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RESEARCH MEMORANDUM

EFFECTS OF INCREASING REYNOLDS NUMBER FROM 2×10^6 TO
 6×10^6 ON THE AERODYNAMIC CHARACTERISTICS AT
TRANSONIC SPEEDS OF A 45° SWEEP WING
WITH 6° LEADING-EDGE DROOP

By James W. Schmeer and J. Lawrence Cooper

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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EFFECTS OF INCREASING REYNOLDS NUMBER FROM 2×10^6 TO
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TRANSONIC SPEEDS OF A 45° SWEPT WING
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SUMMARY

An investigation has been made in the Langley 16-foot and 8-foot transonic tunnels to determine the effects of Reynolds number on a swept wing with camber. The wing had 45° sweepback of the quarter-chord line, an aspect ratio of 4, a taper ratio of 0.6, and NACA 65A006 airfoil sections parallel to the plane of symmetry. Camber was obtained by drooping the leading edge of the wing 6° about the 19-percent-chord line. Two geometrically similar wing-fuselage configurations were used, one three times as large as the other. Data were obtained at Reynolds numbers of 2×10^6 in the 8-foot tunnel and 6×10^6 in the 16-foot tunnel through a Mach number range from 0.8 to 1.03. The angle-of-attack range was from 0° to about 20° at the lower Mach numbers and from 0° to about 12° at the higher Mach numbers. Both models were also tested with roughness strips at the 10-percent-chord line on both the upper and lower surfaces of the wings.

The results indicate that increasing the Reynolds number from 2×10^6 to 6×10^6 had only small effects on the lift and drag characteristics of the model. The general trends of the pitching-moment characteristics, including the lift coefficient at which static instability occurred, were also relatively unaffected by an increase in Reynolds number. However, there was a 2-percent rearward shift of the center of load with increase in Reynolds number. The effects of the roughness strips on the aerodynamic characteristics at either Reynolds number were also small.

INTRODUCTION

Some previous experimental investigations have indicated that the aerodynamic characteristics of swept wings having camber may be greatly modified by an increase in Reynolds number. The low-speed results of tests using relatively thick, highly cambered wings (ref. 1) raised doubts concerning the applicability at full scale of data obtained at a Reynolds number of 2×10^6 or less. At high subsonic speeds the aerodynamic characteristics of a swept wing with camber and twist (ref. 2) also showed large effects of increasing Reynolds number; the effects increased with increasing Mach number. The present investigation at transonic speeds was, therefore, initiated to determine the generality of the effects of Reynolds number upon cambered wings, especially as pertaining to a thin wing with camber obtained by drooping the leading edge. For these tests the leading edge of a 45° swept wing was drooped 6° about the 19-percent-chord line. This type of camber has frequently been proposed as a practical and effective means of improving the high-speed characteristics of thin wings.

Tests were made in the Langley 16-foot and 8-foot transonic tunnels by using two models which were geometrically similar except for a slight modification of the fuselage afterbody. The model used in the 16-foot tunnel was three times as large as the model used in the 8-foot tunnel; the Reynolds numbers of the two tests were 6×10^6 and 2×10^6 , respectively. Data were obtained through an angle-of-attack range from 0° to about 20° at Mach numbers from 0.80 to 0.96 and from 0° to about 12° at Mach numbers of 0.98 to 1.03. The effects on the model characteristics of roughness strips placed on the wings at the 10-percent-chord location were also determined at the two Reynolds numbers.

SYMBOLS

C_D	drag coefficient, D/qS
C_L	lift coefficient, L/qS
C_m	pitching-moment coefficient, $\frac{M_{\bar{c}}/4}{qS\bar{c}}$
\bar{c}	wing mean aerodynamic chord
D	drag, lb
L	lift, lb

M	Mach number
$M_{\bar{c}/4}$	pitching moment about $\bar{c}/4$, in-lb
P_b	base pressure coefficient, $\frac{P_b - P_o}{q}$
P_b	static pressure at model base, lb/sq ft
P_o	free-stream static pressure, lb/sq ft
q	dynamic pressure, $\rho V^2/2$, lb/sq ft
R	Reynolds number based on \bar{c}
S	wing area, sq ft
V	free-stream velocity, ft/sec
α	angle of attack of fuselage center line, deg
$\Delta C_D, \Delta C_L, \Delta C_m$	incremental coefficients produced by leading-edge droop, coefficient for wing with 6° droop - coefficient for plane wing
ρ	free-stream density, slugs/cu ft

MODEL AND APPARATUS

The tests were conducted in the Langley 16-foot and 8-foot transonic tunnels, which are described, respectively, in references 3 and 4. Two models of steel construction which were geometrically similar, except for a slight modification of the fuselage afterbody, were used. In the 16-foot-tunnel tests a large model provided data at a Reynolds number of about 6×10^6 ; in the 8-foot-tunnel tests a model one-third as large provided data at a Reynolds number of 2×10^6 . The models were attached to their respective tunnel sting support systems by means of internal strain-gage balances; six force and moment components were measured in the 16-foot tunnel and three in the 8-foot tunnel. The wings of the models had 45° sweepback of the quarter-chord lines, a taper ratio of 0.6, an aspect ratio of 4, and basic NACA 65A006 airfoil sections parallel to the plane of symmetry. Camber was obtained by drooping the leading edge of the wings 6° about the 19-percent-chord line from 0.15 semispan to the wing tip. The maximum value of the mean-line ordinate was about 2 percent of the chord and was measured from the chord line between the leading

edge and the trailing edge of the cambered section; this chord line was at 1° negative incidence with respect to the fuselage center line. A photograph of the large model with roughness strips on the wings is shown mounted in the 16-foot tunnel in figure 1; a sketch of the test models with dimensions and a table of fuselage coordinates are presented in figure 2.

Surface roughness was added to the wings of both models in the form of geometrically similar strips. These strips were located at 10 percent of the chord line on both the upper and lower surfaces of the wings and extended spanwise for the full extent of the leading-edge droop. The strips on the 16-foot-tunnel test model were 0.375 inch wide and consisted of No. 60 carborundum grains (approximately 0.012-inch diameter) sprinkled on an adhesive; the strips on the 8-foot-tunnel test model were 0.125 inch wide and consisted of No. 180 carborundum grains (approximately 0.004-inch diameter).

TESTS AND CORRECTIONS TO THE DATA

Both models, with and without the roughness strips, were tested through an angle-of-attack range from 0° to about 20° at Mach numbers from 0.80 to 0.96 and from 0° to about 12° at Mach numbers of 0.98 to 1.03. The variation with Mach number of Reynolds number based on the mean aerodynamic chord is shown for both models in figure 3.

The angle of attack of the models in both tunnels was determined by measuring the sting angle and adding a correction for stream angularity and for model deflection due to normal force and pitching moments.

Lift and drag coefficients were adjusted to a condition of free-stream static pressure at the base of the fuselage. The variation with angle of attack of the base pressure coefficients is presented in figure 4.

Although wall-reflected disturbances have some effect on the drag results at a Mach number of 1.03, no evaluation of these effects was made nor any correction attempted. However, in the section on comparison of drag coefficients the qualitative effects are briefly discussed. The effects of sting interference are known to be small for tail-off models and were not evaluated for these tests.

The force and moment coefficients are based on the wing area and mean aerodynamic chord of the basic wing, that is, the wing with no leading-edge droop. The accuracy of the data with the exception of the drag results at a Mach number of 1.03 was estimated to be as follows:

P_b	± 0.005
C_L	± 0.01
C_D	± 0.001
C_m	± 0.004
α , deg	± 0.10

RESULTS AND DISCUSSION

The effects on the aerodynamic characteristics of an increase in Reynolds number from 2×10^6 in the Langley 8-foot transonic tunnel to about 6×10^6 in the Langley 16-foot transonic tunnel at Mach numbers from 0.80 to 1.03 are presented in figure 5. The validity of comparing data from the two facilities to determine Reynolds number effects is indicated in reference 5 which shows from tests of the same model in both tunnels and two different-sized models in the 16-foot tunnel that the tunnel effects are negligibly small except for phenomena associated with wave reflection. The increments of lift, drag, and pitching-moment coefficients due to drooping the leading edge of the wing at the two test Reynolds numbers are compared in figure 6. Figures 7 and 8 show the effect of roughness strips on the aerodynamic characteristics of the model at the two Reynolds numbers.

