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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESTRICTED BULLETIN

PROPOSAL FOR A PROPELLER SIDE-FORCE FACTOR

By Herbert S. Ribner

SUMMARY

Knowledge of the side force on a propeller in yaw — the fin effect — is useful in the design of tail surfaces, in the testing of powered aircraft models, and in formal stability and control analyses. A side-force factor computed from the plan form and pitch distribution is shown to be a good index of the relative effectiveness, per blade, of a yawed propeller in developing side force. By the general use of side-force factors, existing charts of propeller side force may be simply extrapolated to give the side force on any specified propeller in any specified operating condition. The suggestion is made that propeller manufacturers and designers present the side-force factor with the activity factor as a fundamental parameter for all blade designs and that reports of tests of powered models in wind tunnels include the side-force factor for the propeller used.

INTRODUCTION

With current increases in engine power, the blade area is becoming so large that the influence of the propeller on stability and control is considerable. The propeller must now be considered in the design of horizontal and vertical tail surfaces. The disturbing effect is due in part to the slipstream and in part to the air forces on the propeller. A study of the power effects is in progress, and the phase dealing with the forces on the propeller has been completed and is presented in references 1 and 2. Reference 1 provides a general analysis of the forces experienced by a propeller in any deviation from steady axial advance, with detailed treatment of propellers in yaw. Reference 2 summarizes the formulas for propellers in yaw derived in reference 1

and presents a series of computed charts of the side-force derivative with respect to yaw for two representative propellers.

The computations underlying the charts of reference 2 are somewhat tedious. It has been found, however, that the existing charts may be applied to all conventional propellers by a simple extrapolation, and repetition of the computations can thereby be avoided. The method of extrapolation requires the introduction of a new propeller parameter, based on the blade shape, which might suitably be termed a "side-force factor." The present paper defines the side-force factor and describes its uses.

DEFINITION AND SIGNIFICANCE OF SIDE-FORCE FACTOR

The following quantity is suggested as a suitable side-force factor for purposes of extrapolation:

$$\text{S.F.F.} = \frac{100000}{32} \int_{0.2}^{1.0} \frac{b}{D} \sin \beta \, d\left(\frac{r}{R}\right) \qquad (1)$$

where

S.F.F. side-force factor

b blade section chord at any radius r

D propeller diameter

β blade angle at radius r $\left(\text{when } \beta = 25^\circ \text{ at } 0.75R \text{ and } \tan \beta = \frac{p/D}{\pi \frac{r}{R}}\right)$

R radius to tip

p geometric pitch at radius r

This side-force factor expresses the relative effectiveness, per blade, of a propeller in developing side force in yaw or normal force in pitch and may be used in comparing these characteristics of propellers. It is seen to be similar to the activity factor

$$A.F. = \frac{100000}{16} \int_{0.2}^{1.0} \frac{b}{D} \left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right)$$

which is intended to express the relative effectiveness, per blade, of a propeller in absorbing power.

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References 1 and 2 show that the side force on a propeller in yaw is approximately proportional to the projected side area. There is a small correction for aspect ratio. Examination of equation (1) will show that the proposed side-force factor is directly proportional to the projected side area of one blade;[1] the constant of proportionality is chosen to give a value of the order of the activity factor (60 to 140) as a convenient magnitude. The side-force factor is therefore a suitable criterion for comparing propellers having the same number of blades.

USE OF SIDE-FORCE FACTOR

The relative effectiveness in developing side force in yaw of several propellers, when the number of blades is the same and the blades are set to the same angle at 0.75R, may be estimated to be in proportion to the respective side-force factors. By this principle a model propeller may be chosen to experience approximately the side force that would be experienced by the propeller specified by the manufacturer, even though the two propellers are dissimilar in shape. The same principle may be used in airplane design to select from several otherwise almost equally satisfactory propellers the one that is best for stability.

For some purposes such as the design of tail surfaces, detailed knowledge of the side force may be necessary. Computed charts of the side-force derivative

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[1]The side-force factor is also proportional to the product of the side-area index defined in reference 2 and the solidity per blade at 0.75R. The exact relation is

$$S.F.F. = 1645 \frac{\sigma}{B} I_1$$

where

σ total solidity at 0.75R
B number of blades
I_1 side-area index

$$C_{Y'_\psi} = \frac{\partial Y/\partial \psi}{q \frac{\pi D^2}{4}}$$

where

Y side force (body axes)

ψ angle of yaw, radians

q free-stream dynamic pressure

for two representative propellers are given in reference 2. The propellers are the Hamilton Standard 3155-6 and the NACA 10-3062-045, for which the side-force factors are 80.7 and 131.6, respectively. As an estimation, the following relation may be used:

$$\frac{C_{Y'_\psi} \text{ for desired propeller}}{C_{Y'_\psi} \text{ for Hamilton Standard propeller 3155-6}} = \frac{\text{S.F.F. for desired propeller}}{80.7} \qquad (2)$$

A similar expression may be used when the NACA propeller 10-3062-045 is the reference propeller.

