NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED
October 1941 as
Advance Restricted Report

THE SELECTION OF PROPELLERS FOR HIGH THRUST AT LOW AIRSPEED

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NACA

WASHINGTON

L-703

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SUMMARY

An analysis, based on recent propeller data, was made of several methods for improving the thrust of propellers operating at low airspeeds. The analysis consisted of determining the improvements in thrust or efficiency which could be obtained by the following expedients:

(a) Increased number of blades

(b) Increased blade width

(c) Increased diameter

(d) Dual rotation

(e) Two-speed gearing

The analysis indicated that all of the above methods were very effective in increasing the efficiency of highly loaded propellers operating at low airspeeds, particularly the last one listed.

INTRODUCTION

The problem of improving the thrust of propellers at low airspeeds is primarily one of reducing the angle of attack of operation of the sections in order to improve the L/D. Reducing the blade helix angle also improves the thrust for a given power output owing to the effect of rotating the lift vector into a closer alinement with the thrust vector, thereby reducing the rotational loss and at the same time absorbing the engine power. That the low-speed operating conditions of conventional three-blade controllable propellers on present-day high-performance airplanes is not conducive to high efficiency may readily be seen by referring to figure 1, which shows the blade angles, β, for various conditions of power loading and V/nD. Obviously, take-off blade angles of from 30° to 60° correspond to angle-of-attack values ranging well beyond the stall, as may be noted from an inspection of the angle-of-attack curves given in the lower part of figure 1.

Figure 2 presents an L/D curve for the Clark Y section which shows the magnitude of improvement that accompanies any reduction in the angle of attack.

There are several methods for reducing the angle of attack and blade angle for conventional three-blade propellers, which may be enumerated as follows:

(a) Increasing the blade area by

1. Increased blade width

2. Increased number of blades

3. Increased diameter

(b) Increasing the rotational speed for the take-off condition through the use of two-speed gears.

Another method for improving the efficiency is by reducing the rotational loss by dual rotation or through the use of fixed surfaces mounted in the stream ahead of or behind the propeller.

These various methods for improving the thrust of propellers for low-speed operation are herein analyzed on the basis of test data.

PRESENTATION

The data used in making these analyses were obtained during the past 2 years from tests of single- and dual-rotating propellers. The four- and six-blade single- and dual-rotating propeller data discussed herein were obtained from reference 1; the other data discussed herein will be published at a later date. A detailed description of the set-up and testing technique is given in reference 1. Figures 3 and 4 are a photograph and a dimensioned plan view, respectively, of the set-up. Ten-foot propellers, Hamilton Standard drawing Nos. 3155-6 (right-hand) and 3156-6 (left-hand) were used. Plan-form and blade-form curves for these propellers are provided in figure 5.

Symbols.- In the analyses presented herein, standard propeller coefficients and symbols are used, as listed below:

$C_P = \frac{P}{\rho n^3 D^5}$, power coefficient

$C_T = \frac{T_e}{\rho n^2 D^4}$, thrust coefficient

$\eta = \frac{C_T}{C_P} V/nD$, propulsive efficiency

$C_s = \frac{V/nD}{(C_P)^{1/5}}$, speed-power coefficient

V/nD advance-diameter ratio

P power of engine, foot-pounds per second

$T_e = T - \Delta D$, effective thrust, pounds

T total propeller thrust

ΔD increased drag of body due to propeller slipstream

n propeller rotational speed, revolutions per second

D propeller diameter, feet

V air speed, feet per second

ρ mass density of air, slugs per cubic foot

ρ_o mass density of air at sea level (0.002378)

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

b blade width

r station radius

R propeller radius

β blade angle at 0.75R, degree

V_{c_o} speed of sound at sea level

$V_{c_{alt}}$ speed of sound at altitude

V_R helical tip speed of propeller

S_o circular tip speed of propeller

α_∞ section angle of attack at 0.75R for infinite aspect ratio, measured from chord line

Method of presentation.- This analysis consists of computations showing the efficiency or relative thrust that can be obtained from certain propeller and gear arrangements for a constant power input. The thrust ratios and efficiencies are plotted against V/nD or constant values of C_P. Constant C_P represents also constant engine power input, assuming that constant speed propellers are employed and assuming that comparisons are made on the basis of constant altitude.

The V/nD parameter represents velocity for the general case since both n and D are constants. For instance, when n or D was changed, as in the case of two-speed gearing, the plots were based on the V/nD corresponding to the single speed arrangement. The V/nD range is from 0.3 to 3.0 and C_P range is from 0.2 to 0.6.

In figure 6 is a chart giving values of C_P encountered for different airplane designs, presented in terms of high speed and number of blades from three to eight. For nearly all present-day airplanes the propeller is designed to operate at nearly peak efficiency for the high-speed condition at the critical altitude. The power coefficient is defined, therefore, for critical altitude operation, assuming constant power and rotational speed. The power coefficient for the take-off and climb at low altitude will, of course, be lower than that for the critical altitude because of the higher air density, assuming that the engine power remains unchanged. For constant values of power, rpm, and diameter,

$$C_{P_o} = C_{P_{alt}} \frac{\rho_{alt}}{\rho_o}$$

Scales of ordinates for sea-level power coefficients, C_{P_o}, are given for airplanes having critical altitudes of 22,000 and 40,000 feet. This chart shows, for example, that for a high speed of 420 miles per hour at a critical altitude of 22,000 feet, and for an eight-blade propeller the $C_{P_{alt}} = 0.77$ and $C_{P_o} = 0.38$.

The sea-level power coefficient $(C_{P_0} = 0.38)$ applies to the take-off analysis. The chart indicates that take-off power coefficients ranging from 0.05 to 0.6 may be expected for military applications.

Solidity analysis.- The three methods for improving the thrust by means of increasing the blade area, (a) increased number of blades, (b) increased blade width, and (c) increased diameter, will result in essentially the same effect, except possibly for differences in weights and mechanical complications, provided the tip speed is the same.

The method for computing the thrust and efficiency of propellers having various numbers of blades or having blades of different widths is given in the following outline:

Constants: P, C_P, ρ, nD.

(Subscript 3 denotes number of standard-width blades.)

(Subscript x denotes increased number of blades or increased blade width.)

1. For several values of V/nD, β is read at a constant value of C_P from the C_P chart.

2. C_T is read from the C_T chart for values of β and V/nD under (1).

3. The following plots may be constructed:

   (a) C_T vs. V/nD

   (b) C_{T_x}/C_{T_3} vs. V/nD, T_x/T_3 vs. V/nD

   (c) $C_T/C_P \frac{V}{nD}$ vs. V/nD

The outline of the method for improving the thrust by means of increasing the diameter is given as follows:

Constants: P, ρ, nD or tip speed.

(Subscript 3 denotes three-blade propeller of normal diameter.)

(Subscript x denotes propeller of increased diameter.)

1. For several values of V/nD, β_3 is read at a constant C_P from the C_P chart.

2. C_{T_3} is read from the C_T chart for the values of β_3 and V/nD under (1).

3. $C_{P_x} = (D_3/D_x)^2 \; C_{P_3}$

4. β_x is read from C_P curves for several values of V/nD and C_{P_x}.

5. C_{T_x} is read for corresponding values of V/nD and β_x.

6. The following plots may be constructed:

   (a) C_T vs. V/nD

   (b) C_{T_x}/C_{T_3} vs. V/nD

   (c) $C_T/C_P \frac{V}{nD}$ vs. $\frac{V}{nD}$, $\left(\eta \text{ vs. } \frac{V}{nD}\right)$

   $$C_{T_x}/C_{P_x}\left(\frac{V}{nD}\right) \text{ vs. } \frac{V}{nD}$$

In the present analysis a three-blade propeller is compared with a six-blade propeller which absorbs the same power for the peak efficiency condition. The actual blade area is slightly different, owing to the difference in blade interference for the two cases.

$D_6 = 0.75\, D_3$, instead of $D_6 = 0.707\, D_3$, which corresponds to constant area.

Dual rotation. - The method for comparing single- and dual-rotating propellers is the same as that for propellers of different solidities and so will not be repeated here.

Two-speed gearing. - The object of two-speed propeller reduction gears is to provide a means for increasing the propeller rotational speed for the take-off and climb. If the engine could be over-speeded the necessary amount, the results would be the same as those obtained with two-speed gears. The amount that the propeller speed should be increased for take-off depends entirely upon the tip speeds encountered.

Considering the case of single-speed gears, the tip speed for low forward speeds at low altitudes will be a less percentage of the speed of sound than for high-altitude, high-speed operation, owing to differences in the forward speed component of the tip speed, and also to the differences in the speed of sound at different altitudes. In figure 7 is given the relative speed of sound for different altitudes; in figures 8 and 9 are charts giving the ratio of helical tip speed to the circular tip speed, for various values of forward speed, helical tip speed, and circular tip speed. From these charts (figs. 7, 8, and 9) the amount that the propeller can be speeded up for the take-off condition may be read - assuming, of course, that it is desirable to obtain the same tip speed relative to sonic velocity for take-off as that for high speed at altitude.

The following example is given to illustrate the method for using the charts mentioned:

Given:

Air speed, 400 miles per hour

Altitude, 25,000 feet

Helical tip speed = 910 feet per second

To find: gear ratio to produce the same ratio of the tip speed to the speed of sound for take-off.

Solution: from figure 7, $V_{c_o}/V_{c_{alt}} = 1.097$

from figure 8, $V_R/S_o = 1.305$

gear ratio, $n_2/n_1 = V_R/S_o \times V_{c_o}/V_{c_{alt}}$

$= 1.305 \times 1.097 = 1.43$

The method for computing the relative thrust or efficiency obtained at low speeds with two-speed gears may be outlined as follows:

Constants: P, ρ, and D.

(Subscript 1 refers to single-speed propeller.)

(Subscript 2 refers to two-speed propeller.)

1. For a given value of C_{P_1}, β_1 is read at several values of $(V/nD)_1$ from the family of C_{P_1} curves.

2. C_{T_1} corresponding to β_1 and $(V/nD)_1$ is read from the family of C_{T_1} curves.

3. For a given value of n_2/n_1, C_{P_2} is computed; $C_{P_2} = (n_1/n_2)^3 \; C_{P_1}$.

4. $(V/nD)_2$ is computed; $(V/nD)_2 = n_1/n_2 \; (V/nD)_1$.