Effect of Reynolds Number on the Aerodynamic Characteristics

Lift coefficient.- The difference in lift coefficient due to an increase in Reynolds number from 2×10^6 to 6×10^6 is shown in figure 5(a) to be small and generally within the accuracy of the data. The consistent displacement of the lift curves at low angles of attack can be attributed to an uncertainty in correction for either stream angularity or some slight asymmetry in the models or both.

Drag coefficient.- The difference in drag coefficient at the two Reynolds numbers is also generally small and within the accuracy of the data (fig. 5(b)). However, a notable exception occurs at a Mach number of 1.03. At this speed, the higher drag of the small model in the Langley 8-foot transonic tunnel can be attributed to two factors. First, the more highly convergent afterbody of the small model causes an increased pressure drag as compared with that of the large model. Second, wall-reflected disturbances tend to increase the drag of the small model in the 8-foot tunnel and decrease the drag of the large model in the 16-foot tunnel. This difference in the effect of reflected disturbances is due to the difference in the ratio of model length to test-section diameter; this ratio is about 1.4 times greater in the 16-foot tunnel.

Similar effects of reflected disturbances can also be seen in reference 5 for a wing-fuselage combination comparable to the models of the present investigation.

Pitching-moment coefficients.- Figure 5(c) shows that the general trends of the static-longitudinal-stability curves, including the lift coefficient at which the unstable break occurs, are little affected by the change in Reynolds number. However, with an increase in Reynolds number there was a small rearward shift of the center of load which remained fairly constant through the Mach number range for constant values of lift coefficient. The possibility that this shift was due to the difference in afterbody shape was eliminated by the good agreement obtained in a comparison of the pitching-moment curves for the plane wing with both the modified fuselage and the original fuselage (data from refs. 6 and 7, respectively). The data of figure 5(c) indicate that a change in moment center of about 2 percent of the mean aerodynamic chord would bring the two sets of curves into good agreement. In comparison to the effects of Reynolds number on the longitudinal characteristics of a cambered and twisted wing noted in reference 2, the effects shown herein are relatively small. These results might be expected because of the somewhat thicker and more highly cambered sections of the wings in the reference report.

Incremental force and moment coefficients.- These increments were obtained by subtracting the data for the models with the basic wings (small model reported in ref. 5; large model, in ref. 6) from the data of the present tests. The small model and the large model of the reference reports were identical to the small and large models, respectively, of these tests except that the (basic) wing had no leading-edge droop. It is assumed that increments thus obtained would tend to isolate the Reynolds number effects on the wing with leading-edge droop from the effects of any difference in models (such as the modified afterbody) or in tunnel characteristics (turbulence, wall-reflected disturbances, and others).

Figure 6 shows no significant differences in the increments of lift and drag coefficients caused by leading-edge droop at Reynolds numbers of 2×10^6 and 6×10^6 . The increments of pitching-moment coefficient at both Reynolds numbers are identical at zero lift. However, the nearly constant difference through the Mach number range at $C_L = 0.4$ again shows the rearward shift of center of load at the higher Reynolds number. This difference in incremental C_m becomes greater and somewhat erratic at $C_L = 0.8$ which is, however, above the lift coefficient for the unstable pitching-moment break.

Effects of Roughness Strips

As noted previously, the thicker and more highly cambered sections of the wings in reference 2 are probably more sensitive to a change in Reynolds number and, therefore, to a change in surface conditions. Accordingly, the data of reference 2 showed very large effects of surface roughness on the aerodynamic characteristics of a cambered and twisted wing, whereas a similar type of roughness produced no significant effects on the characteristics of the wings of this investigation at either Reynolds number (figs. 7 and 8). The small differences in coefficients, especially noted at a Mach number of 0.96 and moderate angles of attack, are probably due to the finite thickness of the roughness strips. The strips apparently influence the shock pattern in such a way as to cause earlier or more extensive separation.

CONCLUSIONS

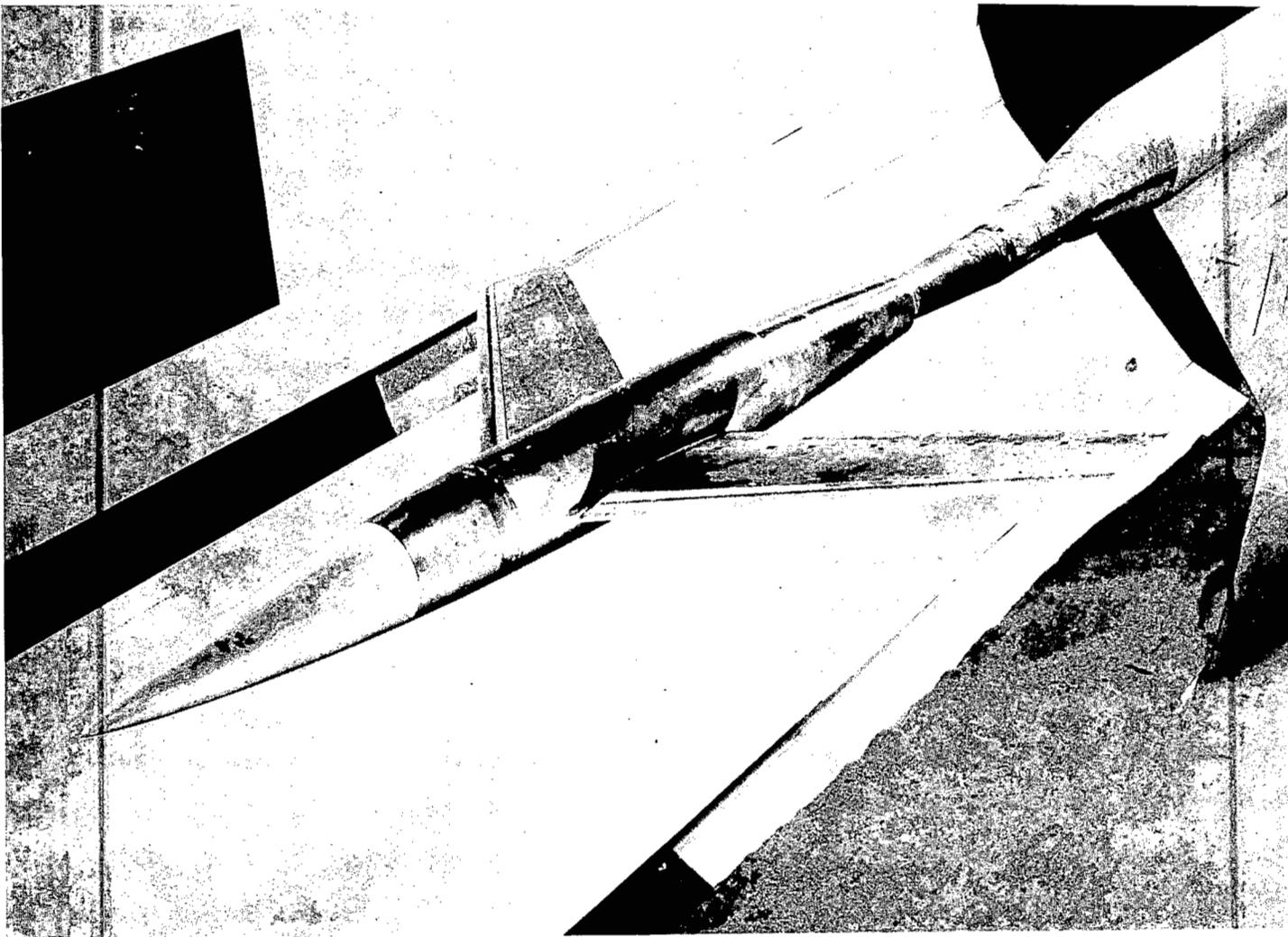
An investigation of the effects of Reynolds number at transonic speeds on the aerodynamic characteristics of a 45° swept wing with camber provided by drooping the leading edge has led to the following conclusions:

1. The effect of increasing Reynolds number from 2×10^6 to 6×10^6 on the lift and drag coefficients was small.
2. The general trends of the pitching-moment characteristics including the lift coefficient at which static instability occurred were unaffected by a change in Reynolds number. However, with increase in Reynolds number the center of load shifted rearward about 2 percent of the mean aerodynamic chord.
3. The addition of roughness strips at 10 percent of the chord had negligible effects on the model characteristics at Reynolds numbers of 2×10^6 and 6×10^6 .

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 29, 1954.

