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RESEARCH MEMORANDUM

AERODYNAMIC CHARACTERISTICS AT HIGH SPEEDS OF FULL-SCALE PROPELLERS HAVING DIFFERENT SHANK DESIGNS

By Julian D. Maynard

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

AERODYNAMIC CHARACTERISTICS AT HIGH SPEEDS OF FULL-SCALE PROPELLERS HAVING DIFFERENT SHANK DESIGNS

By Julian D. Maynard

SUMMARY

Tests of two 10-foot-diameter two-blade propellers which differed only in shank design have been made in the Langley 16-foot high-speed tunnel. The propellers are designated by their blade design numbers, NACA 10-(5)(08)-03, which had aerodynamically efficient airfoil shank sections, and NACA 10-(5)(08)-03R, which had thick cylindrical shank sections typical of conventional blades. The propellers were tested on a 2000-horsepower dynamometer through a range of blade angles from 20° to 55° at various rotational speeds and at airspeeds up to 496 miles per hour. The resultant tip speeds obtained simulate actual flight conditions, and the variation of air-stream Mach number with advance ratio is within the range of full-scale constant-speed propeller operation.

Both propellers were very efficient, the maximum envelope efficiency being approximately 0.95 for the NACA 10-(5)(08)-03 propeller and about 5 percent less for the NACA 10-(5)(08)-03R propeller. Based on constant power and rotational speed, the efficiency of the NACA 10-(5)(08)-03 propeller was from 2.8 to 12 percent higher than that of the NACA 10-(5)(08)-03R propeller over a range of airspeeds from 225 to 450 miles per hour. The loss in maximum efficiency at the design blade angle for the NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers was about 22 and 25 percent, respectively, for an increase in helical tip Mach number from 0.70 to 1.14.

The high drag of the thick inner sections of the NACA 10-(5)(08)-03R propeller was the chief source of efficiency loss, especially at high values of advance ratio corresponding to high forward speeds.

INTRODUCTION

The NACA has designed and constructed a series of full-scale 10-foot-diameter propeller blades to be used in an extensive research program for the purpose of improving the high-speed efficiency of propellers. The program includes investigations to determine the effect of:

Blade-shank design

Blade-section camber (or design lift coefficient)

Propeller solidity

Thickness ratio of the blade sections

Different blade sections (Clark-Y and NACA 16-series)

This program was first delayed by difficulties in the design and construction of a suitable dynamometer with which the full-scale propellers could be tested at high speeds. Subsequently, special war-time projects with higher priority delayed the tests, and an emergency program of tests was begun in the NACA 8-foot high-speed tunnel. These tests were made with model propellers 4 feet in diameter, and the results showing the effect of compressibility, solidity, and camber are reported in references 1, 2, and 3. Further tests of model propellers made in the 8-foot high-speed tunnel (reference 4) have shown that the highest propeller efficiency can be obtained only if the shanks are very broad and thin. Also, wake-survey measurements made in flight tests of one of the NACA designed propellers with round shanks (reference 5) have shown the importance of improving the shank sections of propellers used on high-speed airplanes.

Tests of the full-scale propellers are now being made in the Langley 16-foot high-speed tunnel and, because of the urgent need for design information, the data in the

present paper are presented to determine the effect of blade-shank design. A secondary purpose of the present paper is to compare values of propulsive efficiency as found in the model tests with values of propeller efficiency based on shaft tension as found in the full-scale tests.

The characteristics of two of the NACA propellers that differed only in shank design are presented for blade angles ranging from 20° to 55° at various rotational speeds and at airspeeds ranging from 60 to 496 miles per hour. The resultant tip speeds obtained simulate actual flight conditions, and the variation of air-stream Mach number with advance ratio is within the range of full-scale constant-speed propeller operation.

SYMBOLS

R	propeller tip radius
r	radius at any blade section
β	blade angle at any radius, degrees
$\beta_{0.75R}$	blade angle at 0.75 radius, degrees
c_{l_d}	blade-section design lift coefficient
h	blade section maximum thickness
b	blade width, chord
M	air-stream Mach number
M_t	helical tip Mach number $\left(M\sqrt{1+\left(\frac{\pi}{J}\right)^2}\right)$
V	airspeed, feet per second
n	propeller rotational speed, rps
D	propeller diameter, feet
J	propeller advance ratio (V/nD)

ρ mass density of air, slugs per cubic foot

T propeller thrust, pounds

C_T thrust coefficient $\left(T/\rho n^2 D^4\right)$

P power absorbed by the propeller, foot-pounds per second

C_P power coefficient $\left(P/\rho n^3 D^5\right)$

η propeller efficiency $\left(J\frac{C_T}{C_P}\right)$

APPARATUS

Propeller dynamometer.- A 2000-horsepower propeller dynamometer was used to test the propellers in the Langley 16-foot high-speed tunnel. The dynamometer is powered by two 1000-horsepower electric motors arranged in tandem and coupled for the present tests to allow the power of both motors to be expended through a single propeller. A variable-frequency power supply affords an accurate speed control from 300 to 2100 rpm with a permissible overspeed up to 2280 rpm. The motors are supported in a housing in such a way that their casings are free to rotate and also free to move axially with their shafts. The axial and rotational movements are restrained by pneumatic pressure capsules, thrust and torque being proportional to the pressure required to restrain the motion. Thrust pressure is indicated as thrust force by means of pneumatic scales and torque pressure as torque by means of liquid manometers. The dynamometer is calibrated with the propeller shaft rotating, and both thrust and torque measurements give straight-line calibrations. Figures 1 and 2 are photographs of the dynamometer mounted in the test section of the tunnel, and figure 3 is a sketch showing principal dimensions of the dynamometer fairing and spinner. The shape of the spinner and forebody is designed to produce uniform axial flow at free-stream velocity in the plane of the propeller. Pressure orifices are located between the stationary fairing and the propeller spinner to afford a correction for any change in pressure at the spinner-fairing juncture due to the propeller operation. The holes in the spinner

surface for the propeller blade shanks are made very small (fig. 1) but are not sealed. The diameter of the propeller spinner is 21.7 percent of the diameter of a 10-foot propeller.

Propeller blades.- The two-blade propellers tested are designated herein by their blade design numbers, NACA 10-(5)(08)-03 and NACA 10-(5)(08)-03R. The digits of the blade design numbers have the following significance: The digits in the first group of numbers represent the propeller diameter in feet, the digit in the first parenthesis is ten times the basic design lift coefficient, the digits in the second parenthesis are the thickness ratio in percent at the 0.7 radius, and the digits in the third group represent the solidity per blade at the 0.7 radius. The letter R indicates a blade with a conventional cylindrical shank. The NACA 16-series blade sections are used, and the NACA 10-(5)(08)-03 propeller is designed to obtain very high aerodynamic efficiency, all but the most elementary strength considerations being disregarded. Efficient airfoil sections extend to the spinner surface for this propeller, which is designed to have the Betz minimum induced-energy-loss loading (reference 6) when operating at a blade angle of 45° at the 0.7 radius and an advance ratio of 2.1. The design procedure used consists in finding the optimum loading with profile drag assumed to be zero and then determining the best blade shape for that loading when a thickness distribution is assumed. The NACA 10-(5)(08)-03R propeller represents a structural compromise having cylindrical shanks typical of conventional propellers. The Betz load distribution is maintained except for sections near the spinner surface. Blade-form curves for the two designs are shown in figure 4, and figures 5 and 6 are photographs of the blades. A comparison of the shank sections at two radii is shown in figure 7.

TESTS

Thrust, torque, and rotational speed were measured for each propeller during tests at blade angles of 20°, 25°, 30°, 35°, 40°, 45°, 50°, and 55° at the three-quarter (45-inch) radius. A constant rotational speed was used for most of the tests, and a range of advance ratio $\left(J = \frac{V}{nD}\right)$ was covered by changing the tunnel

airspeed, which could be varied from about 60 to 496 miles per hour. At the higher blade angles the complete range of advance ratio could not be covered at the higher rotational speeds because of power limitations. In order to obtain propeller characteristics at maximum tunnel airspeeds a blade angle (45°) was chosen for which the peak efficiency operating condition could be attained when the tunnel airspeed was a maximum and the dynamometer was operating at its maximum power and rotational speed. For these tests at a blade angle of 45° the rotational speed was varied to obtain data from peak efficiency to the zero-torque operating condition. The range of blade angles covered at the various rotational speeds used in the tests of the two propellers is given in table I.

REDUCTION OF DATA

The test results corrected for tunnel-wall interference and for forces acting on the spinner are presented in the form of the usual thrust and power coefficients and propeller efficiency.

Definition of propeller thrust.- Propeller thrust, as used herein, is defined as the shaft tension caused by the spinner-to-tip part of the blade rotating in the air stream. The indicated propeller thrust has been corrected by the amount of the tare thrust found in operating the dynamometer and spinner without propeller blades at the same values of airspeed as were used in the propeller tests. A further correction was made for the influence of the pressure field of the propeller acting at the juncture between the spinner and the stationary fairing. The change in spinner thrust due to a change in pressure at the spinner-fairing juncture varied with propeller operating conditions and was determined from pressure measurements in the juncture between the propeller spinner and the fixed fairing at the rear of the spinner. Values of thrust coefficient were changed an average of 0.001 by this correction to the spinner thrust.

Correction for wind-tunnel-wall interference.- A correction has been applied to the tunnel datum velocity to obtain the corresponding free-stream airspeed. This correction is necessary because the flow past the propeller is constrained by the walls of the tunnel, and the

axial velocity which occurs in front of the propeller in the wind tunnel differs from that which would occur in free air under the same operating conditions. This equivalent free airspeed has been determined experimentally and was found to agree well with values calculated from Glauert's equation (reference 7); hence, only the theoretical correction has been used for the data obtained in these tests. Also an investigation has been made (reference 8) which indicates that no tunnel-wall effects of significant magnitude exist other than those for which Glauert's correction is applied. The maximum correction for any condition of operation was approximately 7 percent (highest value of thrust coefficient for the lowest value of advance ratio), but for the peak efficiency condition the correction for wind-tunnel wall interference amounted to less than 2.2 percent at all values of advance ratio above 0.7 and to less than 1 percent at values above 1.2.

RESULTS AND DISCUSSION

Faired curves of thrust coefficient, power coefficient, and propeller efficiency plotted against advance ratio are presented in figures 8 through 16 for the NACA 10-(5)(08)-03 propeller and in figures 17 through 22 for the NACA 10-(5)(08)-03R propeller. Test points are shown on the figures giving thrust and power coefficients. The variation of air-stream Mach number and helical tip Mach number with advance ratio is shown on the figures giving propeller efficiency.

In the tests of the NACA 10-(5)(08)-03 propeller at a rotational speed of 1140 rpm a blade-flutter condition was encountered for blade angles of 45° and 50°. The flutter was detected by sound and occurred when the blades were operating in a stalled condition as shown in figure 8.

Several tests were repeated during the test program and the results obtained agreed with the results presented within 1 percent. For purposes of comparison, therefore, the data are considered accurate to within 1 percent and the faired envelopes are believed to be accurate to within much closer limits.

Effect of shank design on maximum efficiency.- The envelope curves of propeller efficiency at the different test rotational speeds are shown in figure 23 for the NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers. The curves show high efficiencies for both propellers, particularly at a rotational speed of 1350 rpm. At this rotational speed the NACA 10-(5)(08)-03 propeller has an envelope efficiency of slightly more than 0.95 at an advance ratio of 2.1. The envelope efficiency of the cylindrical-shank propeller (0.90) is about 5 percent less at the same value of advance ratio and rotational speed. This difference is in agreement with the results reported in reference 4. At 2160 rpm and an advance ratio of 1.1 the difference in maximum efficiency of the two propellers is about 6 percent. This comparison shows that at the lower advance ratios (corresponding to low forward speeds) a large increase in rotational speed has only a small effect on the loss in efficiency caused by the inefficient shank sections of the NACA 10-(5)(08)-03R propeller. This effect was also shown in the flight tests reported in reference 5.

Although there is some difference in the thrust coefficients at maximum efficiency for the two propellers, the lower efficiency of the NACA 10-(5)(08)-03R propeller is due principally to the higher power coefficients at maximum efficiency. A comparison of the power-coefficient curves in figure 18(b) with those in figure 9(b) shows that the values of power coefficient for maximum efficiency are higher for the propeller with cylindrical shanks than for the propeller with efficient airfoil shanks, and the difference increases with increasing values of advance ratio. (Similar results were reported in reference 4.) Since both propellers were designed to have the Betz minimum induced-energy-loss loading when operating in the region of peak efficiency, the difference in power coefficients for maximum efficiency may be attributed primarily to differences in profile drag of the blade sections at the inner radii. The results of computations presented in reference 6 show that profile drag has a large effect on the optimum plan form. Losses in efficiency due to profile drag show up as direct power losses and also as a correction (probably small) to the induced losses due to distortion of the wake.

In figure 24 the envelope curves of propeller efficiency for the NACA 10-(5)(08)-03 and 10-(5)(08)-03R

propellers at 1350 rpm are compared with the optimum efficiency of a propeller with the Betz minimum induced-energy-loss loading. The curve of optimum efficiency was calculated by a method neglecting all profile-drag losses (reference 9) for a two-blade propeller operating at the same values of power coefficient as were obtained with the NACA 10-(5)(08)-03 propeller. The curves in figure 24 show that the profile-drag losses are approximately 3 to 5 percent greater for the cylindrical-shank propeller than for the propeller with efficient airfoil shanks, and the difference increases with increasing values of advance ratio and forward speeds. The efficiency loss due to profile drag for the propeller with efficient airfoil shanks is very small. This result is in agreement with the theoretical analyses of propeller power losses presented in references 6 and 9, which show that the thick inner sections of conventional cylindrical-shank propellers are the chief source of blade-drag loss, especially at high values of advance ratio.

The highest efficiency (approximately 0.95) shown in figure 24 for the NACA 10-(5)(08)-03 propeller may not be achieved unless the gap between the spinner surface and the wide shanks is kept very small, as was done in the wind-tunnel tests. This would be difficult to accomplish for an actual installation of a variable pitch propeller on an airplane, but some means should be devised whereby wide thin blade-root sections could be extended to the spinner surface. The differences between the efficiencies of the NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers are sufficient to warrant considerable effort in overcoming both the structural and the blade-spinner-juncture problems encountered for a practicable design using the shank sections of the NACA 10-(5)(08)-03 propeller.

Effect of compressibility on maximum efficiency.- The variation of envelope efficiency with helical tip Mach number is shown in figure 25 for the NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers at the different test rotational speeds. The variation of air-stream Mach number with helical tip Mach number at each rotational speed is also shown on figure 25. A curve joining the peaks of the efficiency envelopes for each propeller would show the maximum efficiency obtainable at any combination of rotational speed and air-stream Mach number. Unfortunately, the envelope peaks at some of the higher rotational speeds were not definitely established because of the power

limitations previously mentioned. At an air-stream Mach number of 0.35 the envelope efficiency of the NACA 10-(5)(08)-03 propeller dropped 11 percent for a change in helical tip Mach number from 0.90 to 1.08. The corresponding loss in envelope efficiency for the cylindrical-shank propeller was about 12 percent. For a constant rotational speed the envelope curves of propeller efficiency for the two propellers diverge as the helical tip Mach number increases with airspeed. At a constant rotational speed of 1140 rpm the difference between the envelope efficiency of the NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers increased 4 percent for a change in helical tip Mach number from 0.60 to 0.75. This comparison clearly shows the superiority of the propeller with aerodynamically efficient airfoil shanks at high values of advance ratio and forward speeds and also shows that the losses due to inefficient shank sections of conventional constant-speed propellers may be considerable at low values of helical tip Mach number.

The familiar loss in maximum efficiency due to compressibility is shown in figure 26 for the two propellers tested at a blade angle of 45° at the 0.75 radius. The data for the higher helical tip Mach numbers were obtained from the results presented in figures 16 and 22. The maximum efficiency of the NACA 10-(5)(08)-03 propeller decreased from about 0.95 at a helical tip Mach number of 0.70 to 0.73 at a helical tip Mach number of 1.14. The critical tip Mach number for this 22 percent loss was about 0.83. The corresponding decrease in maximum efficiency for the NACA 10-(5)(08)-03R propeller was from 0.90 to 0.65, or a loss of 25 percent. The critical tip Mach number for the cylindrical-shank propeller was also about 0.83. At the highest helical tip Mach number obtained in the tests ($M_t = 1.23$) the maximum efficiency of the NACA 10-(5)(08)-03R propeller was only 0.57. In figure 26 the variation of maximum efficiency with helical tip Mach number for a model propeller (NACA 4-(5)(08)-03, reference 3) is shown for comparison. The difference in critical tip Mach number for the full-scale and model propellers is perhaps due to the difficulty in definitely establishing this point from the available data and does not necessarily indicate serious discrepancies in the data. It should be pointed out, however, that the full-scale tests were extended to include higher helical tip Mach numbers than those obtained in the model tests.

Constant-power propeller operation.- Airplane propellers often operate over an extensive range of advance ratio at constant rotational speed and torque. Since the power-absorption qualities of the NACA 10-(5)(08)-03 propeller differed from those of the NACA 10-(5)(08)-03R propeller, the data were analyzed at several values of constant power coefficient for a constant rotational speed of 1140 rpm. The results of this analysis, presented in figure 27, provide a better comparison of the efficiency of the two propellers than one based on advance ratio alone. At a power coefficient of 0.15 (0.075 per blade) the efficiency of the NACA 10-(5)(08)-03R propeller is almost the same as for the NACA 10-(5)(08)-03 propeller at an advance ratio of 0.9, but at an advance ratio of 3.5 the efficiency of the cylindrical-shank propeller is 14 percent less than the efficiency of the propeller with efficient airfoil shanks. Similar results were reported in reference 4 and were explained by the difference in load distribution shown by wake surveys. The low load-carrying capacity of the cylindrical shank sections of conventional propellers makes it necessary for the more efficient outboard sections to carry more load, which may be accomplished at low speeds without serious detrimental effects. At high speeds, however, the high thrust loads for the sections of the propeller that have the higher resultant section speeds will cause earlier adverse compressibility effects or stall of these sections. The effect of increasing the value of constant power coefficient was similar for both propellers; the efficiency was decreased at the lower advance ratios and was increased at the higher advance ratios. This effect is characteristic for all propellers, and the superiority of the NACA 10-(5)(08)-03 propeller over the NACA 10-(5)(08)-03R propeller is definitely illustrated for both climb and high-speed conditions of operation. In figure 28 the difference in efficiency between the two propellers for a constant rotational speed of 1140 rpm and a constant power coefficient per blade of 0.1 is shown over a range of airspeeds from 225 to 450 miles per hour. Over this range of airspeeds the helical tip Mach number did not exceed 0.79, and the NACA 10-(5)(08)-03 propeller was from 2.8 to 12 percent more efficient than the NACA 10-(5)(08)-03R propeller.

Comparison with results from model tests.- The model of the NACA 10-(5)(08)-03 propeller was tested in the Langley 8-foot high-speed tunnel, and the results are

presented in reference 3. The data from the tests of this model propeller, which was 4 feet in diameter (NACA 4-(5)(08)-03 propeller), have been compared with the data from the tests of the full-scale propeller. Figure 29 shows a comparison of the envelope efficiencies of the full-scale and model propellers over a range of air-stream Mach numbers from 0.175 to 0.56. The envelope efficiency of the full-scale propeller is higher than that of the model propeller by $1\frac{1}{2}$ to $\frac{1}{2}$ percent over the range of advance ratio from about 0.8 to 2.8. The differences over most of this range of advance ratio are perhaps within the limits of experimental accuracy of the two sets of data, but the differences in envelope efficiency may possibly be explained as follows:

(1) The values of thrust for the full-scale propeller are based on shaft tension, whereas the values for the model propeller are based on propulsive thrust and no allowance is made for the change in skin friction due to the propeller operation.

(2) The Reynolds numbers for the model tests were lower than those for the full-scale tests.

(3) The spinner diameter was 0.217 of the propeller diameter in the full-scale tests and 0.333 of the propeller diameter in the model tests.

The characteristics of the full-scale and model propellers are compared in figure 30 by curves showing the variation of power coefficient with thrust coefficient at several blade angles for three values of constant air-stream Mach number. Such a comparison eliminates discrepancies which might show up as a result of a slight difference in blade-angle setting. The curves for the two propellers are in close agreement, particularly in the range of maximum efficiency.

CONCLUSIONS

High-speed wind-tunnel tests of two full-scale two-blade propellers have been made for a range of blade angles from 20° to 55° at airspeeds up to 496 miles per hour. The propellers are designated by their blade design numbers, NACA 10-(5)(08)-03, which has

aerodynamically efficient airfoil shank sections, and NACA 10-(5)(08)-03R, which has thick cylindrical shank sections typical of conventional blades. The results of these tests and comparisons with results obtained from previous tests of a model propeller (NACA 4-(5)(08)-03 propeller) led to the following conclusions:

1. The NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers are very efficient, particularly for the design condition of operation. At a rotational speed of 1350 rpm the NACA 10-(5)(08)-03 propeller has an envelope efficiency of approximately 0.95 at an advance ratio of 2.1. The envelope efficiency of the 10-(5)(08)-03R propeller is about 5 percent less at the same value of advance ratio and rotational speed.

2. Based on constant power absorption (power coefficient of 0.1 per blade) and constant rotational speed (1140 rpm) the NACA 10-(5)(08)-03 propeller is from 2.8 to 12 percent more efficient than the NACA 10-(5)(08)-03R propeller over a range of airspeeds from 225 to 450 miles per hour. For this rotational speed and range of airspeeds the helical tip Mach number does not exceed 0.79.

3. The critical tip Mach number for maximum efficiency at the design blade angle of 45° is approximately 0.83 for both the NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers.

4. The loss in maximum efficiency at the design blade angle of 45° for the NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers is about 22 and 25 percent, respectively, for an increase in helical tip Mach number from 0.70 to 1.14.

5. The high drag of the thick inner sections of the NACA 10-(5)(08)-03R propeller was the chief source of efficiency loss, especially at high values of advance ratio corresponding to high forward speeds.

6. The envelope efficiency obtained for the full-scale propeller, NACA 10-(5)(08)-03, is higher than the envelope efficiency obtained for the model propeller, NACA 4-(5)(08)-03, by only $1\frac{1}{2}$ to $\frac{1}{2}$ percent over a range of air-stream Mach numbers from 0.175 to 0.56.

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TABLE I

RANGE OF BLADE ANGLE AND ROTATIONAL SPEED

Figure	Rotational Speed (rpm)	Blade Angle at 0.75 radius, $\beta_{0.75R}$ (deg)							
NACA 10-(5)(08)-03 propeller									
8	1140				35	40	45	50	55
9	1350	20	25	30	35	40	45	50	
10	1500						45		
11	1600	20	25	30	35	40	45		
12	1800	20	25	30	35	40			
13	2000	20	25	30	35				
14	2100	20	25	30					
15	2160	20	25	30					
16	Varied						45		
NACA 10-(5)(08)-03R propeller									
17	1140				35	40	45	50	55
18	1350	20	25	30	35	40	45	50	
19	1500						45		
20	1800	20	25	30	35	40			
21	2160	20	25	30					
22	Varied						45		

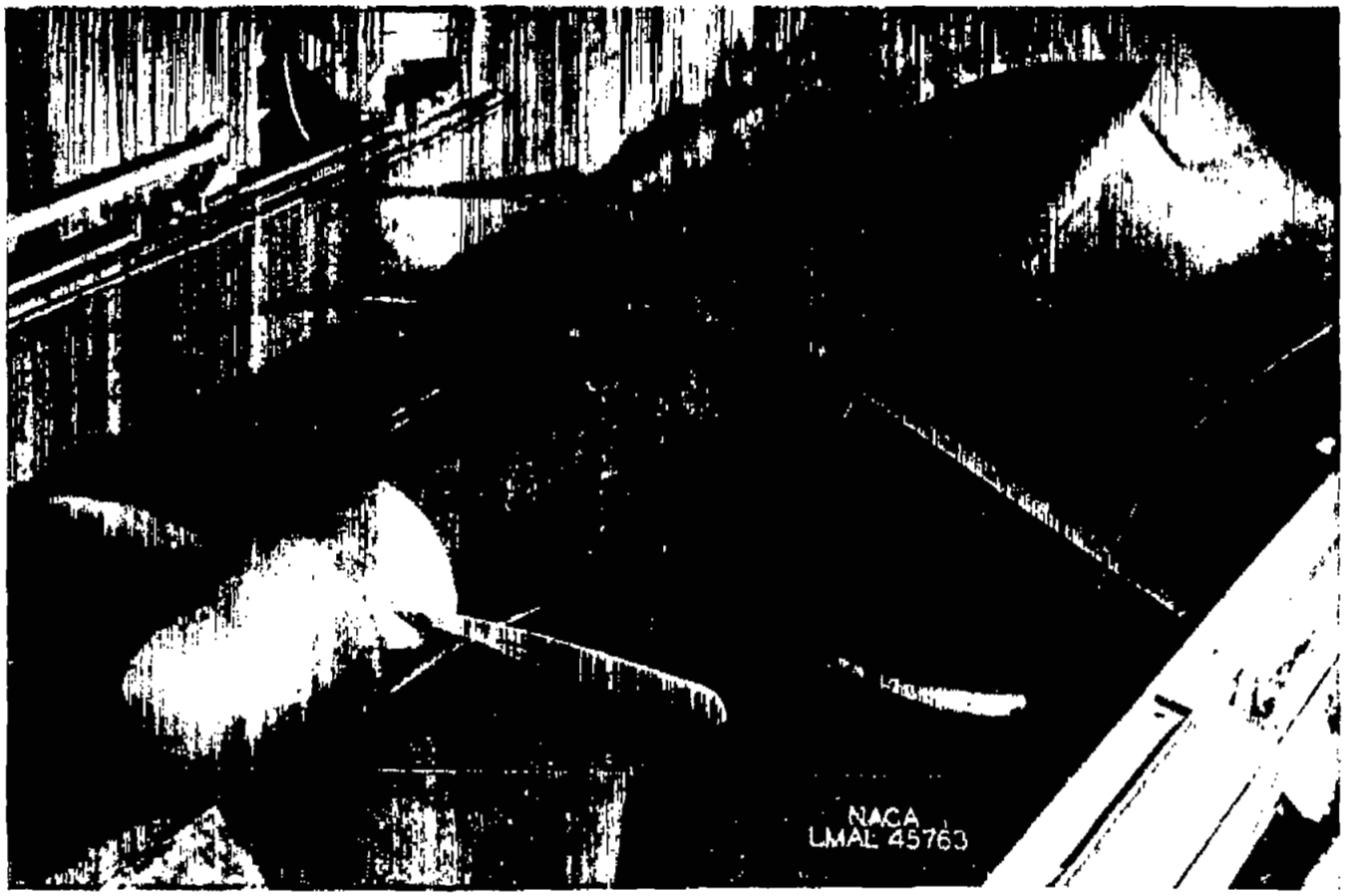

Figure 1.- NACA 10-(5)(08)-03 propeller mounted on dynamometer in test section with tunnel open.

