TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 212

SIMPLIFIED PROPELLER DESIGN FOR LOW-POWERED AIRPLANES.

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SIMPLIFIED PROPELLER DESIGN FOR LOW-POWERED AIRPLANES.

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Summary

The object of this report is to furnish the designer and builder of small airplanes a simple system for the designing of the propeller and the making of the drawing. An empirical design method is used, based on tests of model propellers in a wind tunnel and full scale tests of propellers in flight. The actual designing is accomplished by means of charts and involves very little calculation. The laying out and drawing of the propeller are also reduced to simple operations by the use of a basic or master propeller with dimensions given in terms of the diameter.

Introduction

For every combination of airplane and engine, there is a certain design of propeller which will give the highest maximum speed. A slightly different design having less pitch and usually greater diameter will show the best performance in climb. The best propeller for all-round service will have characteristics between the high speed propeller and the climbing propeller. As the service propeller is the type almost universally used, it is the only one dealt with in this report.

In the case of a tractor propeller, where the fuselage is in the slipstream, the power absorbed is greater than that of the propeller running alone. The amount of this power increase depends on the size and form of the fuselage. In this method of design, it is considered that a tractor propeller is operating in front of an average fuselage.

The accuracy with which a propeller will fit certain operating conditions depends primarily on the correctness of the performance figures (HP., R.P.M., and Speed) of the airplane and engine. If these are not correct the propeller will not give the desired performance. This report is based on data sufficiently accurate for the design of propellers for airplanes ranging from power models of less than one horsepower to airplanes of about fifty horsepower.

Basis of Design

The data necessary for the designing of a propeller are the brake horsepower of the engine, the revolutions per minute of the propeller shaft, and the speed of the airplane. These comprise the required performance of the combination of airplane, engine, and propeller. A non-dimensional coefficient involving the above factors is $\sqrt{\frac{\rho v^5}{P n^2}}$, where

v = Airspeed in ft. per sec.

P = Power in ft.lb. per sec.

n = Revolutions per sec.

ρ = Density of air in mass units.

This relation is developed in N.A.C.A. Technical Report No. 186 by Walter S. Diehl. Using engineering units and the value of ρ for standard atmosphere, the relation becomes

$$\text{Performance coefficient} = .325 \sqrt{\frac{V^5}{HP. \times N^2}}$$

where V = Airspeed in miles per hour

HP. = Brake horsepower of engine

N = Revolutions per minute.

This equation can be readily solved by means of the nomogram in Fig. 1.

The operating conditions of any propeller are governed by the airspeed, the revolutions, and the propeller diameter. These are put into another dimensionless coefficient called J.

$$J = \frac{v}{nd} = \frac{1056V}{ND}$$

where d = Propeller diameter in feet

D = Propeller diameter in inches.

Any propeller of pitch p, and diameter D, or pitch-diameter ratio p/D, has a definite operating condition or value of J at which it works at its maximum efficiency. It also has a value of J at which it should be operating when it is an all-round service propeller on an airplane traveling at maximum speed.

Fig. 2 is a curve made up of a series of these values of J for varying pitch-diameter ratios, plotted against their corresponding values of the performance coefficient $\sqrt{\frac{\rho V^5}{P n^2}}$.

The data for this curve are based on Durand's Navy Model Tests, but are entirely modified by flight tests, a few of which were made under the direction of Professor E. P. Lesley at Langley Field. Most of them, however, are regular propeller performance tests. The curve is for service propellers working in front of a fuselage of average resistance and proportions. The use of the curve is simple, giving directly the values of J and p/D for the performance coefficient obtained from the nomogram (Fig. 1).

The diameter is then given by the relation

$$D = \frac{1056V}{NJ}$$

The pitch is found by multiplying the diameter by the pitch-diameter ratio found in Fig. 2, or $p = p/D \times D$.

Efficiency

The approximate efficiency of the propeller when working at the operating condition or value of J for which it was designed, is shown in Fig. 3. The value of the efficiency is higher for the higher values of J.

A geared-down propeller operates at a higher value of J than a corresponding direct drive propeller, and is therefore more efficient, other things being equal.

The propeller efficiency at the speed for best climb is usually from .87 to .93 of that for high speed.

With the efficiency, HP. and speed known,

$$\text{Thrust in lb.} = \frac{375 \times \text{HP.} \times \text{efficiency}}{V} .$$

Strength

The stresses in a propeller of given proportions vary as the square of the tip speed. Practically, the tip speed varies with the diameter and the revolutions per minute. If the product of the revolutions and the diameter in inches (ND) is less than 170,000, the stresses in the particular design of propeller used in this report will be so low that spruce can safely be used. If it is under 210,000 walnut or white oak will be sufficiently strong, but for anything over this figure, birch or hickory should be used. If, as very rarely happens, ND exceeds 240,000, this design cannot be safely used, and a thicker blade will be necessary, entailing a loss of efficiency.