The simple proportion given as equation (2) is a good enough approximation for many purposes. For greater accuracy, however, the wariation of $C_{Y'_\psi}$ with S.F.F. has been established from the formulas of references 1 and 2; this information has been used to prepare the charts presented herein as figures 1 and 2. Figure 1 gives the ratio of side-force derivatives

$$\frac{C_{Y'_\psi} \text{ for desired propeller}}{C_{Y'_\psi} \text{ for Hamilton Standard propeller 3155-6}}$$

as a function of the side-force factor for the desired propeller; figure 2 gives the ratio of side-force derivatives

$$\frac{C_{Y'_\psi} \text{ for desired propeller}}{C_{Y'_\psi} \text{ for NACA propeller 10-3062-045}}$$

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as a function of the side-force factor for the desired propeller. In both figures 1 and 2, the approximate relation of equation (2) is plotted for comparison. For a four-blade single-rotating propeller, for example, figure 1 may be applied as follows: The ratio

$$\frac{C_{Y'_\psi} \text{ for desired four-blade propeller}}{C_{Y'_\psi} \text{ for four-blade Hamilton Standard propeller 3155-6}}$$

is the ordinate on the four-blade curve corresponding to the abscissa S.F.F. for desired propeller.

The $\frac{p}{D}$-curve for a specified propeller may apply to the angle to the zero-lift chord; whereas β generally applies to the angle to the reference chord. Hence, the label $\beta = 25^\circ$ at 0.75R on a given $\frac{p}{D}$-curve does not necessarily mean that the formula $\tan \beta = \frac{p/D}{\pi \frac{r}{R}}$ would give the same value of β at 0.75R. Either definition will result in approximately the same side-force factor provided that, by this same definition, $\beta = 25^\circ$ at 0.75R. A suitable procedure is to select any available $\frac{p}{D}$-curve and to compute a curve of β against r/R from the relation $\tan \beta = \frac{p/D}{\pi \frac{r}{R}}$. This curve will generally fail to pass through 25° at $r/R = 0.75$. The desired curve is obtained by adding or subtracting from all the values of β the increment that will make $\beta = 25^\circ$ at $r/R = 0.75$.

The fact that the Hamilton Standard propeller 3155-6 has Clark Y blade sections and the NACA propeller 10-3062-045 has NACA 16-series blade sections is of some significance. The charts of Hamilton Standard propeller 3155-6 should be used as the basis of extrapolation for propellers having Clark Y or RAF 6 blade sections, and the charts of NACA propeller 10-3062-045 should be used as the basis of extrapolation for propellers having NACA 16-series sections. This restriction eliminates errors of the order of 5 percent.

The significance of the blade section lies in the difference in angle between the reference chord and the zero-lift chord for the several sections. This difference is of the order of 3° to 7° for the Clark Y and RAF 6 sections and $1\frac{1}{2}^\circ$ to $2\frac{1}{2}^\circ$ for the NACA 16-series sections. The zero-lift chord is fundamental in the evaluation of side force but blade-setting designations generally refer to the geometric reference chord. This convention was retained in the side-force charts of reference 2. The curve for Hamilton Standard propeller 3155-6 designated $\beta = 25^\circ$ at 0.75R thus may also be designated $\beta_0 = 28.2^\circ$ at 0.75R, where β_0 is the blade angle to the zero-lift chord; the corresponding curve for NACA propeller 10-3062-045 may be designated $\beta_0 = 26.8^\circ$ at 0.75R. For accuracy, therefore, comparison should be made of propellers for which the average difference between β and β_0 is nearly the same; that is, propellers with more or less similar blade sections should be compared.

