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LIFT AND DRAG CHARACTERISTICS OF A WING WITH SEVERAL ANGLES OF SWEEP AT HIGH SUBSONIC SPEEDS

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To obtain detailed information on flow around swept and unswept wings at high subsonic speeds, very extensive pressure measurements have been made on and behind a thin, high-aspect-ratio wing with no sweep and with 30° and 45° of sweepback and sweepforward at Mach numbers from 0.60 to 0.96 in the Langley 8-foot high-speed tunnel. Measurements have been made with and without aileron deflections; and for unswept condition they have been made with and without spoilers, dive recovery flaps, and brakes. For the swept configurations measurements have been made with a midwing fuselage present, whereas for the unswept condition they have been made with and without the fuselage present.

The measurements have included static-pressure readings at chordwise rows of orifices at eight stations along the span of the wing and at one station on the fuselage, total pressure measurements at various vertical stations behind the wing, and measurements of the average and fluctuating downwash at the probable horizontal tail location. From these measurements the normal-force, drag, and moment coefficients, the spanwise and chordwise pressure and load distributions, and wake patterns have been obtained for the various configurations. The major portion of the results is now available in NACA classified publications (references 1 to 9). The remainder of the results will be made available in the near future.

Because of the limited amount of time available even a summary discussion of all the results obtained cannot be given. Instead, some of the more interesting published and unpublished results pertaining to the normal force and drag of the unswept and swept wing without aileron or spoiler deflections are discussed briefly in the present paper and some of the other results obtained with aileron deflections are presented in the paper entitled "Effects of Sweep on Controls. I - Effectiveness" by Lowry and Johnson. The present paper includes a brief discussion of some of the variations of the over-all normal-force and profile-drag coefficients with Mach number presented in reference 5, but will deal primarily with a discussion of the section lift and drag characteristics. These factors indicate where the most severe changes in lift and drag occur at high Mach numbers and how the lift and drag characteristics of a wing with a given amount of sweep may be improved. The discussion will be limited to results obtained for conditions which usually occur during level flight at high speeds, but the results presented indicate the general nature of the changes that occur for other conditions.

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The model used in this investigation without sweep or fuselage is shown in figure 1. The unswept wing has an NACA 65-210 section, an aspect ratio of 9.0, and a taper ratio of 0.4. The span of the model is 37.8; the mean chord is 4.2. The model was supported in the tunnel by a vertical steel plate as shown in figure 1. The model extended from both sides of the plate which completely spanned the tunnel and effectively produced two semicircular test sections. The advantages of such a support are described in reference 1.

Sweep was obtained by rotating the wing with respect to the support plate. Pressure measurements made on the tunnel wall indicate that the model on one side of the strut had little effect on the flow on the other side of the strut. A given over-all configuration represents, therefore, not a yawed model but sweptback and sweptforward semispan models. The semispan model with 30° of sweepback is shown in figure 2. The locations of the chordwise rows of pressure orifices are indicated in the same figure. The fuselage was placed in the midwing location. The tip was revised for each sweep to be parallel with the airstream. With these tips the aspect ratios of the wing with 30° and 45° of sweep were approximately 7.5 and 5, respectively. Sweep is based on the quarter-chord line.

With the model in place the tunnel choked at Mach numbers of 0.945, 0.975, and 0.985, approximately, for no sweep, 30°, and 45° of sweep, respectively. The data obtained at these choking Mach numbers are not applicable to the prediction of the wing characteristics in free air and these data are not presented. The data obtained at Mach numbers of 0.925 and 0.96 for the unswept and swept conditions, respectively, are affected to only a slight degree by choking tendencies, and pressure data obtained at these Mach numbers are presented. With the wake-survey support strut in place the tunnel choked at a Mach number of 0.89. Pressure measurements indicate that the tunnel choked at the support strut behind the model and this choking did not affect the field of flow at the model but merely limited the maximum test Mach number. Data obtained at this Mach number are, therefore, presented.

Presented in figure 3 are variations of the wing normal-force coefficients obtained from the pressure measurements with Mach number for the various sweeps at an angle of attack of 2°. The normal-force coefficient for the unswept wing started to decrease due to the onset of shock at a Mach number of approximately 0.75. The normal-force coefficients for the wing with 30° of sweepforward and sweepback started to decrease at a Mach number approximately 0.1 greater than the Mach number at which the coefficient for the wing with no sweep started to decrease. There are no losses in the normal-force coefficients for the wings with 45° of sweepforward and sweepback. Not only is the Mach number at which the normal-force coefficients decrease delayed

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for 30° of sweepforward and sweepback but more important the magnitude of the changes is reduced. The magnitude of the change for the swept-forward condition is less than that for the sweptback condition.

Part of these variations are due to changes in the aspect ratio. However, it is believed that the major portion of the changes is due to the effects of sweep. For the angle of attack for which data are presented, the normal-force coefficients are generally very nearly equal to the lift coefficients and it may be assumed that the variations of the normal-force coefficient with Mach number presented are the same as the variations of the lift coefficient with Mach number.

Presented in figure 4 are variations of the wing profile-drag coefficients obtained from the wake-survey measurements with Mach number for the various sweeps at an angle of attack of 2°. The wing profile-drag coefficient for the wing with no sweep increased rapidly due to the onset of shock at a Mach number of approximately 0.75. The wing profile-drag coefficient for the wing with 30° of sweepback increased rapidly at a Mach number approximately 0.08 greater than the Mach number at which the drag increase occurred on the wing with no sweep. The wing profile-drag coefficient for the wing with sweepforward started to increase gradually at approximately the same Mach number as that at which the rapid increase in drag coefficient occurred for the wing without sweep and increased abruptly at the Mach number at which the similar abrupt increase occurred for the wing with 30° of sweepback. The wing with 45° sweepback experienced no large increase in the profile-drag coefficient.