Layout and Drawing

The layout of the basic propeller is shown in Fig. 4. All dimensions necessary for drawing the propeller are shown in terms of the diameter with the exception of the blade angles and the airfoil sections. A drawing of the master section is shown in Fig. 5.

The blade angles are based on uniform geometric pitch, so for any section

$$\tan \text{blade angle} = \frac{p/D}{2\pi r}$$

where r is the radius of the section in terms of the diameter. Fig. 6 is a series of curves showing the blade angles plotted against the pitch-diameter ratio p/D, for each of the six sections of the basic propeller.

It will be noticed that the centers of gravity of the sections lie on a line which is determined by offsets from the radial center-line (Figs. 4 and 7). This is for the purpose of reducing the stresses.

Care must be taken to distinguish correctly between right-hand rotation and left-hand rotation. A right-hand propeller turns clockwise when viewed from the slipstream. The basic propeller in Fig. 4 is right-hand and the example in Fig. 7 is left-hand.

Actual Steps in Design and Layout

Given: Brake horsepower, revolutions per minute, speed in miles per hour, engine hub dimensions, and direction of rotation.

1. Performance Coefficient (Fig. 1).

(a) A straight edge is run through the given HP. on the horse-power scale and through the corresponding value of N on the revolutions per minute scale, and the point where it crosses the reference line is marked.

(b) The straight edge is then run from the above point on the reference line through the given speed on the miles per hour scale, and the value is read where the straight edge cuts the Performance Coefficient scale.

2. J and p/D (Fig. 2).

(a) The point for the value of the Performance Coefficient is projected to curve.

(b) The value of J is read on scale at left.

(c) The value of p/D is read on scale on the curve itself.

3. Diameter.

(a) $D = \frac{1056V}{NJ}$ inches.

4. Efficiency (Fig. 3).

(a) The efficiency is determined for the value of J found in Fig. 2.

5. Dimensions necessary to laying out the propeller are found by multiplying the dimensions given on the basic propeller (Fig. 4) by the above diameter.

6. The dimensions of the individual blade sections are found by multiplying the maximum blade thickness by the ordinates shown in the master section (Fig. 5). The sections are divided into ten equal divisions with the division nearest the leading edge subdivided into halves and quarters.

The two sections nearest the hub are double cambered. These are figured as if they were two single cambered airfoils placed face to face, but new radii are drawn in at the leading and trailing edges.

7. The blade angles are found for the above p/D on Fig. 6, for the various sections.

8. The layout is made full scale or larger, first drawing the centerlines and lines of the centers of gravity of the sections as shown in Fig. 4. The sections are drawn in around their respective

centers of gravity at the correct blade angles. They are projected up to get the side elevation and plan views. The dimensions marked "scale" in Fig. 4, are measured on these views and checked by the corresponding measurements on the sections.

The lamination lines are drawn in as shown in the example (Fig. 7). Laminations may be from 1/4" to 1" thick, all of the laminations in a single propeller having the same thickness, except the outside ones. The lamination lines should be smooth curves, showing that the propeller is fair and will be without bumps or waves. This is a good check on the dimensions and drawing.

Example

Given: HP. = 20

N = 2000 revolutions per minute

V = 60 miles per hour

Rotation - Left-hand

Hub dimensions as shown in Fig. 7.

1. Performance Coefficient = 1.01 (Fig. 1)
(The solution of this is shown on the figure.)

2. For a value of the performance coefficient of 1.01,

$$J = .484 \quad \text{and} \quad p/D = .560 \quad \text{from Fig. 2.}$$

3. Diameter, $D = \frac{1056V}{NJ} = \frac{1056 \times 60}{2000 \times .484} = 65.5$ inches.

Pitch, $p = p/D \times D = .560 \times 65.5 = 36.7$ inches.

4. From Fig. 3, for $J = .484$ the efficiency is .71 or 71%.

5. The dimensions necessary for layout are found from the basic propeller and the master blade section (Figs. 4 and 5). (These may be checked on the drawing of this example, Fig. 7.)

6. The blade angles for p/D = .560 are found from Fig. 6, as follows:

Section	Angle
.075D	50.0°
.15 D	30.7°
.225D	21.6°
.30 D	16.5°
.375D	13.4°
.45 D	11.3°

7. The complete layout and working drawing of the propeller is shown in Fig. 7.

8. The product of the revolutions per minute and the diameter in inches is

$$ND = 2000 \times 65.5 = 131,000.$$

This is less than 170,000, so that spruce may be used in making the propeller.

References

1. W. S. Diehl: The Application of Propeller Test Data to Design and Performance Calculation. N.A.C.A. Technical Report No. 186.

