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HIGH-SPEED WIND-TUNNEL TESTS OF THE NACA 23012 AND 23012-64 AIRFOILS

By John V. Becker

SUMMARY

Force tests of the NACA 23012 and 23012-64 airfoils of 24-inch chord were made in the 8-foot high-speed wind tunnel at Mach numbers ranging from 0.10 to 0.75. Supplementary tests of a 5-inch-chord NACA 23012 airfoil were made in the 24-inch high-speed tunnel to obtain pitching-moment data at higher loadings than could be attained with the 8-foot tunnel models.

The results, which were corrected as far as possible for tunnel-wall effects, show the variation with Mach number of lift, drag, and pitching-moment coefficients at angles of attack from -4° to 6°. At positive lifts the NACA 23012-64 airfoil had slightly higher critical speeds than the NACA 23012 airfoil. At the higher angles of attack in the supercritical speed region, large increases in the magnitude of the pitching-moment coefficient occurred.

INTRODUCTION

Force tests of 24-inch-chord NACA 23012 and 23012-64 airfoils were made in the 8-foot high-speed wind tunnel in 1937. The results were not published owing to a lack of knowledge of the tunnel-wall interference effects on large models extending through the tunnel walls. Since that time a separate investigation (unpublished) has indicated the nature of these effects and has established corrections for some of them. Although all corrections affecting the absolute magnitude of the results are not known, the corrections that vary with speed are believed to be fairly well understood. The corrected results may therefore be considered adequate for indicating the principal effects of compressibility. In view of numerous requests for compressibility-effect data on the NACA 230 series of airfoils, it has been decided to issue these partly corrected results with a clear statement of their limitations.

In order to obtain data applicable to the high-speed dive pull-out condition it was necessary to make supplementary tests on a 5-inch-chord NACA 23012 airfoil in the 24-inch high-speed wind tunnel. These tests were made in 1940.

APPARATUS

The 8-foot and the 24-inch high-speed wind tunnels are described in references 1 and 2, respectively.

A description of the NACA 230 series of airfoil sections is given in reference 3. The profile ordinates of the NACA 23012 and 23012-64 sections are shown in table I.

The 24-inch-chord models were constructed of wood and sheathed with 1/16-inch steel plate to prevent erosion at high speeds. The NACA 23012 airfoil was completely covered with the metal plate. The NACA 23012-64 airfoil was covered over only the forward 31 percent; the remaining surface was spray-painted. The surfaces were made aerodynamically smooth. It was impossible, however, to eliminate slight waves in the metal sheathing at the points of attachment to the wood. It is also considered possible that the spanwise wood-metal junctures on the NACA 23012-64 model may have sprung slightly at the higher loadings. This method of airfoil construction has been found to be generally unsatisfactory.

The 5-inch-chord NACA 23012 model tested in the 24-inch tunnel was made from solid duralumin and was both aerodynamically smooth and fair.

In both wind tunnels the models completely spanned the jet and passed through the walls to the balance attachments (fig. 1). The gap between the models and the wall was not uniform and varied slightly with angle of attack. Average values for the width of the gap are 3/16 inch and 7/64 inch for the 8-foot and the 24-inch tunnels, respectively. As shown in figure 1, the 8-foot tunnel has flat surfaces on either side. Flat circular rotating end plates attached to the tunnel walls move with the airfoil when the angle of attack is changed. In the 24-inch tunnel, flexible brass end plates that preserve the circular section of the tunnel were used.

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TESTS

The tests consisted of the measurement of lift, drag, and pitching moment. At constant angles of attack (α) the speed was increased as far as possible, the highest speed attained at a given angle being limited either by the maximum allowable load (in the case of the models of 24-inch chord) or by the maximum attainable tunnel speed. Angles of attack ranging from -4° to 6° were covered. The 24-inch-chord models were also tested through the stall at speeds ranging from 75 to 170 miles per hour to permit comparison with variable-density-tunnel results obtained at the same test Reynolds numbers.

