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TECHNICAL METHODS OF DESIGN.
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TECHNICAL METHODS OF DESIGN.

By F. W. Caldwell* and N. S. Clay**.

The aerodynamic design of Micarta propellers is carried out in much the same way as for other propellers. As the molds are quite expensive, however, one is justified in giving considerably more study to the design of a Micarta propeller than would be economical in the case of a wooden propeller.

Perhaps the most direct method of working out the design of a Micarta propeller is to start with the diameter and blade angles of a wooden propeller suited for the installation in question. Applying one of the plan forms suitable for Micarta propellers we may obtain the corresponding blade widths and use these angles and blade widths for an aerodynamic analysis.

It may be well at this point to explain the simplified basis of the aerodynamic analysis which furnishes the most satisfactory starting point for a study of the design.

Consider a small portion of the length of the propeller blade at a radius R from the axis and having a width b and a length dR (Fig. 23), obviously the surface area of this element will be $b dR$.

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In Fig. 24, V_1 represents the forward velocity of the airplane, and V the rotational velocity at the radius R . W represents the resultant velocity of the element with respect to the still air. P is the resultant pressure on the element and is equal to $\frac{\rho}{g} k b dR W^2$ where k is the resultant pressure coefficient and $\frac{\rho}{g}$ is the mass density of air equal to .00237 in ft. lb. sec. units for standard air. $W = \frac{V}{\cos \Phi}$ so that

$K = \frac{\rho}{g} k b dR \frac{V^2}{\cos^2 \Phi}$. The thrust $T = K \cos(\Phi + \beta)$ and the torque force $F_Q = K \sin(\Phi + \beta)$. The thrust

$dT = \frac{\rho}{g} k b dR (2 \pi n R)^2 \frac{\cos(\Phi + \beta)}{\cos^2 \Phi}$. The power in ft.-lb./sec. =

$dP = F_Q (2 \pi n R) dP = \frac{\rho}{g} k b dR (2 \pi n R)^3 \frac{\sin(\Phi + \beta)}{\cos^2 \Phi}$.

The values of k and for various angles of attack (α) are determined by means of wind tunnel tests on various cross-section shapes to be used in propeller design. These tests are usually made on rectangular airfoils 18 inches long and of 3-inch chord.

Having this data at hand a thrust grading curve and a power grading curve, such as those shown in Fig. 25 for the Liberty Micarta propeller may be constructed. The areas under the curves give the total thrust and total power per blade.

In a blade form such as that used in the Liberty propeller and the 300 HP Wright propeller, there is a considerable distortion when the propeller is running at the top speed of the plane. This distortion causes a considerable increase in the blade angles so that the actual power absorbed by the propeller is greater than the computed power. In the case of the Liberty propeller it

is necessary to multiply the computed power by about 1.3 to obtain the actual power absorbed by the propeller. In practice, however, it is better to re-compute the power and thrust, making certain assumptions as to the increase in blade angles, since this unquestionably gives a closer approximation to what is actually going on.

This increase in blade angle is caused partly by the action of centrifugal force and is very pronounced in the Liberty Micarta propeller on account of the forward rake of the propeller tips in connection with the plan form used. It would go beyond the scope of this paper to discuss in detail the method of computing this twisting moment though the calculation is relatively simple. It will perhaps be sufficient to say that a forward rake gives a centrifugal twisting moment tending to increase the blade angles while a rake to the rear, or downstream, produces a twisting moment tending to decrease the angles.

In the case of the symmetrical type of propeller blade used in the adjustable and reversible Micarta blades, there is a different type of centrifugal twisting moment tending to decrease the blade angles. This moment is quite small, however, in the outer flexible portions of the blade, though it is relatively very large near the boss.

The thrust and power grading curves for the 300 HP Wright propeller and for the adjustable and reversible propeller are made up much the same way as those for the Liberty propeller.

In considering the stress analysis of the propeller, the following stresses are of primary importance: (1) Direct tension due to centrifugal force (2) Bending due to thrust (3) Bending due to torque (4) Bending in the thrust plane to centrifugal force (5) Bending in the torque plane due to centrifugal force.

The centrifugal force per inch of radius may be computed from the formula $C.F. = 1.227 w \cdot A \cdot R \cdot n^2$ where w is the weight of a cubic inch of the material, in this case, .0487 lb./cu.in.

A is the cross-sectional area of the blade at the radius R in feet, n is the speed of rotation in revolutions per second.

Fig. 26 shows a curve of this kind for the Liberty Micarta propeller.

By integrating under the curve up to the station under consideration, the total C.F. on the section may be obtained. The direct tensile stress is, of course, obtained by dividing the total centrifugal force on the section by the area of the section in square inches. All of these steps are shown in Fig. 26 as worked out for the Liberty Micarta propeller.

The bending moments due to thrust are obtained from the areas under a series of grading curves obtained by multiplying the thrust at any point by its distance from the section under consideration. The bending moment curves due to thrust on the Liberty Micarta propeller are shown in Fig. 27. The bending moments due to torque are obtained in the same way and are shown in Fig. 28.

The total bending moment on the various sections due to thrust are shown in Fig. 29 and those due to torque in Fig. 30.