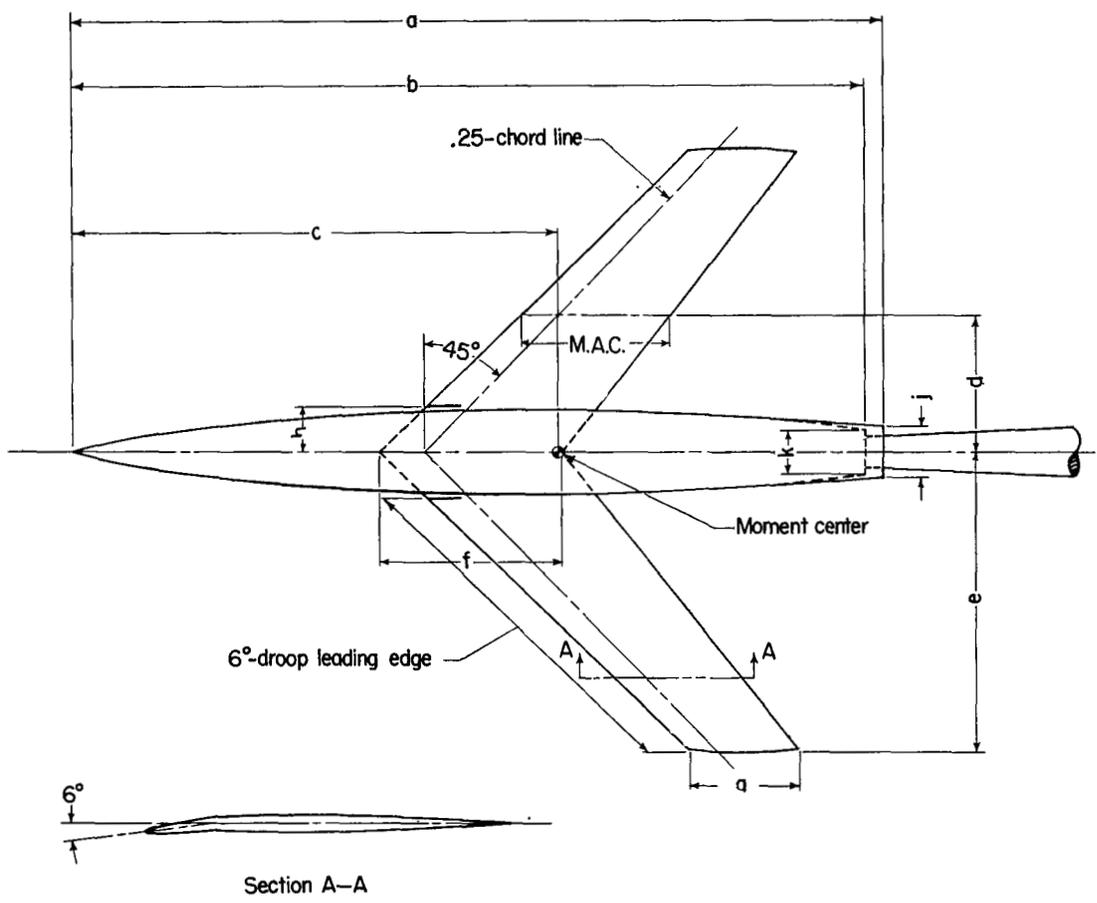
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Figure 1.- Photograph of the large model in the Langley 16-foot transonic tunnel. Roughness strips are on the wing.



Dimensions of models tested in transonic tunnels, in.		
Dimensions	16-foot	8-foot
a	100.0	--
b	--	32.6
c	60.0	20.0
d	16.5	5.5
e	38.0	12.0
f	22.5	7.5
g	13.5	4.5
h	5.4	1.8
j	6.25	--
k	--	1.86
M.A.C.	18.375	6.125

Coordinates of bodies tested in transonic tunnels			
16-foot		8-foot	
Station, in.	Radius, in.	Station, in.	Radius, in.
0	0	0	0
.6	.277	.2	.092
.9	.358	.3	.119
1.5	.514	.5	.171
3.0	.868	1.0	.289
6.0	1.446	2.0	.482
9.0	1.936	3.0	.645
12.0	2.365	4.0	.788
18.0	3.112	6.0	1.037
24.0	3.708	8.0	1.236
30.0	4.158	10.0	1.386
36.0	4.489	12.0	1.496
42.0	4.719	14.0	1.573
48.0	4.896	18.0	1.625
54.0	4.971	18.0	1.657
60.0	5.000	20.0	1.667
66.0	4.955	22.0	1.652
72.0	4.830	24.0	1.610
78.0	4.580	28.0	1.537
84.0	4.245	28.0	1.425
90.0	3.853	30.0	1.251
96.0	3.420	32.0	1.010
100.0	3.125	32.6	.930
Nose radius	.060	Nose radius	.020

Figure 2.- Principal dimensions of the test models.

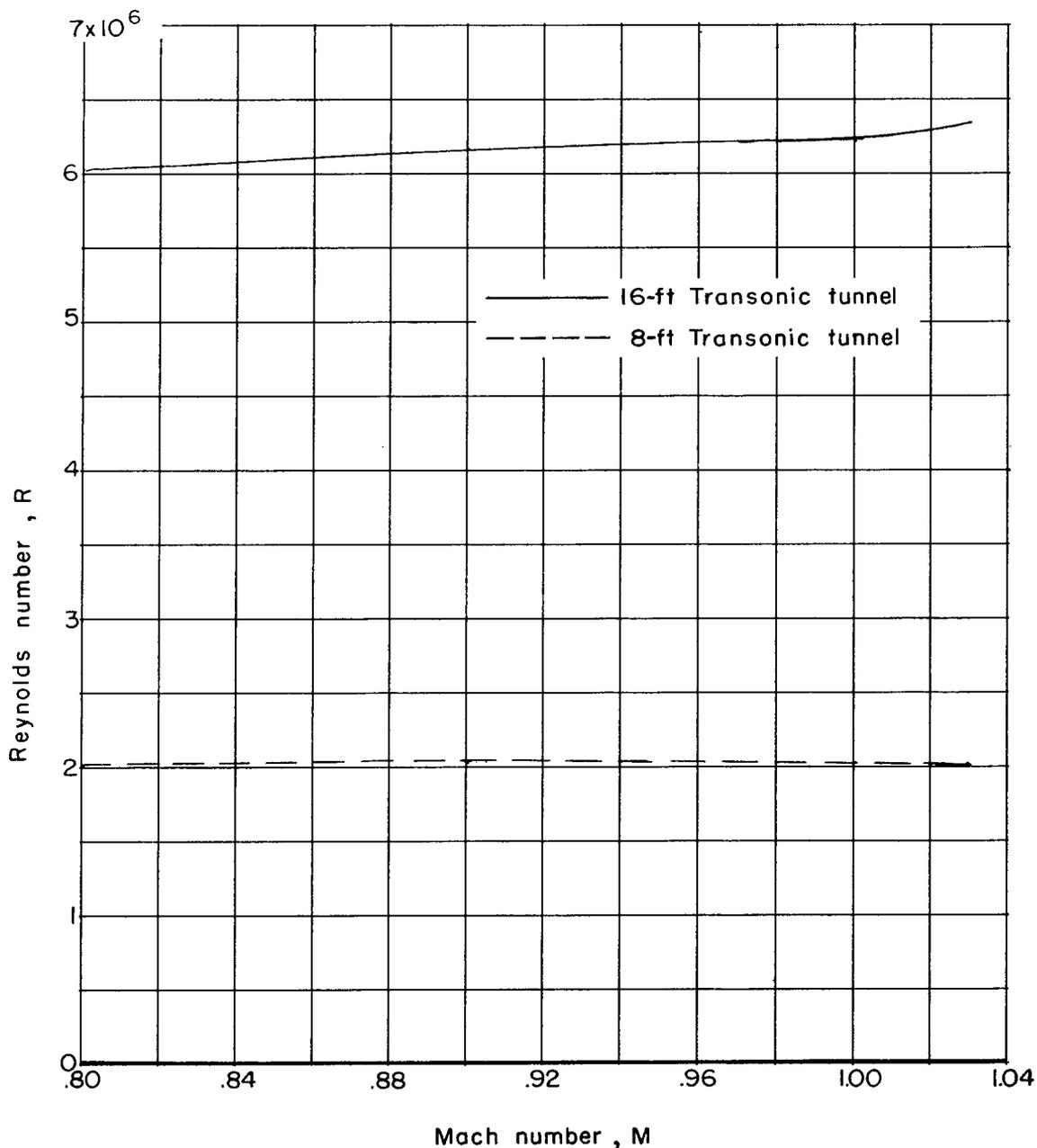


Figure 3.- Variation with Mach number of average Reynolds number for the large model in the Langley 16-foot transonic tunnel and the small model in the Langley 8-foot transonic tunnel.