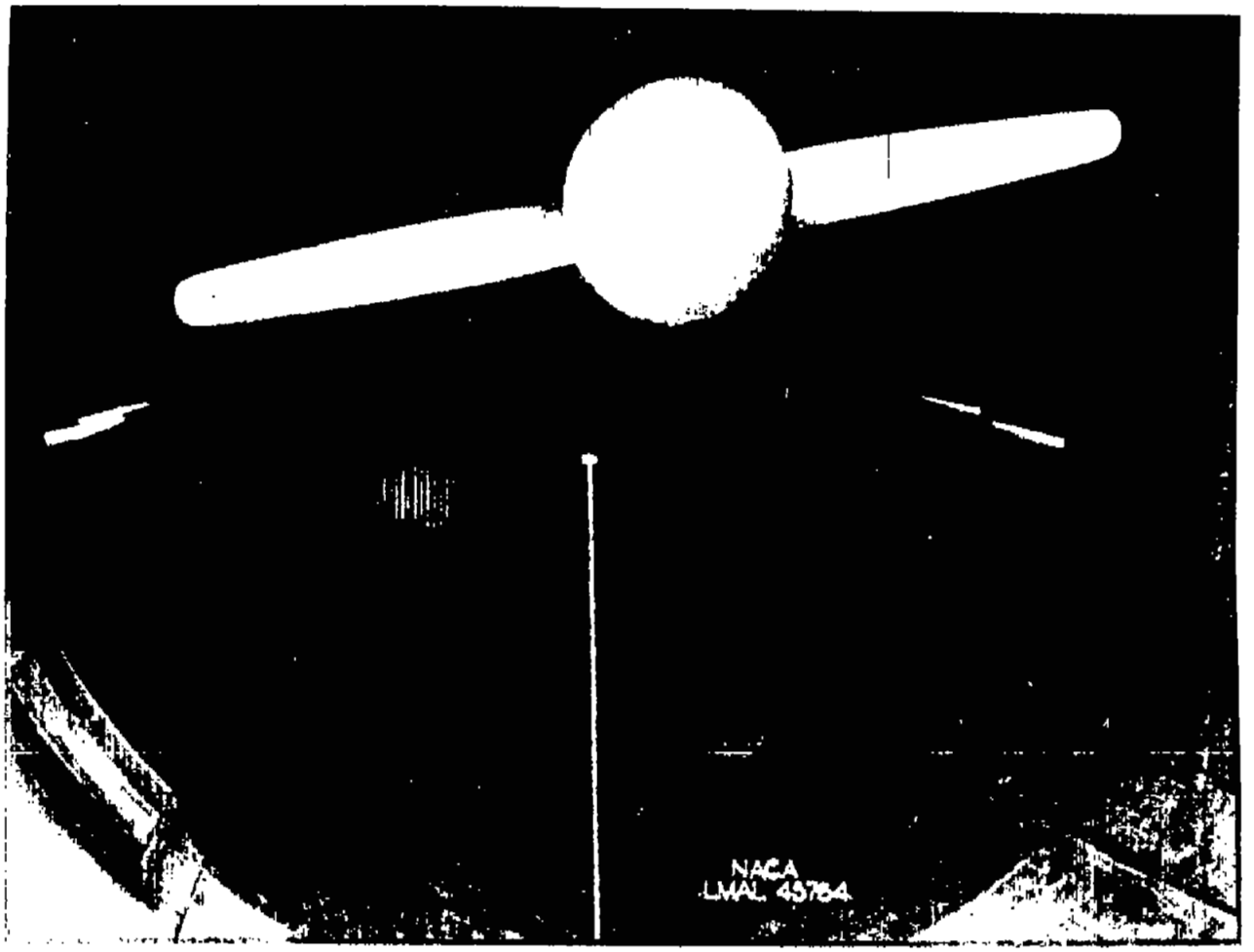

Figure 2.- NACA 10-(5)(08)-03 propeller mounted on dynamometer in test section with tunnel closed.

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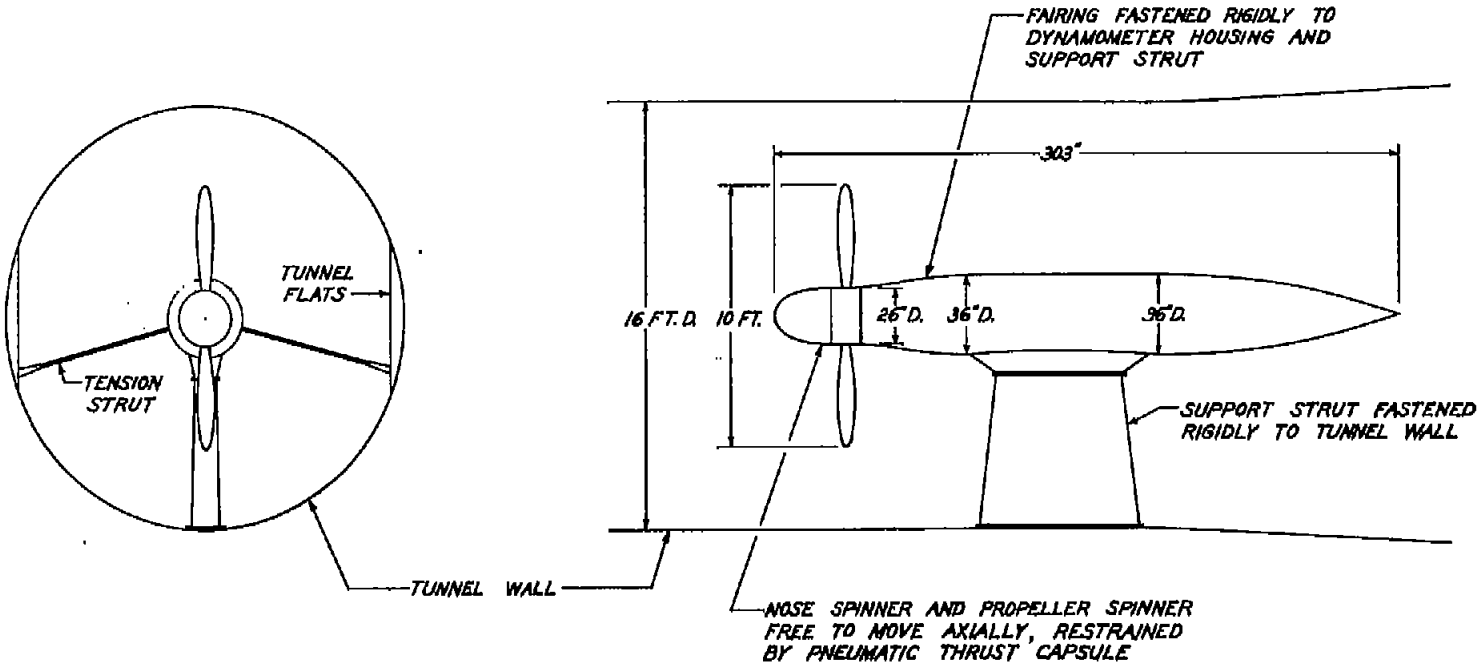

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FIGURE 3.— CONFIGURATION OF DYNAMOMETER FOR TESTS OF NACA 10-(5)(08)-03 AND 10-(5)(08)-03R PROPELLERS.

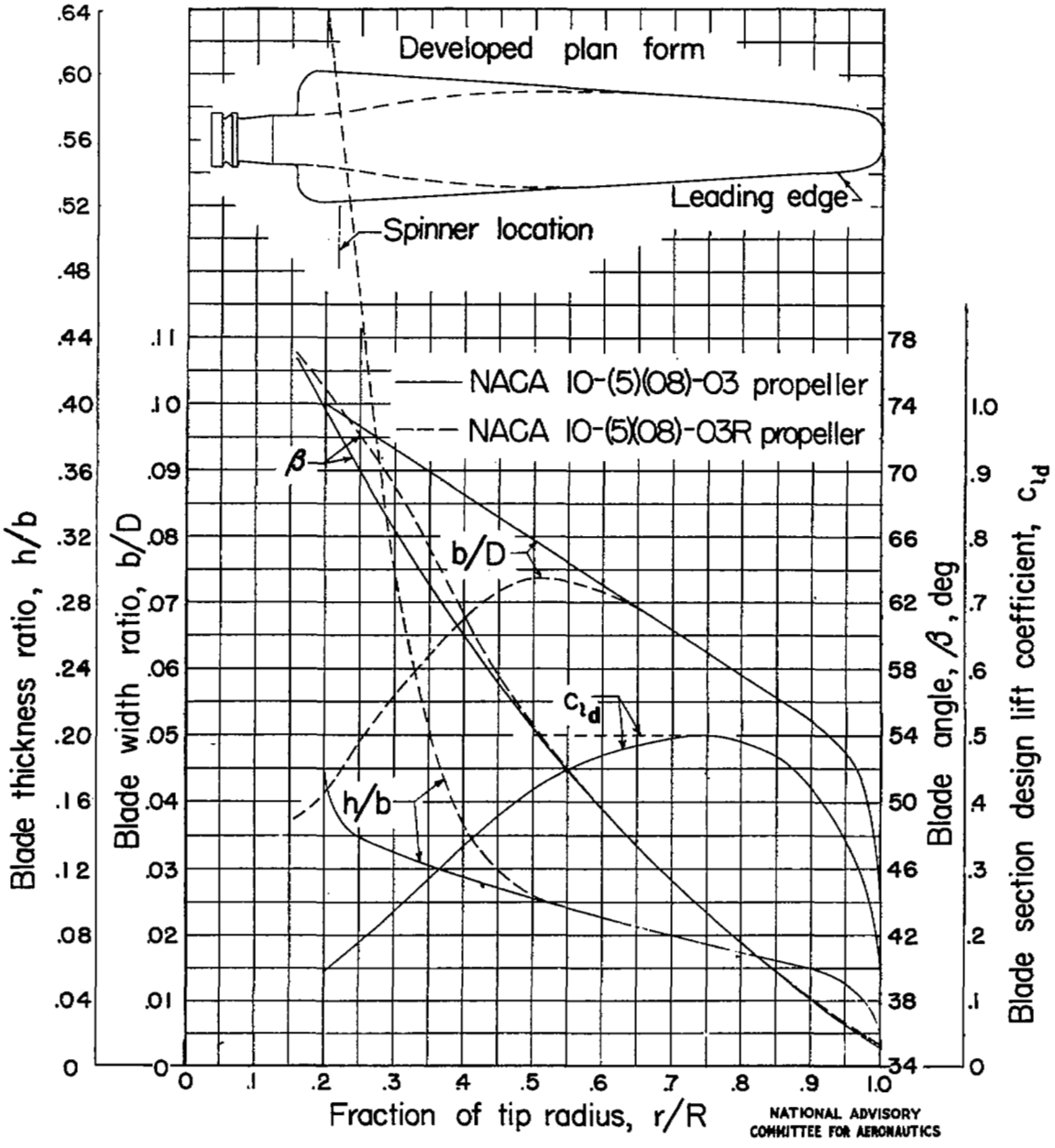


Figure 4.—Blade-form curves for NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers.

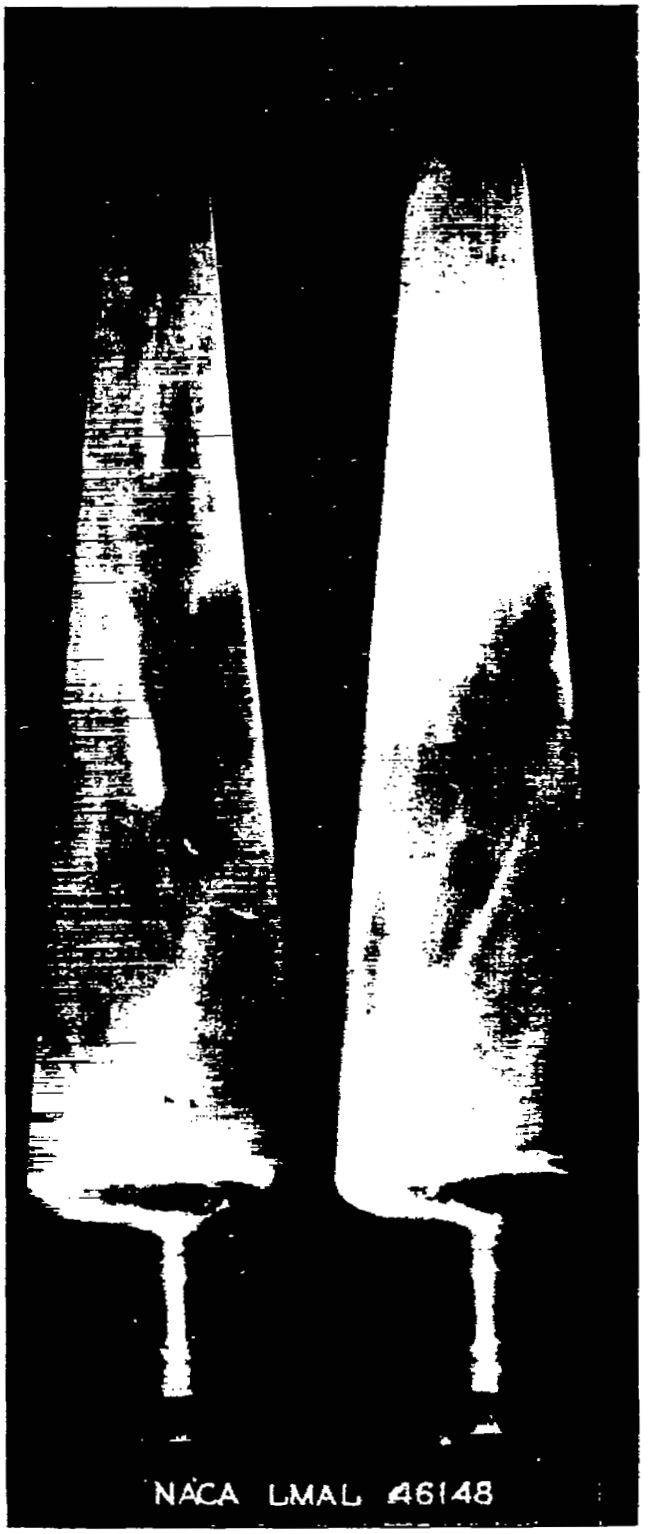


Figure 5.- Blades of NACA 10-(5)(08)-03 propeller.

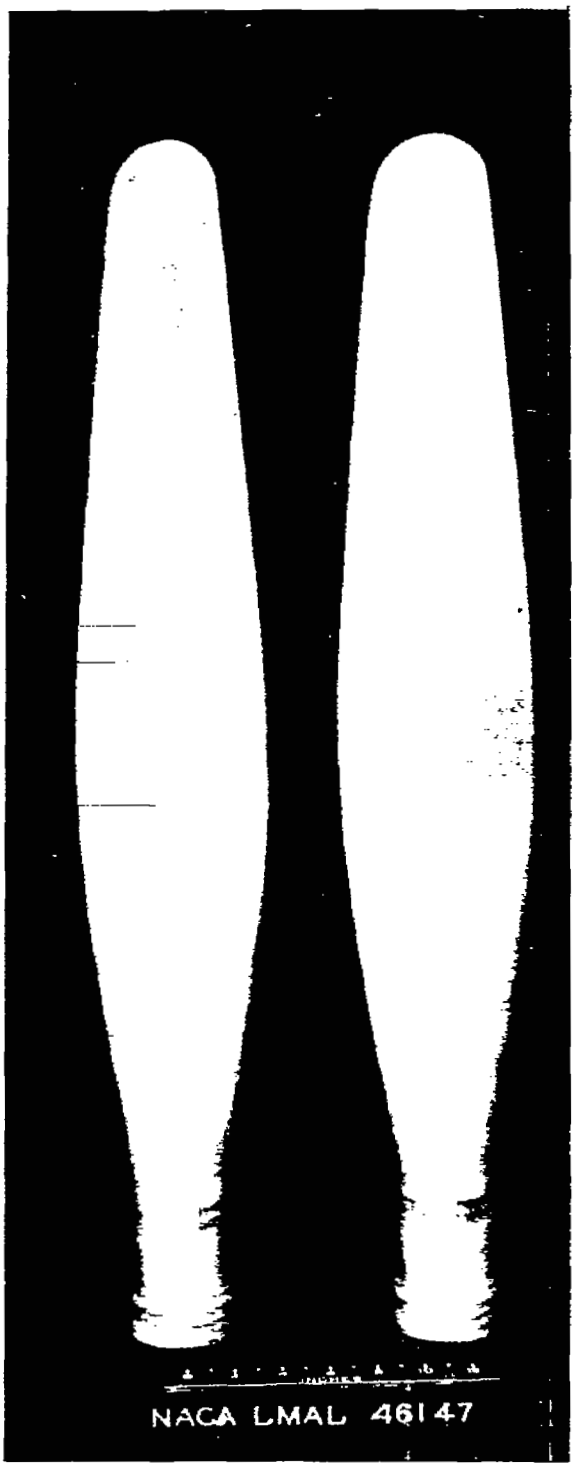


Figure 6.- Blades of NACA 10-(5)(08)-03R propeller.

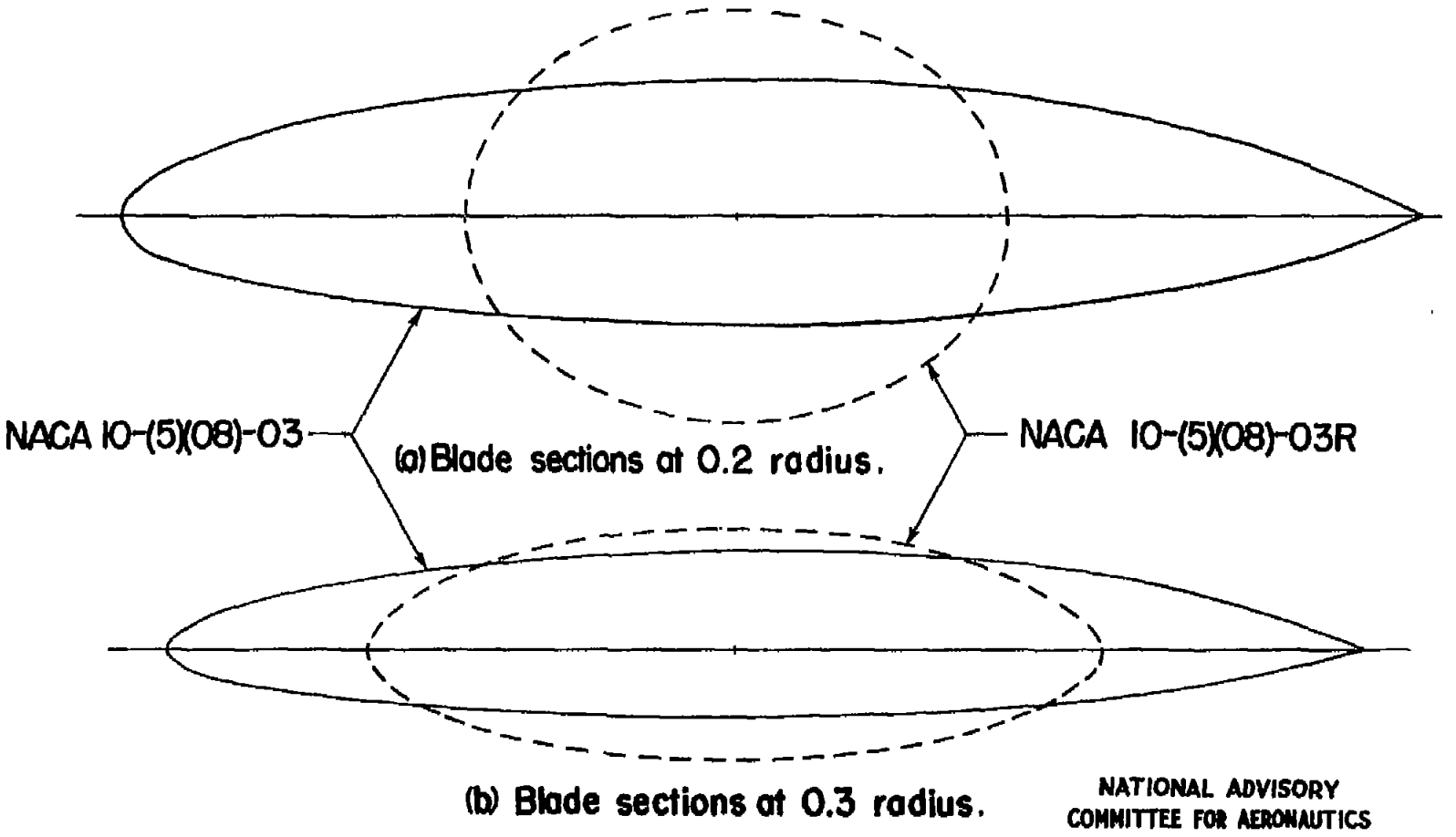
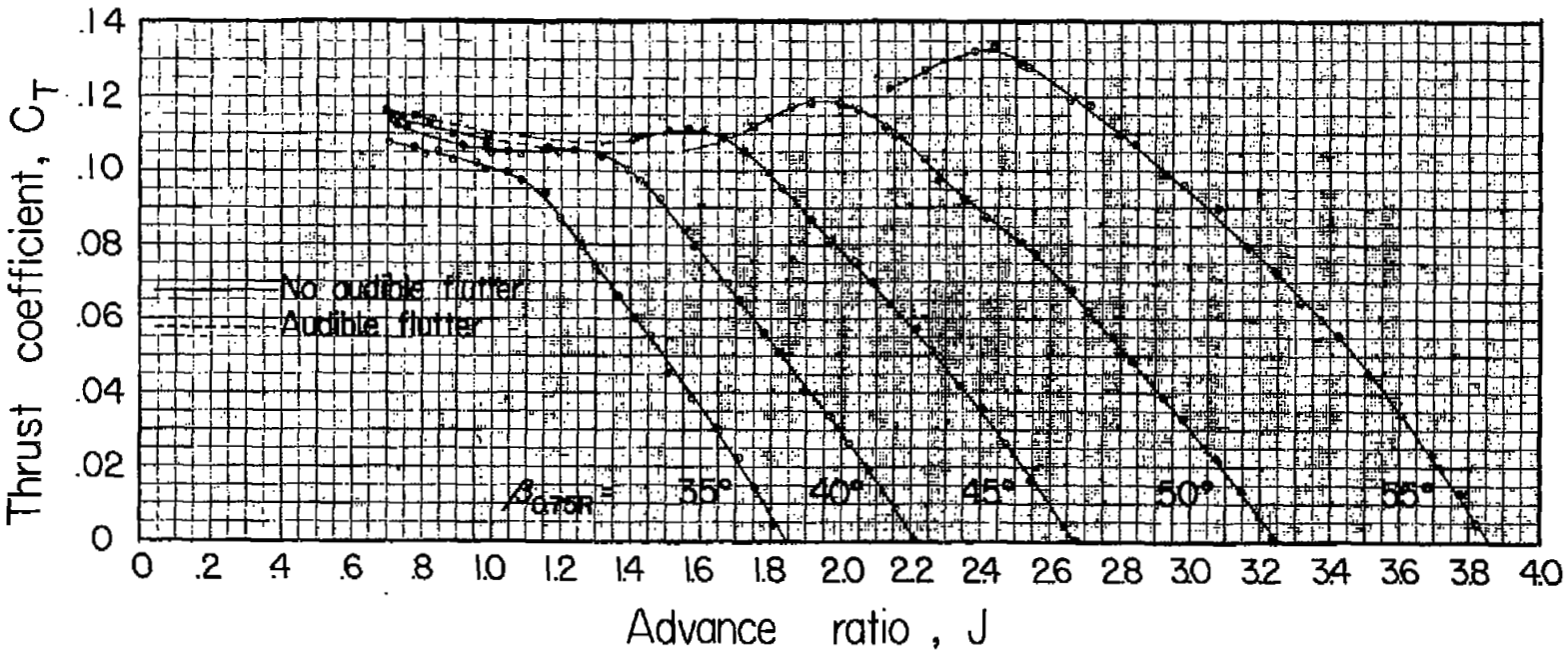


Figure 7.- Comparison of shank sections of NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers.



(a) Thrust coefficient.

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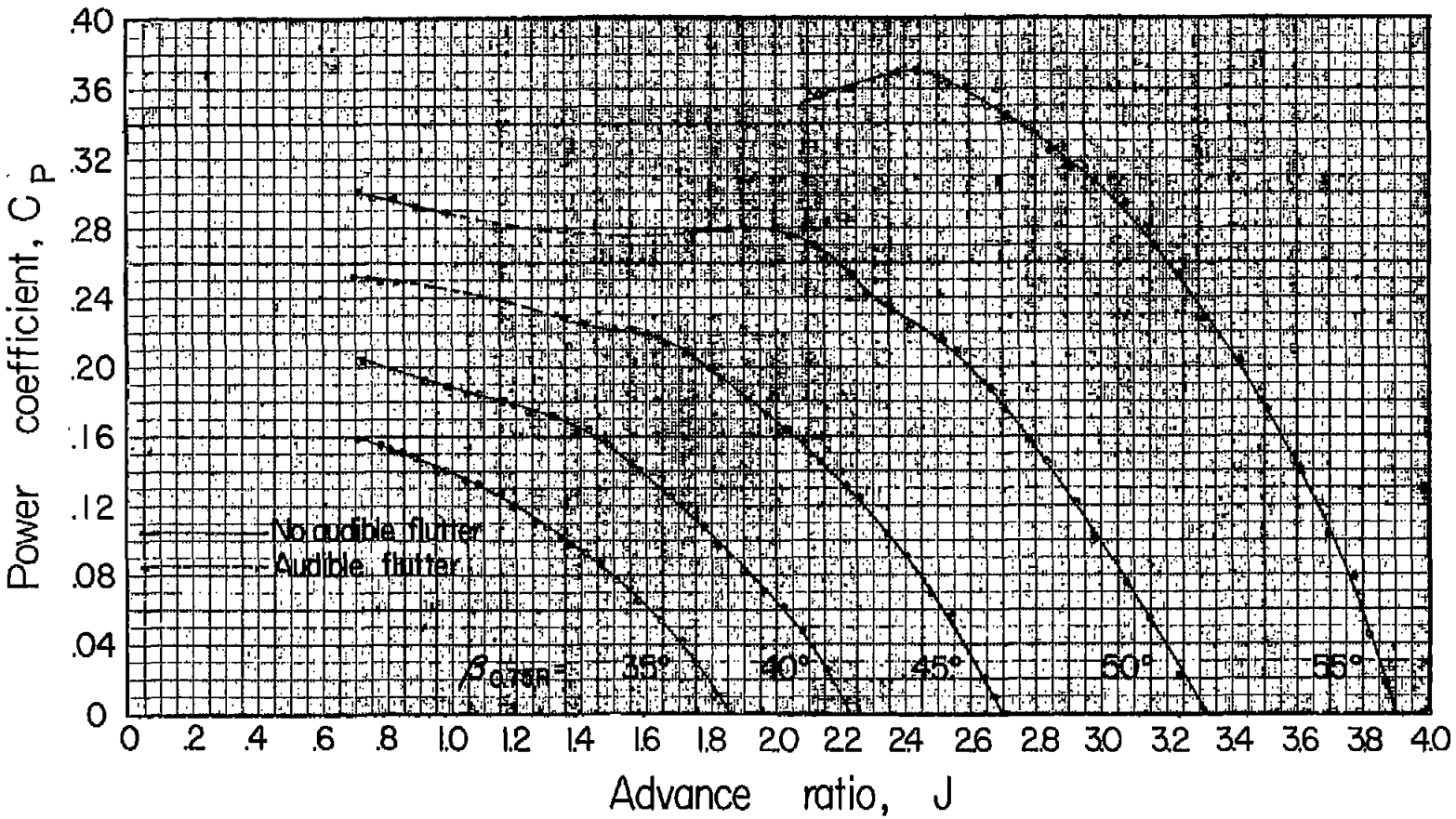
Figure 8.—Characteristics of NACA 10-(5)(08)-03 propeller. Rotational speed, 1140 rpm.