ILLUSTRATIVE EXAMPLE

As an illustrative check, the side-force factor will be used to obtain a value of the side-force derivative $C_{Y'_\psi}$ for a specified two-blade propeller by extrapolation from the two-blade chart of Hamilton Standard propeller 3155-6 given in reference 2. Figure 14 of reference 2 gives both calculated and experimental values of $C_{Y'_\psi}$ for the two-blade propeller of reference 3. Blade-form curves for this propeller are given with corresponding curves for the Hamilton Standard propeller 3155-6 in figure 3. The propeller of reference 3 lacks the spinner of Hamilton Standard propeller 3155-6, but computations show that the shank blade sections provide enough additional area inboard of 0.2R to compensate very nearly.

Given:

The two-blade propeller of reference 3 (data in fig. 3)

Required:

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To determine $C_{Y'_\psi}$, for $\beta = 20.6^\circ$ at 0.75R and the advance-diameter ratio $V/nD = 0.6$, by extrapolation from the two-blade chart of $C_{Y'_\psi}$ for Hamilton Standard propeller 3155-6 in figure 5 of reference 2.

Procedure:

1. Compute the side-force factor for the propeller of reference 3 from its $\frac{b}{D}$- and β-curves in figure 3. The result is 74.6.

2. From figure 1 read the value of

$$\frac{C_{Y'_\psi} \text{ for desired propeller}}{C_{Y'_\psi} \text{ for Hamilton Standard propeller 3155-6}}$$

corresponding to the abscissa 74.6. This value is 0.927.

3. From figure 5 of reference 2 read the value of $C_{Y'_\psi}$ corresponding to $V/nD = 0.6$ and $\beta = 20.6^\circ$ by interpolation between the 20° and 25° curves. This value is 0.115.

4. Multiply the two values found in steps 2 and 3 - that is, multiply 0.927 by 0.115. The result is 0.107, which is the value of $C_{Y'_\psi}$ for the propeller of reference 3 obtained by extrapolation.

5. As a check, from figure 14 of reference 2 read the value of $C_{Y'_\psi}$ on the $\beta = 20.6^\circ$ curve corresponding to $V/nD = 0.6$. This result is 0.104, which is the value of $C_{Y'_\psi}$ for the propeller of reference 3 obtained by direct computation.

A number of other values of $C_{Y'_\psi}$ for the propeller of reference 3 obtained by extrapolation are presented in table I. The values of $C_{Y'_\psi}$ obtained by direct computation, as plotted in figure 14 of reference 2, are [illegible]

included for comparison. Note that the propeller of reference 3 has a noticeably smaller blade area than Hamilton Standard propeller 3155-6 (see fig. 3) but that the values of side-force factor are nearly the same. The agreement of the extrapolated values with the computed values indicates that the side-force factor is a suitable criterion of propeller side force.

The errors introduced by the extrapolation described herein will generally be sufficiently small to be negligible in comparison with the ±10 percent average discrepancy between the computed side-force charts of reference 2 and the available experimental data. Additional errors of the order of 5 percent may be introduced, however, if the restrictions against extrapolating for propellers with NACA 16-series sections from side-force charts for propellers with Clark Y sections, and vice versa, are not adhered to.

CONCLUDING REMARKS

A side-force factor computed from the propeller plan form and pitch distribution is shown to be a good index of the relative effectiveness, per blade, of a yawed propeller in developing side force. An extensive series of side-force charts for two representative propellers are available in reference 2. By the general use of side-force factors, these charts could be made to serve for all conventional propeller designs to provide the propeller side-force data needed in the design of tail surfaces, in the testing of powered aircraft models, and in formal stability and control analyses. It is accordingly suggested that propeller manufacturers and designers present the side-force factor with the activity factor as a fundamental parameter for all blade designs. It is further suggested that reports of tests of powered models in wind tunnels include the side-force factor for the propeller used.

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TABLE I

COMPARISON OF DIRECT COMPUTATION AND EXTRAPOLATION BY USE OF THE SIDE-FORCE FACTOR IN OBTAINING THE SIDE-FORCE DERIVATIVE $C_{Y'_\psi} = \dfrac{\partial Y/\partial\psi}{q\,\frac{\pi D^2}{4}}$

[Extrapolation made from curves of Hamilton Standard propeller 3155-6 from fig. 5 of reference 2. Computed values from fig. 14 of reference 2.]