In finding the bending moments due to centrifugal force, it is only necessary to remember that the centrifugal force of any element acts through its center of gravity and in a direction which is radial and perpendicular to the axis of rotation. If we pass a plane normal to the axis of revolution through the center of gravity of any section, the moment of the centrifugal force of this section in the thrust plane on any other section will be the product of the centrifugal force of the first section by the distance from the center of gravity of the second section to the plane defined above. To find the moment of the centrifugal force in the torque plane, pass a plane through the center of gravity of the first section and the axis of revolution and proceed as above. Due account of sign must be taken in measuring the distance from the c.g.'s to these planes.

Fig. 31 shows the grading curves for centrifugal moments in the thrust plane, and Fig. 32, for those in the torque plane. The total moments due to C.F. in the thrust plane are shown in Fig. 29, and those due to torque, in Fig. 30.

The total resultant bending moments in the thrust torque planes are given in Figs. 29 and 30.

After establishing the bending moments on the various sections it is necessary to find the moments of inertia of the sections about their principal axes and the angle between the minor axis and the chord. This can be done by means of a suitable graphic integrating machine. For the purpose of these calcula-

tions a greatly simplified method has been worked out but this method can not be described in detail here.

Knowing the bending moments, moments of inertia, etc., the maximum fiber stress on any section may be worked out by the method of the neutral axis described in any good text book on mechanics.

The maximum bending stress in the Liberty Micarta propeller at various stations combined with the centrifugal stress, gives the maximum resultant fiber stress on the various sections. This is shown in Fig. 33.

The above shows the method applied to the static stress analysis of the propeller. The centrifugal bending moments are, of course, changed, as the result of deflection. The complete elastic analysis is extremely complicated and has never been carried out in a rigid manner.

Some simple approximations to the effect of deflection, however, are interesting and useful in the case of the reversible and adjustable blades. In this case the static analysis makes all the centrifugal bending moments equal to zero. By making an approximate calculation of the elastic deflection which would occur if no restoring moment were present, and comparing this with the deflection necessary to balance the bending moments due to air pressure by the bending moments due to centrifugal force, an approximate estimate of the elastic stresses may be obtained.

In order to make an estimate of the deflection it is necessary

to make some approximations. For this purpose the minor axes of all the sections are assumed to lie in the same plane and the air forces are all assumed to lie in a plane normal to this one.

The curvature at each section may then be obtained from the value of $\frac{M}{EI}$ where M is the bending moment, E the modulus of elasticity of the material and I the moment of inertia about the minor axis. Plotting the curvature against radius and integrating from the axis out to various stations, the slope at various stations may be obtained; plotting these values and again integrating as before, a curve of deflection may be obtained.

In order to estimate the amount of deflection necessary to balance the bending moments, we may assume that the slope at any point is equal to the air loading per inch of length divided by the centrifugal force per inch of length. Plotting these values of slope and integrating from the axis out a series of values of deflection necessary to balance the air loading is obtained. These curves for the adjustable and reversible propeller are shown in Figs. 34, 35 and 36.

A rough approximation of the elastic stress may be obtained by multiplying the bending stress by the ratio of deflection necessary to balance the air loading to the deflection which would occur without restoring moments. This method is, of course, quite inaccurate but it offers a useful means of comparison of propellers of different materials.

In the case of the adjustable and reversible propeller the

twisting moments in the blade are very important as they partly determine the force necessary to change the pitch while the engine is running.

One of the very important twisting moments from the standpoint of changing the pitch, is the twisting moment introduced by centrifugal force. This can be rather easily evaluated at various stations from the following formula:

$dM = c n^2 (I_{\text{major}} - I_{\text{minor}}) \sin \alpha \cos \alpha dR$ where c is a constant involving the density of the material and α is the angle between the minor axis and the plane of revolution. These values are plotted against radius. An integration under the curve will give the total twisting moment for the blade. Fig. 37 shows the twisting moment due to centrifugal force for various pitch settings of the adjustable and reversible propellers.

This description of the methods used in designing Micarta propellers, is, of course, incomplete. It is hoped, however, that it will serve to illustrate to a certain extent some of the principles of design and indicate how the properties of Micarta can best be utilized when it is applied as a propeller material.

