NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2277

EFFECTS OF COMPRESSIBILITY ON THE PERFORMANCE OF TWO FULL-SCALE HELICOPTER ROTORS

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A D D E N D U M

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Because of inquiries concerning the data of figure 7, the NACA wishes to point out that the angle of attack presented in this figure should be measured, as is customary in helicopter analysis, from the angle of zero lift rather than from the airfoil chord line.

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SUMMARY

An investigation has been conducted on the Langley helicopter test tower to determine experimentally the effects of compressibility on the performance and blade pitching moments of two full-scale helicopter rotors. Two sets of rotor blades were tested which differed only in that the blades of one set incorporated -8° of linear twist, whereas the blades of the other set were untwisted. The tests covered a range of tip speeds from 350 to 770 feet per second and a range of pitch angles from 0° to the limit imposed by extreme vibration.

The results show that the primary effect of compressibility was a rapid increase in the profile-drag torque coefficient once the critical combination of tip speed and tip angle of attack was exceeded. The results also show that the onset of compressibility losses can be predicted by using two-dimensional section data and that negative blade twist (washout) is effective in delaying the onset of compressibility losses and in reducing these losses once they are developed.

INTRODUCTION

The significance of the effect of compressibility on the performance and blade pitching moments of a helicopter rotor has been emphasized by design studies of high-speed helicopters, helicopters with high disk loadings, and convertible aircraft, all of which require higher tip speeds than are now in general use. Although some information is available on the decrease in performance of airplane propellers due to compressibility losses, when the resultant tip speeds approach the velocity of sound, the information is not altogether applicable in that airfoils suitable for propellers are not usually employed in helicopter rotor blades. Consequently, very little experimental data are available on the characteristics of a practical-construction full-scale helicopter rotor operating in the region in which compressibility effects occur. Compressibility losses are expected to occur both in hovering and forward flight and may lead to rotor vibration and loss of control in addition to the expected decrease in performance. A knowledge of the compressibility losses in hovering would therefore provide a limited basis for prediction of the compressibility losses to be expected in forward flight.

It is necessary to determine whether the onset of compressibility losses significantly reduces rotor efficiency before the operating limitation due to vibration or loss of control is reached. It is also of interest to check for the hovering condition the onset of blade stalling losses, as was done for the forward-flight condition reported in reference 1. In order to differentiate the blade stall losses from the compressibility effects, the stall losses should be determined at low tip speeds.

Accordingly, an initial investigation to obtain compressibility and stall data has been conducted on the Langley helicopter test tower. Twisted and untwisted rotor blades were tested for a tip-speed range from 350 to 770 feet per second.

SYMBOLS

R blade radius, feet

b number of blades

c blade section chord, feet

r radial distance to blade element, feet

c_e equivalent blade chord, feet $\left(\dfrac{\int_0^R cr^2dr}{\int_0^R r^2dr}\right)$

x ratio of blade-element radius to rotor-blade radius (r/R)

σ rotor solidity $(bc_e/\pi R)$

σ_x solidity of a blade element at radial distance x $(bc/\pi R)$

ρ density of air, slugs per cubic foot

T rotor thrust, pounds

Q rotor-shaft torque, pound-feet

M_b measured rotor-blade pitching moment, positive for moment tending to increase blade pitch, pound-feet

$M_{b_{ac}}$ blade pitching moment about blade aerodynamic center (measured M_b minus product of centrifugal-force component perpendicular to blade span axis and rearward displacement of chordwise center of gravity of blade from aerodynamic center, assumed to be 0.24c for NACA 23015 airfoil section), pound-feet

Ω rotor angular velocity, radians per second

C_T rotor-thrust coefficient $\left(T/\pi R^2 \rho (\Omega R)^2\right)$

C_Q rotor-shaft induced torque coefficient $\left(Q/\pi R^2 \rho (\Omega R)^2 R\right)$

C_{Q_o} rotor-shaft profile-drag torque coefficient

$c_{m_{ac}}$ rotor-blade pitching-moment coefficient about aerodynamic center $\left(M_{b_{ac}}\Big/\frac{1}{2}\rho(\Omega R)^2 c_e R\right)$

a slope of curve of section lift coefficient against section angle of attack (radian measure), assumed to be 5.73

θ blade-section pitch angle measured from line of zero lift, radians

ϕ inflow angle of blade element, radians

APPARATUS AND TEST METHODS

The investigation was conducted on the Langley helicopter test tower described in reference 2. Two sets of three-blade rotors were tested which differed only in that the blades of one set incorporated -8° (washout) of linear twist, whereas the blades of the other set were untwisted. The blades were plywood-covered and had a radius of 20 feet, a solidity of 0.038, an NACA 23015 airfoil section throughout with 0.1° reflex at the trailing edge, and a chordwise center of gravity approximately 0.2 inch behind the low-speed aerodynamic center. These blades were chosen because of their availability and because compressibility losses could be studied at lower tip speeds from them than for blades having thinner airfoil sections. In addition, the blades allowed a comparison with forward-flight data inasmuch as these are the same blades that were reported on in reference 1. The blades differed somewhat from the true airfoil section as regards leading-edge shape and thickness, although all flat areas and depressions were faired smooth with filler.

The refinished blades are considered representative of smooth and well-built construction. A plan-form view of one of the blades tested is shown in figure 1.

All data were obtained for the hovering condition (wind velocity less than 3 mph) for a range of tip speeds from 350 to 770 feet per second (rotor speed of 167 to 368 rpm) and for a range of pitch angles from 0° to the limit imposed by extreme vibration. The test conditions were chosen to exceed the point of onset of the compressibility losses in order to establish their rate of increase once the combination of angle of attack and tip speed exceeded that value at which drag divergence occurs.