(b) Power coefficient.

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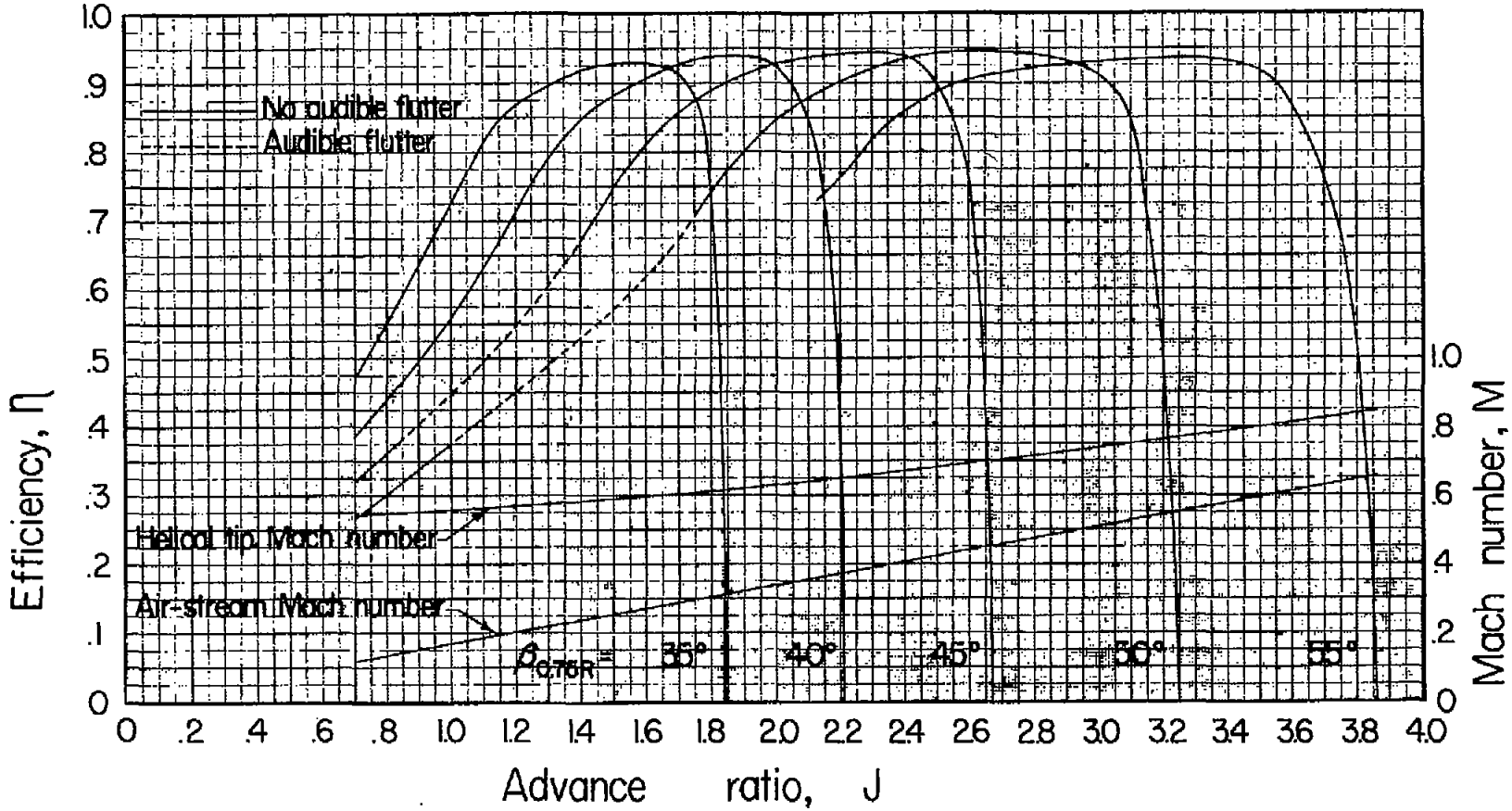
Figure 8.—Continued. Rotational speed, 1140 rpm.



(c)Efficiency.

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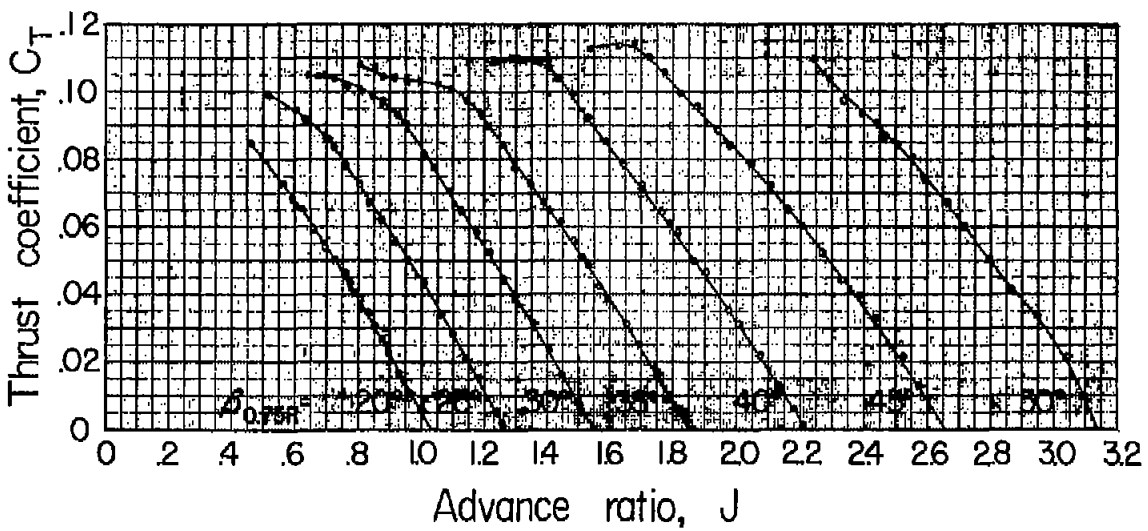
Figure 8 ——Concluded. Rotational speed, 1140rpm.



(a) Thrust coefficient.

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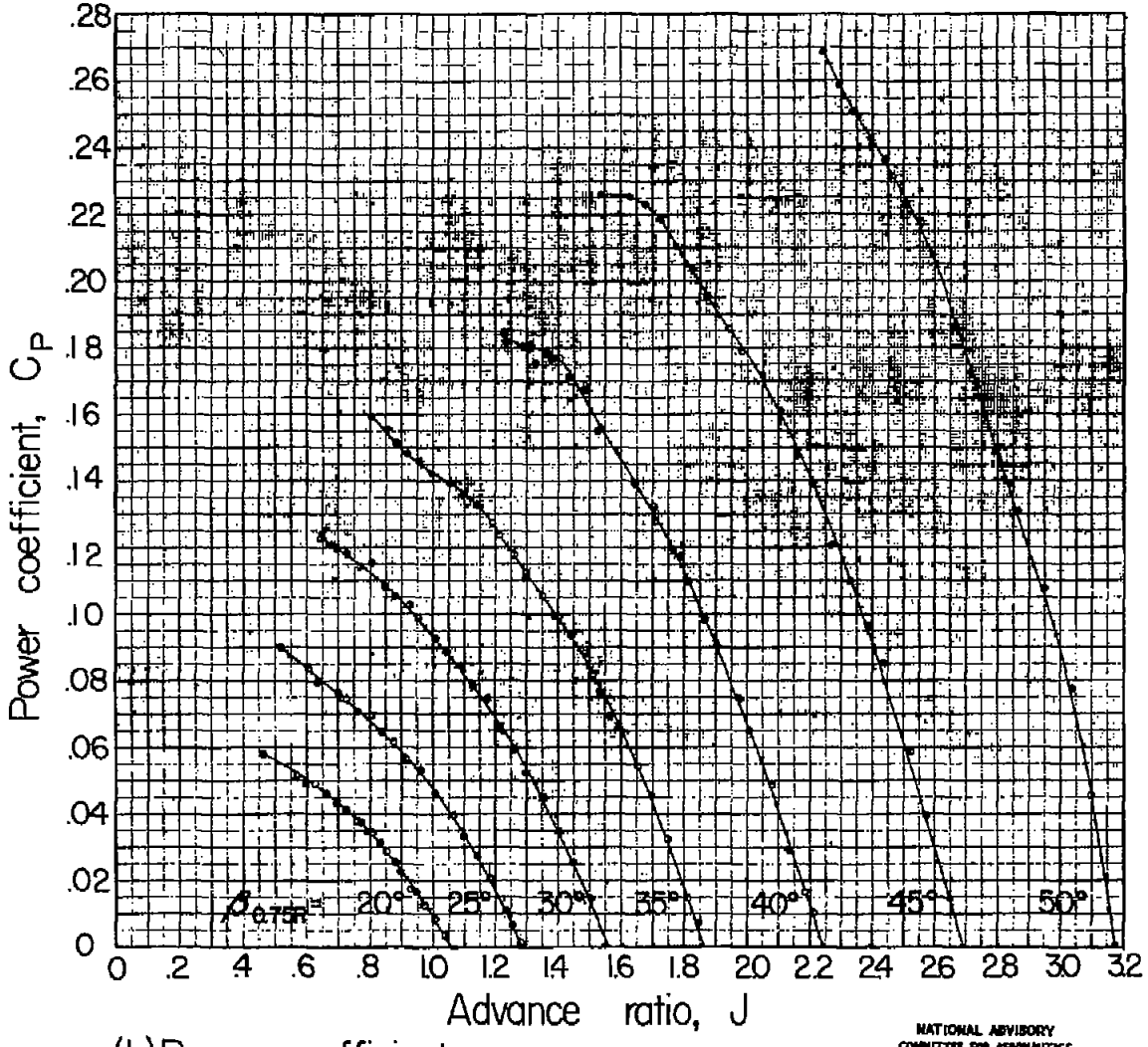
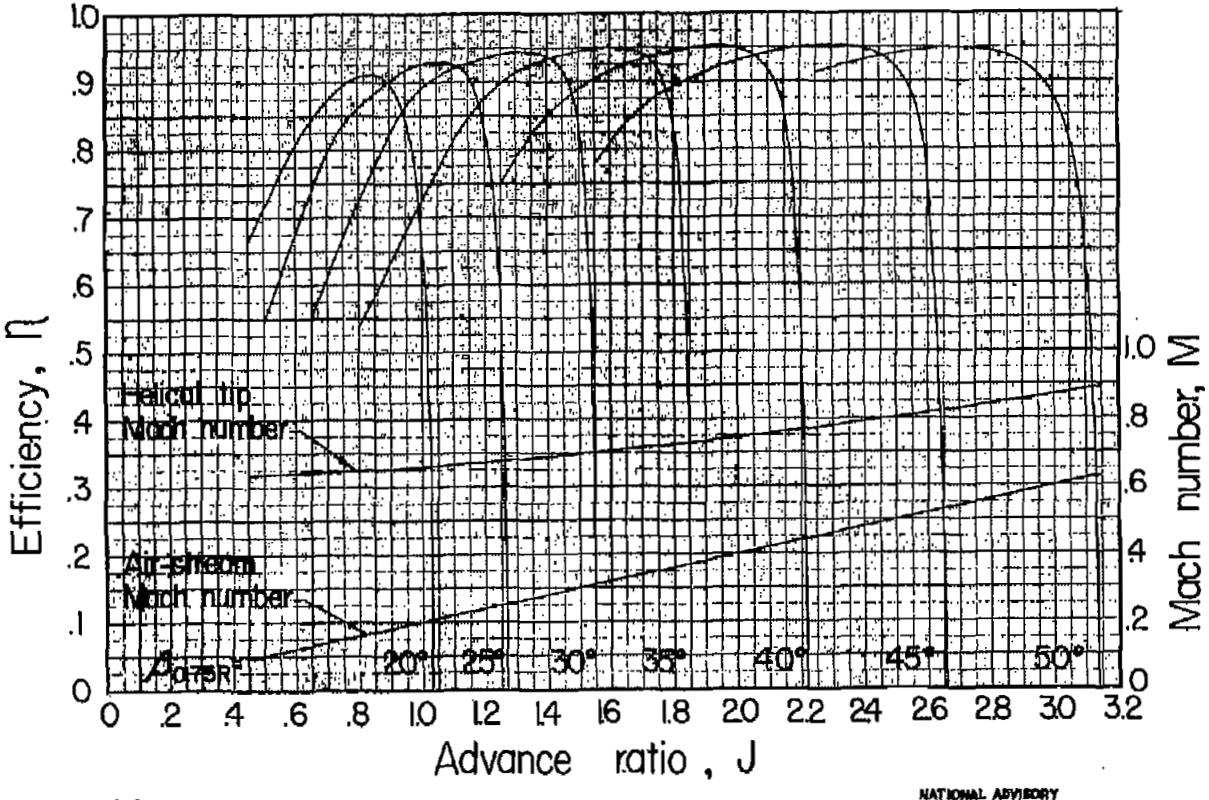
Figure 9.—Characteristics of NACA 10-(5)(08)-03 propeller. Rotational speed, 1350 rpm.



(b) Power coefficient.

Figure 9.—Continued. Rotational speed, 1350 rpm.



(c) Efficiency.

Figure 9.——Concluded. Rotational speed, 1350 rpm.

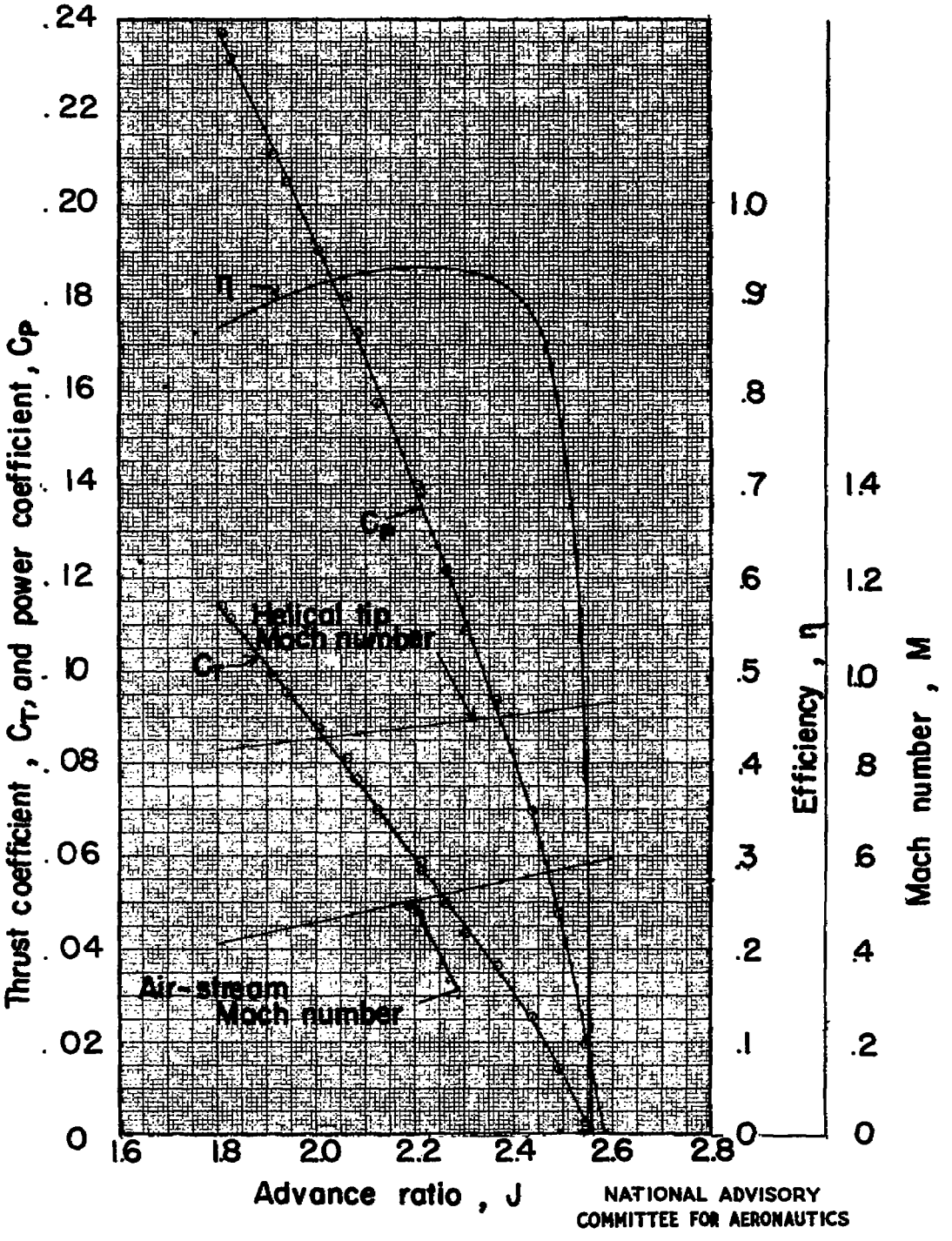
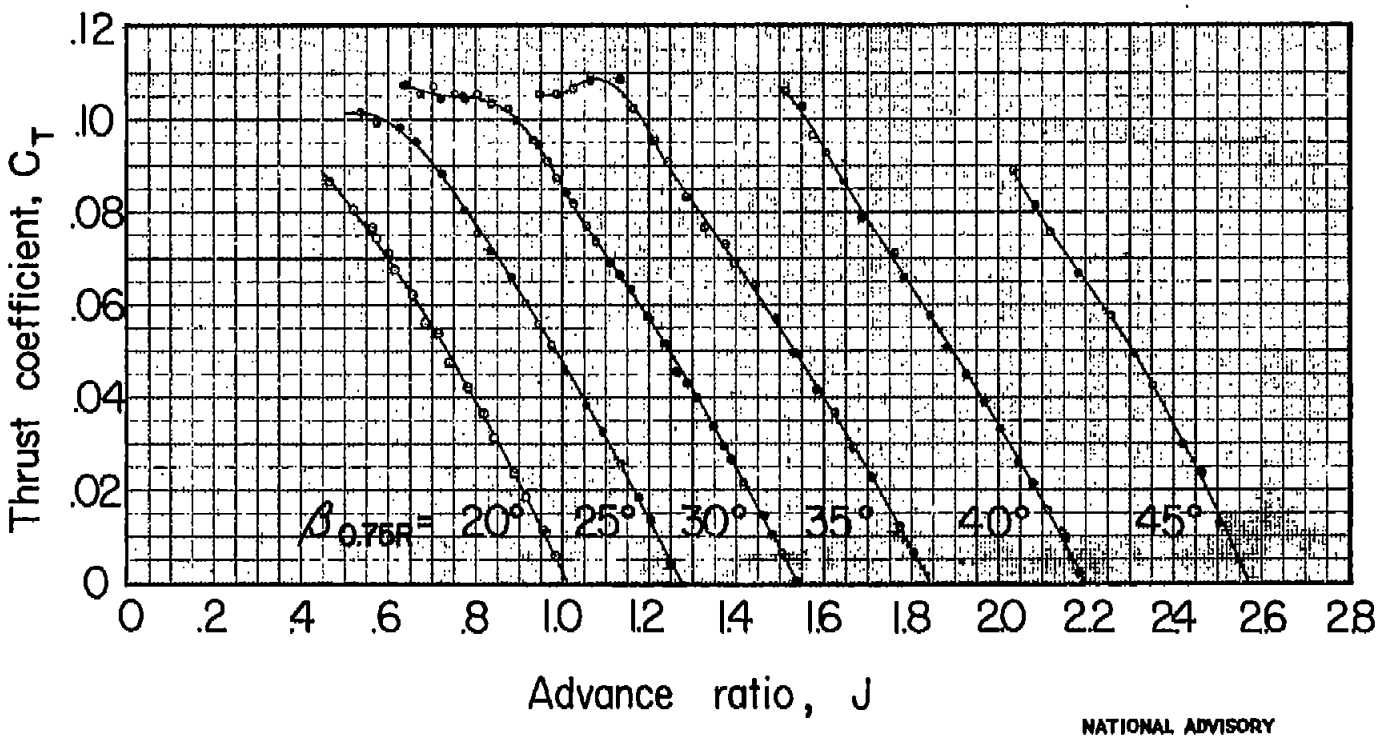


Figure 10.—Characteristics of NACA 10-(5)(08)-03 propeller. Rotational speed, 1500 rpm; $\beta_{0.75R} = 45°$.



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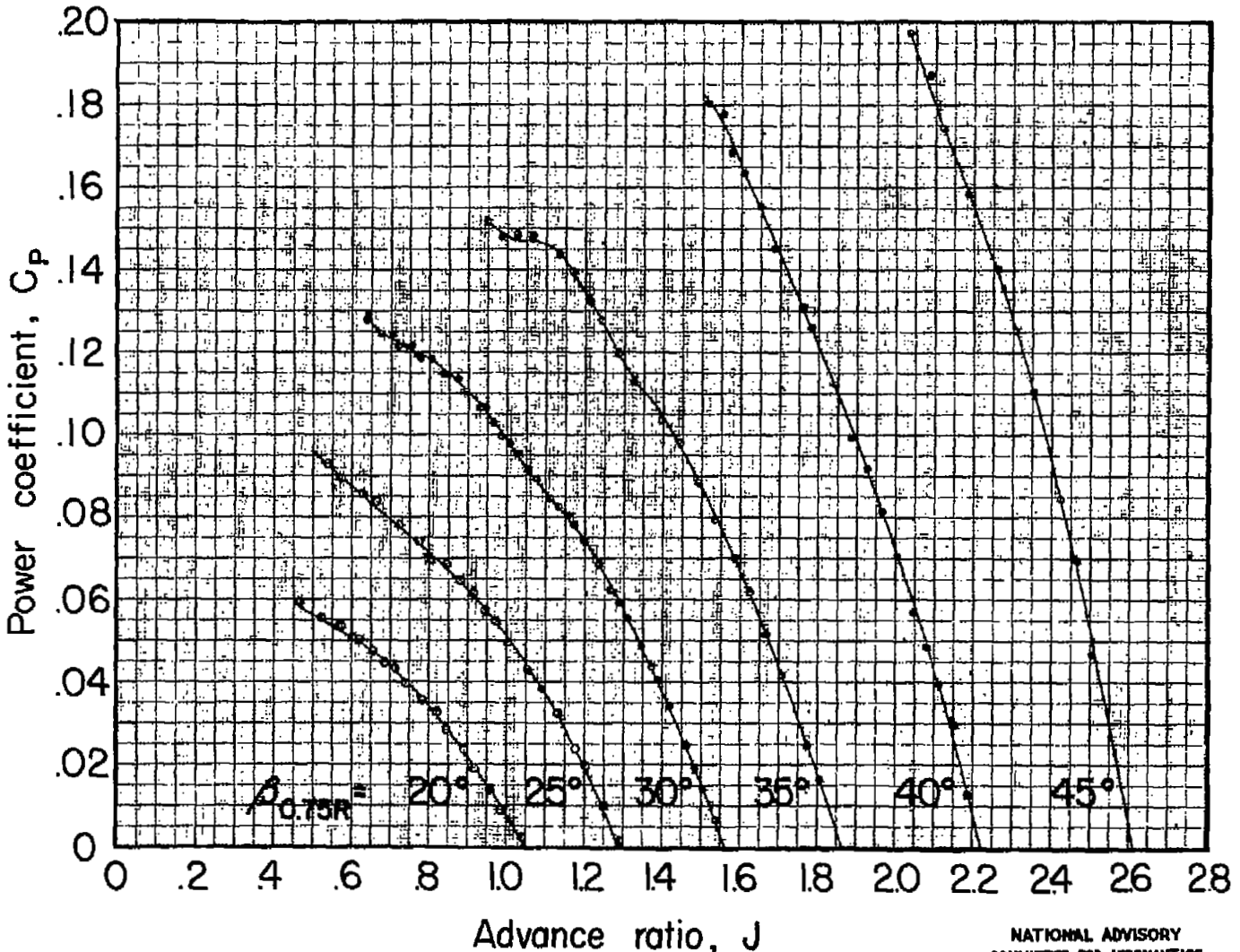
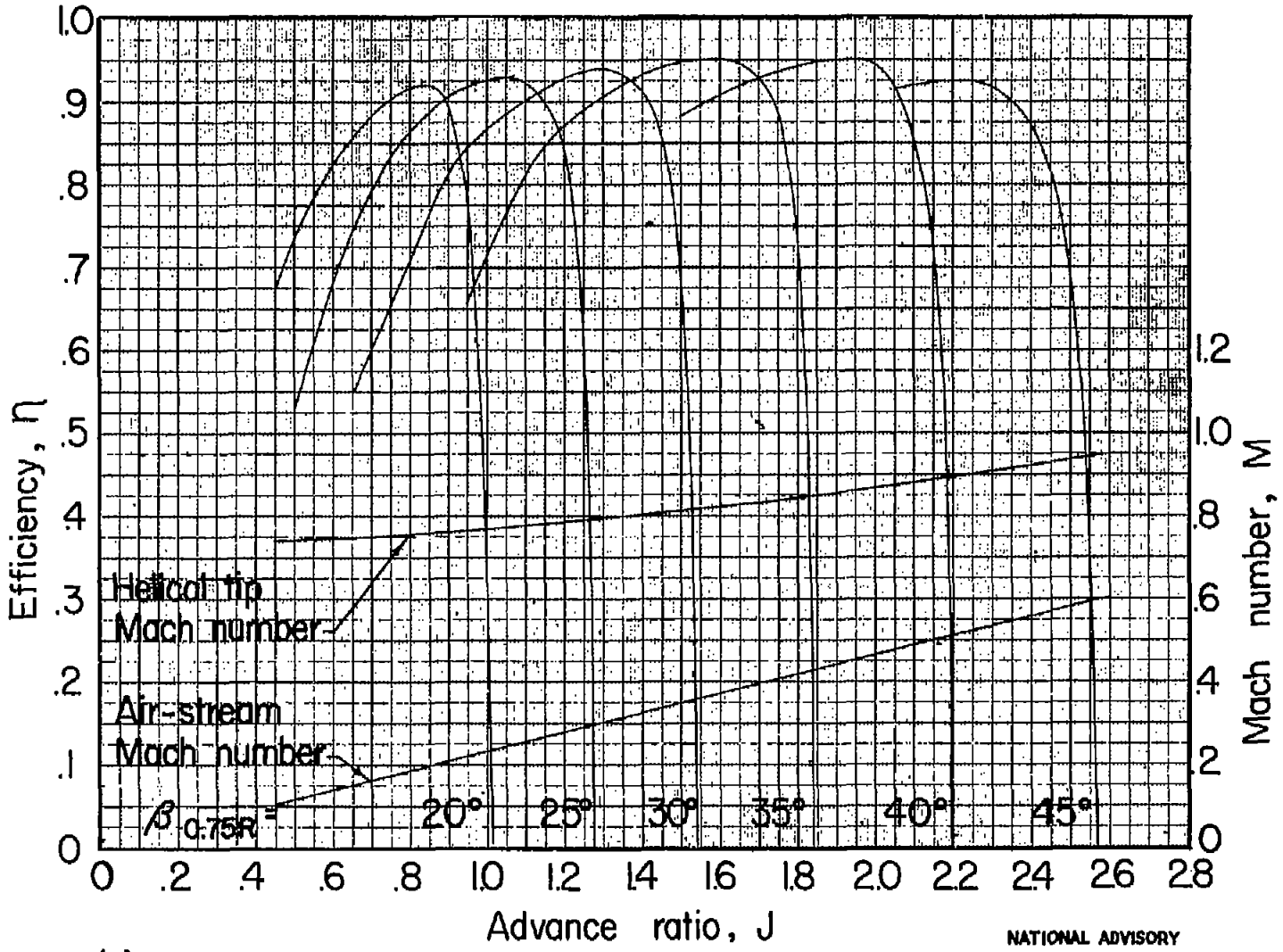
(a) Thrust coefficient.

