NACA TN 2998

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2998

THE EFFECTS OF CAMBER ON THE VARIATION WITH MACH NUMBER OF THE AERODYNAMIC CHARACTERISTICS OF A 10-PERCENT-THICK MODIFIED NACA FOUR-DIGIT-SERIES AIRFOIL SECTION

By Albert D. Hemenover

Ames Aeronautical Laboratory
Moffett Field, Calif.

Washington
September 1953

F

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2998

THE EFFECTS OF CAMBER ON THE VARIATION WITH MACH NUMBER OF THE AERODYNAMIC CHARACTERISTICS OF A 10-PERCENT-THICK MODIFIED NACA FOUR-DIGIT-SERIES AIRFOIL SECTION

By Albert D. Hemenover

SUMMARY

The results of a wind-tunnel investigation to determine the effects of moderate amounts of camber on the aerodynamic characteristics of a 10-percent-thick modified NACA four-digit-series airfoil section are presented for Mach numbers from 0.3 to 0.9. The corresponding Reynolds number variation was from approximately 1×10^6 to 2×10^6. The characteristics of airfoil sections cambered for design lift coefficients of 0.2 and 0.4 on an NACA $a = 0.8$ mean line are compared with those of the corresponding uncambered profile.

The results indicate that the principal effects of increasing camber were an increase in maximum lift coefficient and increases in lift- and drag-divergence Mach numbers at moderate to large lift coefficients.

INTRODUCTION

Considerable interest has been shown recently in the modified NACA four-digit-series airfoil section for high-subsonic-speed applications. Examination of references 1 and 2 reveals that drag-divergence Mach numbers up to moderate lift coefficients for a symmetrical, 10-percent-thick airfoil of this type are superior to those for a comparable NACA 6-series profile. For some applications, notably the high-speed transport airplane, this advantage in drag-divergence characteristics might dictate the selection of a modified four-digit-series airfoil over the commonly used NACA 64-series thickness distribution. It therefore becomes of interest to know the effects of camber on the characteristics of modified NACA four-digit-series profiles.

The present investigation was undertaken in the Ames 1- by 3-1/2-foot high-speed wind tunnel to determine the effects of moderate amounts of camber on the aerodynamic characteristics of a 10-percent-chord-thick modified four-digit-series airfoil section at high subsonic Mach numbers. The airfoils investigated were cambered for design lift coefficients of 0.2 and 0.4 on an NACA $a = 0.8$ mean camber line. (See ref. 3.)

NOTATION

a	mean-line designation, fraction of chord from leading edge over which design load is uniform
a_o	section lift-curve slope, per deg
c_d	section drag coefficient
c_l	section lift coefficient
c_{l_i}	design section lift coefficient
$c_{l_{max}}$	maximum section lift coefficient
$c_{m_{c/4}}$	section pitching-moment coefficient about the quarter-chord point
M	free-stream Mach number
M_d	drag-divergence Mach number, defined as the Mach number at which $\left(\frac{dc_d}{dM}\right)_{\alpha_o = \text{constant}} = 0.1$
M_l	lift-divergence Mach number, defined as the Mach number corresponding to the initial inflection point of curves of section lift coefficient versus Mach number at constant angle of attack
R	Reynolds number
α_o	section angle of attack, deg

DESCRIPTION OF AIRFOILS

The airfoil sections of the present investigation are:

NACA 0010 - 1.10 40/1.051
NACA 0010 - 1.10 40/1.051, $c_{l_i} = 0.2$, $a = 0.8$
NACA 0010 - 1.10 40/1.051, $c_{l_i} = 0.4$, $a = 0.8$

The numbering system for the first airfoil section is that usually employed for the designation of a modified NACA four-digit-series airfoil section. (See ref. 1.) The first digit indicates the camber in percent of the chord; the second, the position of the camber in tenths of the chord from the leading edge; and the third and fourth, the maximum thickness in percent of the chord. The decimal number following the dash is the leading-edge-radius index; the leading-edge radius as a fraction of the airfoil chord is given by the product of the radius index and the square of the thickness-chord ratio. The radius index of 1.10 is standard for the NACA four-digit-series airfoil sections. The two digits immediately preceding the virgule represent the position of maximum thickness in percent of the chord from the leading edge. The number immediately following the virgule is the trailing-edge-angle index, the angle being twice the arc tangent of the product of the angle index and the thickness-chord ratio.

The designation of the second and third airfoils indicates an NACA 0010 - 1.10 40/1.051 basic thickness form cambered for design lift coefficients of 0.2 and 0.4, respectively, on an NACA $a = 0.8$ mean line. (See ref. 3.)

The coordinates of the airfoils investigated are given in table I and the profile shapes are illustrated in figure 1.

APPARATUS AND TESTS

The investigation was conducted in the Ames 1- by 3-1/2-foot high-speed wind tunnel, a low-turbulence two-dimensional-flow wind tunnel.

Six-inch-chord models were constructed of aluminum alloy and completely spanned the 1-foot dimension of the tunnel test section. Contoured sponge-rubber gaskets compressed between the model ends and the tunnel walls prevented end leakage.

Measurements of lift, drag, and pitching moment about the quarter-chord point were made simultaneously at Mach numbers ranging from 0.3 to approximately 0.9 for the models at angles of attack increasing by increments of 1° or 2° from -6° to 12°. This range of angles of attack was sufficient to encompass negative lift at all Mach numbers and the lift stall up to a Mach number of 0.775. The Reynolds number variation with Mach number for these tests is shown in figure 2.

Lift forces and pitching moments were determined, by a method similar to that described in reference 3, from integrations of the pressure reactions on the tunnel walls produced by the forces on the airfoils. Drag forces were determined from wake-survey measurements made with a rake of total-head tubes.

RESULTS AND DISCUSSION

Section lift, quarter-chord pitching-moment, and drag coefficients are presented as functions of Mach number at constant angles of attack in figures 3, 4, and 5, respectively, for the basic NACA 0010 - 1.10 40/1.051 airfoil section and for the same profile cambered for design lift coefficients of 0.2 and 0.4 on an NACA a = 0.8 mean line. The characteristics for the uncambered section were replotted from the original data for the investigation of reference 1. The variations of lift coefficient with angle of attack at constant Mach number are shown in figure 6 for the three airfoils. Corrections for tunnel-wall interference by the methods of reference 4 have been applied to the data. The results shown as dashed portions of the curves should be used with caution because of the possible influence of wind-tunnel choking effects in this region.

Lift Characteristics

The effects of increasing camber on the respective variations with Mach number of lift-curve slope and angle of attack required to maintain a given lift coefficient for the modified four-digit-series airfoil section (figs. 7 and 8) are similar to those noted in reference 5 for NACA 64A-series airfoils of the same thickness.

Maximum section lift coefficient as a function of Mach number is presented in figure 9 for the 3 four-digit-series airfoils. It is observed that increasing camber produced, at least qualitatively, the anticipated increase in maximum lift coefficient at all Mach numbers. The increment noted for the change in design lift coefficient from 0 to 0.2 is unrealistically large and is attributed to the effects of model surface condition on maximum lift coefficient. Recent experiments at the scale of the present investigation have demonstrated that any deterioration of model surface finish from a highly polished state results in significantly reduced maximum lift. The cambered models of the present tests were maintained in a highly polished condition throughout the tests while the symmetrical section of reference 1 was not. The surface of the latter profile was eroded as a result of impingement at high speeds of fine dust and grit particles on the leading-edge region. For this reason the maximum lift coefficients of the symmetrical airfoil are not directly comparable to those of the cambered airfoils.

Lift-divergence Mach number, M_l, as a function of lift coefficient is presented in figure 10 for the airfoils investigated. It is seen that increasing camber reduces the lift-divergence Mach number at low lift coefficients and increases the value of this parameter at moderate to large lift coefficients. These results were also observed for the NACA 64A-series airfoils of reference 5.

Pitching-Moment Characteristics

The variation of pitching-moment coefficient with lift coefficient at constant Mach number is shown in figure 11 for the three airfoils. The effect of camber is to increase negatively the slopes of the pitching-moment curves at the highest Mach numbers.

Drag Characteristics

Drag coefficient is presented as a function of lift coefficient at constant Mach number in figure 12 for the profiles investigated. The anticipated benefits of camber in reducing the drag coefficient at the higher lift coefficients are generally evident in this figure.

The variation of drag-divergence Mach number with lift coefficient is shown in figure 13 for the various airfoil sections. The drag-divergence Mach number is arbitrarily defined as the Mach number for which the slope of the curve of drag coefficient as a function of Mach number at a constant angle of attack equals 0.1. The Mach number for drag divergence is affected by camber in much the same manner as was the lift-divergence Mach number. Too much significance should not be ascribed to this parameter because of its arbitrary definition (which does not take into account the magnitude of the subcritical drag); it should be regarded more as a qualitative figure of merit than as a quantitative standard for airfoil selection.

CONCLUSIONS

The results of a wind-tunnel investigation to determine the effects of moderate amounts of camber on the variation with Mach number of the aerodynamic characteristics of a 10-percent-thick modified NACA four-digit-series airfoil section lead to the following conclusions:

1. An increase in camber from 0 to 0.4 design section lift coefficient resulted in an increase in maximum lift coefficient. The effects on the respective variations with Mach number of lift-curve slope and angle of attack required to maintain a given lift coefficient were similar to those on the corresponding characteristics of an NACA 6-series airfoil of the same thickness.

2. Increasing amounts of camber produced decreases in lift- and drag-divergence Mach numbers at low lift coefficients and increases in the values of these parameters at moderate to large lift coefficients.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., July 7, 1953

REFERENCES

1. Summers, James L., and Graham, Donald J.: Effects of Systematic Changes of Trailing-Edge Angle and Leading-Edge Radius on the Variation with Mach Number of the Aerodynamic Characteristics of a 10-Percent-Chord-Thick NACA Airfoil Section. NACA RM A9G18, 1949.

2. Hemenover, Albert D.: Tests of the NACA 64-010 and 64A010 Airfoil Sections at High Subsonic Mach Numbers. NACA RM A9E31, 1949.

3. Abbott, Ira H., von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA Rep. 824, 1945.

4. Allen, H. Julian, and Vincenti, Walter G.: Wall Interference in a Two-Dimensional-Flow Wind Tunnel, with Consideration of the Effect of Compressibility. NACA Rep. 782, 1944.

5. Summers, James L., and Treon, Stuart L.: The Effects of Amount and Type of Camber on the Variation with Mach Number of the Aerodynamic Characteristics of a 10-Percent-Thick NACA 64A-Series Airfoil Section. NACA TN 2096, 1950.

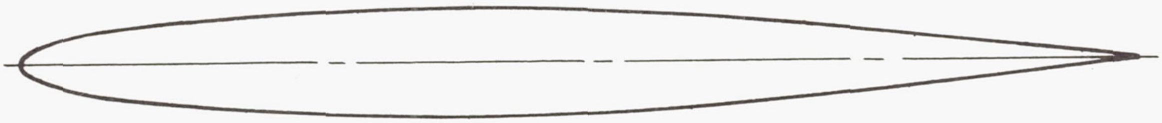
TABLE I.- AIRFOIL COORDINATES

[Stations and ordinates in percent of airfoil chord]

Upper or lower surface	
Station	Ordinate
0	0
1.25	1.466
2.5	1.966
5.0	2.589
7.5	3.009
10	3.337
15	3.845
20	4.240
30	4.791
40	5.000
50	4.783
60	4.197
70	3.338
80	2.305
90	1.193
95	.638
100	.100
L.E. radius: 1.10-percent chord	

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
1.132	1.585	1.368	-1.338
2.366	2.177	2.634	-1.746
4.857	2.953	5.143	-2.217
7.357	3.502	7.644	-2.509
9.860	3.943	10.140	-2.725
14.870	4.640	15.130	-3.046
19.884	5.188	20.116	-3.289
29.916	5.963	30.084	-3.618
39.954	6.305	40.046	-3.694
49.994	6.141	50.006	-3.425
60.030	5.526	59.970	-2.868
70.059	4.545	69.941	-2.130
80.085	3.258	79.915	-1.349
90.061	1.678	89.939	-.704
95.032	.870	94.968	-.405
100.004	.100	99.996	-.100
L.E. radius: 1.10-percent chord Slope of radius through L.E.: 0.097			

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
1.016	1.694	1.484	-1.201
2.234	2.379	2.766	-1.517
4.715	3.310	5.285	-1.837
7.214	3.989	7.786	-2.002
9.720	4.542	10.280	-2.108
14.741	5.430	15.259	-2.242
19.767	6.133	20.233	-2.334
29.832	7.133	30.168	-2.443
39.908	7.610	40.092	-2.388
49.988	7.499	50.012	-2.067
60.061	6.854	59.939	-1.539
70.117	5.751	69.883	-.921
80.169	4.207	79.831	-.390
90.121	2.161	89.879	-.213
95.063	1.100	94.937	-.170
100.008	.100	99.992	-.100
L.E. radius: 1.10-percent chord Slope of radius through L.E.: 0.194			



NACA 0010-1.10 40/1.051 airfoil section

NACA 0010-1.10 40/1.051, $c_{l_i} = 0.2$, $a = 0.8$ airfoil section

NACA 0010-1.10 40/1.051, $c_{l_i} = 0.4$, $a = 0.8$ airfoil section

Figure 1.- NACA airfoil profiles investigated.