β at 0.75R (deg)	V/nD	$C_{Y'_\psi}$ for Hamilton Standard propeller 3155-6	$C_{Y'_\psi}$ for propeller of reference 3	
			Computed directly	Extrapolated (a)
16.6	0.2	0.179	0.169	0.166
	.5	.102	.095	.0945
	.8	.086	.080	.080
20.6	.3	.170	.150	.158
	.6	.115	.104	.1065
	1.0	.098	.090	.091
24.6	.4	.164	.150	.152
	.8	.118	.108	.109
	1.2	.108	.098	.100
28.6	.6	.153	.135	.142
	1.0	.123	.113	.117
	1.4	.120	.108	.111

[a]Side-force factor for propeller of reference 3 is 74.6. From figure 1, for the abscissa 74.6, read:

$$\frac{C_{Y'_\psi} \text{ for desired propeller}}{C_{Y'_\psi} \text{ for Hamilton Standard propeller 3155-6}} = 0.927$$

The values in column 5 are obtained by multiplying the corresponding values in column 3 by 0.927.

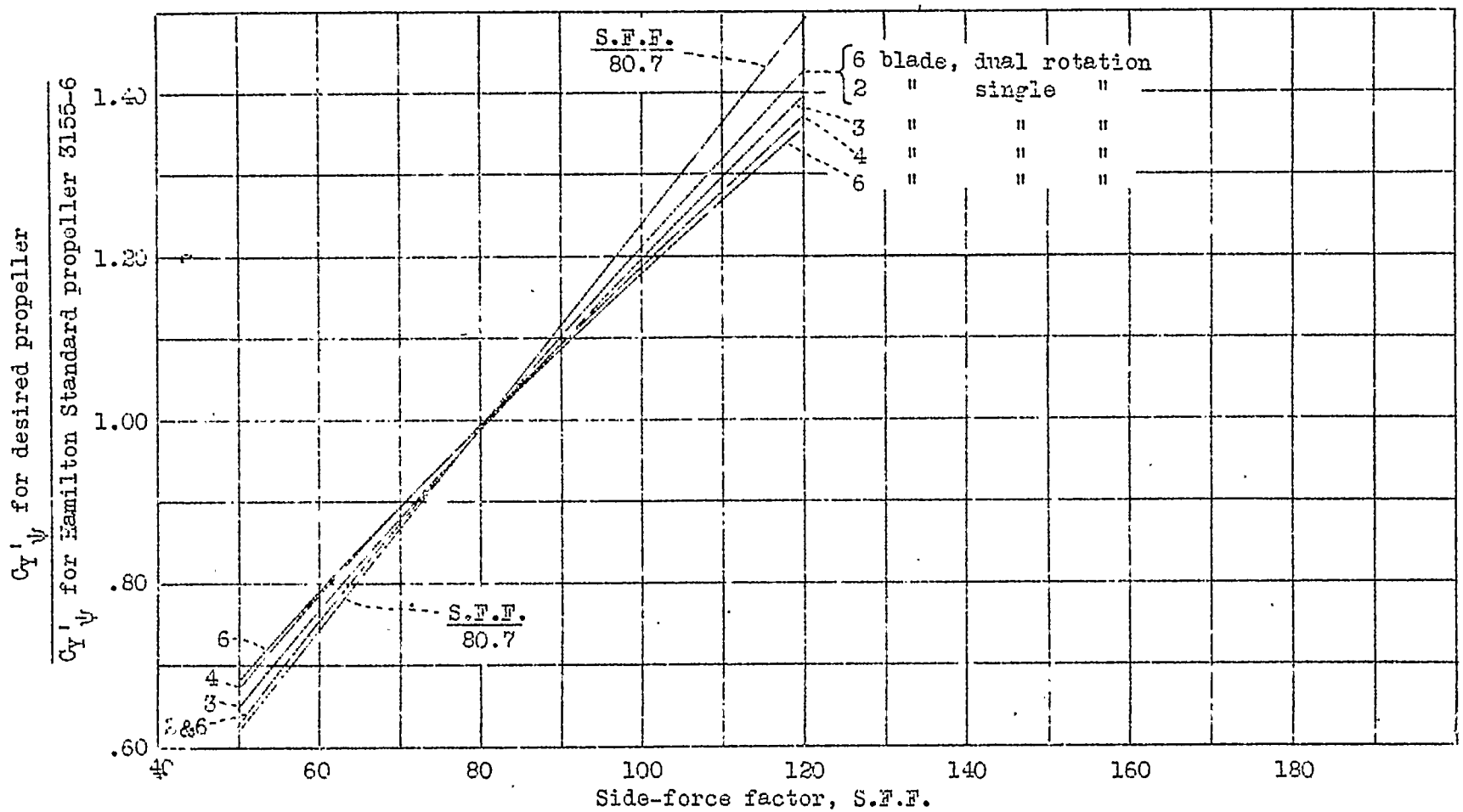

Figure 1.- Ratio of side-force derivatives $\dfrac{C_{Y'_\psi} \text{ for desired propeller}}{C_{Y'_\psi} \text{ for Hamilton Standard propeller 3155-6}}$ as a function of side-force factor of desired propeller. For extrapolation from side-force charts for Hamilton Standard propeller 3155-6, for which side-force factor is 80.7. The approximate ratio S.F.F./80.7 is included for comparison.