A comparison of the measured loss in normal-force coefficient and increase in profile-drag coefficient produced by the occurrence of shock for a sweep angle of 30° and an angle of attack of 2° with the changes predicted for the same condition by use of the characteristics of the unswept wing and the simple sweep theory is presented in figure 5. The measured changes are shown as heavy lines, the predicted as dashed lines. The measured loss in normal-force coefficient is almost exactly the same as the predicted loss. The measured increase in drag coefficients occurs initially at about the same Mach number as does the predicted increase but is more severe than the predicted increase. The agreement between the measured and predicted variations is much closer than any previous similar comparison has shown. The closer agreement is believed to be due to the relieving effect of the midwing fuselage on the flow around the root of the swept wing.

Presented in figure 6 are spanwise variations of the section normal-force and section profile-drag coefficients for the wing without sweep at an angle of attack of 2° at various Mach numbers, obtained from the pressure and wake measurements. Because of the asymmetrical, three-dimensional flow around the wing, the spanwise variations

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of section profile-drag coefficient obtained from wake measurements made behind the wing are not exactly the same as the actual spanwise variations of the coefficients at the wing. The variations for all sweeps are believed to be very nearly correct, however. The spanwise variation of section normal force at a Mach number of 0.6 is very nearly the same as that predicted by use of potential-flow theory. The section profile-drag coefficients for the various sections are very nearly the same value for a Mach number of 0.6.

When the Mach number is increased beyond the critical value, the normal-force coefficients for the various sections decrease and generally the section profile-drag coefficients increase. The increase in normal-force coefficient and the decrease in drag coefficient occur at higher Mach numbers and are much less severe for the sections near the tip and root, however. The delay in the Mach number at which the increase in drag coefficient occurs on the tip is so great that no drag increase occurs at this region up to the highest test Mach numbers.

The delays and reductions of the changes at the tip may be attributed to the three-dimensional flow around the tip. This flow reduces the induced velocities over the tip sections, thus increasing the Mach numbers at which severe shock occurs on these sections. Also, because of this flow the air is directed inward over the upper surface of the tip sections and the tip effectively has sweepforward. The delay and reductions of the changes at the root sections may be attributed to the relieving effect of the midwing fuselage.

Similar spanwise variations of the section normal-force coefficient and the section profile-drag coefficient for the wing with 30° of sweepforward for an angle of attack of 2° at various Mach numbers are presented in figure 7. The spanwise variation of section normal-force coefficient at a Mach number of 0.6 is very nearly the same as that predicted by use of potential-flow theory. The section profile-drag coefficients for the various sections are very nearly the same across the semispan. This spanwise uniformity of section profile-drag coefficient indicates that there is very little spanwise flow of air in the boundary layer on a sweptforward wing at the angle of attack for which these data are presented. When the Mach number is increased beyond a Mach number of 0.8, the section profile-drag coefficients for the root sections increase. The gradual increase in the over-all drag coefficient for the sweptforward wing, which occurs at approximately the same Mach number as shown in figure 4, may be attributed to this rise in the coefficients for the root. When the Mach number is increased up to the highest test value, the section profile-drag coefficients for the root sections become very large. The section profile-drag coefficients for the outboard sections rise only slightly, however. In fact, the increases in the section profile-drag coefficient with Mach number for these outboard sections are less than those predicted by use of the simple sweep theory. As a result, the abrupt increase in the over-all drag coefficient for the sweptforward wing, which occurs at a Mach number of approximately 0.85, may be attributed primarily to the increase in the section profile-drag coefficients at the root sections. There is no severe reduction in the section normal-force coefficients for the root sections associated with the increases in the section profile-drag coefficients for these sections. Similar early and severe changes in the section profile-drag coefficients at the wing-fuselage juncture occur with 45° of sweepforward.

Because of the severe separation of the flow near the wing-fuselage juncture associated with the large increases in drag at these sections, the wake behind this juncture is very large at the higher Mach numbers; and due to the large wake, the downwash at the probable tail location changes by very large amounts at relatively low Mach numbers in comparison with the Mach numbers at which the changes occur behind the wing with a similar amount of sweepback.

The reason for the early abrupt separation of the flow at the root sections is shown by the pressure measurements made on the surface of the wing. Presented in figure 8 are contour maps of the pressures measured on the upper surface of the wing with 30° of sweepforward for an angle of attack of 2° at a Mach number of 0.6. The solid lines show the lines of constant pressure coefficient; the dashed lines indicate the lines of peak pressure. The contours indicate very high negative pressures or high induced velocities at the leading edge of the root sections. Because of these high induced velocities, the critical Mach numbers for the root sections are much lower than the critical Mach numbers for the sections further outboard and it would be expected that severe shock would occur on the root sections and that the flow over these sections would separate at much lower Mach numbers than it would at the outboard sections.

The high negative pressures on the leading edge of the root sections may be attributed to the induced flow associated with sweptforward wings. It is believed that the pressure peaks may be reduced, and thus the critical Mach number and the Mach number at which shock occurs may be increased, by reshaping the fuselage and by washing out the root sections. Reshaping the fuselage alone would probably not completely eliminate the pressure peaks since the effect of such a reshaping would be local, while the pressure peaks extend over a considerable region of the wing leading edge.