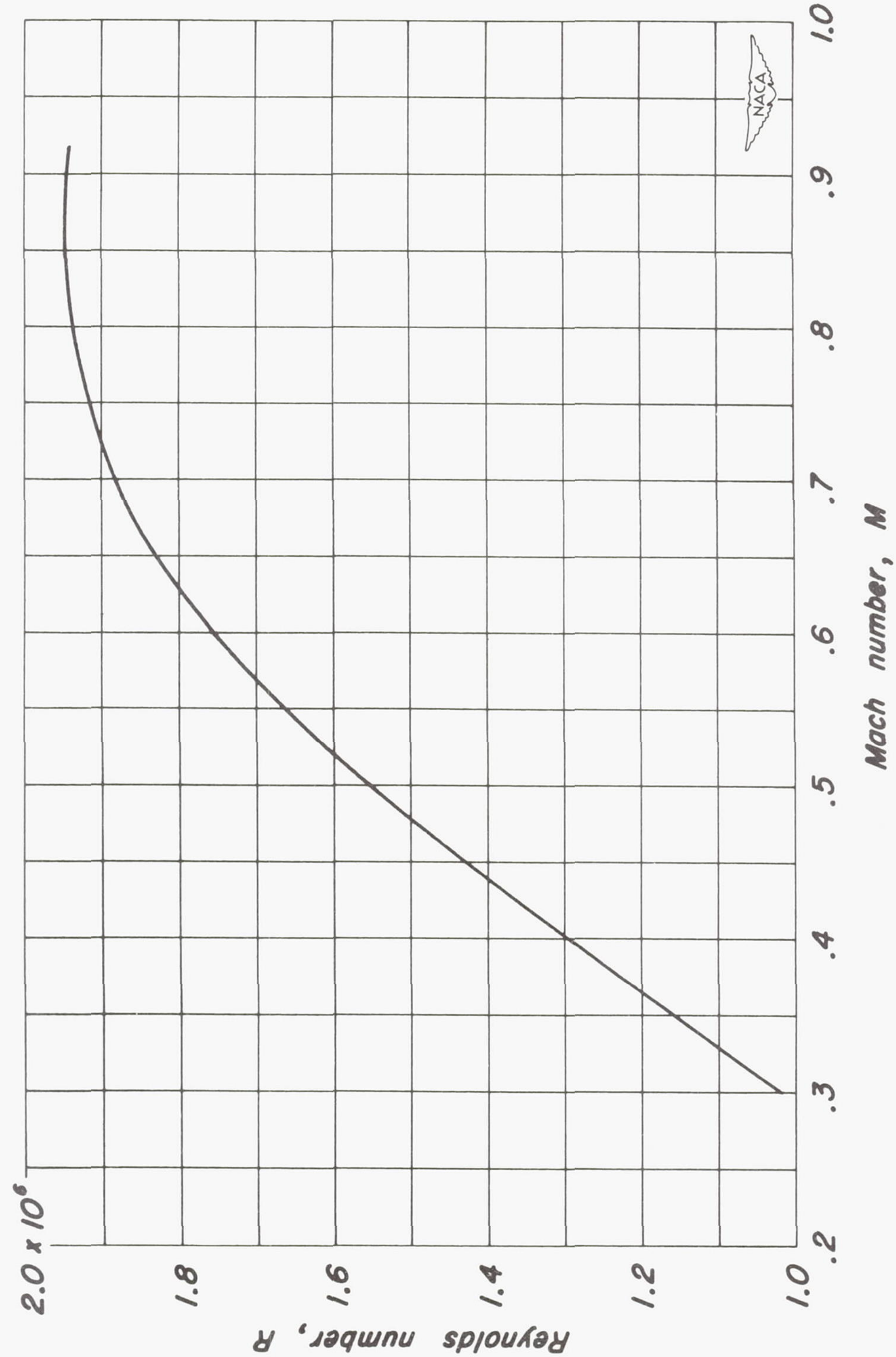
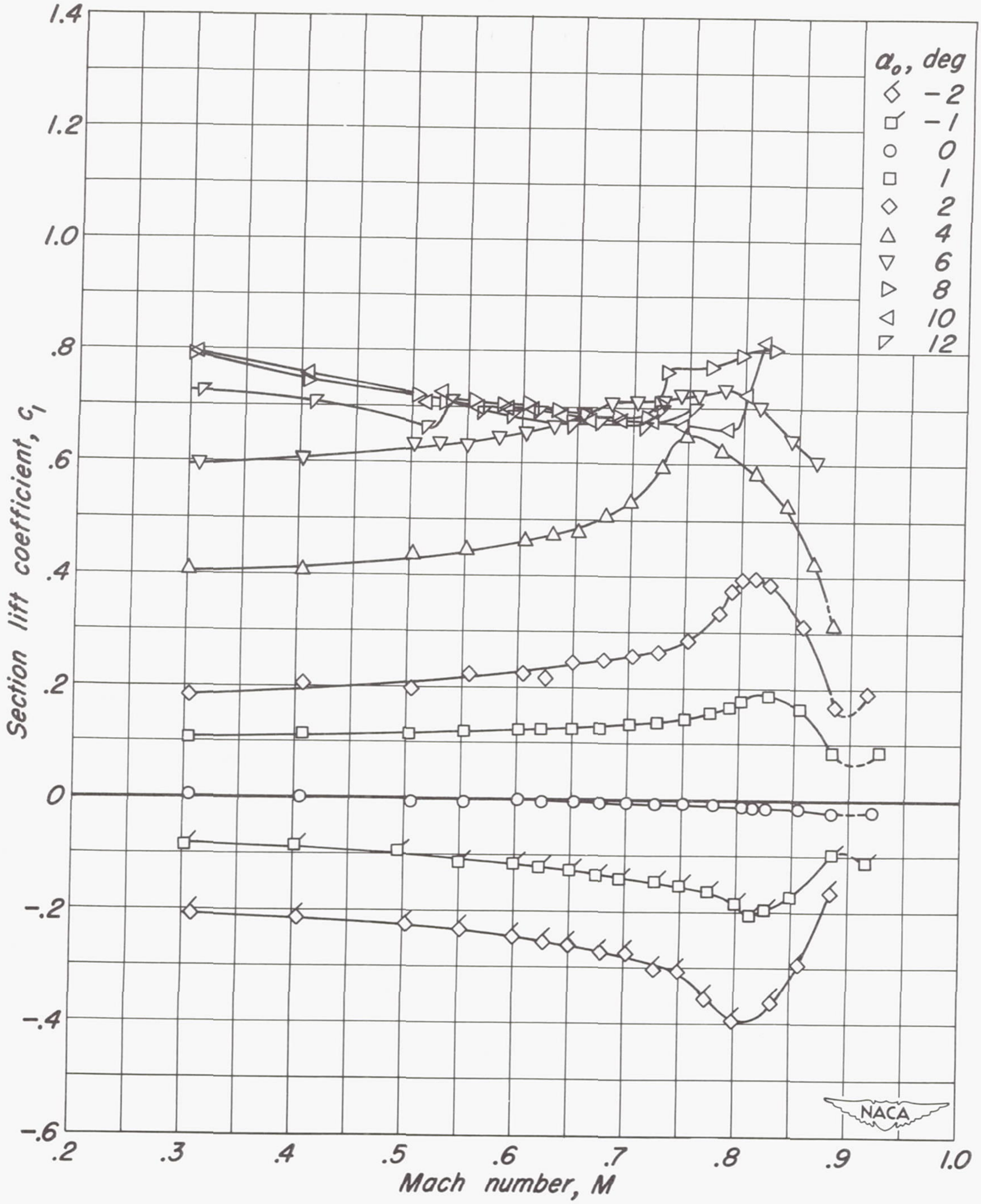
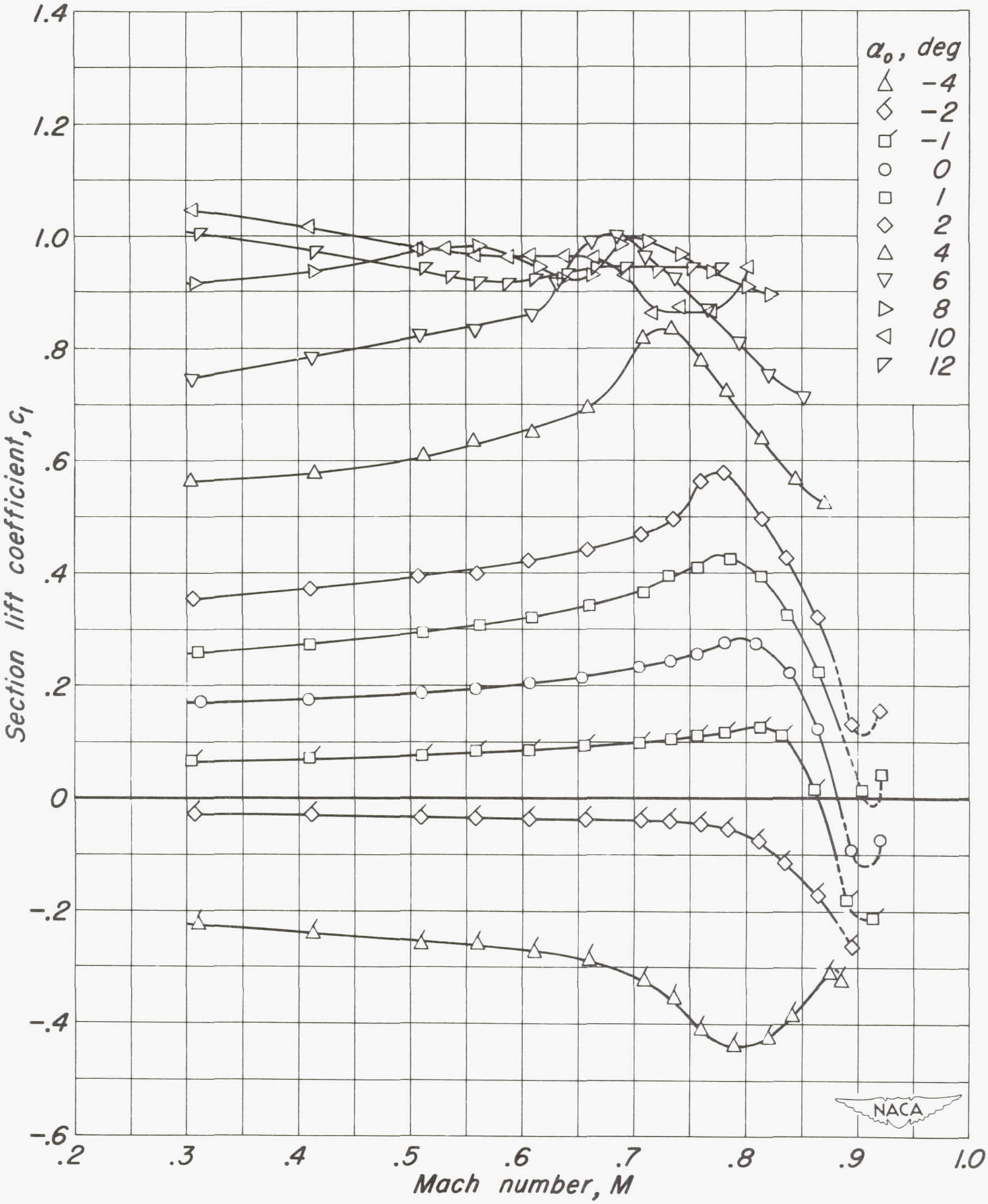


Figure 2.- Variation of Reynolds number with Mach number for 6-inch-chord airfoils in the Ames 1- by $3\frac{1}{2}$-foot high-speed wind tunnel.



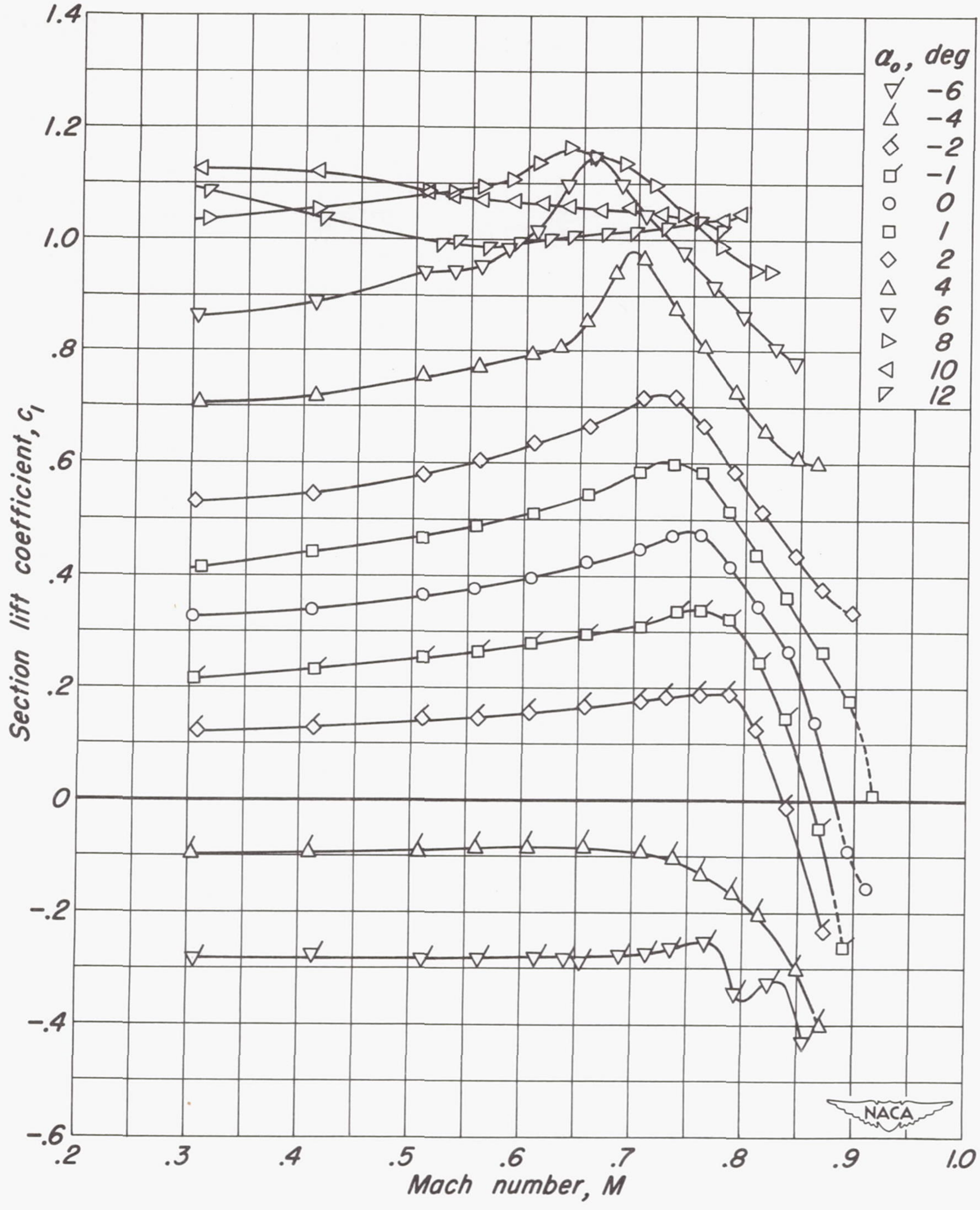
(a) NACA 0010-1.10 40/1.051 airfoil section.