As a check of the critical speed indicated by the force test at $\alpha = 0^{\circ}$, the variation with Mach number of the total pressure at a point 1/8 inch above the surface at the 75-percent-chord station of the 5-inch-chord model was measured.

TUNNEL-WALL EFFECTS

Constriction effect.- The use of models of large size relative to the tunnel diameter results in a jet velocity at the airfoil appreciably higher than would exist if the flow were not restrained by the tunnel walls. The magnitude of this effect was determined in a separate investigation of tunnel-wall effects on NACA 0012 airfoils in the 8-foot tunnel by comparing the chordwise static-pressure distribution with the distribution given by potential theory, which had been verified in tests in the full-scale tunnel. In addition, a spanwise static-pressure survey at the 10-percent-chord location was made at various lift coefficients. It was found that, within the limits of accuracy required for engineering purposes, the wing could be assumed to be operating in a uniform air stream with a velocity greater than that indicated by the standard tunnel calibration.

At low Mach numbers the magnitude of this constriction effect agreed satisfactorily with the results computed by Glauert (reference 4) for incompressible flow. The effect increases with Mach number. The air speed, V, the Mach number, M, the Reynolds number, R, and the dynamic pressure, q, obtained from the standard tunnel calibration in the present tests were corrected by use of the

factors determined from the tests of the NACA 0012 airfoils. The force and the pitching-moment coefficients employed in presenting the results are based on the corrected dynamic pressure, $\frac{1}{2}\rho V^2$, where the values of ρ and V are corrected for the constriction effect.

Induced curvature of the flow.- As a further consequence of the employment of airfoils of large ratio of the airfoil chord to the average depth of the tunnel, c/h, it is shown in reference 4 that the lift and the pitching-moment coefficients are different from the corresponding values for unrestricted two-dimensional flow. This effect results from an induced curvature of the flow. The validity of the theoretical correction factors derived in reference 4 was satisfactorily established by the previously mentioned unpublished tunnel-wall-effect investigation in the 8-foot high-speed tunnel by comparing the results obtained on 15-inch-chord and the 60-inch-chord NACA 0012 airfoils. The correction to the lift is given by

$$\frac{C_L}{C_{L_t}} = 1 - \frac{\pi^2}{24}\left(\frac{c}{h}\right)^2$$

where C_L is the lift coefficient and the subscript t refers to tunnel values. The pitching-moment correction is obtained from

$$C_{m_{c/4}} = \left(C_{m_{c/4}}\right)_t + \frac{\pi^2}{192}\left(\frac{c}{h}\right)^2 C_{L_t}$$

The results presented in this report have been corrected according to these relations.

End leakage effects.- The force-test results corrected for the constriction and the induced-curvature effects would be expected to exhibit infinite-aspect-ratio or section characteristics were it not for the interference effects at either side of the model that result mainly from the leakage of air through the clearance space between the model and the tunnel wall. In order to indicate the approximate magnitude of these effects, the results of the NACA 23012 airfoil for $M = 0.23$ are compared in figure 2 with corrected section characteristics obtained from tests in the variable-density tunnel (reference 5) at about the same test Reynolds number. The low-speed section

lift and the pitching-moment coefficients of the variable-density tunnel were multiplied by the factor $(1 - M^2)^{-\frac{1}{2}}$ (see reference 2) to obtain results appropriate to the Mach number at which the 8-foot high-speed tunnel tests were run. The value of this factor was 1.027, corresponding to the Mach number 0.23 of the high-speed tunnel tests.

It is evident from figure 2 that the lift and the pitching-moment values are inappreciably affected by the end-leakage effects at angles of attack below 8°. The drag, however, was greatly increased. At angles of attack higher than 8° an abrupt breakdown of the flow occurred, apparently as a result of the end leakage. This effect was found to occur at an angle of attack of 8° for various Mach numbers ranging from 0.10 to 0.23, the highest speed at which angles greater than 8° were attained. Similar results were obtained with the NACA 23012-64 airfoil. On account of the large magnitude of this effect and the lack of understanding of the factors involved, the data presented in this report extend only to an angle of attack of 6°. In this range the corrected lift and the pitching-moment values may be taken as approximate section characteristics, but the drag coefficients include large unknown increments due to end interference.