Spanwise variations of the section normal-force coefficients and section profile-drag coefficients for the wing with 30° of sweepback for an angle of attack of 2° at several Mach numbers are presented in figure 9. The spanwise variation of section normal-force coefficient

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for a Mach number of 0.6 is again very nearly the same as that predicted by use of potential-flow theory. The section profile-drag coefficients are very nearly the same for each of the sections along the semispan. When the Mach number is increased from 0.6 to the highest test value, the various sections experience reductions in the normal-force coefficients and increases in the profile-drag coefficients as would be expected. The reductions in the normal-force coefficients and the increases in the profile-drag coefficients occur at lower Mach numbers and are much more severe at the outboard sections than at the inboard sections. The increases in the profile-drag coefficient for the tip sections are so severe that at the highest test Mach number, a Mach number of 0.89, the section profile-drag coefficient for these sections for the sweptback wing are greater than those for the tip sections of the unswept wing. Near the wing-fuselage juncture the drag coefficients measured at the highest test Mach number are the same as those measured at a Mach number of 0.6. These data indicate spanwise variations of the changes in the section characteristics associated with the onset of shock which are exactly opposite to those which were thought to occur on sweptback wings. Instead of the initial and most severe changes occurring at the root, they occur at the tip.

With 45° of sweepback, the spanwise variations of section normal-force and section profile-drag coefficients are nearly the same for all Mach numbers up to the highest test value. However, the wake measurements made behind this wing at a Mach number of 0.89 indicate a slight initial increase in the drag coefficients for the tip sections.

The early and severe changes in the characteristics of the tip sections may be attributed to three factors: Lower critical Mach numbers for the tip sections, the distribution of pressures on the tip sections, and the inflow over the upper surface of the tip section. The contour map of the pressure coefficients for the upper surface of the wing with 30° of sweepback for an angle of attack of 2° at a Mach number of 0.6 is presented in figure 10. Because of the relieving effect of the fuselage, the maximum pressure coefficients at the root sections are less than the maximum pressure coefficients for the sections further outboard. Due to the induced flow, peculiar to sweptback wings, pressure peaks occur on the leading edge of the sections near the tip. As a result of this spanwise variation in peak pressures, the critical Mach numbers for the tip sections are less than those for the root sections. Near the tip the distribution of pressure is changed in such a manner that the region of maximum pressure coefficients slopes forward with respect to the swept span of the wing. Assuming that shock occurs initially in the region of maximum pressure coefficients it may be deducted that the effective sweep of the tip sections is less than the geometric sweep of the wing. Because of the flow around the tip, the flow over the upper surface of the tip sections is directly

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inward and the effective sweepback of the tip sections is further reduced. Each of these factors would lead to earlier and more severe separation and changes in the section normal-force coefficients and section profile-drag coefficients near the tip.

None of the previously mentioned factors explains the extraordinary delay in the increases of section profile-drag coefficients for the root sections. The contour map of the pressures measured on the upper surface of the wing with 30° of sweepback for an angle of attack of 2° at a Mach number of 0.89 (fig. 11) indicates the probable reason for this delay. At this Mach number, there is a severe shock along the entire semispan of the wing as indicated by the very severe adverse pressure gradient near the trailing edge. This shock appears to be normal to the stream and very near the trailing edge at the wing-fuselage juncture. It would be expected that such a strong normal shock would lead to severe separation at the wing-fuselage juncture. The pressure recovery behind the shock indicates, however, that very little separation is produced by the shock.

Since the initial and most severe changes in the section characteristics occur at the tip, it might be expected that the changes in the over-all normal-force and profile-drag coefficient for the wing with sweepback could be delayed and perhaps reduced by washing out the tip sections to reduce the angle of attack of these sections which experience the most severe changes. No data have been obtained to show the effects of washout on the changes in the normal-force and profile-drag coefficients; however, pressure data have been obtained on the wing of the present discussion with aileron deflection of −5° which should simulate to a certain extent a washout condition. The normal-force results obtained with this aileron deflection indicate that a definite reduction in the changes of the normal-force coefficient with Mach number for the wing with 30° of sweepback is produced by such a deflection. Washout applied to the wing to improve the high-speed characteristics would also probably improve the landing characteristics of the wing but might produce adverse changes in the lateral stability and control characteristics of the wing.

The results of detailed pressure measurements made on and behind a high-aspect-ratio wing with and without sweep at high subsonic Mach numbers indicate that the initial and most severe changes in the normal-force and profile-drag characteristics occur at the tip for sweptback wings and at the root for sweptforward wings. The results also indicate means of improving the high-speed normal-force and profile-drag characteristics of a wing with a given amount of sweep.

