6-3/32	6-3/32	6-3/32
M DIA.	3-5/8	4-1/8	4-7/8	5	--	5	5	5	5-1/2	5-1/2
N	3-1/4	3-1/4	3-15/32	3-5/8	--	3-7/8	3-7/8	3-7/8	3-7/8	3-7/8
P DIA.	2-9/16	2-7/8	3-1/4	4-1/4	--	4-1/4	4-1/4	4-1/4	4-5/8	4-5/8
Q	2-1/4	2-1/4	2-5/8	1-3/4	--	1-1/2	1-1/2	1-1/2	1-5/8	1-5/8
R DIA. +.005 -.002	2.008	2.008	2.383	2.383	--	2.633	2.633	2.633	2.633	2.633
S DIA. +.005 -.002	1.789	1.789	2.164	2.164	--	2.414	2.414	2.414	2.414	2.414
T ±.001	.196	.196	.233	.233	--	.259	.259	.259	.259	.259
U DIA.	2-3/16	2-3/16	2-9/16	--	--	--	--	--	--	--
X	1-5/8	1-5/8	2-3/16	2-3/16	--	2-1/4	2-1/4	2-1/4	2-1/4	2-1/4
Y DIA.	2-1/16	2-1/16	2-13/32	2-13/32	--	2-21/32	2-21/32	2-21/32	2-21/32	2-21/32
R1 RAD. ±.005	.156	.156	.156	--	--	--	--	--	--	--
R2 RAD.	1/16	1/16	1/8	--	--	--	--	--	--	--
R3 RAD. ±1/4	1-1/4	1-1/4	1-1/4	--	--	--	--	--	--	--
R4 RAD.	7/16	7/16	9/16	--	--	--	--	--	--	--
Z	6	6	7-3/32	7-3/32	--	7-9/16	7-9/16	7-9/16	7-9/16	7-9/16
AA	17/32	17/32	9/16	9/16	--	17/32	17/32	17/32	17/32	17/32
BB DIA.	2-15/16	2-15/16	3-1/4	3-1/4	--	3-13/32	3-13/32	3-13/32	3-13/32	3-13/32
CC DIA.	2-13/16	2-13/16	3-5/32	3-5/32	--	3-1/4	3-1/4	3-1/4	3-1/4	3-1/4

DIMENSIONS IN INCHES. UNLESS OTHERWISE SPECIFIED, TOLERANCES : FRACTIONS ±1/64.

TABLE V-1. *Ground adjustable hub specifications and standards.*

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SEE SECTION	I	I	I	I	I	I	I	I	I	I	I
NO. BLADES	4	6	2	2	3	6	4	6	3	6	6
BLADE SIZE	1	1	1-1/2	2	2	1	1-1/2	1-1/2	2	2	3
SHAFT SIZE	40	40	40	40	40	50	50	50	50	60	60
A DIA. +.003 -.000	3.878	3.878	4.190	4.503	4.503	3.878	4.190	4.190	4.503	4.503	5.003
B DIA. +.002 -.000	4.247	4.247	4.622	4.997	4.997	4.247	4.622	4.622	4.997	4.997	5.622
C DIA +.010 -.000	3.437	3.437	3.750	3.937	3.937	3.437	3.750	3.750	3.937	3.937	4.390
D +.002 -.000	.875	.875	1.062	1.250	1.250	.875	1.062	1.062	1.250	1.250	1.375
E	13/16	13/16	15/16	1-1/16	1-1/16	13/16	15/16	15/16	1-1/16	1-1/16	1-3/16
F ±.010	3.125	4.6875	2.937	3.187	3.187	4.6875	3.375	5.250	3.500	5.750	6.375
G ±.005	7.750	9.312	8.1875	9.062	9.062	9.312	8.625	10.500	9.375	11.625	12.875
H DIA. +.000 -.005	3.875	3.875	3.875	3.875	3.875	4.562	4.562	4.562	4.562	5.562	5.562
J DIA. +.000 -.005	3.875	3.875	3.875	3.875	3.875	4.625	4.625	4.625	4.625	5.500	5.500
K	6-19/32	6-19/32	6-19/32	6-19/32	6-19/32	6-25/32	6-25/32	6-25/32	6-25/32	8-1/16	8-1/16
L	6	6	6	6	6	6-1/8	6-1/8	6-1/8	6-1/8	7-1/4	7-1/4
M DIA.	5	5	5-1/2	5-7/8	5-7/8	5	5-1/2	5-1/2	5-7/8	6-1/16	6-7/8
N	4-9/32	4-9/32	4-5/32	4-11/32	4-11/32	4-3/32	3-31/32	3-31/32	3-31/32	5-1/16	5-1/16
P DIA.	4-1/4	4-1/4	4-5/8	5	5	4-1/4	4-5/8	4-5/8	5	5	5-5/8
Q	1-3/4	1-1/2	1-5/8	1-5/8	1-5/8	1-3/4	1-5/8	1-5/8	1-5/8	1-5/8	1-13/16
R DIA. +.005 -.002	3.133	3.133	3.133	3.133	3.133	3.812	3.812	3.812	3.812	SAME AS CONTROLLABLE PITCH HUBS SEE AND10529	
S DIA. +.005 -.002	2.881	2.881	2.881	2.881	2.881	3.562	3.562	3.562	3.562		
T ±.001	.306	.306	.306	.306	..306	.377	.377	.377	.377		
U DIA.	--	--	--	--	--	--	--	--	--	--	--
X	2-17/32	2-17/32	2-17/32	2-17/32	2-17/32	2-15/16	2- 5/16	2- 5/16	2- 5/16	3-5/32	3-5/32
Y DIA.	3-5/32	3-5/32	3-5/32	3-5/32	3-5/32	3-27/32	3-27/32	3-27/32	3-27/32	4-27/32	4-27/32
R1 RAD ±.005	--	--	--	--	--	--	--	--	--	--	--
R2 RAD	--	--	--	--	--	--	--	--	--	--	TEST CLUB
R3 RAD ±1/4	--	--	--	--	--	--	--	--	--	--	
R4 RAD	--	--	--	--	--	--	--	--	--	--	
Z	7-1/2	7-1/2	7-1/2	7-1/2	7-1/2	7-11/16	7-11/16	7-3/4	7-11/16	9-1/32	9-3/32
AA	9/16	9/16	9/16	9/16	9/16	9/16	9/16	9/16	9/16	9/16	9/16
BB DIA.	4-1/8	4-1/8	4-1/8	4-1/8	4-1/8	4-3/4	4-3/4	4-3/4	4-3/4	5-3/4	5-3/4
CC DIA.	3-15/16	3-15/16	3-15/16	3-15/16	3-15/16	4-5/8	4-5/8	4-5/8	4-5/8	5-5/8	5-5/8

DIMENSIONS IN INCHES. UNLESS OTHERWISE SPECIFIED, TOLERANCES FRACTIONS ±1/64.

TABLE V–2. *Ground adjustable hub specifications and standards.*

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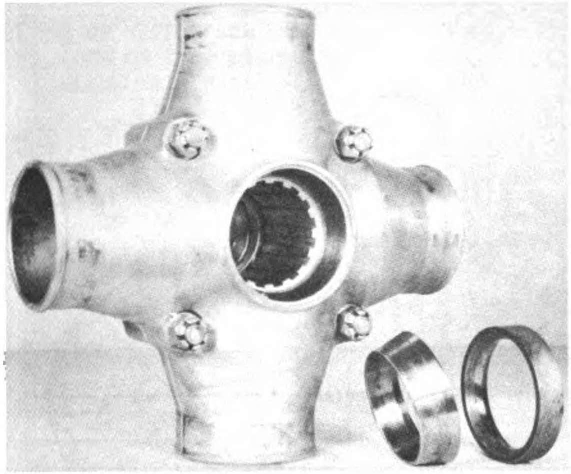


Figure 5.5.—Two piece, four-blade hub for compreg test club.

Typical Specifications and Standards—Ground Adjustable Propeller Hubs

Specification and standards of a typical ground adjustable propeller hub are shown in figure 5.4 and tables V–1 and V–2.

Ground Adjustable Propeller Hub for a Compreg Test Club

A two piece cast steel hub, as shown in figure 5.4, was designed to accommodate a four blade compreg test club. Standard clamp rings and hub bolts were used to hold hub halves together.

The hub was designed for a No. 50 splined shaft which required a one-inch spacer for engine installation. Blade retention in the hub was obtained by use of tapered blade shanks with mating tapered hub blade sockets. Centrifugal force acting on the blade with clamp ring action on hub barrels was utilized to hold the blades in fixed pitch position.

Test clubs similar to the one shown in figure 5.5 are used in preliminary engine running (*breakin*) preparatory to testing propellers. Use of test clubs will eliminate use of comparatively expensive propellers for routine phases of engine test stand operation.

Controllable Propeller Hubs

Hydro-Cam Type

One type of controllable propeller hub, which might be considered as one of the early forerunners of modern hydraulic propeller hubs, consisted of an internal driving torque block identified by the term, *spider* and an independent split barrel. The spider is shown in figure 5.6.

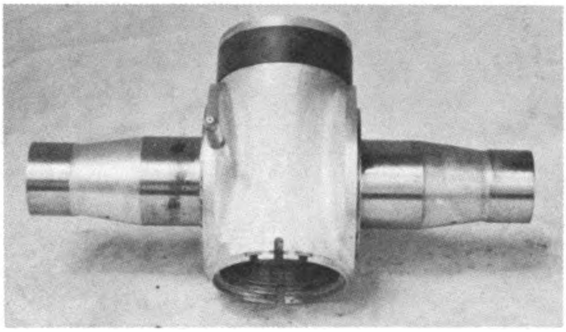


Figure 5.6.—Propeller hub "spider."

The spider driving arms, shown on right and left in the illustration, were machined with bearing surfaces to receive the blade shanks which were taper bored to a depth of approximately 15 inches. Bearing surfaces in the blade shanks were provided by use of bronze bushings pressed into place. Blade retention was obtained by use of single shoulders upset on blade shank and corresponding shoulders in the hub barrel, with roller bearings inserted, between mating shoulders to reduce friction. The boss on the rear of the spider was encircled by a fiber chafing ring to eliminate chafing between the steel boss and the rear half of the steel barrel.

Hub barrel retaining shoulders are shown in the photograph of figure 5.7.

Blade shoulder and mating surface of the bearing race were formed with matching radii and were proven structurally to withstand applied loads.

Various components of the hub assembly are shown disassembled in figure 5.8.

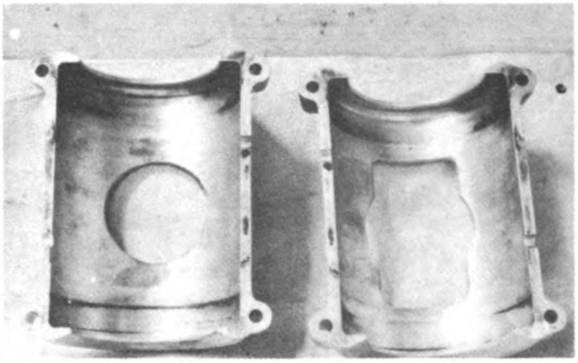


Figure 5.7.—Split hub barrel controllable propeller.

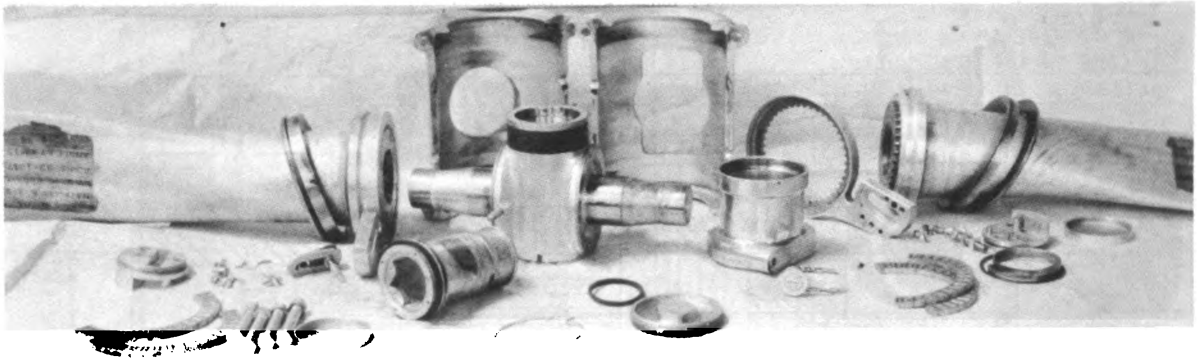


Figure 5.8.—Controllable propeller hub components.

Blade ends shown in this photograph illustrate the blade retention shoulders. In the foreground are the split roller bearing races previously mentioned. The assembled blade bushings were filled with oil to provide lubrication of bearing surfaces of spider arms and bushings.

Blade angle change is accomplished by movement of a piston actuated by hydraulic forces. The blade angle control piston is shown at the left in figure 5.9.

Hydraulic pressure upon the blade angle change piston is obtained by action of engine oil under pressure. Forward movement of the piston simultaneously advances a round cam, ball bearing mounted in each counterweight.

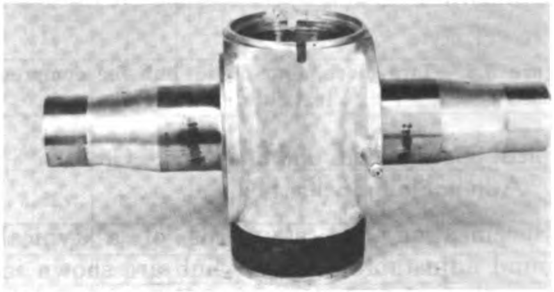
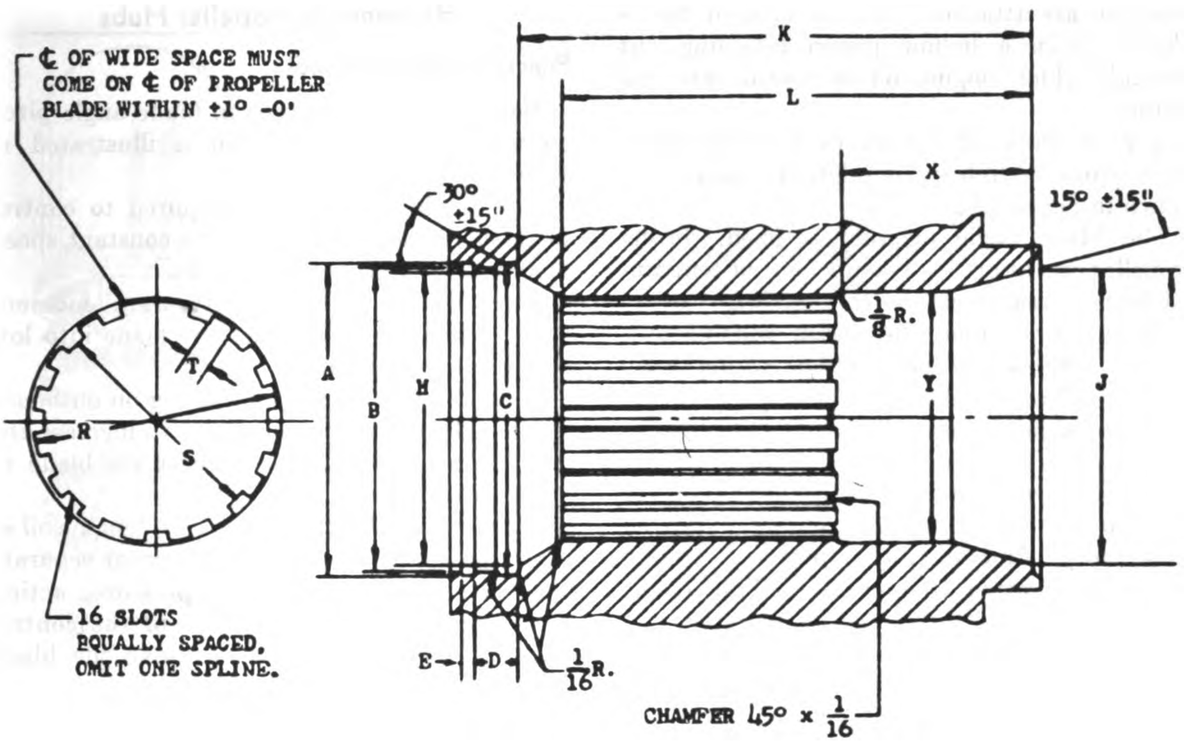


Figure 5.9.—Blade angle change actuating piston, controllable propeller.

The cam follower path, being at an angle with the line of motion of the piston, can remain at a fixed distance from the piston path only by rotation of the blade to which counterweight

Figure 5.10.—Hydraulic controllable pitch propeller hub, disassembled.



SHAFT SIZE	A ±.010	B ±.010	C	D	E ±.005	H +.000 -.005	J +.000 -.005	K	L
7-1/2	2.562	2.500	2- 9/16	17/32	.115	2.375	2.250	5- 3/16	4- 1/2
10	2.937	2.812	2-15/16	17/32	.193	2.750	2.625	5- 3/16	4- 1/2
20	3.250	3.187	3- 1/4	9/16	.193	3.125	2.875	6- 1/4	5-17/32
30	3.406	3.250	3- 5/16	17/32	.193	3.187	3.187	6-21/32	6- 3/32
40	4.125	4.000	4- 1/8	9/16	.193	3.875	3.875	6-19/32	6
50	4.750	4.625	4- 3/4	9/16	.193	4.562	4.625	6-25/32	6- 1/8

SHAFT SIZE	R +.005 -.002	S +.005 -.002	T ±.001	X	Y
7-1/2	1.643	1.461	.161	1- 5/8	1- 3/4
10	2.008	1.789	.196	1- 5/8	2- 1/16
20	2.383	2.164	.233	2- 3/16	2-13/32
30	2.633	2.414	.259	2- 1/4	2-21/32
40	3.133	2.881	.306	2-17/32	3- 5/32
50	3.812	3.562	.377	2- 5/16	3-27/32

DIMENSIONS IN INCHES. UNLESS OTHERWISE SPECIFIED, TOLERANCES ON FRACTIONS ±1/64.

Figure 5.11.—Standard dimensions controllable pitch propeller hub.

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and cam are attached. At the right in figure 5.9 is shown a hollow piston retaining nut through which engine oil is forced into the piston.

A photograph of the hydraulic controllable pitch propeller hub in complete disassembly is shown in figure 5.10.

The blade angle position is fixed, during propeller operation, by a component of centrifugal force acting upon the counterweight or by hydraulic force upon the piston whichever is greater. Release of oil pressure acting upon the pitch change piston results in blade movement to low pitch position by action of centrifugal force. With some minor modifications, that were necessary to meet specific wear problems, this hub-pitch change mechanism design proved satisfactory functionally. However, certain torsional vibration characteristics limited the speed at which the unit could be operated.

Controllable Propeller Hub Standards

Typical standard dimensions of a controllable pitch propeller hub are shown in figure 5.11 for various shaft sizes.

The dimensions shown are representative of accepted practice in hub design for lower powered propellers of variable pitch.

Hydromatic Propeller Hubs

Principle of Pitch Control

Basic principle involved in blade angle pitch control by hydraulic action is illustrated in figure 5.12.

The fundamental forces required to control blade angle changes essential to constant speed operation of a propeller include:

(1) Blade centrifugal twisting moment which tends to twist the blade into low pitch position.
(2) Engine oil pressure acting on outboard side of the control piston to increase the force which tends to twist the blade to low pitch.
(3) Force of oil from governor (engine oil at governor boosted oil pressure or separate oil system under high pressure) acting against the inboard side of the control piston which tends to move the blade into high pitch position.

Pitch Change Mechanism—Hydromatic Propeller

Pitch changing mechanism utilized in a hydromatic propeller is shown in figure 5.13.

The cylindrical cams used in this unit can be laid out by conventional relative motion

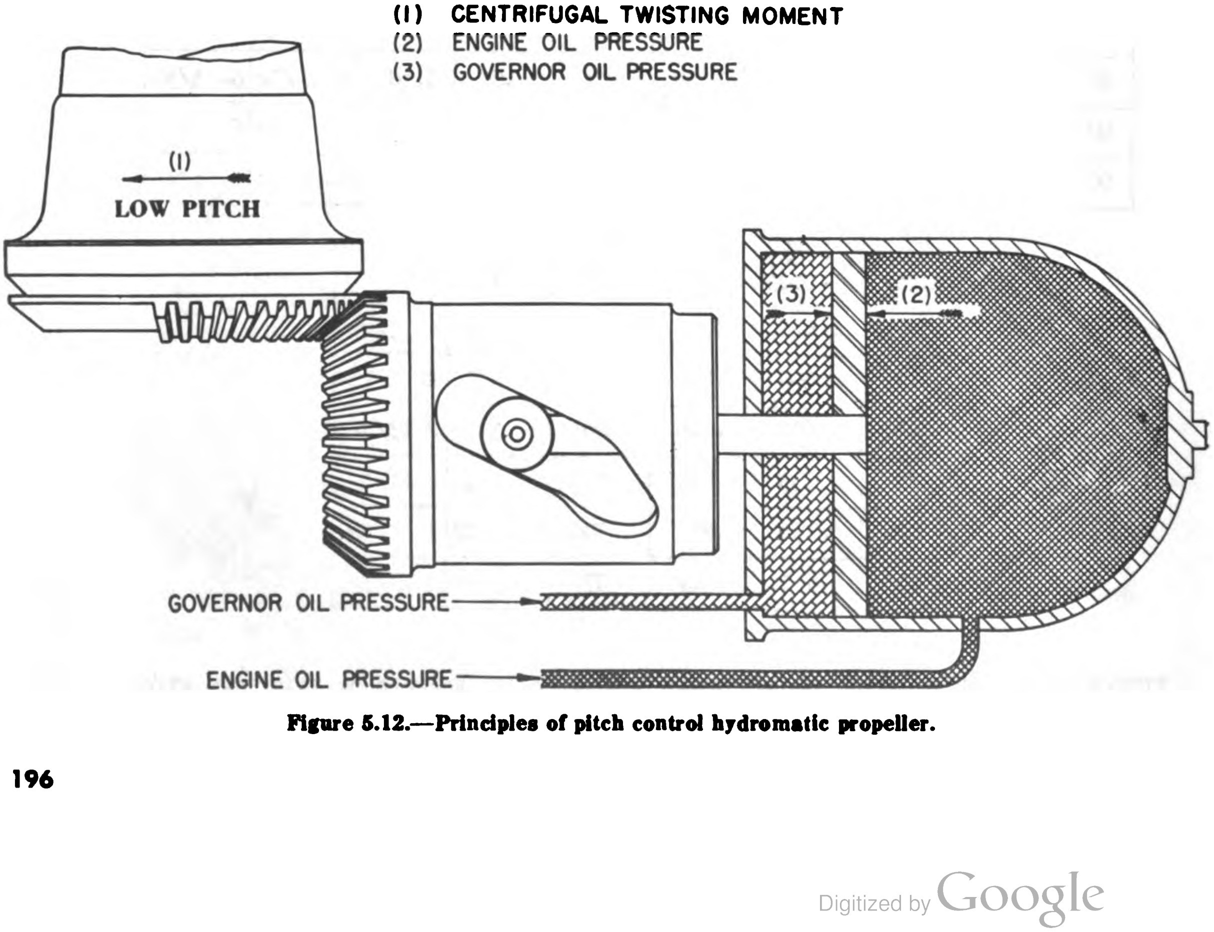

Figure 5.12.—Principles of pitch control hydromatic propeller.

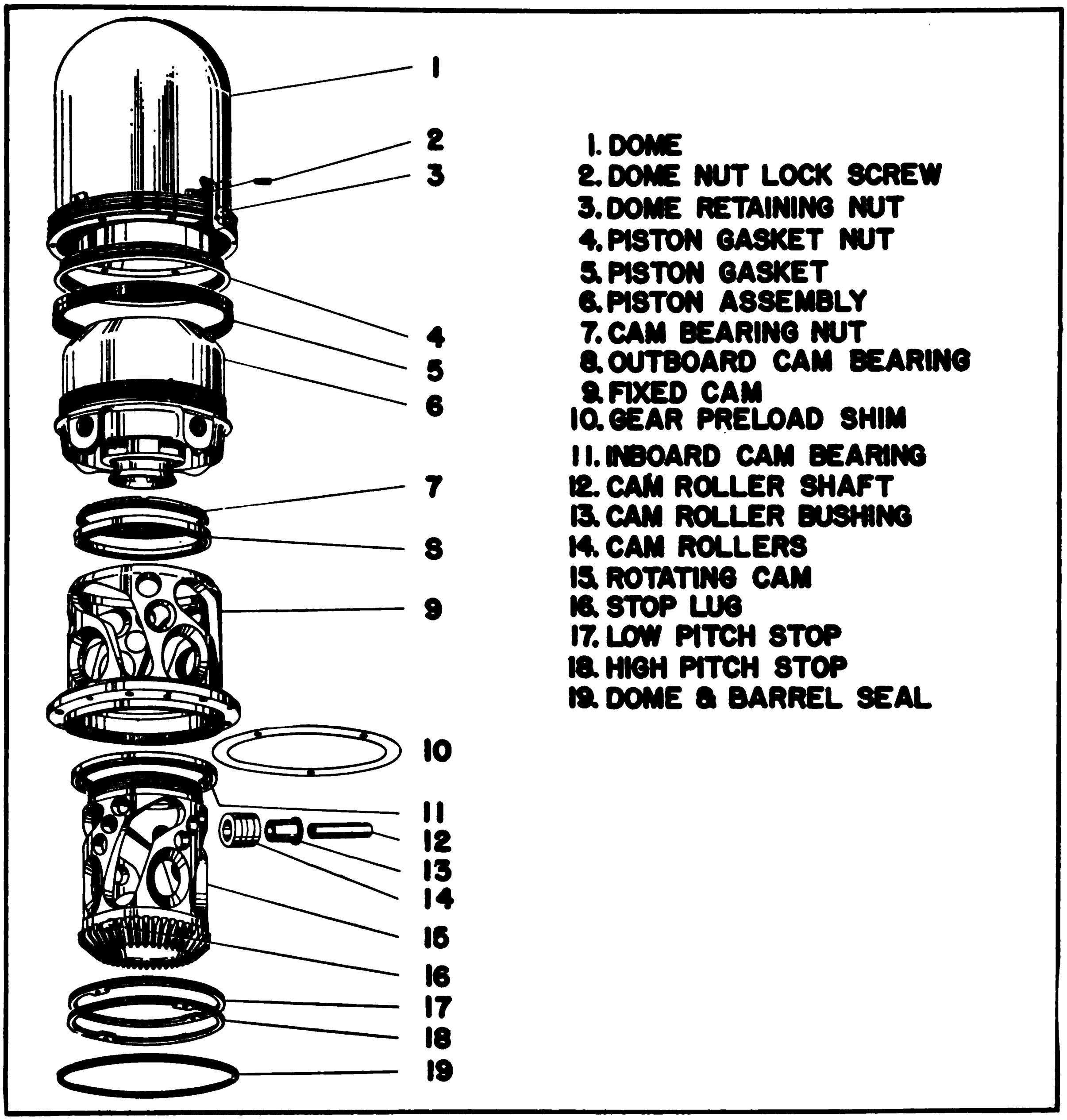

Figure 5.13.—Pitch change mechanism hydromatic propeller.

analysis which will determine the shape and length of cam slots required for blade rotation to the degree necessary for feathering, and reverse pitch. Utilization of cut-out sections in the cams serves to reduce overall weight of the unit.

Hydromatic Hub Assembly

Essential units of a hydromatic hub assembly are shown in figure 5.14.

The spider and barrel are the principal parts of the hydromatic propeller. The spider usually is forged from high grade alloy steel heat treated to give toughness required of this component. The central portion of the rough spider forging is bored and splined to fit the propeller shaft. In each end (inboard and outboard) of the splined section of the spider central bore, a cone seat is ground to receive front and rear cones.

Spider arms forged integrally with the central portion are machined with two ground bearing surfaces (larger surface adjacent to main body

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of the spider and a smaller surface at the outer end of each arm). Each arm is bored to remove metal, thereby lightening the whole assembly. Spider arm bearing surfaces mate with corresponding bearing surface of the blade shank thereby absorbing most of the blade thrust and torque. Each spider arm is drilled to provide passageway for oil to lubricate bearing surfaces of blade bushings and spider arms.

Flat surfaces machined into the spider between blade support arms provide positioning seats for barrel supports. Seals are provided to prevent oil transfer between spider and barrel as well as spider and shaft.

Hub barrel halves, which inclose hub assembly, are forged of alloy steel and heat treated to obtain required strength. Hub barrel shown in figure 5.14 is made of steel but can be made of other metal alloys having the required physical characteristics. Barrel halves are finished and balanced as a unit.

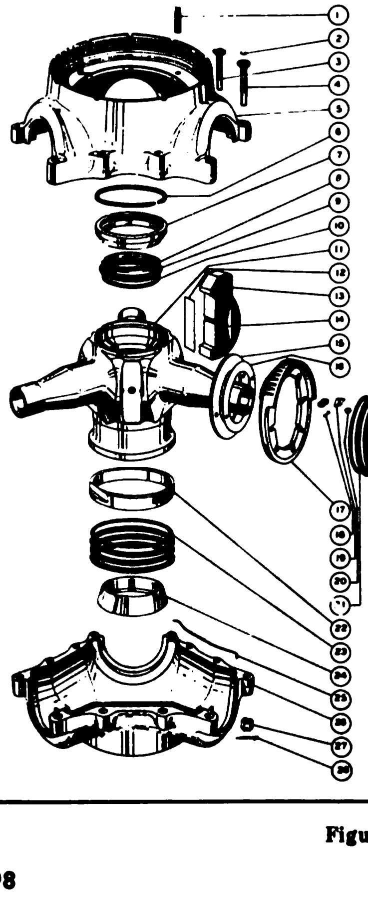
Barrel parting surfaces are grooved to receive barrel half oil seals. Blade packings fit into an annular space formed by a lip at the outer end of blade bores to prevent leakage.

Shoulders are machined into the barrel halves at blade bores to mate with upset surfaces on the blade shank for blade retention purposes. In this design, blade centrifugal loads are transmitted to the propeller hub at these barrel shoulders.

The outboard barrel half is threaded and notched to receive a dome retaining nut lock screw. Also, just inboard of the threaded portion of the outboard barrel half is a ledge which serves as a support for the dome assembly. This ledge also contains a fixed cam locating opening to receive a dowel pin that locates the fixed cam relative to the barrel.

Barrel halves are assembled and held together by hollow bolts that are inserted in bolt holes drilled in hub bosses between blade openings.

Blade gear segments for this hub are forged of alloy steel and so oriented that teeth of the blade gear will mate with the bevel gear teeth of the rotating cam shown in figure 5.13.



1	FIXED CAM LOCATING DOWEL
2,3,4	BARREL BOLTS AND PLUG
5	OUTBOARD BARREL HALF
6	HUB SNAP RING
7 & 24	FRONT AND REAR CONES
8,9,10	SPIDER-SHAFT SEALING UNITS
11	SPIDER
12,13,14	BARREL SUPPORT COMPONENTS
15,16,22,23	SPIDER SHIM PLATE, SHIM, RING & PACKING
17	BLADE GEAR
18,19,20,21	BLADE GEAR & BLADE ASSEMBLY PARTS
25	BARREL SEAL
26	INBOARD BARREL HALF
27,28	ASSEMBLY NUT & PIN

Figure 5.14.—Hydromatic steel hub assembly.

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Integral Oil Reversing Hydromatic Propeller

A hydromatic propeller hub of more recent design encompasses some features that vary considerably from the hubs previously discussed

The blade retention-pitch control system employed by the integral oil reversing hydromatic propeller is composed of four principal units, which are described in some detail in the following paragraphs.

(1) *Hub barrel assembly.* The barrel is formed from a one-piece steel forging, bored and finish machined to accommodate a standard SAE 60A splined propeller shaft. Blade sockets are bored and machined with peripheral blade retention races formed within the blade sockets, against which several rows of steel balls will bear in retaining the blades. Complementary retention ball races are formed upon the blade shank. These races must be hardened and ground to size with very close tolerances.

The barrel extension is bored radially to provide oil passages between the oil control unit and the inboard and outboard side of the hub dome piston.

An internal blade signal brush is mounted at the base of No. 1 blade. The electrical lead from the signal brush fits into a cavity along the hub shaft splines to a point at the rear of the blade arms where it passes through an O-ring sealed opening to the outside of the barrel. The external end of this signal brush lead terminates, through a slip ring assembly, in a propeller control circuit.

(2) *Hub dome assembly.* A dome assembly mounted on the outboard side of the hub barrel encompasses a blade pitch changing mechanism. This mechanism consists of a double acting oil pressure actuated piston directly connected to a cylindrical cam and follower. Movement of the piston, inboard or outboard, is converted to rotary movement of the cam by constrained motion of a fixed link terminating in a slot cut into the cylindrical surface of the cam. The cam slot is shaped so that fixed link movement will cause cam rotation. A bevel gear at the base of the cam transmits rotary motion to blade segmental gears. This blade pitch changing action can be understood by study of the diagram of figures 5.12, 5.13 and 5.14.

This particular unit employs an inverted cam design with both guide feathering and reversing. Cam inversion involves cam slot layout so that the feathering portion of the slot track is at the inboard end of the diagram of figures 5.12, 5.13 and 5.14.

This particular unit employs an inverted cam design with both guide feathering and reversing. Cam inversion involves cam slot layout so that the feathering portion of the slot track is at the inboard end of the cam and reversing portion is located at the cam outboard end.

The annular aluminum piston is provided with a steel sleeve insert to give a smooth sliding surface between piston and a low pitch stop lever assembly as well as furnish a stop for the low pitch stop levers when the mechanism is in low pitch blade angle position.

(3) *Low pitch stop lever assembly.* Functionally, the low pitch stop lever assembly in conjunction with the oil transfer housing delivers oil to the outboard side of the piston. The low pitch stop levers make contact with the outboard side of the piston sleeve to limit piston travel during normal constant speed operation. High pressure oil acting on a piston in the stop lever assembly will cause retraction of the low stop pitch levers, during reversing operation. Hence, blade angle may be reduced to a minimum (or maximum negative angle) by permitting piston travel to extreme outboard position.

(4) *Control assembly.* Blade angle control assembly is comprised of a pump assembly, solenoid valve housing assembly auxiliary pump and motor, and a step motor electric head. Functionally, this unit controls oil flow to the piston which transmits forces to the pitch change mechanism.

Flexibility of the retention system incorporated into this hub design is one characteristic that introduces undesirable vibratory loads on the propeller. The lack of stiffness introduces vibration frequencies of such order that hub failure by fatigue may occur. Studies of this problem have indicated that vibration difficulties of the ball retention system may be circumvented by use of combination roller and ball retention so arranged that additional stiffness is introduced into the system.

Introduction of quick feathering and unfeathering along with reversing features is essential to meet the requirements of modern high speed aircraft.

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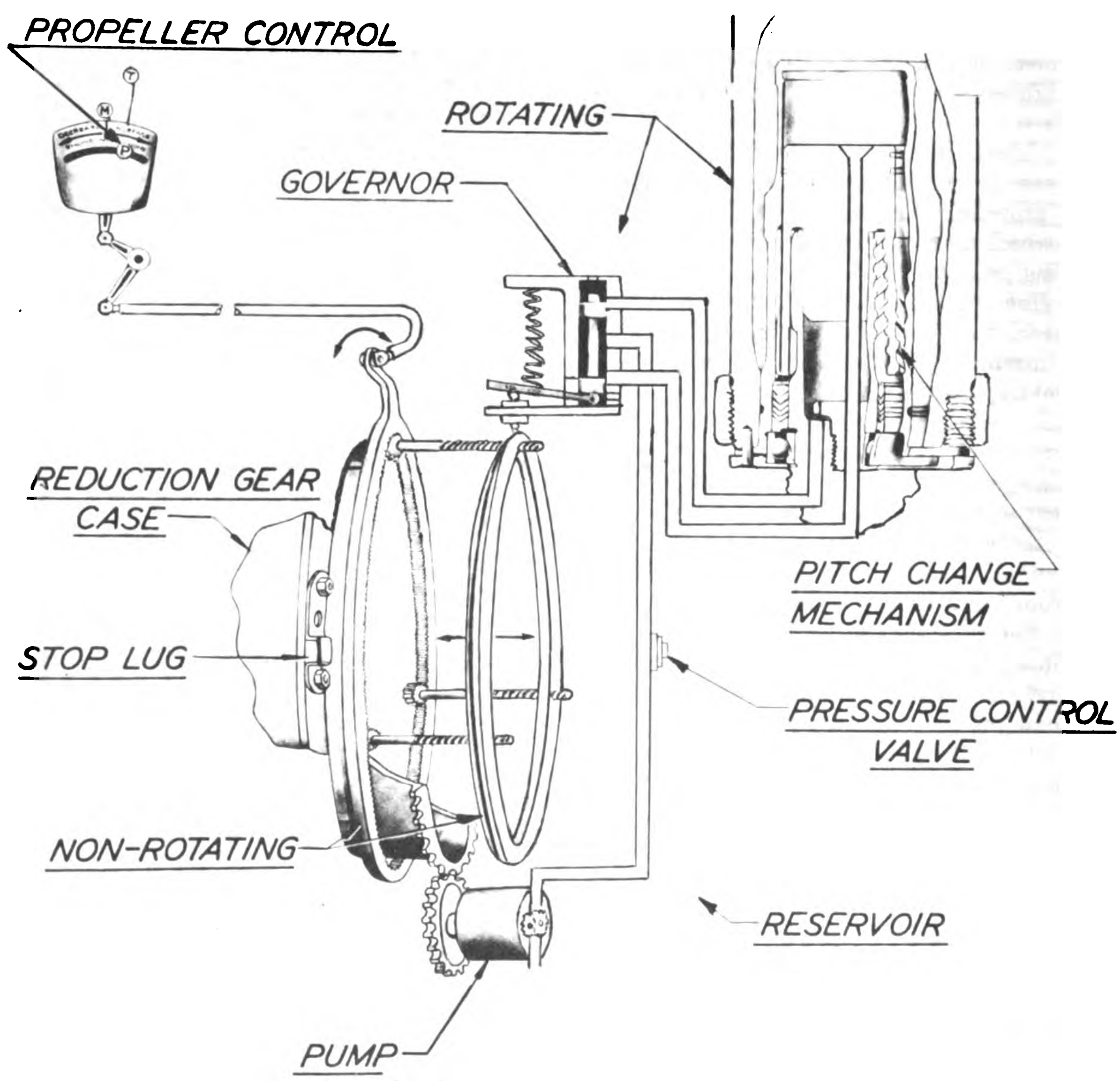

Figure 5.15.—Schematic diagram of hub components hydraulic for constant speed propeller.

Hydraulic Constant Speed Propeller Hub—Self-Contained Unit

General Operating Principles and Structural Features

(1) *Functions of hub components.* Functions of various control components of a hydraulic propeller hub are illustrated in the schematic diagram shown in figure 5.15. Component functions as illustrated are of particular interest since hub design must incorporate necessary structural features to accommodate propeller control units.

The hub assembly, in addition to being a mechanical link between propeller blade and shaft must serve as a housing and structural support of the blade angle change mechanism. In addition, hub design must provide adequate structure in the finished product to retain the blades under all conditions of loading. These requirements of complex and diverse nature have resulted in the development of an intricate hub-retention-pitch change mechanism.

(2) *Working components of a hydraulic constant speed propeller hub.* A cut-away section of a four blade hydraulic propeller hub assembly is shown in figure 5.21. Hub details are not shown clearly in this photograph but a presen-

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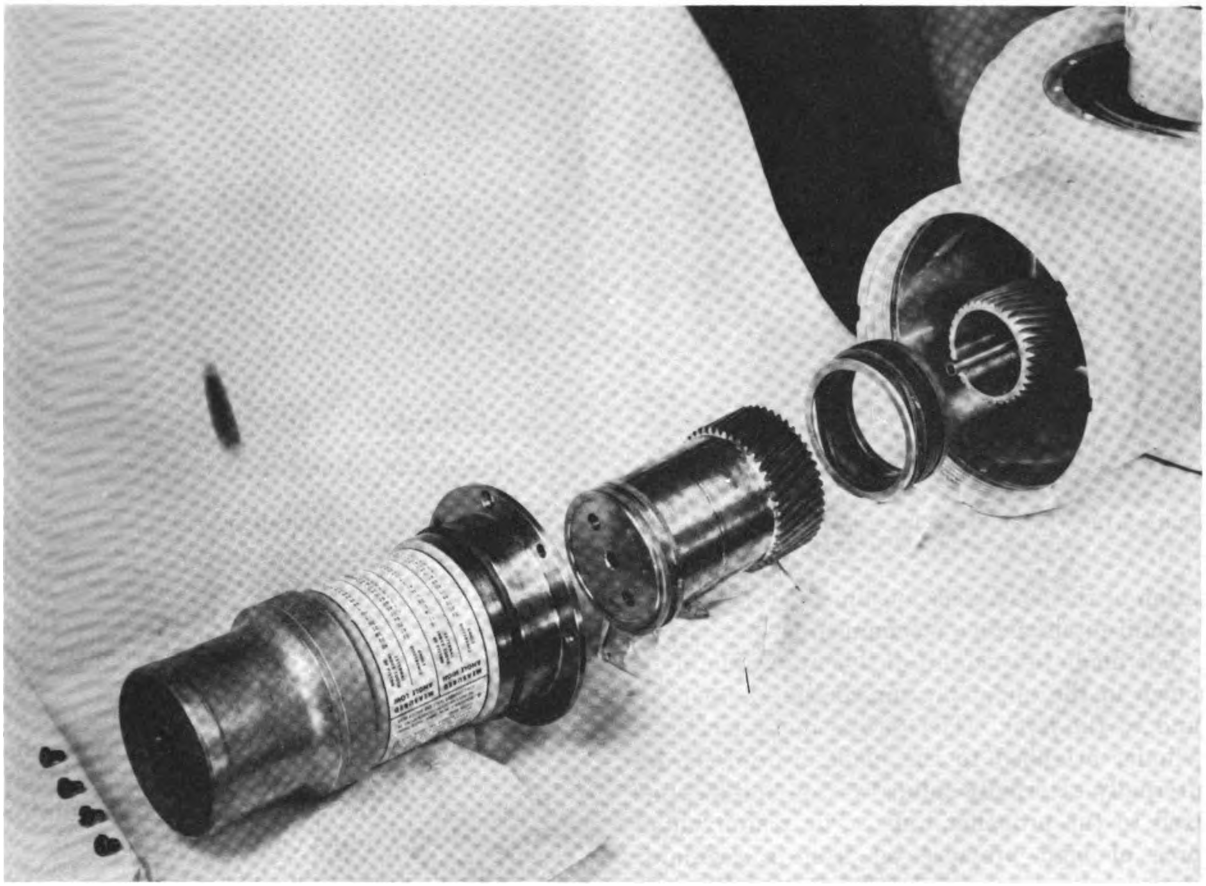

Figure 5.16.—Torque unit, hydraulic constant speed propeller.

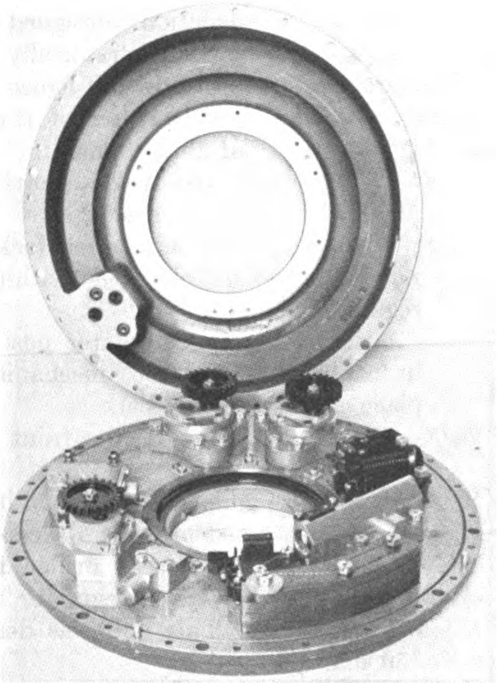

Figure 5.17.—Hydraulic constant speed propeller regulator.

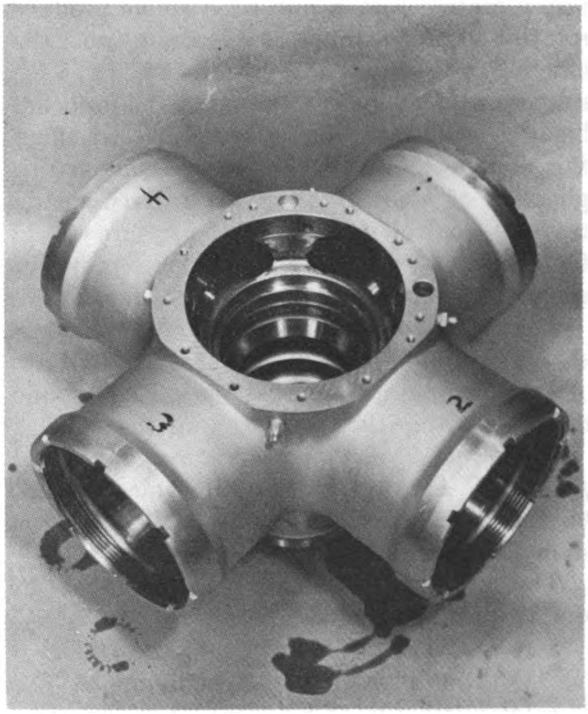

Figure 5.18.—Propeller hub barrel (four blade).

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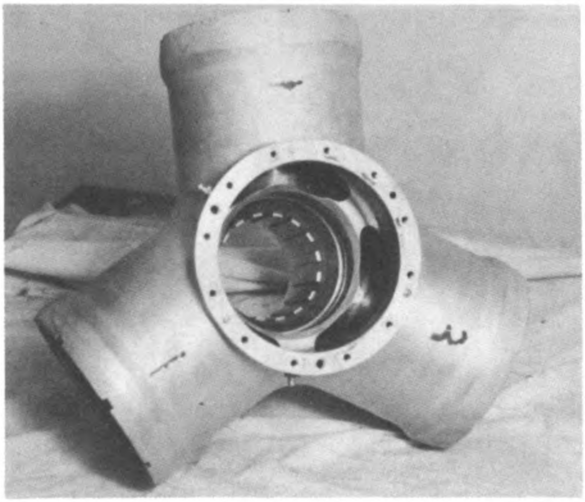

Figure 5.19.—Three blade integral hub (for hydraulically operated, self-contained).

tation of the space relationship between regulator-hub-pitch change mechanism is shown.

The blade torque unit of this hub assembly is shown in the upper portion of the photograph (and to the left). The torque unit includes a cylinder attached to the blade by dowels, an internally-externally splined piston and a spline fixed to the propeller hub. The piston under force of high pressure oil from a regulator (shown in the foregound of fig. 5.21) will move inward or outward. Internal splines of the piston mating with a hub fixed spline produce rotation of the piston. At the same time, the external splines of the piston mating with splines of the cylinder attached to the propeller blade gear produce blade rotation. In effect this double spline arrangement permits multiplication of blade rotation for a given piston travel. Control of actuating oil pressure within the cylinder by a governor introduces propeller speed control by variation of blade angle.

An exploded view of a torque unit in relationship to a hub barrel is shown in figure 5.16. The photograph shows the fixed spline mounted within the hub barrel, at the right.

(3) *Regulator for hydraulic constant speed propeller.* An interior view of a typical regulator for a hydraulic constant speed propeller is shown in figure 5.17.

The units of a regulator for a modern high output propeller include:

- (*a*) Governor (fluid distributive valve).
- (*b*) High pressure gear type pump.
- (*c*) Feathering and pitch reversing controls.
- (*d*) Pressure Relief Valve.

Figure 5.20.—Hub bearing race galling.

The high pressure pump, receiving low pressure oil from the regulator case which serves as an oil storage unit, elevates the pressure to that necessary to force piston movement. The high pressure oil is transferred to a governor which controls flow to the torque unit.

(4) *Hub barrel.* Structural characteristics of a typical hub barrel for a four blade hydraulic propeller is shown in figure 5.18.

This is a front view which shows the regulator mounting base formed on the hub proper.

Typical Hydraulic Propeller Hubs

(1) *Hub for three bladed hydraulic feathering propeller.* A recent three blade propeller hub of single piece construction, designed as a feathering, self-contained, hydraulically operated governor system, is shown in figure 5.19.

Some particular characteristics of this hub assembly are worthy of note, namely:

- (*a*) An external, removable feathering valve and oil filter combination.
- (*b*) Feathering valve and pitch lock tripping mechanism, located within the regulator.
- (*c*) A piston type accumulator positioned in front of the pitch lock mechanism (in place of spinner adapter).
- (*d*) A pitch lock positioned in front of the hub.

The hub body is similar to those used in nonfeathering self-contained propellers except that a special passageway has been drilled in the body to permit oil flow from regulator to the pitch lock assembly. This hub was designed for No. 50 shaft.

Another view of the hub is shown in figure 5.20, which is of interest because galling, which

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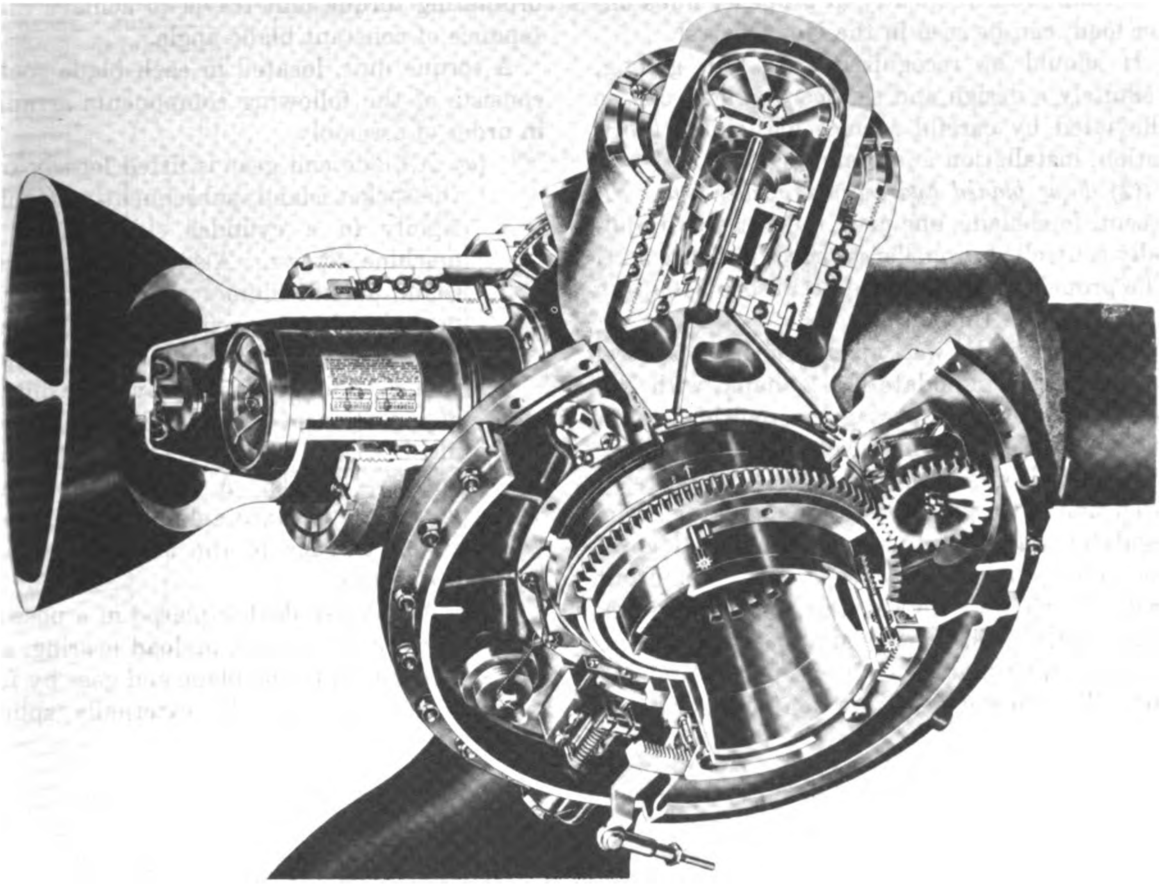

Figure 5.21.—Four blade, one piece hub (hydraulic propeller).

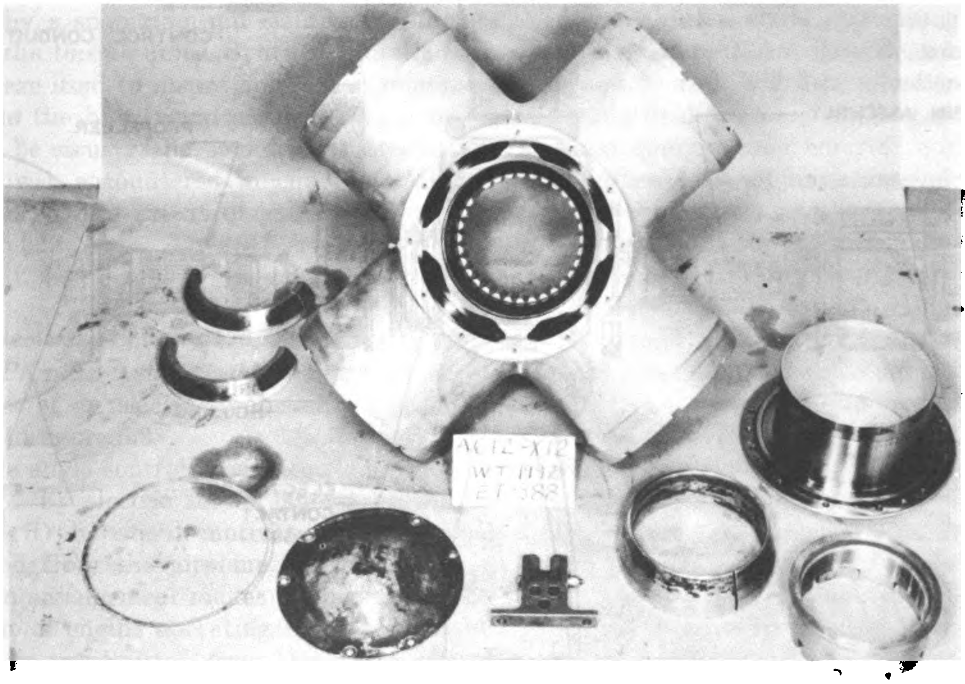

Figure 5.22.—Galled hub and accessories.

is encountered frequently in propeller hubs under load, can be seen in the No. 1 barrel.

It should be recognized that hub galling, definitely a design and service problem, can be alleviated by careful surface hardening, fabrication, installation and maintenance.

(2) *Four bladed hydraulic propeller hub.* A recent, four blade, one piece hub for a hydraulically controlled propeller is shown in figure 5.21. The propeller was designed to absorb 3400 h.p. at 1450 r.p.m. (max.).

The hub body was machined from a steel forging to accommodate No. 2 shank, with No. 60 shaft size. Eight passages were drilled, from hub rear face to islands inside the hub sockets, to permit oil flow from the increase or decrease pitch side of torque units to the regulator. The regulator was mounted upon the rear face of the hub by means of a ring nut. The front base of the hub houses the following units: front cone, master gear and bearing, master gear retaining plate and the propeller retaining nut. The master gear function consists of coordinating torque unit travel to achieve maintenance of constant blade angle.

A torque unit, located in each blade socket, consists of the following components arranged in order of assembly.

(*a*) A blade end gear is fitted loosely over the socket island; subsequently attached rigidly to a cylinder skirt flange by machine screws. A snug fit (to socket island outside diameter) preload bearing next is placed over the socket island extending ¼ inch beyond the end of the island. This bearing fits over the outside of a portion of a fixed spline positioned in the socket island by a fixed spline bolt and five dowels. A 4¼ inch tube, integral with the fixed spline bolt, serves as an oil passage to the outboard side of the piston.

(*b*) A cylinder skirt is placed in a position to circumscribe the preload bearing, and is attached to the blade end gear by four ¼ inch screws. An externally splined

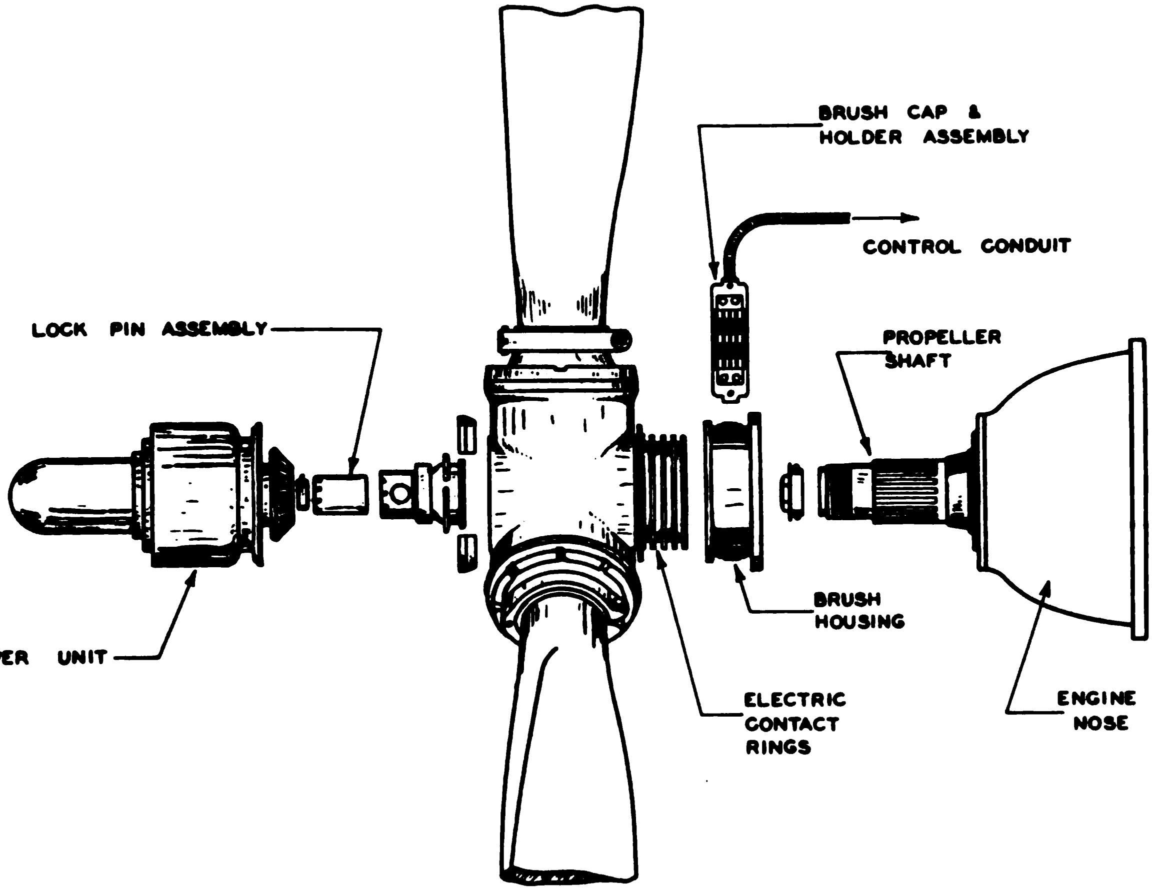

Figure 5.23.—Electric propeller hub subassemblies.

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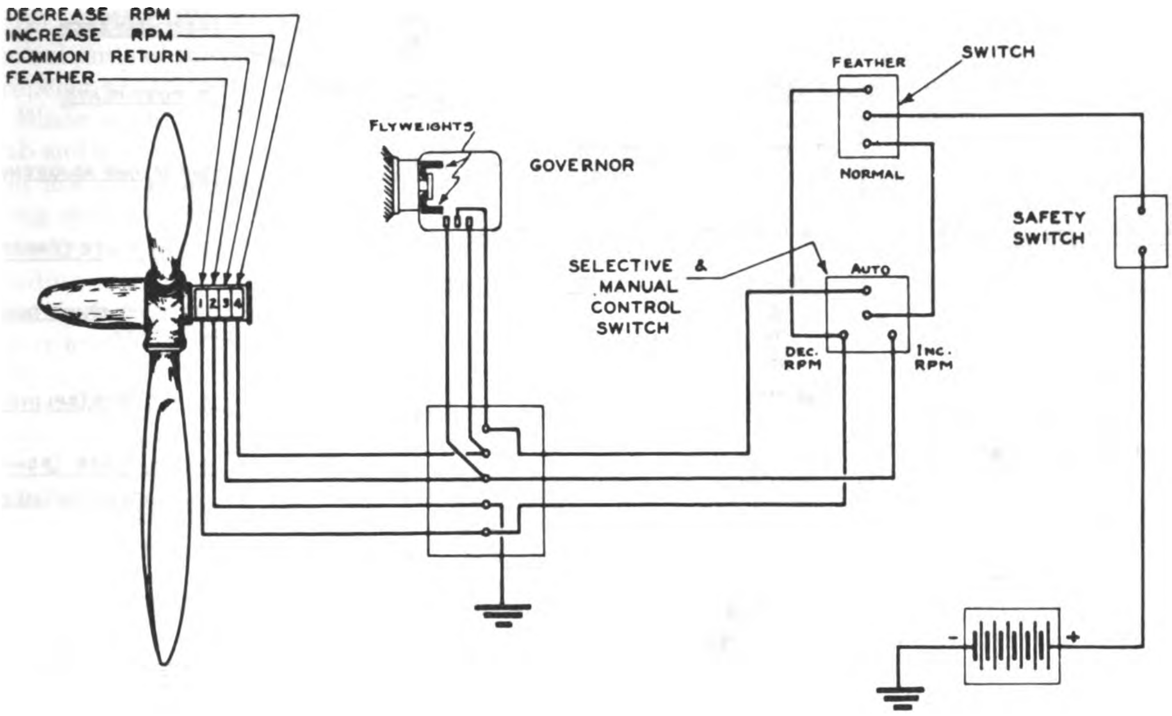

Figure 5.24.—Typical electric propeller pitch control system.

piston assembly is inserted into the cylinder skirt. External splines of the piston mate with cylinder skirt internal splines and internal splines of the piston engage the fixed spline.

(*c*) A cylinder cap is inserted, and retained by a snap ring and clamp, to complete the torque unit. Synthetic rubber seals are used to insure nonleaking joints.

While the hub just described proved under test to be structurally sound, considerable difficulty was encountered in cone seat galling. Evidence of the extent of galling is shown in figure 5.22.

Electric Propeller Hubs

Basic Elements of Electric Propeller Hubs

(1) *Propeller hub assembly.* Principal subassemblies of an electric propeller hub unit are shown in figure 5.23.

Blade angle control in an electric propeller is obtained by electric motor (shown at the extreme left) drive with motivating energy being obtained from the airplane electrical system. Such an arrangement makes pitch control independent of engine operating speed. Electrical energy is transmitted from the electrical system of the airplane to the pitch change motor through brush-slip ring contacts and connector leads that pass through speed reducer and hub. The brushes usually are mounted in a housing attached to engine nose and the slip rings are mounted on the rear of the propeller hub.

The pitch change motor drives a bevel gear meshing with a blade gear through a planetary gear speed reducer. The electric motor is designed to run in either direction by use of a double field winding which permits pitch reversal, readily.

Solid aluminum blade retention is obtained by clamping the blade root in a split steel sleeve containing a bevel gear (meshes with master gear driven by the motor) machined into one of the sleeve halves. The assembly has a stack of matched ball bearings mounted in angular contact type ball races and is retained in the barrel by a blade retaining nut. Hollow steel blade retention is obtained in the same manner; however, the pitch change gear is screwed into the blade root end and pinned in assembly position.

The power unit assembly contains a splined bevel gear and ball bearings mounted in an adapter plate. This bevel gear meshes with the blade gear to obtain change in pitch. The ball bearings absorb power gear thrust.

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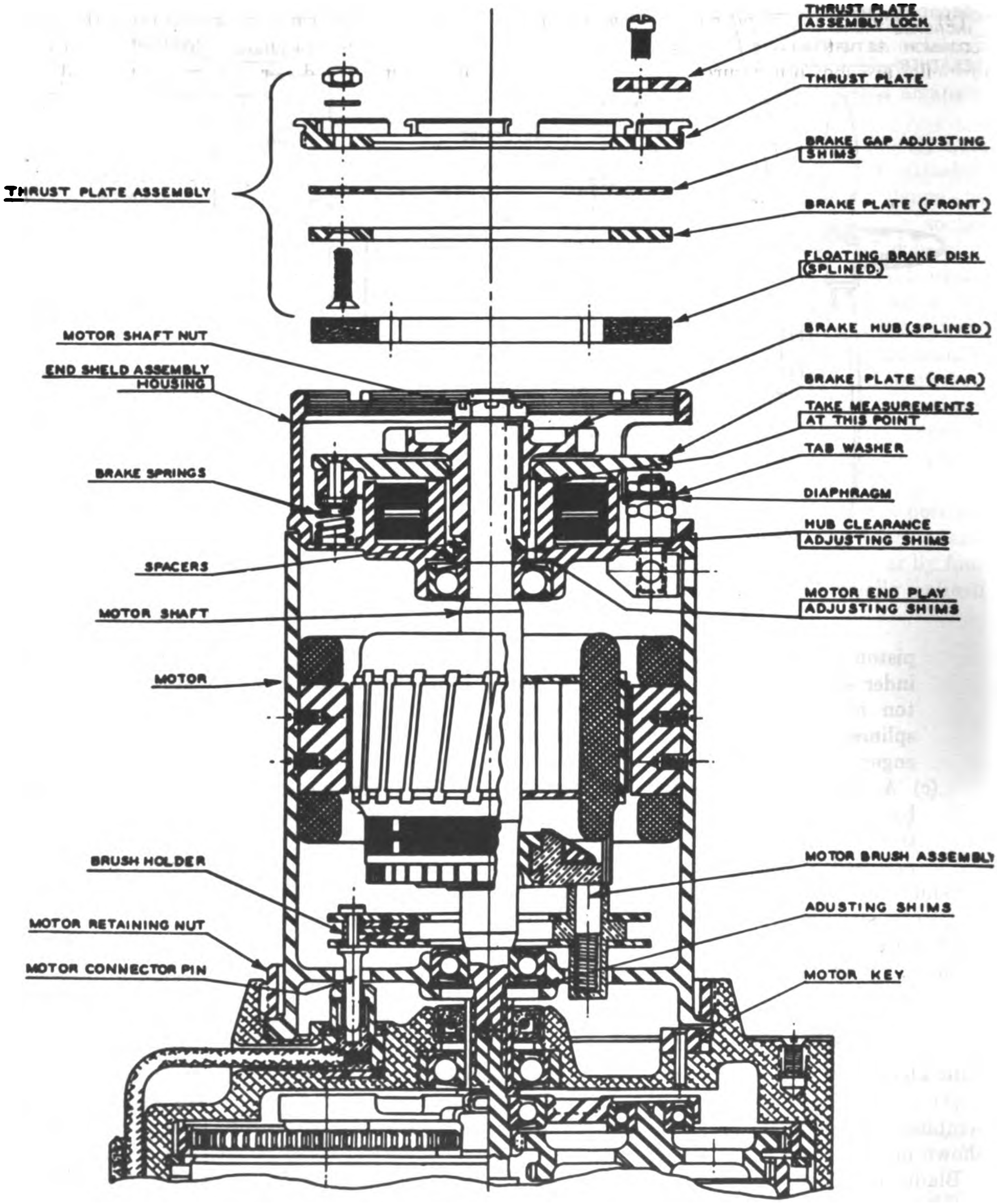

Figure 5.25.—Pitch change motor and brake for an electric propeller.

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(2) *Electric propeller pitch control system.* Essential units of the control system of an electric propeller are shown in figure 5.24.

Blade angle limit switches, located on the hub end of the speed reducer, serve to limit high and low pitch settings to conform to the operating speed range of the propeller. Also, these switches act as pitch change stops at full feather position. In normal use, the switches are operative under constant speed conditions. Feathering is accomplished by using a separate circuit with a by-pass of the high pitch limit switch. This auxiliary circuit is used for manual control of pitch setting, also.

(3) *Pitch change motor and brake assembly.* Details of a motor and brake subassembly for an electric propeller hub unit are shown in figure 5.25.

A reversible electric motor is attached to the front housing of the speed reducer by a retaining nut. The armature wound upon the motor shaft is splined to engage the high speed stage of the speed reducer. A magnetic brake assembly consisting of a diaphragm, brake disk assembly and brake diaphragm assembly, is mounted at the forward end of the hub assembly within an end shield. The brake disk assembly is keyed to the motor shaft, and the brake diaphragm assembly is coil spring loaded to make contact with the brake disk assembly facing. Within the end shield assembly is a brake housing solenoid assembly series connected with the motor.

With a propeller *on speed,* the coil springs force contact between brake disk assembly and brake diaphragm assembly which prevents motor drive to change pitch. When the motor is energized contact between brake disk and diaphragm assemblies is relaxed which permits motor rotation.

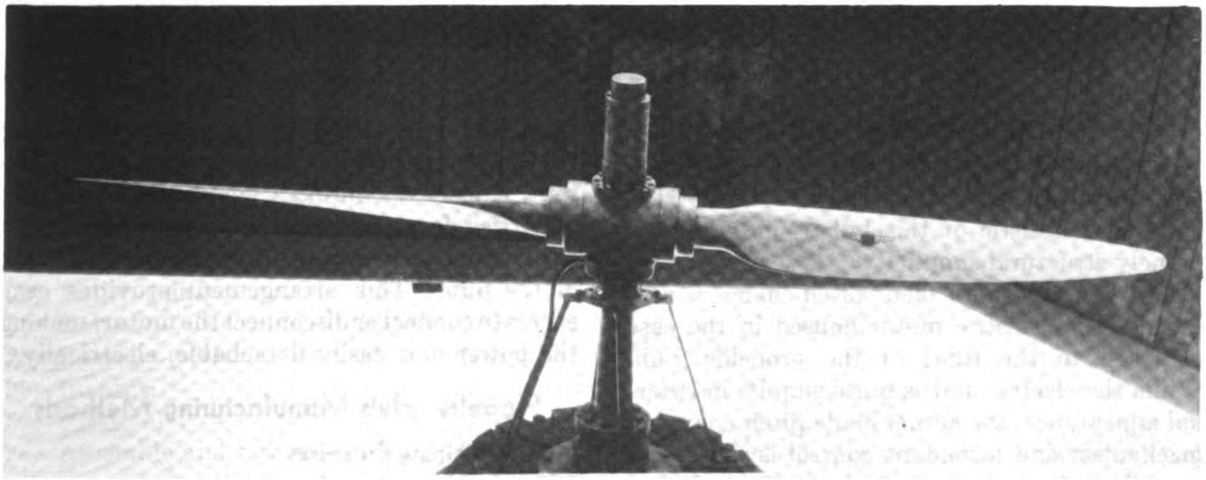

Figure 5.26.—Electric controllable propeller hub.

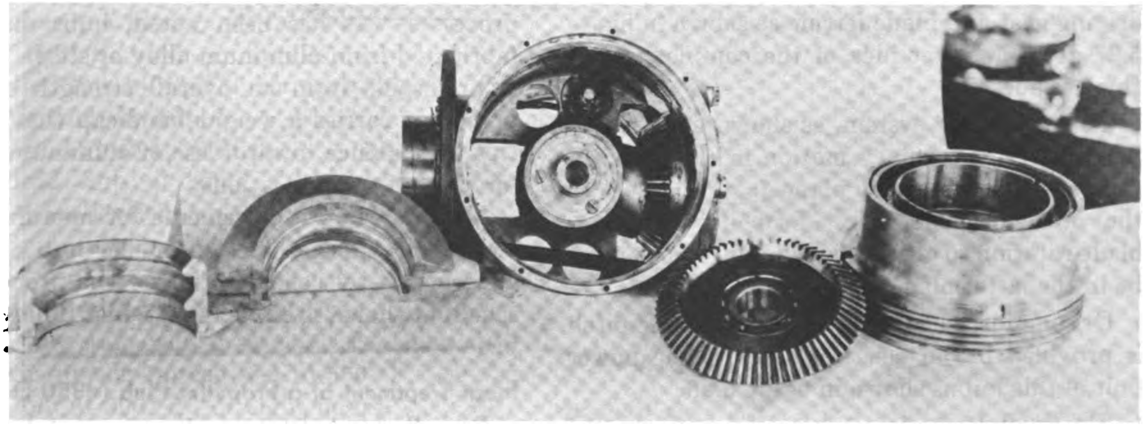

Figure 5.27.—Electric controllable propeller hub internal mechanism.

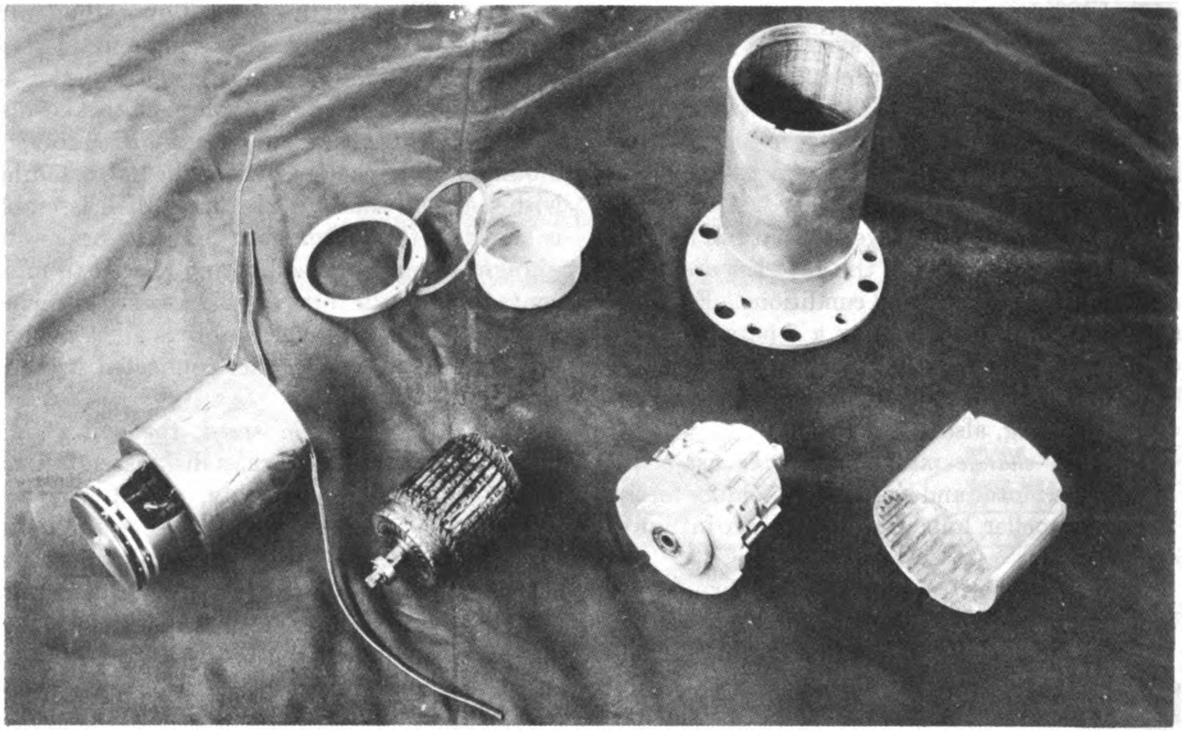

Figure 5.28.—Power unit of an electrically operated controllable propeller.

An Early Electric Controllable Propeller Hub

An external view of the hub of an early electric controllable propeller is shown in figure 5.26. One characteristic of this hub is outstanding, namely structural simplicity.

The motivation for blade pitch change is provided by an electric motor housed in the case attached to the front of the propeller hub. While the electric unit is quite simple, in external appearance, the actual blade pitch changing mechanism and attendant control is somewhat complicated.

An end view of the electric controllable pitch propeller hub with blade retaining collar, blade driving gear and blade ferrule as shown in figure 5.27 gives a better idea of the complexities of this design.

The bevel gear system, as shown here, is utilized to transfer rotary motion in the plane of the propeller disk into a plane at right angles to that of the propeller disk. Propeller shank and blade rotation to obtain blade pitch change must be in the latter plane.

Driving force necessary to change blade pitch is provided by an electric motor. The power unit of this hub is shown in figure 5.28.

Electrical leads for transmission of current necessary to run the pitch change motor, extend from the airplane battery to three wiping ring contacts on the rear of the propeller hub. Current, transferred through wiping ring contacts, is carried forward through the hub on electric wires which terminate in plug sockets at the front of the hub. This arrangement provides easy access to connect or disconnect the motor, making the power unit easily detachable, electrically.

Propeller Hub Manufacturing Methods

Hub Machining Processes

Production of modern high output propeller hubs taxes the ingenuity of designers and requires use of the latest machine tools and shop processes. As has been noted, hubs may be fabricated from aluminum alloy or steel. Steel is preferable from an overall strength standpoint but carries a weight handicap that often tips the balance towards use of aluminum alloy for particular applications.

Machine shop requirements for manufacture of a typical forged steel propeller hub can be appreciated by consideration of the processing schedule shown in table V–3, which follows on page 209.

Heat Treatment of a Propeller Hub (4350 Steel)

Propeller hub heat treatment must be controlled within close limits to produce a material

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having necessary physical characteristics, in fabricated form. An example of heat treatment established for a steel hub is shown in table V–4, which follows below.

TABLE V–3. *Propeller hub processing schedule*

(1) Rough forge (steel hub).
(2) Magnaflux for flaws.
(3) Rough turn and bore rear and front sockets.
(4) Rough Keller.
(5) Mill slots in cross bore.
(6) Heat treat.
(7) Magnaflux.
(8) Finish machine and bore sockets, ball races.
(9) Finish Keller.
(10) Hand grind and grit blast.
(11) Harden ball races.
(12) Magnaflux.
(13) Finish grind cross bore.
(14) Finish grind ID and OD sockets.
(15) Cut shaft splines.
(16) Grind ball races.
(17) Cut front splines.
(18) Bore socket holes and front face hole.
(19) Jig bore rear force holes and counter bore.
(20) Hand tap 1–20 holes in sockets.
(21) Rear end threading.
(22) Thread inside sockets.
(23) Finish grind cones.
(24) Balance.
(25) Burr.
(26) Inspect.
(27) Plate.
(28) Assemble and test.

TABLE V–4. *Heat treatment—Steel hub (Blade Sockets Horizontal)*

(1) After machining, elevate temperature to 600° F.
(2) Hold hub at 600° F. for six hours.
(3) Air cool the hub.
(4) Reheat hub to 900° F.
(5) Hold hub at 900° F. for temperature equalization.
(6) Heat hub slowly to 1325° F.
(7) At still slower rate, heat hub to 1525° F.
(8) Hold hub at 1525° F. for three hours.
(9) Allow slow cooling to 1350° F.
(10) Air quench (forced air) to 500° F.
(11) Hold at 500° F. for eight hours.
(12) Reheat hub to 1175° F.
(13) Hold hub at 1175° F. for four hours to set hardness.
(14) Air cool.

It is not suggested that the heat treatment schedule shown will be satisfactory for all materials and physical requirements. It does indicate approximate conditioning required for this material; the exact process must be established by competent metallurgists at the time of processing, after consideration of established requirements.

Propeller Hub Loading

Hub Centrifugal Forces

Centrifugal forces to which a propeller hub is subjected include blade centrifugal force (CF_B) and centrifugal forces of hub components. A method of determination ot blade centrifugal forces has been presented as a part of a blade strip analysis. Hub component centrifugal forces (CF_H) may be computed using the conventional equation:

$$CF=\frac{W}{g}r\omega^2 \qquad \text{V–3}$$

which may be reduced to a more usable form by combining conversion factors into a single constant as follows:

$$CF=Wr\left(\frac{2\pi}{60}\right)\cdot\frac{1}{12}N^2$$

$$=.000028416\,WrN^2 \qquad \text{V–4}$$

in which:

W=Weight in pounds
r=Radius in inches
N=Speed in revolutions per minute

It should be noted that (r) the radius in this equation is the distance from center of rotation to center of gravity of the hub component. Therefore, the centrifugal force of each hub component must be computed separately, after which a summation of centrifugal force components may be made.

Twisting Moments

The pitch changing mechanism of a propeller hub will be subjected to twisting moments composed of two components, namely,

(1) Centrifugal twisting moment (Q_{CF}).
(2) Aerodynamic twisting moment (Q_A).

The aerodynamic twisting moment acting at a given radius may be determined as outlined in the section pertaining to blade strip analysis.

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The centrifugal twisting moment applicable may be computed from the equation:

$$Q_{CF}=Q_m \operatorname{Sin} 2\ (\beta+\theta) \qquad \text{V–5}$$

In which

Q_{CF}=Centrifugal twisting moment.
Q_m=Maximum blade twisting moment.
β=Blade angle.
θ=Blade deflective angle.

In a windmilling dive condition, both centrifugal and aerodynamic twisting moments are operative tending to decrease pitch. Therefore, in determination of forces and moments effective upon pitch change mechanism, it is necessary to consider the maximum twisting moment as equivalent to the sum of Q_{CF} and Q_A. Determination of total twisting moment is essential to design of the pitch changing mechanism regardless of the type of system utilized (hydraulic or electric).

Air Loading

In propeller hub analyses, the effect of hub air loading has been neglected, generally, on the basis of its relative insignificance. In any hub design or development, such an assumption must be justified by careful consideration of airspeeds and operating conditions which might be encountered in service. Flights under supersonic speed conditions may require investigation of air loading upon hubs as well as the effect of gyroscopic and inertia loading.

Typical Hub Stress Analysis

Allowable Stresses

Inasmuch as fatigue stress conditions represent the most critical situation for the hub socket, blade nut, and blade retaining nut of a hydraulic propeller, the allowable stresses may be determined by interpolation from a fatigue failure curve plotted on a chart of maximum (steady plus vibratory) stress versus mean (steady) stress. The fatigue failure curve is a plotted line from yield strength in tension and endurance limit in bending. Hence, for any value of steady stress, an allowable (maximum, steady plus vibratory) stress may be obtained corresponding to the point of intersection of the constant steady stress line and the fatigue failure curve. It is believed that allowable stresses so found will be conservative and applicable to fatigue loading both in tension and compression.

Allowable stresses for other hub components may be taken as yield strengths in tension, compression and shear, with suitable factors of safety for each application.

Stress Determination for the Principal Hub Structure

(1) *Hub socket stresses.* (*a*) Axial Tensile Stress. Determination of axial tension in a hub socket may be made by use of a conventional stress equation in the form.

$$S_{t_{\max}}=\frac{Mc}{I}+\frac{(CF)}{A} \qquad \text{V–6}$$

In which:

M=Blade bending moment (in pounds).
c=Neutral axis to fibre distance (inches).
I=Moment of inertia (inches).
CF=Blade centrifugal force (pounds).
A=Cross sectional area of socket material under the load CF_B (inches) ^{2}.
$S_{t_{max}}$=Axial stress (lb/in.^{2}).

(b) Hoop (bursting) Stress. Hoop stress in a hub socket may be found using an equation of the form:

In which:

$$S_{t_y}=\frac{F_B \tan\theta}{(2)}\cdot\frac{1}{2tC} \qquad \text{V–7}$$

S_{t_y}=Longitudinal stress (lb/in.^{2}).
F_B=Force (outward) on bearings (lb).
θ=Bearing contact angle.
t=Hub socket thickness (inches).
C=Effective material length factor (inches) as experimentally determined.

(c) Combined Stresses Acting on Hub Socket. Resultant stresses appearing in a propeller hub socket may be computed by assuming $S_{t_z}=0$ and using the following equations:

$$S_s \max=\frac{S_{t_x}-S_s}{2} \qquad \text{V–8}$$

In which,

S_s=maximum shearing stress

and,

$$S_{RT}=\frac{S_{t_x}+S_{t_y}}{2} \pm S_s \qquad \text{V–9}$$

wherein,

S_{RT}=Resultant tensile (or compressive) stress (lb/in.^{2}).

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(2) *Retention stiffness effects.* (*a*) Analytical Computation Correlation with Strain Gage Tests. Determination of vibratory and steady stresses in hub barrels can be made, utilizing strain gage techniques. Further, methods of correlating these stresses with moments and forces derived from strain gage measurements on blade shanks have been utilized to check analytical computations. Barrels of existing propeller hubs have been constructed to withstand $1P$ and $2P$ loads at stress levels compatible with blade shank strength without excessive weight penalties.

(*b*) Retention System Stiffness. However, high performance requirements of modern propellers impose ever greater vibratory excitations thereby rendering previously acceptable hub structures obsolete. Involved in this problem is hub barrel stiffness and, more generally, stiffness of the retention system. Failure of a hub barrel at the inboard loading holes under rigorous engine testing may indicate structural inadequacy. A typical failure of this type is illustrated in figure 5.29. This photograph shows the cracks appearing in loading holes of the No. 3 barrel.

It is believed that $2P$ flatwise, reactionless mode of vibration under abnormal loading induced the high stresses that caused failure. Similar loading hole cracks appeared in three of the four barrels of this one piece hub.

The $2P$ problem with attendant large magnification factors and unpredictable excitations presents a most difficult problem, the solution of which might be attained from two approach avenues, namely:

(*i*) Increasing barrel and blade strength (heavier sections with increased weight) to a point of sustaining higher moments.

(*ii*) Controlling stiffness of various elements so that resonance would fall outside normal operating range.

It is evident that the latter approach offers greater possibilities.

(*c*) Effects of Blade Retention Methods. Extensive investigation has shown that the method of blade retention is a major factor of barrel system flexibility. Steel balls in single or parallel rows circumferentially placed around the blade shank and making point contact (theoretical) with hardened races ground into blade shank and barrel, are especially subject to flexibility or lack of system stiffness. Barrels have been fabricated with thicker arms externally stiffened by rings, oversized steel balls, raceways ground to give radial support and with internal rings, bridges and webs—none of which induced an appreciable rise in frequency.

(*d*) An Empirical Method of Stress Analysis. A stress analysis of a propeller hub may be made by using loads established for the blade shank and adding load coefficients representative of internal loading and deflection produced by external loads. This method of analysis will

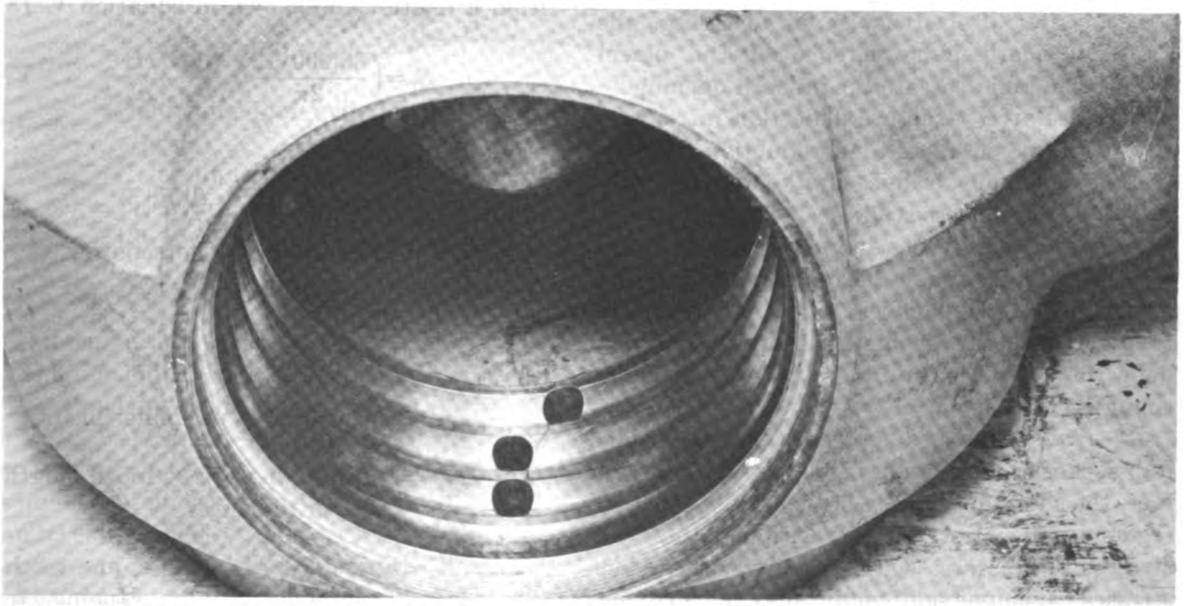

Figure 5.29.—Hub barrel failure.

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permit development of a contour chart of stress distribution for a complete hub structure rather than localized or fragmentary pieces of the stress pictures, as reflected by strain gage data.

There is another possibility for study of hub structures that involves an arbitrary division of the hub into elementary sections with certain known end conditions. By use of energy methods strain energies, deflections and internal bending moments may be determined. From the energy relationships established for the elementary sections, a group of equations may be written, the simultaneous solution of which will interrelate stress effects of component parts. End conditions determined by solution of the simultaneous equations may be applied to the elementary barrel structure to calculate stresses, loads and bending moments.