METHOD OF ANALYSIS

In order to compare the data with the available rotor performance theory which intentionally makes no correction for compressibility effects or stalling losses, the part of the power affected by these losses had to be isolated. A study of the problem indicates that the profile-drag power and hence the profile-drag torque coefficient C_{Q_o} would be chiefly affected. A convenient method of making the comparison with theory is to refer the measured profile-drag torque coefficient to that predicted by the theory and to plot the resulting profile-drag torque ratios $\frac{\left(C_{Q_o}\right)_{measured}}{\left(C_{Q_o}\right)_{theoretical}}$ as a function of the calculated blade-tip angle of attack for the range of tip speeds investigated. The data were plotted against calculated tip angle of attack inasmuch as the tip section angle of attack and tip speed are an index of the compressibility losses.

The measured rotor profile-drag torque coefficients were determined by subtracting a calculated induced torque coefficient (as determined by the method of reference 3) from the measured torque coefficient. Inasmuch as reference 3 does not allow for any tip loss in calculating induced torque coefficient, for this investigation the radius of the blade was decreased by half the tip chord for thrust calculations. The decrease in blade radius amounts to approximately a 3-percent reduction in rotor-thrust coefficient at a given blade angle. The theoretical profile-drag torque coefficients were determined from the minimum measured torque coefficient which was increased as a function of rotor-thrust coefficient as given in reference 3. The rotor-blade-tip angles of attack were determined by subtracting a calculated inflow angle ϕ from the measured collective pitch θ and the known twist. The values of θ were corrected for twist due to aerodynamic and mass forces and represent the true pitch at the 0.75-radius station. The inflow angles were calculated from the following relationship given in reference 3:

$$\phi = \frac{\sigma_x a}{16x}\left(\sqrt{1 + \frac{32x\theta}{\sigma_x a}} - 1\right)$$

The measured blade pitching moment consists of the aerodynamic moment and the mass moments due to chordwise center-of-gravity position relative to the aerodynamic center and chordwise mass distribution. Since the aerodynamic moments about the aerodynamic center (assumed to be 0.24 chord) are the ones considered significant, only these values are presented herein. For purposes of this study, the presence or the absence of abrupt changes of pitching-moment slopes is considered more important than the actual values. These values were obtained to a sufficient degree of accuracy for present purposes by subtracting from the measured moment a mass moment equal to the product of the blade centrifugal-force component perpendicular to the blade span axis and the rearward displacement of the blade chordwise center of gravity from the aerodynamic center.

RESULTS AND DISCUSSION

Figures 2 and 3 show the basic hovering performance of the untwisted and the -8° linear twist rotor blades, respectively, for the range of tip speeds from 350 to 770 feet per second. It is interesting to note that 8° of washout decreased the power required at operating thrust coefficients by about 3 percent at normal tip speeds (350 to 420 fps) as has been predicted by the theory of reference 3. At higher tip speeds, twist is effective in delaying the onset of compressibility losses. In general, the rotor with twisted blades can operate at about 0.0005 greater thrust coefficient for a given tip speed before encountering compressibility losses. This increase in C_T corresponds to a tip speed that is about 70 feet per second faster than the tip speed for the untwisted set before the drag rise occurs for operation at fixed thrust coefficient. When operating in the region of compressibility losses, the twisted rotor blades required less power for the same thrust coefficient. For example, for an extreme operating condition ($C_T = 0.004$ and a tip speed of 770 fps) the twisted blades required approximately 85 percent of the total power required by the untwisted blades.

The dividing line between stalling losses and compressibility losses is not clearly defined by the data and it is possible that some combination of tip angle of attack and tip speed incur both stalling and compressibility losses. In general, however, stalling losses are predominant in the low-tip-speed range at high angles of attack and compressibility losses are predominant at the higher tip speeds and lower angles of attack. For purposes of clarity, the stall and compressibility losses will be discussed separately.

Stall losses.- Figures 4 and 5 present the ratios of $\left(C_{Q_o}\right)_{measured}$ to $\left(C_{Q_o}\right)_{theoretical}$ (for the untwisted and twisted blades, respectively) plotted against calculated tip angle of attack for the range of tip speeds measured. The results indicate that the ratios of profile-drag coefficients are close to unity for tip speeds from 350 to 420 feet per second and calculated tip angles of attack below 12°, since neither stall nor compressibility losses are present. The angles of attack at which stall losses start (about 12°) in hovering show good agreement with the angles of attack measured in forward-flight conditions reported in reference 1 for the same sets of blades. At the low tip speeds, as the tip angle of attack is increased above 12°, the increasing blade stall results in larger profile-drag losses. At a tip angle of attack of 16°, the hovering experimental profile drag is over 3.5 times that calculated without consideration of blade stalling losses; whereas, for the forward-flight condition, where stalling occurs only on one side of the rotor disk, a value of 2 times the calculated profile-drag loss is noted from reference 1.

Compressibility losses.- The curves representing the higher tip speeds in either figure 4 or 5 show the critical combination of tip speed and tip angle of attack at which compressibility losses are first encountered and the rate of increase of these losses with increasing tip angle of attack. In general, once the critical combination of tip speed and tip angle of attack is exceeded, the ratio of measured to theoretical profile-drag torque coefficient approximately doubles for an increase in tip angle of attack of 2°. It is interesting to note that the rates of increase of the compressibility losses in hovering are approximately equal to the rate of increase of the stall losses in hovering. Since the calculated angles of attack at which stall occurs are the same in both hovering and forward flight, the onset of compressibility losses can reasonably be assumed (in the absence of specific information) to occur at the same combinations of tip angles of attack and resultant tip speed at which the compressibility losses were noted in hovering.