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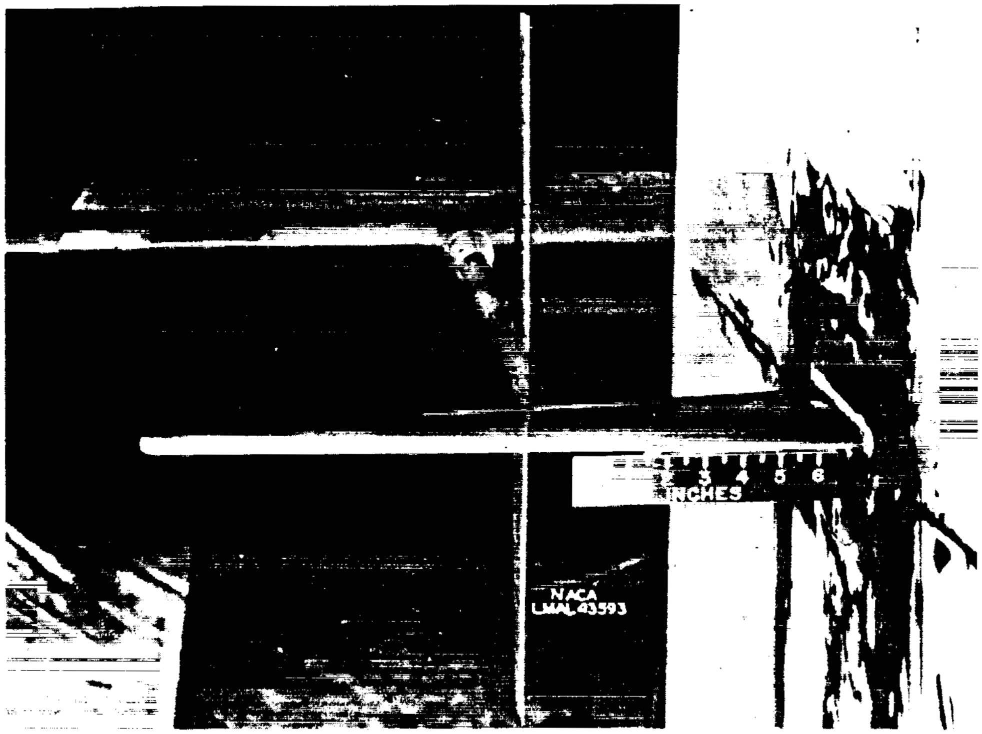

Figure 1.- Photographs of unswept wing without fuselage.

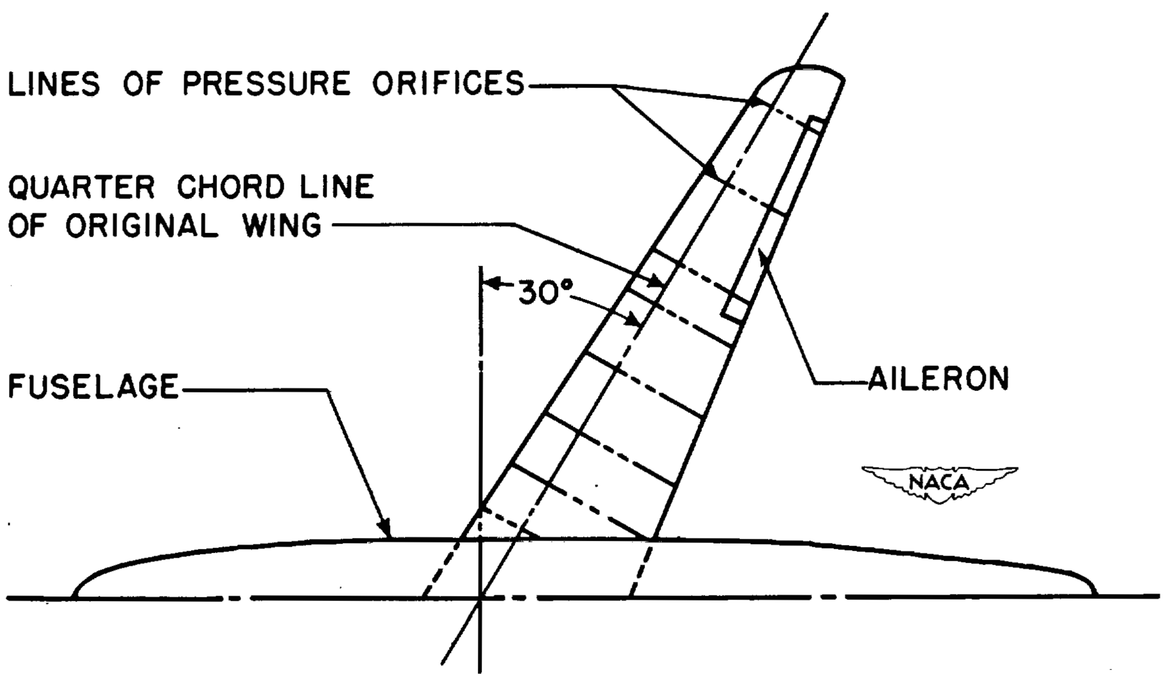

Figure 2.- Plan view of wing with 30° of sweepback.

