ARR No. L5J02b

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

EFFECT OF PROPELLER-AXIS ANGLE OF ATTACK ON THRUST DISTRIBUTION OVER THE PROPELLER DISK IN RELATION TO WAKE-SURVEY MEASUREMENT OF THRUST

By Robert E. Pendley

NACA

WASHINGTON

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ADVANCE RESTRICTED REPORT

EFFECT OF PROPELLER-AXIS ANGLE OF ATTACK ON THRUST DISTRIBUTION OVER THE PROPELLER DISK IN RELATION TO WAKE-SURVEY MEASUREMENT OF THRUST

By Robert E. Pendley

SUMMARY

Tests were made to investigate the variation of thrust distribution over the propeller disk with angle of pitch of the propeller thrust axis and to determine the disposition and the minimum number of rakes necessary to measure the propeller thrust. The tests were made at a low Mach number for a low and a high blade angle with the propeller operating at three small angles of pitch, and some of the tests were repeated at a higher Mach number. The data obtained show that, for small angles of pitch, large changes occur in the energy distribution in the wake which prohibit the use of a single survey rake for thrust measurement in flight tests and limit the use of a single rake in wind-tunnel tests. Under certain conditions, the energy distribution in the wake took on a symmetrical form and two diametrically opposed survey rakes were shown to be satisfactory for obtaining propeller thrust.

INTRODUCTION

In many cases a total-pressure survey rake is a more desirable means for measuring propeller thrust than a force system because not only the total thrust can be obtained from wake-survey data but also the action of the elements along the propeller blade can be analyzed. In flight tests propeller thrust can be measured only by wake surveys since a satisfactory thrust meter has not yet been developed. In wind-tunnel investigations of propellers, however, the thrust obtained by use of a force system often differs considerably from that obtained by single-rake wake-survey measurements.

In reference 1 the lack of agreement between the thrust obtained by wake surveys and by force tests was explained as the result of hub drag and increase in body drag due to the slipstream. In reference 2, published later, propeller-thrust-axis inclination to the free-stream flow was shown to affect wake-survey measurements since large variations in the distribution of thrust over the propeller disk were found to occur with variations in angle of pitch or yaw. Some of the lack of agreement in the measurements of reference 1 might therefore have been caused by a small angle of pitch or yaw of the propeller thrust axis, although the hub drag and the increase in body drag undoubtedly contributed to the lack of agreement. The effect of propeller-thrust-axis inclination to the free-stream flow on wake-survey measurements was further verified by tests made in the Langley 8-foot high-speed tunnel. In these tests, large differences in the thrust measured by a force system and by a single survey rake were found with the model at an angle of attack of 1°, but excellent agreement was obtained when the tests were made at an angle of attack of 0°.

The present tests were made in the Langley 8-foot high-speed tunnel to investigate the variation of thrust distribution over the propeller disk with angle of pitch of the propeller thrust axis and to determine the number and radial position of wake-survey rakes necessary to obtain the propeller thrust. Survey measurements with a single rake were made at six equally spaced radial positions around the propeller disk. The tests were made at three small angles of attack of the propeller thrust axis for a high and a low blade angle and at two Mach numbers. The effect of longitudinal position of the rake was not investigated.

SYMBOLS

The symbols used herein are defined as follows:

D propeller diameter, feet

J advance-diameter ratio (V/nD)

M free-stream Mach number

n propeller rotational speed, revolutions per second

r	station radius, feet
r_s	wake-survey-station radius, feet
R	propeller tip radius, feet
V	free-stream velocity, feet per second
W	section relative air velocity, feet per second
x	radial station (r/R)
x_s	radial station at survey plane (r_s/R)
ΔC_T	wake-survey thrust coefficient minus force-test thrust coefficient
dC_T/dx_s	thrust-coefficient gradient
C_{T_s}	wake-survey thrust coefficient
α_T	angle of attack of propeller thrust axis, degrees
β	section blade angle at 0.75 radial station, degrees
η	propulsive efficiency
ω	angle of rotation measured in direction of propeller rotation from vertical axis (fig. 1), degrees

APPARATUS AND METHODS

The tests were conducted in the Langley 8-foot high-speed tunnel with a two-blade right-hand propeller 4 feet in diameter and having an NACA 4-(3.9)(07)-0345-B blade design of NACA 16-series sections.

Blade form curves for the propeller are given in figure 2. The propeller was designed to have a minimum energy loss in the wake. The pitch distribution used in the design of the propeller is that obtained by assuming all sections of the blades to be operating at the same free-stream velocity. The design conditions were for a free-stream Mach number of 0.600, an advance-diameter ratio of 2.70, and a power coefficient of 0.167.

The body on which the propeller was tested (fig. 3) was designed to have a high critical Mach number. The fuselage shape was the NACA form 111. (See reference 3.) The wing of the model extended through the tunnel walls and was fastened to the balance ring. The airfoil had a 20-inch chord, was 9 percent thick, and had modified NACA 66-series sections.

The forward 7.4 percent of the fuselage was used as a spinner containing the propeller hub. The propeller plane was located at 3.8 percent of the fuselage length to give a spinner diameter equal to 15 percent of the propeller diameter. A small gap between the propeller and the spinner surface was sealed by sponge rubber cemented to the blades in order that no radial outflow from the spinner along the blades could occur.

The 200-horsepower induction motor used to turn the propeller was 10 inches in diameter and 30 inches long and was housed within the fuselage. The motor housing was mounted on ball bearings coaxial with the shaft and was prevented from rotating under the torque reaction by a hydraulic unit that transmitted the torque force to a scale.

Thrust was measured simultaneously by force tests and by wake surveys. The force tests were made by use of the tunnel drag balance, which gives the resultant force on the model along the tunnel axis. Propulsive thrust was computed as this resultant force plus the drag of the model without the propeller. For thrust measurement by wake surveys, a total-pressure survey rake was located radially in a plane perpendicular to the tunnel axis 18 inches (0.375 diameter) behind the propeller plane and bolted to the tunnel wall. The effect of longitudinal position of the survey rake was not investigated; the longitudinal position used approximated that of the tests reported in reference 4. Complete tests were made for the rake mounted in each of the six equally spaced positions around the propeller disk. The rake was free of the model at all times and extended to within about 0.25 inch of the fuselage surface. The tubes of the rake were arranged to measure the wake from radial stations of about 0.35 to 1.15. Although the propeller wake was shifted at the survey station by the fuselage, this arrangement provided complete measurement of the thrust distribution on the blade for all conditions tested. The rake was connected to an inclined-tube manometer and the pressures were recorded photographically.

The force-test data have been reduced to the usual thrust and power coefficients and have been corrected for the equivalent free-stream velocity (reference 5) and for the buoyancy effect on model drag that occurs as a result of tunnel-wall constraint.

Because of the constraint of the tunnel walls, the equivalent free-stream airspeed corresponding to the thrust and torque of the propeller measured at each rotational speed differs from the tunnel datum velocity. This correction was evaluated by surveys of velocity in three planes - immediately in front of, immediately behind, and at the propeller tip. The velocity surveys extended from the tunnel wall to the propeller tip. The correction was evaluated from these data by the method of reference 5. This correction, which was small, has been applied in the determination of the values of the advance-diameter ratio.

Because of the slipstream contraction, the air passing outside the slipstream undergoes an increase in static pressure with distance downstream from the propeller. This increase in static pressure gives rise to a buoyancy force on the model. The measured thrust has been corrected for the buoyancy effect. The correction was determined from measurements of the static-pressure gradient in the tunnel air stream. These measurements were made for the complete range of thrust loading and Mach number covered in this test.

The wake-survey thrust coefficient was computed from measurements of static-pressure and total-pressure changes in the wake of the propeller. An explanation of the method used is given in reference 6.

Data were obtained for blade angles of 26° and 53° measured at the 0.75 radius; the propeller was tested at a blade angle of 26° at a free-stream Mach number of 0.30 and a blade angle of 53° at free-stream Mach numbers of 0.30 and 0.48. The tests were made with the propeller thrust axis at angles of attack of 2° and 4° for the lower Mach number and of 2° only for the higher Mach number because of lift-load limit. At an upper vertical rake position, tests were made at an additional thrust axis angle of attack of 1° for a blade angle of 53°.

The data presented herein may be applied to propeller operation in yaw by rotating the reference axis from which

the survey position is measured through 90° or through the appropriate angle for conditions of combined pitch and yaw.

RESULTS AND DISCUSSION

In computing the thrust coefficient from data obtained with a single survey rake, the assumption is made that no variation in the flow about the propeller blade occurs during a revolution. In other words, it is assumed that the radial thrust distribution is identical for all angular positions around the propeller disk and therefore that the survey-rake measurements are independent of rake position. This condition exists only when the free-stream flow is parallel to the propeller thrust axis and the body interference on the propeller is uniform about the thrust axis. When the propeller thrust axis is inclined to the flow, each blade section operates at a varying angle of attack as it turns through a revolution.

If the propeller axis is at a positive angle of attack and the propeller is operating at a constant advance-diameter ratio, the blade sections in the right half of the disk for a right-hand propeller will have a greater angle of attack than those in the left half. This condition is illustrated by the vector diagram of figure 4 in which it is also evident that changes occur in the resultant velocity of the blade sections. If the effects of induced velocity are neglected, the forward velocity for a section at a propeller-thrust-axis angle of attack of 0° and at any angular location ω is shown by a solid line in figure 4 with the resultant velocity W making an angle of attack α with the section. If the propeller axis is given a small positive angle of attack with the free-stream flow, a section with angular locations of either $\omega = 0°$ or $\omega = 180°$ will have an insignificant change in its angle of attack; but, as the section rotates from $\omega = 0°$, its angle of attack will increase to a maximum value at $\omega = 90°$, will return at $\omega = 180°$ to the value for $\omega = 0°$, and will decrease to a minimum value at $\omega = 270°$ from which it will increase to the original angle of attack at $\omega = 0°$. The velocity-vector diagrams for a section at maximum and minimum angles of attack are also shown in figure 4; the long-dash-line vectors represent the maximum condition at $\omega = 90°$ and

the short-dash-line vectors the minimum condition at $\omega = 270^\circ$. At the conditions of maximum and minimum section angle of attack, the angles between the original and displaced forward-velocity vectors are equal to the propeller-thrust-axis angle of attack. These variations in section angle of attack and resultant velocity cause an irregular wake. This irregularity in the wake is clearly the effect of inclination of the propeller axis to the free-stream flow and is not related to body interference.

The pitched attitude of the propeller results in a shift of the wake relative to the fuselage. Figure 1, which shows the wake shift for angles of attack of 2° and 4°, indicates that a rake located in the upper half of the disk will measure more of the wake than a rake in the lower half.

It is very evident that these wake irregularities render a single survey rake of little value for calculating the propeller thrust coefficient when the thrust axis is inclined to the direction of the free stream. The effect of the wake irregularities is illustrated in figure 5 in which thrust-coefficient-gradient curves are shown at a constant propeller thrust coefficient for rake positions (with the exception of the 300° position) at 60°-intervals for a blade angle of 53° and at an angle of attack of 4°. Very large wake changes are apparent. When the wake-survey thrust coefficient obtained by integration of thrust-coefficient-gradient curves is plotted for a range of advance-diameter ratio, the curves obtained compare as shown in figures 6 to 8 with those of the force-test thrust coefficient for the same conditions of propeller operation.

The change in thrust loading as the blade turns through a revolution is shown in figure 9 as the difference between the integrated wake-survey thrust coefficient and the force-test thrust coefficient at a constant advance-diameter ratio as read from figures 6 to 8. Since the curves in these figures for the wake-survey and the force-test measurements are nearly parallel, this plot will be practically the same for the entire range of advance-diameter ratio up to the point of stall.

From the section angle-of-attack variation of a pitched propeller, the curves of ΔC_T would be expected

to pass through 0 at $\omega = 0^\circ$ and $\omega = 180^\circ$ and their points of maximum amplitude would be expected to be at $\omega = 90^\circ$ and $\omega = 270^\circ$. Rotation of the propeller wake, however, causes a shift of the curves in the direction observed, but this shift is of the order of only 3° to 5°. The large remainder of the shift is unaccounted for but may be caused by the oscillation of the angle of attack of the blade sections with a resulting lag of section forces with angle-of-attack changes.