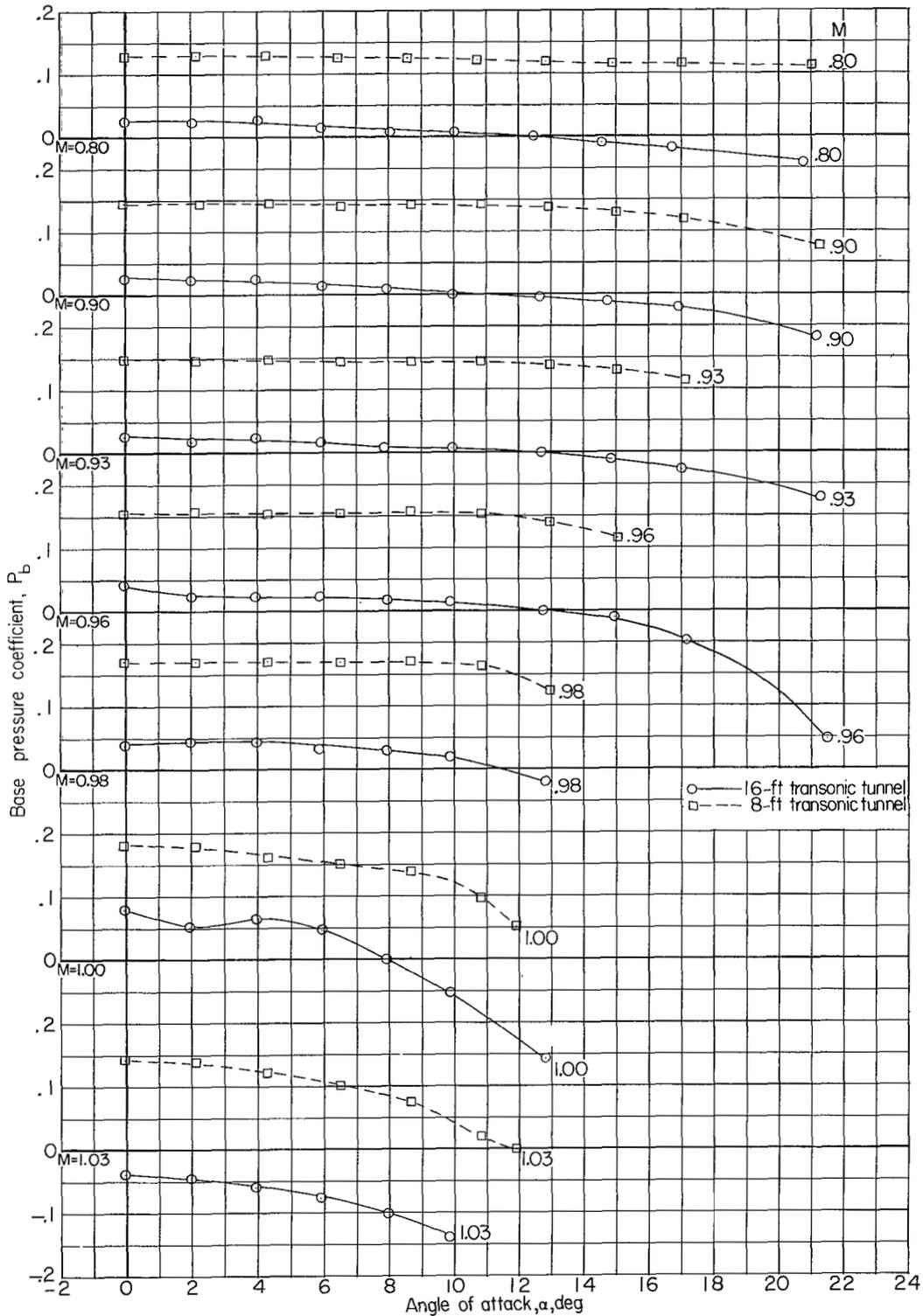
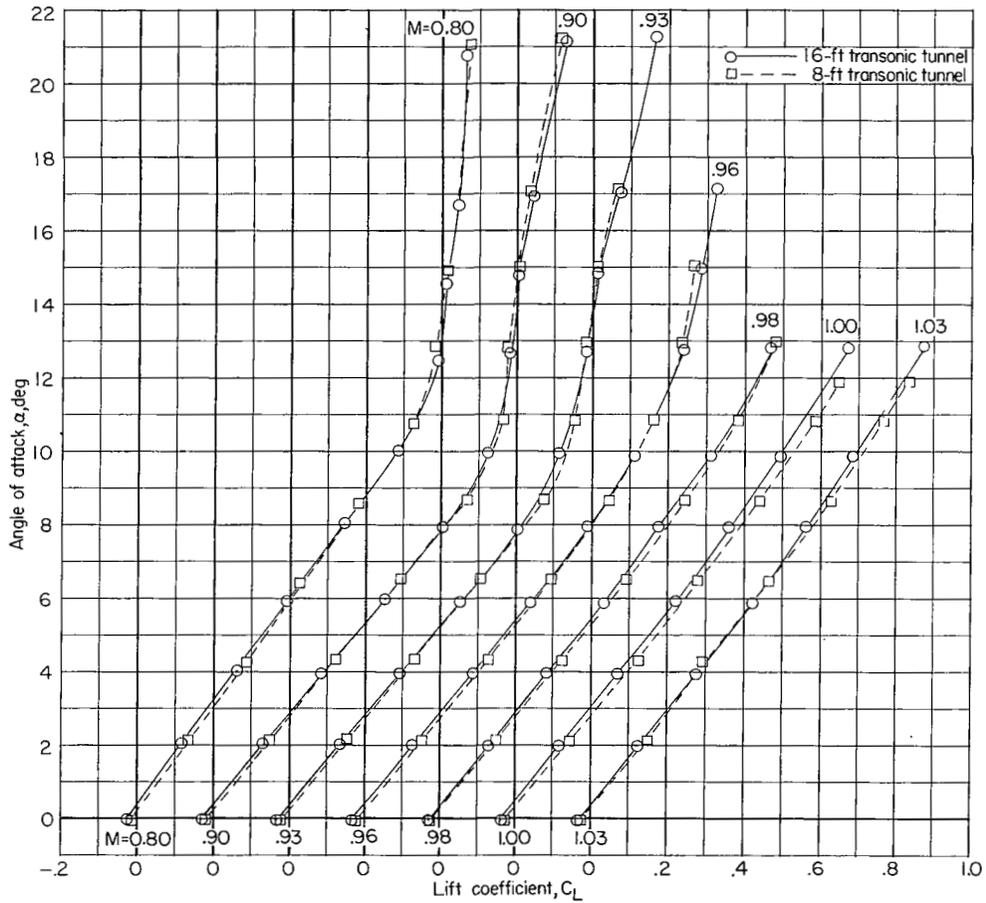
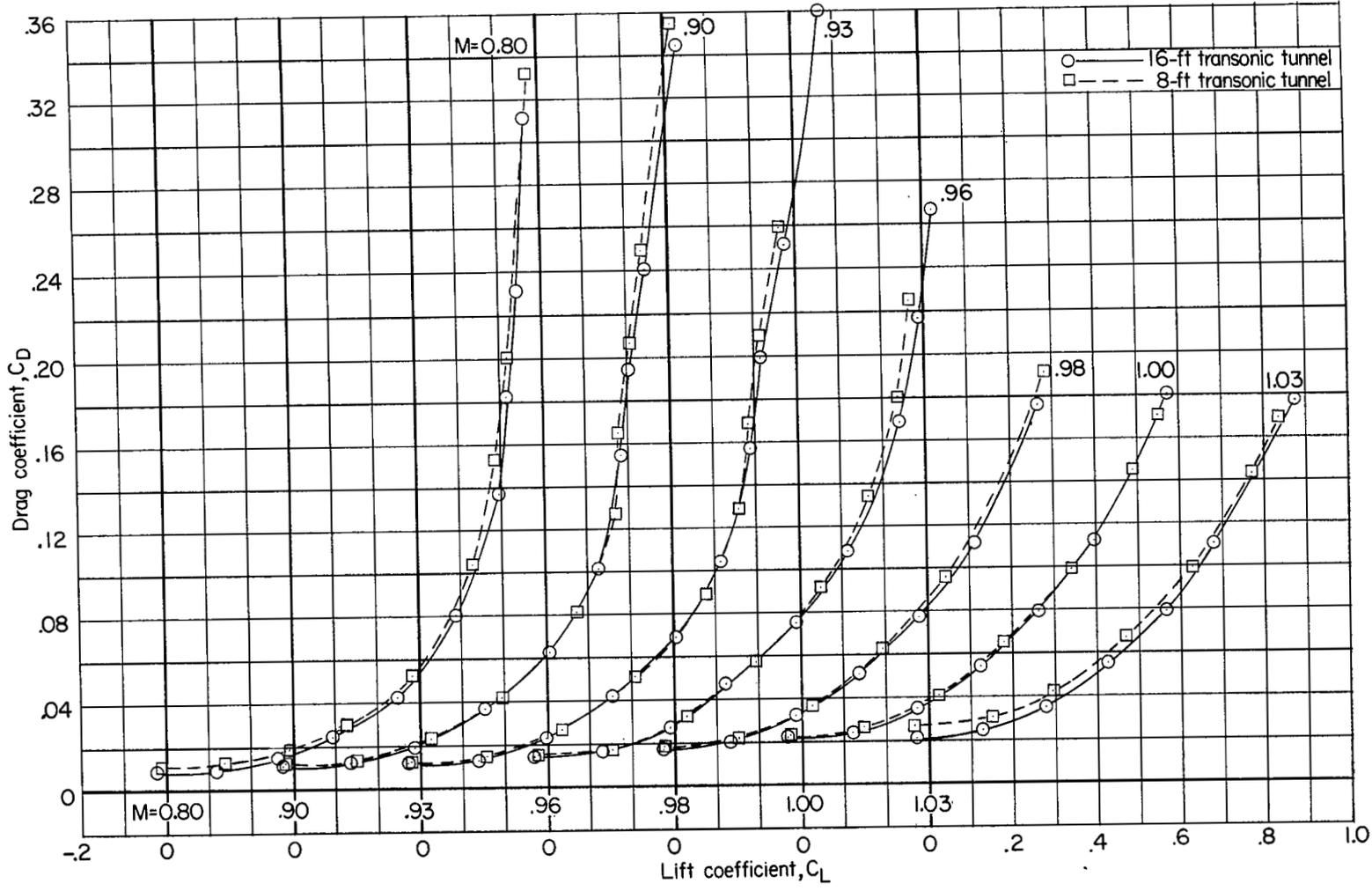