Figure 11.—Characteristics of NACA 10-(5)(08)-03 propeller. Rotational speed, 1600 rpm.



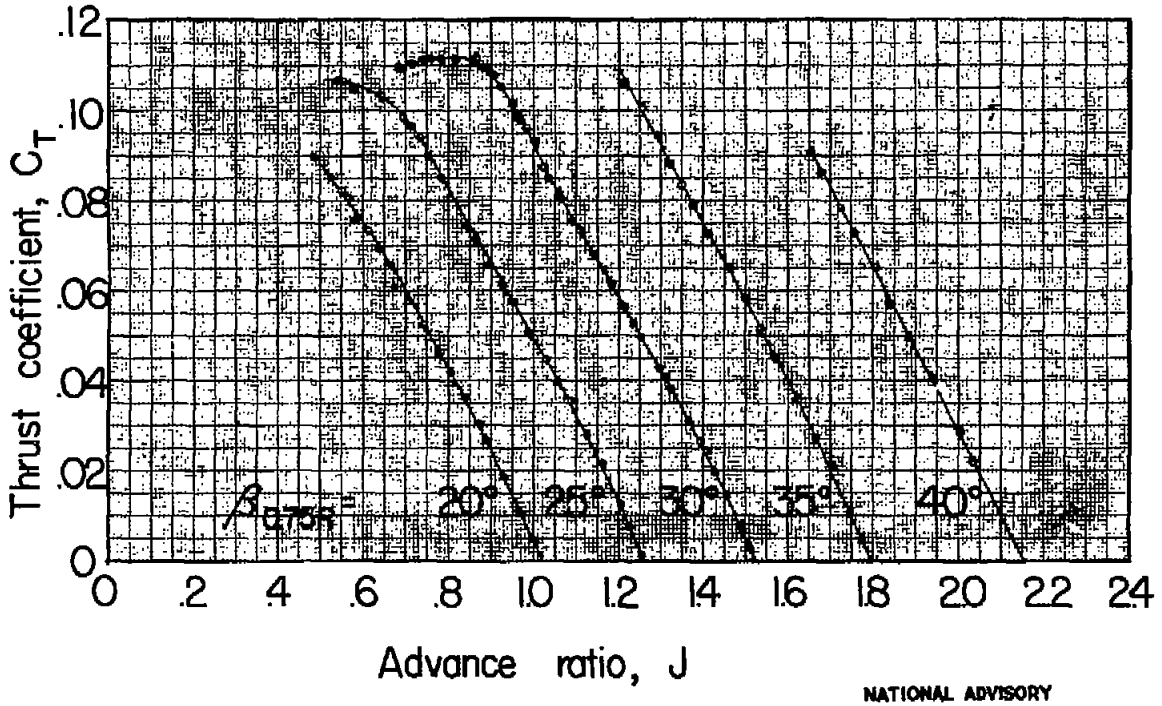
(b) Power coefficient.

Figure 11.—Continued. Rotational speed, 1600 rpm.



(c) Efficiency.

Figure 11.—Concluded. Rotational speed, 1600 rpm.



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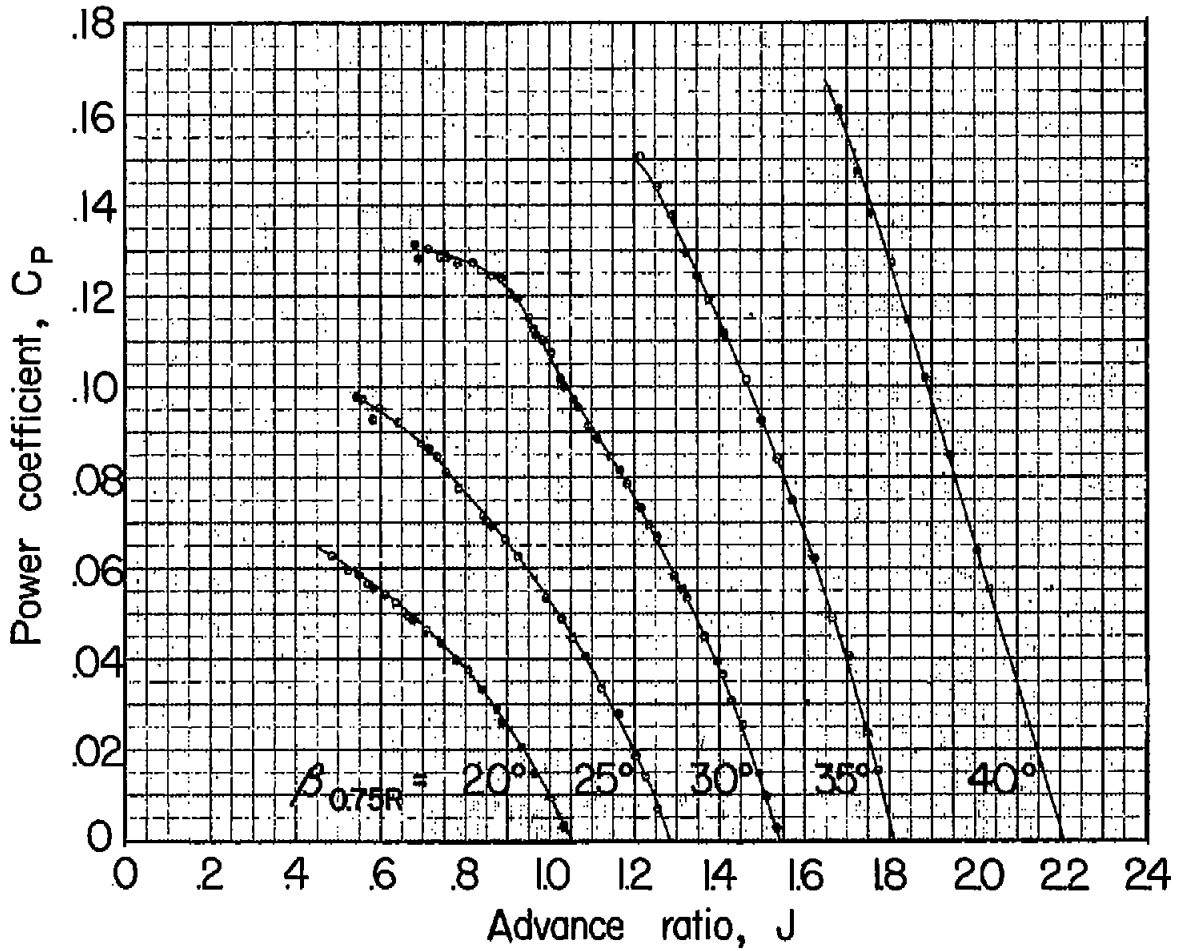
(a) Thrust coefficient.

Figure 12.— Characteristics of NACA 10-(5)(08)-03 propeller. Rotational speed, 1800 rpm.



(b) Power coefficient.

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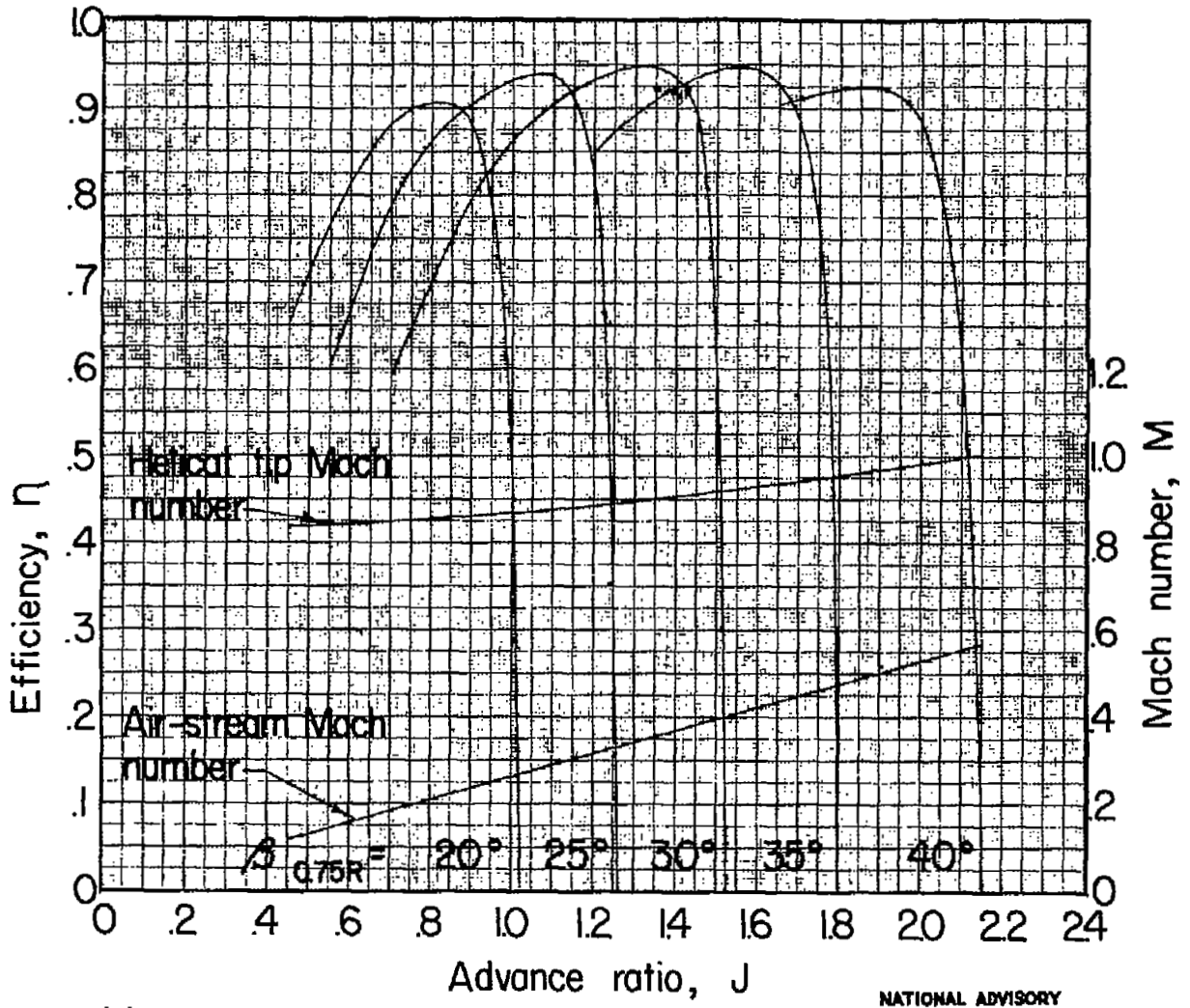
Figure 12.—Continued. Rotational speed, 1800rpm.



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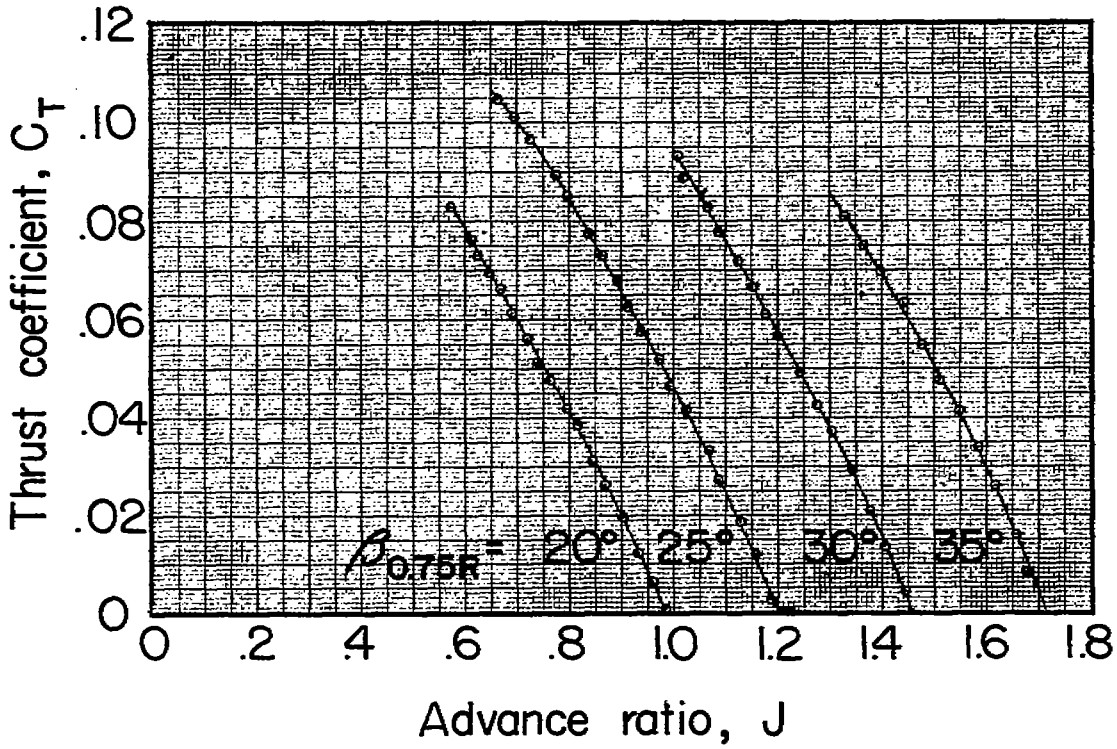
(c) Efficiency.

Figure 12.—Concluded. Rotational speed, 1800 rpm.



(a) Thrust coefficient.

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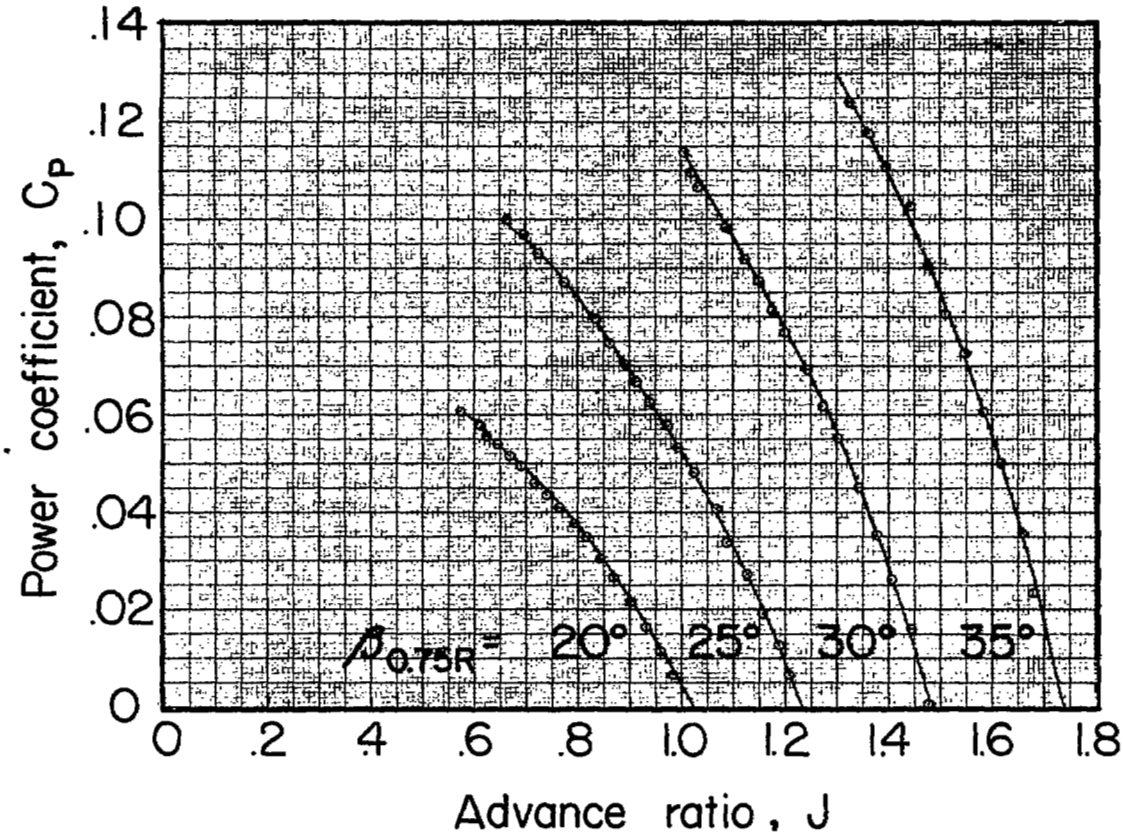
Figure 13.— Characteristics of NACA 10-(5)(08)-03 propeller. Rotational speed, 2000 rpm.



(b) Power coefficient.

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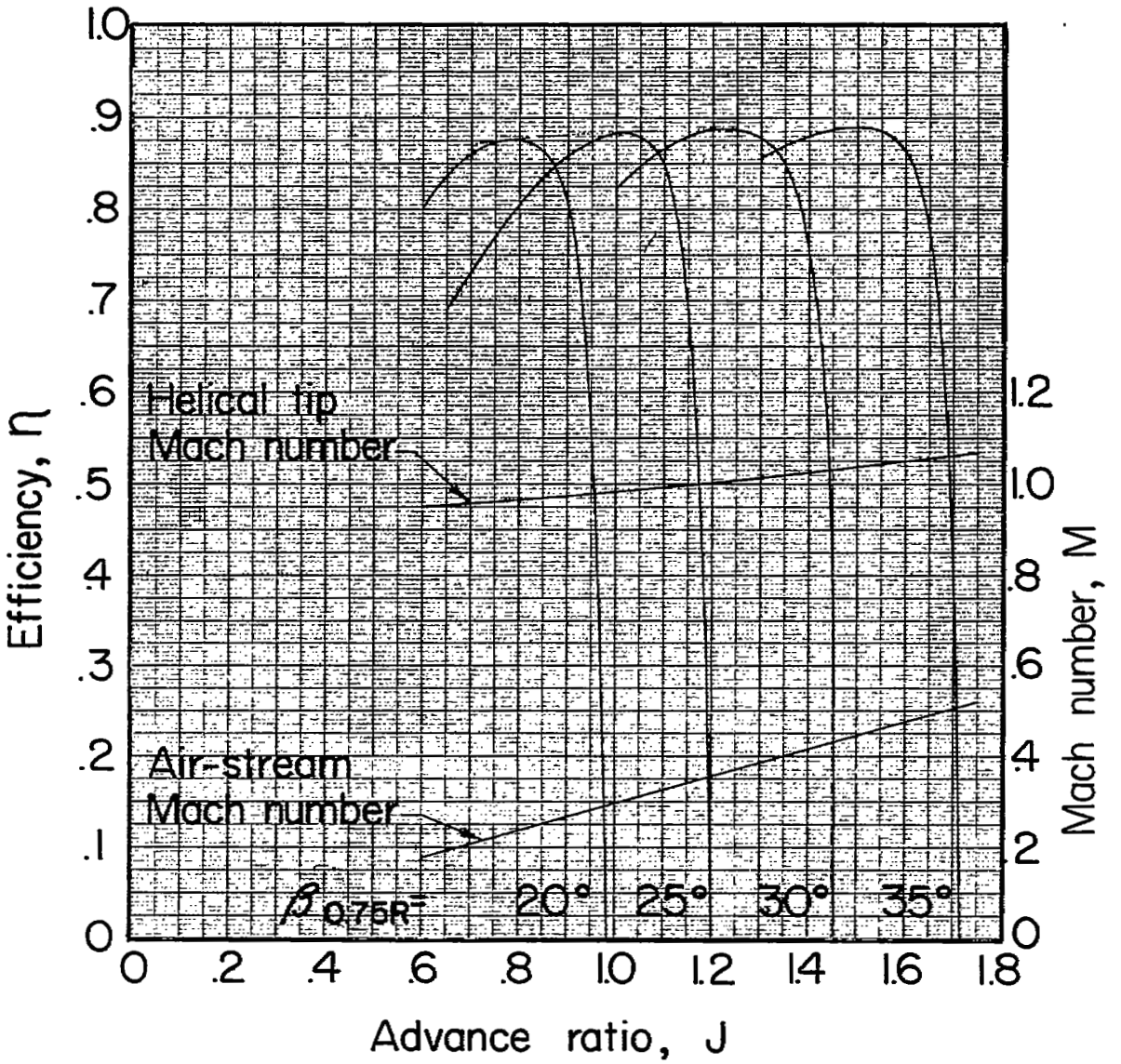
Figure 13.—Continued. Rotational speed, 2000 rpm.



(c) Efficiency.

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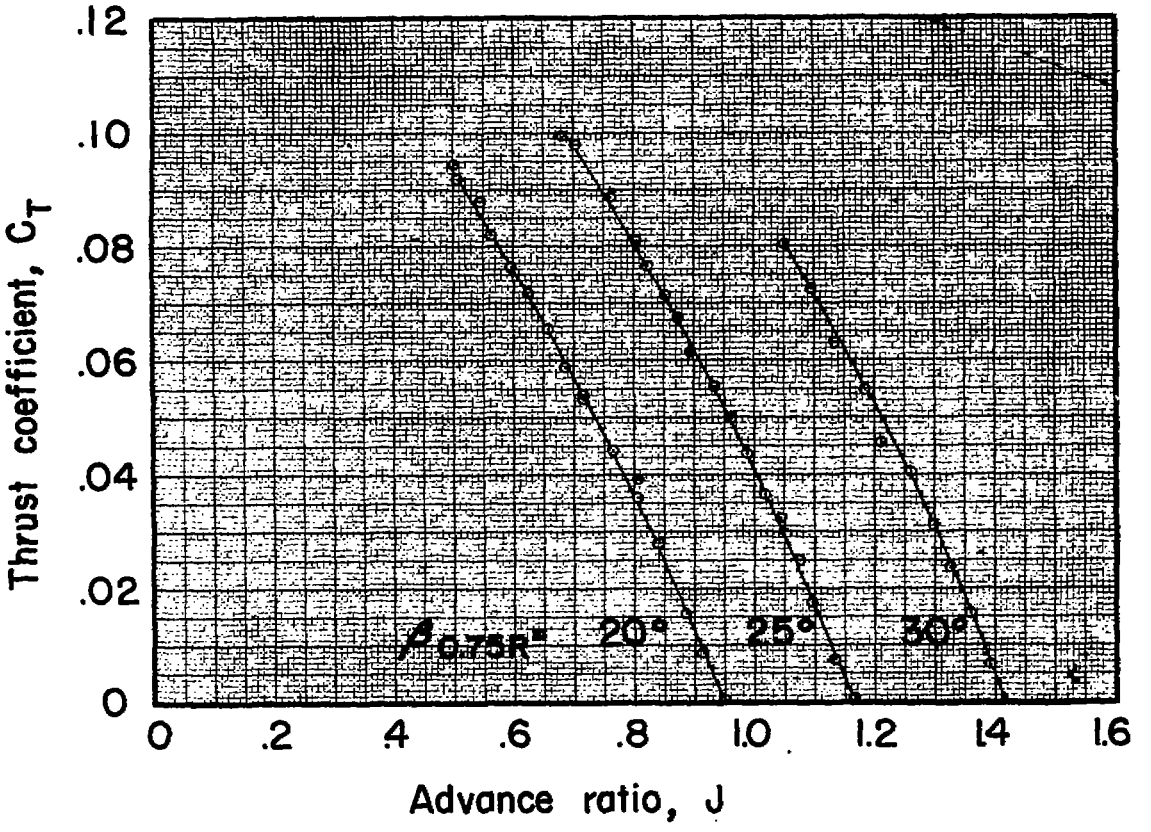
Figure 13.—Concluded. Rotational speed, 2000 rpm.



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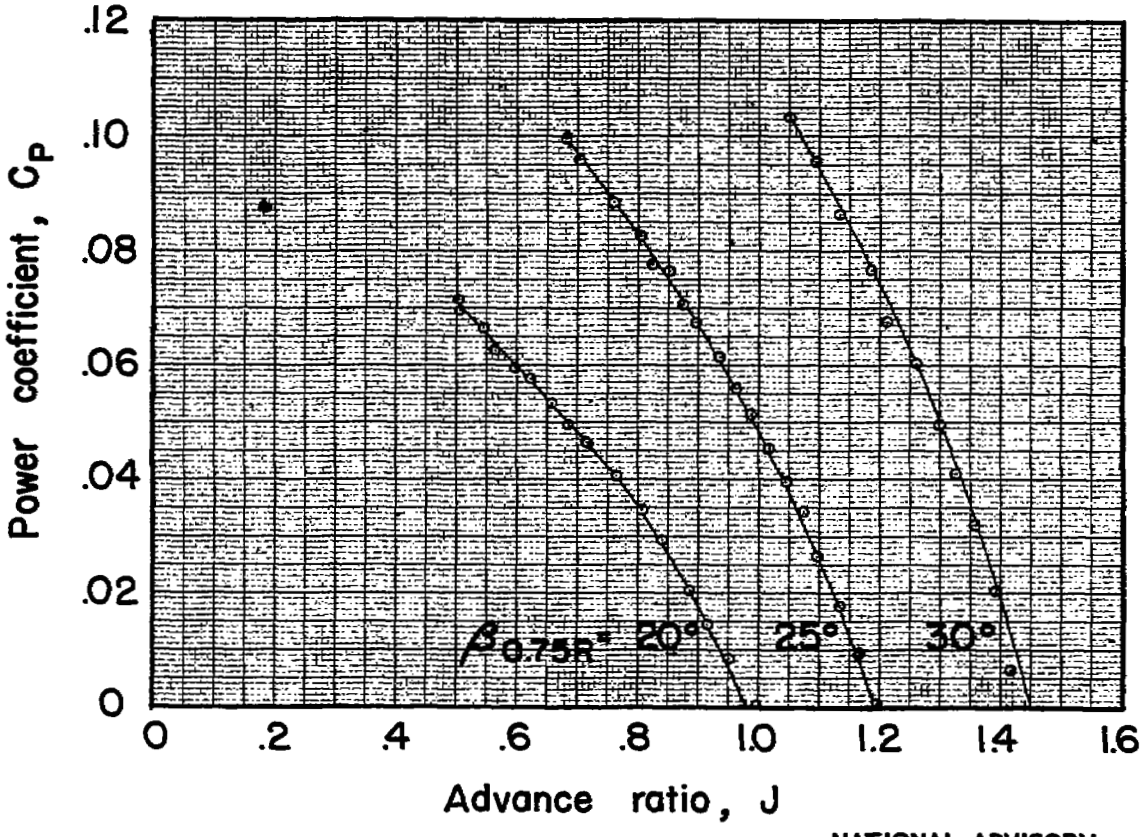
(a) Thrust coefficient.

Figure 14.— Characteristics of NACA 10(5)(08)-03 propeller.

Rotational speed, 2100 rpm.



