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REPORT No. 641

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THE NEGATIVE THRUST AND TORQUE OF SEVERAL FULL-SCALE PROPELLERS AND THEIR APPLICATION TO VARIOUS FLIGHT PROBLEMS

By EDWIN P. HARTMAN and DAVID BIERMANN

1938

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s² or 32.1740 ft./sec.²

m, Mass $=\frac{W}{g}$

I, Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu. ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0, Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s., the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of c.p. from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_0, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By Edwin P. Hartman and David Biermann

SUMMARY

Negative thrust and torque data for 2-, 3-, and 4-blade metal propellers having Clark Y and R. A. F. 6 airfoil sections were obtained from tests in the N. A. C. A. 20-foot tunnel. The propellers were mounted in front of a radial engine nacelle and the blade-angle settings covered in the tests ranged from 15° to 90°. One propeller was also tested at blade-angle settings of 0°, 5°, and 10°.

A considerable portion of the report deals with the various applications of the negative thrust and torque to flight problems. A controllable propeller is shown to have a number of interesting, and perhaps valuable, uses within the negative thrust and torque range of operation. A small amount of engine-friction data is included to facilitate the application of the propeller data.

INTRODUCTION

In 1932 the N. A. C. A. made a series of tests of a 4-foot metal propeller covering the negative thrust and torque range of operation for blade angles from −23° to 22°. These data (reference 1) have been used to a considerable extent though it became evident soon after their publication that the tests had not been carried far enough into the range of positive blade angles to provide all the data required by designers. Contemporarily with the tests of reference 1, a series of dive tests was made by the N. A. C. A. of an F6C-4 airplane to determine the possibilities of using the propeller in reducing the terminal diving speeds of military airplanes. From these tests (reference 2) sufficient propeller data were obtained to provide a set of negative thrust and torque curves covering a range of blade angles from 6° to 22°. In 1936 the negative thrust and torque characteristics of an 18-inch propeller mounted on a complete airplane model were obtained at the California Institute of Technology (reference 3). The tests covered a blade-angle range from 12° to 50° and both 2- and 3-blade propellers were tested. These three sources provide most of the available known data on the negative thrust and torque of metal propellers.

As the possibilities connected with the use of controllable propellers have become more fully realized, the negative thrust and torque range of propeller operation has received an increasing share of the designer's attention. It appeared desirable to make additions to the meager supply of data in this field of propeller operation. A study of negative thrust and torque was therefore made a part of a general full-scale propeller-research program being conducted in the N. A. C. A. 20-foot tunnel.

The final data are presented in this report in a form conveniently applicable to the solution of design problems. Since the negative thrust of a windmilling propeller depends upon its rate of rotation, which in turn depends upon the friction torque of the engine, it is obvious that information with regard to engine friction is necessary for the ready use of the data. A certain amount of friction data, gleaned from various sources, has been included and should enable a reasonable estimate to be made with regard to the friction characteristics of an engine if particular and exact data are not available. As a further means of increasing the utility of the material, examples are included showing how the data may be used for attacking various problems.

APPARATUS AND METHODS

General.—The tests were made in the N. A. C. A. 20-foot wind tunnel described in reference 4. The air speed at which the tests were made varied between 100 and 110 miles per hour, which is the maximum speed of the tunnel.

The propellers were mounted on a water-cooled Curtiss Conqueror GIV 1570-C engine, the direction of rotation of which had been reversed to accommodate the right-hand propellers available for the tests. The engine was enclosed in a dummy radial engine nacelle having a length of about 10 feet and a maximum diameter of 52 inches. The air-cooled cylinders were simulated by a perforated disk whose conductivity, or free-air passage, approximated that of a moderately baffled engine installation. A photograph of the set-up is shown in figure 1.

The variations of engine speed, when the engine was being turned by the propeller, were obtained by the use of a hydraulic brake from an automobile truck. The brake drum was attached to the propeller shaft and the shoe mechanism to the engine gear case.

Propellers.—Six different propellers of modern design, comprising two sets of propellers with 2, 3, and 4 blades, were tested. All the propellers tested had the same diameter (10 feet), blade width, blade thickness, plan form, and pitch distribution. The propellers were of Navy design having Navy drawing numbers 5868–9 and 5868–R6. The 5868–9 propellers had Clark Y airfoil sections and the 5868–R6 propellers had R. A. F. 6 sections. The blade-form curves for the propellers are given in figure 2, which also shows the plan form and airfoil sections.

Method.—The torque and thrust forces were measured by scales in the balance house on the test-chamber floor. The engine speed was measured by an electrical tachometer, the meter of which was located beside the engine controls in the balance house. The engine controls were hydraulically operated.

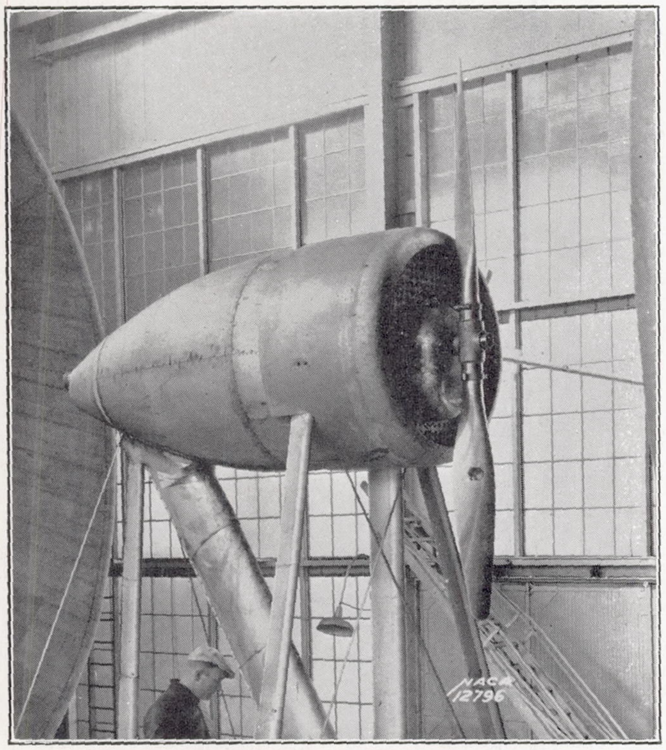


FIGURE 1.—The propeller test set-up.

During tests, the tunnel speed was held substantially constant and the engine throttled step by step to zero throttle opening; the switch was then cut and the braking force applied in increments until the propeller stopped. Through this process, readings were taken at frequent intervals producing a continuous curve in the plotted data. The foregoing method was used for blade angles up to 70°, beyond which only the drag and torque of the locked propeller could be obtained.

RESULTS AND DISCUSSION

Coefficients and symbols.—The thrust and torque coefficient forms used in plotting the data in this report are as follows:

$$T_c=\frac{T_e}{\rho V^2 D^2}$$

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

$$Q_n=Q_c/\frac{nD}{V}=\frac{Q/n}{\rho V D^4}$$

where $T_e=T-\Delta D$, effective thrust, lb.

T, thrust of propeller (axial force in propeller shaft), lb.

ΔD, change in drag of airplane or body due to slipstream, lb.

Q, aerodynamic torque (negative when it assists rotation), ft.-lb.

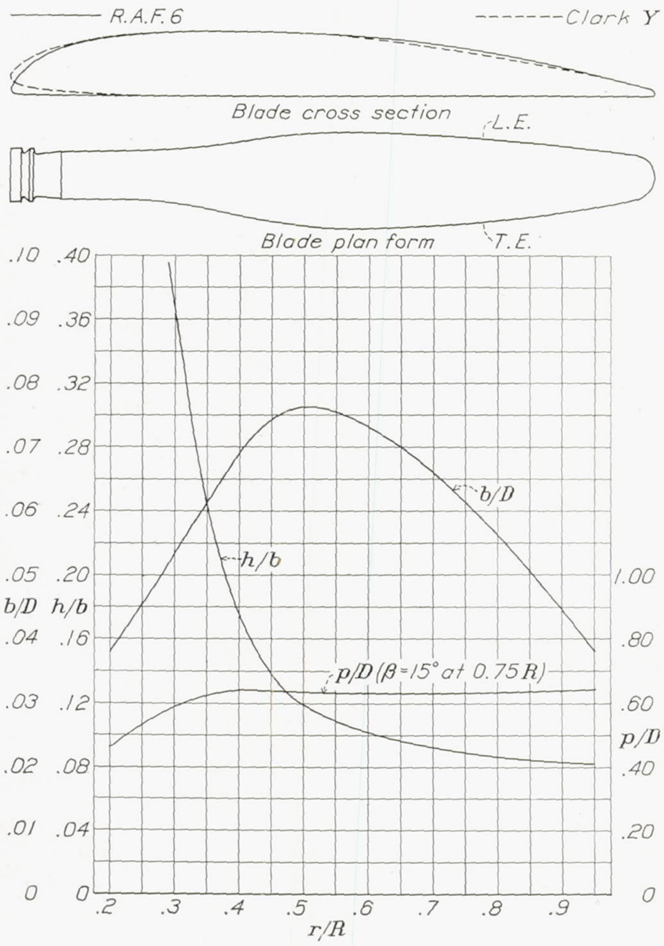


FIGURE 2.—Blade-form curves for propellers 5868–9 and 5868–R6. D, diameter; R, radius to the tip; r, station radius; b, section chord; h, section thickness; p, geometric pitch; β, blade angle.

D, propeller diameter, ft.

V, air speed, f. p. s.

n, propeller speed, r. p. s.

ρ, mass density of air, slugs per cu. ft.

Negative thrust and torque charts.—The principal results of the tests are shown in figures 3 to 9. Figures 3, 4, and 5 present cross-faired curves giving the thrust and torque coefficients for the Clark Y propellers having 2, 3, and 4 blades. Figures 6, 7, 8, and 9 present similar curves for the R. A. F. 6 propellers. In addition to the range covered by the other propellers, the 3-blade R. A. F. 6 propeller tests covered the blade angles 10°, 5°, and 0° (fig. 8).