2. W. F. Durand and E. P. Lesley: Experimental Research on Air Propellers. N.A.C.A. Technical Reports Nos. 14, 30, 64, 109 and 141.

3. H. C. Watts: The Design of Screw Propellers for Aircraft.

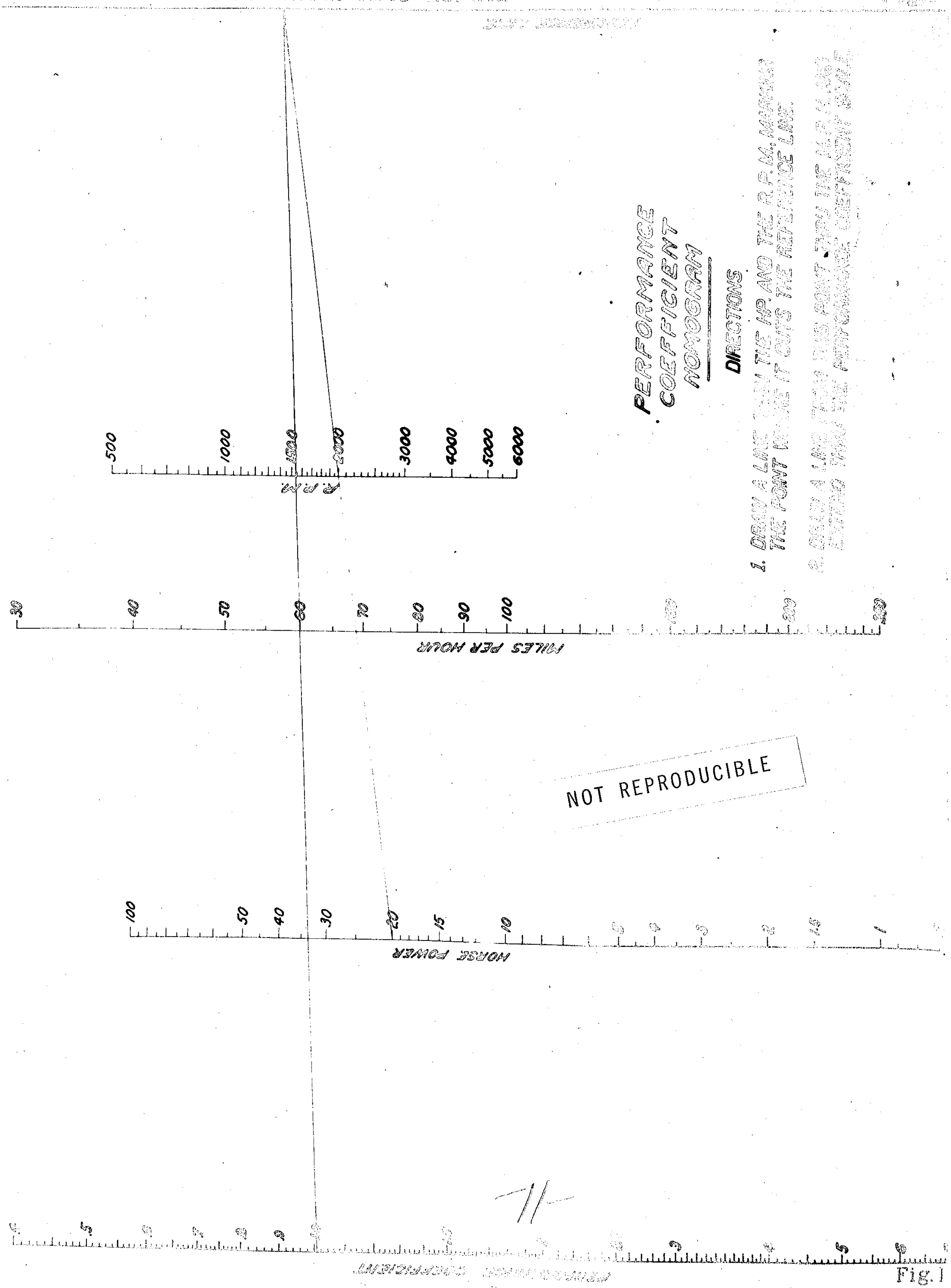

PERFORMANCE COEFFICIENT NOMOGRAM
DIRECTIONS
1. DRAW A LINE THRU THE H.P. AND THE R.P.M. MARKING THE POINT WHERE IT CUTS THE REFERENCE LINE.
R.P.M.
500
1000
1500
2000
3000
4000
5000
6000
MILES PER HOUR
30
40
50
60
70
80
90
100
HORSE POWER
100
50
40
30
20
15
10

