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RESEARCH MEMORANDUM

TRANSONIC WIND-TUNNEL INVESTIGATION OF THE LOW-LIFT AERODYNAMIC CHARACTERISTICS, INCLUDING EFFECTS OF LEADING-EDGE DROOP AND THICKNESS, OF A THIN TRAPEZOIDAL WING IN COMBINATION WITH BASIC AND INDENTED BODIES

By Thomas C. Kelly

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Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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RESEARCH MEMORANDUM

TRANSONIC WIND-TUNNEL INVESTIGATION OF THE LOW-LIFT AERODYNAMIC CHARACTERISTICS, INCLUDING EFFECTS OF LEADING-EDGE DROOP AND THICKNESS, OF A THIN TRAPEZOIDAL WING IN COMBINATION WITH BASIC AND INDENTED BODIES

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SUMMARY

An investigation has been conducted in the Langley 8-foot transonic tunnels to determine the aerodynamic force characteristics at low lift coefficients for a 2-percent-thick trapezoidal wing tested in combination with basic and indented bodies. Effects of wing leading-edge droop and wing thickness are included. Tests extended generally over a Mach number range from 0.80 to 1.43 and an angle-of-attack range from -2° to 6°.

Results indicated that small reductions in drag were obtained at Mach numbers near 1.0 and at a Mach number of 1.43 as a result of body indentation, the reductions at a Mach number of 1.43 being apparently independent of a variation in the body indentation design Mach number from 1.0 to 1.2 for this extremely thin-wing configuration. Effects of wing leading-edge droop on the aerodynamic characteristics were slight. Increasing the wing thickness from 2 to 4 percent resulted in a considerable increase in drag at sonic and supersonic speeds and caused a reduction in the drag-rise Mach number from about 0.93 to 0.90.

INTRODUCTION

A general research program, currently in progress at the Langley 8-foot transonic tunnels, has been established to determine the aerodynamic characteristics of wing-body combinations employing wing plan forms designed for high performance at transonic and supersonic speeds. Included in this program is the determination of both the aerodynamic force and loading characteristics for the various wing-body combinations.

In addition, the effects of body shape, wing camber, twist, incidence, thickness, leading-edge droop, and fixed boundary-layer transition are being studied. Some of these results are available in references 1 to 5.

The purpose of the present investigation was to determine the longitudinal aerodynamic force characteristics at low lift coefficients for a 2-percent-thick trapezoidal wing in combination with basic and indented bodies. Secondary objectives were the determination of the effects of leading-edge droop and of increased wing thickness.

Tests extended generally over a Mach number range from 0.80 to 1.43 and an angle-of-attack range from -2° to 6° at Reynolds numbers from about 2.4×10^{6} to 2.6×10^{6}.

Aerodynamic loading characteristics for some identical configurations have been reported in reference 1.

SYMBOLS

C_D	drag coefficient, $\frac{\text{Drag}}{qS}$
C_{D_o}	drag coefficient at zero lift
ΔC_{D_o}	incremental zero-lift drag coefficient, $C_{D_{o_M}} - C_{D_{o_{M=0.80}}}$
C_L	lift coefficient, $\frac{\text{Lift}}{qS}$
$\frac{\partial C_L}{\partial \alpha}$	lift-curve slope, taken at $C_L = 0$
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment about } \bar{c}/4}{qS\bar{c}}$
$\frac{\partial C_m}{\partial C_L}$	static-longitudinal-stability parameter, taken at $C_L = 0$
c	wing section chord, in.
$\bar{c}$	wing mean aerodynamic chord, in.
$(L/D)_{max}$	maximum lift-drag ratio
M	free-stream Mach number

q	free-stream dynamic pressure, lb/sq ft
S	wing area, including that part within the fuselage, sq ft
t	wing section thickness, in.
α	angle of attack of fuselage center line, deg

APPARATUS

Tunnels

Two tunnel facilities were utilized to obtain the test results presented herein. Data were obtained over the Mach number range from 0.80 to 1.13 in the Langley 8-foot transonic tunnel which is a single-return, dodecagonal, slotted-throat tunnel designed to obtain aerodynamic data through the speed of sound while the usual effects of blockage are kept to a minimum. The tunnel operates at a stagnation pressure which is close to atmospheric pressure and is described in reference 6.

Data for a Mach number of 1.43 were obtained in the Langley 8-foot transonic pressure tunnel which, in its standard configuration, is a single-return, rectangular, slotted-throat tunnel having controls that allow for the independent variation of Mach number, density, temperature, and humidity. For these tests, however, fairings were installed in the longitudinal slots in order to provide a $M = 1.43$ test section (see ref. 7).

Models

A three-view drawing of the configurations tested and details of the wing leading-edge droop are shown in figure 1. Photographs of the basic wing-body combination mounted in the slotted test section of the Langley 8-foot transonic tunnel are presented as figure 2. The steel basic wing used in combination with the bodies was trapezoidal in plan form and had 26.6° sweepback of the quarter-chord line, 0° sweep of the 0.75-chord line, an aspect ratio of 2.61, a taper ratio of 0.211, and 2-percent-thick symmetrical circular-arc airfoil sections parallel to the plane of symmetry with the maximum thickness located at the midchord station. The forward inboard portion of the wing was made removable in order that a drooped leading edge might be installed. (See fig. 1(b).)

The 4-percent-thick aluminum wing, tested with the basic body only, was geometrically similar to the thinner wing except for the location of the point of maximum thickness (0.60c for the 0.04t/c wing and 0.50c for the 0.02t/c wing).

Four body configurations were tested in combination with the 2-percent-thick plane wing. They have been designated as the basic, $M = 1.0$, $M = 1.2$, and elliptical bodies. The basic body (Sears-Haack) was designed to have minimum wave drag for a given length and volume. The $M = 1.0$ and $M = 1.2$ bodies were symmetrically indented configurations designed according to the methods outlined in references 8 and 9. It should be noted that these body indentations were made from a body having a maximum diameter slightly larger than that of the basic body. This body (corresponding to the "modified body" of ref. 2) had a maximum diameter of 3.296 inches, whereas the basic body had a maximum diameter of 3.212 inches. The effects of this modification are discussed in a later section. The elliptical body was a specially designed body which retained the upper and lower basic-body lines and was indented on the sides in the vicinity of the wing-body juncture to provide a desirable area distribution for a Mach number of 1.2. Cross sections in the region of the indentation were made elliptical (fig. 1). Design ordinates for the bodies are given in table I.

TESTS

The thin-wing (0.02t/c) configurations were tested at Mach numbers from 0.80 to 1.43 and through an angle-of-attack range extending generally from -2° to 6°. The basic, $M = 1.0$, and $M = 1.2$ bodies were tested in combination with the plane wing only, whereas the elliptical body was tested with both the plane and drooped leading-edge wings. The 4-percent-thick wing was tested in combination with the basic body only through the Mach number range from 0.80 to 1.43 at 0° angle of attack.

Reynolds numbers for the tests varied from about 2.4×10^{6} to 2.6×10^{6}, based on the mean aerodynamic chord (fig. 3).

MEASUREMENTS AND ACCURACY

Lift, drag, and pitching moment were determined by means of an internal, electrical strain-gage balance. Coefficients are based on the total wing area of 0.859 square foot. Pitching-moment coefficients, based on a mean aerodynamic chord of 7.862 inches, are referred to the quarter-chord point of the mean aerodynamic chord.

From a consideration of factors affecting the accuracy of the results, measured coefficients are estimated to be generally accurate within the following limits at low lift coefficients:

M	C_L	C_D	C_m
0.80	±0.010	±0.0010	±0.004
1.43	±.007	±.0006	±.004

Model angle of attack was measured with a strain-gage attitude transmitter mounted in the model nose and is judged to be accurate within ±0.1°.

CORRECTIONS

Data presented in the present paper have been adjusted to a condition representing free-stream static pressure acting at the model base.

The effects of subsonic boundary interference in the slotted test section are considered negligible and no corrections for these effects have been applied. In addition, no data are presented for the supersonic Mach number range from $M = 1.03$ to $M = 1.13$ in which boundary-reflected disturbances generally affect the data. However, results presented in reference 2 indicate that at a Mach number of 1.13 (the highest Mach number attainable for the present models in the 8-foot transonic tunnel) a body identical to the basic body of the present tests was subject to boundary-interference effects which resulted in the drag at zero lift being too low. Accordingly, the results presented in the zero-lift drag plots of the present paper have been adjusted upward at $M = 1.13$ by an increment in drag coefficient (0.0010) corresponding to that noted in reference 2.

No corrections have been applied to the data to account for the slight increase in diameter made to the basic body, from which the $M = 1.0$ and $M = 1.2$ indented bodies were made. Tests of the basic and modified bodies, reported in reference 2, show that the effects of increasing body diameter are slight and would not affect the comparisons presented here.

RESULTS AND DISCUSSION

Basic force and moment data for the configurations tested are given in figures 4 and 5. Analysis curves, obtained from the basic plots, are presented in figures 6 to 14. In order to facilitate presentation of the data, staggered scales have been used in some of the figures and care should be taken in selecting the proper zero axis for each curve.

Effect of Body Shape

Drag characteristics.- The effects of body shape on the zero-lift and incremental zero-lift drag coefficients for the 2-percent-thick plane wing configurations are shown in figures 6 and 7, respectively. Figure 6 shows that at a given Mach number the drag coefficients for the four configurations generally fall within a range of 0.0020; this small variation indicates that body indentation had only a slight effect on the absolute value of zero-lift total drag for such an extremely thin-wing configuration. It should be noted here that, based upon results presented in figures 6 and 7 and a comparison to be presented later showing the effect of leading-edge droop, the drag data for the elliptical configuration appears to be excessively high at a Mach number of 1.03. The comparison presented in figure 7 between the results of the present tests and those for the basic body alone from reference 2 shows that only slight effects could be expected to result from indentation since the pressure drag associated with the wing (the difference between the solid and dashed curves of fig. 7) at a Mach number of 1.03 and above is about 0.0020 in drag coefficient. Although the differences in drag coefficient for the configurations tested are close to the accuracy of the measurements, favorable effects resulting from body indentation are evident at Mach numbers near 1.0 and at 1.43. It appears further that, at Mach numbers of 1.13 and 1.43, the design Mach number of the indented body becomes somewhat unimportant, with similar reductions in drag noted for both the $M = 1.0$ and $M = 1.2$ indented bodies.