Figure 3.- Variation of section lift coefficient with Mach number at constant section angles of attack.



(b) NACA 0010-1.10 40/1.051, c_{l_i}=0.2, a=0.8 airfoil section.

Figure 3.- Continued.



(c) NACA 0010-1.10 40/1.051, c_{l_i}=0.4, a=0.8 airfoil section.

Figure 3.- Concluded.

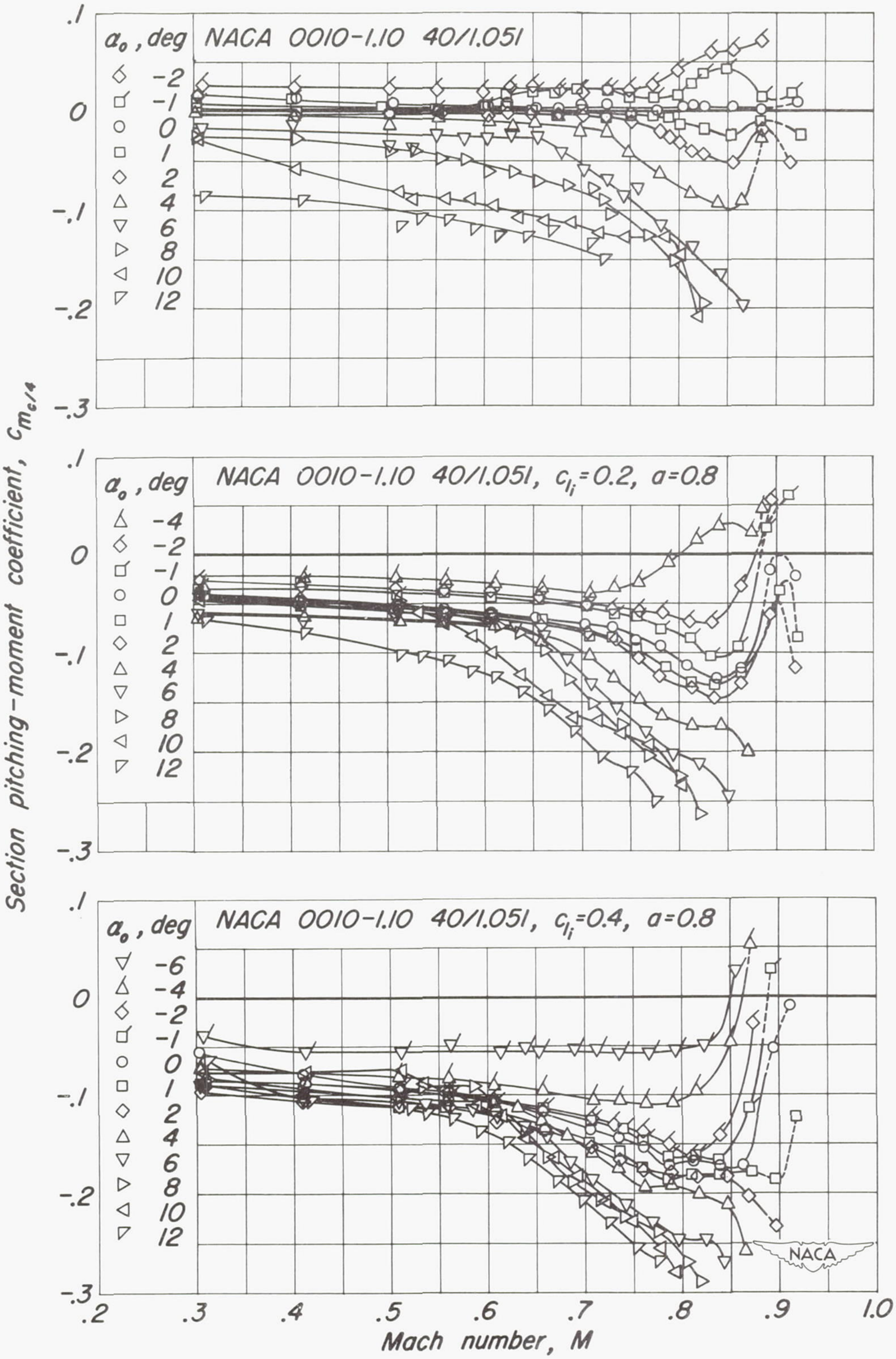
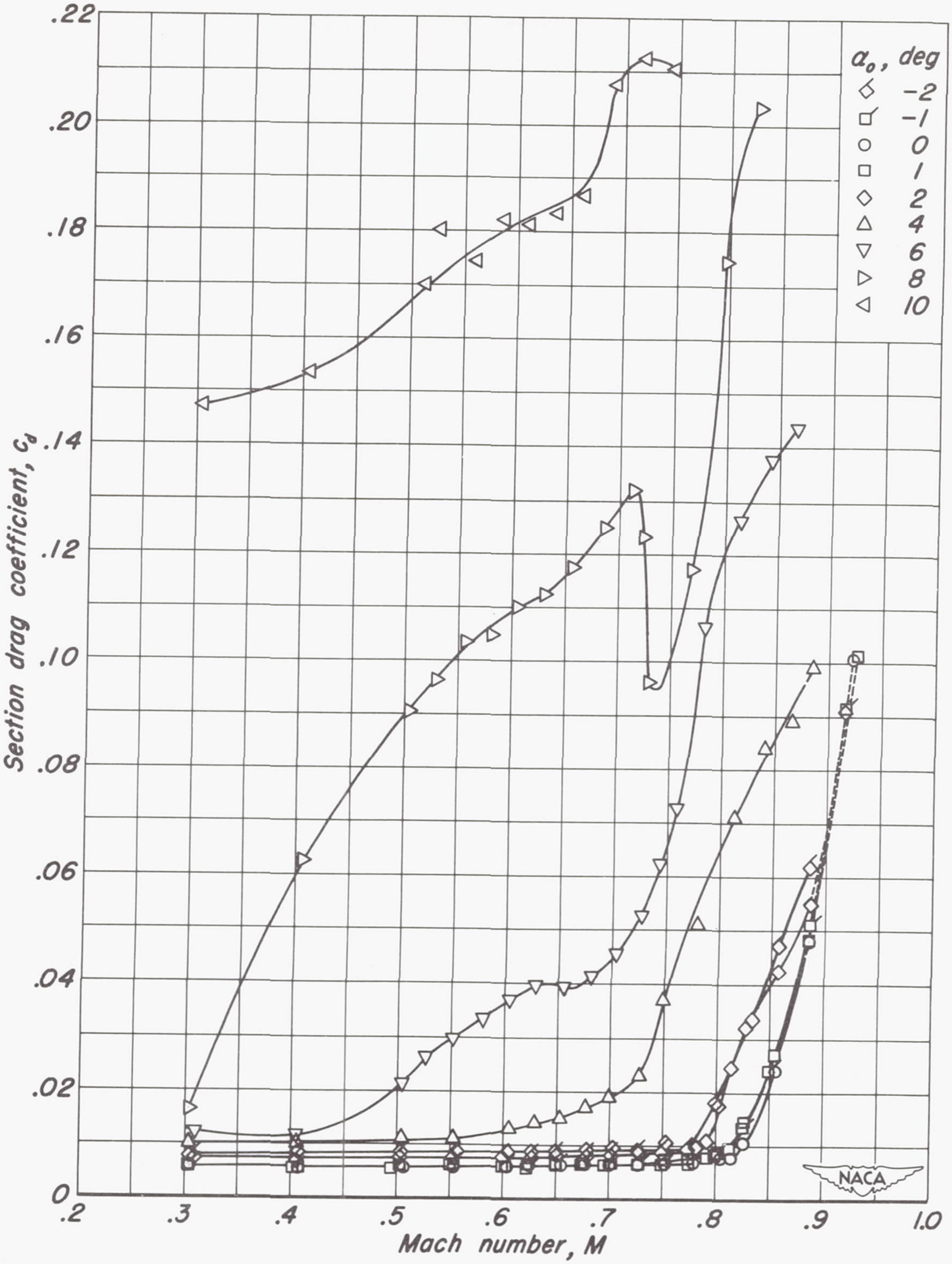
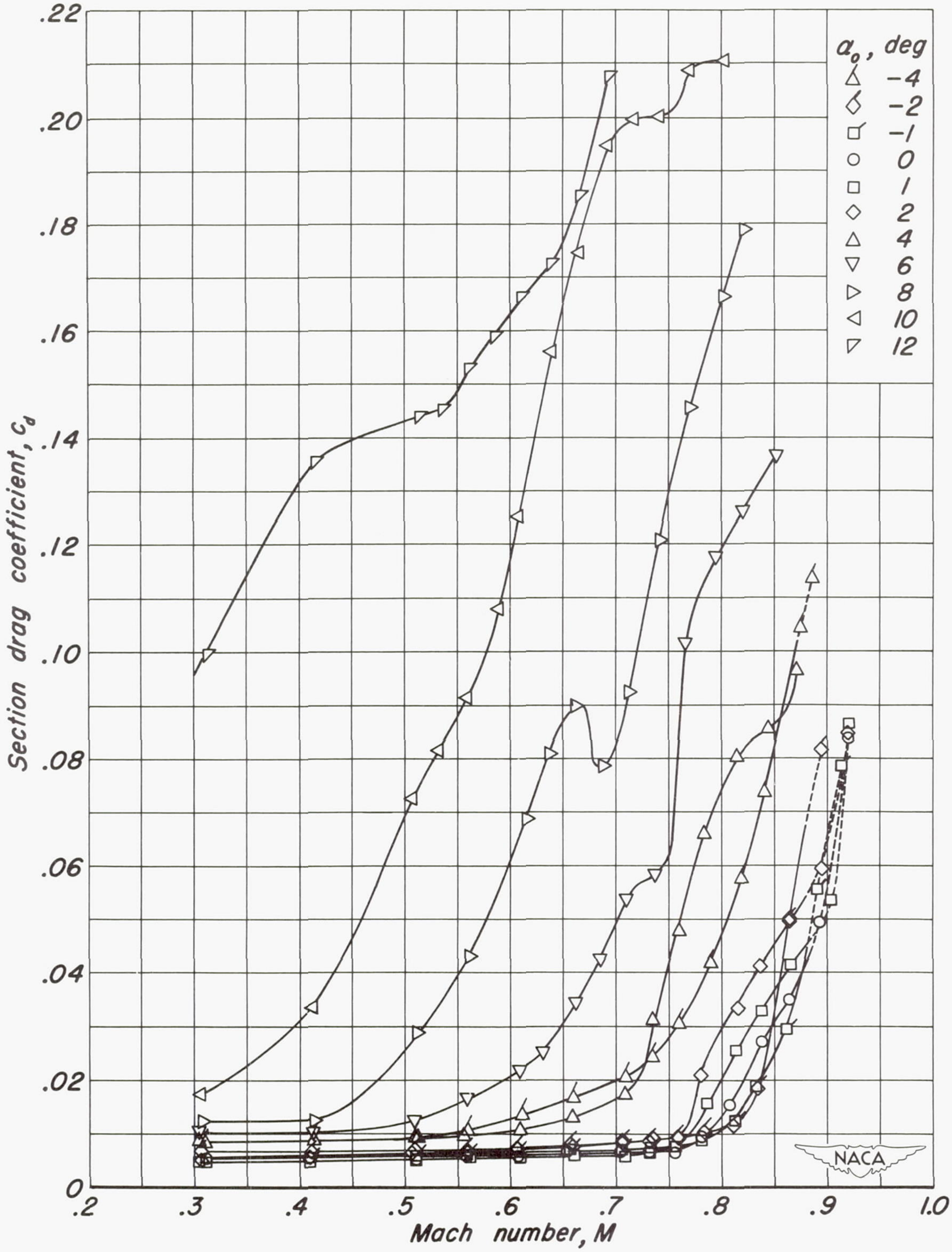


Figure 4.- Variation of section pitching-moment coefficient with Mach number at constant section angles of attack.