The curves of figure 9 show the amount by which the wake-survey thrust coefficient obtained by use of a single rake may differ from the actual propeller thrust coefficient. The difference between these thrust coefficients for the blade angle of 53° at $\alpha_T = 4^\circ$ varies to maximum values about 100 percent greater and 100 percent less than the thrust coefficient for maximum efficiency for that blade angle, which may be read for $\alpha_T = 2^\circ$ from figure 10. The maximum difference for the low blade angle of 26° at the same thrust-axis angle of attack is about 40 percent greater and 40 percent less than the thrust coefficient for maximum efficiency at that blade angle. At propeller thrust coefficients smaller than those at maximum efficiency, these percentages are, of course, larger and, conversely, at propeller thrust coefficients greater than those at maximum efficiency, the percentages are smaller.

An average of measured wake-survey thrust coefficients obtained from surveys made of the irregular wake of a pitched or yawed propeller by a number of equally spaced rakes would be expected to agree with the propeller thrust coefficient more closely as the number of rakes is increased. In figure 11 comparisons are presented of the average wake-survey thrust coefficient for all six rake locations with the corresponding force-test thrust coefficient as read from the curves of figures 6 to 8. At the thrust coefficient for maximum efficiency, for the blade angle of 53°, the average wake-survey thrust coefficient is about 6 percent lower than the propeller thrust coefficient and, for the blade angle of 26°, the wake-survey measurement is about 4 percent lower. These are the maximum values of the difference between the propeller thrust coefficient and the wake-survey thrust coefficient at the thrust coefficient for maximum efficiency; this difference is primarily the result of neglecting the static-pressure variation in the wake.

The effect of neglecting the static-pressure variation in the wake was determined from tests with a rake of both static- and total-pressure tubes. The wake-survey thrust coefficient was calculated by use of the actual static pressure along the rake and then recalculated with the assumption of free-stream static pressure along the rake. The curves of wake-survey thrust coefficient as calculated by these two methods are presented in figure 12. At the thrust coefficient for maximum efficiency, the assumption of free-stream static pressure is shown, for both blade angles, to cause the calculated wake-survey thrust coefficient to be about 4.5 percent lower than that obtained by use of the actual pressure.

The symmetry of the ΔC_T-curves of figure 9 suggests that the average of the thrust coefficients from two diametrically opposed rakes will be equal to the propeller thrust coefficient. The difference, at all points around the disk, between force-test thrust coefficient and average wake-survey thrust coefficient for two diametrically opposed rakes is presented in figure 13. The curves were obtained by averaging values of ΔC_T at points 180° apart on the curves of figure 9 for positions all around the disk and plotting the values obtained against rake position. These curves show the lack of symmetry of the ΔC_T-variation. Except for the curve at the high blade angle and high thrust-axis angle of attack, the curves show that an average of the wake-survey thrust coefficients from two diametrically opposed rakes is lower than the propeller thrust coefficient by an amount equal to 0 to 5 percent of the thrust coefficient for maximum efficiency. This difference indicates that the two-rake installation will prove satisfactory when the static-pressure variation is included in the calculations and when the propeller is operating under conditions similar to those used herein. Two diametrically opposed rakes provide an average thrust coefficient equal to the propeller thrust coefficient because of the symmetry of the ΔC_T-curves; two diametrically opposed rakes will therefore be insufficient in cases in which these curves are nonsymmetrical. Nonsymmetrical body interference around the propeller disk induced by thick wings, large scoops, cockpit canopies, or similar bodies will destroy the symmetry of the ΔC_T-curves and so preclude the use of only two rakes.

The recommended positions for an installation of two rakes is for several reasons at the points of maximum

and minimum loading: First, the early compressibility and stall losses at these points can be observed (reference 4); second, the rate of change of ΔC_T with radial rake position is smaller near these points than at other positions; and last, the installation is more practical for flight tests, in which the rakes should be mounted horizontally because of larger changes in pitch than in yaw.

In two-rake installations in which the rakes are not radial to the propeller axis, the thrust obtained from each rake will correspond to that of a radial rake located in some position between the values of ω for the innermost and outermost survey tubes. If the two equivalent radial positions for the two nonradial rakes intersect at an angle other than 180°, the average of the two thrust values for those positions will be equal to propeller thrust only for the conditions of zero angle of pitch and yaw. If the equivalent radial rake positions occur near the points of maximum amplitude of the ΔC_T-curves, however, the error of the nonradial installation will be less than if the equivalent positions occur near points of zero amplitude where the slope of the curves is steepest.

CONCLUSIONS

From tests made to determine the effect of survey-rake position around the disk of a pitched propeller on the measurement of propeller thrust and to determine the disposition and minimum number of rakes necessary to measure the thrust, the following conclusions can be drawn:

1. Propeller operation at small angles of pitch or yaw causes large variations in the distribution of energy in the wake.

2. Unless the propeller is operating at zero angle of pitch or yaw and the body interference on the propeller is uniform about the thrust axis, one survey rake is insufficient for obtaining propeller thrust since differences of more than 100 percent may occur between actual thrust and thrust calculated from the wake-survey measurements.

3. If the variation of the difference in the wake-survey thrust coefficient and the force-test thrust coefficient with pitch or yaw is symmetrical and if static pressure variations in the wake are considered, two diametrically opposed rakes may be used to measure propeller thrust.

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Langley Field, Va.

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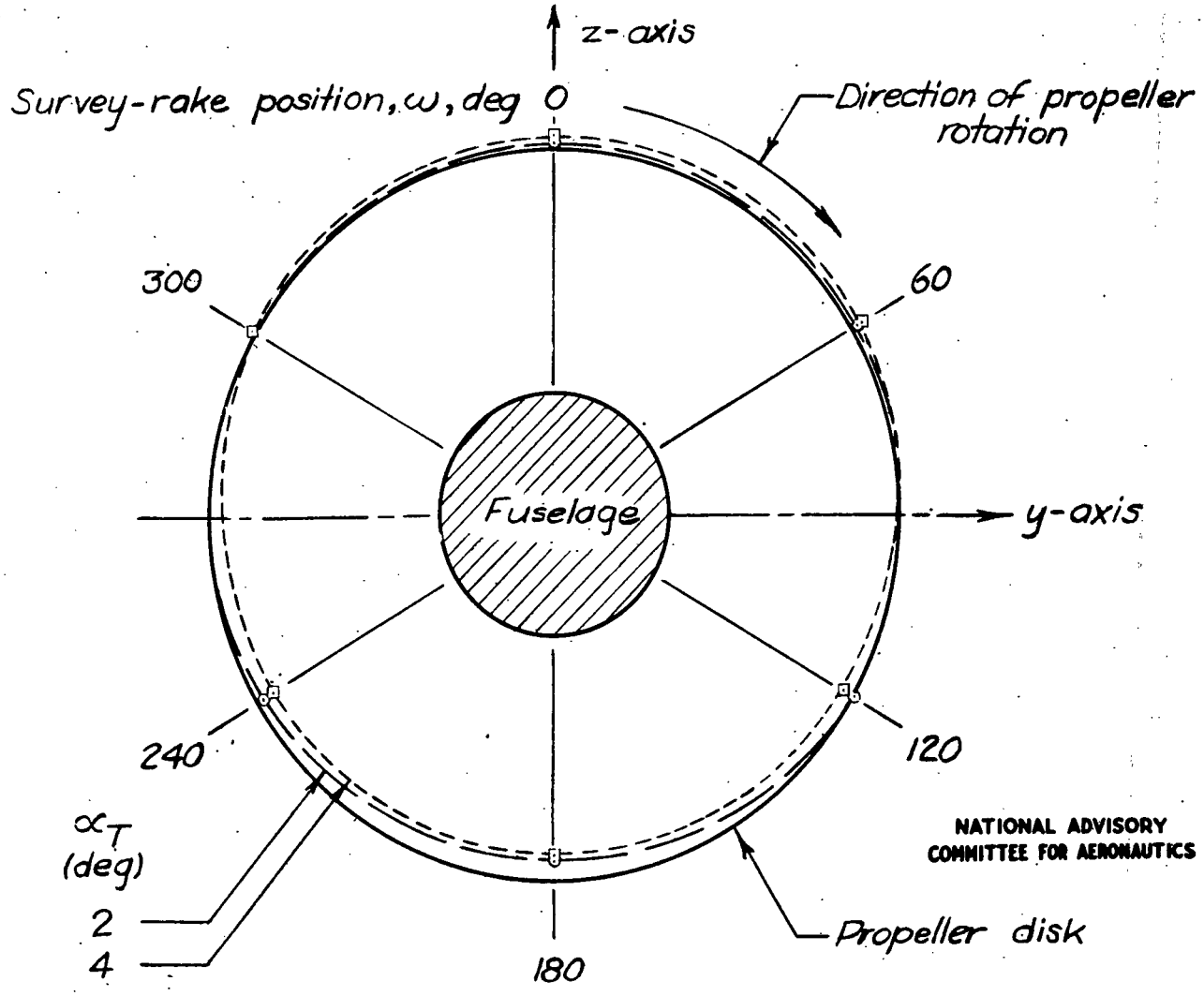

Figure 1.- Effect of angle of attack on wake location. $J = 2.7$; $\beta = 53°$; $M = 0.30$. (As viewed from a downstream point.)

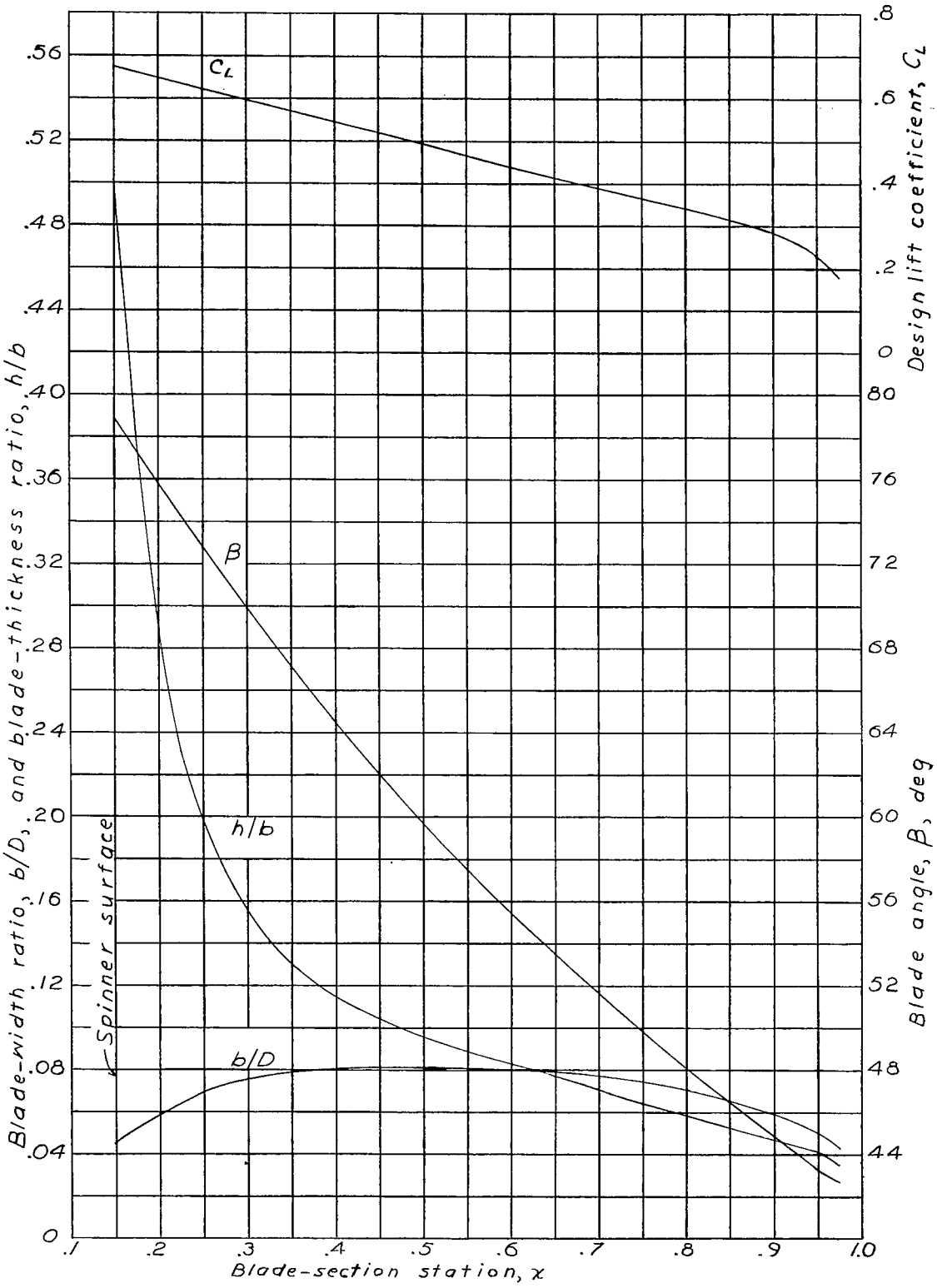

Figure 2. - NACA 4-(3.9)(07)-0345-B propeller blade-form curves.