Figure 4.- Variation with angle of attack of base pressure coefficients for the two models.



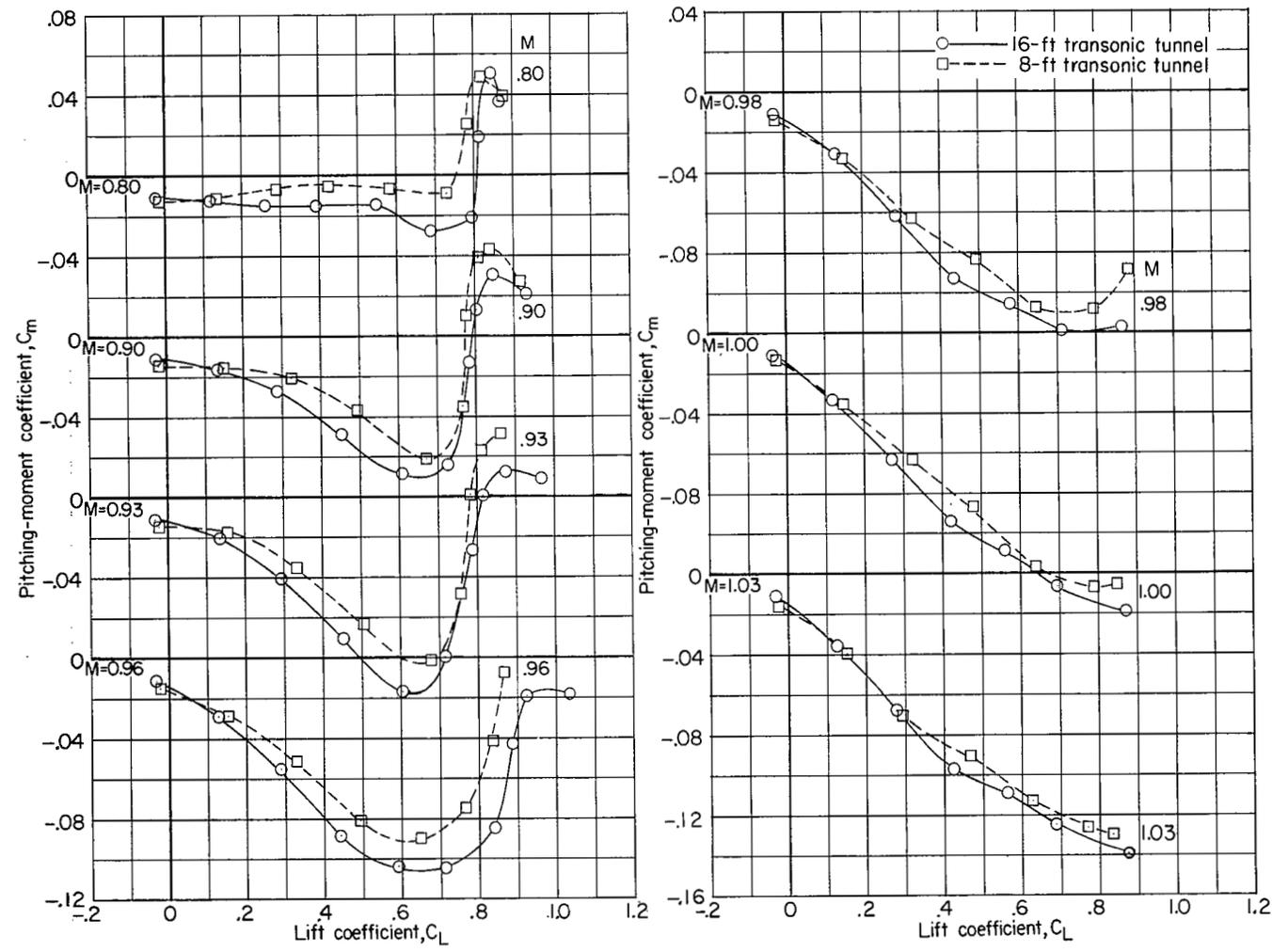
(a) α against C_L .

Figure 5.- Effect of Reynolds number on the aerodynamic characteristics. R is approximately 6×10^6 for tests in the Langley 16-foot transonic tunnel and 2×10^6 for tests in the Langley 8-foot transonic tunnel.



(b) C_D against C_L .

Figure 5.- Continued.



(c) C_m against C_L .

Figure 5.- Concluded.