Fig. 1

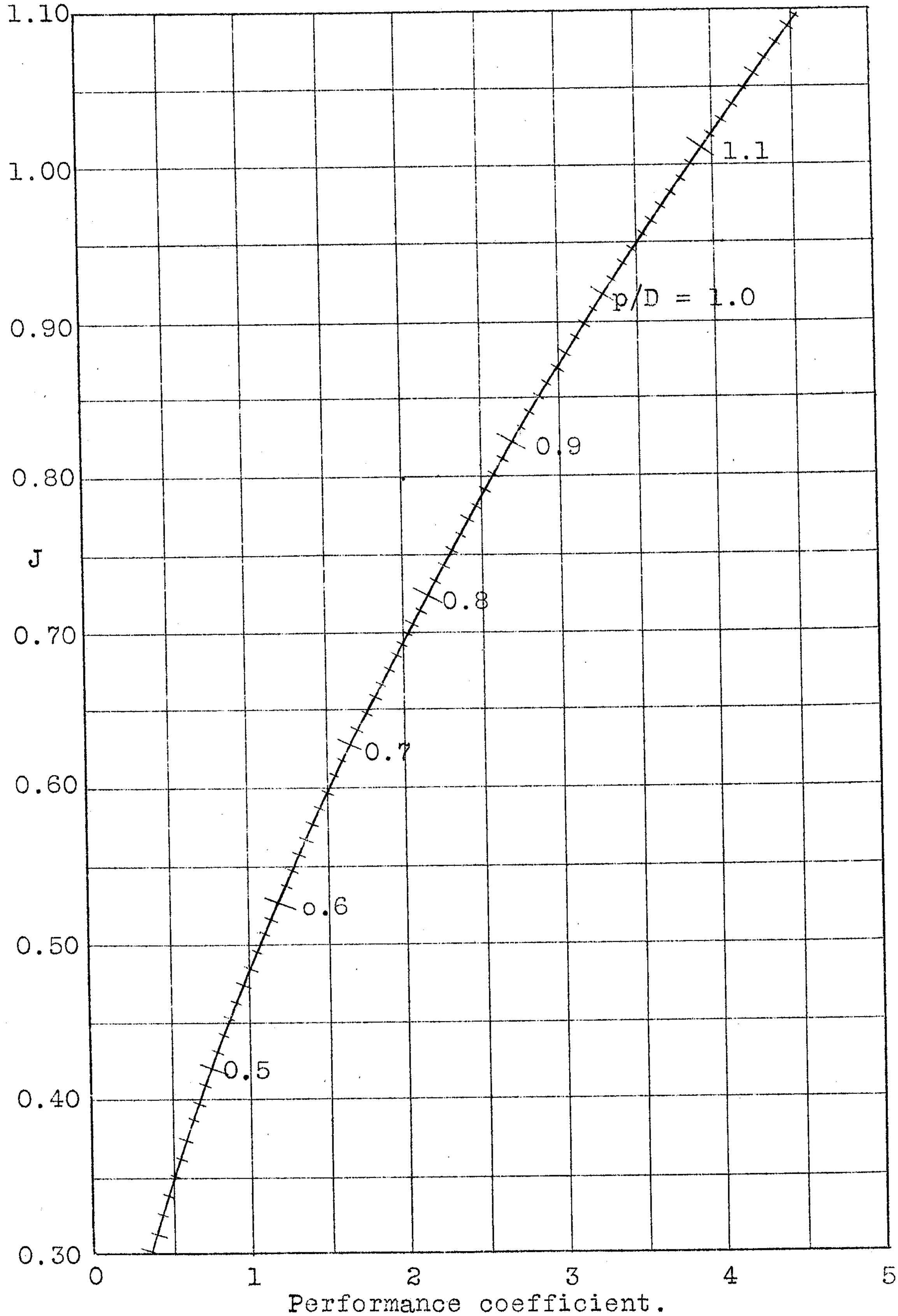

1.10
1.00
0.90
0.80
J
0.70
0.60
0.50
0.40
0.30
0
1
2
3
4
5
Performance coefficient.
1.1
p/D = 1.0
0.9
0.8
0.7
o.6
0.5