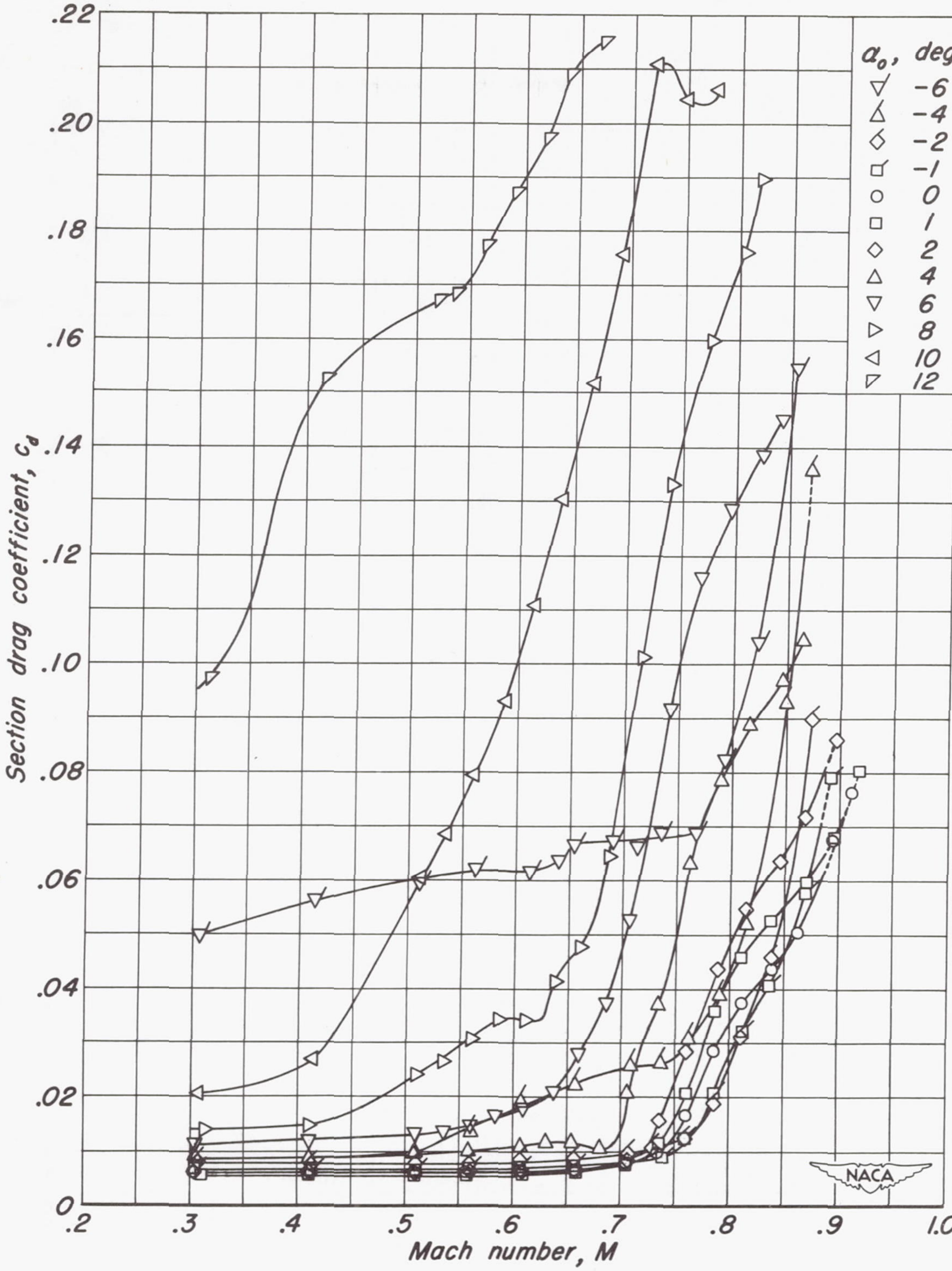
(a) NACA 0010-1.10 40/1.051 airfoil section.

Figure 5.- Variation of section drag coefficient with Mach number at constant section angles of attack.



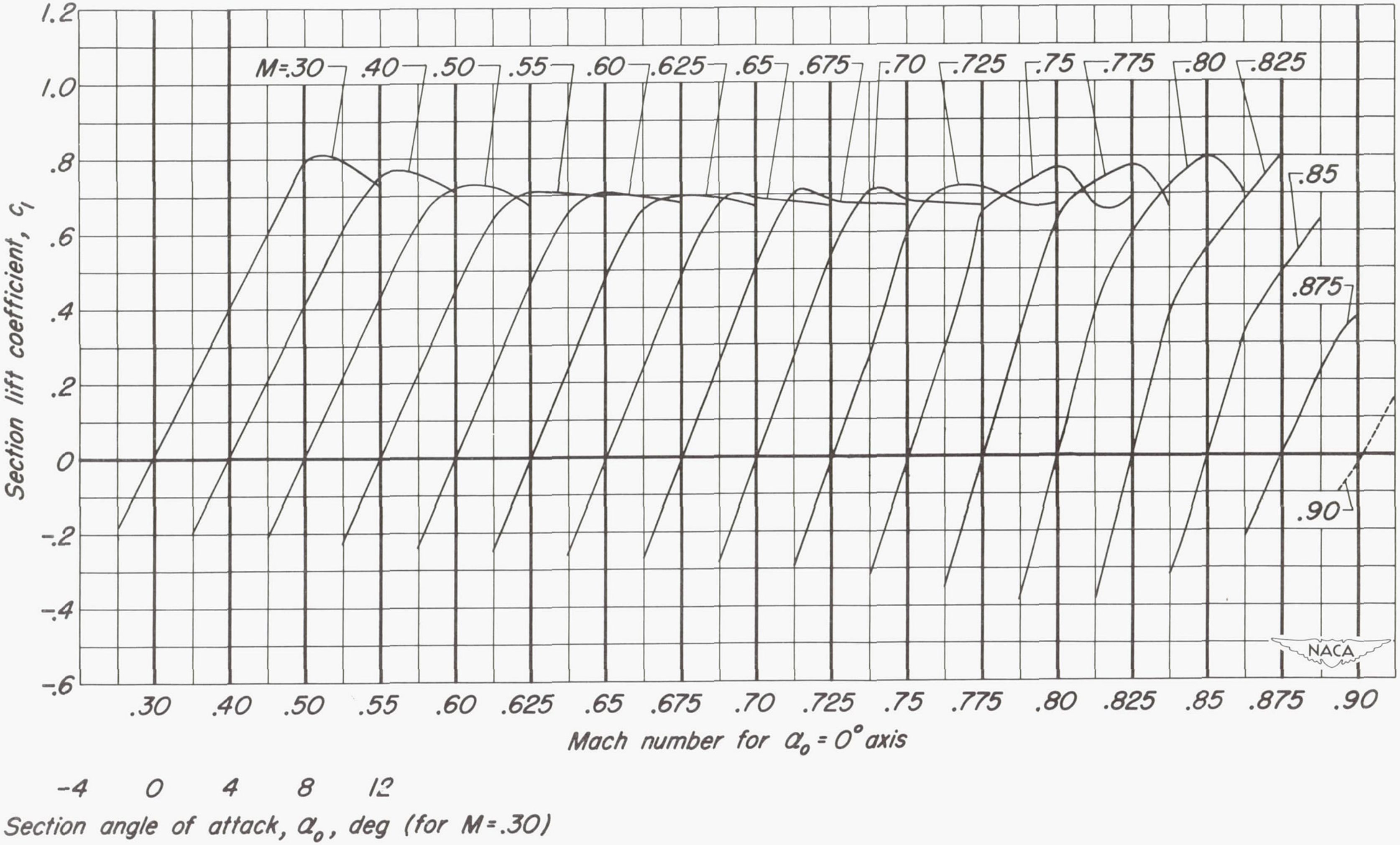
(b) NACA 0010-1.10 40/1.051, c_{l_i}=0.2, a=0.8 airfoil section.

Figure 5.- Continued.



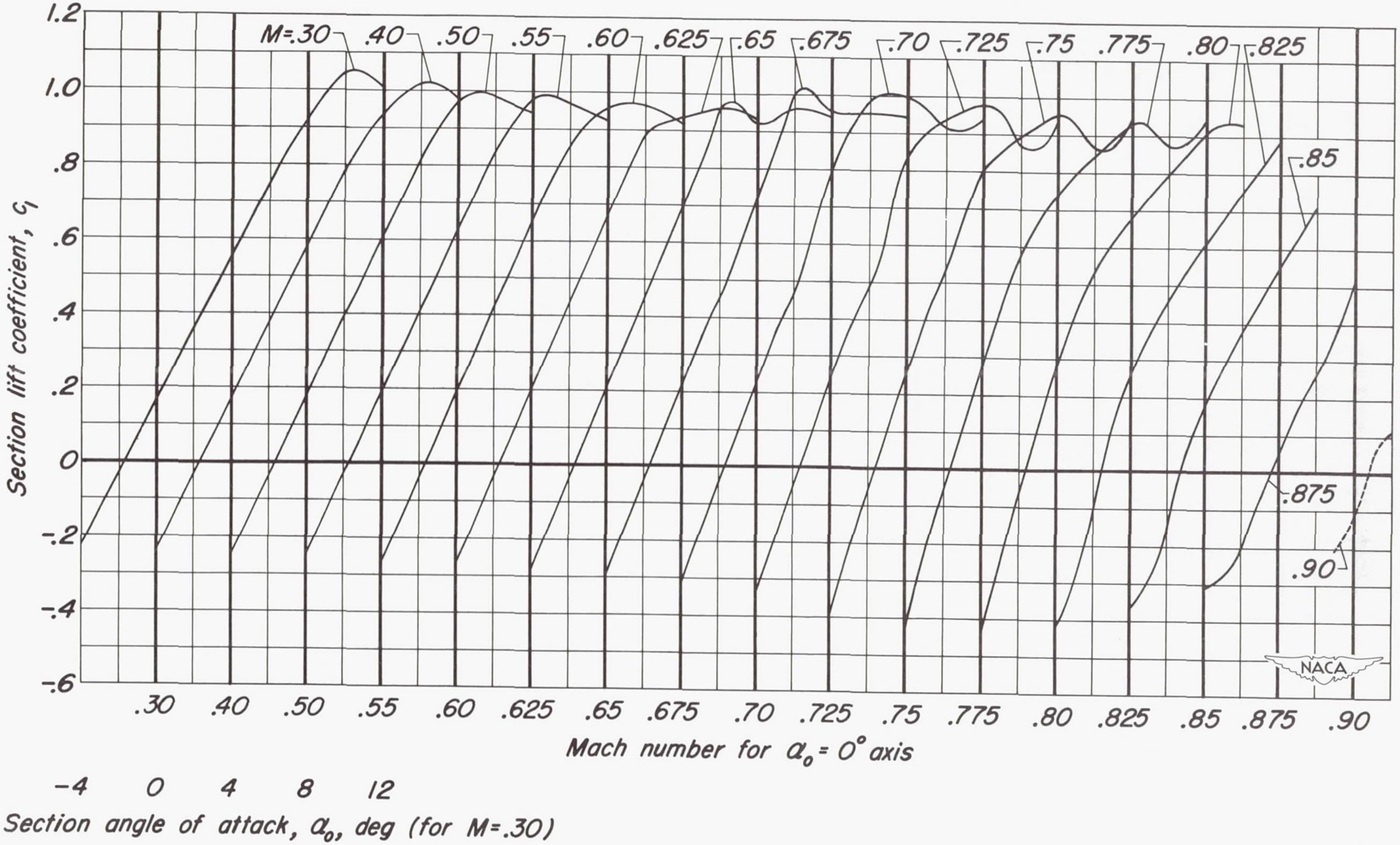
(c) NACA 0010-1.10 40/1.051, c_{l_i}=0.4, a=0.8 airfoil section.

Figure 5.- Concluded.



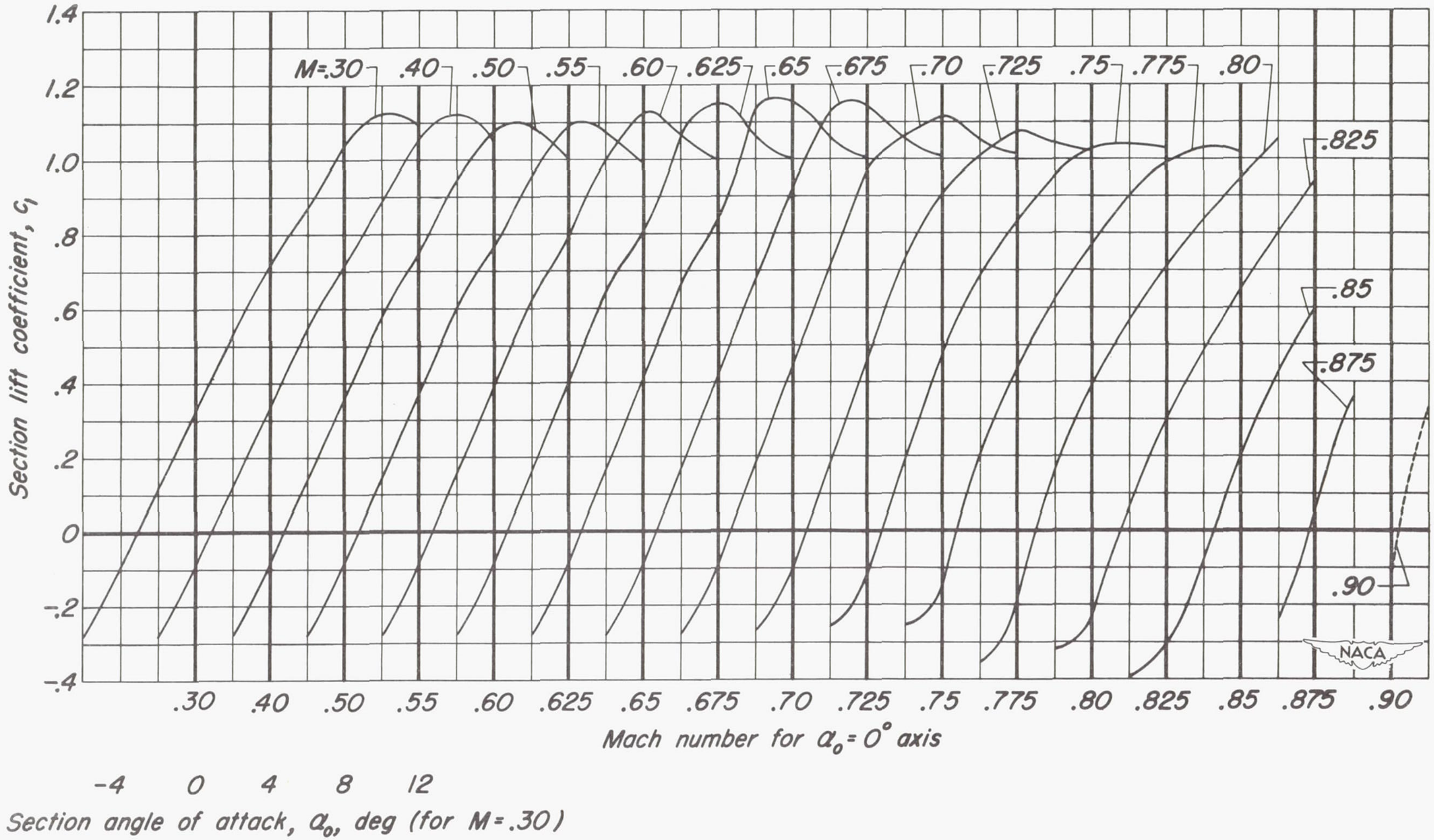
(a) NACA 0010-1.10 40/1.051 airfoil section.