Figure 8 indicates that, at lift coefficients of 0.2 and 0.4, the effects of body shape on drag are similar to those seen at zero lift, with the maximum advantages due to body indentation occurring near sonic Mach numbers. (Portions of the curves presented in figure 8 are from extrapolated curves indicated in figure 4 by the dashed lines.)

The variation with Mach number of the maximum lift-drag ratios for the four configurations (fig. 9) indicates that increases in $(L/D)_{max}$ on the order of 8 percent were obtained at Mach numbers from 0.96 to 1.03 through the use of body indentation. Maximum lift-drag ratios for the basic configuration varied from about 10.5 at a Mach number of 0.93 to about 7.5 at a Mach number of 1.43.

Lift and pitching-moment characteristics.- The effects of body shape on the lift-curve and pitching-moment-curve slopes are generally slight. (See fig. 10.) The largest effects are for the $M = 1.0$ configuration which exhibits an increase in lift-curve slope at Mach numbers of 1.0 and 1.03, a decrease in stability at subsonic Mach numbers, and an increase in stability at supersonic Mach numbers for this configuration when compared with the basic configuration.

Effect of Leading-Edge Droop

Drag characteristics.- The use of leading-edge droop to obtain a reduction in the drag at lifting conditions is well known. (See ref. 4, for example.) For the present tests, the extremely sharp leading edge of the thin wing is conducive to early separation and an increase in drag at lifting conditions. In an effort to delay these adverse effects, the inboard portion of the leading edge of the wing was drooped in the manner shown in figure 1(b). The effects of leading-edge droop on the drag characteristics of the elliptical configurations are shown in figure 11. As noted previously, the drag results for the plane-wing—elliptical-body configuration appear to be somewhat high at a Mach number of 1.03 and at lift coefficients of 0 and 0.2. Figure 11 indicates that the effects of leading-edge droop are slight, the largest effects occurring at subsonic speeds.

The variation with Mach number of maximum lift-drag ratios for the plane and drooped configurations (fig. 12) indicates that increases in $(L/D)_{max}$ at Mach numbers from 0.80 to about 0.93 and at 1.43 on the order of 5 percent were obtained as a result of drooping the wing leading edge. The apparent increase in $(L/D)_{max}$ at a Mach number of 1.03 appears to be due to the questionable low-lift drag results for the plane-wing configuration.

Lift and pitching-moment characteristics.- The effects of leading-edge droop on the lift and pitching-moment characteristics for the elliptical configuration (fig. 13) were again slight. Lift-curve slopes were increased by a small amount at Mach numbers of 1.03, 1.13, and 1.43, and a slight general decrease in stability due to leading-edge droop was noted throughout the test Mach number range.

Effect of Wing Thickness

The effects of wing thickness on the zero-lift drag coefficients of the wing—basic-body configurations are illustrated in figure 14. Zero-lift drag coefficients for the 4-percent-thick wing were obtained by assuming that an angle of attack of 0° resulted in zero lift for the model. Figure 5 indicates this to be true, within the accuracy of the measurements. Based upon results presented in reference 10, the difference in the location of the point of maximum thickness for the two wings would probably have only a very slight effect on the comparison of drag characteristics shown in figure 14. An increase in wing thickness from 2 to 4 percent was accompanied by a considerable increase in drag at sonic and supersonic speeds, as would be expected. The increase varies from about 31 percent at a Mach number of 1.05 to 17 percent at a Mach number of 1.43. The slight decrease at the lower subsonic Mach numbers is attributed to the relative wing surface conditions of the two configurations. As would also be expected, a reduction in the drag-rise Mach number resulted from the change in wing thickness from 2 to 4 percent. Drag-rise Mach numbers were about 0.93 and 0.90 for the 2-percent and 4-percent-thick wings, respectively.

CONCLUSIONS

Results of an investigation conducted in the Langley 8-foot transonic tunnels to determine the effects of body indentation, wing leading-edge droop, and wing thickness on the longitudinal aerodynamic force characteristics at low lift coefficients of several thin-trapezoidal-wing—body combinations have indicated the following conclusions:

1. Small reductions in drag for the 2-percent-thick-wing—body combination were obtained at Mach numbers near 1.0 and at 1.43 as a result of body indentation; the reductions at a Mach number of 1.43 being apparently independent of a variation in the body indentation design Mach number from 1.0 to 1.2.

2. Effects of wing leading-edge droop on the aerodynamic characteristics of the 2-percent-thick wing configuration tested were slight.

3. An increase in wing thickness from 2 to 4 percent resulted in an increase in drag at sonic and supersonic speeds, the increases amounting to 31 percent at a Mach number of 1.0 and 17 percent at a Mach number of 1.43, and caused a reduction in the drag-rise Mach number from about 0.93 to 0.90.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 19, 1957.

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TABLE I

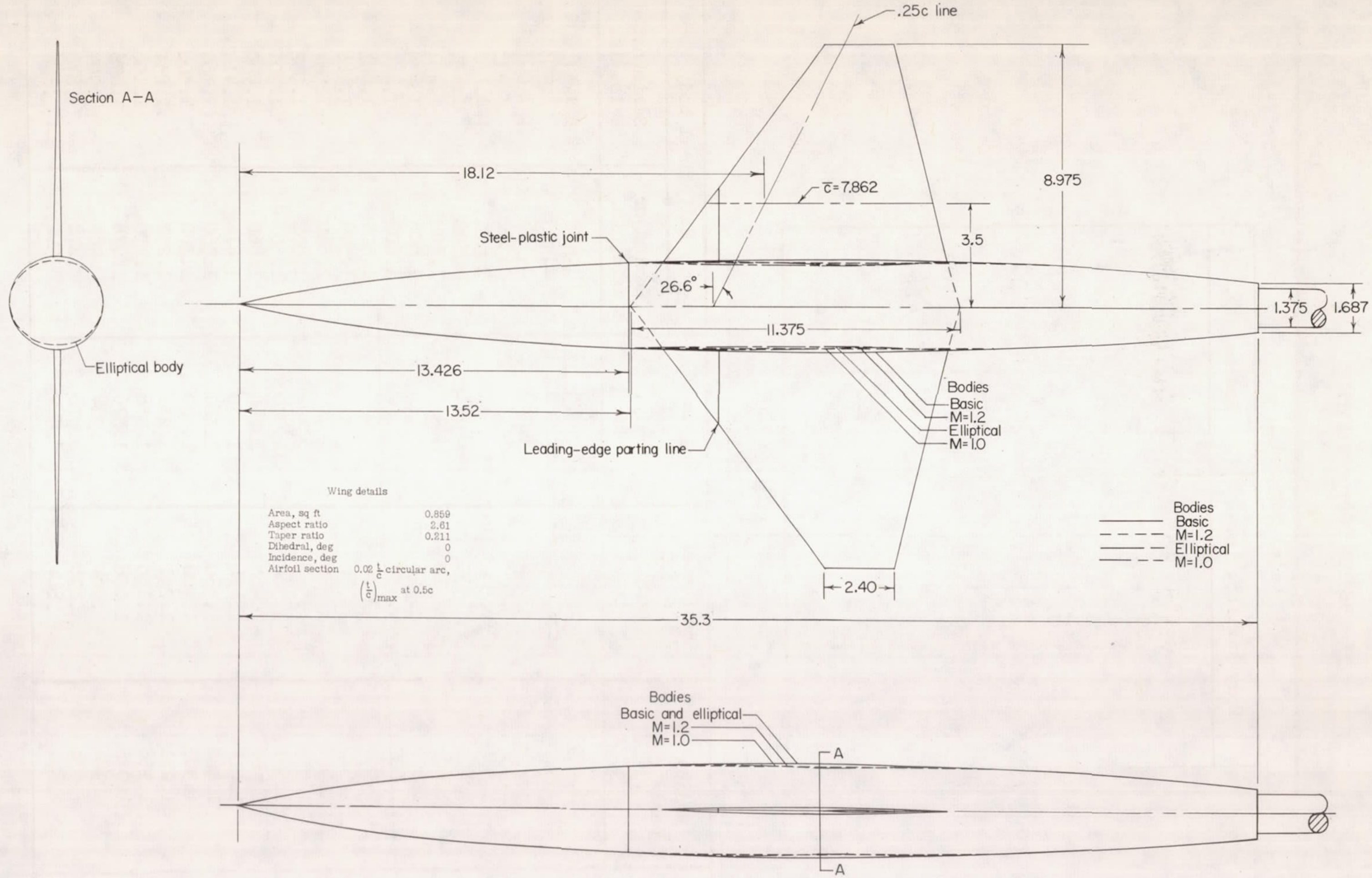
DESIGN BODY ORDINATES

(a) Forebody

Body station, in.	Radius, in.
0	0
.5	.165
1.0	.282
1.5	.378
2.0	.460
2.5	.540
3.0	.612
4.0	.743
5.0	.862
6.0	.969
7.0	1.062
8.0	1.150
9.0	1.222
10.0	1.290
11.0	1.350
12.0	1.404
13.0	1.452
13.426	1.475

(b) Afterbodies

Body station, in.	Radius of basic body, in.	Radius of M = 1.0 body, in.	Radius of M = 1.2 body, in.	Elliptical body	
				Semimajor axis, in.	Semiminor axis, in.
13.426	1.475	1.475	1.475	1.475	1.475
14.0	1.493	1.499	1.500	1.493	1.493
15.0	1.526	1.539	1.520	1.526	1.503
16.0	1.552	1.557		1.552	1.473
17.0	1.575	1.552		1.575	1.451
18.0	1.590	1.537		1.590	1.437
19.0	1.602	1.512		1.602	1.431
20.0	1.606	1.478		1.606	1.434
21.0	1.602	1.458		1.602	1.444
22.0	1.594	1.484		1.594	1.463
23.0	1.579	1.536		1.579	1.488
24.0	1.560	1.572		1.560	1.524
25.0	1.532	1.547		1.532	1.532
26.0	1.501	1.508	1.500	1.501	1.501
27.0	1.460	1.465	1.460	1.460	1.460
28.0	1.414	1.414	1.410	1.414	1.414
29.0	1.360	1.360	1.360	1.360	1.360
30.0	1.300	1.300	1.300	1.300	1.300
31.0	1.231	1.231	1.231	1.231	1.231
32.0	1.158	1.158	1.158	1.158	1.158
33.0	1.076	1.076	1.076	1.076	1.076
34.0	.984	.984	.984	.984	.984
35.0	.878	.878	.878	.878	.878
35.3	.844	.844	.844	.844	.844



Wing details

Area, sq ft	0.859
Aspect ratio	2.61
Taper ratio	0.211
Dihedral, deg	0
Incidence, deg	0
Airfoil section	0.02 $\frac{t}{c}$ circular arc, $\left(\frac{t}{c}\right)_{max}$ at 0.5c

(a) Wing-body combinations.