The investigation of tunnel-wall effect of the NACA 0012 airfoil included a number of runs through the speed range with various end-gap clearances. It was found that, although the absolute magnitude of the drag coefficient increased with gap size, the variation with Mach number was essentially the same for all gap sizes. It may be assumed, therefore, that the results for any gap size are useful in showing changes with Mach number of the drag coefficient.

RESULTS AND DISCUSSION

Drag.- The variation with Mach number of the drag coefficients obtained with the 24-inch-chord models is shown in figure 3. The cause of the large drag increases at the higher Mach numbers is due to the formation of a compression shock at critical air speeds at which the velocity of sound is attained locally on the airfoil. Detailed discussion of this phenomenon is given in reference 2. Briefly, the critical air speed is dependent on any factor that affects the peak local velocity, particularly the angle of attack, the thickness, the thickness distribution, and the camber.

The NACA 23012-64 airfoil (fig. 3(b)) was included in this investigation on the basis of previous tests of symmetrical airfoils (reference 6), which indicated that the 40-percent-chord location of the maximum-thickness station resulted in a higher critical speed than the other distributions tested. A more rational method of prediction of critical speed characteristics based on static-pressure-distribution data is discussed in reference 7. Some increase in critical speed over the NACA 23012 airfoil is indicated for the NACA 23012-64 airfoil at positive lifts. At negative lifts, however, the NACA 23012-64 airfoil develops higher local velocities near the nose on the lower surface than the NACA 23012 and should, therefore, have the lower critical speed. The critical speeds estimated from reference 7 are indicated in figure 3 by arrowheads. It is seen that the Mach numbers at which the drag coefficients begin to increase rapidly agree reasonably well with the predictions based on the pressure-distribution data. The critical speeds indicated by the 5-inch-chord force-test results (not shown) agreed satisfactorily with the 24-inch-chord results. The total-pressure tube located at the 75-percent-chord station of the NACA 23012 airfoil showed rapidly increasing losses at Mach numbers above 0.645. The critical Mach number predicted from the static-pressure data at $\alpha = 0^{\circ}$ was 0.66.

The variation with Mach number of the drag coefficient at subcritical speeds is a consequence of both scale and compressibility effects. On smooth models in air streams of low turbulence such as that of the 8-foot high-speed wind tunnel, the variation with Reynolds number of the location of boundary-layer transition is an important factor in determining the scale effect and should be considered in any attempt to isolate the compressibility effect at subcritical speeds. Data on the transition-point locations on both surfaces of the NACA 23012 airfoil in the 8-foot high-speed tunnel are available in reference 8.

Lift.- The variation with Mach number of the lift coefficients obtained in the 8-foot high-speed tunnel is shown in figure 4. The rate of increase with Mach number at subcritical speeds was somewhat greater than the factor $(1 - M^2)^{-\frac{1}{2}}$ usually used to estimate the increase. This factor strictly applies only to airfoils of very small thickness-chord ratios and would be expected to underestimate the actual rate of lift increase on 12-percent-thick airfoils. The rate of increase of lift coefficient with

Mach number shown in references 2 and 6 for 5-inch and 2-inch-chord models was less than noted in the present tests and more nearly agreed with the $(1 - M^2)^{-\frac{1}{2}}$ factor. These differences may be attributable to the fact that the Reynolds numbers in the present investigation were much greater than in the reference tests.