(*e*) Effects of Load Combinations. An evaluation of the retention problem must encompass the effect of various combinations of vibratory and steady loads acting in or out of phase angle. A steady centrifugal load applied to a retention system involves the following factors in many possible combinations:

(*i*) Variation in barrel thickness longitudinally or circumferentially introduces non-uniformity of load distribution upon ball races, with effective change in end conditions and consequently deflections.

(*ii*) Bending moment produced by forces at ball bearing point and barrel arm center of elasticity tends to enlarge the outboard circumference of the barrel arm and decrease the inboard opening.

(*iii*) Barrel structure deflection introduces strains in races. Introduction of non-continuous bridges in the barrels complicates stress studies.

(*iv*) Grinding tolerances in raceways introduce variable barrel arm deflections.

Other secondary effects will be introduced to a retention by geometric shape variations, deflection at discontinuities and uneven blade shank deflection.

(3) *Hub socket web (or shelf) stresses.* The hub socket shelf, or web, is heavily stressed; in fact, the shelf may be the most heavily stressed region in the hub. If it is assumed that the stresses of this area vary directly with socket stresses, a conversion factor may be evolved based on section properties and loads. In reality, this conversion factor is a ratio of tensile stresses of a hub under study and a tested hub.

Application of the conversion factor, as found in the preceding paragraph, to the stress found to exist in the shelf of the test hub will give an average tensile stress. That is:

$$S_{t_1} = K\,S_{t_o} \qquad \text{V–10}$$

In which,

S_{t_1} = Average tensile stress in a hub under investigation.

S_{t_o} = Stress reflected by strain gage test of a reference hub.

K = Conversion factor

$$K = \frac{\dfrac{CF_1}{A_1} + \dfrac{M_1C_1}{I_1}}{\dfrac{CF_o}{A_o} + \dfrac{M_oC_o}{I_o}} \qquad \text{V–11}$$

It has been found that the average stress calculated by the preceding method may be exceeded by as much as 50 percent in certain regions of concentrated stress. Therefore, it is necessary to apply a safety factor to the value of S_{t_1} to obtain the maximum tensile stress or

$$S_{t_1}\ (\max) = (S_{t_1})\ (SF) \qquad \text{V–12}$$

(4) *Hub shaft splines.* Shearing stress in the teeth of hub shaft splines may be computed from a relationship shown in equation V–13.

$$S_s = \left(\frac{33{,}000 \cdot 12}{2\pi}\right) \frac{BHP}{N \cdot r_p \cdot A_t \cdot k_s} \qquad \text{V–13}$$

In which,

S_s = Shearing stress (lb/in.^{2})

BHP = Propeller brake horsepower.

N = RPM

r_p = Pitch radius of splines.

A_t = Shearing area of spline (in.^{2}).

= Number of teeth × tooth length × tooth thickness.

K_s = Factor representing spline teeth in contact, usually ranging from .20 to .30.

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(5) *Hub thread fillets.* Equations in the form of those shown as V–10, V–11 and V–12 may be established to show relationship between a tested hub (strain gages on hub thread fillets) and a hub under investigation. For hub thread fillets, a stress concentration factor between 1.75 and 2.00 has been found to exist for the inside fillet (of small radius). Hence, axial compressive stresses and bursting tensile stress of the inside thread fillet must be multiplied by such a factor. Combined stresses for the inside and outside thread fillets may be obtained in the same manner as that outlined for a hub socket.

Torque Unit Stresses—Hydraulic Type Hub

Translation of Pitch Angle Change to Piston or Cam Follower Travel

Regardless of whether the pitch change mechanism is of the cam-follower or piston-splined gear type, an analysis of motion must be made to determine the length of travel of the piston or cam follower, required to accomplish a given blade pitch change. Piston travel (*d*) for a given blade pitch change of a piston splined gear mechanism may be computed from the following equation:

$$d=\frac{\pi\Delta\theta}{180\left(\frac{\tan\alpha_{cs}}{pr_{cs}}+\frac{\tan\alpha_{fs}}{pr_{fs}}\right)}$$

In which,

$\Delta\theta$=Total angular range of pitch change. (degrees).
α_{cs}=Helix angle of cylinder spline (degrees).
α_{fs}=Helix angle of fixed spline (degrees).
pr_{cs}=Pitch radius cylinder spline (inches) >
pr_{fs}=Pitch radius fixed spline (inches).

Piston Stresses—Hydraulic Hub

Determination of stresses in the piston of an hydraulic pitch change mechanism may be determined by utilization of equations similar to V–10, V–11 and V–12, after the force applied to the piston has been found. Forces and moments applied to the torque unit piston can be established by consideration of the forces acting upon the cylinder, piston and fixed spline, which can be shown readily in a series of free body diagrams.

Stresses that should be investigated include the following:

(1) Shear in piston skirt threads.
(2) Bursting through threads of piston skirt.
(3) Axial tension through piston skirt threads.
(4) Shear in piston skirt spline backing.
(5) Axial tension piston skirt.
(6) Axial tension in piston skirt spline backing.
(7) Shear in external and internal splines of piston skirt.

In addition, combined stresses of axial tension and hoop tension along with combinations of tensile or compressive stresses with shear should be determined in the same regions in which the separate stresses were found.

Stresses in the Fixed Spline

(1) *Shearing stresses.* The net twisting moment transmitted to the fixed spline will determine the maximum shear (minimum section) in the fixed spline. This shearing stress may be calculated from an equation of the following form:

$$S_s=\frac{(Q_t)(D_o)}{2I_p} \qquad \text{V–15}$$

In which,

S_s=Shearing stress (lb/in.^{2}).
Q_t=Net twisting moment (in./lb).
D_o=Pitch diameter splines (in.)
I_p=Polar moment of inertia (inches^4)

(2) *Tensile stresses (maximum).* Tensile stresses may be computed from

$$S_t=F/A \qquad \text{V–16}$$

In which,

F=Tensile force applied to splines.
A=Net area subjected to loading.

(3) *Combined shear and tensile stresses.* Combined stress may be computed from the equation,

$$S_s(max)=\sqrt{\frac{S_t^2}{2}+S_s} \qquad \text{V–17}$$

Stresses in the Fixed Spline Bolt

If the fixed spline bolt is pretightened, the bolt will be subjected to a force which may be determined by calculation using an equation

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from Norman, Ault and Zarobsky's Machine Design text as follows:

$$F=\frac{T}{\left[r_m\frac{\left(\tan\alpha+\frac{f}{\cos\theta}\right)}{1-\frac{f\tan\alpha}{\cos\theta}}+f_c r_c\right]} \qquad \text{V=18}$$

In which:

F=Applied tensile force (lb.).
T=Pretightening torque (in./lb.).
r_m=Thread pitch radius.
r_c=Radius of concentration of frictional force.
f=Coefficient friction (greasy threads).
θ=Half thread apex angle.
α=Helix angle.
f_c=Coefficient of friction between bolt head and contact surface.

The tensile stress in the spline bolt can be found from $S_t=F/A$. Screw torque, hence torsional shear of the bolt, may be determined by use of an equation similar to V–15. Torsional shear and tension must be combined to establish combined stresses acting in the fixed spline bolt.

Torque Cylinder Stresses

The torque cylinder of a hydraulic pitch change unit must be examined for tensile, shear and compressive stresses both axially and hoop wise to establish maximum values within allowable stresses.

Propeller Hub Testing

The intricate structural shape of a propeller hub makes it necessary to verify theoretical computations of hub stresses by actual test. The indeterminate nature of repeated loads requires strain gage studies of propeller hubs with gages being placed at critical stress sections of the hub. It is extremely important that newly developed hubs be subjected to test programs of sufficient magnitude that airworthiness will be established beyond reasonable question of

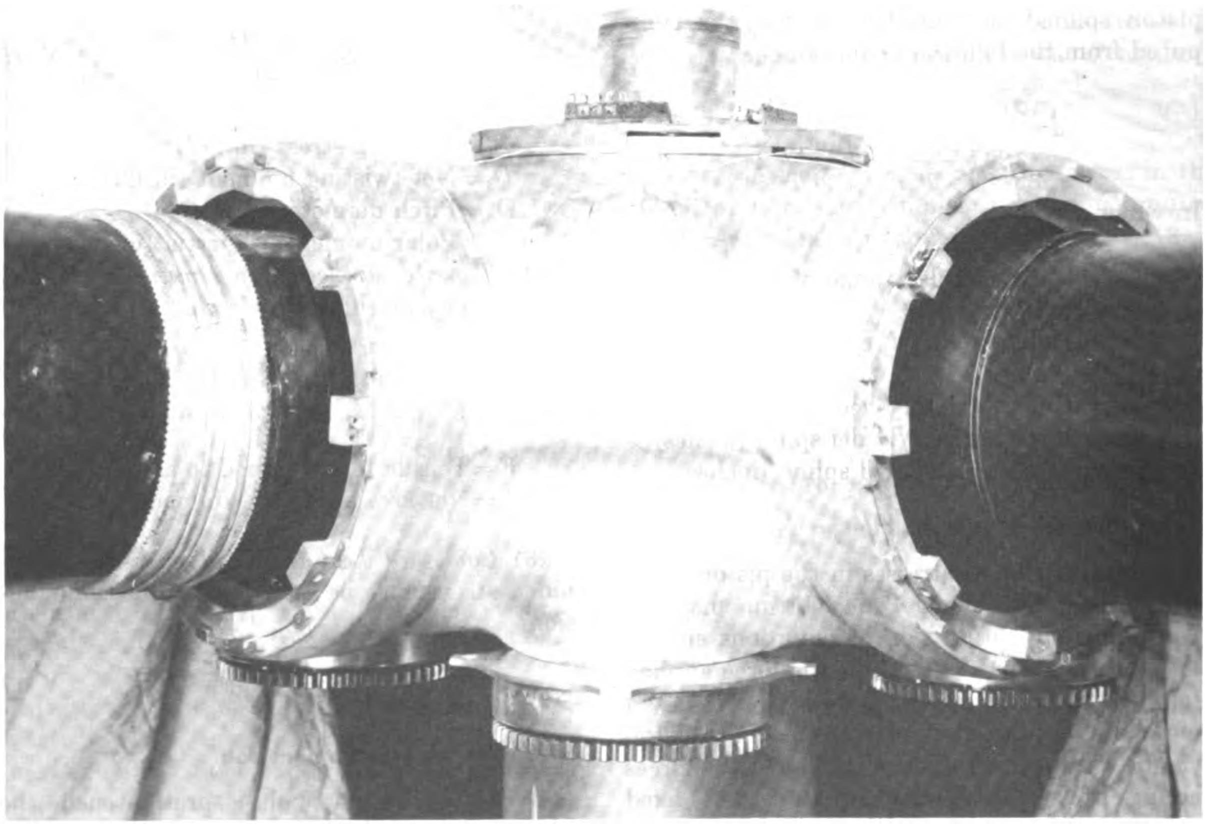

Figure 5.30.—Strain gage installation on a propeller hub.

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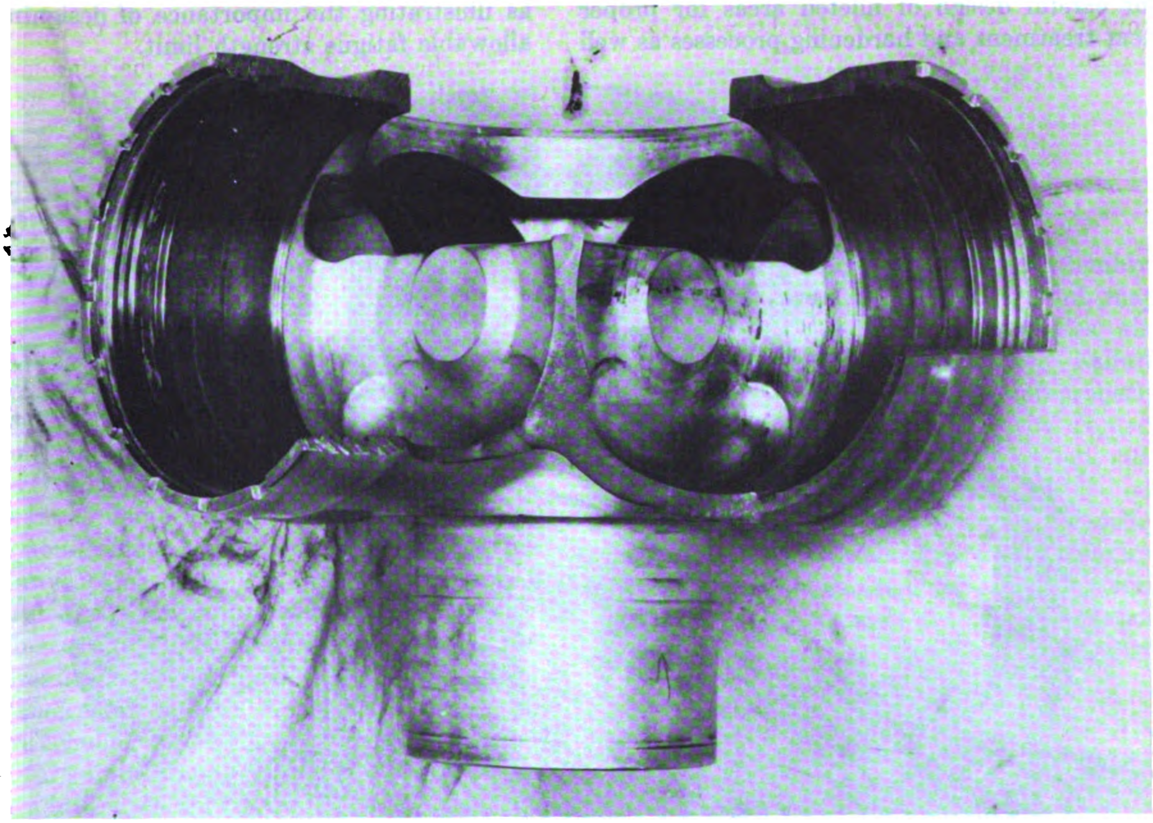

Figure 5.31.—Hub failure from fatigue.

doubt. A typical strain gage installation is shown in figure 5.30.

It should be emphasized that the gages shown here are only a portion of those necessary to complete a thorough stress study of the hub. As previously indicated, strain gages must be attached at critical internal points as well as on external sections.

A Typical Propeller Hub Failure

Hub failures have occurred infrequently under service conditions. However, that they are subject to occasional failure is justification enough, if any be needed, to satisfy a requirement of continuing test. The failures which have occurred have been caused by fatigue, generally.

The hub shown in figure 5.31 is one which failed under fatigue loading.

Investigation of loading conditions, material and method of fabrication established the fact that this failure was due to fatigue. The failure first developed at the shelf fillet and spread across the barrel progressively. Another view of this hub is shown in figure 5.32.

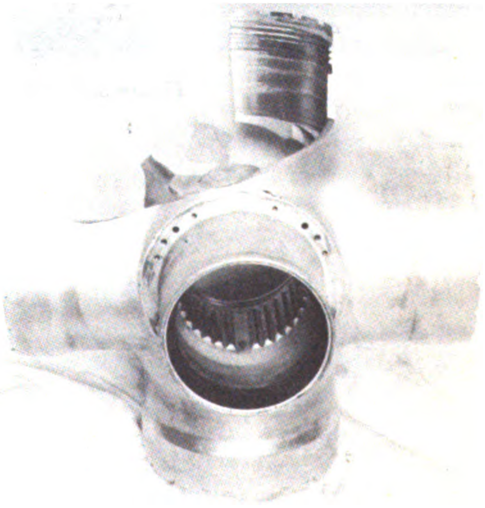

Figure 5.32.—Propeller hub fatigue failure.

This illustration is of additional interest since internal structure of the hub is shown. This hub was designed for application with an electrical propeller.

Another illustration of a hub failure is shown in figure 5.33 which is a barrel external crack.

The failures shown herein point up the need

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for careful design of filleted areas for proper heat treatment and hardening processes as well as illustrating the importance of designing to allowable fatigue strength limit.

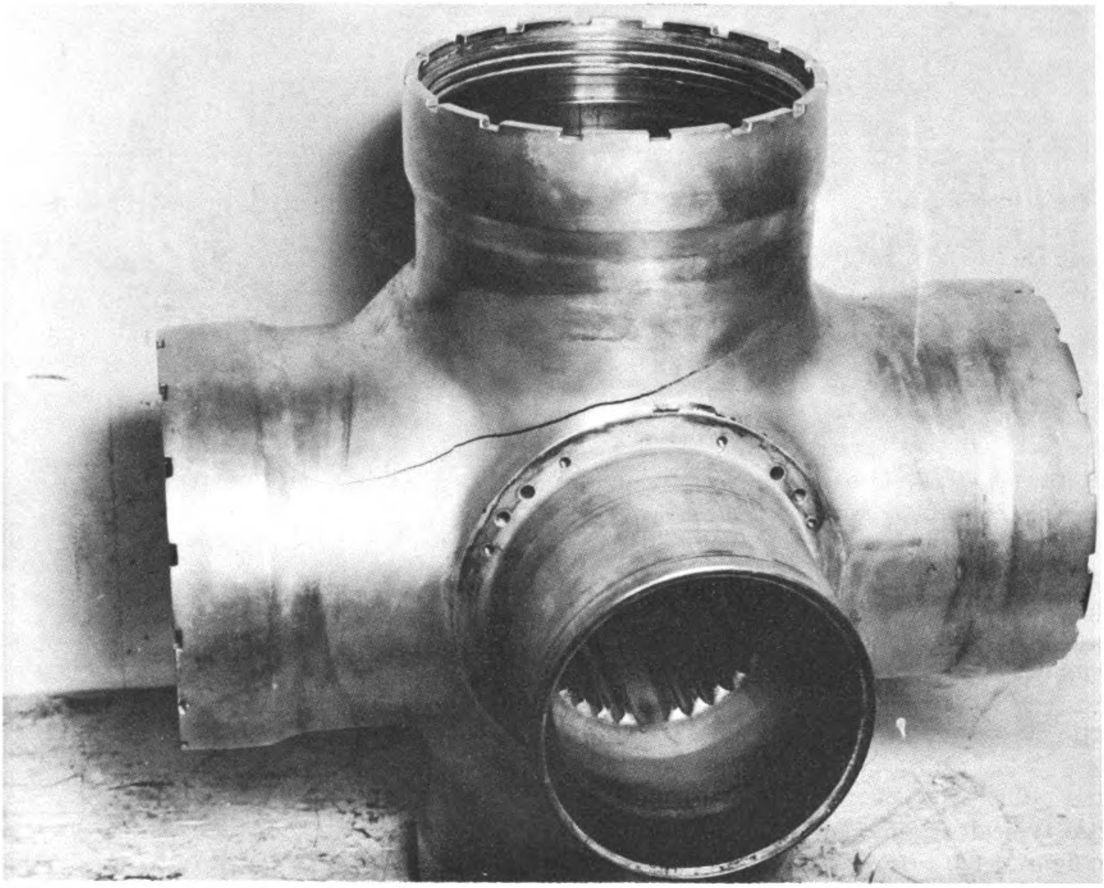

Figure 5.33.—External view hub barrel failure.

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CHAPTER VI. PROPELLER ACCESSORIES

General Requirements of Propeller Accessories

In the early days of the air screw or propeller, it was possible to design and fabricate a simple propeller blade hub combination which, in bare simplicity, would need only to hang together under comparatively light loading conditions. In such a combination, propeller accessories were non-existent. The simple propeller, without any form of electric or electronic speed control or deicing units, was not a radio noise making unit; hence, no requirement existed for suppression of radio interference. Low power airplane engines, generally, did not present severe cooling problems; consequently, little need for spinners and blade cuffs existed.

In addition to a bare minimum of propeller hub-blade assembly, requirements of modern high output propellers have dictated incorporation of many auxiliary devices to accomplish blade pitch angle control, improved engine cooling, radio noise control, deicing, feathering and other operational refinements to improve propeller efficiency. Propeller operational and icing controls are discussed in detail in other sections of this handbook.

The objectives of this handbook will be served if, in this chapter, characteristics and requirements of the following propeller accessories are presented:

(1) Radio Noise Suppressors
(2) Propeller Spinners
(3) Blade Cuffs

It is not feasible to include the innumerable sub-assemblies and parts of various propeller components, especially in view of the fact that, for the most part, functional design rather than structural requirements predominate in development of such pieces as fluid transfer lines, electric conductors, flow valves, etc.

Requirements of modern high speed and power absorbing propellers have become so exacting that malfunction of any propeller accessory under any operating condition may cause complete failure of the propeller assembly. Structural failure of a spinner or cuff may cause serious damage to propeller blades, airplane engine and airframe structure. Failure of noise suppression devices to function properly may cause loss of radio contact with control towers or malfunctioning of navigation aids that might ultimately end in disaster.

Therefore, even as with principal propeller components, the fundamental design requirement of airworthiness exists for each and every accessory. Every element of a propeller system must function with every assurance of maximum safety.

Radio Noise Suppressors

Purpose and Use of Radio Interference Suppressors

Prevention of interference with operation of radio and electronic gear caused by spurious signals of other aircraft electrical equipment is an important phase of aircraft design. Propeller systems, by extensive use of electrical and electronic devices, have become potential sources of undesirable radio interference. Therefore, propeller design must be concerned with methods of elimination of electrical disturbance emanating from propeller components.

Sources of Radio Interference

(1) *Primary sources.* Typical primary sources of radio interference incorporated in propeller systems include the following units:

(*a*) Pitch change motors.
(*b*) Pitch change solenoids.
(*c*) Slip rings.
(*d*) Governors.
(*e*) Synchronizers.
(*f*) Deicing timers.
(*g*) Deicing relays.
(*h*) Inverters.

Such equipment, incidental to its basic operation, will generate rapidly changing currents and voltages. These transients may introduce noise or radio interference of sufficient magni-

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tude to destroy the usefulness of radio or electronic devices.

(2) *Coupling effects.* A certain amount of coupling of electrical effects produced by aircraft components will occur, normally, because equipment placement in close proximity has been dictated by space limitations. Coupling can occur in two principal ways, namely:

- (*a*) Use of common power system and battery for both propeller accessory control and radio or other electronic equipment operation.
- (*b*) Mutual inductance between propeller wiring and antenna lead-ins.

Radio Interference Prevention Methods

(1) *Non-electrical methods.* Experience has proven that it is difficult to add radio-interference suppression devices after completion of a propeller design. For that reason, propeller equipment should be designed with practical methods of radio interference prevention incorporated. Use of non-electrical equipment and non-electronic methods of operation of propeller equipment, in certain cases, may be established with little loss in propeller performance but with substantial noise reduction. In addition, if electrical equipment must be used, the equipment may be arranged so that circuits involving rapid current changes will be placed in engine nacelles rather than in the fuselage. In any case, circuits of this type should not be placed near radio equipment.

(2) *Filtering methods.* Whenever propeller equipment must be serviced from the same electrical distribution system as the radio equipment, effective filtering of power leads must be accomplished. Filtering leads, from propeller noise sources, will require use of the following electrical devices in various combinations:

- (*a*) Capacitors (condenser).
- (*b*) Inductors (choke coil).
- (*c*) Transient suppressors.
  - (*i*) Dry-plate rectifiers (magnesium copper sulfide)
  - (*ii*) Point rectifier (germanium)
  - (*iii*) Non-linear resistors—
    "Globar" type
    Thyrite type
  - (*iv*) Gaseous discharge tubes
  - (*v*) Vacuum tubes
  - (*vi*) Resistor-capacitor networks

Capacitors across electrical lines have received universal application as suppressors of noise, being particularly effective in reducing noise from DC motors and generators. Addition of an inductor between a capacitor and relay contact will prove to be an effective combination for suppressing relay and contactor noise. Additional inductors in series circuits and capacitors in shunt circuits can be used as radio-noise filters for further suppression.

(3) *Shielding.* Whenever propeller equipment having electrical noise potential must be installed near radio or electronic apparatus, the propeller equipment should be placed in shielding containers and all electrical leads should be shielded properly. Proper shielding will require use of metallic (not necessarily magnetic) boxes or containers of non-conducting joints without openings. Size and shape of containers should be that required to house the propeller equipment; wall thickness is unimportant, since any thickness practical from a mechanical standpoint will be entirely adequate for radio interference reduction.

Design Specifications

(1) *Objectives of design specifications.* Amount and type of filtering and shielding to use for elimination of radio interference in a given installation must be stipulated on the basis of previous experience. The final criterion of adequacy of any system will be the degree of elimination of interference to radio and electronic gear operation in the aircraft installation. However, there are obvious disadvantages in judging performance of radio interference equipment after installation in an aircraft. An approach to determination of noise characteristics of equipment prior to installation involves establishment of specifications setting forth maximum allowable limits of radio interference performance.

The purpose of a radio-noise specification for propeller equipment is to establish minimum performance standards to serve as a guide for development of equipment. Undoubtedly, equipment meeting the minimum standards still will cause noise after installation, under some conditions, but noise will be produced in less than ten per cent of actual operational situations. The number of variables involved in any situation will prevent reduction of noise production to an absolute zero. Elimination

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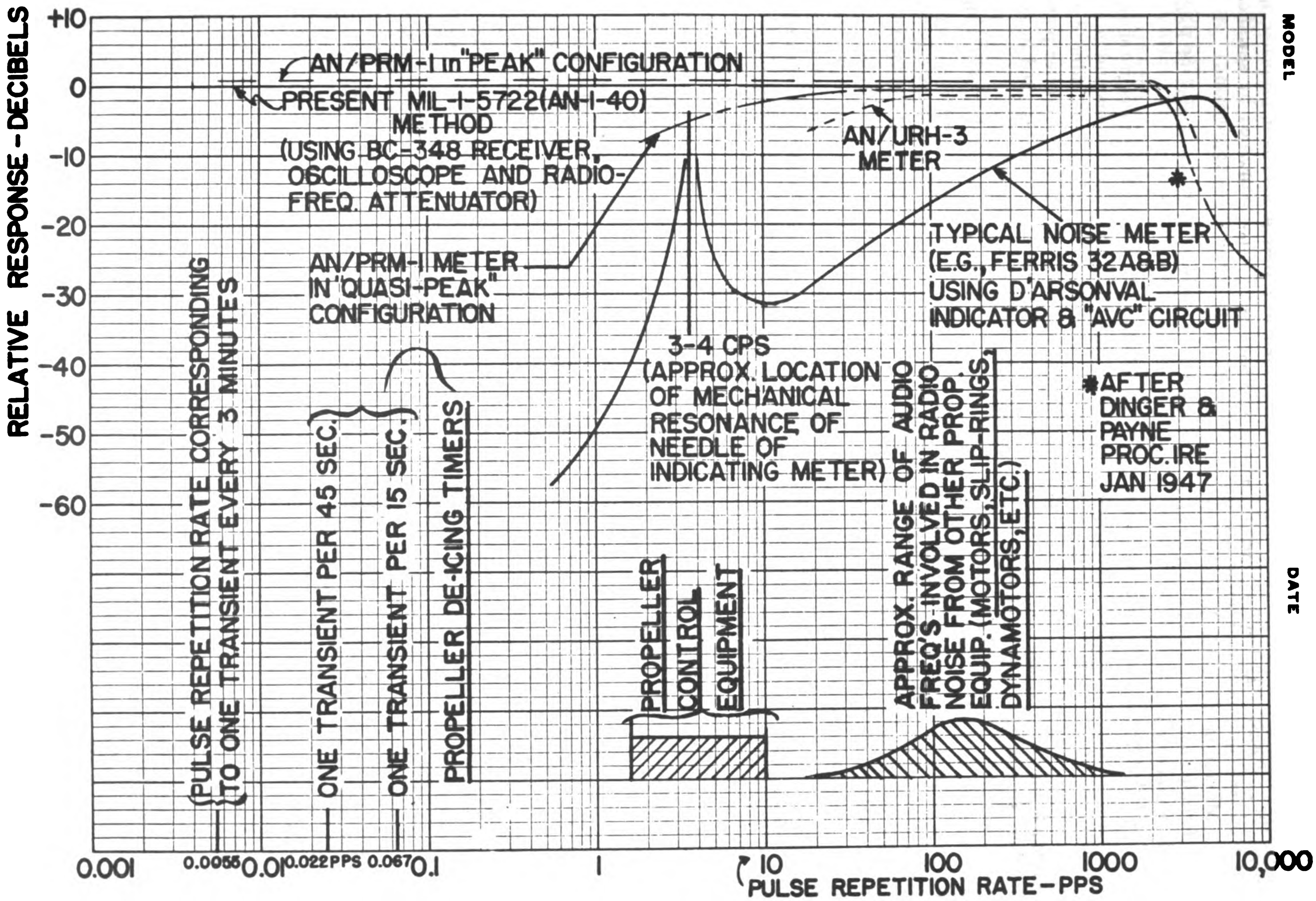

Figure 6.1.—Effect of pulse repetition rate on radio performance.

of noise in the last ten per cent of operational situations must be handled individually, but working that close to zero noise level requires use of good test equipment and sound test procedures. Maximum allowable limits of interference, founded on a sound basis, should be specified whenever possible.

(2) *Established specifications.* Early attempts to set up propeller radio-noise specifications centered around use of available test equipment and procedures established to define acceptable interference limits of motors, dynamometers and other, similar electrical equipment (e. g. Specification JAN–I–225). This approach was found to be inadequate and it became obvious that a more fundamental line of attack was needed. Several intermediate stages of development culminated in a military Specification, "MIL–I–6722 Interference, Limits, Propeller Systems, Radio." Experience has shown that the approach outlined in this specification is basically sound. However, certain serious technical difficulties in important details must be resolved to make the specification most effective.

(3) *Radio interference surveys.* Future plans for use of Specification JAN–I–225 involve development of a *radio-interference survey* to be made as part of the type test of each new propeller design. It is believed that an effective radio-noise survey can be conducted just before or just after the vibration study. The type test approach of noise elimination control was chosen rather than a production inspection method because propeller fabrication conditions are unfavorable to production inspection. Production methods generally require operational checks of propeller system components, but complete propeller assemblies are made, rarely, during production to check system operation. Therefore, complete operational checks of a propeller system could be made only after installation on an airplane. In many cases, new designs of a propeller system will consist of only minor changes from previous designs, or of mechanical changes which will not affect radio interference performance of the system.

It is believed that modifications of an existing propeller system with acceptable radio interference characteristics need not be retested if the proposed modifications of the system do not involve electrical system changes. In this connection, attention must be directed toward Specification MIL–P–5449, Amendment 1, which requires that a proposed propeller installation model be accompanied by specifications of radio interference suppression.

Type Tests Prescribed for Determination of Radio Interference

(1) *Engine test.* Engine test procedure should be used to test all propeller systems and equipment for radio-noise which can be induced by engine rotation, vibration and propeller power loading. These effects can be expected in systems involving such items as:

- (*a*) Electrical current-carrying slip rings in the hub or on blade shanks.
- (*b*) Engine-mounted propeller governors.
- (*c*) Electrical pitch-changing mechanisms.

(2) *Bench test.* A bench test procedure may be used to test all propeller system equipment for radio noise which will be unchanged in magnitude by engine vibration or propeller power loading. Typical examples of such equipment are:

- (*a*) Blade angle indicators involving use of a-c selsyns powered by 400 cps inverters.
- (*b*) Deicing systems using hub mounted generators, and timers.

(3) *Test equipment and techniques.* In its present form, MIL–I–6722 prescribes use of special measuring equipment and techniques for anti-radio noise tests. The measuring equipment, prescribed by MIL–I–6722, must include two standard service receivers, along with a cathode-ray oscilloscope to be used as an indicating instrument. An oscilloscope is specified as the indicating instrument rather than the D'Arsonval meter which is widely used for the purpose in conventional noise meters, because a wide range of so-called repetition rates exist in the types of noise produced in propeller

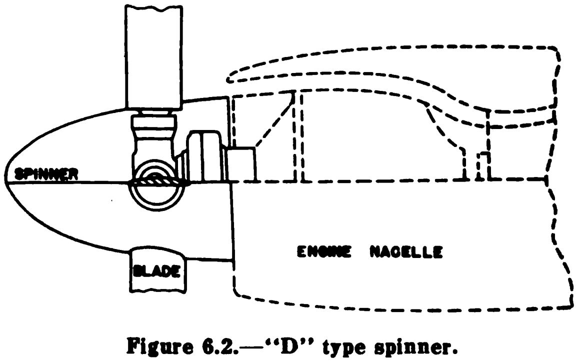

Figure 6.2.—"D" type spinner.

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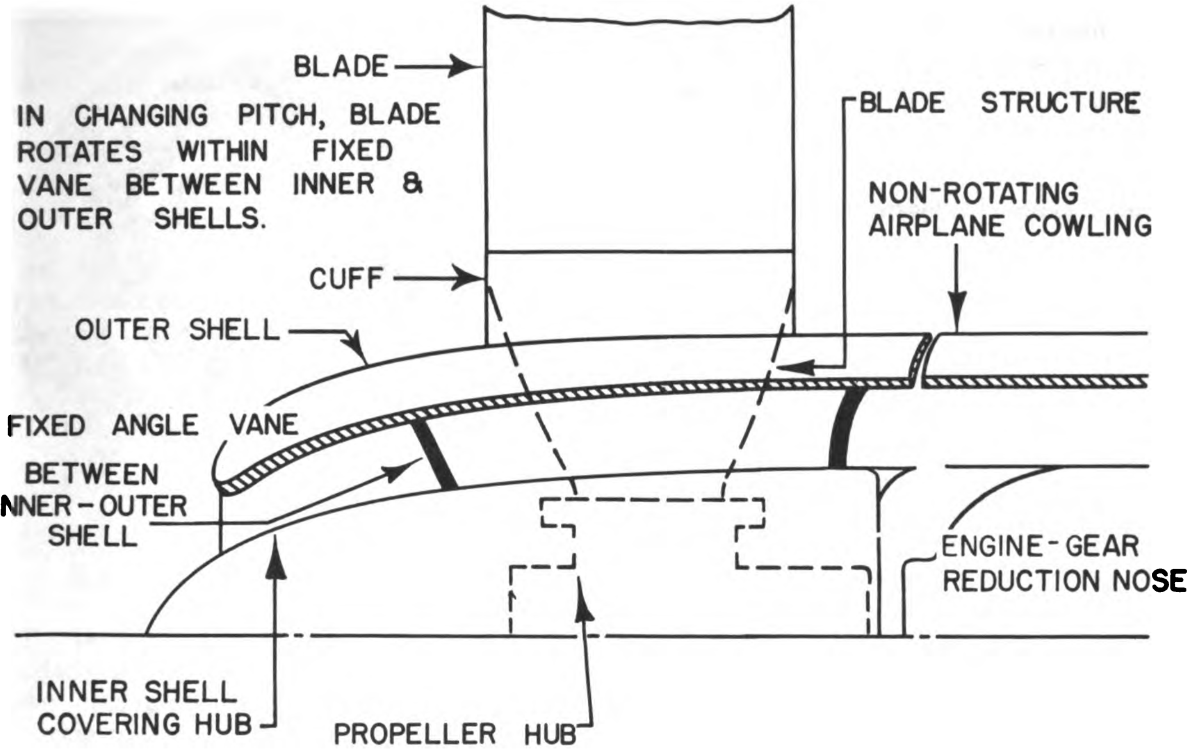

Figure 6.3.—"E" type spinner—sectional sketch.

circuits. Figure 6.1 illustrates the possible range of pulse repetition rate.

Attention should be directed to the low repetition rates involved in the pulsing type noise produced by many propeller control systems and to the very low rates of certain types of deicing timers. This interference may be recognized by a series of intermittent clicks or pops.

Specification Compliance Responsibility

Procedures established in Specification MIL–I–6051 may be used as a general guide for resolution of radio noise problems, but the solutions obtained are incomplete and often produce ineffective *fixes* or attach an undue weight penalty. Elimination of a noise source before equipment installation is the best solution to radio interference problems. Specification MIL–I–6722, as revised, should be adequate as a guide for elimination of radio noise. In any event, current directives of responsible government agencies should be checked carefully to insure full compliance with all radio interference requirements.

Manufacturers of propeller and propeller components will be required to modify propeller equipment whenever elimination of interference is necessary. Responsibility for performing tests to check compliance of propeller equipment with applicable radio interference specifications rests with that agency having jurisdiction over acceptance of the equipment. All questions of compliance, test methods, and equipment design should be referred to the appropriate agency.

Propeller Spinners

Function of Propeller Spinners

Primarily, propeller spinners should serve to improve air flow conditions at the blade-hub juncture, which will permit greater airflow into engine nacelle resulting in more efficient engine operation. Furthermore, improved air flow conditions at the hub section will reduce propeller drag. In addition to aerodynamic purposes of spinners, such structures serve as propeller hub assembly enclosures.

Spinner enclosures for certain low speed propeller assemblies must be provided to protect external working parts of the pitch change mechanism against sand and dust. External contours of these so-called dust-proofing spinners will be controlled by enclosure requirements, primarily, with aerodynamic considera-

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tions playing a minor role. Usually, these spinners of steel sheet have been mounted upon the propeller hub and flared out to enclose the vital pitch change mechanism at the shank end of the blades.

Structural Types of Spinners

Generally, two types of propeller spinners have been used, depending upon requirements of the specific installation. Basic characteristics of the two types are presented in the following paragraphs.

(1) *"D" type spinners.* Of the two general classes of propeller spinners, the NACA *D* type is the one in most common use. This type can be adapted to nearly all applications by careful attention to detail design. The *D* type spinner can provide ram recovery in the order of 0.9. A sketch of this type of spinner is illustrated in figure 6.2.

The *D* type spinner will reduce hub drag effectively and at the same time reduce disturbance to ram recovery or engine cooling to acceptable limits. It is to be noted that the *D* type of spinner is small, simple in construction and of light weight. However, in conjunction with the use of *D* type spinners, adequate airfoils must be provided as a part of the blade to extend to the spinner surface. Blade cuffs will satisfy this requirement quite well.

(2) *"E" type spinners.* For those propeller installations in which ram recovery requirements are more critical than those of *D* type spinner applications, a ducted or blower type spinner may be required. The NACA *E* type spinner, illustrated in figures 6.3 and 6.4 is representative of this class of spinner.

With the *E* type spinner, ram recovery ranging from 0.95 to 0.98 may be obtained. This type of spinner is much more complex than a *D* type, being larger and heavier and in return offers several advantages. For instance, air intake to the engine will be moved forward, effectively, into the undisturbed air stream by use of an *E* type spinner. Air velocity, after entry into the spinner, will be reduced thereby reducing drag of the thick shank regions of the propeller. While changing pitch, the propeller blade shank will rotate within fixed angle vanes inside the spinner.

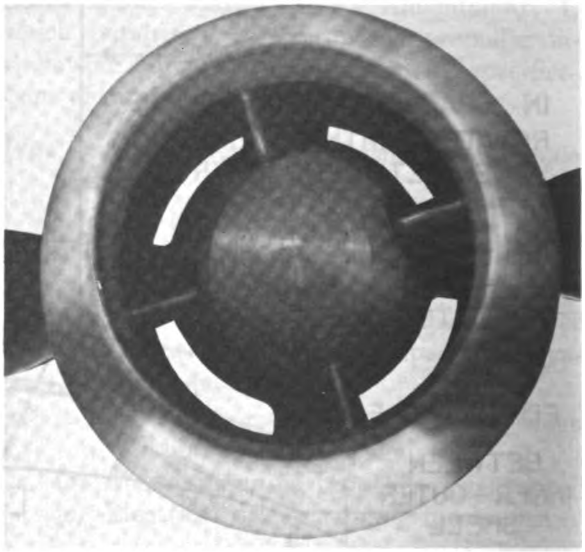

Figure 6.4.—"E" spinner installation.

(3) *Comparison of "D" and "E" type spinners.* For comparative purposes, both types of spinners have been illustrated in figure 6.5 in which relative size of each is shown. In this sketch, the blade cuff requirement of the *D* type spinner is shown clearly by the reduced diameter and frontal area of the spinner.

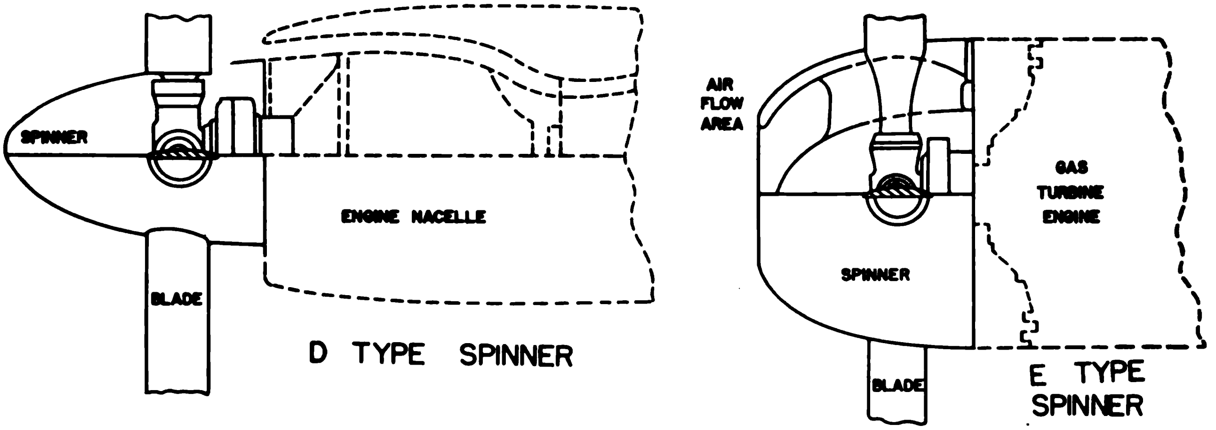

Figure 6.5.—Comparison of "D" and "E" type spinners.

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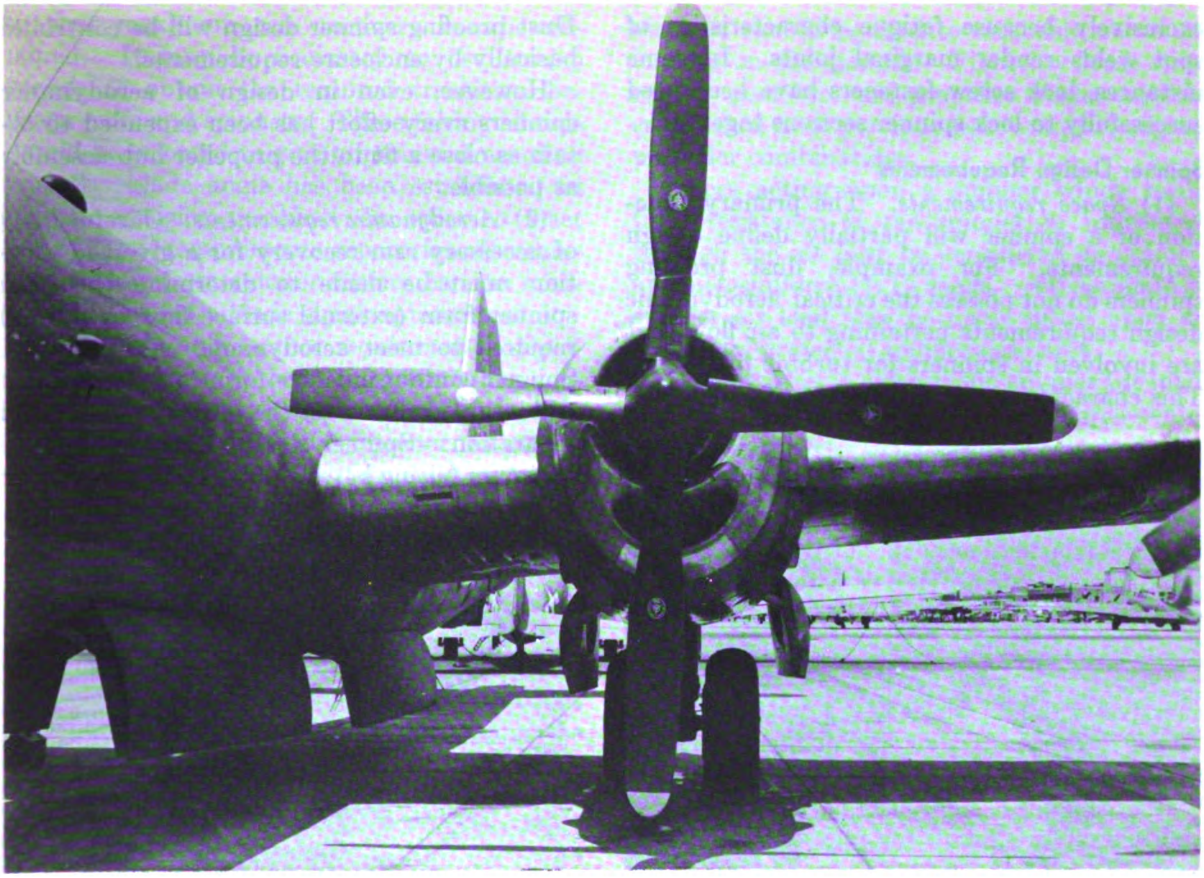

Figure 6.6.—Four blade propeller—"D" type spinner with cuffs.

Typical Spinner Installations

(1) *"D" type spinner installations.* A propeller installation of a *D* type spinner with necessary blade cuffs is illustrated in figure 6.6.

The illustration shows a four blade propeller equipped with *D* spinner and blade cuffs set up in an engine test stand preparatory to propeller test.

A second installation of a *D* type spinner is shown in figure 6.7.

In this installation a *D* type spinner has been adapted to a dual propeller and is of a particular interest because it depicts the design variation in blade cuff-spinner junction from that of the four blade propeller installation of figure 6.6.

(2) *"E" type spinner installation.* A propeller with an *E* type spinner installation is shown in figure 6.8. It is evident from observation of the installation that the *E* type spinner has greater complexity and weight.

The *E* type spinner will cost more to produce and probably increase the cost of propeller maintenance. Experience with subsonic airplane applications has not proven that this increased cost will be absorbed by improved performance. Hence, adoption of the *E* type spinner for propeller installations has not progressed much beyond the experimental stage. Introduction of turbine engine installations with increased air speeds, doubless, will alter the *E* spinner status, considerably.

Materials and Methods of Spinner Fabrication

Spinner structures, generally, have been fabricated of steel, aluminum or magnesium alloy. Spinning or deep drawing of the material to form proper surface contour has proven to be the most successful production process. The shell usually consists of several spun sections with section size being estblished by manufacturing requirements.

The several sections of the spinner must be assembled and attached to the supporting structure by some form of riveted or welded joint. Riveted joints have been used in spinner assemblies and for spinner attachment almost

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exclusively because fatigue characteristics of spot welds render marginal joints. In some instances, lock screw fasteners have been used successfully to lock spinner sections together.

Spinner Design Requirements

(1) *Space requirements.* The primary function of a spinner will partially define design requirements. For example, dust proofing spinners do not possess the critical aerodynamic design requirements pertaining to air flow that are involved in spinners for turbine propellers. This characteristic is illustrated in figure 6.9. Dust proofing spinner design will be controlled basically by enclosure requirements.

However, even in design of aerodynamic spinners every effort has been expended to obtain as close a fit to the propeller hub assembly as possible.

(2) *Aerodynamic requirements.* Careful study of necessary ram recovery for a given installation must be made to determine the basic spinner form (external surface flow or ducted) required to meet aerodynamic considerations. Spinner contour must conform to a pattern that will insure air flow over the surface without fluid separation. Spinner design must incorporate optimum fairing between blade cuff and spinner

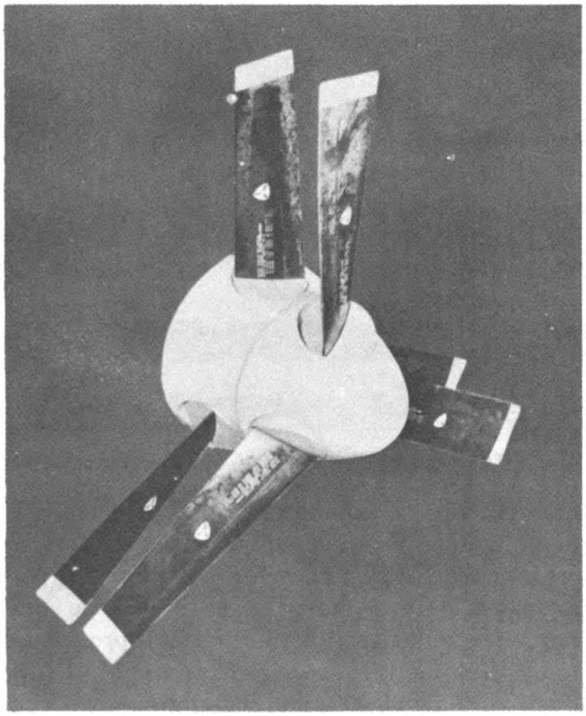

Figure 6.7.—Dual propeller with "D" type spinner.

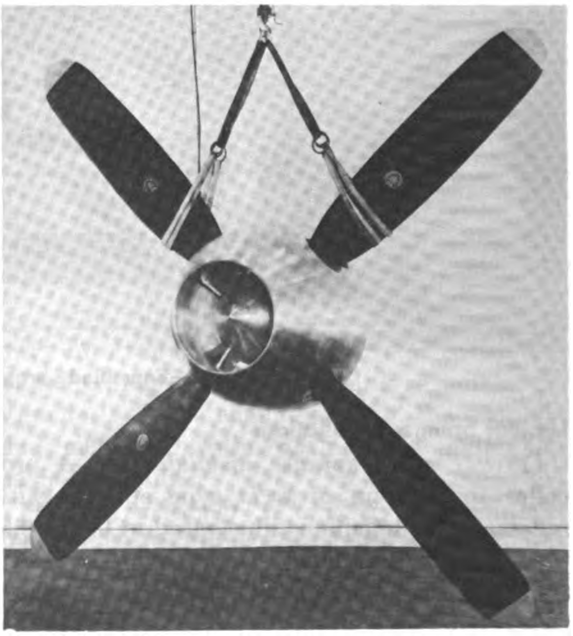

Figure 6.8.—Four blade propeller with "E" type spinner.

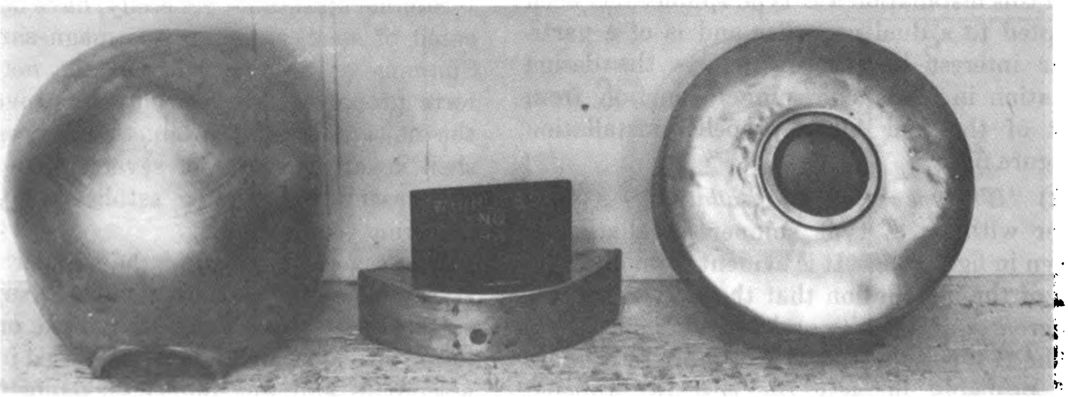

Figure 6.9.—"Dustproof" spinner.

so that maximum ram recovery can be obtained. It may be necessary to use *fairing islands* to obtain the required transition between cuffs and spinners. These fairing islands should be oriented to give minimum drag when propeller blade angle has been established at airplane cruising position. In order to meet aerodynamic requirements, separation of streamline air flow from spinner surface can be minimized by use of a blade shank-spinner seal.

(3) *Weight and balance requirements.* Spinner weight must be held to a minimum consistent with functional and structural integrity. In evaluation of allowable spinner weight, a comparison of airplane performance with and without spinner installation must be made. Ram recovery with corresponding improved propeller efficiency must be great enough to justify the cost involved in fabrication, installation and maintenance, as well as fuel cost of carrying the weight of a spinner in flight.

Obviously, if excessive propeller vibrations are to be avoided, spinner installations must be fully balanced both statistically and dynamically.

(4) *Maintenance.* Design of spinners must provide those features prerequisite to ready access to propeller components, as well as spinner parts, for maintenance purposes. In consideration of maintenance requirements of spinner design, the need for adequate access openings to permit complete inspection must not be neglected.

Spinner Loading

Spinner sections in service will be subject to a combination of six distinct types of loading. Types of spinner loading generally encountered include:

(1) Centrifugal forces.
(2) Gyroscopic forces.
(3) Engine-gear box transmitted vibratory forces.
(4) Propeller blade transmitted vibratory forces (1xP, 2xP. . . . nxP).
(5) Uniform non-uniform (1xP) air applied force.
(6) Magnus effect.

On the basis of an assumed size and weight of propeller spinner, centrifugal and gyroscopic forces acting upon the spinner may be estimated for a given air speed, propeller rotational speed and airplane turning rate. For design purposes, the worst operating conditions of the airplane should be used to establish maximum loading on the spinner. Vibratory loads from engine, gear box and propeller blades may be established from previous test records of engine-propeller combinations.

Forces acting upon a spinner which result from resistance of the spinner to movement through the air may be considered as uniform and non-uniform (1xP) loads. An estimate of spinner air load may be made based upon air speed and projected spinner base area.

Magnus effect is, effectively, spinner lift loading which will exist whenever the spinner center line of rotation is not parallel to the line of action of relative wind acting upon the surface. Quantitative evaluation of Magnus effect loading, of necessity, will have to be based upon estimates supported by experimental data.

Spinner Design Practices

(1) *Contour.* Exact shape of a spinner must be tailored to fit each specific propeller installation. Therefore, definition of spinner contour cannot be established by application of general rules. The contour will be controlled by aerodynamic requirements. Satisfaction of aerodynamic requirements may be obtained by use of an exponential equation of the form:

$$R=K_1(X)^a-K_2(X)^b \qquad \text{VI-1}$$

in which, K_1, K_2, a and b are constants, experimentally determined.

R=radial distance from center of rotation.
X=longitudinal distance measured from the spinner nose.

Spinner base diameter will be fixed by engine nacelle and principal propeller hub dimensions.

(2) *Structural design.* A spinner shell must have some minimum metal thickness to insure that its shape will be maintained under all operating conditions and while being handled during installation or overhaul. Minimum shell thickness will be governed in part by the type of material involved. Experience has shown that with fabrication materials presently in use, spinner shell thickness must be equal to or greater than four one-hundredths of an inch (.04″). Most of the load carried by a spinner will be transmitted by means of bulkheads, to the propeller hub. Spinner nose must incorporate quick detachment features or suitable quick opening apertures provided to facilitate propeller inspection and servicing. An exploded view of a spinner assembly is shown in figure 6.10.

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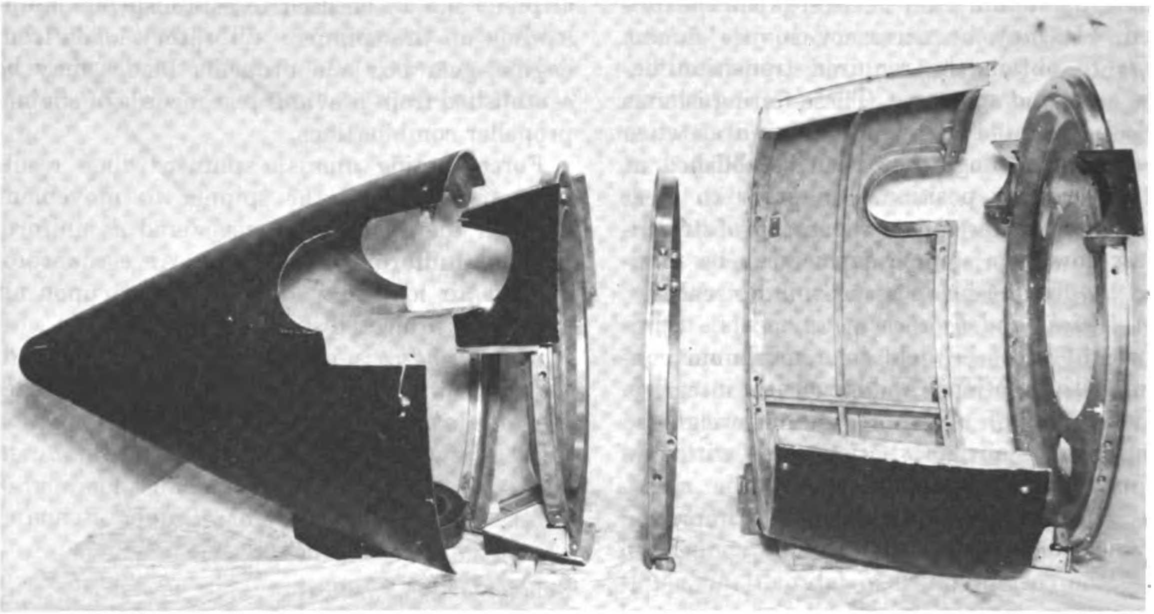

Figure 6.10.—"Exploded" spinner assembly.

Spinner bulkheads must be designed to carry the total spinner load, essentially, with minimum stress concentration and minimum weight. In order to obtain greater support for the spinner, several points of attachment to the propeller hub structure have been used. For example, hub structure, blade nut of the blade retention system, propeller hydraulic dome and electric power unit housing all have been used for spinner structure attachment. All of these spinner designs have as an objective the achievement of a broad base of support thereby lowering the restraining forces. However, blade retention system design may not permit this arrangement, always. Usually, it is most desirable to specify and design spinner supporting components to provide restraint in each degree of freedom. This requirement if properly attained will accommodate large deflections of the spinner.

Every component of a spinner structure must be designed to avoid stress raisers; hence, generous fillets must be employed at every significant sectional dimension change. Spinners may be especially susceptible to fatigue failure because of the relatively thin sections employed unless extreme care has been used in design and fabrication. The spinner bulkhead failure shown in figure 6.11 can be attributed to improper structural design.

It is apparent that rational design of spinners must be supplanted to a large extent by empirical or cut and try methods. Intelligent application of previous design experience in development of new spinners will produce a spinner design that has a reasonable chance of success. In such a design procedure, obviously, spinner testing must play an important role. Essentially, spinners designed on this basis incorporate successful features of previous designs.

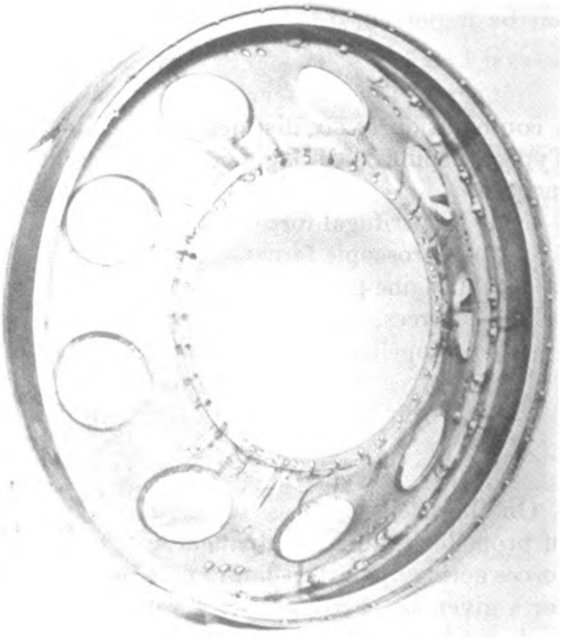

Figure 6.11.—Spinner bulkhead failure.

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Type tests will bring forth design modifications prerequisite to production approval.

(3) *Spinner fabrication.* Until spot welding design and process quality control can achieve the reliability necessary to insure that fatigue failures at welded junctions will not occur, spinner sections and structures must be joined by riveted joints or screw fastenings. Typical riveted joints and screw fastenings along with other structural characteristics of a blower type spinner are shown in figure 6.12.

Quick detachment features of a spinner nose may be attained in a number of ways. The VDM lock ring arrangement has been used successfully for this purpose. In this arrangement, a ring mounted in a bulkhead at the point of attachment will be engaged by studs attached to the removable nose section in assembly. Other spinner designs have used the Aircraftsman modified tapered pin clevis arrangement. This method of attachment utilizes several clevis assemblies, which must be individually unlocked for disassembly, to retain the nose section. Also, shear loaded cowl fasteners have been used successfully for spinner nose section retention. Each method has desirable characteristics, no one of which predominates to the extent that one type of fastener can be proclaimed as "the best."

Cutouts in the spinner shell must be made with sufficient clearance to permit complete blade angle change, from reverse pitch to full feathered position for high power, high speed installations. As shown in figure 6.11, bulkheads may be formed with web cutouts to reduce bulkhead weight while retaining necessary stiffness to support the spinner shell.

Propeller Blade Cuffs

Function of Blade Cuffs

A blade cuff is a metal, wood or plastic structure designed for attachment to the shank end of the blade, with an outer surface that will transform the round shank into a continuation of the airfoil section. Primarily, a cuff must be designed to enhance efficiency of transfer of cooling and combustion air to the engine nacelle. Improved ram pressure recovery is highly desirable during certain maneuvers, namely, climb and ground operation. Cooling requirements of climb and cruise flight regimes are not identical and both vary from ground operational requirements. Blade cuff design should incorporate the optimum compromise of all operational needs.

Blade Cuff Design

A single propeller blade cuff design embodying optimum characteristics in every detail has not been developed, as yet, with little prospect that such a design ever will be forthcoming. An acceptable rational approach to blade cuff design has not been found. Cuff angle of attack and profile must be established to meet aerodynamic considerations which are not

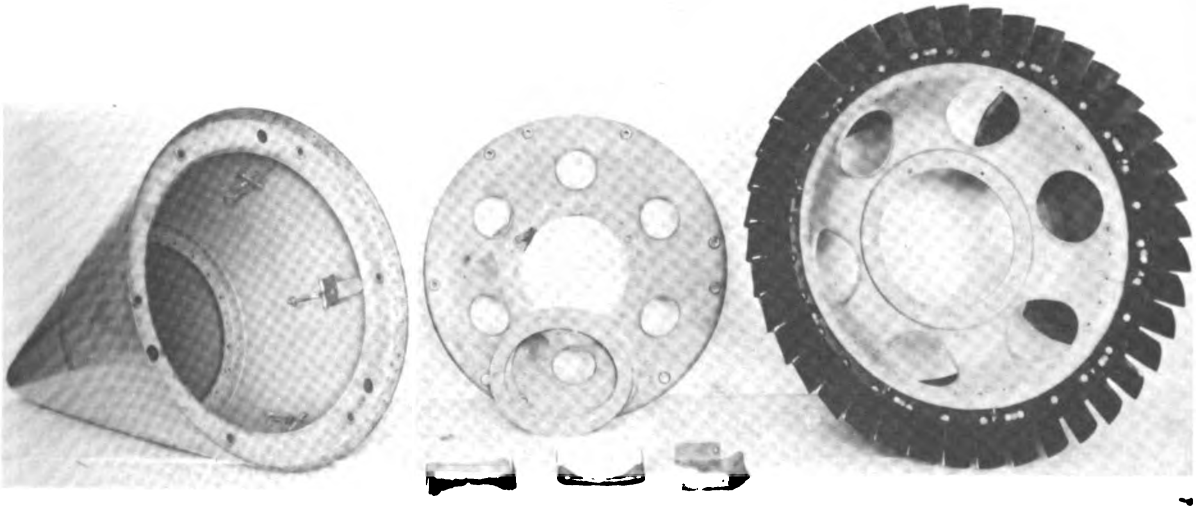

Figure 6.12.—Blower type spinner.

significantly different from those of a propeller blade.

Generally, forces acting upon blade cuffs, as determined by analytical methods, are low enough that structural problems can be solved easily with available materials. The effect of cuff attachment to blade structure, as reflected by stress concentrations at the joint, is of more importance than structural strength requirements, since the latter can be satisfied so easily by cuff materials.

The types and magnitude of blade cuff vibratory loads induced by aircraft-engine-propeller configuration play a commanding part in cuff design. As a means of reducing blade cuff vibratory stresses, designs were established to isolate the cuff from the blade structure. Hence, cuff assemblies have been mounted on an inboard pivot which would permit a certain amount of fore and aft or edgewise freedom. To accommodate controlled fore and aft movement, considerable clearance between propeller blade and rubber chafing strips was provided at the outboard section of the cuff sheet.

Use of *floating* outboard cuff sheets will require sheet reinforcement, greater bulkhead strength and improved joint efficiency at the inboard point of attachment. It would appear that use of removable, expanded rubber type blade cuffs may be the best design solution to the problem of extended cuff freedom with minimum fatigue stresses.

Some measure of stresses induced in a blade cuff by a propeller blade subjected to large power loadings and considerable variation of inflow angle, can be obtained from blade stress studies outlined in another section of this handbook.

Blade Cuff Materials and Construction

Balsa wood, rubber, aluminum and steel have been used as cuff sheet and structural materials. In addition, magnesium has been used successfully in cuff supporting structures. However, joint use of certain metal combinations may introduce severe problems involving galvanic corrosion and varying coefficient of expansion.

Attachment of cuffs to propeller blades has been accomplished either by mechanical clamping devices or by use of bonding materials. The most successful bonding agents have been rubber-base adhesives.

Acceptable cuff-blade bonding has been obtained only under the carefully controlled pressure and temperature conditions specified by the adhesive manufacturer.

Fabricated cuffs, in which an airfoil form of

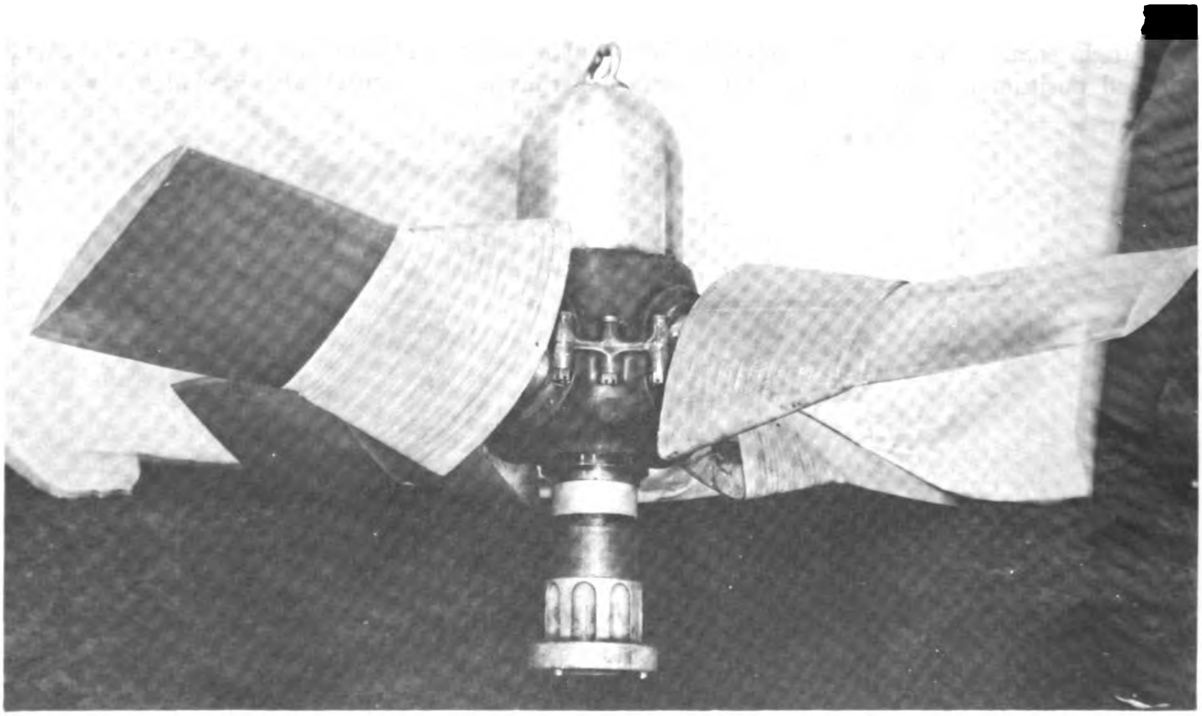

Figure 6.13.—Balsa wood blade cuff.

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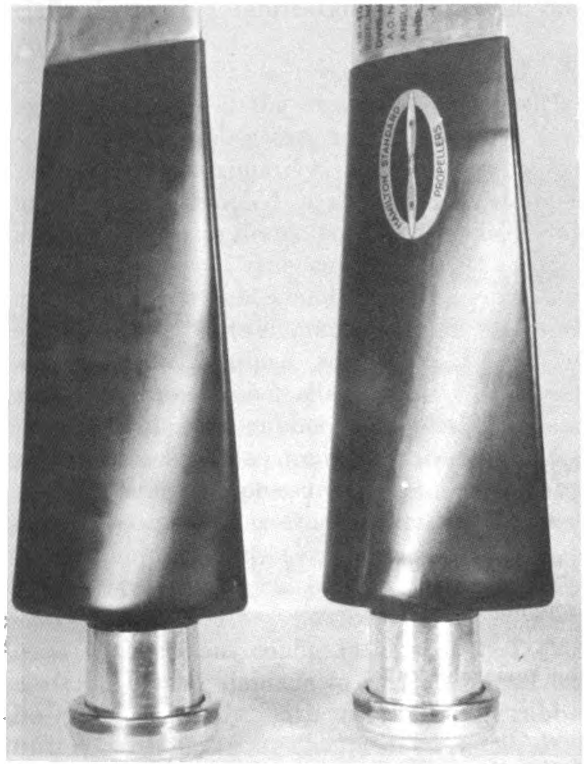

Figure 6.14.—Rubber core and sheet blade cuff.

sheet metal is attached to internal bulkheads, have been constructed using screw fastenings or adhesive bonding. Spot welding has not been successful because of induced corrosion.

Typical Blade Cuffs

(1) *Balsa wood cuffs.* Balsa wood blade cuffs have been fabricated and usually were designed with separate symmetrical thrust and camber sections. This design required assembly of thrust and camber sections on the blade shank; bonding was accomplished by using a casein-latex cement. After curing the juncture, the entire blade cuff was wrapped tightly with overlapping layers of dope impregnated linen tape. This cuff can be repaired, readily, after surface erosion damage, by addition of several layers of prepared linen tape, with appropriate heating and pressing to airfoil contour. A typical balsa wood blade cuff is illustrated in figure 6.13.

(2) *Rubber core and sheet cuffs.* A core of expanded rubber bonded to a rubber sheet to form proper airfoil contour has been used as a cuff for aluminum blades. The technique involved in formation and bonding of such a cuff is especially interesting since it is typical of a spe-

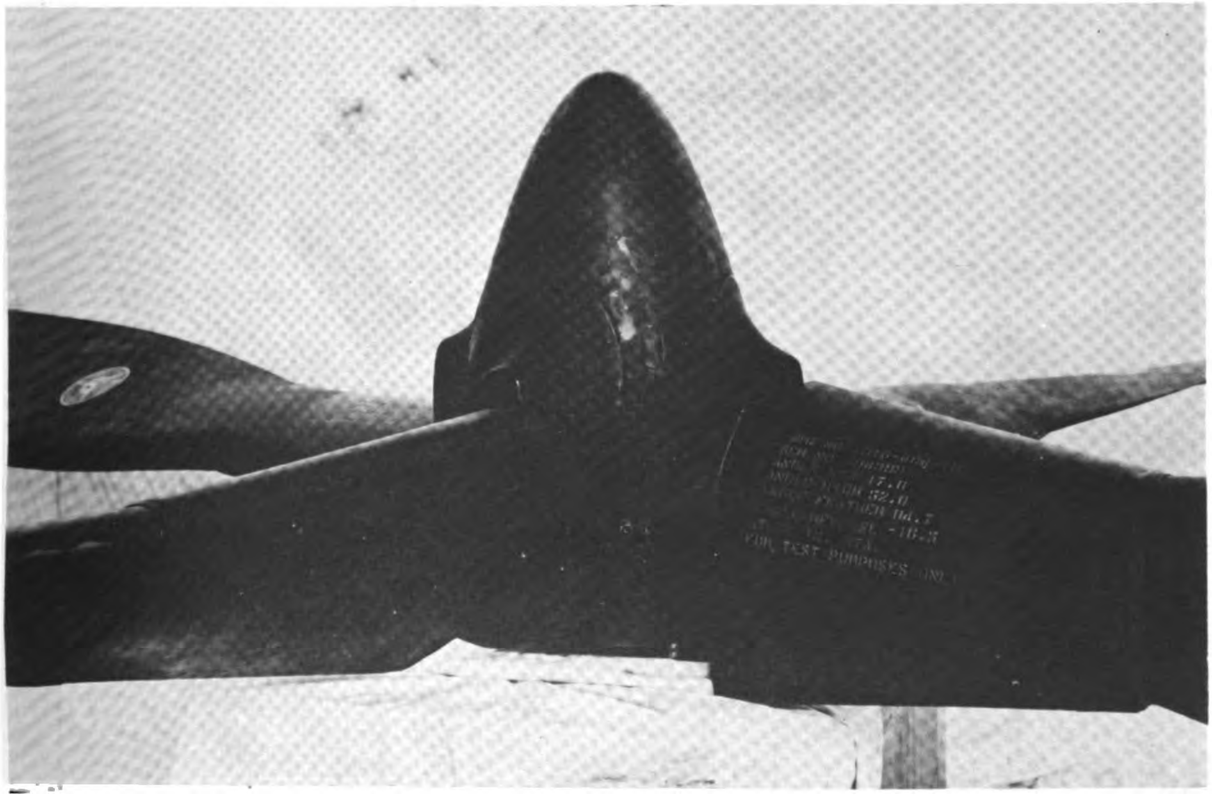

Figure 6.15.—Sheet steel blade cuff.

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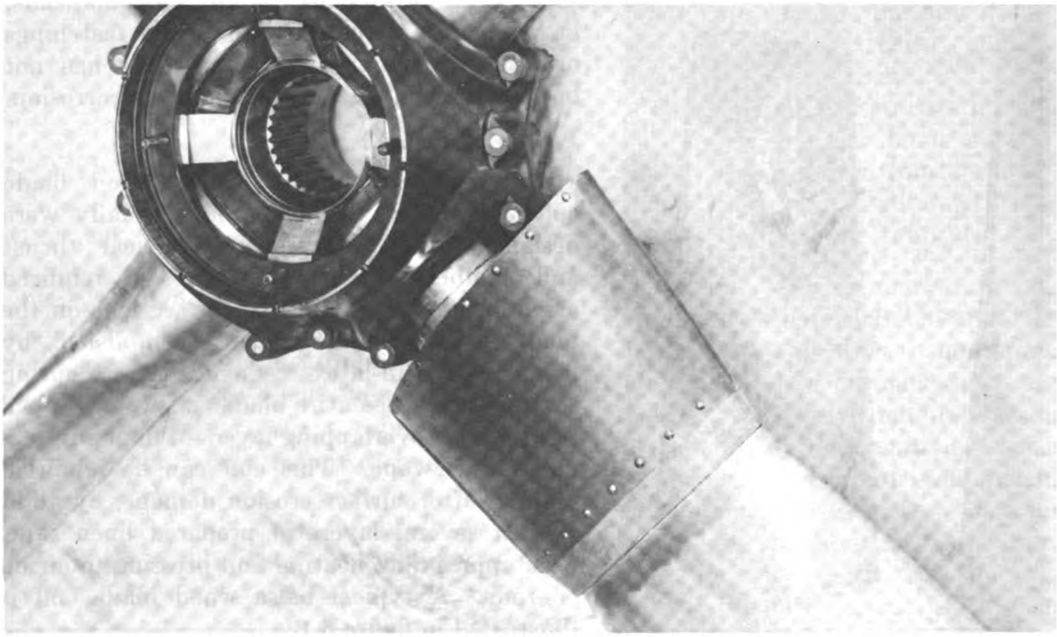

Figure 6.16.—Aluminum removable cuffs.

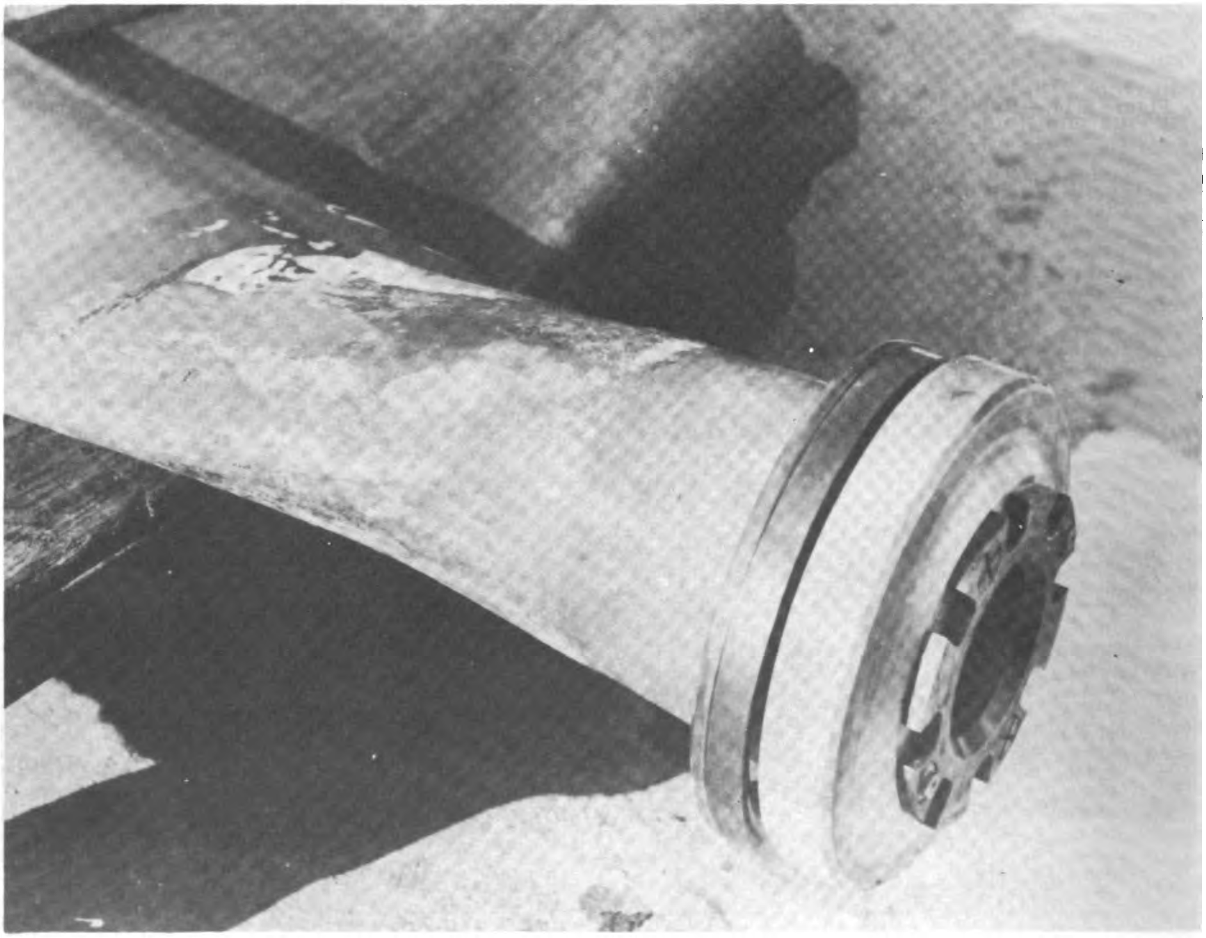

Figure 6.17.—Blade shank corrosion.

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cialized type of fabrication required in propeller development.

In fabrication of a typical rubber cuff, the external surface of the core was covered with a tough, hard rubber external sheet of $\frac{1}{16}$ inch thickness, approximately. The rubber components were assembled in a steel mold clamped around the blade shank, so that the inside surface of the mold was covered by the tough rubber sheet which would form the cuff outer surface. The blade shank, coated with bonding cement, was wrapped with a rubber sheet. Between these rubber sheets within the mold, unexpanded core rubber was placed. Heat addition caused the core rubber to expand and develop sufficient pressure to bond the rubber core, internal and external sheets together and bond the interior sheet to the blade shank.

This type of cuff was especially free of vibration and most other service difficulties when used with certain configurations of P–51 aircraft. Abrasive damage to this blade cuff can be patched easily with cold setting rubber putty without propeller blade removal—a decided maintenance asset. An illustration of a rubber core and sheet cuff is shown in figure 6.14.

(3) *Sheet steel cuffs.* Still another type of blade cuff, which might be designated a semi-floating cuff, was developed for use on early B–29 airplanes. This cuff had a formed, sheet steel shell fastened to an aluminum bulkhead at the inboard section. The aluminum bulkhead was attached, rigidly, to the blade shank by use of a rubber vulcanizing bond whereas the outboard portion of the cuff could float free of the blade. However, some cuff support was furnished by the blade through use of a rubber chafing strip which prevented cuff sheet-blade contact. This design permitted ready inspection access to all portions of the blade shank except those directly under the bulkhead, by removal of the cuff sheet. An illustration of this type cuff is shown in figure 6.15.

(4) *Aluminum removable cuffs.* One of the earliest completely removable cuffs was developed for use on welded hollow steel blades. This cuff was retained in place by use of a cuff ring of steel, approximately $\frac{1}{4}$ inch wide, surrounding the blade shank to which the inboard cuff bulkhead was keyed. Radial movement of the cuff upon the blade shank was prevented by a cuff ring which clamped the halves of the bulkhead around the shank. Cuff rotation around the blade shank was restrained by a cuff ring and a keying arrangement.

Blade cuff contour was formed by a thin sheet of aluminum which was attached to cuff bulkhead by screws. Cuff sheet closure was formed at the cuff training edge using a hinge type joint. Removal of the cuff sheet could be accomplished easily, by removal of bulkhead screws and trailing edge hinge pin. The outboard portion of the cuff was not attached to the blade, but some support to the cuff was furnished by a rubber chafing strip provided to prevent blade-cuff sheet contact. Incidentally, this particular cuff, also, absorbed the centrifugal forces of blade shank electrical deicing slip rings. Aluminum removable cuffs essentially the same as shown in figure 6.16 have been used successfully on some types of B–29 aircraft.

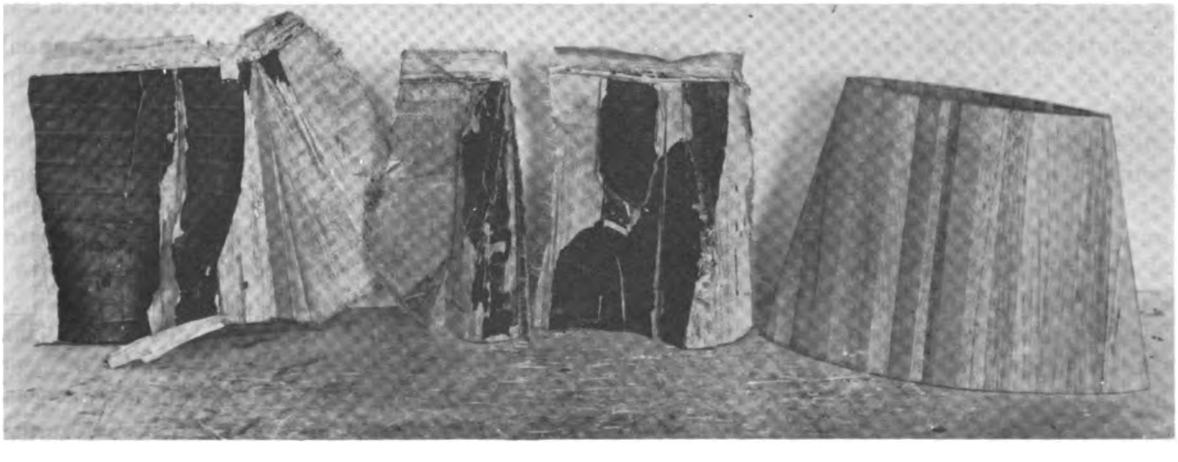

Figure 6.18.—Balsa wood cuff failure.

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Propeller Blade Shank-Cuff Corrosion

Attachment of cuffs to a blade shank by organic adhesives may cause corrosion, which results from moisture entrapment between inner cuff surface and outside surface of the blade shank to which the cuff is attached. Severe corrosion of aluminum alloy blade shanks has developed under direct bonded balsa and molded rubber cuffs. Also, corrosion has been found under attachment rings for sheet metal cuffs. An illustration of corrosion extant under a blade cuff has been illustrated in figure 6.17.

In addition to the corrosion visible in this photograph, microscopic study revealed integranular corrosion existing to a depth of .050 inch below the deepest pits. The experience recorded in this photograph reemphasizes the importance of careful material selection and bonding procedures.

Balsa Wood Cuff Failure

Illustration of a balsa wood blade cuff which failed in test is shown in figure 6.18. The failure of unwrapped balsa wood cuffs was accelerated by blade bonding failure.

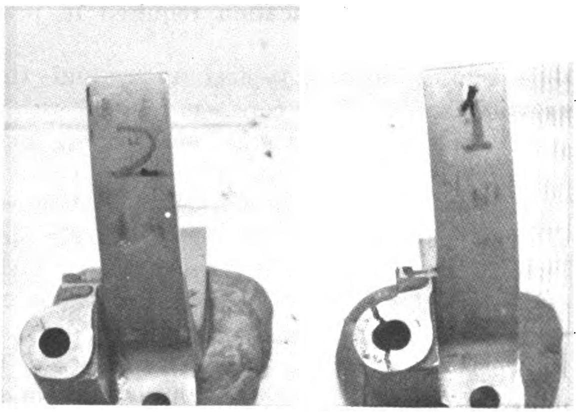

Figure 6.19.—Blade cuff structural failure.

Cuff Structural Failures

Some indication of blade cuff structural failures which may be encountered by virtue of poor design, is shown in figure 6.19. Stress concentration and fatigue, in this case, have combined to cause failure of blade cuff supporting structure.

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CHAPTER VII. ICE CONTROL

Introduction

Influence of All Weather Aircraft Operation Upon Propeller Deicing Requirements

Until 1937, approximately, propeller ice control was not considered to be a design problem. Prior to 1937, airplanes were considered to be more or less fair weather craft. Icing conditions, fog, turbulence, and electrical storms were considered hazardous to the operation of aircraft. Since methods of carburetor and wing surface ice control had not been developed, extensively, emphasis was placed upon avoidance of meteorological conditions that would be hazardous to flight. The direct-coupled propeller, with resultant high propeller rotational speeds, aided removal of ice accretions on the blades thereby minimizing hazardous flying. With emphasis on development of aircraft which could be flown under all conditions at reduced propeller speeds, the need for propeller ice protection assumed greater importance. Some impetus to development of ice control arose from a natural reluctance to operate aircraft under icing conditions; but, recognition of the deleterious effects of ice accretions on propeller blades was a greater stimulus.

Effects of Propeller Icing

Ice formation on a propeller blade, in effect, produces a distorted blade airfoil section which, in turn, causes a loss in propeller efficiency. Generally, ice collects unsymmetrically on a propeller blade which produces propeller unbalance and, very often, destructive vibration. Centrifugal forces acting on large accretions of ice will overcome adhesion to the blade. However, throw-off of large pieces of ice will be a hazard to personnel and airplane structures, especially fuselage and tail sections. The photograph of figure 7.1 shows ice accretion on an unprotected blade, which was accumulated under representative flight icing conditions. Note the ragged break of ice on the leading edge where ice strength was insufficient to withstand centrifugal force and has been thrown off. The remaining irregular accumulations on the blade face contribute to increased aerodynamic losses. The large ice mass on the shank area will produce blade unbalance as well as become a hazard to other aircraft components.

Early Deicing Methods

Before the development of special provisions for propeller ice control, it was common practice to increase propeller speed to obtain ice removal by centrifugal force and blade vibration. The method was unsatisfactory because the increase of centrifugal force was ineffective until large masses of ice were accumulated. However, the method may be used to obtain whatever benefit possible, under emergency conditions.

Icing Parameters and System Performance Requirements

NACA Study of Icing Parameters (NACA Technical Note No. 1855)

(1) *Effective temperature range.* Early studies of the effectiveness of propeller ice control systems were based on an assumed effective temperature range from 25° to 32° F. Recent studies by NACA have shown that air temperatures in the range from 0° to 15° F. are conducive to propeller icing. However, ice adhesion will increase with a decrease in temperature; hence, a greater amount of heat will be required for ice removal.

(2) *Altitude effects upon icing conditions.* The investigations, reported in NACA Technical Note No. 1855, disclosed that under appropriate exposure time, temperature and moisture conditions, propeller icing could occur at any elevation from sea level to 25,000 feet, altitude. Since an increase in altitude is associated with temperature decrease, low temperature icing problems will prevail at high altitudes.

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(3) *Effect of water droplet size.* It has been found that propeller icing may be encountered during considerable time exposure to an atmosphere of low temperatures whenever a mean effective droplet size of 20 microns is in suspension with humidity of one-half a gram per cubic meter.