Figure 1.- Model details. All dimensions are in inches unless otherwise noted.

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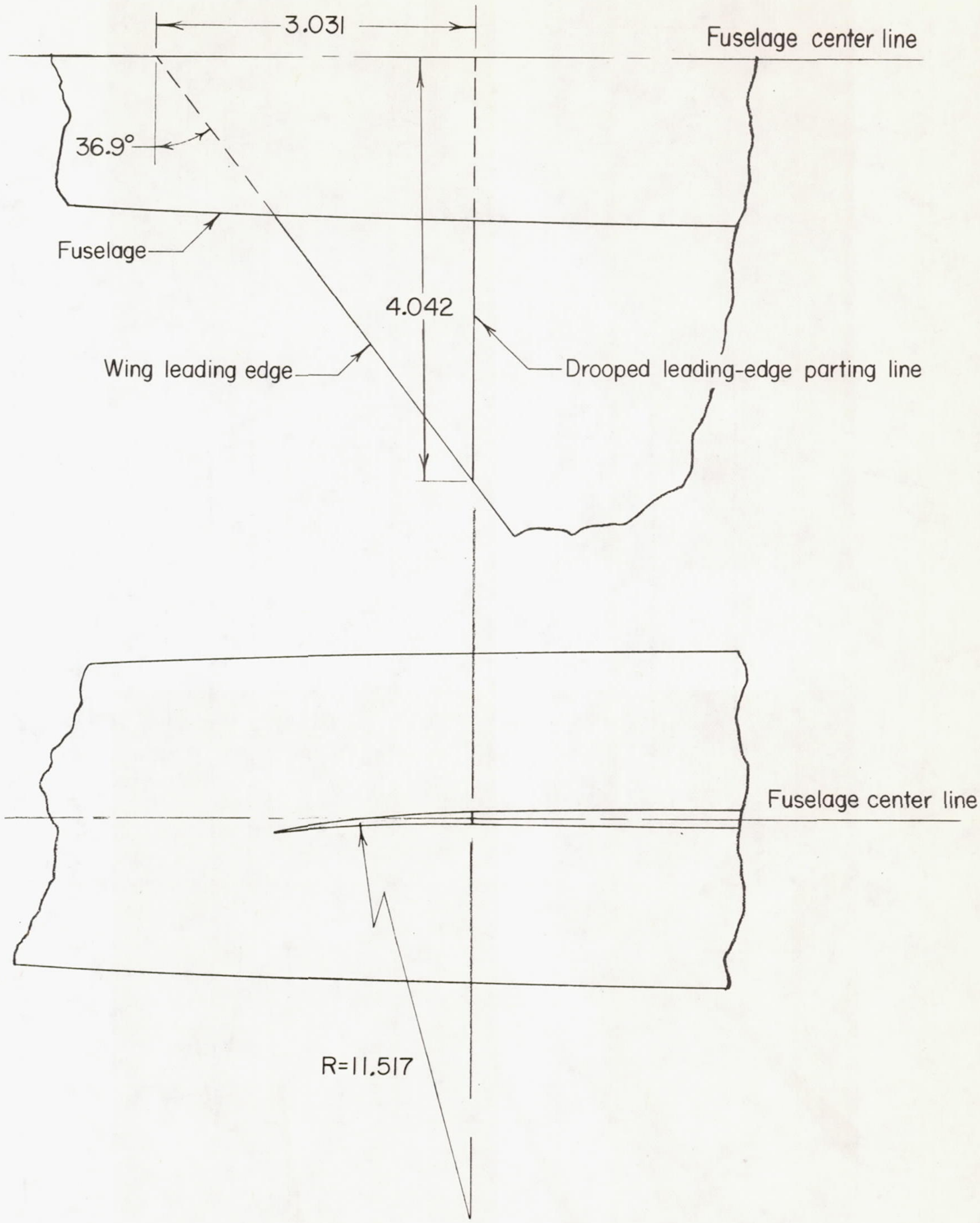
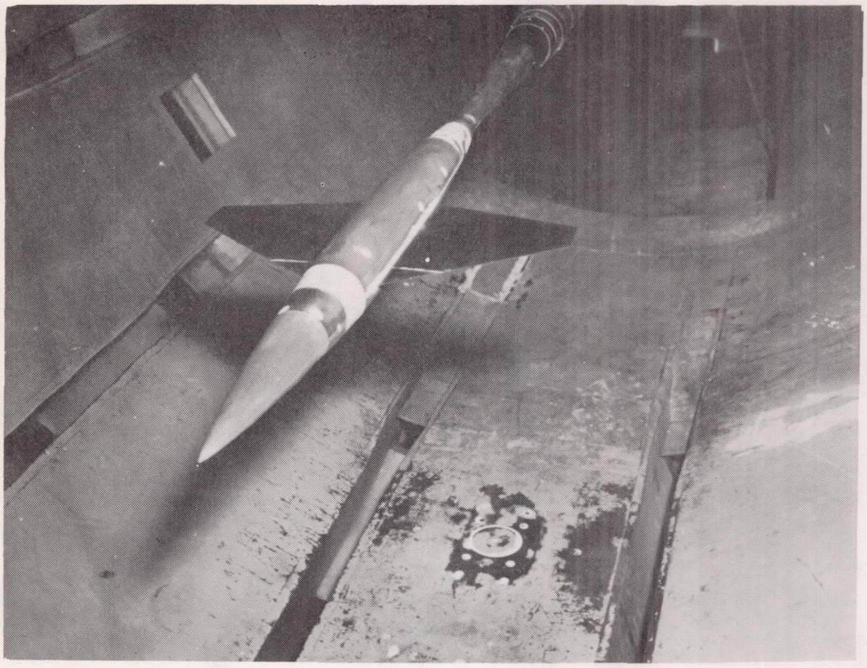


(b) Drooped leading edge.

Figure 1.- Concluded.



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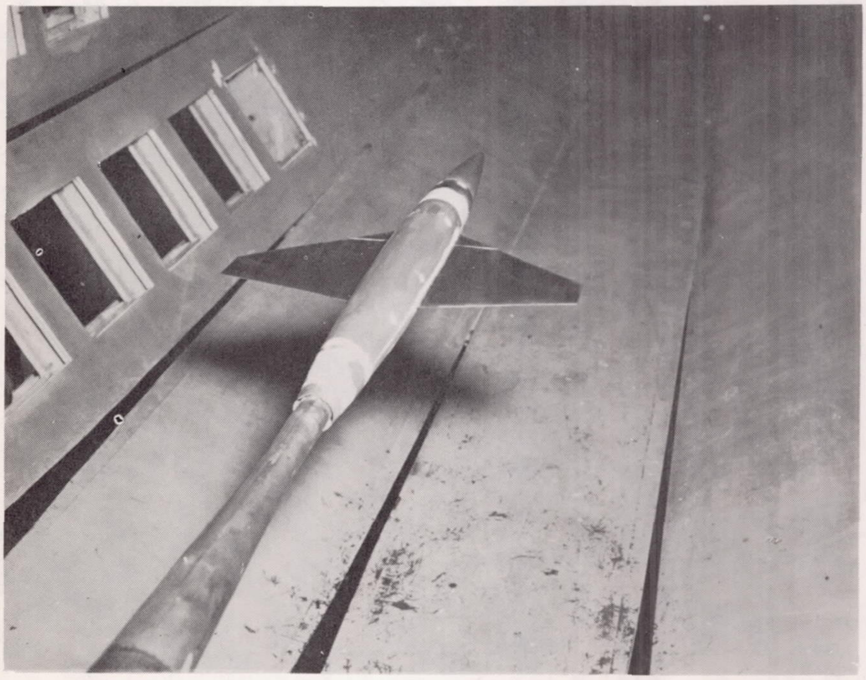

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Figure 2.- The 0.02t/c wing—basic-body combination mounted in the slotted test section of the Langley 8-foot transonic tunnel.