The changes in lift coefficient that occur at supercritical speeds depend on the location and the intensity of the compression shock. Either an increase or a decrease in lift coefficient, corresponding to formation of the shock on the lower or the upper surfaces, might be expected. At small angles of attack where shocks form on both upper and lower surfaces at about the same Mach number, no appreciable lift changes might be anticipated. This situation evidently existed for the airfoils tested at 0° and -1° angle of attack (fig. 4). At the higher angles of attack the shock forms near the nose on the upper surface and a loss of lift coefficient (fig. 4(a), $\alpha = 6^\circ$) is usually noted. (See references 2 and 7.) The decreases in lift coefficient generally start to occur at Mach numbers about 0.05 to 0.10 beyond the estimated critical speeds. The lift-coefficient decreases, in most cases, are not large enough to cause actual decreases in lift with increasing speed. Changes in lift distribution across the wing span due to possible variations in critical speed along the span should, however, be considered in structural design.

Pitching moment.- The NACA 23012 pitching-moment coefficients obtained in both wind tunnels are shown in figure 5(a). For the angles of attack at which direct comparison is possible (0° and 4°), a satisfactory agreement between the results for the two tunnels will be noted. The NACA 23012-64 results are given in figure 5(b).

The variation in pitching-moment coefficient at subcritical speeds was negligibly small for these low-moment airfoils.

Changes in pitching-moment coefficient occurring at supercritical speeds are governed by the same factors that affect the lift, that is, the location and the intensity of the compression shock. At the higher angles of attack, large increases in the negative value of the pitching-moment coefficient occurred. These increased pitching-moment coefficients could be realized in flight

in pull-outs from high-speed dives and should be accounted for in the structural design of pursuit aircraft.

CONCLUDING REMARKS

The critical speeds at which large increases in drag coefficient occurred were slightly higher for the NACA 23012-64 airfoil than for the NACA 23012 airfoil, when compared either at a given angle of attack or at a given lift coefficient in the positive lift region. At zero and negative lifts, the NACA 23012 airfoil has the higher critical speeds. The indicated critical speeds were in fair agreement with those predicted from the theoretical pressure peaks.

At the higher angles of attack in the supercritical region (conditions corresponding to a sharp pull-out from a high-speed dive), large increases in the pitching-moment coefficient and a decrease in lift coefficient occurred.

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TABLE I - AIRFOIL ORDINATES

[Stations and ordinates in percent of wing chord]

Station	NACA 23012		NACA 23012-64	
	Upper surface	Lower surface	Upper surface	Lower surface
0	---------	---------	---------	0
1.25	2.67	-1.23	2.53	-1.20
2.5	3.61	-1.71	3.41	-1.61
5	4.91	-2.25	4.59	-2.00
7.5	5.80	-2.61	5.41	-2.27
10	6.43	-2.92	6.00	-2.50
15	7.19	-3.50	6.70	-3.02
20	7.50	-3.97	7.04	-3.55
25	7.60	-4.28	7.23	-3.96
30	7.55	-4.46	7.37	-4.29
40	7.14	-4.48	7.32	-4.66
50	6.41	-4.17	6.93	-4.70
60	5.47	-3.67	6.21	-4.42
70	4.36	-3.00	5.17	-3.79
80	3.08	-2.16	3.78	-2.86
90	1.68	-1.23	2.09	-1.63
95	.92	-.70	1.15	-.90
100	.13	-.13	.12	-.12