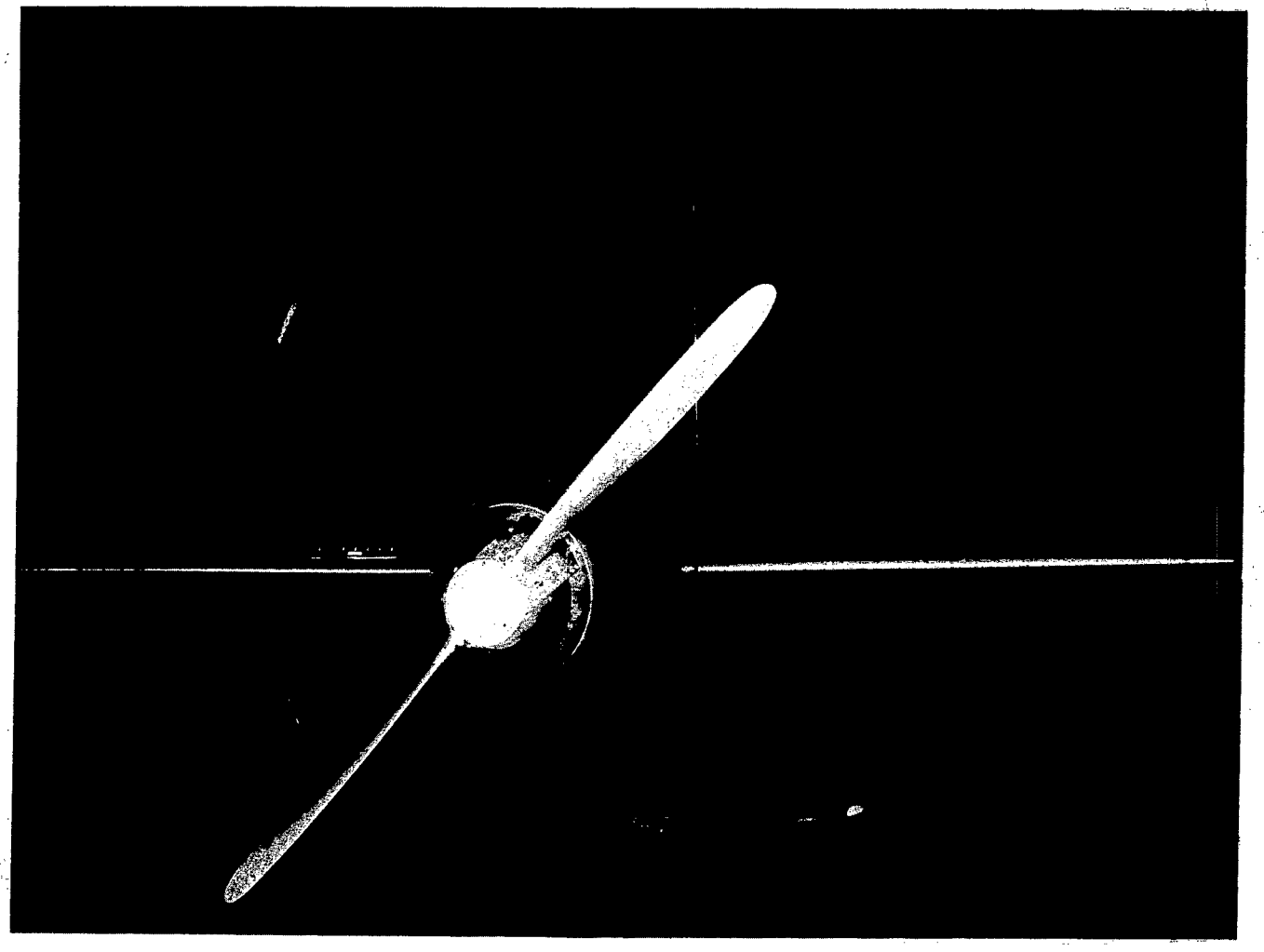

Figure 3.- Propeller setup in the Langley 8-foot high-speed tunnel with rake of both static-pressure and total-pressure tubes in upper vertical position.

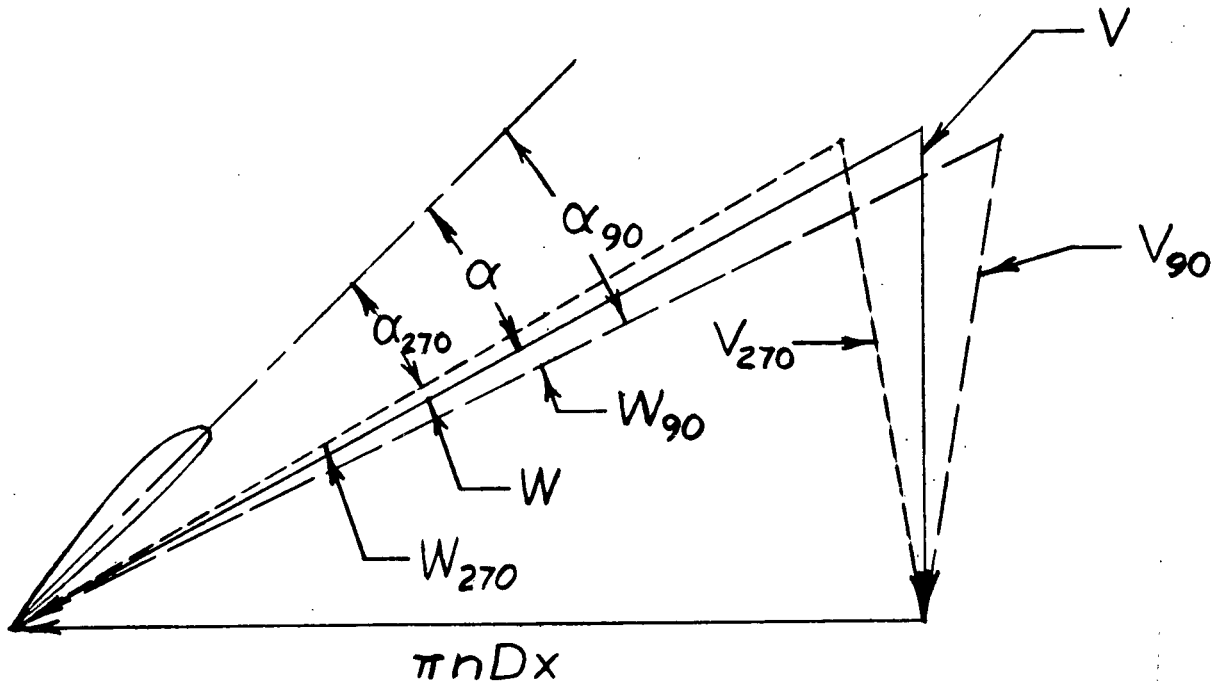

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Figure 4.-Velocity vectors for a section of a pitched propeller (induced velocities neglected).

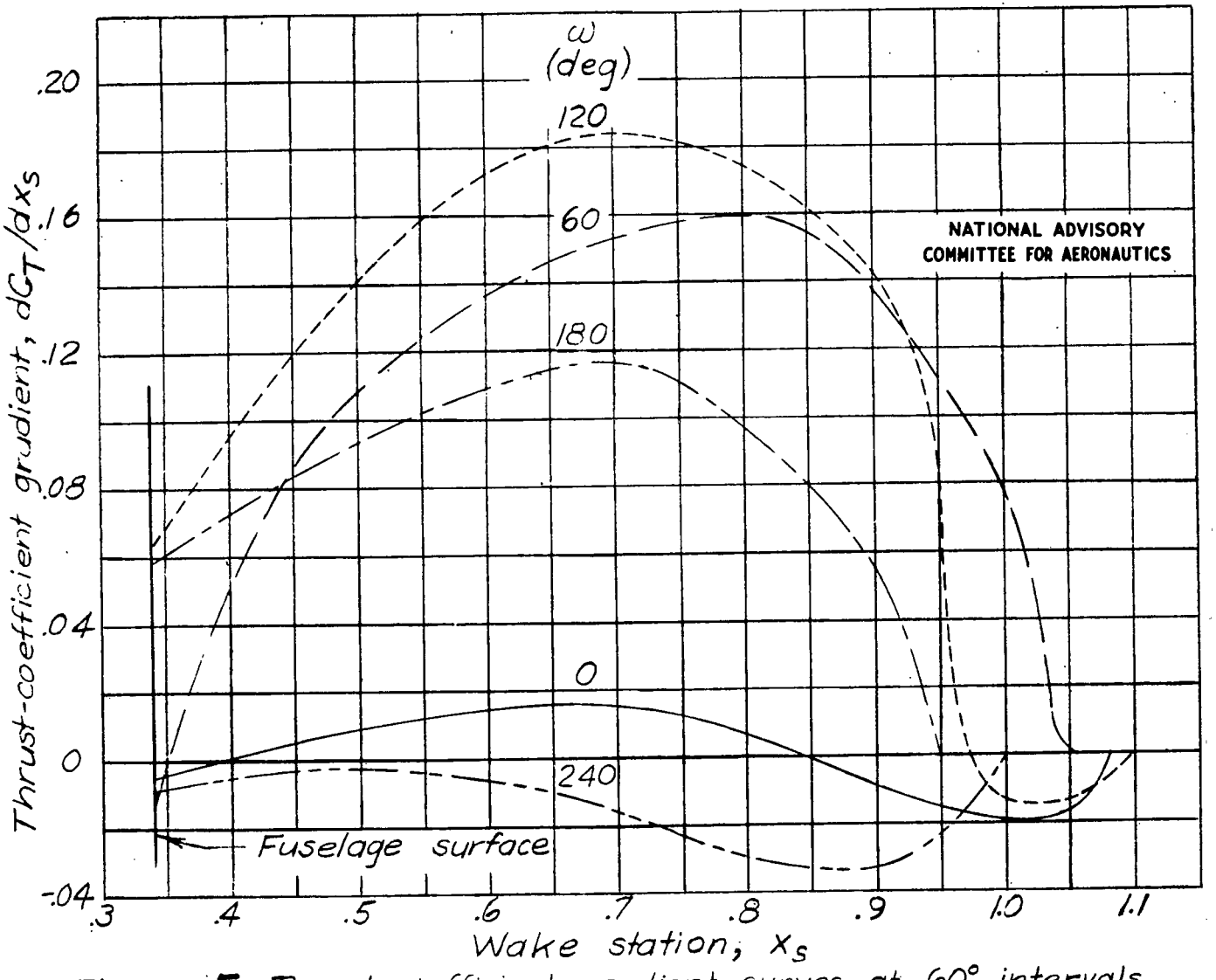


Figure 5.- Thrust-coefficient-gradient curves at 60°-intervals around the propeller disk. $M=0.30$; $C_T=0.0319$; $\beta=53°$; $\alpha_T=4°$.