Fig.2

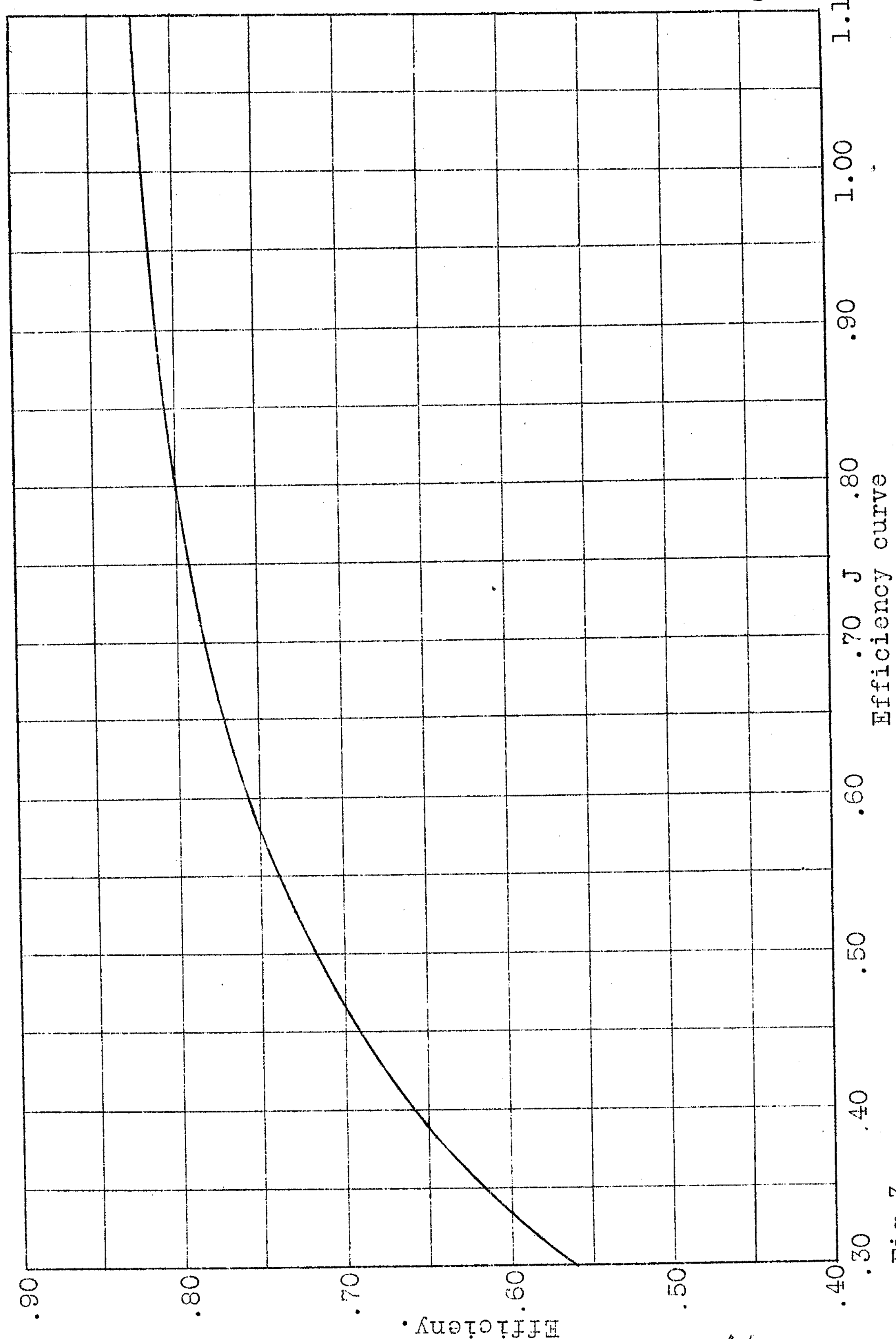
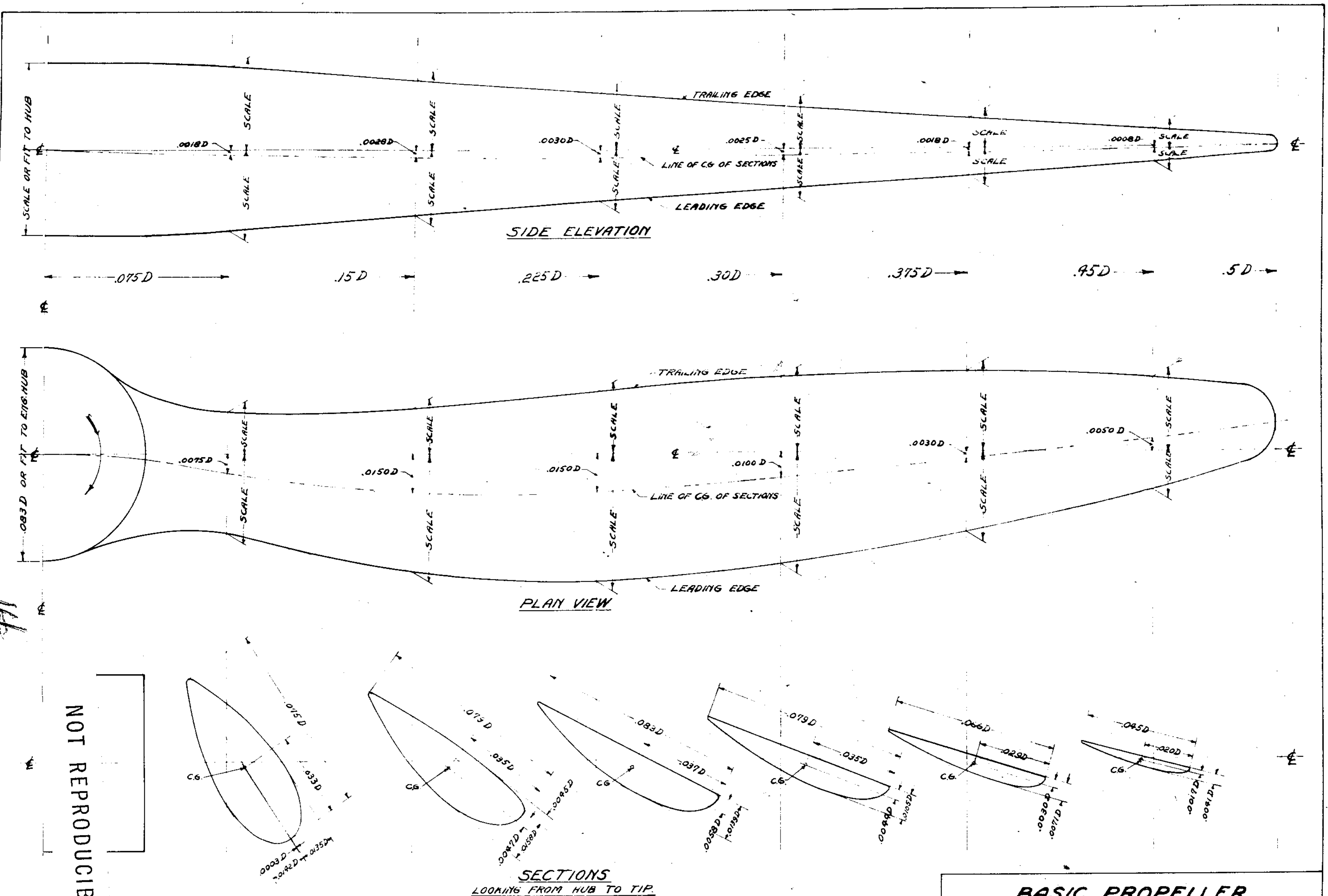