Leading edge radius: 1.58. Slope of radius through end of chord: 0.305

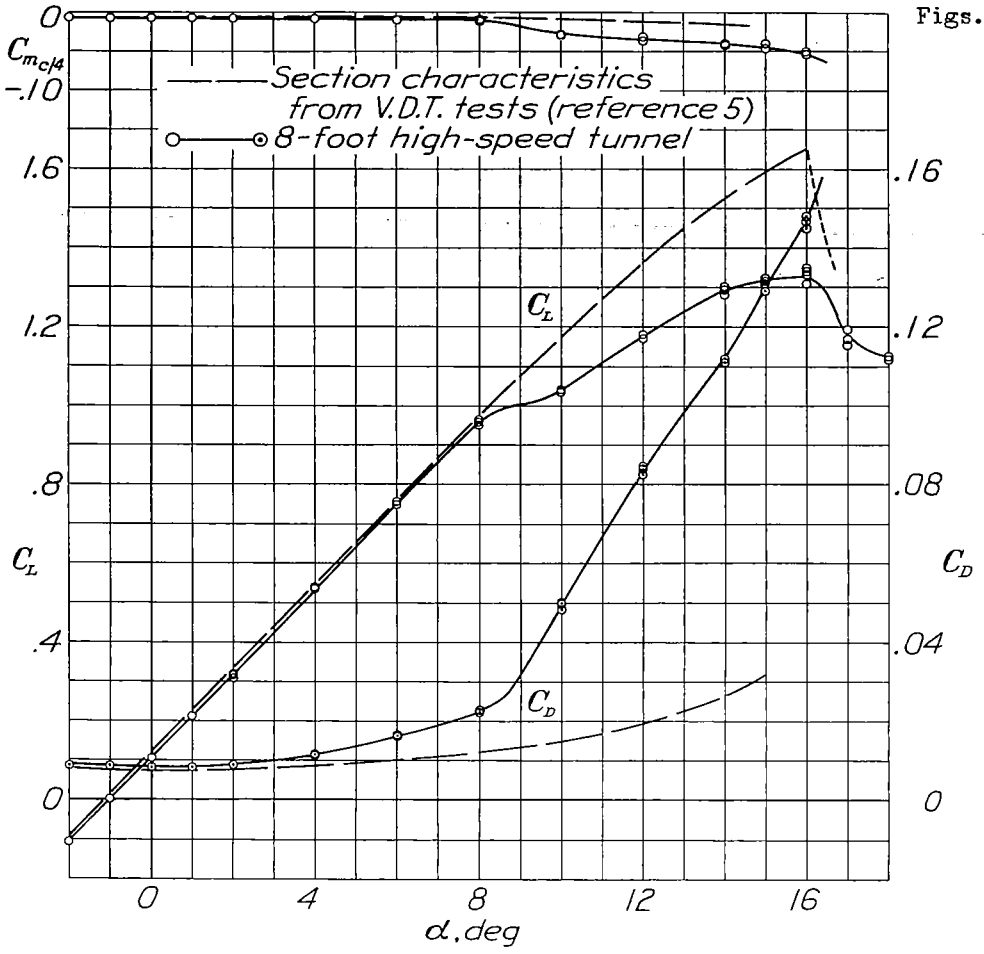


Figure 2.- Comparison of results from the 8-foot high-speed and variable-density wind-tunnels to show magnitude of interference effect due to end leakage in 8-foot high-speed tunnel. M , 0.23 ; R , 3.150,000. NACA 23012 airfoil.