The rate of growth of the forward-flight compressibility losses will vary with flight conditions. Examination of the problem, however, suggests that the rate of growth may lie between the rate of growth of stalling losses in forward flight and the rate of growth of compressibility losses in hovering.

A comparison of figures 4 and 5 shows that the twisted blades appear to encounter compressibility losses at calculated tip angles of attack from 0.5° to 1.5° less than the untwisted blades, although, after the losses are fully established, the magnitudes of the losses for a given angle of attack are almost identical for both sets of blades. If this difference were reliable, it would indicate that the initial delay in the drag rise, which can be achieved by twist, is less than would be hoped for. The exact determination of the point of onset of compressibility losses required an unusually high degree of accuracy, however, and this apparent difference may be due to an accumulation of factors including the straight-line extrapolation of the curves of figures 4 and 5 to determine the point of onset of compressibility losses and the possible difference between the practical-construction blades used.

The effect of tip speed on C_T/σ and $C_{m_{ac}}$ at three representative collective pitch settings of 8°, 12°, and 16° (measured at 0.75R) for both the twisted and untwisted rotor blades is shown in figure 6. The curves show that the tip speed has almost no effect on the thrust-coefficient - solidity ratio (which is directly proportional to mean rotor lift coefficient) for either set of rotor blades. The blade aerodynamic pitching-moment coefficient shows only a small variation for both sets of blades over the range of tip speeds and pitch settings presented. This result is in agreement with results of section data (reference 4) which indicate that the divergence of the pitching-moment curve is delayed beyond the drag-divergence point. For certain combinations of high pitch settings and high tip speeds, there were indications that still more extreme operating conditions might result in large negative pitching-moment coefficients.

Comparison with two-dimensional data.- The problem of predicting the tip Mach number and tip angle of attack at which the drag rise occurs for a helicopter rotor blade would be considerably simplified if reasonable agreement could be obtained with two-dimensional data. Accordingly, the drag-divergence tip Mach number and tip angle of attack for the two sets of blades are compared in figure 7 with some two-dimensional data from reference 4. The rotor data show good agreement with two-dimensional data. Propeller data have shown the drag-divergence tip Mach number to be about 0.06 above the two-dimensional results (reference 5). A similar trend is shown for the case of the helicopter rotor. The increment appears to be somewhat less than 0.06; this fact is not surprising in view of the contour imperfections present. At the higher angles of attack, however, the blades have a lower critical speed than the two-dimensional results. This condition is probably caused by a combination of compressibility and blade stalling losses since blade stalling starts on the blade section at angles of attack of about 12°, whereas an accurate two-dimensional section does not begin to stall until an angle of attack of approximately 16° is reached. The agreement of the section data with the rotor-blade data for the airfoil used provides a basis for estimating the rotor characteristics for cases in which other airfoils are used. For example, with the thinner sections which might be used in high-speed designs, the drag-divergence Mach number would be increased, although the general shape of the curve of drag divergence against angle of attack would be expected to remain the same.

A preliminary study also indicates that the rate of growth of the rotor profile-drag losses, following drag divergence, can be approximated by calculations based on two-dimensional section data.

Operating limitations.- It is significant that the onset of compressibility losses appreciably reduced the rotor efficiency before any evidence of operating limitations due to vibration or loss of control was noted. For the low tip speeds, the limiting vibration and loss of control occurred when the tip angle of attack exceeded by approximately 4° the angle at which the onset of the profile-drag rise occurs owing to stall. The limitations due to vibration were considered reached on the test tower when the random (apparently aerodynamic) oscillations approached an amplitude which shook the whole test tower. Limiting loss of control was reached at the point when the rotor was well into the stall region and the rotor-tip-path plane could not be controlled appreciably by applying cyclic pitch. For higher tip speeds no loss of control was apparent, but a limiting 1-per-rotor-revolution oscillation, which appeared to result from an out-of-track condition, occurred.

CONCLUSIONS

The effect of compressibility and blade stalling on the hovering characteristics of full-scale helicopter rotors has been experimentally determined for two sets of blades. The two sets of blades had similar plan forms, solidities, and airfoil sections and differed only in that one rotor had untwisted blades, whereas the other rotor had blades with -8° of linear twist. From the data obtained, the following conclusions may be drawn:

1. The primary effect of compressibility was a rapid increase in the profile-drag torque coefficient once the critical combination of tip angle of attack and tip speed was exceeded. The mean rotor lift coefficient and blade aerodynamic pitching-moment coefficient showed only a small variation over the range of tip speeds.

2. Negative blade twist was effective in delaying the onset of compressibility losses and was effective in reducing these losses once they were developed. For example, the twisted set of blades required 15 percent less total power than the untwisted set for a tip speed of 770 feet per second and a rotor-thrust coefficient of 0.004.

3. A comparison of rotor experimental results with two-dimensional results of drag-divergence Mach number against angle of attack showed good agreement.

4. The onset of compressibility losses appreciably reduced the rotor efficiency before any evidence of operating limitations due to vibration or loss of control was noted.

5. The stalling losses for the low-tip-speed region began at a tip angle of attack of about 12°. This result is approximately what would be expected for the practical-construction airfoil used and is in good agreement with results obtained with the same rotor blades for forward-flight conditions.