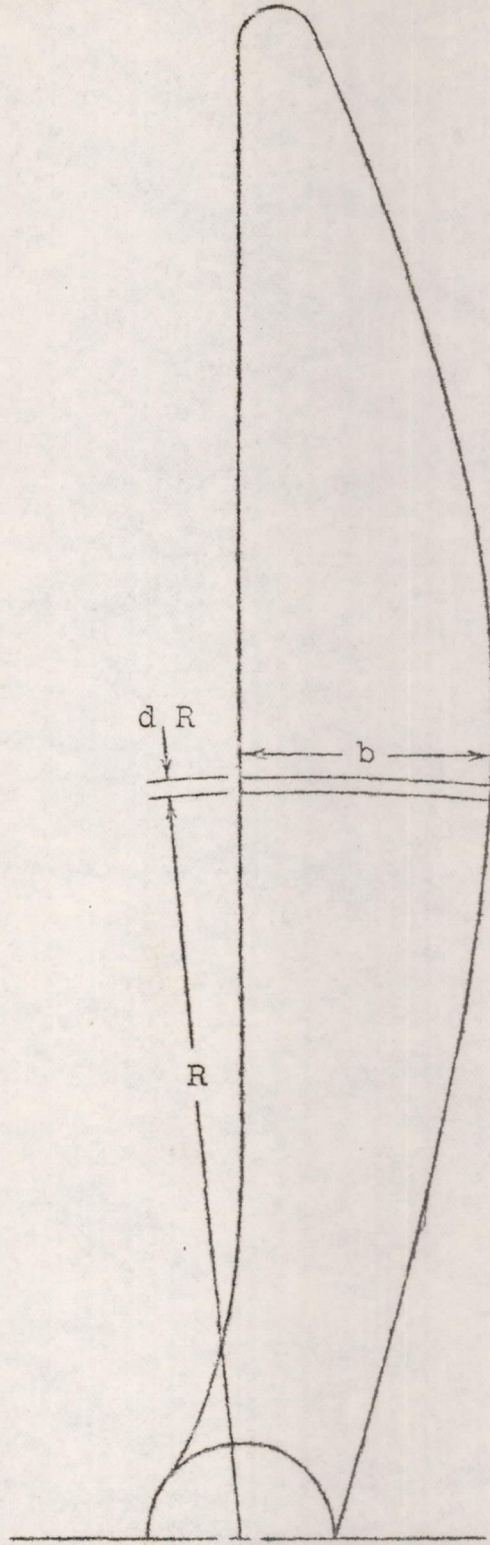


Fig.23

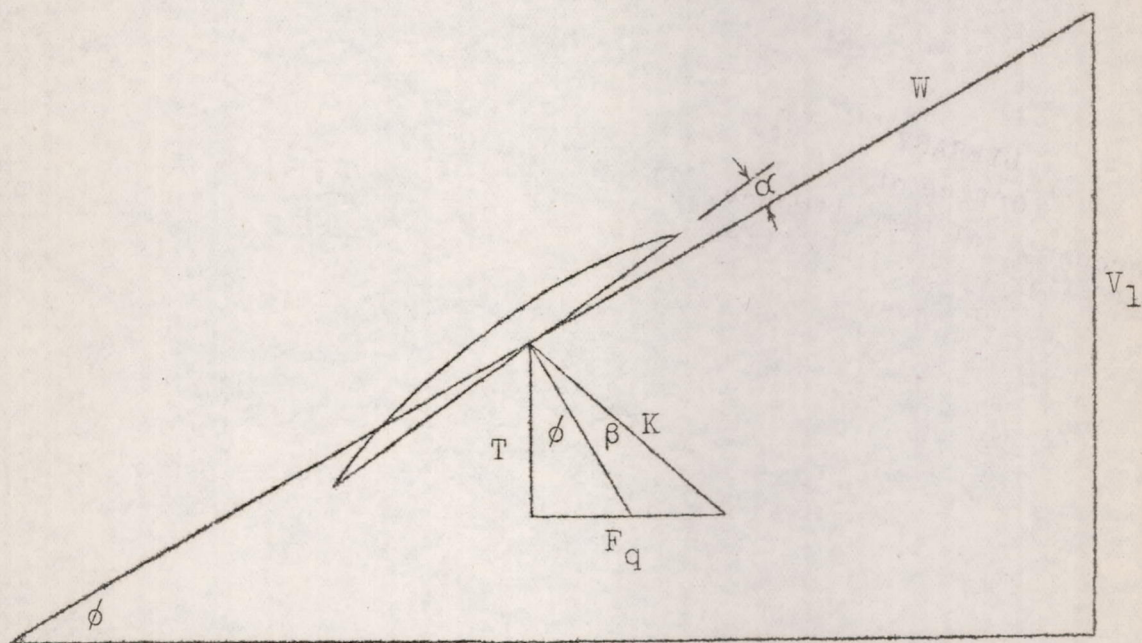


Fig. 24

$$V = 2\pi nR$$

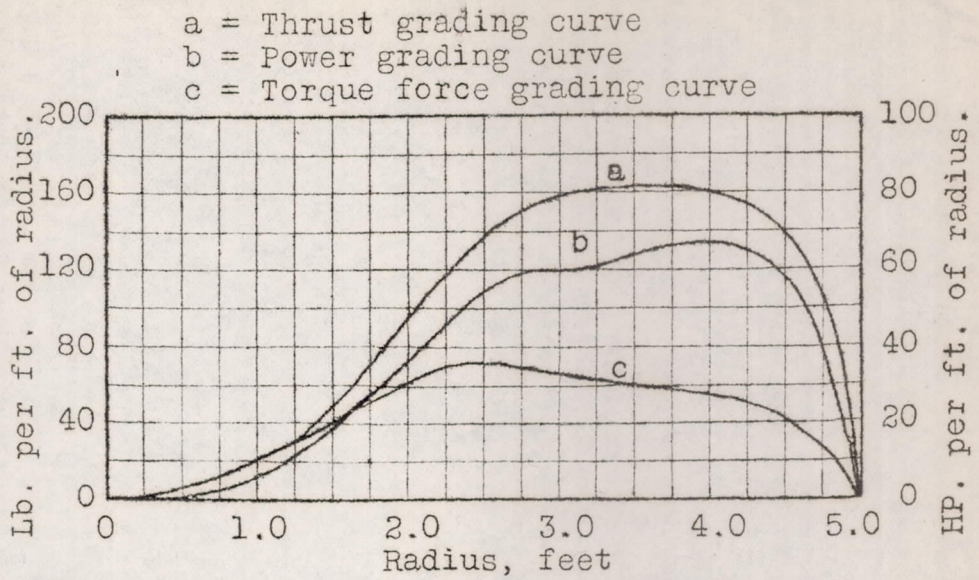


Fig. 25 Thrust and power grading curves for Liberty Micarta propeller.