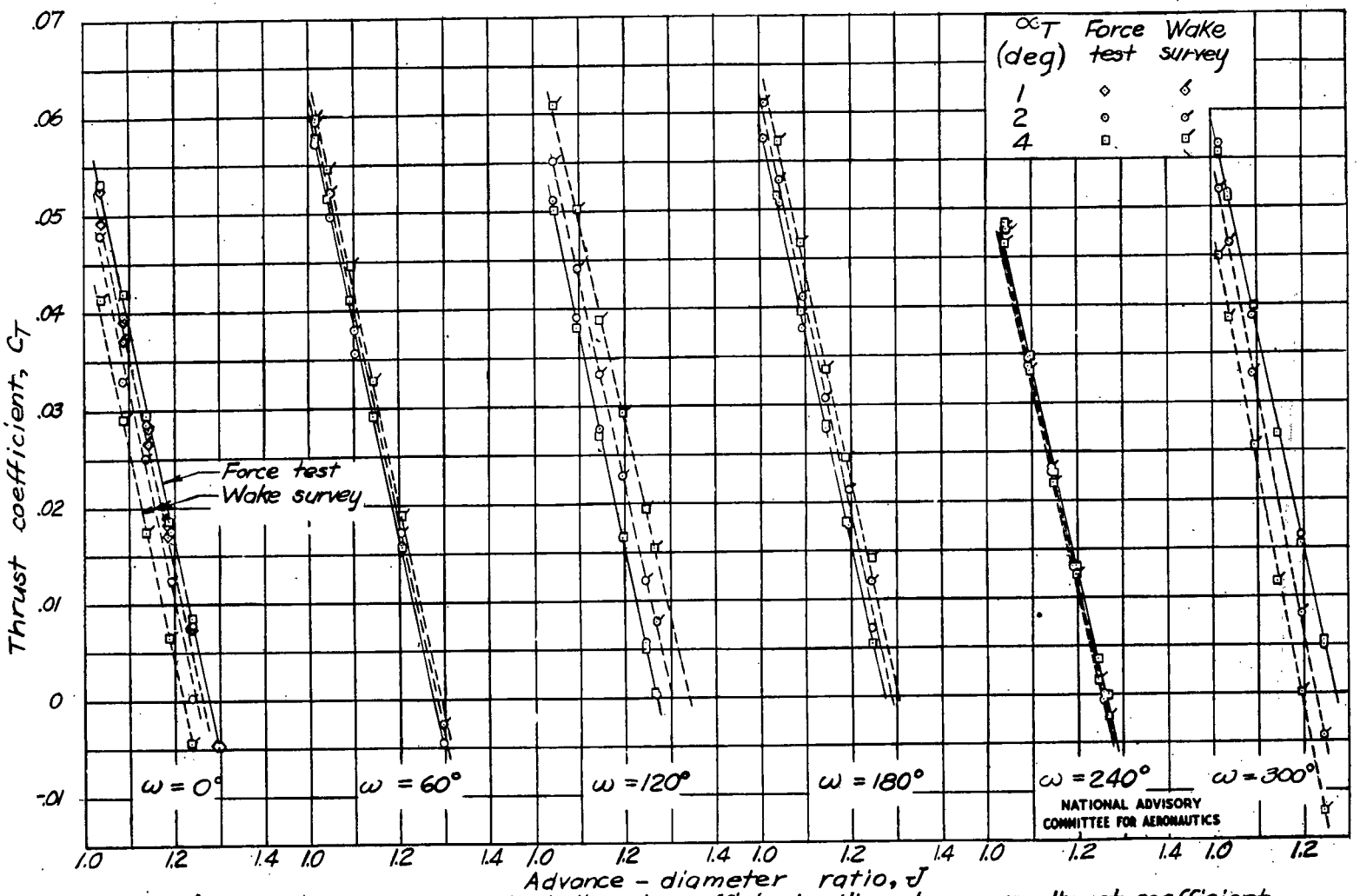


Figure 6.- Comparison of force-test thrust coefficient with wake-survey thrust coefficient from measurements made with a single survey rake. $\beta = 26°$; $M = 0.30$.

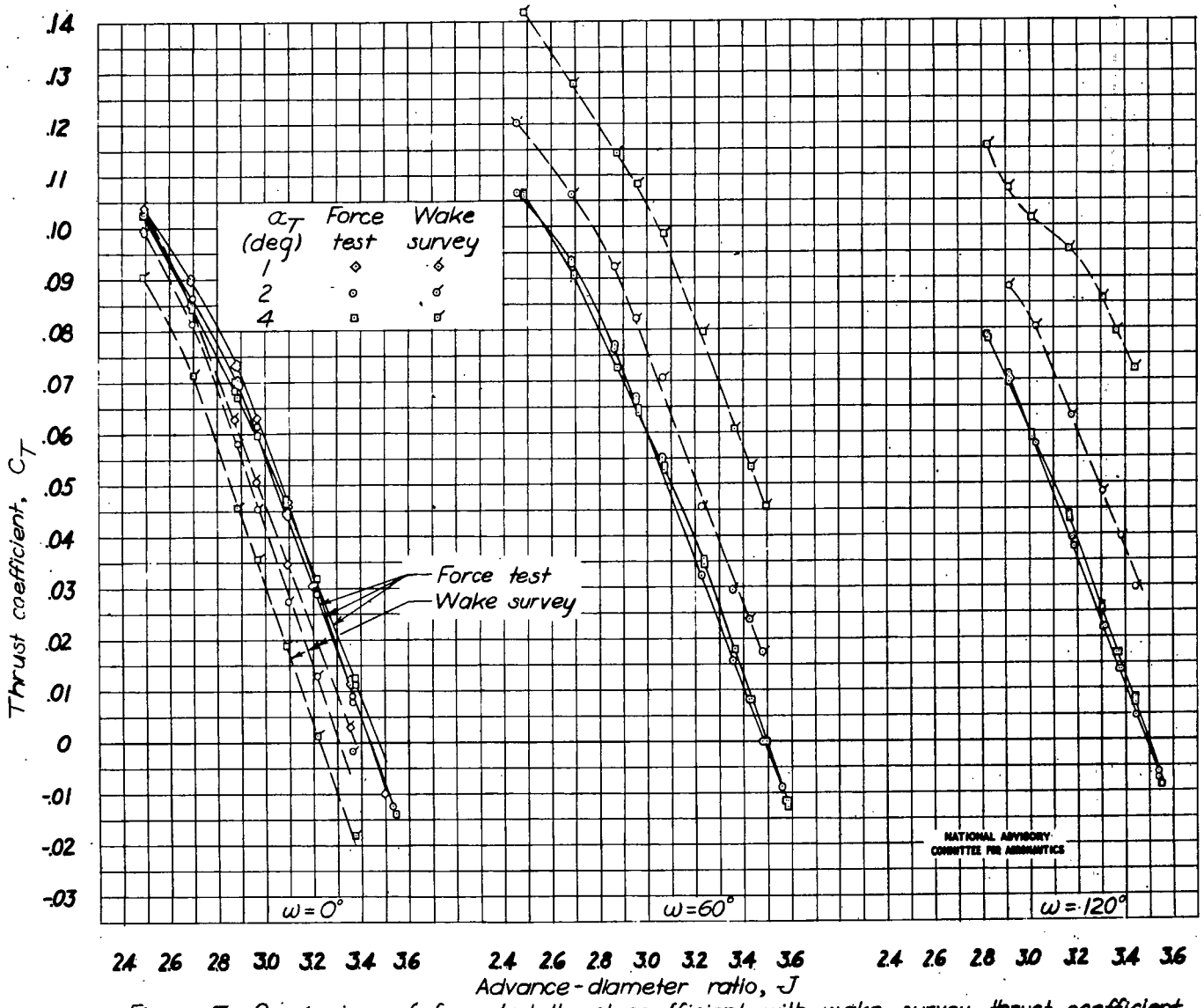


Figure 7.- Comparison of force-test thrust coefficient with wake-survey thrust coefficient from measurements made with a single survey rake. $\beta = 53°$; $M = 0.30$.

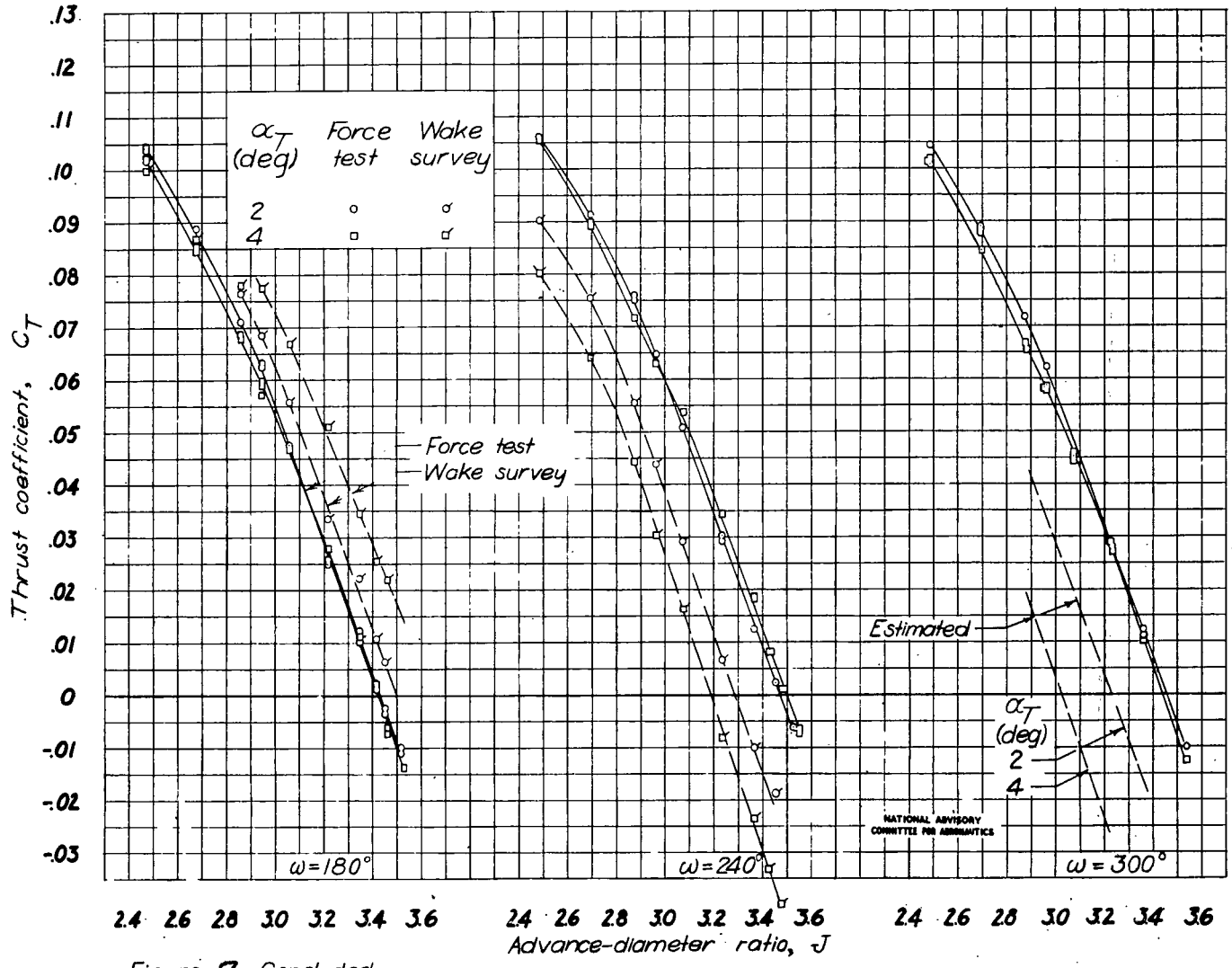


Figure 7.-Concluded.