6. For the low tip speeds (350 to 420 fps), the power required for a given thrust coefficient was about 3 percent less for the blades having -8° of twist than for the untwisted blades as has been predicted by the theory of NACA TN 1542.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., November 16, 1950

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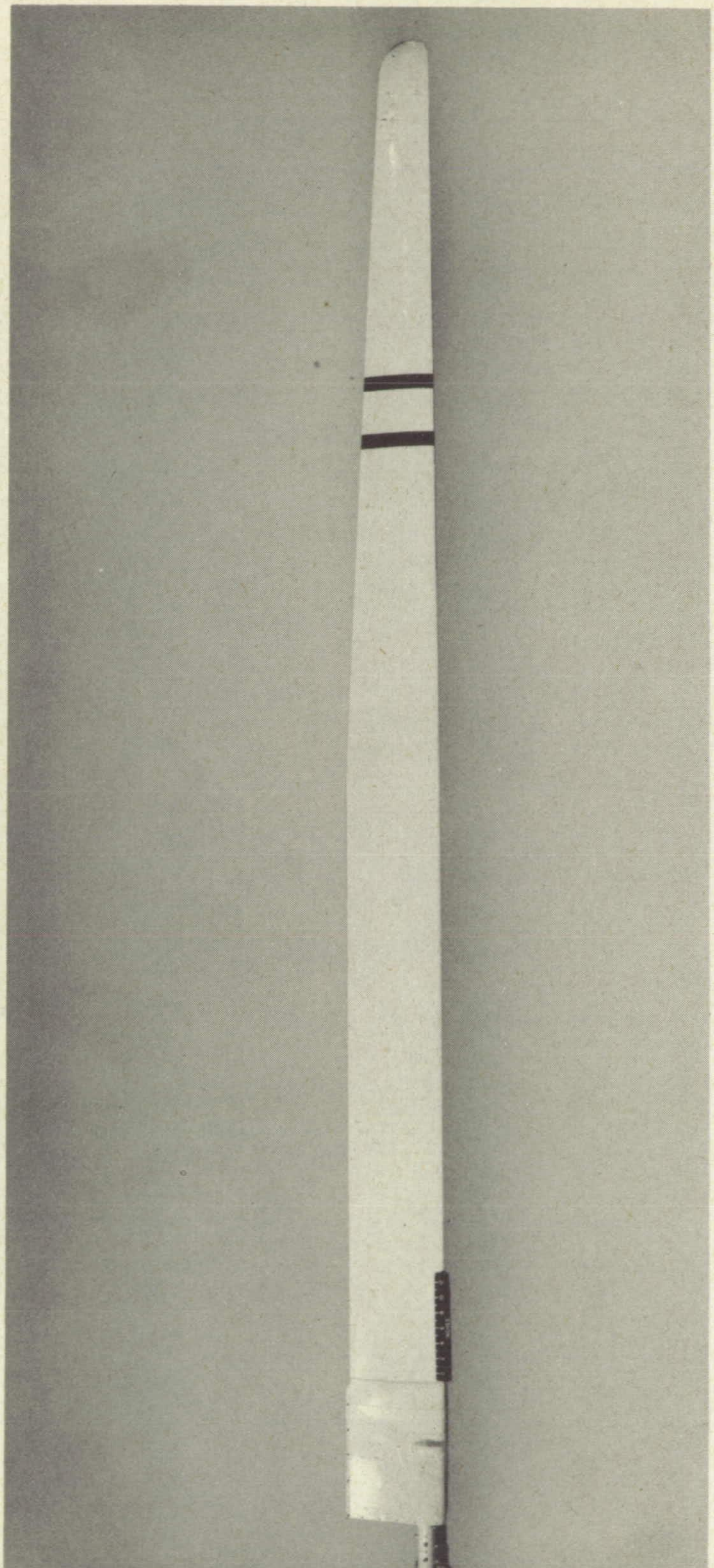

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Figure 1.- Plan-form view of a test rotor blade.