5. β_2 corresponding to C_{P_2} and $(V/nD)_2$ is read from the family of C_{T_2} curves.

6. C_{T_2} corresponding to β_2 and $(V/nD)_2$ is read from the family of C_{T_2} curves.

7. The following plots may be constructed:

   (a) T_2/T_1 vs. V/nD

   $$T_2/T_1 = C_{T_2}/C_{T_1} \; (n_2/n_1)^2$$

   (b) $C_{T_2}/C_{P_2} \; (V/n_2D)$ vs. (V/n_1D)

Calculation of thrust of an ideal propeller.- The thrust of an ideal propeller can be calculated from the momentum theory. This ideal propeller is an actuator disk having no losses other than an axial momentum loss. An expression for ideal efficiency is given by

$$\frac{\eta^2}{1 - \eta} = \frac{2 \rho A V^2}{T} \tag{1}$$

This expression may be resolved into one more convenient to use by making certain substitutions as follows:

$$\eta P/V \text{ for } T$$

$$C_P \rho n^3 D^5 \text{ for } P$$

and

$$\frac{\pi D^2}{4} \text{ for } A$$

$$\frac{\eta^2}{1 - \eta} = \frac{\pi}{2\eta C_P} (V/nD)^3 \qquad (2)$$

To obtain this in terms of thrust, the substitution of $\frac{C_T}{C_P} V/nD$ for η is made

$$\frac{C_T^2/C_P^2}{1 - \frac{C_T}{C_P}\frac{V}{nD}} = \frac{\pi}{2C_T} \qquad (3)$$

Rewriting:

$$C_T^3 + \frac{\pi}{2} C_P \frac{V}{nD} C_T - \frac{\pi}{2} C_P^2 = 0$$

This may be solved to give $C_{T_{ideal}}$ for given values of C_P and V/nD, which may then be compared with the C_T of any desired propeller at the same values of C_P and V/nD.

RESULTS AND DISCUSSION

The results of the analysis are presented in several groups as follows:

		Figures
I	Solidity	
	(a) Effect of increasing the number of blades	10 to 12
	(b) Effect of increasing blade width	13
	(c) Effect of increasing diameter	14

In this analysis the emphasis is placed on methods for improving propeller thrust or efficiency for the take-off and climbing conditions, realizing, of course, that certain other sacrifices may be necessary. The question is always, "What is the best compromise?" The answer depends upon the particular design conditions in question; therefore it cannot be answered here. Information for arriving at good engineering compromises is presented, however, in easily interpreted charts which have a general application.

Solidity.- In figures 10, 11, and 12 the effect of increasing the number of blades up to a total of eight is indicated; the diameter, of course, is kept constant. Although the peak efficiency for each propeller is approximately the same in magnitude, it occurs at different V/nD values for the different solidities. The effect of increasing the number of blades is to unload each individual blade, which allows it to operate at lower values of α and C_L. This increases the L/D and efficiency for the take-off and climb, particularly for the extremely high loadings, but with some sacrifice at the upper end of the V/nD range, the amount depending upon the particular design conditions under consideration.

Of particular interest is the fact that there appears to be little efficiency to be gained at take-off by increasing the number of blades beyond six.

In figure 13 the effect of increasing the blade width 50 percent is shown for a two-blade propeller, the tests of which were made several years ago. (See reference 2.) Although these tests were not very conclusive, owing to their limited scope, the indications are that increasing the blade width has the same effect on the take-off and climbing efficiency as increasing the number of blades. Further extensive tests of wide blades are being conducted at the present time.

In figure 14 a comparison is made of two propellers having substantially the same blade area but different diameters. The relative diameters were determined from considerations of equal power absorption for peak efficiency; the six-blade propeller had slightly greater area than the three-blade propeller. Inasmuch as the efficiencies were about equal over the entire V/nD range, it appears that increased solidity is about an equal substitute for increased diameter up to some limiting value; that value probably corresponds to a six-blade propeller, since an eight-blade propeller was found to be only slightly better than a six-blade one. (See figs. 10 to 13.)

Dual rotation.- In figure 15 the effect of dual rotation is shown for the six-blade propeller; the results were taken directly from reference 1. The principal effect of dual rotation is, of course, to eliminate the rotational component of the slipstream, which results in improved efficiency, particularly for highly loaded propellers operating at low values of V/nD. The test results indicate that dual rotation increases the efficiency over the entire operating range, especially for highly loaded propellers.

Two-speed gearing.- Although the advantages of two-speed gearing have been appreciated for a long time, there has not been any serious attempt to incorporate two-speed gears into propeller drives until recently. The reasons for this are that two-speed gears have not been vitally necessary, up to the present time, in order to obtain satisfactory propeller performance at low forward speeds; and also because the high speeds and cruising altitudes have not been high enough to make possible any large gains.

In figures 16 to 19 are plots indicating the improvements in thrust possible through the use of two-speed gears for a variety of conditions. It may be noted that the advantages are greatest for low solidity propellers which are operated under highly loaded conditions. Also the advantages are the greatest for high ratios of gear change, which can only be used for high-speed, high-altitude airplanes.

Comparisons of methods.- In figures 20 to 25 are both thrust and efficiency comparisons of the various methods for increasing the thrust of propellers operating at low forward speeds. It appears that the method of two-speed gearing offers the greatest return of any single method, particularly in view of the fact that it is not accompanied by any aerodynamic loss for the high-speed condition. Increased solidity, particularly if accompanied by dual rotation, offers further means for improving the low-speed conditions.

With all of the methods combined the ideal efficiency can be closely approached, even for extremely highly loaded propellers.

As these methods are directed toward reducing the angle of attack of the blades, with the exception of dual rotation, it may be of interest to examine the operating conditions. In figure 26 is a plot of β and α for the various methods indicated in figures 21 and 24. It may be noted that as the blade angle and angle of attack at 0.75R are reduced by any method, the efficiency at low speed is increased.

Take-off computations.- In computing take-off distances the problem often arises of determining the characteristics of some particular propeller which has a different solidity or activity factor from one for which test results are available. As most methods for computing take-off distances involve the static thrust, the problem is one of correcting the static coefficients for differences in activity factor.

A chart is presented in figure 27 wherein the static thrust coefficient is plotted against number of blades, which also represents a range of activity factors for the entire propeller on the assumption that the activity factor varies directly as the number of blades for a typical present type propeller design. Although this chart was not derived from test data wherein the activity factor was changed by increasing the blade width, the available information indicates that the effects are substantially the same, irrespective of the method of changing the activity factor.

There are two methods of using the chart, one in which the values of static thrust are used directly; and the other, in which the curves are used as correction factors for other test data. The latter method is recommended because the relative thrust is probably independent of most of the propeller-design characteristics, such as airfoil section, thickness, and pitch distribution. This method of correction consists simply of multiplying the known static thrust coefficient by the ratio of static thrust coefficients taken from the chart corresponding to the different activity factors.

Similar charts may be constructed for different V/nD values by making cross plots from figures 10, 11, and 12.

In tables I and II are listed, for convenience, the activity factors for a number of commonly used Curtiss and Hamilton Standard propellers.

CONCLUDING REMARKS

The problem of increasing the take-off and climbing thrust of highly loaded propellers resolves itself into providing means for reducing the angle of attack of operation and also for eliminating the rotational losses in the slipstream. Of the methods studied to accomplish this purpose, the following remarks apply:

Increasing the number of blades from three to six was found to result in substantial improvements in the low-speed thrust, particularly for the higher power loadings. Eight-blade propellers were found to produce only a slightly higher thrust than six-blade ones. Increased solidities resulted in small reductions in the high-speed efficiency.

Increasing the solidity by means of increasing the blade width was found to result in about the same effects as increasing the number of blades, within the scope of the analysis.

Increasing the blade area by means of increasing the diameter had about the same effect on the low-speed thrust as increasing the solidity, for equal tip speeds.

Dual rotation resulted in a small improvement in the efficiency over the entire operating range, particularly for the more highly loaded propellers.

Two-speed gearing was found to be very effective in increasing the low-speed thrust, particularly for low solidity propellers operating under highly loaded conditions. The advantages of two-speed gearing were greatest for high ratios of gear change, which can only be used for high-speed, high-altitude airplanes. As no efficiency penalty is imposed at high speed, this method appears to be very attractive for a certain class of airplanes.

A combination of six-blade, dual-rotation, two-speed gearing was found to provide means for closely approximating the ideal efficiency for highly loaded propellers.

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1. Biermann, David, and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade, Single- and Dual-Rotating Tractor Propellers. NACA Rep. No. 747, 1942.

2. Hartman, Edwin P., and Biermann, David: The Aerodynamic Characteristics of Full-Scale Propellers Having 2, 3, and 4 Blades of Clark Y and R.A.F. 6 Airfoil Sections. NACA Rep. No. 640, 1938.