(4) *Effect of exposure time.* Substantial accumulation of ice upon an operating propeller is more apt to occur during exposure under icing conditions of long duration. Exposure to severe icing conditions that exist for a minute or less, normally, will not cause an appreciable ice accretion upon a propeller. Therefore, design criteria for ice control systems incorporate an assumption of exposure to icing conditions extant in continuous horizontal configuration.

(5) *General icing study considerations.* The NACA Technical Note has incorporated general ice control system performance requirements, based upon a study of icing parameters, including frequency of occurrence. It should be noted, here, that low temperature conditions must be associated with low atmospheric humidity. Low atmospheric humidity will result in reduced icing rate. However, an increase in airplane speed will override this favorable deicing factor at high altitudes leaving an ice accretion problem, with attending propeller unbalance, to be solved.

Performance Requirements of Ice Control Systems

As to be expected from the discussion contained in the paragraph on NACA study of icing parameters, ice control systems for propellers must be designed to meet icing conditions, existing continuously, that may occur in an altitude range of 0–25,000 feet, where temperature ranges from 0° to 25° F., water droplet size ranges from 15 to 25 microns in an atmosphere of 0.5 gm/cm ^{3} moisture content.

Blade Area Subject to Icing

The area of a propeller blade, including cuff, which requires protection may be considered to extend from the hub to the 75 percent blade radius station and from the leading edge, a distance within the range from 17 to 25 percent chord length. While ice accumulation at greater radial distances has been noted, in several cases, it can be considered that 75 percent coverage will provide necessary protection.

General Icing Control Methods

Anti-Icing Systems

(1) *Basic features.* A complete anti-icing system might consist of all units necessary to distribute sufficient heat to prevent ice formation upon all exposed propeller blade and component surfaces. This type of anti-icing system must dissipate a relatively large amount of heat per unit area. Because of the critical heat requirement, anti-icing systems of this nature can be used only in those applications in which ice accretion, even in small quantities, cannot be tolerated or wherever centrifugal forces will not be available to aid in shedding ice from the surfaces.

Among the earliest methods evolved for propeller anti-icing control were those involving use of fluids and compounds that acted as freezing point depressants, and simultaneously prepared a surface not conducive to ice adhesion. Glycerine, various formulations of alcohol, compounds, lacquers, waxes, plastic surfaces and special metal surface finishes were studied as possible anti-icing methods suitable for propeller use.

Anti-icing systems may be required for ice removal from spinners where ice accretion can cause air flow disturbance to such an extent that engine performance will be seriously impaired, especially in those turbine engine installations having air intakes directly behind the propeller.

(2) *"Running wet" deicing system.* A deicing system in which just enough heat is supplied to the icing surface to convert impinging ice to liquid is said to be *running wet.*

(3) *"Running dry" deicing system.* A deicing system in which enough heat is supplied to the icing surface to convert impinging ice into vapor form is said to be *running dry.*

Deicing Systems

An ice removal system in which just enough heat is supplied to melt the ice face adhering to an exposed surface, with ice accretion removal dependent upon the action of centrifugal force, has been designated deicing system. This type of system is suitable for ice removal from those propeller components having appreciable centrifugal forces upon which small accumulation

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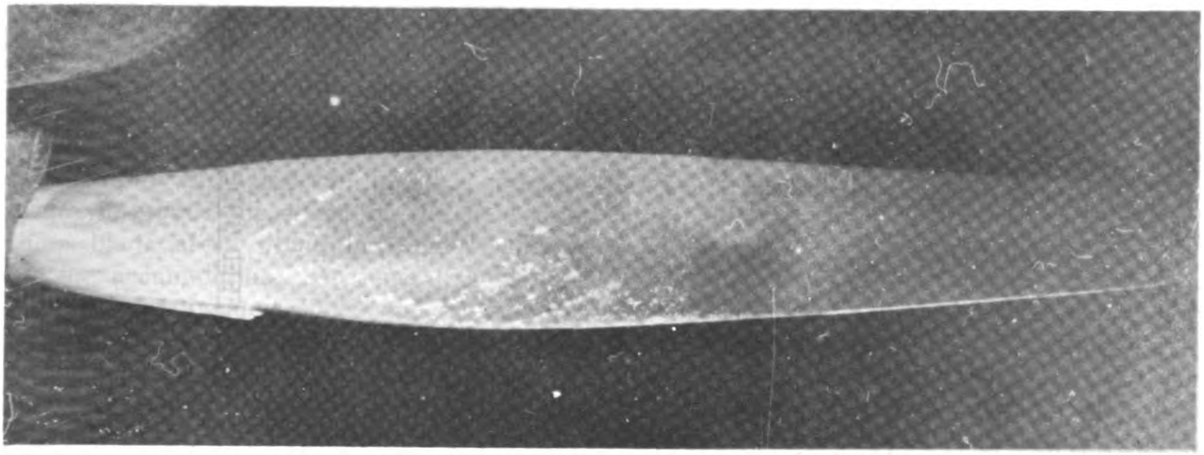

Figure 7.1.—Propeller blade with ice accretion.

of ice can be tolerated. Propeller and fan blades are typical examples of components that may utilize deicing systems.

Combination Anti-Icing and Deicing Systems

(1) *Fundamental principles of the combination system.* In order to reduce heat requirements of anti-icing systems, combinations of anti-icing and deicing have been devised for propeller use. The designs developed utilize a burnout strip to remove ice from the direct impingement area by the anti-icing principle while areas aft of the leading edge depend upon ice removal by cyclic deicing. This arrangement will permit use of air flow over the icing surface to assist in throw off of ice loosened by deicing. Such an intermediate system, requiring much less heat than an anti-icing running dry system, may be acceptable for spinners if the downstream duct and engine can receive loosened ice and water without ill effects.

(2) "*Runback*". If heat supplied to an icing surface is more than that required to melt just the inner ice face, but insufficient to evaporate all the water formed, water will run back over the unheated blade surfaces and freeze. Runback of this nature will cause ice formation on uncontrolled icing areas of the blade, leading to high propeller performance losses. At times, the aerodynamic losses caused by runback may exceed those accruing to blades without any form of ice control.

Chemical-Mechanical Icing Control Systems

Fluid Systems

(1) *Fluid system arrangement.* A typical fluid system, as shown in figure 7.2, includes a tank containing sufficient fluid to give continuous protection during flight equivalent to 20 percent of the aircraft range, or for a minimum of two hours of operation. Anti-icing fluid is forced to each propeller by a gear type pump rheostat controlled at the flight engineer's or pilot's panel. The control system will permit variation in pumping rate so that 3½ to 5 quarts of fluid per hour may be furnished to each propeller, depending upon severity of icing. Fluid transfer from conventional tubing on the engine nose to the rotating propeller is accomplished by means of a slinger ring assembly. This arrangement will permit fluid flow from the stationary nozzle on the engine nose into a circular U-shaped channel mounted on the rear of the propeller assembly. The fluid under pressure of centrifugal force will be transferred through suitable tubing to each blade shank. Since the propeller blade must rotate about the blade radial axis to effect pitch change, the fluid must be deposited in a receiving cup on the blade shank from a stationary nozzle on the hub assembly. Finally, the fluid will be distributed over the blade surface by centrifugal force, aided by air flow across the blade.

(2) *Fluid distribution.* Because air flow around a blade shank tends to disperse anti-icing fluid to areas on which ice does not collect in large quantities, it has been necessary to install feed shoes on the blade leading edge. These feed shoes consist of a narrow strip of rubber on the leading edge, extending from the blade shank to a station at 75 percent radius, approximately. The rubber feed shoes are molded with several parallel open channels in

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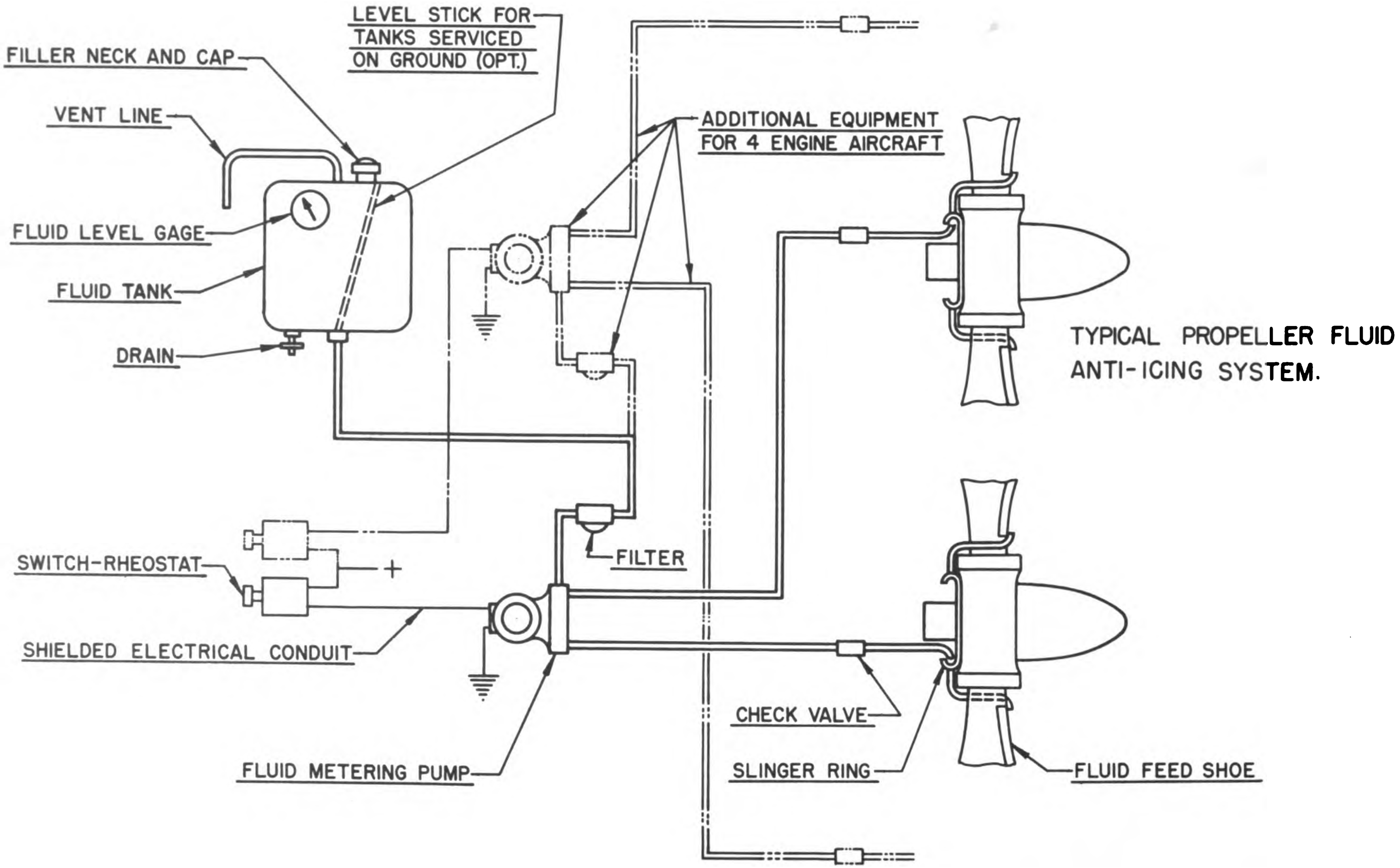

Figure 7.2.—Fluid anti-icing system—propeller.

which fluid will flow from blade shank towards blade tip by centrifugal force. From the radial channels, the fluid flows laterally over the leading edge area of the blade. Maximum deicing efficiency of a fluid system can be attained only through use of fluid feed shoes, to insure improved dispersion of the fluid over those blade areas which have great affinity for ice accumulation. In general, some undesirable aerodynamic effects will be obtained from fluid feed shoe installations during flights when icing conditions are not prevalent. However, these effects may be considered negligible in view of the protection obtained.

(3) *Anti-icing fluid.* Isopropyl alcohol has been used in anti-icing systems because of its availability and low cost. However, isopropyl alcohol is highly inflammable and therefore is not desirable for use under combat conditions. Tests have indicated that trimethyl or triethyl phosphate are comparable to isopropyl alcohol in anti-icing performance and with the advantage of reduced inflammability. But, phosphate compounds are not readily available and, in addition, are comparatively costly.

Compounds and Lacquers

Compounds or lacquers, when applied to propeller blades, produce a surface which will prevent ice adhesion. At the same time, these anti-icing substances in contact with water release a constituent which, in going into solution, depresses the freezing point of the mixture. Both actions of the substance will facilitate ice throw-off by centrifugal force. After exhaustive testing of various waxes, plastics, surface finishes and special compounds, it was concluded that there were several materials which could be used to facilitate ice throw-off. Considering installation and maintenance characteristics, it was concluded that Compound No. 314, Ault-Wiborg, was the most suitable thus far obtained for anti-icing applications. This compound is a heavy non-drying coating material which presents a surface with low ice adhesion property and in contact with ice, releases a freezing point depressant that produces ice liquefaction. Ice which has been loosened by compound action will be thrown off by centrifugal force. The blade area to be coated with the compound normally will cover the inboard section extending radially to a point at 75 percent radius and transversely from leading edge to include 20 percent of the chord, approximately. The compound may be removed readily with gasoline or other solvents generally available to an aircraft facility.

Thermal Ice Control Systems

General Classification

Positive continuous icing protection may be provided by thermal systems, if the heat source has been properly located with respect to those areas most susceptible to ice accretion. Thermal systems may be classified according to the type of heat source employed directly for ice control. Within this classification concept, two important types of thermal ice control systems have been employed, successfully, to control ice accumulation on propellers; namely, electrical power and hot air systems. Further, electrical systems may be identified as internal and external element systems.

Electrical Power Systems

(1) *General characteristics.* An electrical propeller icing control system, basically, is composed of an electrical energy source, a resistance heating element, system controls and necessary wiring to provide a closed loop. The heating elements are mounted internally or externally on the propeller blade. Energy, from the airplane supply system or from special hub generators, is transferred to the propeller hub and blades through electrical leads, which terminate in slip rings and brushes. Flexible connectors are used, frequently, to transfer energy from hub to blade. The system arrangement is independent of energy source, actually, since icing control will be accomplished by conversion of electrical energy to heat energy in the heating element.

As the name indicates, hub generators, located in the propeller hub, rotate with the propeller. Since hub generator size increases as propeller rotation speed decreases and inasmuch as the space between propeller hub and engine is limited, hub generators may be used only on small propellers having comparatively large rotating speeds.

(2) *Electrical circuits for icing control systems.* Balanced ice removal from all propellers must be obtained as nearly as possible if excessive vibration is to be avoided. To obtain balanced ice removal, variation of heating cur-

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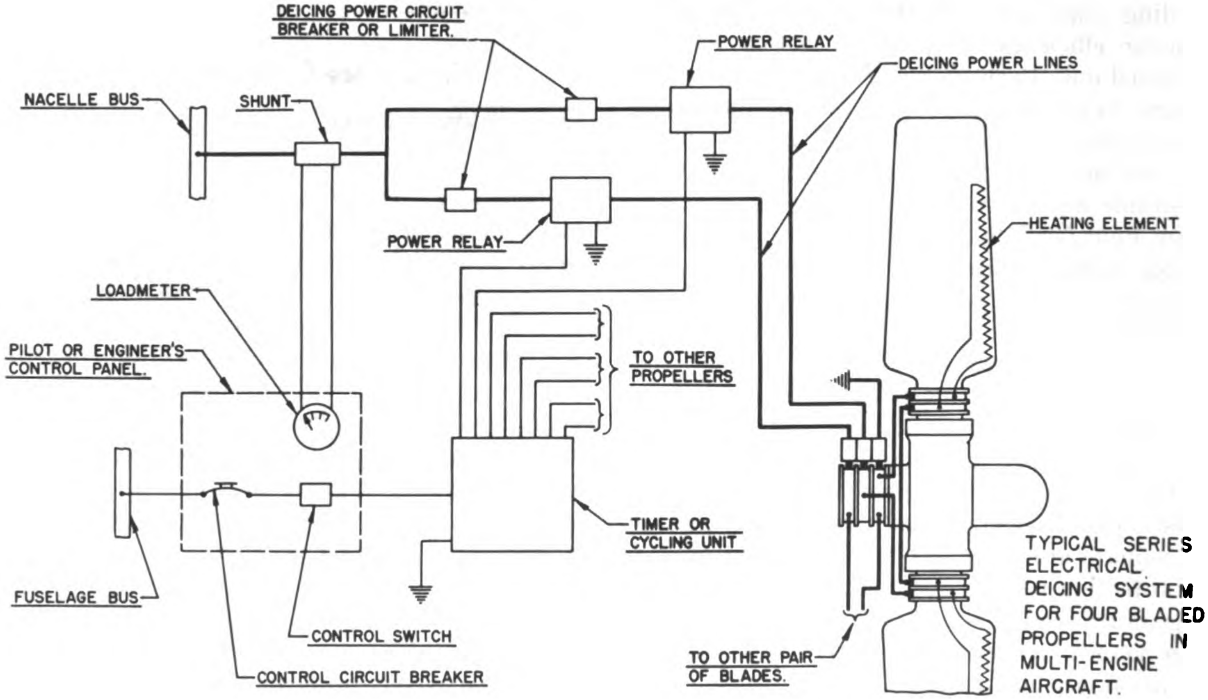

Figure 7.3. **Series circuit—electrical deicing system.**

rent in the blade elements must be controlled so that similar heating effects are obtained in opposite blades. The most practical method of obtaining balanced ice removal in electrical systems using external elements is to connect the elements in series as shown in the diagram of figure 7.3.

Present practice favors use of series circuits for connecting external elements of propeller electrical deicing systems. However, improved reliability of external elements resulting from addition of protective sheaths plus current control requirements of a deicing system have produced a trend towards use of parallel circuits.

Limitations imposed by resistance circuits built up with available resistance wire have encouraged use of parallel circuits for three blade propellers. One such system is illustrated in figure 7.4.

Early systems of this type included a protective relay to open the circuit whenever element damage would cause large current variation with subsequent unequal ice removal and propeller unbalance. But, unreliability of protective relays led to modification of parallel systems to include ammeters which would indicate circuit current.

Properly designed internal elements now have sufficient reliability to permit use of parallel circuits with internal element systems. This arrangement permits use of smaller size wire with reduced losses since, effectively, the heating element may operate at higher voltage. Series-parallel circuit combinations, in which internal blade elements are connected to external cuff elements, have been evolved to obtain necessary protection against unbalanced deicing.

(3) *Power requirements.* (*a*) External Heating Elements. The range of temperature in which present day aircraft have encountered ice most frequently, extends from 25° to 32° F. Within this temperature range, approximately six watts per square inch of blade leading edge area must be dissipated in conventional external heating elements to protect the leading edge that may accumulate ice by direct impingement of water droplets. The area extending aft from the leading edge area a distance equal to 17 to 25 percent of the chord length must receive heat equivalent to three watts per

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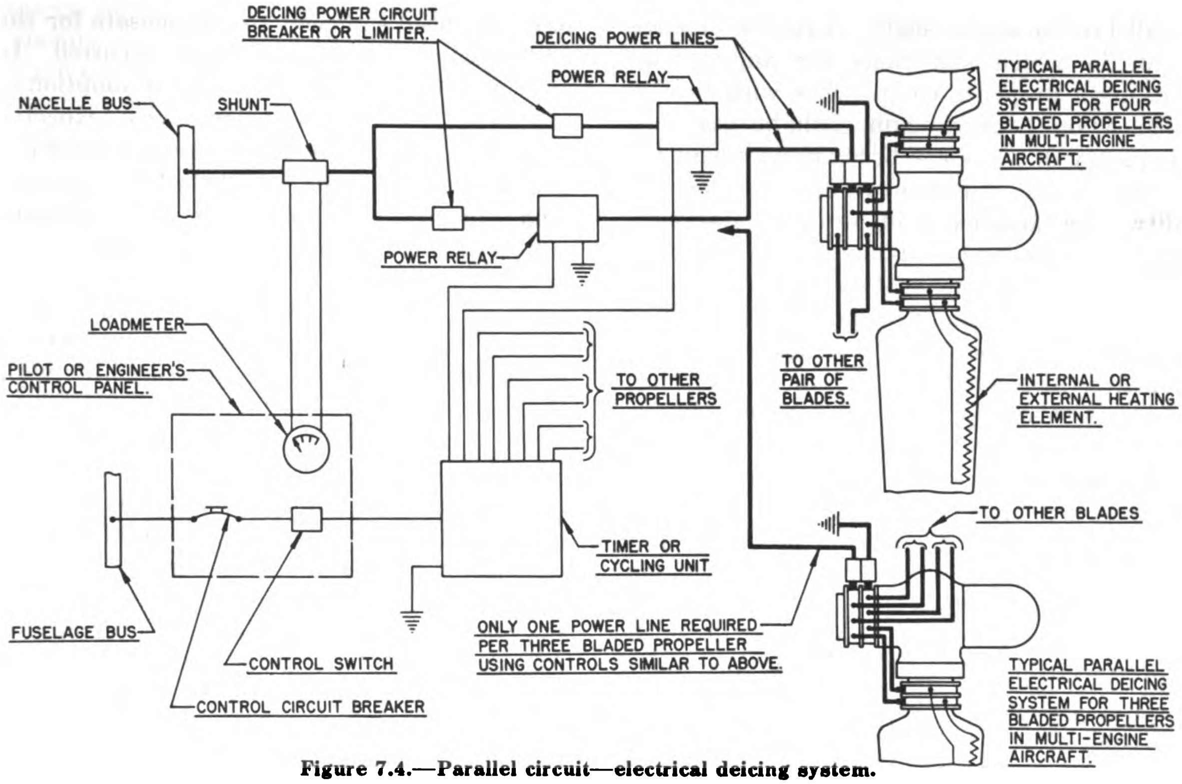

Figure 7.4.—Parallel circuit—electrical deicing system.

square inch of deicing area, under the same conditions. With increased confidence in capability of aircraft to traverse icing conditions, successfully, an increase in frequency of icing encounters at low temperatures may be expected.

Within a temperature range of 0° to 15° F., all icing surfaces would require approximately 8 watts per square inch of affected area to control blade icing. Nonavailability of electrical power in this amount (8 watts per square inch) has made a compromise necessary. Frequently, propeller ice control systems have been designed using combinations of 7 and 4 (or 5) watts per square inch of affected area to obtain protection of leading edge and back blade surface, respectively. At least, this combination of heat dissipation will furnish improved icing protection within the available power. It should be noted that all heat developed from applied electrical energy will not be available for direct deicing action. With present heating element designs, approximately one-half of the heat released will be transferred to blade areas unaffected by ice accumulation.

(*b*) Internal Heating Elements. The heat required for internal electrical element deicing installation will be considerably more than that required for external elements. Before sufficient heat can be furnished to an ice accumulating surface, the whole blade structure between the element and external surface must be heated. This blade mass introduces inertia to the system, which decreases the rate of heating and cooling of the blade surface thereby decreasing the effectiveness of cycling. With a small structural mass, the inertia effect is sufficient to require a longer heating period, but cycling still may be effective. Internal elements for blades having heavier leading edge mass are in the development stage, so exact inertia effects of large mass deicing cycling have not been established. However, studies of related heat transfer problems indicate that this large mass may impair cycling effects to such an extent that continuous energization may be required, since operating temperatures of the internal element must be held to reasonable limits. Each internal element installation must be evaluated under design icing conditions.

(4) *Power transfer components.* (*a*) Slip Ring Configuration. Available space, very often, will establish the general slip ring configuration. A face type arrangement may be used wherein slip rings are mounted on the rear of the propeller hub assembly. In this design, the rings will rotate in a plane parallel to the propeller disc and will make contact with stationary brushes that are mounted on the engine nose

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parallel to the engine shaft. A reverse arrangement, in which slip rings are mounted on stationary propeller components with brushes mounted on the rotary hub, could be used, also. Frequency of necessary brush replacement will determine the requirement of brush accessibility. In another configuration, stationary radial brushes have been mounted on the engine nose in such a manner that contact will be made with a series of axially disposed slip rings attached to the rear of the hub assembly. This arrangement is similar to electric motor brush-armature design practice. The brushes must be lifted or removed during propeller installation or removal. To keep slip rings narrow for space conservation and to assure complete brush face-slip ring bearing with uniform brush pressure, a comparatively large number of brushes has been used, in parallel.

Current densities used in slip ring-brush designs vary from 200 to 400 amperes per square inch, approximately, depending upon the brush material. Usually, brushes have been made of carbon or carbon metallized with copper or silver. Use of smaller current densities will reduce brush wear and may compensate for higher rubbing velocities. Generally, low brush rubbing velocity with low current density must be incorporated into the design to obtain long brush life. Slip ring-brush configurations must be provided for ground lines as well as hot lines to provide a current circuit independent of engine bearings, if deleterious effects on engine bearings are to be avoided.

(*b*) Brush Design Requirements. Transfer of current from a stationary engine to a rotating propeller is a major problem. In order to use available power efficiently, circuit losses other than those of deicing heating elements must be held to a minimum. A measure of the difficulty involved in control of circuit losses is reflected by the magnitude of total resistance existing in a 24 volt circuit (between 0.1 and 0.2 ohms). Soft brush materials must be used to hold brush losses at low levels; but soft materials have a comparatively high wear rate. Since higher maintenance required by soft brushes may be undesirable, a deicing system must be penalized with greater power losses by use of harder, longer wearing brushes. Some consideration has been given to brush designs providing lift-off during periods of non-operation. Thus far, benefits obtained from lift-off brush designs have not been sufficient to compensate for the additional complexity and weight incurred. In order to provide a realistic basis for adoption of any type of current transfer device, expected brush life, along with the range and extent of power losses, must be established by adequate laboratory testing of the design. A compromise will be required, probably, between low loss and long life. A life of 200–300 hours of aircraft operation, including periods with and without deicing current flow, is considered a reasonable minimum life for brushes. Increased life without higher losses would be desirable, of course.

(*c*) Pigtail or Flexible Lead Design. Transfer of electrical current from connection on the hub assembly to blade internal or external elements must be made without limitation of blade angle variation. Either slip rings or flexible leads may be used for current transfer depending on the installation. A flexible lead or pigtail may be used if the blade angular change is small and a pigtail of sufficient length can be provided in such a manner as to avoid damage by centrifugal force or rubbing on adjacent parts. For minimum flexing, a pigtail should be designed so that terminals will be loaded in tension under the effects of centrigugal forces on the electrical leads. Excessive lead length, which would be required for feathering and reversing propellers, encourages the use of slip rings. Somewhat lower electrical losses may be expected in pigtail current transfer devices but maintenance could be high. Pigtail design should incorporate ready replacement features. Blade shank slip rings are subject to short arcs of rotation during normal propeller operation but must be designed to permit blade feathering and reversing. Furthermore, slip rings should be designed for minimum interference with blade assembly removal from the hub. The number of slip rings to be used is dependent on circuit configuration.

(5) *Heating element design.* (*a*) General Requirements. Design of a heating element for a propeller deicing system is closely related to the electrical system voltage and circuit arrangements of a given airplane. The heating element must be designed to deliver the required amount of heat distributed over the proper propeller area, and to withstand vibratory and centrifugal forces developed during operation. External elements, in addition, must be designed to resist rain erosion and severe abrasion of stones, sand and dirt encountered during landing and

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take-off operations. Furthermore, the heating elements must be flexible to permit forming to complex contours of propeller blades. Internal elements consisting of resistances securely mounted inside the blade leading edge have been designed and fabricated as an integral part of the blade; therefore, these elements must be considered irreplaceable. Hence, internal heating elements must be designed to have a service life in excess of that of the blade, since loss of the heating element is equivalent to loss of blade usefulness, operationally.

External heating elements convert electrical energy into heat by use of metallic resistance wire or conductive rubber. The resistance element is contained in a molded rubber sandwich bonded into an assembly using appropriate cements under heat and pressure. Metallic resistance wire has received preferential treatment in application because it is less subject to resistance variation than conductive rubber. A comparision of resistance variation shows:

Metallic wire resistance, variation range = ±5 to 7 percent

Conductive rubber, variation range = ±15 percent

Use of standardized resistance wire alloys permits design over quite a wide range of temperatures to meet particular application requirements. However, limitation of blade element temperature to 200° F. has been necessary to prevent damage to the element or element-blade bond.

(*b*) Heating Element Thickness. External deicing element thickness must be held to a minimum, if objectionable aerodynamic effects upon propeller blade performance are to be avoided. For moderate speed aircraft, the maximum acceptable element thickness is .09 inch. An increase in operating Mach number of the blade will require reduction of section discontinuities and distortion to a low point. Considerable improvement in blade contour may be obtained by reducing element thickness even to the point of complication of fabrication and installation. Indentation or recessment in the blade leading edge may be employed to receive the element, but blade structural problems will be introduced. Indentation of the blade leading edge will make it possible to design a heating element which, when installed on the blade, will complete a desired airfoil section. A stainless steel sheath may be employed to cover the leading edge of the outboard section of the heating element to protect it from damage. For fatigue resistance, stranded wires should be used. Small variation of electrical resistance with temperature change is highly desirable.

(*c*) Heating Element Installation. Heating element installations on propeller blades have been made by hand, in the past. The blade leading edge surface must be prepared with a priming cement, after which a coat of bonding cement must be spread smoothly on both blade and element assembly surfaces. The rubber assembly containing the element must be stretched or compressed and worked without injury to the element, until upon installation, the heating element assembly will form a smooth airfoil surface. This process is a technique of skillful workmanship acquired by long experience. Basic rudiments of the process have been expounded in appropriate Air Force Technical Orders. The heating element assembly may be removed from blade or cuff by heating to a temperature of 175° F.

At this temperature, the bonding cement will be soft enough to permit hand removal of the element. However, element removal will usually damage the rubber or wire to such an extent that the element cannot be reused. A separate heating element should be mounted on the blade cuff to permit removal without disturbing the blade element.

(6) *Intermittent heating.* Usually, deicing systems have been designed for intermittent application of energy to the heating elements to remove ice after formation but before excessive accumulation. Proper control of heating intervals will aid in prevention of runback, since heat can be applied just long enough to melt the ice face in blade contact. Cycling or intermittent operation of heating elements will reduce the steady power demand by scheduling *power on* to propeller sections in sequence. Length of the interval of power application to an internal element must be increased beyond that required for external element systems, to furnish the extra heat required of internal systems. Cycling timers have been designed to energize heating element circuits for periods of fifteen or thirty seconds, with a complete cycle time of two minutes. A cycling timer may be built most simply by using an electric motor driven contactor which controls power

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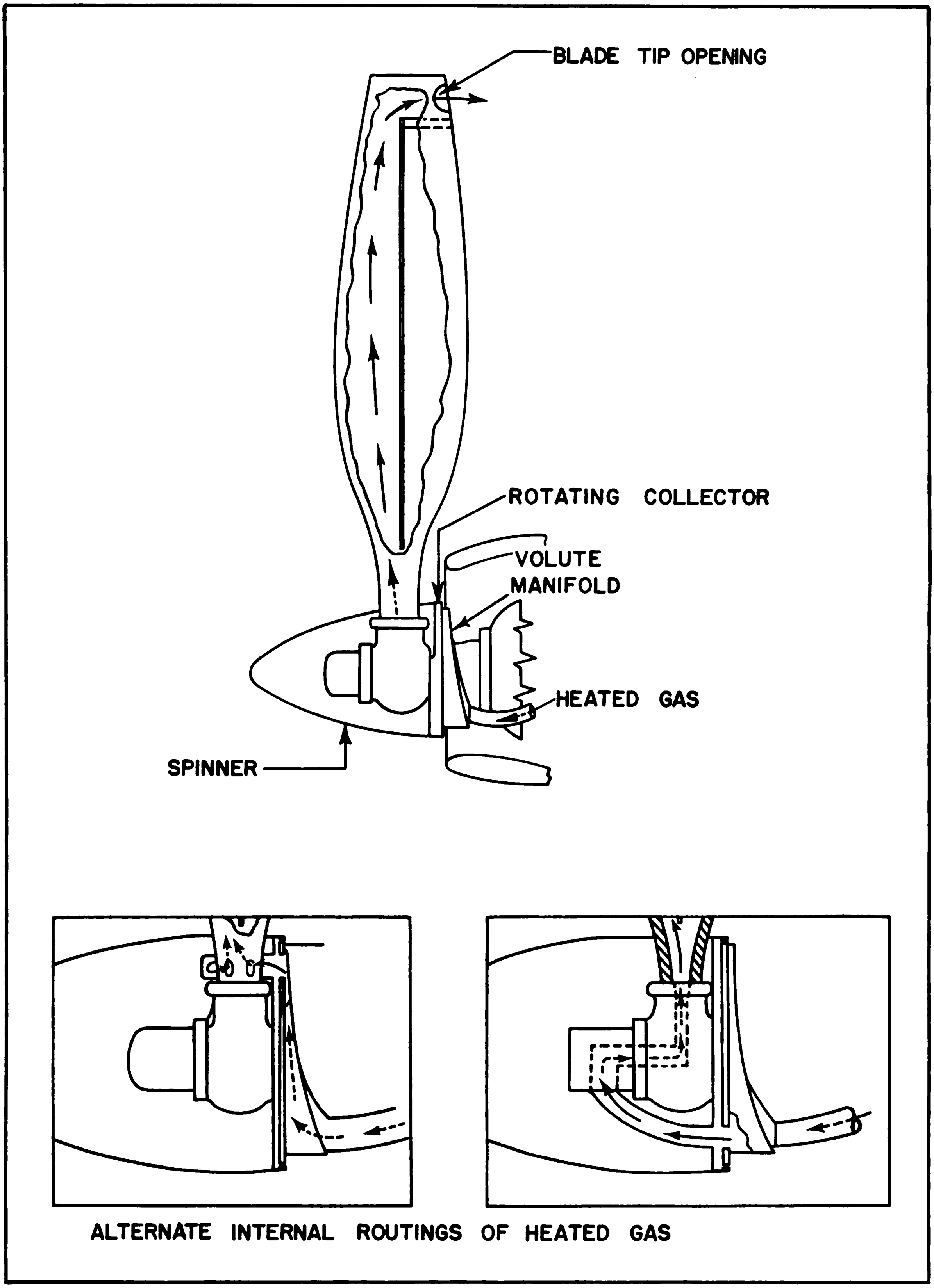

Figure 7.5.—Hot air deicing distribution system.

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contactors in separate sections of the circuit. Such timers have been used for as much as 1000 hours without maintenance.

(7) *Controls for electrical deicing systems.* Controls for propeller electrical deicing systems include on-off switches, ammeters or loadmeters to indicate current in the circuits, and protective devices, such as current limiters or circuit breakers, for the aircraft electrical system. Intermittent operation of sections of the deicing circuit requires installation of a protective device which will open the circuit whenever an overload occurs. However, a current limiter, in a 150 amp deicing circuit having a continuous rating of 150 amps, which would carry approximately 300 amps for 30 seconds, would offer very little protection to an aircraft electrical system if the overloaded circuit were energized for only 15 seconds. Therefore, for such an installation, a current limiter with a continuous rating of 100 amps and a 30 second rating of approximately 200 amps should be used. A similar analysis should be made in selecting a circuit breaker. As noted in figure 7.4, the two circuits on a four-way propeller energized from a single nacelle bus or terminal may be controlled from a panel containing a single ammeter. Proper wiring of ammeters will permit indications of individual circuit currents and reflect efficacy of the timer. Timing sequence should start at Nacelle No. 1 and proceed to successive nacelles in accordance with accepted aircraft practice. In order to prevent element overheating, use of the on-off switch should be restricted so that the propeller deicing system will be energized only when all propellers are rotating.

Hot Air System for Icing Control

(1) *Characteristics.* Hot air systems for propeller ice control depend upon a continuous flow of heated air through hollow propeller blades to effect deicing. An appropriate quantity of hot air must furnish sufficient heat to melt the layer of ice adhering to the blade, which will permit ice removal by action of centrifugal force. Air circulation can be obtained by the centrifugal pumping action of propeller blades or air bleed from turbine engine compressors. In existing designs, heated air or gas mixture has been supplied to a volute manifold on a fixed portion of the propeller from which air is ducted to a rotating collector mounted on the hub. Provision has been made for heated air or gas mixture to move from the collector to blade shank interior either through the front of the hub and thence through passages in the blade base or through holes in blade shanks outside the hub. Hot air, in movement radially through the blade, will transfer heat to the metal blade. Heat absorbed will be transferred by conduction to surfaces to be protected. In those installations in which centrifugal pumping action has been employed, an air exit must be provided; usually, it has been located in the camber face at the trailing edge near the blade tip. Tip exit of the air will produce undesirable aerodynamic disturbances with slight lowering of overall installation efficiency. In systems employing heated air obtained from a turbine compressor, centrifugal pumping action will not be required and air discharge may be accomplished without undesirable aerodynamic effects. A typical air distributing system has been illustrated in figure 7.5.

(2) *Heat sources.* Air or gas mixture of a hot air deicing system may receive heat from one of several sources:

(*a*) Engine exhaust heat exchanger.
(*b*) A gasoline fired combustion heater mounted on a stationary component of the manifold.
(*c*) Engine exhaust gas mixed with air, to reduce mixture temperature to acceptable operating limits.

(3) *Air flow control.* In order to reduce heat requirements, and consequently, air flow requirements, it has been found desirable to provide partitions inside the blade which will limit air flow to leading edge areas. Generally, this practice must be limited to those blade structures which can provide such a partition in the form of a longitudinal rib. Heavy leading edge structures necessarily have longer heat flow paths than other blade regions. Hence, it has been necessary to provide excessive heat for other than leading edge areas in order to insure adequate heat flow to the leading edge. Effective use can be made of a ribbed structure to concentrate heated air flow close to the leading edge. Also, internal structures can be used for redirecting the air to the atmosphere through a tip exit or, by reversed return, through the trailing edge section to a blade shank or spinner exit. The entire inner surface

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of a heated air blade must be protected from corrosion by a coating of phenolic resin.

(4) *Temperature variation.* Relatively high heat transfer rates that exist at high temperature differentials between heated air and metal blades, require that deicing systems be operated at limiting temperatures of materials and equipment. Designs have been based on a temperature of approximately 400° F. air in the blade shank, at 15,000 to 20,000 ft. pressure altitude, and propeller rotational tip speed of 700 feet per second. A method of estimating heat requirements for ice protection of gas heated hollow propeller blades has been established in NACA Technical Note No. 1494 which may be used as a guide for preliminary design. Extensive laboratory studies of air flow through proposed design configurations must be made to insure that the required heat actually will be delivered. Inertia of the heat transfer process through a metal blade has prevented use of a satisfactory deicing cycle in the heated air system. Controls for hot air systems must include shut-off and/or by-pass valves along with protective devices to prevent excessive temperatures.

Effectiveness of Icing Control Systems

Fluid and Compound Systems

(1) *General considerations.* Variations in effectiveness of both fluid and compound anti-icing methods result in less control of ice throw-off, with subsequent higher order of propeller unbalance than encountered with thermal ice control methods. Use of compounds and fluids for icing control has proven to be ineffective in meeting demands of modern aircraft for positive continuous protection. These methods can be recommended and have been used as emergency or interim measures for service aircraft propellers subjected to icing conditions, which have not been equipped with thermal systems. If a fluid system has been installed, impoved propeller protection can be obtained by using compounds, in addition.

(2) *Fluid systems.* In general, fluid system anti-icing installations on high speed aircraft are not as effective as those installed on low speed aircraft. The ineffectiveness of high speed aircraft installations can be attributed to fluid loss from the blade by force of the airstream, even when feed shoes have been used. Similarly, large low speed propeller fluid system installations are not as effective as those on small diameter higher speed propellers because of low centrifugal forces available to assist fluid distribution over the large blades. In addition, large blades possess greater area requiring ice control.

(3) *Compound systems.* Usually, compounds offer better protection than fluids because fluid distribution is poor and fluid system effectiveness is dependent upon flow pattern. Effectiveness of a compound is limited by the compound resistance to water erosion and by loss of freezing point depressant during icing operation. Propeller operation in rain for some time before icing begins, will reduce effectiveness of the compound to negligible proportions. Generally, rain exposure of about four hours or icing exposure of one hour will exhaust the compound.

Electrical Systems

Design of propeller electrical deicing or anti-icing systems requires considerable care, since small increases in circuit component resistances or contact resistances easily can reduce current flow, appreciably, with large decrease in effectiveness. Use of higher voltages (110 AC or DC, single or multiple phase) will improve ice control effectiveness, in general. Use of higher voltages means reduced currents but higher resistances in blade heating elements. In addition, design of power contactors and brush slip rings must be based upon higher voltage.

The internal type heating element, by virtue of blade structure protection, is not susceptible to damage. But this advantage is offset, largely, by the higher heat intensities and power requirements to obtain equivalent icing protection.

Hot Air Systems

Hot air systems add complexity to propeller structures with considerable aerodynamic loss in performance. Hot air systems have proven effective in icing control and have an advantage of not imposing additional power requirements upon the airplane electrical system. Unfortunately, an adequate hot air system has not been devised for use with solid blades.

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CHAPTER VIII. PROPELLER CONTROLS

Evolution of Propeller Controls

Propeller controls of ever greater complexity have been developed to meet constantly changing critical control requirements that invariably are associated with propeller performance. Of course, fixed pitch propellers did not have control problems inasmuch as blade angle could not be varied in flight. Fixed pitch propellers were set so that the engine would run at rated speed under full throttle with the airplane in level flight. Obviously, such operation involved a loss in engine-propeller performance.

In order to improve overall performance of engine-propeller combinations, a two position blade angle propeller was developed. Particular blade angle settings made available to meet specific flight conditions were low pitch (maximum power) for take-off and climb, and high pitch (cruise economy) for specified air speed at established altitude. This propeller (controllable pitch) was the first successful flight variable pitch propeller. It possessed a positive means of pitch control with a minimum number of parts featuring constructional simplicity, light weight, dependability and long service life.

The mechanism of a controllable pitch propeller, which has been illustrated in figure 8.1, consists of a simple mechanical linkage, from pilot's control to pitch angle change lever.

The pinion turn shaft located in the lower left hand corner of the photograph is connected to the pilot's control. By contact between pinion and pitch change gear, the propeller blade can be rotated about its longitudinal axis.

The constant speed propeller, as the name suggests, was merely an extension of the two pitch position controllable idea to encompass automatic control of all intermediate pitch positions in such a manner as to maintain constant engine speed at preset levels. Engine speed can be held constant with this type propeller by automatic (governor) control of blade angle to meet varying conditions of airplane attitude, altitude and throttle setting. Control units incorporated into a constant speed propeller system permit independent setting of engine power and speed at any time. Hence the engine can operate at any power and speed combination within design operating limits of the engine and propeller; the preset engine speed and power will be maintained constant, until modified by control readjustment, under all flight conditions encountered.

The governing range of the constant speed control unit, along with mechanical stops in the propeller pitch change mechanism, will establish the limits of constant speed operation. A greater blade angle range may be employed with a constant speed propeller than with a two position controllable propeller by use of these positive automatic controls.

Propeller Control Classifications

Propeller Controls

Propeller controls are devices or combinations of devices used in aircraft to select and maintain predetermined engine speed by manual and automatic action. Further, this general classification should include special features designed to control and establish propeller feathering and reversing operations.

Propeller Governors

Propeller governors are constant speed control units that automatically provide blade angle adjustment necessary to maintain constant engine speed under variable flight conditions. Synchronizers, in reality, are types of governors employed to control speeds of several engines on multi-engine aircraft.

(1) *Governor Types.* Propeller governors may be classified into two broad general groups, namely, hydraulic and electric governors. Further sub-division of hydraulic governors into single and double acting categories may be made. Designation of *single acting* or *double acting* essentially will depend upon the method employed (fluid action) to cause control piston movement within the governor.

(2) *Phase Synchronizers.* Devices (essentially governors) which maintain a constant relative blade angle position between various propellers of multi-engine aircraft have been

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designated phase synchronizers. Phase synchronizers assist, materially, in reduction of noise and vibration.

(3) *Self-Contained Controls.* Self-contained propeller controls are those wholly contained within an assembly attached to a propeller hub and blade assembly. Such units contain individual control fluids that are independent of engine oil supply and obtain operating impetus from rotation of the propeller.

Propeller Characteristics and Control Parameters

Propeller control system design is complicated by projection of aerodynamic characteristics of the propeller into the control system. These characteristics vary, considerably, over normal operating range of the airplane. For example, change in propeller torque resulting from a change in blade angle, or rotational speed, varies with airplane velocity and altitude. Such variations in propeller parameters require careful analysis of the control system, to establish governor characteristics necessary for satisfactory propeller operation, under all flight conditions. In general, propeller stability increases with power and air speed, and decreases with increase in operating altitude.

Requirements of Propeller Control Systems

A given propeller control system must be designed to obtain satisfactory operation over the complete, anticipated range of flight conditions. To meet the requirement of satisfactory operation, a propeller control system must be designed to incorporate the following characteristics:

(1) Engine speed control, regardless of operating conditions or throttle manipulation.
(2) Flexibility of propeller operation over full range of engine speeds.
(3) Speed control sensitivity to maintain preset speeds accurately and obtain synchronization with those given speeds.
(4) Blade position phase control with reference to phase position in plane of rotation (certain applications).

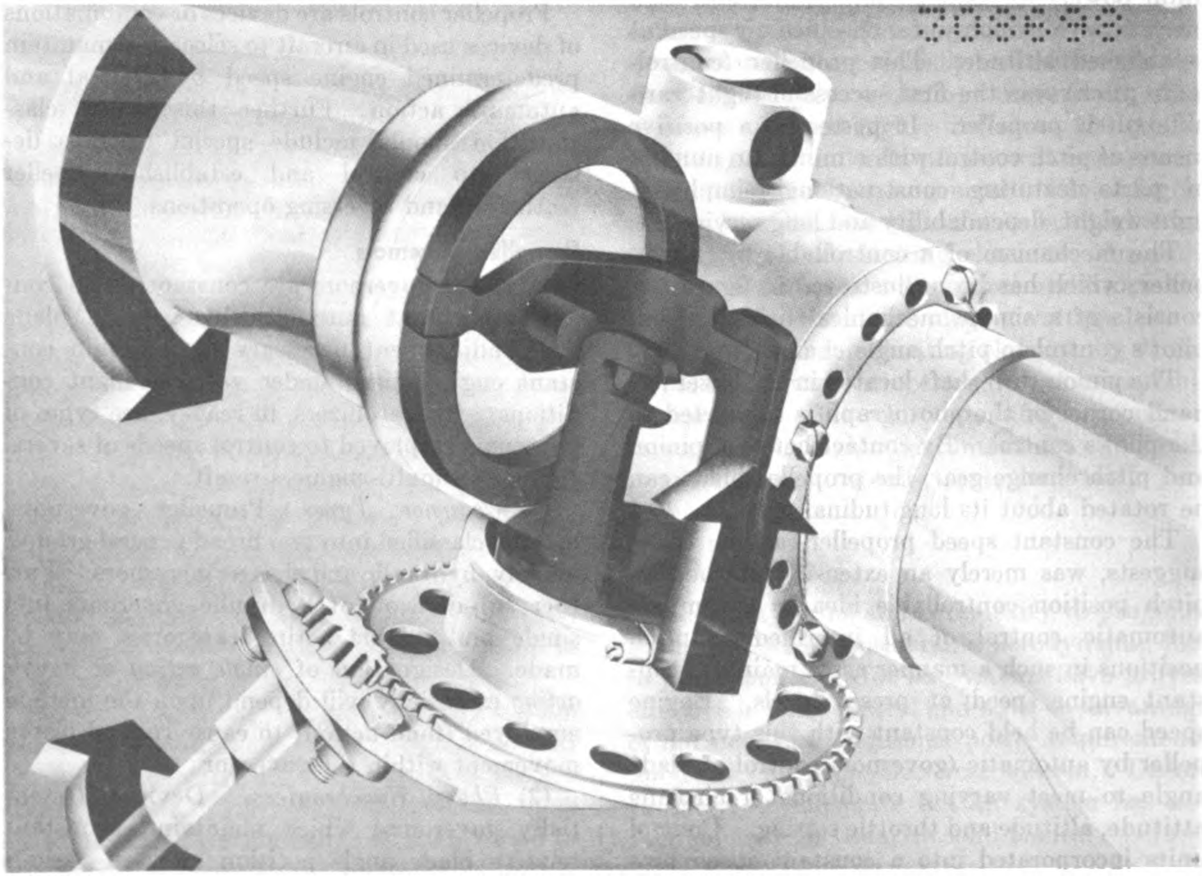

Figure 8.1.—Mechanical pitch control mechanism.

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Propeller Control System Analysis—Piston Engines

Symbols Used in Control System Development

c	Damping ratio	Dimensionless
τ	Time constant	Seconds
N_β	RPS blade angle characteristic	1/Seconds
w_f	RPS fuel flow characteristic	1/lb
N_{w_f}	Fuel flow	lb/second
s	Overall governor sensitivity	Dimensionless
K_1	Governor sensitivity (proportional)	Dimensionless
K_2	Governor sensitivity (acceleration)	Seconds
n_g	Governor speed setting	Revolutions/seconds
Q	Torque	Lb-Ft
n	Rotational speed	Revolutions/second
β	Blade angle	Degrees
V	Velocity	Ft/Sec.
J	Mass moment inertia	Lb-Ft-Sec.^{2}
α	Acceleration	Radians/Sec.^{2}

Scope of Control System Analysis

For optimum design, propeller control system analysis must include more extensive investigation of operating points within a given range of operating conditions than would be required for other servo mechanisms. Design of a propeller control system varies from that of other servo mechanisms only in the number of points of control that must be investigated. The equations developed herein are predicated upon use of a conventional piston type engine driven propeller.

Control System Design Conditions

Actually, a propeller control system will be a non-linear system. However, by restricting the control motion to small displacements and investigating, at any one time, only small deviations from the reference point, any system may be considered as a linear system. Response characteristics can be determined by examining, separately, points distributed over the control region. Furthermore, actual behavior of the system under all conditions may be predicted, accurately.

In development of fundamental relationships, the following conditions will be assumed:

(1) Propeller rotational speed to be controlled by varying blade pitch.

(2) Engine power to be controlled by throttle setting, i. e., automatic control will not be used to regulate fuel flow.

(3) Torque and rotational speed are those on the engine side of the propeller reduction gearing.

(4) Airplane speed and altitude to be constant.

Engine Variables

Output torque of an aircraft engine is a function of several variables. However, for given conditions of altitude and ram pressure ratio, engine torque may be considered a function of only two variables, namely, engine rotational speed and fuel flow. The functional relationship may be written in mathematical form as follows:

$$Q_e = f(n, w_f) \qquad \text{VIII–1}$$

In which:

Q_e = engine output torque at the engine shaft, lb-ft.

n = engine rotational speed, revolutions per second (r. p. s.).

w_f = fuel flow to the engine, lb. fuel per second.

$$\Delta Q_e = \frac{\partial Q_e}{\partial w_f}\Delta w_f - \frac{\partial Q_e}{\partial_n}\Delta_n \qquad \text{VIII–2}$$

A delta prefix before the symbol of a variable signifies deviation from the reference operating point.

Propeller Power Absorption

In a similar manner, torque absorbed by a propeller may be expressed as a function of propeller blade angle, rotational speed, and

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airplane forward velocity. The basic relationship may be written:

$$Q_P=f(n, \beta, V) \qquad \text{VIII-3}$$

In which:

Q_P=torque absorbed by a propeller, at the engine shaft, lb-ft.

β=propeller blade angle at 0.75 radius, degrees.

V=velocity of airplane, ft. per second.

Specifically:

$$\Delta Q_P=\frac{\delta Q_P}{\delta\beta}\,\Delta\beta+\frac{\delta Q_P}{\delta n}\,\Delta n+\frac{\delta Q_P}{\delta V}\,\Delta V \qquad \text{VIII-4}$$

Since a condition of this analysis stipulated constant airplane velocity and altitude, equation VIII-4 may be simplified and written in the form:

$$\Delta Q_P=\frac{\delta Q_P}{\delta\beta}\,\Delta\beta+\frac{\delta Q_P}{\delta n}\,\Delta n \qquad \text{VIII-5}$$

This simplification will not affect the validity of the analysis since the control system is being considered as a linear system. Therefore, the superposition theorem will apply, so that the effects of changing air speed may be considered separately.

Combined Engine-Propeller Equation of Motion

Any unbalance between engine output torque and aerodynamic torque of the propeller will produce an acceleration. The unbalanced torque may be expressed in terms of total mass inertia (propeller plus engine rotating parts) and resulting acceleration, by the well-known relationship: torque equals mass moment of inertia times angular acceleration. In equation form, the statement becomes:

$$J\alpha=\Delta Q_e-\Delta Q_P \qquad \text{VIII-6}$$

In which:

J=combined mass moment of inertia of propeller and engine rotating parts, referred to engine shaft, lb-ft-sec^2.

α=angular acceleration, radians per second^2.

In a more convenient form:

$$2\pi J\Delta\dot{n}=\Delta Q_e-\Delta Q_P \qquad \text{VIII-7}$$

Combining equations VIII-2, VIII-5, and VIII-7 gives:

$$2\pi J\Delta\dot{n}=\frac{\delta Q_e}{\delta w_f}\,\Delta w_f-\left(\frac{\delta Q_e}{\delta n}+\frac{\delta Q_P}{\delta n}\right)\Delta n-\frac{\delta Q_P}{\delta\beta}\,\Delta\beta \qquad \text{VIII-8}$$

Transposing the second term of the right side of equation VIII-8 to the left side of the equation and dividing through by the coefficient of Δn to get the equation in a more convenient form, yields the expression:

$$\frac{2\pi J}{\frac{\delta Q_e}{\delta n}+\frac{\delta Q_P}{\delta n}}\,\Delta\dot{n}+\Delta n$$

$$=-\left(\frac{\frac{\delta Q_P}{\delta\beta}}{\frac{\delta Q_e}{\delta n}+\frac{\delta Q_P}{\delta n}}\right)\Delta\beta+\left(\frac{\frac{\delta Q_e}{\delta w_f}}{\frac{\delta Q_e}{\delta n}+\frac{\delta Q_P}{\delta n}}\right)\Delta w_f \qquad \text{VIII-9}$$

Now for convenience let:

$$\tau=\frac{2\eta J}{\frac{\partial Q_e}{\partial n}=\frac{\partial Q_P}{\partial n}},\ \text{a time constant (seconds),}$$

and,

$$N_\beta=\frac{\frac{\partial Q_P}{\partial\beta}}{\frac{\partial Q_e}{Qn}+\frac{\partial Q_P}{\partial n}},$$

change in equilibrium speed per unit change in propeller blade angle, revolutions per second,

$$\left(\frac{1}{\text{sec}}\right)\ \text{per degree,}$$

and

$$N_{w_f}=\frac{\frac{\partial Q_e}{\partial w_f}}{\frac{\partial Q_e}{\partial n}+\frac{\partial Q_P}{\partial n}},$$

change in equilibrium speed per unit change in fuel flow revolutions per second per pound per second,

$$\left(\frac{1}{\text{lb}}\right)$$

Then, equation VIII-9 becomes:

$$\Delta n+\tau\Delta\dot{n}=-N_\beta\Delta\beta+N_{w_f}\Delta w_f \qquad \text{VIII-10}$$

Equation VIII-10 is the equation of motion of a propeller-engine combination. Solution of this equation, for a sudden change in either fuel flow or propeller blade angle, will be exponential in form. That is:

$$\Delta n=1-(e)^{\frac{-t}{\tau}} \qquad \text{VIII-11}$$

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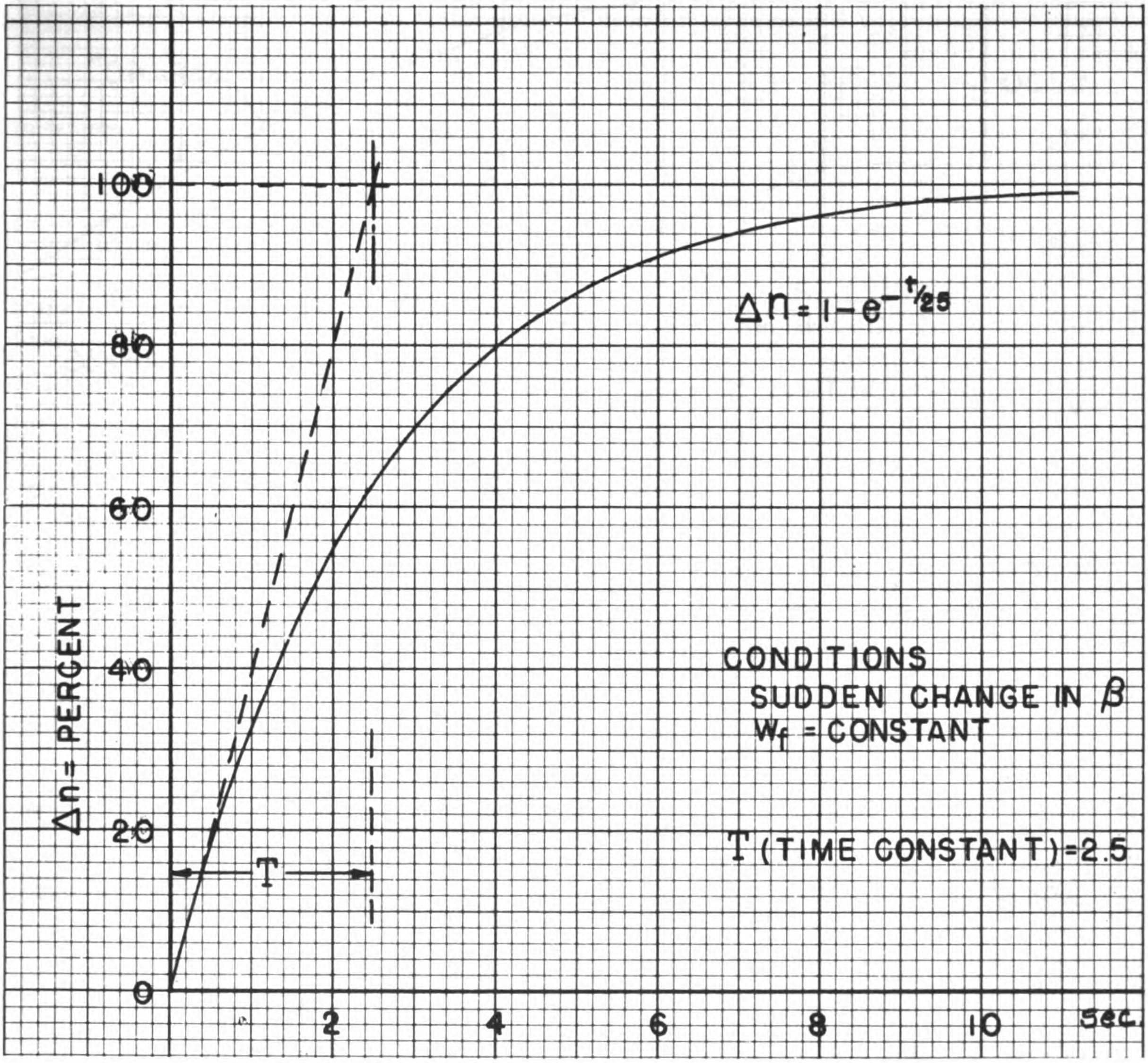

Figure 8.2.—Solution to equation 8.10.

Control System Time Constant

The quantity, τ, has been designated *time constant* for the system. The time constant is the time required for a system to reach 63 percent of its final control position, or the time that would be required to reach final control position if the entire change were made at the initial rate.

The diagram of figure 8.2 illustrates the basis of evaluation of the time constant for solution of equation VIII–10 for the particular case of sudden blade angle change with fuel flow constant.

Determination of partial torque derivatives, with subsequent evaluation of the coefficients of equation VIII–10, may be obtained from graphs of engine and propeller characteristics. A typical graph of engine-propeller characteristics is shown in figure 8.3.

The characteristics may be considered constant over small speed ranges. Therefore, for small deviations from the operating point, equation VIII–10 may be considered as a differential equation with constant coefficients.

Proportional Governor Control Characteristics

(1) *Propeller governor sensitivity.* It may be assumed that a propeller control system employs a simple proportional governor in which rate of blade angle change is proportional to speed variation.

Then,

$$\beta = K_1(n - n_s)$$

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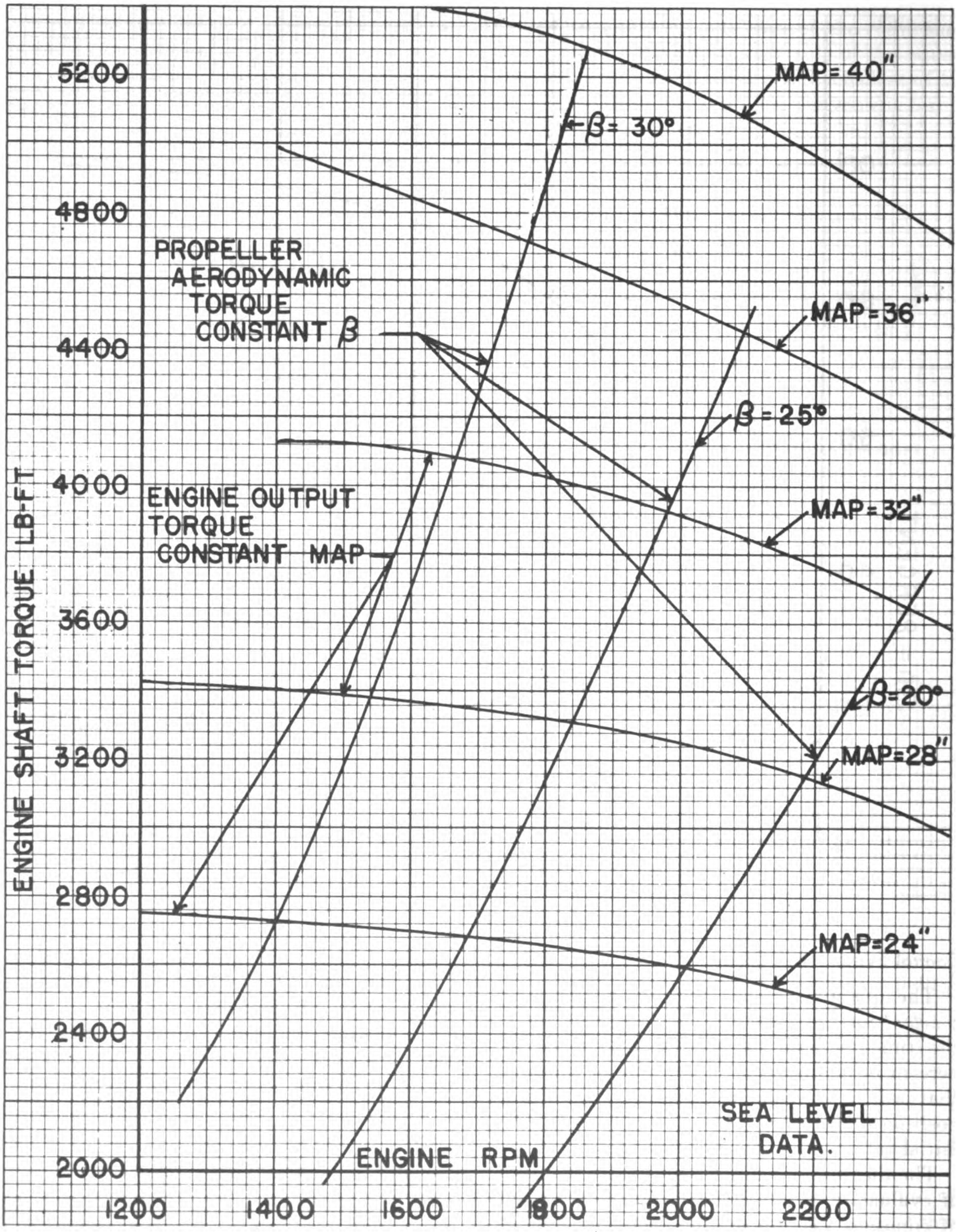

Figure 8.3.—Engine-propeller torque characteristics.

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or, for deviations from an initial operating point,

$$\Delta\beta = K_1(\Delta n - \Delta n_g) \qquad \text{VIII–12}$$

In which,

K_1 = the governor sensitivity, degrees per second per unit speed deviation (dimensionless).

n_e = governor setting (revolutions per second).

Differentiating equation VII–10 with respect to time

$$\tau\Delta\ddot{n} + \Delta\dot{n} = -N_\beta\Delta\beta + N_{w_f}\Delta\dot{w}_f \qquad \text{VIII–13}$$

Combining equations VIII–12 and VIII–13

$$\tau\Delta\ddot{n} + \Delta\dot{n} = -N_\beta K_1(\Delta n - \Delta n_g) + N_{w_f}\Delta\dot{w}_f \qquad \text{VIII–14}$$

Rearranging and multiplying through by τ,

$$\tau^2\Delta\ddot{n} + \tau\dot{n} + N_\beta\tau K_1\Delta n = N_\beta\tau K_1\Delta n_g + \tau N_{w_f}\Delta\dot{w}_f \qquad \text{VIII–15}$$

For convenience let,

$$N_\beta\tau K_1 = S \qquad \text{VIII–16}$$

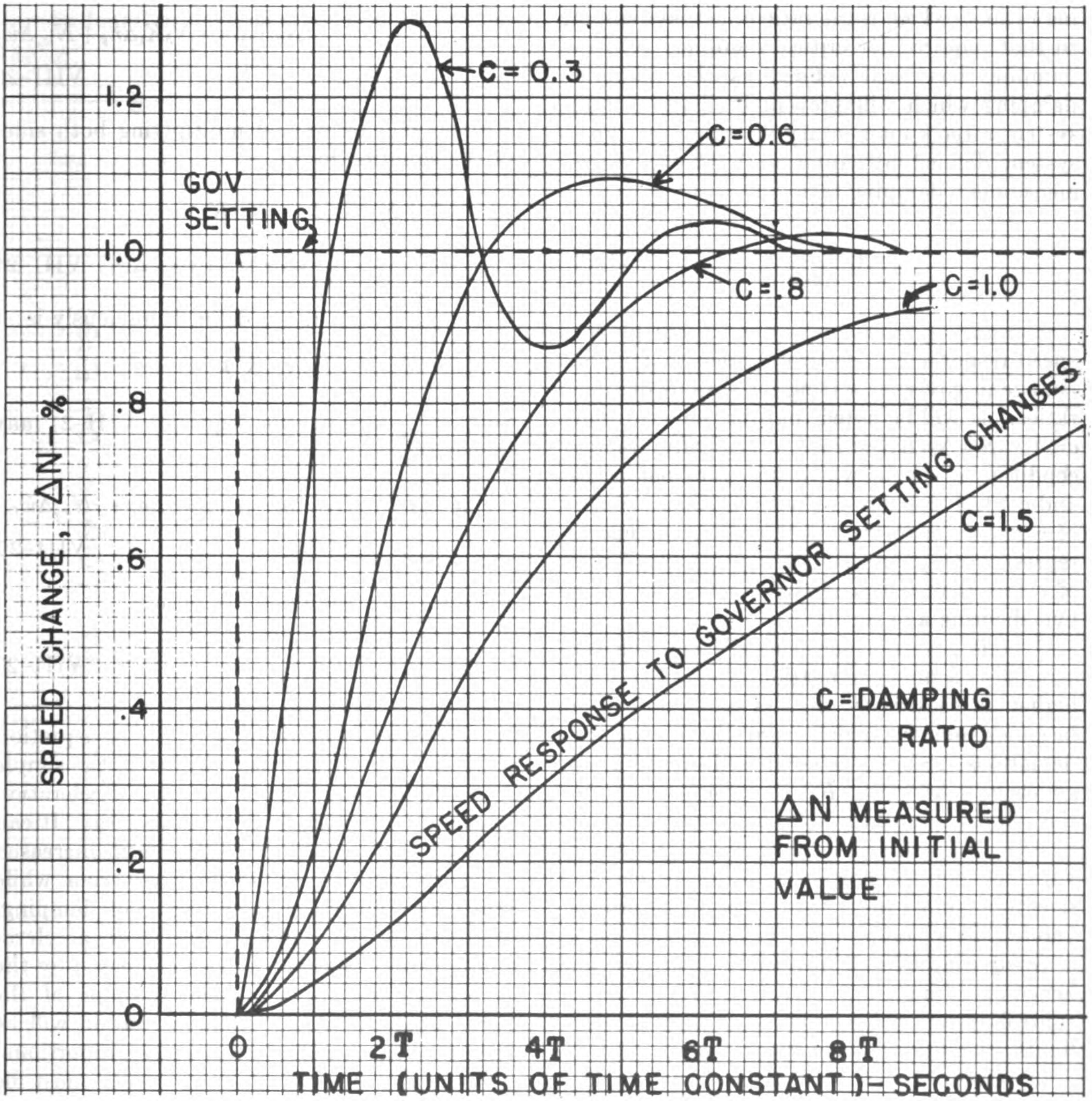

Figure 8.4.—Propeller speed change response to governor control.

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and,

S=Dimensionless factor for overall governor sensitivity.

Then,

$$\tau^2\Delta\ddot{n}+\tau\Delta\dot{n}+S\Delta n=S\Delta n_g+\tau N_{w_f}\Delta\dot{w}_f \qquad \text{VIII–17}$$

(2) *Control system damping (stability).* Equation VIII–17 is the equation of a simple second order system similar to that of a mass suspended on a spring having viscous damping. Behavior of such a system has been covered adequately in other literature. A measure of stability of a control system may be represented by a damping ratio, c, which is the ratio of actual damping to that required for critical damping. Critical damping has been defined as the minimum damping which will prevent oscillation of the system after a momentary disturbance. For a system defined by equation VIII–17, the dimensionless damping ratio is

$$C=\frac{1}{2\sqrt{S}} \qquad \text{VIII–18}$$

The curves shown in figure 8.4 are plots of speed response of a control system to a sudden change in governor setting for various damping ratios. It will be noted that for the conditions, $c=1$, ($S=N_\beta\tau K_1=0.25$), a critically damped condition exists in which no overshoot occurs and control response is reasonably fast. Values of c greater than one, as shown by the curves, represent very sluggish control systems. Values of c less than 0.6 generally result in excessive overshooting and oscillation.

Overall governor sensitivity s may be considered as a direct indication of stability. The higher the sensitivity, the less stable the system becomes and the more rapid the response to deviations. Since s is composed of the actual governor sensitivity, K_1, the time constant of the system, τ, and the RPS-blade angle characteristic, $N\beta$, and since the latter two both vary with the flight condition, the actual governor sensitivity must be picked at some compromise value. This compromise value should be so selected that overall governor sensitivity and hence operating characteristics of the propeller control system will be held within satisfactory limits over the expected flight regime.

(3) *Control system acceleration sensitivity.* Response time and hence the amount of overshoot can be improved by introducing acceleration sensitivity into the control system. This improvement can be accomplished by a modification of the governor that will give governor characteristics defined by the following relationship:

$$\Delta\dot{\beta}=K_1(\Delta n-\Delta n_g)+K_2\Delta n \qquad \text{VIII–19}$$

In this equation, K_2, acceleration sensitivity of the governor, is the rate of blade angle change per unit rate of speed change (seconds). Combining equations VIII–13 and VIII–19·

$$\tau\Delta\ddot{n}+\Delta\dot{n}=-N_\beta K_1\Delta n-$$

$$N_\beta K_2\Delta\dot{n}+N_\beta K_1\Delta n_g+N_{w_f}\Delta\dot{w}_f \qquad \text{VIII–20}$$

Rearranging terms and multiplying both sides of the equation by τ,

$$\tau\Delta\ddot{n}+(1+K_2N_\beta)\tau\Delta\dot{n}+N_\beta\tau K_1\Delta n$$

$$=N_\beta K_1\tau\Delta n_g+\tau N_{w_f}\Delta\dot{w}_f \qquad \text{VIII–21}$$

Governor sensitivity as defined previously is:

$$S=N_\beta K_1$$

So that, by substitution, equation VIII–21 may be written as:

$$\tau\Delta\ddot{n}+(1+K_2N_\beta)\tau\Delta\dot{n}+S\Delta n=S\Delta n_g+\tau N_{w_f}\Delta\dot{w}_f \qquad \text{VIII–22}$$

For this case, the damping ratio is:

$$C=\frac{1+K_2N_\beta}{2\sqrt{S}} \qquad \text{VIII–23}$$

As expected, the damping ratio of equation VIII–23 becomes identical to that of the simple proportional governor when the acceleration sensitivity term, K_2, is reduced to zero. It can be seen that sensitivity, s, has been increased beyond that of a proportional governor while still maintaining the same degree of damping. In addition, the response time of an acceleration sensitive system has been decreased by the factor $(1+K_2N_\beta)$. The general shape of the speed-time graph for this configuration will be the same as that for the simpler proportional governor. However, the time scale must be divided by $(1+K_2N_\beta)$. One big advantage of

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introduction of acceleration sensitivity is the reduction in magnitude and duration of overspeeds, that can occur during violent maneuvers or throttle bursts, coupled with excellent stability during normal operating conditions.

In this discussion, time lags of the governor mechanism have not been considered. Appreciable governor time lags have a de-stabilizing effect on overall operation and must be held to a minimum. The analysis of a control system with governor mechanism time lag variables included cannot be presented in a general case. Detailed methods of analysis can be found in references given in the bibliography.

The effects on a control system produced by changing propeller aerodynamic characteristics caused by changing flight conditions may be summarized as follows:

(*a*) Control system stability increases with increased airplane forward velocity and throttle setting.

(*b*) Control system stability decreases with altitude.

The curve shown in figure 8.5 is a plot of damping ratio vs. airplane forward velocity.

Propeller Control System Analysis—Turbine Engines

The preceding paragraphs have given a general outline of a method of analysis of a pro-

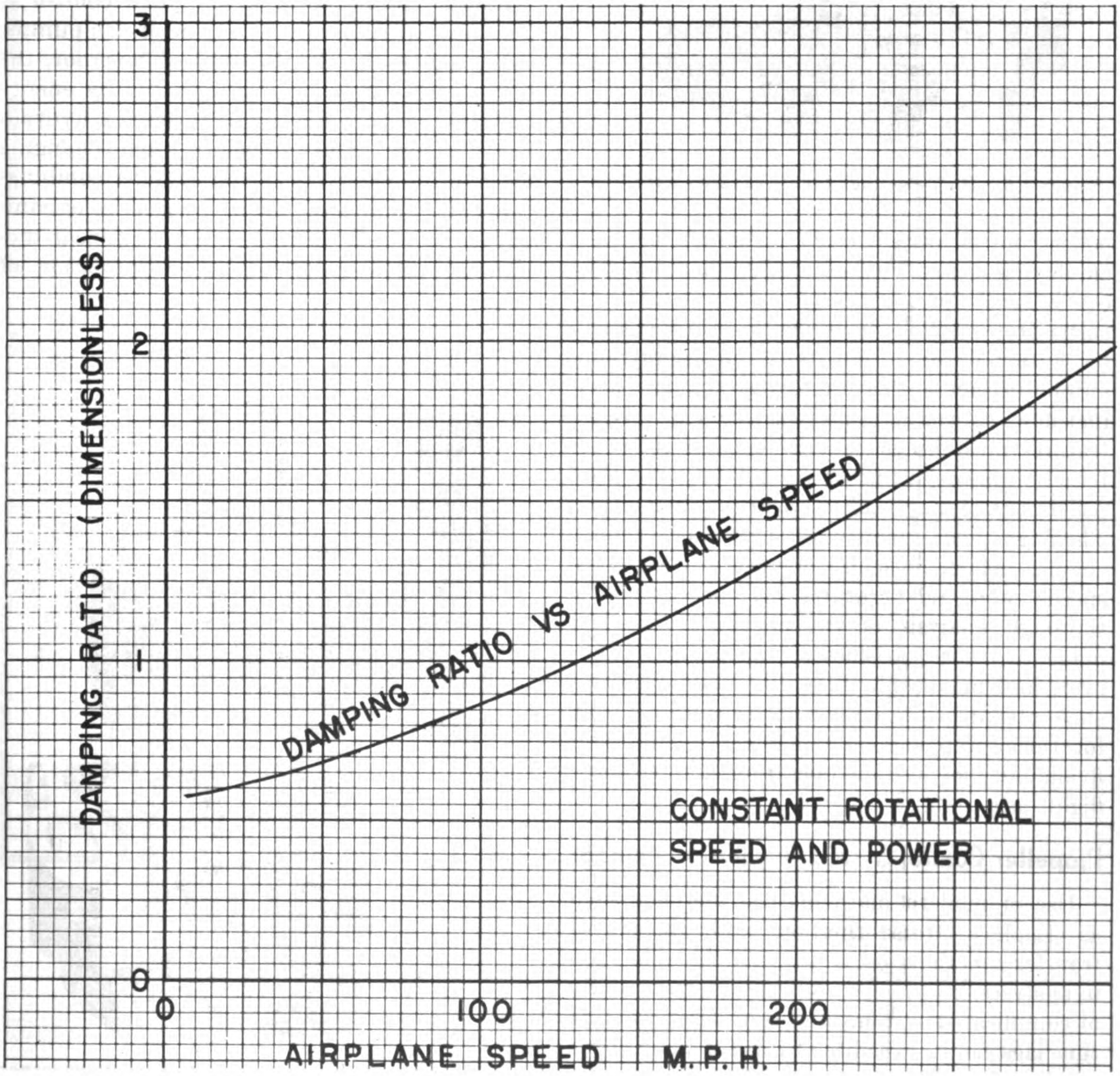

Figure 8.5.—Damping ratio vs. airplane velocity.

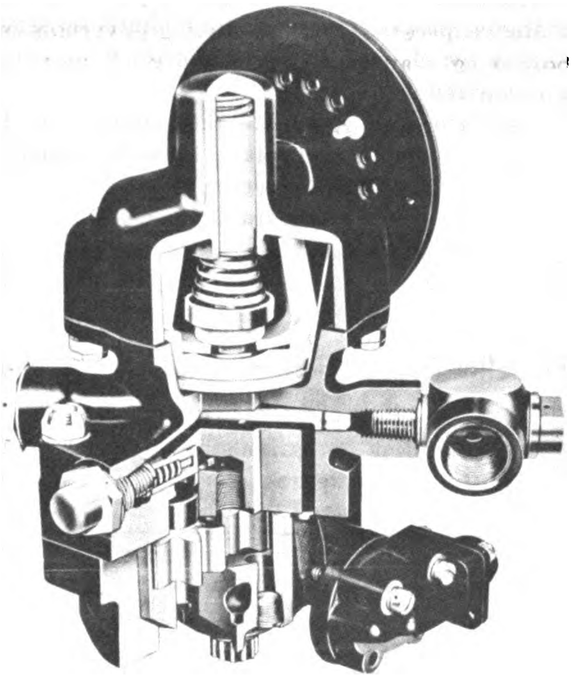

Figure 8.6.—Single acting, double capacity governor.

peller control system used in modern aircraft employing piston engines. A similar analysis can be made of a control system used with a turbo-prop engine. However, a control system for a turbo-prop engine must incorporate an automatic control feature for the regulation of fuel flow, as well as a propeller control. Both features must be considered together since interaction between fuel flow regulation and propeller control may lead to operating difficulties. The high polar moment of inertia of turbine engines, which normally operate at very high speeds and temperatures, requires that a thorough analysis of the control system be made to insure satisfactory operation. However, insurmountable difficulties should not be encountered in the design of propeller controls for turbo-prop engines being dependent upon availability of system operating and airplane flight data.

Propeller Control System Analyses Methods

Use of modern mathematical methods such as Laplace transformation and theory of transfer functions prove to be invaluable tools in analyses of propeller control systems. Study of complicated systems and consideration of all time lags can be expedited by use of an analogue or digital computer to make the numerous separate calculations required. Study of transient behavior during large excursions from a given operating point can be handled by a step-by-step method of analysis wherein a digital computer can be used to great advantage.

Basic Governor Operating Principles

Hydraulic Governors

The term hydraulic propeller is somewhat misleading in that by implication such a propeller could be considered as one in which power would be transmitted for propeller rotation by a fluid drive. However, as presently applied, hydraulic propeller is a constant speed, full feathering propeller in which pitch control is obtained hydraulically by engine driven pumps, using engine oil. In this type of governor, the blade pitch/change gear is actuated by energy transmitted from the engine through a hydraulic coupling. The propeller pitch changing mechanism includes a piston-cylinder combination connected to the blades by a series of cams and gears which convert piston rectilinear motion into blade-gear rotation. Translation of

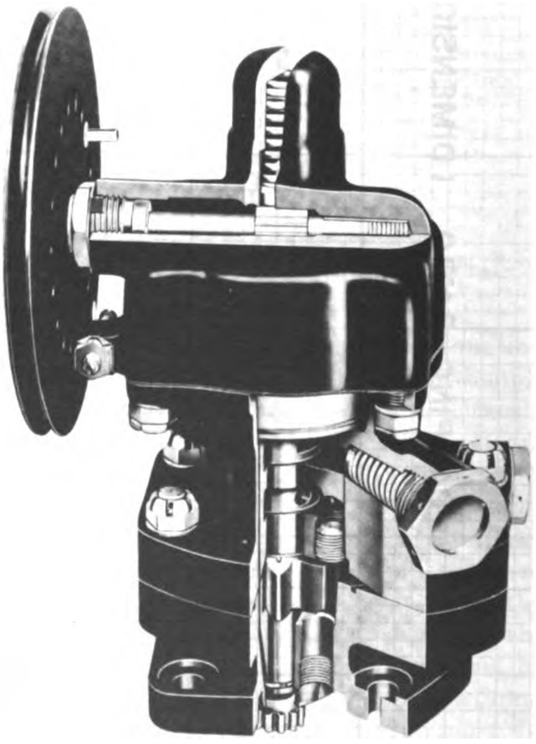

Figure 8.7.—Single acting, double capacity governor.

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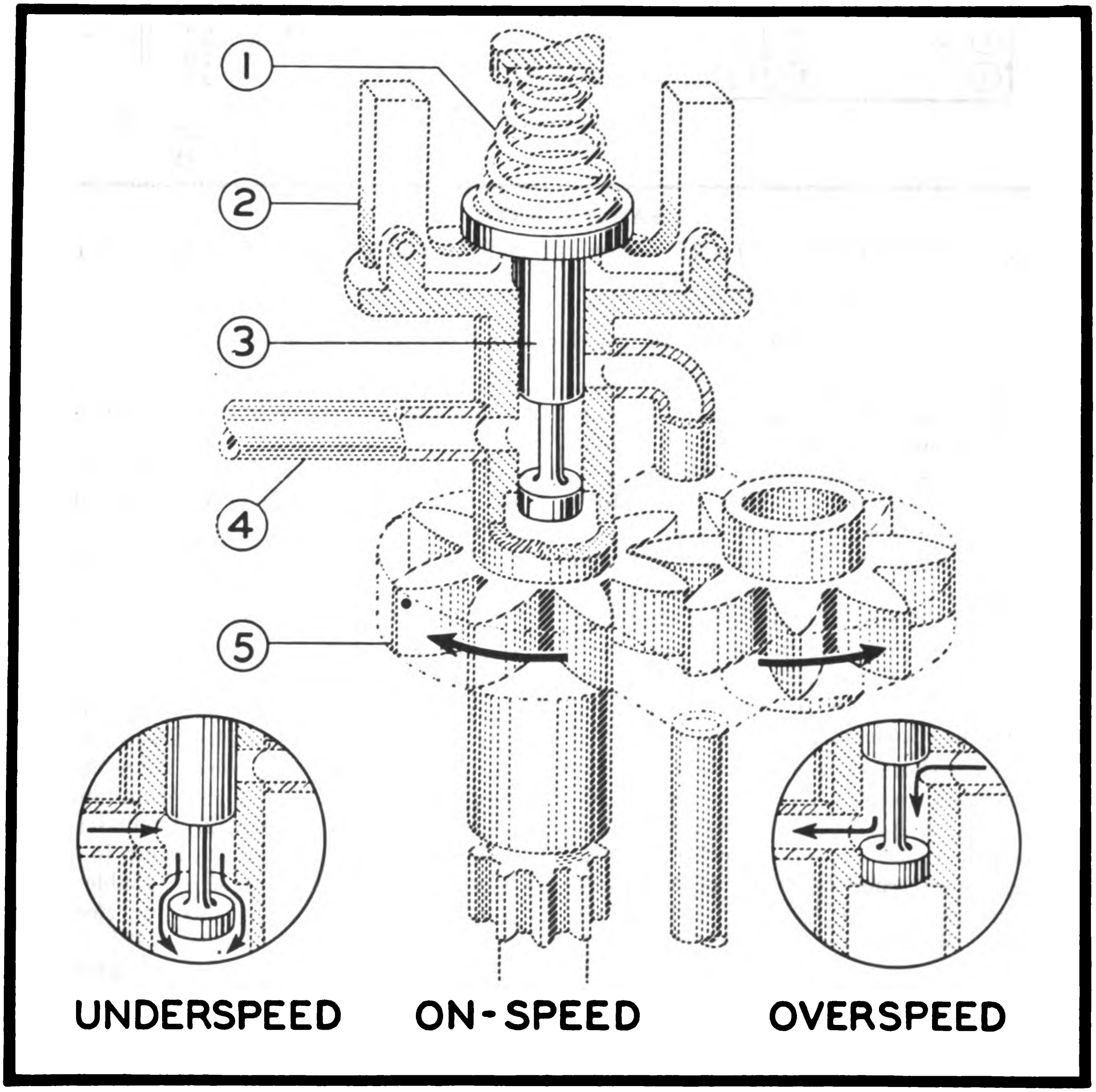
the piston within the cylinder is forced by energy of the oil under pressure.

A front cutaway view of a double capacity, single acting hydraulic governor is shown in figure 8.6.

A side cutaway view of the same governor is shown in figure 8.7.

Single Acting Governors

Basic operation of single acting governors of both single and double capacity along with accumulator types may be explained best by reference to figure 8.8 which illustrates essential elements, positioned for various propeller operating conditions.



PARTS IDENTIFICATION

1 .. Speeder spring 2 .. Fly weights 3 .. Pilot valve

4 .. Propeller passage 5 .. Booster gear pump

Figure 8.8.—Single acting governor operating diagram.

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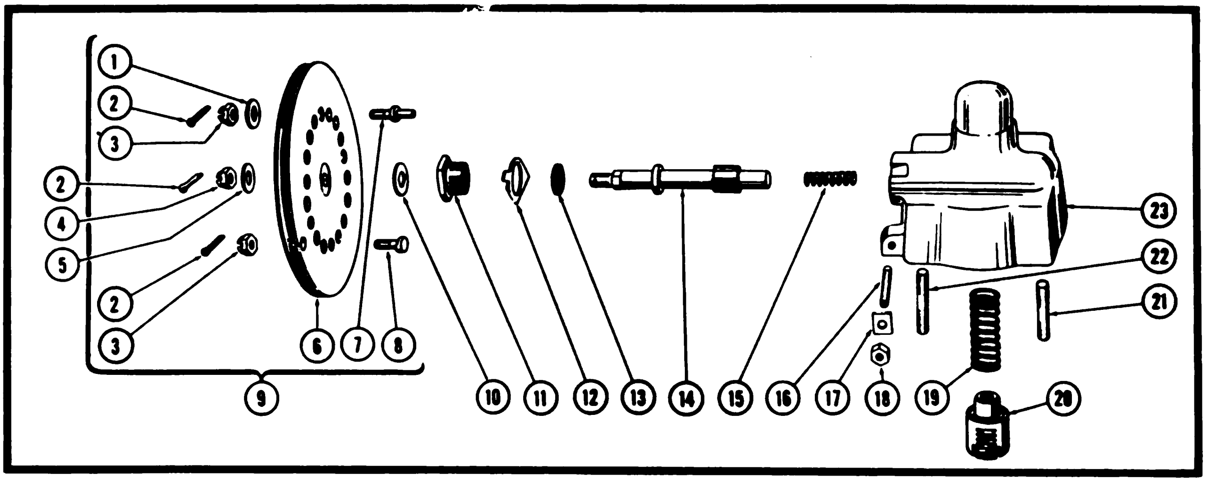

PARTS IDENTIFICATION

9 ... Pulley assembly 11 - 15 ... Control shaft assembly 16 - 18 ... Stop assembly

19 - 20 ... Speeder spring assembly 21 - 23 ... Head housing and studs

Figure 8.9.—Head assembly—Exploded view single acting governor.

Whenever engine speed drops below a value preset into the propeller governor, rotational speed of the engine driven governor flyweights (2) will decrease. Then, the speeder spring (1) will force the pilot valve (3) downward. Movement of the pilot valve into its low position will permit oil from the pitch changing piston cylinder space to flow from the supply tube (4), as shown in the lower left insert of figure 8.8, thereby reducing blade pitch. Decreased blade pitch will reduce engine loading to a point where engine speed will increase until *on speed* condition has been reached.

