NACA RM L51H28

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# RESEARCH MEMORANDUM

## AERODYNAMIC CHARACTERISTICS AT TRANSONIC SPEEDS OF A WING HAVING 45° SWEEP, ASPECT RATIO 8, TAPER RATIO 0.45, AND AIRFOIL SECTIONS VARYING FROM THE NACA 63A010 SECTION AT THE ROOT TO THE NACA 63A006 SECTION AT THE TIP

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
January 15, 1952

E R R A T U M

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Attached are replacement index cards for those inserted through error in this report.

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## SUMMARY

An investigation has been conducted in the Langley High-Speed 7- by 10-foot tunnel to determine the transonic aerodynamic characteristics of a wing having a spanwise variation in thickness ratio. The wing investigated had 45° of sweepback, aspect ratio 8, taper ratio 0.45, and airfoil sections tapered from an NACA 63A010 section at the root chord to an NACA 63A006 section at the tip chord. The test Mach number range was from 0.60 to 1.05 at Reynolds numbers of the order of 500,000.

The results of this investigation, when compared with those of a previous investigation of a 12-percent-thick wing having the same plan form as the present wing, show that the outboard losses in lift and adverse shifts in center of load at transonic speeds were considerably less severe for the wing of the present investigation. Theoretical subsonic aerodynamic parameters were in fairly good agreement with experiment for both the 12-percent and tapered-in-thickness-ratio 10- to 6-percent-thick wing.

Throughout the test range of Mach numbers, the minimum-drag coefficient of the tapered-in-thickness-ratio 10- to 6-percent-thick wing was substantially lower than that of the constant 12-percent-thick wing. At transonic speeds the differences in minimum drag for the two wings are attributed primarily to the difference in average wing thickness. Drag due to lift at subsonic speeds was more favorable for the 12-percent constant-thickness-ratio wing than for the thinner tapered-in-thickness-ratio wing, but at a Mach number of 1.00, the thinner wing showed slightly better drag-due-to-lift characteristics than the thicker wing.

## INTRODUCTION

As an outgrowth of an extensive transonic research program proposed to study the effects of wing variables on the aerodynamic characteristics of wings believed to be applicable to high-speed flight, a limited investigation is being conducted in the Langley high-speed 7- by 10-foot tunnel to determine the basic aerodynamic characteristics of tapered-in-thickness-ratio wings. These wings are identical in plan form to some of the constant-thickness-ratio wings investigated under this transonic program. Previous investigations of relatively high aspect ratio wings have shown that important aerodynamic advantages can be realized from the use of thickness taper while no appreciable reductions in the structural qualities are incurred for comparable wings of approximately the same average thickness (see reference 1).

The wing of this investigation had 45° sweepback, aspect ratio 8, taper ratio 0.45, and an NACA 63A010 airfoil section at the root chord tapered in thickness by straight-line elements to an NACA 63A006 airfoil section at the tip chord. This wing was investigated as a reflection-plane model over a Mach number range from 0.60 to 1.05. Results of previous investigations of wings tapered in thickness ratio are given in references 2 and 3.

This paper presents the experimental results of this investigation and an analysis of the data in conjunction with data obtained from a previous investigation (reference 4) of a wing having the same plan form but of a 12-percent constant section thickness. Comparisons also are made with theoretical values at subsonic speeds of lift-curve slope, aerodynamic center, and lateral center of lift.

## COEFFICIENTS AND SYMBOLS

All force and moment data presented are referred to the wind axes.

$C_L$ lift coefficient (Twice semispan lift/qS)

$C_D$ drag coefficient (Twice semispan drag/qS)

$C_m$ pitching-moment coefficient referred to $0.25\bar{c}$ (Twice semispan pitching moment/$qS\bar{c}$)

$C_B$ bending-moment coefficient due to lift about root chord $\left(\text{Root bending moment}\Big/q\,\frac{S}{2}\,\frac{b}{2}\right)$

| | |
|---|---|
| $C_{D_{min}}$ | minimum drag coefficient $\left(C_D \text{ at } C_L = 0\right)$ |
| $\Delta C_D$ | drag coefficient due to lift $\left(C_D - C_{D_{min}}\right)$ |
| $q$ | effective dynamic pressure over span of model, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$ |
| $\rho$ | mass density of air, slugs per cubic foot |
| $V$ | free-stream velocity, feet per second |
| $S$ | twice area of semispan model, square feet |
| $\bar{c}$ | mean aerodynamic chord of wing, using theoretical tip, feet $\left(\frac{2}{S}\int_0^{b/2} c^2\, dy\right)$ |
| $c$ | local wing chord, feet |
| $b$ | twice span of semispan model, feet |
| $E$ | modulus of elasticity in bending, pounds per square inch |
| $y$ | spanwise distance from plane of symmetry, feet |
| $M$ | effective Mach number over span of model |
| $M_l$ | local Mach number |
| $M_a$ | average local chordwise Mach number |
| $y_L$ | lateral center of lift, percent semispan $\left(100\,\frac{\partial C_B}{\partial C_L}\right)$ |
| $\alpha$ | angle of attack, degrees |
| $\alpha_D$ | local angle of streamwise twist, degrees |
| $\frac{\alpha_D}{qC_L}$ | local streamwise twist parameter, degrees per pound per square foot |

## MODELS AND METHODS

The steel wing semispan model had 45° of sweepback referred to the quarter-chord line, aspect ratio 8, taper ratio 0.45, and an NACA 63A010 airfoil section at the root chord, measured parallel to the free stream, joined by straight-line elements to an NACA 63A006 airfoil section at the tip chord. A plan-form drawing of the model is presented in figure 1 and the variation of thickness ratio along the model semispan is presented in figure 2.

This investigation was conducted in the Langley high-speed 7- by 10-foot tunnel. As a means of testing the semispan model at subsonic and low supersonic Mach numbers in a region outside the tunnel boundary layer, a reflection plane was mounted about 3 inches from the tunnel wall as shown in figure 3. The reflection-plane boundary layer was such that a velocity equal to 95 percent of the free-stream velocity in the testing region was reached at a distance 0.16 inch from the surface at the balance center line for all test Mach numbers. This distance represents about 2.7 percent of the model semispan.

At Mach numbers below 0.95 there was practically no velocity gradient in the vicinity of the model. At higher test Mach numbers, however, both chordwise and spanwise Mach number gradients were evident. The variations of local Mach number in the vicinity of the model location are shown in figure 4. The effective Mach numbers were obtained by using the relationship

$$M = \frac{2}{S}\int_0^{b/2} cM_a \, dy$$

For the subject model, a spanwise Mach number gradient of generally less than 0.03 was obtained up to a Mach number of 1.05. At this Mach number the maximum chordwise gradient was 0.03.

Spanwise Mach number gradients over the semispan of the comparison wing (reference 4), which was investigated on a transonic bump, ranged from 0.06 at subsonic Mach numbers to 0.10 at $M = 1.00$ and above. The maximum chordwise gradient was 0.01. It has been found that no large or consistent differences are shown from the test results of identical wings tested on the transonic bump and on the reflection-plane setup (reference 5). A discussion of many of the factors that must be considered in the evaluation of bump and reflection-plane tests can be found in reference 5.