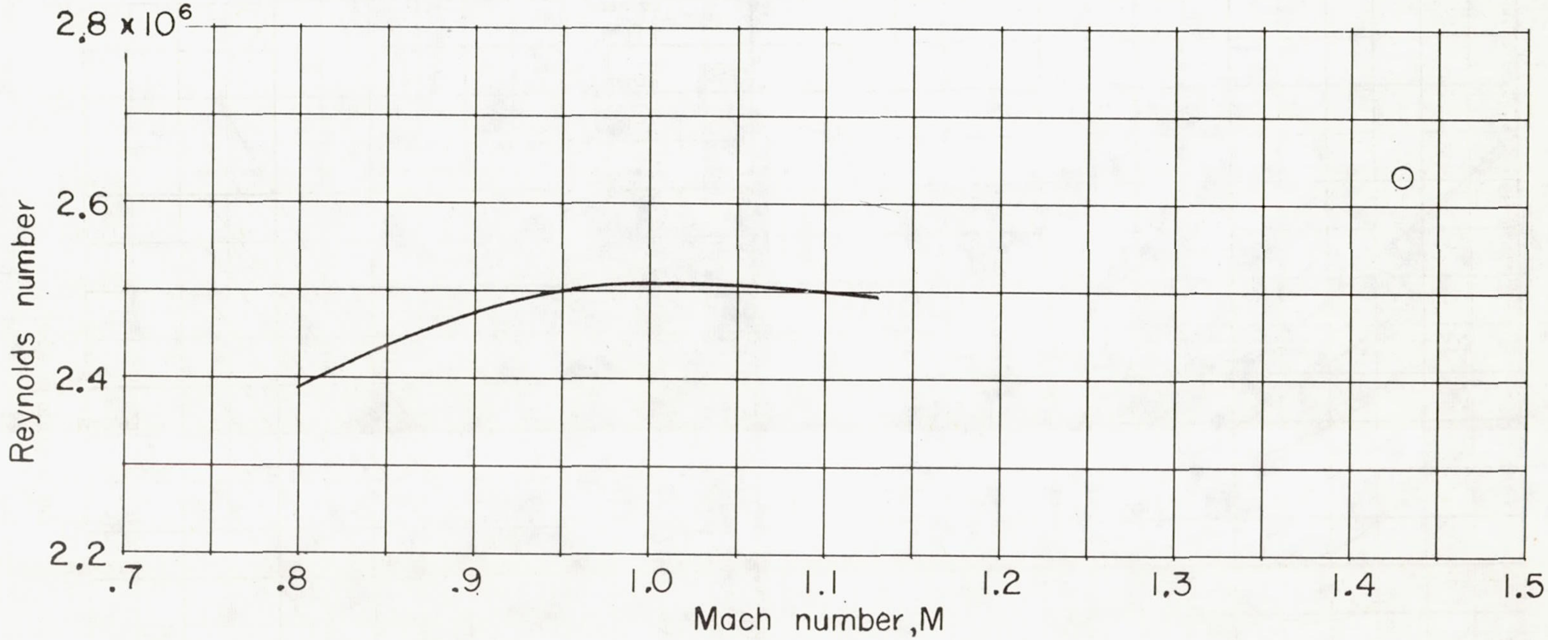
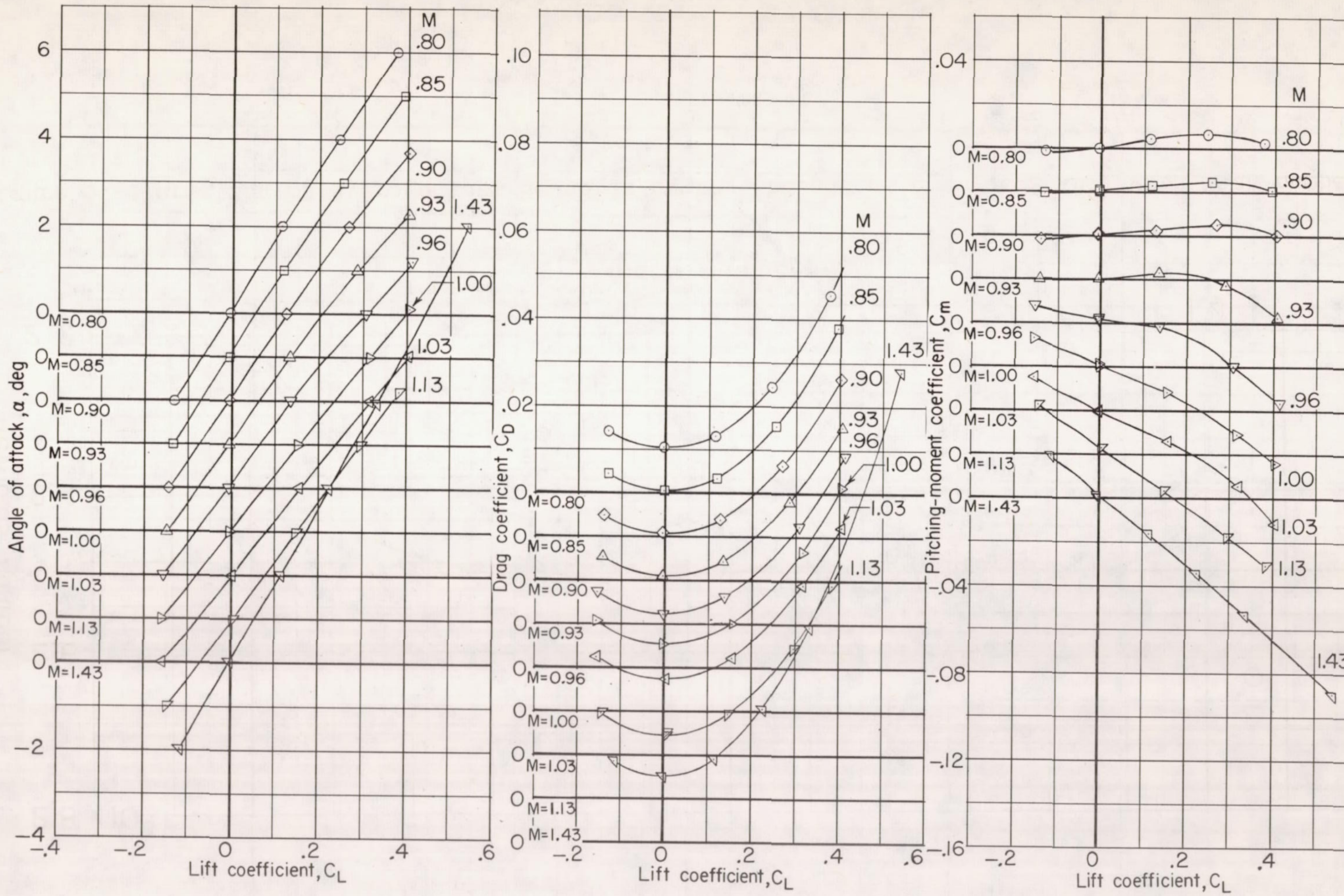
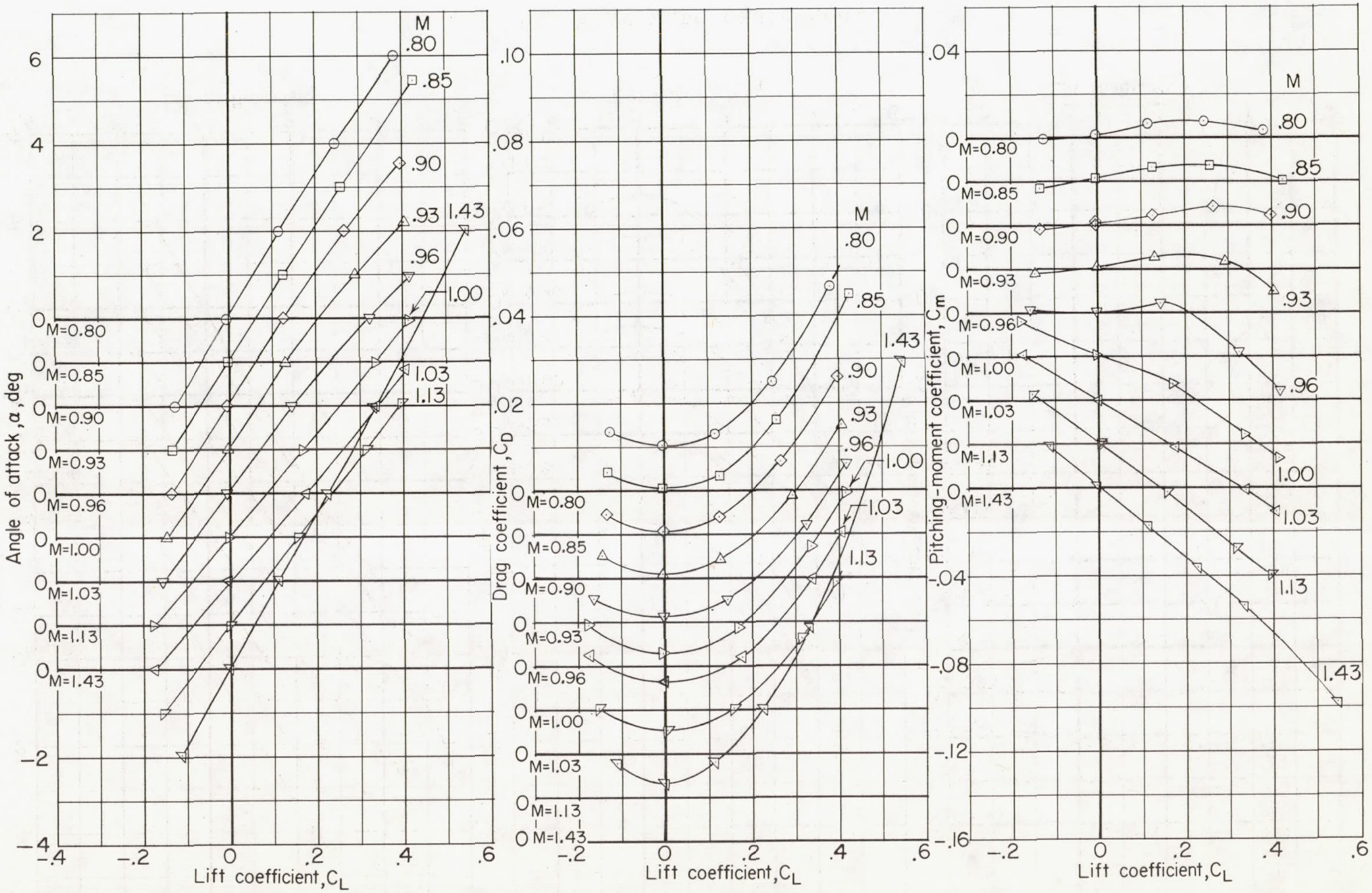


Figure 3.- Variation of average test Reynolds number (based on $\bar{c}$ = 7.862 in.) with Mach number.