TABLE I

Activity Factors of Curtiss Propeller Blades

Blade drawing number	Basic diameter (ft)	A.F.
512 and 551 -0	11.0	66.9
-6		74.9
-12		82.7
-18		90.9
614 and 615 -0	12.0	66.5
-6		74.1
-12		81.5
-18		88.5
652 and 653 -0	12.0	68.0
-6		75.0
-12		81.5
-18		88.6
714, 715, and 722 -0	13.0	65.8
-6		73.6
-12		81.2
-18		89.1
-24		96.4
814 -0	15.0	67.0
-6		73.0
-12		79.0
-18		84.7
-24		90.5
88996, 89303, 89318 -0	13.0	66.6
-6		75.3
-12		83.5
-18		89.6
-24		93.7
-30		103.6
89301 -0	11.25	78.8
-3		82.7
-9		90.5
-15		98.0
-21		105.7
89304 -0	15.0	58.5
-6		66.3
-12		74.3
-18		81.5
-24		86.5
-30		90.5
-36		98.6
89306 -0	11.83	58.9
-4		65.6
-10		75.5
-16		85.6
-19		90.4
-22		89.9
-28		96.1
89316 -0	15.0	71.6
-6		78.0
-12		85.0
-18		91.5
-24		98.5

TABLE II

Activity Factors of Hamilton Standard Propeller Blades

Blade drawing number				Basic diameter (ft)	A.F.
Controllable blade		Hydromatic blade			
3155-6				10.5	90
6091	-0			10.5	83
6095 6167 6237	-0 -6 -12 -18 -24	6181	-0 -6 -12 -18 -24	9.5	71 83 95 107 120
6101	-0 -6 -12 -18 -24	6183	-0 -6 -12 -18 -24	10.0	77 87 97 108 119
6103 6111	-0 -6 -12 -18 -24	6139	-0 -6 -12 -18 -24	11.5	63 72 82 91 100
6105 6249	-0 -6 -12 -18 -24	6153 6229	-0 -6 -12 -18 -24	13.0	66 75 83 92 100
6109 6135	-0 -6 -12 -18			9.0	66 78 90 101
6127	-0	6185	-0	10.75	65
6165	-0 -6 -12 -18	6239	-0 -6 -12 -18	8.0	66 81 96 110

TABLE II (Cont.)

Blade drawing number		Basic diameter (ft)	A.F
Controllable blade	Hydromatic blade		
6227 -0	6247 -0	10.5	87
6157 -6	6179 -6		98
-12	-12		108
-18	-18		119
6241 -0		9.0	73
-6			85
-12			96
-18			107

Blade drawing number Hydromatic blade	Basic diameter (ft)		A.F.
6155 -0	14.0		75
6159 -6			83
-12			92
-18			101
-24			109
6175 -0	17.0		61
6187, 6189 -0	15.0		65
6193 -0	11.5		93
-6			104
-12			114
-18			125
6235 -0	12.5		90
6243 -0	15.0		81
-6			88
-12			94
-18			101
-24			108
6245 -0	17.0		75
-6			80
-12			86
-18			91
-24			96

TABLE II (Cont.)

Blade drawing number Hydromatic blade		Basic diameter (ft)	A.F.
6257	-0	13.0	79
	-6		87
	-12		96
	-18		104
	-24		112
6259	-0	11.5	79
	-6		88
	-12		97
	-18		106
	-24		116
6261		11.5	88

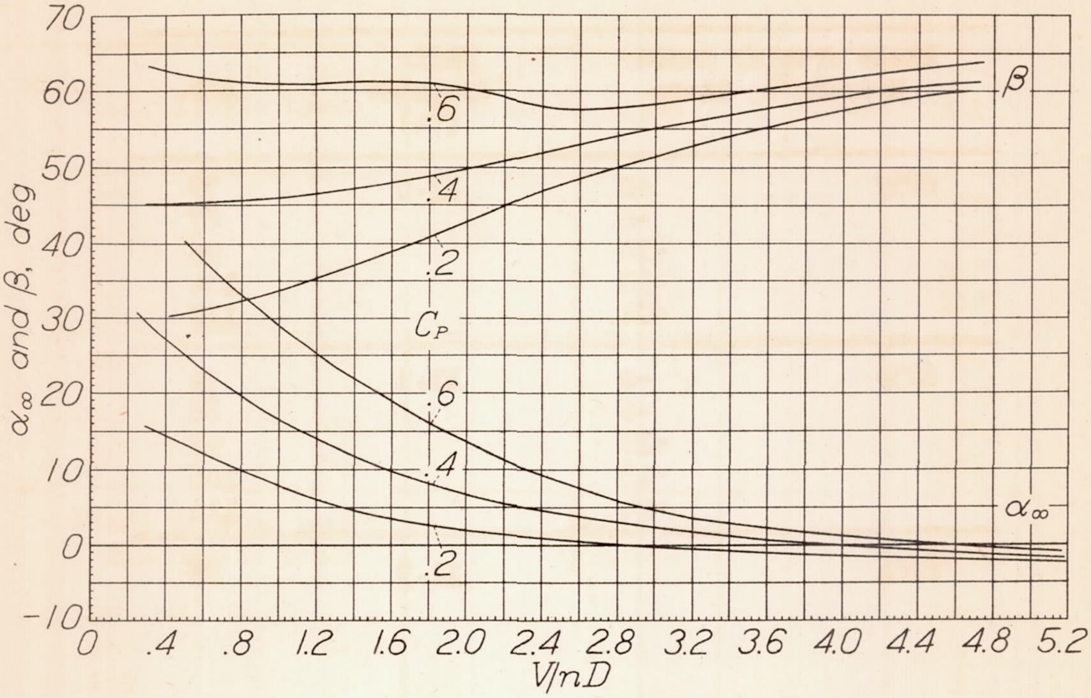


Figure 1.- Variation of β and α_∞ with V/nD for a three-blade controllable propeller at C_P = 0.2, 0.4, and 0.6.

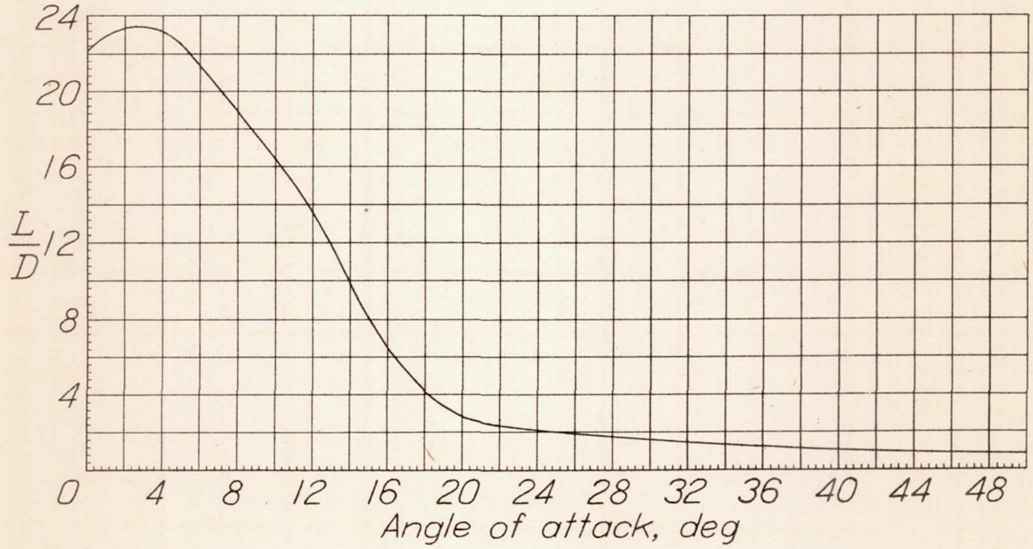


Figure 2.- The L/D curve for a Clark Y airfoil.

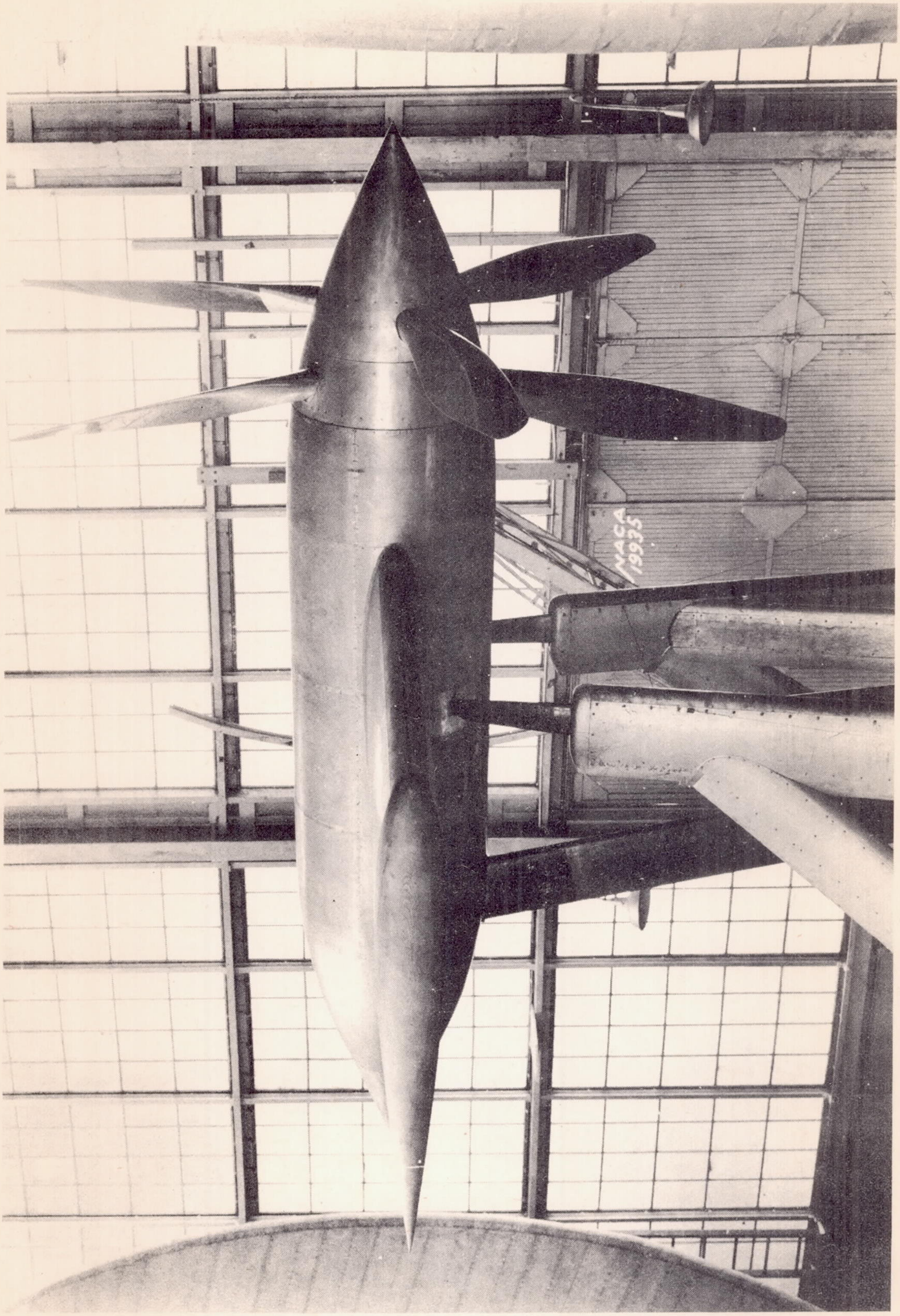
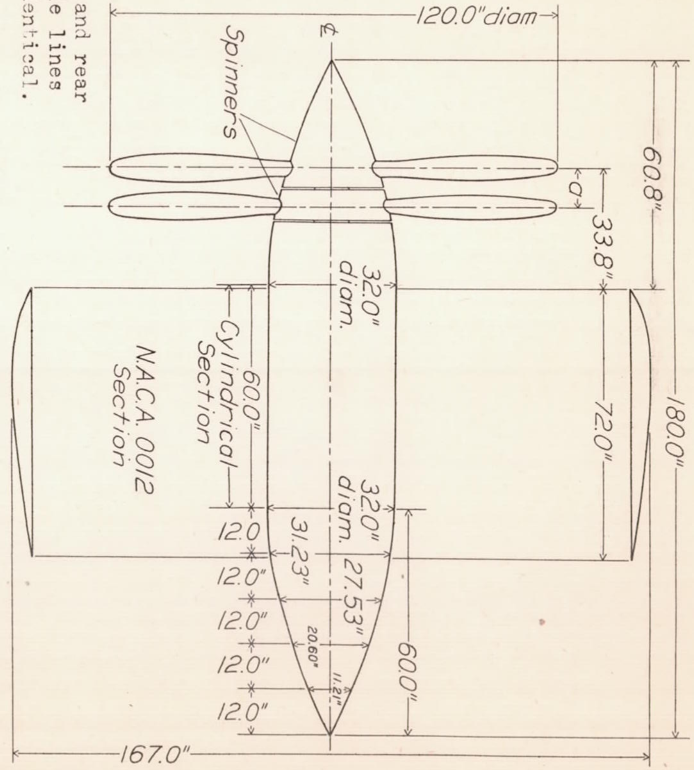