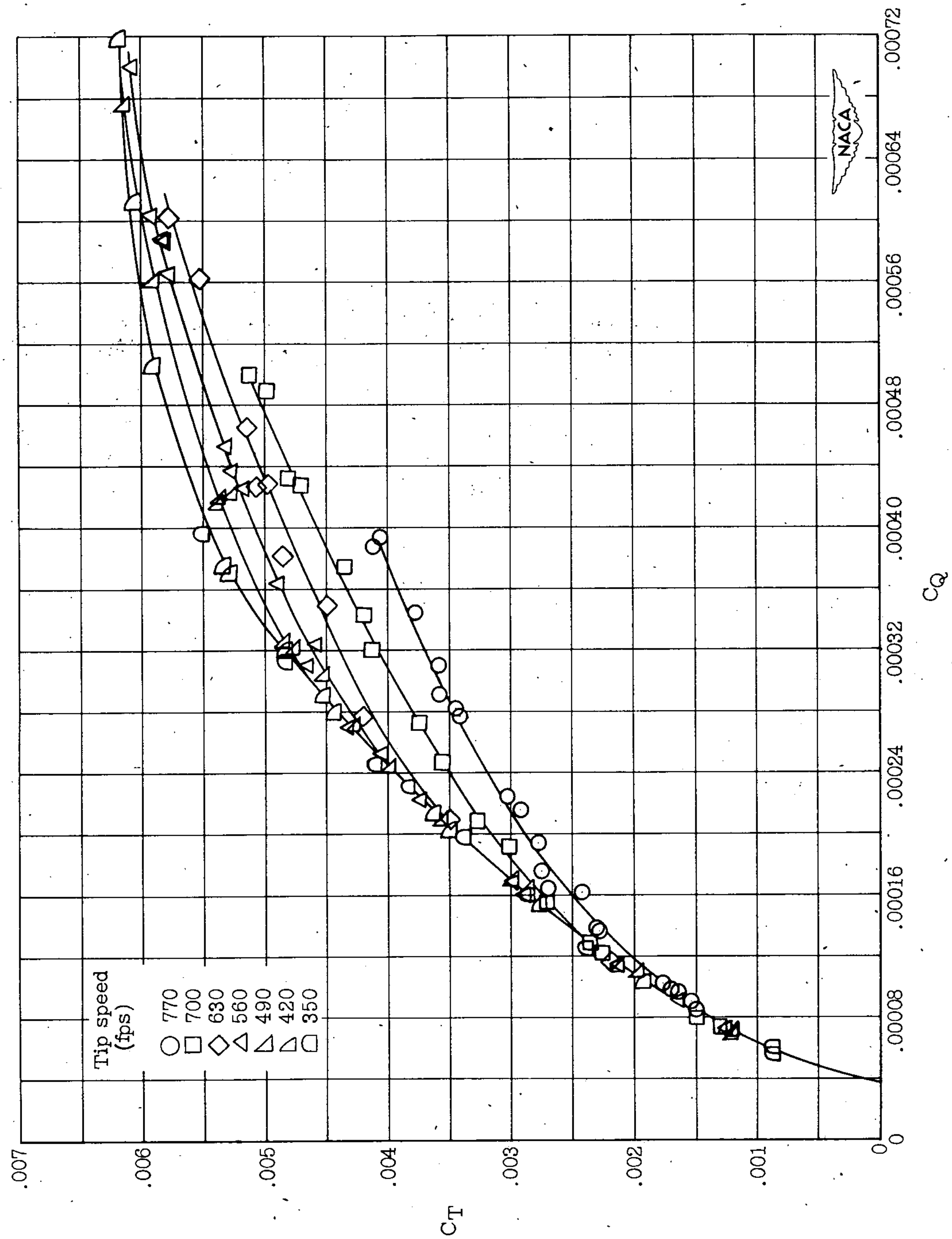

Figure 2.- Hovering performance of the untwisted rotor blades over a range of tip speeds from 350 to 770 feet per second. $\sigma = 0.038$.

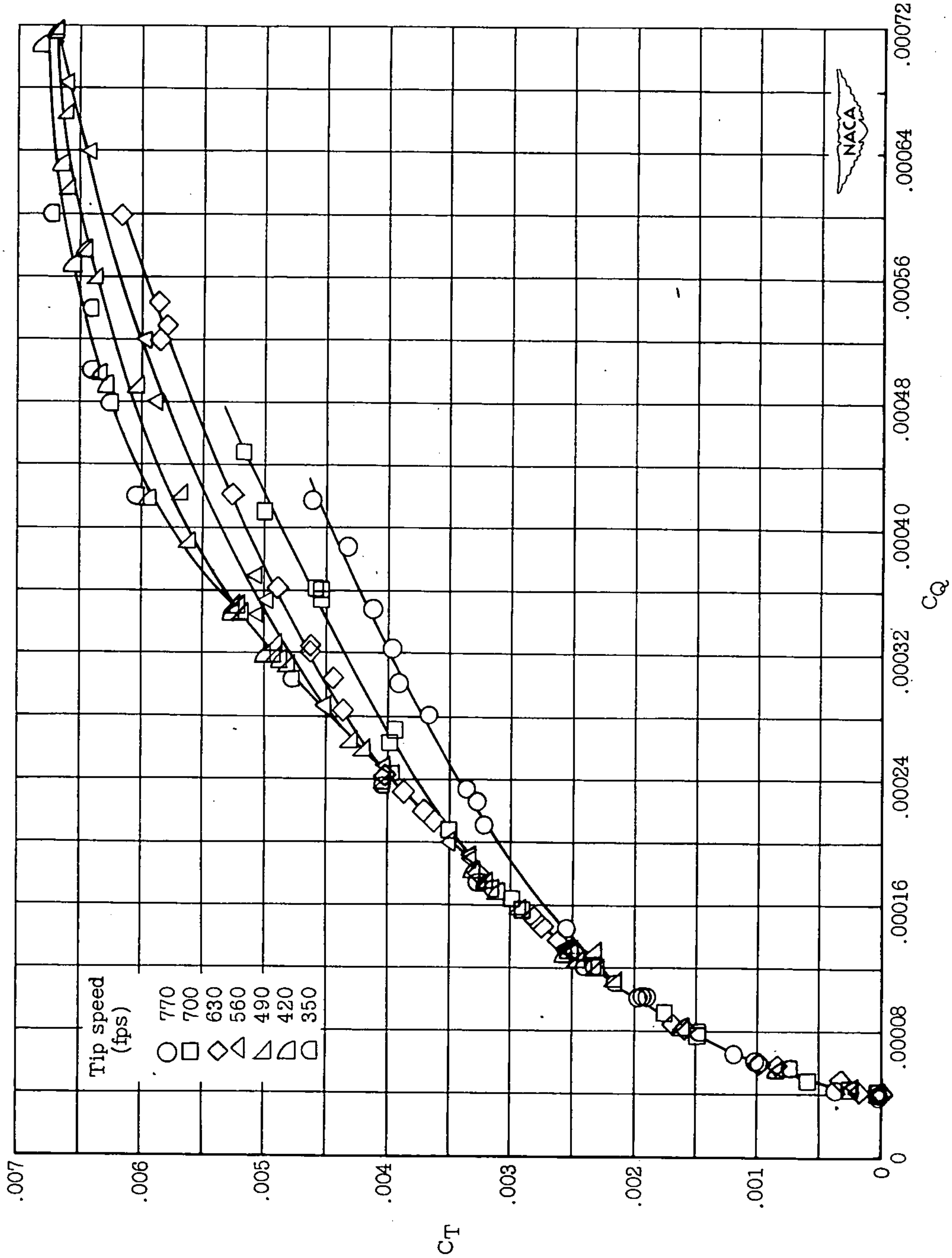

Figure 3.- Hovering performance of the rotor blades having -8° of linear twist over a range of tip speeds from 350 to 770 feet per second. $\sigma = 0.038$.