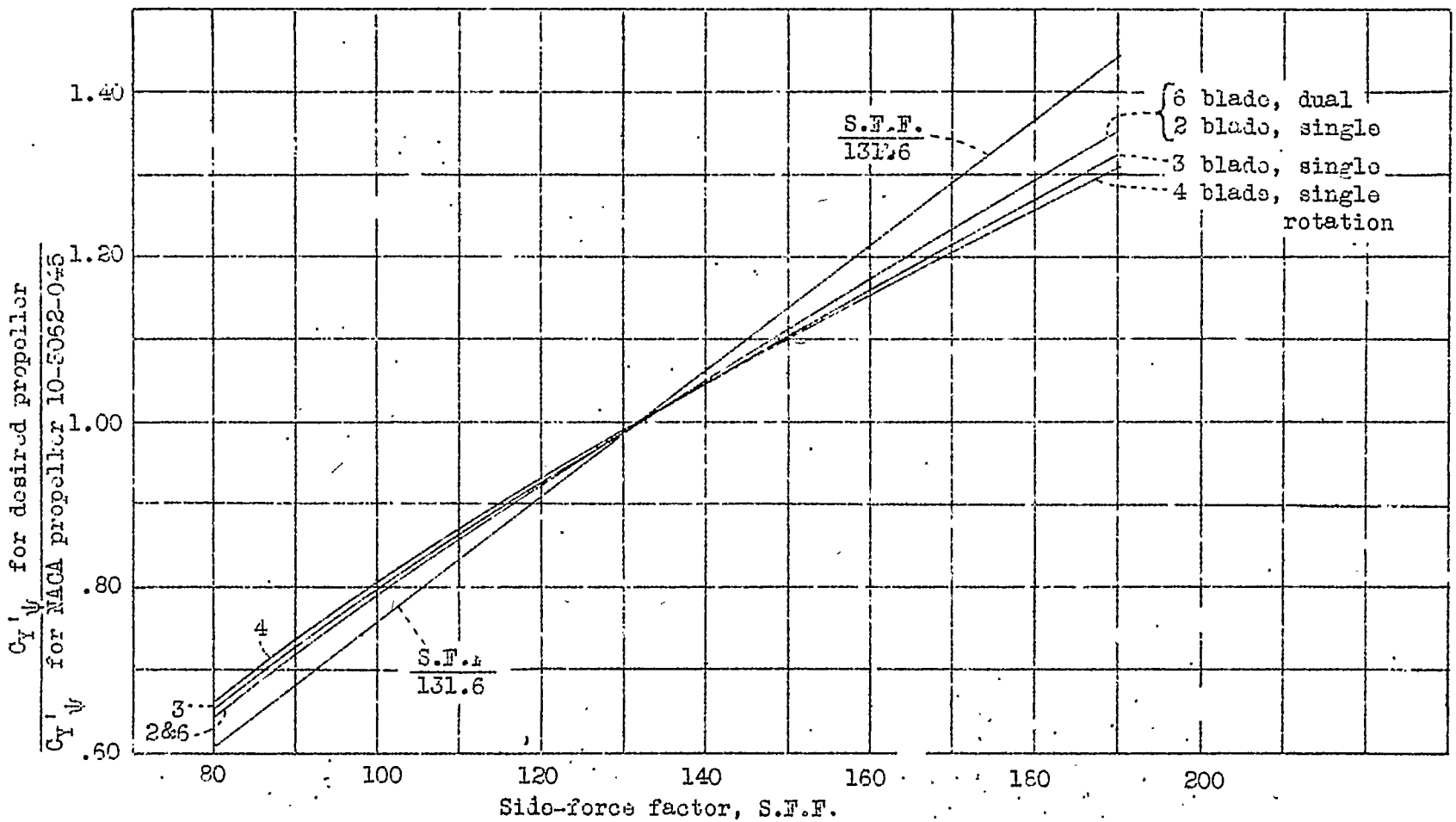

Figure 2.- Ratio of side-force derivatives $\frac{C_{Y'\psi} \text{ for desired propeller}}{C_{Y'\psi} \text{ for NACA propeller 10-3062-045}}$ as a function of side-force factor of desired propeller. For extrapolation from side-force charts for NACA propeller 10-3062-045, for which side-force factor is 131.6. The approximate ratio S.F.F./131.6 is included for comparison.