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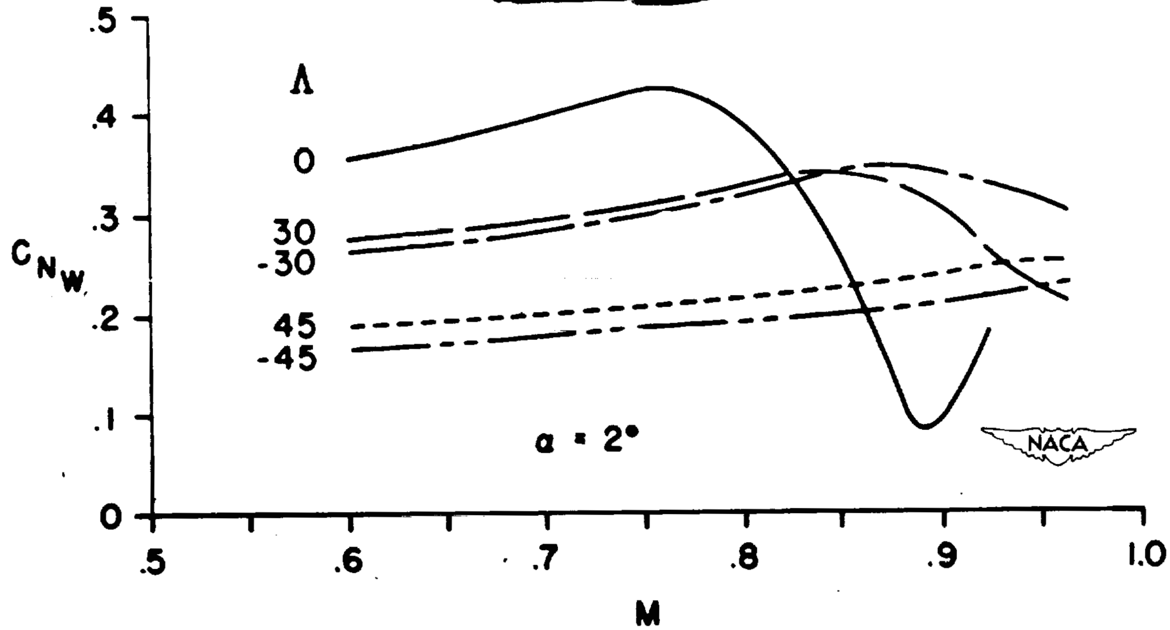

Figure 3.- Variations of wing normal-force coefficient with Mach number for $\alpha = 2^{\circ}$.

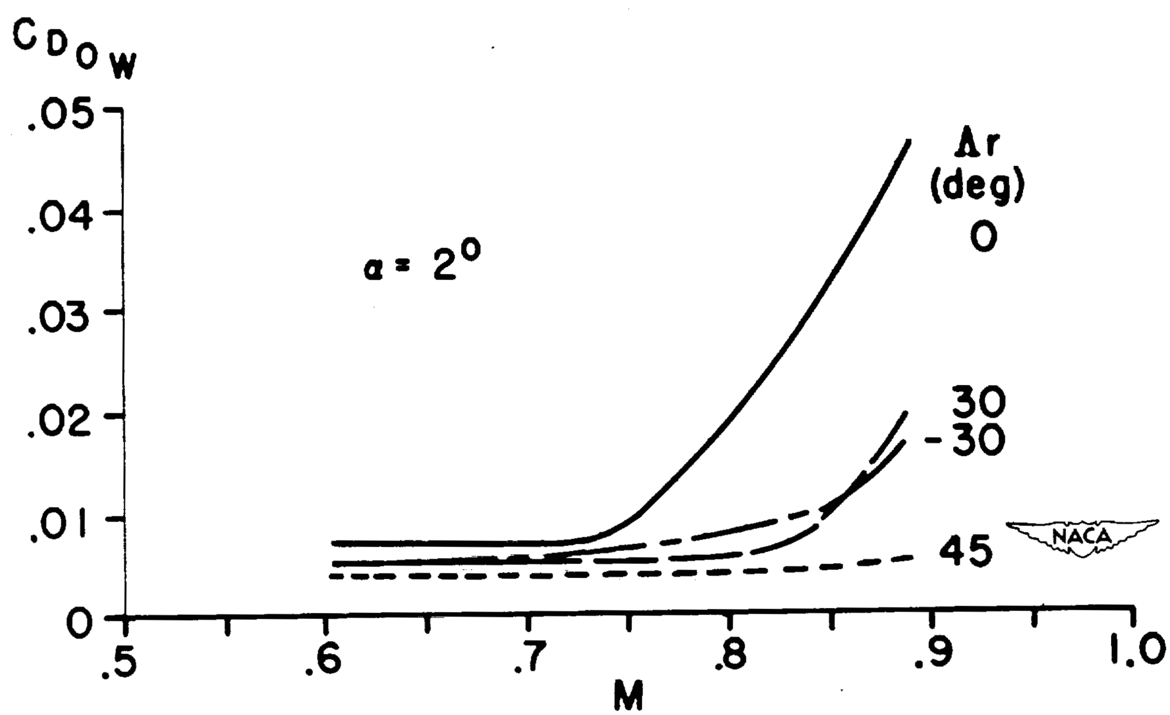

Figure 4.- Variations of wing profile-drag coefficient with Mach number for $\alpha = 2^{\circ}$.