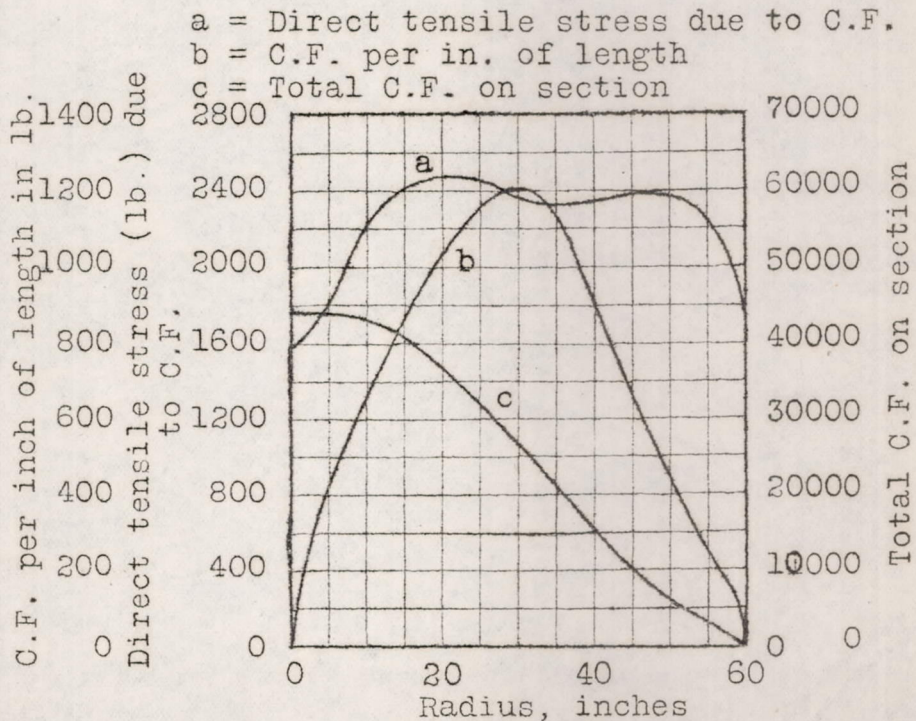


Fig. 26

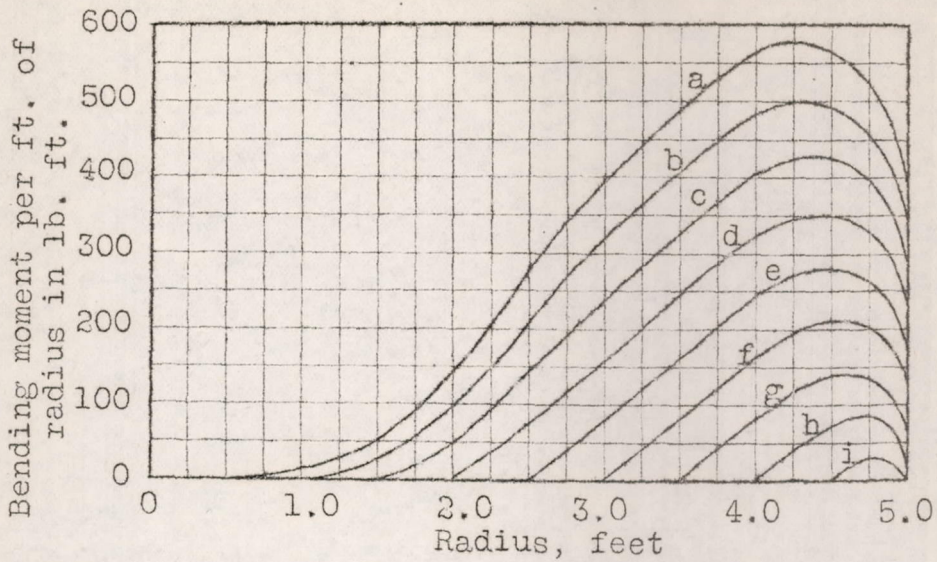


Fig. 27 Bending moment grading curves about various stations due to thrust. Liberty Micarta propeller.

a =	Moment about	0.5'	station
b =	"	"	1.0'
c =	"	"	1.5'
d =	"	"	2.0'
e =	"	"	2.5'
f =	"	"	3.0'
g =	"	"	3.5'
h =	"	"	4.0'
i =	"	"	4.5'