Forces and moments were measured by means of an electrical strain-gage balance system which was mounted outside the tunnel test section. Leakage through a small clearance gap between the turntable (located flush with the reflection-plane surface) and the wing root was restricted by a sponge seal attached to the wing butt and wiping against the inside of the turntable. The variation of mean Reynolds number, based on $\bar{c}$, is shown in figure 5.

In order to determine the aeroelastic qualities of the wings used in the analysis of this paper, static loads were applied to the wings at two spanwise locations on the quarter-chord lines and the variation of the angle of streamwise twist was measured at four spanwise locations. The loads were applied at the loading points indicated in figure 6 and in proportions which were intended to simulate roughly the theoretical span loading.

## THEORETICAL CONSIDERATIONS

Theoretical calculations of lift-curve slope, aerodynamic center, and lateral center-of-lift locations for subsonic speeds were made by the methods used in reference 2 to provide comparisons with the test results. These theoretical parameters were corrected to the elastic condition by the strip theory method used in reference 2. After applying twist corrections to the aerodynamic parameters of both wings, it was found that only a 2-percent error would result by using an average of the two deflection curves presented in figure 6. Therefore, only one theoretical curve is presented for the lift-curve slope, aerodynamic center, and lateral center of lift for both wings.

## RESULTS AND DISCUSSION

The basic data of the present investigation are presented in figure 7. Summary plots, including comparisons of aerodynamic characteristics with those of the constant 12-percent-thick wing of reference 4 are presented in figures 8 and 9. Slopes presented in the summary figures were measured through zero lift up to a lift coefficient where obvious departure from linearity occurred.

It should be pointed out that there are many shortcomings of both the reflection-plane and transonic-bump results presented in this paper. The Reynolds numbers are extremely low (see fig. 5), there are both spanwise and chordwise variations in Mach number, and the flow over the bump is slightly curved. However, it is felt that the results will give at

least a qualitative indication of the type of compressibility effects that may be encountered in the transonic speed range and a fairly reliable indication of trends in the aerodynamic characteristics resulting from systematic changes in wing geometry.

## Lift Characteristics

The variations at low lift coefficients of lift-curve slope with Mach number are presented in figure 9 for both the tapered 10- to 6- and constant 12-percent-thick wing. From this figure it can be seen that large reductions in lift occur on both wings at transonic speeds; however, these lift losses were not as large or abrupt for the tapered 10- to 6-percent-thick wing. The reductions in lift-curve slope apparently result largely from losses in lift over the outboard portions of the wings as indicated by the inboard movements in lateral centers of lift (fig. 9). From the results of reference 2 it can be concluded that for wings having relatively thick airfoil sections, inboard shifts in lateral center of lift increase with increased tip section thickness. Therefore it appears that the lift improvements realized for the tapered-in-thickness-ratio wing over the constant 12-percent-thick wing are in a large measure due to the thinner tip sections of the tapered 10- to 6-percent-thick wing. It must be realized that the difference in the root thickness of these two wings will also have some effect on the lift characteristics, but it is believed that these effects are overshadowed by the appreciable tip effects.

Subsonic theoretical values of lift-curve slope and lateral center of lift appear to be in fair agreement with theory for both the tapered-in-thickness and constant 12-percent-thick wing.

## Drag Characteristics

Minimum drag characteristics for the subject and comparison wing are presented in figure 9. Minimum drag of the tapered 10- to 6-percent-thick wing is lower subsonically than that of the constant 12-percent-thick wing and does not show as rapid or as large a rise supersonically. At a Mach number of 1.05, $C_{D_{min}}$ of the 10- to 6-percent-thick wing is about 45 percent lower than that of the constant 12-percent-thick wing. An estimation of the pressure drag coefficient for the tapered 10- to 6-percent thick wing was made by use of equations presented in reference 6. Addition of this value of pressure drag coefficient to the subsonic drag coefficient (essentially viscous drag) results in very good agreement with the measured value of $C_{D_{min}}$ at a Mach number of 1.05, as is shown in figure 9. The large reduction in $C_{D_{min}}$ for the tapered

10- to 6-percent-thick wing below that for the constant 12-percent-thick wing is attributed to the difference in average thickness.

Drag due to lift $\Delta C_D$ at the lift coefficients investigated and at a Mach number of 0.80 is appreciably lower for the 12-percent-thick wing than for the tapered 10- to 6-percent-thick wing (see fig. 8). This difference in $\Delta C_D$ is probably due to a loss in leading-edge suction from the thinner wing, resulting from leading-edge flow separation common to airfoils having a small leading-edge radius. This flow separation generally is found to be particularly evident at low Reynolds numbers. At Reynolds numbers higher than those of the present tests, therefore, the difference in $\Delta C_D$ for the two wings may be somewhat less than that indicated herein. At a Mach number of 1.00 the tapered 10- to 6-percent-thick wing realizes slightly lower drag due to lift at all lift coefficients investigated. This increase in $\Delta C_D$ of the 12-percent-thick wing over the tapered 10- to 6-percent wing is probably attributable to the greater separation losses resulting from the thicker section.

## Pitching-Moment Characteristics

From figure 9, it can be seen that very adverse shifts in aerodynamic-center locations, referred to $\bar{c}/4$ (positive values of $\partial C_m/\partial C_L$ for aerodynamic-center forward of $\bar{c}/4$), are realized for both the tapered 10- to 6-percent-thick and the constant 12-percent-thick wings. These shifts are due to the aforementioned loss in tip load which is made evident by forward shifts in the section aerodynamic-center locations and by an inboard shift in the lateral center of lift. Although there is an appreciable aerodynamic-center movement in the transonic speed range for both wings, the tapered 10- to 6-percent-thick wing does not exhibit the large unstable shifts shown by the thicker wing. The more rearward aerodynamic center of the tapered 10- to 6-percent-thick wing at subsonic Mach numbers may be due in a large measure to leading-edge separation from the thin tip sections, resulting in a chordwise shift in center of loading. Theoretical low-speed values of aerodynamic-center location appear to be in fair agreement with the experimental results for both the tapered 10- to 6-percent-thick wing and the constant 12-percent-thick wing.

## CONCLUSIONS

Wind-tunnel tests have been made to determine the aerodynamic characteristics at transonic speeds of a wing of aspect ratio 8, having 45° of sweepback, and tapered in thickness ratio from 10 percent at the root chord to 6 percent at the tip chord. These data are compared with the results previously obtained for a wing of identical plan form but of a constant 12-percent thickness. The following conclusions were drawn from these comparisons:

1. Although losses in lift-curve slope and inboard shifts in lateral center of lift were evident for both wings at transonic speeds, they were considerably less severe for the tapered-in-thickness-ratio 10- to 6-percent-thick wing than for the constant 12-percent-thick wing.

2. Throughout the test range of Mach numbers, the minimum drag coefficient of the tapered 10- to 6-percent-thick wing was substantially lower than that of the constant 12-percent-thick wing. At transonic speeds, the differences in minimum drag for the two wings are attributed primarily to the difference in average wing thickness.

3. Drag due to lift at subsonic speeds at the lift coefficients investigated is more favorable for the constant 12-percent-thick wing than for the tapered 10- to 6-percent-thick wing, but at a Mach number of 1.00 these drag-due-to-lift characteristics are slightly better for the tapered 10- to 6-percent-thick wing.