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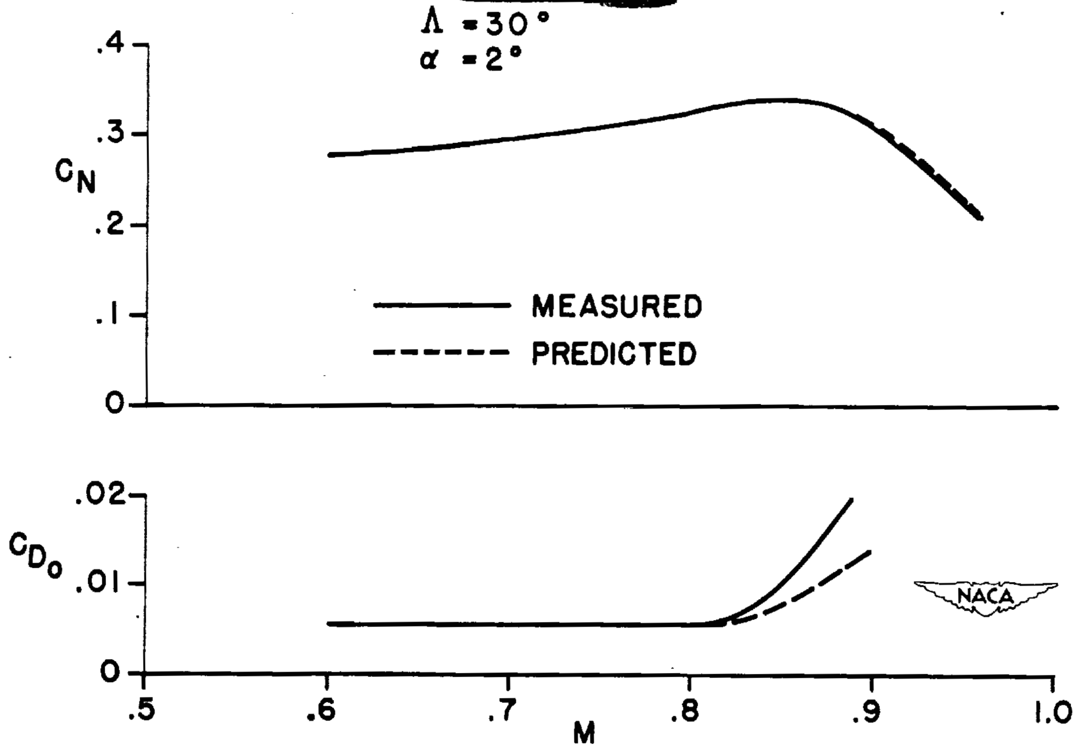

Figure 5.- Comparisons of measured and predicted variations of wing normal-force coefficient and wing profile-drag coefficient with Mach number for $\Lambda = 30^{\circ}$.

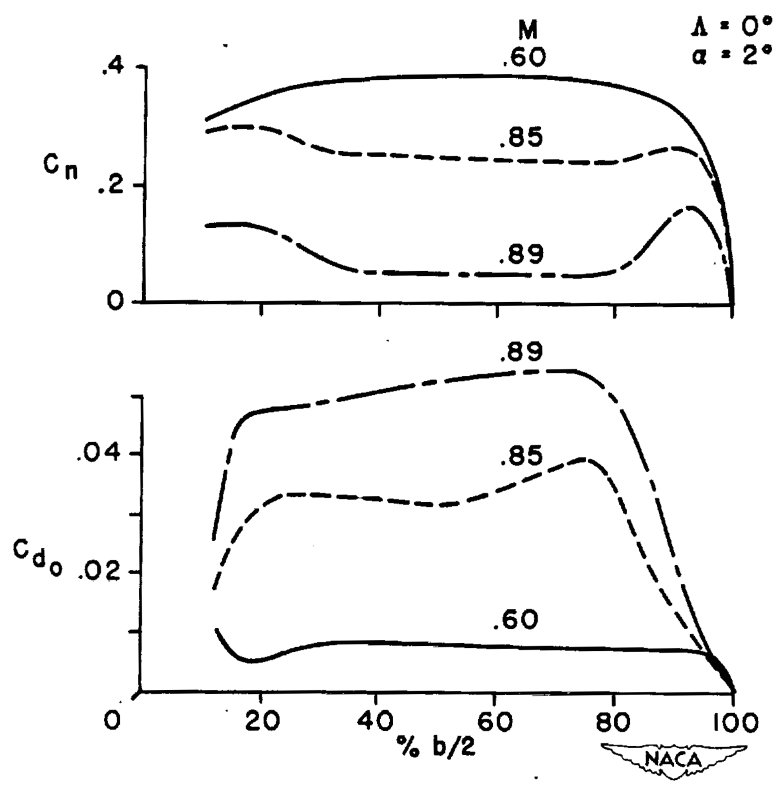

Figure 6.- Spanwise variations of section normal-force coefficient and section profile-drag coefficient for $\Lambda = 0^{\circ}$ and $\alpha = 2^{\circ}$.

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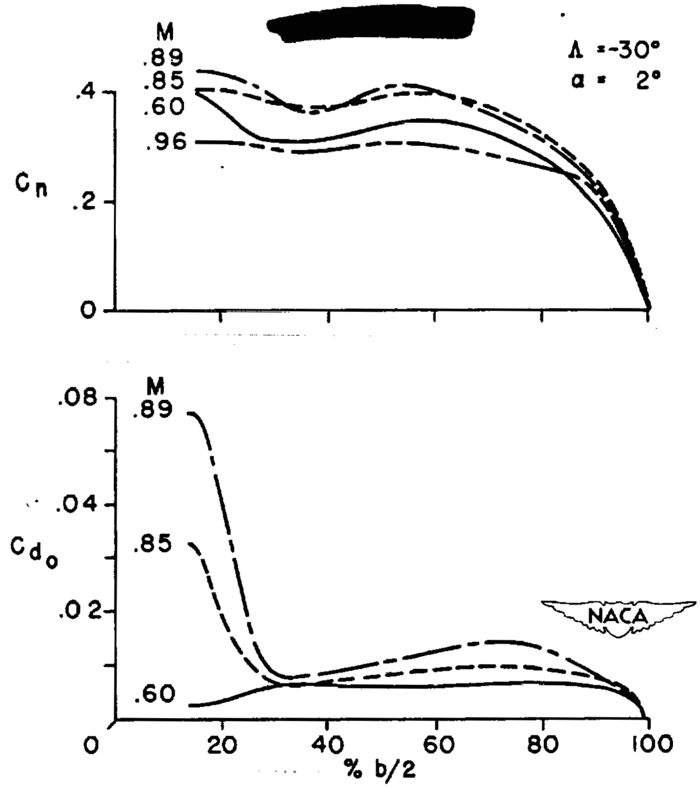

Figure 7.- Spanwise variations of section normal-force coefficient and section profile-drag coefficient for Λ = -30° and α = 2°.