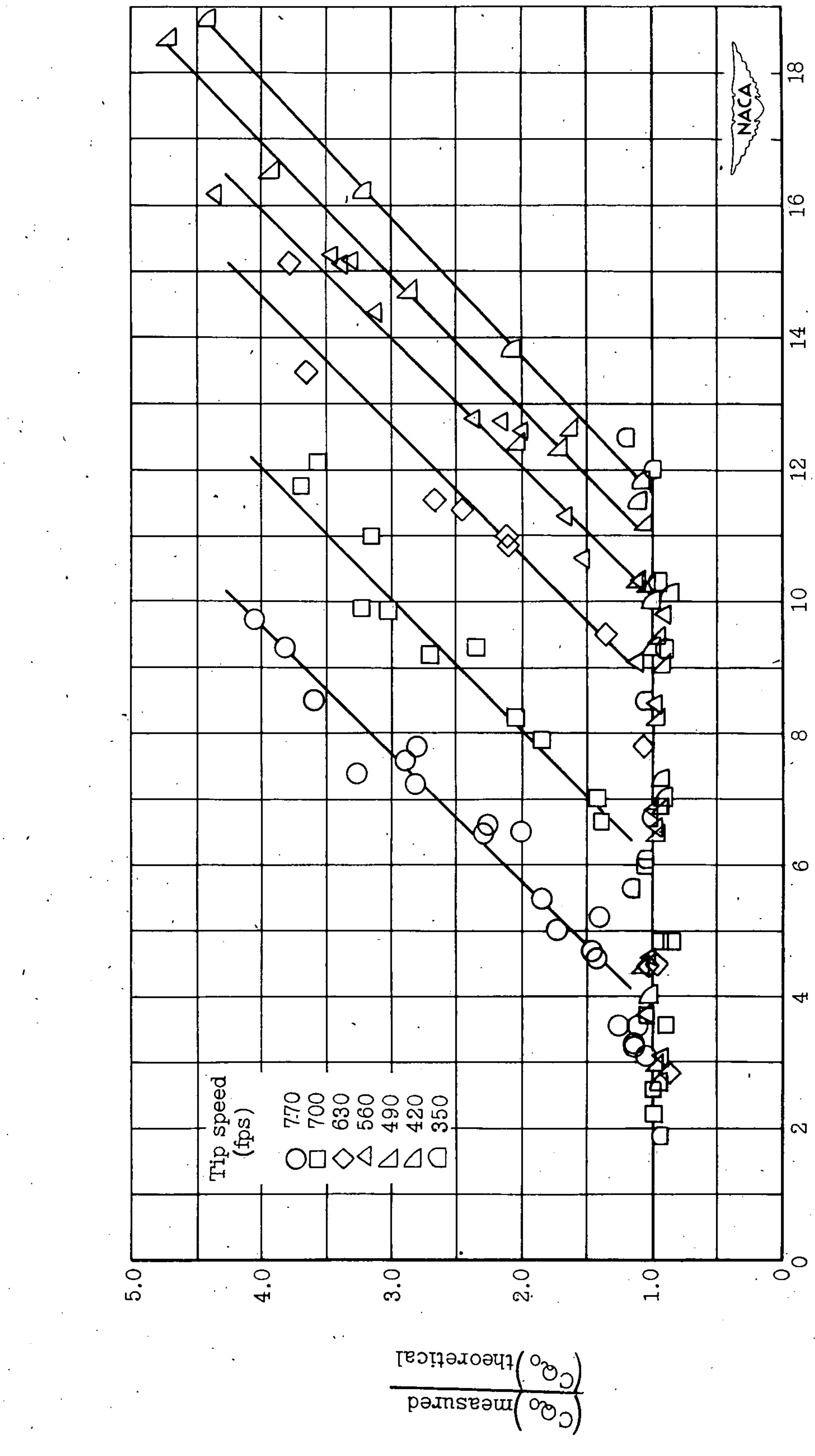

Figure 4.- Ratios of measured to theoretical profile-drag torque coefficients for the untwisted rotor blades at various calculated tip angles of attack.