Figure 3.- Test set-up showing six-blade propeller.



Note: Front and rear nacelle lines are identical.

Figure 4.- Plan view showing dimensional details of wing and nacelle. Dimension a for four-blade propeller = 9.7" and for six and eight blade propeller = 10.0".

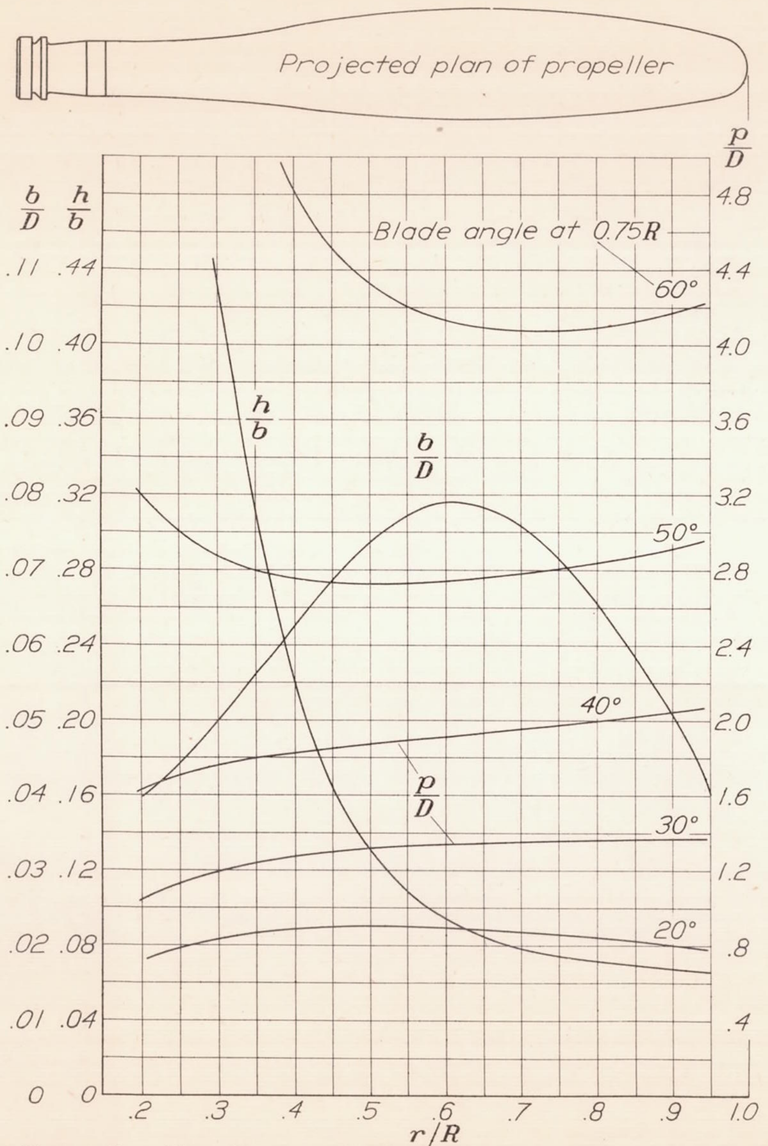


Figure 5.- Plan-form and blade-form curves for propellers 3155-6 and 3156-6. D, diameter; R, radius to the tip; r, station radius; b, section chord; h, section thickness; p, geometric pitch. Propeller 3155-6 (right hand) and 3156-6 (left hand).

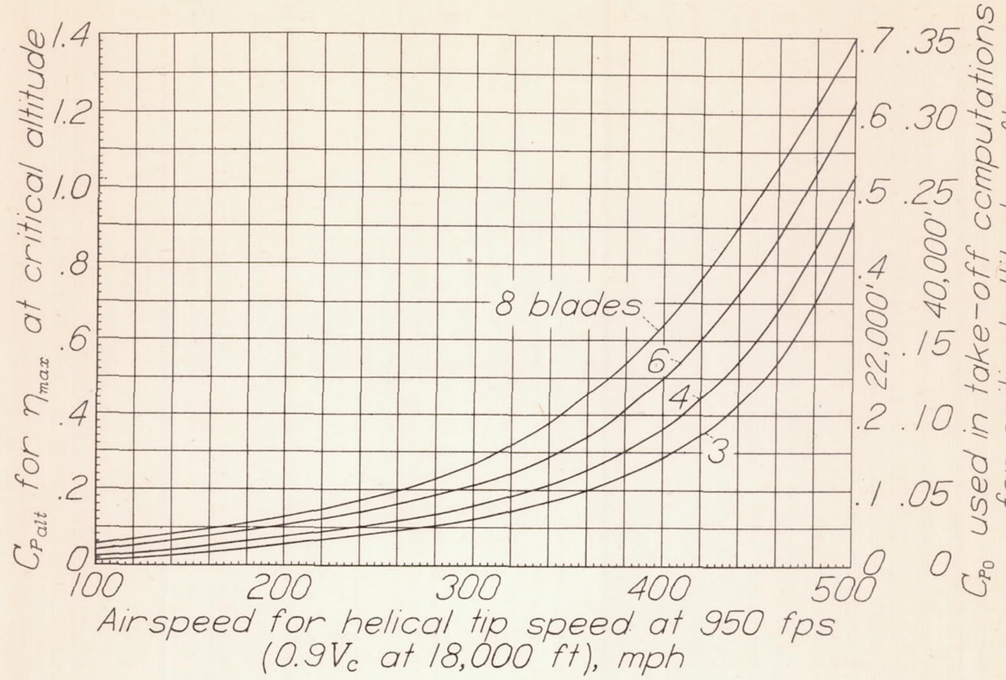


Figure 6.- Variation of C_P for η_{max} with airspeed for different propeller solidities.

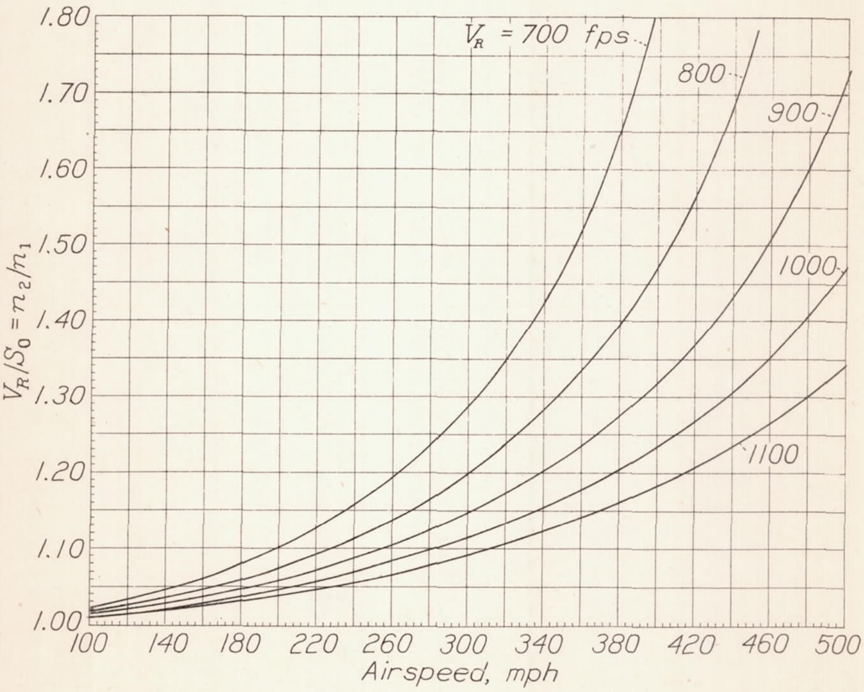


Figure 8.- Gear ratios made available for take-off by design speed conditions. Lines of constant helical tip speed. V_R, helical tip speed; S_0, circular tip speed.