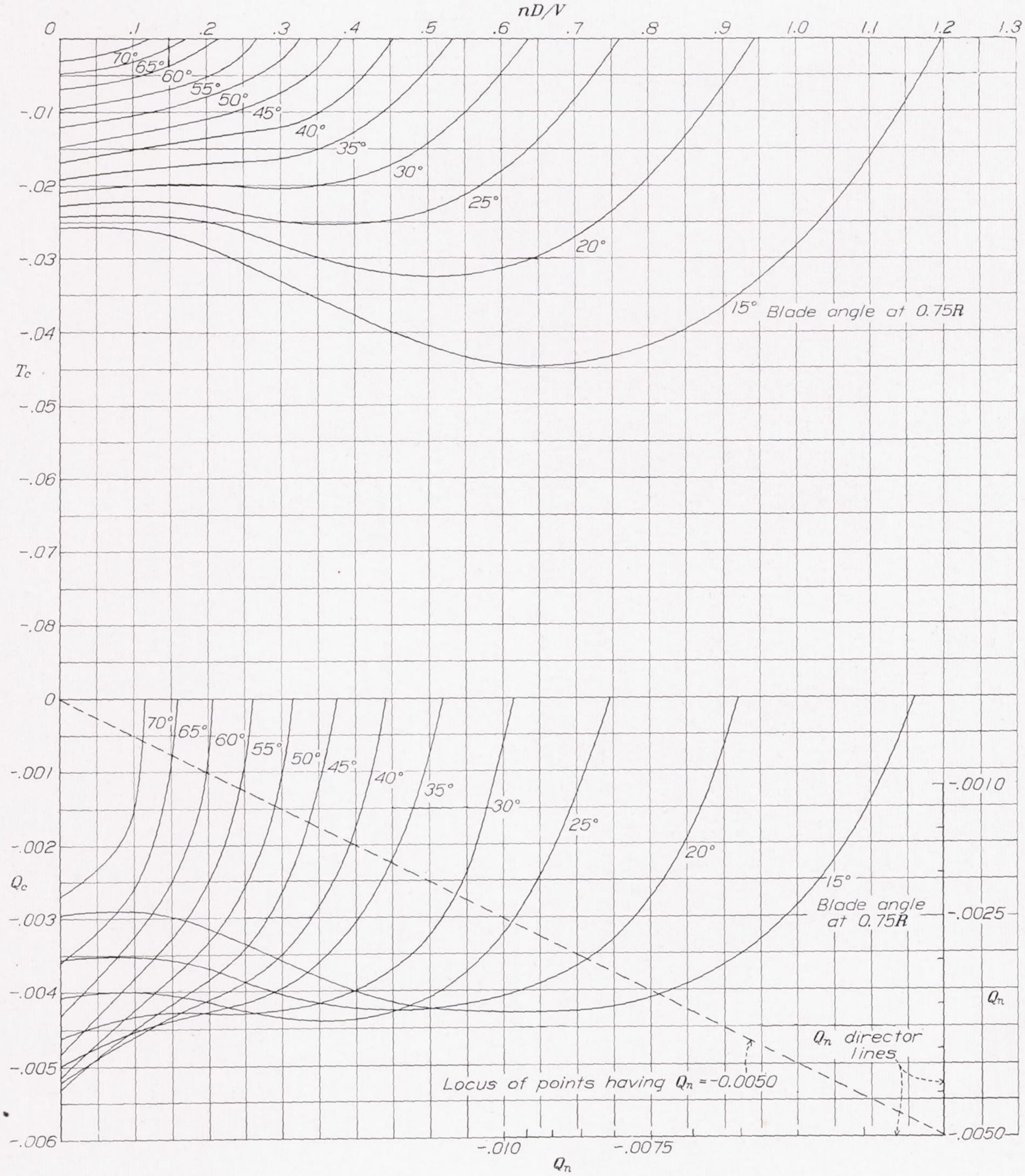


FIGURE 3.—Negative thrust and torque coefficients for propeller 5868-9, Clark Y section, 2 blades.

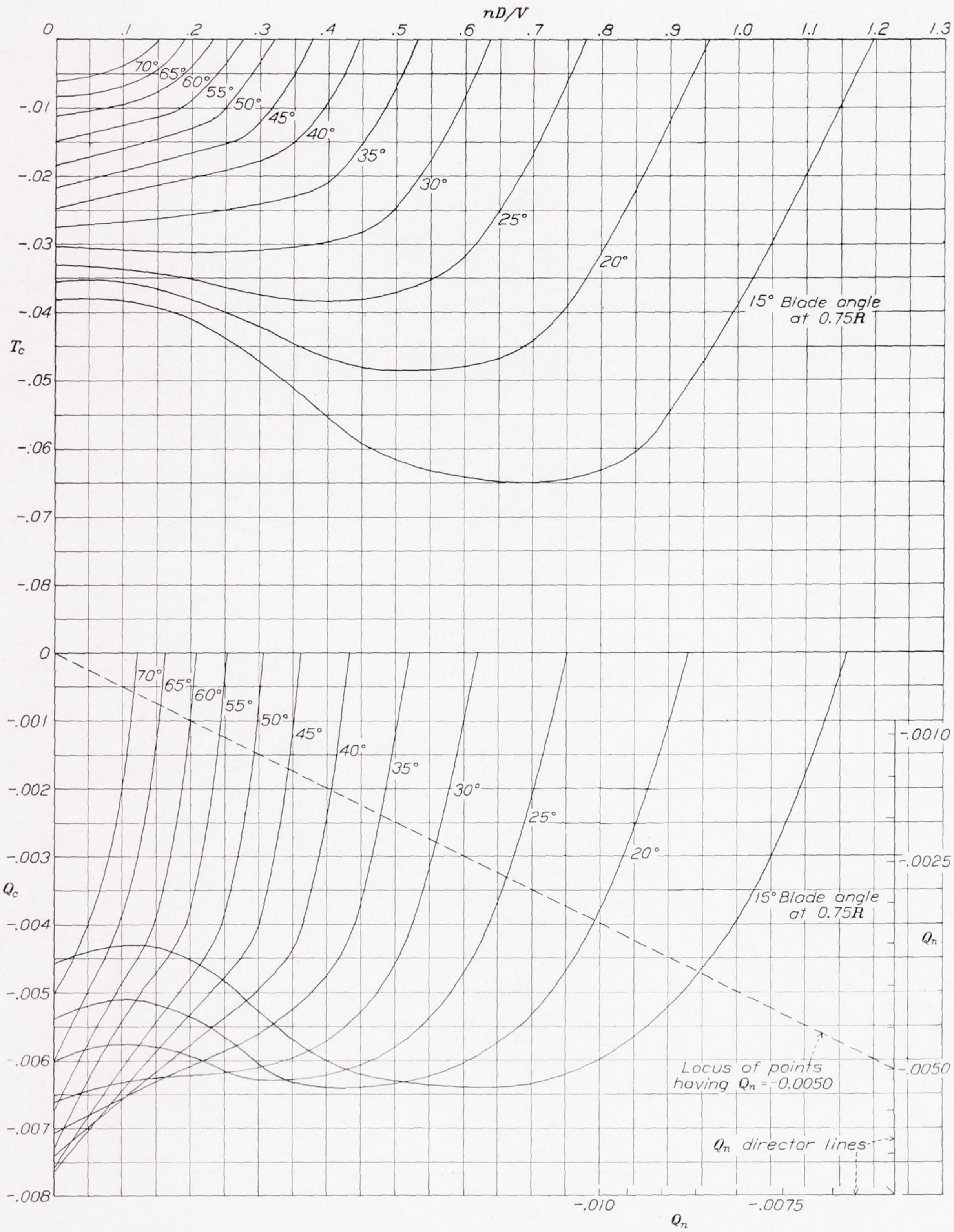


FIGURE 4.—Negative thrust and torque coefficients for propeller 5868-9, Clark Y section, 3 blades.