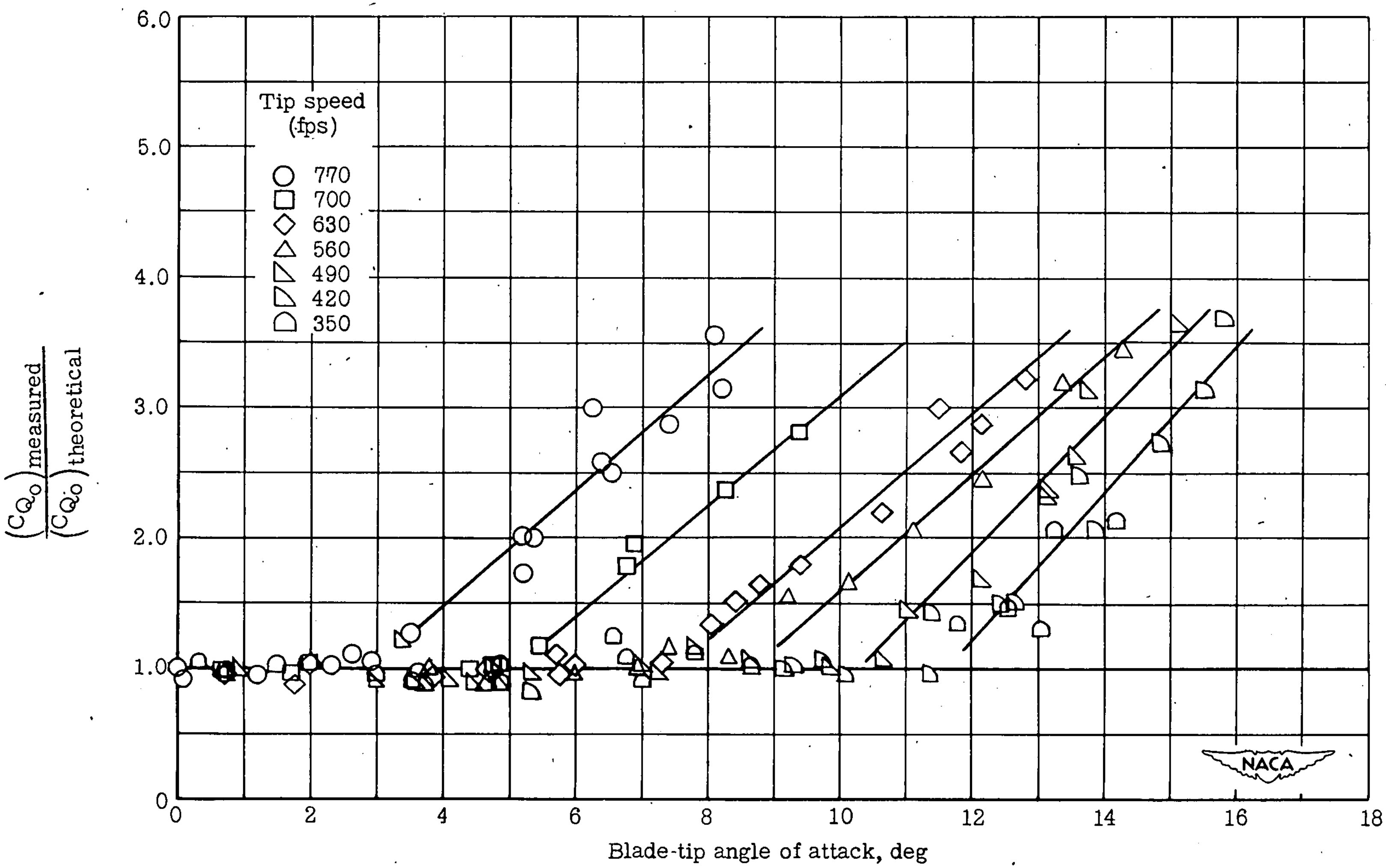

Figure 5.- Ratios of measured to theoretical profile-drag torque coefficients for the rotor blades having -8° of linear twist at various tip angles of attack.