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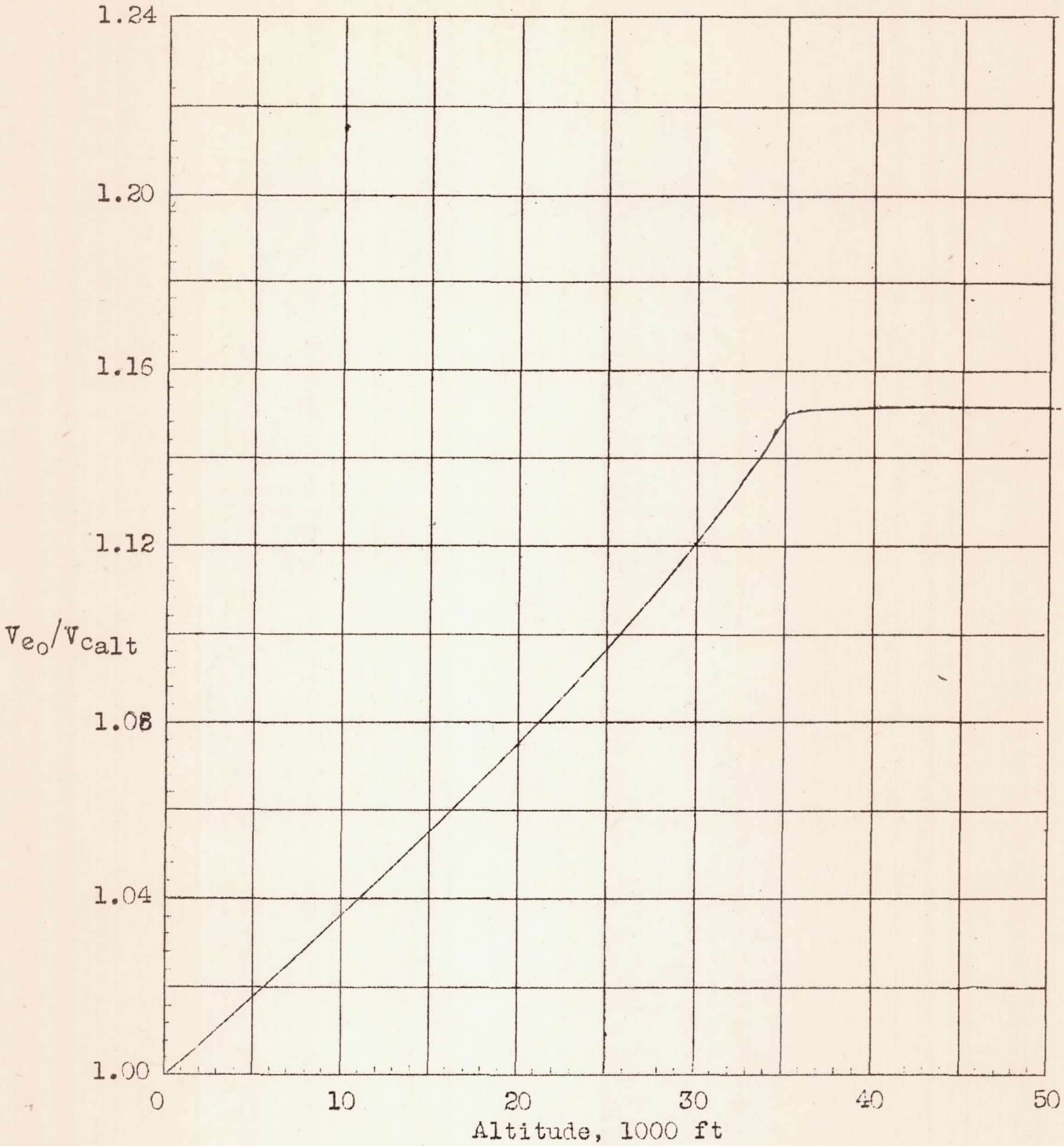

Figure 7.- Variation of ratio $\frac{\text{speed of sound at sea level}}{\text{speed of sound at altitude}}$ with altitude.

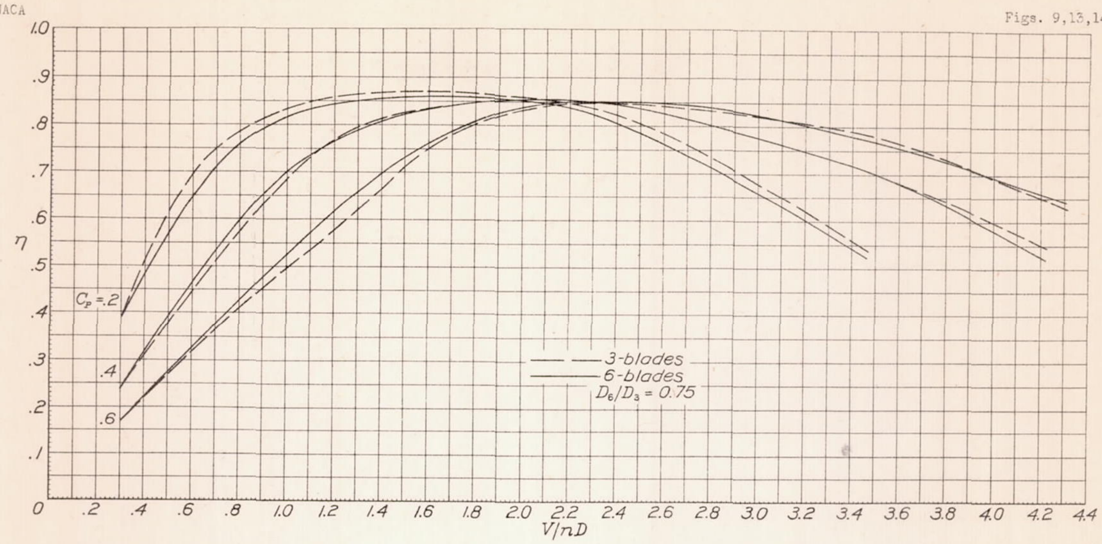

Figure 14.- Comparison of efficiencies of propellers having different diameters and numbers of blades but having substantially the same blade area. (Tip speed of both propellers is the same, as well as power absorption.)

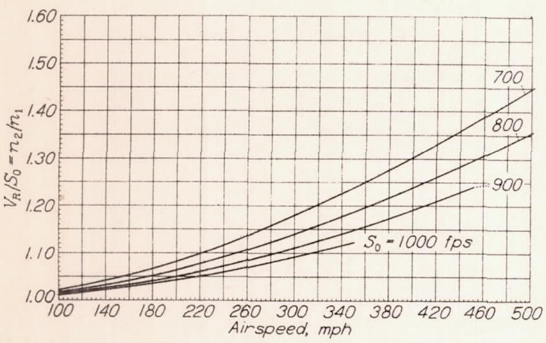

Figure 9.- Gear ratios made available for take-off by design speed conditions. Lines of constant circular tip speed. V_R, helical tip speed; S_0, circular tip speed.

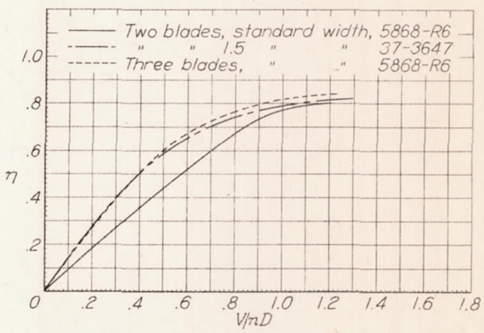

Figure 13.- Effect of blade width on efficiency. Cp = 0.14. Data from reference 2.

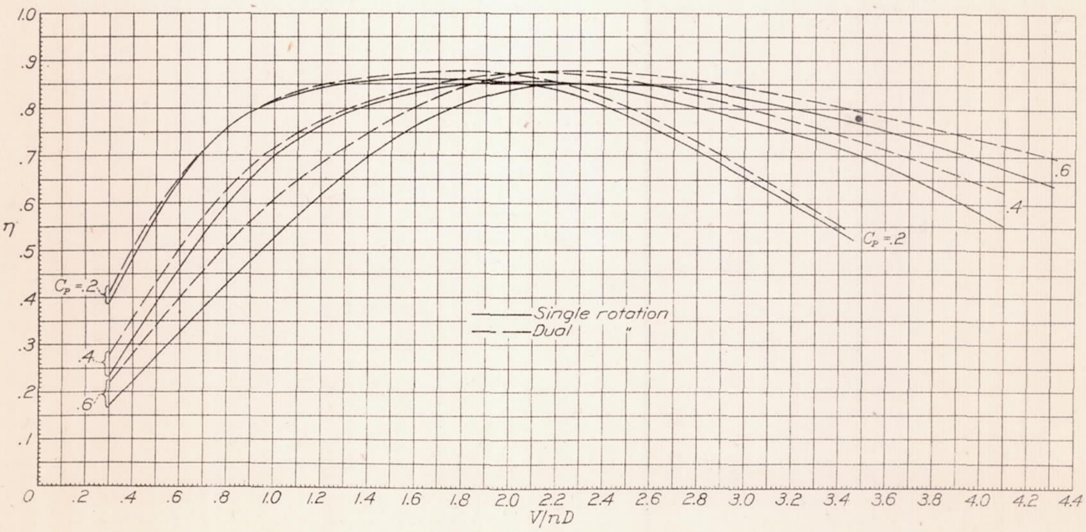

Figure 15.- Effect of dual rotation on efficiency at Cp = 0.2, 0.4, and 0.6. Six-blade propeller.