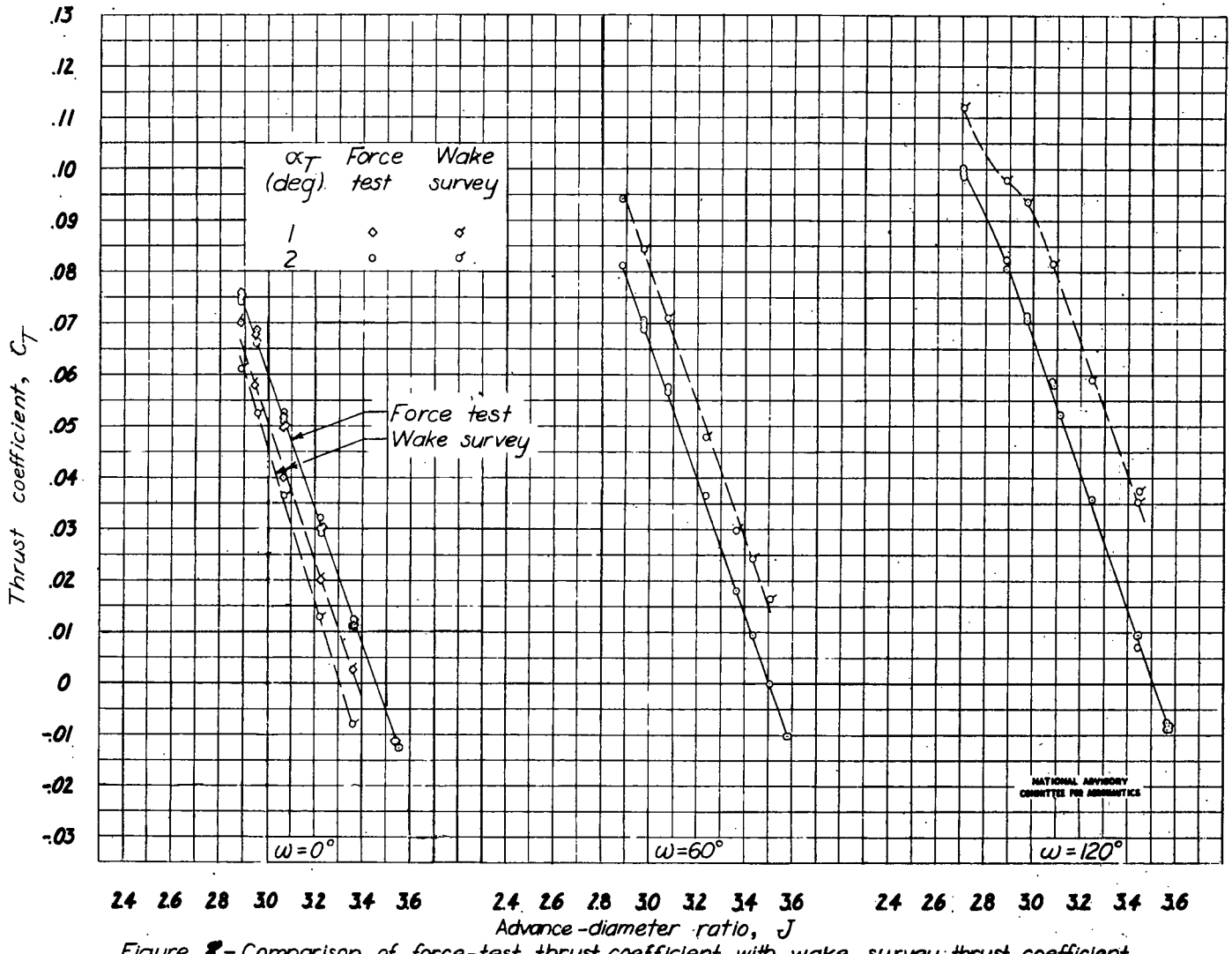
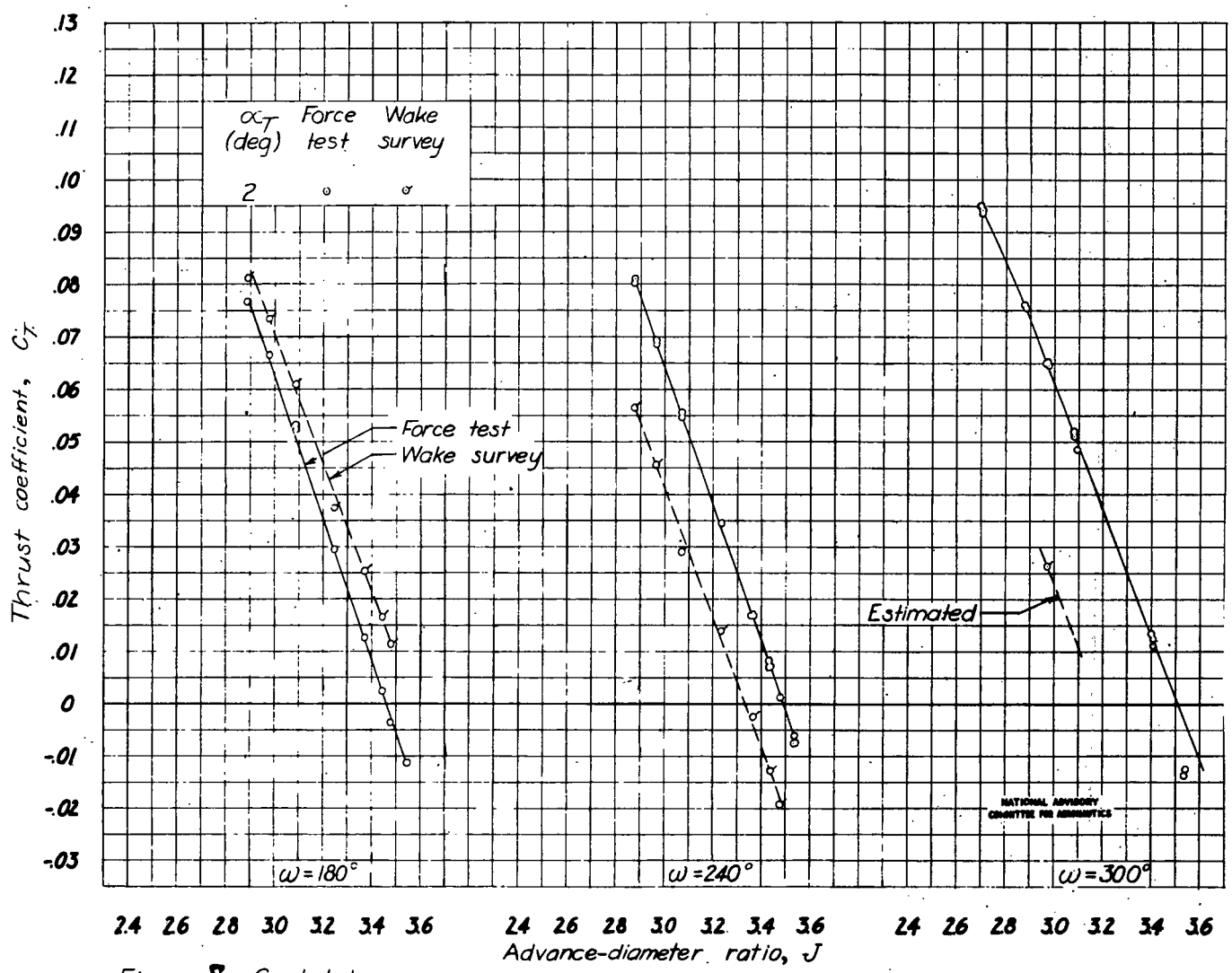


Figure 8.- Comparison of force-test thrust coefficient with wake-survey thrust coefficient from measurements made with a single survey rake. $\beta = 53°$; $M = 0.48$.



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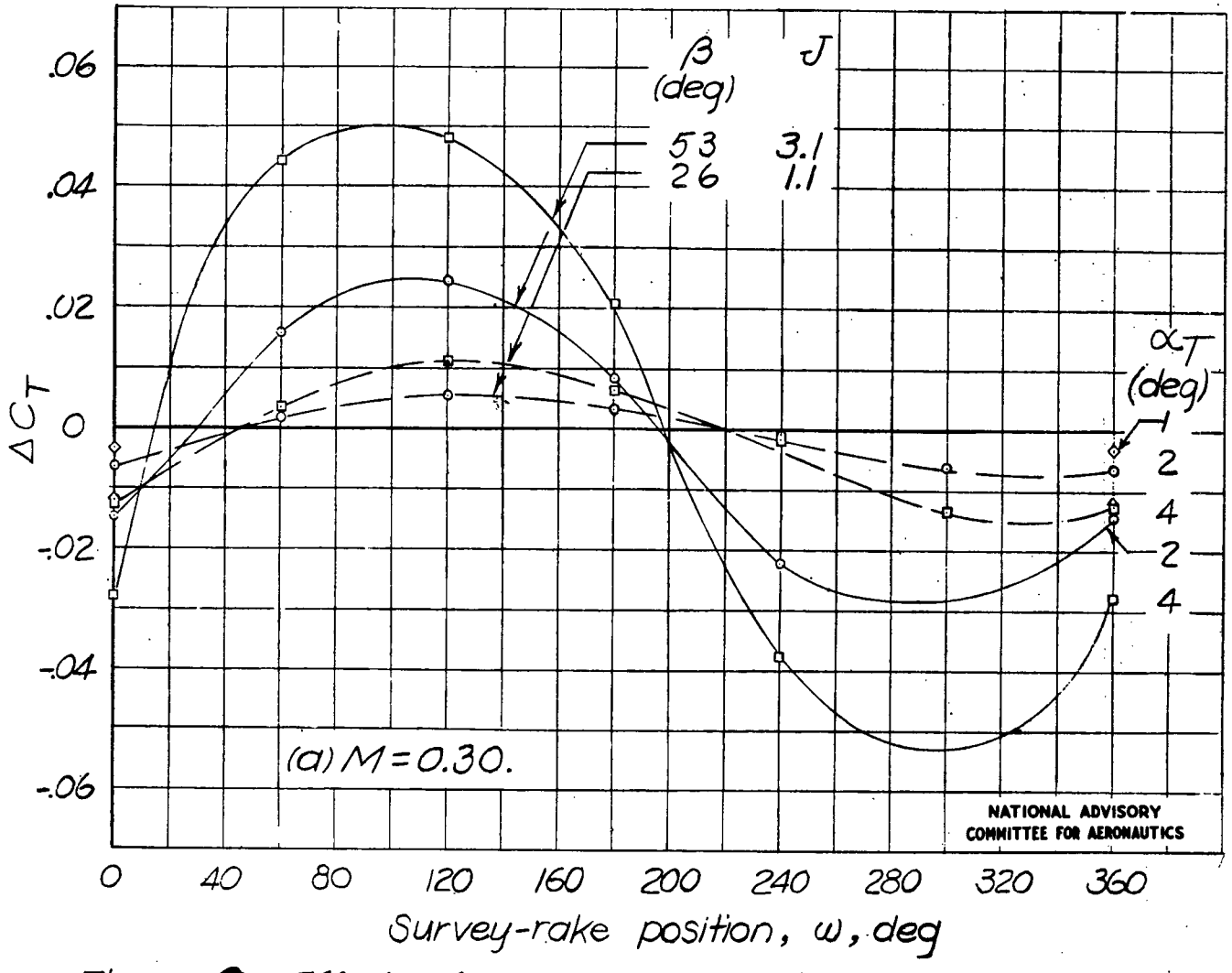


Figure 9.- Effect of survey-rake position around a propeller disk on the difference between wake-survey thrust coefficient and force-test thrust coefficient.