4. Theoretical subsonic values of lift-curve slope, aerodynamic center, and lateral center of lift are in fair agreement with experiment for both the tapered 10- to 6-percent- and constant 12-percent-thick wings.

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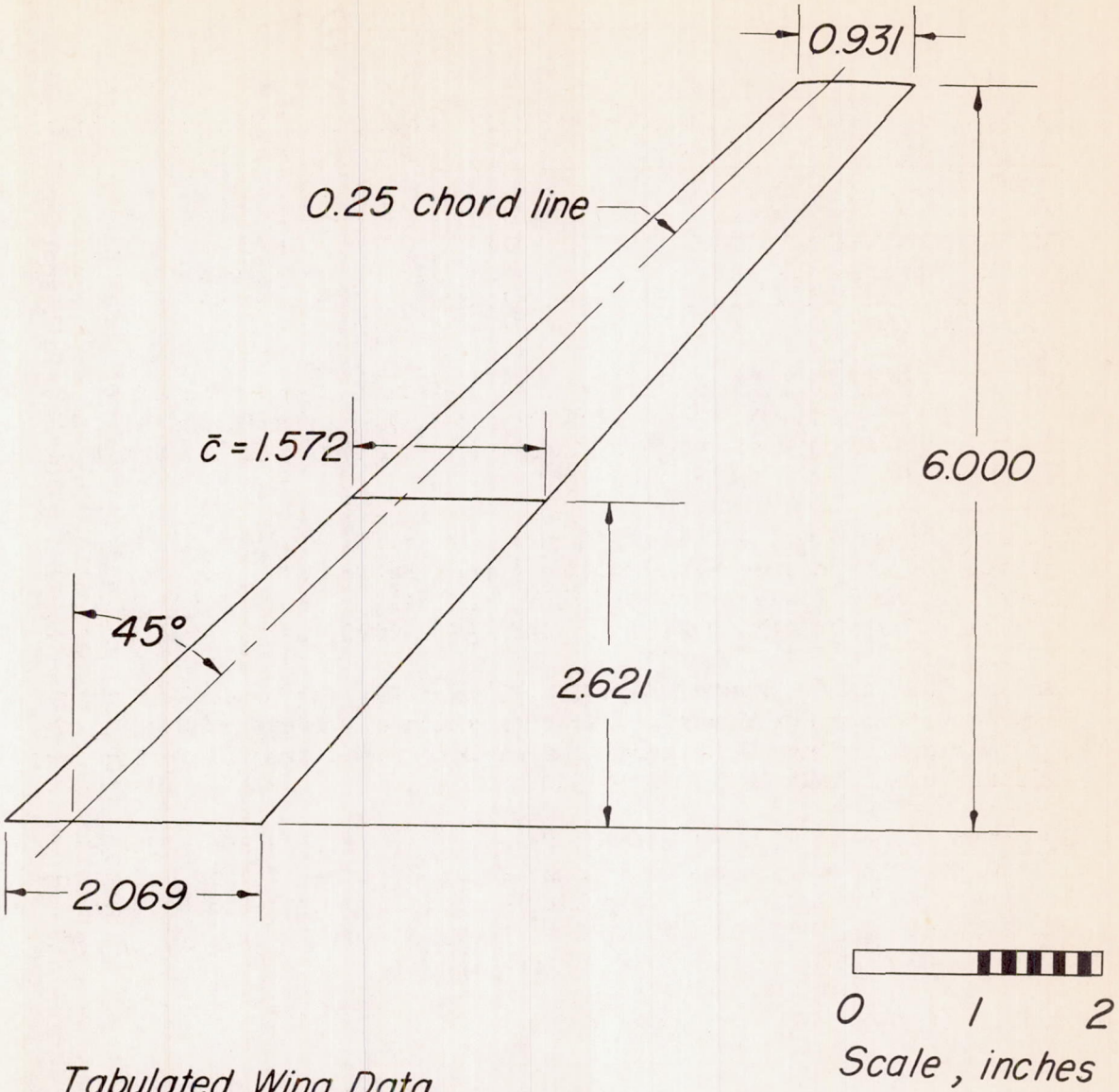



| Tabulated Wing Data | |
|---|---|
| Area (Twice semispan) | 0.125 sq. ft. |
| Aspect ratio | 8 |
| Taper ratio | 0.45 |
| Airfoil section parallel to free stream | NACA 63A010 at root to NACA 63A006 at tip |

Figure 1.- Plan-form drawing of a wing having 45° of sweepback, aspect ratio 8, taper ratio 0.45 and NACA 63A010 airfoil section at root chord tapered to NACA 63A006 airfoil section at tip chord.