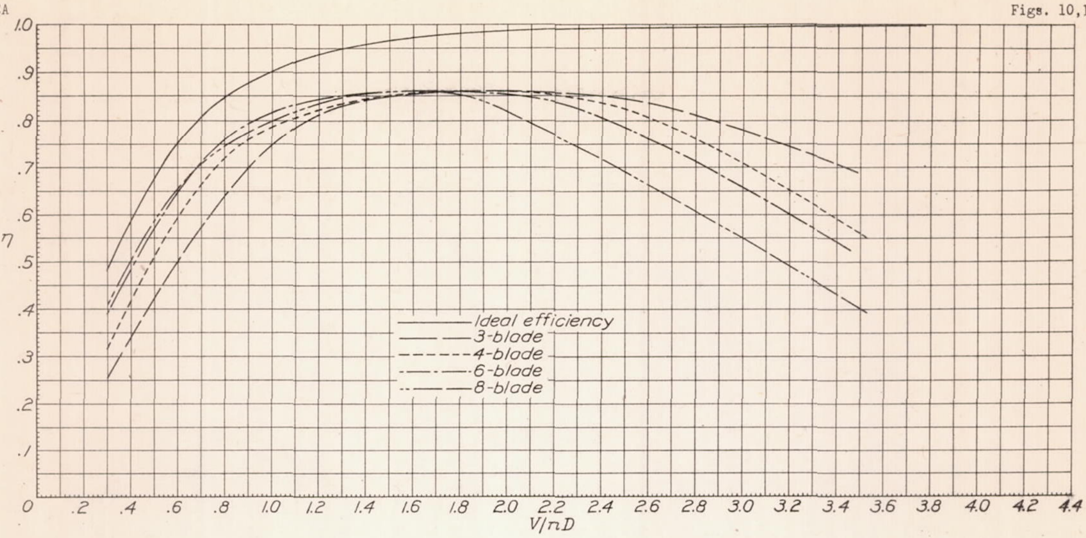

Figure 10.- Effect of number of blades on efficiency. $C_P = 0.2$.

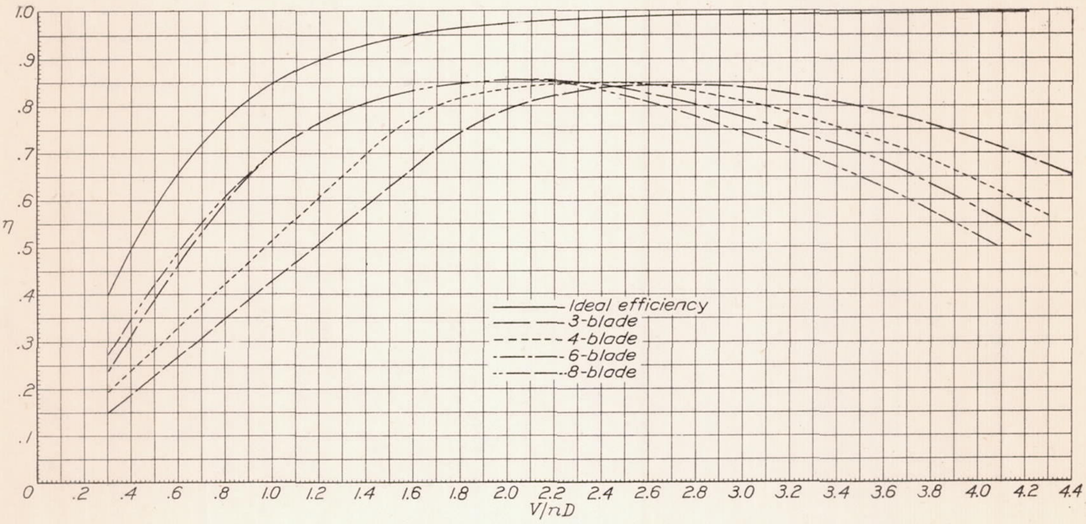

Figure 11.- Effect of number of blades on efficiency. $C_P = 0.4$.

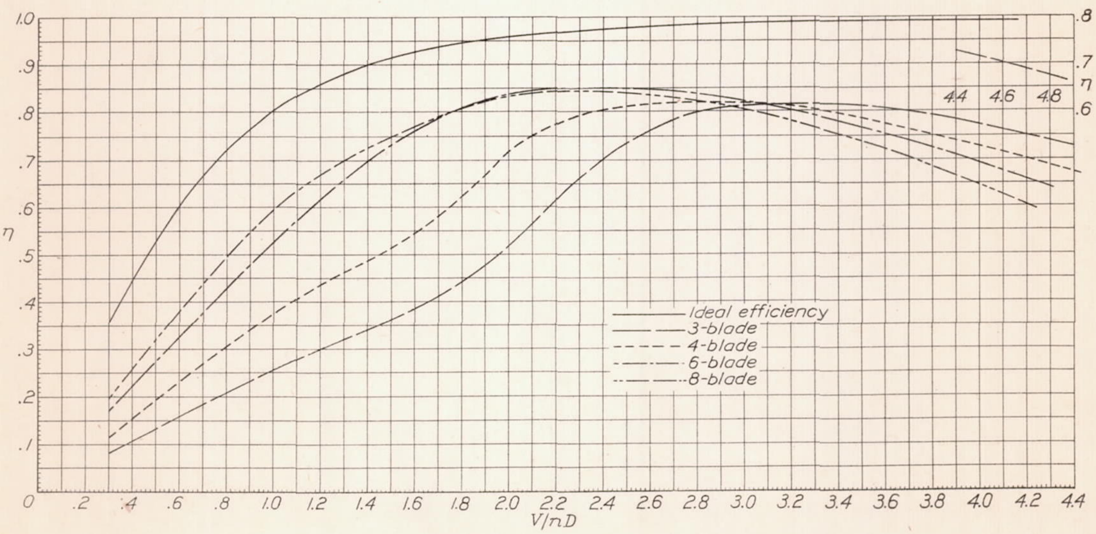

Figure 12.- Effect of number of blades on efficiency. $C_P = 0.6$.

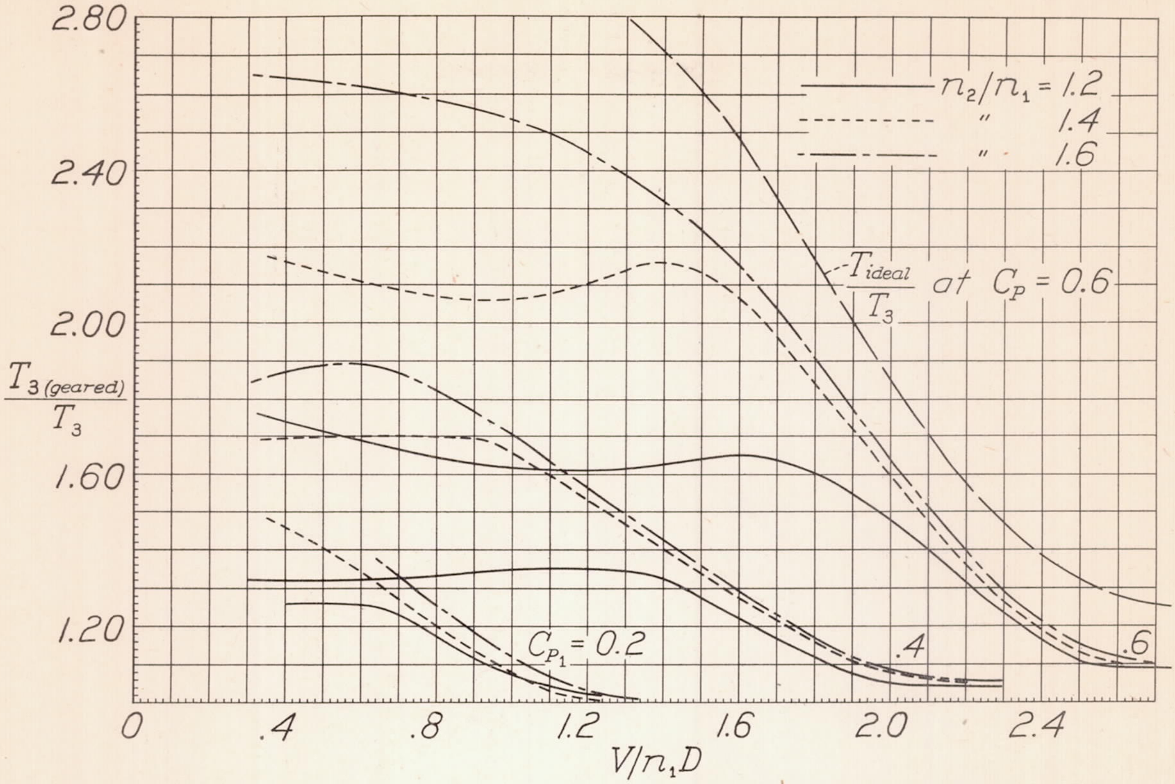

Figure 16.- Effect of two-speed gearing on thrust at low speeds. Three-blade propeller.

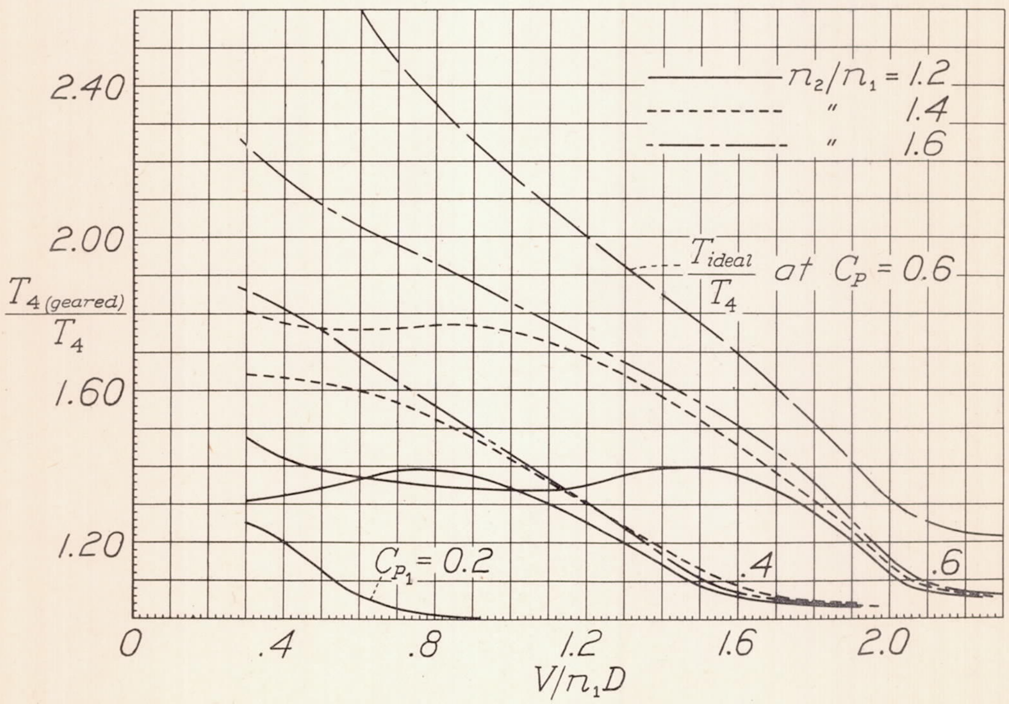

Figure 17.- Effect of two-speed gearing on thrust at low speeds. Four-blade propeller.