(a) Wing with basic body.

Figure 4.- Aerodynamic characteristics for the 0.02t/c plane wing in combination with various bodies.



(b) Wing with M = 1.0 body.

Figure 4.- Continued.

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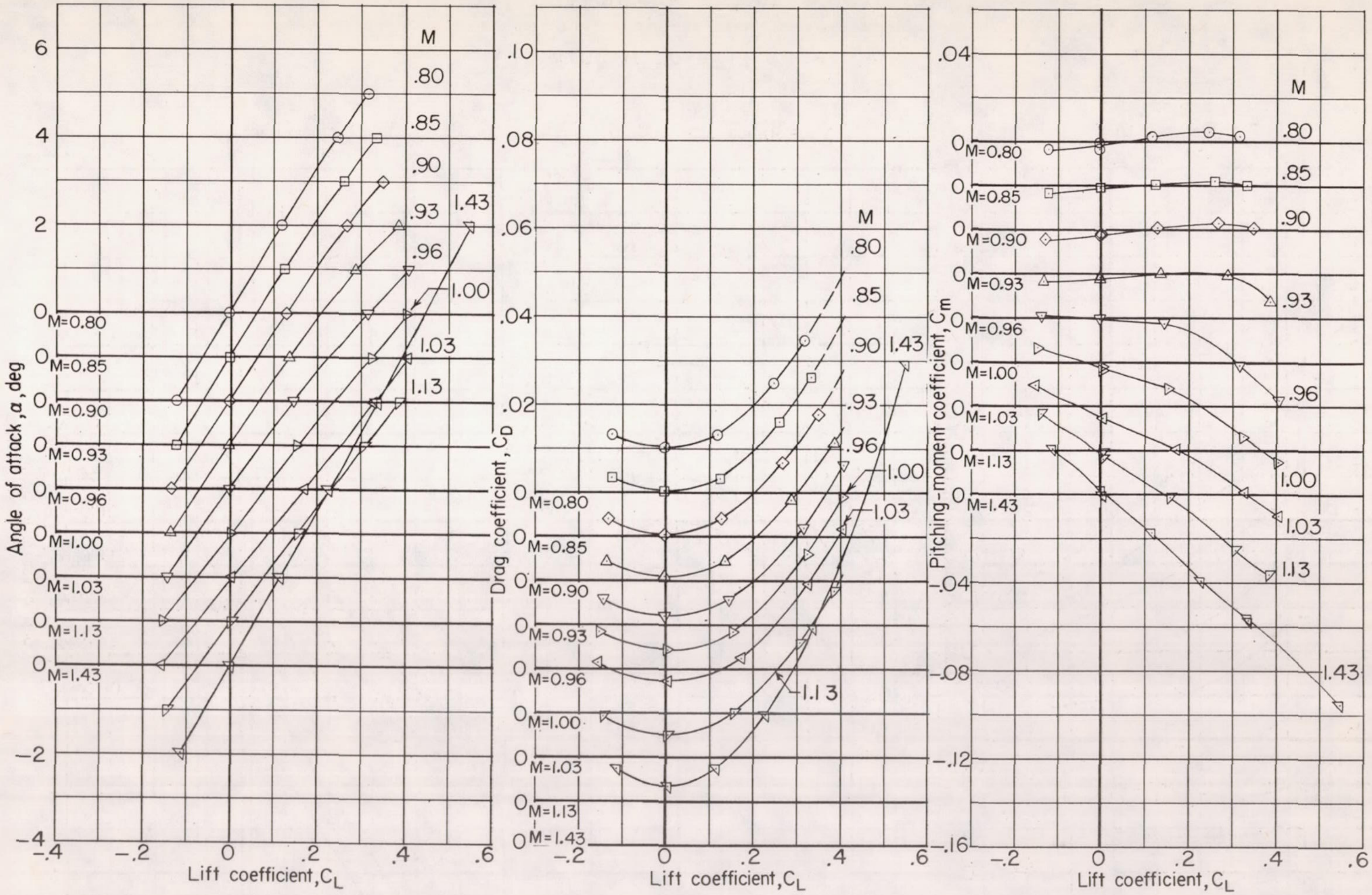

(c) Wing with M = 1.2 body.

Figure 4.- Continued.

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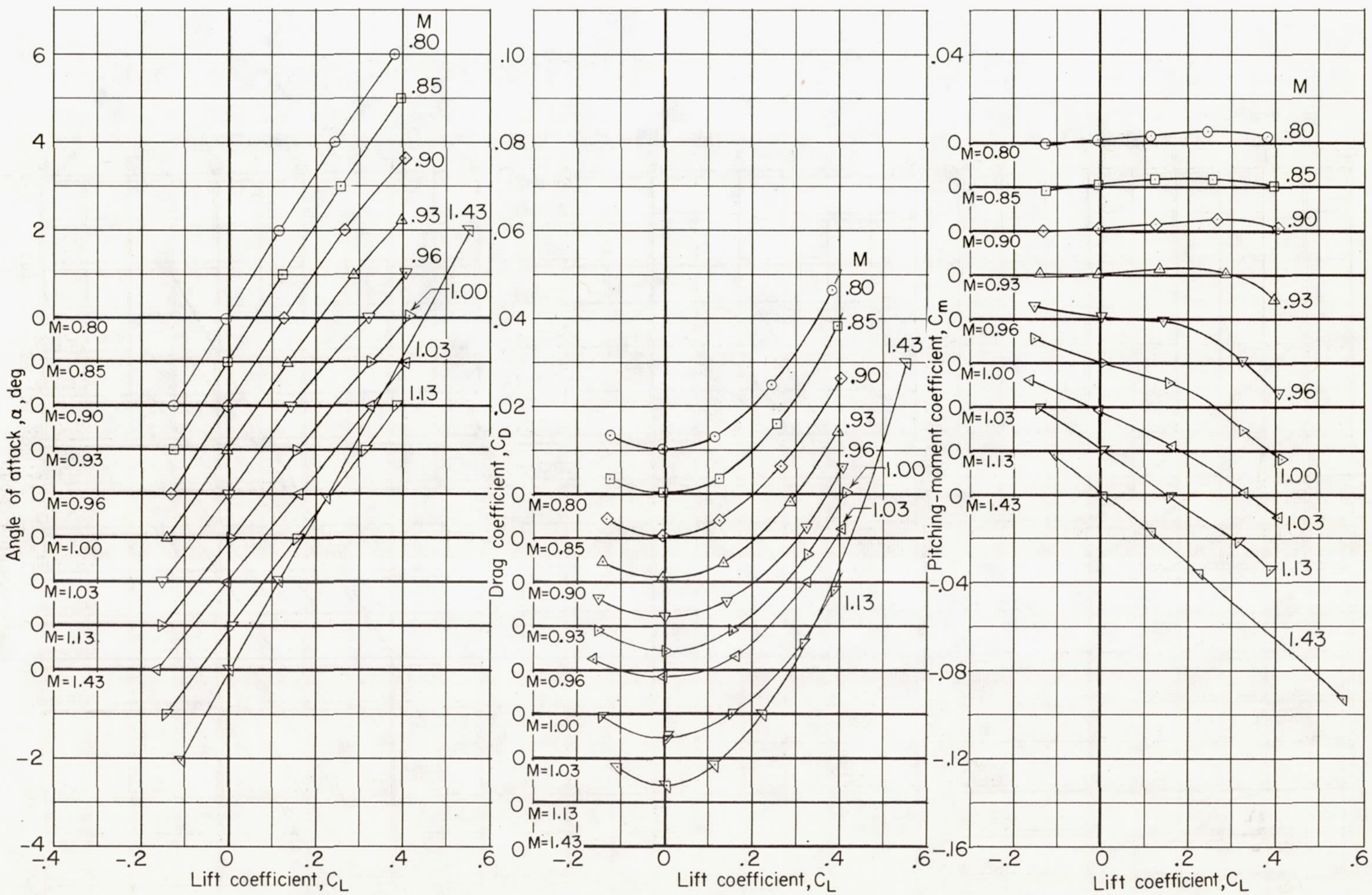

(d) Wing with elliptical body.

Figure 4.- Continued.