The insert sketch at the lower right in figure 8.8 illustrates position of the governor pilot valve when *overspeed* condition exists. Whenever engine speed exceeds governor *on speed* setting, the governor flyweights (2) move outward overcoming feeder spring (1) force thereby raising the pilot valve (3) to permit oil flow from the governor pump (5) to the piston of the blade angle control mechanism. The increased oil pressure will move the piston to a position (increased pitch) where the propeller will be operating *on speed.*

During *on speed* operation, the pilot valve (3) is located in a neutral position, a condition wherein oil is not supplied to the pitch control mechanism, neither is oil drained from the pitch control cylinder. Governor speed setting can be adjusted by increasing or decreasing feeder spring (1) tension.

Exploded view of the head assembly of a double capacity, single acting governor is shown in figure 8.9.

The body assembly of this governor exploded to show working parts is illustrated in figure 8.10.

The base assembly of the single acting governor of figures 8.9 and 8.10 exploded to show internal parts is illustrated in figure 8.11.

Double Acting Governors

Operation of a double acting governor is very similar to that of a single acting governor except that pump output oil can be directed to either the inboard or outboard side of the pitch change piston as required by flight conditions. Oil returning from the pitch control cylinder will be directed to intake side of the pump to be used over again. Operation of a double acting governor can best be described by reference to the operating diagram of figure 8.12.

During the engine underspeed operation, oil from the gear pump (6) goes through the oil line (5) to the outboard side of the propeller pitch control piston. Oil pressure will cause blade movement to a lower pitch with subsequent decrease in engine load. Decreased engine load will allow propeller speed increase until *on speed* setting has been reached. In *on-speed* condition, both lines to the pitch control piston of the propeller are closed by lands on the pilot valve (3). During overspeed operation, the pilot valve will be raised to open line (4)

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to the inboard side of the pitch control piston. Oil entering the propeller pitch control cylinder will cause blade movement to a higher pitch position. Consequently, the propeller will return to on speed operation. Oil returns through line (5) to the intake side of the pump.

Electric Governor Control

The electric governor constant speed propeller control system includes a flyweight type governor, relay assembly, brush assembly, slip ring housing assembly, cockpit propeller control connected to the governor and cockpit control switches.

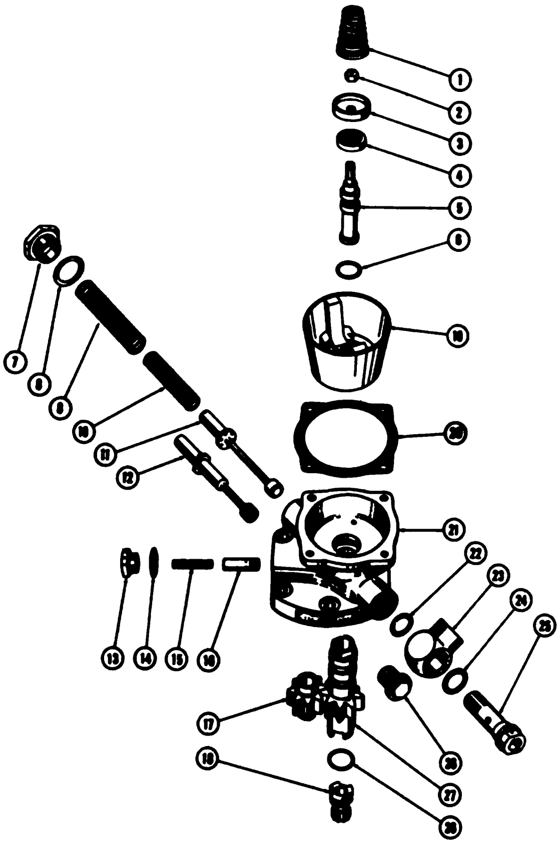
In electric governor control systems, blade angle is changed by an electric motor connected to blade gears through a speed reducer and power transfer gear. Electrical energy for changing propeller blade angle established by the governor is transferred through brushes on the engine nose to a slip ring assembly on the rear of the propeller hub, thence to a power unit motor through special leads. The power unit motor is a direct current reversible motor which will permit either an increase or decrease of blade pitch.

An assembly of electric propeller governor is shown in figure 8.13.

Proportional Booster Governor

The proportional booster governor is a flyweight type governor utilizing oil to actuate a piston upon which electrical contacts are mounted to *make and break* an electrical circuit to the pitch change motor. The proportional booster governor diagram shown in figure 8.14 will be most helpful in analyzing the principle of operation of this pitch control system.

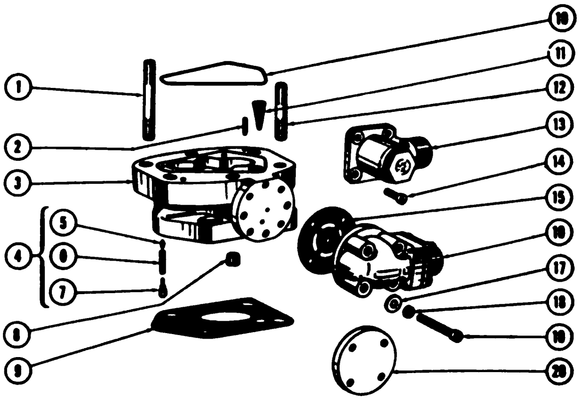
Flyweight action actuates a valve which in turn controls the flow of oil from engine governor drive pad to a movable oil piston. A contact point is mounted on the oil piston shaft.



PARTS IDENTIFICATION

1 .. Speeder spring
2 - 5 .. Pilot valve assembly
7 - 12 .. Feather transfer valve assembly
13 - 16 .. Relief valve assembly
17 and 27 .. Pump assembly
18 and 28 .. Drive spline assembly
20 and 21 .. Housing body and gasket
22 - 25 .. Feather line swivel assembly
26 ..Closing plug, nonfeathering application
6 and 19 .. Flyball cup assembly

Figure 8.10.—Body assembly of single acting governor.



PARTS IDENTIFICATION

1, 2, 3 and 12 .. Base housing with studs
10 .. Body base gasket
11 .. Oil screen strainer
4 .. Dump valve assembly
8 .. Directional (rotation) plug
9 .. Governor-engine mounting gasket
13 and 14 .. Two-wire pressure cutout
15, 16, 17, 18 and 19 .. One-wire pressure cutout
20 .. Nonfeathering closure plate

Figure 8.11.—Base assembly of single acting governor.

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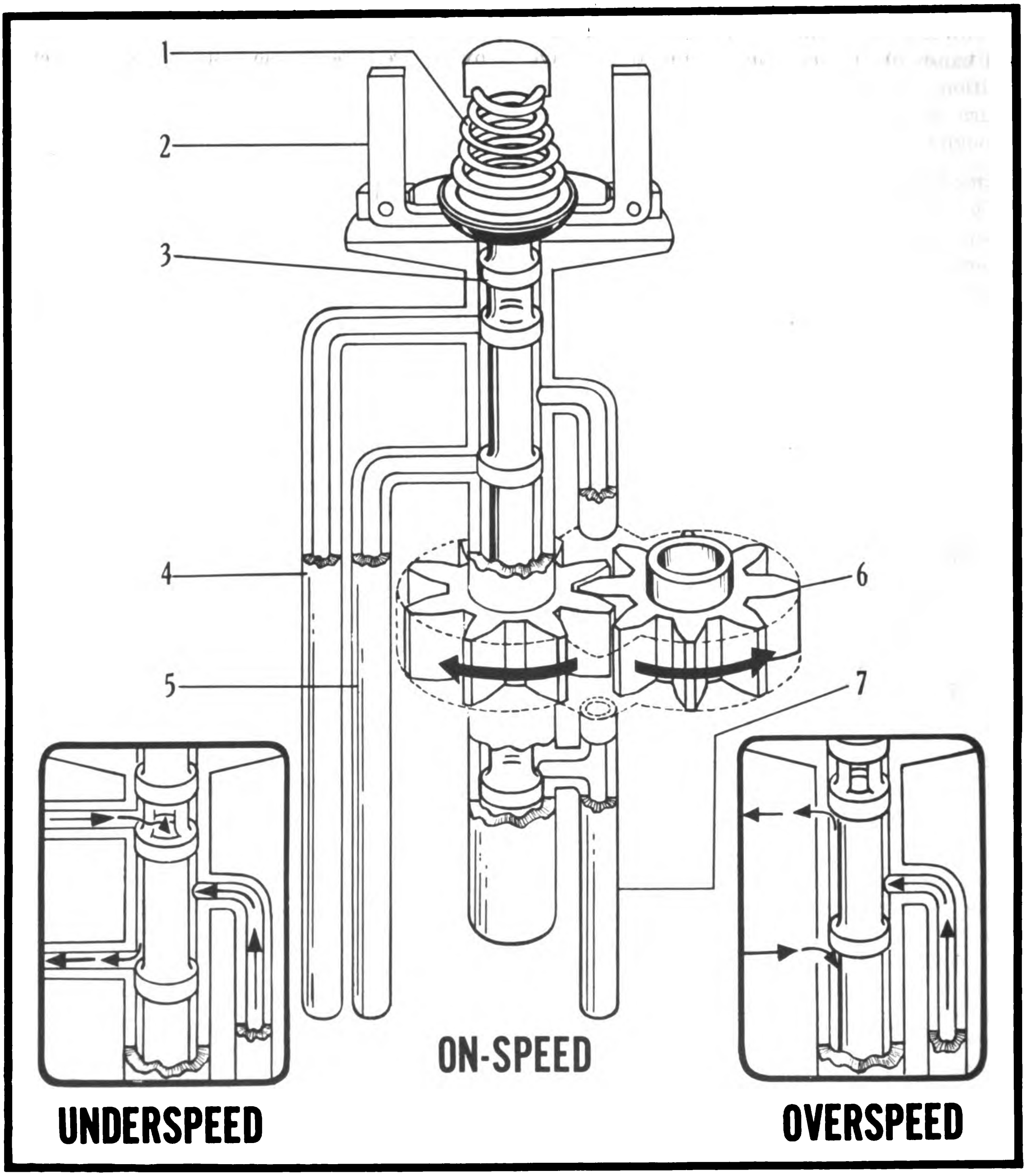

PARTS IDENTIFICATION

1 .. Speeder spring 2 .. Fly weights 3 .. Pilot valve

4 .. Propeller inboard line 5 .. Propeller outboard line

6 .. Booster gear pump 7 .. Engine oil intake

Figure 8.12.—Double acting governor operating diagram.

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Increase and decrease speed contacts are mounted on an oscillating cam driven plunger shaft. An oil pressure pump and relief valve maintain constant oil pressure to the spindle valve, independent of any change in engine oil pressure. Governor contacts operate a propeller relay which opens and closes the power circuit to the pitch change power unit motor.

The governor can be set to maintain any engine speed, within its range, by adjusting a cockpit control. This control actuates the governor rack which in turn increases or decreases the pressure exerted on the flyweight proportional range spring. Increasing pressure on the spring increases the speed at which the flyweight must rotate for *on-speed* condition. Decreasing the pressure decreases the speed at which the flyweights must rotate for *on-speed* operation. Since flyweight rotational speed is directly proportional to engine speed, any desired engine constant speed setting may be selected. The flyweight assembly controls the spindle valve and oil pressure to the piston is regulated by the position of this valve. The position of the center contact will be established by oil pressure on the piston, since the center contact is mounted on the piston shaft.

When the engine is *on-speed*, governor flyweights hold the spindle valve in a position which throttles oil pressure to a valve just high enough to balance the oil piston spring pressure, holding the center contact in a neutral position. When the engine overspeeds, the governor flyweights, in response to increased centrifugal force, move outward. Governor flyweight movement changes the position of the spindle valve in such a manner that oil pressure on the oil piston increases, thereby raising the center contact into touch position with the decrease speed contact. Hence, automatic decrease speed control circuit will have been set up to the propeller relay which will cause the power unit motor to increase blade angle. Increased blade pitch will decrease engine speed by action of the increased load.

Whenever the engine speed decreases to a

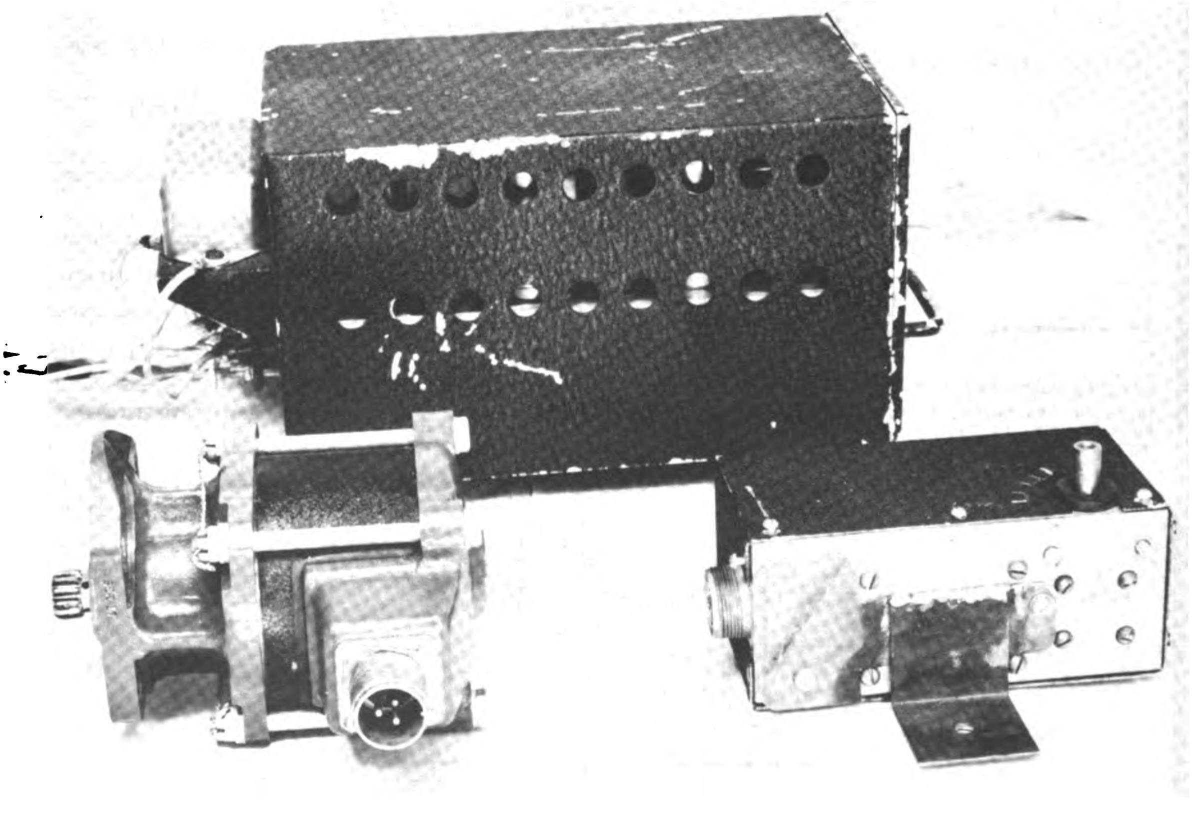

Figure 8.13.—Electric propeller governor.

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valve less than governor preset speed, the flyweights move inward by action of centrifugal force. Hence, the oil valve will change position so that oil pressure upon the piston will be less. Decreased oil piston spring pressure will permit movement of the center contact downward to touch the increase speed contact. Engagement of these contactors will close the automatic increase speed circuit to the propeller relay, which will cause the power unit motor to decrease blade angle. Decreased blade angle will increase engine speed by virtue of a load reduction.

During small *off-speed* condition, contact closures will be intermittent, since the contacts are oscillated by the cam shaft assembly. Time duration of contacts closure increases as deviation from *off-speed* increases. For large *off-speed* conditions, a continuous contact will occur. This feature is the proportional characteristic of this governor.

A voltage booster is included for accelerated feathering under emergency conditions. With the feather switch in *feather position* the normal propeller circuit has been opened and the booster voltage feather circuit closed. Feathering a propeller may be accomplished at normal rate of pitch change by holding the blade angle selector switch in *decrease r. p. m.* position until feather angle has been reached.

Synchronizers

(1) *Functions and types.* A propeller synchronizer is in reality a governor used in multi-engine aircraft to automatically control the speed of each engine with all engines maintaining identical speeds. A synchronizer may be set by the pilot to control engines at any desired speed.

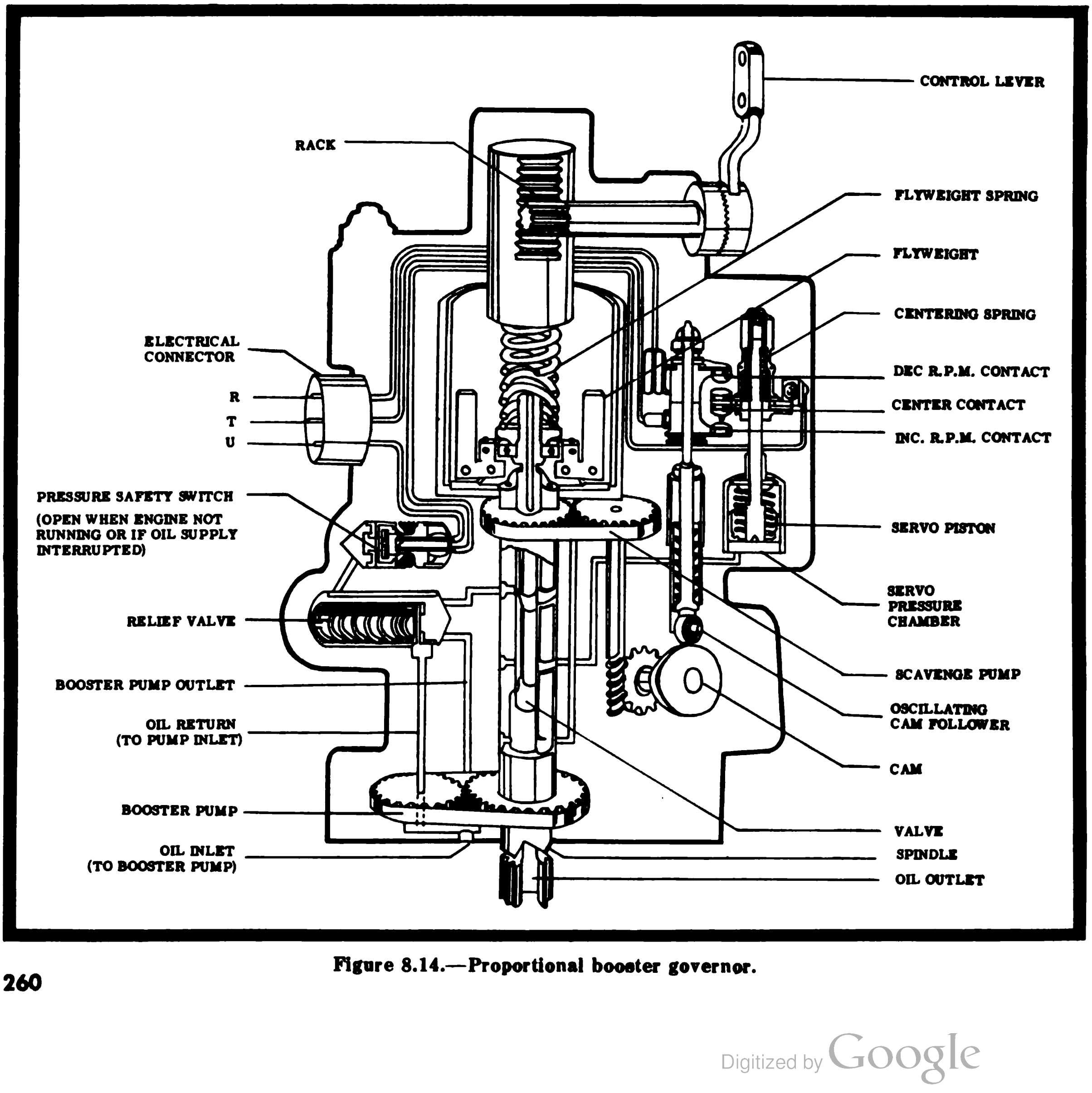

Figure 8.14.—Proportional booster governor.

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There are three basic types of synchronizer in use at this time: master motor, one-engine master (limited range) and electronic. The master motor type makes use of a master motor set to operate at predetermined speed with which the aircraft engine speeds are matched. The one-engine master type synchronizer uses one-engine as a predetermined speed governor with which all other engine speeds are matched. The electronic synchronizer uses a master oscillator to select the desired speed. Aircraft engine speeds are matched to this oscillator speed setting by matching frequencies.

(2) *Master motor synchronizer principle of operation.* The master motor synchronizer consists of a direct current motor and a suitable number of contactor units (one per engine) mounted on and driven by the master motor. The master motor is a manually adjustable, constant speed motor of the amplidyne type. The center point of the two fields is connected to a contact point of a flyweight governor by means of brushes, a collector ring, and the flyweight assembly frame. A single phase generator (AC), with armature mounted on the master motor shaft, is an integral part of the flyweight assembly. A protective relay circuit, located in the motor frame, connects ground leads of the contactor units to the negative side of the power circuit. The individual contactor assembly consists of a stator, rotor and relay assembly. An alternator (3 phase AC) mounted on the engine governor mounting pad is the other major component of the installation.

In operation, frequency of the alternating current generated by the engine driven alternator is proportional to engine speed. Each alternator is connected electrically to a contactor unit mounted on the master motor. In the contactor unit, three sets of brushes and slip rings carry current from the alternator to the stator, around which a rotating magnetic field will be set up. This magnetic field will rotate at the same speed as the engine driven alternator. With stator stationary, the rotor will turn at the same speed as the rotating magnetic field.

With the complete system working, the constant speed master motor drives the stator in a direction opposite to that of the magnetic field. With the engine *on-speed,* speed of the magnetic field will be equal to that of the contactor stator, since the magnetic field rotates in a direction opposite to that of the contactor stator. The magnetic field stands still with respect to space; therefore, when the engine is *on-speed* the rotor will be stationary.

When the engine is *off-speed,* either above or below a preset speed, rotational speed of the magnetic field will become greater or less than that of the stator. Hence, an effective magnetic field will be established, that is rotating at a speed equal to the difference between the speeds of stator and magnetic field. Then the rotor will turn at a speed equal to and in the same direction as the effective magnetic field rotation. As the rotor turns, the commutator, mounted on the rotor shaft, and the brush holder assembly, mounted on the commutator, will turn also. However, the brush assembly will rotate only until its contact point meets one of the fixed directional contact points, at which time the brush assembly stops turning causing the brushes to slide over the commutator surface. As the rotor turns, the commutator transmits current impulses through the brushes to one of the fixed directional contacts. Consequently, one of the control relays will be energized when the interrupter relay contacts are closed, if commutator brushes touch a live segment of the commutator. At the instant that the preceding action sequence is initiated, the interrupter relay will be de-energized; therefore, under these conditions, the control relay will be energized for a short time before interrupter relay points open. When the interrupter relay points open, the control relay will be de-energized. The control relay contacts *make* or *break* an electrical circuit to the respective propeller relay coils. Closure of control relay contacts will initiate blade angle change through a propeller relay. Commutator rotation will effect cycle repetition. It can be seen readily that duration of blade angle change (energization time of propeller relay contacts) is a function of the number of *drop-outs* of interrupter and control relays.

Energization time is adjustable by means of a *drop-out* time adjusting mechanism. During large *off-speed* operation, current impulses across the commutator are rapid enough to prevent interrupter relay *drop out.* As commutator brushes touch live and dead segments of the commutator, alternately, the control relay will be unable to *drop out* before it is

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re-energized. Hence, the control relay and propeller relay will be operative continuously.

(3) *One engine master type synchronizer* (*limited range*). The one-engine master synchronizer utilizes a step motor electric head governor and a tachometer generator with each engine and a synchronizer assembly located in the cockpit. The synchronizer assembly for a four engine installation contains nineteen relays, three differential motors and commutator switch combinations, one reversible direct current motor and commutator switch combination, a mechanical electrical follow-up system, and a uni-directional motor with four commutator switches.

The principle of operation of this type of synchronizer is based on the stepmotor electric head system in which governor speed setting is controlled by operation of a commutator switch that energizes the stepmotor field in the head. Rotation of the commutator switch causes changes in polarity of voltages applied to the stepmotor field winding which results in movement of the rotor with subsequent change in speeder spring setting.

For purposes of explanation, synchronization between two engines will be considered as illustrated in figure 8.15. Engine A has been designated the master engine and engine B the the slave. Master engine speed is controllable by commutator switch A. The three-phase output of a tachometer generator is directed electrically to stator winding of the front motor of a differential motor assembly. Output of the slave tachometer generator is directed electrically to the rear motor of the differential motor assembly. The differential motor output shaft will turn only when frequencies of the front and rear motors are different. The output shaft will rotate in a direction determined by higher or lower frequency of the slave engine relative to master. The output shaft is mechanically linked to a commutator switch (B) which regulates the stepmotor head (B). Any difference between frequencies of master and slave tachometer generators will cause the differential motor to drive the slave commutator switch until synchronization has been obtained.

In this system, the slave engine is entirely dependent upon the master engine for speed determination. Should master engine fail, the slave, normally, could be expected to follow master engine speed, decreasing to minimum speed setting of the governor. However, a mechanical limiting device has been attached between differential motor and the slave com-

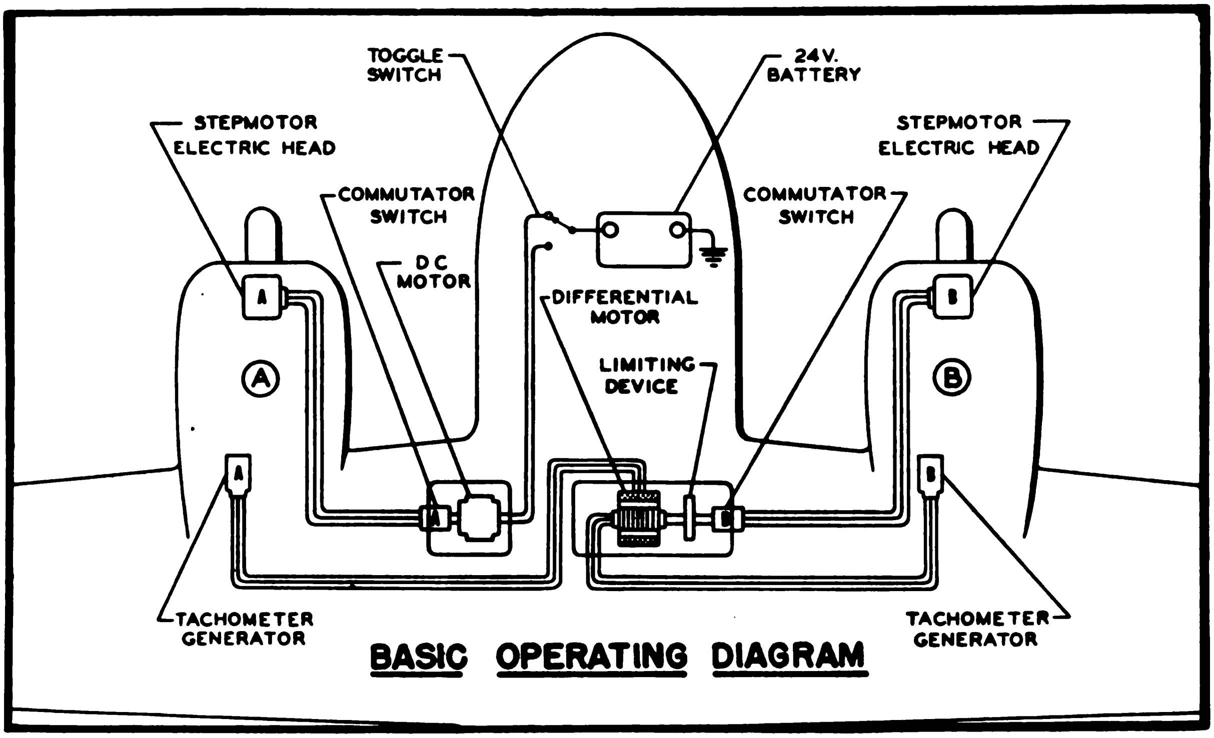

Figure 8.15.—One engine master synchronizer diagram.

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mutator switch to prevent slave engine speed decrease to this extent. The slave engine speed limiting device physically restricts rotation of the commutator switch to a range approximately ±3 percent of the original master speed. This feature is the limited range characteristic of the one engine synchronization system. Individual engine speed selection adjustment is incorporated for manual operation.

(4) *Electronic Synchronizer.* (*a*) General Operation. Principal elements of an electronic synchronizer are: hydraulic governor with a magnetic head and a tachometer generator for each engine as well as a rectifier and amplifier channel for each engine along with a master oscillator.

Primary speed control is obtained from comparison of rectified output voltage of the tachometer generator, which is proportional to engine speed, with a direct current reference voltage. Any variation between these voltages indicates an *off-speed* condition that promotes operation of the magnetic head to restore *on-speed* operation. In order to govern at variable selected speeds, the reference voltage must be varied by use of a master speed control. Any existing voltage difference, after amplification, will be applied to the magnetic head on the governor which actuates the pilot valve.

Output of a master oscillator provides a reference speed control. Output voltage of the oscillator is distributed to synchronizer channels (one for each engine). A voltage signal from each tachometer generator is directed into corresponding channels by means of an adjustable control. The synchronizing circuit carries output voltage dependent upon phase relationship between oscillator output and tachometer generator signal. Oscillator frequency is controlled by a master speed control. Magnitude of synchronizer output which is directed into the amplifier of the governing system, is dependent upon propeller *off-speed* condition. A cut-off feature has been incorporated into the synchronizer system that will become effective when speed error is large.

(*b*) Phase Synchronizing. Phase synchronizing is presently used only with an electronic synchronizer. Each engine has a phasing control consisting of a circular potentiometer with three fixed taps located 120° apart and a variable position tap which may be set in any position. Three phase tachometer generator voltage from a representative engine is applied to the fixed taps. The phase of the voltage between movable tap and ground can be set at any desired value by adjusting the point of contact. A change in setting will effect a voltage change which may vary from the voltage differential between one tap and ground to one-half that value. Since phasing control provides the synchronizer with a signal, the phase of which can be adjusted through a full range of 360°, it is possible to synchronize the engine at any phase angle desired.

Propeller Pitch Reversing Operation

Propeller reversing is an operation whereby the propeller blades are placed in a negative angle for the purpose of retarding forward speed of the aircraft on the ground after landing. Landing roll is reduced by producing a reverse thrust resulting from introduction of a negative blade angle.

Propeller controls for reversing operation must be interlocked so that it is impossible to place the propeller in reverse pitch angle, inadvertently, until the aircraft has landed. Normally, a detent, built into cockpit controls, must be released manually to permit aft movement of the control lever which will initiate blade rotation into reverse pitch position.

Hydraulic propellers may incorporate reversing features by use of a double acting governor, extension of cam slots in a direction opposite to that required for feathering and an auxiliary high pressure oil supply operated from cockpit controls. Serrated stop rings, limiting rotation of the cam, provide for adjustment of the reverse blade angle. Reversing control is obtained by use of throttle levers. An extended quadrant is provided and movement of the control lever back through a mid-position detent will reverse propeller blade angles while simultaneously reopening engine throttles, as necessary.

For propeller reversing operation with throttles set in normal landing approach, immediately after touching down the pilot must move the throttle back through detent position. This action will cause oil flow through the governor to one side of the propeller piston and energize the auxiliary oil pump. At the end of the operation, a cutout switch stops the auxiliary pump. Continued movement of the

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throttle rearward will increase engine power thereby providing control of negative thrust. To move a propeller from reverse pitch position, the throttle must be moved forward past the detent The same sequence of operations as reverse pitch action follows except that in this case, high pressure oil will be supplied to the opposite side of the blade pitch control piston.

Self-Contained Propeller Controls

(1) *General features of self-contained units.* There are three distinct types of self-contained controls; however, a number of characteristics and principles are common to all three types, namely:

- (*a*) Controls consist of a rotating part firmly attached to the propeller hub and a stationary part attached to the engine nose by a bracket, dowel pins or linkage.
- (*b*) Controls are combinations of hydraulic and mechanical assemblies.
- (*c*) All self-contained controls have a high pressure oil pump, oil reservoir and high pressure relief valve.
- (*d*) Synchronizer operation is provided in all types for multi-engine installations.

(2) *Solenoid oil valve control.* One type of control has solenoid operated valves that port oil to disc type clutches for propeller speed control, feathering and unfeathering operation, and reversing at variable rates. Control solenoids are operated from the cockpit to actuate clutches that engage a ring gear to accomplish blade pitch change. A sump pump is included to supply oil to the intake side of the high pressure oil pump. The solenoid assembly is constructed so that solenoid valve operation for feathering overrides all other valve operations for speed control and reversing. An electric feather motor for propeller feathering operations at speeds below 200 r. p. m. is incorporated. Whenever propeller rotation causes the high pressure pump to reach an output pressure of 150 pounds per square inch, a pressure control switch will open the feather motor circuit. The unit cannot be operated until output oil pressure has decreased to a point below 150 pounds per square inch. The ring gear is driven by the feather motor drive gear reduction system; however, when operating hydraulically, the feather motor will be disengaged by oil pressure. Either manual or synchronizer operation will cause energization of the solenoid to meet particular pitch change demand and subsequent hydraulic pressure application to the proper clutch will give desired blade gear movement.

(3) *Double acting hydraulic governor control—Self-contained unit.* A second type of control has a built-in double acting hydraulic governor with a stepmotor electric head and a hydraulic pitch change propeller. This governor functions much the same as a double acting governor, mounted on an engine nose, that uses engine oil for propeller blade angle operation. A scavenging system returns all internally discharged oil to a sump for recirculation through the system by means of a pressure pump. The governor, pressure pump and scavenger pump are driven by a ring gear on a rotating portion of the control. The governor, by action of flyweights and speeder spring, meters oil to the hydraulic propeller dome to accomplish changes in blade angle. Oil is transferred from control unit propeller dome through transfer sleeves, one of which rotates with the propeller while the other remains fixed to the pump housing of the control assembly. A solenoid valve assembly consisting of increase pitch solenoid and decrease pitch solenoid valves is used for all blade angle changes.

Throttle movement into reverse pitch range will initiate propeller reversing action. This action energizes the decrease pitch solenoid valve which directs high pressure oil to the reversing land of the pilot valve. The pilot valve, then, is forced into *underspeed* position. Also, high pressure oil is directed to the inboard side of the piston forcing the blades into reverse angle. Movement of the throttle into forward position on the quadrant will complete the circuit to the increase pitch solenoid valve and de-energize the decrease pitch solenoid. Hence, high pressure oil will be directed to the outboard side of the blade pitch control piston thereby moving blades towards high pitch angle. A blade switch opens the solenoid circuit when the blade angle reaches a positive pitch range.

Feathering operation is accomplished by means of an auxiliary pump, driven by an electric motor. The motor driven pump, located in the control oil sump, is controlled by a feather switch in the cockpit. The feather switch when depressed automatically locks in closed position thereby energizing the increase pitch solenoid valve and auxiliary feather motor.

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Oil from the feathering pump and the high pressure pump passes through the increase pitch solenoid valves to raise the pilot valve into overspeed position. With pilot valve in overspeed position oil is directed to the outboard side of the blade pitch control piston causing blade movement to feather position. As soon as the blades reach feather position, the circuit to the feathering pump and solenoid valve is broken, automatically, and the feather switch opens. The feather switch in *pull-out* position completes an electrical circuit which energizes the decrease pitch solenoid valve thereby moving the pilot valve into underspeed position and at the same time energizing the feathering pump motor. As soon as the propeller begins to windmill, oil output of the high pressure pump is added to that of the feather pump to cause blade movement to a lower angle. Defeathering operation will cease with feather switch release or when the blade switch opens the feather motor circuit, whichever occurs first.

(4) *Ring gear driven pump control—Self-contained unit.* A third type of control has a ring gear attached to the stationary portion of an assembly which drives a gear pressure pump. The pump, relief valve, governor feathering valve and minimum pressure valve are all mounted in the rotating part of the unit. Steel transfer tubes are cast into the housing to carry fluid from pump to governor to hydraulic torque unit in each hub socket. A filter assembly receives oil from the pressure pump and directs flow to a pressure control valve which establishes maximum operating pressure. From the pressure control valve the fluid goes to a governor which controls the hydraulic force applied to the torque units.

This governor consists of a piston that can move in a cylinder thereby controlling fluid flow to the inboard or outboard side of the torque units. Piston movement is controlled by centrifugal force opposed by a spring force which reacts directly on a lever. One end of the lever engages the governor piston; the other end of the lever is supported by a movable fulcrum roller. The fulcrum roller is mounted on a carriage which may move fore and aft on carriage ways. Mounted on the carriage opposite the fulcrum roller, is a governor stop roller. At low propeller speed, the lever will rest on this roller. A curved steel shoe extends from the underside of the carriage and rides in a stationary groove of the control mechanism, to provide speed control from the cockpit by mechanical linkage. An adjusting screw bearing on the spring will permit adjustment of the maximum governing speed. Moving the cockpit control rotates a lever which is integral with a ring gear having teeth on an internal diametral member. These internal teeth mesh with three small pinions which form the heads of control screws. Moving the control lever rotates the control screws which, in turn, transmit a fore and aft motion to the control ring groove. Control ring groove movement causes roller fulcrum movement. Fluid is forced, during normal operation of the control unit, through the feather valve into an accumulator at a given pressure where it is held in storage by a check valve. When feathering becomes necessary, control movement will cause fluid from the accumulator to be forced through the feathering valve of the governor and then to the inboard side of the torque units, which will feather the propeller. Unfeathering may be accomplished by moving the governor fulcrum to change the governor piston position. This causes fluid from accumulator to be directed to the outboard side of the torque units, thereby reducing blade angle to normal operating range.

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CHAPTER IX. PROPELLER INSTALLATION

Propeller Clearances

External Clearances

Operational and maintenance requirements are such that certain minimum clearances between rotating propellers and adjacent objects must be specified, if flying safety is to be assured. The following requirements must be met in every propeller installation.

(1) The distance between propeller disc and fuselage, landing gear or other structural member must be not less than 9 inches with 12 inches being preferred, under all possible blade pitch positions.

(2) The distance between propeller disc and ground must be at least 9 inches. Further, with one landing gear tire fully deflated and landing gear shock absorber completely depressed the clearance between propeller disc and ground must be not less than 3 inches.

(3) Clearance between propeller disc and water (Navy carrier based or water landing aircraft) must be equivalent to 40 percent of installed propeller diameter.

(4) Tip clearances between adjacent propeller discs of multiengine installations should be not less than 9 inches. Under no circumstances should propeller discs overlap.

(5) Propeller blade in all possible pitch positions must not be closer to engine cowling than 1 inch.

Positioning Propeller Relative to Airplane Personnel Spaces

Airplane personnel spaces must be located so that people will not be located in the plane of propeller rotation or in postions that fall within an angle of ±5° measured from the center of the propeller hub.

Effects of Improper Clearances

Propeller and aircraft maintenance has been found to be increased greatly when established clearances are not provided. Specifically, any combination of the following difficulties may be encountered in cases of insufficient clearance.

(1) Sheet metal work of the fuselage opposite the propeller disc may be damaged in the blade tip passage by structural failure of rivets or fuselage skin rupture.

(2) Blade tips along with landing gear and auxiliary equipment may be damaged severely if propeller blades pick up or hit foreign elements on the runway. Proper clearance will reduce such damage to a tolerable value.

(3) Water spray can cause severe damage to propeller blades by corrosive action of salt in the water or by structural loading of the blade beyond the elastic limit.

(4) Propeller blade tip failures may occur and subsequently, flying metal parts can produce loss of life or severe injury. Therefore, personnel positioning out of probable range is considered a safety-of-flight requirement that should be observed in all cases.

(5) Insufficient clearance between propeller discs or propeller components and engine cowling can produce rapid deterioration of propeller blades, cuffs, blade bearings and gears. Aerodynamic and structural loads induced by inadequate clearance are not considered in the basic propeller design.

Propeller Spinner Installation Requirements

When spinners are used, they must be quickly detachable. By quickly detachable is meant that a sufficient portion of the spinner can be removed in one minute or less to permit propeller removal from the engine and subsequently engine removal in minimum time.

Propeller System Equipment Clearances

Removal or Replacement Clearance Requirements

Installation of propeller system equipment must be accomplished with clearance provided to insure accessiblility for adjustment, repair,

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testing and removal. Clearances must be provided to permit equipment removal without disturbing other equipment, electrical leads to other equipment or hydraulic lines.

Hydraulic and electrical leads must be positioned in such a manner that these control elements do not offer a convenient step for maintenance personnel working upon airplane components. There are specifications and standards, usually made a part of propeller contracts, which specify exact dimensions, locations and installation procedures. Absence of contract specifications will place responsibility for installation in accordance with stipulations of the propeller manufacturer.

Requirements of Hydraulic Propeller Systems

Pump inlet oil line from the oil tank should have a minimum inside diameter of 1 inch with 1¼ inch or 1½ I. D. preferred for high altitude airplanes. Pump outlet lines should be ⅝ inch I. D. minimum. Inlet lines should slope towards the pump with constant pitch. An oil drainage sump should be located at a point in the hydraulic system well below the lowest part of the entire sytem.

Blade Cuff and Electrical Deicing Unit Clearance

Projecting parts of deicing units or blade cuffs with the propeller blade in feather position should not approach engine nacelle cowling or other structural parts closer than 1 inch. Electric propeller installations having blade cuffs may require access to propeller slip ring brushes through the spinner after body. In such a case, the split should be made at a point approximately one inch aft of the plane of the rear spinner mount.

Propeller System Equipment Installation

Selection and Installation of Auxiliary Equipment

The selection of auxiliary equipment for propeller systems is dependent upon the type of propeller employed, service requirements, space-weight requirements and functional objectives. For example, a hydromatic propeller for multiengine installation operating within a normal temperature range would use an engine oil tank for storage of oil necessary to operate feathering control units. But, if a wide range of temperature might be encountered, a self-contained fluid system propeller would be required.

Also, if passenger comfort is immaterial, a simple governor will suffice for propeller speed control. However, if passenger comfort is a prerequisite, as it is in commercial air lines, a propeller speed synchronizer is desirable.

Propeller Electrical Installations

(1) *General requirements.* Propeller nacelle harnesses—service experience on propeller nacelle harnesses has dictated the necessity of adhering to strict design and installation procedures on all propeller nacelle harness installations. Service tested and approved propeller harnesses have met two basic requirements:

(*a*) Emergency circuits, such as feathering and reversing, must be operational under both severe fire and vibration conditions.
(*b*) Normal circuit continuity must be maintained at all times in order to provide satisfactory propeller operation.

(2) *Harness installation requirements.* It has been found that the following propeller harness installation requirements for both production and retrofit service aircraft are essential:

(*a*) Stainless steel flexible conduit forward of fire wall and steel ferrules at the ends of the conduit must be used.
(*b*) Only approved fire resistant, high temperature cable should be used for all propeller wiring.
(*c*) All cable bundles must be covered with an approved asbestos sleeve. All sharp bends and bundle ends must be covered with vinal tubing, properly tied at the ends, before cables are placed in the conduit.
(*d*) Scintilla fire proof disconnect plugs will be required at the fire wall for all harnesses as well as at the fire seal or diaphragm for all harness, except the propeller control harness.
(*e*) A removable split steel cutout, or similar device must be installed at the propeller control conduit fire seal opening to permit removal of the harness at time of engine change without disassembly of disconnect plugs attached to the ends of the harness assembly.
(*f*) Steel clamps, protected with a fire resistant cushion on the clamp next to the conduit, spaced approximately 12 inches to 18 inches apart, must be used

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throughout engine nacelle for all propeller harnesses.

(*g*) A small *J* box will be provided at the engine nose, whenever electrical propeller deicing is used. This box will permit grounding of the deicing circuit ground at the engine nose, thereby providing a better electrical circuit as well as reducing cable length.

Propeller electrical harness configurations embodying the preceding features have been service tested with satisfactory results, i. e., satisfactory for fire and abrasion resistance. It was found that such a harness will withstand a temperature of 2000° F. for five minutes. It should be noted that a propeller control harness does not have disconnect plugs at the fire seal; a minimum number of disconnect plugs are incorporated in order to provide the safest electrical control of the propeller possible, at all

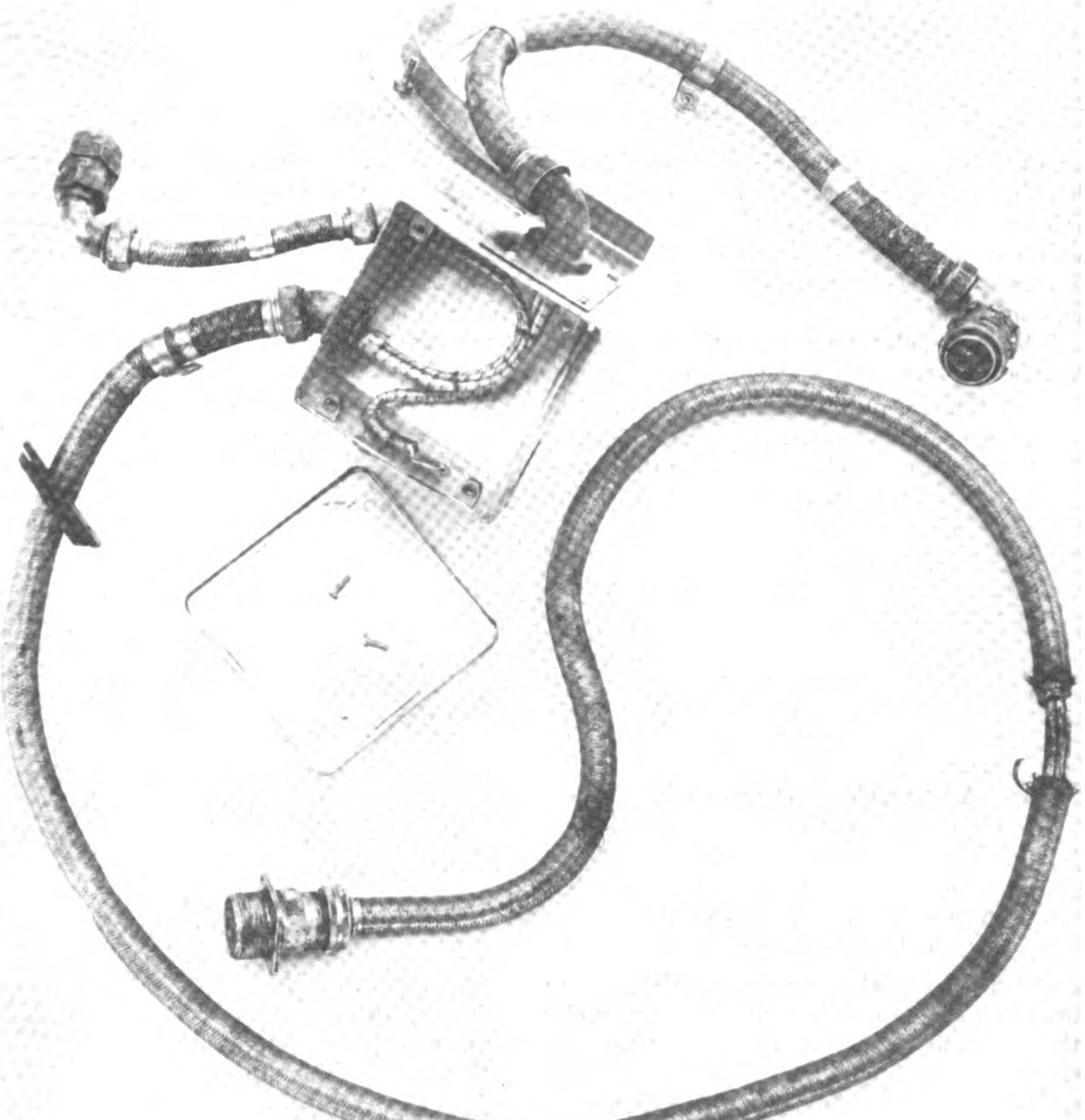

Figure 9.1.—Conduit and shielding failure..

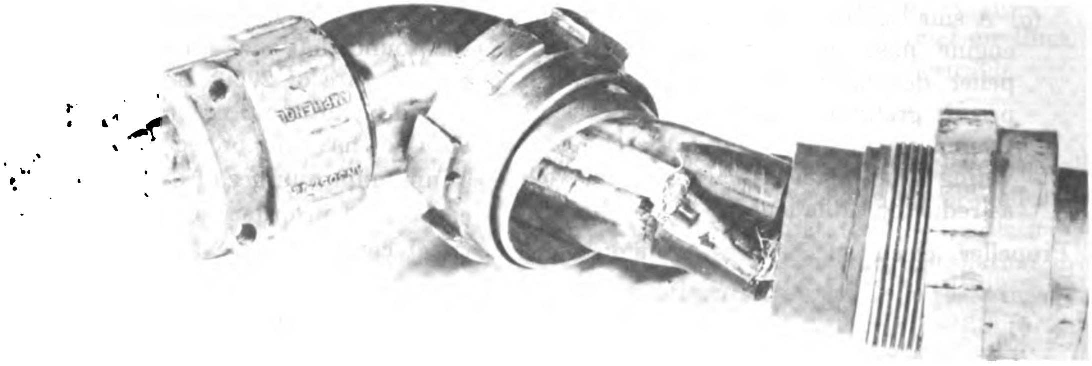

Figure 9.2.—Control harness installation.

times. The significance of electrical harness installation requirements can best be shown by reference to typical service difficulties that have occurred because of improper installation. Figure 9.1 shows a worn and broken conduit and shielding.

That such failures occur is sufficient proof of the need for meeting the following requirements:

(*i*) Equipment will be mounted in such a manner that excessive vibration cannot be transmitted to electrical leads, conduit or shielding, which may result in failure of electrical leads.

(*ii*) Electric leads will be installed in such a way that excessive stress will not be imposed upon the leads by other adjacent equipment.

(*iii*) When necessary, electric conduit and and shielding will be protected by shock mounting vibration producing equipment.

(*iv*) All propeller electrical equipment will meet MIL specifications.

(*v*) Electric conduit and shielding will be placed so that normal personnel travel in loading, or maintenance will not induce failure of electrical leads.

(3) *B-50 Propeller wiring installation.* An installation of propeller control harness under the shroud at the firewall of a B-50 airplane is shown in figure 9.2.

There is a pin on the shroud base and mating hole in the cover which, when separated, causes wire chafing and induces wire movement that results in wire breakage at the plug.

Here again is reflected maintenance problems that develop from improper wiring practices in placement of a propeller control harness. In this case, two broken wires were replaced by maintenance personnel. Chafing of wire insulation is discernible in the illustration. Such installations are a definite hazard to flight as well as a source of increased maintenance.

Another source of difficulty in the B-50 electrical system developed from installation procedures in joining conduit at the firewall. Ineffective makeshift attempts to remedy conduit breaks should not be tolerated. A good illustration of this type of installation defect is shown in figure 9.3.

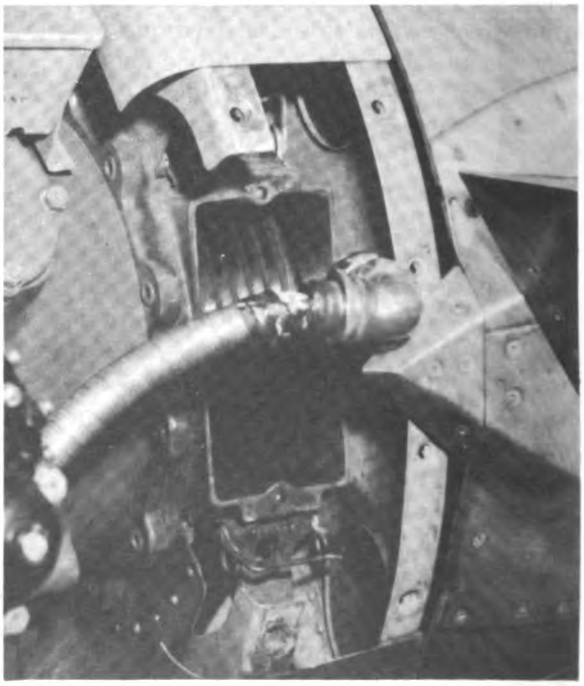

Figure 9.3.—Wiring conduit junction at fire wall.

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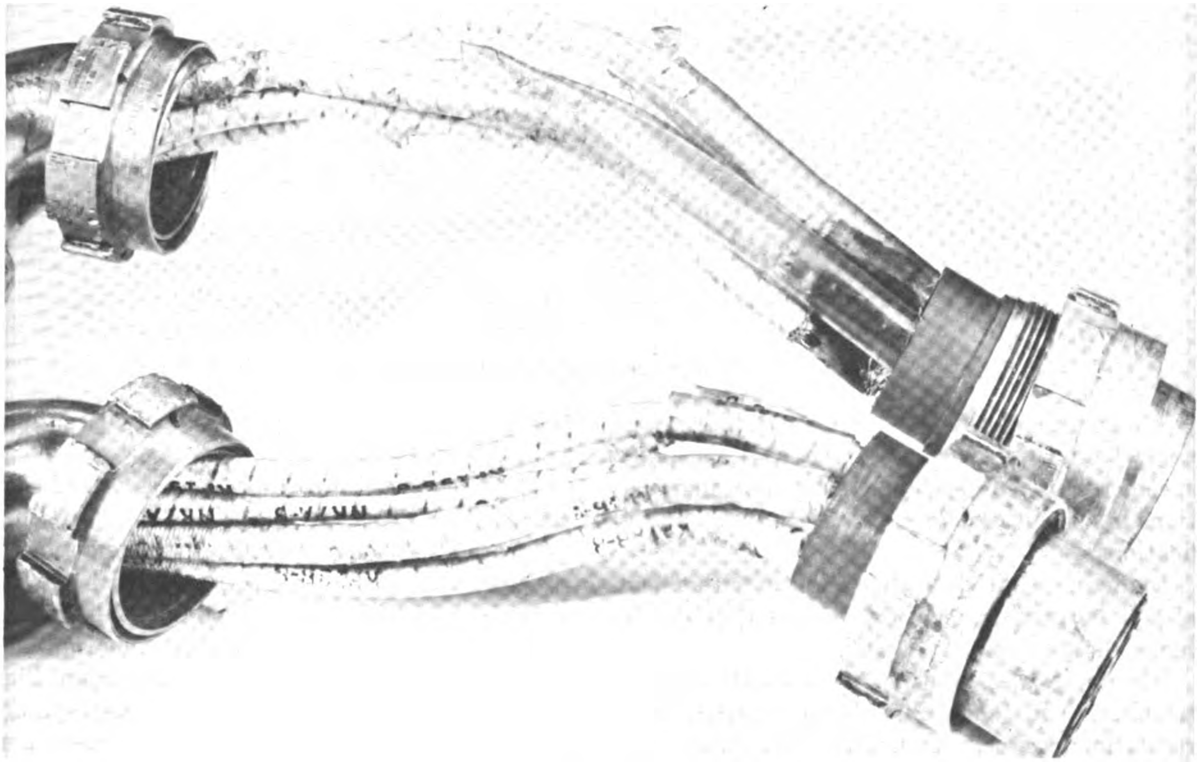

Figure 9.4.—Inadequate vinylite protection—B–50 control harness.

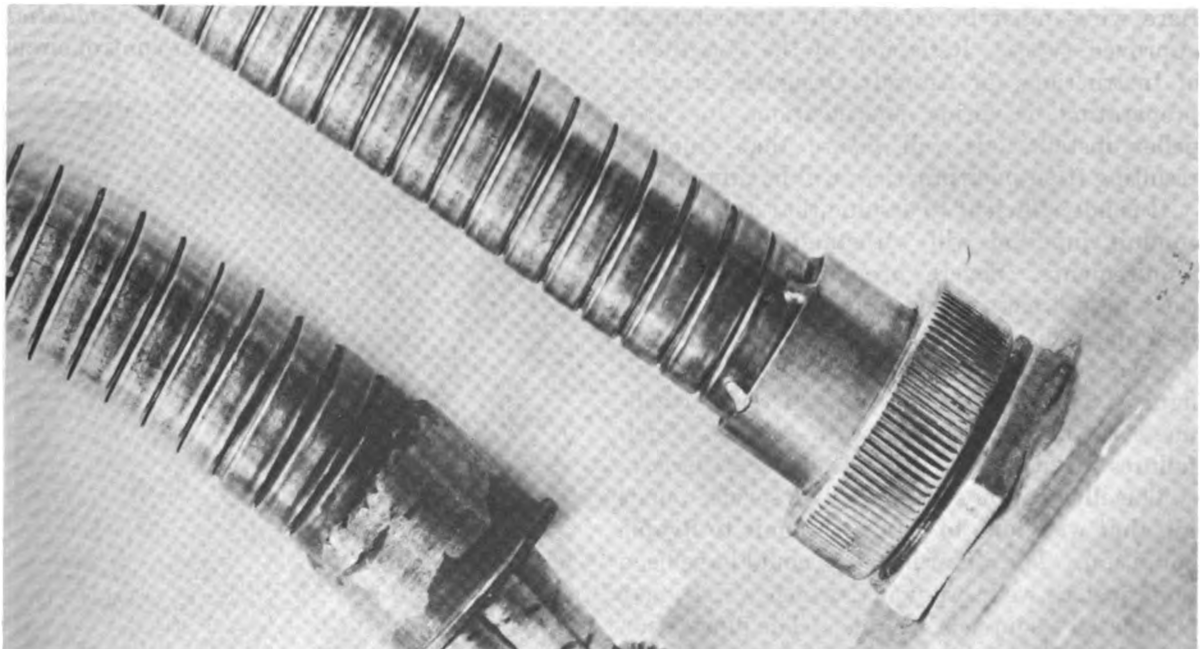

Figure 9.5.—Failure of spot welded ferrule attachment.

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Figure 9.6.—Broken electrical plug and chafed conduit.

All electrical wiring, switches, terminals, connectors and plugs must meet MIL-W-5088 specifications. Relays and relay box installations must conform to appropriate MIL specifications.

Inadequate vinylite protection at either end of a B-50 propeller control harness is shown in figure 9.4.

Electric cables or wires are critical items of installation in that failure for any reason may result in disaster. Therefore, wire sizes must conform to Air Force-Navy requirements and be installed in accordance with MIL-W-5088. Bare wires must be covered by protectors of approved types. Reference to the Handbook of Instructions for Aircraft Designers prior to preparation of wiring specifications for propeller installations will insure that troubles resulting from poor practices will be minimized.

It is not sufficient to assume that any ferrule-conduit junction will withstand rigid service requirements. Severe propeller-engine vibrations may break welded joints or loosen bolted fastenings unless carefully secured.

As a case in point, attention is directed to figure 9.5 in which a spot welded ferrule attachment is shown, that broke in service. Such failures mean increased maintenance at best.

This illustration shows the field service repair job that was done to return the unit to flyable condition. The repair initiated could have been done just as well, originally, which would have eliminated a source of trouble. The illustration points up the need to consider vibratory stress effects in auxiliary equipment, with original cost of production being a secondary consideration.

Another illustration of electric wiring failure is shown in figure 9.6. In this photograph of an electric head wire and conduit, a possible end product—an oil-soaked electrical lead—resulting from a broken plug and chafed conduit, is shown.

(4) *Cable seals at entrance to pressurized compartments.* Propeller cables or conduits that are routed through pressurized compartments of an airplane must be equipped with special purpose connectors or a device that will seal the opening in such a manner that *blow through*, with attendant blow torch effect, from high pressure region to low pressure space cannot occur. These sealing devices must meet performance requirements established in Specification MIL-C-5015.

(5) *An electric propeller conduit installation.* A typical installation of propeller control circuit

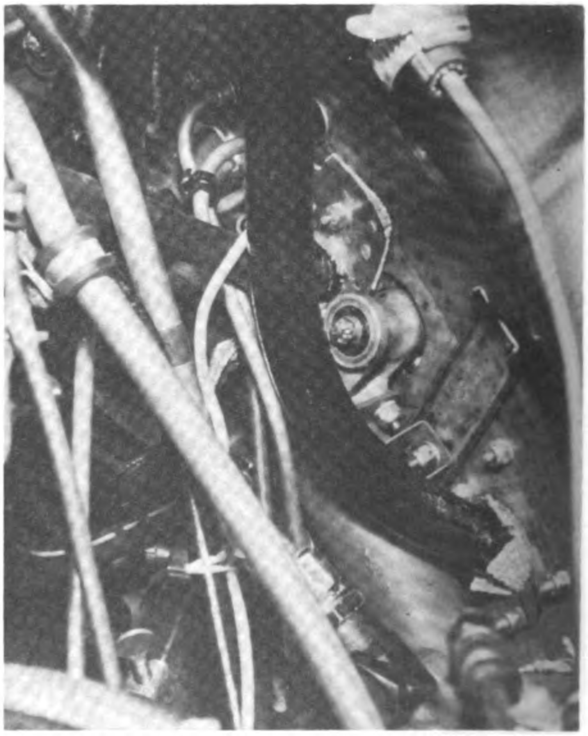

Figure 9.7.—Conduit fire wall passage.

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conduit at the point where it passes through the fire wall is shown in figure 9.7.

This installation was made on a C–54. The conduit furnishes protection to electrical leads passing through the fire wall, ultimately connecting with collector rings on the propeller.

(6) *Electrical circuit breakers.* (*a*) Applications. Circuit breakers of both non-trip free and trip free types may be used in conjunction with a propeller system.

In propeller system emergency circuits, i. e., feather, reverse or direct speed control, nontrip free, push-button type circuit breakers are incorporated. This type breaker is designed to protect electrical equipment and wiring in event that damage or system failure causes flow of excess current in a propeller circuit.

However, when necessary, circuit breakers may be overridden by force to close the circuit necessary for handling an emergency. Of course, when overridden, circuit breakers offer no protection to equipment or wiring.

(*b*) Nontrip Free Circuit Breakers.—Whenever current requirements exceeds 50 amperes, it is necessary to use two nontrip free type circuit breakers with a 5 ampere circuit breaker remotely controlling the large amperage propeller breakers. Normally, this remotely controlled breaker will be located in the engine nacelle, and may be controlled from the flight engineer's, pilot's, or co-pilot's position. Remote control circuit breakers usually are designed as thermal types with the closed position being maintained by flow of current through a holding coil during an emergency.

Under normal conditions, this circuit breaker may be reset after the fault has been cleared and the thermal disc has cooled; i. e., by closing the indicating and reset breaker, which will allow current to flow to the holding coil of the remote breaker.

However, this indicating breaker of the nontrip free type, usually located in the cockpit, will trip when released, if an overcurrent condition still exists. The overcurrent condition will maintain if the thermal disc has not cooled enough to return to its normal shape.

Nontrip free type breakers are being used in

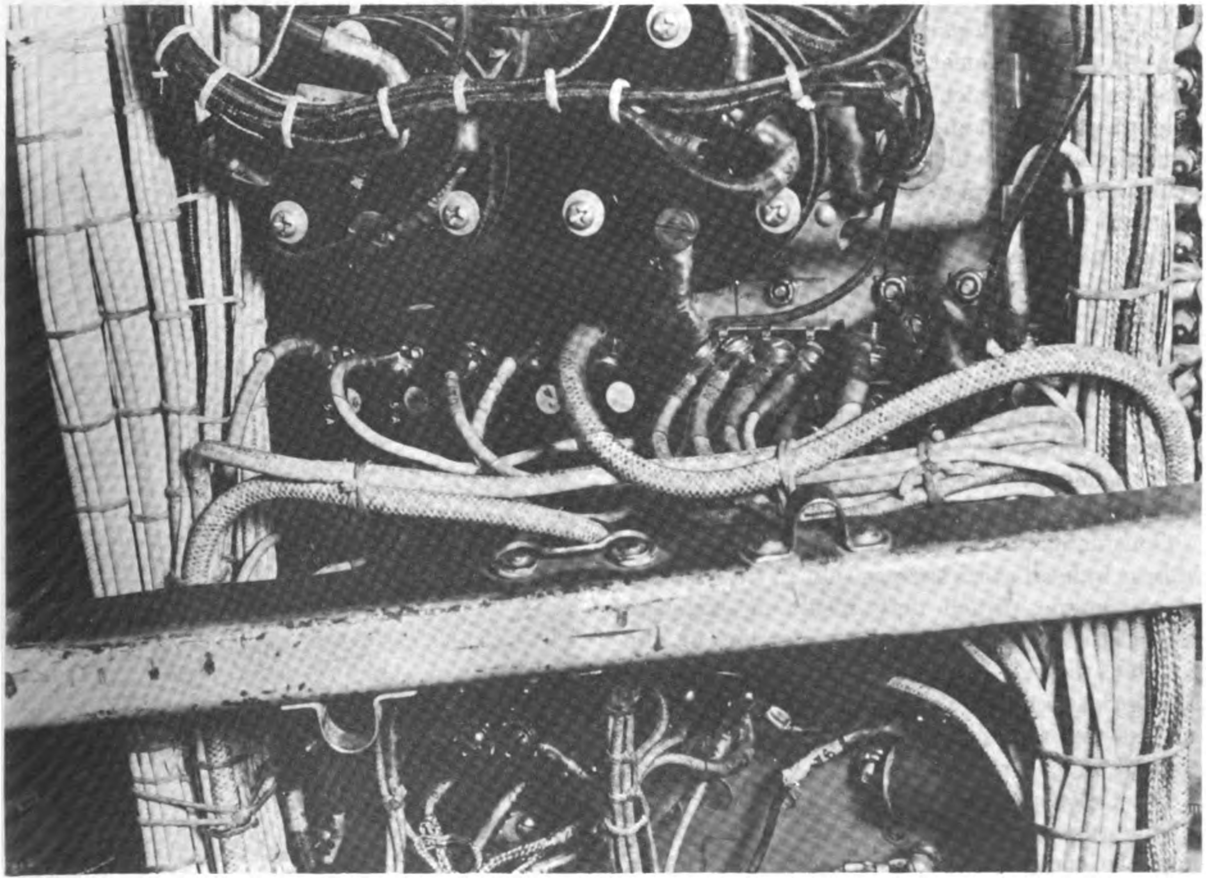

Figure 9.8.—C–54 auto pilot circuit with circuit breakers.

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emergency circuits for reciprocating and turbo-propeller installations and in synchronizer circuits for turbo-propeller installations. Circuit breaker protection has been deemed necessary in order to obtain propeller control under any operating condition that might develop during flight.

(c) Trip Free Circuit Breakers. Trip free type circuit breakers are used on propeller circuits not considered absolutely critical insofar as safety of flight is concerned. Typical circuits of this nature include indicating lights, deicing and synchronizer loops of reciprocating engine aircraft. This circuit breaker is a push-to-reset type. However, the breaker cannot be reset until the fault has been cleared and the thermal disc has cooled enough to return to its normal shape.

A typical circuit breaker wiring installation is shown in figure 9.8.

This photograph shows electrical wiring circuit for autopilot control with an approved circuit breaker installed.

Propeller Control System Installation

(1) *Mechanical linkage installation.* Installation of a mechanical linkage control system must be made in such a manner that objectionable creep or movement resulting from loads or system vibration will be avoided. Rigidity and deflection of control system parts as well as the ultimate strength of the system are of considerable importance.

Greater stability can be achieved through use of direct routing. Wherever control elements are routed through areas subject to appreciable deflection, such as wing sections for example, control system stability may be seriously affected, unless precautions are taken to minimize deflection effects upon propeller control components.

Consideration should be given to the effect of heat in local areas such as that in the vicinity of an engine, which may result in excessive temperatures in the adjacent portion of the control system. High temperature in a control linkage can cause excessive expansion of links with attendant seizing and complete loss of control of the propeller.

(2) *Cable type control system installation.* In a cable type control system, provision should be made to compensate for slack and lost motion caused by the effect of temperature changes. When mechanical tension regulators are used, they should be of a type that will maintain rigging tensions over the full range of temperatures expected. Cable guide tubes or fairleads should be used to reduce misalignment with pulleys and to prevent damage from chafing.

Fail safe washers should be used at all moving joints in a system employing rods and bell cranks. This is necessary in order to maintain partial control of the system in the event of failure of the flexible portion of the joint. Necessary precautions should be taken to limit bell crank motion sufficiently so that stopping on dead center position will not occur. Mechani-

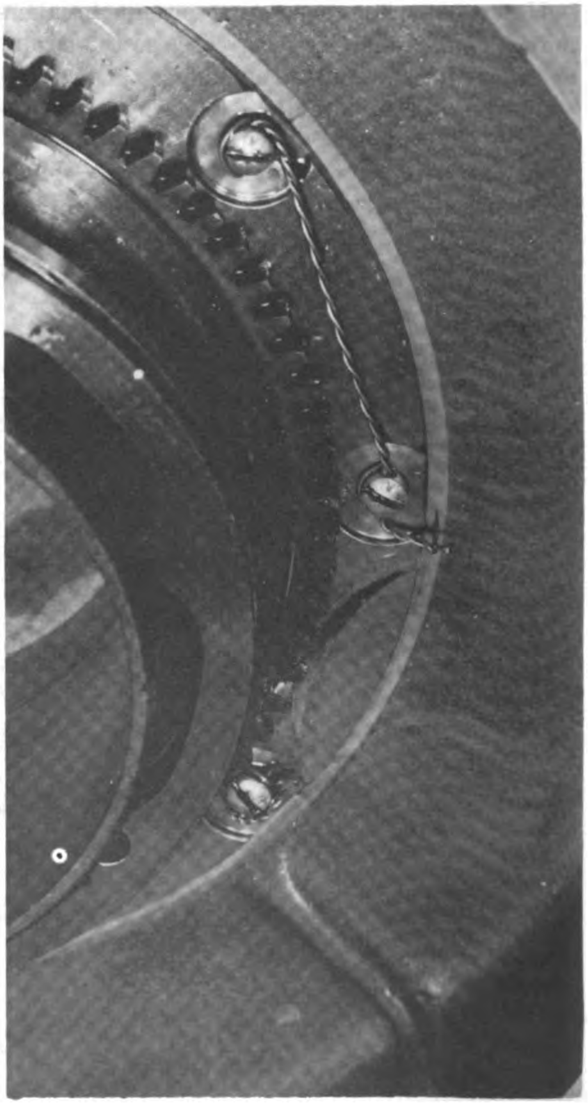

Figure 9.9.—Safety wire failure.

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cal stops should be used to limit the approach to critical positions.

Significance of failure to use proper safeguard to prevent loosening of fittings or joints is shown in figure 9.9 in which improper safety wire installation permitted bolt loosening.

Propeller Feathering Equipment Installation

(1) *Feathering tanks.* Independent feathering oil tanks are used in conjunction with hydromatic type propellers that utilize engine oil for operation to insure satisfactory feathering of the propeller during extremely low temperature (−65° F.) operation.

A separate or independent oil supply system for propeller feathering provides only one-way feathering fluid and is more commonly called an open loop hydraulic system. The oil tank for this system is usually mounted in the nacelle in a location such that, in normal flight attitude, there will be a positive head on the feathering pump.

Tank fluid capacity should be sufficient to cycle the system completely 1½ times (feathering-unfeathering-feathering) after the system has been filled with operating fluid.

The fill opening tank inlet should be provided with a screen or filter to prevent passage of foreign particles into the tank. Tank inlet should be located in a convenient position for easy servicing.

A suitable decal or identification must be placed on the tank, where it will be readily available for reference. The placard should include the following information:

(*a*) Total tank capacity.
(*b*) Type of fluid or mixture to be used.
(*c*) Applicable publication reference.
(*d*) Quantity or reference point to which tank will be filled.

Feathering tanks should be mounted, in the nacelle, in a location readily accessible for servicing. Tank mounting should not be subjected to excessive vibratory conditions.

(2) *Feathering pumps.* Feathering of most hydromatic type propellers is accomplished by introducing high pressure, auxiliary oil from an independent source or supply to the increase pitch side of an actuating mechanism. The feathering pump and motor comprise the actuating mechanism and produce the actuating force.

The capacity of a feathering pump must be such that it can produce adequate pressure together with sufficient oil flow to move the propeller blades to full feathered position with a minimum loss of time.

Feathering pumps are mounted in the engine nacelle generally. This pump location is chosen because the fluid used for propeller feathering, regardless of whether it be engine oil or a special fluid, is always available in or near the engine nacelle. Feathering pumps should be located close to fluid sources between propeller and supply or independent feathering tank. To provide maximum positive head, feathering pumps should be located below the independent feathering tank or source. Tanks should be located in such a manner that they can be easily removed for inspection and servicing.

When independent feathering tanks are used, a check valve should be installed in the feather-in-line, aft of the propeller governor, Which will prevent backflow of engine oil into the separate feathering oil reservoir.

(3) *Hydraulic feathering lines.* Hydraulic lines to and from propeller feathering pumps should be as short as possible and free from sharp bends or restrictions. The intake line from the tank to the pump, usually should be a length of flexible hose of a size sufficient to accommodate any flow necessary with negligible pressure drop. Since this hydraulic line will carry fluid at relatively low pressure, it need not be high pressure hose.

The pump output line to the governor must be made of high pressure hose or tubing. Stainless steel tubing may be used wherever the line is not subject to severe vibration. Drain hose from the pump may be fabricated from low pressure flexible hose or tubing.

Feathering Booster Installation

The voltage boosters should be located in a readily accessible place that will provide freedom from possible damage by operating personnel and other equipment. If the propeller control system is a remote control type with relays located in the nacelle, the voltage booster should be located close to the aircraft electrical control panel.

If the propeller control system is a standard type rather than the remote control type, boosters should be located on the flight deck close to the feather and reverse control mechanism.

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Boosters should be mounted in a horizontal position. A mounting bracket should be attached permanently to the voltage booster. Installation of a voltage booster may be accomplished by securing the complete assembly (booster and bracket) to the aircraft structure.

Synchronizer Installation

(1) *Synchronizer location.* Propeller synchronizer assemblies should be located in a protected area in order to be free from damage by operating personnel, movable cargo or other equipment. The synchronizer unit should be mounted as close to the synchronizer speed control mechanism as possible and in a readily accessible place. A location close to the synchronizer speed control mechanism is desired in order that the length of mechanical connectors between the two units will be as short as possible. Also, a readily accessible location is desirable for installation and maintenance purposes. Propeller synchronizer should be mounted in a horizontal position.

(2) *Mounting methods.* There are two methods presently used to install a synchronizer. The preferred method now being used in new aircraft is known as the rack assembly method. In this installation, a shock mounted rack assembly is secured to the aircraft structure. A synchronizer assembly is installed in the rack assembly by placing the synchronizer in drawers which slide into the rack assembly. A rack assembly should be shock mounted, to isolate the unit from vibration.

Another method of synchronizer mounting, used in many aircraft presently in service, involves use of a bracket assembly permanently attached to synchronizer assembly. The complete installation must be shock mounted and secured to the aircraft structure. The major advantage of rack assembly method over a bracket method is that the synchronizer assembly can be installed and removed more easily for periodic adjustments and maintenance.

(3) *Vibration tolerance.* The synchronizer must be mounted to insure vibration free operation for relay sensitivity protection and to prevent damage to other components of the assembly.

(4) *Synchronizer mechanical controls.* The types of mechanical connectors used between synchronizer and speed setting mechanism are:

(*a*) Pulley and cable system.
(*b*) Teleflex system.
(*c*) Flexible shaft system.
(*d*) Combinations of systems.

Routing of the mechanical connectors should be in accordance with good practices to assure that mechanical friction will be minimized. Sharp bends should be avoided and the overall length of the system should be as short as possible.

The control system should be protected from possible damage by personnel or equipment. The synchronizer system must be adjusted so that master motor speed will be set at takeoff speed when the synchronizer speed control mechanism (lever or knob) has been placed in the most advanced position (increase speed).

Automatic Feathering Equipment

Operating Characteristics

It should be noted that automatic feathering, as applied to reciprocating engines, is required and designed for use only during takeoff, when immediate feathering of a failed engine is of prime importance, and human delays or mistakes in diagnosing a power loss can be fatal. The propeller auto-feather system automatically feathers the propeller of an engine in event of failure after takeoff power has been applied. The system operates by automatically causing an appropriate manual feathering button to be magnetically drawn in to feathering position if engine torque pressure falls to 40 p. s. i. or below after the throttles have been advanced beyond a position corresponding to 45 inches Hg manifold pressure. The system is powered by direct current through an auto-feather switch, a torque pressure switch at each engine, and microswitches in the pedestal quadrant that close as throttles are advanced. If torque pressure at one of the engines later falls, due to failure, or, if in some airplanes, power is reduced with the throttle, the torque pressure switch will close and connect direct current to a solenoid and holding coil at the corresponding manual feathering button. The feathering button will be drawn in and the propeller will automatically feather. A green indicator light shows when the auto-feather switch is turned to ON position and remains lighted until the propeller has been automatically or manually feathered, or until the auto feather switch has been moved to OFF, as is normally done after

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power has been reduced, following initial climb. The system will not feather a second propeller if one propeller has already been feathered either automatically or manually. A test system is provided for testing auto-feather operation prior to takeoff.

The autofeather system is provided for use during takeoff only. The system is armed by turning the autofeather switch to ON just before takeoff. If torque pressure drops to 40 p. s. i. or less after the power has once been advanced beyond 70 p. s. i. torque pressure on some airplanes, or 45 p. s. i. torque pressure on most airplanes, and beyond 45 inches Hg manifold pressure, the controlled propeller will be feathered automatically. One autofeathering operation disarms the system to prevent inadvertent autofeathering of another propeller in event of a power reduction below 40 p. s. i. torque pressure. Manual feathering of a propeller also disarms the autofeather system.

In addition, a time delay mechanism is placed between the torque sensing device and the autofeather relay which prevents automatic feathering as a result of momentary power loss, such as that caused by engine back-fire.

Propeller Reversing System Installation

Standard design practice in the post World War II era has involved employment of a reverse sense throttle for use with reversing propellers. In conjunction with such throttles, various methods of triggering the propeller to go into reverse pitch have been employed.

A basic requirement of reverse pitch controls is that initial movement of the throttle into reverse pitch range must close one or more switches that initiate propeller reversal.

The recommended practice, which is universally followed in existing reverse sense throttle installations, requires use of two switches in series to insure against inadvertent reversal resulting from single switch failure.

These switches can be mounted inside the pedestal and actuated directly by a throttle component, such as a cam lobe on the throttle pulley wheel. Switches can be remotely located and actuated by a mechanical linkage from the throttles. Neither system possesses any significant advantage, the choice being determined by such design factors as space and accessibility.

When remotely actuated switches are used, they are inclosed in a box, normally known as a reversing control box, with one or more relays in the circuit energized by the switches. This assembly is designed for unit replacement. The only adjustments permitted by field maintenance personnel should be adjustment of the remote linkages.

When directly actuated switches are used, adjustment of the actuation point may be accomplished by moving the switch and/or actuating member. Actuating switches are singly replaceable, with wiring to the switch being disconnected wire by wire, instead of by use of a cannon plug connector. In conjunction with reverse sense throttles, past practice has been to provide a lock-out arrangement that will prevent throttle movement into the reverse sector until aircraft weight is supported by the landing gear.

Reverse pitch lock-out has been accomplished by a switch, mounted on or near one or more landing gear oleo struts which is actuated by closing of a strut. The electrical signal conceived actuates (through suitable relays) a blocking mechanism in the pedestal. The blocking mechanism is provided also with a manual override for emergency use.

Such reverse pitch control designs are subject to many kinds of invisible failures that usually result in a false electrical actuation or failure to actuate. In this regard, the importance of adequate electrical hardware is obvious. Malfunctions of this type of system also have been due to interaction between the throttle lock circuit and other circuits which utilize the same landing gear switch.

Propeller Installation Standards

Cockpit Installation—Hydraulic Requirements

(1) *Location for accessibility and adjustment.* (*a*) Provisions will be made in the location of hydraulic equipment for accessibility for adjustment, repair testing, and/or removal.

(*b*) Equipment will be so located that it can be removed without disturbing other equipment, lines running to other equipment or attaching lines.

(2) *Mounting provisions for equipment.* (*a*) Hydraulic equipment will be mounted in a location where it will not be subjected to extreme cold or heat (+160 to −65).

(*b*) Hydraulic equipment will be mounted in such a manner that it cannot conduct or radiate heat to adjacent equipment thereby affecting operation of adjacent equipment.

(*c*) Hydraulic equipment will be mounted in such a manner that excessive vibration cannot be transmitted to connecting lines and in turn cause failures.

(*d*) Hydraulic equipment shall not be mounted in such a manner that excessive stress will be imposed upon it by connecting lines.

(3) *Instrumentation problems.* (*a*) Pressure gages shall not be of a type that require high pressure lines in the cockpit area.

(*b*) Adequate lighting shall be provided to illuminate the face of pressure or flow gates located in the cockpit.

(*c*) Hydraulic gages, when used, must meet the standards required by the committee of cockpit standardization as to size and location.

(*d*) Lights will not be used on cockpit panels to indicate pressure or flow.

(*e*) Hydraulic equipment will not be mounted in areas where vibration frequency is known to be excessive.

(4) *Installation and support of hydraulic lines.* (*a*) High pressure hydraulic lines will not be run in the cockpit area.

(*b*) All hydraulic lines installed in the cockpit area will be designed for minimum length.

(*c*) Individual lines and fittings will meet MIL standard as to size and capacity as required by Specification MIL–H–5440.

(*d*) Each individual hydraulic line will be supported in accordance with Specification MIL–H–5440, Section 3.8.31.9.

(*e*) Each support point shall consist of a rubber grommet fastened to the line by a clamp (see Dwg AN 742, Type C).

(*f*) When hydraulic lines are run through bulkheads or ribs they shall be protected by rubber or fiber grommets (no metal-to-metal contact).

(5) *Protection of equipment.* (*a*) Hydraulic equipment and lines will be placed so that normal work movement and travel of aircraft crew members will not subject equipment to damage.

(*b*) Hydraulic circuits will be provided with high pressure relief valves located in accessible places for easy adjustment by crew members during flight.

(*c*) High pressure relief valves will be vented to atmosphere only; return lines for high pressure valves will not terminate in the cockpit area.

(6) *Use of special tools and locking devices.* (*a*) Adjustment of hydraulic equipment shall not require use of special tools.

- (*i*) Allen type wrenches, sockets, screwdrivers, and open end wrenches, are considered standard tools.

(*b*) Adjustment locking for hydraulic equipment shall be of the type that can be accomplished with standard tools.

- (*i*) Allen type wrenches, sockets, screwdrivers, and open end wrenches, are considered standard tools.

Cockpit Installation—Electrical Requirements

(1) *Location for accessibility and adjustment.* (*a*) Electrical equipment will be located for ready accessibility to permit adjustment, repair, testing and/or removal.

(*b*) Equipment will be so located that it can be removed without disturbing other equipment, lines servicing other equipment, or attaching lines.

(*c*) When circuit breakers are used for circuit protection they shall be located in a position accessible to crew members in flight.

(2) *Mounting provisions.* (*a*) Electrical equipment will be mounted in a location where it will not be subjected to extreme cold or heat, (−65° F. to +160° F.).

(*b*) Electrical equipment will be mounted in such a manner that it cannot conduct or radiate heat to adjacent equipment.

(*c*) Electrical equipment will be mounted in such a manner that excessive vibration cannot be transmitted to connecting lines which might cause failures.

(*d*) Electrical equipment shall not be mounted in such a manner that it receives excessive stress imposed upon it from connecting lines.

(*e*) Electric equipment shall be mounted or shielded in such a manner that no radio interference will result, within limits established in MIL–I–6722.

(*f*) Shock mounting shall be provided for equipment operation of which would be jeopardized by vibration or shock.

(3) *Electrical equipment shall meet MIL specification.* (*a*) All electrical equipment must meet MIL specifications, if physically possible.

(*b*) Electrical wiring, switches, terminals, con-

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nectors and plugs shall meet Specification MIL–W–5088. Relays and relay boxes shall meet the required MIL specifications. MIL–E–5272, MIL–R–6106 and MIL–E–7563.

(4) *Electrical wire installation requirements.* (*a*) High amp. lines will not be placed in the cockpit area.

(*b*) Lightly insulated high-tension or radio wires should clear all parts normally at ground potential by at least ¾ inch.

(*c*) Reversing and feathering circuit control wires shall be isolated from other hot leads.

(*d*) All wiring should be properly identified.

(5) *Instrumentation installations.* (*a*) Electrical gages and meters when used must meet the standards established by the Committee of Cockpit Standardization, as to size and location.

(*b*) Adequate lighting shall be provided to illuminate the faces of cockpit gages or meters.

(*c*) Indicator lights will not be used for indication of propeller operation at the pilot's or copilot's station. (Use of lights at flight engineer's station is subject to approval by the procuring agency).

(6) *Protection of equipment.* (*a*) Electrical equipment and lines will be placed so that normal work movement and travel of aircraft crew members will not inflict equipment damage.

(*b*) Where circuit breakers are used they shall be of the non-trip free type.

(*c*) Circuit protection shall not be accomplished by fuses.

Cockpit Installation—Mechanical Requirements

(1) *Location for accessibility and adjustment.* (*a*) Accessible location of mechanical equipment must be established to permit adjustment, repair, testing, and/or removal.

(*b*) Equipment will be so located that it can be removed without disturbing other equipment, lines running to other equipment, or attaching lines.

(*c*) Clearances in all primary parts of mechanisms should be kept to a minimum so that lost motion or play will be practically eliminated.

(2) *Mounting provisions.* (*a*) Mechanical equipment shall not be mounted in a location where it shall be subjected to extreme cold or heat (−65° to + 160° F.).

(*b*) Mechanical equipment shall not be riveted or installed permanently in place.

(*c*) Equipment shall be mounted in a location where it will be free of vibration or shock loading.

(3) *Linkage and connector requirements.* (*a*) Standard MIL connectors and linkages shall be used in conjunction with mechanical equipment and control systems.

(*b*) Total backlash in a mechanical system shall be held to an absolute minimum.

(*c*) The total number of joints or connections shall be held to a minimum to maintain the highest possible overall system efficiency.

(4) *Protection of equipment.* (*a*) Mechanical equipment shall be located with adequate space for elimination of interference problems with other equipment, controls, and lines.

(*b*) Mechanical equipment, controls and connecting linkages will be placed so that normal work movement and travel of aircraft crew members will not subject equipment to damage.

Airframe Installation—Hydraulic Requirements

(1) *Location for accessibility and adjustment.* (*a*) Hydraulic equipment or lines will be so located that they can be easily removed without disturbing other equipment.

(*b*) Equipment will be so located that it is accessible for adjustment, repair, testing and/or removal.

(2) *Mounting requirements.* (*a*) Hydraulic equipment will be mounted in a location where it will not be subjected to extreme heat or cold (160 to −65° F.).

(*b*) Equipment will not be mounted where it is subject to excessive vibration or shock.

(*c*) Hydraulic equipment will not be supported by connecting lines only.

(*d*) Hydraulic equipment will not be permanently mounted on the airframe structural members.

(*e*) Equipment will be mounted in such a manner that excessive vibration cannot be transmitted to connecting lines, that might cause failures.

(*f*) Hydraulic equipment shall not be mounted in such a manner that excessive stress will be imposed upon it by connecting lines.

(*g*) Installation of hydraulic equipment shall meet the requirements of Specification MIL–H–5440.

(3) *Installation and support of hydraulic lines.* (*a*) All hydraulic lines will be designed for minimum length.

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(*b*) Hydraulic line connection must meet HIAD requirements as listed in section 10.21, PP 10–3.

(*c*) Individual hydraulic lines and fittings shall meet MIL Standard Specifications as to size, capacity, and vendor as required by Specification MIL–H–5440.

(*d*) Each individual hydraulic line will be supported in accordance with Specification MIL–H–5440, Section 3.8.31.9.

(*e*) Each support point shall consist of a rubber grommet fastened to the line by a clamp (see Drawing AN 742 Type C).

(*f*) When hydraulic lines extend through bulkheads, ribs, or structural members, they shall be protected by rubber or fiber grommets. (No metal to metal contact.)

(*g*) Hydraulic lines shall be placed with adequate clearance, to prevent chafing with other lines, or equipment, under vibration conditions extant in the aircraft.

(*h*) The use of flexible hydraulic lines in the airframe shall be prohibited.

(*i*) Hydraulic lines shall not be run in areas subjected to extreme cold or heat (−65° to 160° F.).

(4) *Protection of equipment.* (*a*) Hydraulic circuits will be provided with high pressure relief valves located in accessible places for easy adjustment by aircraft crew members in flight.

(*b*) Hydraluic equipment and lines will be placed so that normal work movement and travel of aircraft crew members will not inflict equipment damage.

(*c*) High pressure relief valves will be vented to atmosphere only.

(5) *Tool requirements.* (*a*) Special tools shall conform to the requirements of Specification MIL–D–8512.

(*b*) If possible, adjustment of hydraulic equipment shall not require use of special tools.

(*c*) Adjustment locking shall be of a type that can be accomplished with standard tools.

Airframe Installation—Electrical Requirements

(1) *Location for accessibility and adjustment.* (*a*) Location of electrical equipment in accessible places will be made to permit adjustment, repair, testing, and/or removal.