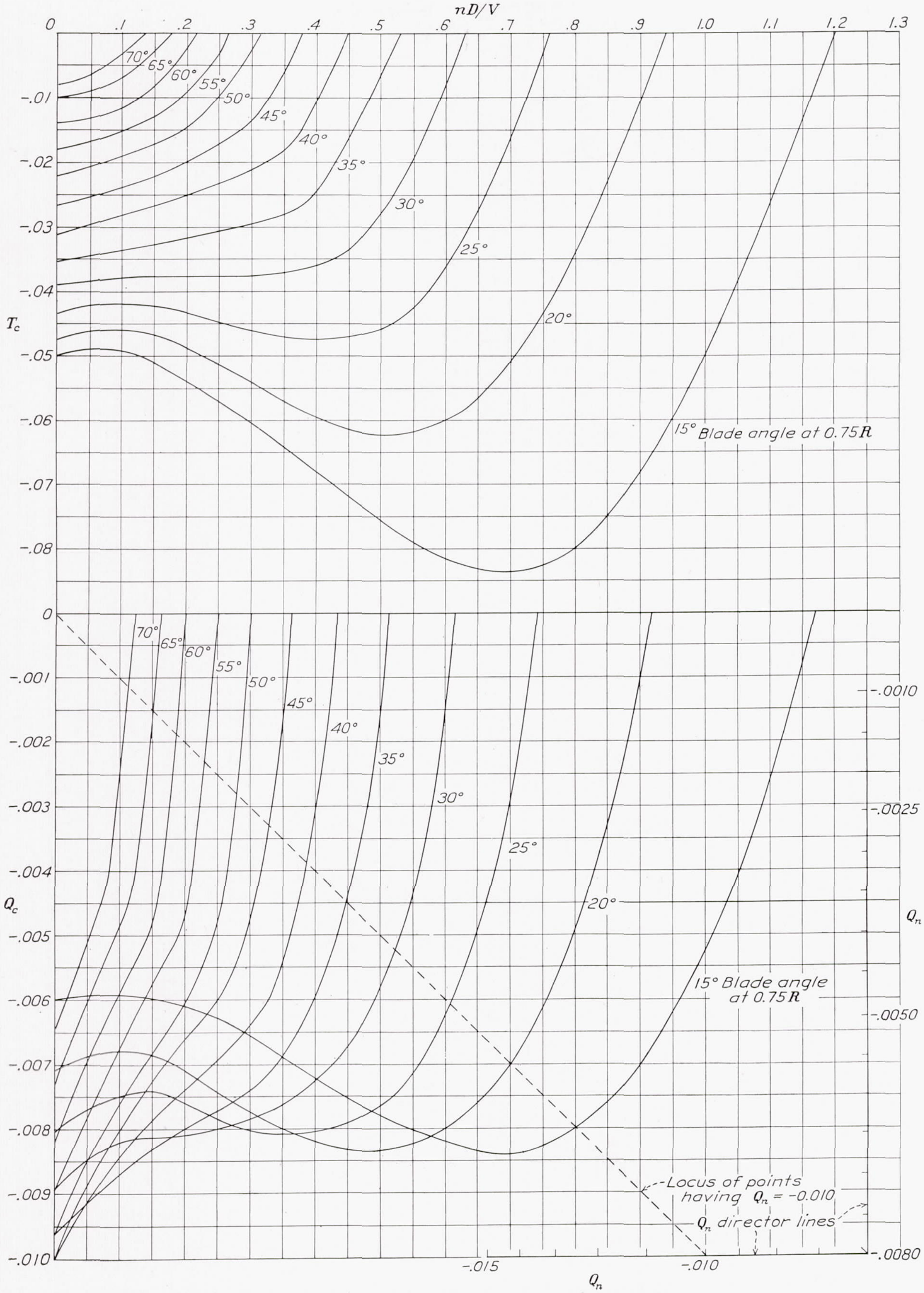


FIGURE 5.—Negative thrust and torque coefficients for propeller 5868-9, Clark Y section, 4 blades.

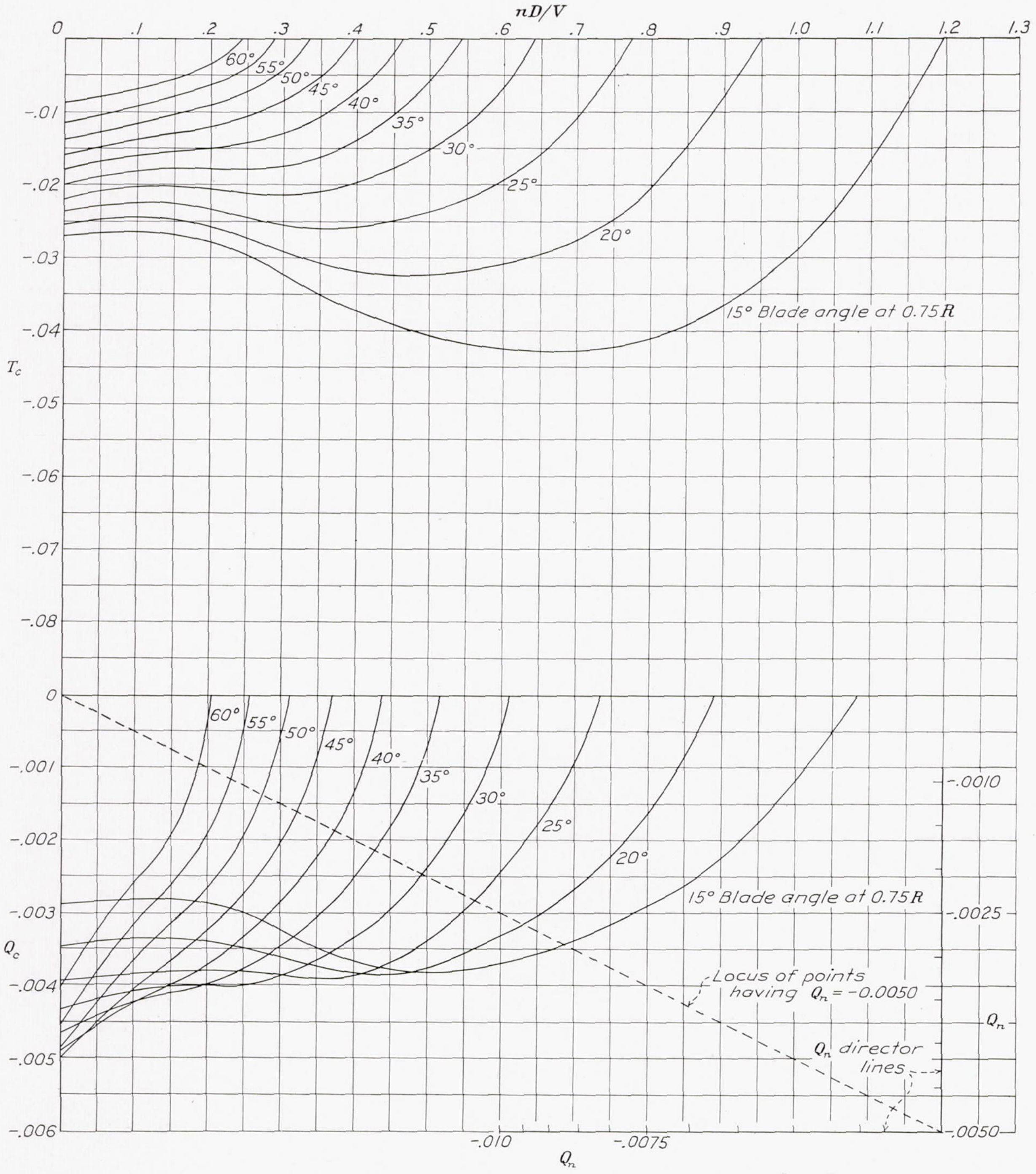


FIGURE 6.—Negative thrust and torque coefficients for propeller 5868-R6, R. A. F. 6 section, 2 blades.

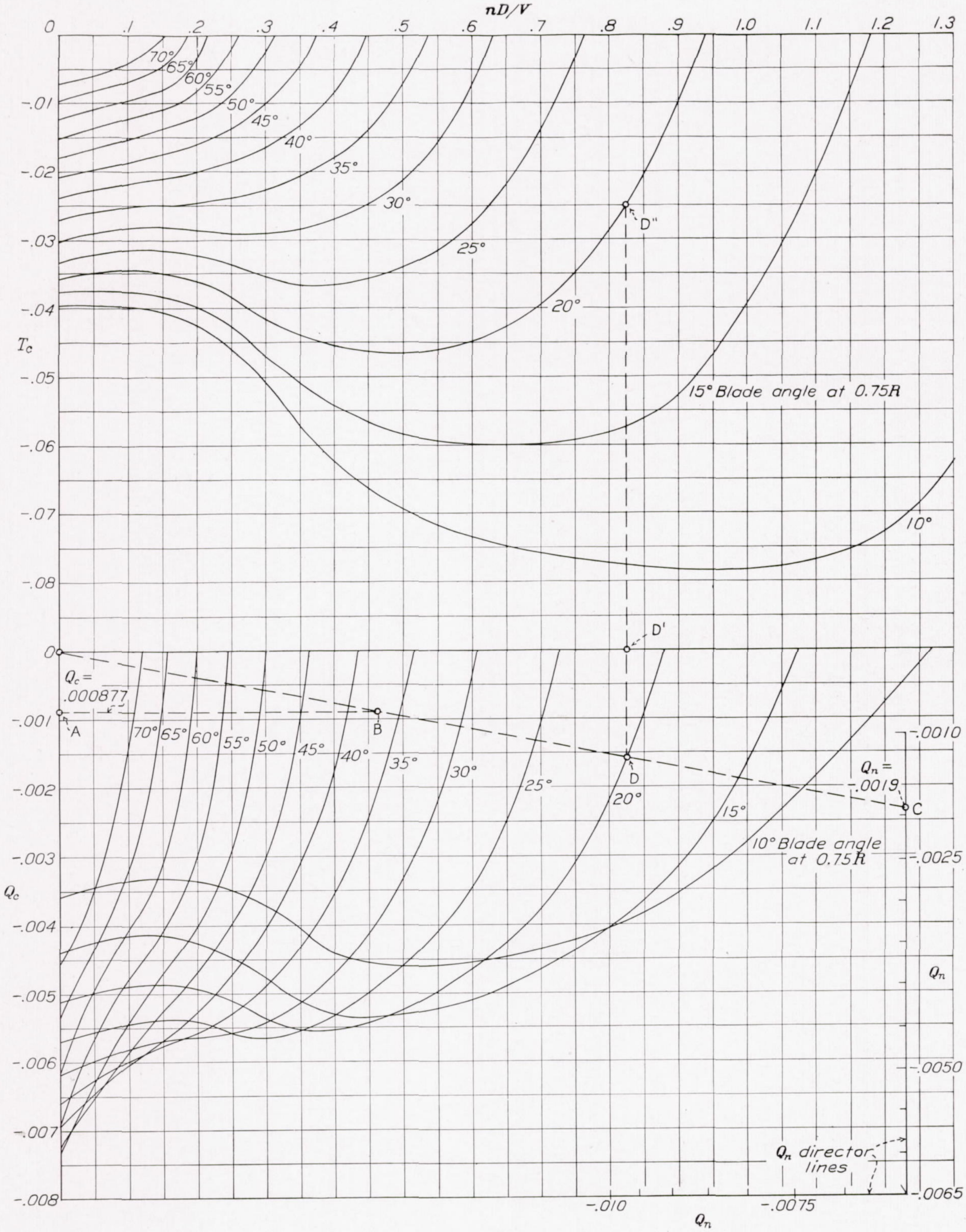


FIGURE 7.—Negative thrust and torque coefficients for propeller 5868–R6, R. A. F. 6 section, 3 blades.