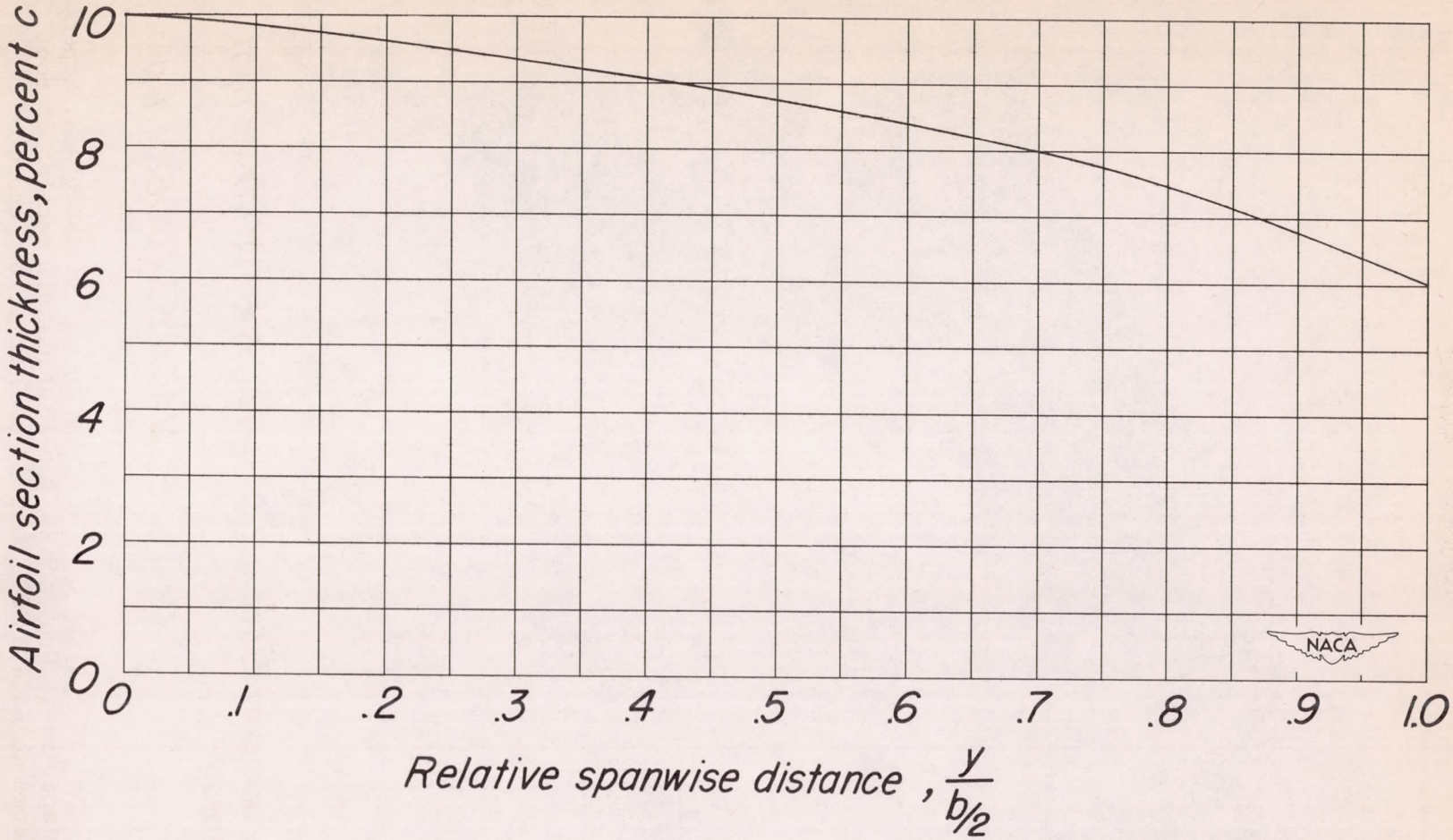



Figure 2.- Percent-thickness distribution along semispan of model having 45° of sweepback, aspect ratio 8, taper ratio 0.45 and NACA 63A010 airfoil section at root chord tapered to NACA 63A006 airfoil section at tip chord.

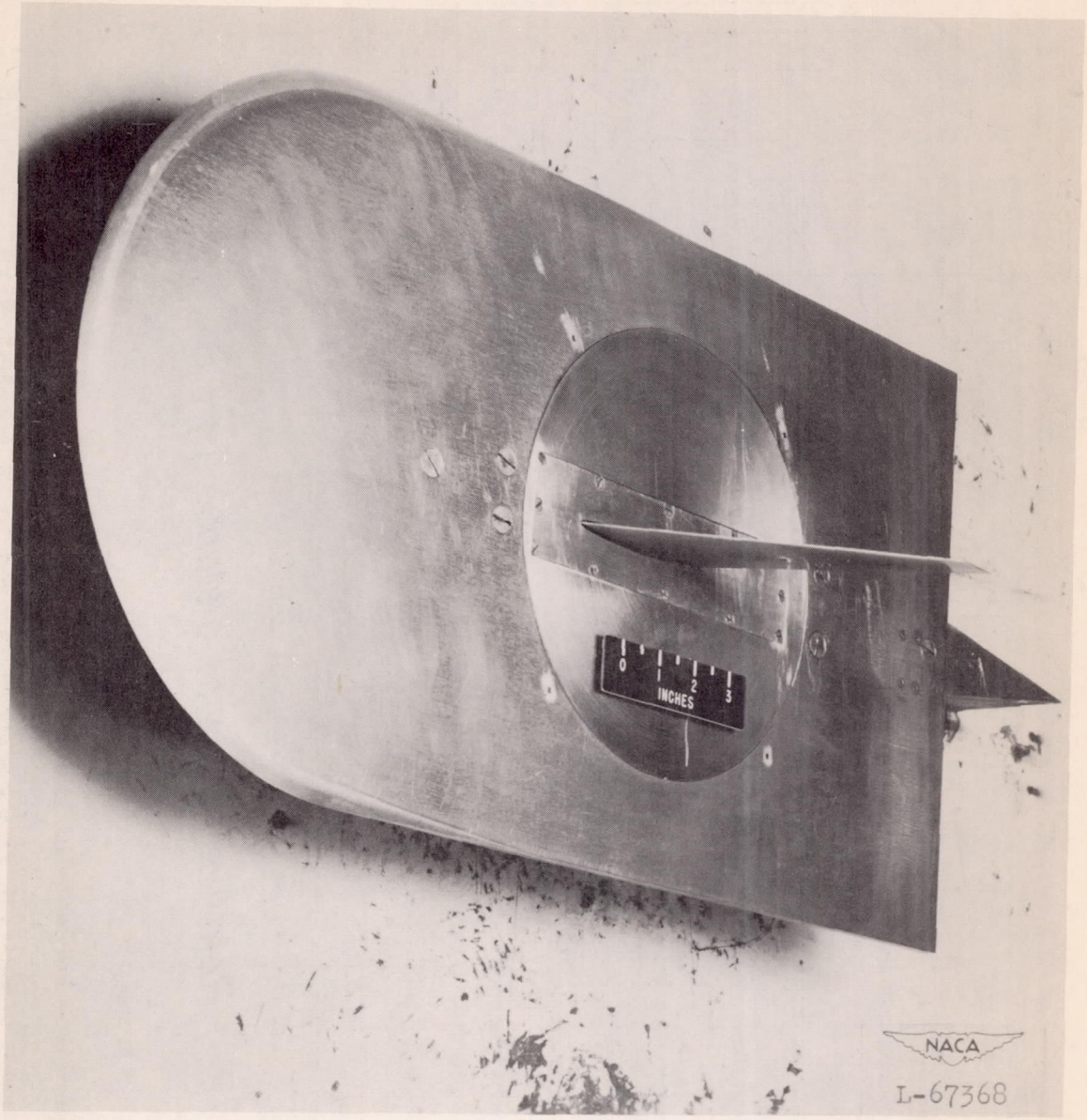



Figure 3.- Photograph of a wing on reflection-plane setup.