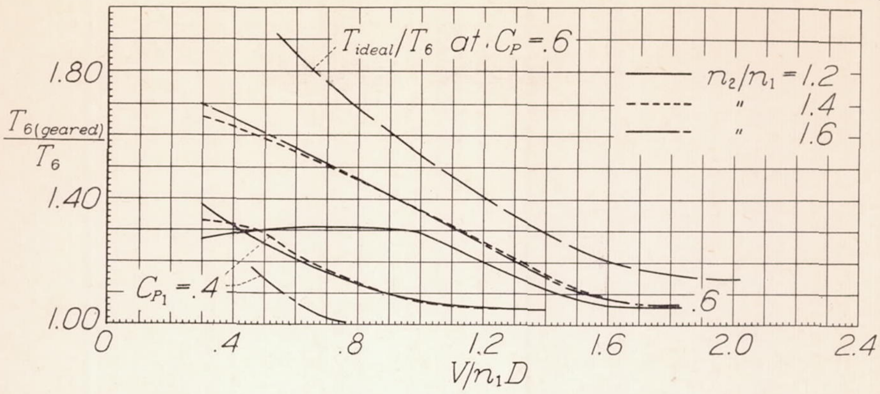

Figure 18.- Effect of two-speed gearing on thrust at low speeds. Six-blade propeller.

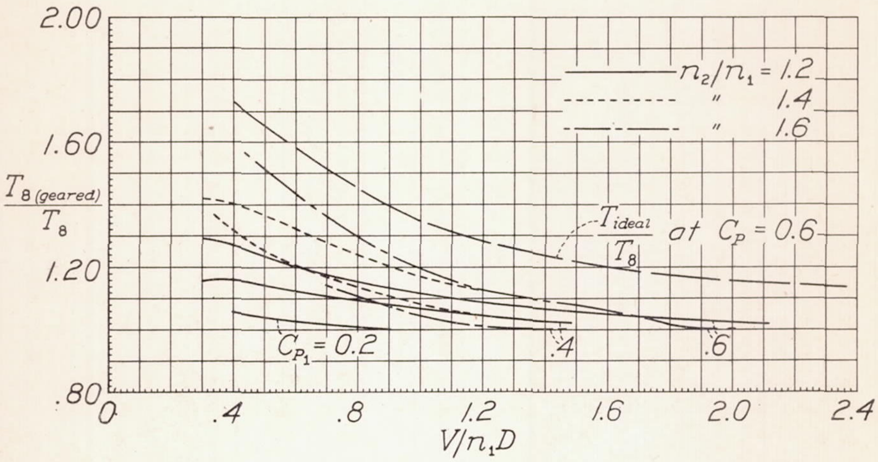

Figure 19.- Effect of two-speed gearing on thrust at low speeds. Eight-blade propeller.

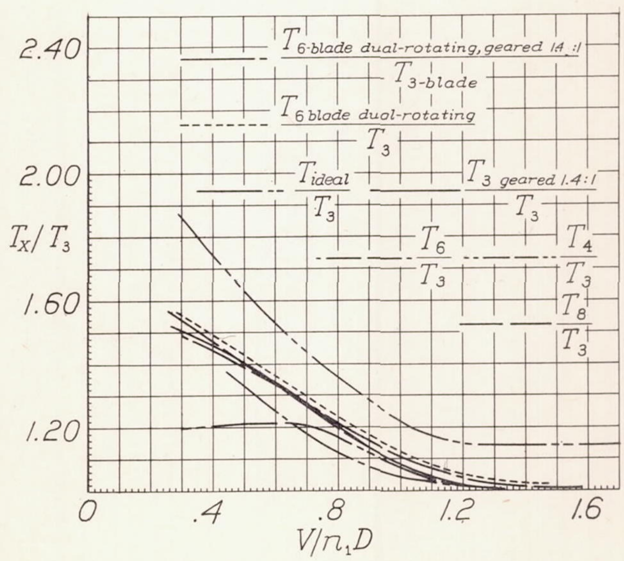

Figure 23.- Comparison of methods for increasing thrust. C_{P_1} = 0.2.

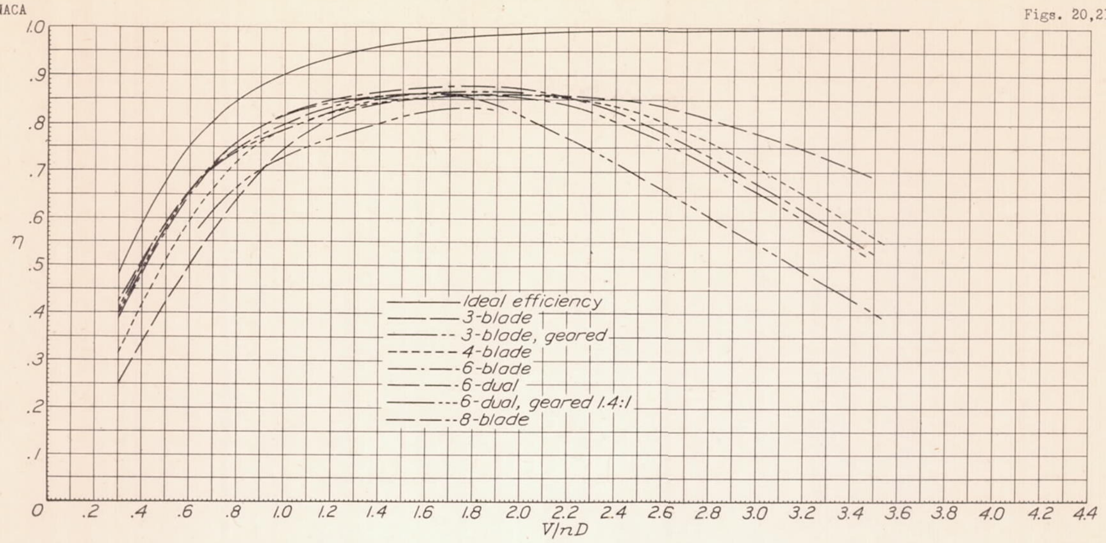

Figure 20.- Comparison of efficiencies for different methods of increasing thrust. C_p = 0.2.

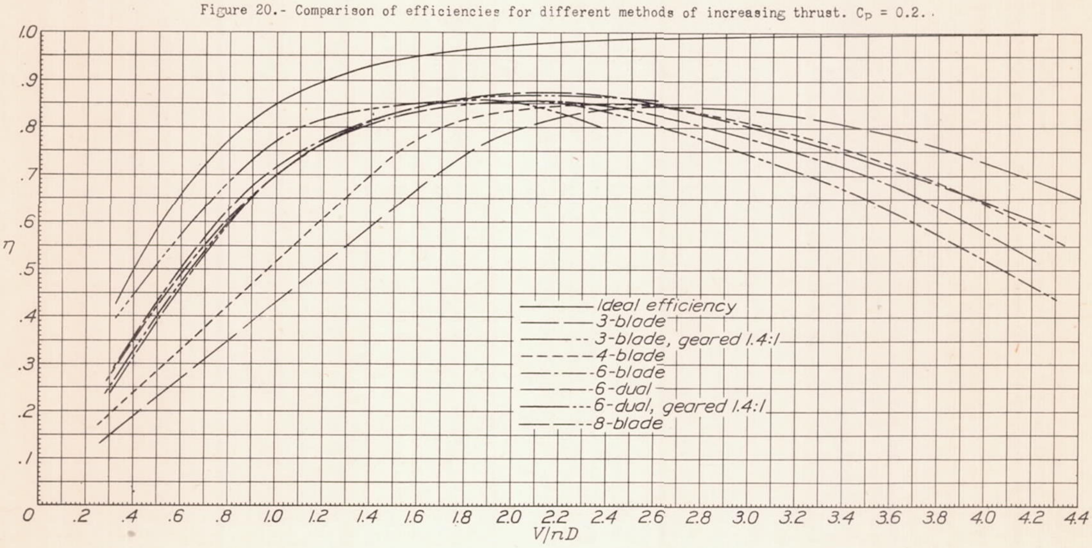

Figure 21.- Comparison of efficiencies for different methods of increasing thrust. C_p = 0.4.

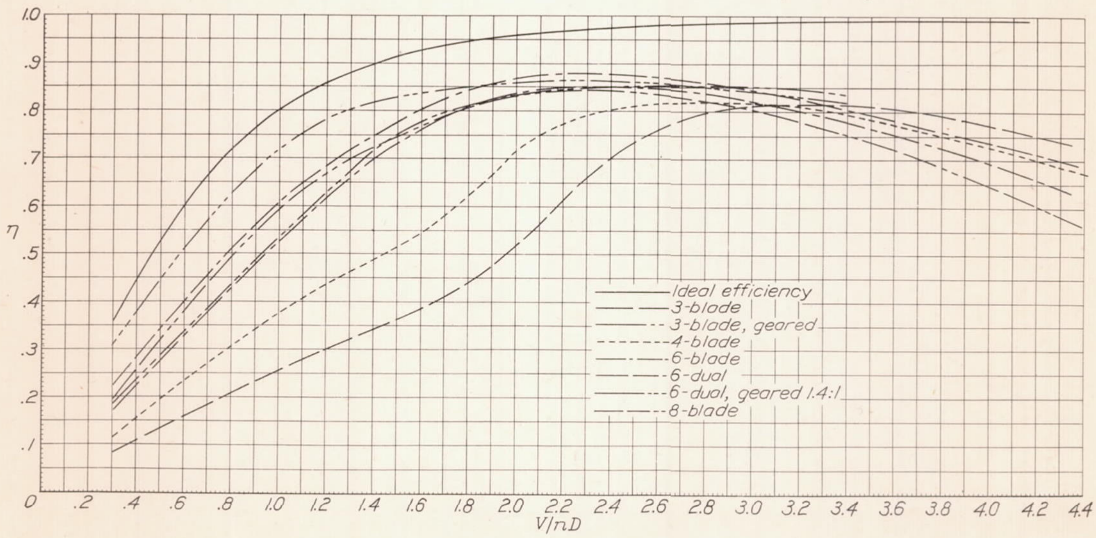

Figure 22.- Comparison of efficiencies for different methods of increasing thrust. C_p = 0.6.