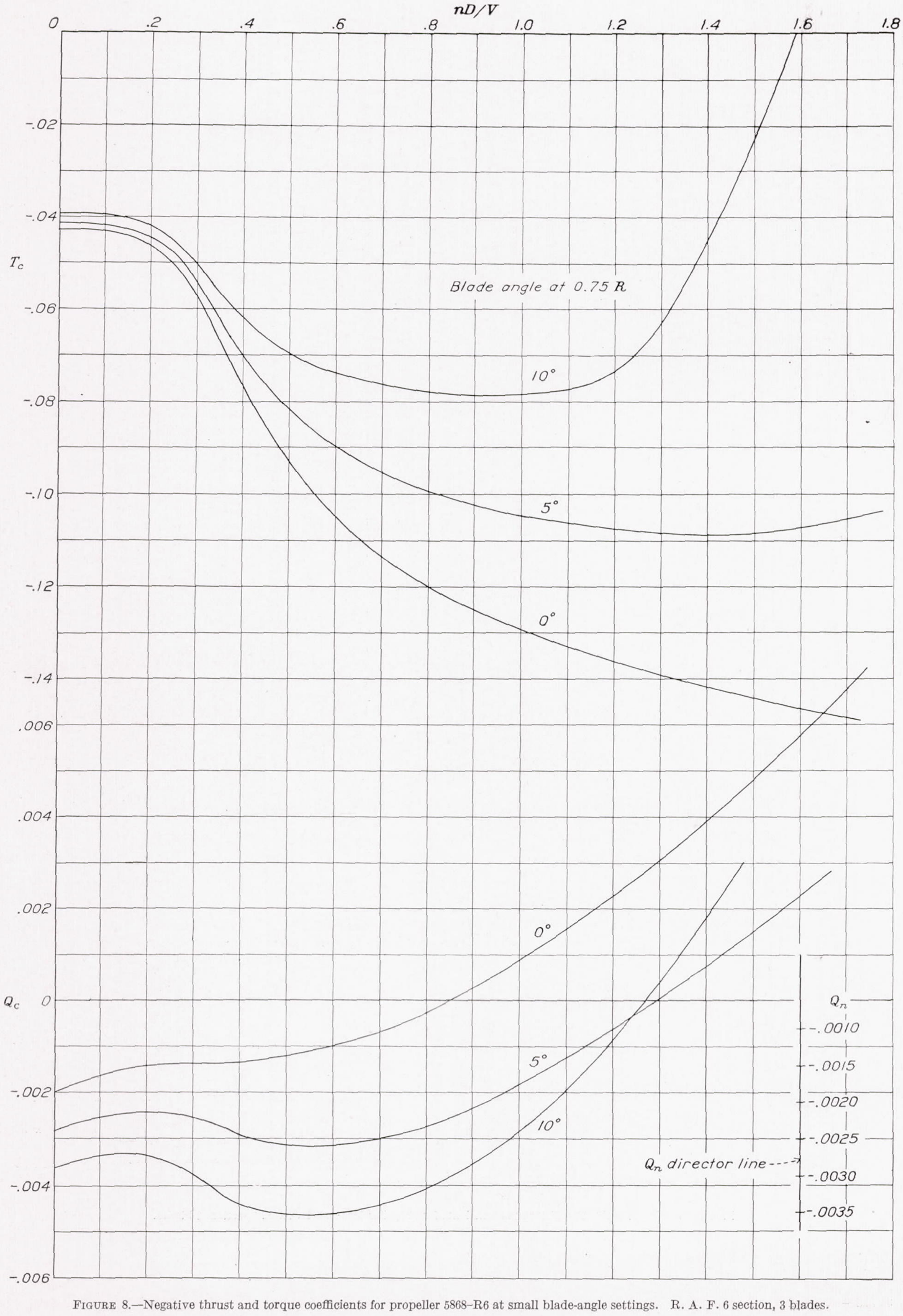


FIGURE 8.—Negative thrust and torque coefficients for propeller 5868-R6 at small blade-angle settings. R. A. F. 6 section, 3 blades.

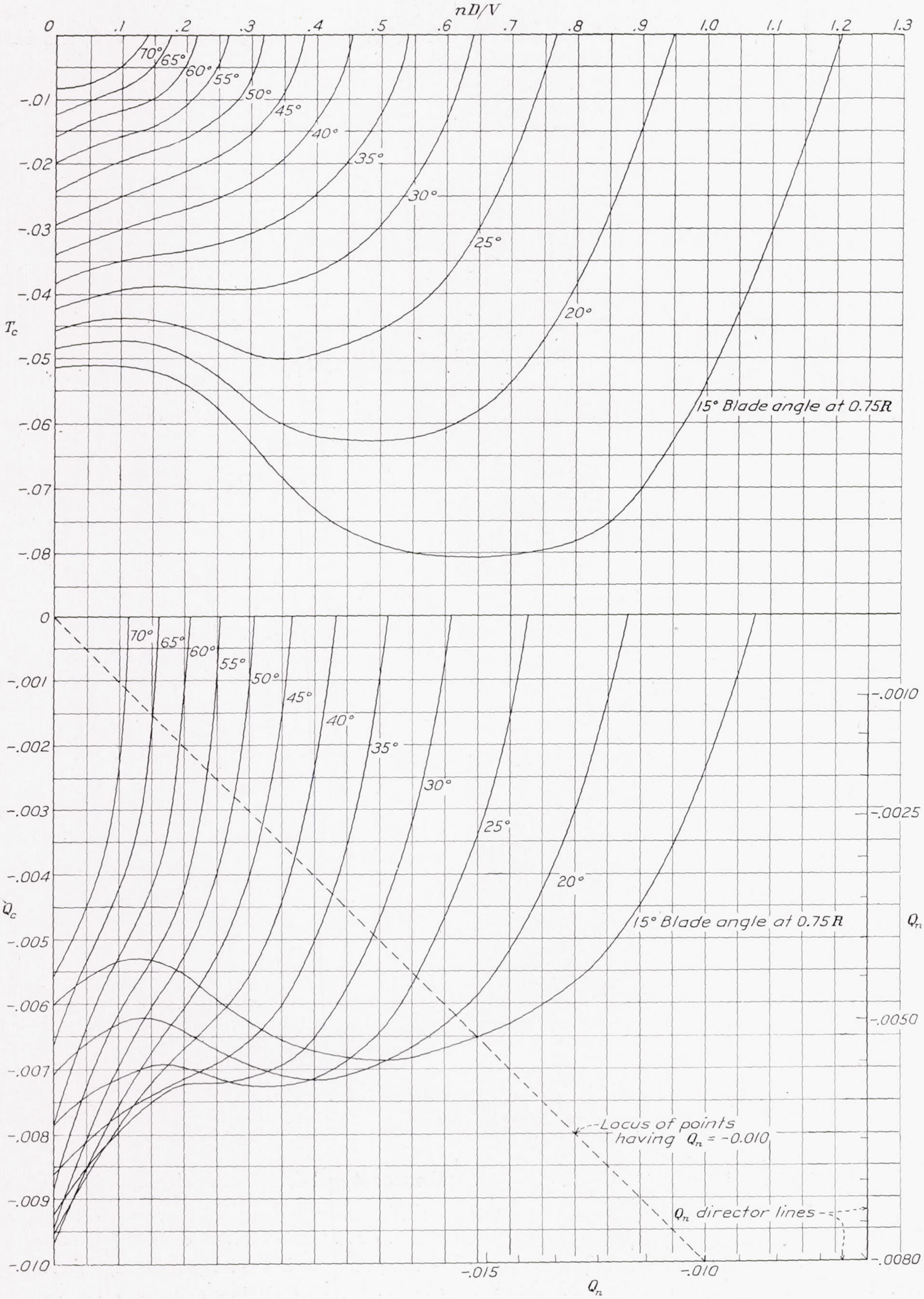


FIGURE 9.—Negative thrust and torque coefficients for propeller 5868-R6, R. A. F. 6 section, 4 blades.

Although the original plotted curves of thrust and torque coefficient were, in general, fairly smooth, the few irregularities in some of the curves and their spacing made it seem desirable to cross-fair them. An illustration of the appearance of one of the typical original plots is given in figure 10 to show the extent of the dispersion of the test points.

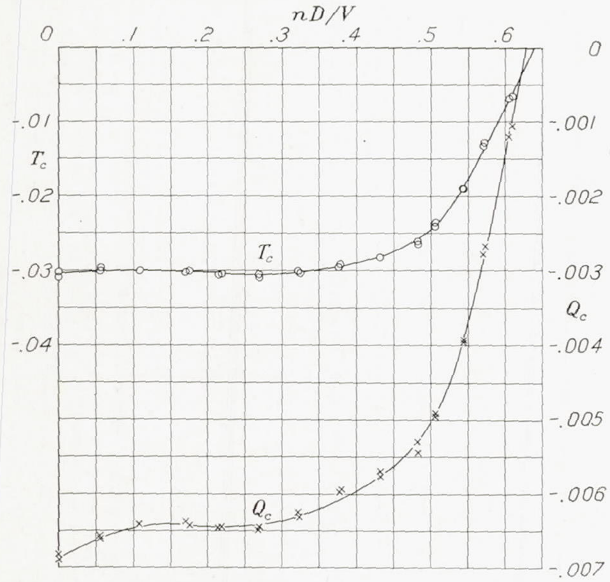


FIGURE 10.—Typical pair of negative thrust and torque curves showing test points. Propeller 5868-9, 3 blades, set 30° at 0.75 R.

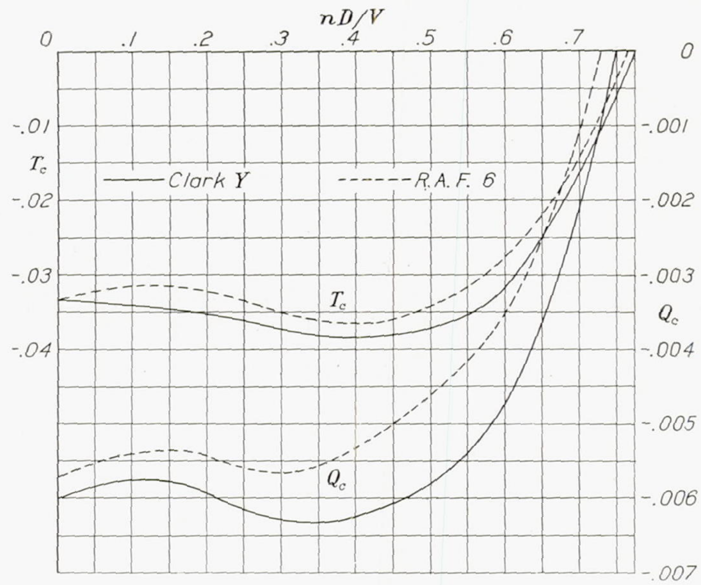


FIGURE 11.—Comparison of thrust and torque coefficients for propellers having Clark Y and R. A. F. 6 sections; 3-blade, 10-foot propellers set 25° at 0.75 R.