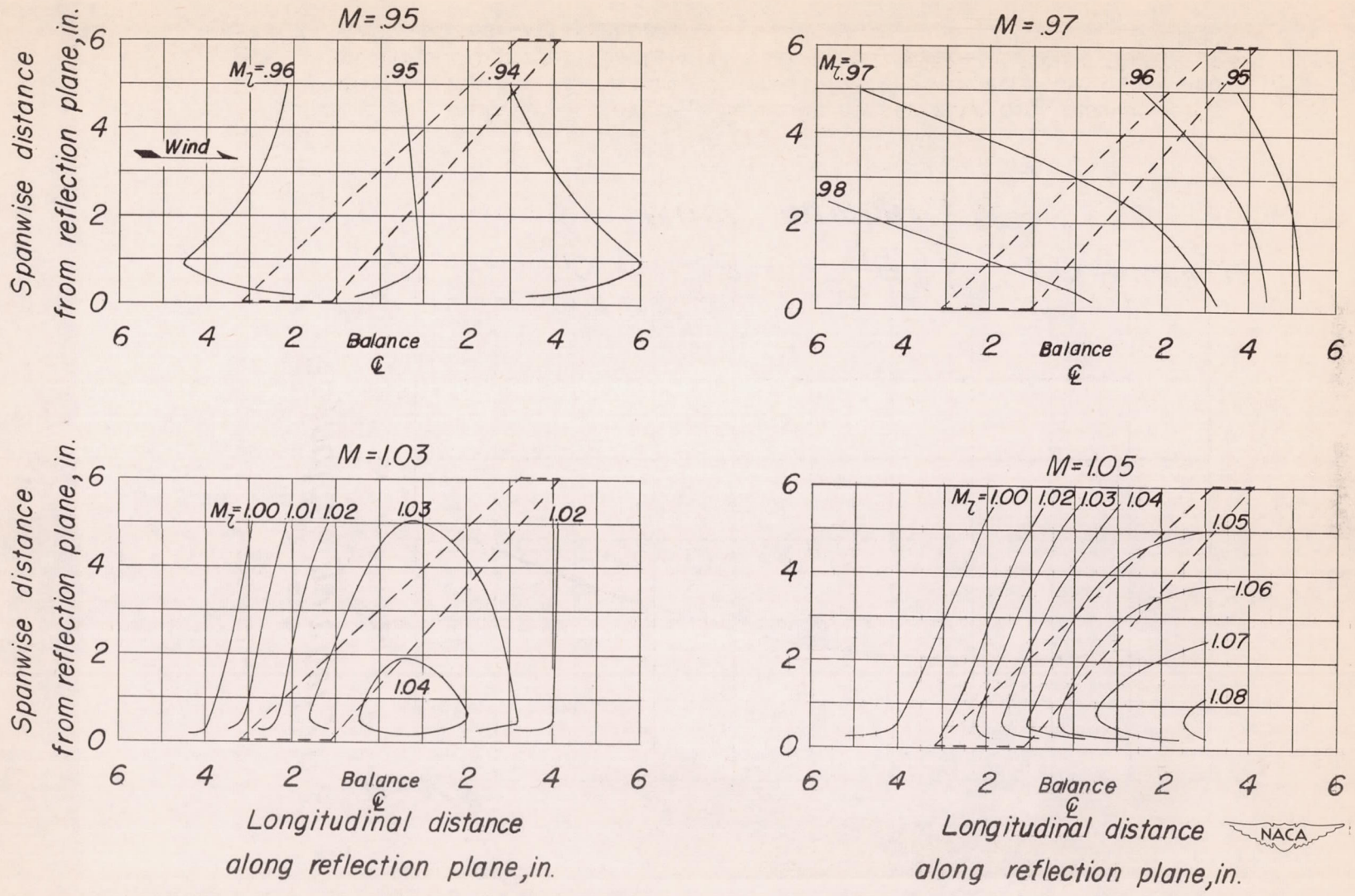



Figure 4.- Typical Mach number contours over side-wall reflection plane in region of model location.

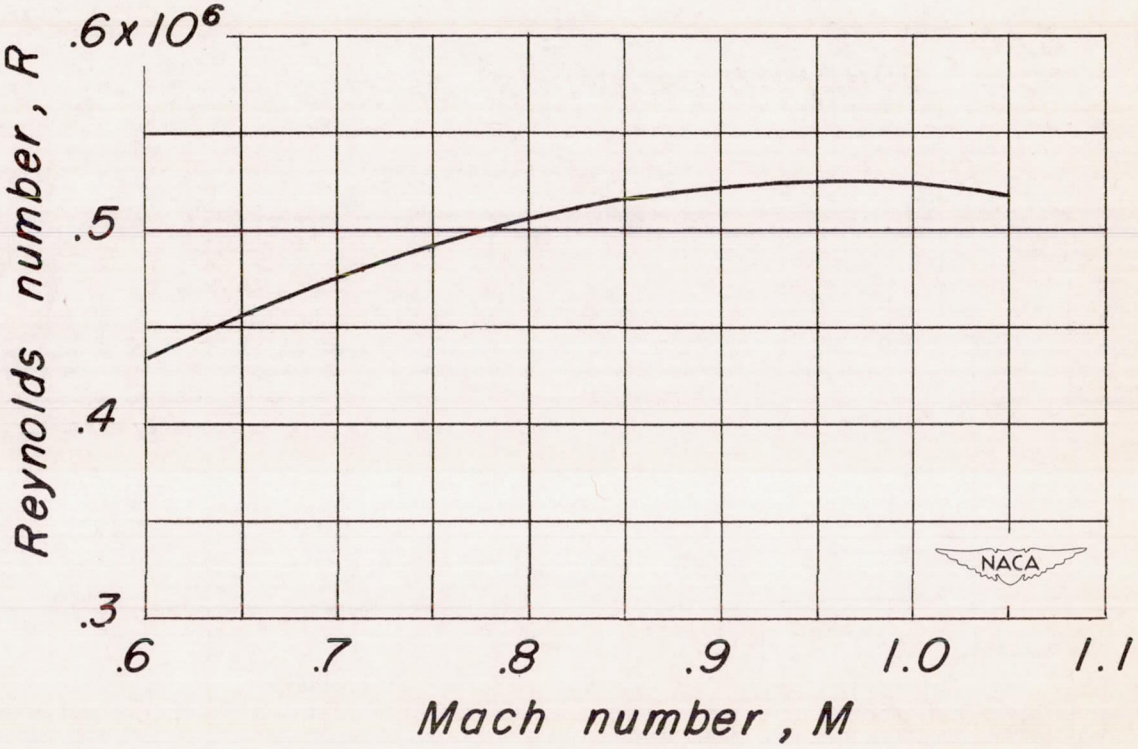



Figure 5.- Variation of average Reynolds number with Mach number for a wing having 45° of sweepback, aspect ratio 8, taper ratio 0.45, and NACA 63A010 airfoil section at root chord tapered to NACA 63A006 airfoil section at tip chord.