(*b*) Equipment will be located to permit removal without disturbing other equipment or attaching lines.

(*c*) When circuit breakers are used, for circuit protection, they shall be located in places accessible to crew members in flight.

(2) *Mounting requirements.* (*a*) Electrical equipment will be mounted in a location where it will not be subjected to extreme cold or heat (−65° to +160° F.).

(*b*) Electrical equipment will be mounted in such a manner that it cannot conduct or radiate heat to adjacent equipment.

(*c*) Electrical equipment will be mounted in such a manner that excessive vibration cannot be transmitted to connecting lines.

(*d*) Electrical equipment shall not be mounted in such a manner that stress will be imposed upon it by connecting lines.

(*e*) Electrical equipment shall be mounted or shielded in such a manner that radio interference will not result from its use, within limits established by MIL–I–6722.

(*f*) Shock mounting shall be provided for equipment whose operation would be jeopardized by vibration or shock.

(3) *Electrical Equipment Shall Meet MIL Specification.* (a) All electrical equipment, if at all possible, shall meet MIL Specifications.

(*b*) Electrical wiring, switches, terminals, connectors and plugs shall meet Specification MIL–W–5088. Relays and relay boxes shall meet MIL–E–5272, MIL–R–6106, and MIL–E–7563.

(4) *Electrical wire installation requirements.* (*a*) The reversing and feathering circuit control wires shall be isolated from other hot leads.

(*b*) All wiring shall be properly identified.

(5) *Protection of equipment.* (*a*) Electrical equipment and lines will be placed so that normal work movement and travel of aircraft crew members will not subject equipment to damage.

(*b*) When circuit breakers are used, they shall be of the non-trip free type.

(*c*) Circuit protection shall not be accomplished by fuses.

Airframe Installation—Mechanical Requirements

(1) *Location for accessibility and adjustment.* (*a*) Mechanical equipment must be located in accessible places to permit adjustment, repair, testing, and/or removal.

(*b*) Equipment will be so located that it can be removed without disturbing other equipment or attaching lines.

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(2) *Mounting provisions.* (*a*) Mechanical equipment shall not be riveted or installed permanently in place.

(*b*) Mechanical equipment shall not be mounted in a location subject to extreme cold or heat (−65° to +160 F).

(*c*) Equipment will be located where it will be free of vibration or shock loading.

(3) *Linkage and connector requirements.* (*a*) Standard MIL connectors and linkages shall be used in conjunction with mechanical equipment and control systems.

(*b*) Total backlash in a mechanical system shall be held to an absolute minimum.

(*c*) The total number of joints or connections shall be held to a minimum to maintain the highest possible overall system efficiency.

(4) *Protection of equipment.* (*a*) Mechanical equipment, controls, and connecting linkages will be placed so that normal work movement and travel of aircraft crew members will not subject equipment to damage.

(*b*) Mechanical equipment shall be located so that adequate space is available to circumvent interference problems with other equipment, controls, and lines.

Engine Nacelle Installation—Hydraulic Requirements

(1) *Location for accessibility and adjustments.* (*a*) Auxiliary hydraulic equipment or lines will be so located that they can be easily removed without disturbing other equipment or lines.

(*b*) Hydraulic equipment will be located so that it is accessible for repair, test, adjustment, and/or removal.

(2) *Mounting requirements.* (*a*) Hydraulic equipment will not be mounted where it will be subject to extreme heat (above 160° F).

(*b*) Hydraulic equipment will not be mounted where it will be subject to excessive vibration or shock.

(*c*) Hydraulic equipment will not be supported by connecting lines only.

(*d*) Hydraulic equipment will not be permanently mounted on airframe or engine structural members.

(*e*) Hydraulic equipment will be mounted in such a manner that excessive vibration cannot be transmitted to connecting lines.

(*f*) Hydraulic equipment shall not be mounted so it receives excessive loads from connecting lines.

(*g*) Hydraulic equipment will be mounted in a manner that does not require alteration of engine parts.

(3) *Installation and support of hydraulic lines.* (*a*) All hydraulic lines will be designed for minimum length.

(*b*) Individual lines and fittings will meet MIL standard specifications as to size, capacity, and vendor as required by Specification MIL–H–6000.

(*c*) Each individual hydraulic line will be supported in accordance with Specification MIL–H–5440.

(*d*) Each support point shall consist of a rubber grommet fastened to the line by a clamp (see Drawing AN 742 Type C).

(*e*) When hydraulic lines extend through bulkheads, ribs, or structural members, they shall be protected by rubber or fiber grommets. (No metal-to-metal contact.)

(*f*) Lines shall be placed with adequate clearance to prevent chaffing from other lines, equipment, or power plant under vibratory conditions established during aircraft operation.

(*g*) Hydraulic lines will not extend into spaces where they will be subjected to heat in excess of 160° F.

(*h*) The use of flexible lines will be held to an absolute minimum.

(4) *Protection of equipment.* (*a*) An effort shall be put forth in the placement of hydraulic equipment, in the engine area, to so position the equipment so that it does not offer a convenient step for maintenance crew members.

(*b*) Hydraulic circuits will be provided with high pressure relief valves located in accessible places for easy adjustment by crew members.

(5) *Tool requirements.* (*a*) Special tools shall conform to the requirements of Specification MIL–D–8512.

(*b*) Whenever possible, adjustment of hydraulic equipment shall not require use of special tools.

(*c*) Adjustments locking shall be of a type that can be accomplished with standard tools.

Engine Nacelle Installation—Electrical Requirements

(1) *Location for accessibility and adjustment.* (*a*) Location of electrical equipment must provide accessibility for adjustment, repair, testing and for removal.

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(*b*) Equipment will be located so that it can be removed without disturbing other equipment or attaching lines.

(2) *Mounting provisions.* (*a*) Electrical equipment will be mounted in a location where it will not be subjected to extreme heat (+160° F).

(*b*) Electrical equipment will be mounted in a location where it will not be subjected to excessive vibration.

(*c*) Shock mounting shall be provided for equipment whose operation would be jeopardized by vibration or shock.

(*d*) Electrical equipment shall be mounted or shielded in such a manner that radio interference will not result from its use, within limits set up in Specification MIL–I–6722.

(3) *Electrical equipment shall meet MIL specification.* (*a*) All electrical equipment, where possible, shall meet MIL specifications.

(*b*) Terminals, connectors and plugs shall meet Specification MIL–W–5088. Relays and relay boxes shall meet the required MIL Specifications, MIL–E–5272, MIL–R–6106, or MIL–E–7563.

(4) *Electrical wire installation requirements.* (*a*) All wiring shall be properly identified.

(*b*) Feathering and reversing circuit control wires shall be isolated from other hot leads.

(*c*) Control harnesses—propeller control, alternator or governor and ice control system harnesses furnished by or recommended by a propeller contractor must be approved by the procuring agency for a specific installation. A harness will consist of separate stainless steel flexible conduit, with steel ferrules properly brazed or welded thereon. The cable shall be of high temperature type, and shall be protected by high temperature resistant material, such as asbestos sleeving, with additional abrasion protective covering required at sharp bends and cable bundle ends (vinyl tubing perforated every 6 in.). Propeller circuit conduit will be disconnected only at the firewall, the same as alternator and deicing harnesses. Electrical control harnesses must withstand a temperature of 2000° F. for five minutes.

Connectors shall be fire-resistant and moisture-proof.

(5) *Protection of Equipment.* (*a*) Electrical equipment will be placed so that it will not be endangered by normal work movement of maintenance crews.

(*b*) Non-trip free circuit breaker protection for electrical circuits will be provided. Circuit breakers will not be located forward of the firewall.

(*c*) Circuit protection shall not be accomplished by the use of the firewall.

Engine Nacelle Installation—Mechanical Requirements

(1) *Location for Accessibility and Adjustment.* (*a*) Mechanical equipment must be located in accessible places to facilitate adjustment, repair, testing, and/or removal.

(*b*) Equipment will be located so that it can be removed without disturbing other equipment or attaching lines.

(2) *Mounting requirements.* (*a*) Mechanical equipment shall not be riveted or installed permanently in place.

(*b*) Propeller spinners shall meet the requirements of Specification MIL–P–5450.

(3) *Linkage and connector requirements.* (*a*) Standard MIL connectors and linkages shall be used in conjunction with mechanical equipment and control systems.

(*b*) Total backlash in a mechanical system shall be held to an absolute minimum.

(*c*) Total number of joints or connections shall be held to a minimum so that highest possible overall system efficiency will obtain.

(4) *Protection of equipment.* (*a*) Mechanical equipment shall be located with adequate space to circumvent interference problems with other equipment controls and lines.

Electric Relay Installation

A propeller relay, energized by a low current passing through heavy duty governor contacts, must carry the current required to run the propeller-pitch-change-motor. The relay assembly includes a relay-base and relay-box subassemblies.

The relay should not be located at any point in the aircraft in which ambient temperature is greater than 190° F. If absolutely necessary, the relay may be located in a place having an ambient temperature in excess of 190° F. if an air blast is provided to keep relay temperature to a point below 190° F. Propeller relays should be mounted aft and away from the engine fire wall to give protection from extreme heat should a fire develop.

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If the relay is mounted upon engine-mount structural members, baffles, or other places subject to excessive vibration, a shock absorbing mount must be furnished for relay installation.

Drain holes should be drilled in the corners of relay boxes to provide an outlet for water or other fluids that might collect in the relay box.

A low resistance grounding strap must be provided to accomodate grounds for both electric motor and filtering units. This strap should have a current carrying capacity of 30–50 amperes, minimum.

Installation drawings and specifications for relays may be obtained from appropriate technical orders, HIAD or propeller manufacturer for any particular installation.

Electric System Filter Installation

The static charge potential generated by propeller rotation may be lowered by installation of a bond across propeller shaft bearings which will also serve as a ground for the structure that shields the electric pitch change mechanism. Some such installation is necessary to reduce electrical interference.

Synchronizer installations utilize filter units placed in engine nacelles and master unit or within the principal synchronizer assembly. Nacelle filters should be located aft of and off of the engine fire wall in locations that are not subjected to extreme heat (190° F. ambient maximum). Nacelle filters should not be mounted on engine structural mounts, since excessive vibration may induce filter failure.

Resistance between filter box and airframe should not exceed .004 ohms, normally. Terminals with pre-insulated shanks should be used for wire termination on screw studs.

Master unit filter should be located conveniently close to synchronizer master unit in pressurized compartment of high altitude aircraft on vibration free mounts. Wiring between master unit and connector plugs must be shielded, completely. Conduits should be removable for testing purposes.

In remote control systems, filter components are incorporated into synchronizer assemblies, lead shielding being unnecessary. Filtering of normal voltage pitch change current usually is accomplished within the engine nacelle relay assembly.

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CHAPTER X. PROPELLER TESTING

General Characteristics of Propeller Testing

Test Justification

New propeller designs must be subjected to close scrutiny and tested mathematically by known theoretical and empirical relationships before final fabrication is undertaken. However, complexity of modern propeller design with numerous variables makes it impossible to evaluate propeller structural and functional capabilities, completely, by rational analytical methods. Improvements in processes and techniques of propeller development have eliminated many unknowns but each new design or application introduces new problems which cannot be analyzed mathematically. Furthermore, the demand for optimum performance at very high speeds has made it necessary to introduce unusual configurations of propeller components along with a reduction in the ratio, design stress/ultimate stress. Therefore, adequate testing of propellers and propeller components has become absolutely necessary to insure safety, efficiency and reliability.

Testing procedure for conventional propellers has been fairly well established, but it may be desirable to deviate from the normal type test in order to facilitate propeller or component development. Functional tests may be accomplished prior to structural tests if that be desirable to promote most effective use of limited test equipment. It may be desirable to test propeller components for known or anticipated weaknesses early in the development schedule in order to minimize overall time delays. Expeditious accomplishment of tests as well as early scheduling will insure introduction of corrective action whenever necessary to produce an acceptable propeller. In addition, to insure functional design with propeller airworthiness, testing procedures and equipment must be evolved that will eliminate possible damage to equipment and personnel to the greatest possible extent.

Types of Propeller Tests

Complete propellers must be tested to establish structural suitability for anticipated application. Whirl tests and vibration tests have been devised that will provide reliable structural data. Special test stands have been designed to conduct whirl testing on the ground, where possible propeller failure will not inflict extensive damage. Vibration testing procedures have been developed that will permit further propeller structural evaluation either in special test stands or in airplanes on the ground or in aerial flights.

A final evaluation, performance test, must be made to establish flying characteristics of a propeller. Normally, the first phase of performance testing will be accomplished in wind tunnels. Upon satisfactory completion of wind tunnel tests, the complete propeller must be given a performance test in aerial flight.

Objectives of Whirl Tests

It has been recognized that laboratory propeller testing can never be truly representative of service conditions. Accepting this basic fact, two pertinent questions of intent assume importance, namely:

(1) What is the purpose of propeller testing?

(2) What is the basis of determination of appropriate tests?

In a general way, the objective of laboratory testing is to provide satisfactory propellers for aircraft service use. But this generalization immediately poses the question: "What is a satisfactory service propeller?" Recognition of a satisfactory service propeller is not easy because of special conditions which frequently are imposed. For example, a satisfactory propeller must have optimum performance characteristics that are compatible with specific limitations of application. Propeller weight must be a minimum yet the propeller must be safe, durable, reliable and so constructed as to promulgate simplified maintenance. It is quite evident that the answer to the question, "What is a satisfactory service propeller?", will not be forthcoming from laboratory testing alone. An extensive record of a fair number of propellers of a given type must be accrued before a reason-

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able accurate evaluation of service characteristics can be made.

Specifically, whirl testing of propellers has become a necessity to reveal structural weaknesses, if any exist, prior to actual aircraft installation and flight. Whirl testing may be accomplished on test stands of stationary test cells in which the propeller is driven by electric motor or internal combustion engines. In the whirl rigs, propellers may be subjected to power loading and operating speeds far in excess of those for which designed. During such tests the propeller may be calibrated for power and thrust at given rotational speeds. In addition, blade deflections may be established and, of course, structural capacity evaluated. Since electric motor torque application is smooth, propeller force variation must be of aerodynamic origin. Propeller vibrations simulating those encountered in flight may be produced in the test stands by introducing controlled aerodynamic excitations.

Limitations of Whirl Tests

In spite of the fact that it is impractical to duplicate service conditions in a laboratory, the tests devised for laboratory use have contributed greatly to elimination of unserviceable propellers. Usually, only new propellers of selected material and fabrication quality are subjected to type tests. Whirl testing has made it possible to subject new propellers to abuse that will insure safety in flight even after a great number of service hours.

To what extent do laboratory propeller tests reflect service life? An exact answer to that question cannot be provided but an insight to the possibilities is contained in a tabulation of factors affecting service life that are not revealed in the results of laboratory testing. The following factors may adversely affect propeller service life:

(1) Material quality deterioration with time caused by corrosion, erosion, galling, friction oxidation and rot.
(2) Non-compatibility of laboratory simulated and actual flight conditions of propeller operation.
(3) Effects of inadequate servicing.
(4) Variations between laboratory test and production line propellers.
(5) Effect of cumulative vibration stress-cycle history of previous service.
(6) Effects of heavy vibratory stresses that may occur during all ground operations and flight regimes.
(7) Damaging effects of propeller operation during marginal conditions.

Occasionally, propellers having extensive service records must be subjected to laboratory tests in order to establish validity of existing test procedures or to formulate new methods of test. A background of service and laboratory testing experience can be invaluable in identifying propeller features that will not perform under service conditions, even though proven adequate in laboratory tests. This inadequacy of laboratory testing is reflected in the Type Test Specification by inclusion of an escape clause, which effectively permits propeller rejection on the grounds, "In the opinion of the procuring agency, the propeller is unsafe for flying," even though all laboratory tests have been acceptable.

Basis of Determination of Appropriate Propeller Tests

A general basis for establishing appropriate propeller tests to evaluate performance under all operating conditions has not been found. But certain phases of testing have been devised to reflect specific propeller characteristics. For example, propeller ultimate strength can be determined from overspeed and overload tests. Vibration tests, simulating flight vibration conditions, may be conducted to determine propeller resistance to fatigue failure, if flight conditions have been established. Flight vibration surveys have been set up as a part of recognized test procedures for the express purpose of acquiring data under actual flying conditions. To insure a margin of safety, in excess of normal service requirements, propellers should be tested under conditions of speed, load and vibration conditions more severe than actual service conditions anticipated. Functional design can be adjudged during performance testing.

Formulation of reasonable laboratory propeller tests must be based upon experience of previous laboratory performance testing and in-service use. In fact, propeller testing procedures must be developed simultaneously with propeller evolution and utilization. Validity of application of existing test procedures to new

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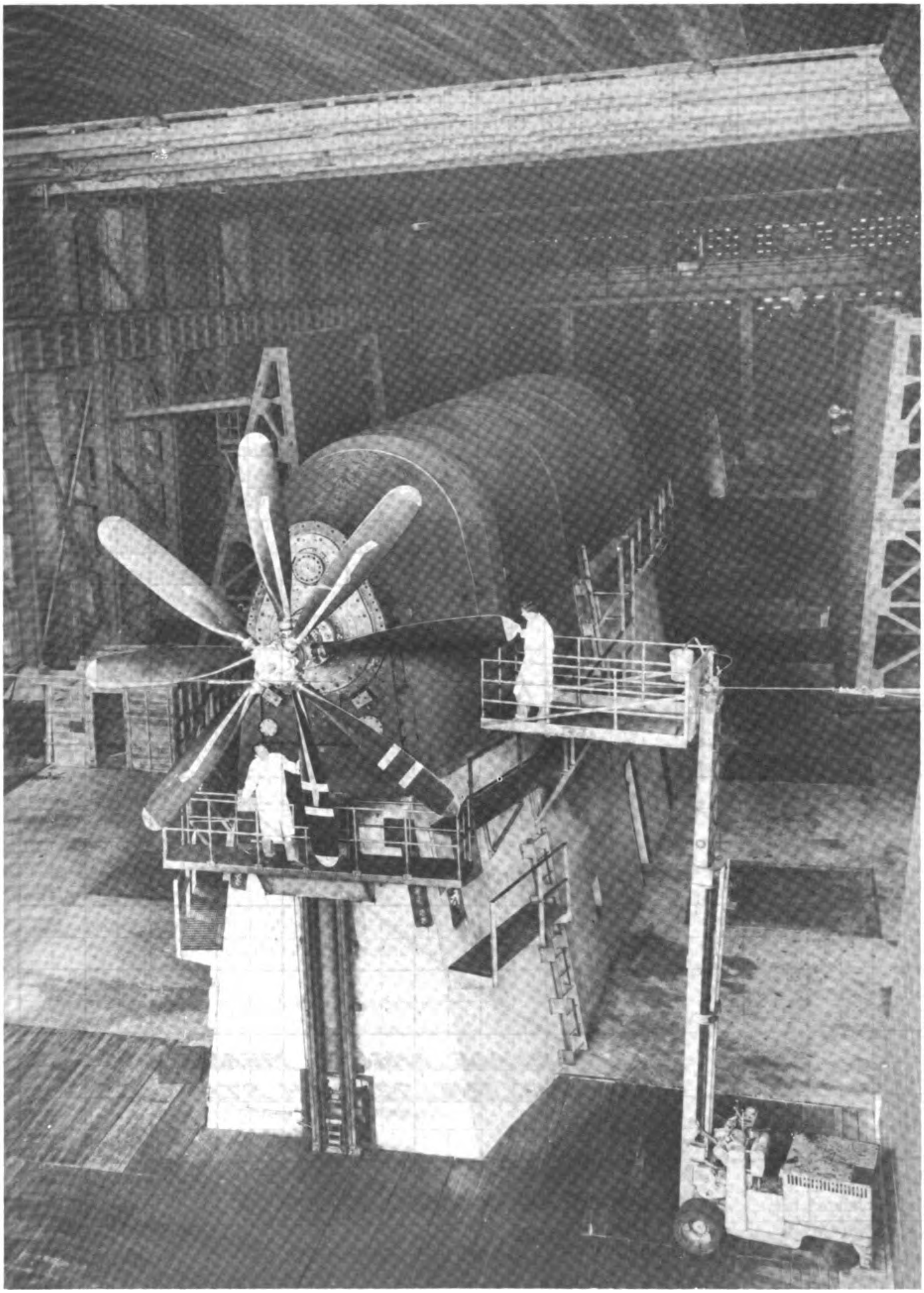

Figure 10.1.—Propeller installed for electric motor whirl testing.

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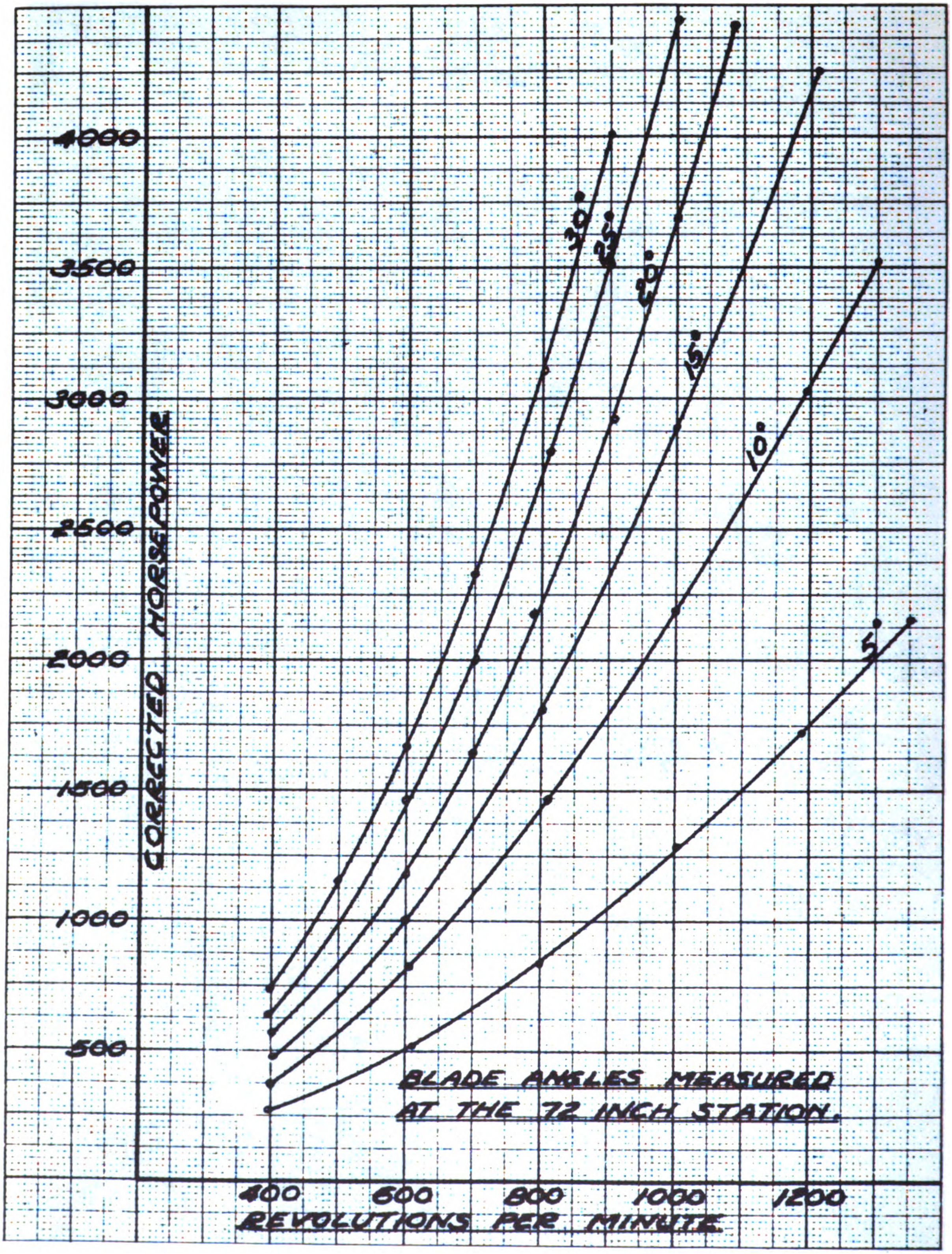

Figure 10.2.—Propeller power absorption curves.

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propeller developments can be established, in part, by consideration of probable effects of design modifications upon performance characteristics. If too many unknowns result from standard tests (valid for conventional propellers) when applied to new propeller types, new test methods and procedures must be devised. Hence, Type Test Specifications stipulate minimum tests but definitely include requirements for inclusion of *any additional tests considered necessary to determine safeness of a propeller for flying.*

Vibration Testing

It has been well established that very high vibration stresses in a propeller will cause fatigue failure. Since most propeller failures are fatigue failures, it is important that thorough vibration tests be conducted under significant vibration conditions. Propellers, during electric motor whirl tests, do not receive vibration excitations comparable to those introduced by conventional reciprocating engines. In view of this fact, propeller endurance tests have been established in which a propeller may be subjected to vibration excitations of piston engines for a considerable length of time. Ideally, a propeller under test should be subjected to a number of cycles of stress fluctuation which would be in excess of probable service life requirements. At the very least, endurance testing should be adequate to insure complete propeller safety under flying service conditions. However, this goal of achievement for endurance testing has not been attained completely for the following reasons:

(1) Exact duplication of all flight service conditions, in the laboratory, cannot be achieved.

(2) With existing equipment, time required to develop fatigue failures in all possible cases is excessive.

(3) Simulation of propeller service age, exposure and usage has not been established.

Electric Motor Whirl Test Procedures

Preliminary Inspection

Before physical testing, a propeller should be given a complete visual, magnetic and dimensional inspection. Radiographic inspection may be used, especially if soundness of nonferrous propeller parts is involved. Weights of propeller hub, blades, sub-assemblies and complete propeller should be recorded. The polar moment of inertia can be determined using a torsional pendulum. After complete inspection, a propeller should be assembled and balanced, after which electric motor whirl testing may be initiated.

Power and Thrust Determination

An electric motor whirl test stand should be equipped with an electric driving motor and a shaft extension mount which has been machined to receive standard propeller hubs. The test stand must be equipped with controls to permit propeller speed variation within limits of the electric motor. A wattmeter may be used to measure power input to the electric motor. The motor should be calibrated so that corrections for electrical and mechanical power loss at various speeds and powers may be applied to obtain true shaft power. Propeller thrust may be determined by measuring the pressure acting against a diaphragm in a hydraulic support of the motor shaft. Thrust in pounds can be obtained directly from a thrust meter after adjusting the meter scales to balance initial pressure. To compensate for intital pressure acting against the diaphragm, a correction must be applied to indicated thrust. This correction must be determined before each run, by adjusting the scale to balance diaphragm pressure, with the propeller operating at idle speed. This correction should be checked again after the test run. Propeller testing on an electric motor test stand should include calibration, endurance and overspeed, as well as control tests of the pitch change mechanism. A propeller mounted on an electric motor for whirl testing is shown in figure 10.1.

Propeller Calibration

Propeller calibration should include determination of horsepower absorption and thrust at various rotational speeds and blade angle settings. With blades set at a desired angle, measurements of horsepower and thrust should be made at various speeds up to the maximum considered safe for the propeller. Thrust and power should be corrected for instrumentation errors to obtain true data for the propeller.

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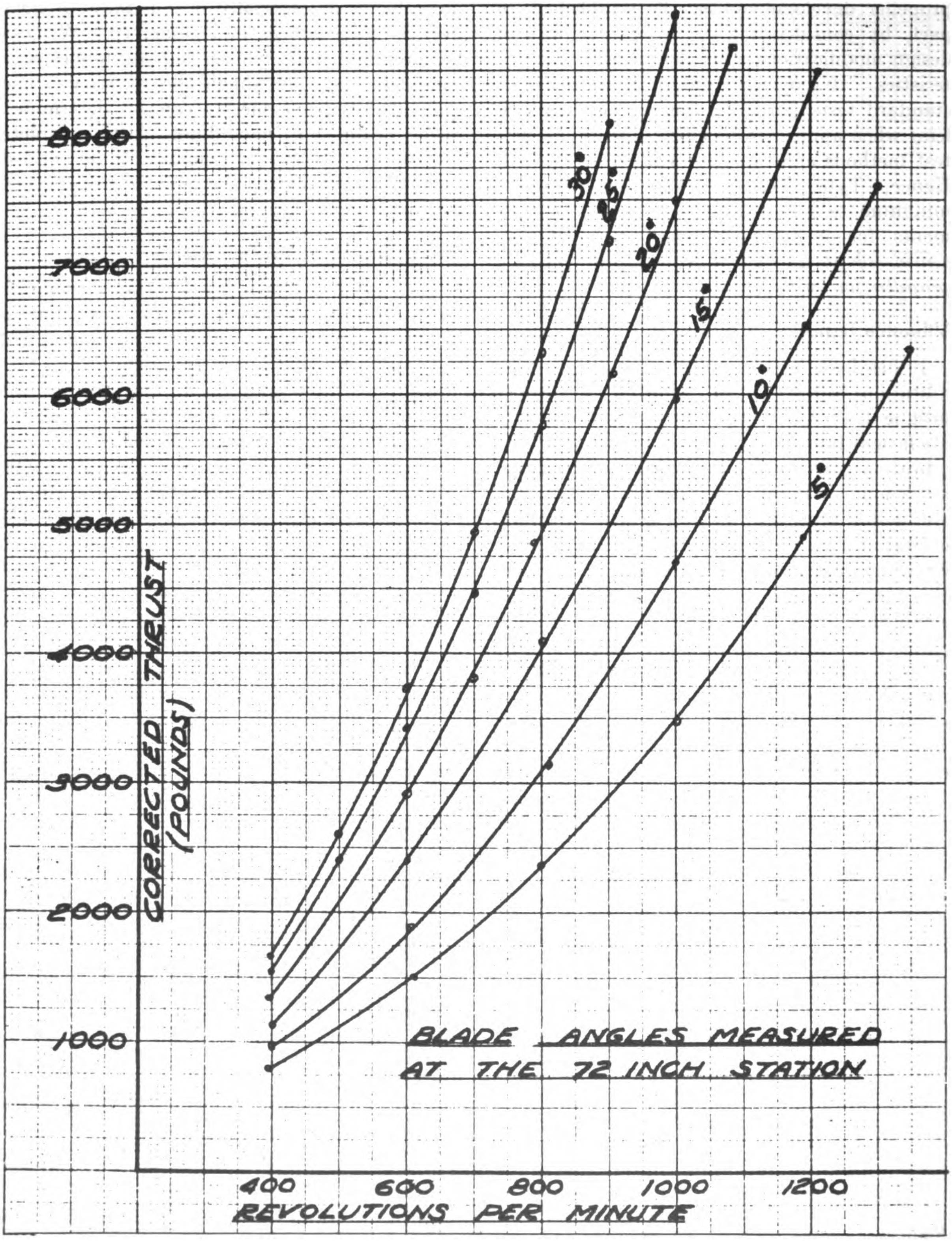
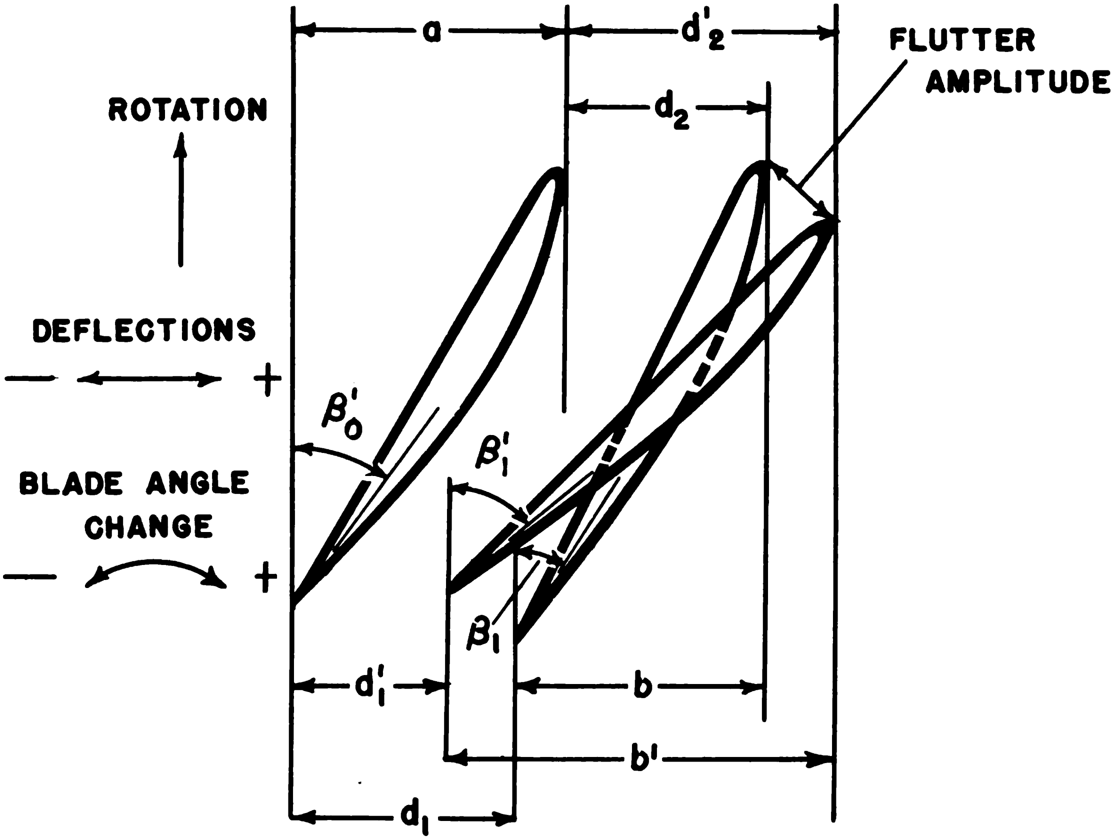


Figure 10.3.—Propeller thrust curves.



OBSERVED TEST DATA

d_2 & d'_2 = DEFLECTION OF LEADING EDGE

d_1 & d'_1 = DEFLECTION OF TRAILING EDGE

a = INTERCEPTED WIDTH-IDLE

β_0 = ANGLE SETTING-IDLE

CALCULATED DATA

b & b' = INTERCEPTED WIDTH-RUNNING

β_1 & β'_1 = ANGLE SETTINGS-RUNNING

$\Delta\beta$ = ANGLE CHANGE $\beta_1 - \beta_0$

$\Delta\beta'$ = ANGLE CHANGE $\beta'_1 - \beta_0$

$\Delta\beta = \frac{\beta_0}{a} \times d_2 - d_1$ EQUATION 10.1

$\Delta\beta = \frac{\beta_0}{a} \times d'_2 - d'_1$ EQUATION 10.2

$\Delta\beta' - \Delta\beta$ = FLUTTER AMPLITUDE EQUATION 10.3

Figure 10.4.—Propeller blade deflection.

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Frequently it will be desirable to reduce the data to standard atmospheric conditions (15° C. and 29.92 inches of mercury). Curves should be drawn showing corrected horsepower and thrust at various speeds for each blade angle. Sufficient information should be obtained to cover the complete operating range of the propeller, including both negative and positive blade angles. Determination of the blade angle requiring minimum power or torque should be made. Calibration at negative blade angle will provide information indicative of propeller effectiveness for aircraft deceleration. Propeller pitch reversal will permit shorter landing roll or decreased time requirement for descent from altitude. Also, information should be acquired indicating minimum torque obtainable in starting turbine engines. Figures 10.2 and 10.3 present typical horsepower and thrust curves, which may be plotted from the data obtained during propeller calibration tests.

Propeller Blade Deflection[1]

Propeller blade deflection should be measured during calibration runs. This may be done by using a telescopic sight to observe leading and trailing edges of the blade. The telescope, equipped with a reticle and mounted on a carriage may be moved either across the plane of propeller rotation to align the reticle vertical hair with leading or trailing edge of the blade, or along the plane of propeller rotation to align the horizontal hair with any radial blade station. A micrometer screw adjustment should be provided with the telescope carriage to facilitate accurate alignment of hairline and blade edge. The blade stations, at which deflections are measured, may be painted white, for better contrast with the reticle and for ease of identification. Stroboscopic light may be used to illuminate only the blade under observation at the proper radial and rotational position. With propeller at idle speed, the reticle should be aligned with the blade leading edge at a selected station by moving the telescope carriage across a supporting truss. Then, a scale may be locked in place on the truss so that the carriage index and scale zero are aligned. Blade trailing edge alignment with zero index of another scale may be established in a similar manner. The projected width of the propeller blade may be determined from the scale first positioned on the truss, or by measuring the distance between zeros of the two scales. Deflections may be read directly from the scales after adjustment of the carriage to align propeller leading and trailing edges with the telescope reticle, at increased rotational speeds. Normally, deflection should be measured simultaneously with power and thrust data determinations. By convention, positive deflection has been assumed to be in the direction that the thrust load normally would bend the blade, that is, upstream or in the direction of flight. Negative deflections are those in a down-stream direction. Deflections may be measured at more than one station, depending on propeller diameter, blade stiffness and test objectives. Propeller blade deflection measurements are illustrated in figure 10.4.

Performance Tests

(1) *Propeller endurance test.* Electric motor endurance testing involves propeller operation at greater than normal rated power. Such tests may be of twenty hours' duration, or longer, but not necessarily continuous. With blade angle set for rated power at normal speed, operation of the propeller should be maintained at a speed at which endurance test power (commonly 200 percent rated power) will be absorbed. Shut downs should be made for visual inspections as often as necessary to find incipient failures in early stages. Evidence of failure will be sufficient justification to discontinue testing. When necessary replacements of a failed part have been made, a new endurance test of the repaired propeller should be started and carried to completion unless additional failures occur.

(2) *Overspeed tests.* A propeller overspeed test should consist of one hour operation at ten percent above design maximum permissible engine speed. For most reciprocating engines, ten percent above design maximum engine speed will be, approximately, four-thirds normal rated speed. The propeller blade angle for an overspeed test should be set so that the power being absorbed will be between one and two times rated power.

(3) *Propeller control test.* Control tests may be conducted on an electric motor test stand. The test will involve actuation of pitch change mechanism through a specified number of com-

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[1] See Appendix for computation method.

plete cycles during propeller rotation. Propeller speed, number of pitch change cycles and blade angle range will be established at levels which will disclose suspected weaknesses or faults most likely to develop during service life.

After completion of electric motor whirl tests, a propeller should be disassembled for complete inspection. If there is no evidence of failure or other disqualifying features, the propeller is ready to be subjected to engine whirl tests.

Engine Whirl Tests

Engine Test Stands

Comparatively smooth operation will be obtained on an electric motor test stand. Consequently, operating conditions of propeller-engine combination cannot be reproduced on an electric whirl rig. The engine test stand will provide a suitable means for testing a propeller with the engine for which it was designed. The stand should include an inclosure in which provisions have been made to mount an engine, with equipment necessary to provide for accurate control of engine temperatures, pressures, speed and fuel rates, so that desired power conditions may be maintained during propeller testing. A circular throat or an orifice should be provided to minimize the possibility of undesirable induced vibration caused by unfavorable air flow patterns.

Endurance Tests

Endurance testing on an engine test stand should incorporate combined propeller-engine operation over a wide range of speed and power, of sufficient time duration to insure structural suitability of a given propeller. Usually, a minimum of 100 hours at normal rating and 10 hours at takeoff rating should be established as a prerequisite for propeller approval. However, a portion of the test may be conducted at that power condition at which maximum vibratory stress will occur in the propeller. The proper power setting should be determined by making a vibratory stress survey. If stresses prove to be marginal, additional tests may be run to determine the possibilities of fatigue failure. Duration of additional endurance tests may be determined from the time requirement for ten million stress reversals. Visual inspection of the propeller should be made frequently during test to lessen the possibility of a major propeller failure, with subsequent damage to engine and equipment.

Control Tests

Propeller control tests may be conducted in engine test stands to determine the effect of engine induced vibration upon the control system. The pitch change mechanism should be operated over a range from 1,000 to 10,000 complete cycles. Power and speed requirements of a propeller control test should be determined from expected aircraft use, or past experience with similar applications. Stability of the control system, rate of pitch change and response of propeller-engine combination to control must be checked, also. Modification of a propeller or any part of the control system may be made whenever sufficient testing has established suitability of the modification.

Evaluation of Whirl Test Results

Correction of difficulties experienced during laboratory development and testing will not prove, necessarily, suitability of a propeller for extended use. Occasionally, faults may exist which have not been revealed during laboratory tests. Further, it must be recognized that production propellers may vary considerably from the selected test item, which may have been hand worked, largely. It is highly desirable that a service test be conducted on an airplane for which the propeller has been designed. At least 100 hours of operation should be obtained with each of several propellers, so that test results can be considered conclusive. Where possible, suitability of a propeller should be established first under normal climatic conditions, after which it may be tested under more severe conditions, such as: extremely high and low temperatures, wide range of humidity and simulated dust storms. After a propeller has been approved for aircraft general usage, malfunctions still may arise. Continuing studies should be carried on to develop improvements that will make the propeller safe, more reliable and efficient.

Special Whirl Tests

Objectives

Specialized whirl tests should be conducted, as required, for propeller development studies.

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The tests should be developed to investigate special propeller characteristics and should not be established to fulfill the requirements of MIL–P–5452. Special whirl tests may involve conventional propellers or advanced experimental propeller designs and may be conducted using electric motor whirl rig facilities. Advanced experimental propeller designs include those designed especially for whirl test, wind tunnel and flight test to accumulate specific test data. Specialized aerodynamic tests vary in that type and extent of the test program, methods of securing data and amount of additional propeller instrumentation required will be fixed by test objectives. However, the special test program will usually include one or more of the following phases: aerodynamic calibration, flutter, endurance and overspeed test.

Special Propeller Test Procedures

(1) *Inspection and preparation.* The propeller to be tested should be inspected and prepared for test in accordance with the procedure outlined for standard propeller whirl tests.

(2) *Aerodynamic calibration.* Calibration should be conducted essentially in accordance with the procedure outlined for a propeller type test, except for the following:

- (*a*) Horsepower, thrust, blade deflections and flutter characteristics should be determined over complete speed range in 100 r. p. m. increments.
- (*b*) Usually, a stress survey should be conducted in conjunction with calibration.
- (*c*) Limits of calibration must be based upon propeller design speed, horsepower rating, and stress limitation.

(3) *Flutter tests.* Thin propeller blades have proven to be susceptible to torsional flutter. A flutter test should be conducted in conjunction with aerodynamic calibration, with usual calibration procedure being followed until flutter has been detected. Flutter will be accompanied by a simultaneous increase in vibratory stress, and intercepted width fluctuation in the deflection sighting device and by a characteristic increase in noise level. After flutter has been detected, the increment of speed increase should be changed to 20 r. p. m., approximately. Complete test readings should be taken at the initial flutter point and after each successive speed increase increment, in accordance with calibration procedure. Speed increase by small increments should be continued until propeller speed, horsepower or stress test limits have been reached. Blade angle settings for the test should be selected so that a flutter boundary curve (flutter speed vs. blade angle setting) can be determined for the given propeller within its operational limits. A sketch showing blade deflections during flutter was presented as part of the discussion of "Blade Deflection." Figure 10.5 presents an illustration of the flutter boundary curve of the propeller blade shown in figure 10.4.

A plot of blade deflection versus propeller speed is illustrated in figure 10.6. The curves are significant only for a particular propeller blade under established test conditions. Therefore, magnitude of deflection, angle change and flutter amplitude at specific speeds are not pertinent to this discussion. However, the curves illustrated are representative of blade deflections to be expected at critical speeds.

(4) *Endurance and overspeed tests.* A standard established endurance or overspeed test ordinarily would not be conducted as a regular part of these special tests. The necessity for test, as well as the type and extent of test program, must be determined expecially for each propeller. Propellers which are to be used for

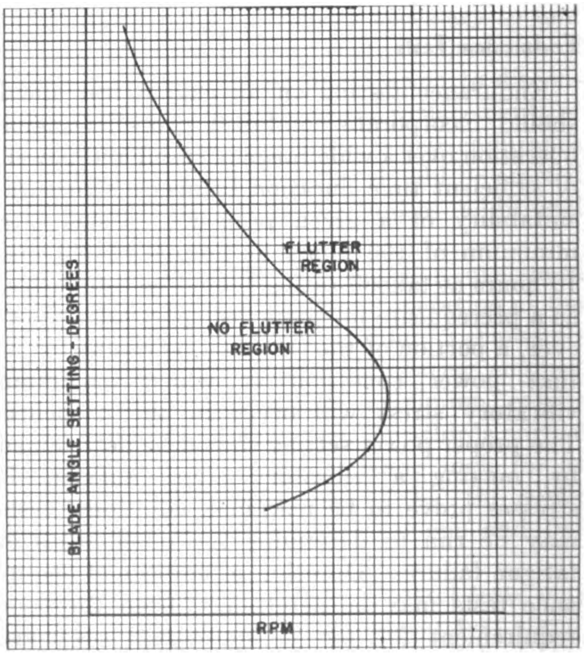

Figure 10.5.—Typical propeller flutter boundary curve.

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subsequent wind tunnel or flight test must be subjected to endurance and overspeed tests of sufficient duration to assure future safe operation.

Propeller Type Test

General Requirements

The following presents minimum general requirements for a type test of complete propeller assemblies. A type test includes electric motor whirl tests, aircraft engine whirl tests, and vibration surveys during whirl tests and actual flight. These requirements have evolved from piston engine propeller experience. Doubtless, experience with turbine driven propellers, especially at high speeds, will dictate considerable modification of the type test

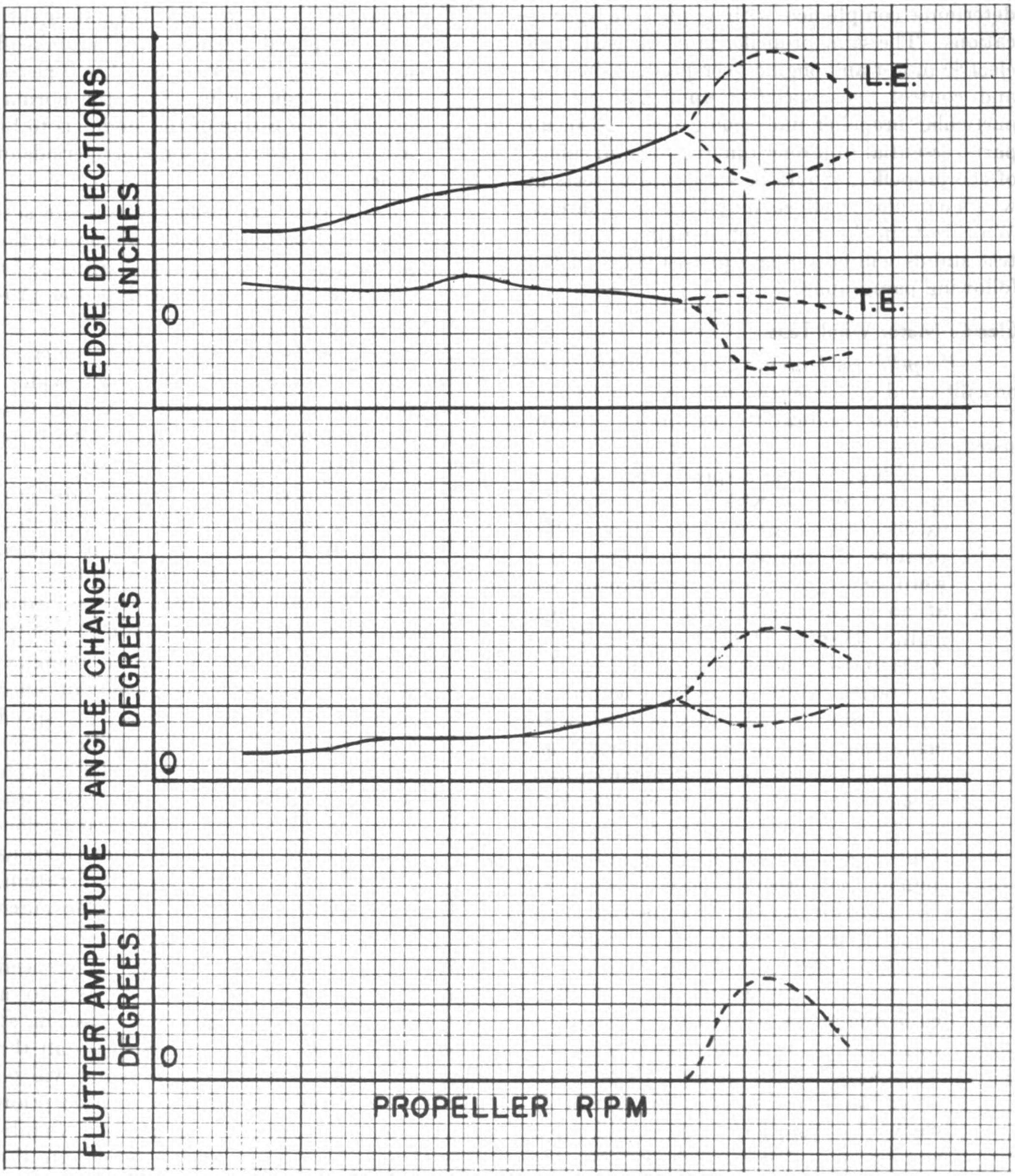

Figure 10.6.—Blade deflection propeller speed.

requirements. Appropriate portions of the type test should be applied to all new components of a propeller.

Propellers and test apparatus will be subject to inspection and tests at places designated by the procuring agency. If, by agreement, inspection and tests have been established at the manufacturer's plant, a procuring agency inspector must be given all necessary facilities to determine compliance with applicable specifications. The same propeller must be used in all electric motor and engine overspeed, endurance and control tests specified applicable to the particular propeller undergoing test. Also, all parts, essential to proper functioning and safety of the propeller, should be subjected to tests in which cumulative effects may become apparent. Whirl tests in electric motor and aircraft engine test stands will encompass phases listed in the following paragraphs.

Electric Motor Whirl Tests

(1) *Propeller calibration.* The propeller should be calibrated under several different conditions. The principal calibration conditions usually specified are:

(*a*) Calibration over a speed range up to a speed of rotation which is five percent in excess of the maximum speed of propeller rotation on ground run-up without forward velocity, with the blades being set at an angle used for high speed level flight. Display of objectionable flutter characteristics at any speed during this calibration will be cause for disapproval.

(*b*) A second calibration may be made with blade angles set to absorb, without forward velocity, normal rated engine power at normal rated engine propeller-shaft speed over a speed range up to a speed of rotation five percent in excess of rated engine propeller-shaft speed. Display to objectionable flutter characteristics af any speed during calibration will be cause for disapproval.

(*c*) A third calibration may be made with blade angles set to absorb, without forward velocity, a certain power at a certain speed, which corresponds to over-power and over-speed respectively, to which the propeller-engine combination may be subjected in flash performance during actual flying service. Due consideration must be given to engine-propeller gear ratio, in establishing test conditions. In this type of test, the calibration should be carried out over a speed range up to a speed five percent higher than that of flash performance. Display of objectionable flutter characteristics at any speed during calibration will be cause for disapproval. This test should be applied only to those propellers subject to special demands during takeoff and interceptor service, or other types of flash performance in which the normal power-speed rating of the engine is to be exceeded, materially, for short periods of time.

(*d*) Calibrations at other blade angle settings may be run if, in the opinion of the procuring agency, the information to be obtained will be pertinent to the propeller evaluation.

(2) *Propeller endurance tests.* For the purpose of developing weaknesses which become evident after extended service, a propeller will be subjected to endurance tests. The conditions usually specified for endurance tests are:

(*a*) An endurance test will include propeller operation over a period of twenty hours at two hundred percent normal power load with blade angle setting for normal power absorption under normal rotational speed without forward velocity.

(*b*) Propellers subject to flash performance in flying service will be given endurance tests of five hours duration at a speed five percent above flash performance overspeed. For this test, blade angle setting should be that at which the propeller will absorb, without forward velocity, the same power at the same speed as over-power and over-speed operation, respectively, under flash performance service.

(3) *Overspeed tests.* To establish overspeed capacity, a propeller will be subjected to a centrifugal test of at least one hour duration, at a minimum speed ten percent greater than the maximum speed at which the propeller will be operated in service, and at a power absorption rate not less than rated engine power. Conditions of the test will be chosen to eliminate the vibration factors, if practical.

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Engine Whirl Tests of Propellers

(1) *Vibration survey.* An engine whirl test of a propeller should be conducted using an engine of type and model for which the propeller has been designed. A vibration survey should be made as an essential part of an engine whirl test of a given propeller. Scope of the survey should be broad enough to include:

(*a*) A survey of vibratory stress existing in the given propeller when operating on a particular engine chosen for the endurance test. When specified by the procuring agency, measurements of torsional vibration of the engine crankshaft will be made, also.

(*b*) Technique and instrumentation (including number and distribution of strain gages) to be used in making the vibration survey, range of operating conditions and length of time interval for test must be acceptable to the procuring agency.

(*c*) If, in the opinion of the procuring agency, results of vibration tests indicate that the propeller under test will be subjected to dangerously high stress loading or that the engine crankshaft will be subjected to dangerously high-torsional vibration, that propeller will be disapproved for use with the particular type and model engine used in the test.

(2) *Propeller endurance tests.* An adequate engine endurance test of a propeller should develop marginal fatigue weaknesses, chafing, galling tendencies, and other weaknesses susceptible to engine induced vibrations. Within the scope of engine endurance tests, the following requirements should be considered as minimum:

(*a*) A propeller endurance test of 100 hours duration should be conducted. At lease 50 hours of the test will be conducted at normal rated engine power and speed. At the option of the procuring agency, the remaining 50 hours may be run at other engine power absorption and speed rates wherein high vibratory stress has been indicated during the propeller vibration survey. The amount of time to be expended in test at the selected power absorption and speed rates will be determined by the procuring agency.

(*b*) Propellers subject to flash performance in flying service will be given engine endurance test runs of ten hours each at overpower and overspeed conditions comparable to flash performance. The test engine will be of the same type as that on which the propeller will be used in service. Flash performance power and speed tests may be run either continuously or intermittently, depending upon engine cooling requirements, but only that time spent under full flash power and speed will be counted towards fulfillment of the ten-hour requirement. The grade of fuel used in test will be established so that the same conditions obtain during the test as in actual service.

(3) *Propeller functioning tests.* Functioning tests may be run with a propeller on an aircraft engine mounted in a test stand. These tests might be conducted in aircraft during flight or on motor whirl rigs; the choice of method will be at the discretion of the procuring agency. Tests will consist of the following:

(*a*) Manual Control. Five hundred cycles of operation of the control mechanism will be completed, with each cycle to include operation at maximum rated engine power and speed. At high pitch angles of the cycle, rotational speed must be maintained as high as safe operation of the engine will permit. In no case will the throttle setting be reduced for the purpose of easing the load on the propeller control mechanism.

(*b*) Automatic Control. Fifteen hundred cycles of operation of propeller blades by the automatic control mechanism will be completed, with each cycle to include maximum rated engine power and speed. At high blade angles of the cycle, rotational speed will be maintained as high as safe operation of the engine will permit. In no case will the throttle setting be reduced for the purpose of easing the load on the propeller control mechanism.

(*c*) Feathering and Reversing Control. The propeller will be subjected to such tests as are deemed advisable by the procuring agency in order to determine satisfactory operation of feathering and pitch reversal controls.

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Aircraft Tests

(1) *Function and flight performance tests.* Ground and flight propeller tests may be conducted on an airplane equipped with the particular type and model engine designated for use with the proposed propeller.

(*a*) Functional Tests. The propeller must function in flight under all conditions required to obtain specified performance on the engine-airplane combination involved. Functional tests will be conducted in flight to satisfy this requirement.

(*b*) Flight performance tests may be conducted if such tests are pertinent to approval of a given propeller.

(2) *Propeller vibration survey on aircraft.* Serious propeller vibrations may be encountered in flight; the nature, and magnitude of the vibrations and the operating conditions under which they may be encountered can be established only by flight test. The following minimum requirements must be met in conduct of propeller vibration surveys:

(*a*) A survey will be made of vibratory stress existing in a propeller during ground and flight operation with the engine-airplane combination involved. Measurements of torsional vibration of the engine crankshaft will be made at the option of the procuring agency. Any modification of the engine mount after completion of a vibration survey which, in the opinion of the procuring agency, could affect vibratory stress in the propeller, or torsional vibration of the crankshaft, will make it necessary to complete a new vibration survey including torsional vibration measurements.

(*b*) Technique, instrumentation (including number and distribution of strain gages), range of operating conditions, and test duration of flight vibration surveys must be acceptable to the procuring agency.

(*c*) If, in the opinion of the procuring agency, the results of flight tests indicate that a given propeller will be subjected to dangerously high stress, or that the engine crankshaft will be subjected to dangerously high torsional vibration, the propeller will be disapproved for use on the engine-airplane combination used for the test.

Manufacturer's Tests

When required tests are conducted by a propeller manufacturer to obtain approval of a procuring agency, such tests will be witnessed by a qualified representative of the procuring agency. In lieu of required tests, the procuring agency may grant approval of any specific type and size of propeller, if at least one propeller has accumulated 1500 hours or more of satisfactory service in flight. Flight service of the propeller must have been obtained on an identical type and model engine proposed for installation.

Additional Testing

The procuring agency may conduct any additional tests considered necessary to determine service safeness of a propeller. Any propeller which, in the opinion of the procuring agency, is unsafe for flying will be rejected. As previously explained, type test is not limited to the tests outlined, but may be augmented by any other tests deemed necessary to demonstrate safeness of the propeller. This provision (other tests to demonstrate airworthiness), should be included in the specifications for type tests, in recognition of the effects introduced by variables which cannot be anticipated in considering tests of new propellers. Furthermore, testing that should be pursued depends very much upon developments during tests which cannot be anticipated.

Representative Type Test Recapitulation

A representative type test procedure will include the following:

(1) *Electric motor testing.* (*a*) Calibrations. Reverse and positive pitch angles will be checked throughout normal operating range (approximately, −25° to +50°) in increments of 3 to 5 degrees. A vibratory stress survey usually will be conducted concurrently with calibrations of propellers over twelve feet in diameter.

(*b*) Twenty Hour Endurance Run. An endurance test will be made under load equal to twice normal rated power, with blade angles set to satisfy the condition of rated power at rated speed.

(*c*) One-Hour Overspeed Run. An overspeed test of one hour duration will be run at 110 percent maximum permissible engine speed, with blade angles set to absorb at least normal rated power at overspeed condition; blade angles may be set to absorb up to double normal rated power.

(*d*) Fifteen hundred to three thousand positive and reverse pitch change cycles will be made for those propellers incorporating control mechanisms adaptable to operation on an electric motor test stand.

(*e*) Additional testing of ten to one hundred hours duration may be conducted with baffles designed to excite stresses in the propeller equivalent in magnitude to those anticipated in service.

(2) *Engine testing.* (*a*) Vibration stress survey will be made.

(*b*) Ten test periods[2] must be conducted, each period to include the following:

(*i*) Ten hours of endurance at normal rated power and speed.[3]

(*ii*) One hour operation at takeoff power and speed.

(*iii*) One-half hour of flash performance operation at War Emergency rating.

(*iv*) One hundred and fifty cycles of automatic pitch control (actuated by throttle).

(*v*) One hundred cycles of manual pitch control (actuated by governor control).

(*vi*) One hundred and fifty cycles of pitch reversal.

(*vii*) Ten feathering cycles.

Final Propeller Evaluation

Because type tests may be made on NEW propellers, and since the type test does not simulate all conditions to which a propeller may be subjected in service, it is recognized that many propeller designs which might pass type tests would not be safe for service use. Therefore, experience with propeller manufacturing practices and service usage must be the basis for a final evaluation of propeller safeness in service. If appraisal be unfavorable, the right to reject must be reserved even though a propeller has passed the type test.

Other Propeller Tests

Functional Tests

There are many tests other than the so-called type tests to which propellers and propeller components may be subjected. Water spray (or droplets) projected on a whirling propeller has been used as an abrasion or erosion test, for a long time. This kind of an erosion test may be used to test blades, metal shielding, blade deicers, plating and finishes. Sand has been used, also, to a very limited extent for the same purpose, but cannot be controlled as well as water; furthermore, sand has greater nuisance potentialities. Water spray tests have never been used for other than comparative purposes, but a large background of experience renders water erosion comparisons quite valuable. Such tests have no direct interpretation in terms of service usage.

By use of special baffles placed in the propeller flow stream or by an auxiliary air blast projection into the propeller air stream, unequal aerodynamic loading on rotating propeller blades may be created. By this unequal blade loading procedure, certain propeller vibration stresses, which occur in service, may be simulated. Such tests have been the basis for determining allowable vibration stresses in propellers for service use. Whirl tests can be used to study air flow through hollow blades designed for hot-air deicing and to test burners designed to heat air for deicing systems. Durability and radio interference of propeller slip rings for propeller pitch controls and electric deicing may be determined during propeller whirl tests. Hubs should be tested in cold chambers to study functioning of pitch changing and control elements at low temperatures.

Significant Vibration Surveys

Not only may a propeller-engine vibrating system be significantly different in an airplane than in test stands, but also, vibration excitations occurring in the two situations may be much different. Especially, aerodynamic conditions will be much different in the two cases. Hence, it is imperative that propeller vibration surveys be conducted in the aircraft, both on the ground and in flight to insure safety. Stationary and taxiing ground tests should be conducted with winds variable in direction and magnitude. Flight vibration tests using vari-

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[2] Various pitch control, reversing and feathering cycles should be spread out over the period of testing to eliminate engine overheating or damage to auxiliary test equipment.

[3] The last five periods of endurance testing should be conducted at peak stress condition. Attempts should be made to artificially excite 1xP and 2xP stresses of the magnitudes expected under service conditions and the last fifty hours of propeller endurance testing should be accomplished with this stress condition existing.

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able loads, speeds, flight regimes, and flap conditions should be made. While it is highly desirable to have propellers free from operating restrictions, safety must come first. Many restrictions can be tolerated without inconvenience or risk. Sometimes a propeller restriction will prove to be a more practical solution of a vibration problem than a propeller, engine, or installation design change.

Propeller Vibration Testing

Definition of the Vibration Problem

The danger to an airplane in flight from a broken propeller is very great. Initial propeller failures nearly always may be classed as fatigue failures which result from excessive vibratory stresses in the propeller; therefore, propeller vibration tests must be conducted to determine structural safety of a propeller.

Vibration of a propeller depends upon the presence of exciting forces, response to excitation, and the degree of damping present in the vibratory system. A propeller vibratory system is not limited to the propeller alone but may include engine, airplane, or any combination of component parts. Nearly all modes of propeller vibration, which are important to propeller safeness, together with sources of excitation and vibration frequencies can be predicted or easily determined experimentally. Vibration amplitude which depends on excitation and damping factors cannot be predicted. Therefore, it is necessary to resort to actual measurement of vibratory stresses as a step in the process of determining propeller safeness for service usage.

Purpose of Vibration Testing

Extensive propeller vibration testing should be done during development and type testing. Development vibration testing will be done to

Figure 10.7.—Vibration survey instrumentation.

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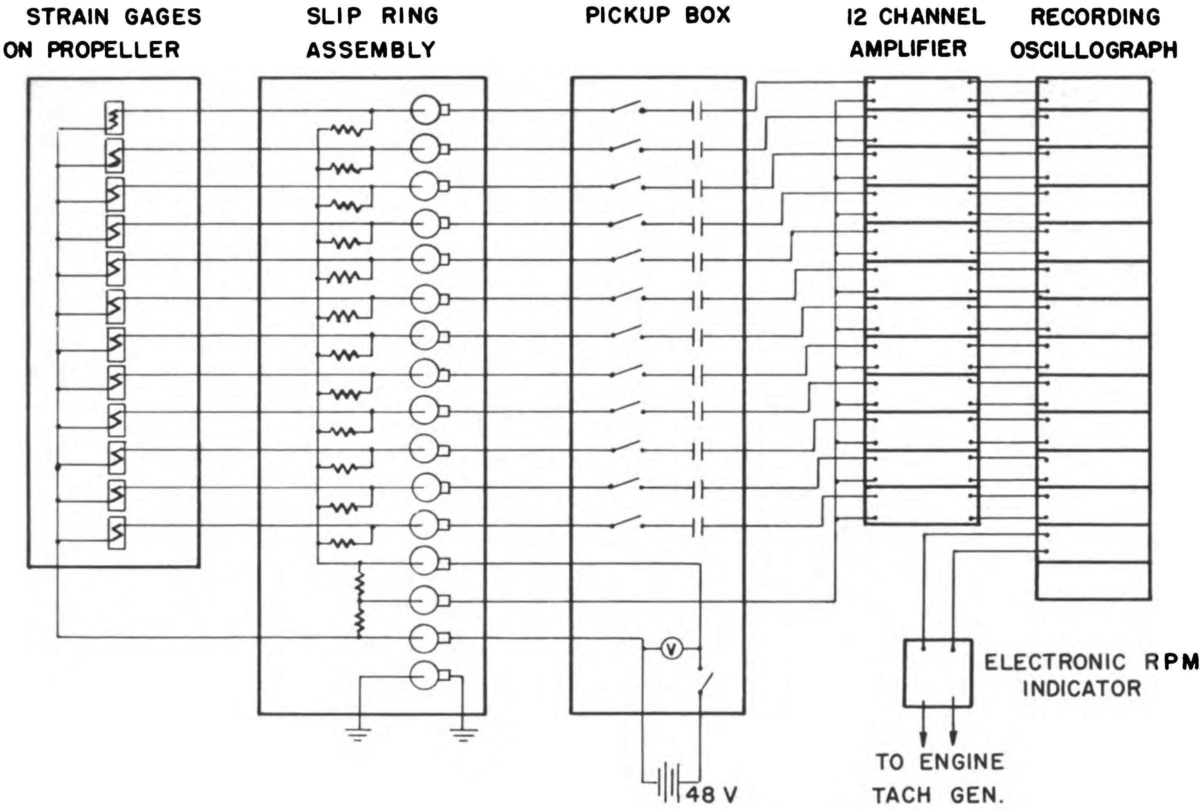

Figure 10.8.—Typical propeller vibration recording circuit.

find resonant modes and frequencies, which are required to estimate propeller structural suitability for a proposed installation. In addition, the data accumulated during development can be used frequently in establishment of propeller modification requirements. Vibration studies can be made to determine maximum stress in various blade sections and to establish blade deflection or flutter tendencies. Vibration testing should be done during type testing to insure structural suitability for required operation on electric whirl rigs or in engine test stands. A study of test stand data can be used to predict vibration effects when operating as a part of the airplane installation. A propeller vibration flight test should be made on the airplane for which the propeller was designed as a part of the propeller structural evaluation. Furthermore, a vibration flight survey may reveal further vibration endurance testing which should be run on electric motor or engine test stands.

Excitation and Modes of Vibration

(1) *Sources of excitation.* Vibratory forces, torques, or moments which may produce severe vibratory stresses in propellers arise from two principal sources; first, variation in aerodynamic loading on the blades which depends upon the nature of airflow through the propeller; and second, vibratory forces that originate in the aircraft engine.

(2) *Order of vibration.* Presence of the fuselage, wing or other portions of an airplane may distort airflow through the propeller disc in a complicated manner. Irregular airflow will cause variations in aerodynamic forces acting on rotating propeller blades. A propeller operating in a distorted airflow field will vibrate in frequencies of one, two, three or higher integral multiple of propeller rotational speed. The number of cycles of vibration per propeller revolution has been designated, *order of vibration.* By conventional use, the order of vibration may be written as $1P$, $2P$, $3P$, etc. Sometimes it may be more appropriate to refer the order of vibration to engine speed, as: $2E$, $4E$, $7E$, etc.

(3) *Propeller aerodynamic whirl—Shaft reactions.* A propeller, vibrating from aerodynamic excitation at orders that are integral multiples of the number of propeller blades, exerts a fore and aft force on the shaft. If the order of the vibration is one more or one less

than an integral multiple of the number of propeller blades, the shaft will be subjected to a rotating couple. The vibration resulting from this force couple has been named propeller aerodynamic whirl. Propellers, having an even number of blades greater than two, will produce aerodynamically excited modes having orders which are multiples of the number of blades plus or minus two, or an even submultiple of the number of blades. These vibration modes exist within a propeller; significantly, blade vibratory forces will not induce propeller shaft reactions. Therefore, these vibration modes are called reactionless modes.

First order propeller vibration is caused by first order variation in thrust experienced by a rotating blade. First order thrust variation arises when airflow of uniform velocity through a propeller follows a path not parallel to the propeller shaft. The magnitude of thrust variation will be proportional to the square of airplane airspeed multiplied by the angle between the propeller shaft and airflow direction. First order vibration of a propeller having more than two blades, uniformly spaced, induces a fixed

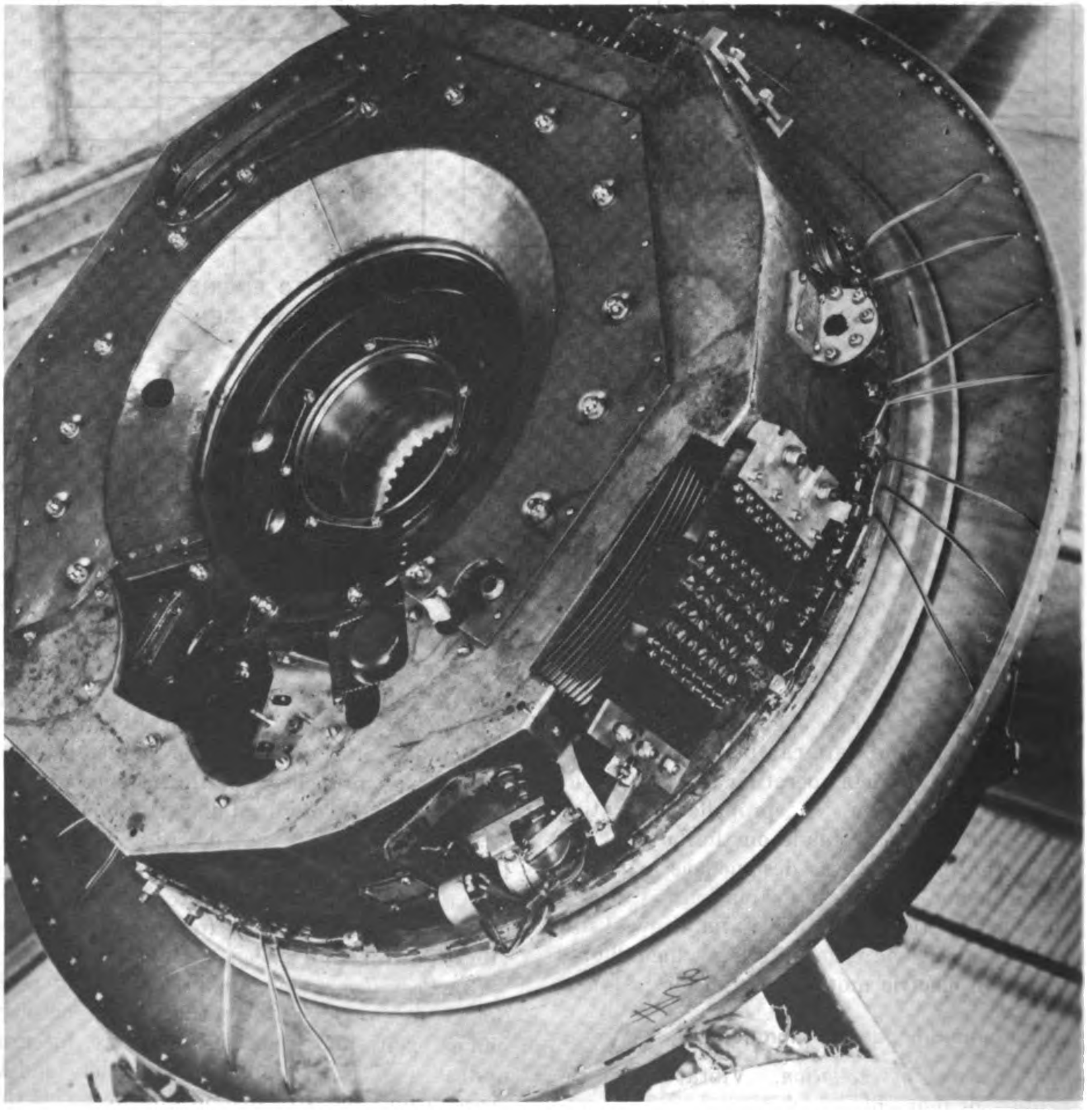

Figure 10.9.—Hub for propeller test.

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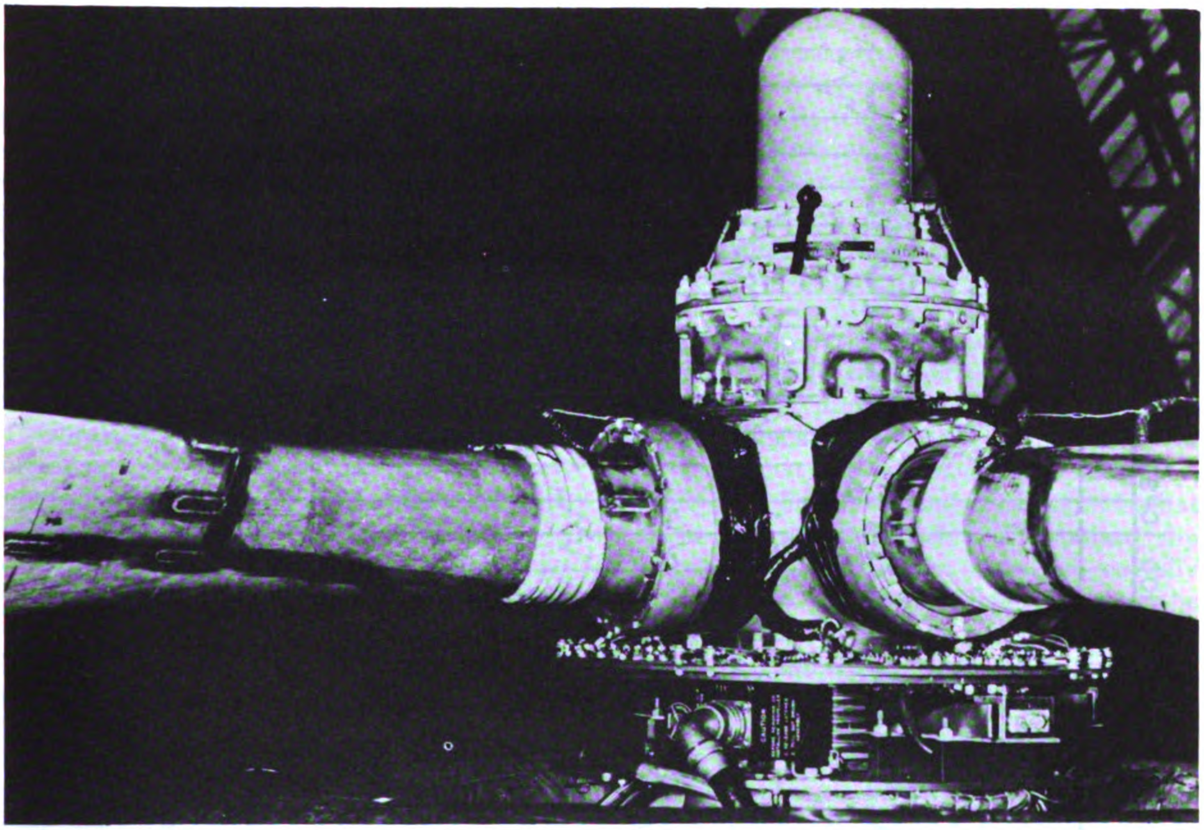

Figure 10.10.—Test hub—slip ring configuration for B–29.

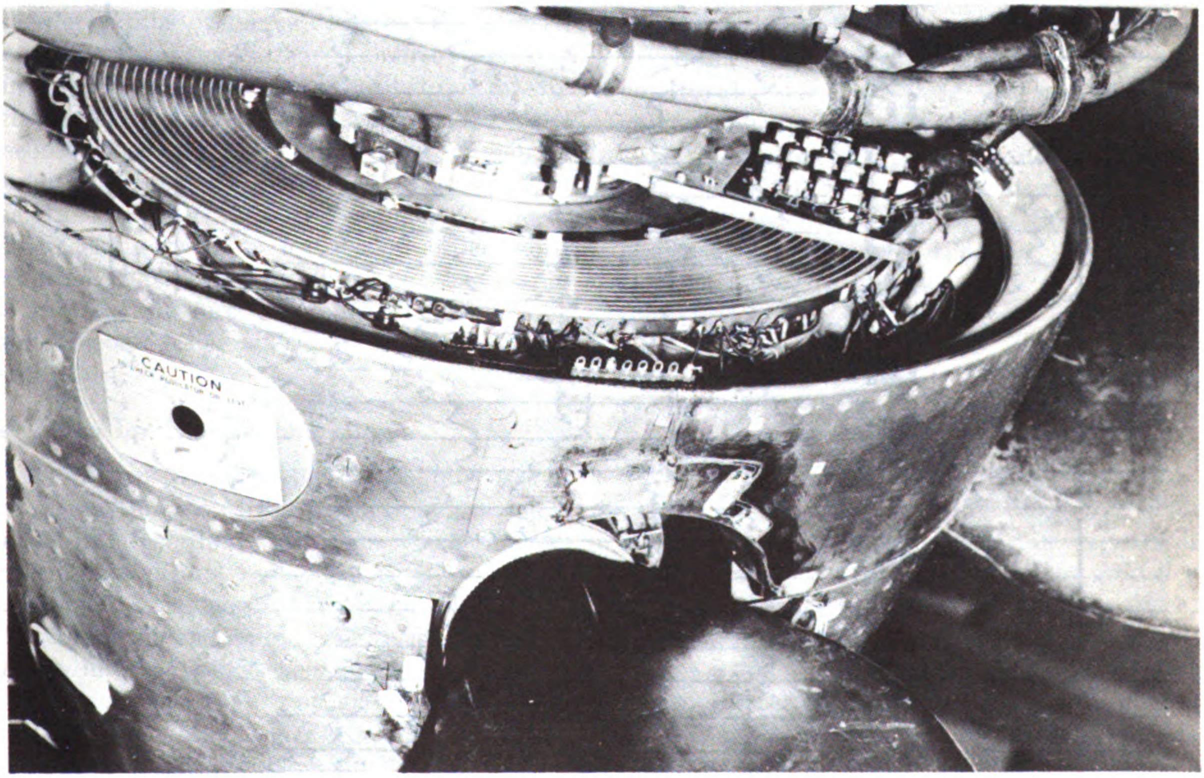

Figure 10.11.—Test hub—slip ring configuration for P–82.

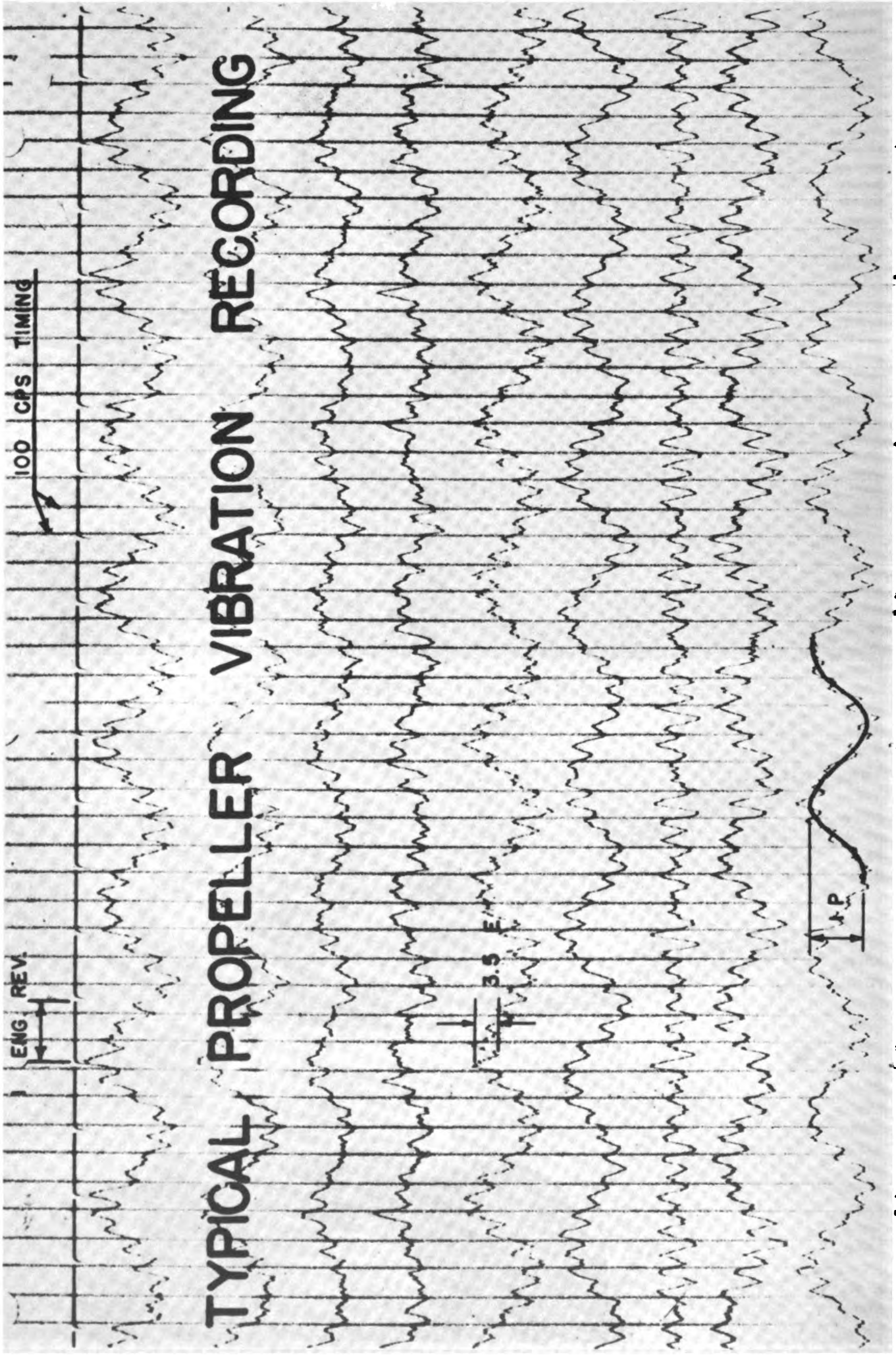

Figure 10.12.—Typical propeller vibration recording.

couple which acts on the propeller shaft bearing supports.

(4) *Engine excited propeller vibrations.* Engine excited forces (firing impulses or torque variations) are a troublesome source of propeller vibration excitations. These forces may be classed as gas forces or inertia forces. Gas forces, which arise from explosions and compressions, occur at frequencies that are multiples of one-half engine speed. Firing frequency or one-half the number of engine cylinders in one row multiplied by engine speed, will predominate in radial engines usually, in spite of vibration dampers. The reaction of gas forces on an articulated engine crankshaft results in whirling motions of the engine nose. The predominate engine whirls are those having a frequency equal to the firing frequency plus or minus one. These whirls will produce propeller whirls equal to engine whirl frequency plus or minus the reduction gear ratio, depending upon the direction of propeller rotation with respect to engine whirl.

Inertia forces of radial engine crankshaft components give rise to engine nose whirls of frequencies that are one or two times crankshaft speed. These whirls will produce propeller whirls of frequency equal to engine nose whirl frequency plus or minus reduction gear ratio, as in the case of gas whirls. The first order (one time speed) whirl may be cancelled out readily with a crankshaft counter weight. But, the second order whirl (two times speed frequency) cannot be cancelled completely with counterweights rotating at twice crankshaft speed. When counterweights for second order whirl are used, they do not rotate in the same planes as the exciting forces. Hence, there must be some second order whirl, under all operating conditions.

Vibration Test Instrumentation

(1) *General requirements.* The purpose of vibration test instrumentation is to provide a means for recording vibrations which may be examined and analyzed to determine vibration magnitude, frequency, phasing and, ultimately, the source of excitation. Vibration measurements may be taken using a multiplicity of strain gages arranged to pick up various modes of propeller vibration. The electrical output of a strain gage may be transmitted through slip rings, connecting cables, and electronic amplifiers to a recording oscillograph. Proper strain gages must be selected for each test, considering such factors as: type of measurement required, available space, temperature stability, operating temperature range, calibration factors and sensitivity. The equipment necessary to make a vibration survey is illustrated in figure 10.7.

A schematic diagram of a typical propeller vibration recording circuit is shown in figure 10.8.

(2) *Slip rings ("Pineapples").* Slip rings must be used to transmit strain gage signals from a rotating propeller to the cable that leads to amplifiers and recorders. The number of slip rings that can be used in an assembly, usually, will limit the number of channels that can be run simultaneously. A standard slip ring, called a pineapple, has been used generally for test stand work, but a flight ring must be designed and built for each new type propeller hub to be subjected to flight test. The propeller test hub design must provide for mounting slip rings. Figures 10.9, 10.10, and 10.11 show typical slip ring installations.

(3) *Amplifiers.* Amplifiers must be used to receive strain gage signals and reproduce them with enough magnification to drive oscillograph galvanometers. The amplifier must reproduce signals without distortion over the frequency range that is desired. Also, some means must be provided for calibrating the amplifier and galvanometer prior to each test run.

(4) *Oscillographs for vibration surveys.* A recording oscillograph may be used to record galvanometer deflections and a time base on photographic paper. In addition, it is general practice to record impulses from an electronic speed indicator which receives a speed signal from a tachometer generator. A typical propeller vibration recording is shown in figure 10.12.

Vibration Test Procedure

(1) *Location and number of strain gages.* The number and distribution of strain gages will depend very much on the nature of the propeller blade and hub structure. A simple, one piece, fixed pitch propeller with solid blades may require only 20 to 30 gages along the blade and around the shank for an adequate stress survey. Propellers having hollow steel fabricated blades with controllable pitch hub structures often require several hundred gages for an adequate

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survey. Even with a large number of gages, there will be important stress concentrations at points that are not accessible. Fatigue vibration data should be taken during blade development programs; this data will become a ready reference for preparing test propeller gage position layouts. A standard recording equipment set will have 12 channels. But if allowable equipment space is limited, as in single place and two place aircraft, a four channel set may have to be used. Strain gage position layouts must be designed so that groups of gages can be recorded simultaneously, to define strain patterns or modes of vibration.

(2) *Simulated flight endurance tests.* Vibration surveys should be made on propellers during calibration on electric whirl rigs to safeguard against destructive aerodynamically excited resonance during calibration, or overspeed and overpower running. Propeller vibration surveys should be made on engine test stands, to safeguard against failure during the standard (engine running portion) type test. Engine excited propeller vibrations should be investigated, thoroughly, during this portion of the test. The last half of engine endurance running should be done at the highest level of engine excited stress. Aerodynamic propeller vibra-

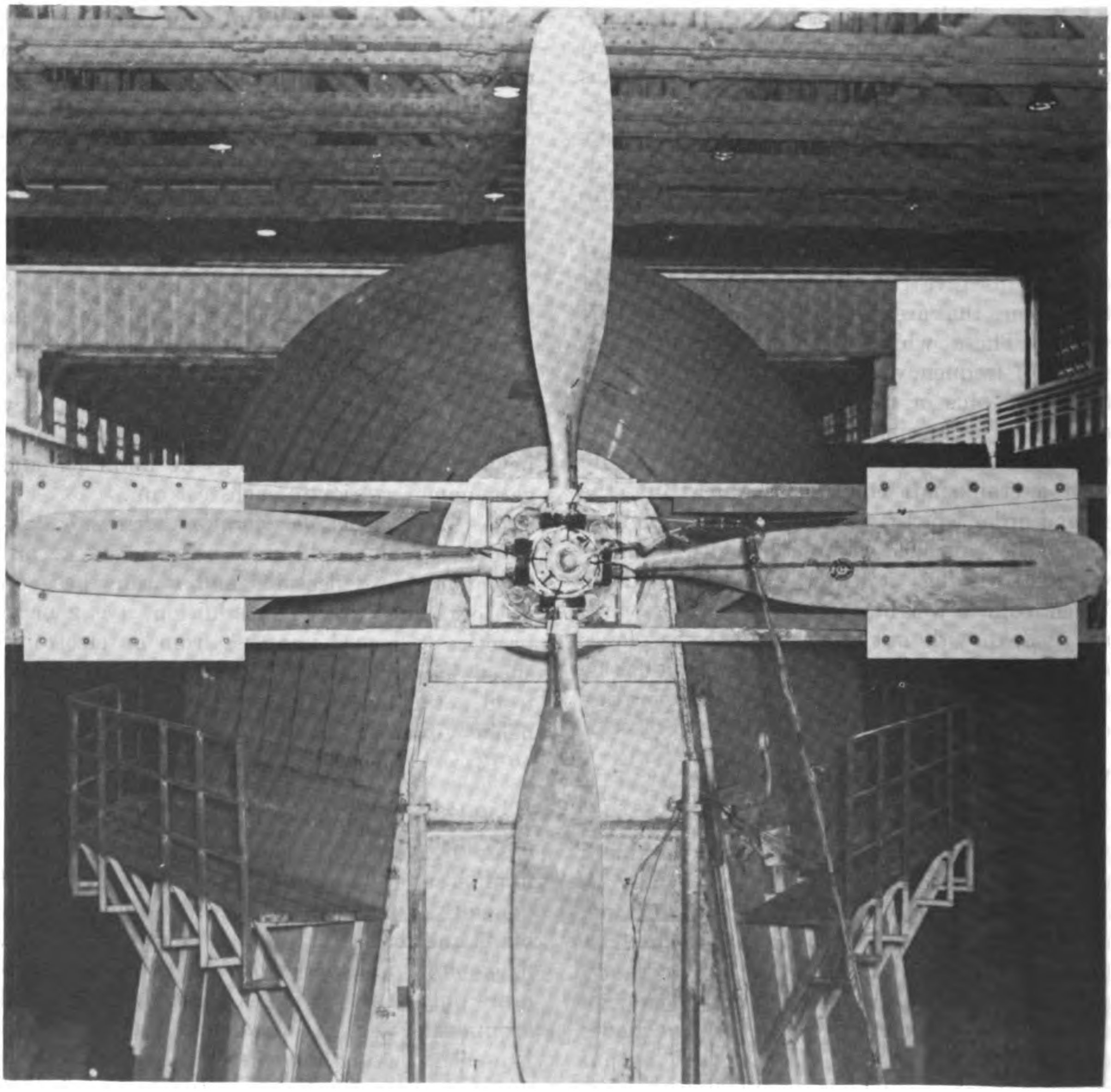

Figure 10.13.—Propeller airstream baffle.

tions, particularly reactionless modes, sometimes show up in test stand operation. An effort should be made to provide smooth airflow so that these excitations will be negligible. However, if the engine test is to be conducted after the flight test, or if flight stress levels can be predicted, the test propeller should be excited aerodynamically. An airstream baffle may be used to force aerodynamic vibrations. A typical airstream baffle used by the Air Force Propeller Laboratory is illustrated in figure 10.13.