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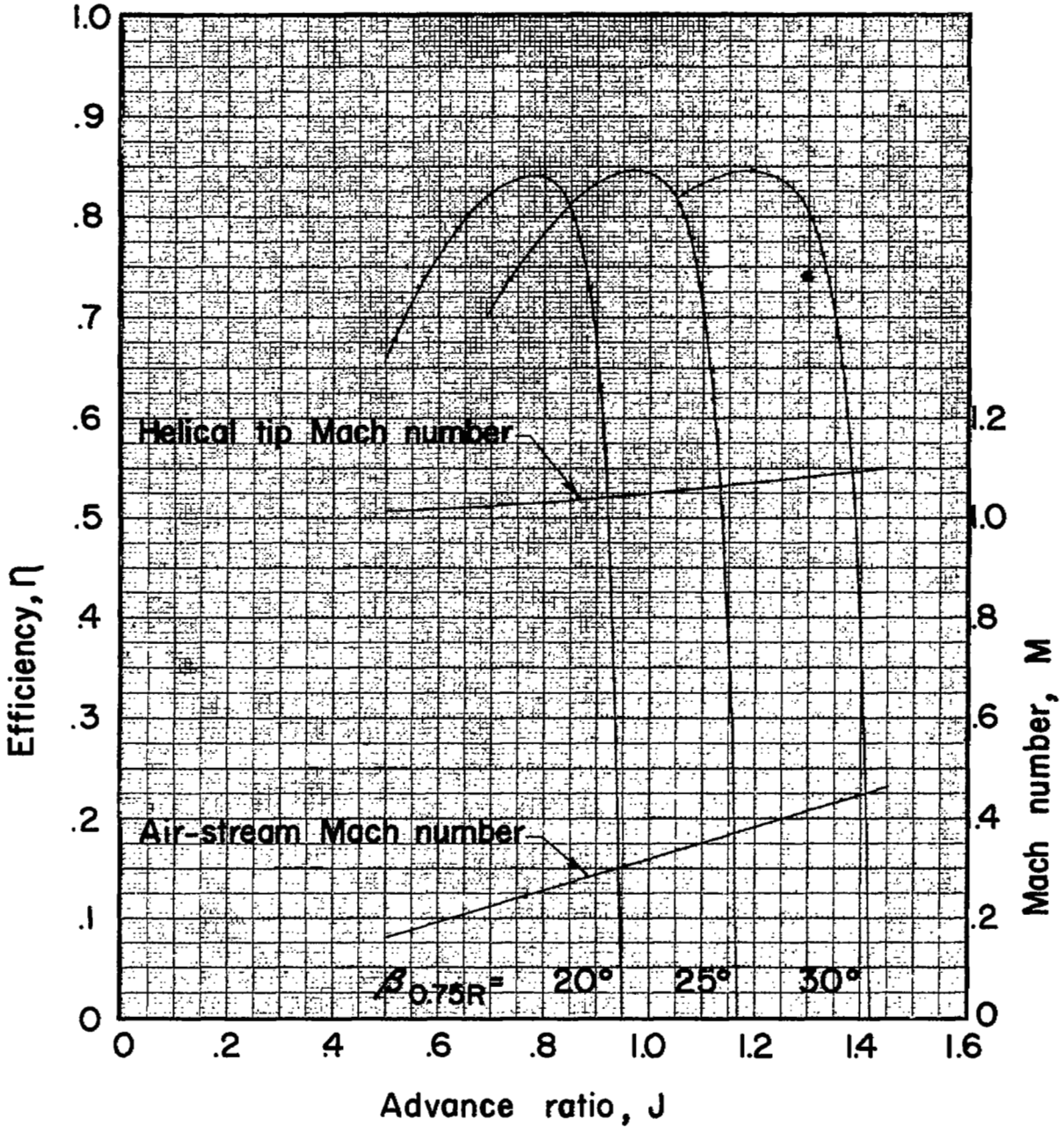
(b) Power coefficient.

Figure 14.—— Continued. Rotational speed, 2100 rpm.



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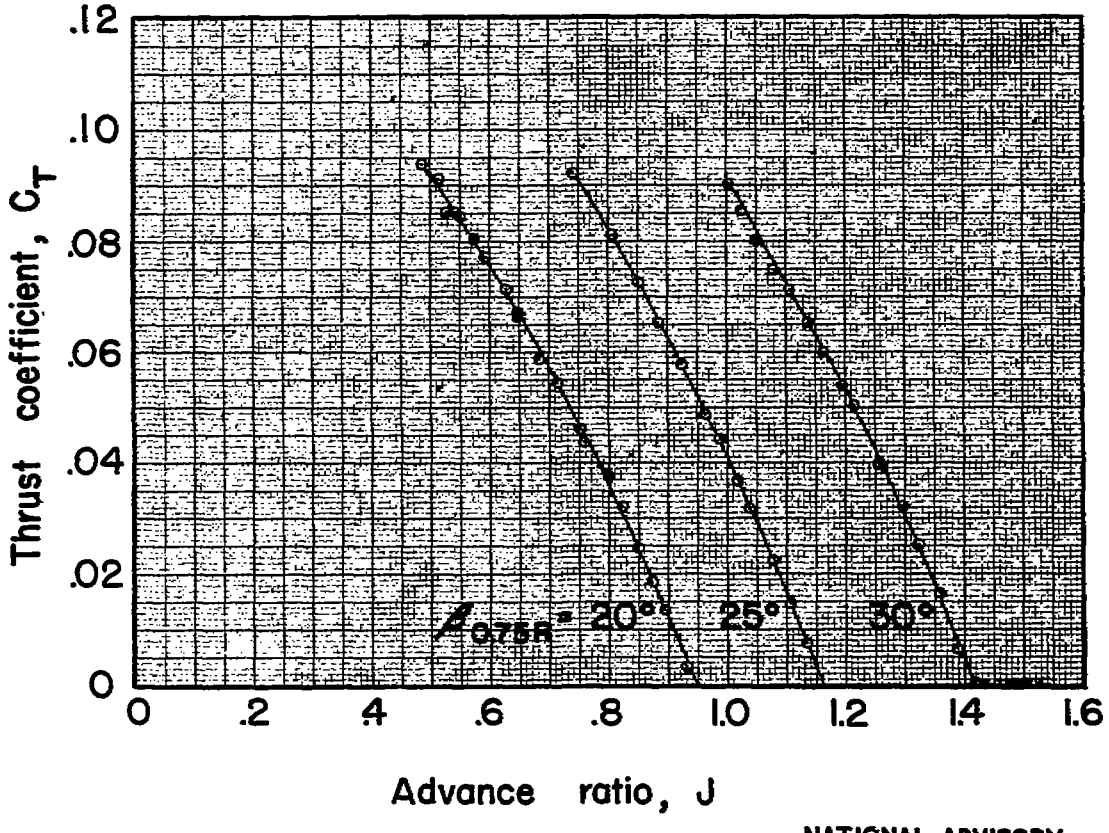
(c) Efficiency.

Figure 14.— Concluded. Rotational speed, 2100rpm.



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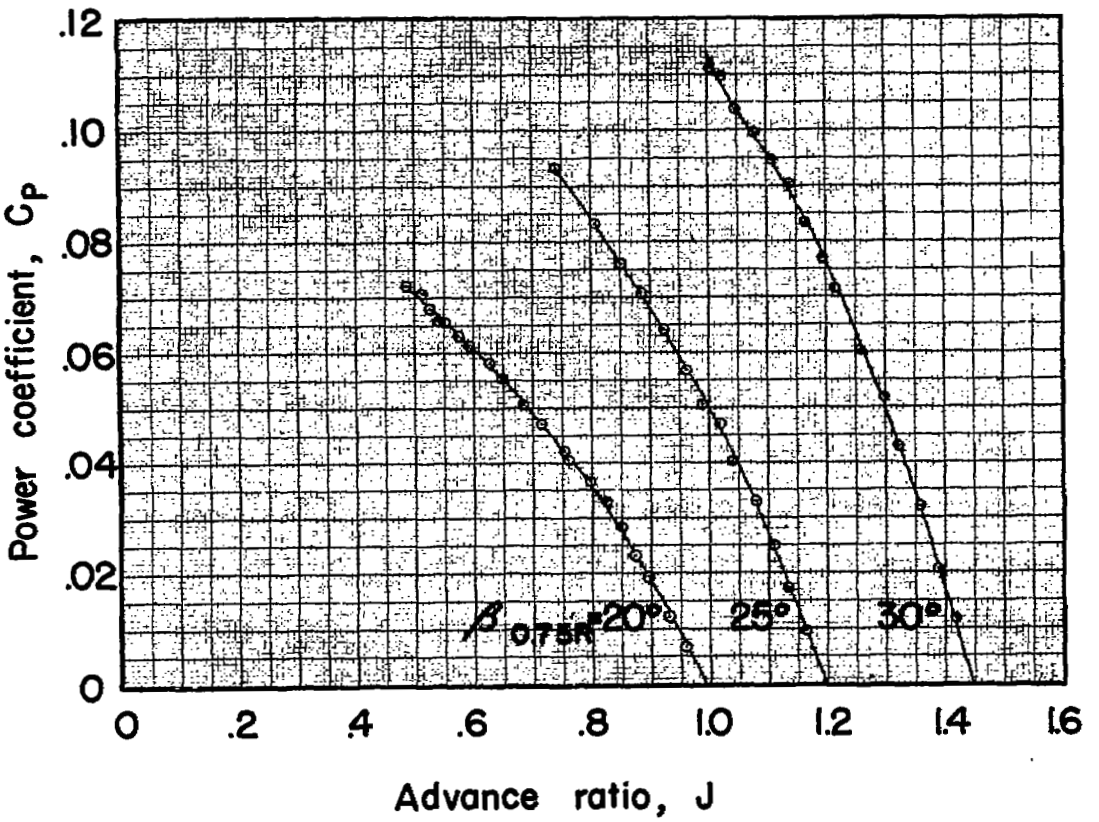
(a) Thrust coefficient.

Figure 15.—Characteristics of NACA 10-(5)(08)-03 propeller.

Rotational speed, 2160 rpm.



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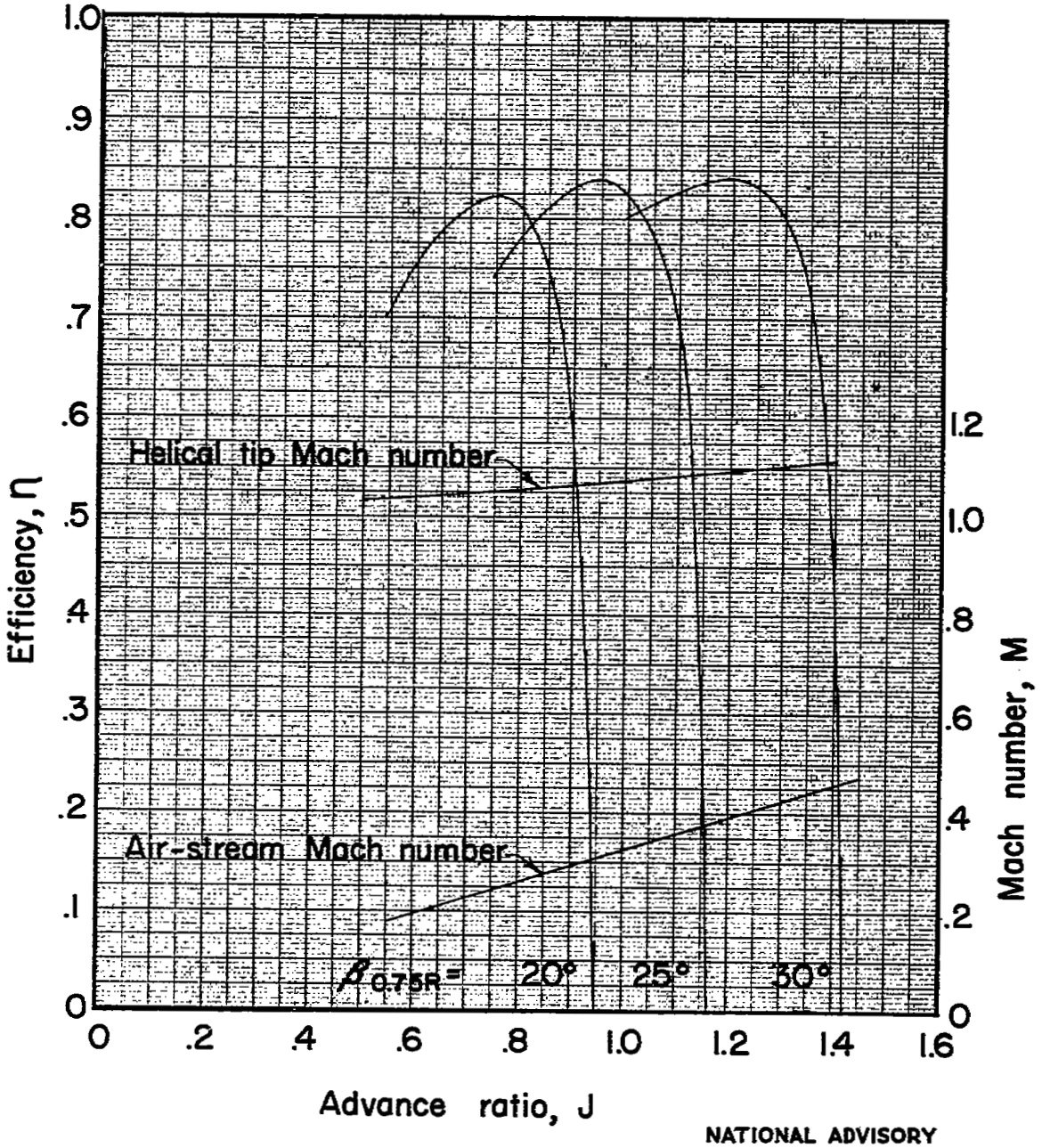
(b) Power coefficient.

Figure 15.— Continued. Rotational speed, 2160 rpm.



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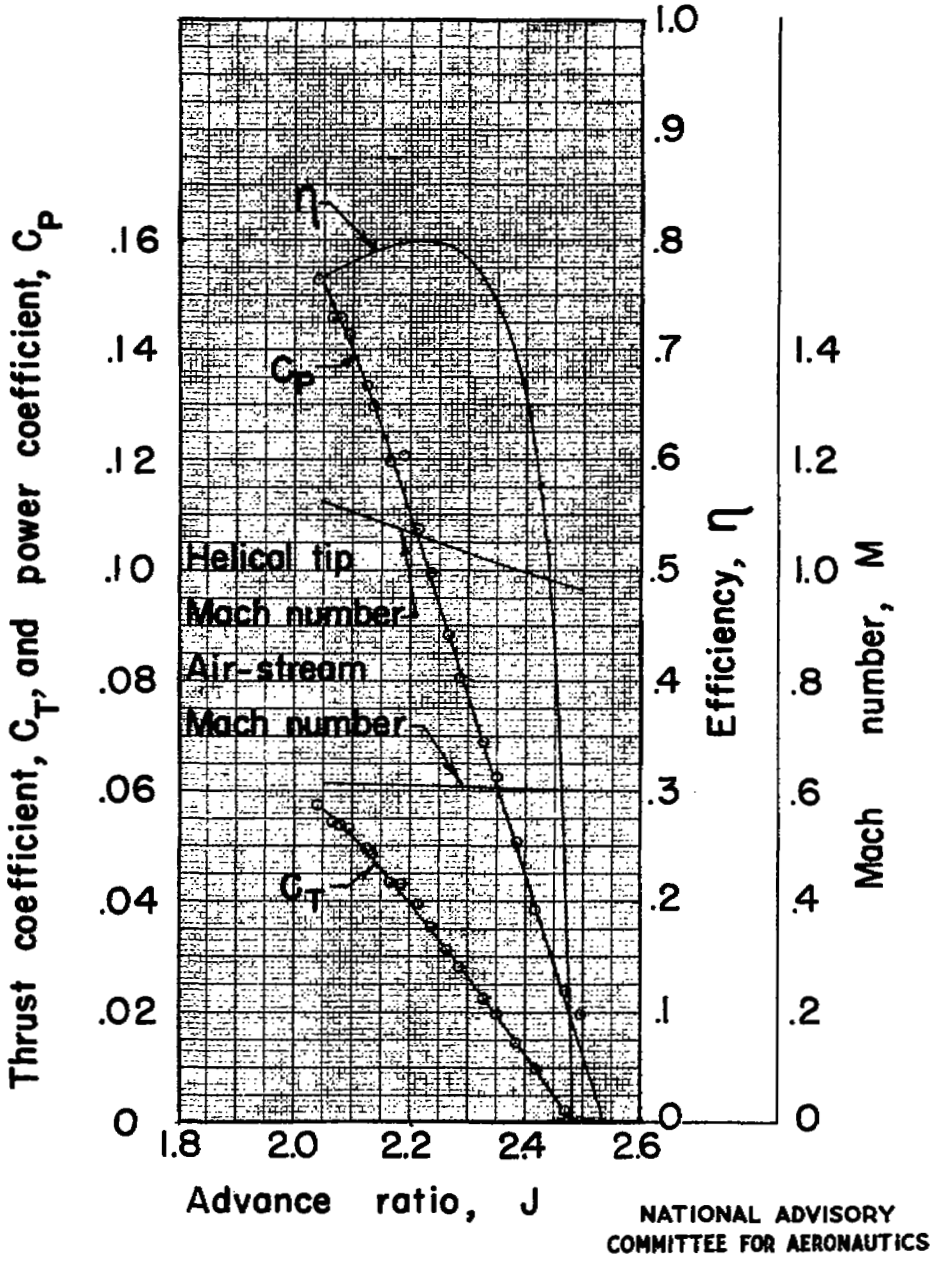
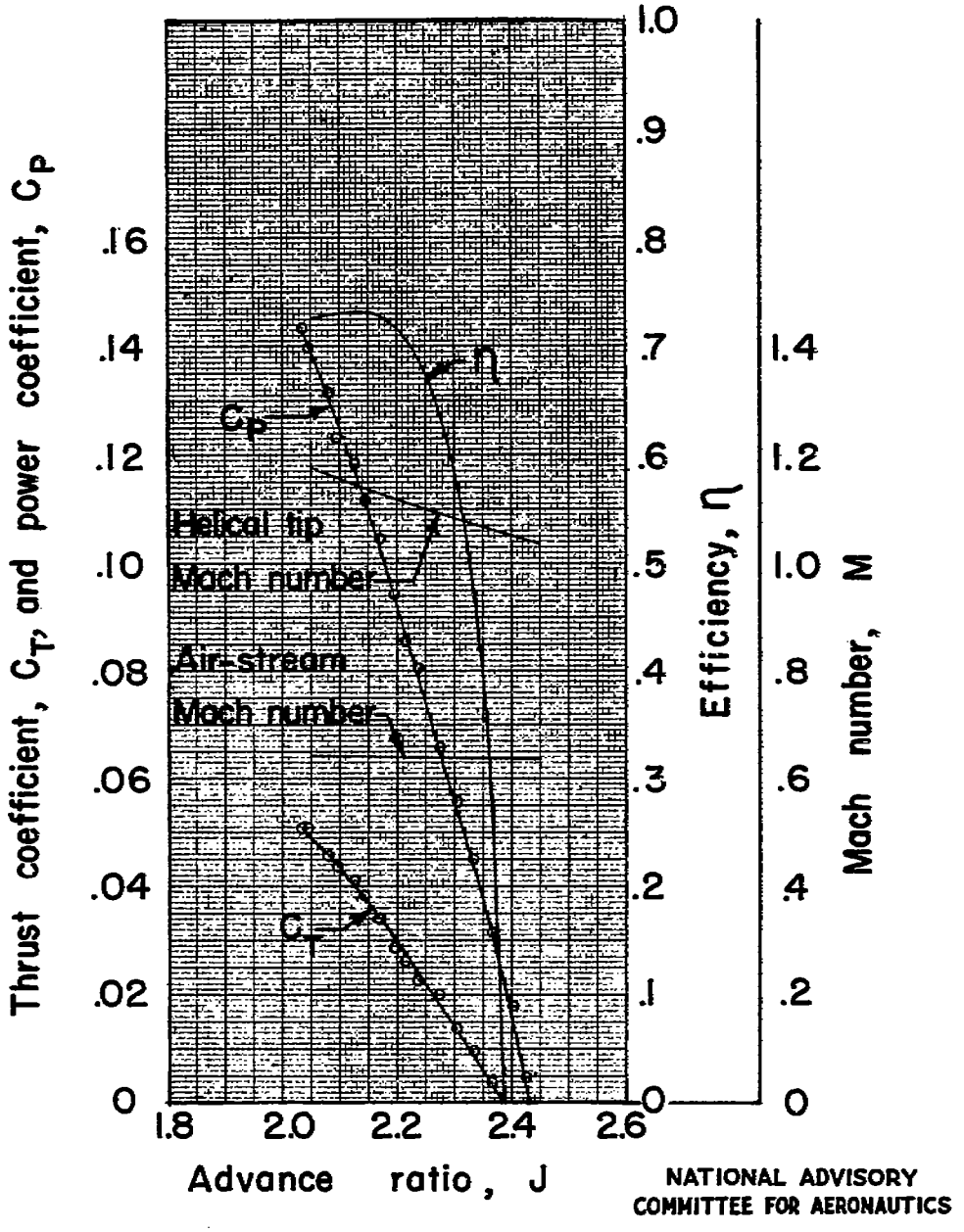
(c) Efficiency.

Figure 15.— Concluded. Rotational speed, 2160 rpm.



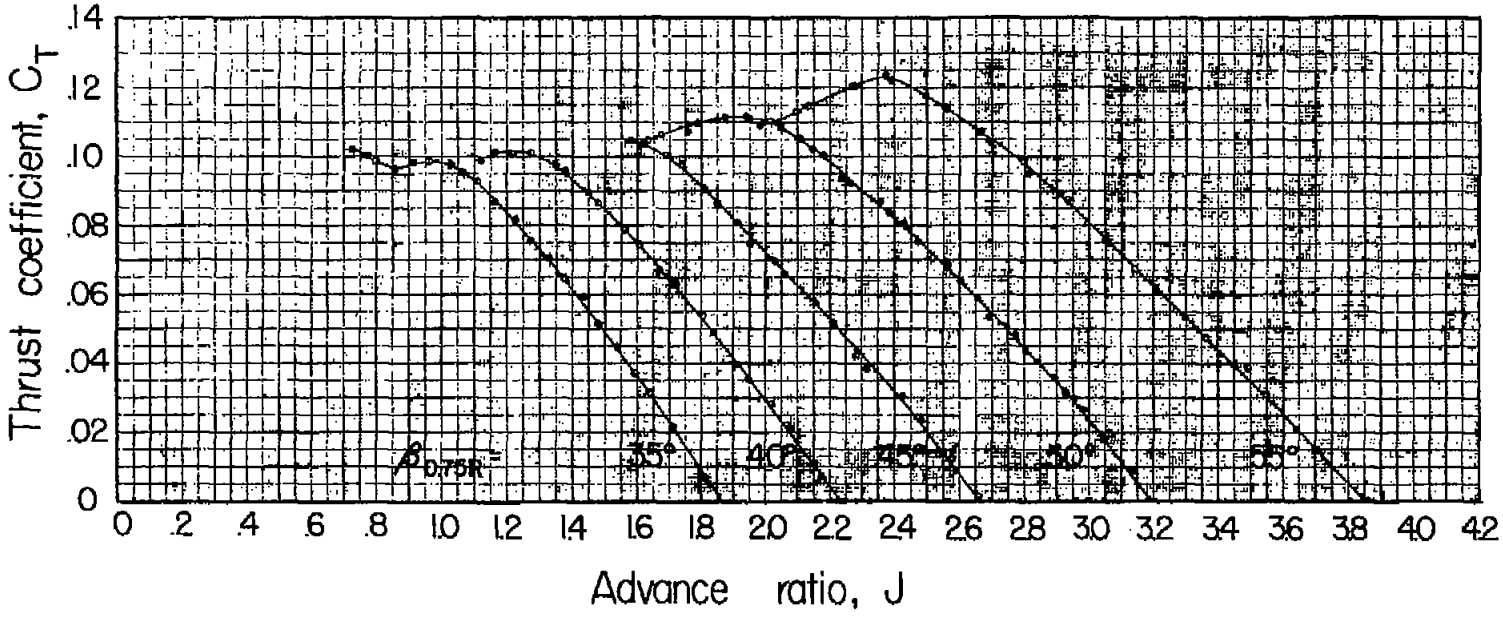
(a) Air-stream Mach number at maximum efficiency, 0.611.

Figure 16.— Characteristics of NACA 10-(5)(08)-03 propeller at high forward speeds. $\beta_{0.75R} = 45°$



(b) Air-stream Mach number at maximum efficiency, 0.641.

Figure 16.—Concluded.



(a) Thrust coefficient.