.30
.40
.50
.60
.70
.80
.90
1.00
1.10
J
Efficiency curve
.90
.80
.70
.60
.50
.40
Efficiency.

Fig.3



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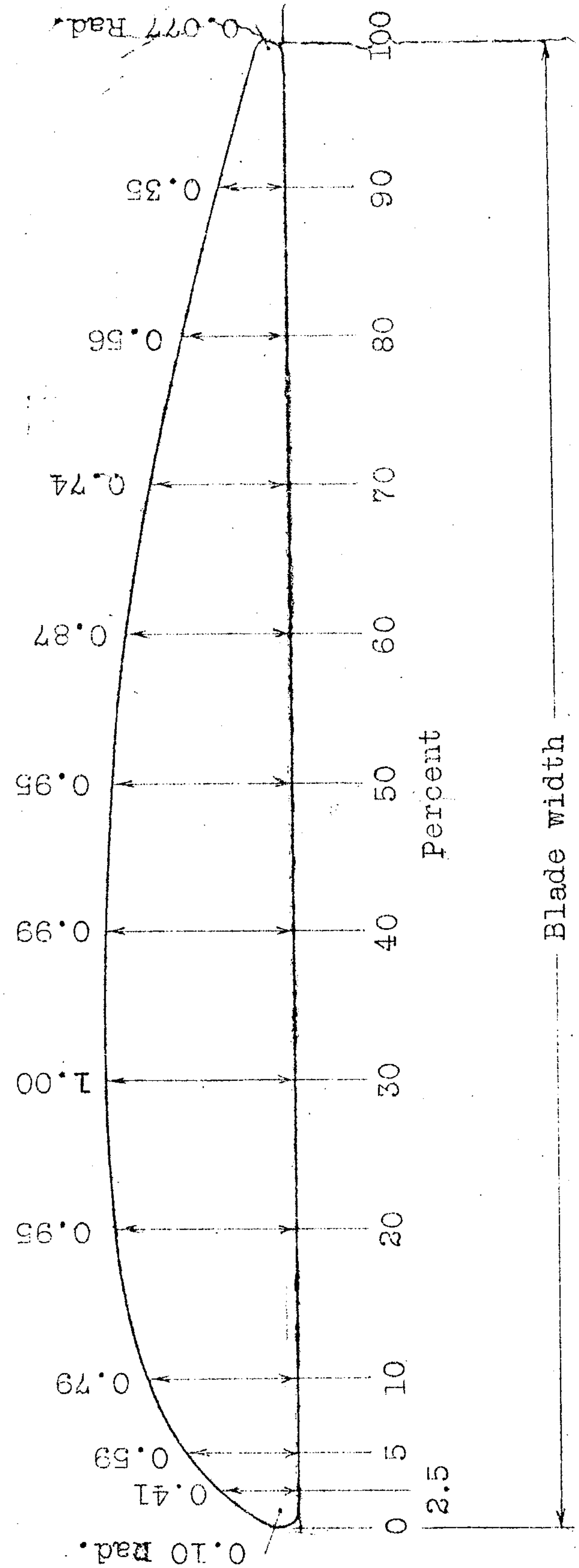
BASIC PROPELLER