The stress level may be changed by adjusting baffles until flight stress levels, as previously determined or predicted for the propeller, are reflected. This endurance or fatigue test is of value because it will prove a propeller structure under the worst operating condition. Engine propeller endurance tests are considered more reliable than static fatigue tests because static vibrators cannot duplicate operating loads. Results of endurance fatigue tests must be studied, carefully, prior to propeller approval for airplane installation.

(3) *Vibration flight surveys.* Flight tests should be conducted using the airplane for which a propeller has been designed. A complete ground and flight survey should be run to insure that the propeller structure will be satisfactory for every operating condition. A complete ground and flight survey will require that propeller tests be conducted at all altitudes, speeds, powers, attitudes, gross weights, and maneuvers to which the airplane may be subjected. Normally, a propeller would be subjected to a type test before being tested on an airplane. Vibration data obtained during whirl rig and engine test can be used to estimate requirements for a minimum complete test flight. Flight test results may show a necessity for repeating some of the endurance test. Alternate type tests and flight tests should be conducted until the given propeller has been proven safe for all airplane operating conditions.

Analysis and Conclusions

(1) *Analysis methods.* Analysis of propeller vibration records may be made by measuring strain gage output amplitudes, measuring phase angles, determining frequencies and engine speeds, after which stresses may be calculated. Normally, the results will be presented as curves plotted on a chart using ordinates for vibratory stress and abscissa for engine speed, airplane speed or other significant variables. The order of vibration and phase relationships, when required, should be recorded on the curve sheet to aid in determination of vibration modes and stress patterns. The term *stress*, as generally used in propeller vibration work, has a value equal to strain multiplied by the modulus of elasticity of the material from which the strain gage reading was obtained. It is recognized that *stress*, so determined can be considered only approximately true, but adequate for propeller vibration survey purposes.

(2) *Conclusions.* To judge propeller structural safety under airplane operating conditions, it is necessary to compare the stresses existing in a propeller operating on an airplane on the ground and in flight with known vibratory fatigue stress limits of the propeller. Fatigue limits may be determined either by propeller static fatigue tests or by fatigue endurance tests in whirl test stands under artificially excited stress conditions. A propeller should be approved for unrestricted airplane use only after successful completion of an endurance fatigue test at stress levels higher than any encountered during ground and flight test. If the flight test shows stresses higher than those at which the propeller can operate safely, airplane propeller operation must be restricted so that the actual stresses will be less than allowable stresses.

Fatigue Tests

Testing Structural Samples

(1) *General methods.* Fatigue testing of complete propellers may be accomplished on engine or electric whirl rigs where actual service loading conditions are simulated as closely as possible. Component parts (or structural samples) of a propeller may be tested separately in the laboratory. However, in laboratory testing of propeller components, it is quite difficult to simulate loading conditions that a given part may encounter in service.

Blades fabricated from a homogeneous metal, such as solid aluminum alloy, present the simplest problem of establishing fatigue stress limits since the failure nucleus nearly always appears upon the outside surface. But, in hollow propeller blades, stress concentrations occur near holes, sharp corners and internal

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fillets of small radius. Therefore, in fatigue testing, hollow blades should be subjected to loadings that will produce maximum stresses in the regions of stress concentrations.

It should be noted that most of the fatigue testing machines used for propeller and propeller component testing make use of mechanical resonance in order to obtain the high stress levels required to effect controlled failure. The only power required by the test machine is the equivalent of damping losses inherent in the specimen and test machine for the operating

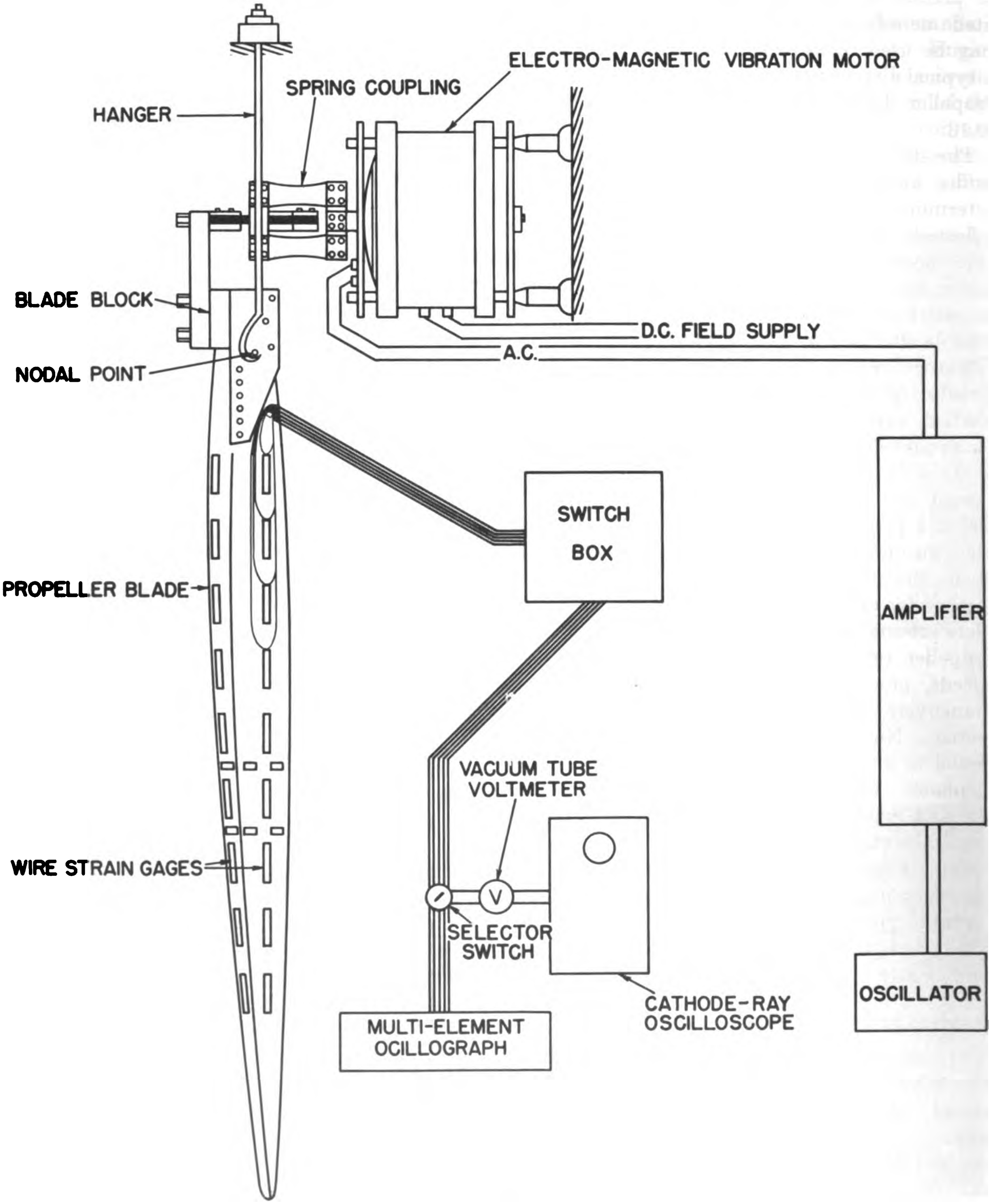

Figure 10.14.—Diagrammatic view of vibration test set-up.

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level involved. (The energy loss per cycle due to friction, windage and hysteresis in the metal depends only on the amplitude and frequency of vibration.)

Stress levels obtained during fatigue testing may be measured by use of strain gages wired together in some form of bridge circuit. The signal output from the strain gage must be amplified, after which the signal may be read from an electronic voltmeter or recorded by an oscillograph. A schematic diagram of a typical propeller vibration test setup is shown in figure 10.14.

A considerable amount of fatigue testing has been accomplished on small structural samples cut from actual blades to evaluate various fabrication methods, fillet designs, surface finishes and heat treatments. The sizes and shapes of these test samples often require that special fatigue testing machines be designed and constructed.

(2) *Simulated stress loading.* A common method of testing structural samples involves the use of fatigue machines which simulate stress loading, both steady and vibratory, that a particular section of propeller may encounter under actual service conditions. Blade shank and retention test machines have been designed and built for simultaneous application of centrifugal loads and vibratory bending moments equivalent in magnitude to those encountered in service. The steady load applied by the test machine quite accurately simulates actual service loading, because, under operating conditions, the variation of steady stress with blade radius is quite small in the shank region. However, for the mid-blade section, loading equivalence does not exist, even as an approximation. A satisfactory method of simulating steady loading distribution in the mid-section and tip region of a propeller blade has not been found. It has been common practice to test the mid-blade section without steady stress application and subsequently apply a correction to the observed stress, using correction factors obtained from a modified Goodman diagram or equivalent. (A complete discussion of diagrams of this type has been presented in *University of Illinois Engineering Experiment Station Bulletin No. 26*, dated 17 February 1942,

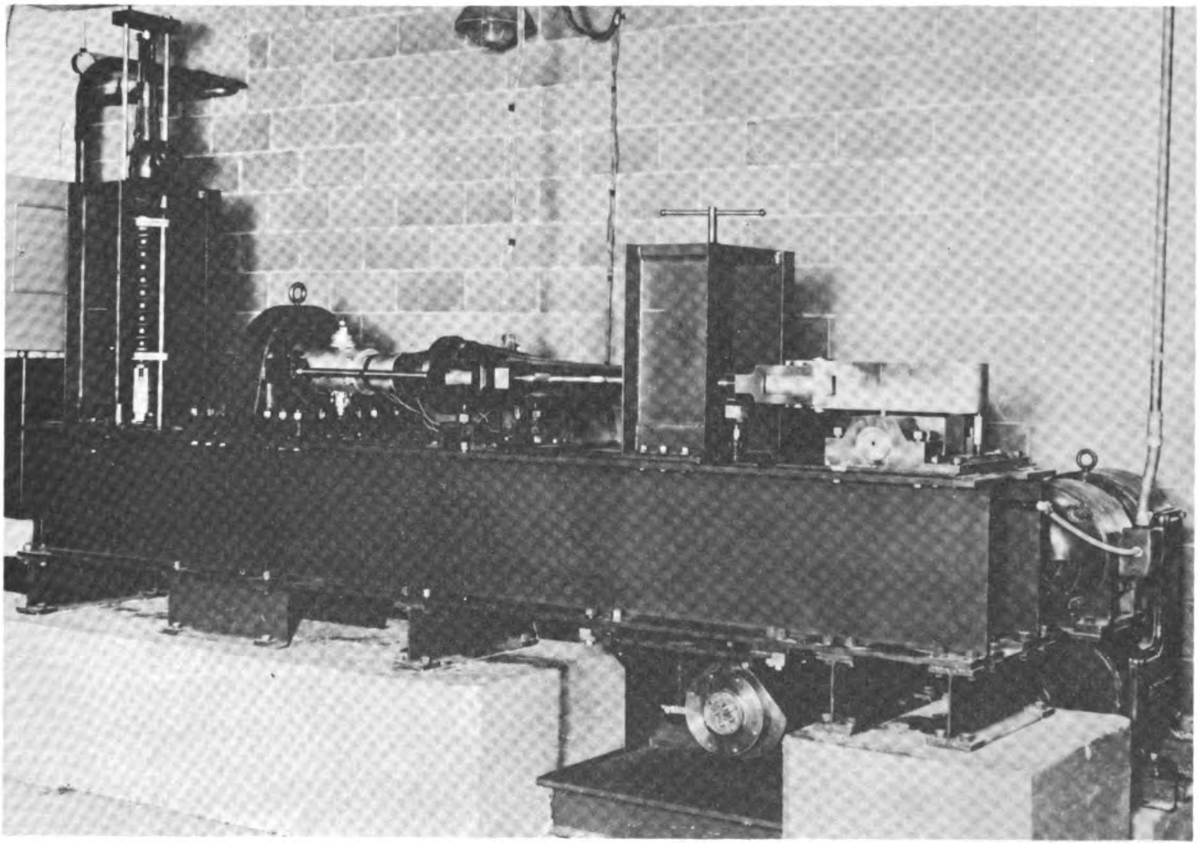

Figure 10.15.—Shank and retention test machine.

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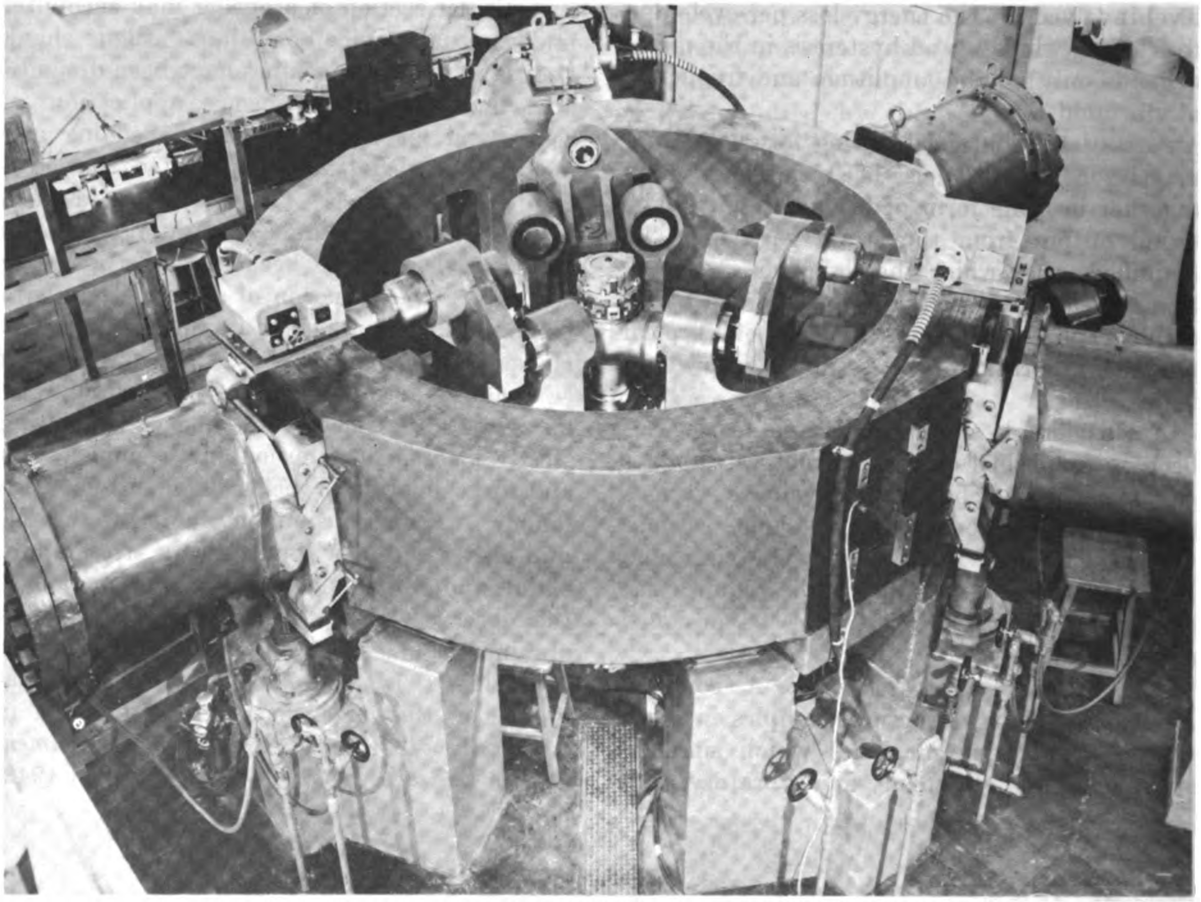

Figure 10.16.—Hub testing machine.

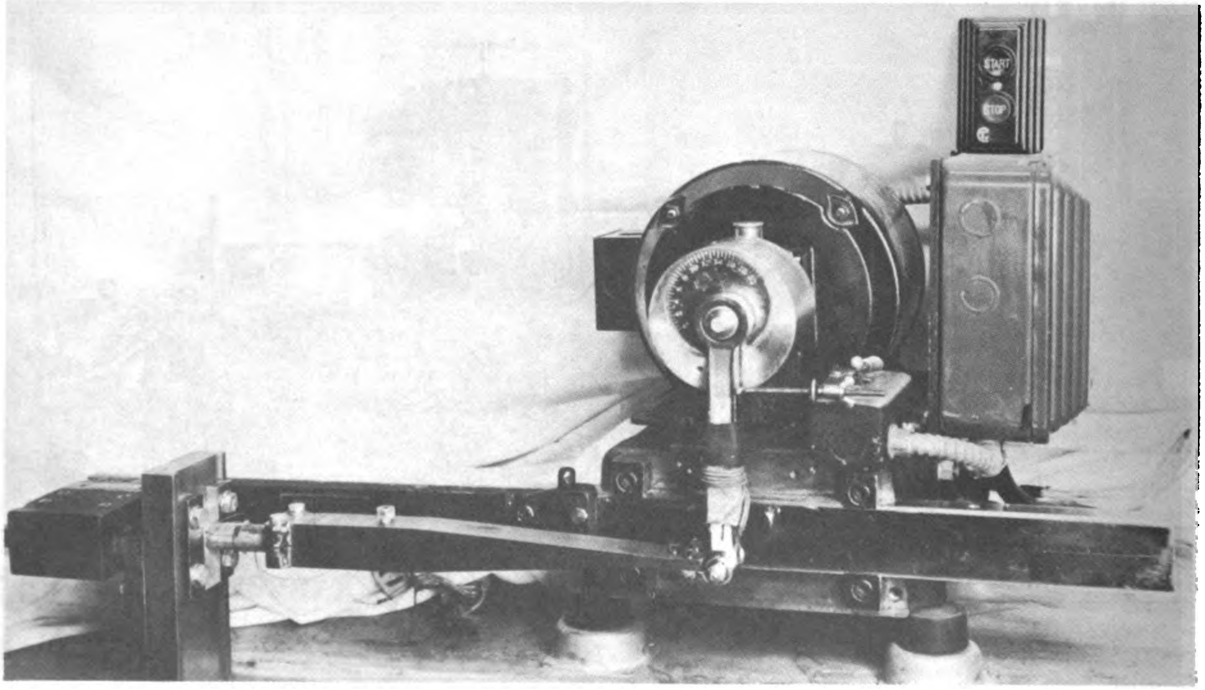

Figure 10.17.—Swivel pin testing machine.

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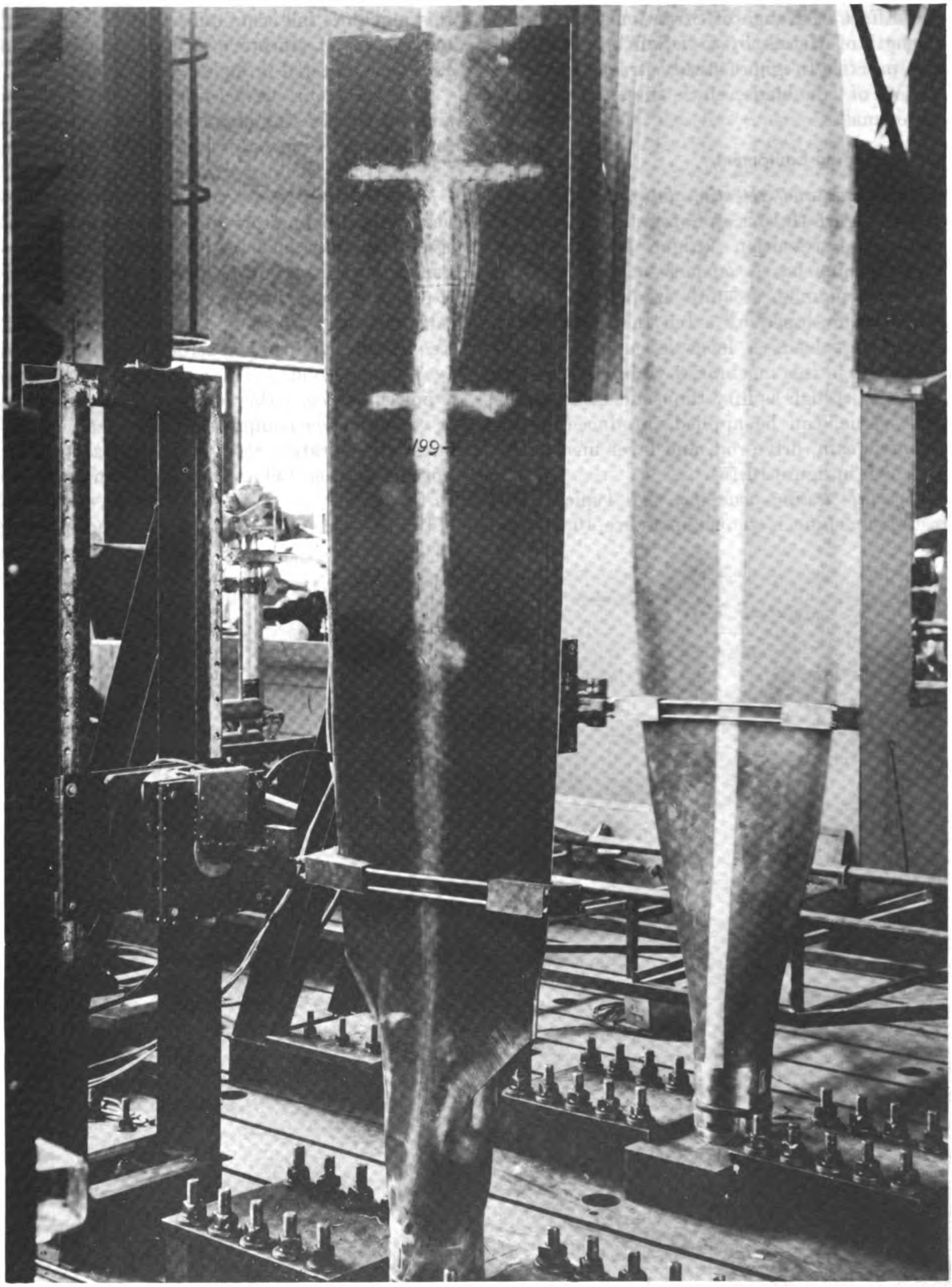

Figure 10.18.—Resonance Blade test.

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The Effect of Range of Stress on the Fatigue Strength of Metals, by J. O. Smith.) It is common practice to ignore steady stresses in the tip section of the blade, since these stresses are quite small.

Fatigue Testing Equipment

(1) *Shank and retention fatigue testing machine.* Figure 10.15 is a photograph of a typical shank and retention fatigue test machine. This machine has a capacity of two hundred thousand pounds, steadily applied axial load which is developed by a ten thousand pound spring that loads a lever assembly. Simultaneously, in this machine, a vibratory bending moment, as high as fifty thousand inch pounds peak value, can be applied (produced by an eccentric cam, drive rod, and lever mechanism as shown in figure 10.15).

(2) *Hub testing machine.* A typical hub testing machine is shown in figure 10.16. In this machine, full scale hubs may be subjected to steady and vibratory stresses equivalent to those encountered in flight.

(3) *Swivel pin (rotor) testing machine.* The adaptation of a standard Krause plate machine for use as a helicopter rotor tail swivel pin test machine is illustrated in figure 10.17.

(4) *Resonance test equipment.* Electromagnetic vibration motors have been used extensively for resonance testing of propeller components. This type of equipment is available to operate over a wide range of output force ratings (a few to thousands of pounds with frequencies ranging from zero to fifteen hundred cycles per second). These units may utilize as a power source, either audio power amplifiers or rotary power equipment. A typical electromagnetic vibration test setup used at the Air Force Propeller Laboratory is shown in figure 10.18.

In this instance, propeller blades were

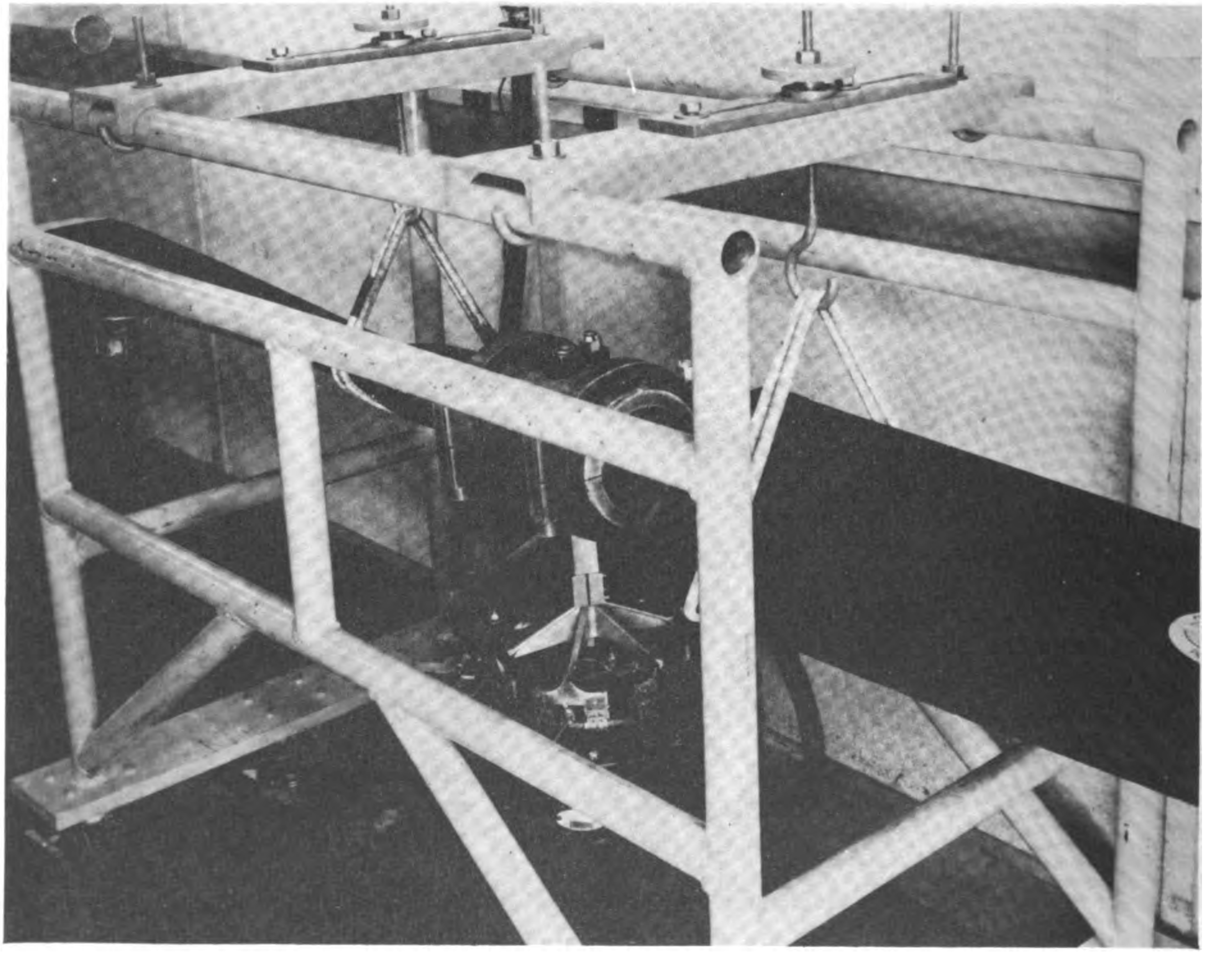

Figure 10.19.—Fatigue test set-up for blade pair.

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being subjected to test with the blade root clamped and an exciting force applied outboard. Under conditions imposed, the blades were vibrated in an edgewise bending mode.

In some cases it may be desirable to test propeller blades in pairs, with the exciting force applied at the geometric center of the configuration. A test set up in this manner is illustrated in figure 10.19.

The schematic diagram shown in figure 10.14 illustrates the use of a vibrator motor to test blades in bending with the root effectively unrestrained. In this case, the greatest vibratory stresses will be developed in the mid-blade and tip regions.

Baffle Test of Propellers

The technique of baffle testing has been developed in an attempt to simulate, in the laboratory, actual steady stress distribution for prediction of vibration modes occurring under service conditions. This technique involves the use of a baffle plate placed in a position downwind of the propeller and parallel to the plane of propeller rotation. The baffle, if properly sized and placed, will induce large aerodynamic loads on a propeller. By elevation of operating stress to failure levels, this type of test will become a form of destructive fatigue testing. A typical test set-up has been shown in figure 10.13.

Wind Tunnel Testing

Wind Tunnel Data Requirement

Theoretical analysis, strongly supported by mathematical calculations, contributes heavily to evolution of new propeller developments. However, rational methods always reach unexplored regions in theory that are beyond current experience. Therefore, in an attempt to solve propeller problems, assumptions have been substituted for unknown facts. In the field of fluid flow especially, any rigorous mathematical analysis will lead inevitably to non-linear differential equations for which solutions are unknown. To obtain solutions, simplifying assumptions must be made which will change the general equations to special linear forms. Hence, proof of the theory evolved must rest, finally, on experimental data. In the field of propeller aerodynamics, the primary tool for obtaining such data is a wind tunnel. Most standard textbooks of aerodynamics discuss wind tunnel design and testing techniques, adequately. Therefore treatment of those subjects will not be presented in this handbook. Data to be obtained during wind tunnel tests will be established by consideration of the propeller test objective. Aerodynamic studies must be made to determine section and overall propeller efficiencies under various operating conditions. Variables involved in wind tunnel testing include: propeller speed, power, Mach number, Reynolds number, and blade angle. Accumulation of this data including pressure determination will permit calculation of: power, thrust, torque, moment and pressure coefficients, along with advance ratio and propulsive efficiencies.

Primary Objective of Wind Tunnel Testing

In general, the primary objective of wind tunnel testing is to duplicate, as closely as possible, flight conditions and determine by accurate measurement the forces and stresses to which a propeller will be subjected in order to predict propeller flight performance. Generally, wind tunnel testing is done on small scale models because the cost of construction and operation of full scale wind tunnels would be prohibitive. However, extensive experience has shown that final full scale flight performance can be predicted, with reasonable accuracy, from proper treatment of small scale wind tunnel test data. Aerodynamically, scale is not a function of size, strictly, but of Reynolds number which, by definition, includes velocity, density, size and viscosity. For example, if testing is performed at higher density than that which will be encountered in flight, the effective scale or Reynolds number of the tests will be closer to full scale condition than a simple ratio of physical dimensions would indicate. While most propeller tests are conducted on small models, every attempt is made to duplicate full scale conditions in every respect except size. Ideally, the following conditions should obtain in any wind tunnel test of a propeller:

(1) Full scale values of power coefficient (C_P).

(2) Full scale Mach numbers, both axial and rotational.

(3) Model should have exact geometrical similarity to the full scale propeller (solidity, activity factor, number of blades, airfoil camber, pitch distribution, thick-

ness distribution and airfoil type, should be small scale replicas of the full scale propeller).

(4) Data should be expressed in terms of dimensionless coefficients, i. e. advance ratios, power and thrust coefficients, to permit direct application of the data to full scale propellers by substitution of appropriate dimensions.

For any combination of existing wind tunnel and propeller dynamometer, it is not possible, usually, to achieve all idealized conditions. Compromises must be made to adapt the desired testing program to available equipment.

Interpretation of Wind Tunnel Data

In addition to pure aerodynamic data, much valuable information pertaining to structural aspects and dynamic response of propellers to applied forces can be obtained in wind tunnel tests. The most difficult problem encountered in such tests will be one of interpretation of the results in terms of full scale propellers. Inasmuch as small models have been of solid construction while many full scale propellers were hollow, the dynamic similarity between model and full scale propeller has been questionable. The usefulness of wind tunnel tests has been confined to determining changes of dynamic response of a propeller with respect to changes in geometry rather than for prediction of absolute force values to which the propeller will be subjected. Nevertheless, the importance of such fundamental data should not be underestimated.

Wind Tunnel Equipment

(1) *Requirements.* Wind tunnel equipment and testing techniques are constantly changing. Each time a wind tunnel test program becomes advisable, a survey of the current status of available wind tunnels, propeller test equipment and latest testing techniques must be made to ascertain the type and extent of program which will meet the requirements. In order to test model propellers in wind tunnels, a propeller dynamometer must be provided. A dynamometer, essentially, consists of a cradle type electric driving motor mounted in a stream line capsule with suitable torque and thrust measuring devices by means of which aerodynamic characteristics of model propellers can be

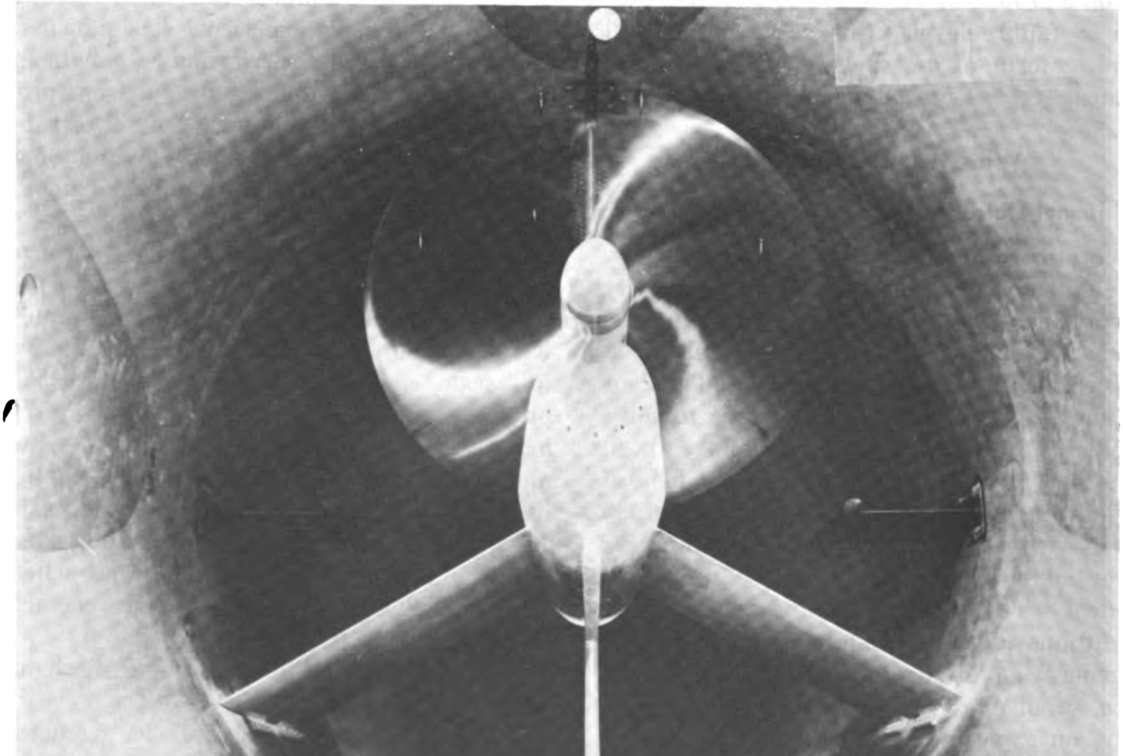

Figure 10.20.—NACA dynamometer.

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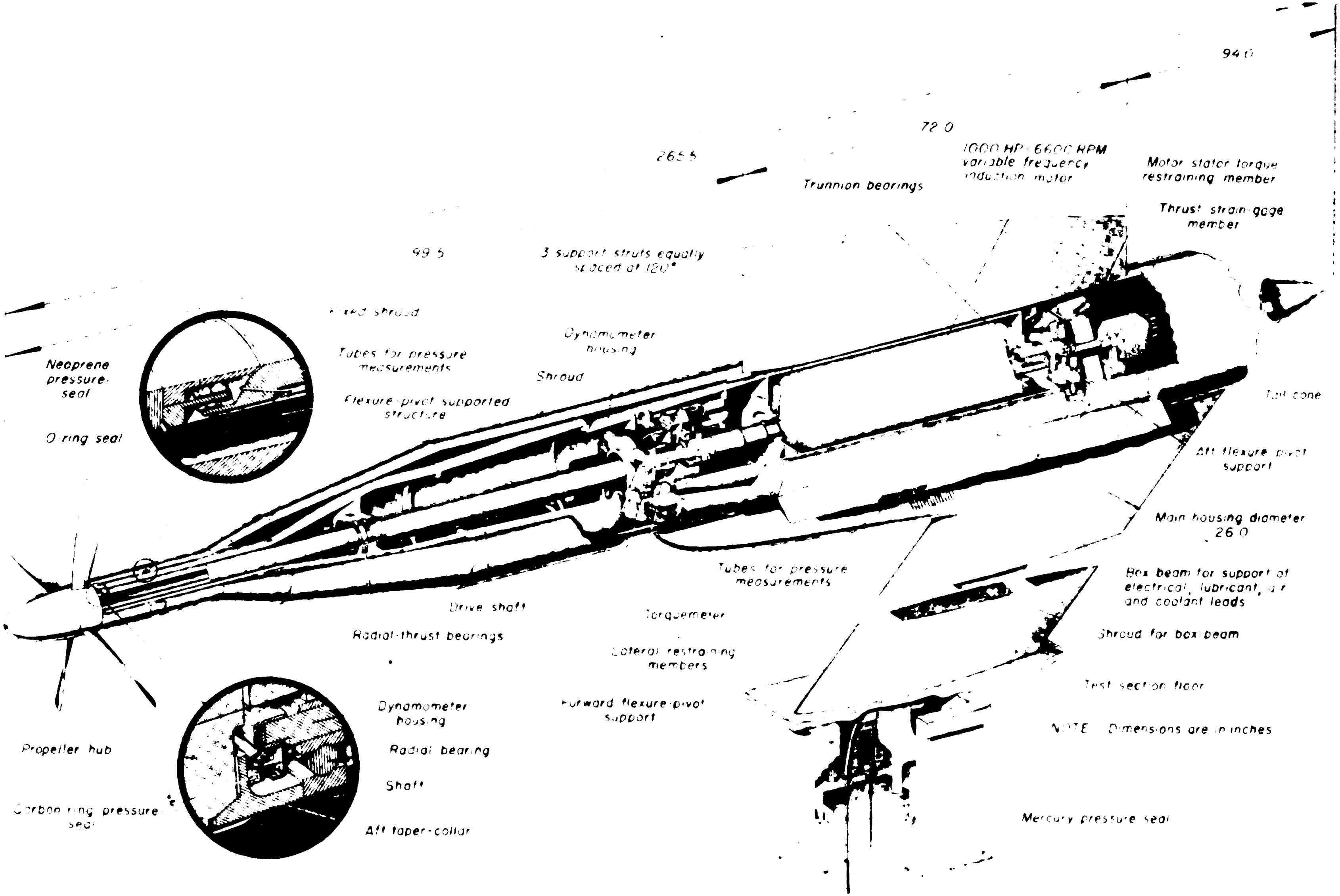

Figure 10.21.—NACA dynamometer cross-sectional view.

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determined. The requirements of dynamometers depend on type and range of data desired and the wind tunnel characteristics. The characteristics of wind tunnel equipment can be depicted best by description of some existing dynamometers.

(2) *NACA dynamometer* (*1000 h. p.*). (*a*) General Arrangement. A photograph of the NACA 1000 horsepower dynamometer mounted in the Ames twelve foot wind tunnel is shown in figure 10.20. This dynamometer has a nominal rating of one thousand horsepower at sixty-six hundred revolutions per minute. Continuous speed control of a two-pole constant torque induction motor can be obtained through a variable frequency power supply.

Essentially, the dynamometer structure is made up of two major subassemblies, namely, the fixed external housing and the floating dynamometer unit. These subassemblies are interconnected structurally at only two flexure-pivot supports as shown in the cross-sectional view of the dynamometer in figure 10.21.

The shroud, main housing, tail cone, support struts, box beam shroud, thrust strain gage members, and motor-stator torque restraining member make up the fixed external housing assembly. The propeller, spinner, hub, drive shaft, torquemeter, motor box beam, and dynamometer housing subassembly constitute the floating unit of the dynamometer. The flexure-pivot supports prevent lateral motion and carry the weight of the floating dynamometer unit. When deflected longitudinally by a thrust loading, the flexure-pivot supports have enough stiffness to produce a stabilizing moment equal to the destabilizing moment produced by the floating unit of the dynamometer. Therefore, the floating subassembly, as suspended on flexure-pivot supports, is stable longitudinally.

A pair of cantilever beam strain gage members permit measurement of dynamometer thrust and restrain the floating unit of the dynamometer from longitudinal motion. The line of action of the stream gage links is in the horizontal plane containing the dynamometer center line and parallel to the center line. The links are equidistant from the dynamometer center line.

The motor-stator is supported in the dynamometer housing on trunnion bearings. Rotation of the stator is prevented by a pair of forked torque arms, supported by radial bearings mounted in a structure attached to the main housing. The torque arms are attached to the motor-stator so that reaction forces in the arms form a couple with reference to the dynamometer center line. The inner races of the radial bearings, supported by the fixed structure, are rotated continuously in opposite directions by a motor drive, so that only the difference between rolling friction of the two bearings will be present in the thrust system. In this system of stator support and stabilization, the flexure-pivot supports do not transmit reaction torque loadings of the stator to the fixed housing structure. Hence, the torque arm fork and radial bearing arrangement permit nearly frictionless longitudinal movement of the floating unit with the motor-stator restrained from rotation.

(*b*) Dynamometer Air Pressure Control. Complete control of air pressure inside the dynamometer relative to air pressure in the test section should be maintained during operation of the dynamometer. In operation, air will be introduced into the dynamometer during actuation of the torquemeter brush-advance mechanism, for cooling torquemeter brushes, and through the oilmist lubrication system of the motor and drive shaft bearings. Air and oilmist is ejected from the dynamometer by vacuum pumps. Three pressure seals (see fig. 10.21) are employed to separate the dynamometer system from the tunnel. A flexible, continuous (circumferential) neoprene pressure-seal joins the floating dynamometer unit to the fixed shroud, a short distance behind the propeller spinner. A carbon ring, bonded to a flexible molded-neoprene diaphragm is spring-loaded to make contact with the aft face of the rear propeller hub taper-collar. This diaphragm provides a pressure seal between dynamometer housing and rotating drive shaft. A mercury pressure seal, located beneath the box beam shroud in the tunnel balance chamber, separates the interior of the dynamometer from the balance chamber. All electrical, lubricant, air and collant leads to the dynamometer pass through airtight packing glands in the floating member of this mercury pressure-seal.

(*c*) Instrumentation of the Dynamometer. Instrumentation has been provided in the dynamometer for measuring thrust force necessary to restrain the floating dynamometer unit,

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drive shaft torque, drive shaft rotational speed, and pressures inside and outside of the fixed and floating portions of the dynamometer. Thrust forces can be measured by means of two cantilever beam resistance-type strain gages, which may be designed for any thrust up to the limiting load of the dynamometer radial thrust bearings. The output of the strain gage system will be reflected on a scale of a self-balancing potentiometer. Calibrations of strain gages must be made to establish the relationship between potentiometer readings and applied thrust loads.

The torque developed in the drive shaft can be measured by means of a variable inductance torquemeter which has a nominal torque capacity of 800 pound-feet. Output of the torquemeter will be indicated on a manual balancing potentiometer. The torquemeter must be calibrated to determine the effect of rotational speed on the relationship of potentiometer reading and applied torque. Torque calibrations which were made with torquemeter rotating show indicated torque error to be less than five-tenths of one percent of rated torquemeter capacity through the torque range, zero to about one-third maximum capacity of the torquemeter, and less than one percent of rated torquemeter capacity for torque in excess of one-third maximum rated capacity.

Output of an eight pole variable reluctance, alternating current generator mounted on the aft end of the motor shaft will be transmitted to a logarithmic frequency meter which will indicate rotational speed of the drive shaft. Accuracy of five one-hundredths of one percent of indicated speed can be obtained, in the speed range between 240 and 6600 r. p. m.

Pressures existing inside and outside of the neoprene pressure seal, used in applying spinner base pressure thrust corrections, can be obtained from a manometer.

(*d*) Dynamometer Adaptability. The NACA single-rotation propeller dynamometer described can be converted for tests of dual rotation propellers by removing a portion of the dynamometer housing ahead of the forward flexure-pivot support and substituting, in its place, a

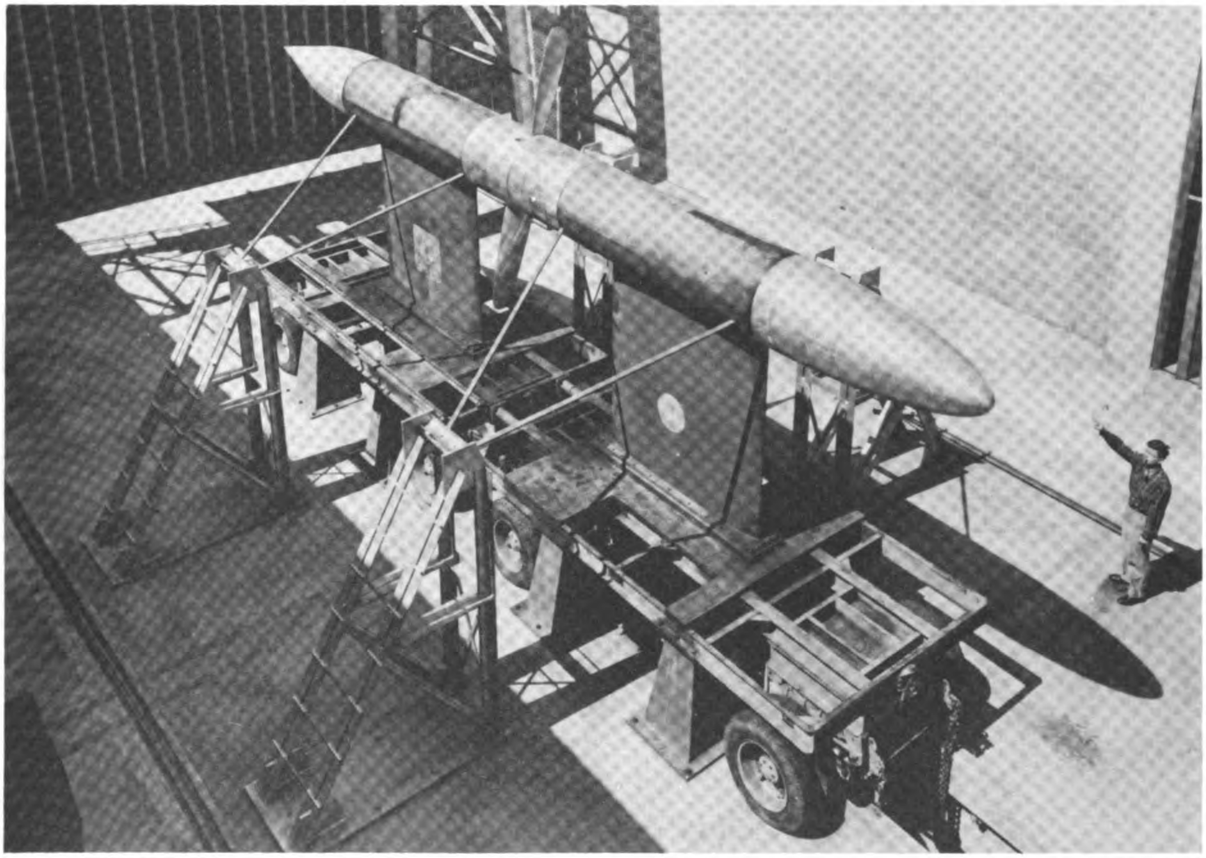

Figure 10.22.—NACA 6,000 h. p. dynamometer.

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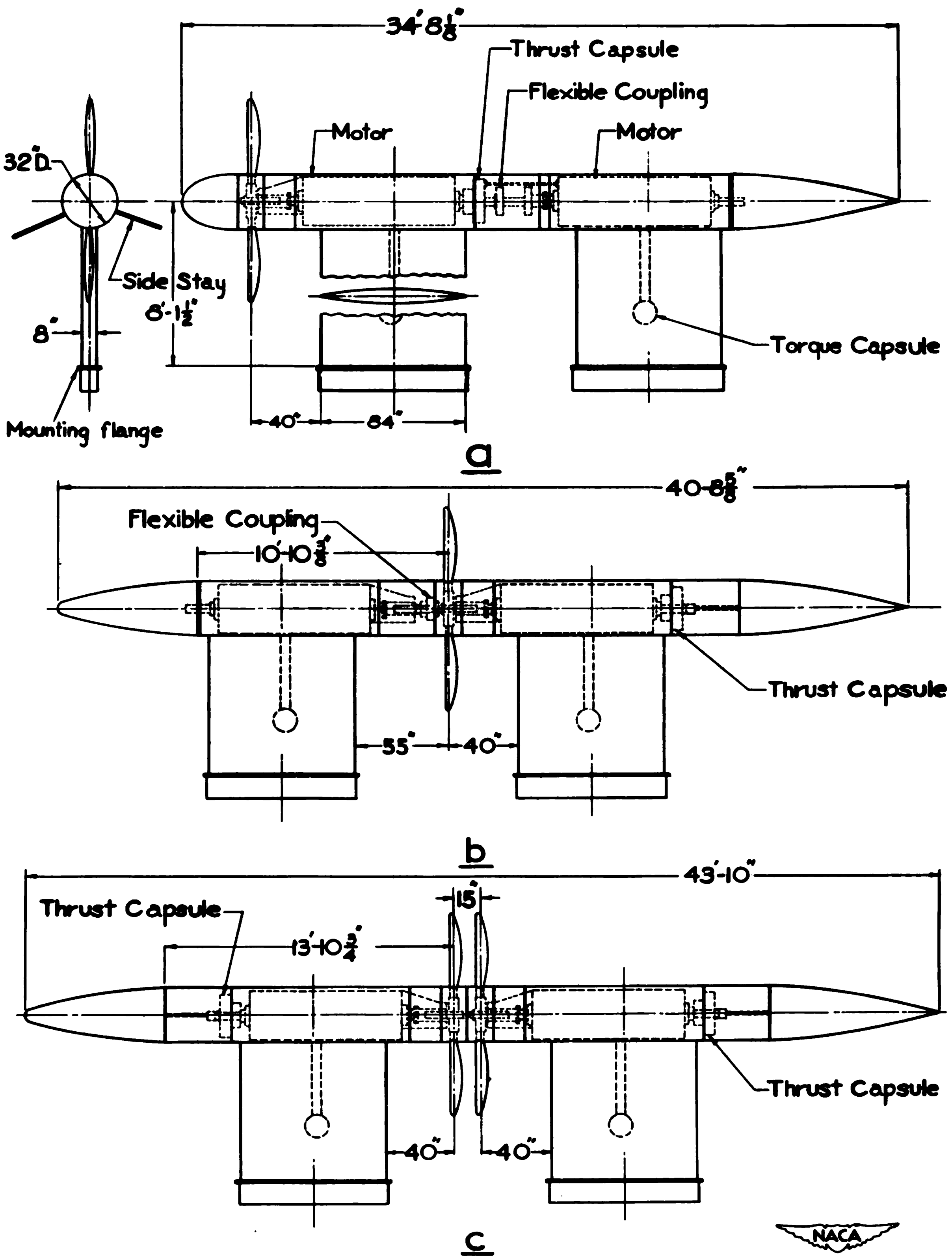

Figure 10.23.—NACA 6,000 h. p. dynamometer arrangements.

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dual rotation unit. The dual rotation unit must contain concentric shafts with separate torquemeters (four hundred pound-feet capacity each) and a gear box for reversing the direction of rotation of the outer shaft.

(3) *NACA 6000 Horsepower Dynamometer.* (*a*) General equipment arrangement and capacity. The NACA six thousand horsepower propeller dynamometer of the Langley 16 foot wind tunnel is a research device for determining aerodynamic characteristics of large scale propellers. A photograph of the dynamometer is shown in figure 10.22.

The dynamometer consists of a pair of 3000 h. p. units that can be operated independently. Joint operation with the two power units connected will provide a 6000 h. p. unit.

The three principal arrangements of the dynamometer are shown in figure 10.23.

Various arrangements of the thrust capsule make it possible to determine propeller characteristics in the presence of a hub fairing or air inlet cowling (fig. 10.23a) and without hub fairing or air inlet interferences (figs. 10.23b and 10.23c). The propeller blades shown in figure 10.23c are arranged in two stages; each stage can be rotated in either direction, independently of the other.

The dynamometer can measure torque in magnitude up to 12,000 ft-lb. within a speed range of 300 to 2400 revolutions per minute. Propeller thrust of +40,000 to −12,000 pounds can be measured over the same speed range. The dynamometer is driven by 4600 volt, three-phase, water cooled induction motors with hollow shafts. Each motor is rated at 3000 h. p. for a time interval of one-half hour or 4000 h. p. for an interval of five minutes. Spacing between the two stages shown in figure 10.23 can be varied from about 12 inches to 27 inches. However, existing hub fairings are 15 inches and will accommodate blade chords up to 12 inches.

(*b*) Thrust and Torque Measurements. In

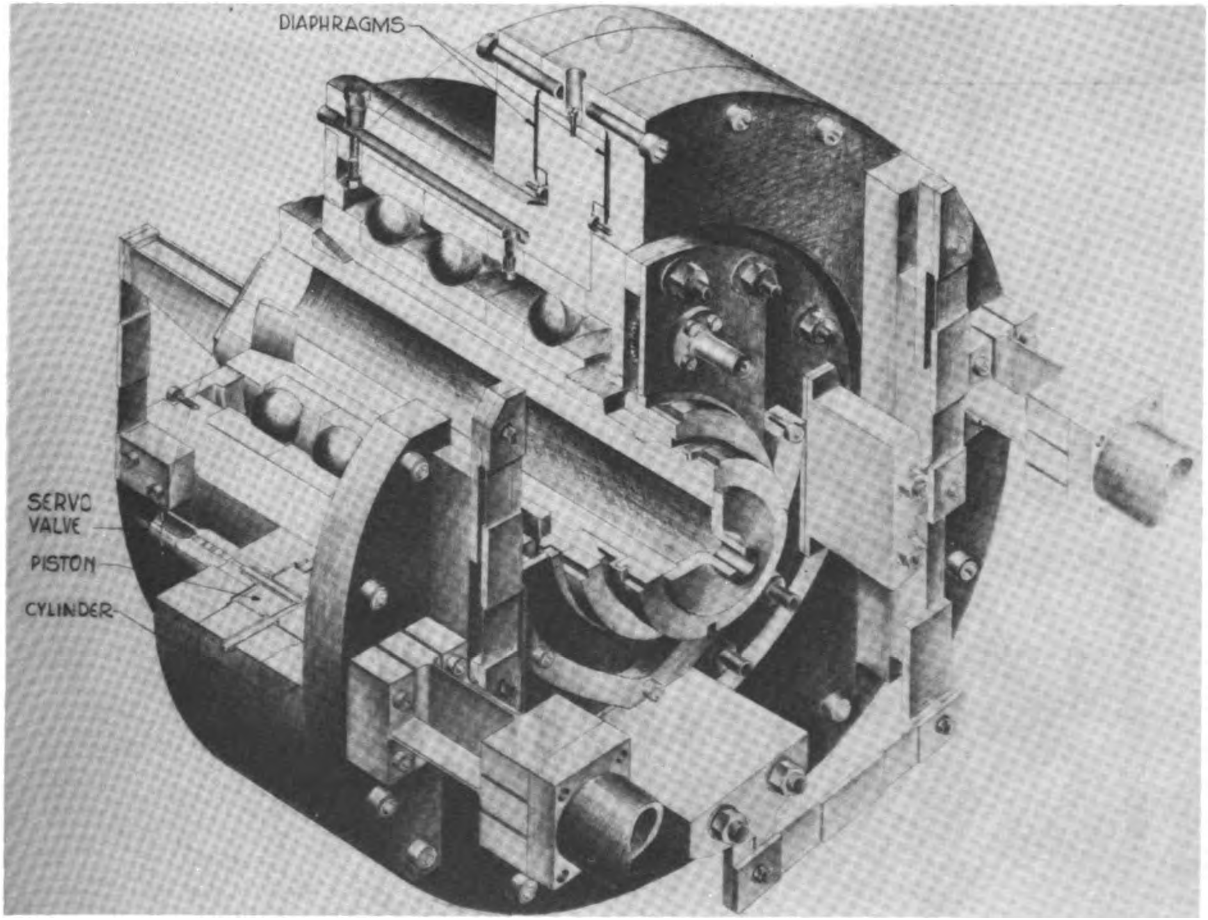

Figure 10.24.—Thrust capsule NACA 6,000 h. p. dynamometer.

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the NACA 6000 h. p. dynamometer, thrust and torque measurements can be obtained by balancing thrust and torque reactions of the propeller using calibrated pneumatic capsules. A thrust pneumatic capsule in this dynamometer consisting of three major parts, namely: piston, cylinder and servo valve is shown in figure 10.24.

Diaphragms are used to seal the gaps between pistons and cylinders. The servo valve consists of two parts, one part fixed to the cylinder and the other actuated by piston movement. Capsule cylinders are fixed in the direction of applied reaction. When reaction varies, the piston moves and the servo valve adjusts air pressure so that piston force is equal to applied reaction. In order to measure negative reaction, the capsule must be preloaded by applying air pressure to the opposite side of the piston. Pressure differential on the two sides of the piston will indicate reactions, which makes the system independent of ambient pressures. In order that measurements of thrust and torque reactions do not include frictional and interacting forces, a system of flexure plates must be used to support the capsule cylinders and drive motors.

A torque capsule which operates in the same manner as the thrust capsule is shown in figure 10.25.

The propeller and capsule pistons are mounted rigidly to the motors. Figure 10.26 shows the motor support flexure plate system which is employed at each end of the motors.

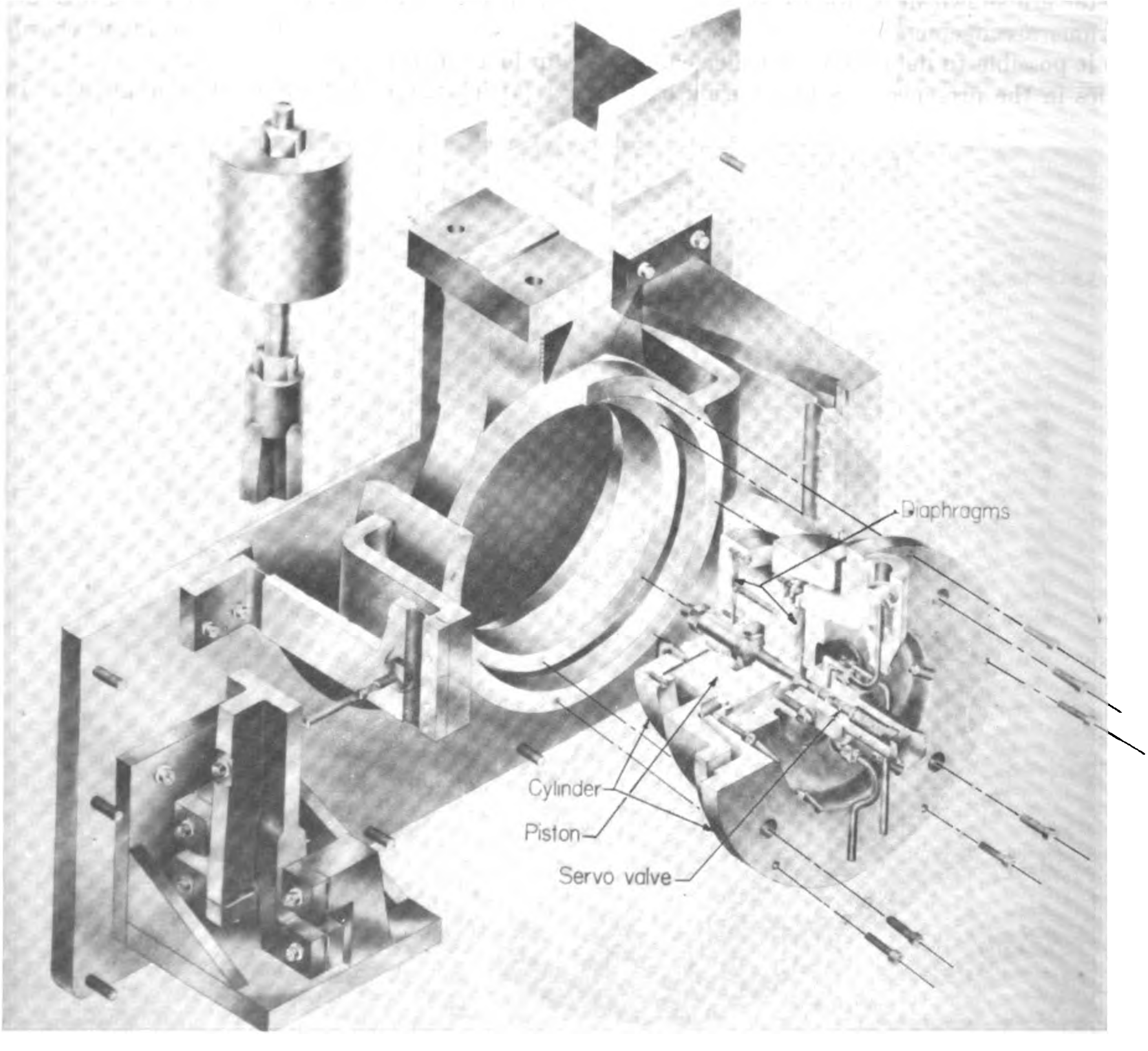

Figure 10.25.—Torque capsule NACA 6,000 h. p. dynamometer.

The motors, capsule pistons, and test propellers are given a small degree of freedom of movement both axially and rotationally in this system.

(*c*) Other Instrumentation. In operation, dynamometer thrust and torque reactions may be obtained simultaneously, from direct reading scales. Any speed may be preset on an indicator so that speed of the drive motor may be adjusted until indicated and actual motor speeds are equal. Conventional aircraft tachometers have been installed to obtain approximate speed indication. Speeds within the range 1175 to 1225 r. p. m. must be avoided because of peculiar drive equipment characteristics. Blade settings may be measured with a spirit level for test of ground adjustable blades. The pitch adjusting mechanism of variable pitch propellers must be coupled with a calibrated pitch indicating instrument.

(4) *Cornell propeller dynamometer.* (*a*) Dynamometer Drive System. The Cornell propeller dynamometer differs from the other NACA dynamometers that have been discussed, principally, in the drive system employed. Major components of the three dynamometers are the same. However, the Cornell dynamometer also contains two magnetic couplings, three sets of bevel gears and one planetary gear system for each shaft. Two 1000 h. p. synchronous motors are located outside and behind the working section of the tunnel. These motors are placed upon a platform attached to the north and south legs of the tunnel. Also, the two magnetic couplings as well as the first set of bevel gears are located on this supporting platform. As shown in figure 10.27, the motor drive shafts enter the tunnel sphere below the working section floor, the change in plane of rotation being accomplished by use of right angle bevel gears.

From point of entrance, the shafts rise vertically, again using bevel gears to transfer drive to the nacelle. Inside the nacelle, the shafts become coaxial by use of another set of bevel gears. A planetary gear system has been placed in each drive system between propeller attachment and last set of bevel gears (counting

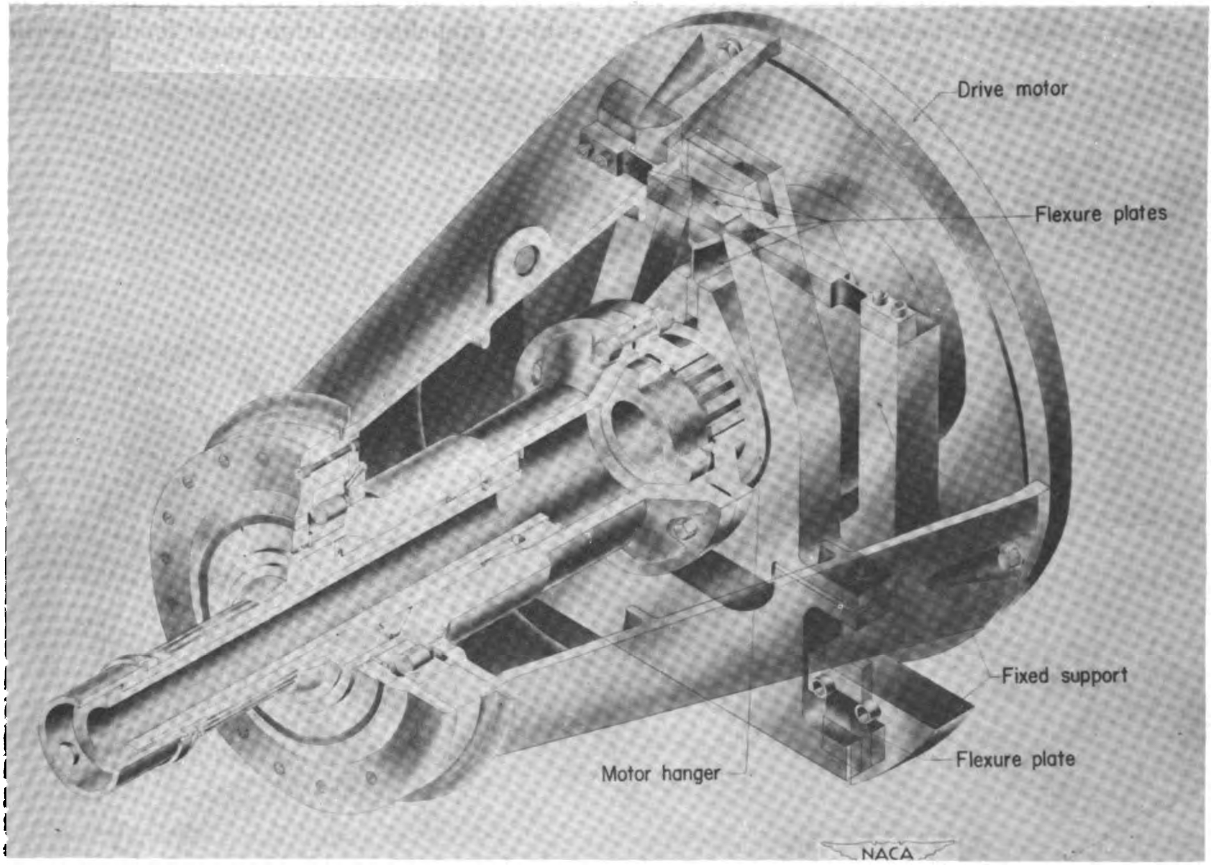

Figure 10.26.—Motor support flexure plate system.

sets from the motor) to simplify measurement of thrust and torque. Rubber couplings have been inserted in the extension shaft to minimize the range of torsional vibration critical frequencies in the system. Nacelle and pedestal have been mounted permanently on a cart which forms the wind tunnel test section. The dynamometer may be removed from the tunnel by disconnecting the shafts at a point beneath the cart floor and moving the self-propelled cart along permanent steel rails, out of the tunnel.

(*b*) Power Speed Range. The power supply system consists of two 4,800-volt, 3-phase, 60-cycle, alternating-current synchronous motors using magnetic couplings for speed control. Each propeller shaft has a maximum rating of 1,000 h. p. at speeds ranging from 3,750 revolutions to 8,200 revolutions per minute. Power ratings of the propeller shafts at speeds less than 3,750 revolutions per minute are fixed by characteristics of the drive system. The speed control of each propeller shaft for any drive arrangement can establish true shaft speed within one-fourth of 1 percent of the selected shaft speed throughout a speed range from 3,750 to 8,200 revolutions per minute. Below a speed of 3,750 revolutions per minute, the true shaft speed will not differ from selected speed by more than one-fourth of 1 percent of 3,750 revolutions per minute. The propeller shafts are so designed that they may be rigidly coupled together. Hence, single rotation propeller testing for power absorption up to 2,000 h. p. through the entire speed range may be provided. Alternate arrangements permit single rotation testing on either shaft or dual rotation testing.

(*c*) Distinctive Physical Characteristics. Dimensions of the nacelle structure are considerably less than those of the NACA 2,000 h. p. dynamometer. Maximum diameter of the Cornell dynamometer nacelle is 12 inches as compared to 36 inches diameter of the NACA dynamometer. This small diameter permits a more realistic relation between propeller-nacelle size in comparison to airplane installations. Furthermore, extension shaft, gears, and bearings introduce a number of problems into design and operation of the Cornell dynamometer that are not present in NACA installations. In the absence of relatively large diameter electric motors in the tunnel throat, it is possible to subject propellers to large power loading in the

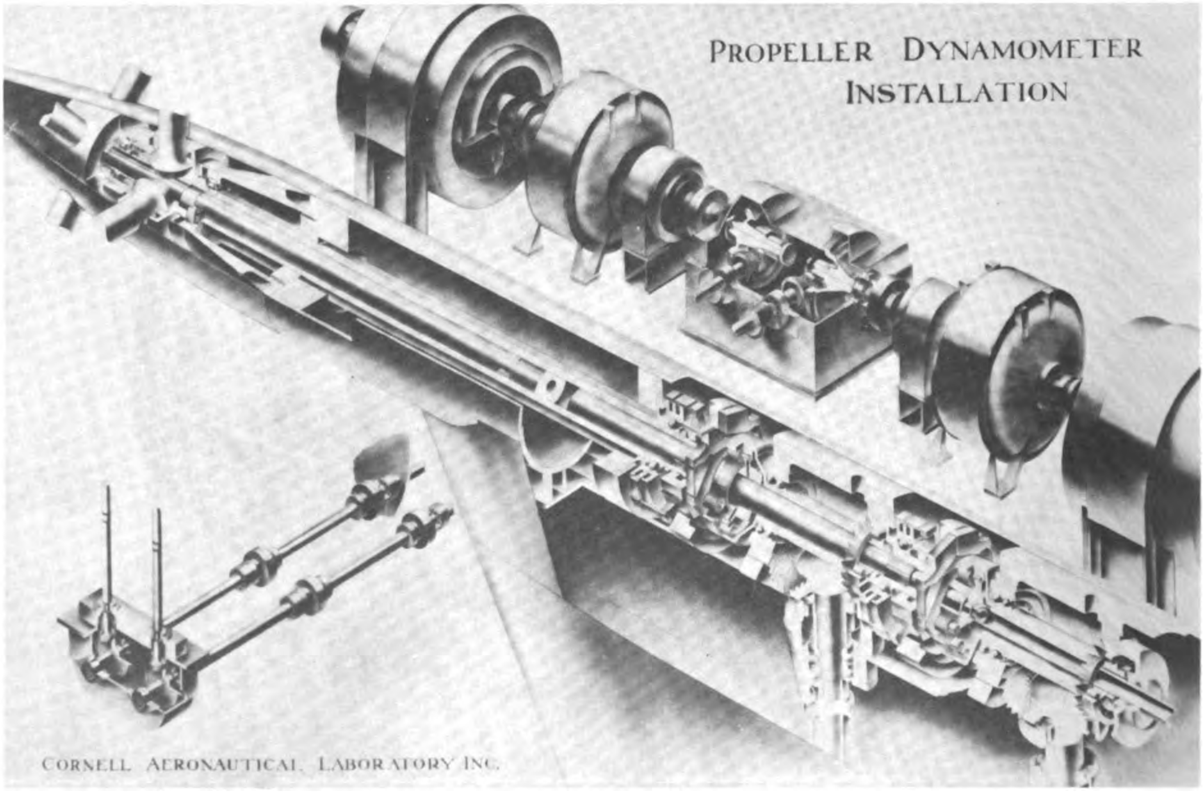

Figure 10.27.—Cornell propeller dynamometer.

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Cornell installation, obtaining tunnel Mach numbers greater than 0.90 without wind tunnel choking.

Propeller Aerodynamic Flight Testing

Flight Test Methods

(1) *Scope.* Flight test methods in general, including those employed in obtaining test data and those used in reduction of data obtained, are considered beyond the scope of this handbook. This exposition will consider only methods of analysis and specialized instrumentation and techniques related to propeller aerodynamic flight testing.

(2) *Methods of comparative analysis.* Methods of comparative analysis of standard performance flight test data are used, frequently, for evaluation of propeller performance. But these methods are valid only when applied to data obtained by flight test of two or more propellers on the same airplane. Comparative analysis of propellers is made on the basis of one or more of the following comparisons in which the data used is that obtained during actual flight test:

(*a*) Speed versus power at constant density altitude.

(*b*) Rate of climb versus altitude at specified conditions of power and air speed versus altitude.

(*c*) Takeoff distance at constant power.

Performance of propellers may be adjudged by comparing the variation of:

(*i*) Brake horsepower required at constant speed and density altitude.

(*ii*) Rate of climb at constant density altitude, brake horsepower, and air speed.

(*iii*) Takeoff distance at constant power.

In the first case, the ratio of propulsive efficiences of propellers being compared will be equal to the inverse ratio of brake horsepower required. In the other case, only relative performance of propellers being compared, in terms of the airplane performance variables involved will be obtained.

Precaution to be Observed in Obtaining Flight Test Data

Special precautions must be observed to insure that all test data will be comparable. Since a change in drag will affect airplane performance to the same degree as an equal change in thrust, it becomes necessary to identify the cause of any change in performance. Changes in external configuration of a test airplane should not be permitted during conduct of a test program. The test airplane should be washed down at frequent intervals to prevent any accumulation of dirt on the surfaces. Airplane speed will be affected by change in position of cowl flaps, inter-cooler flaps or oil cooler flaps when operating at constant power. Therefore, it is apparent that automatic flap control, under varying atmospheric conditions, for different propellers will introduce uncontrolled variables that affect the data to such an extent as to make the results useless. If, however, calibrated instrumentation for measurement of various flap angles were installed and the flaps operated at constant angle during each flight, temperature changes in the internal flow systems would result in variation of internal drag which would affect airplane performance. It would be possible, by installing extensive instrumentation, to evaluate the internal drag. However, such an undertaking would lead to more work than would be involved in measurement of propeller thrust, directly.

Propeller Flight Test Specilized Instrumentation

(1) *Types of thrust measuirng devices.* Use of either a thrust meter or a wake survey rake will permit comparison of relative propulsive efficiences of two or more propellers, independently of airplane drag. Furthermore, comparison can be made of relative propulsive efficiences of propellers on the basis of advance ratio or power coefficient, within limitations of the test airplane. Regardless of the type of thrust measurement used, indicated thrust will include the force required to overcome that airplane drag increment due to increase in slipstream velocity.

(2) *Thrustmeter.* (*a*) Principle of Operation. A thrustmeter is a device used to measure propeller shaft thrust. Usually, the thrustmeter is located in the nose of the propeller reduction gear box near the propeller shaft thrust bearing (regardless whether the gear box is integral with the engine or remotely mounted and connected by extension shafting). A thrustmeter will abosrb thrust bearing reactions and transmit signals, proportional to thrust magnitude, to a suitable indicating device.

Thrustmeter operation may utilize either electric or hydraulic methods of force transfer to appropriate indicators. The electric type thrustmeter utilizes strain gages whereas the hydraulic type utilizes oil pressure variation to reflect the extent of applied thrust variation.

(*b*) Hydraulic Thrustmeter. Essentially, the hydraulic thrustmeter of figure 10.28 is an instrument utilizing high pressure oil in conjunction with a piston to balance propeller shaft thrust.

Several engine modifications must be made to use this instrument, effectively, which include the following:

- (*i*) Axial oil pressure differential between propeller shaft and crankshaft must be eliminated.
- (*ii*) An auxiliary sleeve bearing must be employed in the engine nose to absorb radial loads of the propeller shaft, which will insure that the thrst bearing will be subjected to thrust loads only.

A detailed drawing of the metering valve of a thrustmeter is shown in figure 10.29. Various entrance and discharge ports, along with significant control oil spaces, have been identified by letter designation, in the drawing. Operation of the thrustmeter can be described best in terms of this sketch.

In operation, oil is admitted to the thrustmeter cylinder by two metering valves. Each valve consists of three parts: a housing which is press fitted into the cylinder, a piston which is free to slide fore and aft within the housing, and a spring which tends to force the piston into a closed position.

Oil under pressure enters the cylinder through Port A from which the oil will flow to Annulus B. Upon application of a thrust load to the spacer rear face, by the propeller shaft thrust bearing, the piston will be forced forward. This piston movement, in turn, will actuate the valve piston, which will align Port C and Annulus B. By alignment of Port C and Annulus B, oil

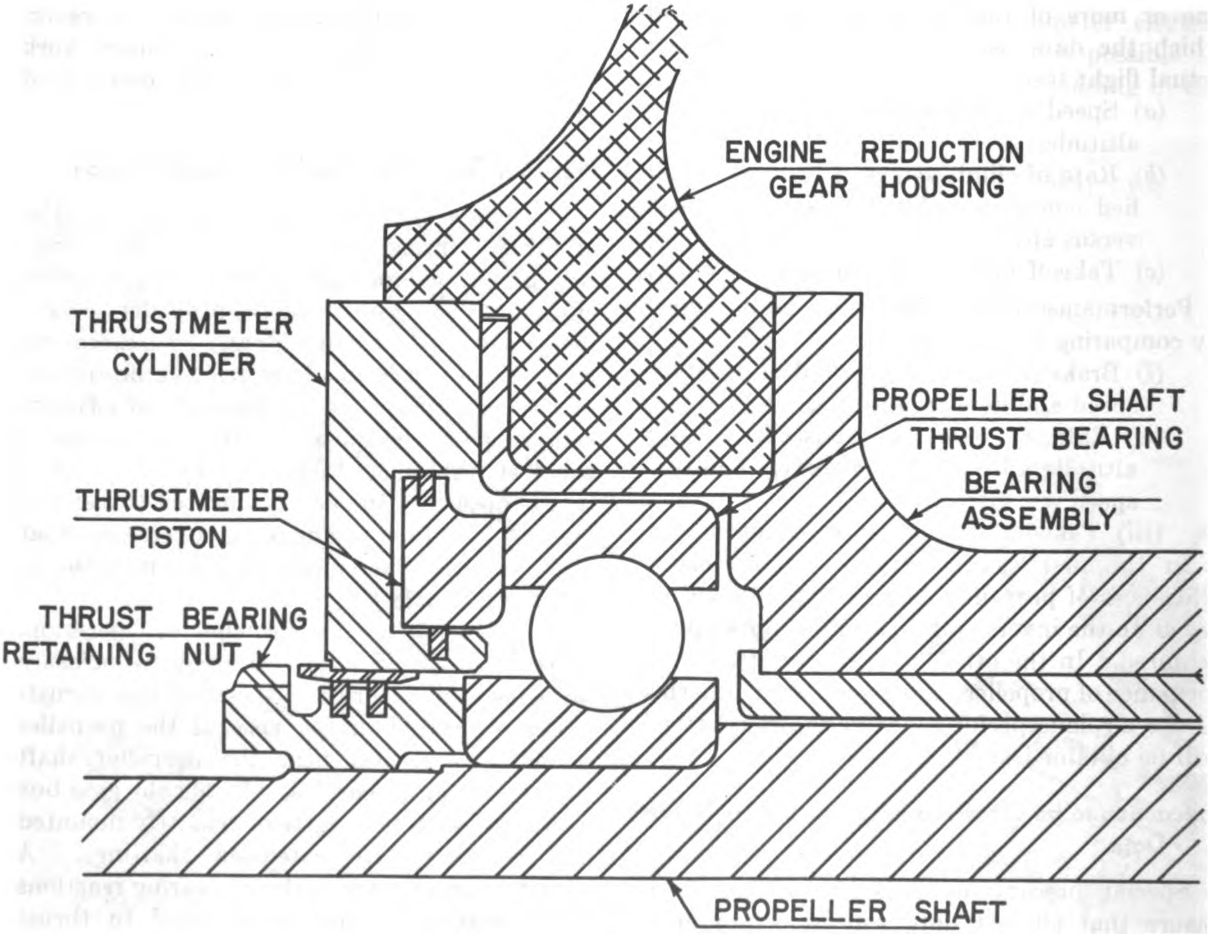


Figure 10.28.—Hydraulic thrustmeter.

under pressure will be admitted to the annular Cylinder E, after passing through the interior of the piston and Port D. After sufficient pressure has been built up to overcome the thrust load, the thrustmeter annular piston will be forced rearward. This action will allow the metering valve piston to move rearward, covering Port C and thereby reducing oil pressure on the spacer.

The sealing rings are not perfect oil seals, hence a very small amount of oil will flow past the rings. Therefore, the valves must be opened, slightly, so that for a given thrust load, incoming oil flow will be sufficient to overcome leakage. Any increase in thrust loading will be absorbed by similar action. For small decreases in thrust loading, closing of Port C and continued leakage past the seal rings will be adequate to produce acceptable response. However, for sudden or large changes of loading, the relatively slow rate of leakage, if unaided, would result in very slow response. When a sudden decrease in thrust loading occurs, excessive oil pressure in the annular Cylinder E will force the thrustmeter piston to its extreme rearward position. When the thrustmeter piston is in the rear position, the release port, F, will be open, relieving the pressure, thereby allowing thrust correction to occur more rapidly. In normal operation, Port F will be closed. The pressure existing in annular Cylinder E will be a direct function of load imposed upon the thrustmeter piston. A pressure gage, calibrated to read load imposed directly, can be used as a load indicator.

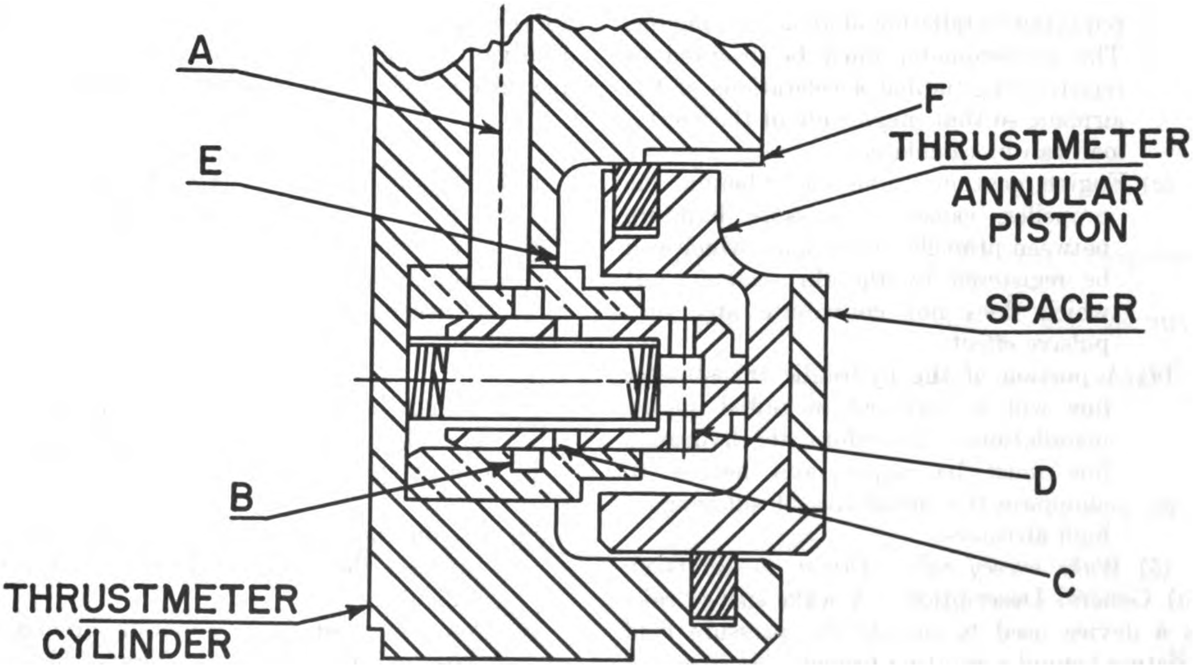
(3) *Analysis of thrustmeter data.* Propeller shaft thrust, corrected for inertia effects, may be inserted into the formula:

$$\eta_s = \frac{T_s V}{550\,BHP} \qquad \text{X-1}$$

in which

η_s = Propeller shaft efficiency
T_s = Propeller shaft thrust (lb.)
V = True air speed (ft./sec.)
BHP = Brake horsepower

Efficiency calculations of this nature may be used in comparing various propellers operated at identical advance ratios and power coefficients as determined from propeller flight test



ENLARGED VIEW
SHOWING METERING VALVE INSTALLATION
IN THRUSTMETER PISTON

Figure 10.29.—Thrustmeter control valve.

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data. Of course, flight test data for different propellers must incorporate similar conditions such as air speed, density altitude, propeller speed and brake horsepower.

(4) *Advantages and disadvantages of thrustmeter use.* Both types of thrustmeter have certain inherent advantages and disadvantages which have been listed in the following paragraph for comparative purposes.

A study of desirability of thrustmeter use must of necessity consider the following:

Thrustmeter Advantages

(*a*) Only one indicator will be required, thereby saving much space in the instrumentation compartment.

(*b*) Only one pressure line need be routed through the airplane.

(*c*) A lengthy data reduction process will not be required.

Thrustmeter Disadvantages

(*a*) Engine nose or gear box must be modified to incorporate the thrustmeter.

(*b*) Inertia effects of propeller and propeller shaft induce an error in indicated thrust requiring installation of an accelerometer. The accelerometer must be oriented to register longitudinal accelerations of the airplane so that magnitude of the inertia load can be calculated.

(*c*) Engine location, immediately behind the propeller, causes a pressure build-up between propeller and engine which will be registered by the thrustmeter, but which does not contribute any propulsive effect.

(*d*) A portion of the hydraulic thrustmeter line will be exposed in radial engine installations. Therefore, the hydraulic line must be lagged and heated to eliminate the possibility of sludging at high altitudes.

(5) *Wake survey rake—Thrust measurement.* (*a*) General Description. A wake survey rake is a device used to sample the pressure field existing behind a rotating propeller at carefully selected points. Integration of pressure readings over the effective area behind an operating propeller, properly corrected, provides a measure of propeller thrust. The principal structural component of a survey rake is a streamlined strut, the axis of which intersects, and is perpendicular to, the propeller shaft axis. Rake heads or probes, which may be total heads only, or total heads in combination with static heads, or yaw heads, are mounted on the leading edge of the rake strut. The rake heads axis are placed perpendicular to the strut axis and parallel to the propeller shaft axis.

(*b*) Location and Number of Survey Rake Heads. A sufficient number of heads must be used to insure satisfactory definition of the shape of the blade loading curve. The heads may be spaced at equal intervals along the rake strut, or heads may be spaced at distances which vary inversely with slipstream radius. In the latter case, survey heads are centered in annular spaces of equal area.

The survey plane of figure 10.30 should be located as close to the propeller as possible. But, location of the survey plane will be determined, largely, by structural considerations of rake mounting. It is important that the survey plane be located, if possible, forward of any obstruction which would affect the slipstream, such as wings or large airscoops.

(*c*) Advantages and Disadvantages of a Survey Rake. The inherent advantages and disadvantages of wake survey rake as a thrust measuring device may be listed as follows:

Advantages

(i) Distribution of aerodynamic loading along a propeller blade can be obtained.

(ii) A rake installation is independent of the power plant and can be interchanged between aircraft.

Disadvantages

(i) Readings must be corrected for the effect of oscillating pressures in the tubing.

(ii) A large space will be required for instruments.

(iii) The number of pressure lines to be routed through the airplane introduces space difficulties.

(iv) Complexity of data reduction prevents data checking between flights; hence, poor data might not be discovered before flight testing has been completed.