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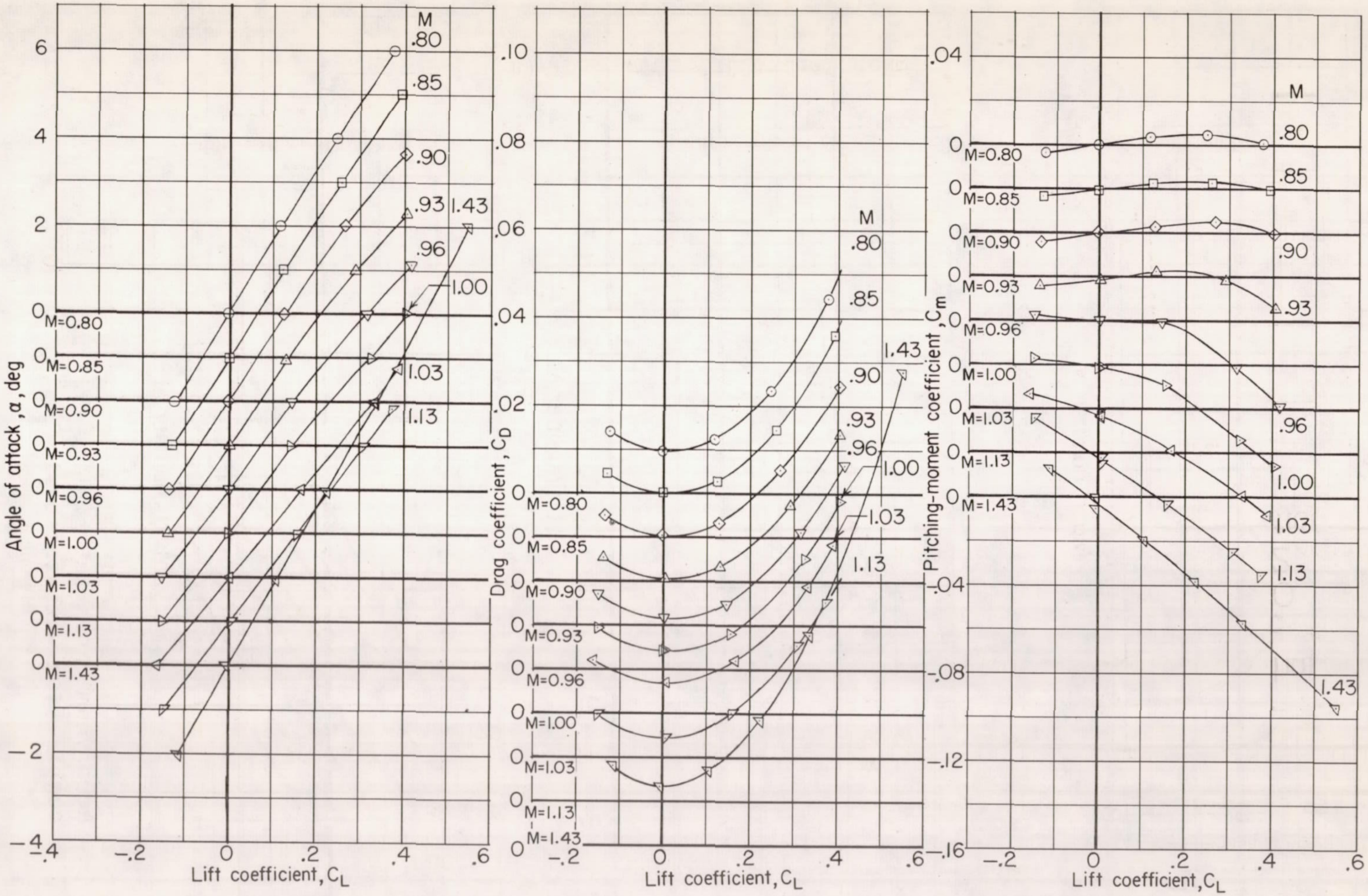

(e) Drooped leading-edge wing with elliptical body.

Figure 4.- Concluded.

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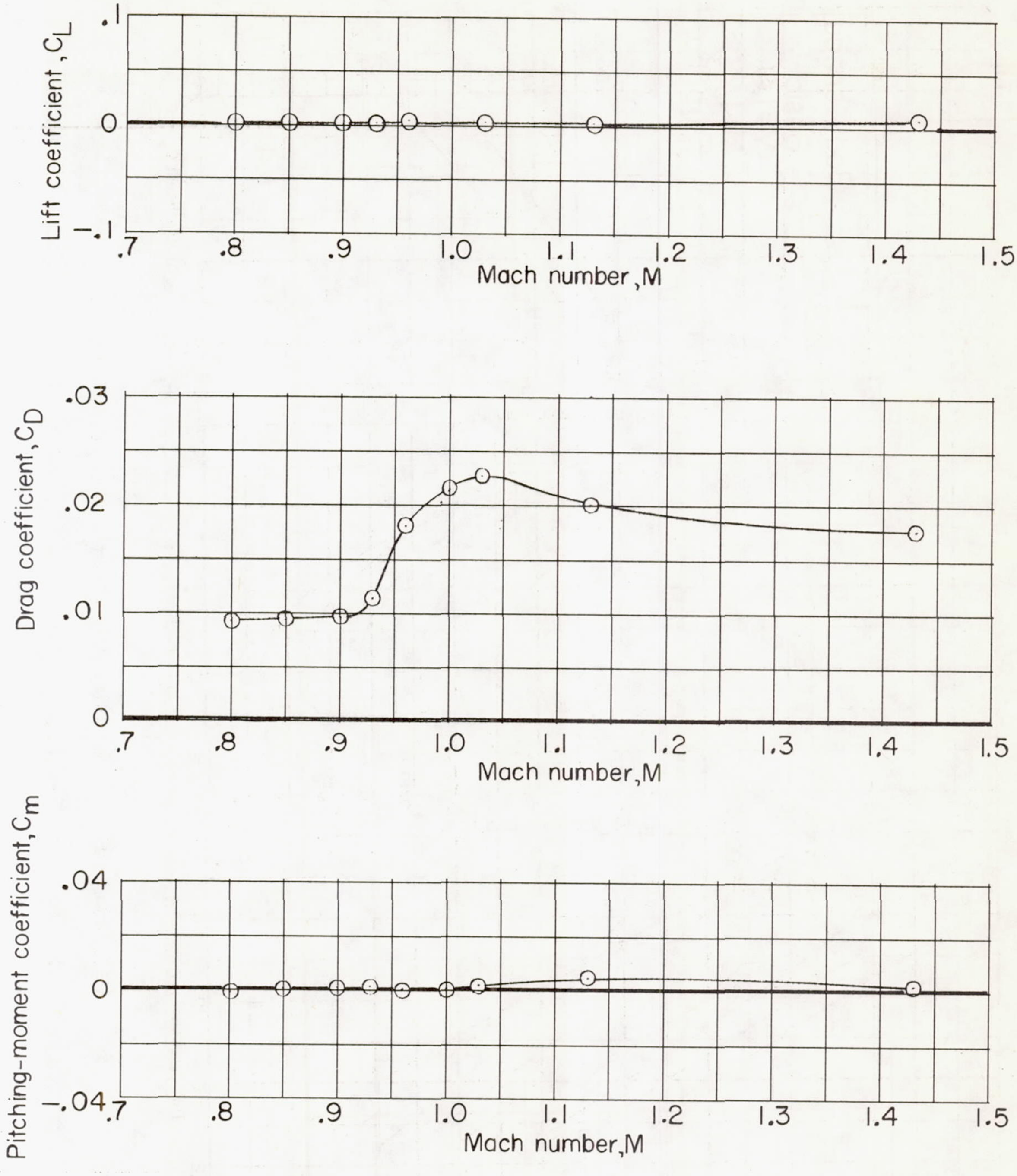

Figure 5.- Aerodynamic characteristics for the 0.04t/c wing in combination with the basic body. $\alpha = 0^{\circ}$.

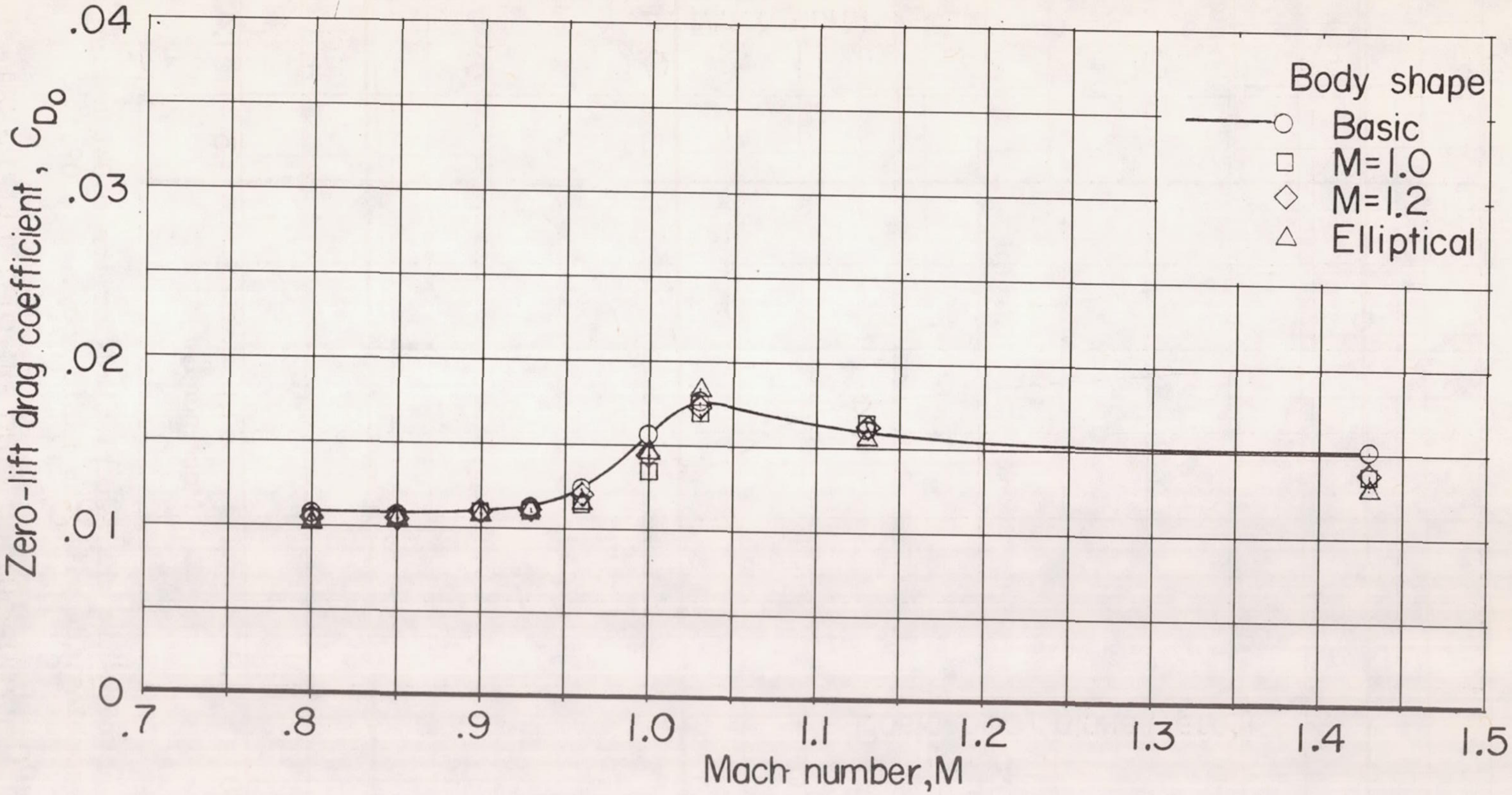

Figure 6.- Zero-lift drag coefficients for the 0.02t/c plane-wing configurations.