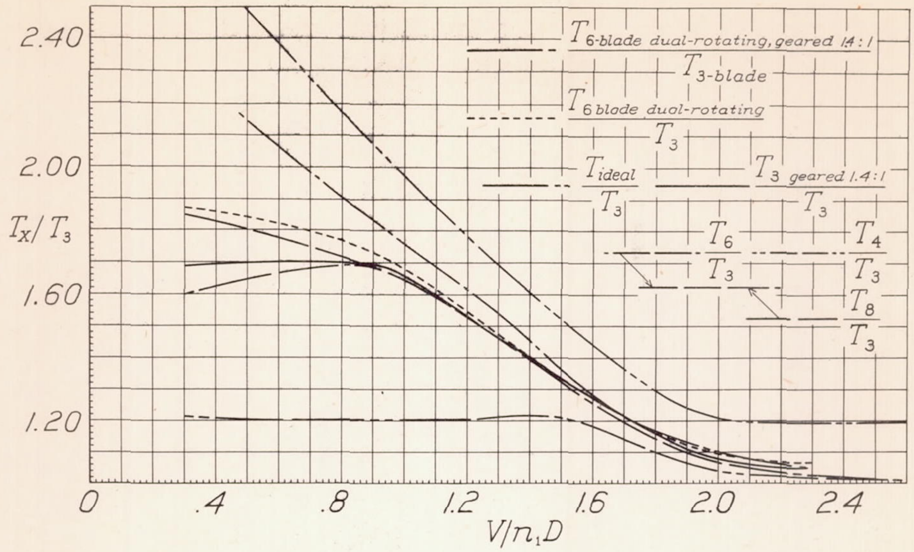

Figure 24.- Comparison of methods for increasing thrust. $C_{P_1} = 0.4$.

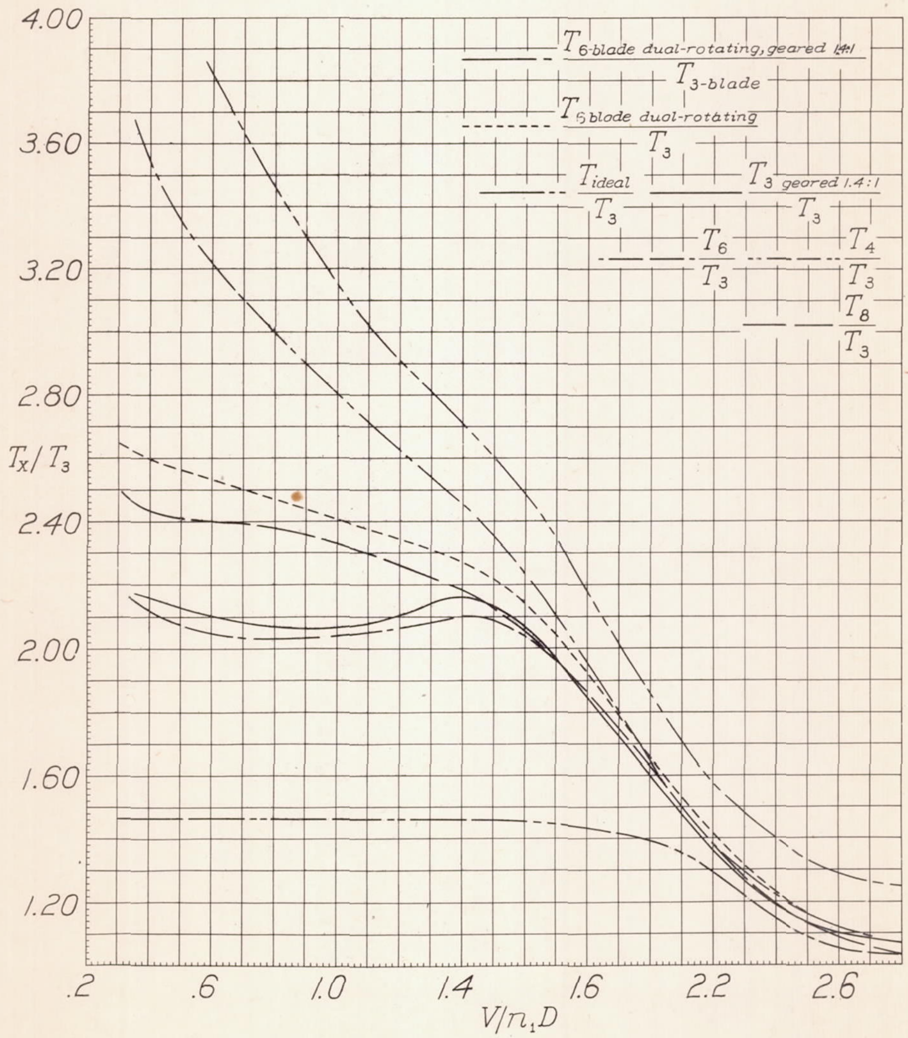

Figure 25.- Comparison of methods for increasing thrust. $C_{P_1} = 0.6$.

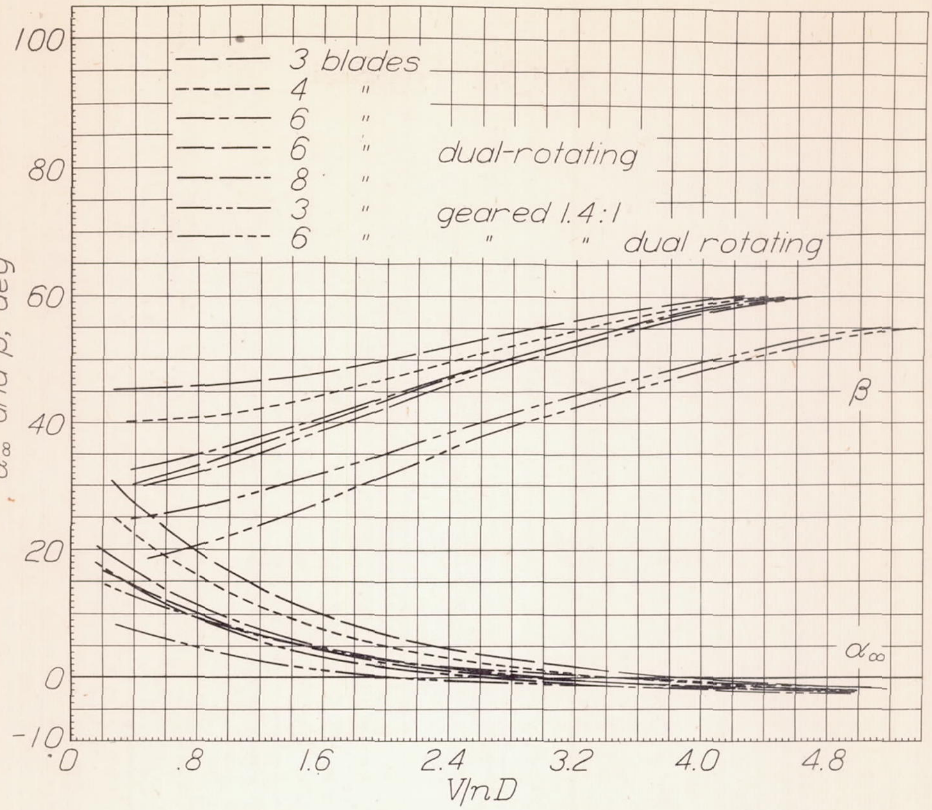

Figure 26.- Variation of α_∞ and β with V/nD for several propellers at C_P = 0.4.

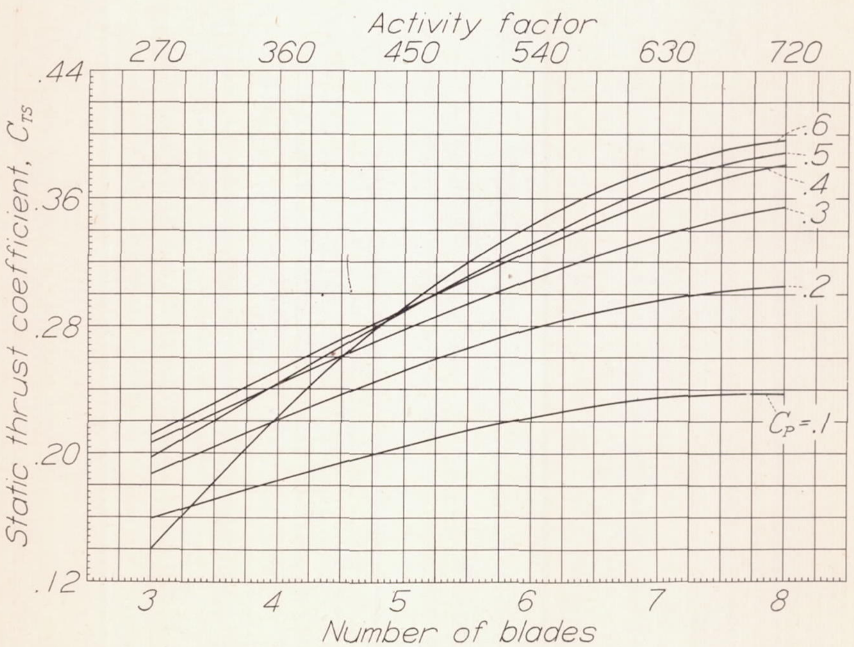

Figure 27.- Variation of static thrust with solidity.