Comparison of Clark Y and R. A. F. 6 propeller characteristics.—It will be noted that, in general, the values of thrust and torque coefficients are greater for the Clark Y propellers than for the R. A. F. 6 propellers. For an easier comparison, figure 11 was prepared to show the thrust-coefficient and torque-coefficient curves for the 3-blade Clark Y and R. A. F. 6 propellers set at a blade angle of 25°. At zero nD/V, the thrust coefficients of the two propellers are nearly the same; however, the difference in the shapes of the two sections (see fig. 2) causes a considerable difference in both thrust and torque throughout most of the nD/V range.

Comparison of propellers having 2, 3, and 4 blades.—A comparison of propellers having 2, 3, and 4 blades is shown in figure 12. The coefficients of the three propellers were divided by the number of blades and then multiplied by 2 to permit comparison on the basis of two blades. The curves in figure 12 show no consistent variation, probably owing to the process of cross-fairing. They do show that, compared on this basis, there is no great difference between the characteristics of propellers with 2, 3, and 4 blades.

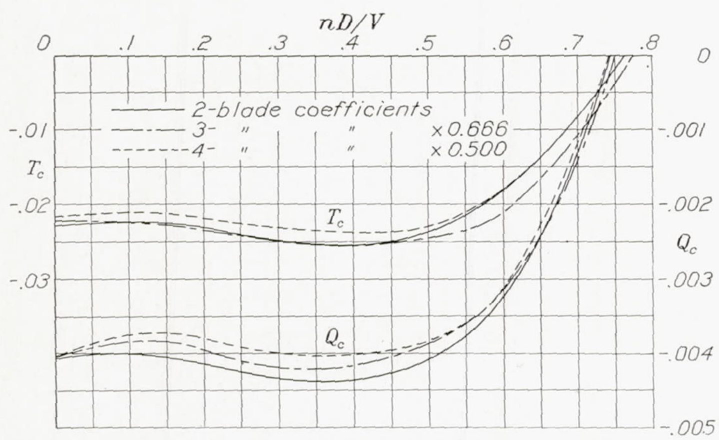


FIGURE 12.—Comparison of thrust and torque coefficients for propellers having 2, 3, and 4 blades of Clark Y section; set 25° at 0.75 R.

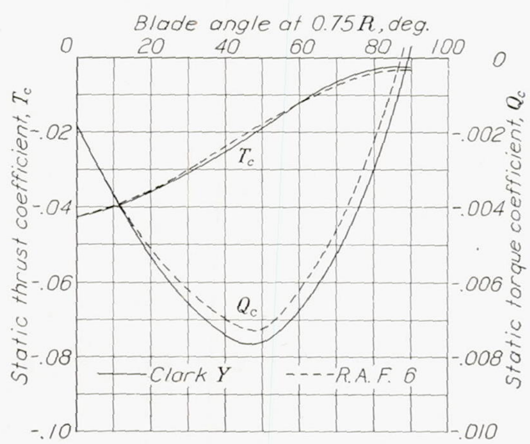


FIGURE 13.—Thrust and torque coefficients with propeller locked ($nD/V=0$); blades.

Coefficients for locked propellers.—Figure 13 shows the thrust and torque coefficients, at $\frac{nD}{V}=0$ (propeller locked) and through a 90° blade-angle range, for both the R. A. F. 6 and Clark Y 3-blade propellers.

The difference in the torque curves, which is negligible at 0° and quite large at high angles, may be attributed to the difference in the shape of the leading edges of the two airfoil sections. The static thrust has apparently not reached its peak at 0°.

CONSIDERATIONS IN APPLYING NEGATIVE THRUST AND TORQUE DATA TO THE SOLUTION OF PROBLEMS

Coefficients.—The thrust coefficient T_c is especially suited to a negative-thrust analysis because it does not involve the engine speed and because of its similarity to the usual drag coefficient. It is not convenient to use the normal propeller thrust coefficient $C_T=T_e/\rho n^2D^4$ because C_T approaches infinity as nD/V approaches zero, and difficulty in plotting arises. With the diameter and velocity known, the thrust may be easily calculated for any value of T_c.

Effect of engine.—In most problems involving negative thrust, the propeller is mounted on an airplane engine, which may be "dead" (switch off and being turned over against its own friction), partly throttled, or operating at full throttle. The main difficulty in calculating the negative thrust of a propeller operating under any given condition, especially the one where it is turning a dead engine, is found in determining the engine speed. In the special case of the "freewheeling" propeller, the thrust coefficient is easily found, it being the value corresponding to the nD/V where the torque coefficient is zero. When the propeller is turning a dead engine, however, the revolution speed depends upon the friction torque of the engine, which is itself an extremely variable quantity.

The coefficient Q_n.—In reference 5 it was pointed out that flight tests indicated the rotational speeds of propellers turning dead engines on multiengine airplanes to be from 35 to 50 percent of rated engine speed. It was also pointed out that, through this range of engine speeds, the friction torque of the average airplane engine might be represented by an equation of the following type:

$$Q_f=k_1N_e\Delta(1+k_2h)/k_3/G.\ R.$$

where Δ is the engine displacement, cu. in.

N_e, crankshaft revolution speed, r. p. m.

$G.\ R.$, the ratio of propeller speed to crankshaft speed.

k_1, k_2, and k_3, appropriate constants.

For a particular engine and at a given altitude h, the equation is simplified to:

$$\frac{Q_f}{N_e}=\text{constant }(K)$$

This approximation was used in reference 5 to develop the following form of coefficient:

$$Q_n=\frac{Q}{\rho V^2D^3}\times\frac{V}{nD}=\frac{Q/n}{\rho VD^4}$$

This relation may be put in a more useful form:

$$Q_n=17{,}200\times\frac{Q_f/N}{\sigma V_1D^4}$$

where Q_f is engine friction torque (considered negative), ft.-lb.

N, propeller revolution speed, r. p. m.

V_1, air speed, m. p. h.

σ, relative density, ρ/ρ_0.

ρ_0, mass density of the air at sea level, slugs per cu. ft.

In references 3 and 5, charts are presented having thrust coefficient T_c plotted against Q_n. Thus, when the value of Q_f/n is known for the engine in question, the value of Q_n, at any given altitude and for any given propeller diameter, will depend only on the velocity. The plot of T_c against Q_n then becomes, for any particular case, a plot of the thrust against the inverse of the velocity. It appears likely, from the friction data shown in references 3 and 5, that the usefulness of the relation $Q_f/N_e=K$ will extend over a greater range of engine speeds than previously indicated.

The Q_n modification to negative-thrust charts.—In the present report it is shown that a slight modification of the usual plots of T_c and Q_c against nD/V will provide the equivalent of a plot of T_c against Q_n, such as given in references 3 and 5.

The necessary modification to the usual charts is explained as follows: Since $Q_n=\frac{Q_c}{nD/V}$, it is clear that the locus of all points having a single value of Q_n may be represented on plots of Q_c against nD/V (figs. 3 to 9) by a straight line passing through the origin. The position of this line for any particular value of Q_n is easily determined on the chart from the fact that $Q_n=Q_c$ where $\frac{nD}{V}=1$. Although the position of this line is easily determined, a scale, or rather a director line, has been placed on each chart showing the intersections of the Q_n lines for various values of Q_n.

In actual use a straightedge placed from the origin to the desired value of Q_n on the scale will permit values of the coefficients to be read without drawing the line.

Examples of use of Q_n.—As an example, suppose the friction torque of the engine and the velocity are such as to make the value of $Q_n=-0.0019$ and that it is desired to find the value of T_c at a blade angle of 20°. The solution of this problem is indicated in figure 7. The broken line O–C represents a constant value of Q_n. Where this line intersects the 20° blade-angle curve at point D, project up along the line D–D″ to the point D″. The T_c coordinate of the point D″ is the desired value.

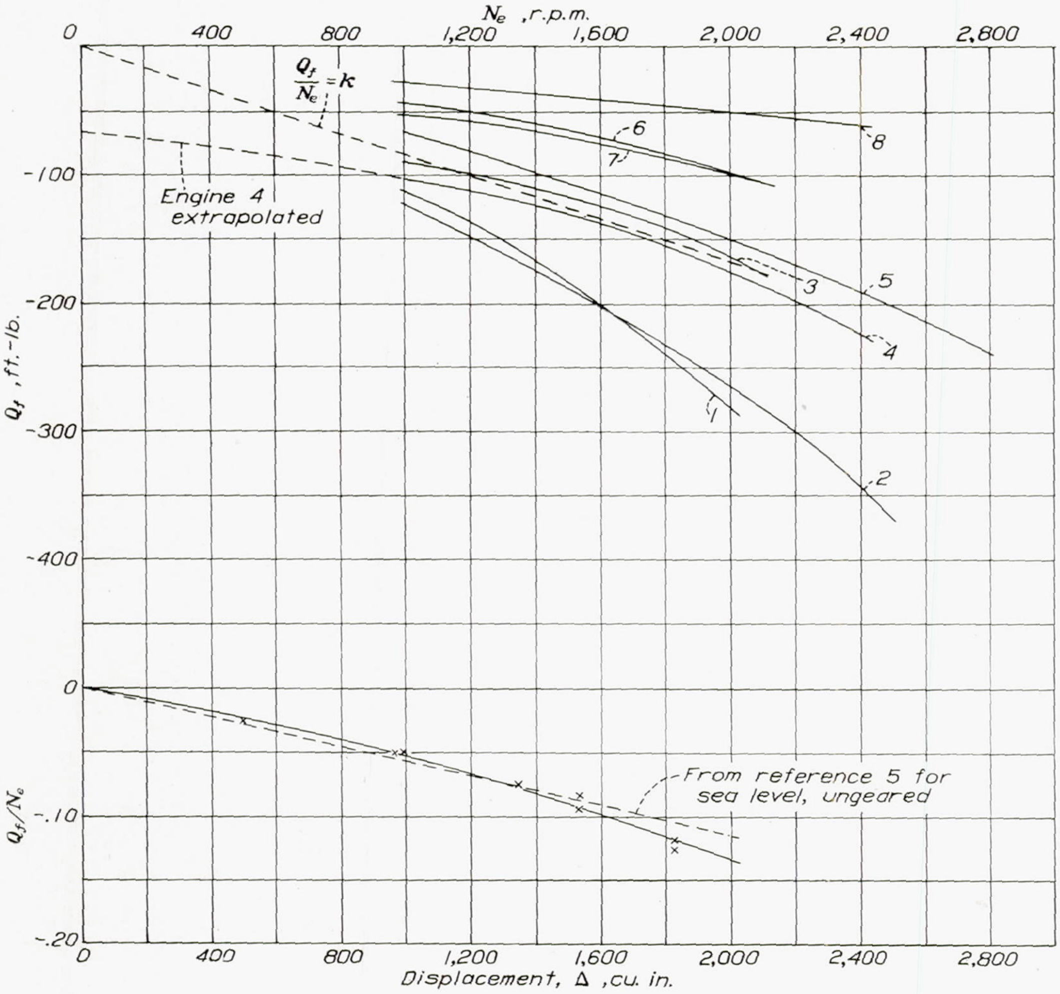
The propeller speed may be calculated from the value of nD/V at point D′ as follows:

$$N=\frac{nD}{V}\frac{V_1\times 88}{D}$$

FRICTION TORQUE OF ENGINES

Relation to problems.—In many cases the friction of the engine has a large effect on the values of thrust coefficient under which the propeller operates. It is then obvious that, for the ready use of the data herein presented, some information regarding the friction torque of engines is required. As particular and exact engine-friction data are seldom available for the solution of negative-thrust problems, it is considered necessary to include in this report sufficient data to permit an intelligent estimate of friction torque to be made.

Engine-friction data.—Figure 14 shows friction-torque curves, obtained from various sources, for eight modern aircraft engines covering a fairly wide range of power and displacement. Some of these curves have been extrapolated to bring them to 1,000 r. p. m. From these curves may be judged the quality of the assumption that the friction torque is a linear function of N, which can be represented by the relation $Q_f/N_e = K$ for any particular engine. This equation indicates that the torque for any engine may be represented by a straight line through the origin, as the one drawn in for engine 3 in figure 14.



Engine	Δ	hp.	N_e	Q_f/N_e
1	1,823	768	1,950	−0.120
2	1,820	700	1,950	−.125
3	1,535	850	2,150	−.085
4	1,535	750	2,500	−.095
5	1,340	450	2,100	−.075
6	985	300	2,000	−.050
7	975	330	2,000	−.050
8	499	145	2,050	−.025

FIGURE 14.—Friction-torque curves for eight typical airplane engines.

The curves in figure 14 indicate that this approximation is not far wrong for values of N_e from 1,000 to 2,200 and for the temperature and pressure conditions under which the tests were run. It is certain, however, that this approximation does not hold at low values of N_e for it assumes that the torque becomes zero at $N_e=0$. The torque does not become zero at $N_e=0$, as is indicated by the extrapolated curve for engine 4, and there is evidence to show that this deviation becomes greater as the temperature decreases. Fortunately, however, the deviation from the linear formula in the range of low engine speeds usually occurs in a range of blade angles where large changes in torque cause but small changes in thrust coefficient and also where the values of thrust coefficients are low so that, although the relative error may be large, the absolute value of the error is small.

It is also seen that, at high values of engine speed (above 2,000 r. p. m.), the friction torque increases faster than the straight-line assumption, so that, in problems involving high values of N_e (fast dives), it will be advisable to increase Q_f/N_e by a small amount.

Estimation of a value of Q_f/N_e.—On the assumption that the friction torque can be determined by the equation $Q_f=\Delta N_e K$, it is clear that a plot of Q_f/N_e against displacement Δ for a group of engines should be a straight line like the dotted line, taken from figure 5 of reference 3, in the lower plot in figure 14.

Straight lines were drawn through the friction torque curves, as illustrated for engine 3 (fig. 14), and the values of Q_f/N_e represented by these lines were plotted against Δ in the lower chart. The solid faired line through these points may possibly provide a more accurate selection of Q_f/N_e values than the broken line from reference 3.

Where no specific friction data are available, a reasonable estimate of the value of Q_f/N_e, for any engine, may be obtained from this curve. In the case of a geared engine, Q_f/N_e must be converted to Q_f/N when calculating the coefficient Q_n.

Applicability of friction data.—The friction torque of engines varies with many factors; such as the mechanical condition of the engine, the cylinder barrel and oil temperatures, the barometric pressure, the throttle opening, the oil viscosity, and the gear ratio.

In the selection of a value of Q_f/N_e from figure 14, some allowance should properly be made for these factors. Some of the factors, however, tend to cancel each other; some, such as mechanical condition, have an unpredictable effect; and others have but a small effect. In general, there will probably be little justification for making any corrections but, under extreme conditions, these factors should not be overlooked.

The effect of altitude is to reduce the friction torque (pumping losses), but this gain is balanced by the increased friction due to the lower temperatures existing at the higher altitudes. Corrections for altitude are therefore unnecessary in most cases. Gearing an engine should not alter the friction torque by more than 10 to 20 percent at rated engine speed. Changes in temperature will have a considerable effect and may change the specific friction torque Q_f/Δ by as much as 0.004 per 10° F. change in outside-air temperature. It is beyond the scope of this report to consider in detail the quantitative aspects of the effects of the many factors that affect the friction torque of engines. Considerable information of this nature is given in reference 6.

APPLICATION OF NEGATIVE THRUST AND TORQUE DATA

The development of the controllable propeller has greatly increased the opportunities for using the negative thrust of a propeller to advantage or, in other instances, for avoiding the bad effects of negative thrust at one blade angle by changing to another angle where these effects are less severe. Some of the ways in which negative thrust and torque data may be used to deal with such problems are given in the following paragraphs.

DRAG OF PROPELLER ON DEAD ENGINE OF A MULTIENGINE AIRPLANE

One problem of interest to the operators of multiengine airplanes concerns the question of flying with one or more engines dead. In this situation it is necessary to reduce the drag of the airplane to a minimum so that the power of the remaining engines will be sufficient to maintain the altitude required to clear all obstacles on the path to the nearest airport. It is of considerable interest, therefore, to know just where to set the blade angle of the dead-engine propeller to absorb the least power. Such problems may be readily solved by the data given in this report.

Example.—An example of one such problem is carried through to show the method of attack. The assumed conditions are as follows:

Airplane flying at 135 miles per hour with one engine dead.

Engines (2)—750 horsepower; $\Delta=1{,}500$ cubic inches; $N=1{,}450$; $N_e=2{,}000$.

Propellers—R. A. F. 6 section; 3 blades; 11-foot diameter.

Altitude—5,000 feet; $\sigma=0.862$; $Q_f/N_e=-0.09$ from figure 14; $Q_f/N=-0.1715$ and, after adding 10 percent for gearing, becomes -0.1885.

$$Q_n=17{,}200\times\frac{Q_f/N}{\sigma D^4 V_1}=\frac{17{,}200\times-0.1886}{0.862\times 11^4\times 135}=-0.0019.$$

In figure 7 the line representing Q_n is drawn in (line O–C) and its intersection with the Q_c curve for any blade angle represents the value of Q_c for that particular blade angle and the corresponding value of T_c may be obtained by projecting up from this intersection to the T_c curve for the corresponding blade angle (line D–D′′).

As previously pointed out, the assumption that the friction torque approaches zero at low values of N_e (low values of nD/V) does not hold very well, though the absolute value of the error resulting from this assumption is small. As an added refinement, this error may be reduced as follows:

Estimate the value of friction torque at $N_e=0$ and from it calculate a value of Q_c at which the propeller will stop turning. From that point on the Q_c ordinate scale, project horizontally along a line of constant Q_c until an intersection is made with the previously drawn radial line of constant Q_n (such as line A–B intersecting line O–C at B). Now the locus of the desired points is assumed to be line A–B–C rather than the radial line O–C used in the less-refined method.

The value of the static friction torque will probably lie somewhere between 20 percent and 60 percent of the friction torque at rated engine speed depending upon the engine temperatures.

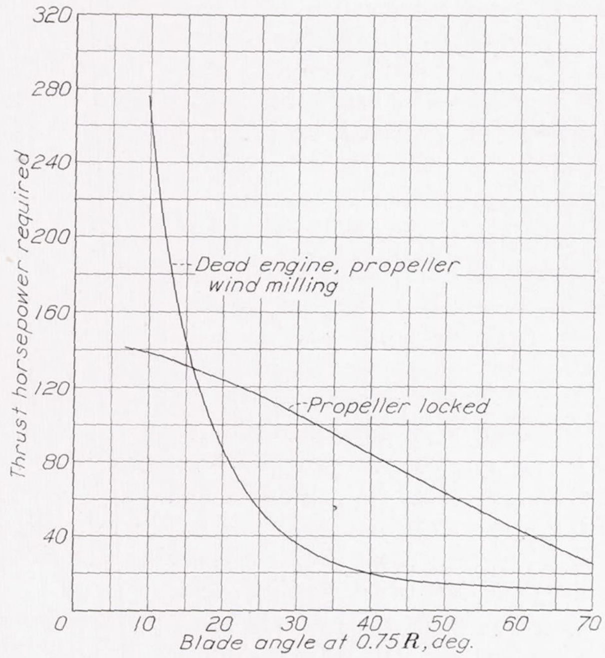


FIGURE 15.—Calculated power required to overcome the drag of a dead engine, idling and locked propeller, at 135 m. p. h. on a transport airplane. Propeller 5868–R6, 3 blades, 11-foot diameter.

In this example a value of 34 percent is used which, at 135 miles per hour, gives a value of $Q_c = -0.000877$ and the projected line on the chart in figure 7 is the line A–B.