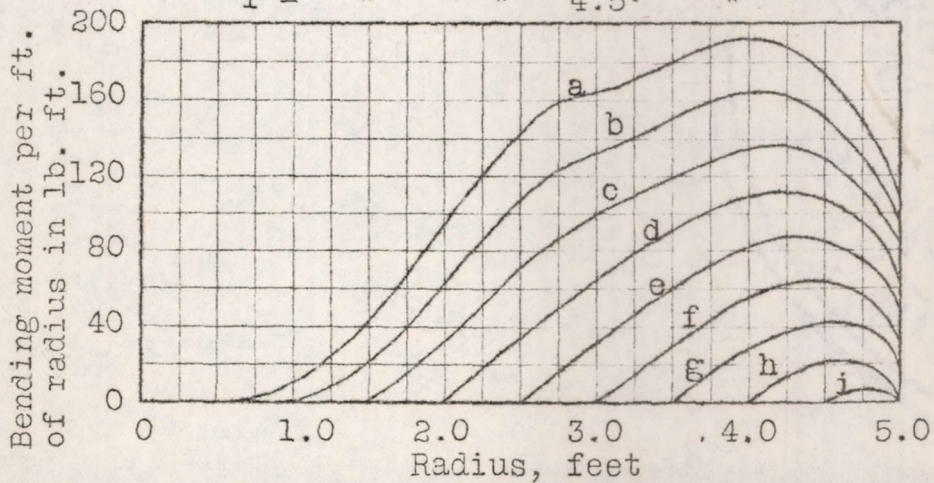


Fig. 28 Bending moment grading curves about various stations due to torque. Liberty Micarta propeller.

a = B.M. due to thrust
 b = Resulting B.M.
 c = B.M. due to C.F.

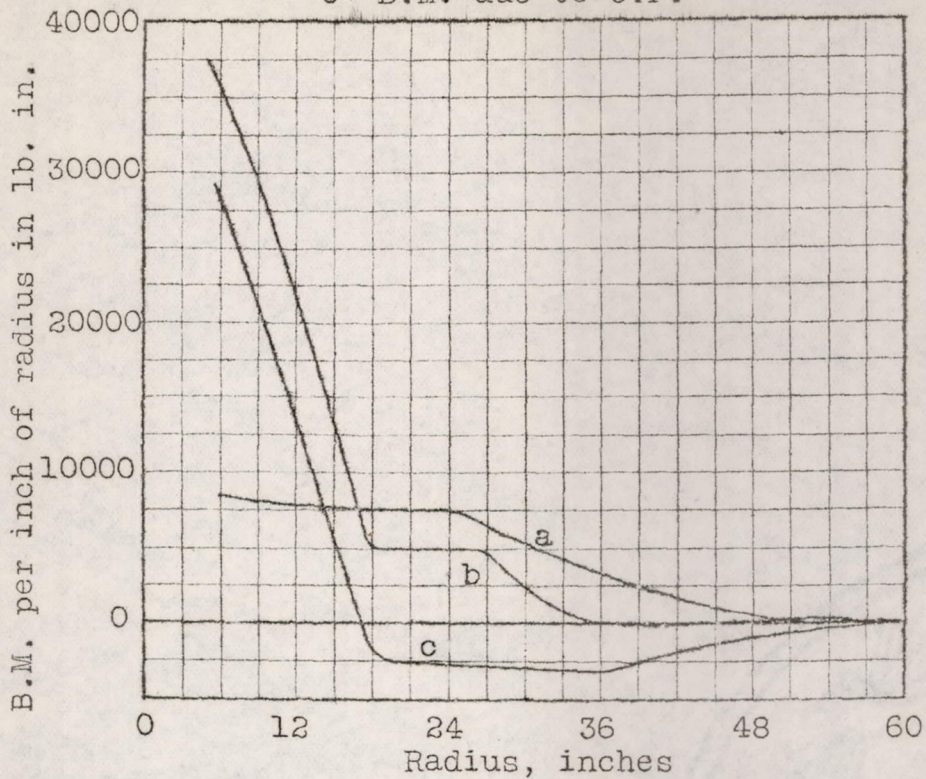


Fig. 29 Bending moments in the thrust plane.
 Liberty Micarta propeller.

a = B.M. due to torque
 b = Resulting B.M.

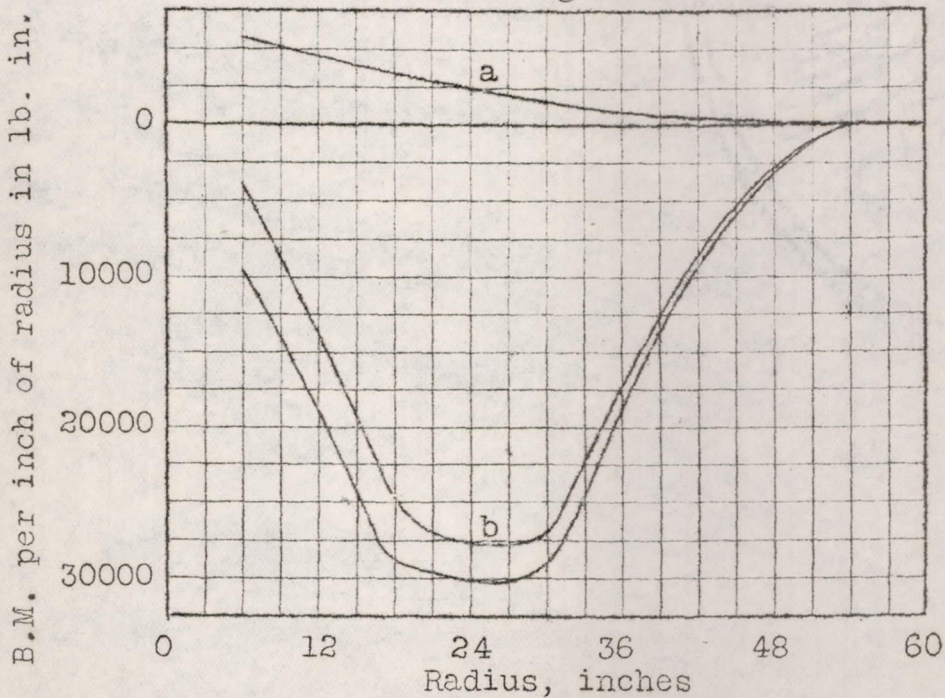


Fig. 30 Bending moments in the torque plane.
 Liberty Micarta propeller.