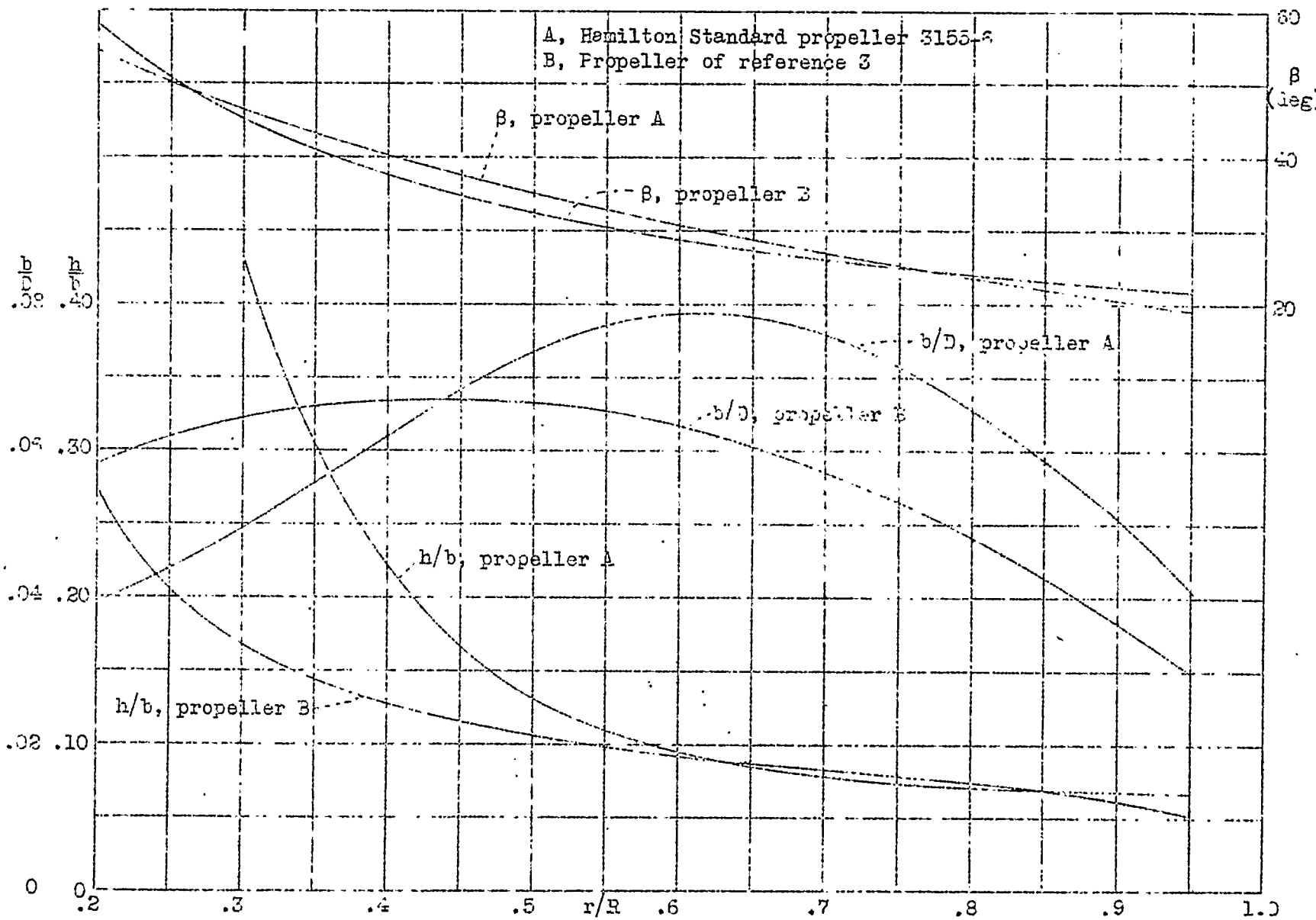

Figure 3.- Plan-form, thickness-ratio, and blade-angle-distribution curves for Hamilton Standard propeller 3155-6 and for the propeller of reference 3.
D, diameter; R, tip radius; r, station radius; b, chord; h, thickness.