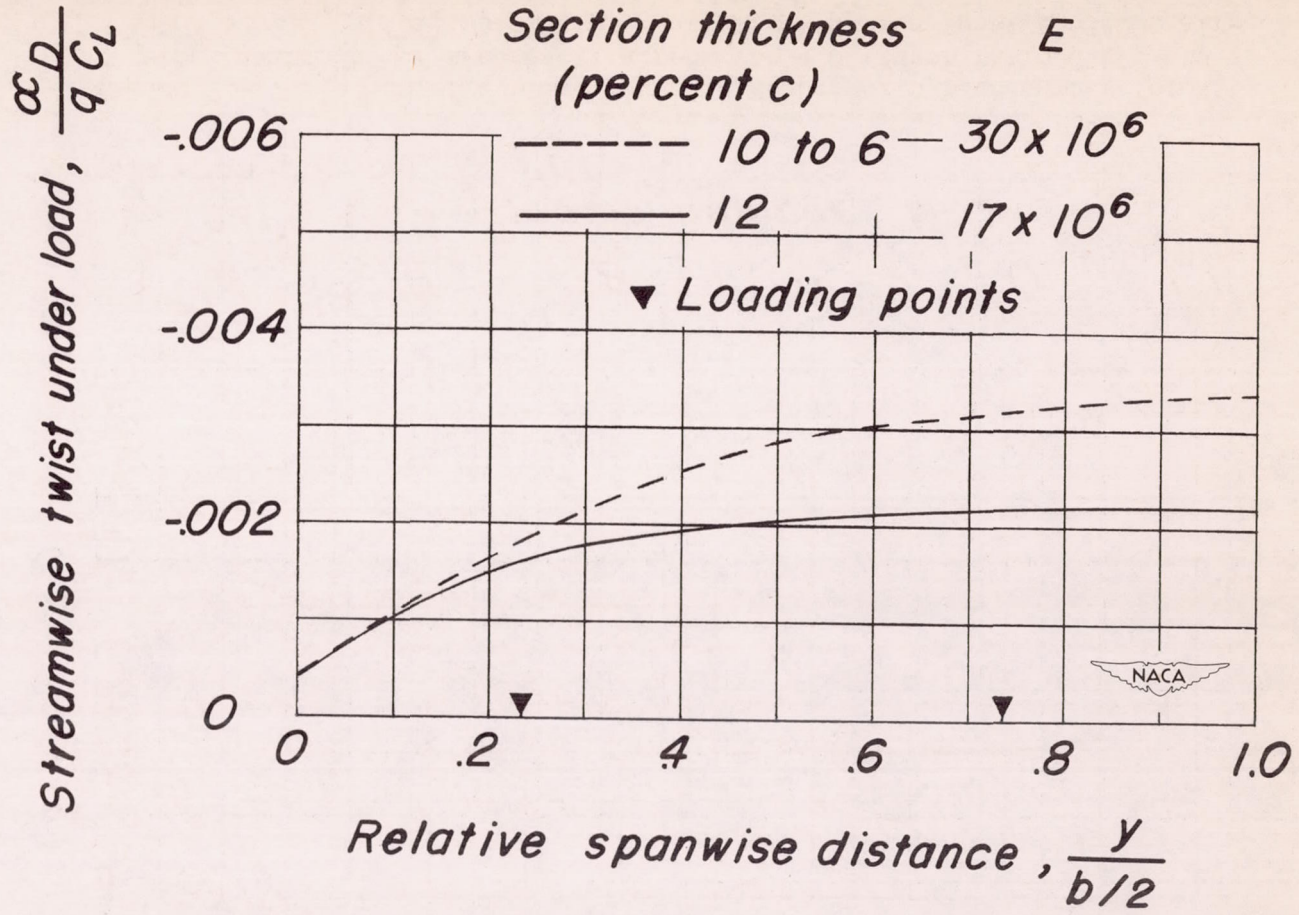
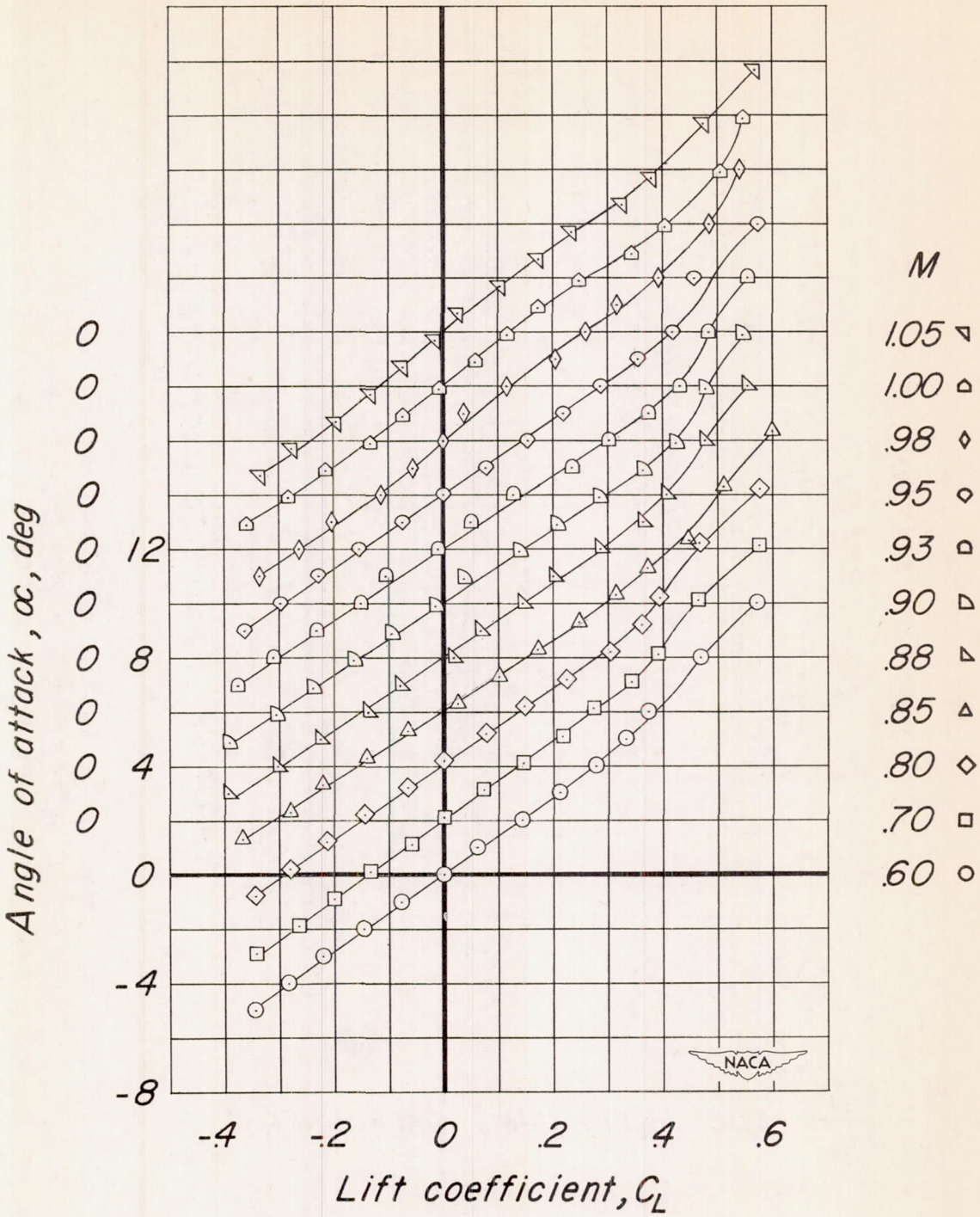
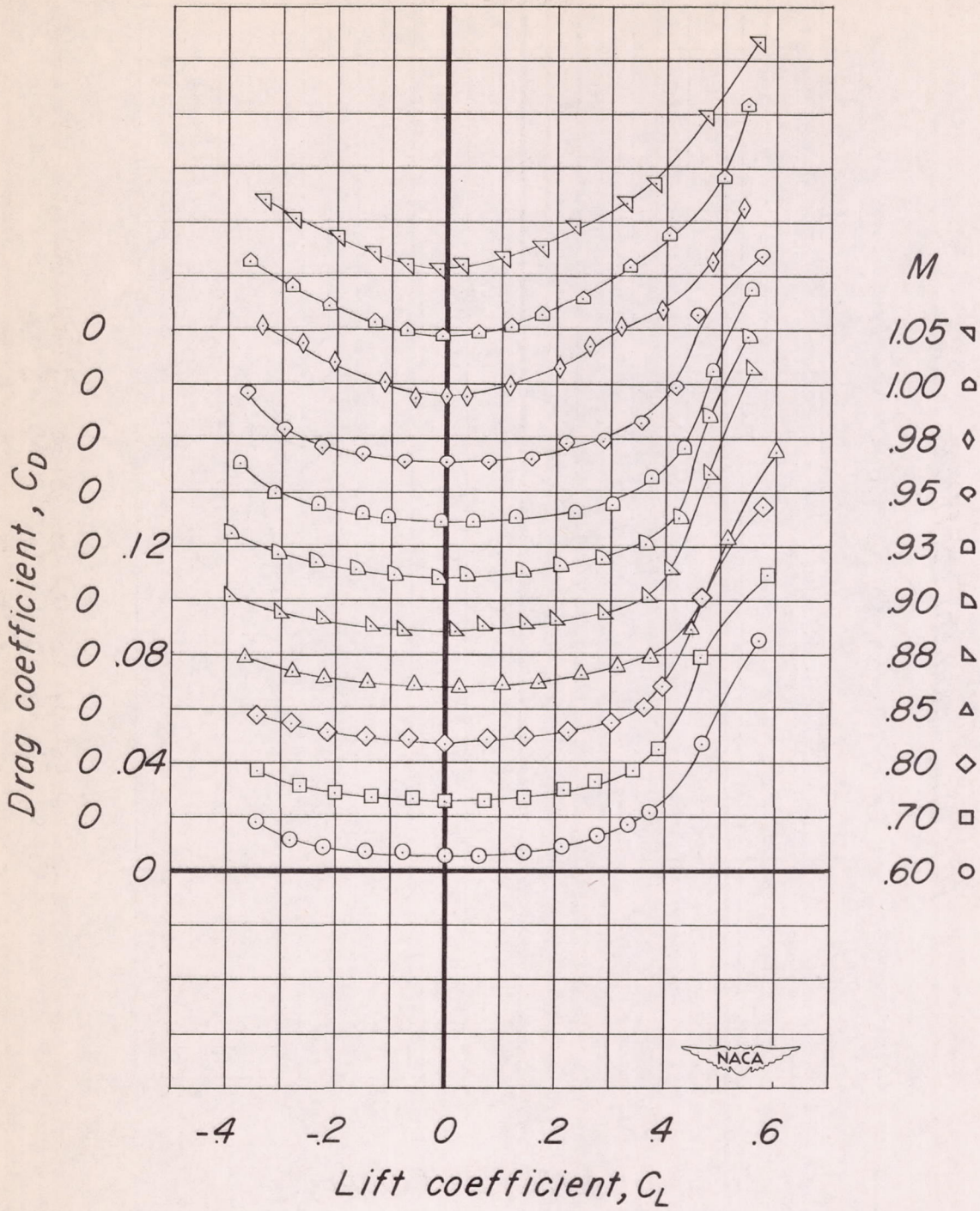