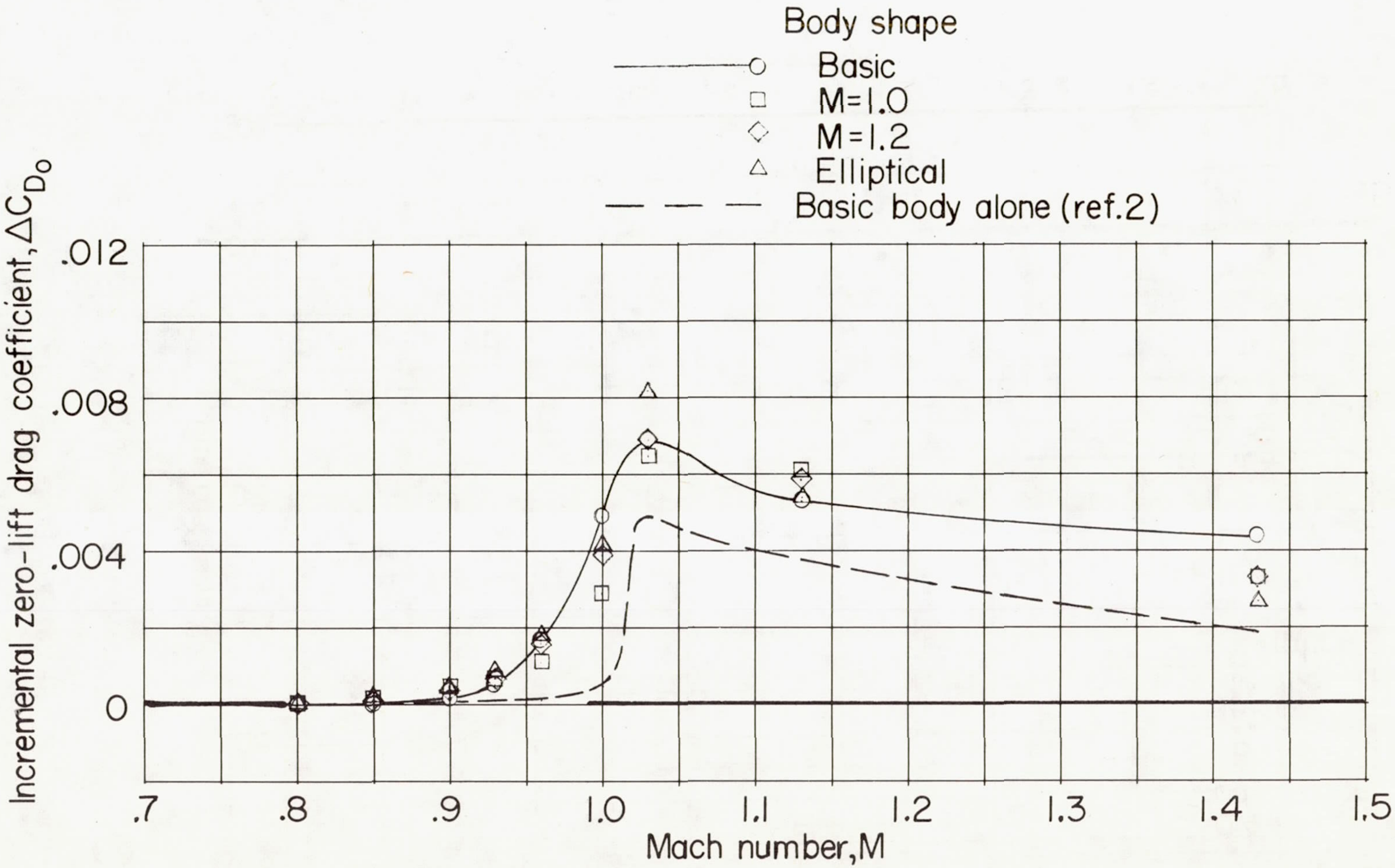

Figure 7.- Incremental zero-lift drag coefficients for the 0.02t/c plane-wing configurations.

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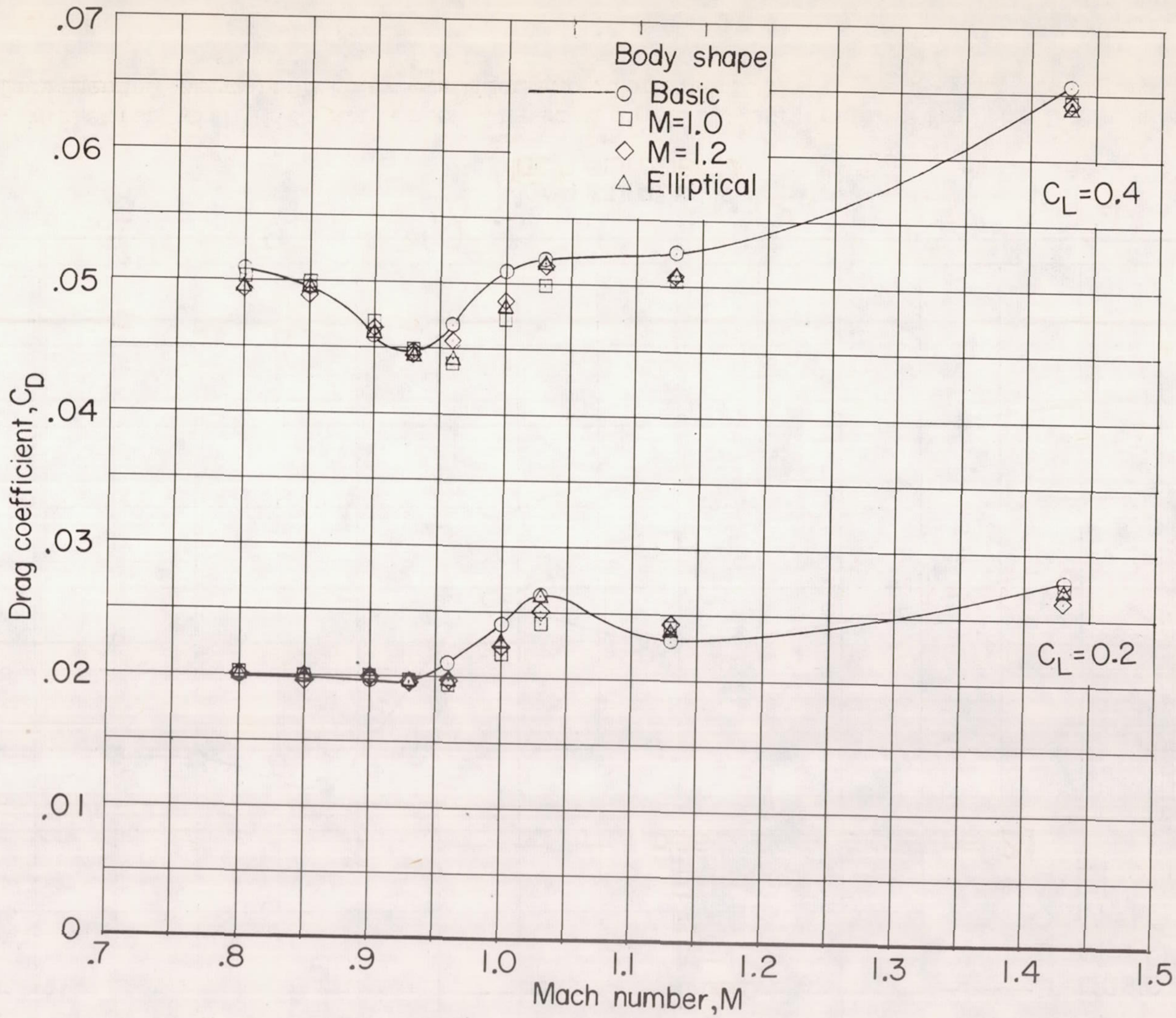

Figure 8.- Drag coefficients at constant lift for the 0.02t/c plane-wing configurations.