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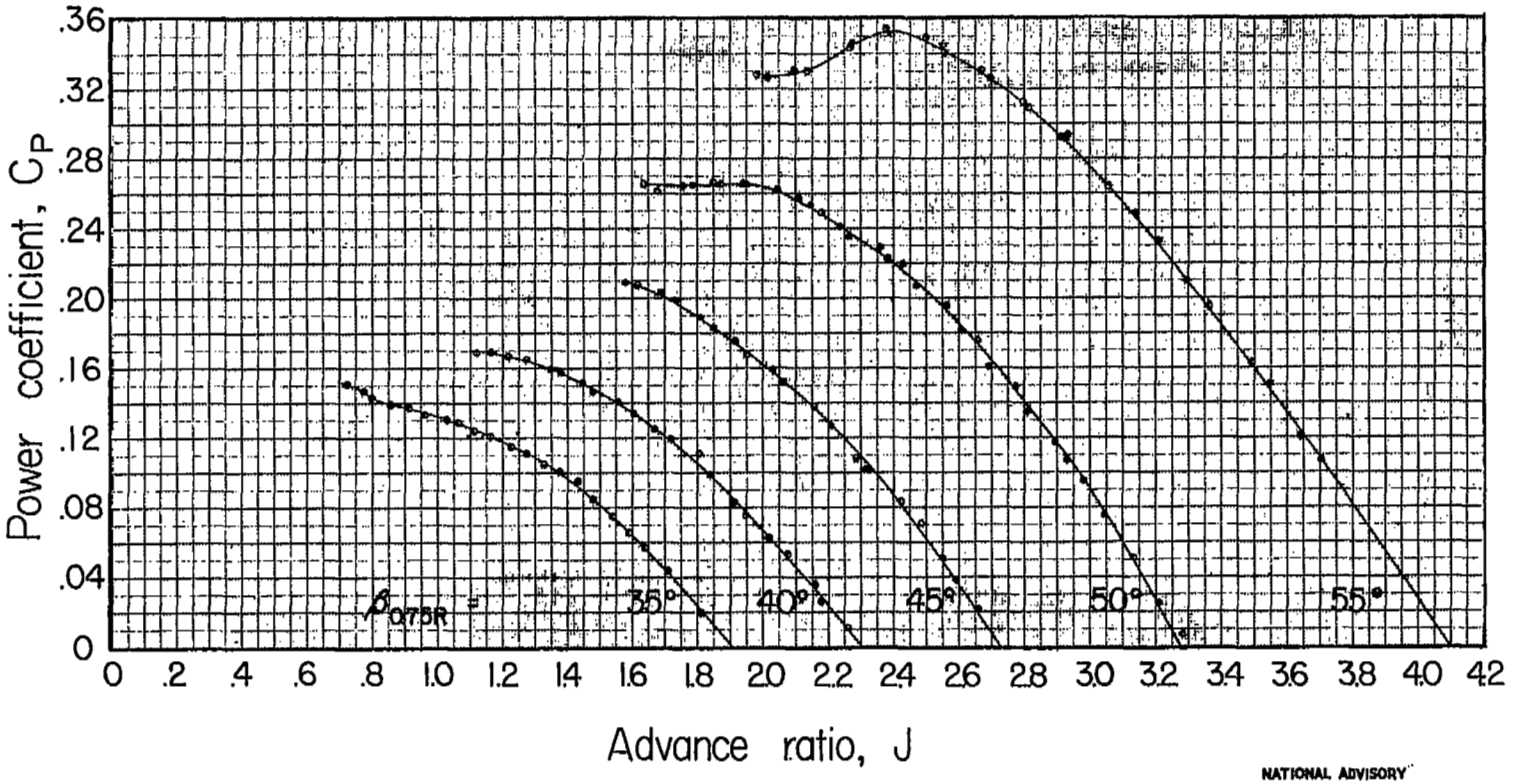
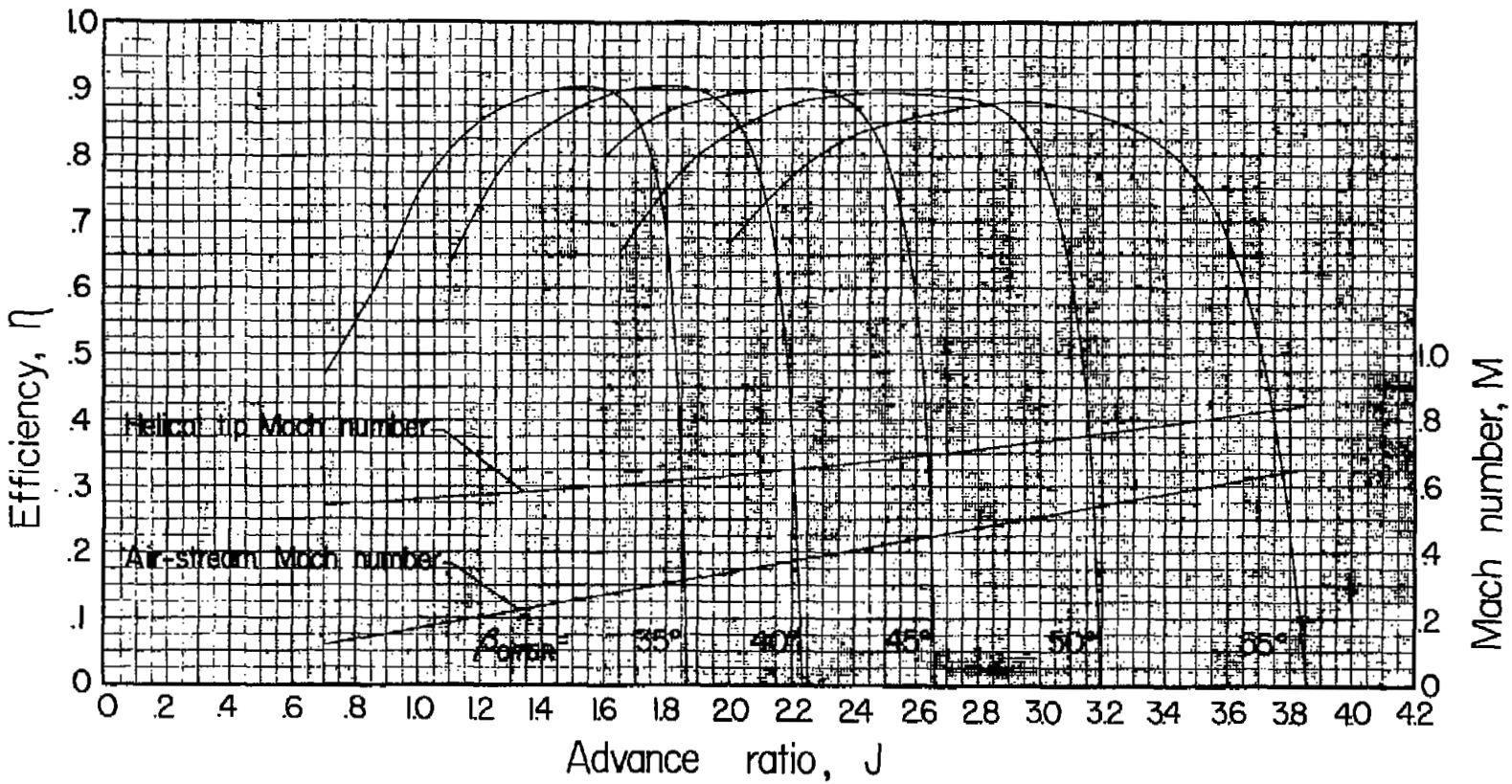
Figure 17.—Characteristics of NACA 10-(5)(08)-03R propeller. Rotational speed, 1140 rpm.



(b) Power coefficient.

Figure 17.—Continued. Rotational speed, 1140 rpm.



(c) Efficiency.

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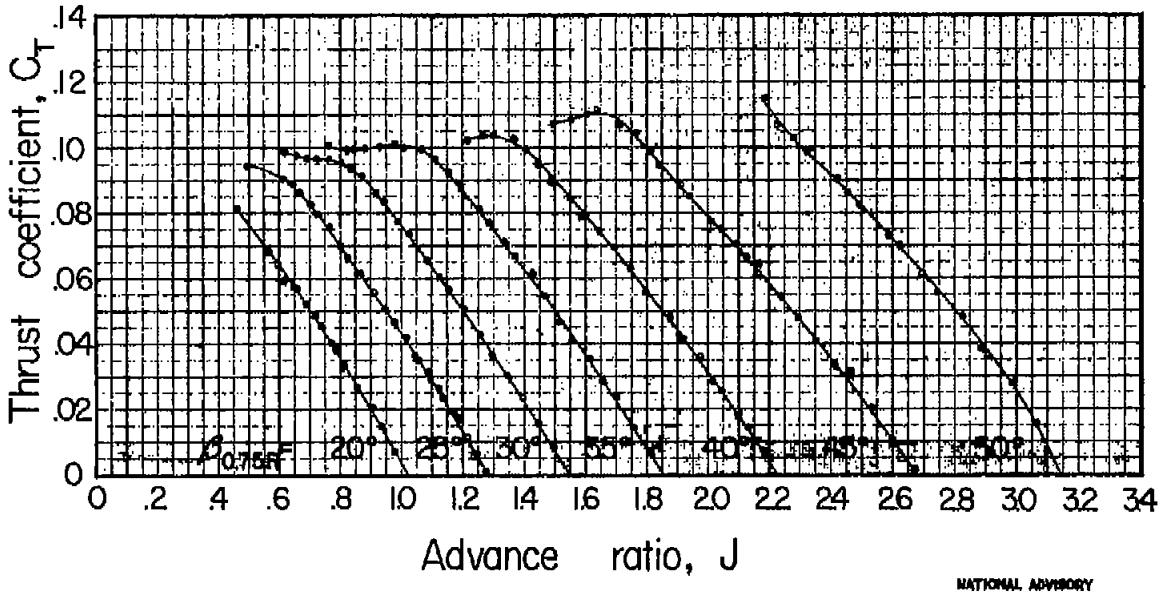
Figure 17.—Concluded. Rotational speed, 1140 rpm.



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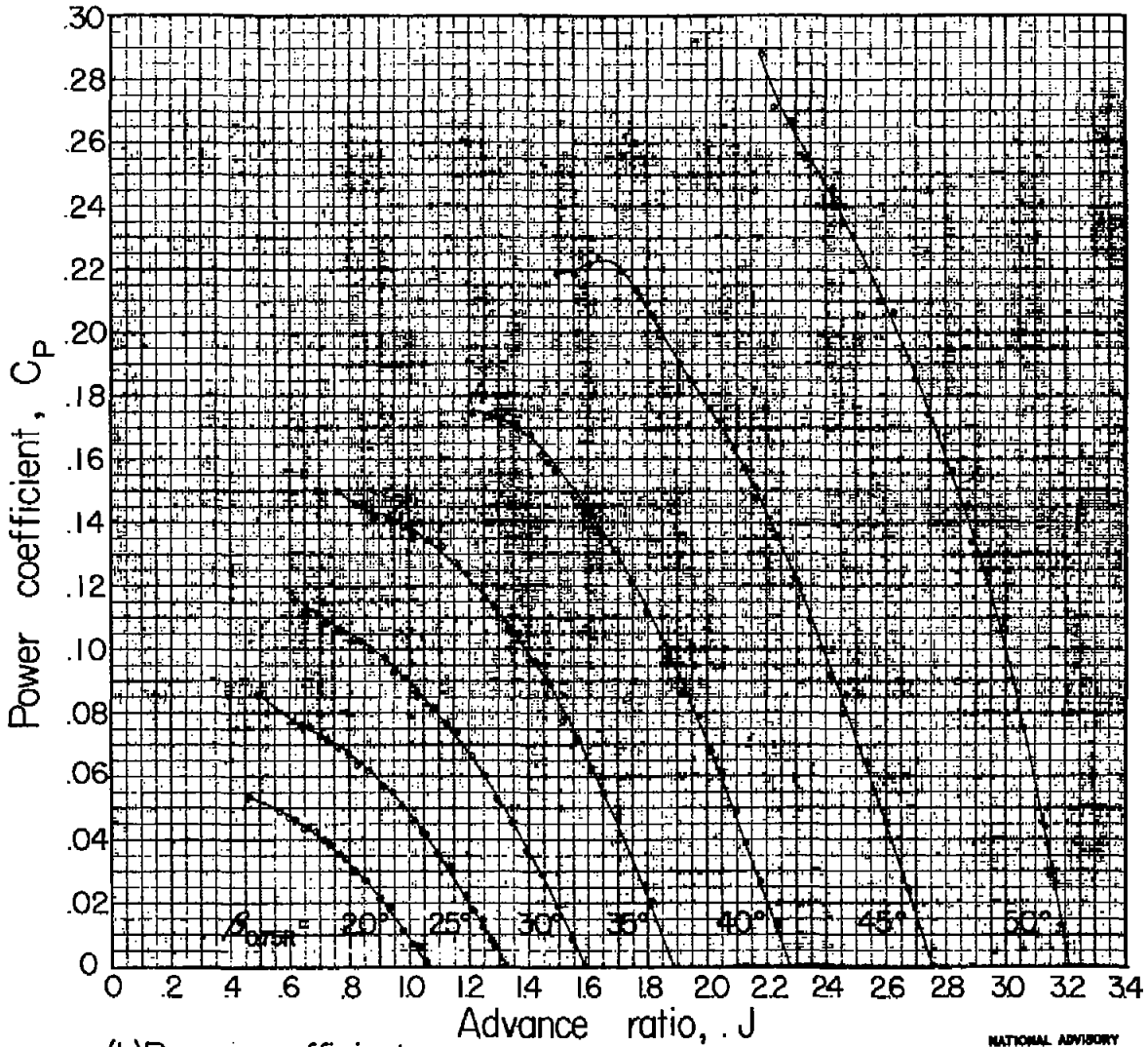
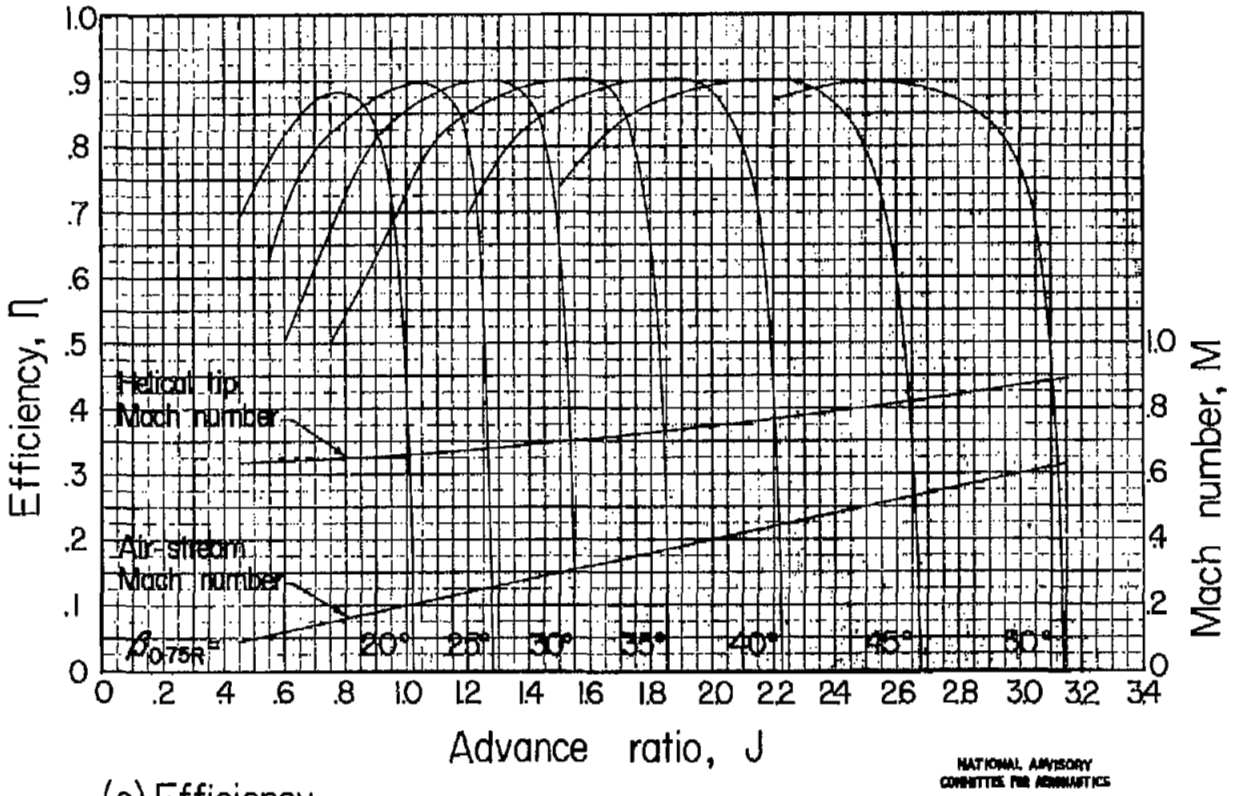
(a) Thrust coefficient.

Figure 18.— Characteristics of NACA 10-(5)(08)-03R propeller. Rotational speed, 1350 rpm.



(b)Power coefficient.

Figure 18.—Continued. Rotational speed, 1350rpm.



(c) Efficiency.

Figure 18.—Concluded. Rotational speed, 1350 rpm.

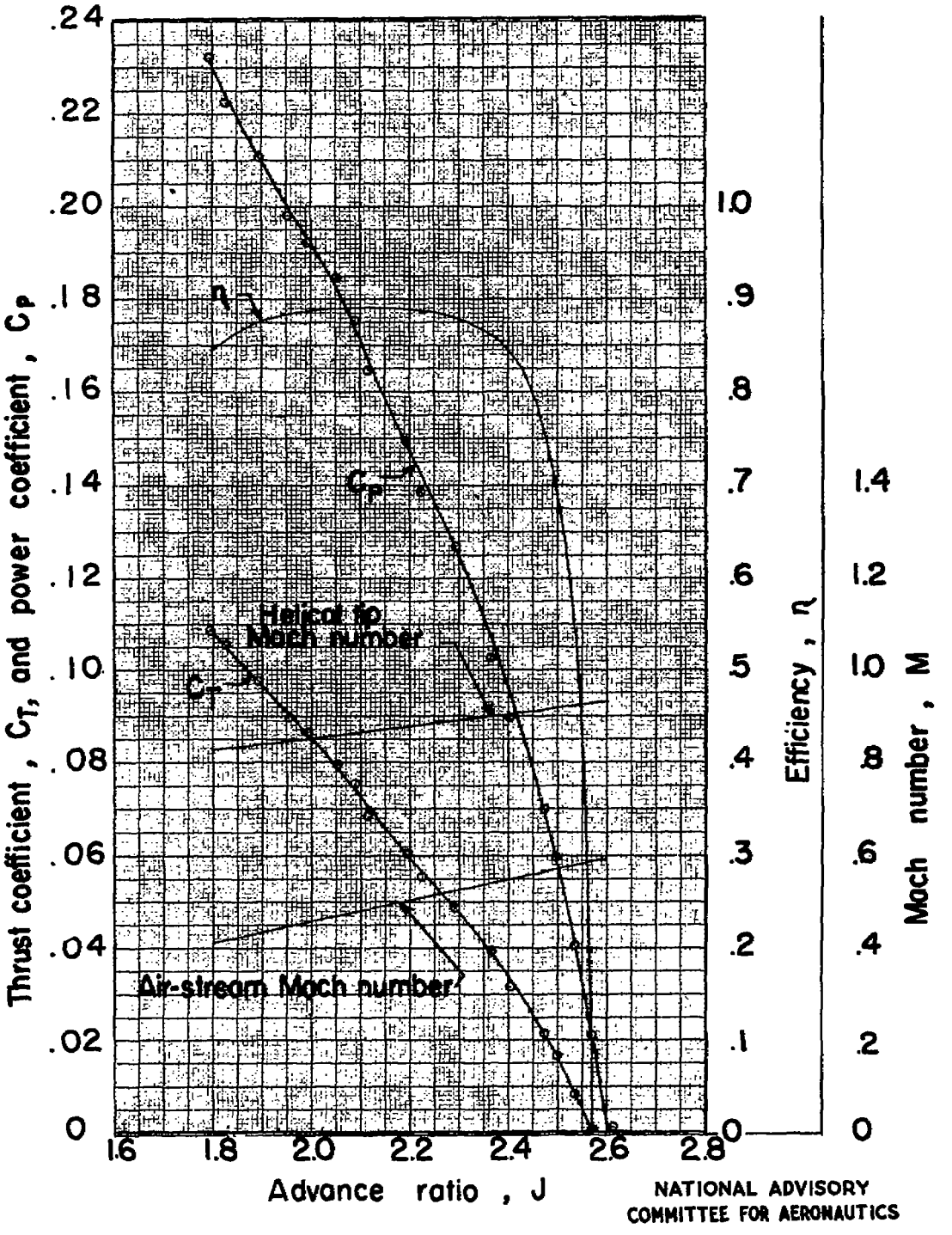
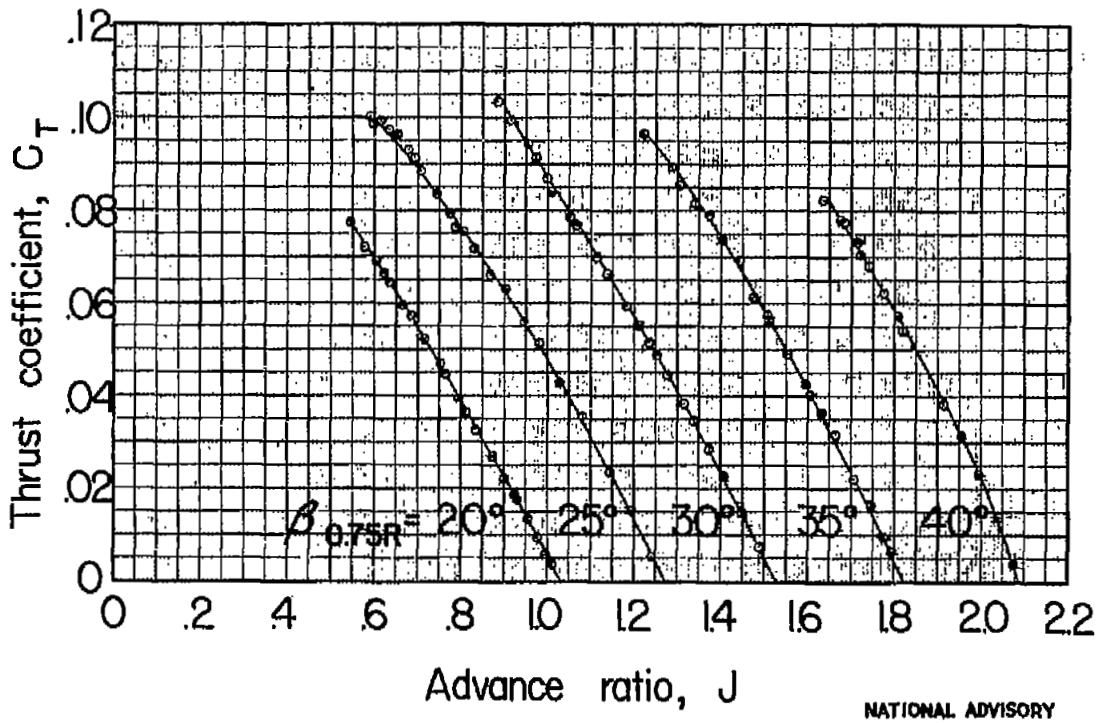


Figure 19.—Characteristics of NACA 10-(5)(08)-03R propeller. Rotational speed, 1500 rpm; $\beta_{0.75R} = 45°$.



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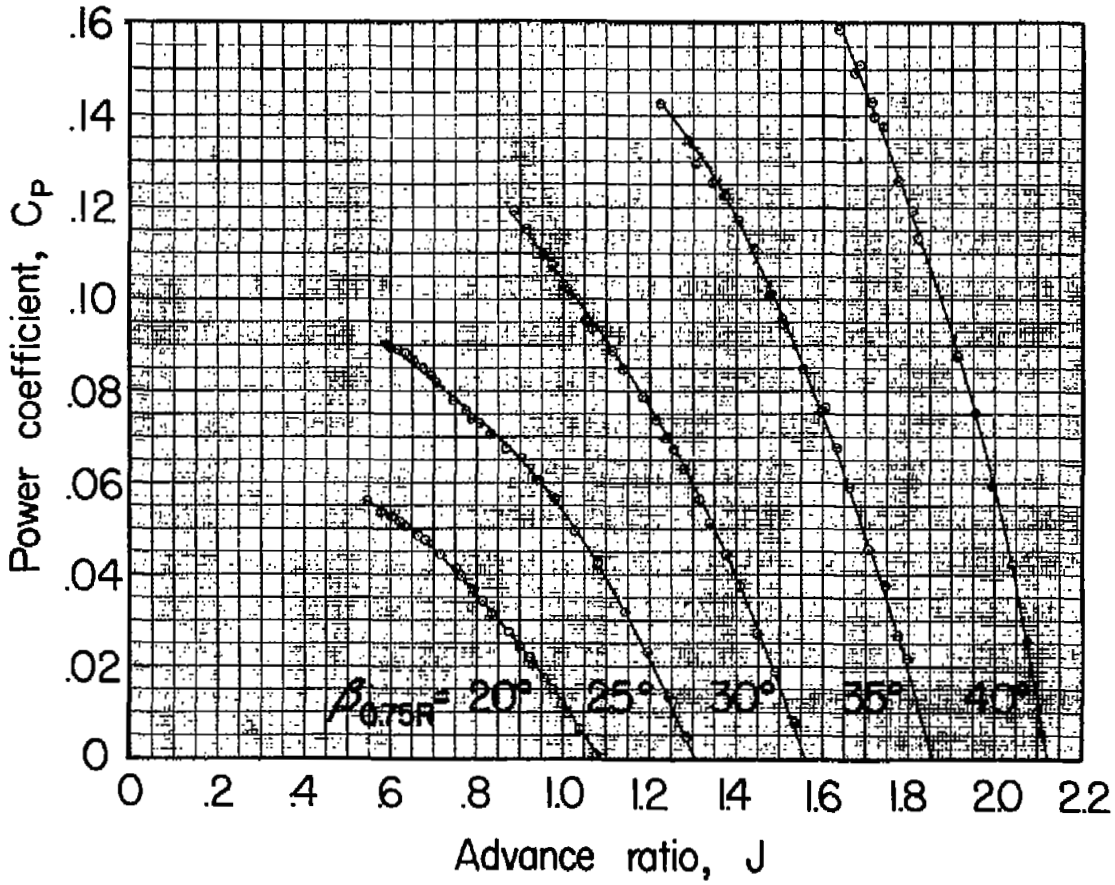
(a) Thrust coefficient.

Figure 20.—Characteristics of NACA 10-(5)(08)-03R propeller. Rotational speed, 1800 rpm.



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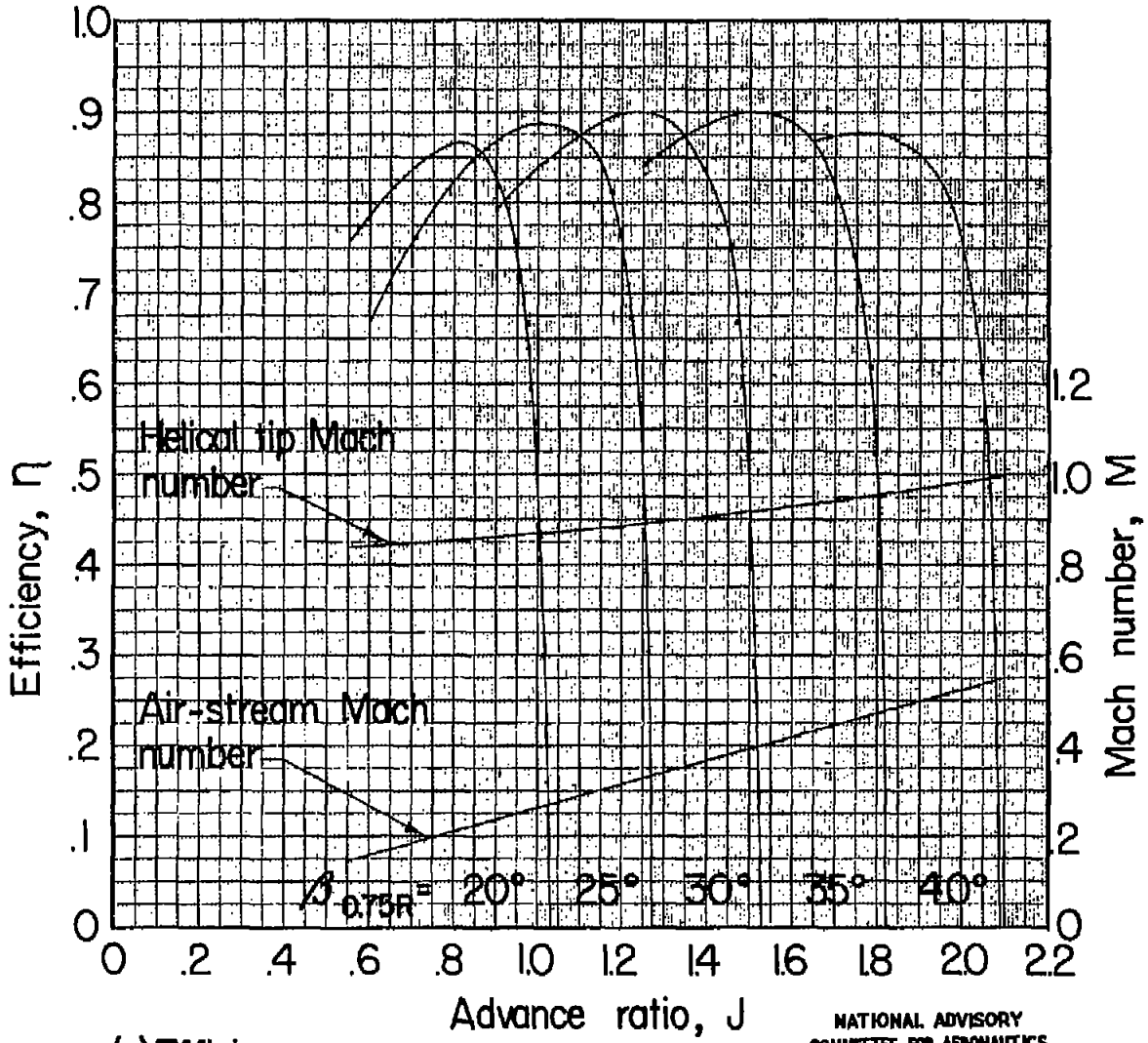
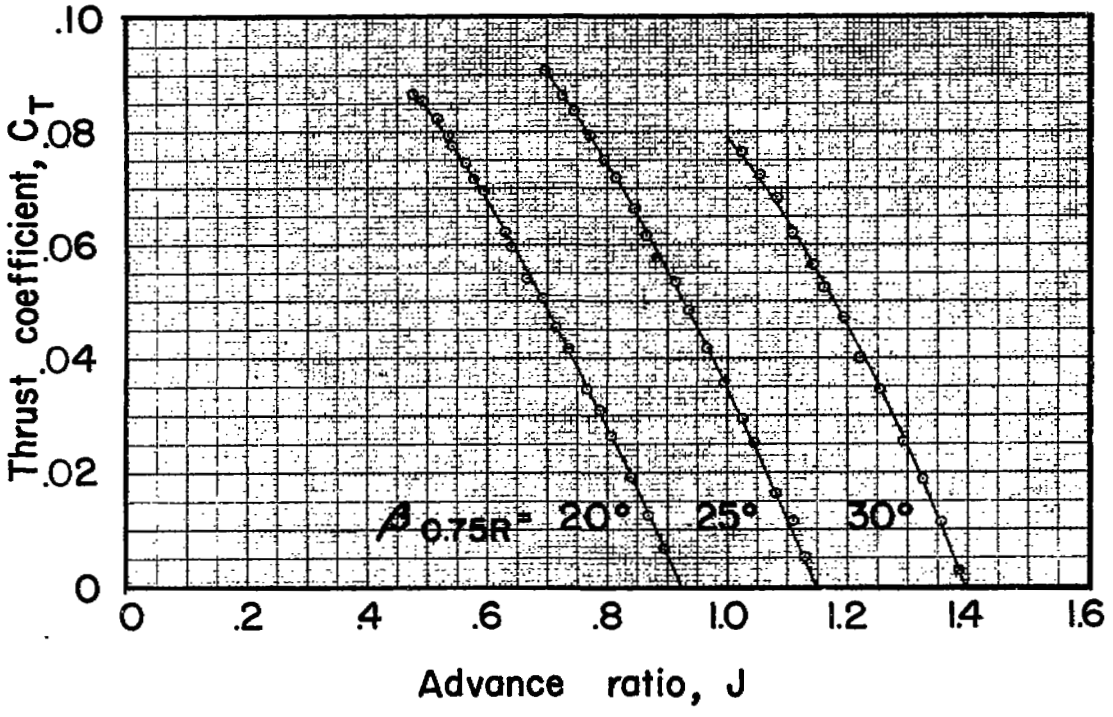
(b) Power coefficient.