Figure 6.- Variations of angle of streamwise twist along model span for wings having 45° of sweepback, aspect ratio 8, and taper ratio 0.45.



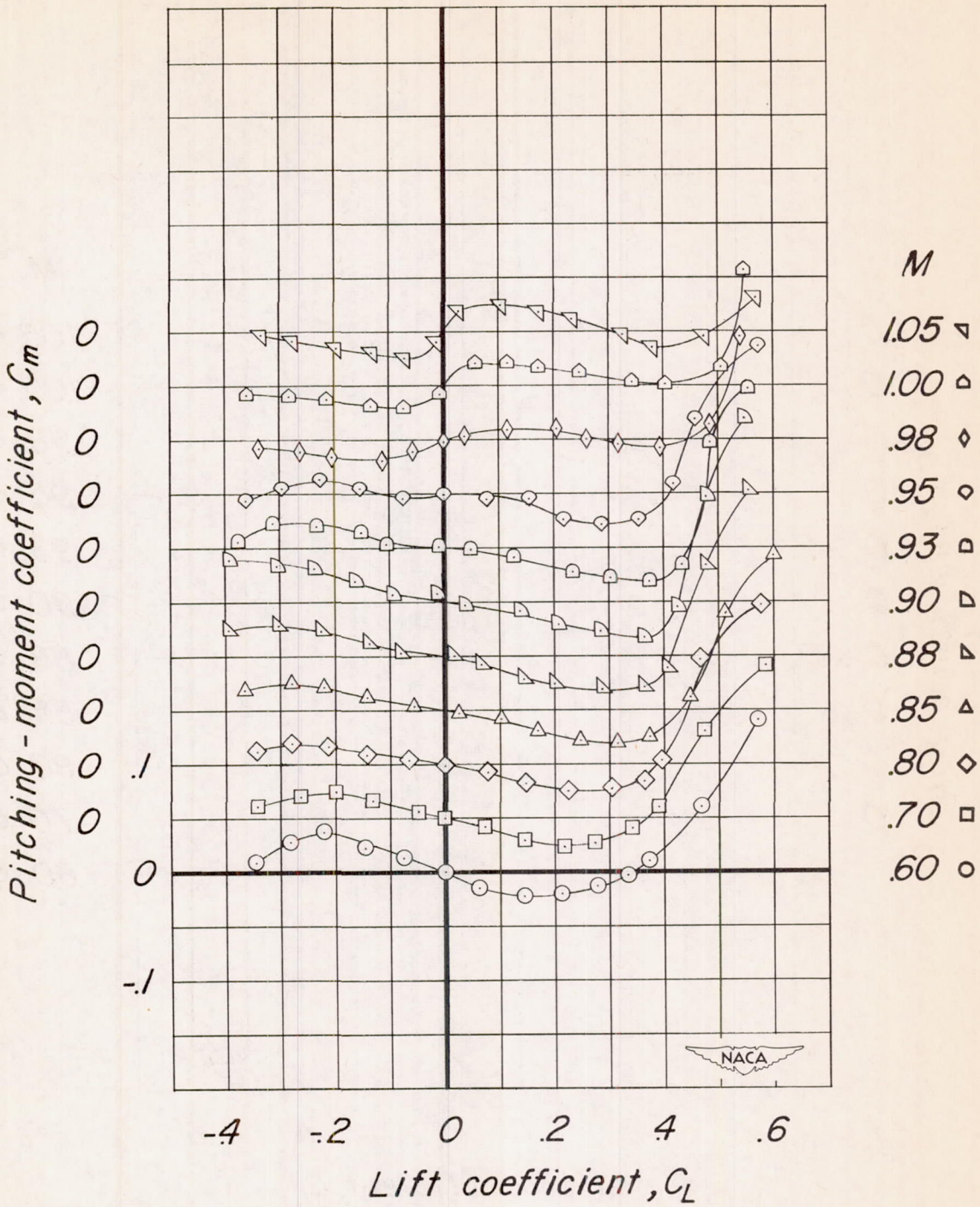

(a) α against $C_L$.

Figure 7.- Basic aerodynamic data for a wing having 45° of sweepback, aspect ratio 8, taper ratio 0.45, and NACA 63A010 airfoil section at root chord tapered to NACA 63A006 airfoil section at tip chord.