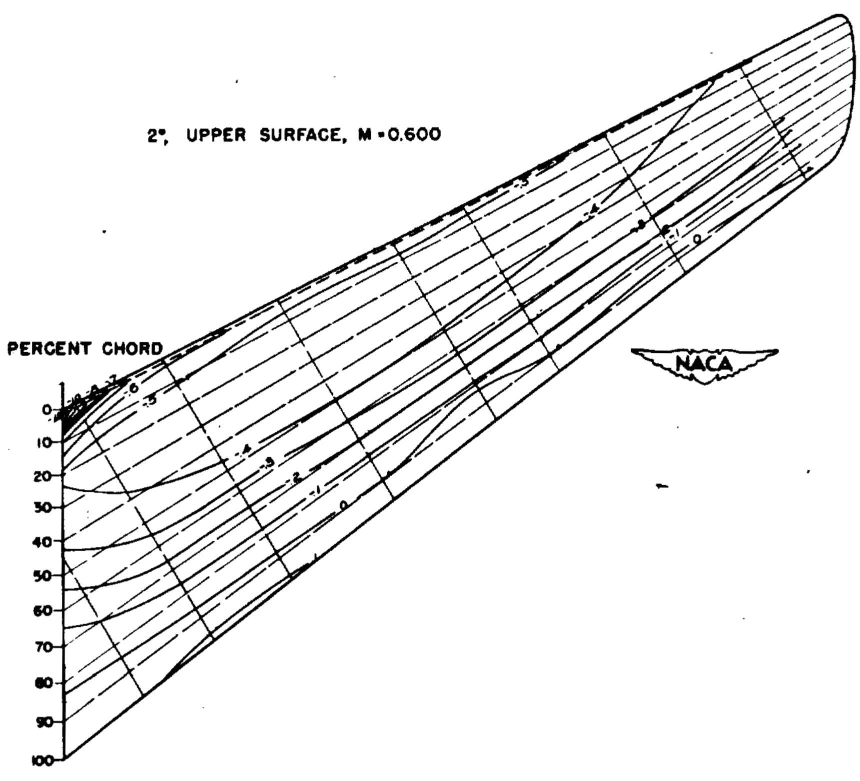

Figure 8.- Equal pressure-coefficient contours for Λ = -30°, α = 2°, and M = 0.60.

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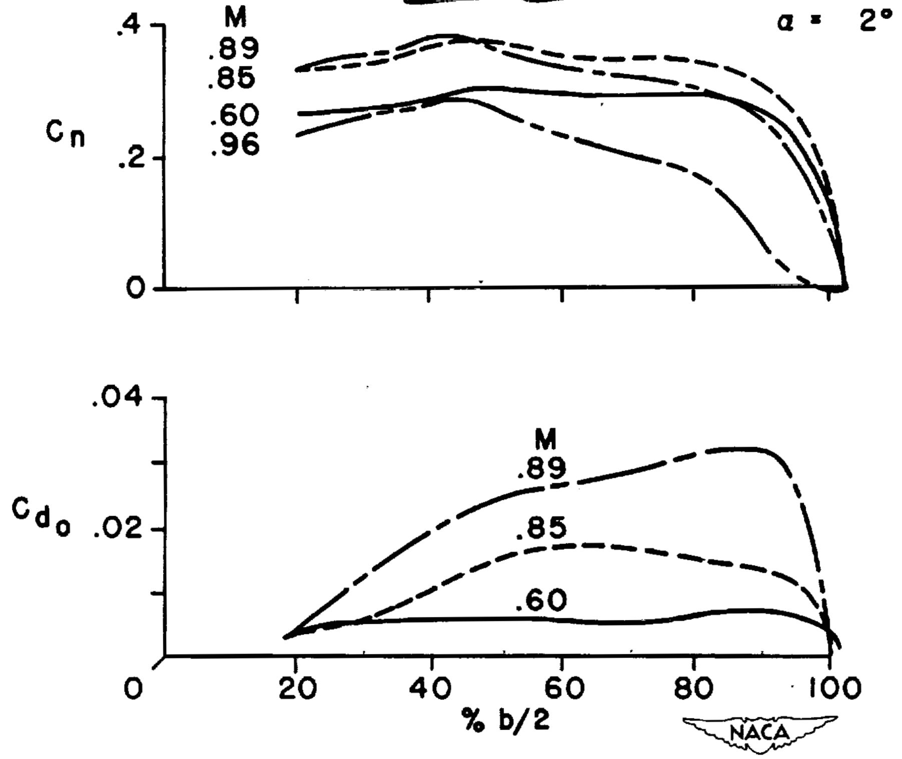

Figure 9.- Spanwise variations of section normal-force coefficient and section profile-drag coefficient for $\Lambda = 30^\circ$ and $\alpha = 2^\circ$.