The rest of the calculations may conveniently be put in tabular form:

β (deg.)	$-Q_c$	nD/V	$-T_c$	$-T_e$ (lb.)	t. hp. ($-T_e V_1/375$)
10	0.00205	1.08	0.0772	748	270.0
15	.00187	.987	.0414	402	145.0
20	.00157	.825	.0250	242	87.0
25	.00132	.692	.0155	150	54.0
30	.00112	.583	.0107	104	37.5
40	.000877	.420	.0055	53	19.1
50	.000877	.292	.0037	36	13.0
60	.000877	.193	.0046	45	16.2
70	.000877	.109	.0036	35	12.6

The results are plotted in figure 15 along with those for the same propeller when locked $\left(\frac{nD}{V}=0\right)$. For this particular example, it is seen that, through the greater part of the blade-angle range, the power required to overcome the drag of the locked propeller is considerably greater than for the windmilling condition. It is also seen that most of the benefit gained from increasing the blade angle on the windmilling propeller is obtained at 35° or 40°, which is not far above the normal operating range. In case the engine fails in such a manner that it locks or if it is desired to stop the rotation to prevent damage to the airplane or the engine, it will be necessary to feather the propeller to about 85° to 90° where it will stop turning and at the same time have a very low drag.

THE USE OF PROPELLER BRAKING EFFECT IN REDUCING DIVING SPEEDS

The rapid development in the aerodynamic cleanness of modern airplanes has resulted in a large increase in their terminal diving speeds; in fact, it is questionable whether some of them could resist the destructive forces to which such a dive would subject them. Most airplanes are not called upon to make such dives but in certain military maneuvers, such as dive bombing, the vertical or nearly vertical dive is a routine requirement.

The accuracy of dive bombing is adversely affected by the high diving speeds, and various methods of slowing up the dive have been considered. Some of these methods depend upon a split structural surface, such as a strut or wing flap, which opens up to produce an effective air brake.

The airplane is already equipped with a convenient and very rugged mechanism for producing a large positive or negative thrust. The controllable propeller, if set at low blade angles, will provide a very effective air brake, as is shown by the curves in figure 16. The curves were obtained from the test data by a method that will shortly be explained. They represent the terminal velocity and engine speed for the modern pursuit airplane, shown in figure 17, for various blade-angle settings of its 3-blade controllable propeller. The effects of compressibility on both airplane and propeller have been neglected. In the important part of the curves (low blade angles), these effects are small.

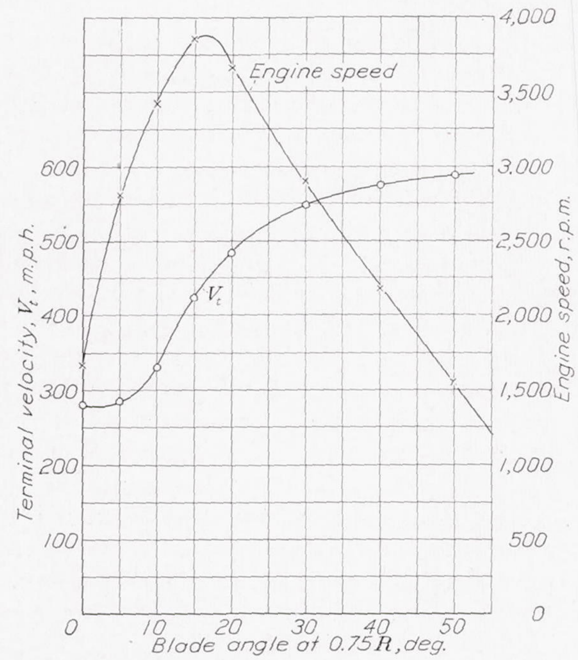


FIGURE 16.—Calculated values of terminal velocity and engine speed for a modern pursuit airplane. Vertical descent; 8,000-foot altitude; 3-blade propeller.

This airplane with its propeller set at 35° has a terminal velocity of 565 miles per hour; whereas at 2° its velocity has dropped to 277 miles per hour, or to 49 percent of its value at 35°. It will be noticed that the engine speed rises to excessive values at blade angles around 15°. These destructive engine speeds can be avoided by setting the blade angle somewhere between 5° and 0° before the dive is started, indicating that a quick-acting pitch-control mechanism would be advantageous.

If still more braking effect is required, the propeller may be set to negative angles and engine power applied.

Method of calculating V_t.—Although the method of calculating terminal velocity still remains a cut-and-try process, it is made considerably easier by the use of the relation $\frac{Q_f}{N_e}=K$ and the coefficient Q_n. The basic formula for a vertical dive is as follows:

$$V_t=\sqrt{\frac{W}{\frac{\rho}{2}A+KT_c}}$$

where

V_t, terminal velocity, f. p. s.
W, weight of airplane, lb.
$K=\rho D^2$
$A=\left(\frac{\text{parasite drag}}{\frac{1}{2}\rho V^2}\right)$, equivalent parasite area.

From this formula, V_t may be calculated as follows:

1. Knowing Q_f/N_e (from fig. 14), estimate a value of V_t and calculate Q_n.
2. From suitable charts (figs. 3 to 9) obtain a value of T_c for the desired blade angle.
3. Substitute T_c in terminal-velocity formula and obtain V_t calculated.
4. If V_t estimated does not equal V_t calculated, make a new estimate and repeat.

With a little experience two trials should be sufficient. The value of engine speed is obtained in the usual way from the value of nD/V (such as point D′, fig. 7).

Stability in dive.—The destabilizing effect of a braking propeller is frequently brought up as an argument against the use of the propeller as a brake in reducing the terminal velocity of airplanes. The question will be briefly considered here in relation to the directional stability of the airplane. The stability in pitch presents a similar problem that may become critical if the center of gravity is displaced far from the thrust axis.

In a vertical dive with braking propeller, the negative thrust of the propeller will normally act upward in the vertical plane through the center of gravity. If a small displacement in yaw occurs, as shown in figure 17, the thrust and gravity forces will produce an upsetting couple that must be balanced by a lateral aerodynamic force on fin and fuselage. The situation is aggravated by the loss of energy in the slipstream, which usually passes over the tail surfaces.

An examination of forces and moments acting on the airplane, the diving characteristics of which are shown in figure 16, will be given as an example.

The upsetting-moment slope for a small displacement is given by the relation

$$\left(\frac{dN}{d\psi}\right)_u=\frac{T_e r_1}{57.3}$$

where

N, yawing moment, ft.-lb.
ψ, angle of yaw, deg.
r_1, distance from center of gravity to propeller disk, 6.5 ft.

For the airplane operating with a blade angle of 5°,

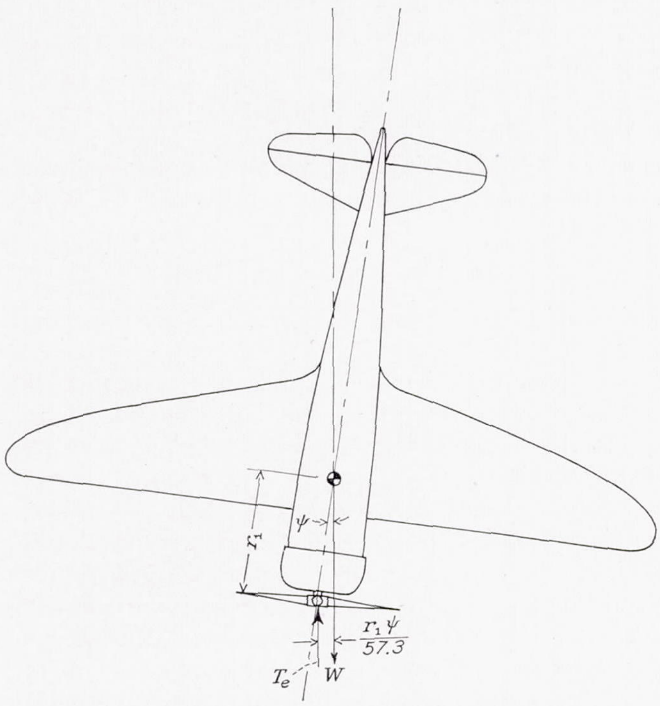


FIGURE 17.—Airplane in vertical dive showing unstable effect caused by propeller when used as a brake. Span, 35 feet; weight, 4,500 pounds; propeller diameter, 10 feet; 3 blades.

$T_e=2T_cD^2q_0$, where T_c is -0.106, D is 10 feet, and q_0 is the dynamic pressure.

Therefore

$$\left(\frac{dN}{d\psi}\right)_u=\frac{2\times-0.106\times10^2\times6.5}{57.3}q_0=-2.4q_0$$

The normal stabilizing yawing moment for this airplane may be taken from Diehl (reference 7) who gives as a reasonable value for directional stability:

$$\left(\frac{dN}{d\psi}\right)_r=0.00005\times Wbq_1$$

where

W is the weight.
b, the span.
and q_1, the dynamic pressure.

For this example

$$\left(\frac{dN}{d\psi}\right)_r=7.9q_1$$

Owing to the reduced velocity in the slipstream of the braking propeller, $q_1 < q_0$ so that the upsetting-moment and the righting-moment slopes, as expressed in the foregoing formulas, cannot be directly compared.

The ratios of these two values of q may be obtained from the following slipstream-velocity formula:

$$\frac{q_1}{q_0}=\frac{w^2}{V^2}=1+2.545T_c$$

where w is the air velocity in the slipstream and V is the velocity of the airplane, which in this example is 285 miles per hour.

For this airplane, then,

$$\frac{q_1}{q_0}=1+(2.545\times -0.106)=0.73$$

Therefore

$$\left(\frac{dN}{d\psi}\right)_r=7.9\times 0.73\times q_0=5.77q_0$$

and the resulting slope of the yawing-moment curve with the propeller operating as a brake is

$$\frac{dN}{d\psi}=\left(\frac{dN}{d\psi}\right)_r+\left(\frac{dN}{d\psi}\right)_u=5.77q_0-2.4q_0=3.37q_0$$

and the airplane is found to be stable by a good margin. From this brief analysis, one should say that little trouble from directional instability will be encountered in a dive where the propeller is being used as a brake unless the airplane was originally designed with little lateral stability.