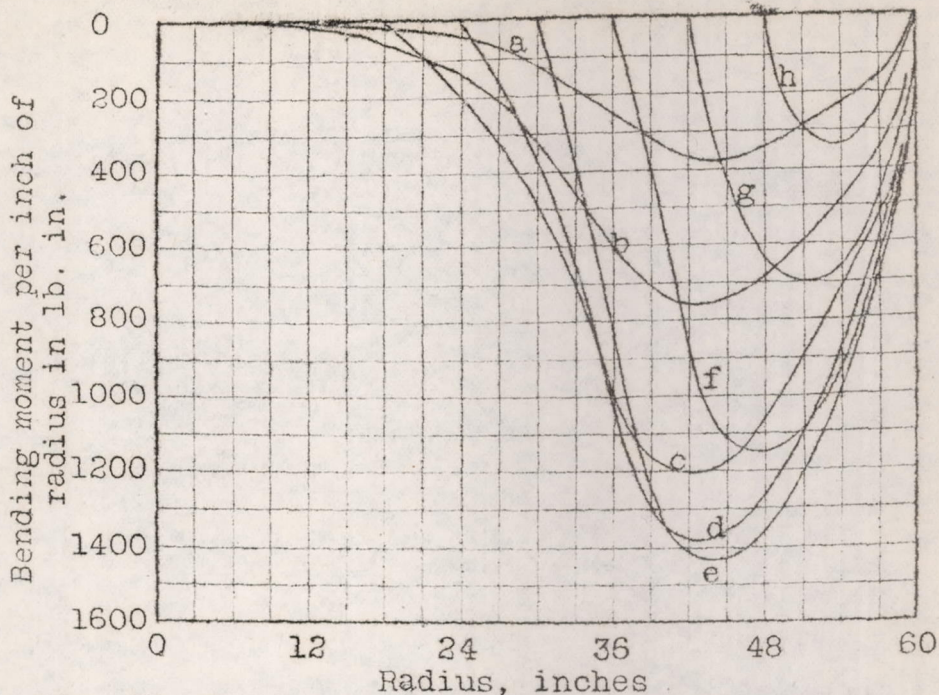


Fig. 31 Bending moment grading curves about various stations due to C.F. in the torque plane. Liberty Micarta propeller.

a = 6" station	e = 30" station
b = 12" "	f = 36" "
c = 18" "	g = 42" "
d = 24" "	h = 48" "

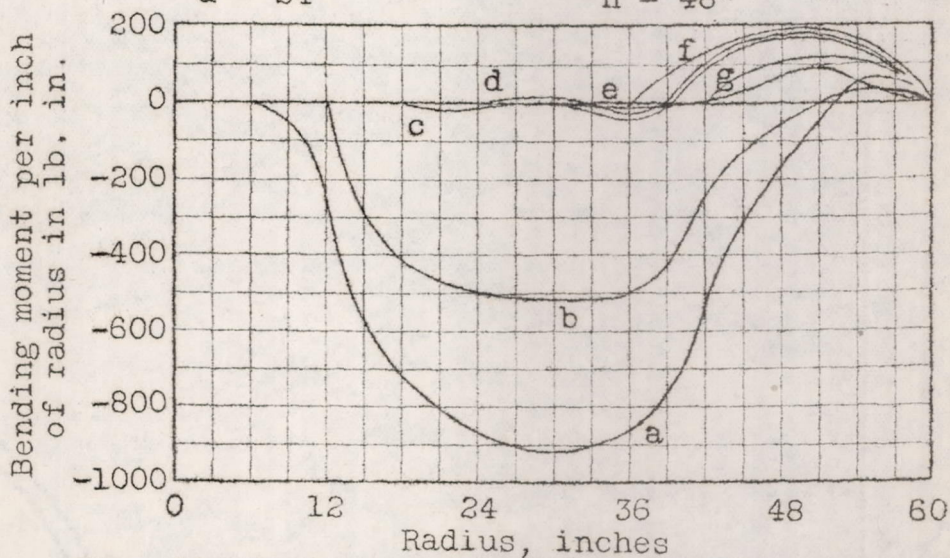


Fig. 32 Bending moment grading curves about various stations due to C.F. in the thrust plane.