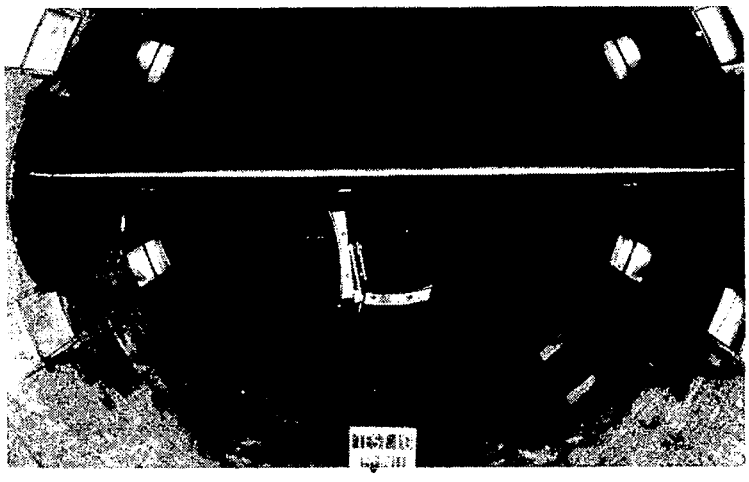
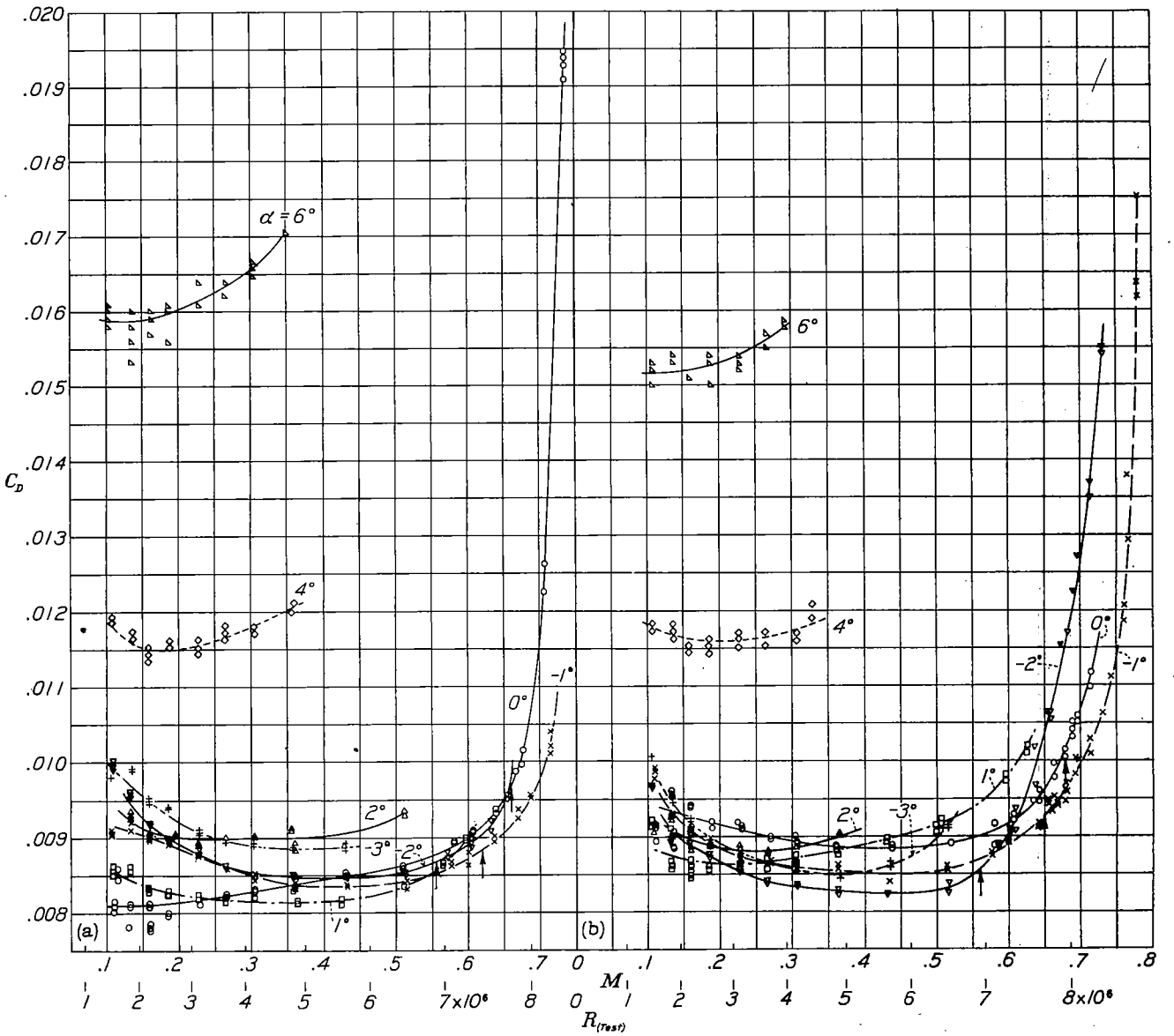