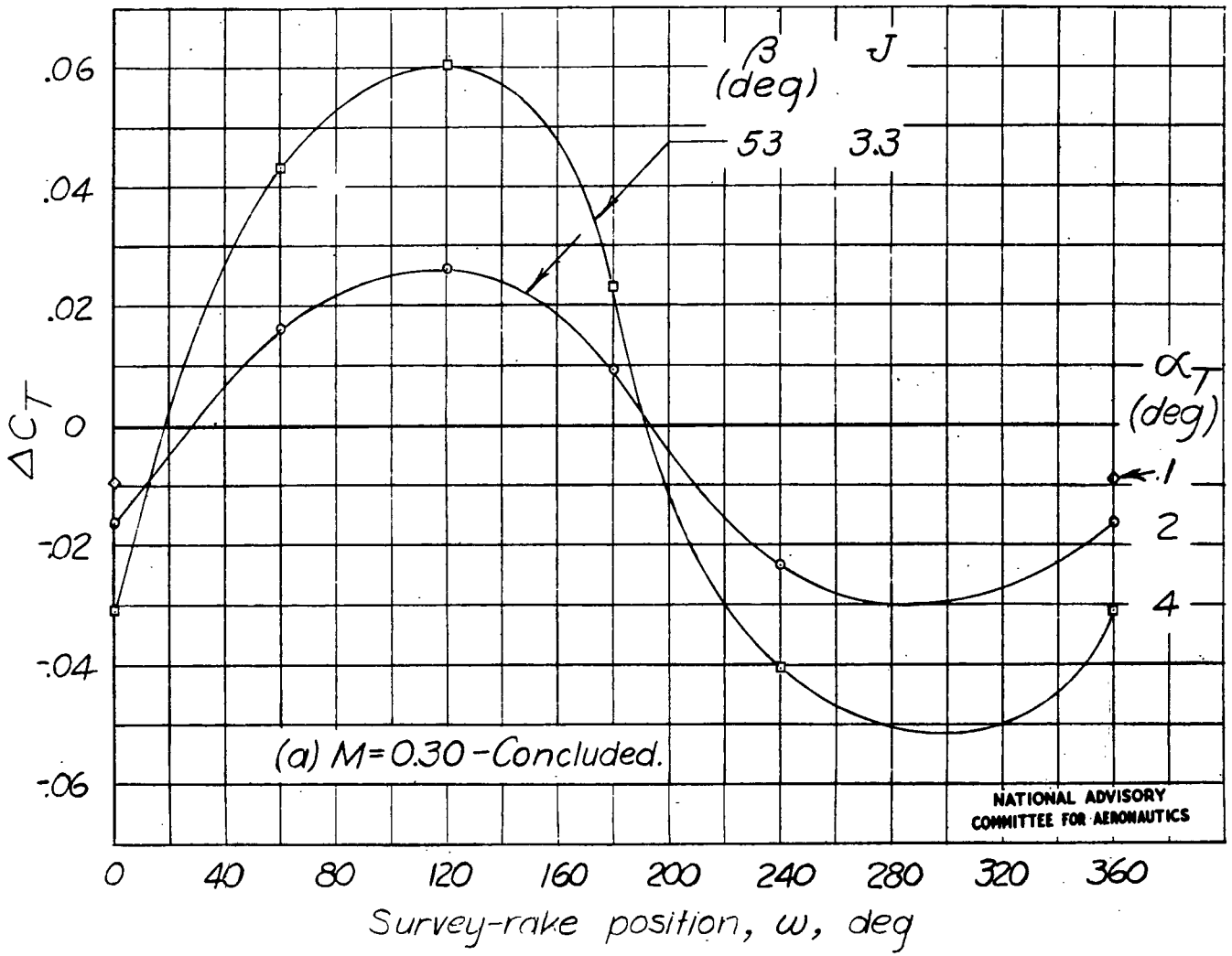
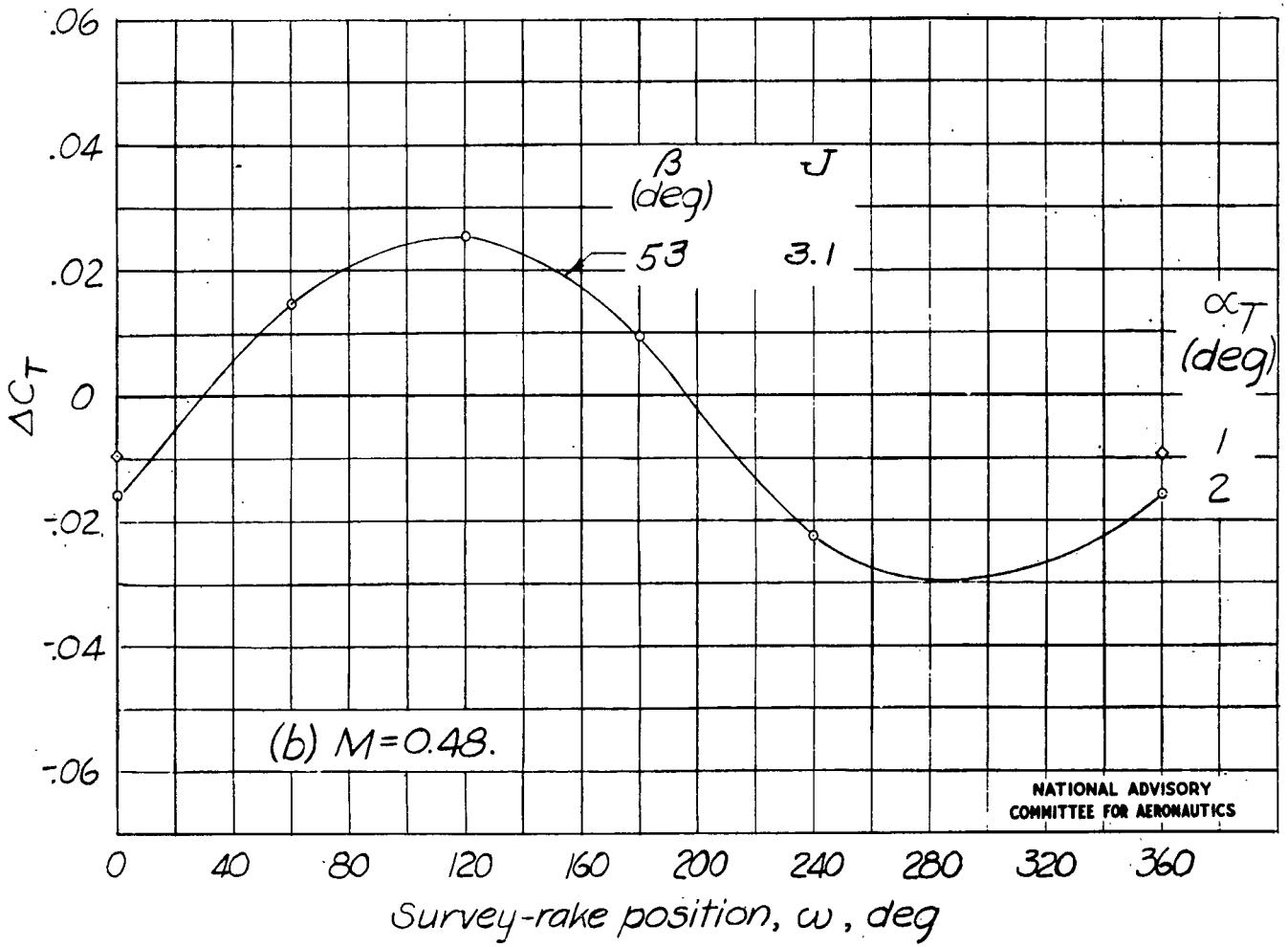


Figure 9.- Continued.



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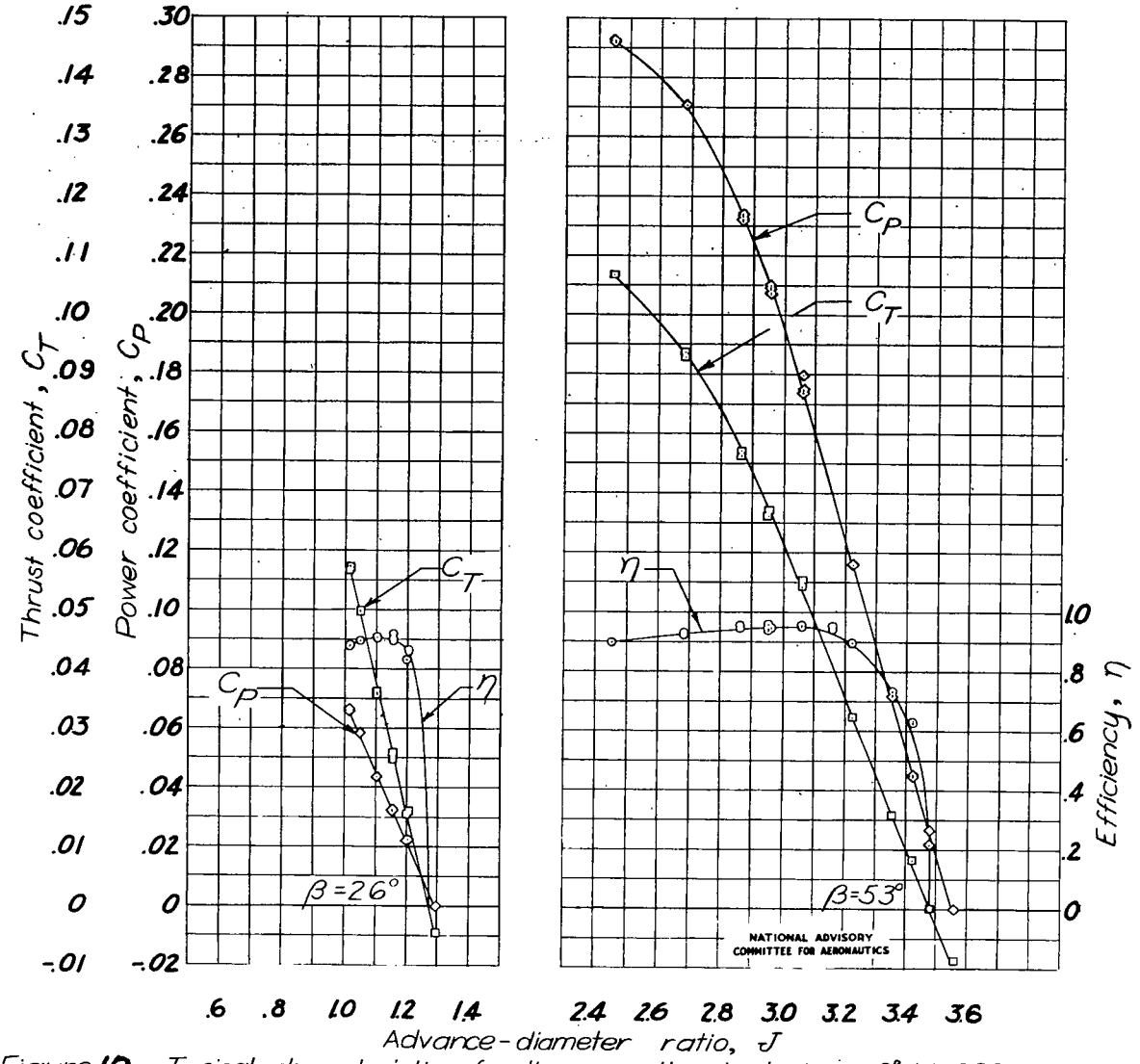


Figure 10.- Typical characteristics for the propeller tested. $\alpha_T = 2°$; $M = 0.30$.

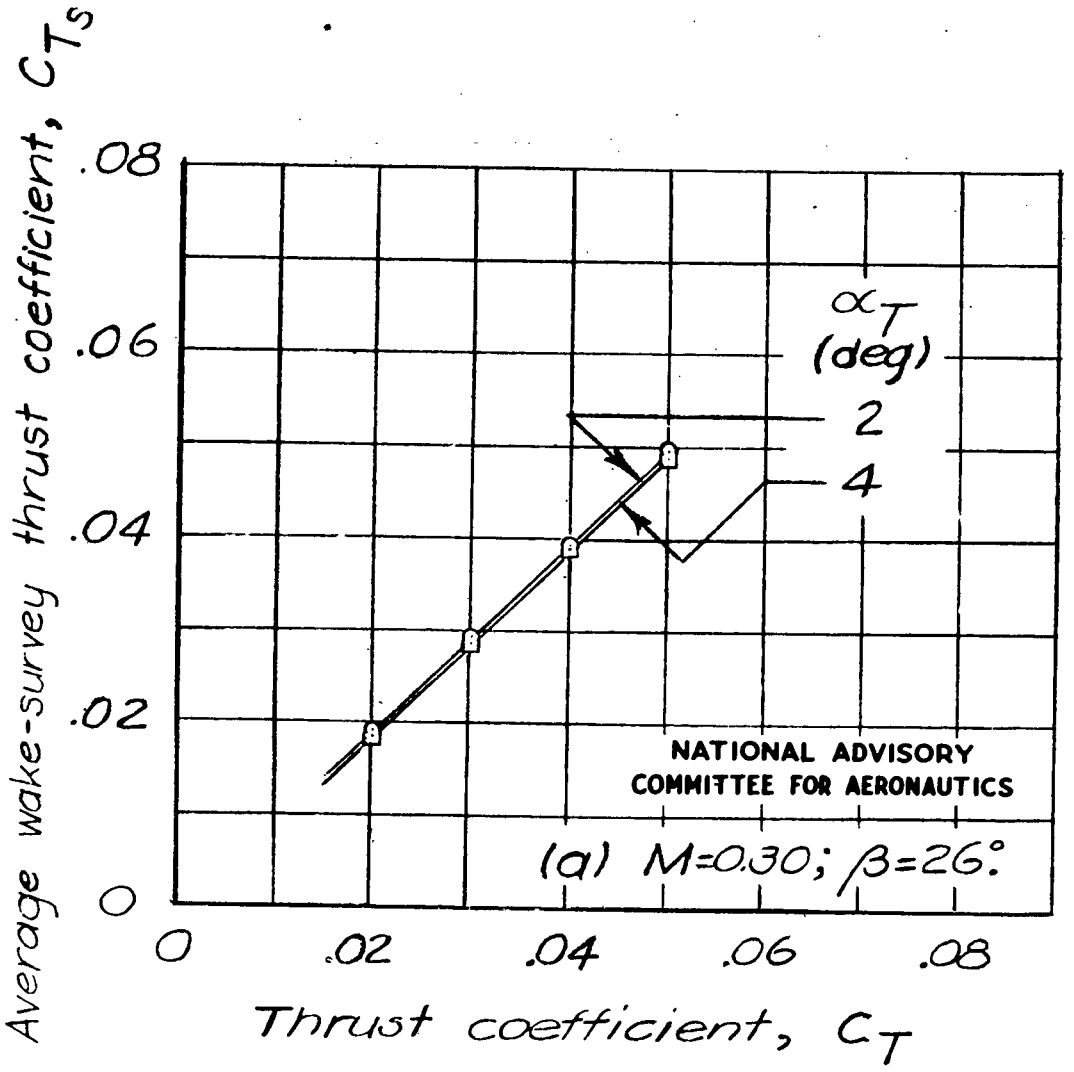


Figure 11.- Comparison of the average wake-survey thrust coefficient measured by six rakes with the force-test thrust coefficient.