Figure 6.- Variation of section lift coefficient with section angle of attack at various Mach numbers.



(b) NACA 0010-1.10 40/1.051, $c_{l_i}=0.2$, $a=0.8$ airfoil section.

Figure 6.- Continued.



(c) NACA 0010-1.10 40/1.051, c_{l_i}=0.4, a=0.8 airfoil section.

Figure 6.- Concluded.

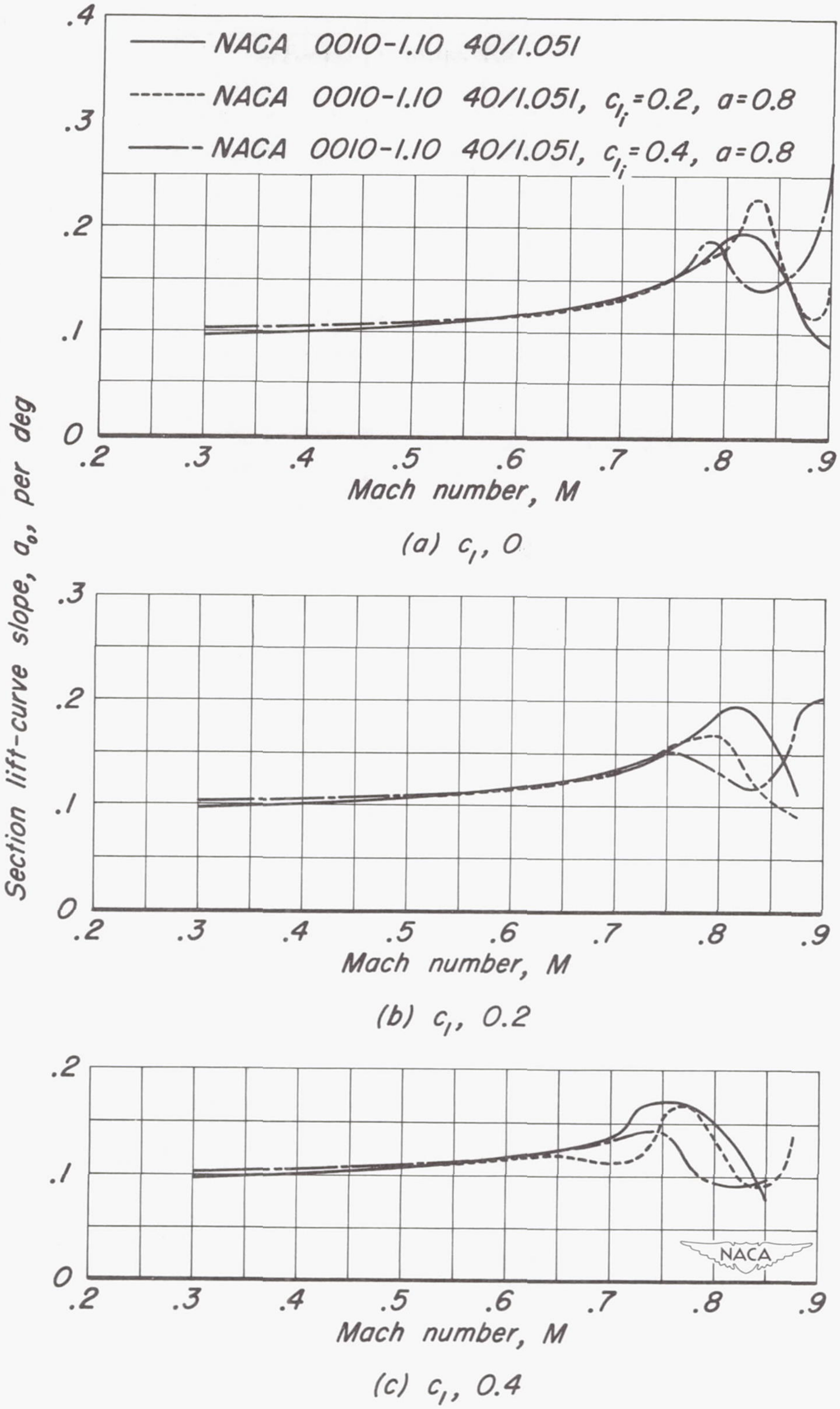
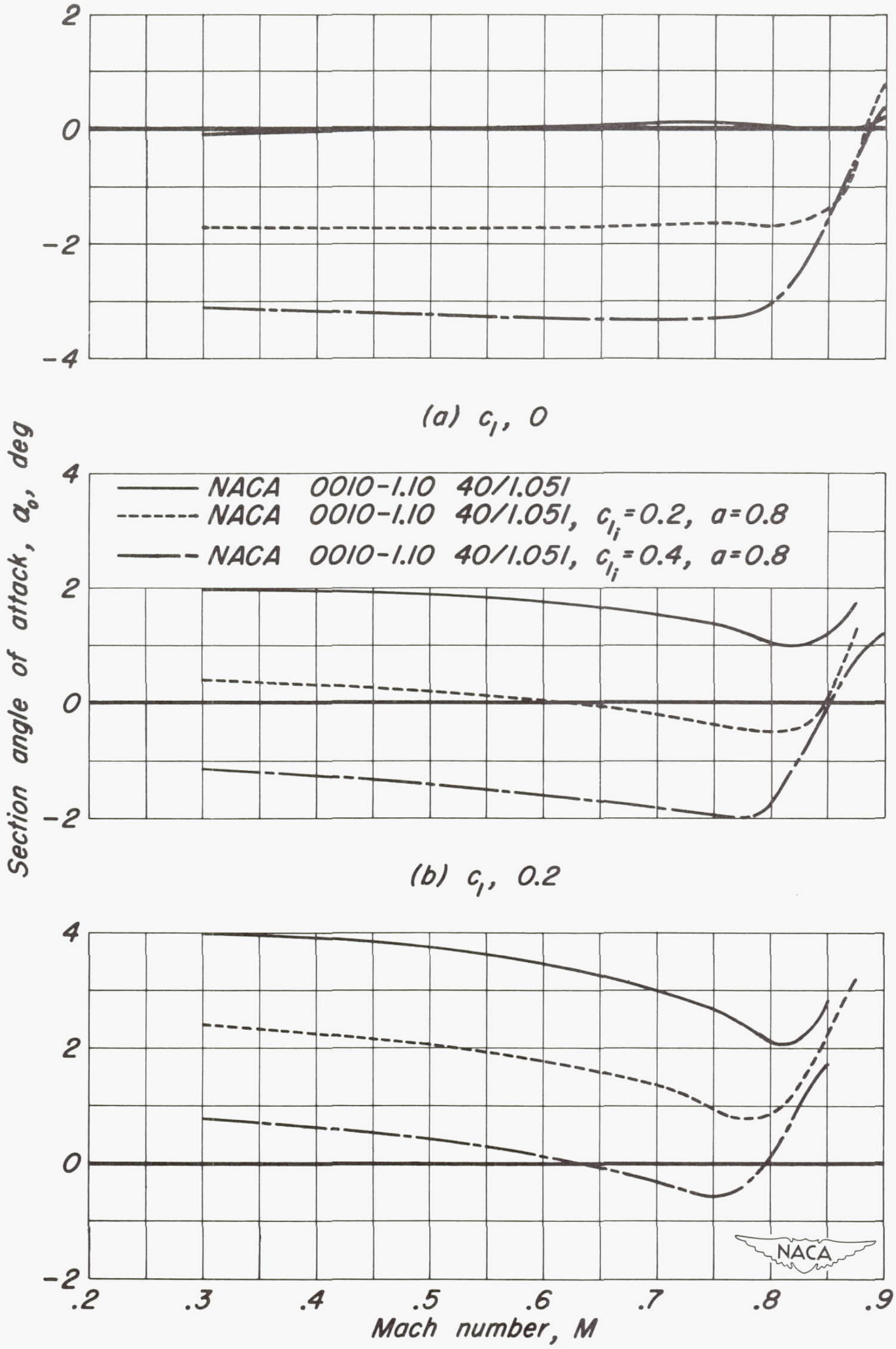


Figure 7.- Effect of camber on the variation of section lift-curve slope with Mach number.



(a) c_l, 0

(b) c_l, 0.2

(c) c_l, 0.4

Figure 8.- Effect of camber on the variation with Mach number of section angle of attack required at several values of section lift coefficient.

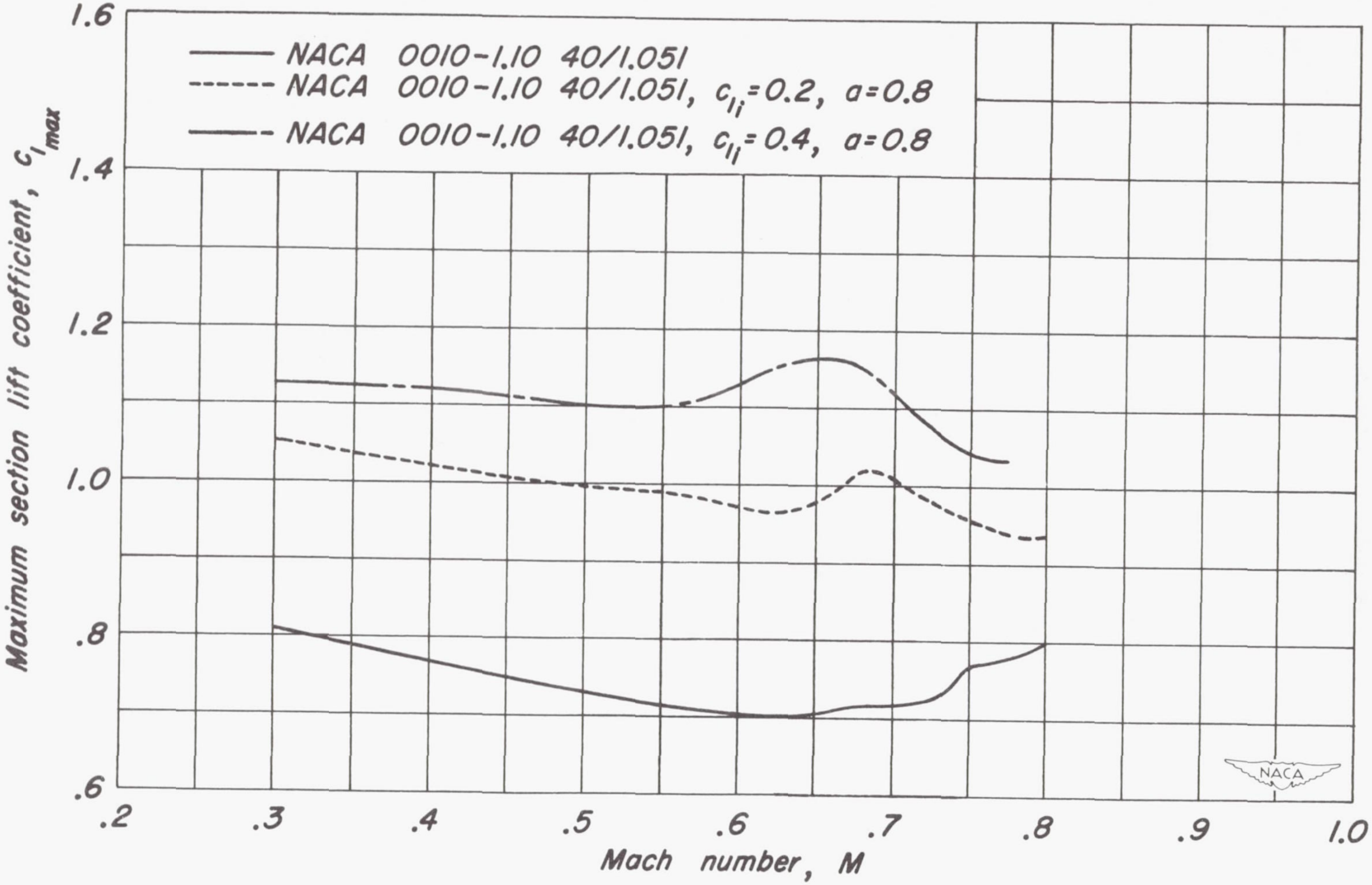


Figure 9.- Effect of camber on the variation of maximum section lift coefficient with Mach number.