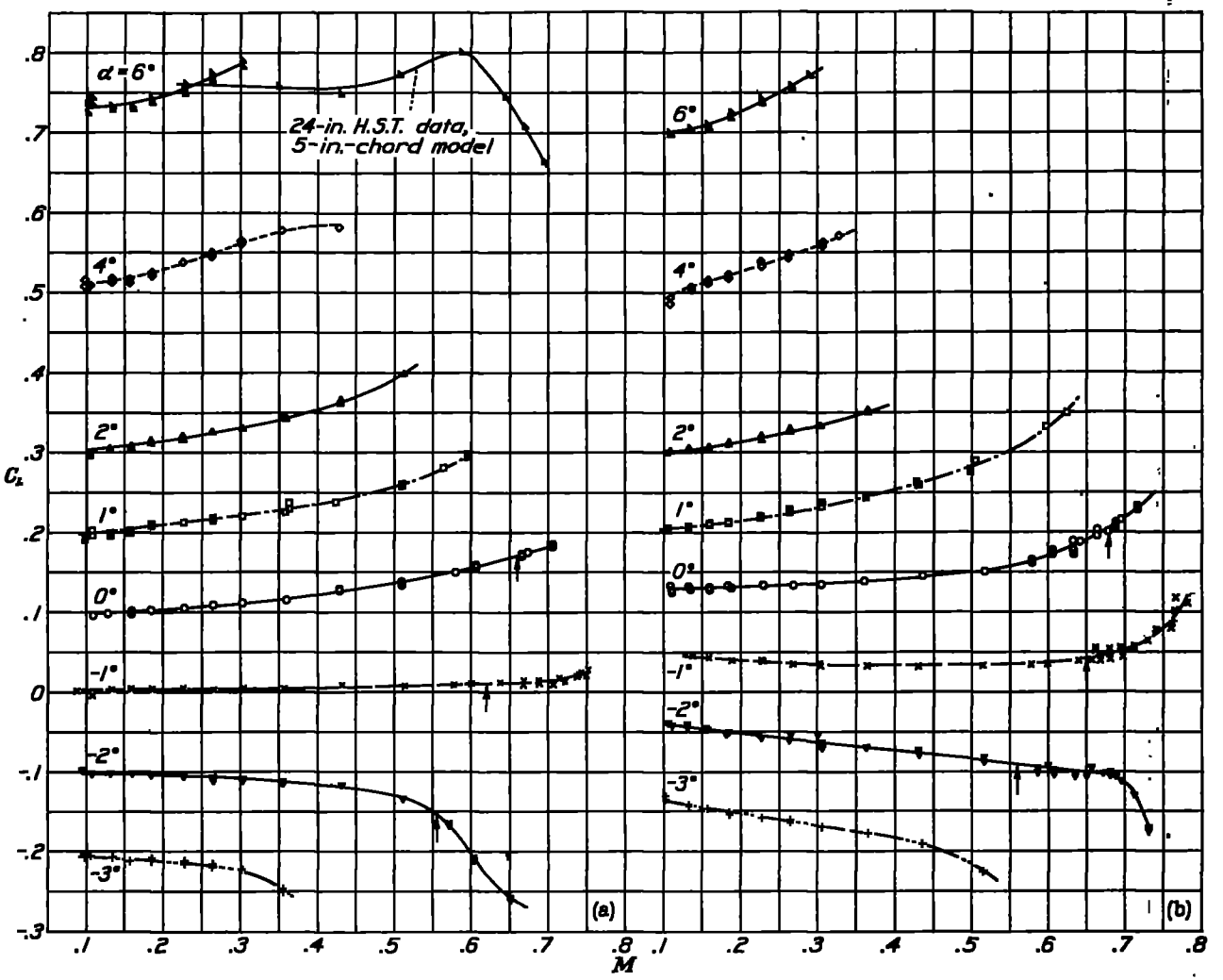
Figure 1.- The 24-inch NACA 23012-64 airfoil mounted in the 8-foot high-speed wind tunnel.

(a) NACA 23012 airfoil.

(b) NACA 23012-64 airfoil.