DIMENSIONS IN TERMS OF THE DIAMETER.

RIGHT HAND SHOWN



Master blade section

Fig. 5

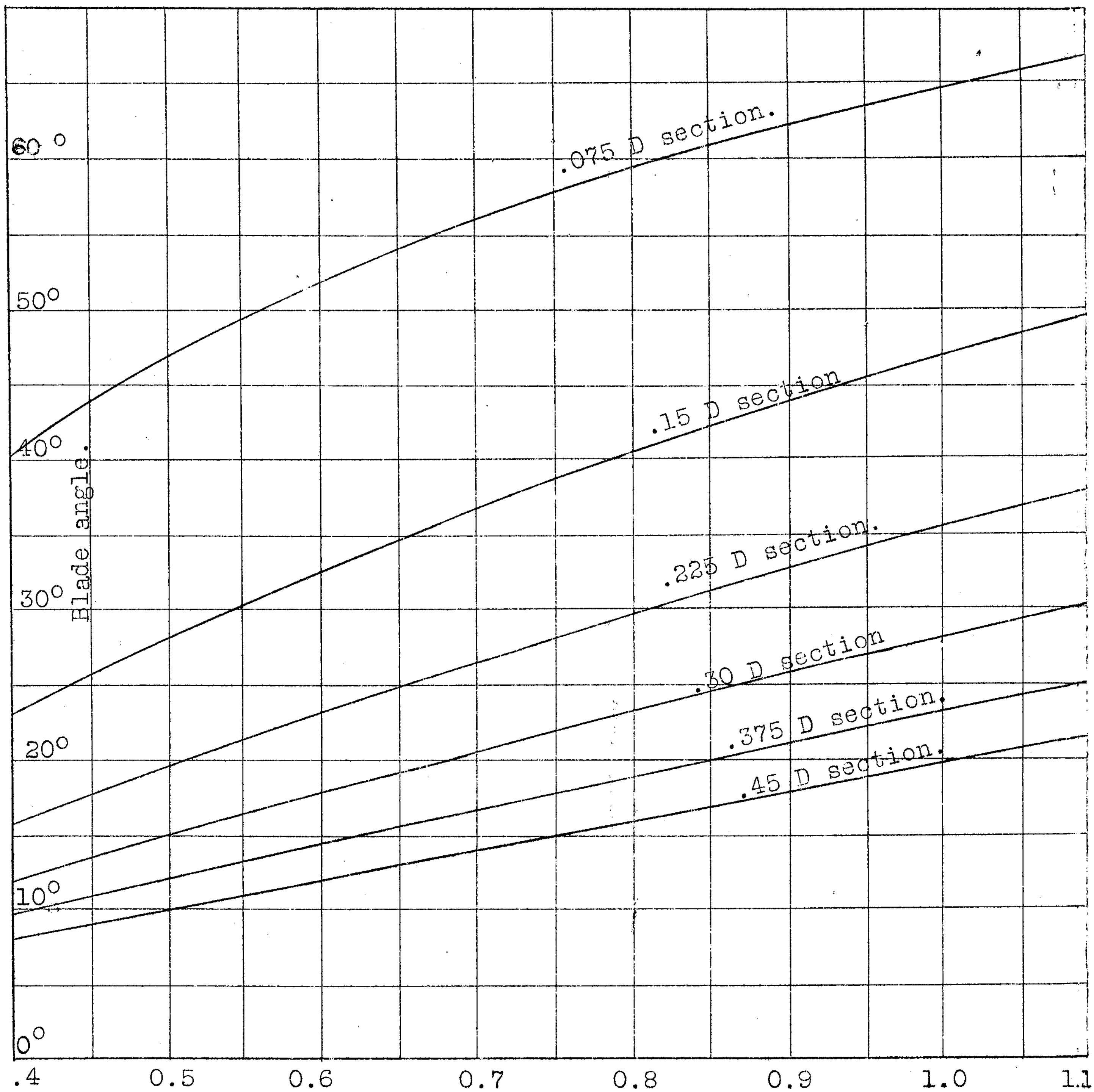


Fig.6 Blade angle curves.