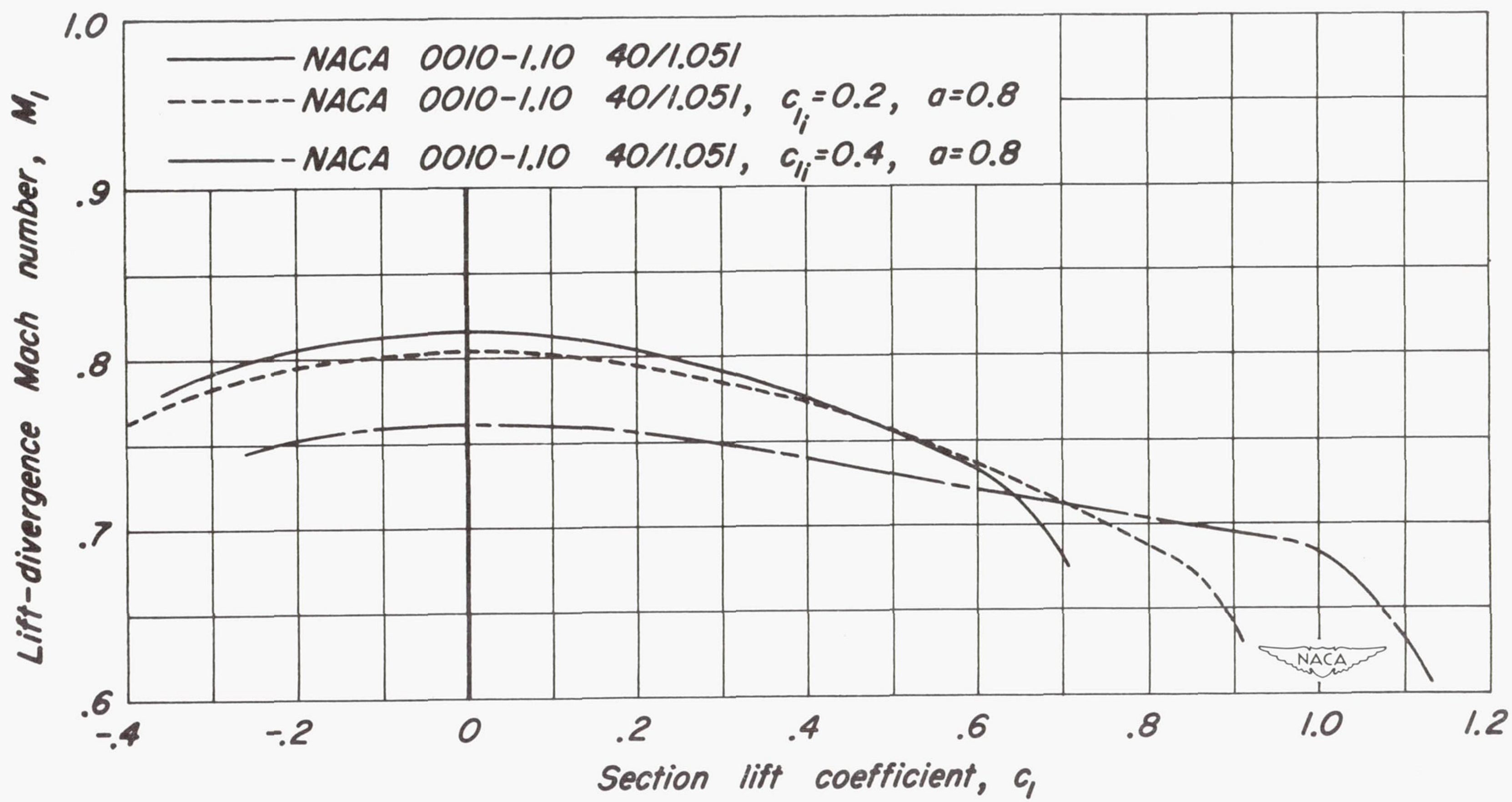
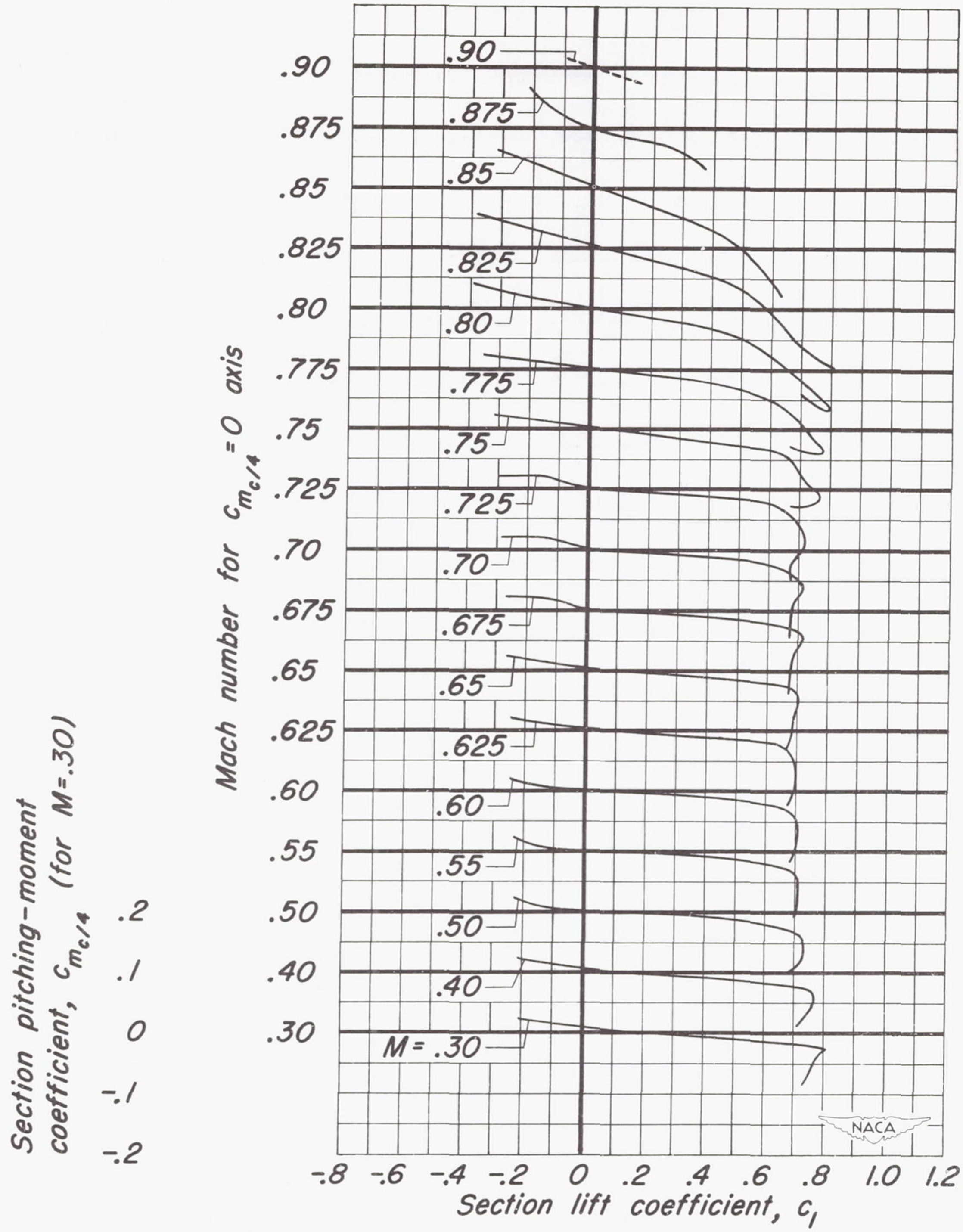
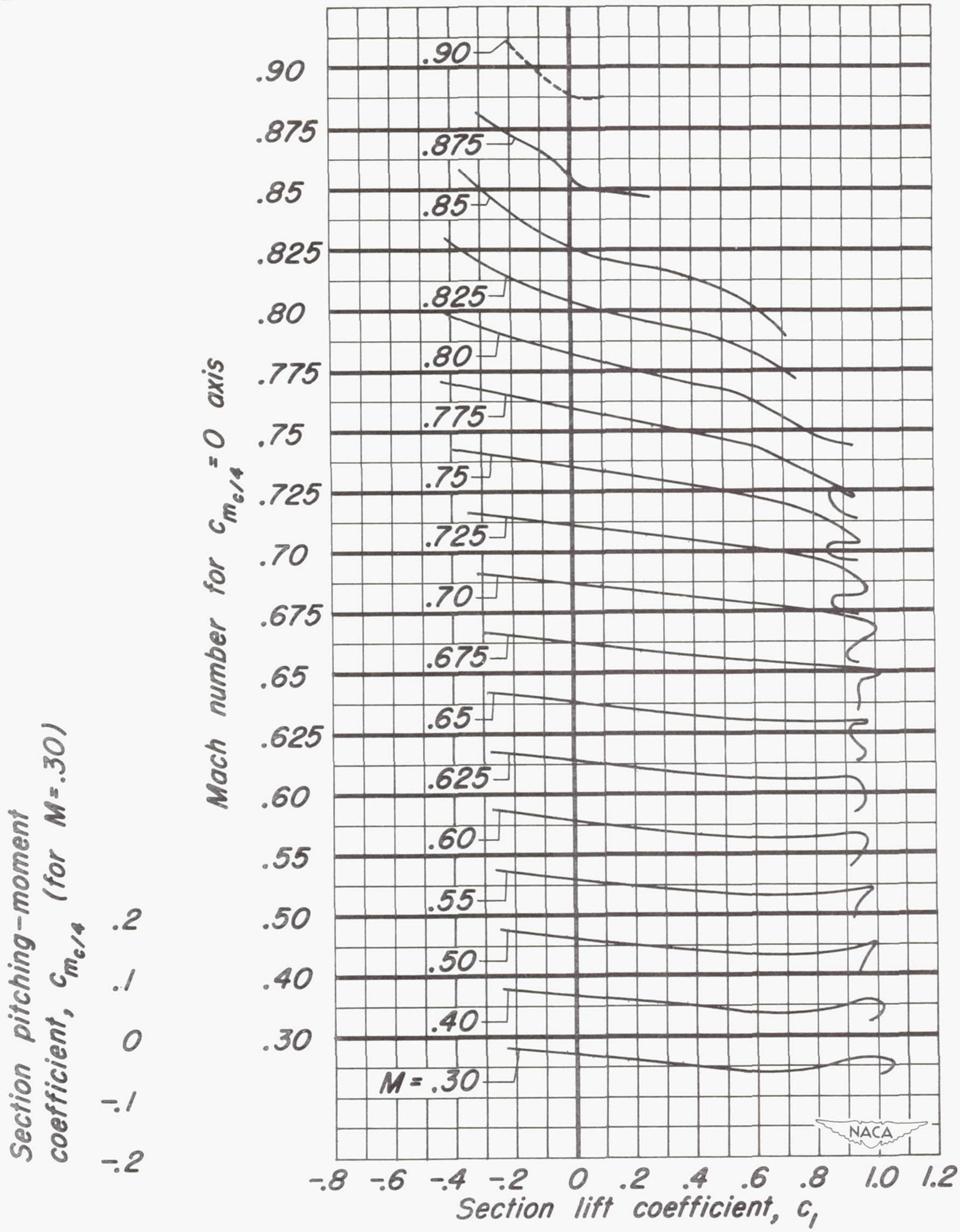


Figure 10.– Effect of camber on the variation of lift-divergence Mach number with section lift coefficient.



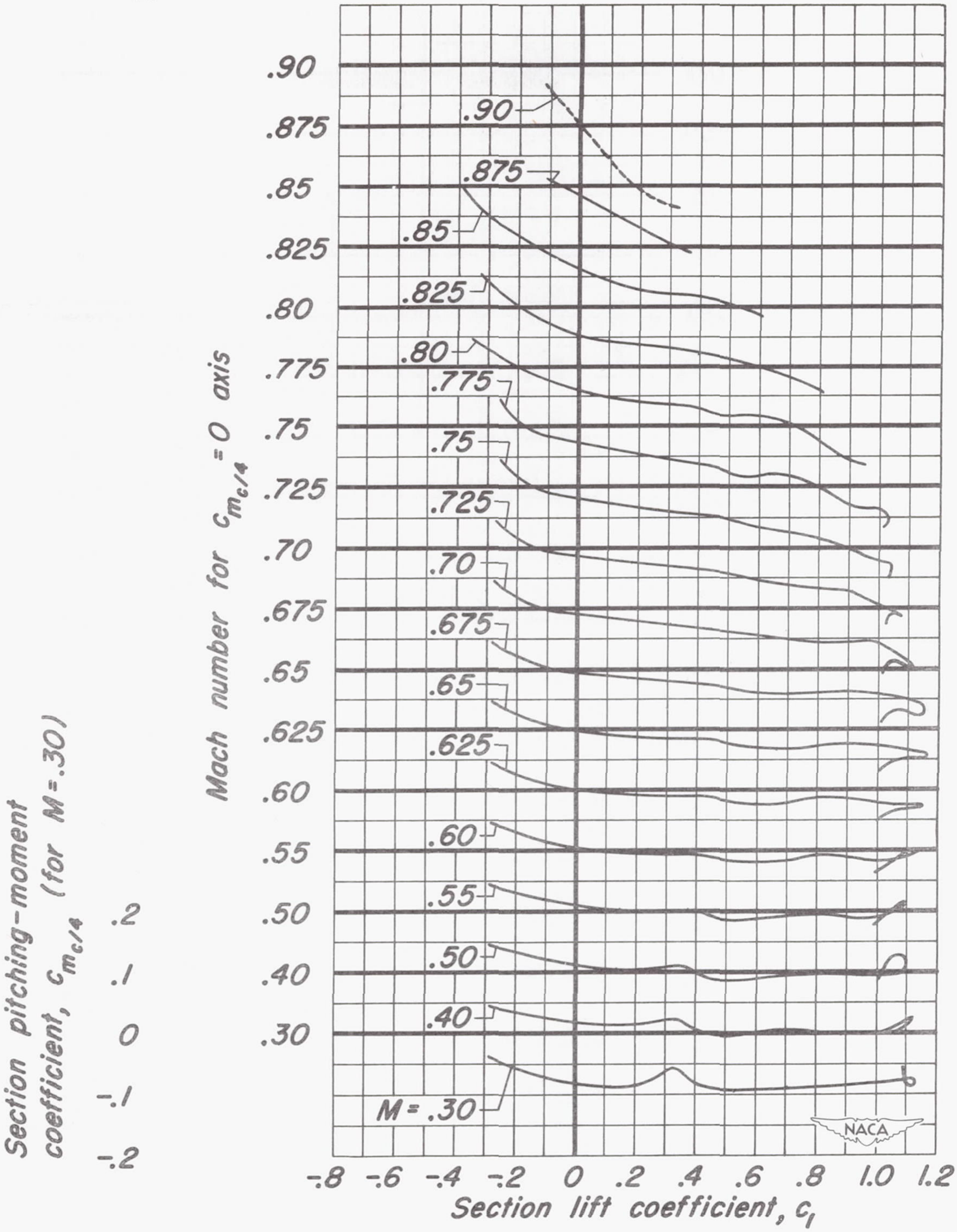
(a) NACA 0010-1.10 40/1.051 airfoil section.