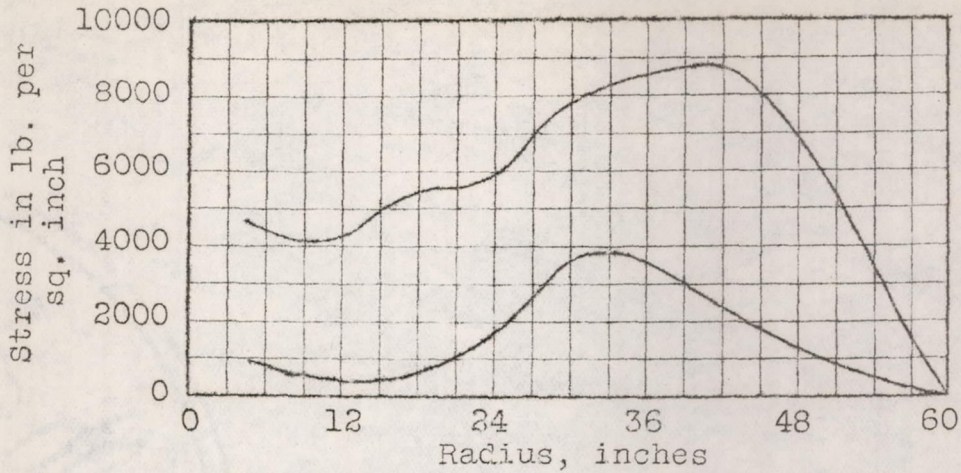


Fig. 33 Compressive and tensile stress at various stations. From static stress analysis, Liberty Micarta propeller

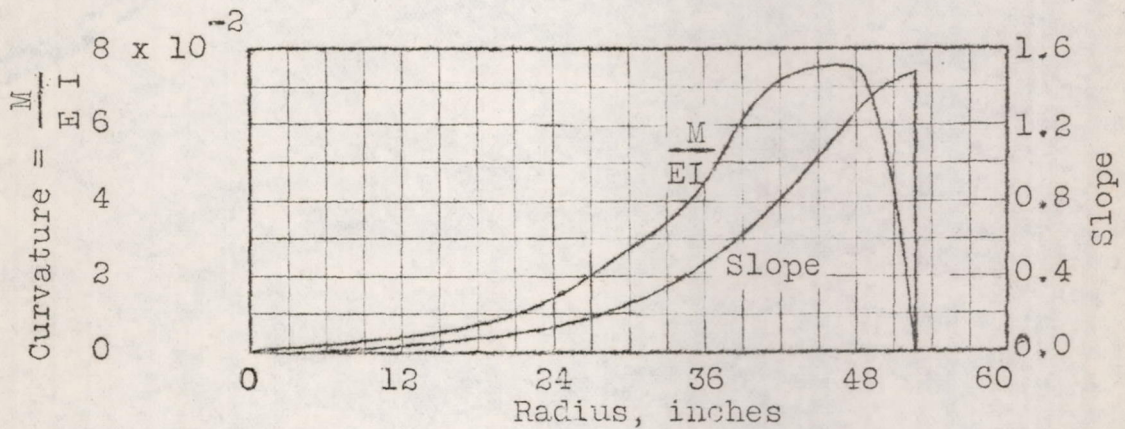


Fig. 34 Curvature and slope at various stations. Adjustable and reversible propeller. Approximate elastic analysis.

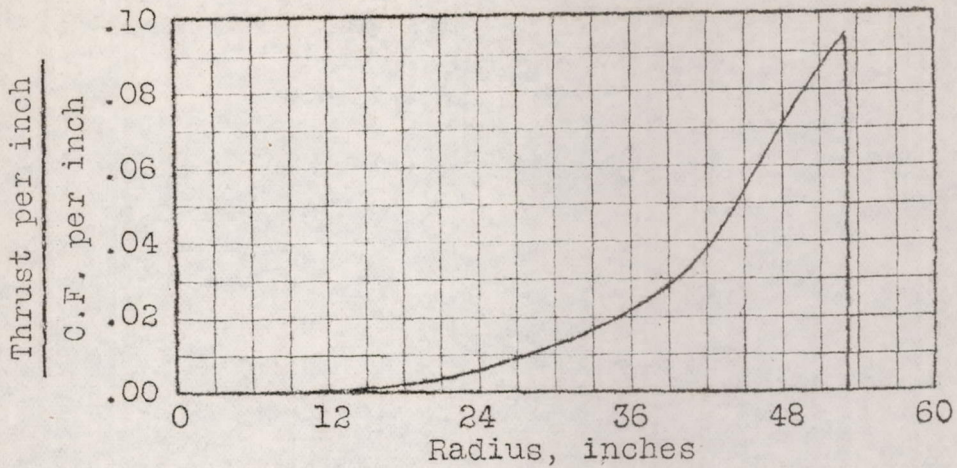


Fig. 35 Angular slope at various stations necessary to balance bending moments due to air loading with those due to C.F. Adjustable and reversible propeller. Approximate elastic analysis.