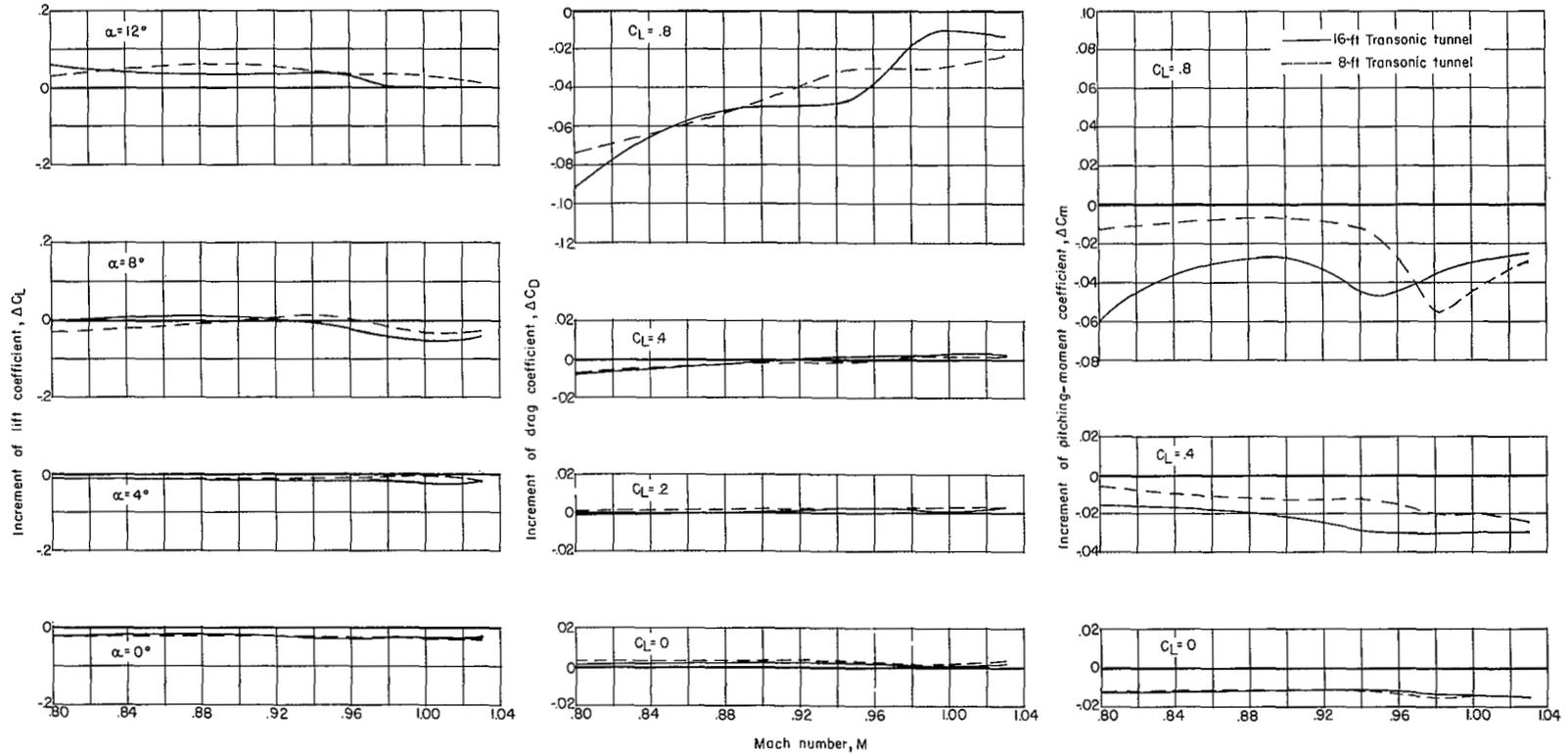
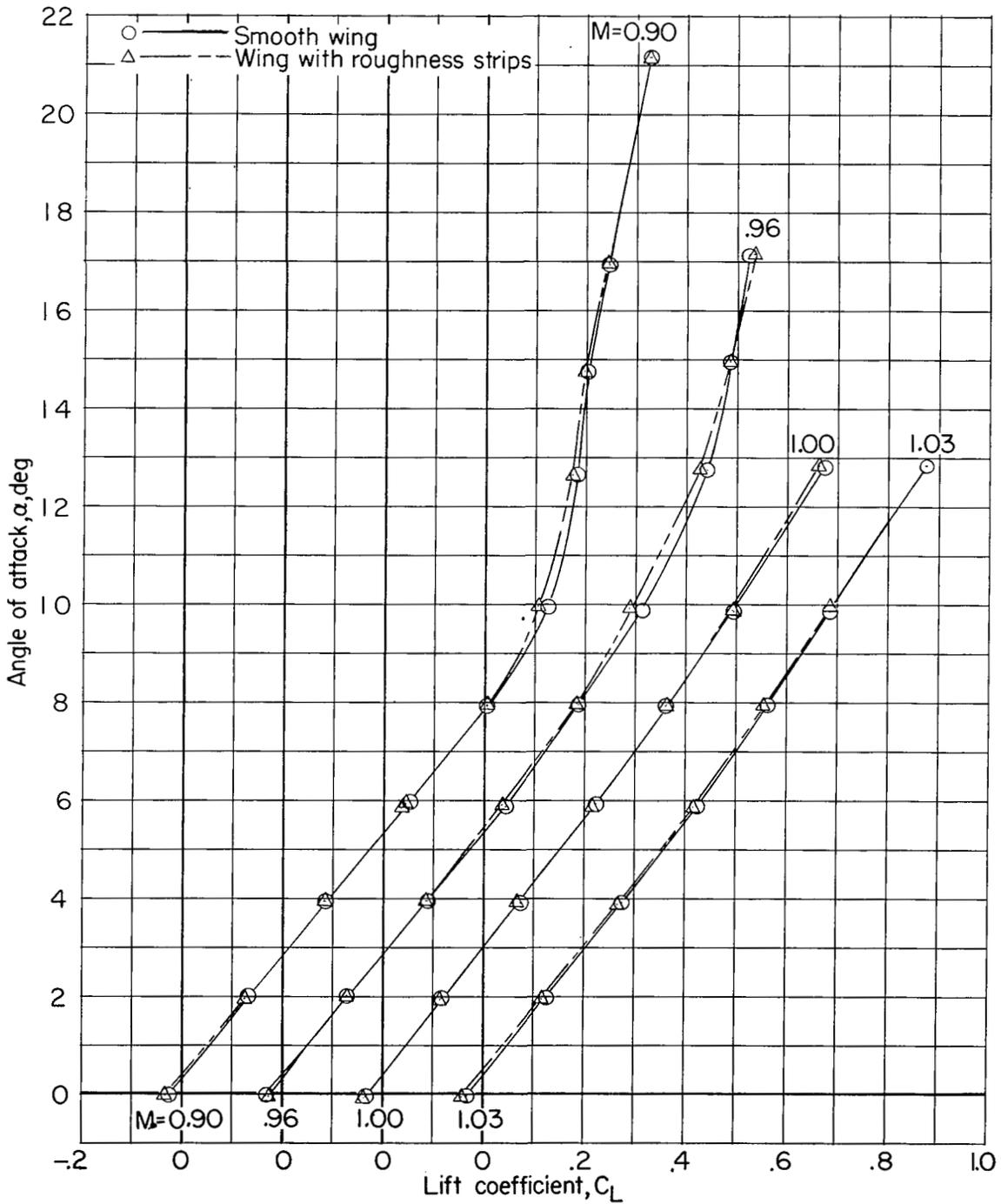


Figure 6.- Incremental lift, drag, and pitching-moment coefficients due to drooping the leading edge of the wing. R is approximately 6×10^6 for tests in the Langley 16-foot transonic tunnel and 2×10^6 for tests in the Langley 8-foot transonic tunnel.



(a) α against C_L .

Figure 7.- Effect of roughness strips on aerodynamic characteristics of the large model in the Langley 16-foot transonic tunnel. $R \approx 6 \times 10^6$.