Figure 11.- Variation of section pitching-moment coefficient with section lift coefficient at various Mach numbers.



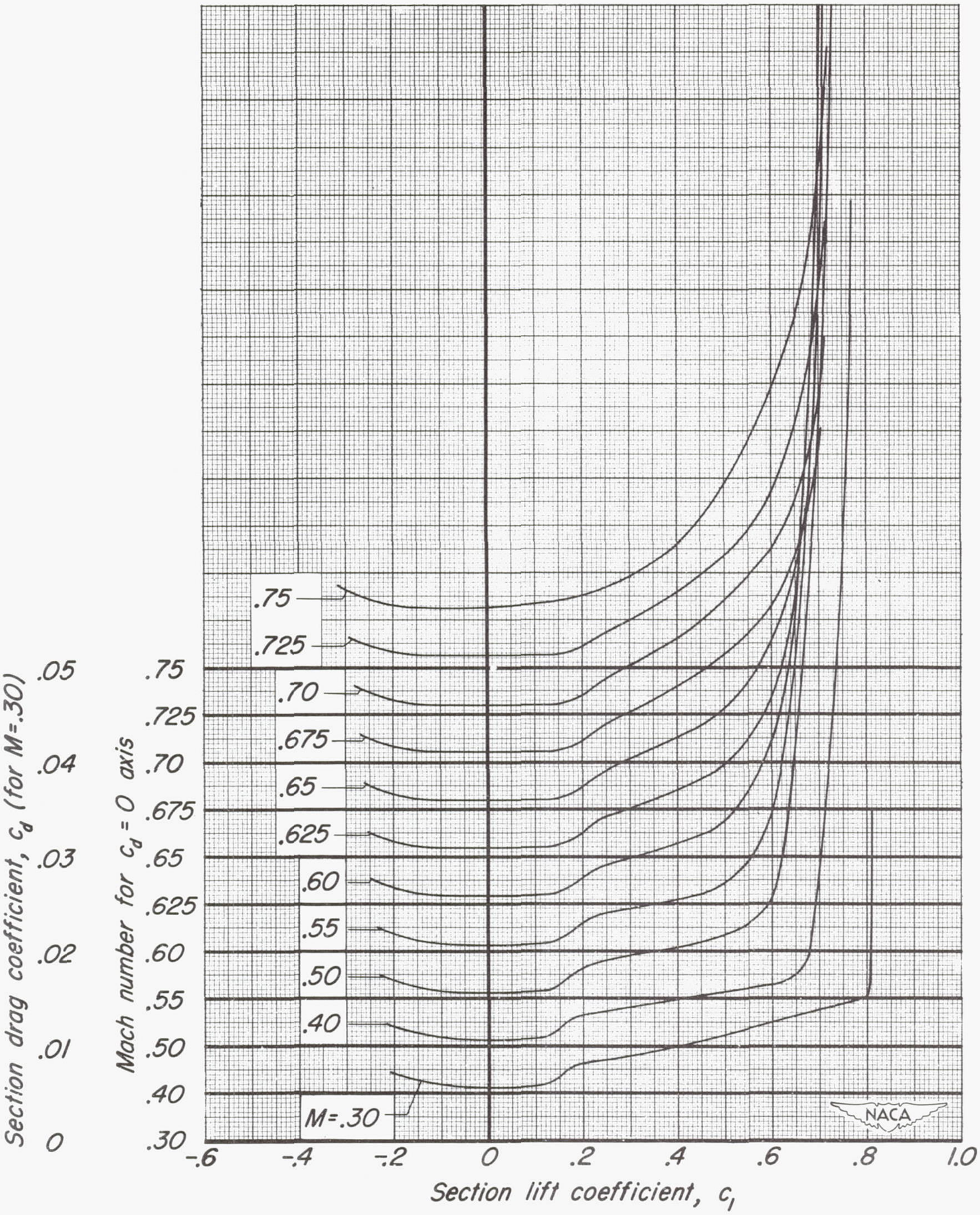
(b) NACA 0010-1.10 40/1.051, c_{l_i}=0.2, a=0.8 airfoil section.

Figure 11.- Continued.



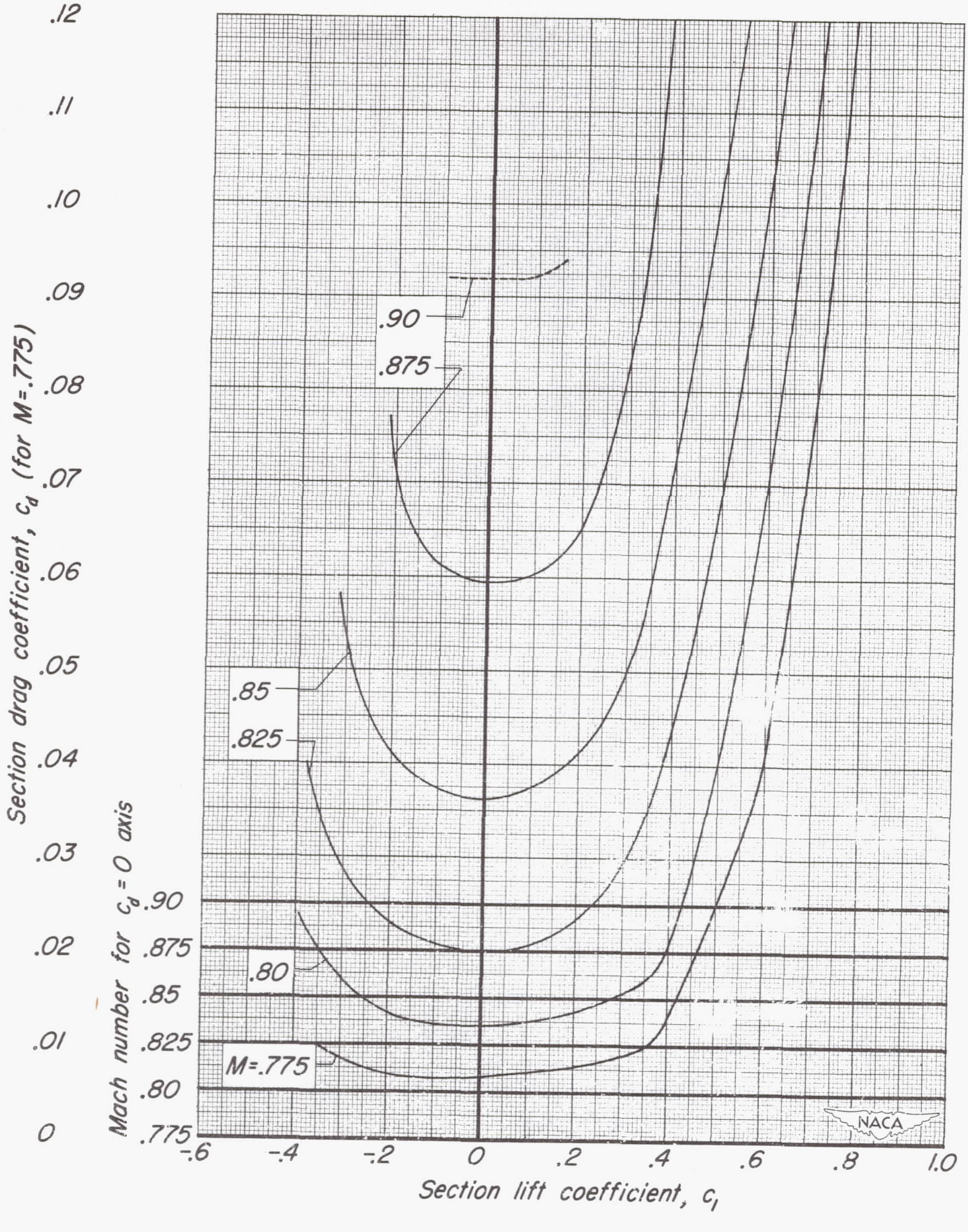
(c) NACA 0010-1.10 40/1.051, c_{l_i}=0.4, a=0.8 airfoil section.

Figure 11.- Concluded.



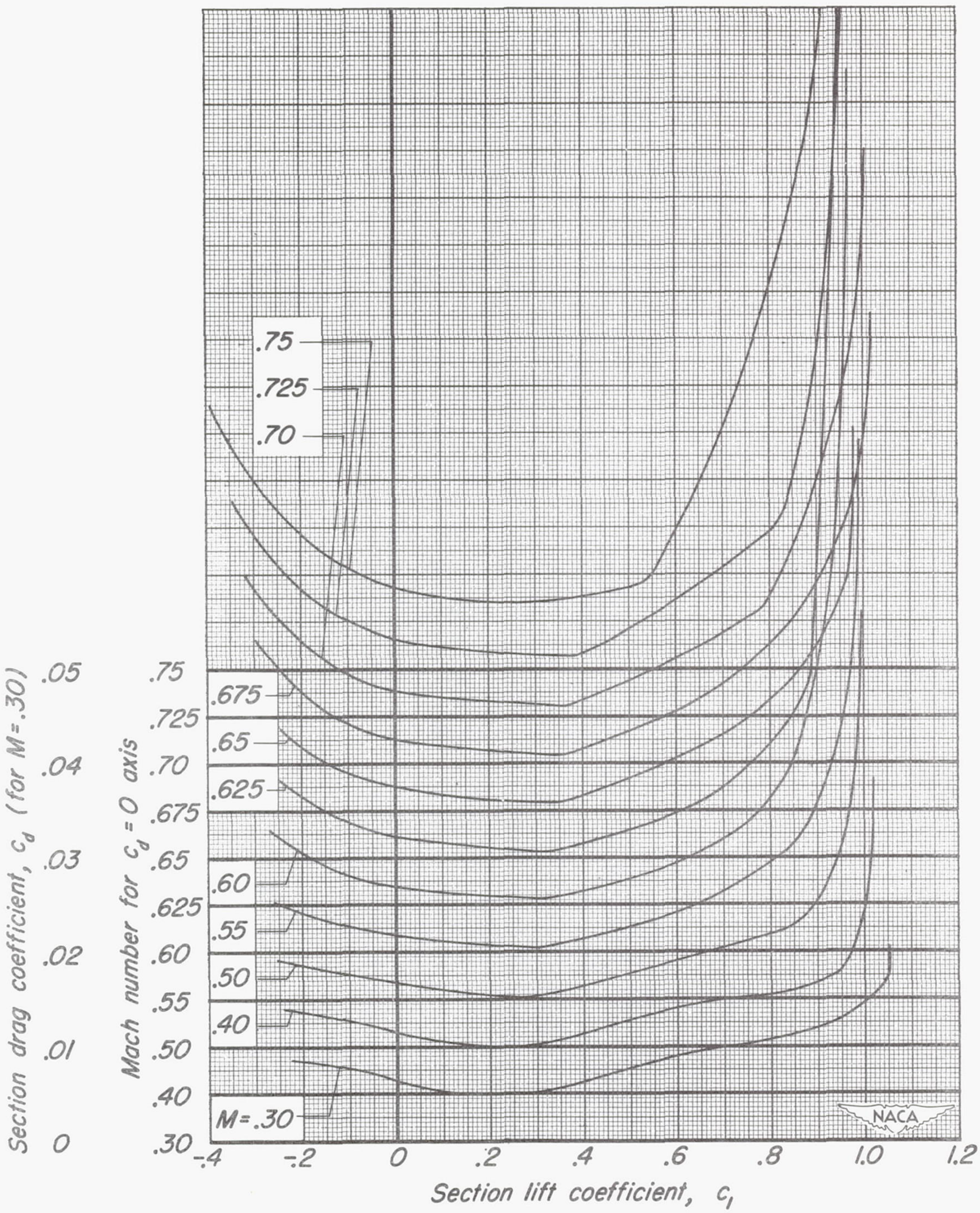
(a) NACA 0010-1.10 40/1.051 airfoil section; M, 0.30 to 0.75.

Figure 12.- Variation of section drag coefficient with section lift coefficient at various Mach numbers.



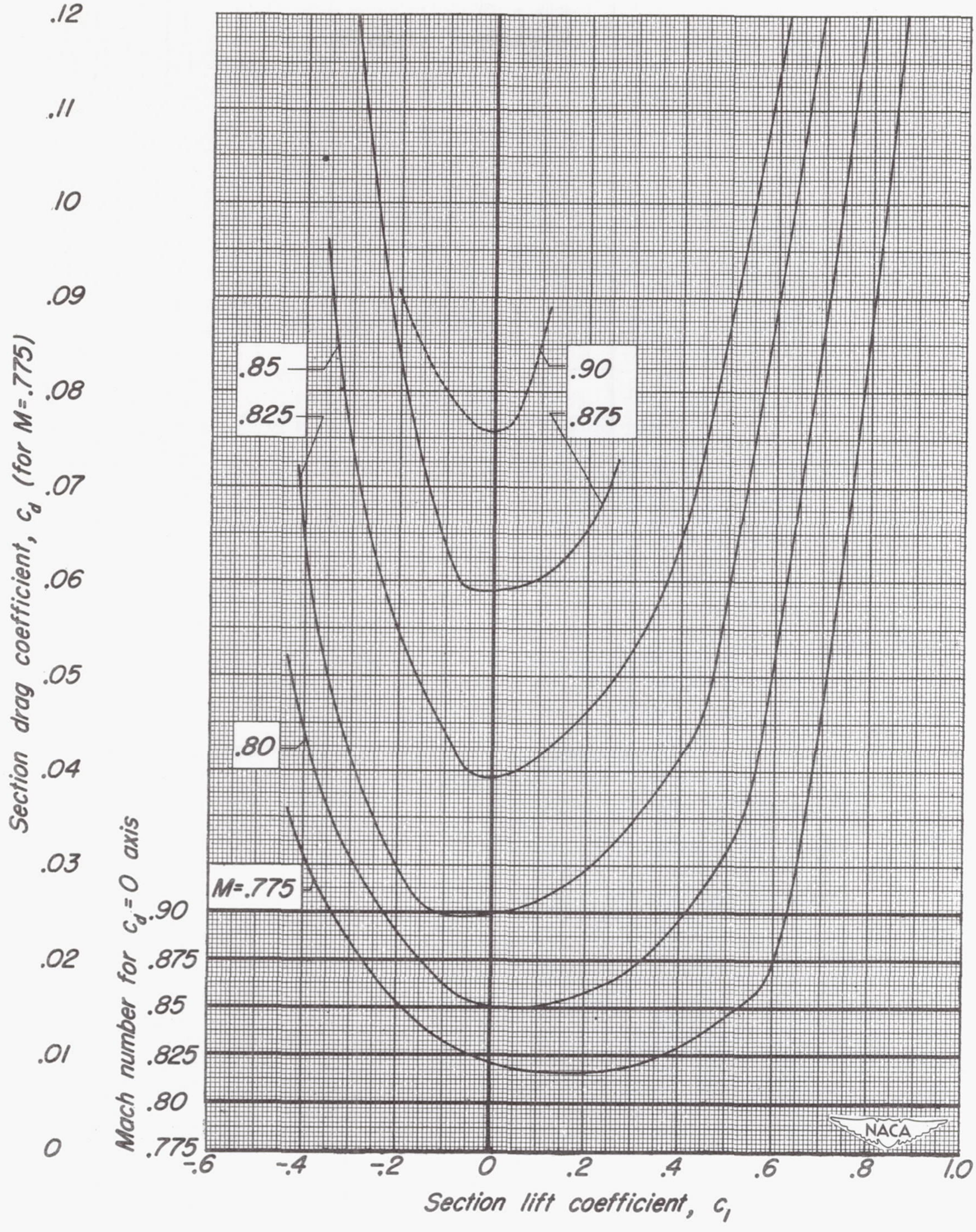
(b) NACA 0010-1.10 40/1.051 airfoil section; M, 0.775 to 0.90.