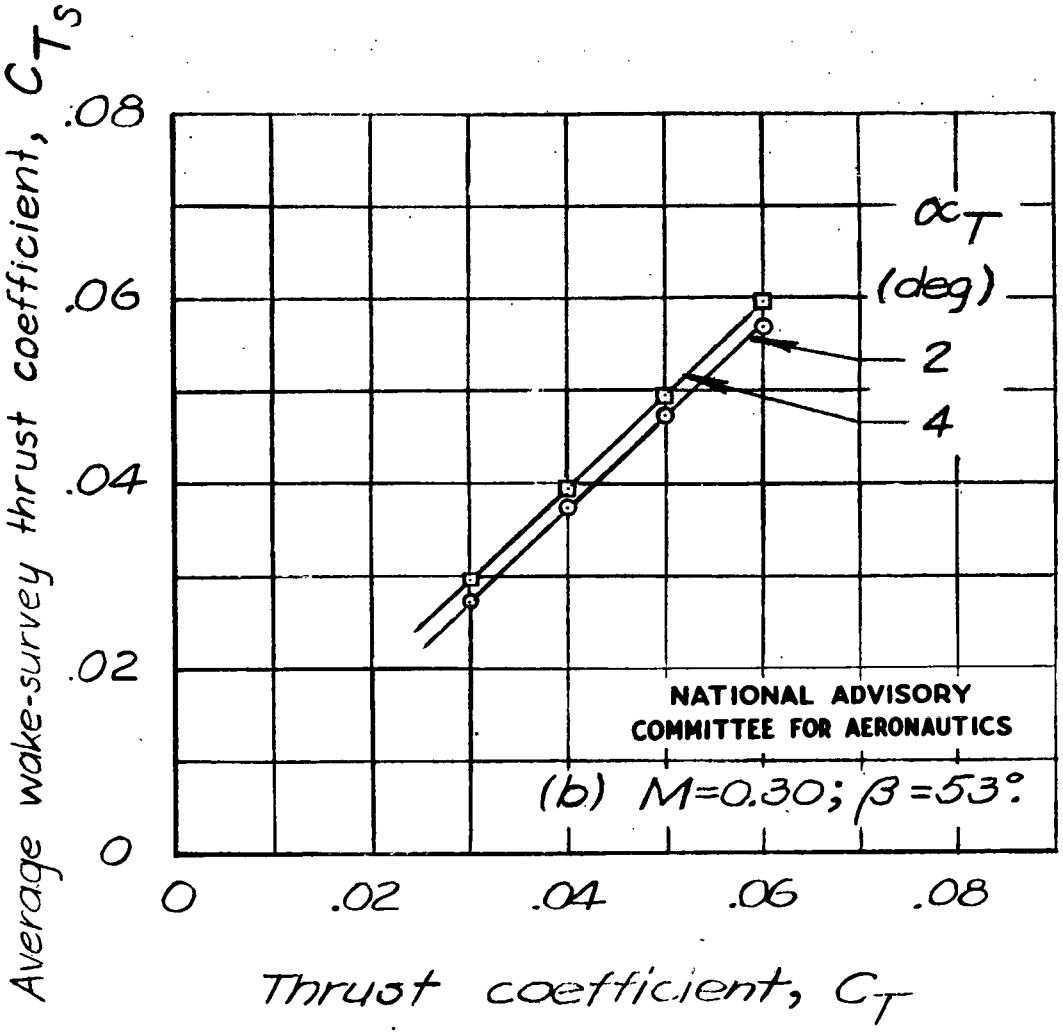
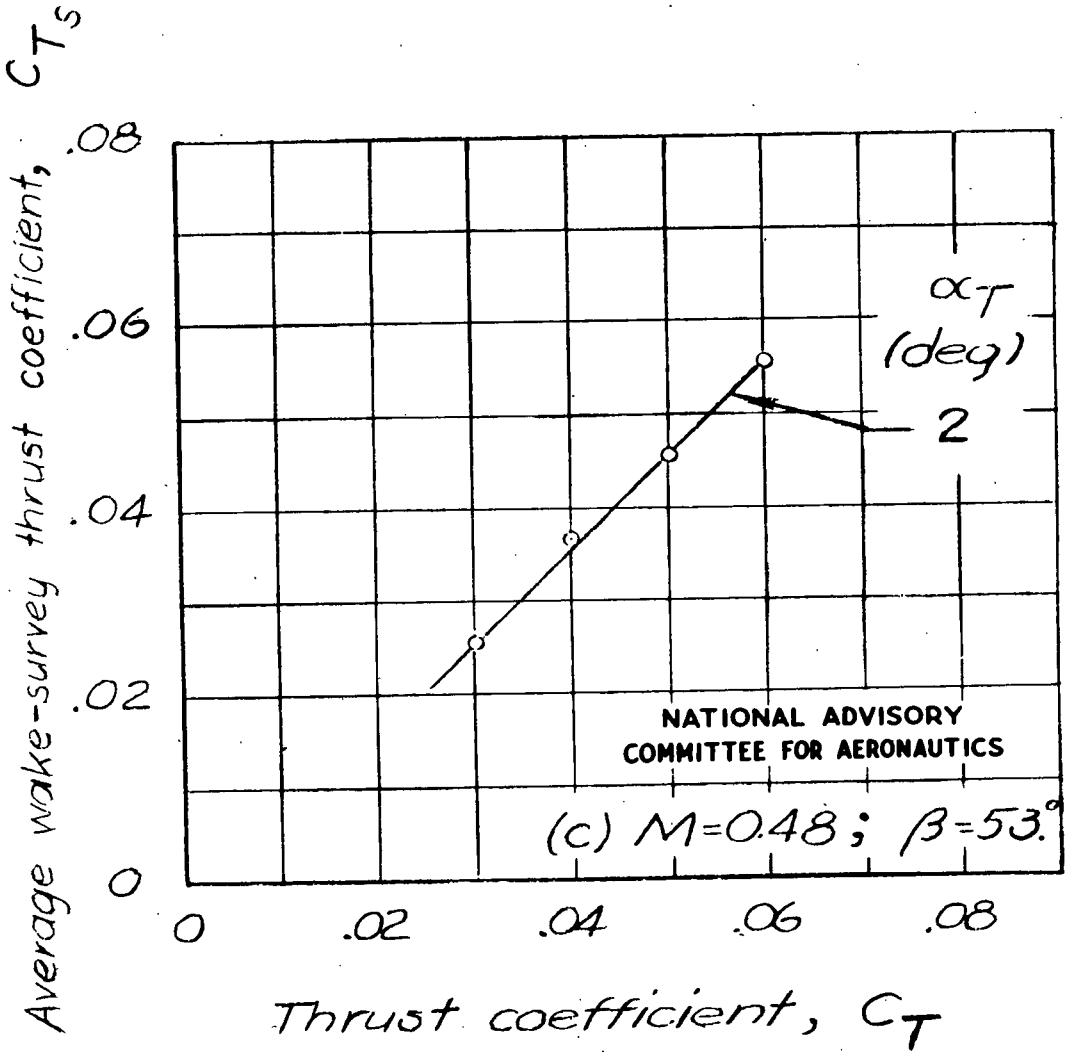


Figure 11.-Continued.