This conclusion seems to agree with the evidence obtained in the dive tests reported in reference 2, where no instability was noted even when the propeller was producing its maximum braking effect. This evidence, however, must not be taken as entirely conclusive, for it represents only two specific examples. It is conceivable that conditions of airplane weight, propeller-braking effect, and the basic stability of the airplane could be such that trouble from directional instability might be difficult to avoid.

GLIDE CONTROL AND REDUCTION IN LANDING RUN

There are a number of situations in the flight range of every airplane where an air brake could be used to advantage. With the great increase in functional flexibility given to the propeller through recently acquired control mechanism, the propeller now provides an ideal air brake; if the propeller is set at negative blade angles and engine power is applied, it becomes a powerful, though nicely controlled, power brake, which need not rely on the speed of the airplane for braking power.

One situation in which a power brake could be used to advantage on an airplane is in the glide to a landing and also during the landing ground run. In these situations it is conceivable that the use of the propellers as brakes would find its best application in multiengine airplanes. Consider, for example, the new 4-engine transport and bombing airplanes. The landing distance of such airplanes is excessive and only a certain few fields throughout the country are large enough to accommodate them. It is entirely possible that their landing distances (glide over 50-foot obstacle+ground run) could be reduced one-third to one-half by the use of propeller braking power. The blade angles of the two outboard propellers could be set to negative values of 15° or 20° before the landing glide started and the blade angles of the inboard propellers left in their normal take-off position so that in an emergency the airplane could fly off again on these two engines. By a differential use of the throttles for the inboard (thrust-producing) and outboard (braking) engines a very nice control of the glide path could be obtained, thus making spot landings possible and making the best use of landing-field size.

Once on the ground the pilot could open his braking engines wide and reduce the ground run by a large amount. The sum of both of these maneuvers would reduce the landing distance by 25 to 50 percent. There is a possibility, of course, that the reduced velocity in the slipstream of the braking propellers might have a bad effect on the wing lift or on the cooling of the engines.

The following table presents the results of landing-run calculations that were made to show the effect on the total distance to land over a 50-foot obstacle of using the propellers as power brakes. The example airplane was a fictitious 4-engine transport having a gross weight of 32,000 pounds and a landing speed of 100 feet per second. Calculations were made for two conditions of landing, as follows: (1) where the propellers were producing no thrust or drag during the glide and ground run; and (2) where the four propellers were producing thrust as indicated in figure 18, i. e., the inboard propellers producing zero thrust and the outboard propellers 2,000 pounds negative thrust each. The value of $L/D=8$ was assumed for landing, with flaps and landing gear down and no propeller thrust.

Case	γ	l_1 (ft.)	l_2 (ft.)	l_1+l_2 (ft.)	Ratio
1	7° 8′	400	1, 900	2, 300	1. 00
2	14° 2′	200	1, 260	1, 460	. 63

In the foregoing table γ is the gliding angle; l_1 is the distance from the obstacle to the point of contact with the ground; and l_2 is the ground run. In the last column, the ratio of the total distance to the total distance for case 1 is shown. It is observed that in this case the glide angle has been nearly doubled and the total landing distance reduced by 37 percent by the use of propellers as power brakes. If all four propellers had been used as brakes, the landing distance could have been reduced still more.

LONG-RANGE OPERATION

A difficult problem in the design of efficient long-range airplanes is that of obtaining sufficient power for the take-off and at the same time obtaining a low rate of fuel consumption at the low power output necessary for cruising at maximum *L/D*. Frequently the engines are throttled so much at cruising speed that high rates of fuel consumption result. Several methods of combating this difficulty are available, three of which follow:

1. By the use of catapults, which is perhaps the most efficient method but requires an elaborate outlay of equipment.

2. By designing for high-altitude flight, where maximum *L/D* occurs at higher velocities. The gain here must be paid for in terms of supercharger power for engines and cabin, added supercharger, propeller, and structural weight.

3. By the use of a controllable propeller, the blade angles for cruising may be increased and at the same time the throttle opened to maintain the desired engine speed. This method is frequently used but its use is limited by engine-operating restrictions and by the fact that it usually entails a loss in propeller efficiency, which tends to offset the lower rate of fuel consumption.

As indicated, these methods have their limitations and it is not the purpose of this report to take them up in detail. It is not out of place, however, to suggest another, though not a new method, which has some connection with the subject of this report.

This plan, applicable to multiengine airplanes, consists merely in cutting out one or more engines after the take-off has been accomplished and feathering the dead-engine propellers to some angle around 85° to 90° where they will not turn and where the power required to overcome their drag will be very small. Combining this method with method 3 should result in a worthwhile decrease in fuel load and a corresponding increase in pay load over that obtained with method 3 alone.

Consider, as an example, the case of a 4-engine flying boat having a high speed of 190 miles per hour but which, in long transoceanic flights, cruises at 35 percent power at a speed of about 125 miles per hour. Other specifications for the airplane are as follows:

Engines (4)—rated 850 horsepower at 1,450 r. p. m.

Propellers—3 blades; 11-foot diameter; controllable through 90°.

In long-distance cruising, assume that the engine speed is reduced to 950 r. p. m., or 65.5 percent of rated speed, and that the propeller and the throttle are adjusted to give 53.4 percent of rated torque. The cruising power is then 35 percent of rated power and the rate of fuel consumption (from fig. 7 of reference 8) is found to be 0.56 pound per horsepower-hour. The propeller efficiency for cruising is 84 percent.

Now assume that two engines are cut out and their propellers set at 90°. The torque of the other engines is raised to 80 percent of rated torque and the engine speed to 1,270 r. p. m., or 87.5 percent of rated speed. The cruising power is now 70 percent of the rated power but the propeller efficiency drops to 82 percent. The fuel consumption, however, drops to 0.485 pound per horsepower-hour. The two dead propellers absorb 18 horsepower, which is equivalent to decreasing the efficiency of the working propellers by 1.5 percent or to a value of 82—1.5=80.5 percent. The required fuel load for the two cases is directly proportional to their specific fuel consumptions and inversely proportional to their propeller efficiencies, so that the required fuel load with the two engines dead is $\frac{0.485}{0.56}\times\frac{84.0}{80.5}=90.5$ percent of the fuel load required for the normal cruising condition. The 9.5 percent saving in fuel load (or increase in pay load) would amount to about 950 pounds on a 2,000-mile flight. The results of such a comparison depend a great deal on the assumed values of engine torque and engine speed; however, in this example the assumed values of these variables are considered reasonable. Other cases may be found where the saving is either greater or less than in this example.

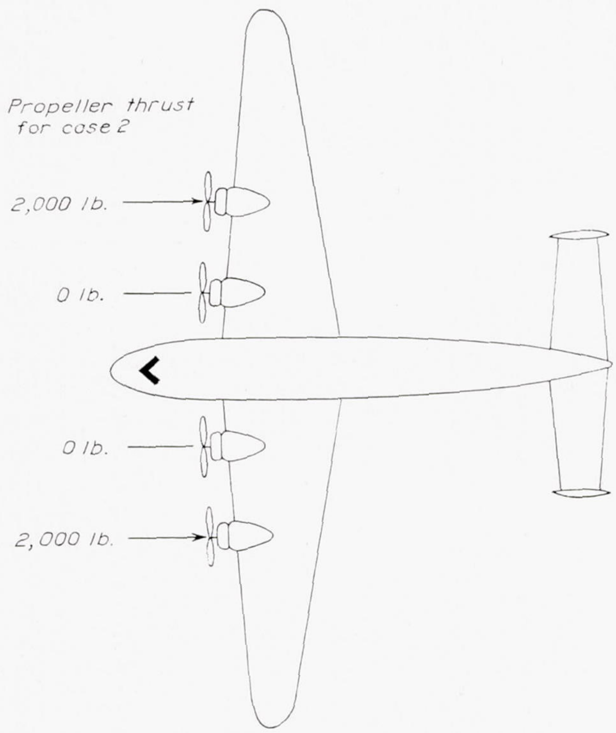


FIGURE 18.—Illustration of method of using propellers as power brakes to reduce landing distance. Gross weight, 32,000 pounds; landing speed, 100 feet per second.

An obvious disadvantage of this method is the increased wear on the operating engines, though this disadvantage may be offset by the absence of wear on the dead engines.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *November 15, 1937.*

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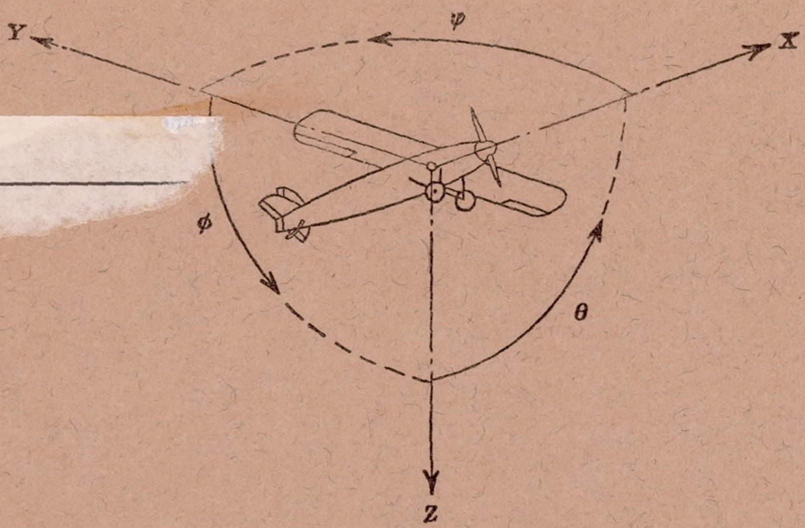
16.14 Reserves



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	[illegible]	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	[illegible]	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	[illegible]	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control s[illegible] (relative to neutral position), δ. (Indicate sur[illegible] by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coeffic[illegible] $C_P=\frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient [illegible]
η, Efficiency
n, Revolutions per second, [illegible]
Φ, Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp.=76.04 kg-m/s=550 ft-lb./sec.
1 metric horsepower=1.0132 hp.
1 m.p.h.=0.4470 m.p.s.
1 m.p.s.=2.2369 m.p.h.

1 lb.=0.4536 kg.
1 kg=2.2046 lb.
1 mi.=1,609.35 m=5,280 ft.
1 m=3.2808 ft.