Figure 12.- Continued.



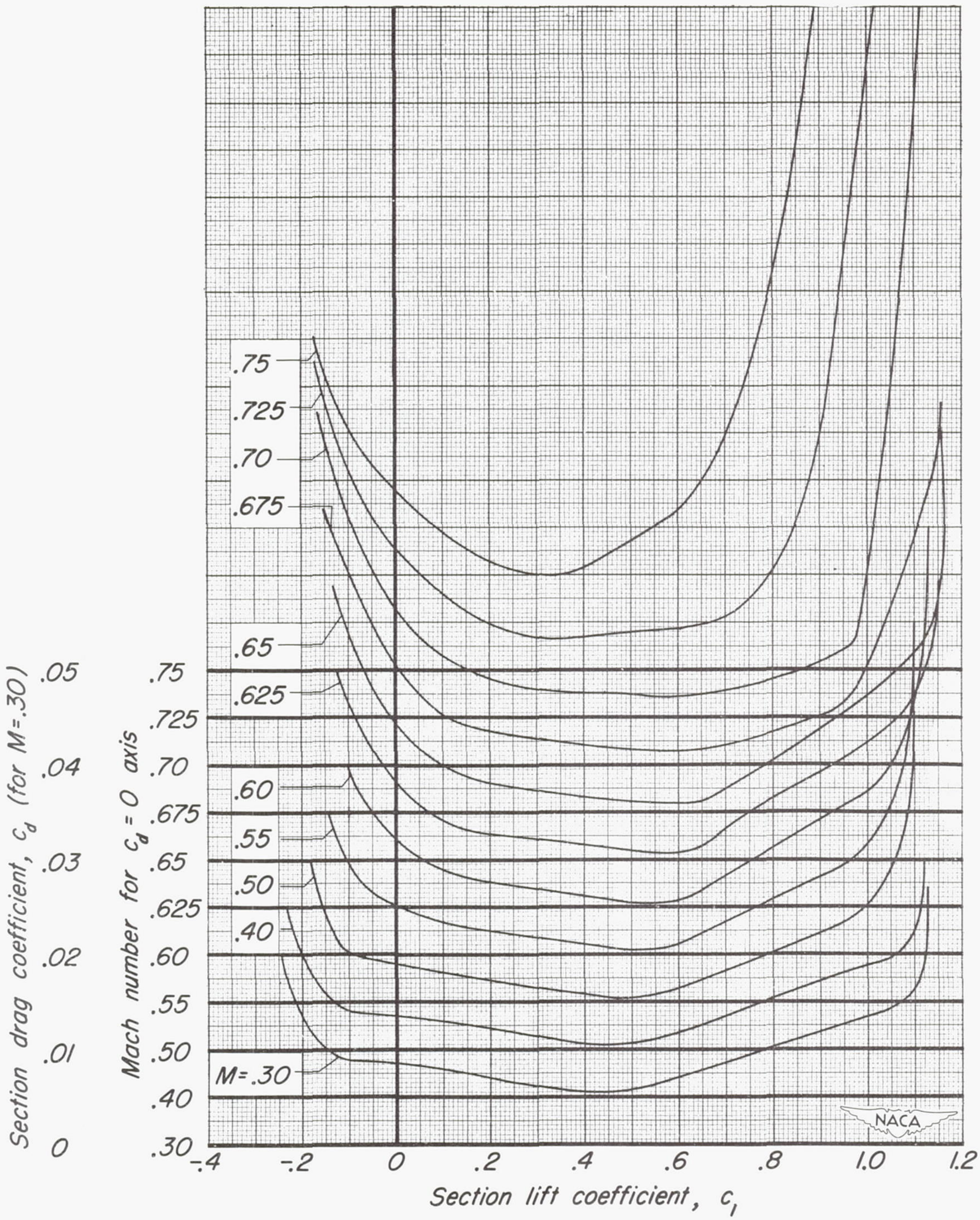
(c) NACA 0010-1.10 40/1.051, c_{l_i}=0.2, a=0.8 airfoil section; M, 0.30 to 0.75.

Figure 12.- Continued.



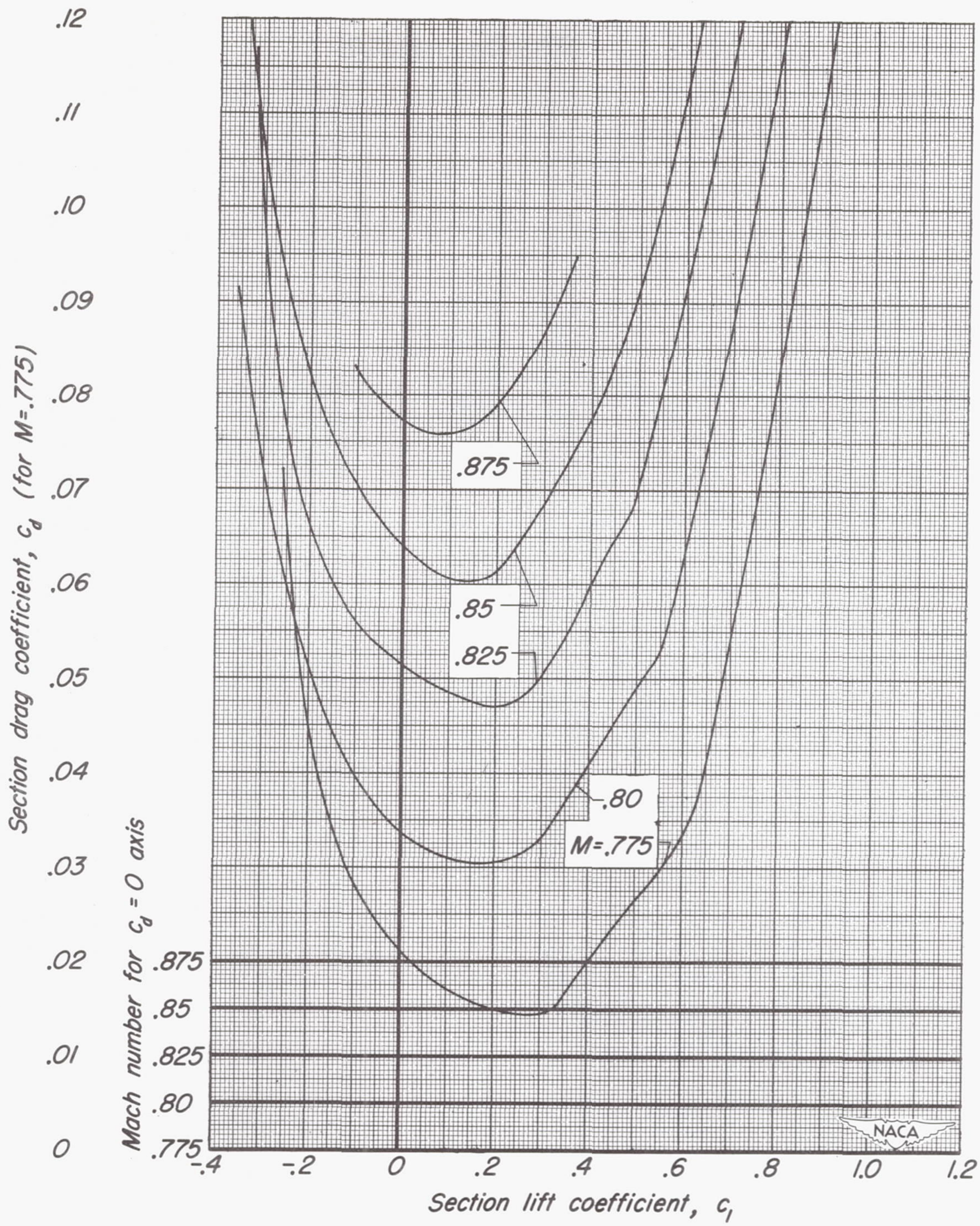
(d) NACA 0010-1.10 40/1.051, c_{l_i}=0.2, a=0.8 airfoil section; M, 0.775 to 0.90.

Figure 12.- Continued.



(e) NACA 0010-1.10 40/1.051, c_{l_i}=0.4, a=0.8 airfoil section; M, 0.30 to 0.75.

Figure 12.- Continued.



(f) NACA 0010-1.10 40/1.051, c_{l_i}=0.4, a=0.8 airfoil section; M, 0.775 to 0.875.

Figure 12.- Concluded.

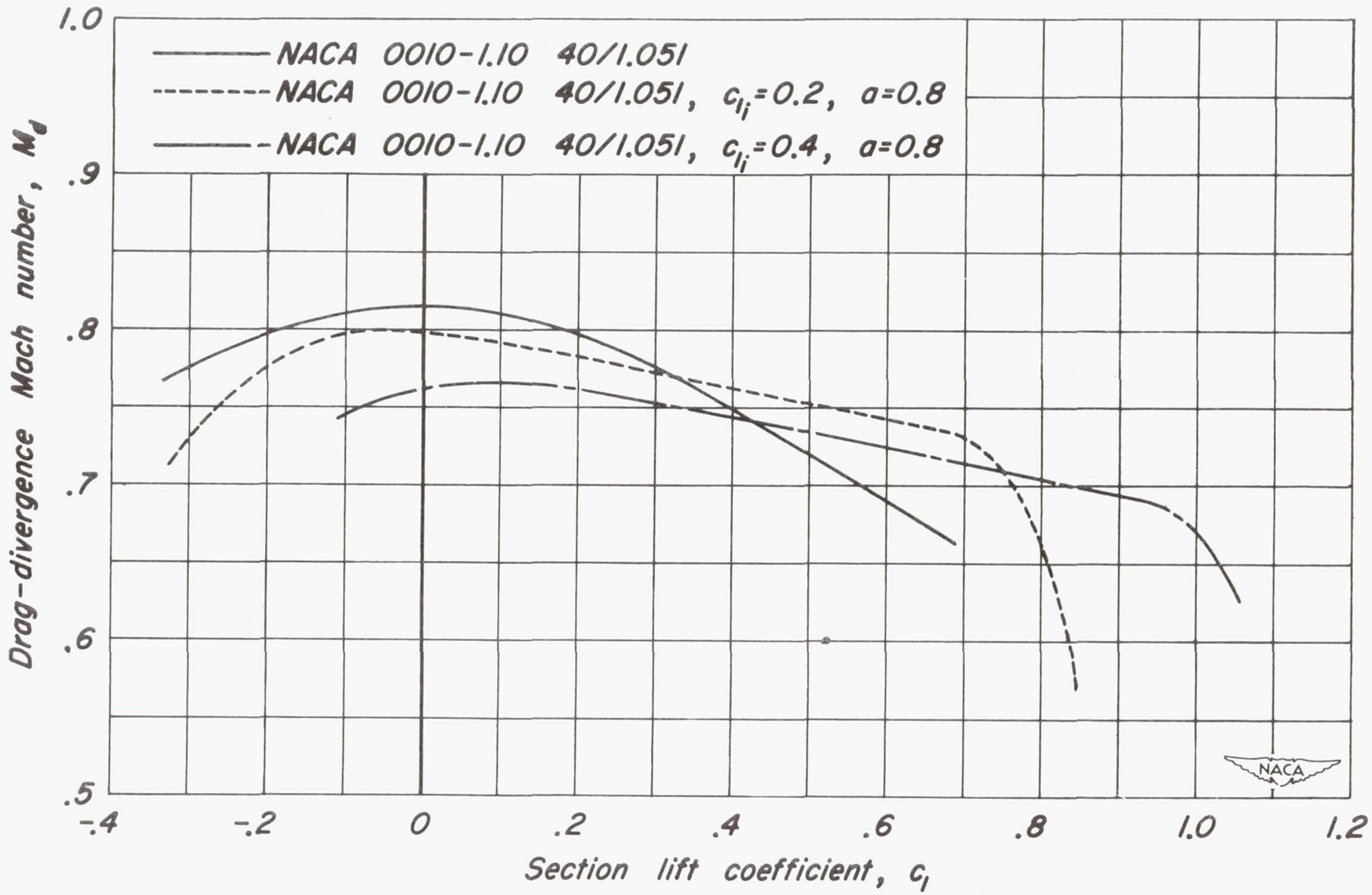


Figure 13.- Effect of camber on the variation of drag-divergence Mach number with section lift coefficient.

NACA-Langley - 9-3-53 - 1000