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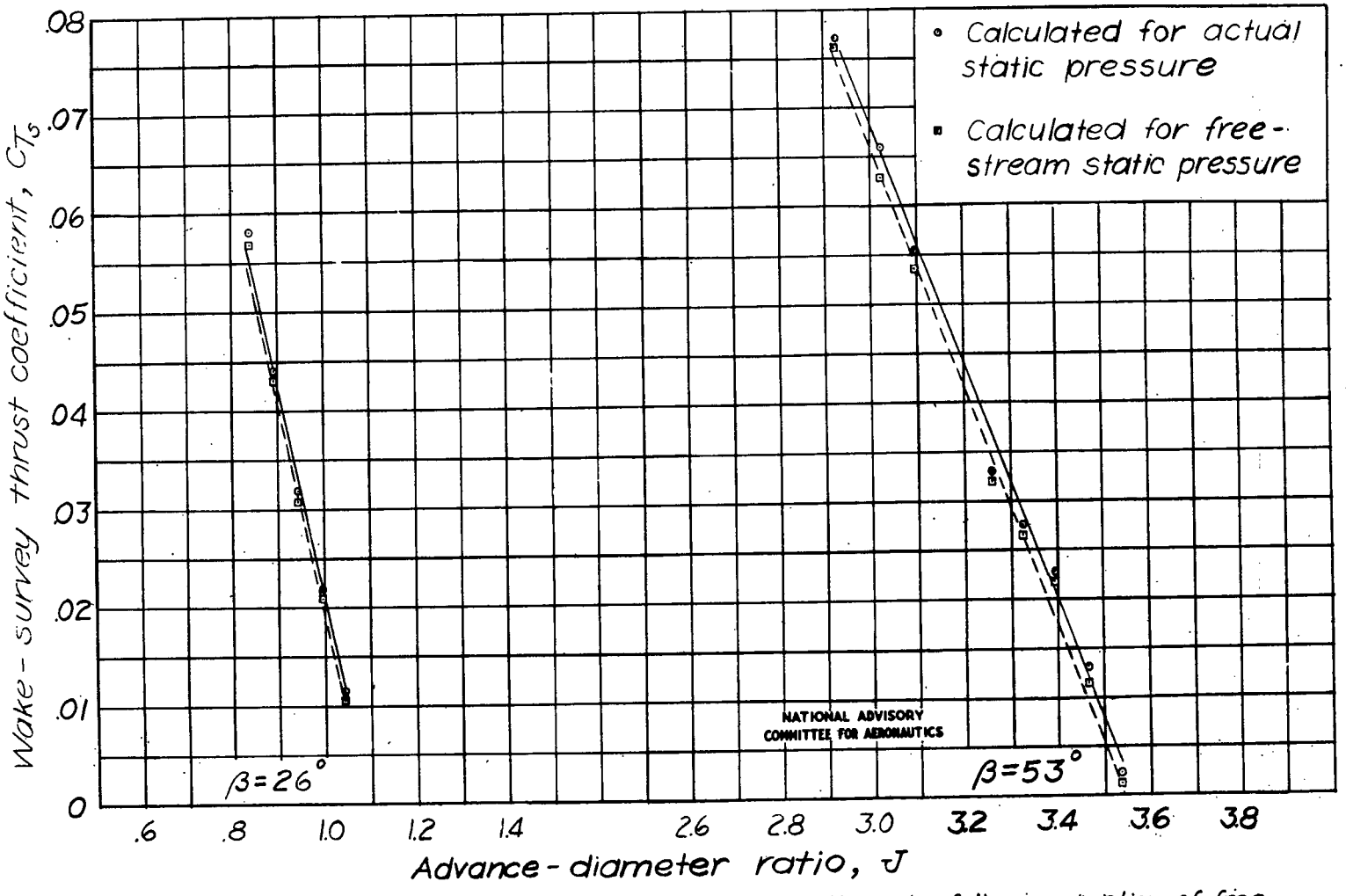
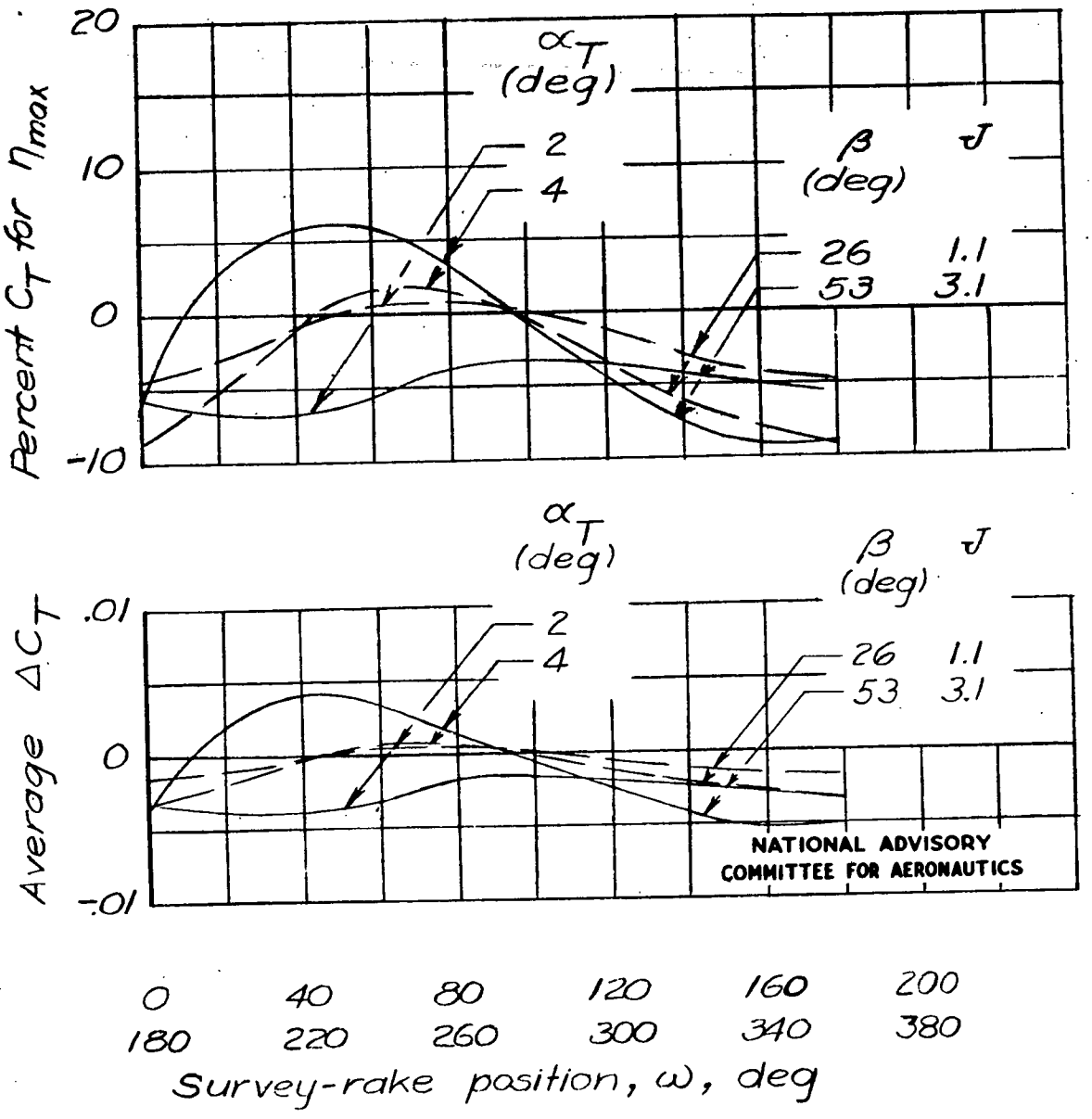
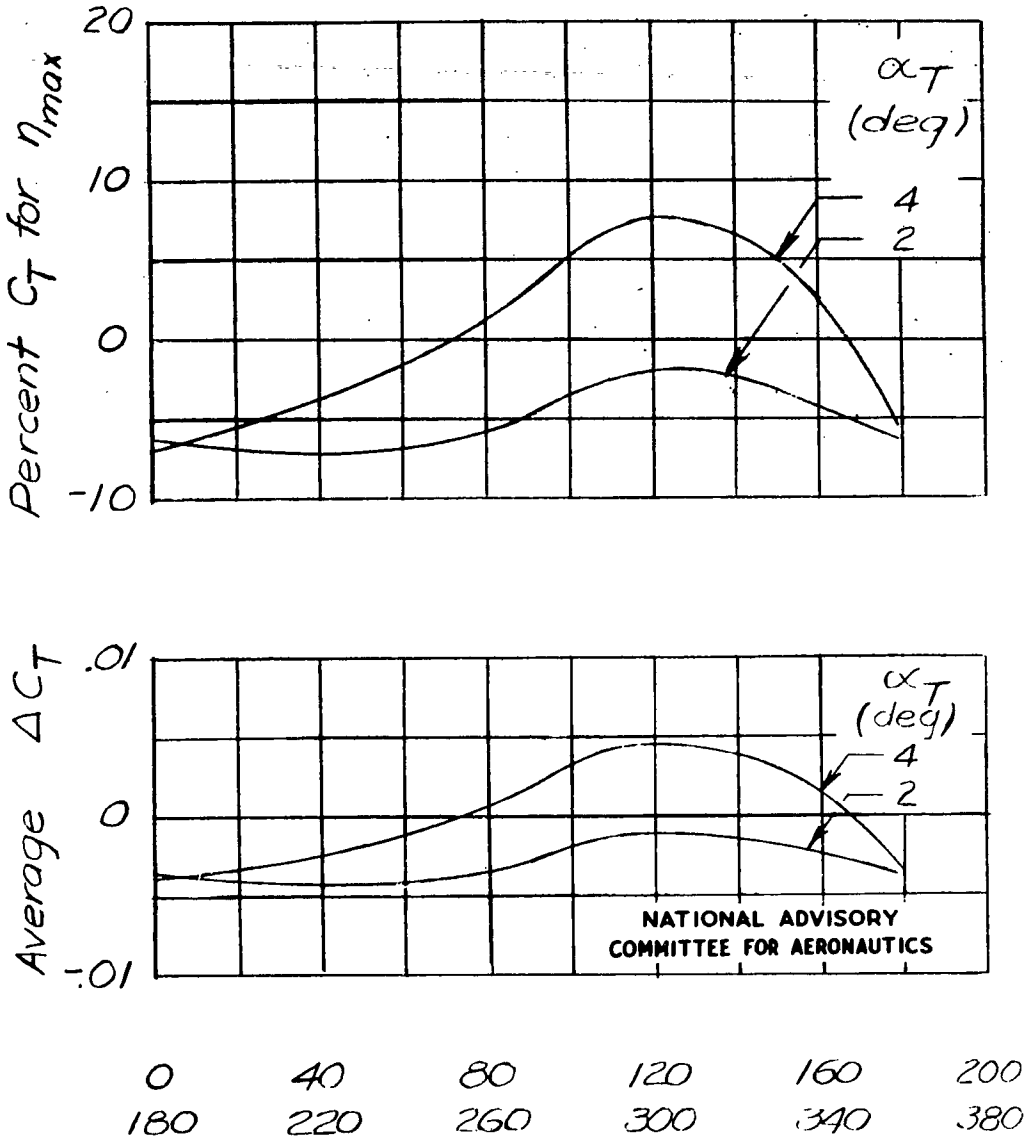


Figure 12.-The effect on wake-survey thrust coefficient of the assumption of free-stream static pressure along the survey rake. M=0.30.



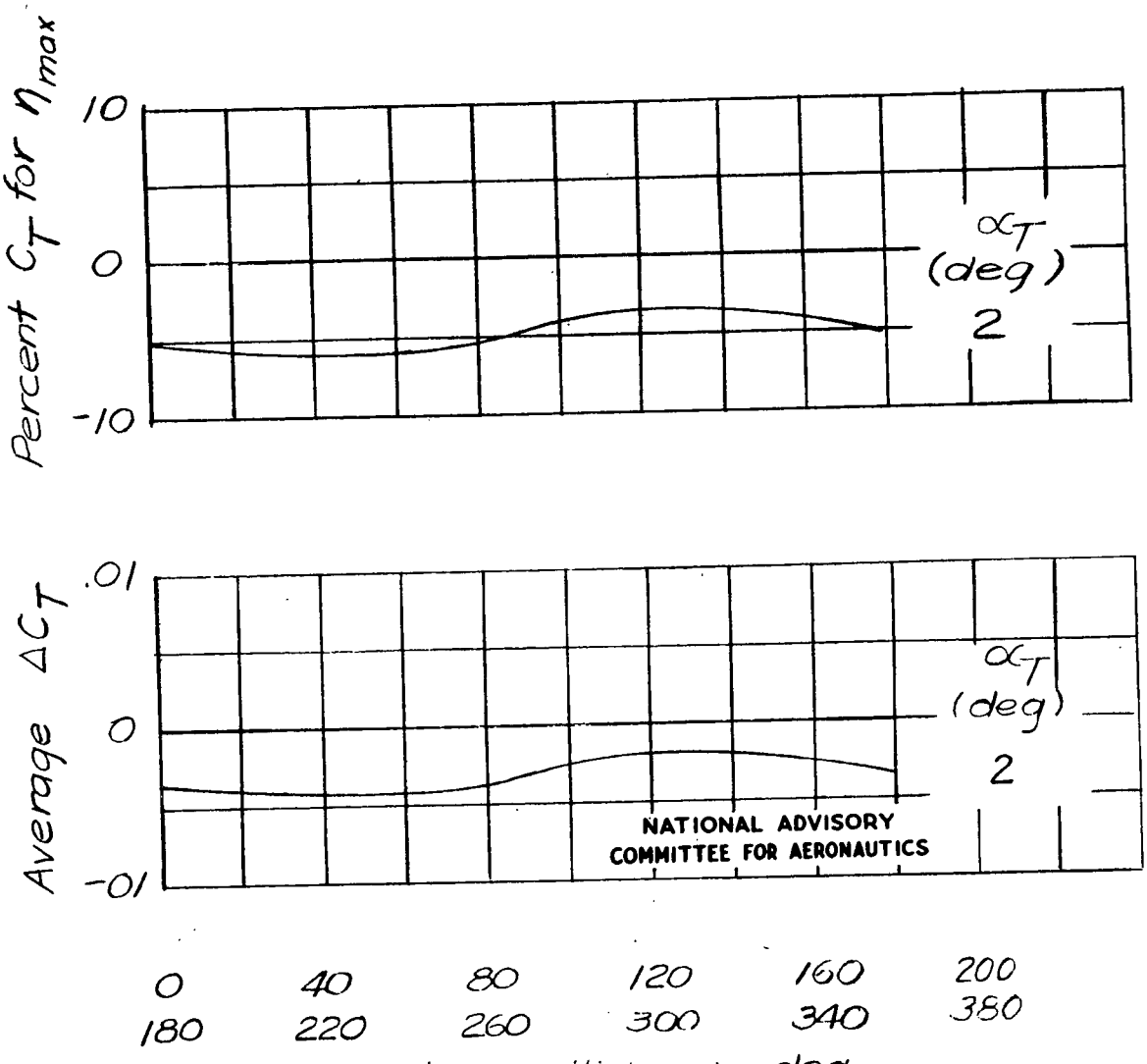
(a) $M = 0.30$.

Figure 13.- Error in using two diametrically opposed survey rakes for measurement of propeller thrust coefficient.



(b) $M=0.30$; $\beta=53°$; $J=3.3$.

Figure 13.- Continued.



(c) $M=0.48$; $\beta=53°$; $J=3.1$.

Figure 13.--Concluded.

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