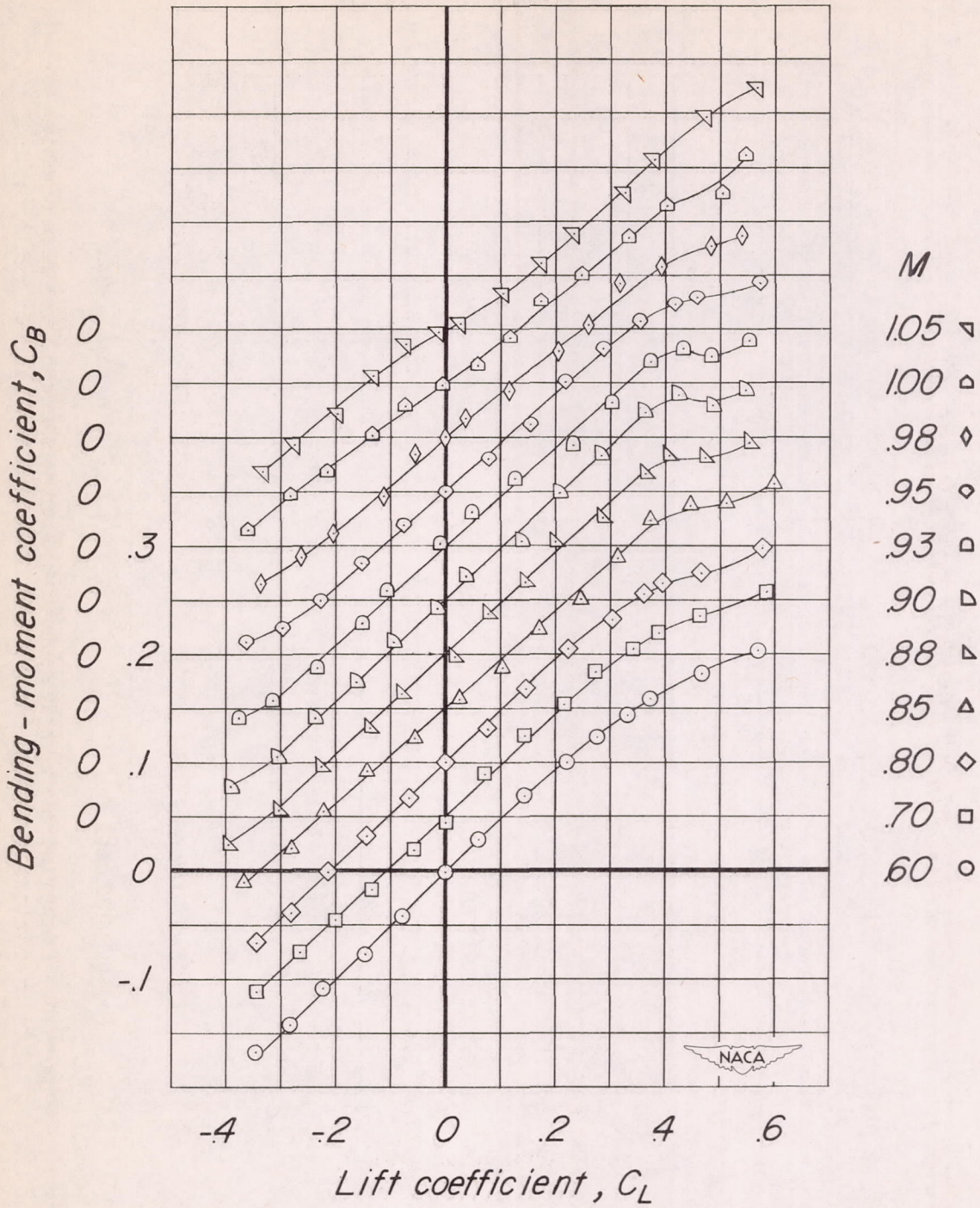

(b) $C_D$ against $C_L$.

Figure 7.- Continued.



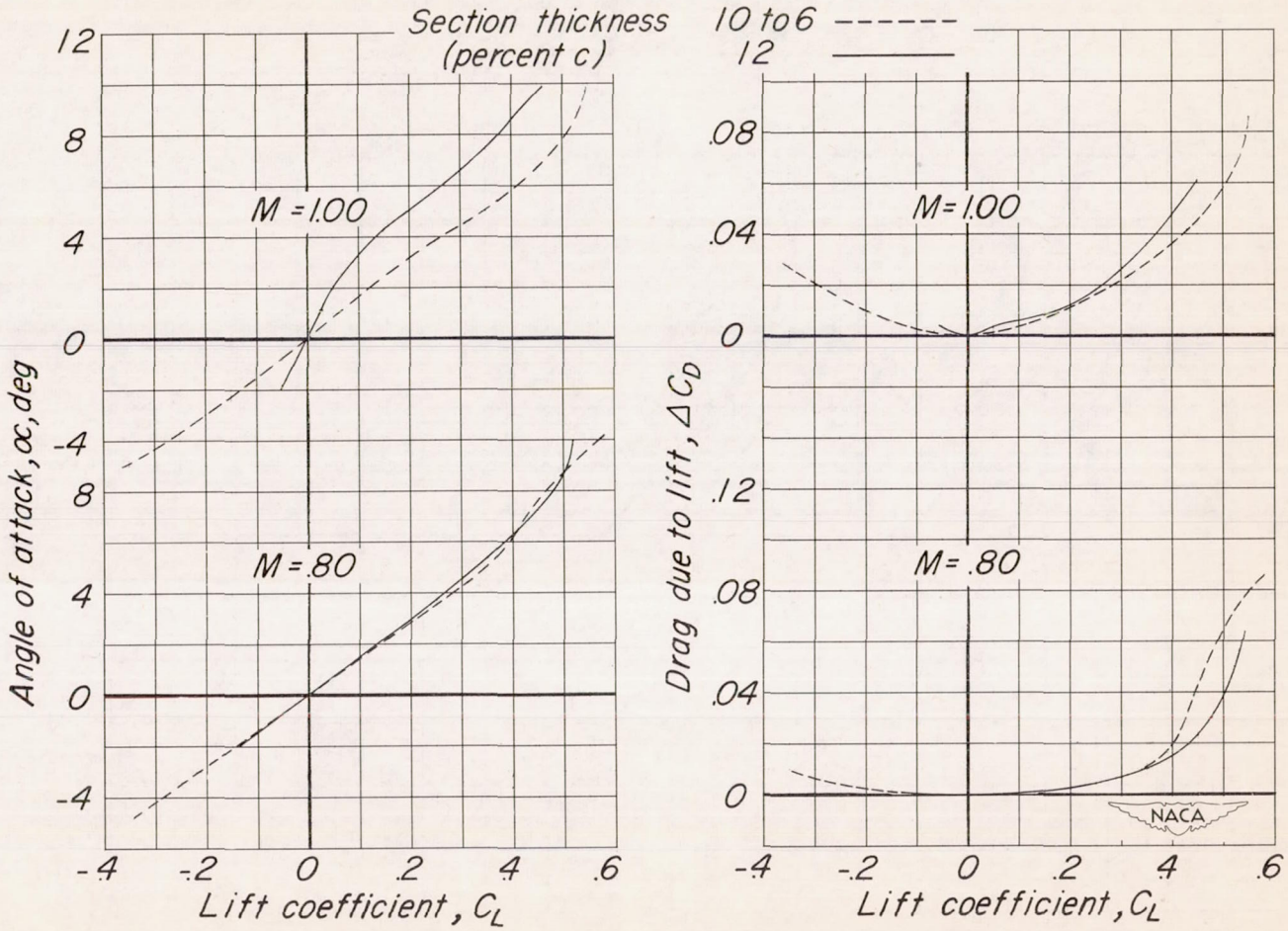

(c) $C_m$ against $C_L$.

Figure 7.- Continued.




(d) $C_B$ against $C_L$.

Figure 7.- Concluded.




(a) $\alpha$ against $C_L$.

(b) $\Delta C_D$ against $C_L$.

Figure 8.- Comparisons at representative Mach numbers of the aerodynamic characteristics of wings having 45° of sweepback, aspect ratio 8, and taper ratio 0.45.