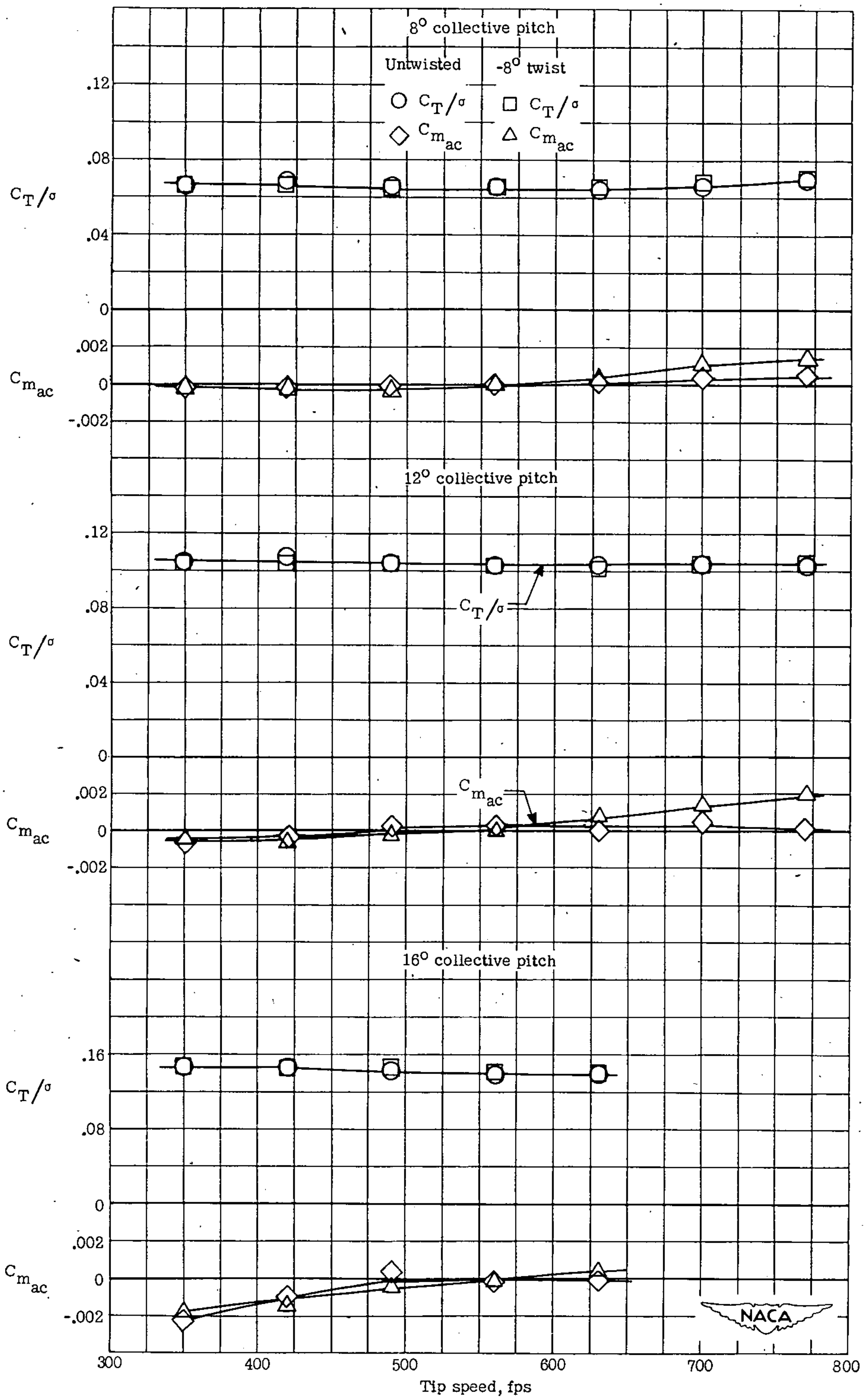

Figure 6.- Comparison of C_T/σ and $C_{m_{ac}}$ for both untwisted and twisted blades over a tip-speed range from 350 to 770 feet per second for three representative collective pitch settings of 8°, 12°, and 16°.

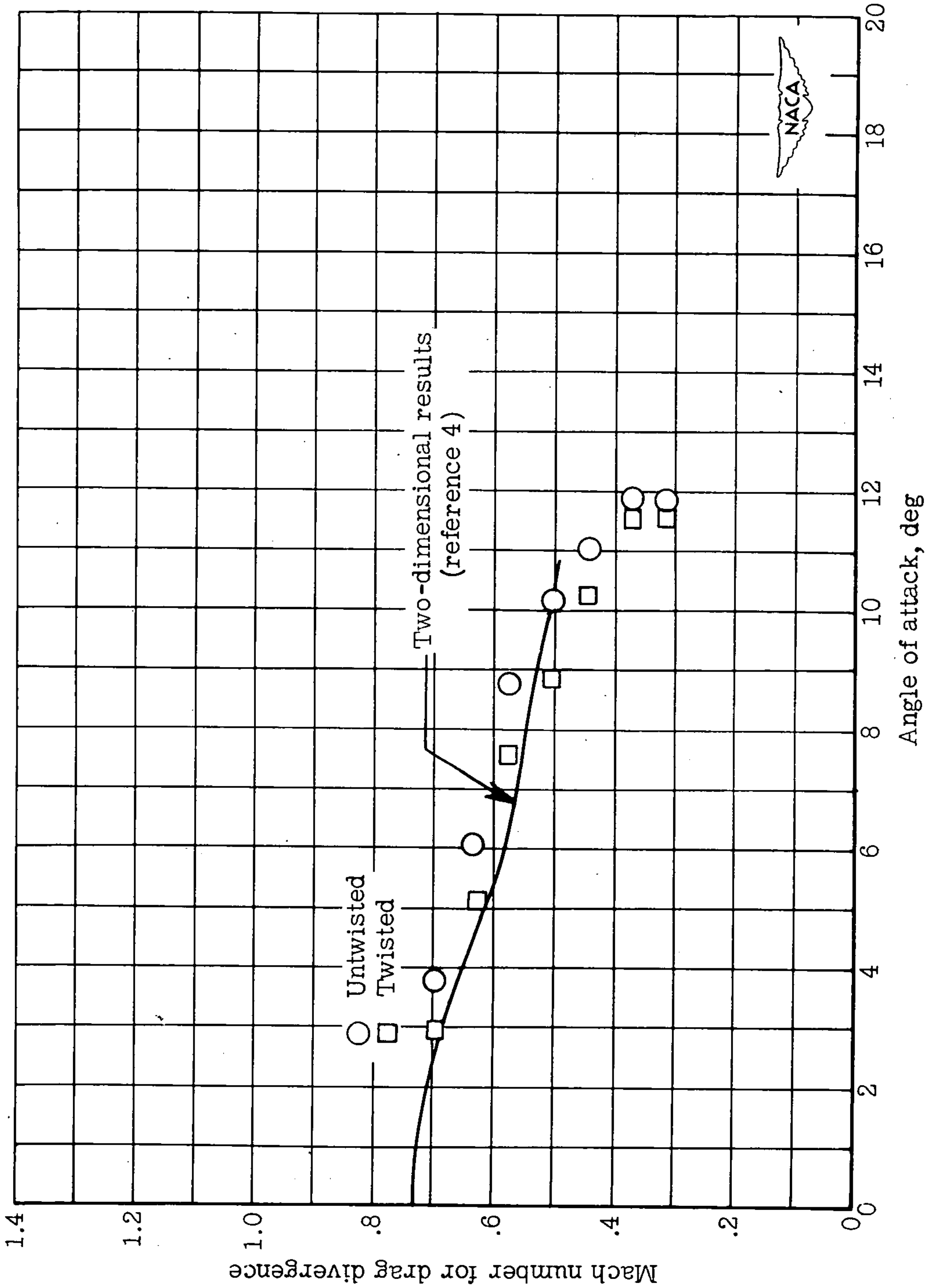

Figure 7.- Comparison of rotor experimental results with two-dimensional drag-divergence Mach number against angle of attack for NACA 23015 airfoil section.