Figure 20.—Continued. Rotational speed, 1800 rpm.



(c) Efficiency.

Figure 20.—Concluded. Rotational speed, 1800 rpm.



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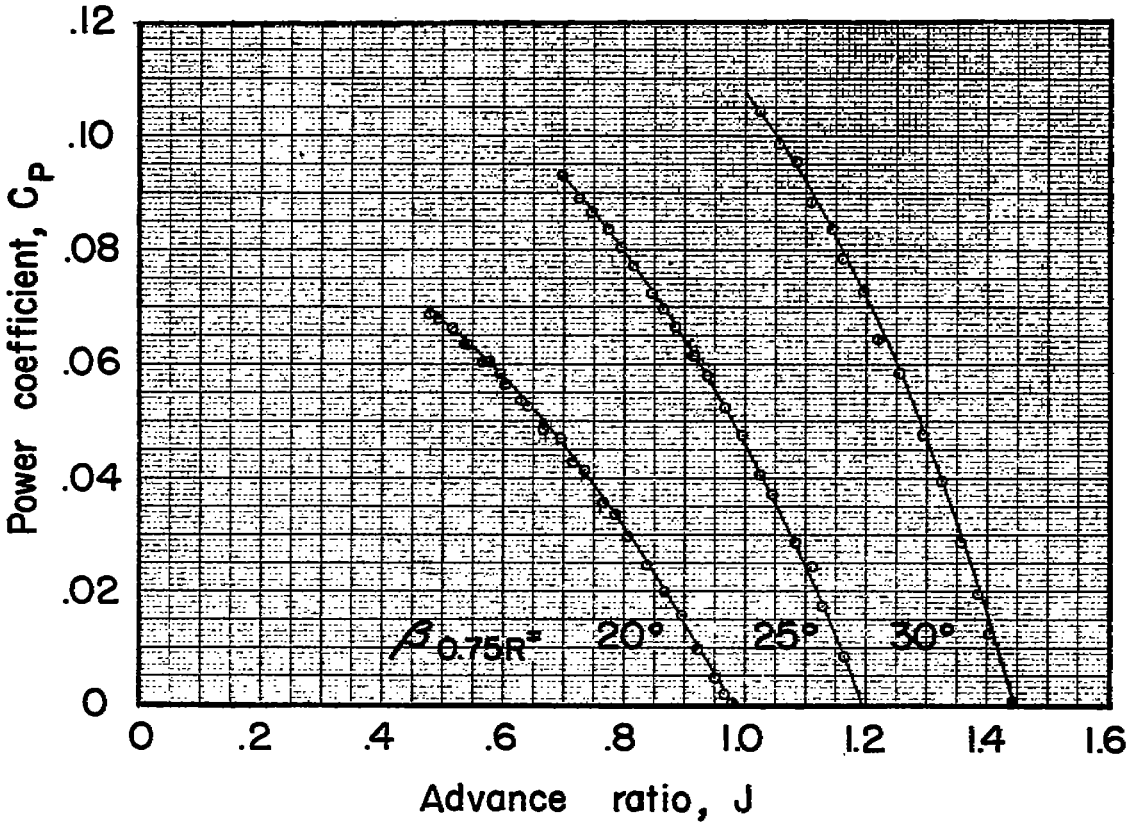
(a) Thrust coefficient.

Figure 21.—Characteristics of NACA 10-(5)(08)-03R propeller.

Rotational speed, 2160 rpm.



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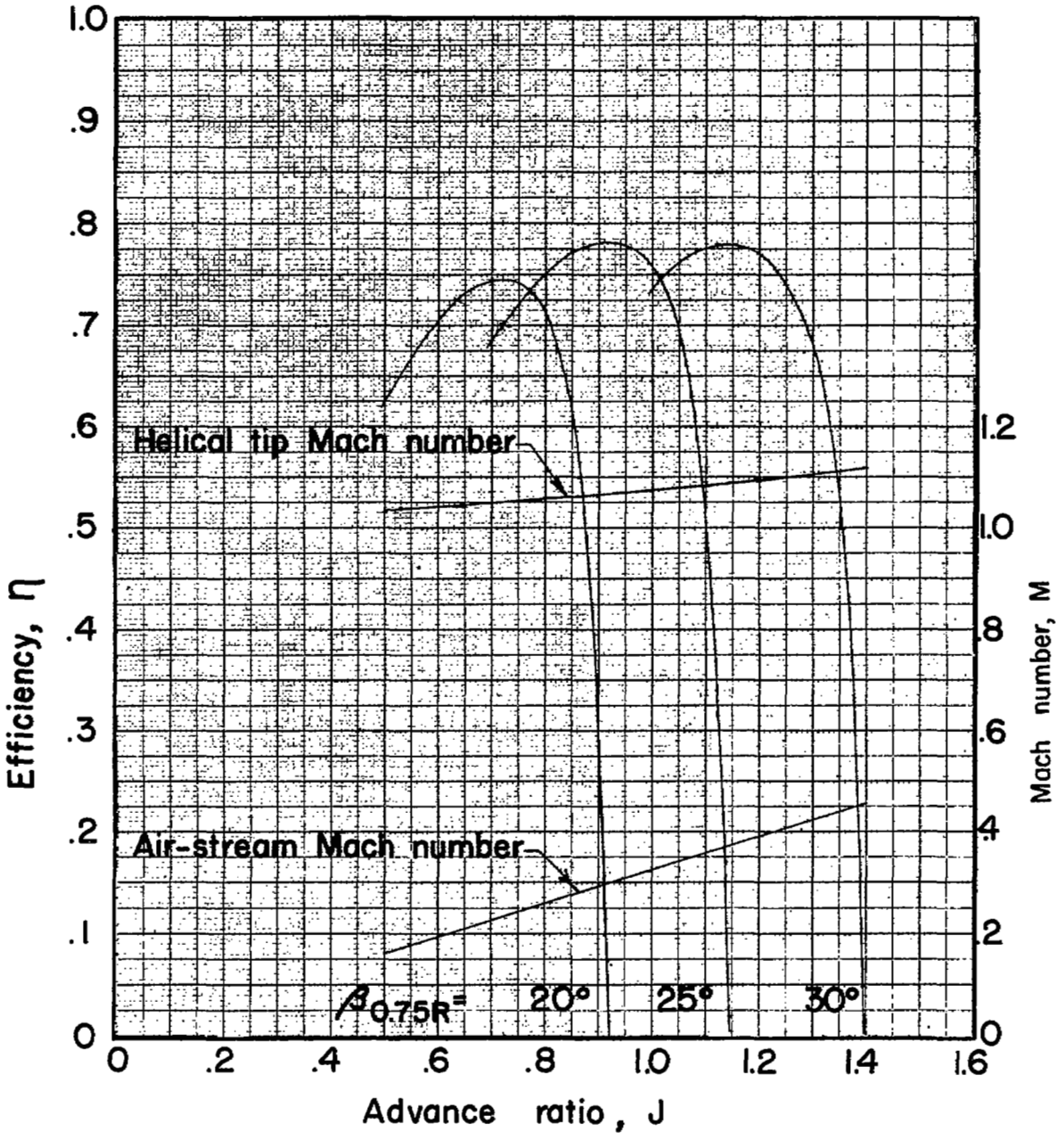
(b) Power coefficient.

Figure 21.—— Continued. Rotational speed, 2160 rpm.



(c) Efficiency.

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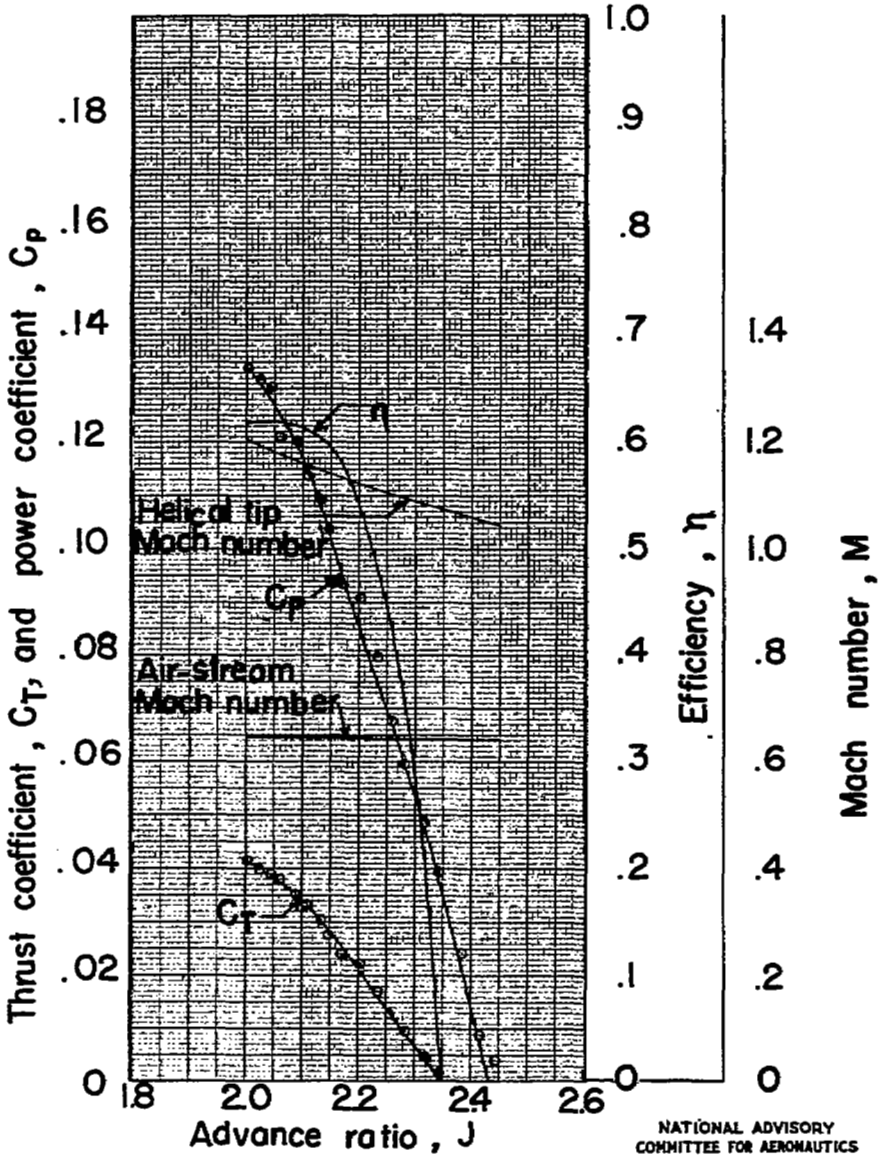
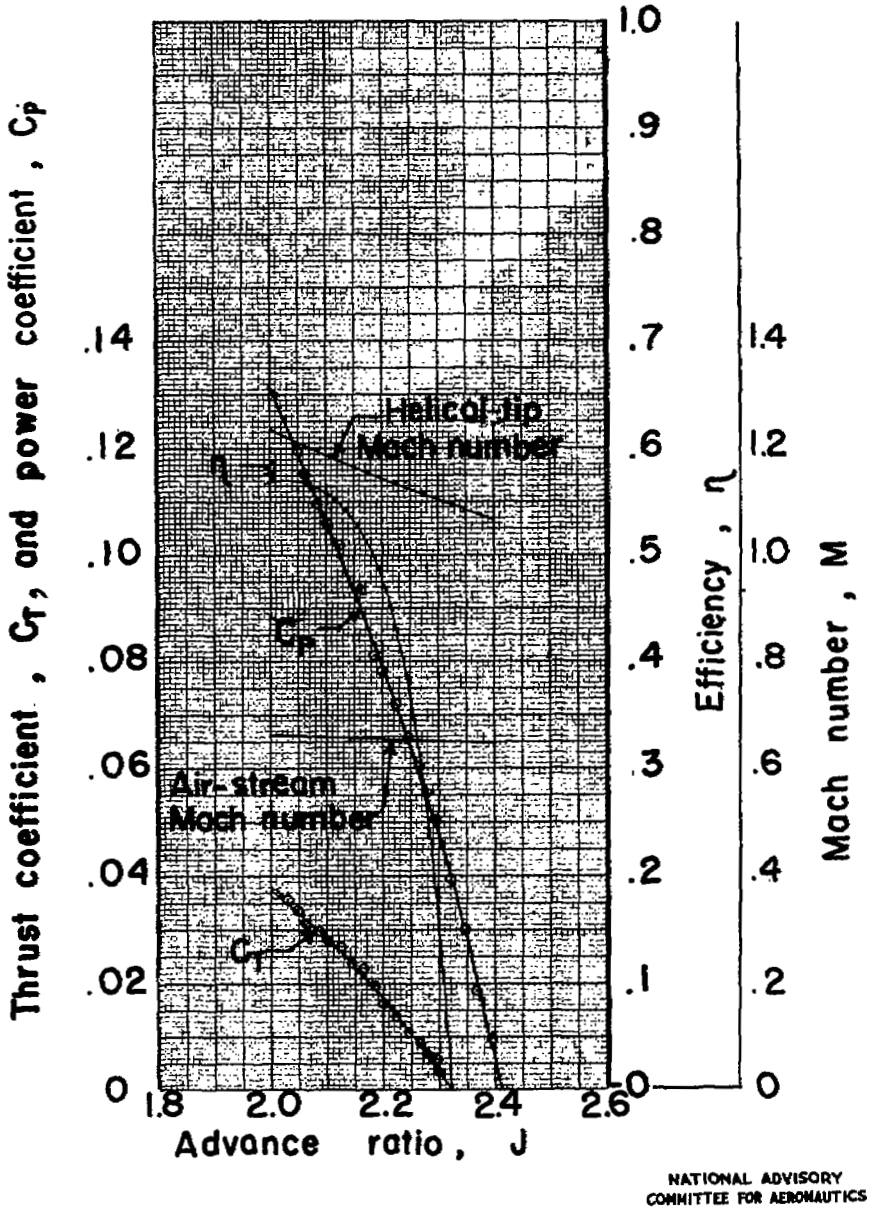
Figure 21.—Concluded. Rotational speed, 2160rpm.



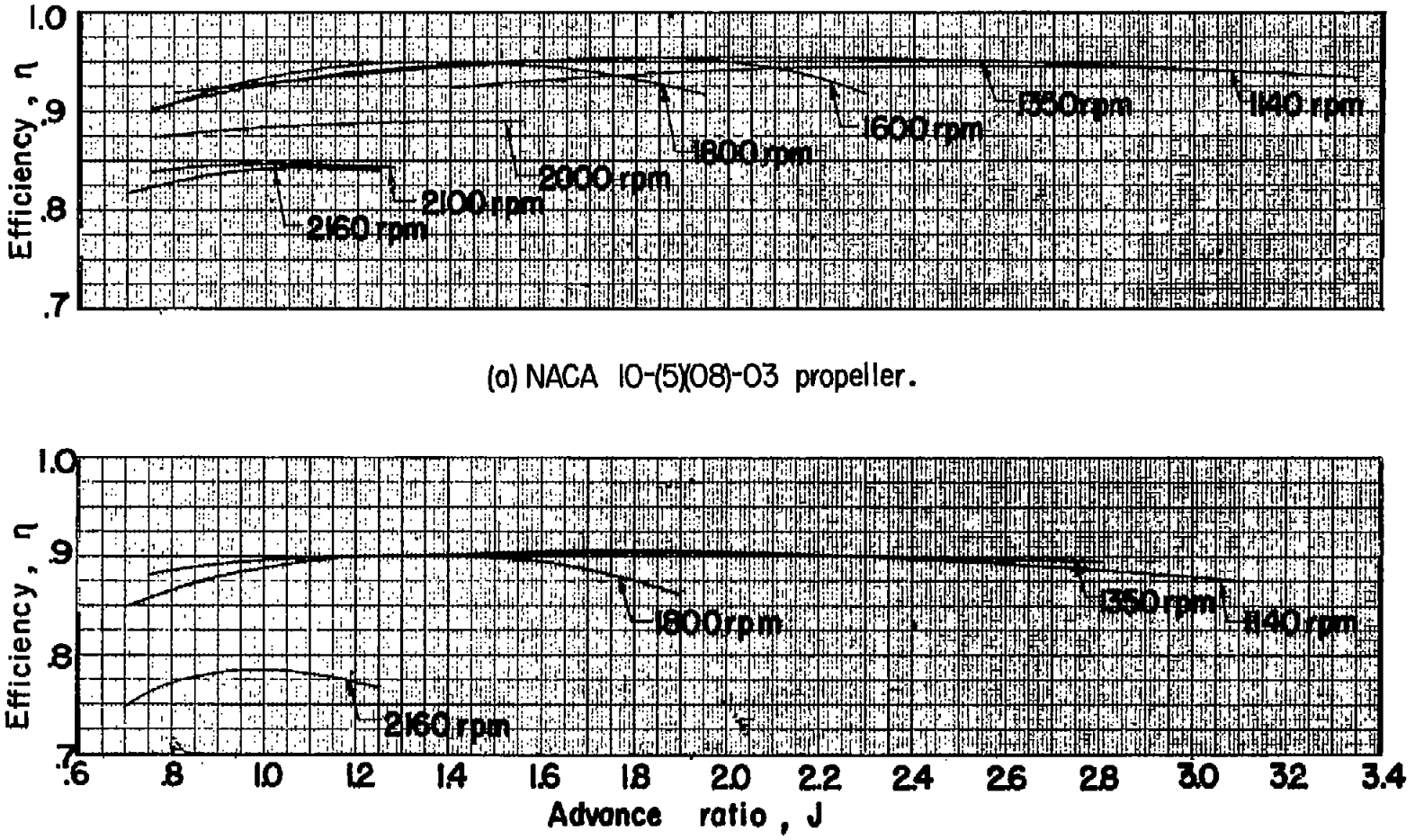
(a) Air-stream Mach number at maximum efficiency = 0.645.

Figure 22.—Characteristics of NACA 10-(5)(08)-03R propeller at high forward speeds. $\beta_{0.75R} = 45°$



(b) Air-stream Mach number at maximum efficiency = 0.661.

Figure 22.- Concluded.



(a) NACA 10-(5)(08)-03 propeller.

(b) NACA 10-(5)(08)-03R propeller.

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Figure 23.—Envelope curves of propeller efficiency.

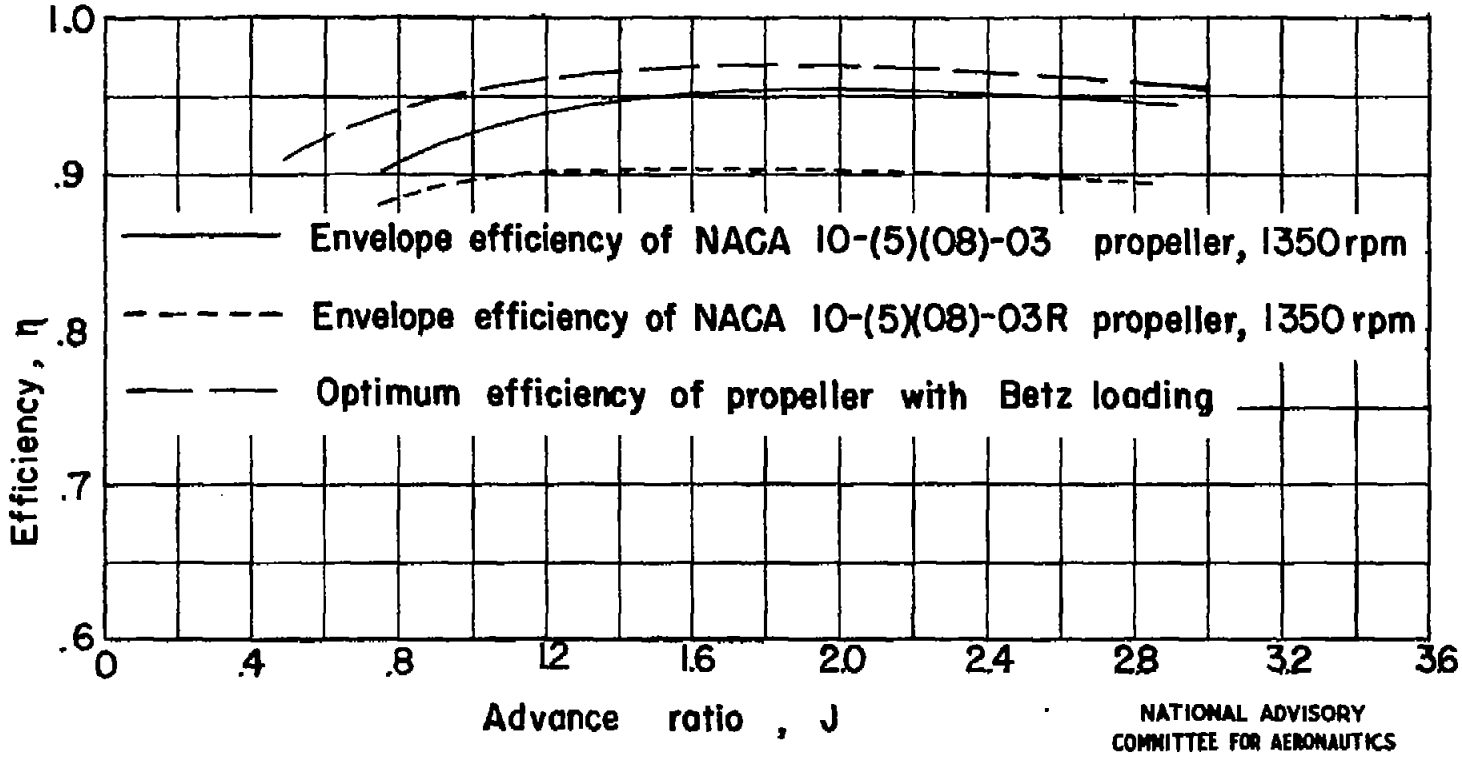


Figure 24.—Comparison of the envelope efficiency of NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers at 1350 rpm with the optimum efficiency of a two-blade propeller with the Betz loading.

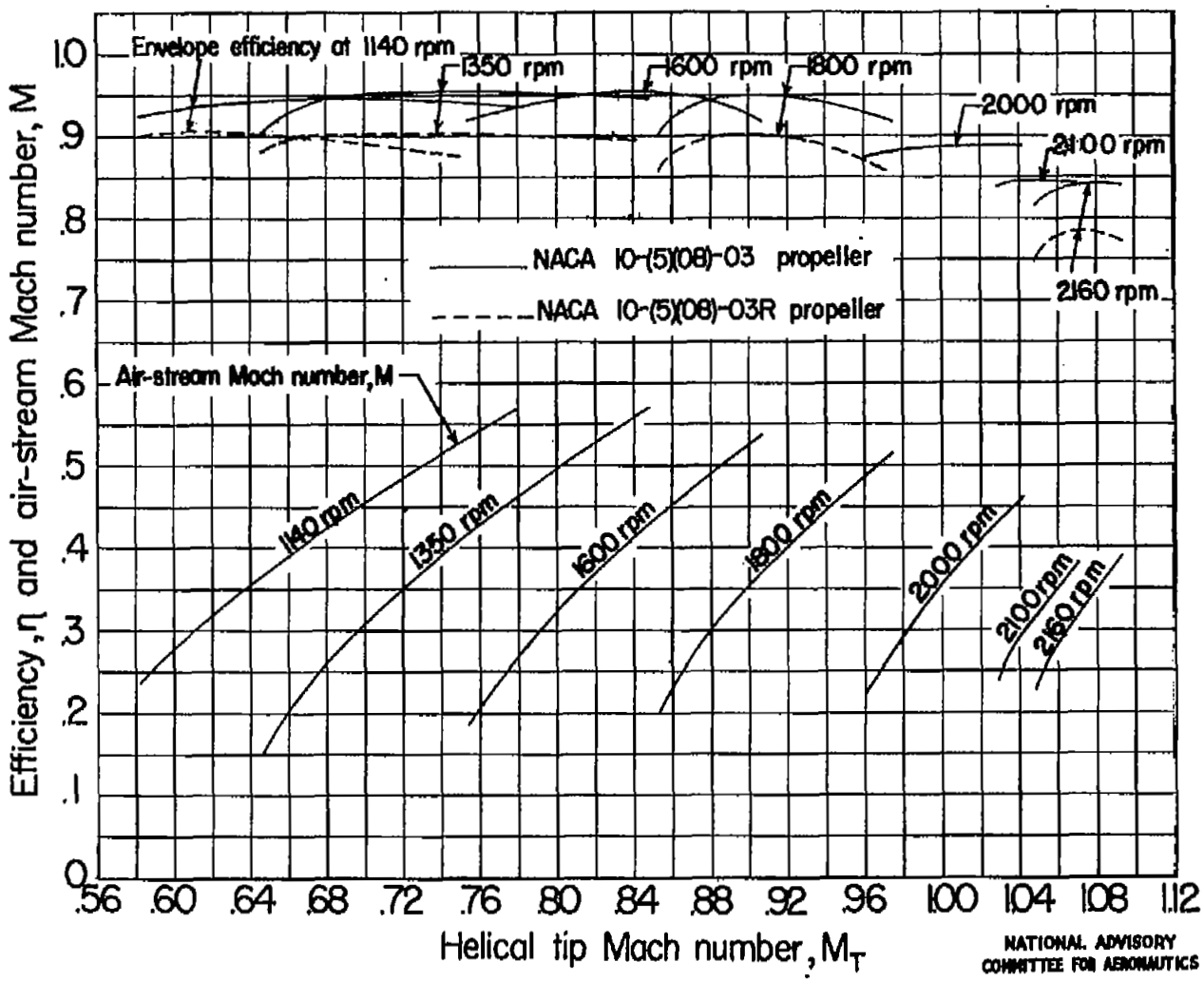


Figure 25.—Effect of compressibility on envelope efficiency for NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers.