(v) Aerodynamic loads imposed on the rakes may necessitate special mounting that will require structural reinforcements in the airframe.

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(*d*) Analysis of Wake Survey Data. Determination of pressure field characteristics by a wake survey rake will permit determination of radial aerodynamic loading distribution in the slipstream. Proper integration of a pressure distribution curve, plotted from this data, will give the aerodynamic load. Figure 10.30 shows air flow through a propeller, location of the survey rake, along with reference stations and symbols used in development of appropriate formulas.

Use of the most elementary form of wake survey is predicated upon an assumption of incompressible flow. Propeller analysis derived from rake survey data is based on measurement of total head increase through the propeller disc, assuming that the change in total head is equal to the change in static head. The final formula derived for thrust coefficient distribution is:

$$\frac{dC_T}{dx}=\frac{\pi x}{4}\cdot J^2\cdot\frac{\Delta H}{q_o} \qquad \text{X–2}$$

in which ΔH is the change in total head through the propeller disc, measured in pounds per square foot. ΔH measured by a shielded total head tube includes the effect of slipstream rotation which may be considered negligible, usually. This effect can be evaluated during a torque survey which may be conducted by mounting yaw heads on a rake strut with the yaw tube plane perpendicular to the rake strut axis. A formula for torque coefficient distribution may be derived, the final equation being:

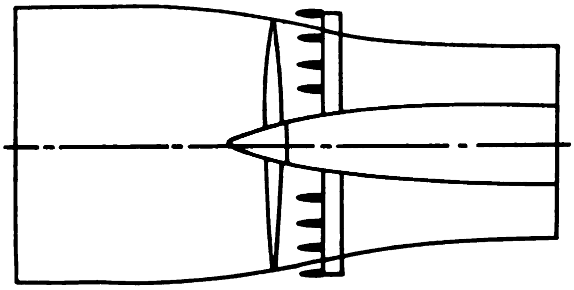
$$\frac{dC_Q}{dx}=\frac{\pi x^2}{8}\cdot J^2\cdot\frac{P_y}{Kq_o} \qquad \text{X–3}$$

in which P_y is the pressure differential across the tubes of the yaw head, in pounds per square foot and K is the calibration constant for the yaw head.

Additional methods, based on compressible flow, have been developed at Langley Aeronautical Laboratory and are described in NACA papers. One method, by making several simplifying assumptions, produces the following expression for the thrust load distribution.

$$\frac{dT}{\pi d(r^2)}=\left(\frac{p_o}{H_o}\right)^{5/7}\Delta H \qquad \text{X–4}$$

in which: p_o and H_o represent static and total pressures, respectively, in the free stream and ΔH has the same significance as in equation X–2. By a more complete development, the final equation will be:



	FREE STREAM	SURVEY PLANE	SLIP-STREAM
STATION	0	1	2
VELOCITY	V_0	V_1	V_2
TOTAL PRESSURE	H_0	H_1	H_2
STATIC PRESSURE	P_0	P_1	P_2
DENSITY	ρ_0	ρ_1	ρ_2
TEMPERATURE	T_0	T_1	T_2

Figure 10.30.—Wake survey rake location.

$$\frac{dC'_T}{\pi d\,(r^2)}=2\left(\frac{\rho_1}{\rho_o}\right)^{1/2}\left(\frac{q_1}{q_0}\right)^{1/2}\left[\left(\frac{\rho_2}{\rho_o}\right)^{1/2}-\left(\frac{q_2}{q_o}\right)^{1/2}\right] \qquad \text{X–5}$$

in which:

$$C'_T=\frac{4T}{\pi D^2\,q_o};$$

The quantity $2\left(\frac{\rho_1}{\rho_o}\right)^{1/2}\left(\frac{q_1}{q_o}\right)^{1/2}$ can be expressed as a function of M_0, P_1, and $\frac{\Delta H}{q_o}$, and the quantity $\left[\left(\frac{\rho_2}{\rho_o}\right)^{1/2}-\left(\frac{q_2}{q_o}\right)^{1/2}\right]$ as a function of M_o $\frac{\Delta H}{q_o}$, and $\frac{T_1-T_o}{T_o}$.

Therefore, magnitude of the following terms must be determined:

M_o=Free stream mach number

$$P_1=\frac{\rho_1-\rho_0}{q_0} \qquad \text{X–6}$$

$$\frac{\Delta H}{q_0}=\frac{H_1-H_0}{q_0} \qquad \text{X–7}$$

$\frac{T_1-T_0}{T_0}$=Stagnation temperature rise coefficient.

It can be seen that measurement of the above items entails use of a wake survey rake containing total pressure, static pressure and temperature probes, which would require an unwieldy amount of instrumentation. It is common practice to assume the quantity $\frac{T_1 - T_0}{T_0}$ to be negligible, thereby eliminating the need for temperature probes.

As a further simplification, P_1 can be assumed constant across the slipstream, requiring only one static pressure probe on the rake. The resultant plot of thrust loading data versus radius permits evaluation of the effects of changes in blade planform, blade angle distribution, tip Mach number effects and design lift coefficient. By use of four rakes, properly disposed about the nacelle, variation of thrust loading on the propeller disc, with change in angularity of flow, can be determined.

Specialized Propeller Flight Test Techniques

Propeller performance at speeds beyond normal operating range of the test airplane may be obtained by diving the plane. This technique will permit measurement of compressibility effects upon propeller performance under full scale conditions at speeds much in excess of that obtainable in level flight. Successful employment of this technique will require thrust measuring instrumentation that will permit elimination of that thrust produced by gravitational force. Utilization of this technique without thrust instrumentation on the airplane would require accurate measurement of airplane longitudinal acceleration and determination of instantaneous gross weight.

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CHAPTER XI. PROPELLER PRODUCTION INSPECTION

Purpose of Inspection

Fundamentally, the purpose of inspection is to determine suitability of a given article for a specific usage. Determination of conformity of an article to appropriate specifications, in which minimum acceptable characteristics are described, may be considered adequate inspection. However, it is extremely difficult, if not impossible, to anticipate and specify standards for innumerable physical features and processes involved in propeller production. Therefore, a competent inspector must understand thoroughly, design requirements, function and service usage of the propeller or propeller component subject to inspection. Even then, occasions may arise when the propeller designer should be consulted regarding some unusual feature which had not been evaluated previously.

Normally, inspection will be conducted at the manufacturing plant, although it may be performed any place that circumstances may dictate. It should be noted that, as herein used, the word inspection is limited to association with requirements for a specific purpose. Further, by use of the phrase, complete inspection, in this handbook, the intent is to convey the thought: every manufactured item will be given, or has received, thorough inspection.

Types of Propeller Inspection

General Classification

Inspection always must be associated with specifications and, in fact, can be considered an integral part of any specification. Functions of specifications include statements of specific propeller requirements both permissive and restrictive. Specification inspection may be classified into three types, namely, performance, physical detail and production process. The specification for packing propellers (MIL–P–6074) may be regarded as a performance type. This specification does not specify how packing boxes should be built, but does outline certain tests which must be met before a propeller packing box can be considered acceptable. A specification for aluminum alloy propeller blades (MIL–P–5446) is a detail specification. This specification does not prescribe propeller performance but does give specific construction details. The specification for heat treatment of aluminum alloy (MIL–H–6088) is an example of a process type of specification. Complexity of the problems involved, has made it impractical to utilize propeller performance specifications, alone. Therefore, reliance must be placed on detail specifications, which, in turn, govern the types of propeller inspection required.

Propeller Performance Inspection

Of the various types of propeller inspection, performance has been considered ideal. The performance specification prescribes certain tests, usually functional, which must be completed successfully for propeller acceptance. Inspectors must perform or witness these tests and certify successful completion. This type of specification and inspection is the least restrictive on manufacturer or designer in that new materials, processes, and improved designs may be used at will. It has been found impracticable to prescribe and adhere to such propeller performance tests. The final criterion of aerodynamic performance of a propeller type must be founded in actual airplane flight tests. However, it is not practicable to give each propeller a flight performance test before acceptance. Furthermore, there are certain propeller requirements aimed at safety, service suitability and life which cannot be tested by simple flight tests Certain tests have been devised to determine the sufficiency of structural strength of propeller assemblies. These tests are so expensive that it is impracticable to test all propellers. Hence, it has been necessary to establish detail specifications to insure similarity and interchangeability with prototypes that have been proved by adequate tests.

Detail Inspection

The primary purpose of detail inspection is to insure conformity to specifications even to

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the point of interchangeability. Interchangeability of bolts, screws, and standard replaceable hardware items is especially important. Items of the same specified size and usage must be identical within certain limits (specified tolerances). Similarly, propeller blades, hubs, cones and component attachments of the same specified size and usage should be given detail and dimensional checks to insure interchangeability. Propeller components should be checked not only for dimensions but also for flaws, cracks and similar defects that would affect overall strength. Further, the material should be checked for composition by chemical or spectroscopic analysis. Pull tests may be made on representative material samples. Material hardness checks should be made (Rockwell tests usually) to determine the quality of heat treatment. Since only one defective part of a propeller assembly can cause failure and subsequent loss of an airplane, every structural part of a propeller must be given complete inspection.

Production Process Inspection

(1) *Forging process.* Propeller fabrication frequently involves forging processes. Forgings should be inspected carefully for determination of direction of grain flow and forging lapses or folds, which can be accomplished by sectioning representative samples. Radiographic inspection may be employed for detection of discontinuities.

(2) *Extrusion process.* Control of extrusion method of blade forming involves control of work movement rates, die design and material quality. Inspection requirements established for forgings are applicable to extrusion process work.

(3) *Welding, brazing and soldering.* It has been recognized that quality of welds in the finished blade is difficult to evaluate. Therefore, attempts have been made to control weld quality by controlling the welding process. Specification MIL–W–6860 for welding aluminum and magnesium alloy, MIL–W–6873 for flash-welding of steel and MIL–W–6858 for general welding of steel have been established to effect such control. However, these specifications have not been applied particularly to propeller blades. Welding plays such an important part in fabrication of hollow steel propeller blades that use of a more or less general specification will not guarantee a final acceptable weld. Various methods have been employed in attempting to evaluate quality of a finished weld, the most common being magnetic particle and radiographic inspection. Recently, the reflectoscope has been employed as an inspection tool.

Copper brazed or silver-soldered joints are more difficult to evaluate than welded joints. In magnetic particle and radiographic inspection, brass or silver in a joint appears as a discontinuity, whether a void exists or not. The welded joint even though solid with identical material as the base plates will act as a metallurgical notch. The effect of a metallurgical notch cannot be determined by any existing method of inspection. Even though absence of voids or inclusions may be determined by inspection, true joint quality ever must be determined primarily by welding technique. Welding has been employed extensively in blade fabrication, but not in production of other propeller parts. The only reason blade welding has been used is that no other satisfactory method has been developed for making hollow steel blades.

(4) *Heat treatment inspection.* Specification MIL–H–6875 outlines a general process for heat treatment of steels. Most propeller manufacturers have used a process that varies in some degree from this specification. Small inexpensive propeller parts may be destroyed in pull tests to establish proper control of a required heat treating process. Since it is not economical to destroy large, expensive parts, material coupons may be used in lieu of components for test to obtain process control. The coupons must be cut from the same batch of material or machined from identical stock, if possible, and processed along with the propeller component. Where practical, either Rockwell or Brinnell tests of each component and coupon should be made to obtain an indication of proper heat treatment quality. Tables may be used to translate hardness test data into tensile strength for a given alloy. In case of doubt, actual tensile tests of the coupon must be made to establish strength of the material in use.

(5) *Machine process inspection.* (*a*) General Machine Work. Most common machine processes are employed in making propellers. Inspection for workmanship and compliance with dimensional tolerances, usually has been considered adequate control of machining

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processes. Since there is no definite specification or standard of workmanship, reliance must be placed in the judgement of an inspector as to what constitutes good workmanship. The applicable specification (such as MIL–P–5641) and drawings establish dimensions and allowable tolerances of propeller parts.

(*b*) Finishing. Surface finishing of propeller blades and accessories may involve many processes. Some surfaces must be buffed, ground or given a smooth machine finish; other surfaces must be plated or anodized. For example, anodized blade finish has been applied to aluminum and magnesium surfaces. Control of an anodized finish must be a process control procedure. Requirements of plated surfaces are given by the following specifications: QQ–Z–325 for zinc plating, MIL–P–6859 for nickel, MIL–P–6871 for chromium and QQ–P–416 for cadmium. The only practical way of assuring surface plate quality is to exercise close control of the plating process. There are methods of determining plate thickness without destruction or marring the finished article but these methods cannot be adapted to propeller production control.

Visual inspection is employed, most commonly, in evaluation of ground, buffed and machine finished surfaces. SAE Specification AS107 may be used in quantitative evaluation of smoothness of a finished surface. This method stipulates use of a profilometer to measure depths and heights of surface imperfections in millionths of an inch. The "root mean square" of profilometer readings is used as an index of smoothness.

Limitations of Inspection

It cannot be assumed that, because complete inspection has been specified, defective parts will never appear in service. Human frailties being what they are, some defective parts will slip through in spite of complete inspection. This slippage may be attributed to inspection fatigue. Considerable investigation of this phase of inspection has been made. Consequently, tables have been prepared, as shown in MIL–Std–105A for lot sizes, to reflect adequacy of various random sampling plans. These tables have been developed from mathematical probability theory. A point can be reached where random sampling will reflect the same probable percentage of defective parts as that obtained with complete inspection.

Propeller production quantities are relatively small compared to machine screw production, for example. Therefore, undetected faults may occur as a result of a time lag between adequate inspectional procedures and development of new processes, types of construction, or materials. A new process may be developed to correct a certain condition, which in turn will introduce variables not encountered, previously. Some time may be required to recognize and correct faults of the new process.

Inspectional Methods and Procedures

Company vs. Government Inspectors

Usually, even in a large plant, government inspectors, being limited in numbers, must concern themselves with overall inspection of production operations. Generally, it is a physical impossibility for government inspectors to give personal attention to all finished articles, let alone numerous component details. Therefore, the contractor must be required to provide a complete acceptable system of inspection of all material, fabrication methods and finished parts. Since the government must depend upon an inspection system for which a manufacturer has been paid, the function of governmental inspectors should be generally, supervisory and administrative. Government inspectors should be concerned with details for checking purposes only, or when production has become particularly troublesome or when a new type of propeller or process requires precedent decision.

A company inspectional system works to the advantage of both contracting parties. In this system, a manufacturer will be free to establish capabilities, provide proper training and experience of inspectors with respect to all details of each operation peculiar to a given propeller production. The government, absolved from inspector training responsibilities, will not require as many inspectors. Hence, the government inspector's job will not be one of policing, but one of supervising and advising the propeller plant management. The government inspector will be responsible for insuring that inspection personnel, equipment and methods are sufficient and properly managed to yield propellers of quality and quantity required by contracts.

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The government inspector should protect the manufacturer's interests by providing exact records of condition, quality, and quantity of material or finished propellers shipped from the factory.

Random Sampling

Spot checking or random sampling may be employed in place of complete every item inspection under some conditions. This type of inspection is acceptable when:

(1) Large quantities are involved.
(2) Production process is reliable.
(3) Some defects or defective parts can be tolerated without serious risk.

A typical example of justifiable use of random sampling involves screw production from an automatic screw machine. Spot checking of screws from such a machine should be employed for the following reasons:

(*a*) To insure maintenance of machine setting and die condition that will insure production of screws within permissible tolerances.
(*b*) To eliminate expense of complete inspection of every screw (it is more economical to have screw rejection by the user for the small number of imperfections that will be produced in such a reliable process).

Chemical Analysis

Chemical analysis, ordinarily, will not be performed by the inspector, but will be furnished by the material supplier. Determination of alloy composition will require services of a fully equipped chemical testing laboratory which may be the manufacturer's laboratory, a government laboratory, or an independent commercial testing laboratory. Close control must be exercised over alloy composition since variation in proportions and presence of impurities may seriously affect propeller strength characteristics. Sometimes, in lieu of a wet chemical analysis, a spectrographic analysis can be employed. However, in cases of doubt, results of a wet chemical quantitative analysis will be accepted as final.

Dimensional Inspection

Dimensional inspection involves the use of most of the standard measuring devices such as micrometers, calipers, verniers, thread gages, face plates, parallel bars, Johansson blocks, sine plates, protractors, height gages, and dial indicators. All propeller dimensions must be within specified tolerances and allowances.

Special Gages for Inspections

Certain special gages peculiar to propellers may be employed to facilitate propeller inspection. Templates can be used for checking airfoil sections and effective angles. In fact, to measure effectiveness angles, it will be necessary to use templates because many airfoil sections do not have a flat surface upon which a protractor could be used. A propeller blade checking buck, while primarily a fixture, is also a gage. The spline and cone gage can be used for checking spline, and cone seats for integrity to insure that the propeller hub will fit the engine shaft. Also, this gage can be used to check reworked cone seats. In the latter case, cone seats should be checked for amount of material removed, concentricity and sufficiency of bearing area (75 percent minimum).

For initial acceptance inspection, splines may be checked with *go* and *no go* gages. The *go* gage should be machined as close as possible to specified dimension. The *no go* gage should be machined to a dimension just beyond maximum tolerance. If the *go* gage will fit and the *no go* will not enter, the splines will be acceptable. The same type of gage may be used for plain and tapped holes.

Etching and Anodizing for Inspection

Etching, for inspection purposes. consists of surface cleaning with a mordant in order to detect flaws or determine grain pattern. In this operation, a small amount of the surface actually will be removed. Etching has been employed, usually, on sectionalized specimens to determine direction of grain flow during forging or upsetting operations, primarily. Specification MIL–P–4546 outlines an acceptable method for etching aluminum alloy. Aluminum alloy can be etched with caustic solutions. If anodic finish has been applied to aluminum alloy blades, etching will not be necessary. Anodic treatment has proven to be as effective as etching in disclosing defects.

Magnetic Particle Inspection Process

The magnetic particle method of inspection consists of magnetizing a specimen and then applying very fine iron filings to the surface. This process is outlined in Specification MIL–

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P–6868. Cracks or subsurface defects in a propeller part permit magnetic field leakage around the defect which in turn causes the iron particles to collect in the leakage field to form a pattern on the surface. Usually, iron particles are applied wet; i. e. suspended in a fluid, but may be used dry. The observer must be well-trained in order to differentiate between patterns caused by cracks, defects and those caused by some non-harmful irregularity, such as abrupt thickness changes. Magnetic particle inspection can be effective only for inspection of ferrous parts. This method will not disclose deep-seated flaws in all cases. If two ferrous parts have been joined by brazing or silver soldering, the seam will appear as a surface break. Before usage, parts must be demagnetized.

X-Ray Inspection

Many deep-seated flaws can be detected by X-ray inspection. In application, X-rays are passed through a material to record thickness variations on a photographic plate. X-ray inspection will be most effective on specimens of uniform thickness. In application to hollow steel blades, in which wide changes in thickness may be present, considerable skill must be employed to obtain satisfactory results. For example, since blade shanks are round and hollow, sufficient X-ray intensity will be required to penetrate the maximum shaft thickness to register properly on photographic paper. In this application, penetration must extend through two layers of material almost parallel to the photographic plates at the center. At the edges, penetration will be through material almost perpendicular to the plate. Hence, it will be difficult to regulate X-ray intensity so that a good picture will be obtained over the entire projected shank diameter. Shank center will be overexposed while the edges will be underexposed.

Reflectoscope Inspection

Use of a reflectoscope for propeller inspections is a comparatively recent development but has shown considerable promise. In reflectoscope inspection, a crystal vibrator will generate waves of supersonic frequency in the material under test. These waves will be transmitted through the material and picked up by a receiver, which may be a separate device, but which usually will be the crystal transmitter. Any material break or discontinuity will cause wave reflection and creation of a wave pattern entirely different from that of a defect free specimen. With practice, exact location of the flaw can be determined. Further refinement of technique may permit determination of the approximate size of the flaw.

Fluorescent Light Inspection

Fluorescent light method of inspection has been used principally for checking non-ferrous parts that cannot be inspected magnetically. In application of the method, as described in Specification MIL–I–6866, the specimen must be cleaned, then coated with a fluorescent oil. Excess oil must be removed from the surface of the specimen. Placement of the part in a beam of ultra-violet light will produce fluorescence of the oil trapped in cracks and flaws, thereby bringing defects into sharp relief. This method of inspection will disclose only surface imperfections.

Material Inspections

Scope of Material Inspections

Propeller material inspection has prime importance in all production processes. Fabrication of a hub or blade without first assuring material integrity is a sure way to invite disaster. Furthermore, usage of those articles containing serious defects resulting from processing can be equally hazardous.

Of course, material actually incorporated into a finished propeller cannot be tested by any means which will result in destruction or damage. Likewise, propeller components subjected to final acceptance inspection must not be damaged by inspection processes. Therefore, all types of testing which result in damage must be limited in application to control samples for determining correct processing methods and for checking continuous maintenance of correct production operations. Beyond control sample testing and use of non-destructive tests, reliance must be placed in process repetition by automatic control. Because of the necessity for complete inspection of propellers, much effort has been devoted to evolving and applying more powerful and trustworthy non-destructive testing methods. X-ray, magnetic particle inspection, and sonic reflection methods are

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representative of the most outstanding nondestructive tests developed for inspecting material defects.

Propeller Wood Inspection

Blanks for so-called solid wood propellers are composed of laminated wood sections. Inspection of the wood for propellers involves several steps. The boards, from which laminations are made, first must be inspected for species. This inspection may be visual although a specific gravity test (oven dry) may serve as a better indication of species. Then, boards should be checked for straightness of grain, moisture content and freedom from defects. Chemical or spectrographic analysis cannot be used since wood does not lend itself readily to that type of analysis. Also, a check should be made to determine the extent of case hardening. Wood inspection procedures may be found in ANC–19, "Wood Aircraft Inspection and Fabrication." Specification MIL–L–6061, Lumber, Aircraft Propeller, outlines specific requirements of wood propeller material. Specification MIL–A–397 adhesives, thermosetting-resin (phenolic, resorcinol, and melamine base), contains requirements for glue to be used in propeller blanks. Glue cannot be inspected easily by analysis; therefore, a producer's certification of glue conformity to specification will be accepted as sufficient, normally. Glue acceptance tests are outlined in detail in Specifications MIL–A–397 and ANC–19.

Propeller Veneer Inspection

Inspection of veneer for laminated wood propellers or blades can be accomplished using the procedures established for propeller lumber. Less attention need be paid to slope of grain in propeller veneer than in boards. Also, defects in material will not be quite as critical and therefore, inspection of veneer can be more liberal. Moisture content of veneer should be held to a lower percentage than that specified for propeller boards. In addition, since practically all veneer will be rotary cut, inspection must be made for tightness of cut. Specification No. MIL–P–5444 detachable propeller blades (laminated veneer uncompressed) establishes requirements for propeller grade veneer. Requirements and inspection of glue for veneer appears in Specification MIL–A–397 or MIL–A–5534 adhesive (phenol, melamine and resorcinol base).

Compreg Inspection

Compressed impregnated wood was used at one time in considerable quantities for propellers, but no longer is being used extensively. Compreg specifications were established but have been cancelled because of disuse. Compreg requirements are more exacting than those outlined for wood veneer. More information may be obtained from Forest Products Laboratory Bulletins Nos. 1380 and 1381.

Propeller Plastic Inspection

Plastics have had but limited use as propeller materials. Generally, manufacturers' specifications have been used for inspectional purposes. However plastics should be checked to see that the following minimum properties exist:

Specific gravity	1.38
Mod. of E (Tension)	1.8 x 10^6
Yield (Tension)	11,000 p. s. i.
Yield (Compression)	5,000 p. s. i.
Moisture absorption	6% (maximum)
Shear	4,000 p. s. i.

Plastic inspection requires availability of a well equipped testing laboratory.

Aluminum Alloy Inspection

The most extensively used aluminum alloy (25ST) must conform to Specification QQ–A–367, Grade 2. The 76 ST aluminum alloy has been used to a much lesser extent. Normally, a raw material supplier's certificate of alloy composition analysis will be accepted. However, if necessary, chemical content of the alloy may be checked by chemical or spectographic analysis. Normally, forging tongs will remain attached to a propeller forging and heat-treated along with the formed blade. Forging tongs should be checked at intervals and at least once for each heat or melt. The following mechanical properties must be evaluated: Ultimate tensile strength, yield point, percentage elongation, and Brinell hardness. Forgings may be checked by X-ray for presence of inclusions and sub-surface imperfections. Whenever an upsetting operation has been included in processing, specimens should be cut from upset regions and checked by etching for grain flow and forging lapses. Detail procedure for inspection of aluminum alloy is contained in Specification QQ–M–151A. (Metals, general specification for inspection). The chemical composition of 25 ST aluminum alloy is given in Specification QQ–A–367 (aluminum-

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alloy, forgings, heat-treated). Physical properties of aluminum alloy suitable for use in propeller blades are given in Specification MIL–P–5446 (propeller blades, general specification for solid, aluminum alloy).

Steel Inspection

The usual inspectional tests applied to metals in general, as outlined in Specification QQ–M–151A, are applicable to steel. The same inspectional procedure used for aluminum should be used to evaluate steel being used for propeller components. In addition, an Izod impact test should be included. Specification MIL–P–7715 outlines desirable physical properties of steel for propeller blades. Specification MIL–S–5000 (4340) stipulates, in detail, the requirements of one steel commonly used for propeller blades. Also, blade material may be inspected for decarburization and weldability.

Magnesium Inspection

Use of magnesium has been so limited in application that a general specification has not been drafted. Magnesium blades have been in an experimental stage and reliance has been placed in material manufacturer's specifications. As a general rule, more emphasis has been placed upon physical tests to assure certain properties than upon chemical analysis to determine composition. Specification MIL–M–5354 (ZK–60) for magnesium alloy might applicable to material for propeller blades. Inspectional methods employed to ascertain suitability of this material can be similar to those used for aluminum.

Propeller Component Inspections

Propeller Blades

Before final assembly, various components of each propeller must be inspected. Blades must be checked dimensionally with applicable drawings and specifications. To facilitate dimensional check, a blade to be inspected may be mounted on a fixture called a *buck* which is illustrated in figure 11.1.

Essentially, a buck consists of a face plate indexed with station lines, that is, equipped with some form of clamping device which will allow rotation about the blade longitudinal axis. A buck usually will be provided with accessories for measuring blade width, blade thickness, face alignment, edge alignment and angular twist.

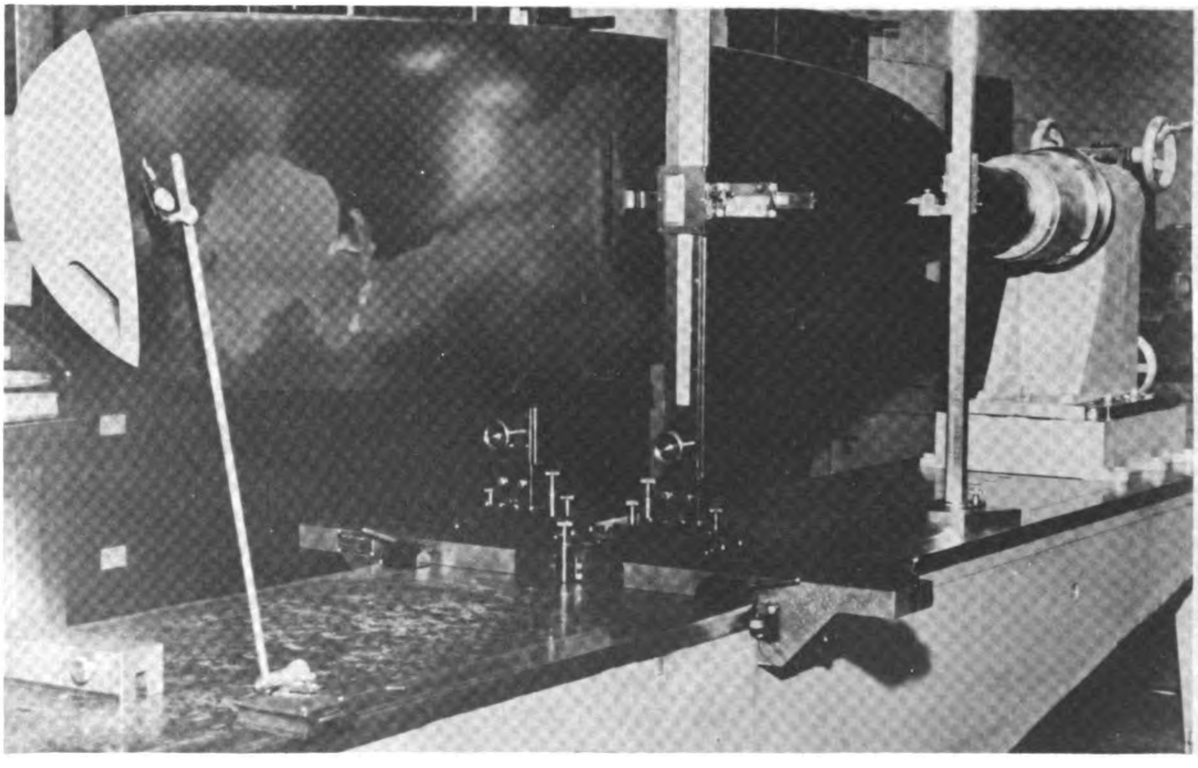

Figure 11.1.—Blade inspection fixture (Buck).

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Blade tolerances have been established and published in Specification MIL-P-7715 or MIL-P-5446. Blade measurements should be taken at each station (points established at each six inch increment of distance from the nominal centerline of the propeller shaft). In addition, airfoil contour should be checked at each blade station by use of templates. These templates should be made of steel and constructed to specified ordinate dimensions to a tolerance ranging from .002 to .005 inch. Also, blades must be checked for balance in both horizontal and vertical directions. Blade balance may be checked by mounting the blade in a two-way hub, or similar fixture, with a master moment device as one blade. The whole assembly then must be balanced on knife edges using a mandrel and an adaptor. Blade balance may be accomplished by a fixture which will reflect amount of unbalance as a scale reading, if equipment is available. After a balance check, blades must be checked for flaws, which for aluminum blades, may be done by etching and/or anodizing, fluorescent light and visual inspection. Steel blades may be inspected by using magnetic particle, X-ray or reflectoscope methods.

Hub Inspection

Propeller hubs should be inspected dimensionally using a face plate, micrometers, calipers and special gages. A typical hub inspection fixture is illustrated in figure 11.2. The principal gage required for hub inspection is a spline and cone seat gage by means of which internal splines, cone seats and hub thickness may be checked in a single operation.

A propeller hub must be checked for balance using knife edges, mandrel and suitable adaptors. Also each hub must be checked for flaws using magnetic particle and/or X-ray inspection. Rockwell or Brinell tests should be made to verify proper heat treatment.

Governor Inspection

Propeller governors should be checked for functional operation on a fixture specifically

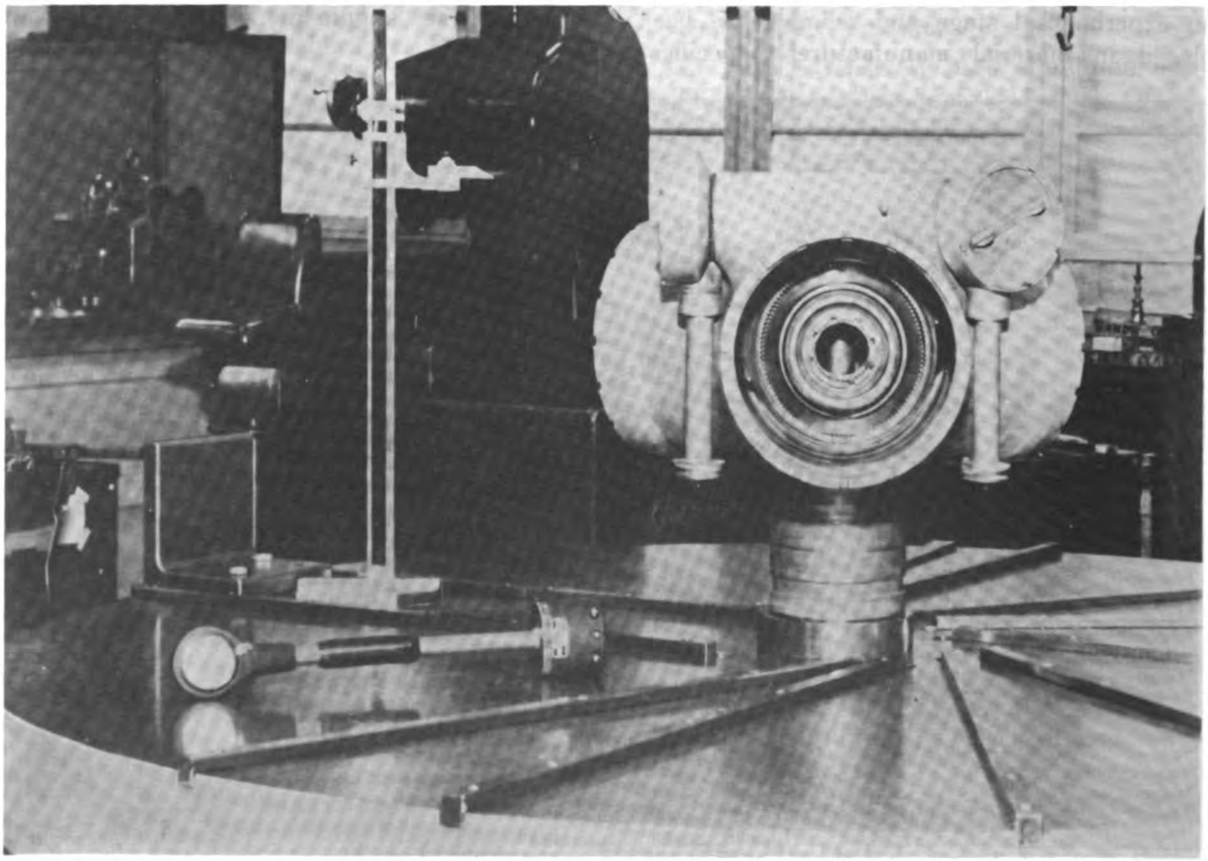

Figure 11.2.—Hub inspection fixture.

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designed for that purpose For example, one type of regulator and governor can be checked on a fixture described in Specification MIL-S-5496. This check will assure an operational governor for all design conditions. Governors must be checked dimensionally, at the factory, to insure interchangeability.

Spinner Inspection

Propeller spinners should be checked dimensionally against applicable drawings and Specification MIL-P-5450. Spinner material should be checked carefully for flaws, by an appropriate method which will depend upon the type of material used. Proper balancing should be included in the inspection of a spinner.

Accessory Inspection

All propeller accessories must be examined dimensionally to insure interchangeability. Most accessories should be checked by Rockwell or Brinell tests to insure that the parts have received proper heat treatment. Propeller accessories may be subjected to magnetic particle or X-ray inspection, as well.

Functional Inspection—Pitch Change Mechanism

Assembled controllable propellers must be given functional tests before installation. By using a suitable source of power, the pitch changing mechanism can be checked to insure that blades will turn in the hubs, before the assembly leaves the shop. The test should be made on a test stand in which flight operating conditions can be duplicated as closely as possible. The governor must function to accurately control the propeller pitch changing mechanism.

The functional test stand should be equipped with hydraulic fluid under pressure and electric power for actuation of hydromatic and electric pitch changing mechanisms, respectively. Gages and instruments should be furnished that will reflect not only governor functioning but also rate of response to given stimuli, usually changes in engine speed.

Propeller Balancing

The standard method of checking propeller assembly balance involves the following sequence of operations:

(1) Insert a bushing in the engine shaft hole of the propeller.
(2) Insert a mandrel through the bushing.
(3) Place assembly so that ends of the mandrel are supported upon knife edges with the propeller free to rotate.
(4) Rotate the propeller to different positions by hand.

If properly balanced, statically, a propeller will remain at any position of rotation to which it has been placed. Of course, the test room must be free of vibration and strong air currents.

If a propeller assembly should be unbalanced, weight slugs or modeling clay can be added to the light blade at a given known distance from hub centerline to achieve complete balance. After balancing, the balance weights added should be weighed. Weight of the material multiplied by the radial distance from the hub centerline will give the magnitude of the moment which must be introduced into the assembly to achieve balance. Moment balancing may be accomplished by attaching weights (permanently) to the hub, or by adding weight (usually lead) to the light blade shank in a space provided for that purpose (propeller must be disassembled).

If one blade is too heavy, some of the previously placed balancing lead in the blade shank may be removed to obtain balance with the master moment requirement. Specification MIL-P-5447 stipulates a maximum moment tolerance of .0005 inch eccentricity multiplied by propeller weight. Normally, this moment tolerance will represent sensitivity of available balancing equipment. A propeller must be so balanced that it will remain in any given position without tendency to rotate.

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CHAPTER XII. PROPELLER MAINTENANCE PROBLEMS

Definition of Propeller Maintenance Terms

Maintenance

As used in this handbook, the term propeller maintenance encompasses inspection, servicing, and repair. Definitive boundaries of propeller maintenance can be obtained best by further exposition of the terms: inspection, servicing, and repair.

Propeller Inspection

Propeller inspection must consist of thorough examination of all components and details of the system to acquire accurate information pertaining to the state of repair along with determination of remedial action necessary to reestablish serviceability. It is apparent that the term inspection means much more than mere observation or looking at.

Propeller Servicing

Servicing will include performance of acts necessary to prevent functional failure, undue deterioration, loss of operational efficiency, defacement and replacement or replenishment of consumable propeller elements. Frequently, this type of work is referred to as preventative maintenance.

Repair

Propeller repair involves replacement, reconstruction, or repair of those parts (relatively non-consumable) which, through breakage, distortion or wear, have been damaged to a point of impairment of efficiency, functional use, or safety.

Propeller Roughness

The expression, rough propeller, appears frequently in discussions and technical papers pertaining to propeller service problems. As used, in most cases, the expression has reference to the vibratory phenomena, associated with propeller or engine unbalance, that can be recognized readily by vibration of airplane structure, controls and instruments which occurs during engine runup to high speed.

Propeller Service Problem

Propeller service problems as used in this handbook should be considered as problems that have evolved or that may develop in the course of service usage of propellers. The manifestation of propeller operating difficulties, then, can be considered as but one phase of the broader term maintenance problems.

Propeller Maintenance Problems

General Survey of Maintenance Problems

Propeller tests have been integrated into development programs to permit evaluation of structural and functional suitability of propeller designs, but the ultimate and final proof of suitability will be obtained only after extensive service use. After accumulation of considerable operating time, a true perspective of propeller service suitability and life span will become evident. Information gathered from experiences encountered during propeller operation under all kinds of atmospheric conditions and loading situations can be utilized advantageously in redesign to overcome operational problems. Furthermore, service experience has proven to be most useful in prediction of probable service problems that may arise in use of new propeller designs.

In view of the close relationship that exists between good propeller design and maintenance, it is most imperative that propeller maintenance be given top priority consideration in the course of design development. Improper design, frequently, is the basic cause for poor inspection or servicing. That the design is faulty does not obviate the necessity for adaquate maintenance. It must be recognized that without proper maintenance any propeller will be hazardous to operate.

One of the greatest obstacles to proper propeller maintenance is inaccessibility of

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critical components of the system. The chain of sequence operations, with the large amount of work involved to complete certain inspections and the attendant servicing, tends to discourage thorough maintenance. Under the press of work loads, complete inspections if time consuming, will be reduced to a calculated risk basis in which it will be assumed that inaccessible components will function properly unless some external manifestation of malfunctioning exists. Some design faults may not be revealed until after lapse of considerable service time. In this category are stress raisers (abrupt section changes or sharp corners) which ultimately produce fatigue failures. Further, improper design may enhance the possibility of improper assembly or installation.

Safety in flight and ground operation of propellers is imperative. Achievement of maximum safety can be obtained only if propeller maintenance is performed faithfully on an ever-continuing basis. Certain recurring problems requiring continuous attention are common to all propellers. To insure proper maintenance, it is most important that the propeller service problems be recognized, causes understood and appropriate corrective action be prescribed. Many service problems develop from improper maintenance which, in turn, may be traced to:

(1) Non-availability of authoritative propeller service information in aircraft handbooks, service manuals or technical orders.

(2) Failure to use properly the technical information furnished for propeller maintenance.

(3) Incomplete, incorrect or inconsistent technical data.

Propeller Maintenance Inspections

(1) *Scope of inspection.* Propeller inspections must be performed regularly and faithfully. Upon further consideration, regular performance of inspection can mean only that propeller inspection must be accomplished in accordance with an established schedule. The schedule of inspections must incorporate two distinct features, namely:

(*a*) Frequency of inspection.
(*b*) Extent of inspection.

Findings of inspections will include general statements of servicing or repair necessary to return the propeller system to active duty.

(2) *Frequency of inspections.* The exact time interval specified for particular propeller inspections has been published in the form of technical orders so far as the Defense Department is concerned. It is not the purpose of this manual to supplant those instructions. It is appropriate, however, to present representative periodic inspection intervals so that an adequate appreciation may be had of service problems which may be influenced by inspection frequency. It is believed that a propeller inspection schedule which conforms to the following frequency requirements would be adequate for most all operating conditions:

(*a*) Daily line inspection.
(*b*) Twenty-five hour inspection.
(*c*) Fifty hour inspection.
(*d*) One hundred hour inspection.
(*e*) Special inspection.

It must be re-emphasized that specific propeller inspections must be accomplished in accordance with official technical orders insofar as Military aircraft are involved. Civilian and commercial operators should carry out propeller inspections in accordance with CAA requirements and propeller manufacturer's recommendations. In any event, it is significant to note that inspections must be conducted at such frequency as necessary to prevent hazardous flying.

(3) *Inspection requirements.* (*a*) Typical inspection (Line 25, 50 or 100 hours):

(*i*) Inspect blades, spinners and other external surfaces for appearance of excessive oil or grease deposits.

(*ii*) Inspect weld and braze sections of blades and hubs for incipient fatigue failure.

(*iii*) Examine blade spinner, hubs and other visible structural parts carefully (magnifying glass if necessary) for nicks, scratches, bruises or other damaging flaws.

(*iv*) Check spinner or dome shell attachment screws for tightness, if applicable.

(*v*) Appearance of any abnormality observed in this cursory examination should be followed by a complete teardown inspection.

(*vi*) Check level of operating and lubricating oils.

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(*b*) Special inspection:

(*i*) Propeller accidents in which a possibility exists that internal damage may have occurred, must be followed by complete disassembly and inspection.

(*ii*) Whenever a propeller has been removed from the shaft for any reason, hub cone seats, cones and other contact parts should be examined to detect undue wear, galling or corrosion.

(*iii*) All controls must be examined and tested for faults.

(*iv*) Feathering, reversing and pitch changing devices must be inspected to insure functional integrity.

(*v*) Steel propeller parts must be subjected to magnetic inspection; aluminum alloy parts will be inspected using anodic treatment or other approved methods.

(*vi*) All electrical circuits must be inspected and checked for continuity.

(4) *Inspection procedures.* (*a*) Prior to every flight, aircraft propellers should be given a functional check to encompass one complete pitch change cycle.

(*b*) Visual inspection of propeller blades, hubs, controls and accessories does not mean careless, slovenly or casual observation. Visual inspection should be a meticulous study of every part of the propeller system to find every flaw or defect. Visual inspection may require the use of magnification to enlarge defects to the extent necessary to become visible to the naked eye.

(*c*) Every available device should be used to set forth defects that may exist.

(*d*) When magnetic inspection is employed to check moving parts, the electric terminals should be attached to the propeller part in such a manner that arcing will not damage polished or ground surfaces.

Servicing Propellers

(1) *Scope of propeller servicing.* Propeller servicing must include cleaning, adjusting, testing and lubricating as well as replacing consumable materials. All of these servicing actions follow logically from requirements established by adequate inspection. Much improper servicing can be traced directly to improper inspectional techniques or schedules.

(2) *Cleaning propeller surfaces.* Caustic substances will not be used on propeller parts except for etching purposes in which caustic activity will be controlled carefully. Removal of paint, enamel or varnish must be accomplished by use of approved lacquer and paint thinners and solvents. Immediately upon return from flight in which salt water has been encountered, salt traces must be flushed from the propeller with fresh water after which the parts should be dried and coated with a thin film of clean oil.

Steel hubs should be cleaned with soap and fresh water, unleaded gasoline or kerosene using a soft brush or cloth. Abrasives or tools should not be used, nor should acids or caustics ever be used on these components.

Aluminum alloy blades may be cleaned with soap and water, unleaded gasoline or kerosene using a cloth or soft brush. Scrapers, power buffers, steel wool or other scratching devices (substance) will not be used in cleaning operations.

A good grade of metal polish may be used to give a propeller blade the desired polish if all traces of the polish are removed after the operation. After polishing, the blade should be cleaned and coated with a film of oil.

Cleaning substances must be removed from all propeller parts, after which components must be thoroughly dried and coated with an oil film. Cleaning fluids must be kept clean by use of screens and filters and should be renewed periodically.

(3) *Propeller lubrication.* Hydromatic propellers operated with engine oil do not require lubrication. Electric propellers will require oils and greases for speed reducers, hub lubricants and pitch change drive mechanisms in accordance with specifications established by appropriate technical orders.

Indicative of propeller lubricant requirements, table XII–1 shows some specifications of oils and greases that have been used.

It must be emphasized that oil and grease specifications indicated herein are cited only for general reference. Proper propeller lubrication, with oil and grease specifications for particular installations, has been published in the form of technical orders or manufacturer's operating instructions. These official directives must be followed implicitly and those publications take precedence over this handbook in servicing procedures.

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Table XII–1. *Typical Lubricants*

Propeller type	Speed regulator	Lubricant	Controls
Hydromatic	Engine oil	Grease specification MIL–L–7711.	Engine oil.
Electric	Oil specification MIL–L–7870.	Grease specification MIL–L–7711.	Clean engine oil.
Hydraulic constant Speed.	MIL–O–6086	Grease specification MIL–G–3278.	Engine oil.

(4) *Replacement of consumable materials.* Propeller inspection, if properly accomplished, will produce evidence which will show the need for replacement of consumable materials. For example, careful inspection should reveal the need for replacement of oil for self-contained hydraulic units. Evidence of oil leakage will indicate a need for gasket or seal replacement.

Damaged, worn or loose deicing elements must be repaired or replaced before a propeller can be released for further flight.

Worn propeller control parts should be replaced whenever any wear is shown that might hamper functional requirements.

Grease replacement through attached pressure application fittings must be accomplished strictly in accordance with established specifications and maintenance procedures. Oiling and greasing schedules must be established and followed to insure proper lubrication of moving parts.

Propeller Repair

(1) *General considerations.* As with propeller servicing, adequate inspection should not fail to detect worn or defective parts or components of the propeller system. Discovery of defective units demands that immediate action be taken to replace or repair the unacceptable parts.

If acceptable repair cannot be accomplished, the part must be scrapped; under no circumstances should parts which cannot be repaired be stored in parts cabinets containing new and serviceable parts. Before undertaking repair of any part, applicable instructions or technical orders should be reviewed to ascertain what specific procedures have been dictated, if any. Multiplicity of propeller parts precludes inclusion of detailed repair procedures in this handbook. However, certain general procedures will be outlined in the following paragraphs.

(2) *Repairing steel parts.* Nicks, burrs, galls and similar damage can be removed from steel parts by using a fine grained stone, emery or crocus cloth to grind out and polish the affected surface. Only that amount of material necessary to remove surface damage completely should be ground from the propeller part. Sharp edges or nicks should not be in evidence upon completion of the repair.

(3) *Aluminum propeller parts repair.* As with steel parts, all nicks, scratches and burrs must be removed from aluminum parts by using fine emery cloth or equivalent. Excessive removal of material must be avoided.

In view of the importance attached to repair of aluminum alloy propeller blades, greater detail in repair procedures may be justified. Certain blades have been formed by cold rolling blade fillet and shank sections to some specific radial station (six to eight inch station, often) with shot-blasting being used in the more extended outboard sections after forming. This forming procedure has established initial compressive stresses in the propeller blade, which must be preserved throughout any repair undertaken. Minor repair should be accomplished only in the shot-blasted and tip sections.

As a means of insuring that excessive material will not be removed during blade repair, periodic etching and inspection, in process, will serve to indicate when cuts or nicks have been eliminated. Sandpaper or emery cloth of proper grade may be used in the process. If material removal, necessary to efface deep nicks or cuts, results in a blade below minimum dimensions, the blade must be scrapped. Field service repair of blades having nicks or sharp cuts of one-eighth inch depth or more, should

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not be attempted. Blades having deep dent damage should be sent to a depot or an approved overhaul station for repair.

The only acceptable method of repairing cuts or deep cracks in propeller blades requires removal of metal from the section surrounding the damage in such a manner as to leave a smooth well-faired surface. Metal relocation by cold working to cover or conceal the damage is not acceptable blade repair. It is not necessary to *saucer out* all of a sharp deep nick in the blade unless the bottom of the nick has sharp edges. Metal surrounding longitudinal surface cracks or cuts should be removed in such a manner that a shallow saucer shaped depression will be formed. Wide scars or nicks can be repaired by rounding off sharp edges and grinding the whole surface to form smooth depression.

Pitted leading edges of propeller blades, which have been formed during normal service use and wear, may be repaired by metal removal as performed in repair of other cuts. Usually, metal should be removed by beginning at the thickest section and working forward over the leading edge. Abrupt changes or blunt edges should be avoided.

(4) *Bronze part repair.* Since bronze parts are not highly stressed, usually, complete removal of cuts or scars will not be necessary. Burrs or surface roughness should be removed by use of emery cloth or sandpaper of suitable abrasive characteristics.

(5) *Plated parts repair.* Surface plating that has been damaged to a point of base metal exposure must be removed completely, after which the damaged propeller part may be replated.

(6) *Synthetic rubber part repair.* It should be recognized that good maintenance practice requires replacement of all gaskets and seals at overhaul. Repair of deicing boots should not be attempted if damage has been severe enough to expose or injure electrical leads. Loosened rubber boots may be rebonded to the blade if only minor sections are involved.

(7) *Phenolic parts repair.* Except for minor nicks which may be sanded out, phenolic parts that are worn or damaged should be replaced.

(8) *Molded fairing repair.* Damaged molded blade fairings may be repaired by use of patching compounds especially prepared for that purpose. Repair of damaged sections in excess of three square inches should not be attempted. Patching compound is supplied in stick form. Repair procedures usually involve the following basic steps.

(*a*) Clean cavity, removing oil and dirt, and dry thoroughly.

(*b*) Undercut surrounding cover stock slightly.

(*c*) Fill cleaned cavity with compound melted from the compound stick (soldering iron or flame). The compound must be in molten state to fill all voids (avoid damage to fairing from flame, if used).

(*d*) Work compound into cavities using hot knife.

(*e*) Compound patch (complete hole fill) should be allowed to cool.

(*f*) Sand patch surface to conform to fairing surface profile.

(*g*) Repaint, if necessary.

Propeller Service Problems

Identification and Classification of Service Problems

(1) *Delineation of service problems.* Service problems differ from propeller servicing in that they consist of recurring difficulties encountered during operation. Whereas servicing, in reality, encompasses the field of preventative maintenance, a service problem evolves whenever a propeller or any of its components fails to perform its normal function. In consideration of the preceding statement, it becomes evident that there exists an infinite number of possibilities for development of propeller service problems. However, although malfunctions may result from any one of a large number of unit failures, propeller service problems may be categorized into one of several general functional difficulties. These classifications along with general discussions of them, have been set forth in the following paragraphs.

(2) *Propeller roughness.* Propeller roughness is a continual recurring service problem that may spring from a great many causes. It should be recognized at once that propeller roughness may be caused by unstable engine operation or from improper engine mounting. Since this treatise is concerned only with propeller problems, aircraft engines and mountings, as roughness sources, will not be investigated or discussed here.

In reality propeller roughness is another expression for propeller unbalance. In the

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light of propeller unbalance, roughness may be the by-product of:

(*a*) Unbalanced component assembly.
(*b*) Improper propeller mounting upon the shaft.
(*c*) Improper mating of individual blade gears and the master pitch changing gear.
(*d*) Blades of unlike aerodynamic characteristics jointed in an assembled propeller system.
(*e*) Blade seal failure to permit oil or grease entrance into blade cavities.
(*f*) Wooden blade moisture absorption.
(*g*) Early stages of blade or hub structural failure.

Since roughness elimination is primarily a propeller balancing problem, it might be well to give some consideration to the balancing equipment. Basic principles of vibration, damping and balancing must be employed in design of balancing equipment. In addition, construction and installation of the balancing equipment must not in any way compromise those principles. Failure to satisfy these conditions surrounding use of balancing equipment can yield only unsatisfactory results in propeller balancing problems.

Improper mating of individual blade gears with the master pitch changing gear will produce a pitch angle variation between individual blades assembled, that exceeds allowable tolerances. In operation under engine power, the blade pitch angle variation will cause propeller aerodynamic unbalance, since individual blades will have unequal air loadings. Of course, the effect is the same as a weight unbalance. Improper design, fabrication or installation of blade gears may result in galling or other damage such as that illustrated in figure 12.1.

(3) *Erratic Control of Propeller Speed.* (*a*) Underspeed at airplane takeoff. This condition represents a most dangerous condition since maximum power must be available for takeoff conditions. Probable causes of this operating situation will be discussed in greater detail in a subsequent paragraph. Therefore, at this point, it will be sufficient to direct attention to the need for careful inspection to eliminate interference with control movement.

(*b*) Overspeed at Airplane Takeoff. Propeller

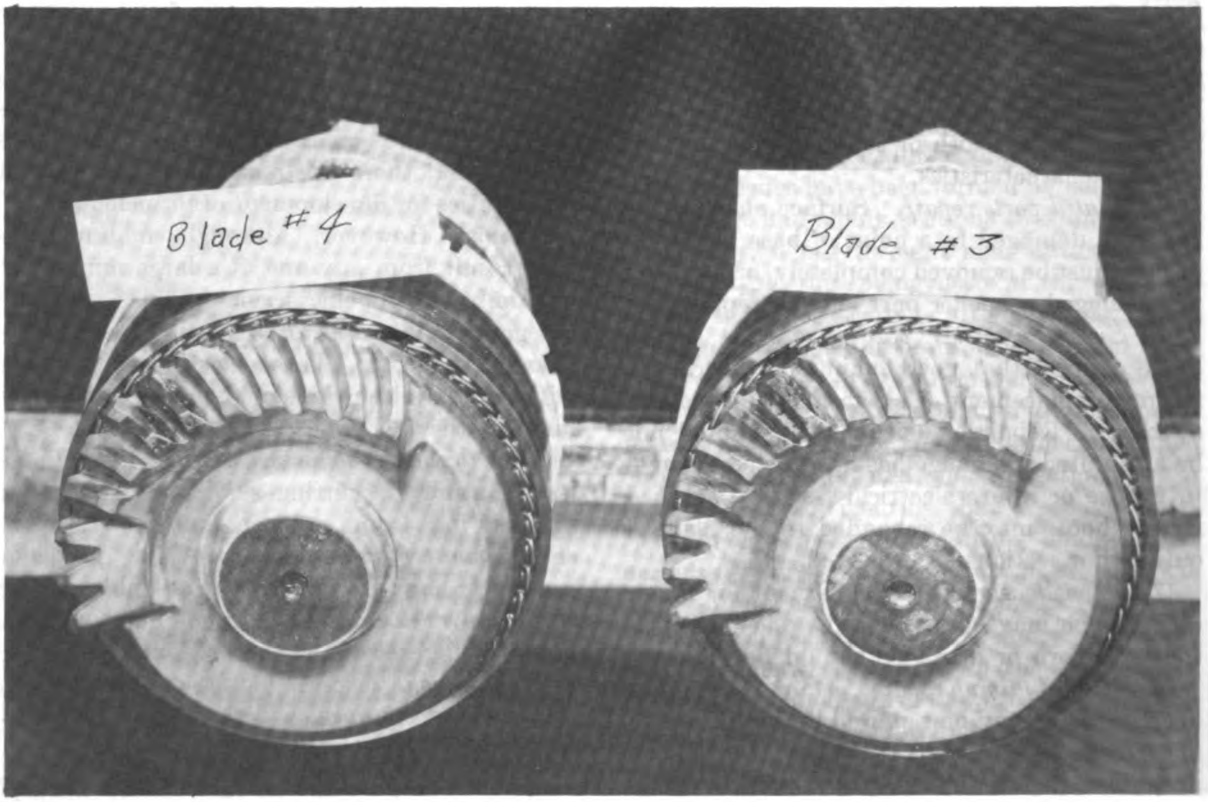

Figure 12.1.—Blade gear galling.

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overspeed at takeoff also represents an extremely hazardous operating condition. Extended overspeed operation with attendant vibration difficulties might easily result in complete power plant installation destruction. Extremely low pitch angle settings or engine overspeed for a variety of reasons might contribute to propeller overspeed.

(*c*) Erratic Speed Control in Flight. Erratic speed control might develop at any time during flight introducing propeller roughness with subsequent overstressing in critical propeller sections. The nature of this difficulty suggests that improper blade angle control is the basic difficulty.

(*d*) Speed Synchronization. If individual propellers of a multi-engine aircraft are not synchronized properly, interference between air flow stream of individual propeller discs will produce unbalance effects that manifest themselves as propeller roughness.

(4) *Cone galling.* A strict definition of galling would encompass such penomena as surface roughening, irritation or material growth beyond normal size. As applied to mating parts of a propeller and service problems incidental thereto, galling implies material pick up by one or more parts from respective mating parts. For example, most cone galling which occurs during propeller operation involves the rear cone, frequently fabricated of a bronze alloy. Under galling conditions, the steel hub and propeller shaft will pick up bronze from the rear cone.

After a cone has been in service, discoloration or darkening of mating surfaces (hub, cone and shaft) will become evident but, unless actual material pick-up occurs, the mating part combination may be considered satisfactory for further service. Use of rear cones and hubs having galled surfaces will promote operating difficulties of propeller roughness and probable structural failure.

(5) *Oil and grease leakage.* Excessive leakage of propeller operating oil or hub lubricant can be a source of serious difficulty since normal, as well as emergency feathering, operation may be impaired by lack of oil to actuate the mechanism. It should be noted that propeller leakage may be caused by use of oils other than those specified for a given propeller.

(6) *Propeller feathering failures.* Failure to obtain full feathering under emergency conditions arising from engine failure may result in propeller windmilling with subsequent loss of engine and nacelle with possible wing structure failure. Full feathering may not be obtained at either high or low speed because angle stop settings are improper. More serious than failure to obtain full feathering would be failure to achieve any feathering of a propeller in response to demand. Such a failure would be due probably to propeller control failure or failure of feathering oil pumps.

(7) *Pitch reversal or propellers.* Pitch reversal of propellers has become accepted practice to assist in shortening runway roll of heavy airplanes, during landing operations. In practice, pitch reversal is a practical method of reversing the direction of thrust applied to an airplane, by propellers. Service problems arising from use of pitch reversal stem principally from complaints of pitch reversal during flight or in landing operations. Analyses of these problems show that pitch reversal problems are pitch control problems, in reality.

It is desirable to link pitch reversing features to engine throttle controls, but, in arranging the control mechanism in this manner, the possibility of inadvertent pitch reversal is increased. Movement of the engine throttle or power control, if carried too far, may cause the propellers to move into reverse pitch position with serious consequences. To eliminate this possibility, some form of stop must be provided to limit throttle travel in normal operation but to permit further movement, if necessary, to reverse propeller pitch. One such control has been designated lift-to-reverse. Servicewise, it is extremely important to eliminate any possibility of pitch control failure which may be chargeable to wear, improper lubrication, or electrical or mechanical failure.

(8) *Propeller corrosion.* Corrosion problems have been discussed elsewhere in this handbook. It is relevant, at this time, to reiterate that corrosion of propeller components must be prevented insofar as humanly possible. Surfaces subject to salt water contact must be plated with substances that will resist corrosion, or be given some form of protective coating. Hidden surfaces must be examined frequently to find and correct corrosion problems before major repair or replacement becomes necessary.

Causes of Service Problems

(1) *Significance of service problem origin.*

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Before proper corrective action can be taken to remedy service problems, origins of the problems must be established. In considering identification of the causes of propeller service problems, attention once more is directed towards the importance of maintenance inspections. Only through careful and complete inspection can causes of propeller service problems be diagnosed properly. Good service inspection will detect faults before serious damage can be done and, doubtless, will reveal obvious remedial action to prevent occurrence of similar faults in the future. Generally, service problems will develop from one or more of the following:

(*a*) Normal wear and tear.
(*b*) Improper assembly or installation.
(*c*) Improper maintenance.
(*d*) Faulty design or fabrication.
(*e*) Abuse.

It might be helpful to examine in detail some examples of service problems caused by some of the most prevalent problem sources listed.

(2) *Normal Wear and Tear Service Problems.* (*a*) General survey of normal wear and tear. Normal wear and tear service problems are recurrent problems that vary only in some detail. Causes of these types of problems have been established fairly well, although alterations in design may introduce unique variations of an old problem. Typical problems in this category include such items as:

(*i*) Abrasion of propeller blades during ground operation.
(*ii*) Aging and deterioration of oil seals with ultimate leakage.
(*iii*) Erosion of gear teeth from repetitive contact.
(*iv*) Wear and surface hardening of brake linings.
(*v*) Wood absorption of moisture after seal coat breakdown.
(*vi*) Propeller blade damage from hail, rain and sleet.
(*vii*) Corrosion.

The scope of normal wear and tear propeller service problems can be illustrated best by discussion of some of the most important causes of such problems, which are presented in the following paragraphs.

(*b*) Propeller Roughness Induced by Wear or Aging. Blade seal failure caused by wear will permit oil or grease leakage into the blade bore. Accumulation of gobs of lubricant in nonsymmetrical patterns throughout blade interior will produce propeller unbalance or roughness. At the very least, operating fluid or hub lubricant leakage is a distinct nuisance. Oil or grease leakage may be caused by loosened lubrication fittings producing results similar to those produced by worn seals.

Early stages of structural failure resulting from fatigue of repeated loadings may show up as propeller roughness. In this instance, blade deflections may be great enough to allow a weight shift that will produce blade unbalance. This type of problem is an infrequent occurrence because of the care used in propeller design, development, inspection and testing prior to flight approval.

Wood propellers, that have been idle for a considerable period of time, may absorb moisture from the atmosphere in a nonuniform manner throughout its entire length. Unequal moisture absorption by wood propeller blades will introduce an unbalance characterized by vibration or roughness. Warping of wood propellers may produce similar results.

(*c*) Erratic Speed Control Resulting from Wear and Aging. Excessive wear of joints in a mechanical linkage, that controls propeller governor setting, may introduce backlash to such an extent that erratic speed control in flight will occur. Sticking metering valves of hydraulic units in a propeller speed control governor also, will produce erratic flight speed control.

Faulty connectors and burned or sticking contacts of electrically controlled propeller systems will produce undesirable fluctuations of propeller speed.

Fixed pitch wood propeller blades have a tendency to warp. Hence, with passage of time, fixed pitch wood propellers will begin to operate at speeds other than those of original design.

It is evident from the foregoing that diagnoses of erratic speed control difficulties may involve consideration of a great variety of possible causes. Further identifying symptoms may be evident in only certain functional situations with all other operational phases being perfectly normal.

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(*d*) Propeller Windmilling in Feather Position. Accumulation of sludge from engine oil in the dome of certain propellers may restrict movement of the actuating piston. Piston movement restriction may reduce blade angle range to such an extent that a propeller cannot be feathered, properly. Tell tale evidence of this type of malfunction will show up as windmilling propeller with controls in feather position; other operating characteristics of the propeller might be unaffected.

In a similar manner failure of cut out switches of an electric propeller can produce windmilling by undershooting or overshooting specified feather blade angle in response to feather demand of the control system.

In self-contained propellers, loss of operating fluid from the pitch control system may induce failure to reach feather angle with subsequent windmilling of the propeller after controls have been set in feather position.

(*e*) Stone, Rain, Hail and Sleet Damage. Foreign objects such as gravel, rain, hail and sleet will impose certain damage upon propeller blades in the normal course of propeller operation. Sharp nicks and gouges produced by foreign object contact with the whirling blades are points of stress concentration with excellent probability of subsequent overstressing and possible fatigue failure. It is not always a large gouge that is the most dangerous to blade life. Small sharp cuts produce very high stress concentrations and should be ground out in accordance with approved methods of repair.

(*f*) Corrosion. Most evidence of propeller corrosion will appear on exposed portions of hub and blade. Rust and corrosion will develop where blade coating or paint has been damaged. Salt laden air will be especially active in attacking certain propeller parts. Moisture entrapment within closed portions of a propeller may induce rust and corrosion in places where inspection is difficult.

Moisture entrapment may occur during sustained periods of idleness or during normal service usage of a propeller. Moisture entrapment during normal service occurs as a result of operation at both low and high altitudes. Alternating high and low pressures existing within inclosed spaces of the propeller induces a breathing action in response to altitude changes. In operation at variable altitude, moisture laden air will be drawn into such propeller equipment as governors and synchronizers producing moisture entrapment and, by virtue of temperature variations, moisture condensation. Moisture condensed upon interior propeller surfaces will produce rusting which may affect functional performance of component parts. Structural failure can occur from corrosion, if the oxidation process advances without check.

By direct impingement of rain, some water may be forced into propeller components during normal flight operations. Regardless of source or method of entrapment of moisture, corrosion will follow unless proper steps are taken to eliminate the moisture or protect exposed surfaces from oxidation processes.

(3) *Improper assembly or installation.* (*a*) Effects of Poor Installation. Every effort has been made to design and adopt foolproof components which can be assembled into the complete propeller only in the proper manner. Unfortunately, not all components lend themselves to design which will achieve that objective. Improper sealing and packing can produce serious corrosion problems. Bearings designed for loads to be applied in one direction can be expected to fail if the bearing is installed in reversed position. Failure to include front or rear cones in propeller installations will produce malfunction, without doubt. Similarly, improper tightening torque applied to propeller retaining nuts will produce severe unbalance.

(*b*) Propeller and Shaft Misalignment. Failure to insure clean surfaces on a propeller shaft, in cones and hub may produce improper alignment of propeller and shaft. Not only must the propeller center of gravity coincide with the axis of rotation (propeller shaft centerline), but corresponding portions of various blades of the propeller must rotate in a plane perpendicular to the axis of rotation. In other words, a propeller should *track* throughout.

(*c*) Improper Adjustment of Blade Angle Change Stops. If the low blade angle setting or the range of blade angle travel of a controllable propeller has not been established in accordance with specifications, improper speed control will result. Improper range of blade angle setting will produce undesirable high speed, high angle propeller control. With restricted range of blade angle, the propeller blade will move into position against the blade angle stop under certain speed conditions

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thereby limiting further angle change or blade movement.

Similar difficulties will be encountered by improper installation of governors or synchronizers on constant speed propellers. The pulley or control arm may not be coordinated properly or possess sufficient travel, which would restrict the operating range.

(*d*) Cone Seat and Retaining Nut Adjustment. When a propeller is being installed, every effort must be made to insure that the cone seats properly on the propeller shaft and against the thrust bearing of the engine. There must be no foreign material or burrs between mating surfaces; therefore, these surfaces must be clean and dry before installation if galling and unbalance of the system is to be avoided. To achieve proper adjustement of cones and seats, the propeller retaining nut must be tightened with a torque measuring wrench. Improperly tightened nuts will produce galling in rear cones, which, in turn, will produce rough propeller operation and, possibly, structural failure. Probably it is better to replace the cones whenever a propeller is removed and subsequently reinstalled on an airplane, since cones are relatively inexpensive. However, it may be practical to reuse the cones furnished with a given propeller, if they are properly serviced and inspected prior to reinstallation and providing cone service damage has not accrued.

(*e*) Use of Improper Blade Seals. Some sealing problems are caused by mold flash which is formed by improper seating of parting surfaces of a molding flask used in fabrication of the seal. This mold flash must be removed prior to use. Seal material, frequently a synthetic rubber compound, is not always adaptable for use with all propeller oils and greases. Some of these compounds show undersirable rates of swelling when used with incompatible oils or greases. For instance, some seals that are suitable for use with MIL-L-7711 grease cannot be used with MIL-G-3275 grease. In all of these cases, an undue amount of leakage can be expected. Further, leakage of oil or grease may be traced to improper installation of lubrication fittings or filter caps. Seal treatment involving warm oil bath immersion for "curing" should not be used unless specifications require that treatment. Solution to most sealing problems can be obtained by proper shop installation and rigid inspectional procedures. Oil seals worn to a point of nonretention of oil must be replaced.

Propeller components must be properly sealed to exclude moisture, or appropriate vents provided to insure breathing of the component thereby exhausting water vapor entrained in the air. In other words, just as a human lung inhales and exhales air and accompanying moisture, closed propeller components must expel moisture laden air to insure minimum corrosion.

(4) *Faulty maintenance.* Evolution of service problems from faulty maintenance is fairly common and readily recognizable. Service problems will ensue whenever worn parts are not replaced at the proper time, sliding surfaces are improperly lubricated or general servicing requirements are ignored. Damaged blade surfaces if not repaired will lose life expectancy by fatigue failure. Failure to resurface parts exposed to corrosive atmosphere will induce functional or structural failure.

A large proportion of all service problems have roots in faulty maintenance. Therefore, the importance of careful, complete, periodic maintenance of propeller systems cannot be overemphasized. A key to major reduction of service problems is composed of rigid inspection coupled with scheduled maintenance.

(5) *Improper design and fabrication.* Faulty fabrication and insufficient quality control frequently introduce serious service problems. Factory inspectional procedures have been designed to minimize introduction of service problems that arise from poor quality control. However, some defective parts continue to get by inspection and show up in propeller installations to cause service difficulties.

Tool marks and scratches introduce fatigue failures; poor plating or sealing can cause corrosion. Lack of quality control in production of propeller cone material may be instrumental in developing cone galling. Poor workmanship in cone production can produce the same effect.

Improper design of any of the components of a propeller system can produce serious service problems, or at least complicate propeller maintenance. The effect of stress raisers has been discussed previously but it is not amiss to point out that failure to design a properly faired or filleted section will introduce fatigue failure—a service problem.

Assembly of blades and components into a

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complete propeller system must entail careful balancing of individual parts and the complete unit. Aerodynamic balance of blades is essential if dynamic balance of the complete propeller system is to be attained. Economy and production requirements dictate use of larger allowable blade tolerance than desired. To compensate for aerodynamic differences existing between blades produced under large tolerance conditions, each blade has been assigned a correction factor. This correction factor (determined after dimensional inspection) indicates the adjustment to index blade angle necessary to obtain equivalent thrust of a reference (perfect?) blade. In this case, design effort has been directed towards reduction of propeller roughness.

Selection of an appropriate propeller feathering angle must be a compromise of conflicting requirements. Selection of a feathering angle based upon low forward speed will give a control that will permit propeller rotation at high speed. Tightness and friction effects of the airplane engine will exert an influence upon propeller rotation when in feathered position. Failure to consider such problems early in the propeller design phase may cause improper stop settings with a subsequent windmilling service problem.

Propeller design that fails to provide adequate seals or vents can be a basic cause of involved corrosion problems.

(6) *Abuse of propeller systems.* There is little excuse for existence of service problems that develop from propeller abuse. However, human errors and indifference being ever present, cognizance must be taken of the probability of acquisition of service problems from this cause. During assembly, bolt overstressing frequently results from tightening with improper wrenches. Operation of a propeller system under conditions other than those for which designed can only result in failure. For example, a feathering pump motor designed for short time cycle duty can be burned out by excessive continuous operation.

Solution of Propeller Service Problems

Fundamentals of Service Problem Solution

Recognition and statement of a propeller service problem, as such, is the first phase of solution of a difficulty. As with most other problems, solution can be attained easiest by systematic logical reasoning. Known facts of equipment behavior or malfunction must be the starting place for problem solution. Since application of a remedial action for one service problem may create another more serious difficulty, solutions must be formed that are based upon careful analysis of causes and effects. A good solution can be obtained only if founded on thorough knowledge of the equipment, its function and construction. Therefore, a thorough survey of all available instructions and technical information pertaining to a specific propeller should be made prior to initiation of any corrective action. Further, a review of previous service problems involving the propeller type involved, along with a study of all possible solutions, will aid materially in arriving at a suitable solution of a particular service problem.

Propeller agencies and laboratories of the military services should be contacted immediately by operating units to request assistance in solving service problems. Since these agencies are staffed with personnel who have been closely associated with the development of a given propeller system from its earliest conception, reliable solutions will be forthcoming from those agencies quicker than from any other source.

Training Service Personnel

Propeller maintenance shop performance will be only as good as personnel engaged in servicing and repair make it. Shop mechanics and supervisors cannot perform their functions properly unless adequate training has been given in propeller construction, production and functional characteristics with operational factors and limitations included. There is no requirement for training in propeller theory insofar as effective job performance by mechanics is concerned. But greater knowledge of all phases of propeller activity will insure better shop performance in solution of propeller service problems. Shop personnel assigned to propeller maintenance must be cognizant of possible ramifications involved in particular service problems and trained in all aspects of propeller business necessary to completion of the shop mission. Were a propeller shop mechanic's course curriculum established, most assuredly it would contain:

(1) Propeller assembly—allowable dimension limits and tolerances.

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(2) Approved propeller balancing methods—shop adaptability.
(3) Propeller assembly methods—parts required and function of each, along with physical relationship of assembled units.
(4) Propeller operating characteristics—normal, malfunctioning and marginal operation.
(5) Methods of repair of propeller components.
(6) Standards for rejection of propeller parts.
(7) Inspectional methods—visual, magnetic.
(8) Propeller airworthiness.
(9) Propeller trouble shooting (diagnosis of service problems).
(10) Use of propeller tools.

While this handbook cannot present training requirements of aircrew personnel, it is appropriate to indicate the information needed from flying personnel to initiate propeller malfunction studies. Specific information that is helpful in tracing development of propeller malfunction includes:

(*a*) Propeller speed range over which malfunction occurs.
(*b*) Aircraft altitude and airspeed at which difficulty developed.
(*c*) Engine power, control settings and physical manifestations of trouble.

The pilot or observer should be able to furnish an accurate and complete account of propeller behavior and should be familiar enough with normal operation to recognize marginal conditions.

Some random samples of typical service problems are presented herein to illustrate the scope of service problem solution. Certainly, an exact and complete compilation of all service problems with approved solutions is impossible but perusal of those presented will demonstrate forcibly the need for training of service personnel.

Importance of Use of Special Tools in Solving Service Problems

In the course of design and development of propellers, consideration has been given to utilization of standard tools in order to reduce to a minimum the number of special tools required for assembly, disassembly or servicing. However, propeller design requirements of important, dominating factors are so difficult and exacting that avoidance of all special tools is precluded. Use of specified tools for propeller assembly and installation must follow, since the extent of service problems will be influenced significantly by malpractice in maintenance.

For example, static unbalance resulting from improper shop assembly can produce roughness in propeller operation. The same result might be obtained by improper installation of the propeller. In what way does use of special tools influence shop assembly induced roughness or installation unbalance? Special propeller balancing equipment must be used with certain systems to obtain static balance. In the latter case, a specified torque wrench for a given installation must be used to insure that the propeller retaining nut is tightened to a proper degree.

Blade nut spanner wrenches, regulator or dome nut wrenches and many other special tools are required for component and propeller assembly. Misapplication of tools or wrenches to propeller parts induces improper propeller assembly and, in addition, enhances the possibility of damage to propeller components during assembly. Special tools and equipment must be used in the manner specified to accomplish the design objective, safely.

For example, even though a blade retaining nut wrench is being used to tighten the nut, if proper care is not taken, the wrench may slip off of the nut and strike the blade shank or some other part with sufficient force to damage the part. Other instances of use of improper equipment are far too numerous. To illustrate a specific case, it has been the practice, at times, to use a conventional hoisting sling for handling a propeller in the shop or during installation, in spite of the fact that special hoisting or handling features have been affixed to the hub that eliminate sling contact with propeller blades. Use of this special handling feature will eliminate damage to external deicing elements since sling contact will be eliminated.

The special inspectional equipment furnished for determination of compliance with specified tolerances and dimensions is just as important to good maintenance as special assembly tools. Such equipment is extremely susceptible to

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damage which nullifies the accuracy and functional utility. Hence, care must be exercised in using inspectional equipment and frequent check of its accuracy is most desirable. Included in this category are: torque wrenches, balancing equipment, pressure gages, tachometers and various shop dimensional and testing devices. In this technological age, quality of finished products (propellers) will be only as good as the accuracy of inspectional equipment and skill of shopmen permit.

That so much attention has been given to special tools and equipment in preceding paragraphs should not detract from outstanding requirements for using common tools and shop processes. Appropriate box or end wrenches should be used for propeller bolts and nuts and use of inadequate tools, such as those used by inept mechanics, should be avoided (monkey wrenches, pipe wrenches, pliers, adjustable types and alligator wrenches). Use of such hand tools will reduce quality of a propeller system by multilation of surfaces to which the nondescript tools have been applied.

Service Problem Records

As a means of obtaining better propeller service with a minimum amount of maintenance, use of an Individual Propeller Log or Historical Record, as a standardized record keeping system, should be considered as an absolute necessity. Such a record system will reflect time intervals between overhaul, nature of service interruptions, current status of each propeller and will aid in establishing appropriate inspection schedules. A propeller log will show all types and frequencies of unscheduled propeller removals along with labor and parts or repair necessary to return the unit to service.

In addition to being extremely valuable to all propeller maintenance effort, a carefully maintained propeller log will be an invaluable source of authentic information that can be utilized in development of new propellers. Furthermore, the log can be used to good advantage in redesign or modification of components that have been causing trouble.

As a minimum, a Propeller Log should incorporate all of the following data, and in addition should include every unusual incident and service interruption:

(1) Propeller hub and blade serial numbers.
(2) Engine and aircraft upon which propeller is installed.
(3) Service time since last overhaul (hours).
(4) Shop time propeller out of service (hours).
(5) Total service time (hours).
(6) Date and time of technical order directed modifications.
(7) Date and time of component replacements.
(8) Non-directed modifications and purpose.
(9) Unusual operating conditions to which propeller has been subjected.
(10) Record of shops or depots making overhauls or modifications.

Service Trouble Shooting

Unfortunately, only generalized instructions can be given for procedures to be followed in solving propeller service problems. Even though observed phenomena of propeller malfunction are identical, the difficulty may stem from a great variety of causes. Therefore, some form of systematic approach and analysis is essential to effective trouble shooting. One great step towards solution has been taken after the nature of propeller malfunction and conditions surrounding its occurrence have been established, definitely. Therefore, accurate descriptions of propeller behavior must be obtained. Having established the nature of a propeller malfunction, reconstruction of conditions of failure should be made with the propeller operating through its complete design range in order to cause repetition of the malfunction. These tests for failure should be repeated a large number of times under close observation to isolate the cause. Tests should be continued even after cause of failure has been found, so that frequency of failure, effect of variation of operating conditions and all symptoms of malfunction can be recorded. Isolation of the cause of propeller malfunction may become a trial and error process of elimination based upon a shrewd analysis of the situation. Obviously, trouble shooting experience and records of previous problems will be most helpful in this phase of service problem solution.

Because certain types of propeller service problems have been studied and complete records kept in the past, it is possible to present,

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in tabular form, some of the most common of these difficulties. In presenting this table, no claim is made that it is all inclusive—in fact, it is not and could never be complete. Many of the remedial actions proposed must be performed after partial or complete propeller disassembly. In general, line maintenance facilities do not permit propeller overhaul; hence, those operations requiring disassembly should be performed at depots or overhaul shops. Since detailed procedures of adjustment, assembly and disassembly of propellers and related components have been published in the form of technical orders or service bulletins by propeller manufacturers, no attempt will be made to present that material in this handbook. Thorough study of current technical orders and service bulletins is essential to propeller maintenance. Overhaul of a specific propeller type should never be undertaken until information contained in those documents applicable to the propeller under consideration has been absorbed.

TABLE XII-2. *Propeller Trouble Shooting Chart*

Propeller Roughness

(Propeller Unbalance)

Probable Cause	*Remedial Action*
Iced blades or hubs	Use anti-icing or deicing devices.
Mismatched blades	Replace with matched set.
Blade angle variation (between blades)	Reset blade angles using protractor, blade scribe marks.
Blades out of track	Realign or replace blades.
Damaged blades	Repair and rebalance entire assembly.
Oil or grease deposits	Oil—replace blade cylinder; grease—replace cylinder seal ring.
Engine malfunction	See engine maintenance manuals.
Loose propeller shaft nut	Tighten nut—torque (in foot pounds) as specified for given propeller.

Non-Synchronization

Probable Cause	*Remedial Action*
Engines not synchronized	See engine manuals.
Sludge in governor pilot valve or relief valve	Disassemble and remove sludge.
Piston of dome assembly sticking	Clean and lubricate piston gasket or replace gasket, polish piston contact area of dome with crocus cloth.
Loose piston gasket	Tighten piston gasket nut.
Governor control system backlash	Adjust or rerig control system.
Air in propeller control system	Manipulate controls from high to low pitch, during run-up.
Low oil pressure	Disassemble regulator, clean screen and control valve filter; check actuating pressures of pressure control valve; check oil level; replace oil pump seal—or pump, if damaged; replace governor piston, if binding; look for blown gaskets.
Governor binding	Replace or adjust warped base—tighten mounting screws properly.
Poor electrical connections	Check wiring, clean and tighten connections.

TABLE XII–2. *Propeller Trouble Shooting Chart*—Continued

Failure to Feather or Unfeather

Probable Cause	*Remedial Action*
Low battery voltage	Recharge batteries.
Faulty electrical system	Check and repair feathering pump and control circuit wiring system.
Auto-disengagement of control push button	Check and correct battery voltage, and low pressure setting cutout switch.
Failure to stay feathered with push button engaged.	Reset cut-out switch, check and adjust electrical control circuit.
Feathering pump coupling failure	Replace coupling.
Defective feathering pump	Replace pump.
Insufficient oil supply to feathering pump	Clean pump fluid inlet lines.
Windmilling in high pitch angle	Reset high pitch stop ring.
Leakage of distributor valve	Reinstall distributor valve.
Damaged gasket, governor base-engine mounting pad.	Replace.
Leakage—engine transfer rings	Replace rings, see engine manuals.
Power unit failure	Replace power unit; correct electrical circuit failures.

Oil Leakage

Probable Cause	*Remedial Action*
Damaged seals, gaskets or packing	Replace as necessary: dome breather hole seals, dome barrel seal, barrel half parting line seals, engine thrust plate seal, breather cap gaskets, blade barrel bore packing, spider barrel packing or spider shaft seal.
Damaged chaffing rings (split or moulded)	Replace chaffing rings.
Non-closing line barrel halves	Remove burrs from parting surfaces.
Loose master spline screws, dome nuts	Tighten retaining nuts and screws.
Too many dome preload shims	Remove surplus shims after preload check.
Loose distributor valve	Tighten valve or engine shaft extension.
Poor engine seals, parts or excessive engine blow-by.	See engine manuals for remedies.

Failure to Achieve Takeoff Speed

(Propeller r. p. m.)[1]

Probable Cause	*Remedial Action*
Erroneous tachometer or pressure gage readings	Calibrate all instruments.
Incorrect governor setting	Reset governor.
Improper installation of low pitch stop	Reset low pitch stop ring.
Insufficient warm-up of propeller mechanism	Move controls through complete speed range while running.
Damaged gaskets	Replace gaskets.
Sticky governor pilot or relief valve	Disassemble and clean all parts.
Rapid throttle opening	Advance throttle evenly and slowly.
Engine transfer ring leakage	Replace rings (see engine manuals).
Low engine power	See engine manuals.

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[1] In some installations, takeoff speed cannot be obtained on *the blocks* even though takeoff manifold pressure is achieved.

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CHAPTER XIII. PROPELLER MAINTENANCE TOOLS AND EQUIPMENT

Special Tools and Equipment—Scope of Discussion

Perspective of Broad Objectives

Development of special propeller tools can be justified only on the basis of improved flight safety of assembled propellers, decreased maintenance or installation time expenditure, inapplicability of existing standard tools and equipment, or any combination of those factors. Whenever use of an especially designed tool will insure propeller airworthiness that cannot be obtained by use of standard equipment, such tools should be developed and specified as appropriate installation, assembly or disassembly equipment.

However, indiscriminate use of special propeller tools, most assuredly, will lead to an intolerable situation in which nearly every maintenance operation would require a particular tool. Therefore, use of special tools and equipment must be held to a minimum by propeller design that will permit use of standard tools to the greatest extent possible. But this restriction should not operate to prevent development and use of those special tools that will result in considerable saving of maintenance time.

It should be apparent that complete detailed description of function and application methods pertinent to every special tool cannot be presented in such a publication as this. To emphasize the value and need for such tools, a variety of special tools that depict functional utility will be presented and discussed. Fundamentally, the objective of this section of the handbook is to present requirements and usefulness of special propeller tools.

General Definition of Propeller Special Tools

Throughout the discussion presented herein, the term *special tools* will have a meaning as defined in MIL–D–8512. Tools specifically designed to aid in accomplishment of a specific function in assembly, disassembly, inspection or maintenance of propeller components have been designated propeller special tools. Of course, the general definition just stated will include those tools which are standard tools modified to meet some peculiar functional requirement in application to propeller assembly. Propeller special tools include all special jigs, fixtures, test equipment, hand tools and handling equipment required for propeller assembly, installation and maintenance.

The generally accepted definition of propeller special tools excludes all general utility tools that normally are carried as commercial stock items—i. e., box wrenches, screw drivers, pliers, socket wrenches, etc.

Propeller Special Tool Requirements

General Considerations

(1) *Purpose of supplying special tools.* Complex aerodynamic and structural requirements imposed upon propeller design force adoption of unique configurations that deviate greatly from conventional propulsion systems. To attain necessary propeller airworthiness with minimum weight penalty while retaining ready assembly and disassembly characteristics, for maintenance purposes, it is necessary to develop special tools that facilitate functional operations essential to assembly. It must be recognized that the costs involved in development, logistics and maintenance of special propeller tools represent a penalty paid for safe propeller propulsion systems. However, every special tool adopted must stand the test of contributing achievement towards improved assembly, greater operating safety or reduced maintenance.

(2) *Insufficiency of general commercial tools.* Propeller special tools have distinctive applications to assembly of structural components that have no similar counterparts outside of the aeronautical field. Further, even within the propeller industry, peculiar requirements of particular types of installations require use of special tools that are not applicable to other

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types of propellers. Therefore, commercial production and stocking of such special tools is not economical or profitable for tool suppliers engage in "over counter" sales of standard tools. This is not to imply that every effort will not be made to utilize standard tools whenever possible in propeller work. Recognition of the conditions which demand development and use of special tools and those in which standard tools will suffice is one of the propeller designers' problems.

(3) *Special tool economic factors.* It would be possible to design a propeller which would require a special tool for each separate handling and assembly operation. Or, it might be possible to develop a propeller which could be assembled using only standard *off-the-shelf* tools. Obviously, neither approach would be acceptable; the first because the expense and awkwardness of a multiplicity of tools would be unwelcome while the second, doubtless, would introduce conflicts with aerodynamic requirements or introduce potential hazards to flight. Between these economic extremes will lie the best procedure in adoption and use of special tools for propeller application.

Even though special tools are required and adopted for use with specific propeller installations, careful attention must be given to the design of those tools to make sure that simplicity consistent with functional compatibility has been incorporated into the design. Observance of this precaution, concurrently, will insure that special tool cost for a given propeller installation is not prohibitive. But, cheap, flimsy special tool construction that renders a unit having doubtful functional integrity is false economy and may be a flight safety hazard.

(4) *Adaptability to field service conditions.* Inasmuch as a propeller assembly is a mechanism composed of moving parts, wear is inevitable. In order to retain usable propellers in continuous service, it is necessary to conduct periodic inspection, servicing and repair of the propeller components. To determine the extent of wear and functional integrity of a propeller, it may be necessary to perform some field service testing (at depots, usually).

Special propeller tools must be designed to perform under field service conditions. Here again, the importance of simplicity becomes apparent. Simplicity of design will materially reduce the amount of special tool maintenance required. Special propeller tools required for repair and servicing must be held to a minimum, so that remote service installations will not have to carry a great variety of tools. Further, special tools devised for propeller installation and maintenance must be adaptable to field service use, where temperatures and humidities may vary widely. It must be assumed that limited power availability may exist at some outlying stations where propeller installation, assembly, disassembly, or servicing must be performed.