Figure 3.- Variation with Mach number of drag coefficient. Arrowheads show predicted critical Mach numbers. 24-inch-chord models.

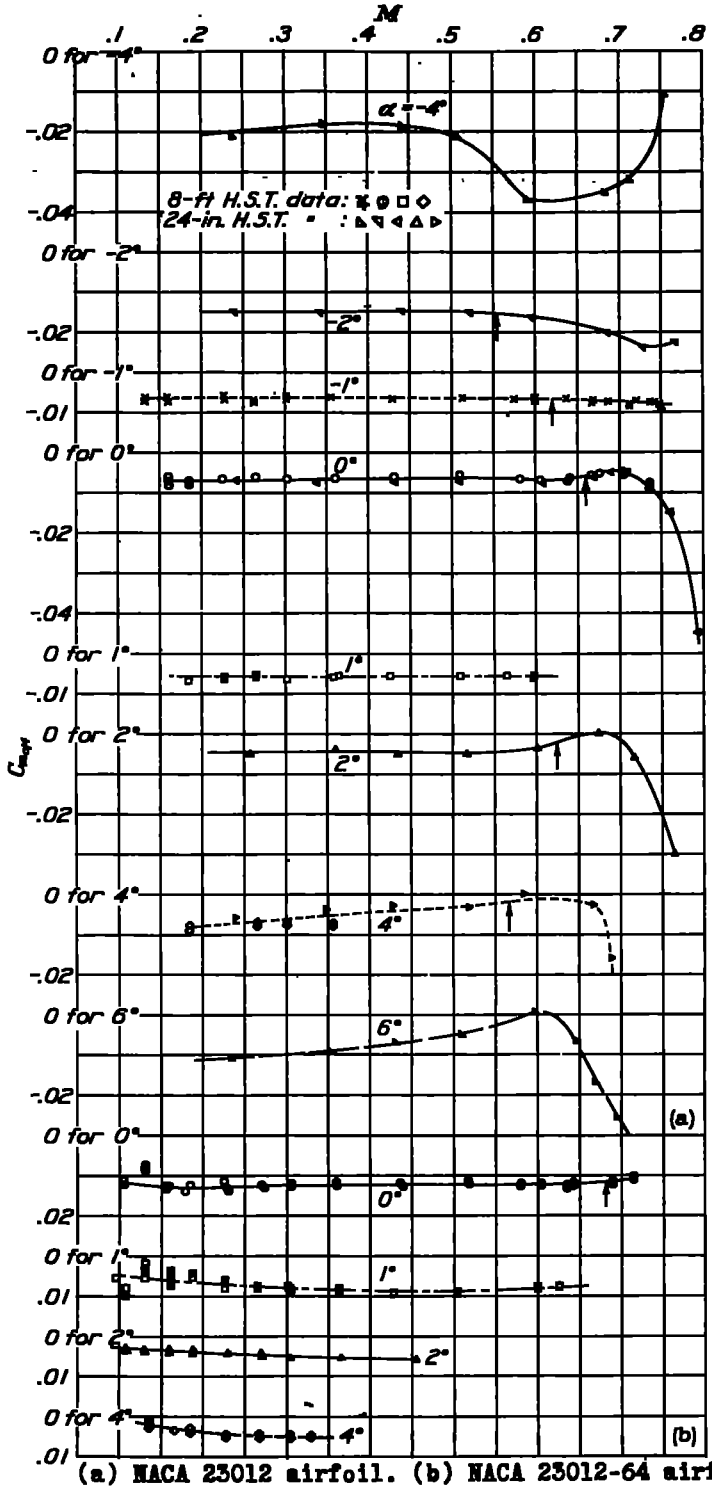




(a) NACA 23012 airfoil.

(b) NACA 23012-64 airfoil.

Figure 4.- Variation with Mach number of the lift coefficient. 24-inch-chord models except as noted.



(a) NACA 23012 airfoil. (b) NACA 23012-64 airfoil.

Figure 5.- Variation with Mach number of pitching-moment coefficient.

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