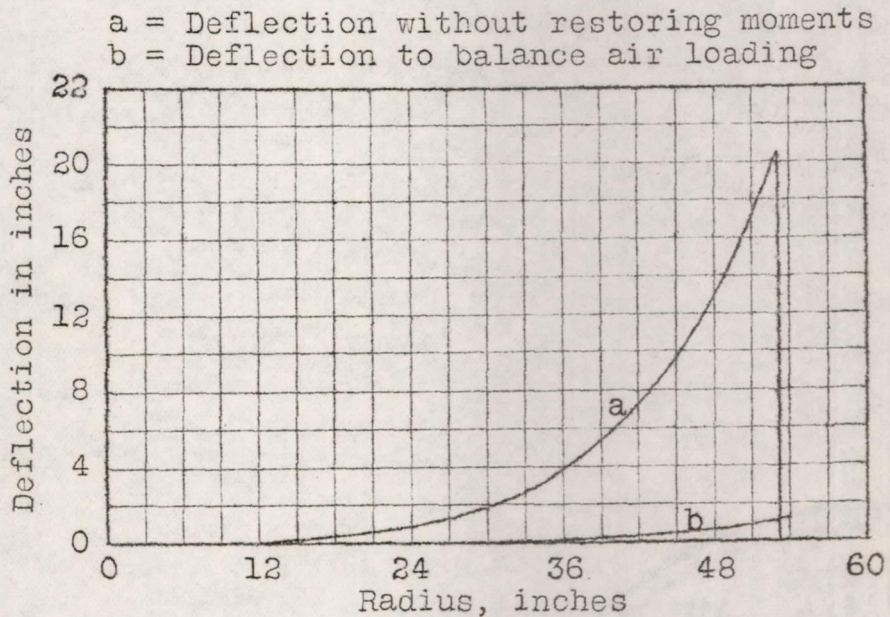


Fig. 36 Deflection without restoring moments compared with deflection necessary to balance air loading. Adjustable and reversible propeller. Approximate elastic analysis.

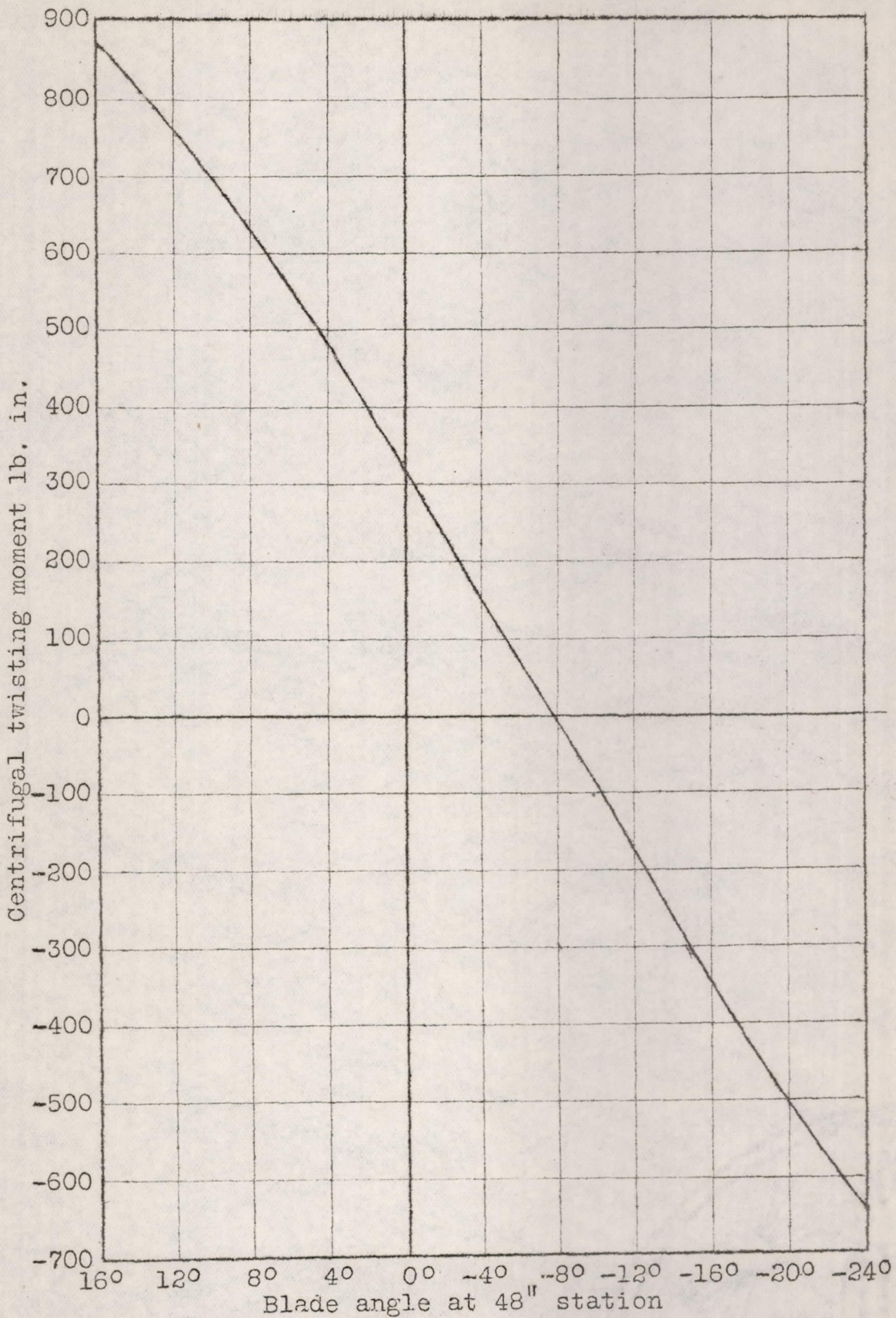


Fig. 37 Centrifugal twisting moment for various pitch settings. Adjustable and reversible Micarta propeller.