Specific Requirements of Special Propeller Tools

(1) *Functional.* Special propeller tools have been developed to facilitate operations involved in inspection, maintenance or installation of propeller assemblies. As has been noted previously, justification for adoption of a special propeller tool must include an affirmative an-

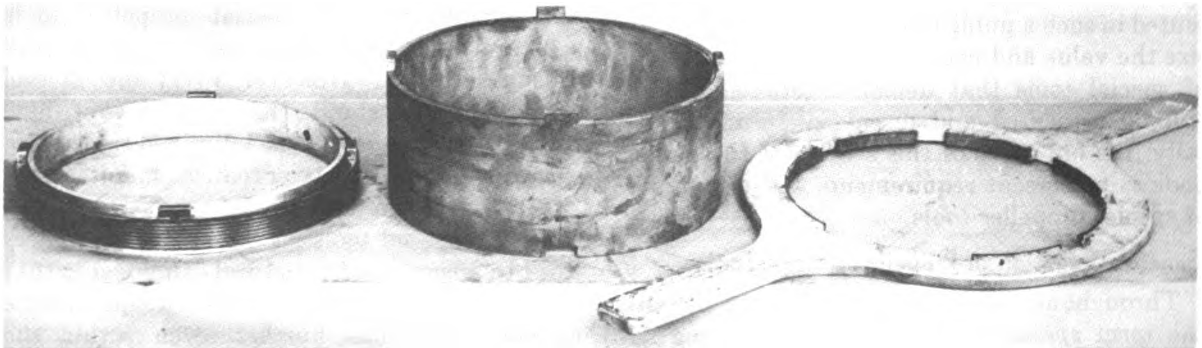

Figure 13.1.—Propeller dome retaining nut wrench.

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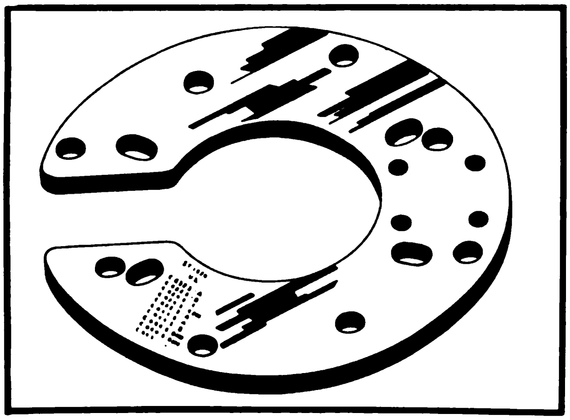

Figure 13.2.—Propeller assembly inverter plate.

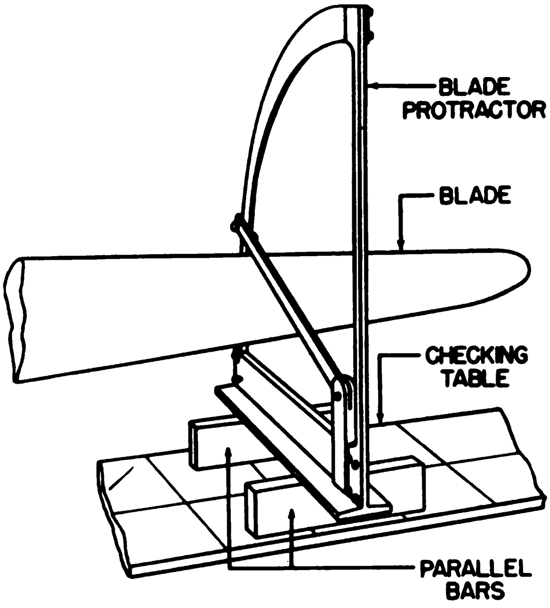

Figure 13.3.—Blade angle protractor.

swer to the question, "Is the adoption of this tool necessary to perform inspection, maintenance or installation of propeller assemblies that cannot be accomplished just as effectively by use of standard tools?" Functional requirements of special propeller tools permit further tool classification which has wide acceptance.

(*a*) Single Purpose Tools. Single purpose propeller tools have configurations required to mate specific detail components of propeller assemblies. An illustration of a typical singular purpose tool is shown in figure 13.1.

The propeller dome retaining nut wrench is shown in the right hand side of the photograph. It is apparent that the slots of the wrench will mate with the lugs on the propeller dome retaining nut sleeve assembly (center of the photograph). Slots in the lower edge of the sleeve assembly must mate with the projecting lugs on the propeller dome retaining nut (the threaded component shown at the left of the sleeve assembly).

(*b*) Multiple Purpose Propeller Tools. Multiple purpose tools are designed for use in assembly or disassembly of several (two or more) propeller components. An illustration of this type of propeller tool is shown in figure 13.2. Certain types of gages, alignment tools and drifts fall into this category, also.

Use of this device permits assembly or disassembly of any one of several propeller units.

(*c*) General Purpose Tools. A general purpose propeller tool is one which is adaptable for use in assembly or maintenance of several types or makes of propellers. Doubtless, the best illustration of this type is that of the blade angle protractor shown in figure 13.3. Regardless of the propeller make, this tool can be used to measure blade angle.

Other examples of general purpose tools would include propeller slings and hoists. Because of the peculiar configuration of propellers and the risk involved in flight with blade or other propeller components scarred inadvertently during handling, special handling equipment is fully justified, in many cases.

Since propeller components are designed to standards prescribed by military services and the propeller industry, the tools necessary to maintain the components are built to common standards and designated general tools. Such tools are applicable to all propellers of the same shaft size and are designed to meet two objectives, namely, to achieve standardization and to reduce procurement costs by broadening the supplier base. General propeller tools include the following:

(*i*) Propeller assembly stand.
(*ii*) Assembly posts, nuts and spacers.
(*iii*) Assembly and balancing bushings.
(*iv*) Hub cone seat distance gages.
(*v*) Hub cone lapping tools.
(*vi*) Lifting slings.
(*vii*) Balancing stand and ways.
(*viii*) Propeller balancing mandrels.
(*ix*) Blade angle checking protractors.
(*x*) Shaft end thread protector.

(*d*) Functional Objectives. In general, special propeller tools, apparently, are justified to

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attain the following functional objectives:

(*i*) Lift, handle and transport propeller units weighing more than fifty pounds.

(*ii*) Tighten screw threaded elements (such as nuts or studs) to specific torque load. Such torquing tools should be indexed and calibrated to provide direct reading gages or scales of torque loads.

(*iii*) To tighten screw threaded elements not requiring specific torque loads, by application of steady moments. Impact loading to tighten threaded parts will require tool retaining features to prevent bounce with subsequent damage to propeller components when struck by the flying tool.

(*iv*) To insert and remove, press fit propeller components. This type of tool may be of general gear puller or sliding knocker design. An illustration of this type of special tool is shown in figure 13.4.

(*e*) Unresolved Functional Requirements. There is a military service requirement for universal tools to perform the following functions:

(*i*) Automatic and reliable application of preset (variable) torque loads to propeller blade nuts of all existing propeller types without damaging contact with adjacent propeller components.

(*ii*) Securely gripping commercial standard or AN bolts and nuts, by a chuck fixture for knocker ram tools, to facilitate insertion and removal of press fit propeller parts. Development of such a holding fixture will materially reduce press fit tool maintenance.

(*iii*) Accurate blade angle measurement (±.05°) with adequate checking of blade contour. A durable instrument for field maintenance that will retain accuracy under rough handling must be developed. Measurements of this instrument must be orientated with blade leading edge. The "lands" or stabilizing positions of the blade form template must have a span equivalent to 55 percent of the projected plan of the blade section. The template must be of such form that contact will be made with the propeller blade surface.

(2) *Tool availability.* Special propeller tools must be made available simultaneously with submission of the first experimental propeller item. Special tools in quantity sufficient to meet requirements of service facilities of the military services must be made available at the

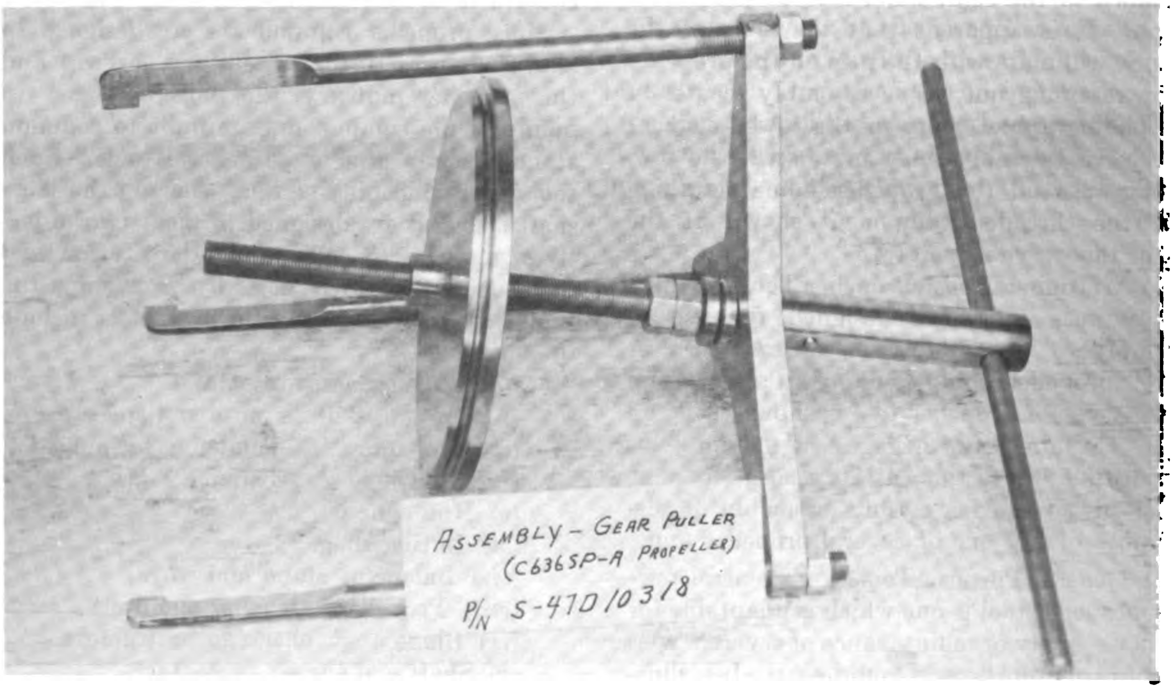

Figure 13.4.—Gear puller.

time that propeller production in quantity is started. Further, anticipated replacement parts for special propeller tools must be provided to insure that adequate safe propeller service can be maintained.

(3) *Safety of flight considerations.* A basic requirement of all special propeller tool design, consisting of incorporation of those features that will enhance safety, must be met. Such features include provisions that will prevent tool slipping with possible attendant damage to propeller blades or other propeller subassemblies. Functional operation of propeller tools must be reliable under all conditions.

(4) *Special tool physical characteristics.* The most effective and safest tool to be used in any given assembly operation is usually the simplest consistent with functional requirements. Every effort must be made to design special propeller tools with this thought in mind. In addition, consideration must be given to conditions of use, which in almost all cases, will require tool ruggedness to withstand abuse beyond that of laboratory service.

Utility Influence Upon Special Tool Design

Weight Factors

Special propeller tools designed without regard to weight will not be used as readily as lighter more portable tools even though the latter are not designed for the service to which applied. Of course, in addition to encouragement of maintenance personnel to use special tools, lightweight propeller tools will be cheaper since, in general, cost is proportional to material weight.

Service Accessibility

The best special tool will be useless, in fact, unless it is accepted by service personnel. Therefore, every effort must be expended to develop tools that facilitate propeller servicing, assembly or disassembly with safety. Special propeller tools must be designed to perform under maintenance conditions that exist in field facilities as well as to meet new propeller assembly and installation requirements under factory or depot conditions.

Propeller Special Tool Design

Influence of Propeller Type

Inasmuch as there is a great deal of variation in structural and mechanical features of various types of propellers, a requirement for an equally large number of special tools might be expected to exist. However, by the use of special adapters some special tools designed for use with a particular propeller type may be utilized to accomplish similar functions with other propellers. An example of this adaptation of special tools for multiple propeller type use is shown in figure 13.5.

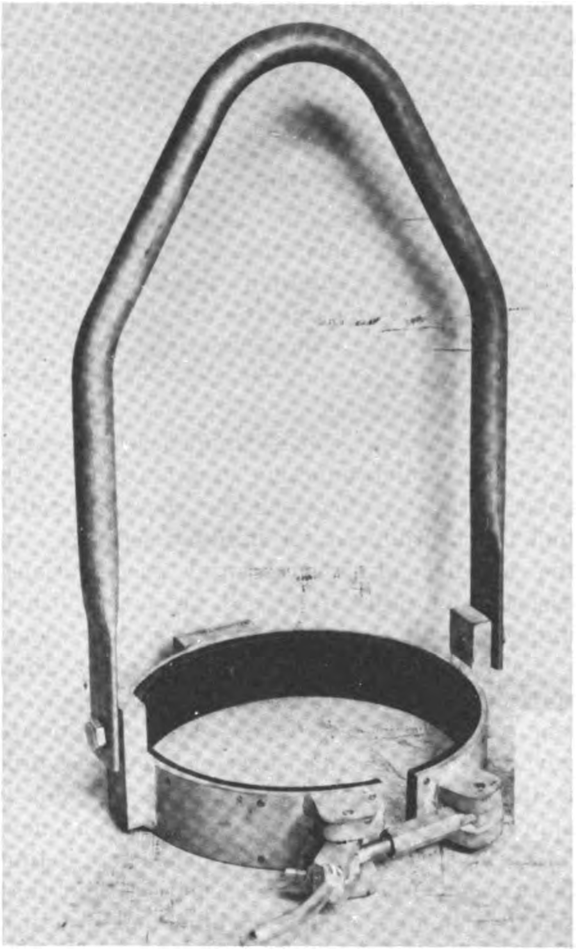

Figure 13.5.—Power unit sling assembly.

This sling assembly was designed as a lifting device for a particular power unit of an electric propeller. By use of a liner for the grip assembly, this lifting device has been used for lifting the dome of a hydraulic type propeller. Further improvement and adaptation has permitted use of the same type of lifter for heavier units of electric propellers. This application is shown in figure 13.6.

With different systems of blade retention, basic variations in methods of obtaining blade pitch control and multiplicity of assembled

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propeller and component configurations, it is evident that for each propeller system there must be a complete, distinct set of special tools that will facilitate servicing, assembly and installation of the propeller.

Materials and Workmanship

Materials specified for use in fabrication of special propeller tools must be of high quality and particularly adapted to the proposed application. In general, the materials selected will be the same as those identified with comparable tool functions in other than aeronautical applications.

Heat treatment will be applied as necessary to special tool production in accordance with government specifications for those propeller tool items produced for military services. In the absence of governmental specifications, special tool fabrication will be accomplished under propeller manufacturer's specifications.

Special metal tools made of other than corrosion resisting steel must be cadmium or zinc plated in accordance with appropriate governmental specifications, or otherwise protected from corrosion by methods previously approved by the responsible procuring agency.

Workmanship involved in special tool manufacture must be equal to or better than that specified in high grade machine tool practice. Tool articles must be free of abnormal scale, burrs or defects which might detract from tool utility in service.

Tool Marking and Identification

A tool part numbering system, acceptable to the procuring agency, must be adopted and all special tools will be identified by stamping appropriate numbers in conspiciuus places on the tool parts. Tool identity by part number and name will be included in specifications and drawings of special tools. Complete lists of required special tools, identified by part number and name, must be furnished with specifications and drawings of each accepted experimental or production model propeller.

Safety Features

Every effort must be made to incorporate into all propeller tools and equipment safety features that will prevent, insofar as possible, structural damage to blades or other components by misuse or accidental misapplication. Slipping tool grips can inflict serious damage that may result in fatigue failure. Torque wrenches must be equipped with direct reading meters, carefully calibrated to reflect accurately the torque applied in tightening threaded joints. Torque wrenches may be of manual or power application type but if designed as the latter must be equipped with safety features that will prevent overstressing screw threads.

Special Tool Specifications

Design, fabrication, identification and graphical presentation of special propeller tools must meet all stipulations of the Military Specification MIL–D–8512; Design; Special support equipment; (For aeronautical and associated equipment.) In lieu of this requirement, a propeller manufacturer's specification for spe-

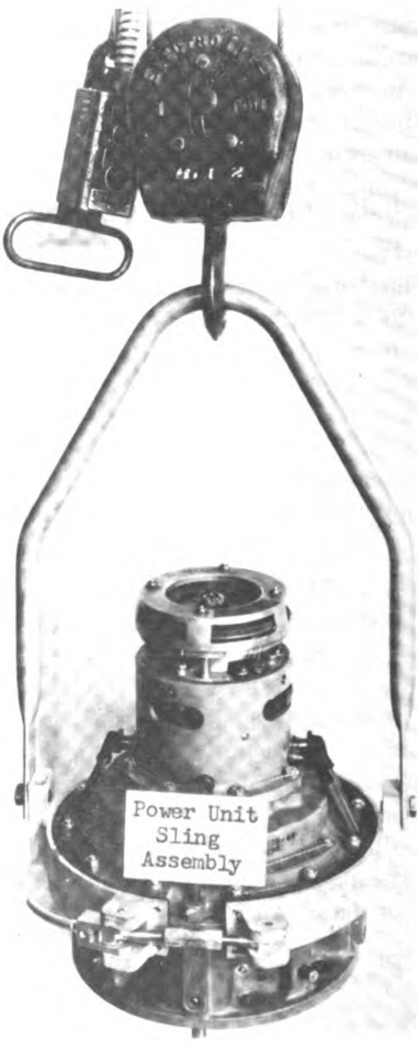

Figure 13.6.—Hoisting an electric power unit.

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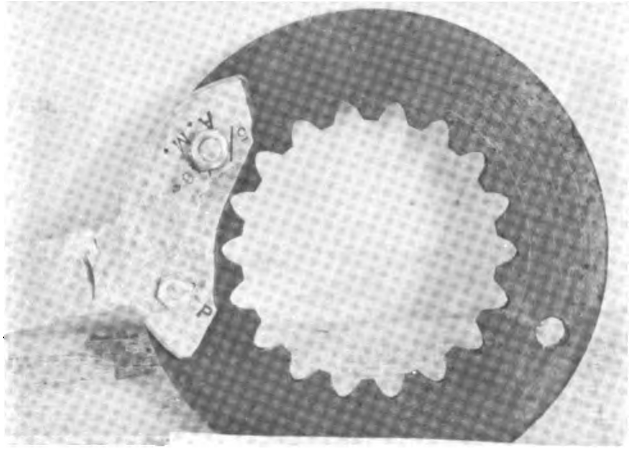

Figure 13.7.—Electric power unit brake holder.

cial tools may be used if prior approval has been obtained from the procuring agency.

Functional Design

The most important phase of special tool design is to insure that tool function in propeller assembly or maintenance is accomplished safely and expeditiously. A simple illustration of functional utility of a special tool is shown in figure 13.7.

This tool was devised to prevent the power unit brake hub from turning while the brake shaft nut is being removed from the shaft. Note that the serrated portion of the brake holder is fabricated from brake disk material that will prevent injury to the brake hub. In this particular case, the tool illustrated is a modification of a previous type holder which consisted of a serrated segment with locating pins for positioning but without the hand grip shown in this photograph. Adoption of the design shown was made to reduce shop maintenance time.

Types and Applications of Propeller Tools

General Note

Within this section, a number of propeller tools will be illustrated and described, not with an idea of all inclusive presentation but rather for the purpose of showing general classes of tools, design features, utility and structural characteristics. Complete detailed lists and illustrations of propeller special tools can be obtained from appropriate technical orders for propellers of interest.

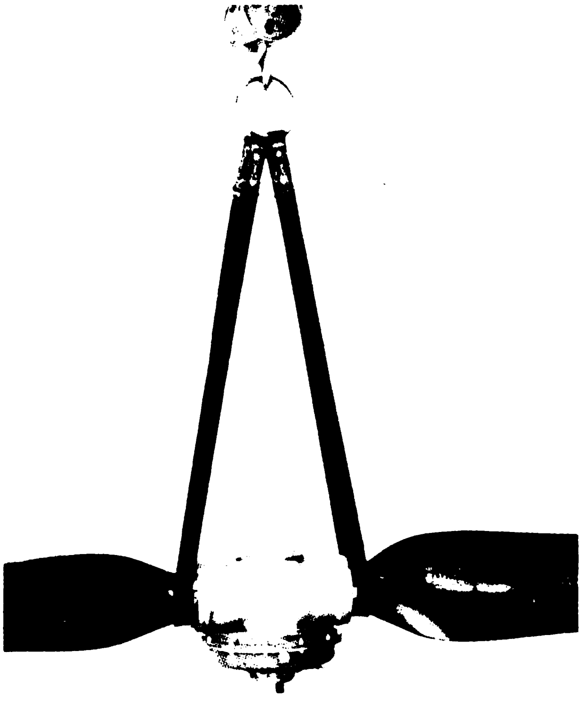

Figure 13.8.—Hoisting slings.

Propeller Handling Devices

Structural characteristics along with susceptibility of blades, deicing units and other components require use of special devices to handle and move propellers during repair, assembly or installation. Some of the devices used are extremely simple as illustrated in figure 13.8, which shows fabric slings frequently used for handling propeller blades.

It is to be noted that by using fabric hoisting slings with a commercial type chain hoist, pro-

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Figure 13.9.—Propeller dolly.

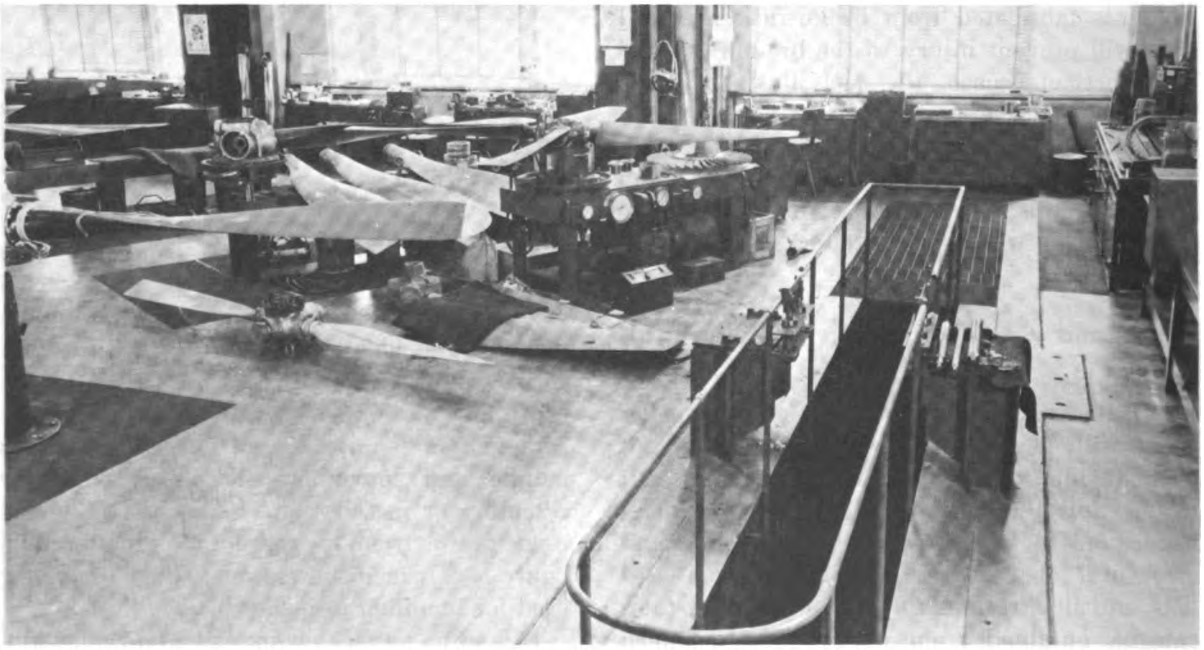

Figure 13.10.—Propeller shop balance pit.

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peller blade assemblies can be handled without risk of damage. Another type of hoisting sling was shown in figure 13.5 and still another type will be presented in a subsequent discussion of universal type power tools. Fundamentally, one basic characteristic has been incorporated into all of these propeller handling devices, namely, non-damaging propeller contact.

Hoisting slings and lifting devices shown thus far serve well for shop handling of propellers but cannot be used for propeller movement or transfer to installation points along the flight line. For this purpose, it is most desirable to use a special propeller dolly that has been designed with proper clearances to prevent blade contact with the ground. A typical propeller dolly is shown in figure 13.9.

In this photograph, a three-blade propeller is being mounted on the dolly preparatory to movement to the propeller shop for overhaul. Of interest in this dolly design is the use of a tipped hub spindle to permit retention of low center of gravity of the propeller loaded vehicle while still obtaining necessary blade ground clearance.

Propeller Balancing Equipment

As has been shown previously, propellers must be carefully balanced before installation on an airplane. The overall diameter of a propeller requires use of special equipment that will permit free movement of the propeller about its axis of rotation. A photograph of the balance pit in the propeller shop at Wright Air Development Center is shown in figure 13.10.

The balance pit is shown in the right foreground with the knife edge supports on either side of the pit shown clearly. This pit is

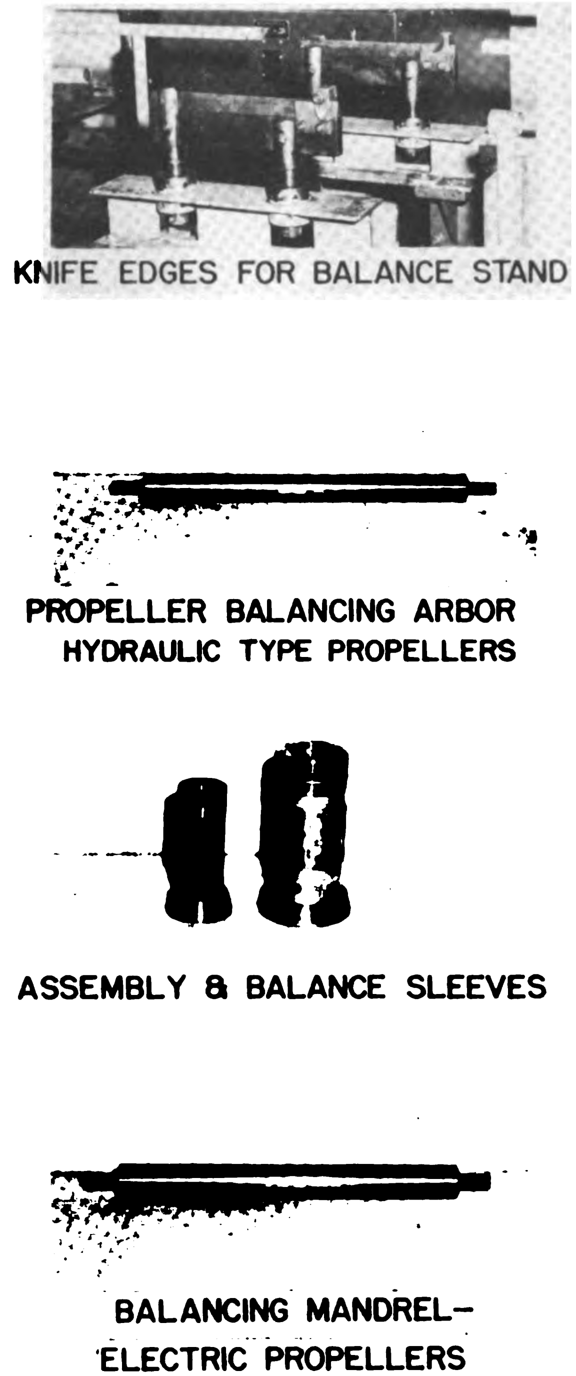


Figure 13.11.—Propeller balance pit equipment.

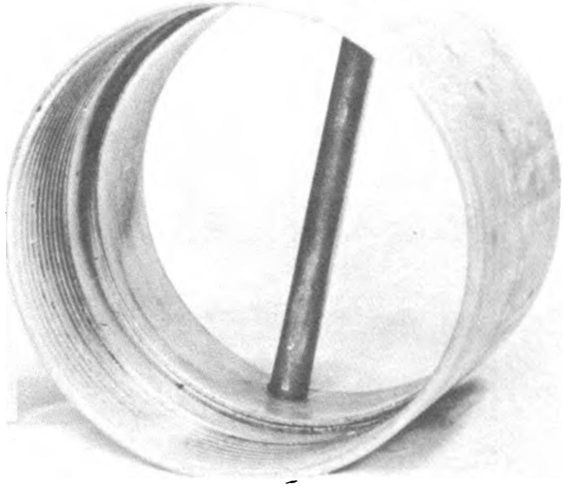


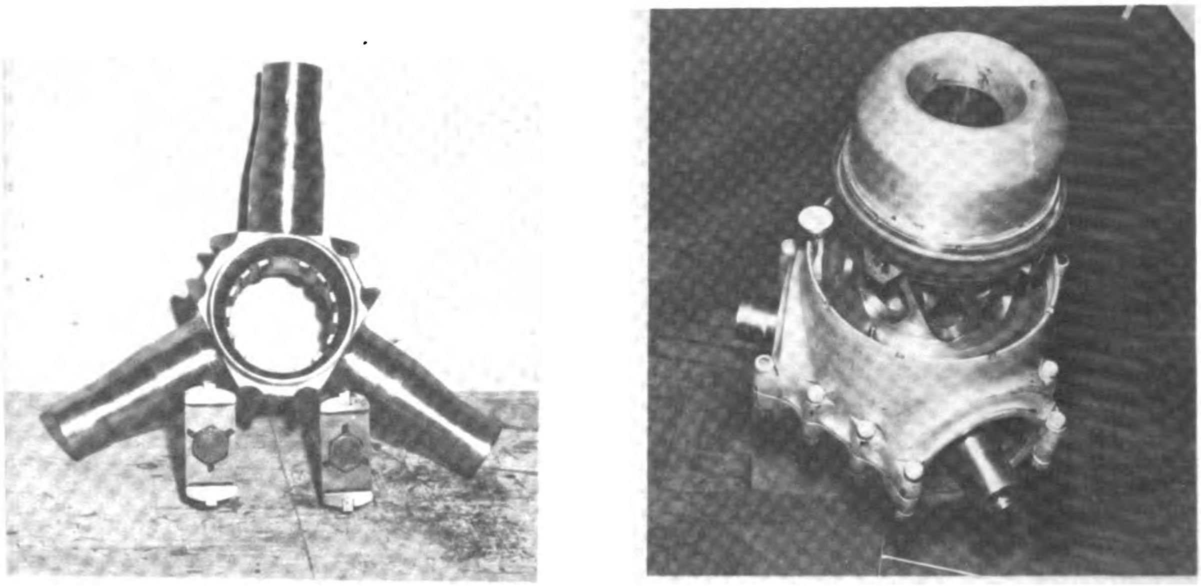
Figure 13.12.—Shaft end thread protector.

approximately 12 feet deep, measured from floor level, which would accommodate propellers of 30 foot diameter. The knife edges are mounted upon adjustable I-beams with normal minimum distance between them being 26 inches. The knife edges are not shown in this photograph.

The other essential components of the balancing pit unit along with an enlarged view of knife edges are shown in figure 13.11.

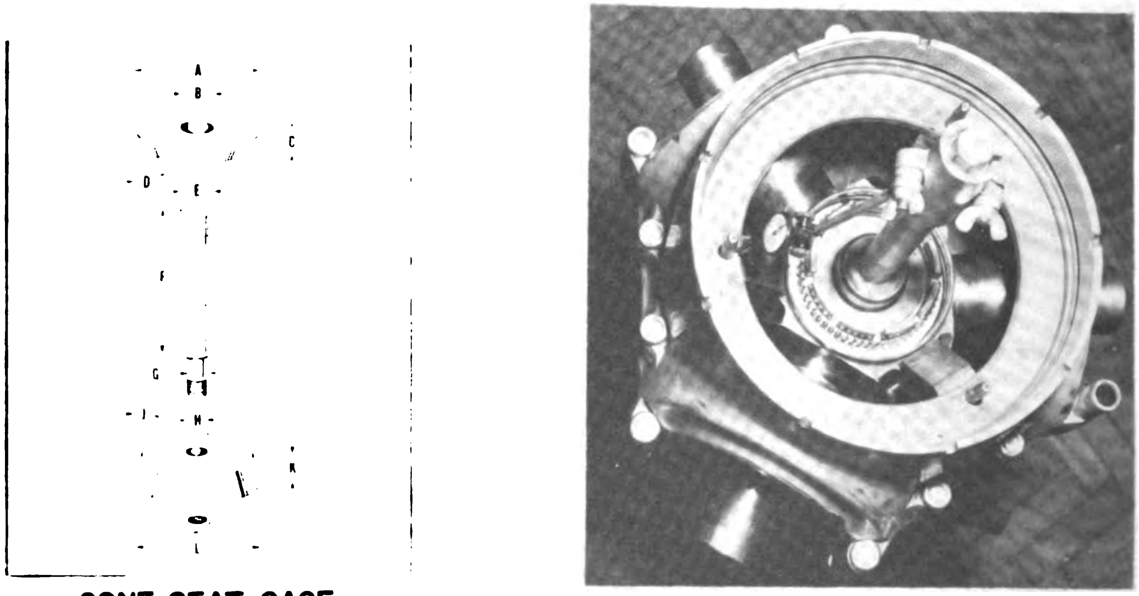
General Propeller Shop Equipment

A well equipped propeller repair shop must contain a carefully selected list of general propeller tools and commercial shop tools such as socket, box and crescent wrenches, grinding and cutting tools, clamps, vises, work benches and power hoists. Essential to proper maintenance is a propeller assembly stand. Representative assembly stands can be seen in the background shown in figure 13.10. Attached



SPIDER SPLINE, GO-NO GO GAGES

PRELOAD GAGE



CONE SEAT GAGE

CONCENTRICITY GAGE

Figure 13.13.—Some inspectional equipment.

to the assembly table surface is an assembly post which will accommodate the assembly and balance sleeves shown in figure 13.11.

A most useful device for protecting propeller shaft threads is a propeller shaft end thread protector shown in figure 13.12.

Since propeller shaft sizes have been standardized, a set of thread protectors may be used for any make or type of propeller. Use of such protective devices for propeller components particularly vulnerable to impact damage that may impair propeller integrity is justified even though some time may be required for installation.

Certain inspectional type equipment is essential to propeller shop operations. Typical equipment (but, by no means all inclusive) is shown in figure 13.13.

Splines of the spider for a hydraulic type propeller should be checked dimensionally to insure maintenance of manufacturing tolerances by use of a go and no-go gage similar to those shown in this illustration. Loose fits will introduce serious vibration that might induce failure. Proper pressure must be maintained between meshing teeth of blade gear segments and rotating cams of hydraulic propellers. The gage shown here is particularly useful in field servicing work to determine the proper number of shims to be inserted between dome and barrel assemblies. Spider barrel concentricity and squareness can be checked with the gage and attachments shown in figure 13.13. The cone seat gage can be manufactured locally with dimensions being fixed by propeller manufacturer or technical order for specific SAE shaft sizes.

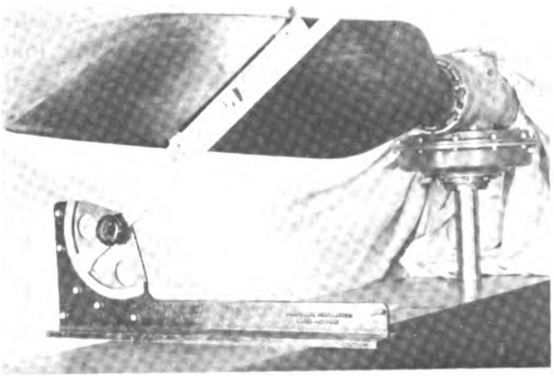


Figure 13.14.—Blade angle check equipment.

There are other inspectional devices that play important roles in adequate propeller installation and maintenance. Various forms of feeler gages aid materially in establishing the extent of wear as well as indicating manufacturing accuracy. Figure 13.14 illustrates a method of measuring blade angle setting at a given station using a blade template.

In addition to determining propeller blade angle, using the equipment shown in figure 13.14, blade contour can be checked for accuracy at the given station.

Propeller Service Tools

Frequently, cone galling and wear results from installing rear cones in cone seats without grinding the mating surfaces to obtain contact at all bearing points. As an aid to obtaining

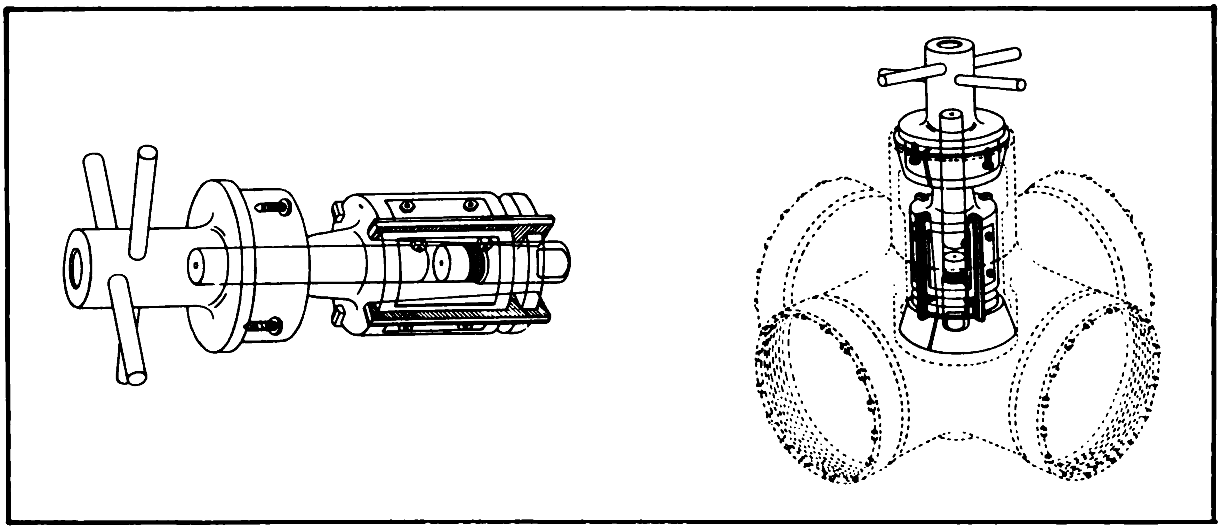


Figure 13.15.—Lapping rear cone-to-cone seat.

better fits between cones and seats, lapping tools similar to that shown in figure 13.15 have been developed.

By application of lapping compound and rotation of the chuck of the lapping tool, the cone seat can be smoothed to a degree that the rear cone will seat properly. Cone galling will be a minimum if not completely eliminated in well lapped cone seats.

A typical screw thread inserter and a puller are shown in figure 13.16.

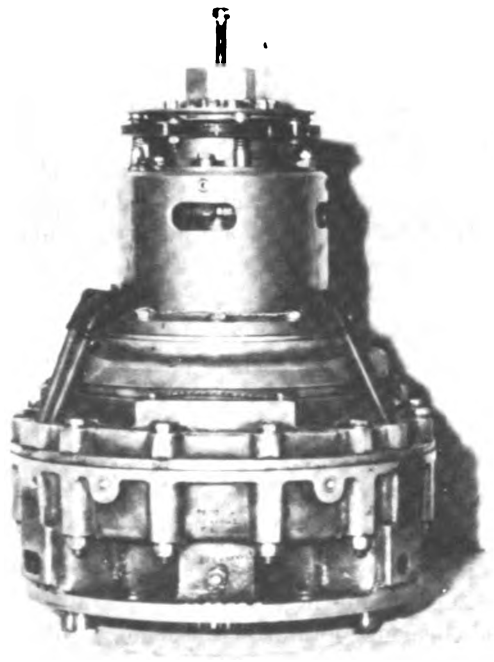
It is not to be considered that the tools shown here are universal tools—rather that they are representative of this whole class of devices that are necessary to assembly or disassembly of propellers. They are special tools in that the shape and sizes of grips must be designed to fit particular propeller parts.

In addition to these service tools, there exists a multitude of special wrenches, drifts, blade turning devices that contribute to safe, rapid propeller maintenance. Reference to propeller technical orders or manufacturers' service manuals will show the complete set of tools necessary to propeller shop work.

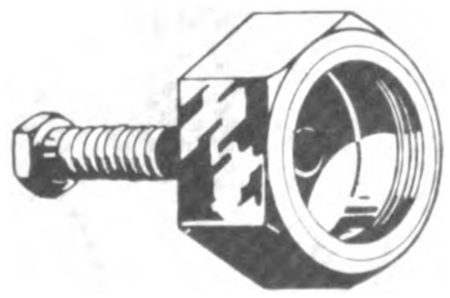
Universal Power Wrenches—Propeller Installations

(1) *Nomenclature and description of a power wrench.* The essential units of a power wrench and lifting assembly unit are shown and identified in figure 13.17.

The *C* shaped lifting hooks are attached to the lift arms by a pivot pin. A locking device is provided in the right hand lift hook by means of which the lift arm can be locked in any one of three positions. The lock is a spring loaded plunger which can be released by pulling upon



BRAKE HUB SCREW TYPE PULLER



BLADE BUSHING INSERTER

Figure 13.16.—Press fit inserter and extractor.

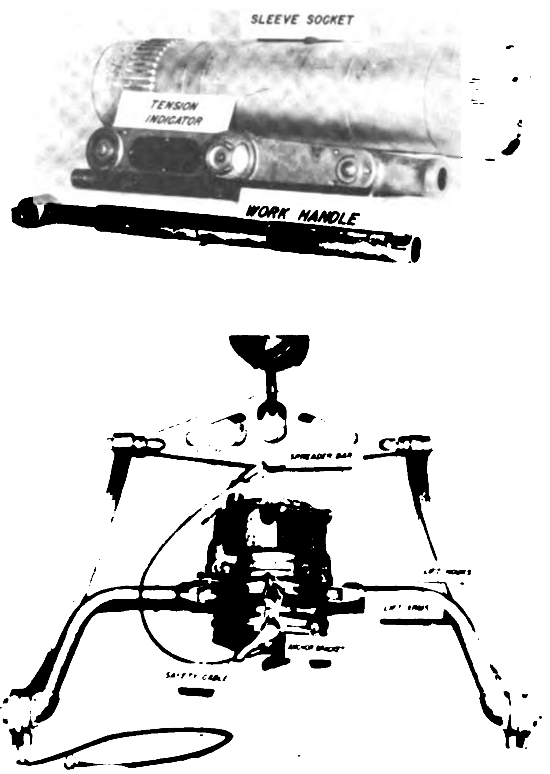


Figure 13.17.—Power wrench and lifting unit assembly.

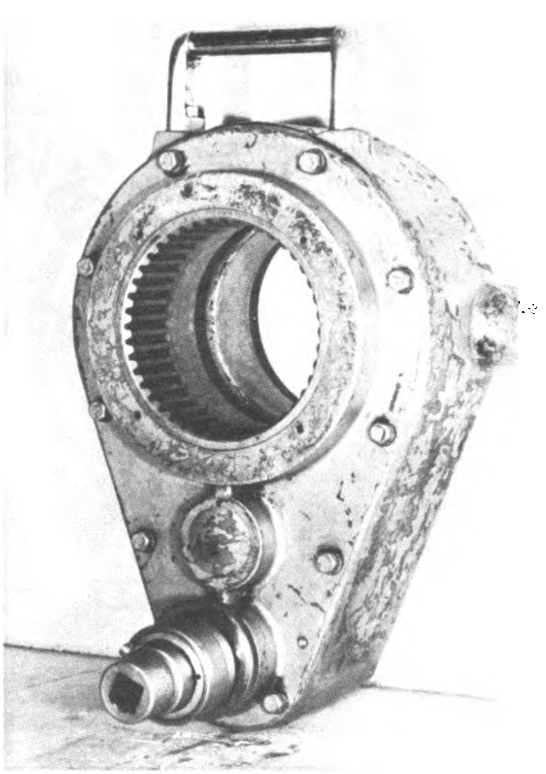


Figure 13.18.—Power unit.

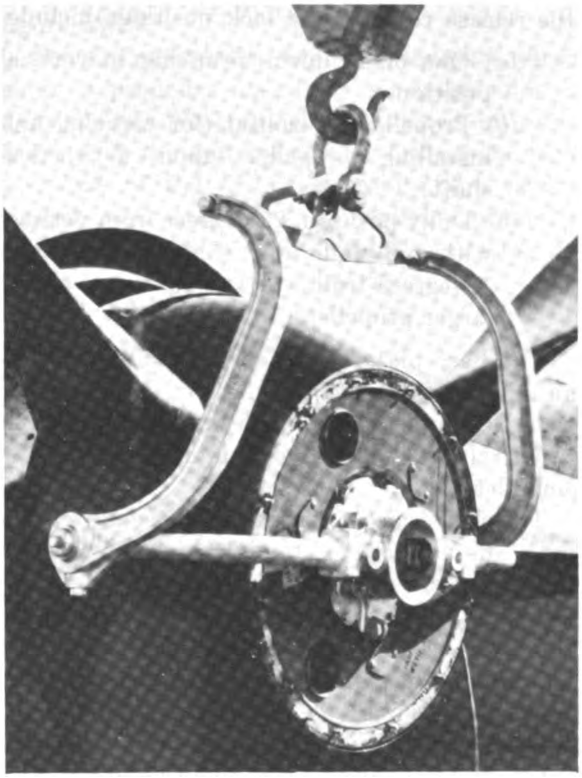


Figure 13.19.—Propeller-anchor plate attachment.

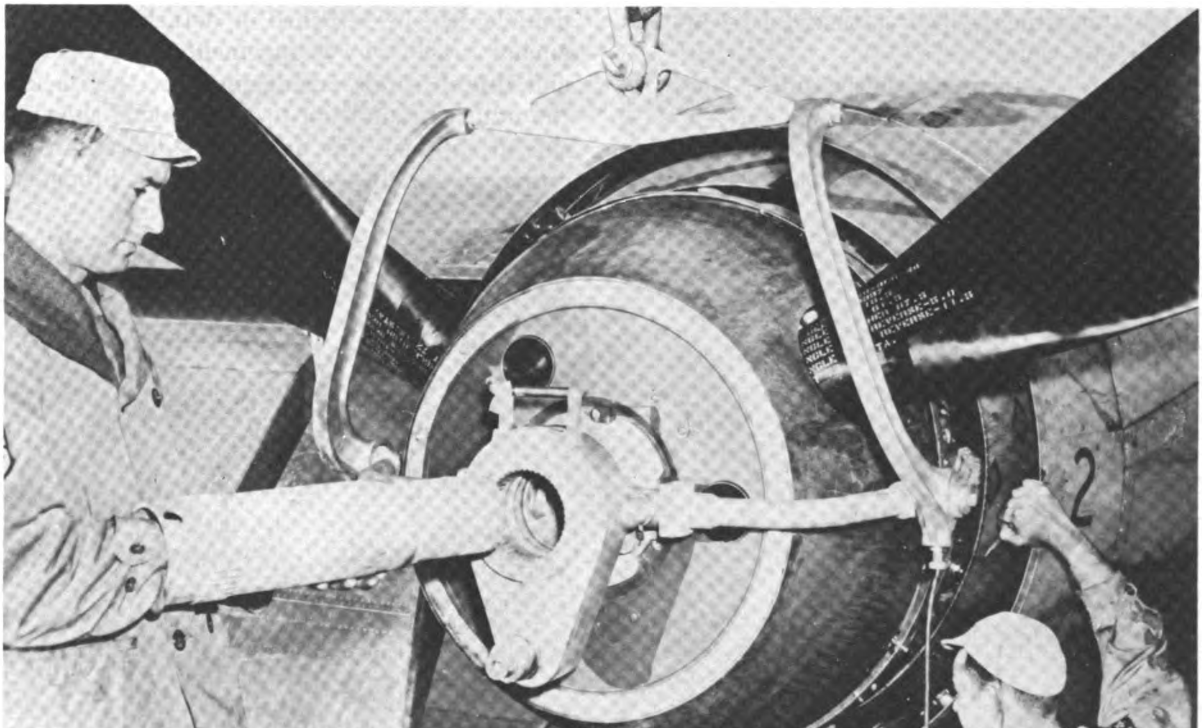


Figure 13.20.—Sleeve socket insertion.

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the release cable. The lock positions include:

(*a*) One blade down, propeller in vertical position.

(*b*) Propeller horizontal (for carrying and installing propeller upon a vertical shaft).

(*c*) Dolly position, 22 degrees from vertical with one blade up. (Shorter arms with 7 degrees from vertical for some of the larger propellers.)

The base plate of aluminum alloy serves as an adapter for attaching the anchor bracket to propeller hub. Crane hook may be inserted in a central eyelet provided in midposition of the spreader bar.

The sleeve socket, splined on one end to mesh with the propeller retaining nut and on the other end to mesh with the output gear of the power unit, has a handle half way down inside the sleeve socket to facilitate handling. The handle may be folded out of position to permit sighting for lining up splines.

The tension indicator (capacity 500 ft.-lb.) threaded to receive an extension handle, should be used in final tightening the propeller retaining nut. Use of the ratchet adapter will permit ratcheting either right or left hand drive applied to the power unit.

Greater detail of the power unit is shown in figure 13.18. The output power ratio is 11.2 to 1. Input attachment will accommodate ¾ inch square male insert front and rear.

Figure 13.21.—Propeller retaining nut removal.

The power unit, weighing approximately 40 pounds, can be attached or detached from the anchor bracket by engagement of anchor pins and thumb screw arrangement at the back of the unit. In addition to components shown, a special retainer nut and hub adapter are required to handle certain hydraulic propellers.

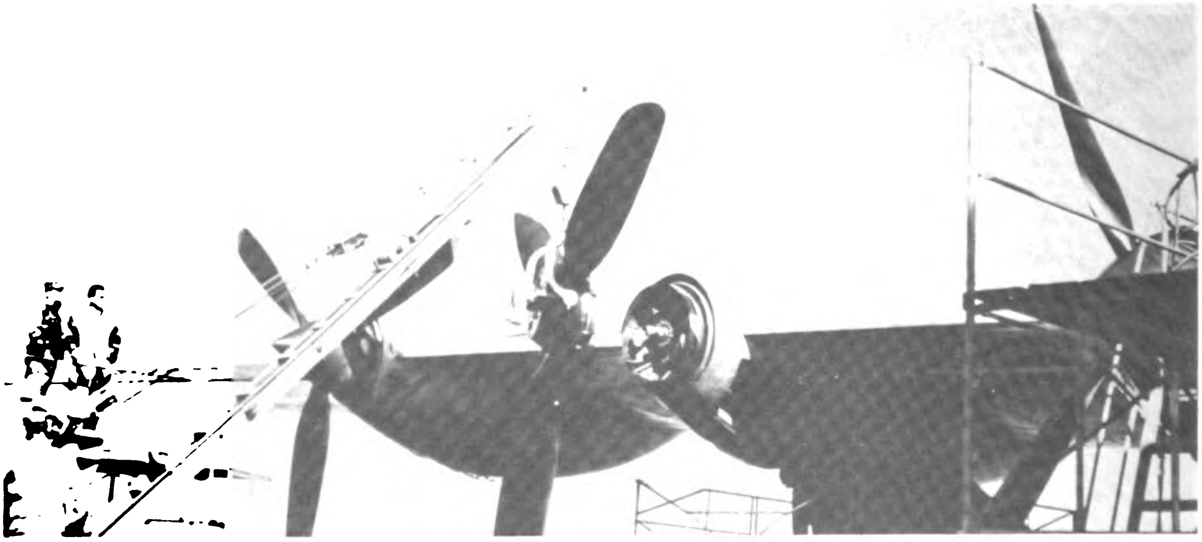

Figure 13.22.—Propeller locked in "two blade up" position.

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(2) *Power wrench applications.* Utility of the power wrench assembly is shown best in reference to the following series of illustrations. It will be observed that the operations in progress as shown in the photographs are not necessarily in sequence order of arrangement. Figure 13.19 shows the lifting anchor plate bolted to the propeller.

Prior to removal of a propeller from engine shaft, the propeller retaining nut must be removed. The illustration of figure 13.20 shows action of sleeve socket insertion preparatory to application of torque necessary to loosen and remove the nut.

Note the method of handling the sleeve socket employed by the airman. Rapid removal of the propeller retaining nut can be achieved by use of the tube handle as shown in figure 13.21.

Removal of the propeller retaining nut permits lifting and removal of the propeller from the engine shaft. Lifting and movement of a propeller in "two blade up" position is shown in figure 13.22.

For transportation from airplane to repair shop, a propeller usually is mounted upon a dolly in *one blade up* position tilted at some angle with the vertical plane. One of the lock positions of the lifting assembly of a power wrench was established to facilitate propeller mounting upon a dolly. This operation in progress is shown in figure 13.23.

Propeller transfer from dolly to vertical spindle stand in a repair shop can be easily accomplished by use of a power wrench, since the lifting assembly has been designed to establish propeller center of gravity upon a line passing through the pivot points of the lift arms at the outer end. Hence, very little effort is required to swing the propeller into any desired position. This transfer operation is depicted in figure 13.24.

Prevention of cone galling is dependent, in part,

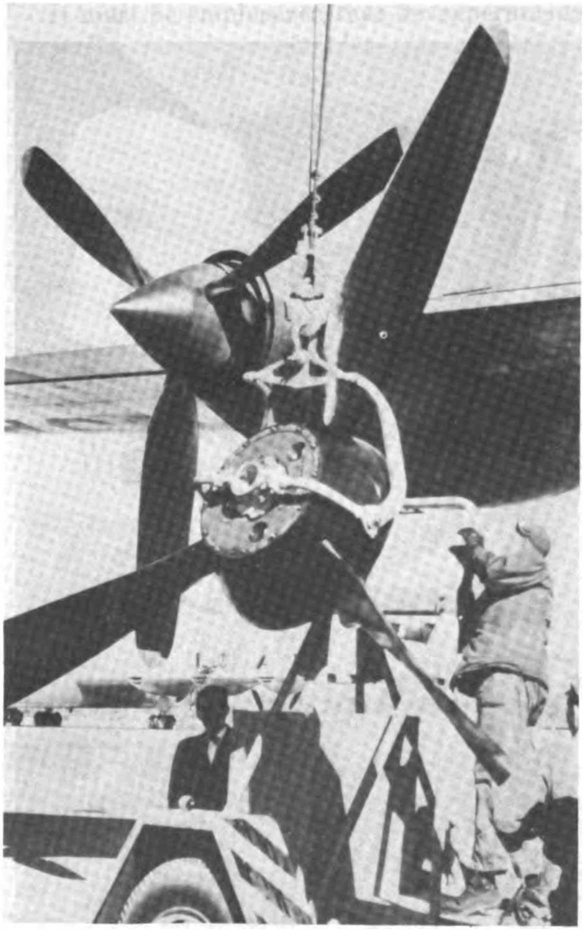

Figure 13.23.—Mounting propeller upon dolly.

Figure 13.24.—Propeller transfer to vertical spindle.

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upon proper tightening of the propeller retaining nut. To insure that proper torque is applied in tightening the propeller retaining nut, a tension indicator, or torque wrench, has been adapted to use with the power unit of the power wrench. By use of appropriate gear ratios in the power unit, the required torque (2000 ft-lb. in this case) can be applied easily by a man pulling on the tension indicator extension arm. A retaining nut tightening operation in progress is shown in figure 13.25. It should be observed that proper torque application can be ascertained by observation of the direct reading indicator which can be seen just below the sleeve socket in figure 13.25.

The power wrench power unit may be employed to remove or tighten the propeller blade nut, also. The additional attachments necessary to accomplish this operation are shown in figure 13.26. This photograph was taken in the Propeller Shop at Wright Air Development Center during a propeller reassembly process.

Special Tool Design and Development Responsibility

Initial Responsibility

Initially each propeller manufacturer or contractor-producer is responsible for design and development of special tools and equipment required to assemble, disassemble, repair, overhaul, inspect, install and service the propellers supplied. Since the propeller contractor will design and fabricate propeller components that require distinctive application tools for assembly and servicing operations, it is essential that those special tools be developed simultaneously with propeller development to insure that the finished propeller can be maintained and serviced in the field. Normally, this requirement is included in the propeller development contract entered into by the Government and the manufacturer. The requirements of MIL–D–8512 must be met in fulfilling the special tool phase of the contract.

Figure 13.25.—Tightening propeller retaining nut.

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It is not intended by placement of initial responsibility with the propeller contractor to discourage or prevent development of special tools by specialized tool producers. On the contrary, every possible improvement by any contractor or tool supplier will be welcomed by procuring agencies in order to improve the effectiveness of maintaining propellers in flyable condition.

Prior to an acceptance test, or type test, of the first production model of a propeller, the contractor must furnish a list of all special tools required to maintain, inspect, assemble, disassemble, repair, overhaul and handle the propeller. This special tool list must be accompanied by blueprints (2 copies plus a Van Dyke) of drawings of each tool shown in the list along with complete information pertaining to application of the tool in propeller maintenance or installation. Of course, this finalized tool list will include modified tool items found necessary in progressing from experimental to production propeller models.

It must be emphasized that for experimental propeller models, a complete special tool list must be furnished at the time of the acceptance test of the experimental model.

Physical prototypes of special tools will be furnished simultaneously with the production model propeller for acceptance testing. Each tool will be tested to ascertain functional usefulness and necessity.

Responsibility for Standardization

Governmental procuring agencies ever must be alert to possibilities for standardization of special tools and equipment to make them adaptable to various types and sizes of propellers. Standardization, where possible, will operate to limit the number of special tools that must be available for propeller maintenance and at the same time serve to broaden the base of production (number of tool suppliers) of special tools. In discharge of the standardization responsibility, the procuring agency will determine, at the time of propeller acceptance test, that the special tools required are necessary and that standard tools or existing special tools have been adopted, wherever possible.

Special Tool Availability Time Table

When propeller experimental or production model is ready for test, propeller special tools and equipment must be furnished for evaluation.

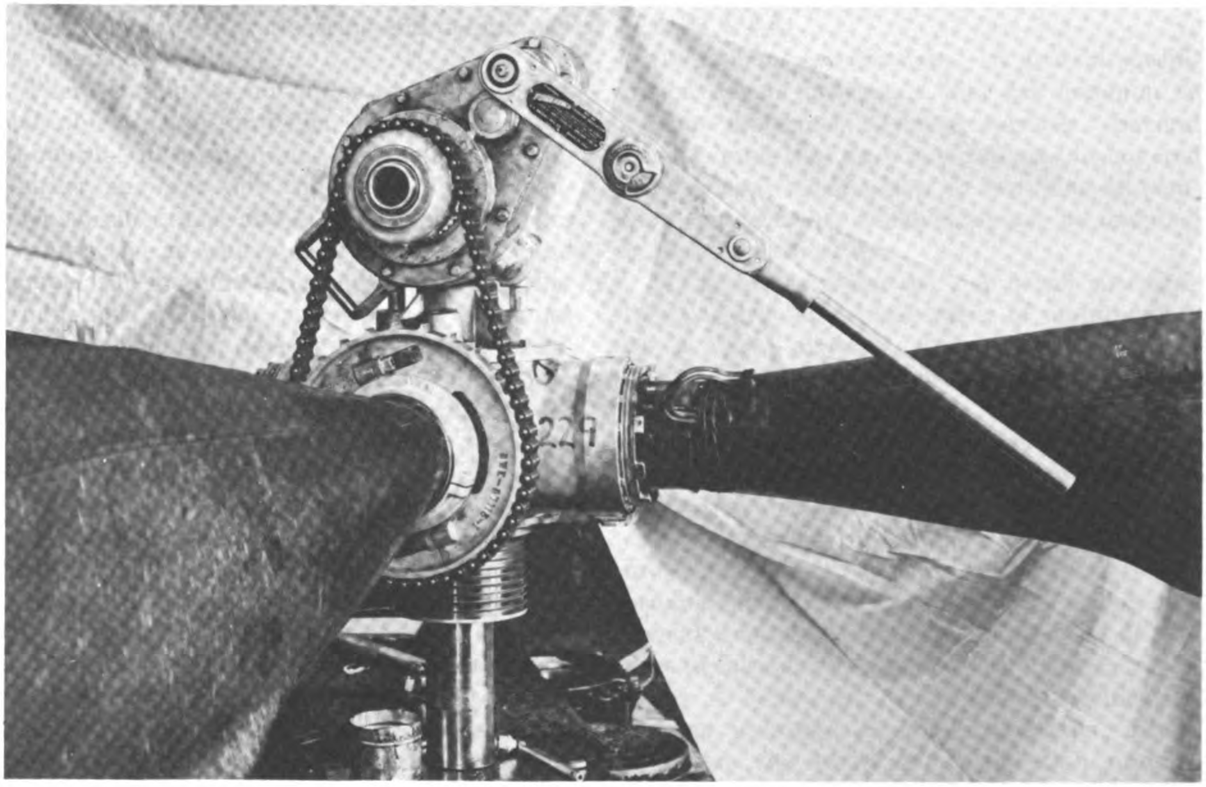

Figure 13.26.—Tightening a blade nut with a power wrench.

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CHAPTER XIV. PROPELLER SPECIFICATIONS AND STANDARDS

Introduction

Lest there be misunderstanding of the purpose and intent of the discussion presented in this chapter of the propeller handbook, it is imperative that all who may use this publication thoroughly realize that the contents in no way replaces or supplants official specifications and standards included in contracts drawn by procuring agencies of the Government.

Rather, as an aid to propeller manufacturers and newcomers to the field of propeller propulsion, this portion of the handbook will fill in some background and underlying philosophy involved in promulgation of applicable specifications and standards. It is proposed to present a partial list of specification references with information about the contents of each so that guides to improved engineering and design may be obtained readily.

There should be no doubt ever, about the real objective of propeller specifications and standards; it is insurance of quality control. Neither engineer nor contractor should consider specifications and standards as obstacles or restrictive measures designed to harass and hamper the manufacturer engaged in propeller production. Written specifications serve as guideposts along a development highway leading towards a goal of improved propellers. This kind of document serves to formalize the ideas in the "collective mind" of a procuring agency, thereby informing all interested parties of specific minimum requirements. A specification is a mutually protective device for the benefit of contracting parties.

Inasmuch as ramifications of governmental procedure have produced a variety of types of approval and specifications, it is essential that exact meanings of terms employed be understood. Further, it will be helpful to recognize the principal propeller requirements upon which specifications and standards are based.

Propeller Specifications and Standards Definitions

Specifications

(1) *Government specifications.* The term specification may include written stipulations, drawings and standards used as engineering data for procurement or technical requirements included in the text of a contract. Strictly, a specification is a clear, accurate description of technical requirements for material, functional item or service, including a statement of procedure by means of which a purchaser can determine whether or not requirements have been met. Basic categories of government specifications commonly used in propellers include:

(*a*) Federal.
(*b*) Military (Mil. Specs.).
(*c*) CAA.

(2) *General specifications.* A general specification covers provisions that are common to various materials, items or services. Several similar items that vary in detail may be covered by a general specification by including all common requirements which need not be included in detail specifications.

(3) *Detail specifications.* A detail specification is a formalized statement of requirements for a single material, item or service which includes all particular design features of the item, material or service. This specification may refer to but will not repeat requirements set forth in the applicable general specification.

(4) *Developmental specifications.* A specification for control of item development in which broad general requirements are set forth to test producibility and practicality, is identified as a developmental specification by addition of prefixes to the specification number. For example, prefix *X* before an *AF* tentative specification number indicates experimental status. Prefix *Y* before the tentative specification number designates prototype status.

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(5) *Industrial specifications.* Specifications prepared by contractors or vendors of their own volition to present stipulations governing production and use of equipment not included in existing governmental specifications are designated industry specifications.

Type Classification of Propeller Equipment

(1) *Development type.* Any propeller or propeller component undergoing development, development or operational suitability testing that has not been released as a satisfactory prototype for quantity procurement will be classed as a development item.

(2) *Adopted type.* Any propeller or propeller component which falls into any of the following groups will be classed as an *Adopted Propeller Item.*

- (*a*) Standard. A completely acceptable propeller or propeller component proven functionally and structurally sound enough to meet requirements in service will be identified as a standard item. Normally, standard propeller items for a specific application will be limited in numbers.
- (*b*) Substitute Standard. A substitute standard propeller item is one that does not fully qualify as a standard item, but is a usable substitute available for production and use in lieu of the standard item.
- (*c*) Limited Standard. Limited Standard appellation will be affixed to stock propeller items below standard or substitute standard quality that are usable in lieu of standard or substitute standard items, pending exhaustion of stock quantity. Procurement of Limited Standard propeller items will be restricted to replacement of repair parts, normally.
- (*d*) Tentative Standard. A propeller item given tentative approval on the basis of promising operational performance reflected during incomplete functional and suitability tests, will be identified as tentative standard. This classification will be used to release an item for initiation of limited quantity production pending completion of acceptance tests. Tentative standard propeller items will be reclassified to *Standard* as soon as practicable.

Propeller Approvals

(1) *Engineering approval.* Approval of engineering or design of a propeller or propeller component indicating compliance with Governmental requirements is reflected by the designation Engineering Approval.

(2) *Qualification approval.* Qualification approval will be given to specific propellers or propeller components upon certification that the items conform to government specifications containing qualification tests as a basis for approval.

(3) *Installation approval.* Installation approval denotes acceptability of a system of specific components or propeller for a particular application.

(4) *Preproduction approval.* Propeller items that have been certified as conforming to specification, contracts, or other requirements containing pre-production tests as a basis of approval will be given pre-production approval.

(5) *Industry developed equipment (IDE) approval.* IDE approval may be given to propeller components for which governmental specifications do not exist, if those components prove acceptable for specific governmental use.

Propeller Quality—General Specification Requirements

Requirement Groups

A great many factors must be considered to insure requisite quality of propellers and propeller components. Some factors presented herein may appear to have but little place in design and development of substantially safe and functionally sound propellers. Further study of the factors will show interrelation and, in some cases, reveal conflicts between requirements. Therefore, compromise of conflicting requirements must be made. Even though all factors are not related, an arbitrary grouping of closely associated factors has been made to facilitate presentation of propeller needs. Propeller requirements seem to fall into three broad general groups; namely, operational, production and economic. Each of those general groups may be subdivided into more specific groups as will be shown in subsequent sections. While the factors presented are not all inclusive, major considerations involved in preparation of specifications are shown.

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Operational Requirements

(1) *Functional.* The primary goal in propeller design apd development is production of a propulsive device that has the necessary capacity to perform a specific task. Four principal prerequisites must be integrated into a propeller design to attain that goal. They are:

- (*a*) Performance. Performance being a measure of functional quality must include such items as power absorbing capacity, efficiency and reliability.
- (*b*) Suitability. This characteristic is a measure of applicability of a propeller for a specific mission under conditions peculiar to service life.
- (*c*) Versatility. Normally, propellers are designed for specific applications, However, propellers or propeller components that are adaptable to various configurations and applications with little or no modification are of greater value than single purpose design. Achievement of this objective in propeller development may be unattainable in many cases.
- (*d*) Dependability. Propeller equipment and systems must be designed for utmost reliability and dependability to enhance airworthiness which, in turn, will insure confidence of operators.

(2) *Environmental adaptability.* Propeller components must operate in a wide range of environmental conditions with capability of automatic adjustment or compensation to accommodate sudden changes from one extreme to another. Design for environment must include:

- (*a*) Temperature Variation. Extremes of temperature to which propeller systems may be subjected include:
  - Minimum air temperature at earth's surface, −65° F.
  - Maximum air temperature at earth's surface, +130° F.
  - Maximum surface (solar exposed propeller) temperature, +160° F.
  - Minimum equipment temperature (in storage at earth's surface) −80° F.
  - High altitude minimum air temperature, −100° F.
  - Heat absorption at high speed may cause temperature rise of several hundred degrees resulting from air friction and low heat transfer rates of bodies in rarefied air. Abnormal heat absorption by virtue of proximity to engines and electronic equipment must be controlled.
- (*b*) Humidity. High atmospheric humidity is conducive to corrosion, by causing moisture condensation upon cold surfaces, fungi growth and general deterioration. Low atmospheric humdity encourages drying or moisture loss from propeller components. Propeller equipment must be designed to function in humid conditions ranging from zero to 100 percent relative humidity.
- (*c*) Corrosion. Propeller equipment must withstand corrosive effects of electrolytic processes, introduced by moisture presence, and chemical reactions between dissimilar materials.
- (*d*) Solar Effects. In addition to deleterious heating effects of radiant energy impacting upon propeller surfaces, material protection may be required against actinic ray effects.
- (*e*) Rain, Ice and Sand or Dust. Foreign particles of rain, ice, sand or dust may render propeller components inoperative by corrosive or erosive action, electrical short circuiting, freezing, delubricating effects or deterioration of aerodynamic functional characteristics. Protective features must be built into all propeller parts subject to such damage.
- (*f*) Insect and Fungi Damage. Propeller materials or systems subject to attack by insects or fungi growth must be *bug proofed* by surface treatment or protection.
- (*g*) Pressure Altitude. Rapid change of pressure or unequal pressure distribution effect upon propeller equipment must be considered early in design stages.

(3) *Operating safety.* Propeller operating safety must be required by incorporating into appropriate specifications minimum requirements of all features that might be influenced by both active and passive safety factors.

- (*a*) Electronic Interference. Radio and electronic equipment of an aircraft must be protected from electrical interference by propeller components to insure safe operation of the airplane. Propeller

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components must be designed to hold such interference to an absolute minimum.

(*b*) Passive Defense and Radiation. Propeller components for military airplanes must be designed and fabricated with sufficient reserve capacity or strength that reasonable damage from enemy action will not render the propulsion system inoperative. Signal emanating devices of the propeller system must be eliminated or shielded in such a manner that enemy detection devices will not be effective. This requirement should be included in all military airplane procurement specifications.

(*c*) Explosion Proofing. Propeller components should be so designed that explosion of gas vapors will not be initiated by electrical features of the propeller system.

(*d*) Operator Comfort. As a safety factor, operator relief from fatigue should not be overlooked in preparation of suitable propeller specifications.

(4) *Propeller maintenance.* The adverse operating conditions during combat require that serious consideration be given to repair methods, servicing, minimum use of non-standard parts and special tools, accessibility and design simplicity. Specifications should be drawn with this requirement considered paramount.

Fabrication and Construction Requirements

(1) *Material specifications.* Propeller materials must possess required physical strength and durability to meet specified loading with some margin of safety. Material quality must be controlled to insure minimum strength scatter, in a large number of units. Whenever possible, substitute materials should be used in lieu of uneconomical, critically short supply or strategic materials.

In preliminary design, material selection must consider effects of vibration and shock, and sudden accelerations. Only those materials which possess service characteristics that are suitable for such loading conditions can be specified.

(2) *Fabrication design requirements.* If propeller production in quantity is to be obtained, specifications must provide as much liberality in requirements as possible. In particular, the following production problems must be considered:

(*a*) Producibility. Tolerances must be maximum consistent with functional integrity. Constructional simplicity must obtain throughout to facilitate assembly and maintenance. Components producible by unskilled labor with acceptable functional characteristics are most desirable.

(*b*) Material Procurability. Materials and parts must be readily available even during periods of emergency.

(*c*) Standardization, Interchangeability, Dimensional Requirements. Propeller design should be directed towards use of standard components, dimensions and practices wherever possible. Standard dimensions are important in interchangeability. Dimensions must be established to conserve space and weight whenever possible. Space allocations frequently fix the size of certain components.

(*d*) Workmanship. Propeller fabrication and installation workmanship requirements must be such that available facilities and labor can produce an acceptable item.

(*e*) Handling. Packaging including adequate identification marking that will prevent damage from careless handling, moisture, heat, cold and storage, must be provided for propeller equipment. Propeller components should be marked and accompanied by instructions to aid assembly, maintenance, operation and, in general, promote safety.

Economic Considerations

(1) *Propeller costs.* While all factors of propeller production, operation, maintenance and service have economic repercussions, certain elements merit special considerations. Cost is one of the most important design factors even though it may not be the overriding consideration, always. Cost computations involving use of a given item must include costs of design, production, maintenance and servicing.

(2) *Procurability.* In cost consideration, propeller procurability introduces design problems, time elements which may be direct or indirect costs depending upon the urgency of quantity production, and material available. Specifica-

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tions that require rare materials or complicated fabrication processes increase the cost of a finished propeller.

(3) *Service life.* Propeller endurance should be such as to permit repetitive operation without causing fatigue or failure that will unduly affect life, performance or integrity. Inadequate life span incorporated into a propeller will result in an unsuitable article in that the number of successful missions may be curtailed. Or a propeller service life in excess of anticipated airplane service life may increase propeller cost, needlessly.

(4) *Propeller weight effect upon cost.* Light weight commensurate with safety and performance will reduce propeller cost in all phases of operation, production and maintenance.

Propeller Specification Sources

Government Specifications

(1) *Specification indices.* In general, specifications and related documents may be obtained from the appropriate approving agency. A list of government specifications is contained in the publication, *Index of Specifications and Related Publications Used by the Department of Air Force, Military Index, Volume 4,* which may be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C.

"Use of Specifications and Standards," *ANA Bulletin No. 143,* sets forth the order of precedence for selection of specification and standard drawings to be used by the government and government contractors in design of aeronautical equipment and material.

(2) *Handbook of instructions for aircraft designers.* Design requirements of military aircraft for the AF have been collected and consolidated into a "Handbook of Instructions for Aircraft Designers," *AMC Manual No. 80–1.* This handbook is a technical publication in which principles of the most satisfactory solutions to engineering problems associated with military aircraft design have been summarized. The handbook stipulations apply to component parts and systems as well as the whole aircraft. Usually, compliance with handbook requirements will be established by terms of the specific contract entered into by a contractor and the procuring agency. The handbook may be obtained from Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

(3) *Technical and memorandum reports.* Bibliographies of propeller design publications, technical and memorandum reports may be obtained from government approving agencies.

Non-Governmental Specifications

Non-governmental specifications and standards acceptable for use in propeller fabrication have been listed in the publication, "Specifications and Standards Applicable to Aircraft, Engines, and Propellers, Use of," *ANA Bulletin No. 343.* This publication may be obtained from Commanding General, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

Equipment Approvals

Purpose and Quality Classifications of Approvals

In general, the practice of granting various types of approval of airplane propellers has been established to insure continued improvement by use of quality control methods. For purposes of definition and assignment of responsibility, propeller quality might be subdivided into functional quality and logistical quality.

Functional quality includes those factors involved, primarily, in propeller design, engineering and development. Logistical quality encompasses procurement, production, maintenance and supply of propeller systems or components. Actually, of course, functional and logistical quality control overlap.

Approval Requirements and Limitations

(1) *Requirements.* Propeller equipment must receive applicable approval indicating requisite quality and performance characteristics. This does not mean that every item must undergo extensive tests. It does mean that equipment items must be accepted by the responsible approving agency at the earliest possible date during development.

It is not the intent to increase time and cost of propeller procurement by rigid and comprehensive approval requirements. The primary consideration is functional satisfaction of a propeller system with minimum expense involved in testing and approving the items. Not all items will require all types of approval and test. Approvals (various types) may be granted simultaneously, if conditions pertinent to item adoption justify that action. Some propeller items may be approved on the basis

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of drawings, test data or inspections. Subsequent to engineering approval, consideration of a propeller item for approval will be dependent upon proof of successful compliance with requirements of prior approvals.

(2) *Approval limitations.* Approval, under no circumstances, will be construed as a shift of responsibility for quality or performance from a contractor to a governmental agency nor will it be considered as a waiver of contractual requirements. Approval of a propeller item does indicate that a contractor has demonstrated capability to produce the item and that the design is released for further development or production.

Normally, requests for approval will not be entertained except by governmental agency invitation or in accordance with contractual requirements. Testing and approving facilities of the government cannot be utilized by propeller manufacturers to attain markets or for advertising purposes. This policy will not restrict use of governmental propeller testing facilities whenever such use will be in the best interests of the Government.

(3) *Propeller approval extensions.* Approval of propeller items will apply only to the product manufactured at the plant producing the sample tested. This approval may be extended to include the same propeller item produced in other plants of the same manufacturer or of other manufacturers when the product of those plants has been proven to be equal or better than the originally approved item. This approval extension can be granted only upon established equality of all phases of propeller quality.

Approvals will be required only as set forth in a government specification, official contract or agreement. Propeller equipment produced under government specifications must meet approval requirements established by the specification. Propeller items procured under contract must meet approval requirements established in the contract. Approval requirements established by contract or specifications subject to multiple interpretations should be referred to the appropriate procuring agency for clarification and adjudication.

The following general considerations apply to propeller approvals:

(*a*) The approval program herein outlined will not abrogate procedures established by Department of Defense regulations or government specifications; rather, this program is supplemental.

(*b*) Engineering changes and modifications to production and in-service propeller equipment will require applicable approvals.

(*c*) Equipment in stock or under procurement contract, made and accepted in accordance with government specifications and drawings will be considered to have approval.

(*d*) Propeller equipment in stock or under procurement for which detailed government specifications and drawings do not exist, will be considered acceptable if prior approval has been given.

(*e*) Non-standard equipment required by government specifications and drawings as a part of an end product by a contractor will be considered as approved equipment if amenable to government supervised inspection.

(*f*) An approved item must receive application or re-approval if it is to be used in a new application or installation.

(*g*) Quality deviations may be authorized for development type propeller equipment but such deviation must be necessary and held to a minimum.

(*h*) Satisfactory service may be used as a basis for approval at discretion of approving agency.

Responsibilities for Propeller Development

(1) *Governmental agencies.* The governmental agency responsible for engineering development and continuing technical excellence of a specific propeller component, installation or end product will be responsible for approval and for granting deviations or waivers therefrom. Approving agencies, usually, are designated in government specifications contracts or special instructions. The agency or laboratory supervising design or development of propellers will be responsible for the following:

(*a*) Determination of need for item approval.

(*b*) Establishment of specific approvals required by particular items.

(*c*) Establishment of tests required prior to approval.

(*d*) Determination of time and place of

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approval testing and designating a test agency.

(*e*) Inclusion of test and approval requirements in government contract and specifications.

(2) *Contractors or manufacturers.* Propeller manufacturers, contractors or vendors will be held responsible for the following:

(*a*) Development and supply of propeller equipment that will meet government requirements.

(*b*) Conduct approval testing under governmental agency supervision, when required.

(*c*) Submit approval requests along with ample substantiating data to the appropriate agency.

(*d*) Submit requests for relief from approval requirements if approval procedures will cause propeller delivery delay, or if technical problems prevent timely availability of an entirely suitable propeller item.

Propeller Approval Procedures

(1) *Engineering approval.* (*a*) Scope. Engineering approval encompasses acceptance of engineering proposals, design data, drawing schematics, layouts, mock-ups, manufacturing processes, methods of analysis, procedures not directly related to propeller design and industry specifications. In addition, engineering approval may apply to propellers in design or development stage including modifications to production items prior to acceptance. Further engineering approval will:

(*i*) Include acceptance of engineering or design of a complete propeller or, with applicable qualifying statements, to any component.

(*ii*) Be considered as a prerequisite to other approvals, except qualification approval.

(*iii*) Apply to specific components, systems of components, installations and end propellers.

(*iv*) Be required of government contract and non-contract items.

(*v*) Not to be required of propeller equipment built to conform to government detail specifications.

(*vi*) Apply primarily to data, but may be applied to mock-ups and other physical items that are constructed to prove design concepts.

(*b*) Propeller Quality Requirements. Propeller quality requirements stipulated in government specifications must be fully met before an engineering proposal or design can receive engineering approval. This requirement demands that essential quality and performance characteristics of the finished propeller, as established by the approving agency, must obtain.

(*c*) Contractor's Responsibilities. A contractor supplier of a propeller system amy be required to design components or subassemblies that become a part of the propeller or propeller system. Or, the contractor may design a propeller item to meet certain performance characteristics of functional requirements established by the user. Such engineering and design data will require engineering approval.

(*d*) Procedure. Requests for engineering approval will be directed to the governmental agency identified in applicable specifications, contract or instruction. Approval requests pertaining to components or subassemblies will be processed through the prime contractor.

(2) *Qualification approval.* (*a*) Scope. Qualification approval may be obtained only for propeller items for specific applications. The following provisions apply to qualification approval:

(*i*) Applicable only to individual items.

(*ii*) Propeller item involved must be covered by a government specification.

(*iii*) Specified qualification tests must be completed satisfactorily.

(*iv*) Approval will be sought prior to production contract.

(*v*) The propeller item can be classified as a standard article for a specific airplane-engine combination.

(*b*) Procedures. Qualification approval requests should be prepared and submitted by manufacturers or suppliers in accordance with procedures established by the procuring agency. Quality and performance characteristics of an item as indicated in applicable specifications must be satisfied prior to qualification approval.

(*c*) Qualification Tests. The approving governmental agency will conduct such testing as necessary to insure that the propeller item subject to approval, fully meets specified requirements.

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(3) *Installation approval.* (*a*) Scope. Installation approval will be granted upon proof of actual physical installation of propeller systems and components that are acceptable, and not merely upon submission of data for the installation. Installation approval may be granted simultaneously with other approvals or as corollary action to other approvals, as deemed advisable by the approving agency.

Normally, engineering approval will be a prerequisite to installation approval. Propeller items involved under an installation approval of components or systems must have previously received qualification, preproduction or industry developed equipment approval (IDE).

Installation approval of a propeller system or assembly automatically includes acceptability of each component of the system which otherwise may not have received qualification, preproduction or industry developed equipment approval. Included in this category would be such items as wiring and plumbing.

In addition, installation approval will:

(*i*) Apply to government and non-government specification equipment.

(*ii*) Apply to equipment under non-government contract as well as that under government contract.

(*b*) Procedure. Requests for installation approval must be processed through the prime contractor and will be referred to the government activity responsible for design and development of the propeller system or end item for action.

(4) *Preproduction approval.* (*a*) Scope. Preproduction approval, usually, is confined to complete propellers or propeller systems in which the government would not expect to receive samples for qualification. This type of approval applies only to propeller items procured under production contract. The responsible governmental agency will determine applicability of preproduction or qualification tests of a propeller item.

Normally, preproduction approval will be granted upon successful accomplishment of preproduction tests of a sample propeller, submitted under a contractor or purchase order, proving that the design established by the contractor meets technical requirements and will be acceptable for production.

Propeller design and development are conducted under a developmental type contract until a usable propeller has been made, after which a production contract may be awarded contingent upon successful preproduction approval. Detail specifications need not be prepared until after first article acceptance, if at all.

In addition, preproduction approval will be subject to the following provisions:

(*i*) Components and systems incorporated into a propeller subject to preproduction approval will have been subject to engineering, qualification, IDE, installation and preproduction approval, as applicable.

(*ii*) Preproduction approval may apply occasionally to propellers built to detail Government specifications.

(*b*) Procedure. Requests by prime contractor will be processed in accordance with requirements established in contracts between user and producer.

(5) *Industry developed equipment approval* (*IDE*). (*a*) Scope. Industry developed equipment approval, usually, will apply to single items. However, in some cases IDE approval may be granted to assemblies of more than a single component if the individual parts make up an inseparable unit with a single part identification number.

Propeller items requiring IDE approval are developed for specific application or installation, usually. Therefore, the approval letter will specify item application or limit its use to certain installations. Specific application must receive installation approval in addition to IDE approval.

Whenever detail government specifications become available, subsequent to IDE approval of propeller items, procurement of those items after the date of specification availability must be contingent upon compatibility with the government specifications. Exact procedures for existing contract modification in this eventuality must be negotiated between interested parties and reflected in a joint agreement or amendment to the contract.

Further, the following provisions apply to IDE approval:

(*i*) Propeller item must be a system component or end article.

(*ii*) Item is not covered by existing government detail specification.

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(*iii*) Item will not be listed in qualified products list.

(*iv*) IDE and installation approval may be granted simultaneously.

(*b*) Procedure. Requests for approval will be submitted to the using agency and may be sought prior to award of production contract or at any time during development or production. IDE approval normally will be granted for items previously approved for engineering or built to approved industry specifications.

Quality Evaluation Tests

(1) *General requirements.* In most instances, approval of propeller items, systems, or installations is contingent upon product quality evaluation tests. Test requirements depend upon propeller type and proposed application. In establishing test requirements, necessary performance and conditions of propeller use must be established, after which tests may be specified that will prove functional and operational suitability. Numerous tests exist that include procedures to determine propeller output, durability, life, strength, efficiency, safety, speed and environmental suitability. No effort will be made herein to describe actual test procedures.

Test requirements are set forth in government specifications and may be included in design manuals and instruction letters. Propeller evaluation tests by non-governmental laboratories should not be conducted until adequacy of proposed tests and completeness of test data has been established as sufficient for approval purposes.

(2) *Types of evaluation tests.* (*a*) Service Tests. Service testing includes all evaluation testing required to insure that delivered propellers are reliable, airworthy, logistically supportable, operationally effective and maintainable by average service personnel. The following schedule of testing necessary to development and approval of propellers has been established:

(*i*) Phase I—Contractor conducted airworthiness and functioning tests.

(*ii*) Phase II—Government conducted compliance tests.

(*iii*) Phase III—Contractor performed design refinement.

(*iv*) Phase IV—Government conducted performance test.

(*v*) Phase V—Government all weather testing.

(*vi*) Phase VI—Government conducted functional development.

(*vii*) Phase VII—Government conducted suitability testing.

Included in these test phases are research and development tests necessary to certain approvals; factory acceptance testing applicable to qualification, IDE, installation and preproduction approvals; and operational suitability testing for tactical evaluation.

(*b*) Qualification Tests. Qualification testing includes all inspection, operating and testing of a propeller necessary to establish compliance with all qualification test requirements of applicable specifications. These tests are necessary prerequisites to production contracts.

(*c*) Verification Tests. Verification tests are appraisal tests conducted after award of production contract to establish conformance to contractual requirements. Such tests include preproduction or first article engineering and production sample appraisals.

(*i*) Preproduction Tests. These tests are confined to propeller production items not proven by qualification tests prior to contract award. The purpose of preproduction testing is to establish prior to actual production that proposed production methods (and design detail of performance specifications) will yield propellers that meet contract requirements.

(*ii*) First Article Engineering Tests. These tests, conducted by or under direction of government approving agency engineers, are tests of finalized propeller production items to accomplish preproduction appraisal, in reality. The objective of first article testing is to expedite procurement availability in quantity while insuring introduction of only airworthy propeller equipment. Quantity production normally will be withheld until completion and evaluation of first article testing.

(*iii*) Production-sample Engineering Tests. Production sampling tests are appraisals designed to establish conformance and maintenance of propeller equipment quality equal to or above the originally established standards. Such tests must

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be conducted under surveillance of the procuring governmental agency and will be made during propeller production.

(*d*) Inspection Tests. These tests are quality control tests conducted after propeller production to insure compliance with specifications and drawings under which production was authorized.

(*e*) Environmental Tests. These tests are applicable to all propeller approvals and consist of appraisal of equipment serviceability under all environmental conditions in which the equipment must function. Service conditions applicable to propellers include: wide temperature variations, solar radiation, ice, rain, hail, snow, high winds, sand, fungi, wide humidity variation, corrosion, shock, and vibration.

(*3*) *Test procedures.* (*a*) Test Location. Tests may be conducted at vendor's facility, commercial testing agency site or at governmental test laboratories, as specified by the approving agency. A manufacturer or vendor should not undertake official propeller testing unless specifically directed to do so by the approving agency.

(*b*) Test Samples. The number of test items required and allocation of transportation expense usually will be placed in the contract.

(*c*) Government tests.

(*i*) Contract Items. This category includes propeller items obtained under production or research and development contracts, that are to be given preproduction tests at government expense.

(*ii*) Non-Contract Items. Propeller articles submitted for qualification approval, along with some IDE items, usually are non-contract items. As a rule, items of this nature are shipped at contractor's expense with a request for test and/or approval. Policy agreements for test of non-contract items must be negotiated prior to submission for test. In addition, specific application of the propeller item, copies of vendor's specification and drawings, Governmental specification references along with other pertinent information necessary to proper evaluation, must be furnished.

(*iii*) Test Observers—Vendor's Representatives. With testing agency approval, vendors representative may be present during actual propeller test. Vendor's representatives may make on-the-spot repairs prior to test if parts have been damaged in transit. Certain minor modification of the propeller equipment may be made on the test floor with approval of the test supervisor, but cut and try methods aimed at ultimate approval usually will not be tolerated.

(*iv*) Test Discontinuance. Any test may be discontinued, whenever a propeller fails to meet requirements of the approving agency.

(*d*) Non-government Tests. The approving agency may authorize use of contractor's or commercial test facilities to conduct propeller tests. In this case, a detailed test report will be required which will include test procedure and facilities used. In addition, the test must be witnessed and certified by an engineering representative of the approving agency. The representative must certify that described tests were performed on representative samples by qualified personnel using facilities described. Further, certification of authenticity of propeller manufacture must be included.

Specific information required from the propeller manufacturer will include:

(*i*) Report number, data, title, propeller unit description, function, rating, aircraft upon which propeller will be used, manufacturer's designation and applicable Government specifications.

(*ii*) Complete assembly and detail drawings.

(*iii*) Photo or sketch and description of test facility.

(*iv*) Description of test procedures.

(*v*) Detailed test results.

(*e*) Notification of Final Action on Test Results. For Government conducted tests, after the tests have been completed and results evaluated, the supplier will be notified of the results; approval status; reason for disapproval if applicable and use limitations if imposed.

Non-government tested equipment will be evaluated on the basis of test results as reported and the supplier advised of approval status, along with reason for disapproval if applicable. If testing has been deemed incomplete, specific instructions for further testing will be furnished by the approving agency.

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