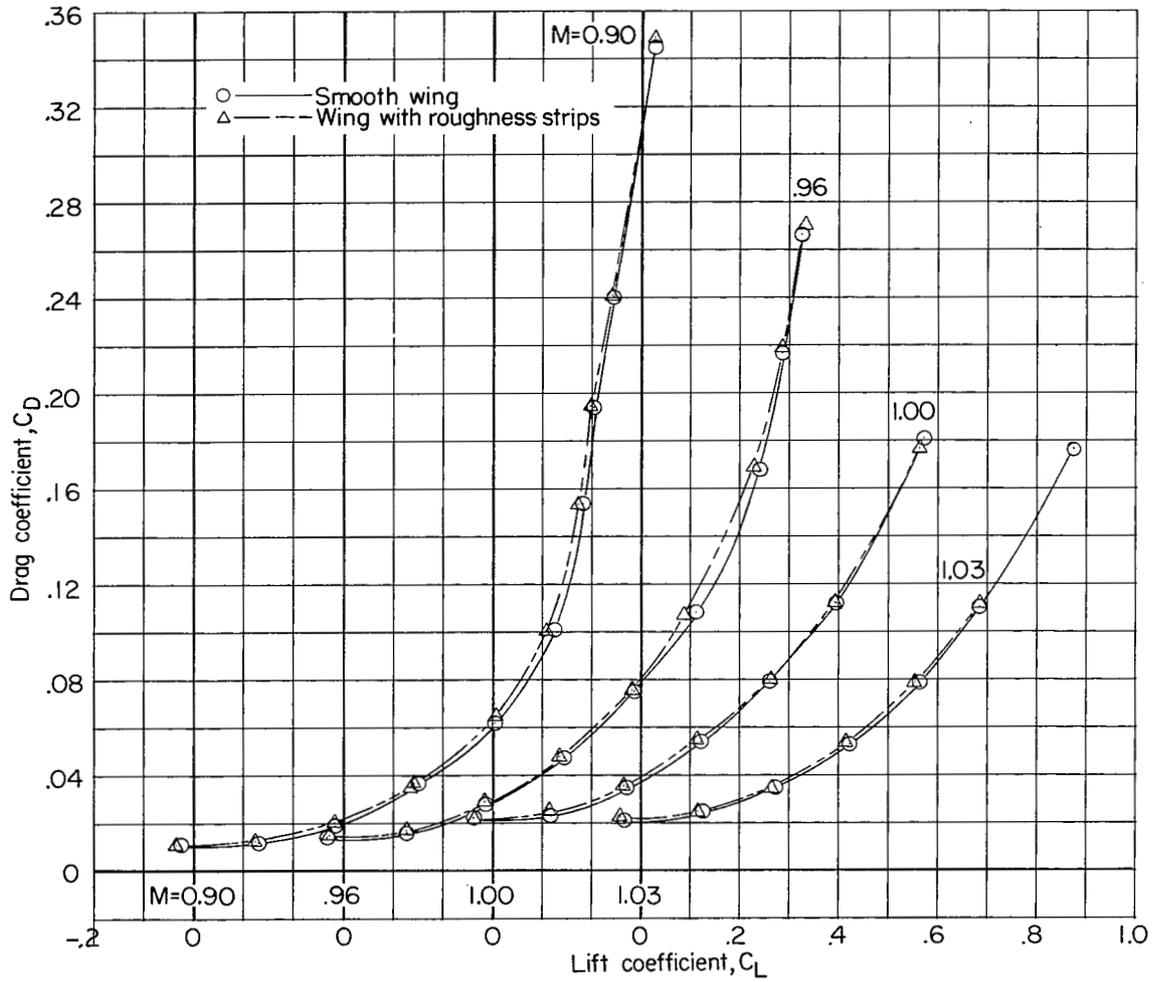
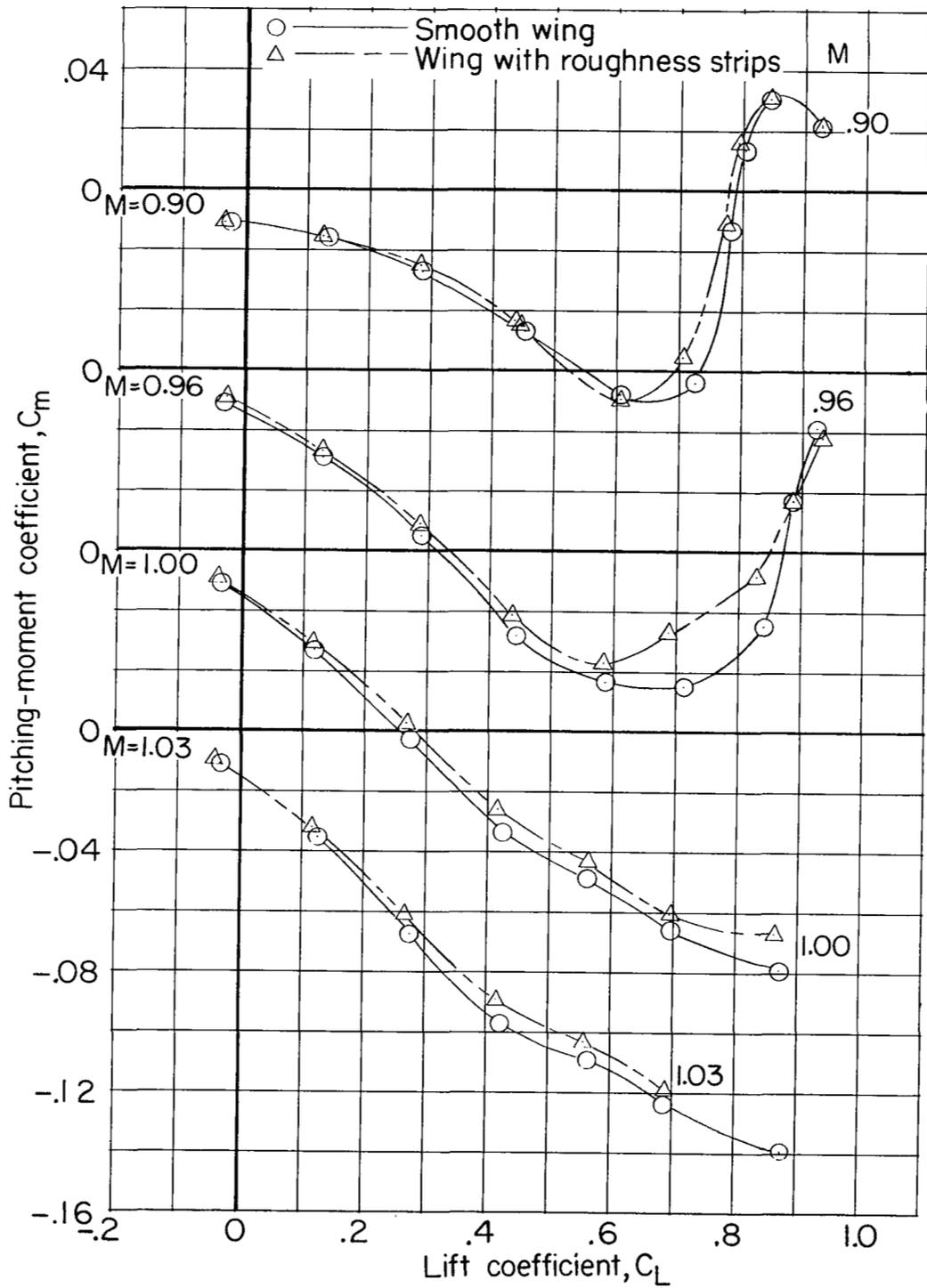
(b) C_D against C_L .

Figure 7.- Continued.



(c) C_m against C_L .

Figure 7.- Concluded.