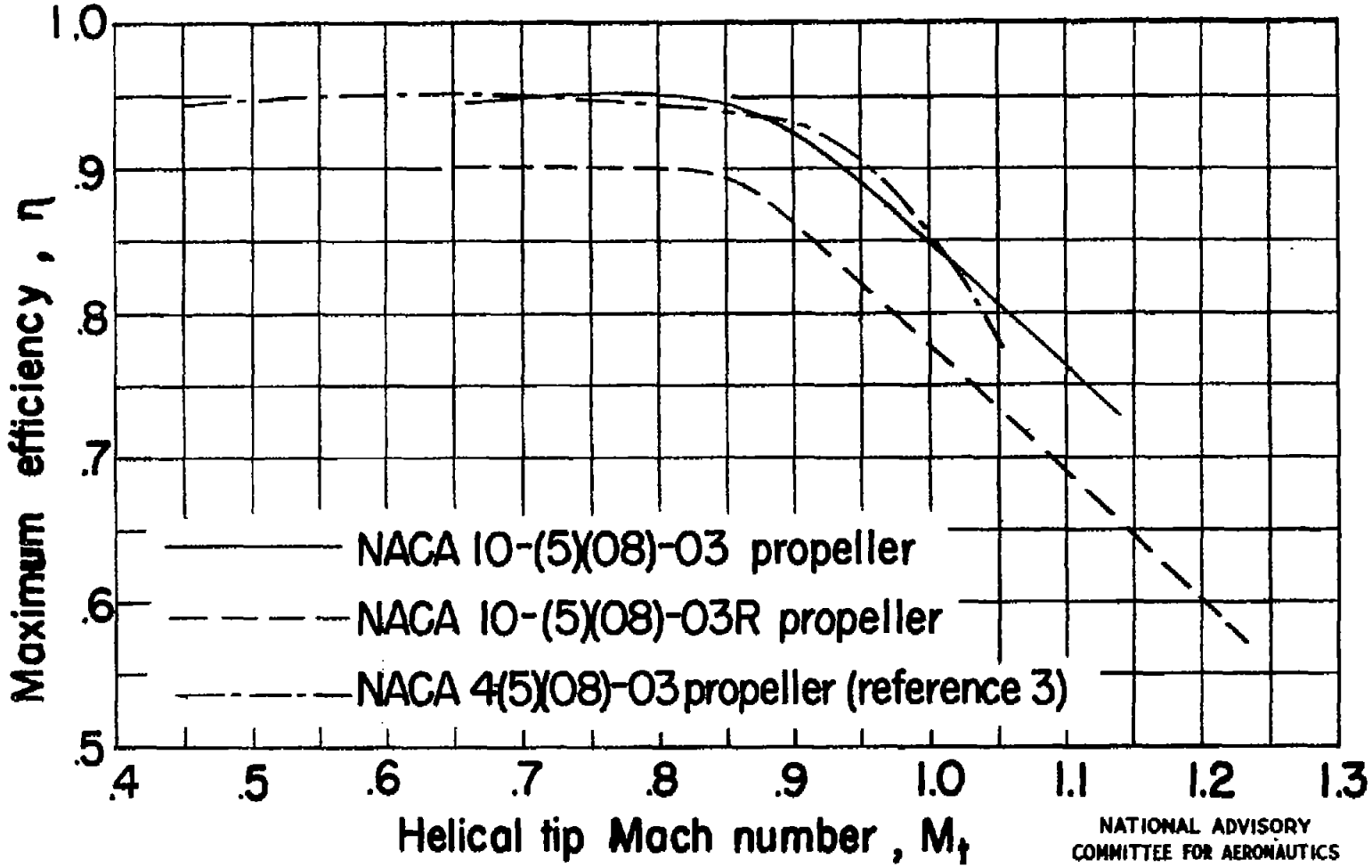


Figure 26.— Effect of compressibility on maximum efficiency. $\beta_{0.75} = 45°$.

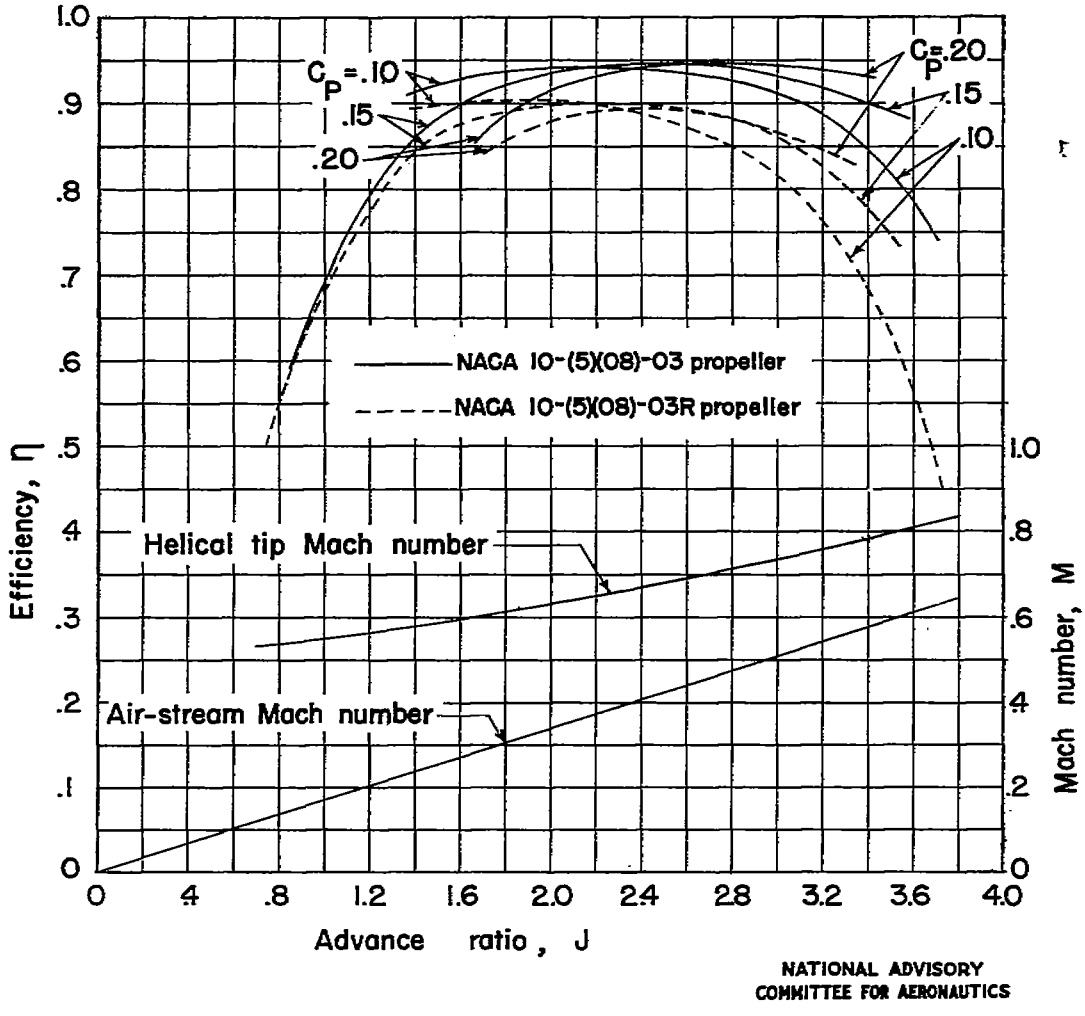


Figure 27.— Efficiency of NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers at constant power coefficients and constant rotational speed of 1140 rpm.

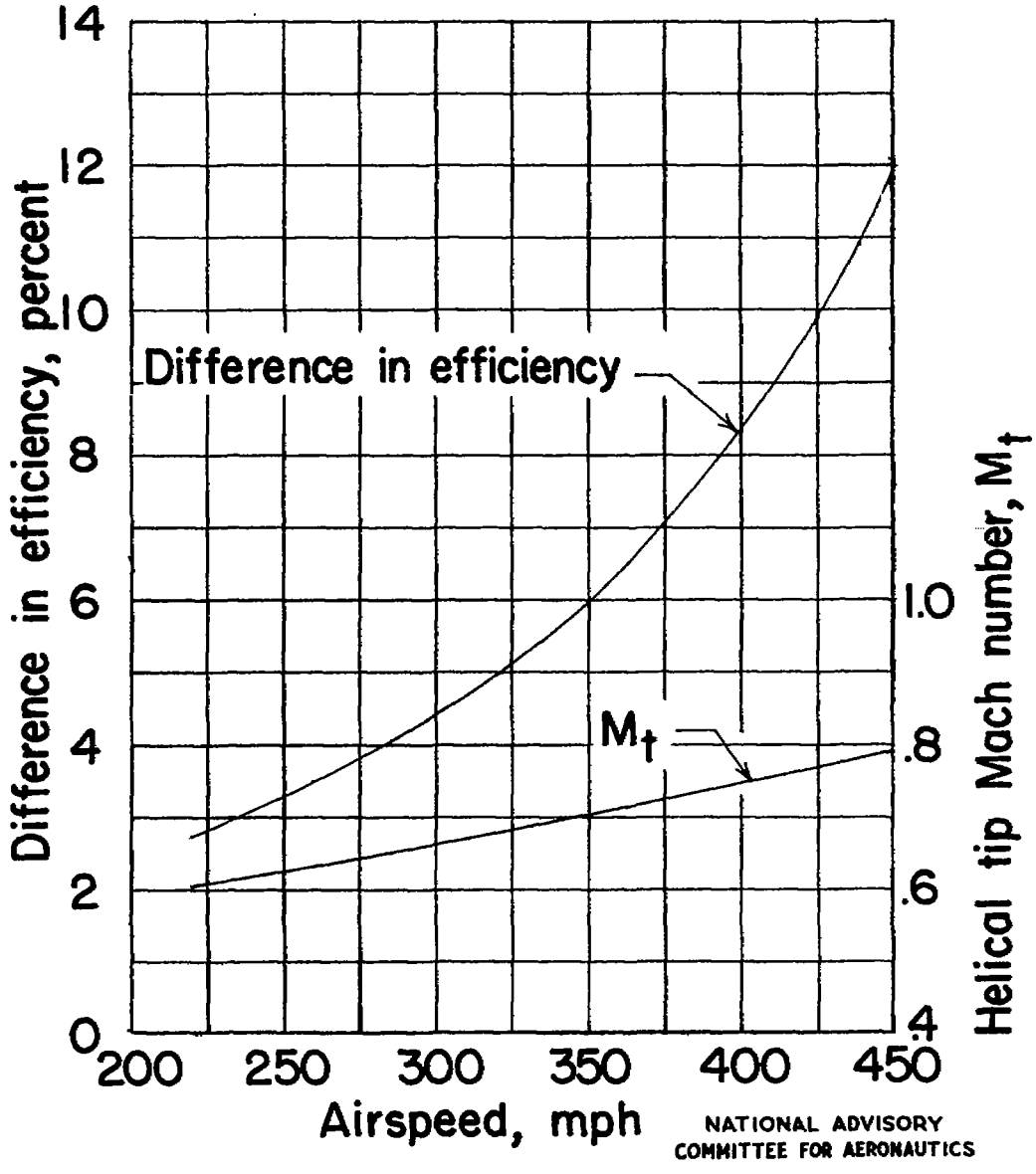


Figure 28.–Variation of the difference in efficiency between NACA 10-(5)(08)-03 and 10-(5)(08)-03R propellers with airspeed. Constant propeller rotational speed, 1140rpm; constant power coefficient per blade, 0.1.

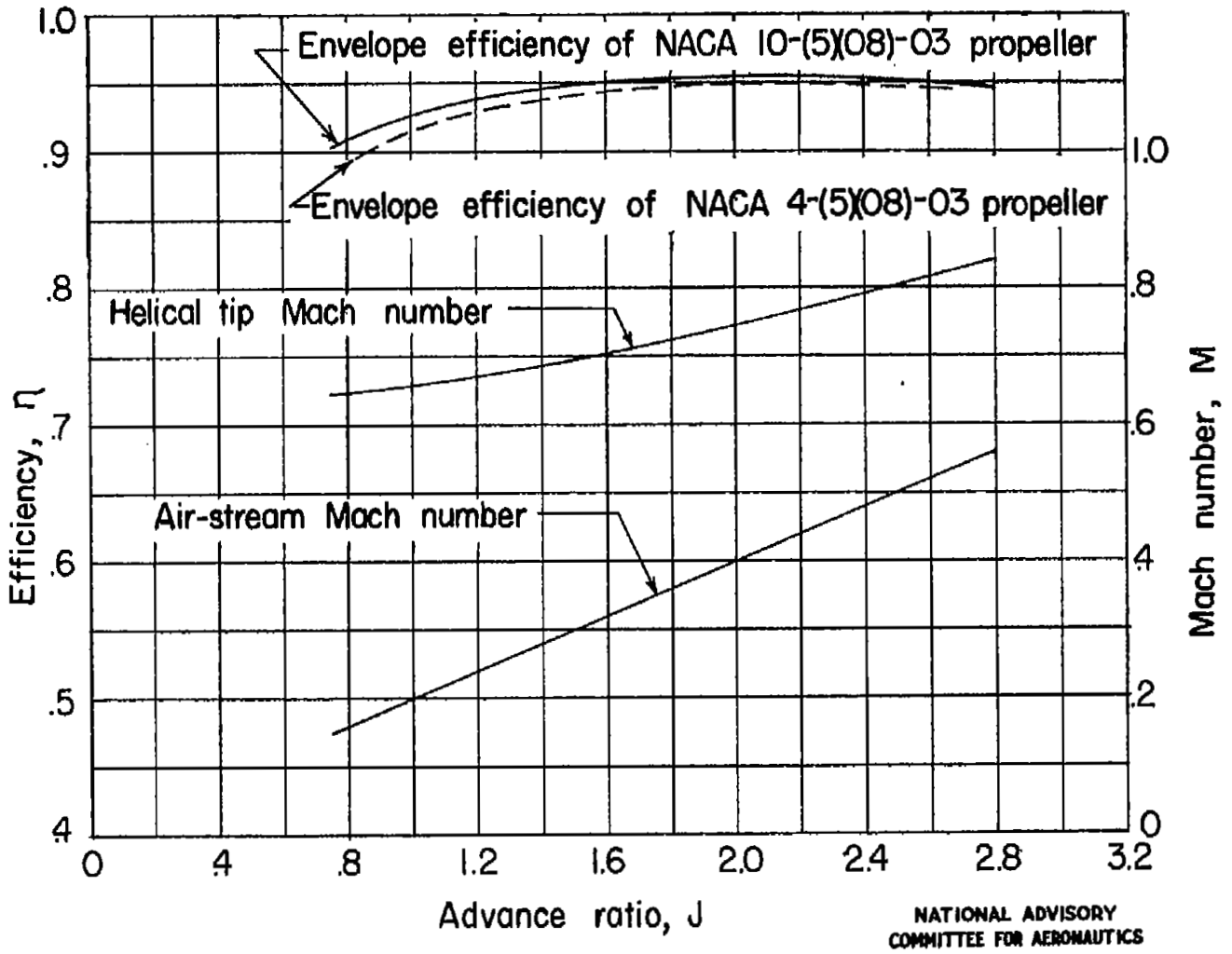
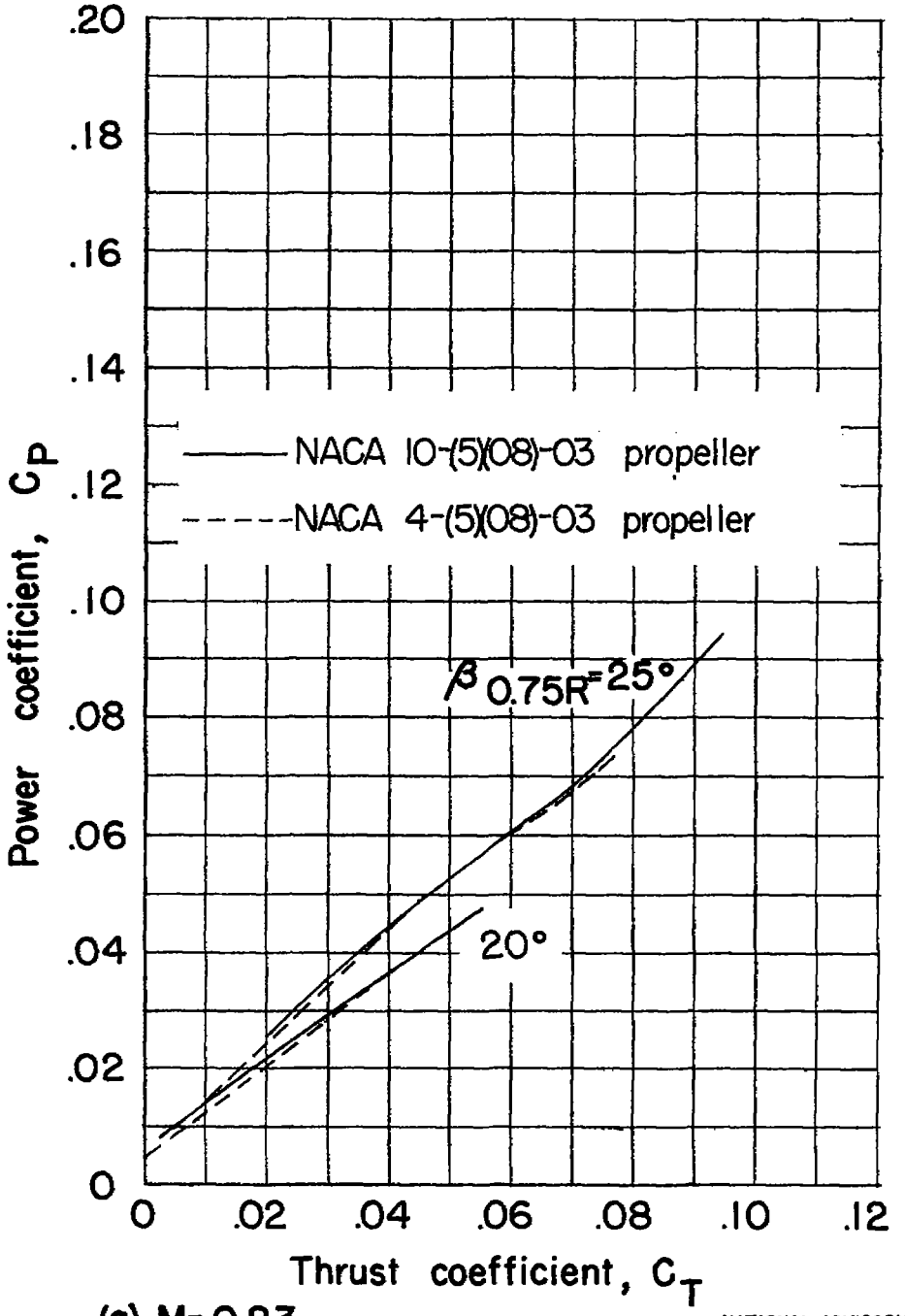


Figure 29.—Comparison of envelope efficiency for NACA 10-(5)(08)-03 and 4-(5)(08)-03 propellers. (Data from reference 3.)



(a) M= 0.23.

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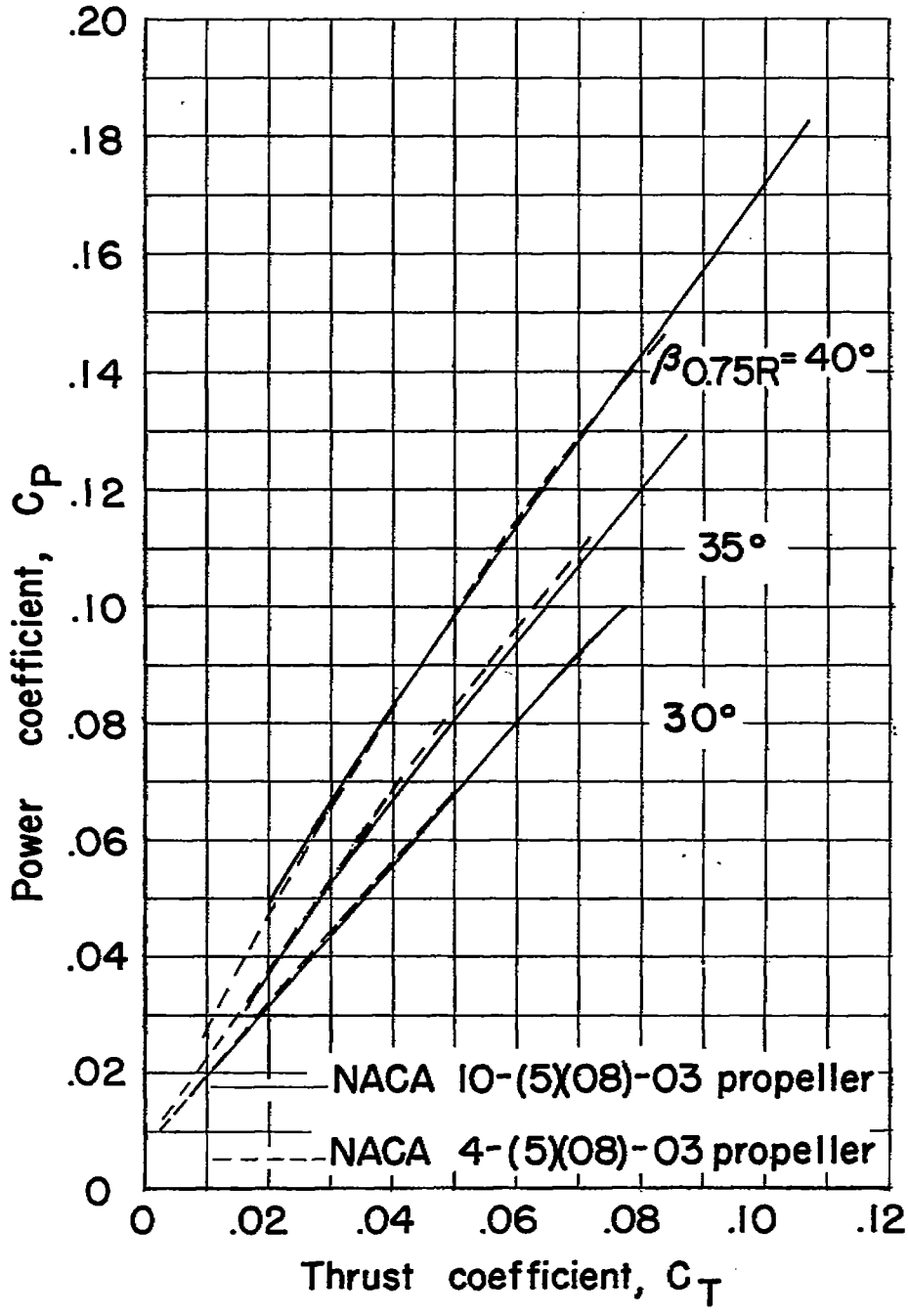
Figure 30.—Comparison of characteristics for NACA 10-(5)(08)-03 and 4-(5)(08)-03 propellers. (Data from reference 3.)



(b) M=0.35.

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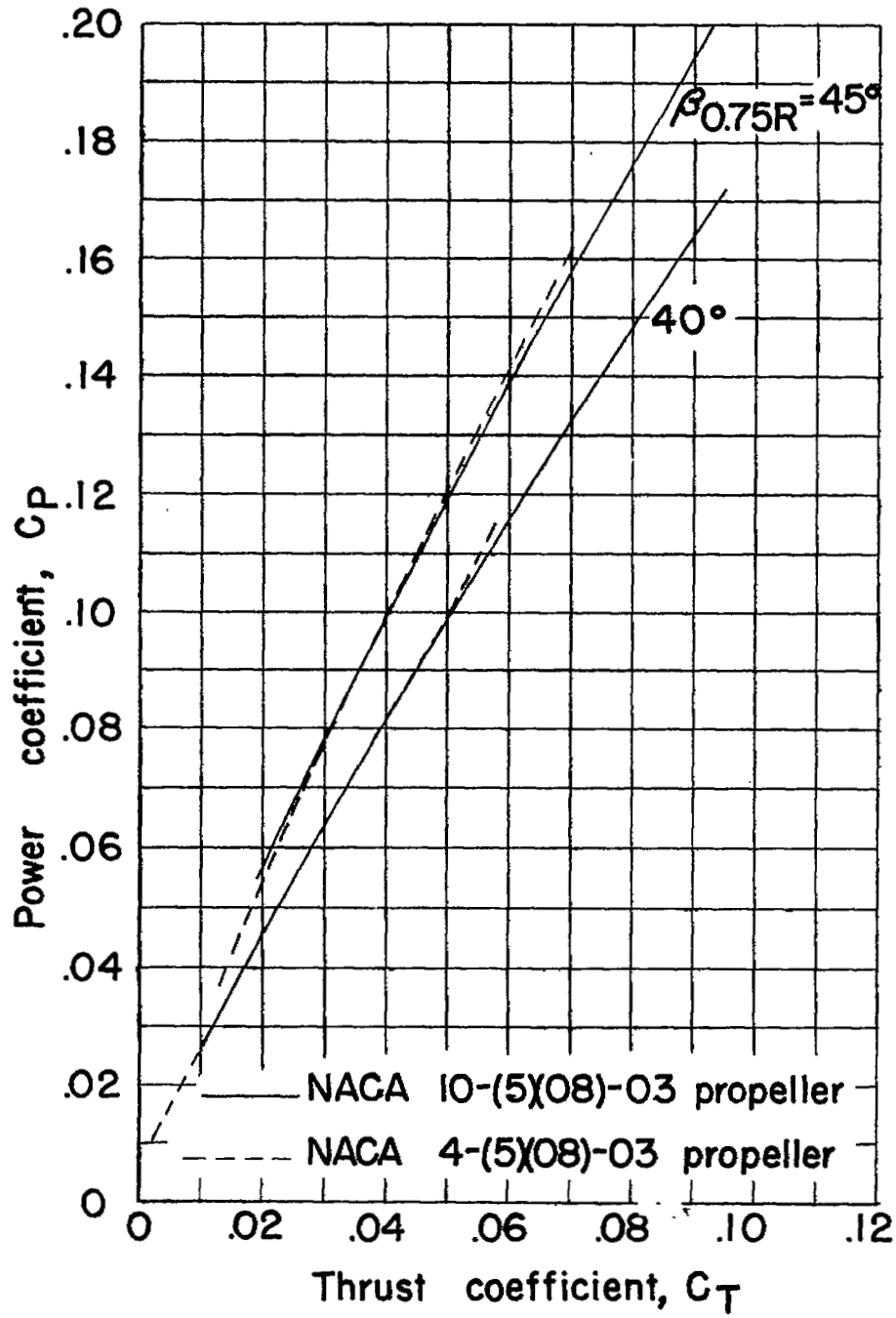
Figure 30.— Continued.



(c) M=0.43.

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Figure 30.— Concluded.