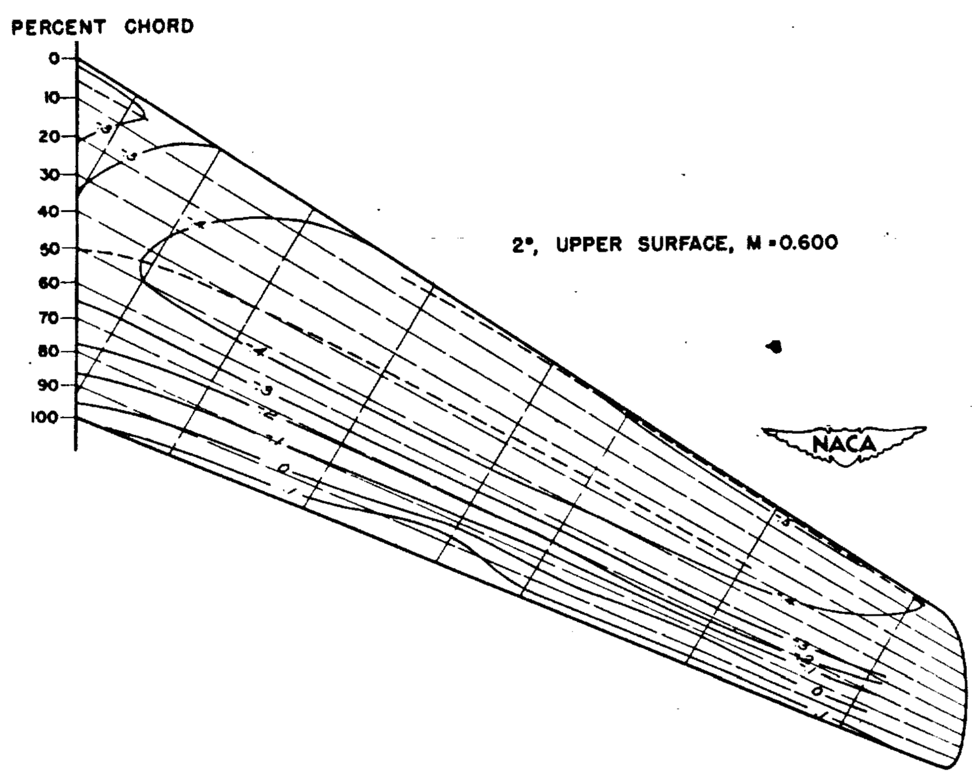

Figure 10.- Equal pressure-coefficient contours for $\Lambda = 30^\circ$, $\alpha = 2^\circ$, and $M = 0.60$.

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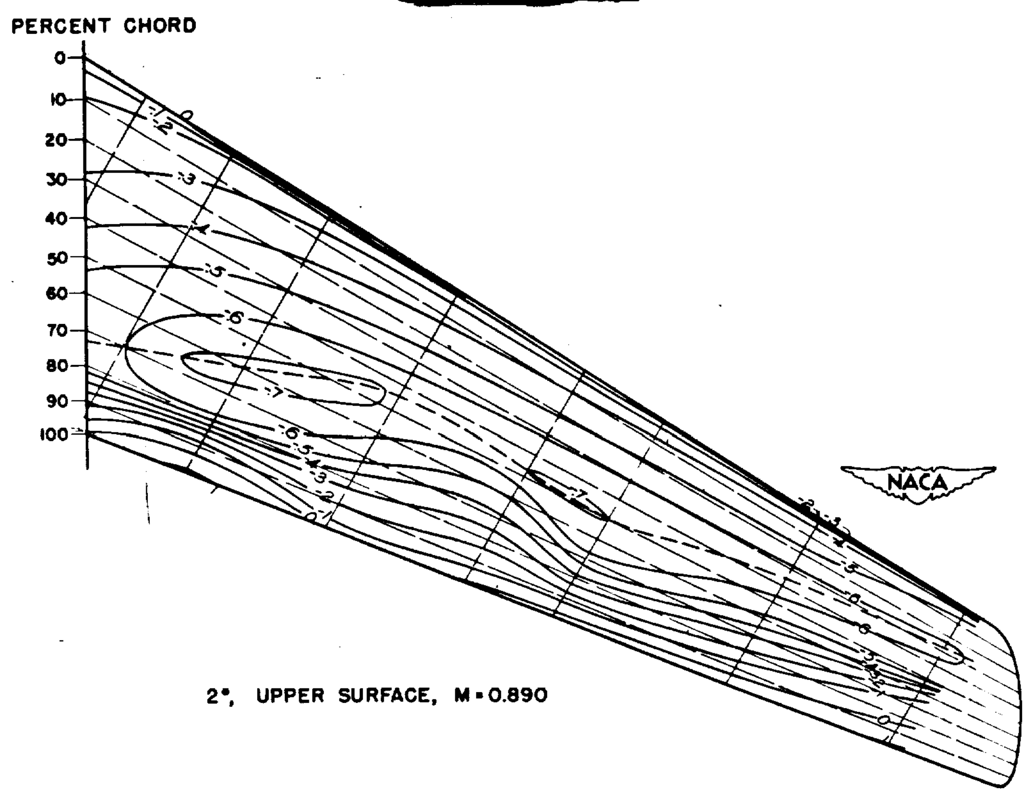

Figure 11.- Equal pressure-coefficient contours for $\Lambda = 30^{\circ}$, $\alpha = 2^{\circ}$, and $M = 0.89$.

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