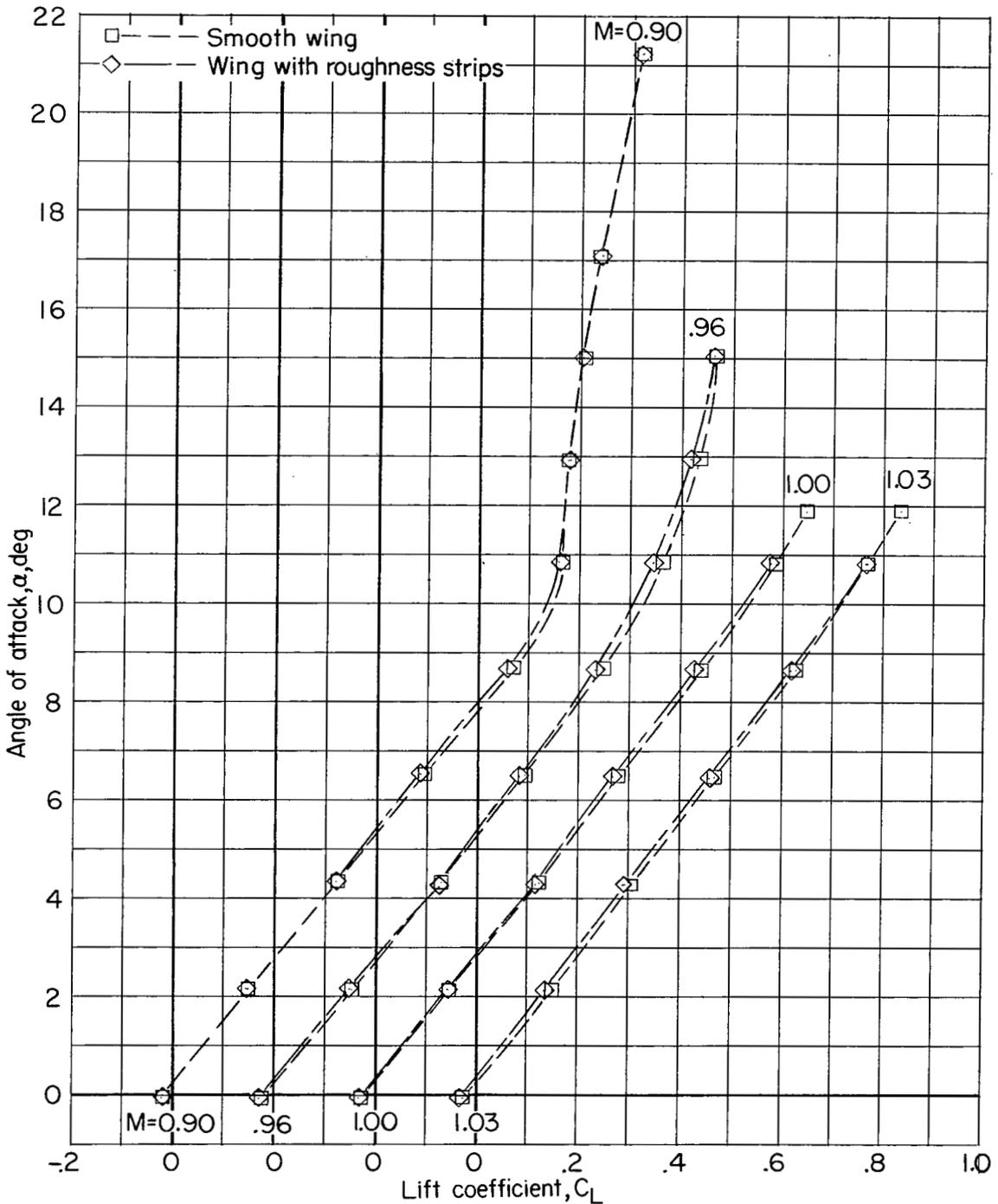
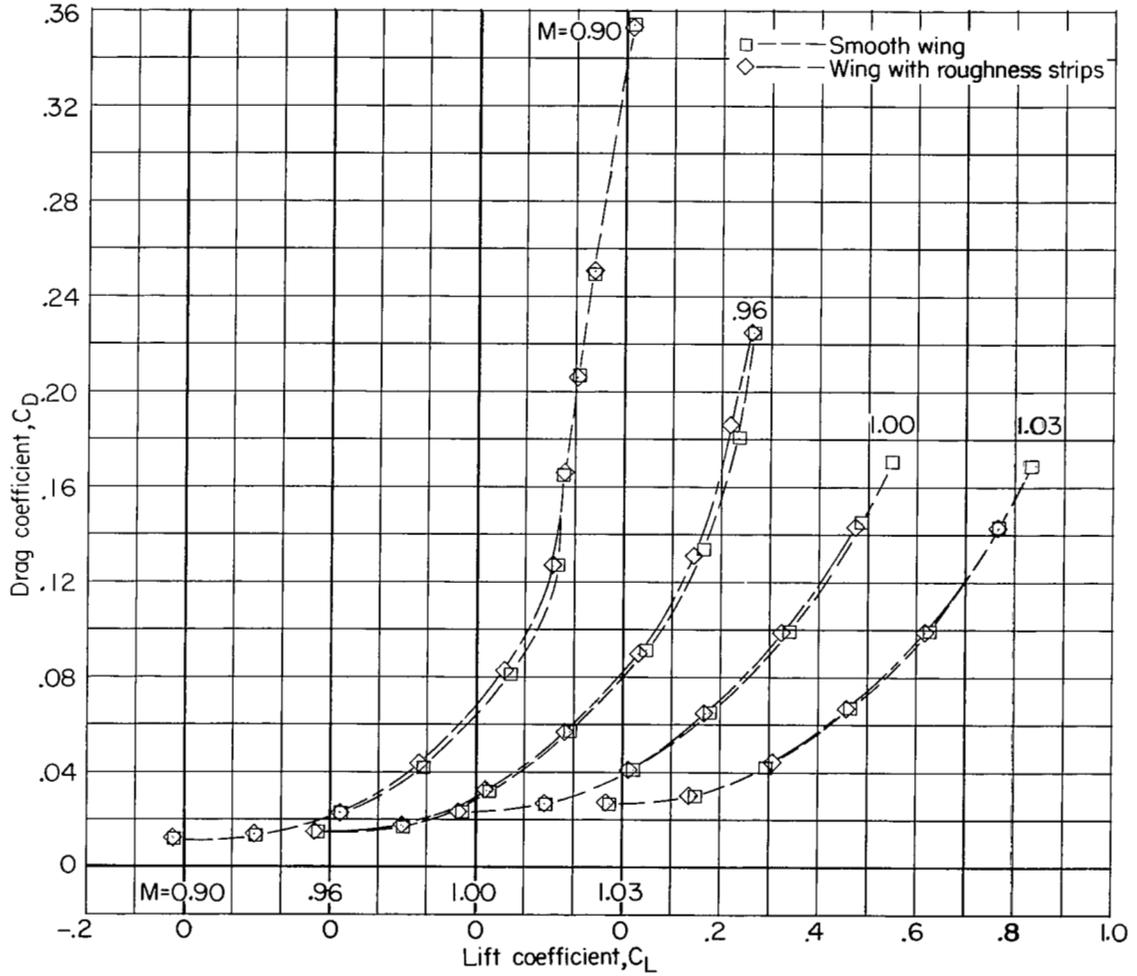
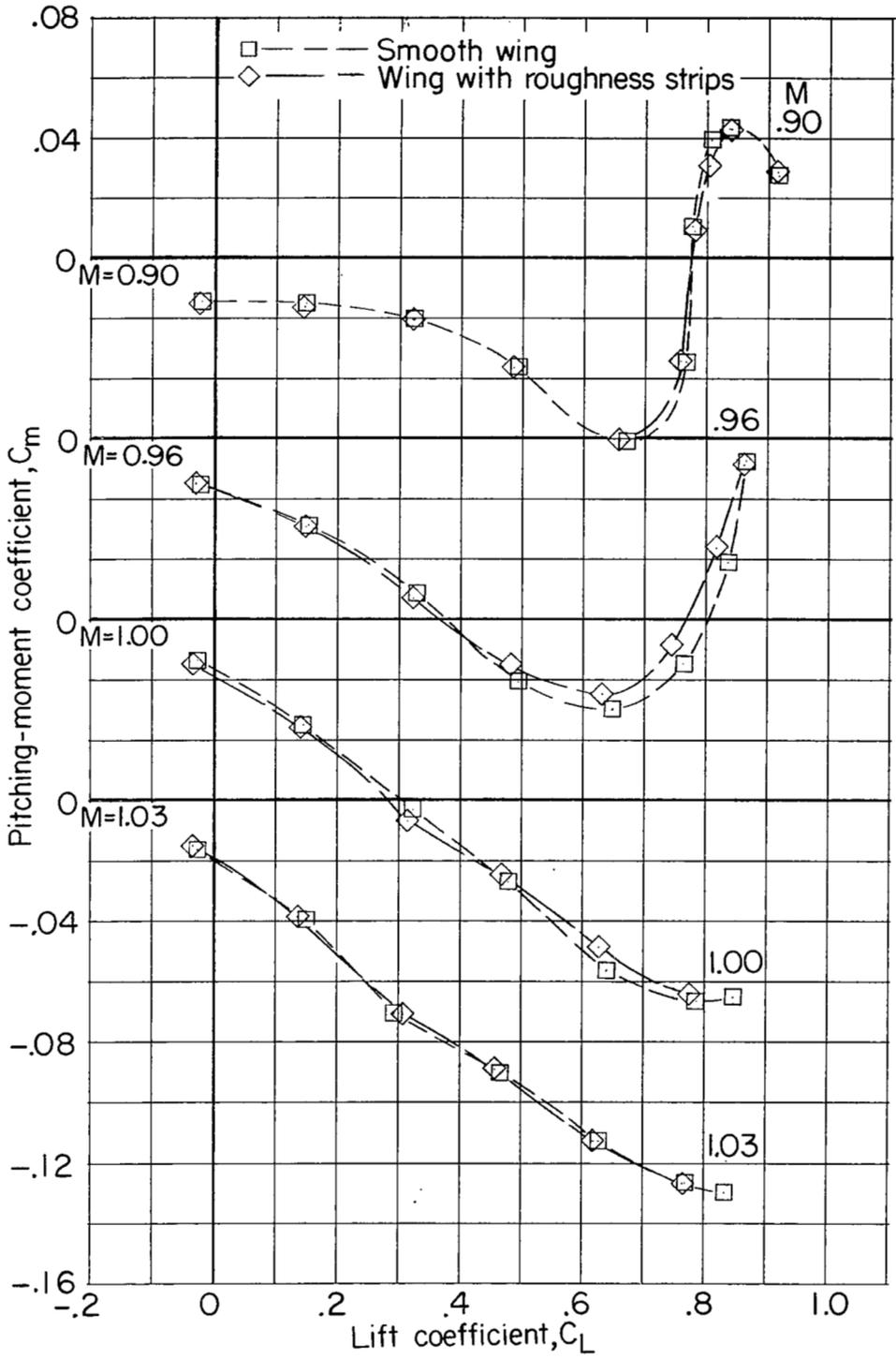
(a) α against C_L .

Figure 8.- Effect of roughness strips on aerodynamic characteristics of the small model in the Langley 8-foot transonic tunnel. $R \approx 2 \times 10^6$.



(b) C_D against C_L .

Figure 8.- Continued.



(c) C_m against C_L .

Figure 8.- Concluded.



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