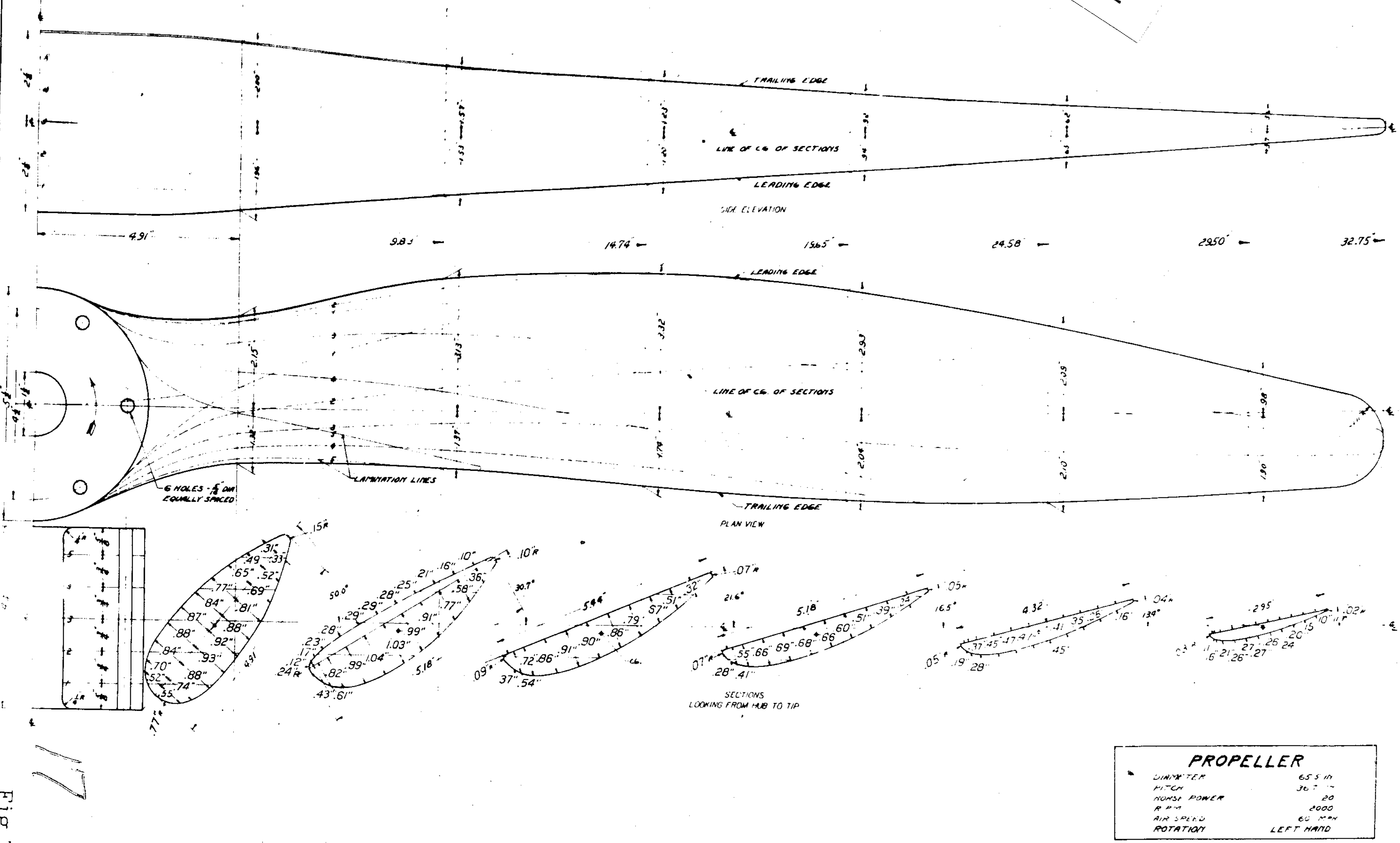

TRAILING EDGE
LINE OF C.G. OF SECTIONS
LEADING EDGE
SIDE ELEVATION
4.91"
9.83"
14.74"
19.65"
24.58"
29.50"
32.75"
LEADING EDGE
LINE OF C.G. OF SECTIONS
6 HOLES - 5/8 DIA EQUALLY SPACED
LAMINATION LINES
TRAILING EDGE
PLAN VIEW
SECTIONS
LOOKING FROM HUB TO TIP
PROPELLER
DIAMETER 65.5 in
HORSE POWER 20
R.P.M. 2000
AIR SPEED 60 M.P.H.
ROTATION LEFT HAND

Fig. 7