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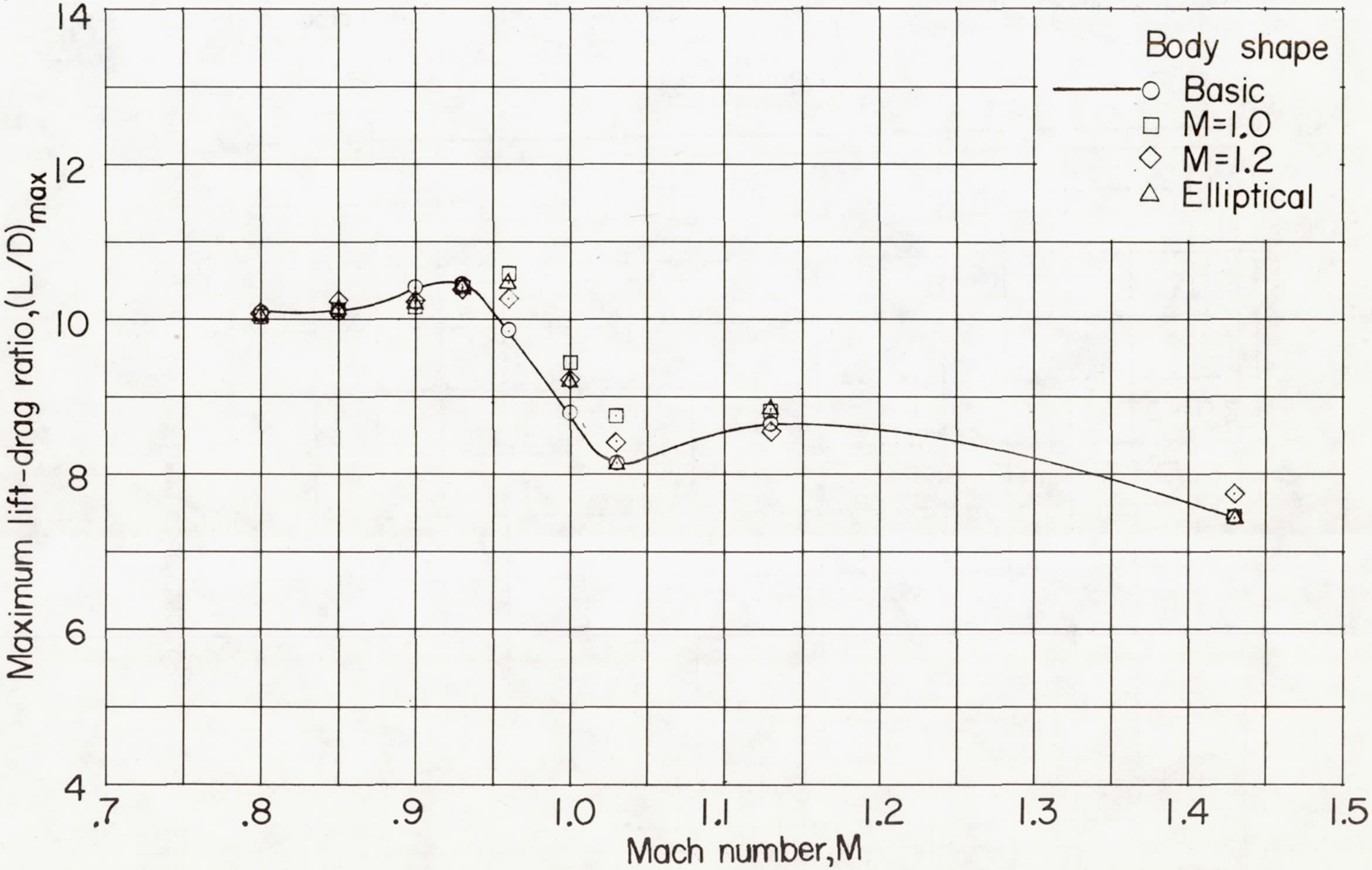

Figure 9.- Variation with Mach number of the maximum lift-drag ratios for the 0.02t/c plane-wing configurations.

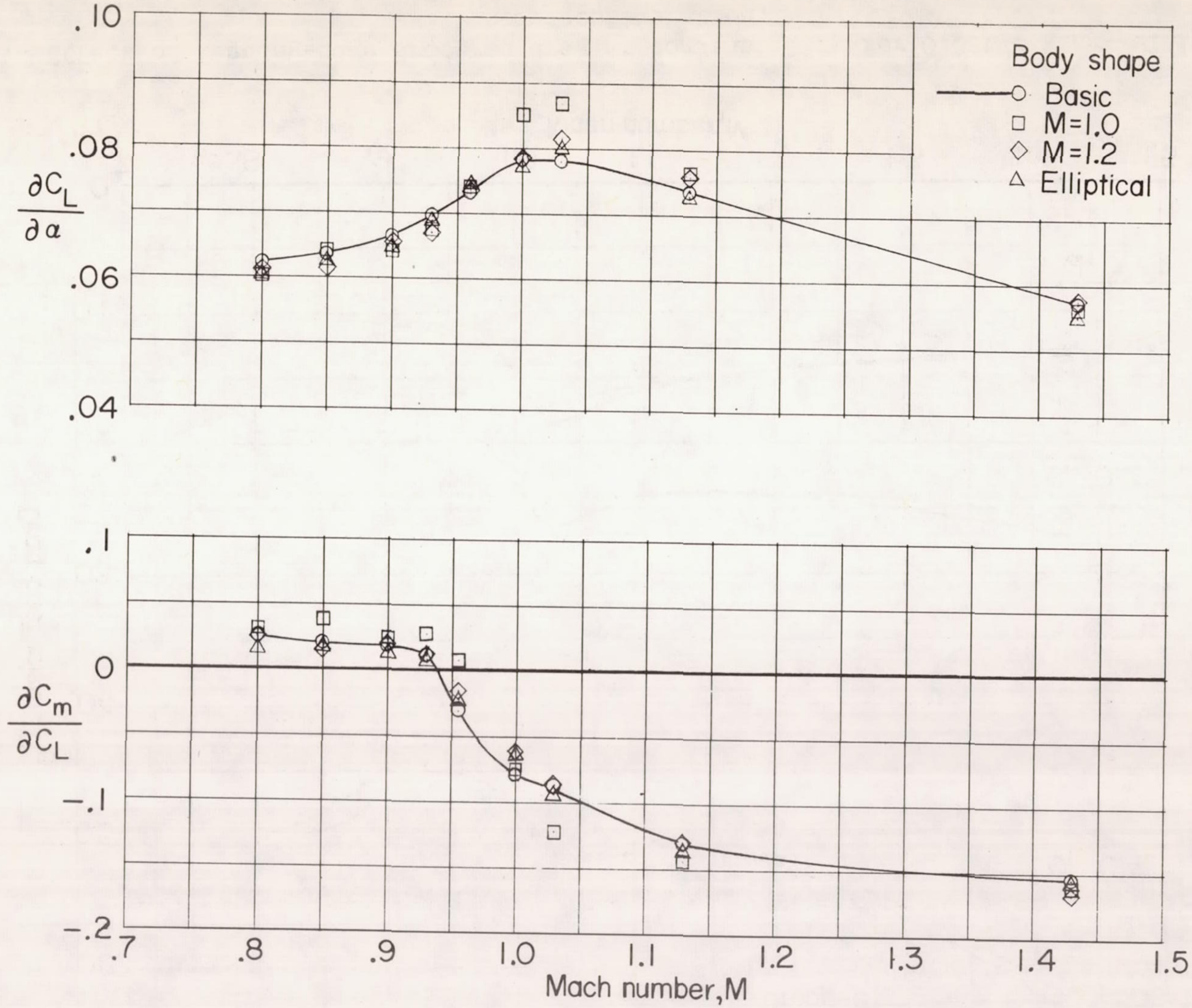

Figure 10.- Variation with Mach number of lift-curve and pitching-moment-curve slopes for the 0.02t/c plane-wing configurations. $C_L = 0$.

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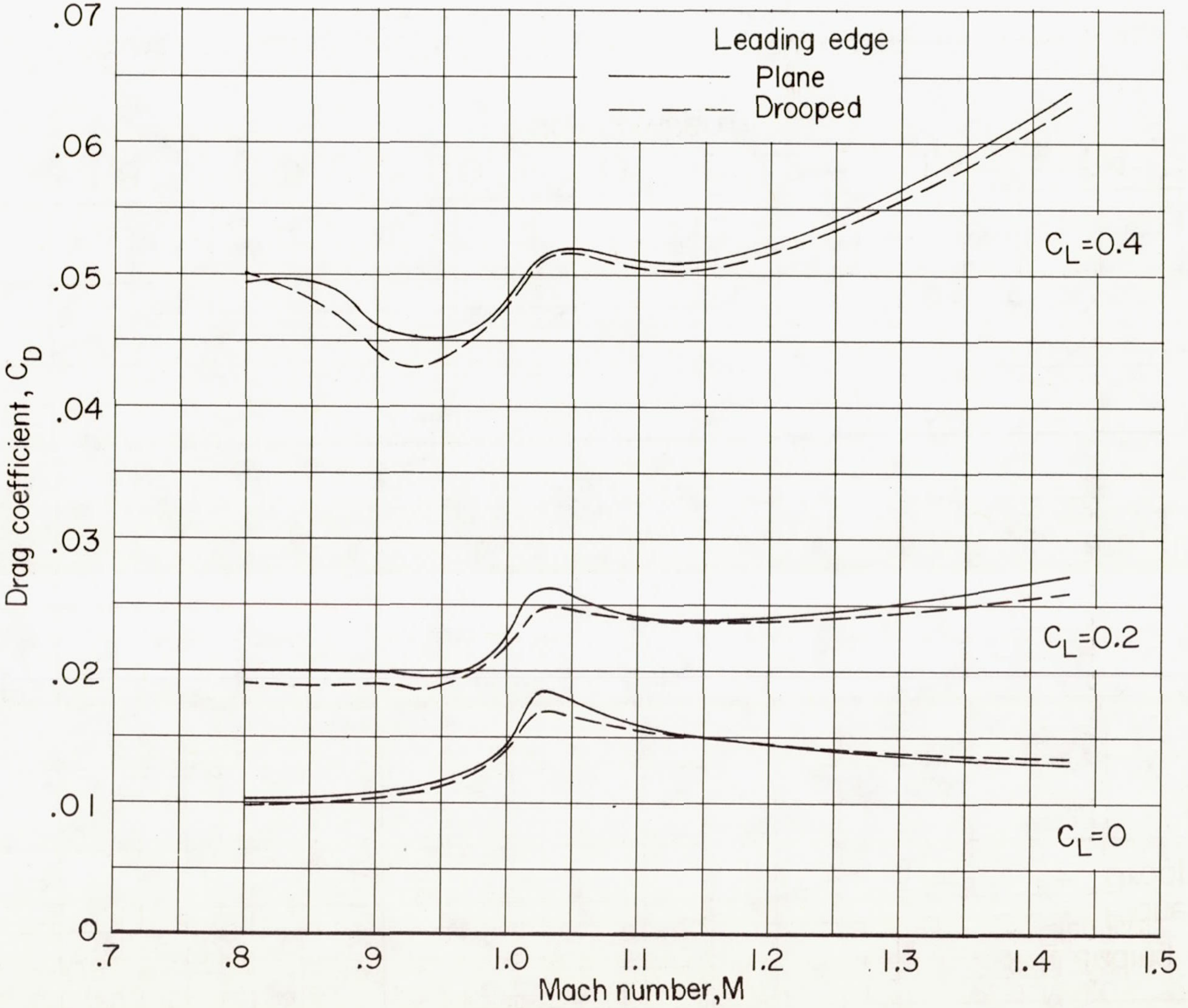

Figure 11.- Effect of leading-edge droop on drag at constant lift for 0.02t/c wing—elliptical-body configuration.

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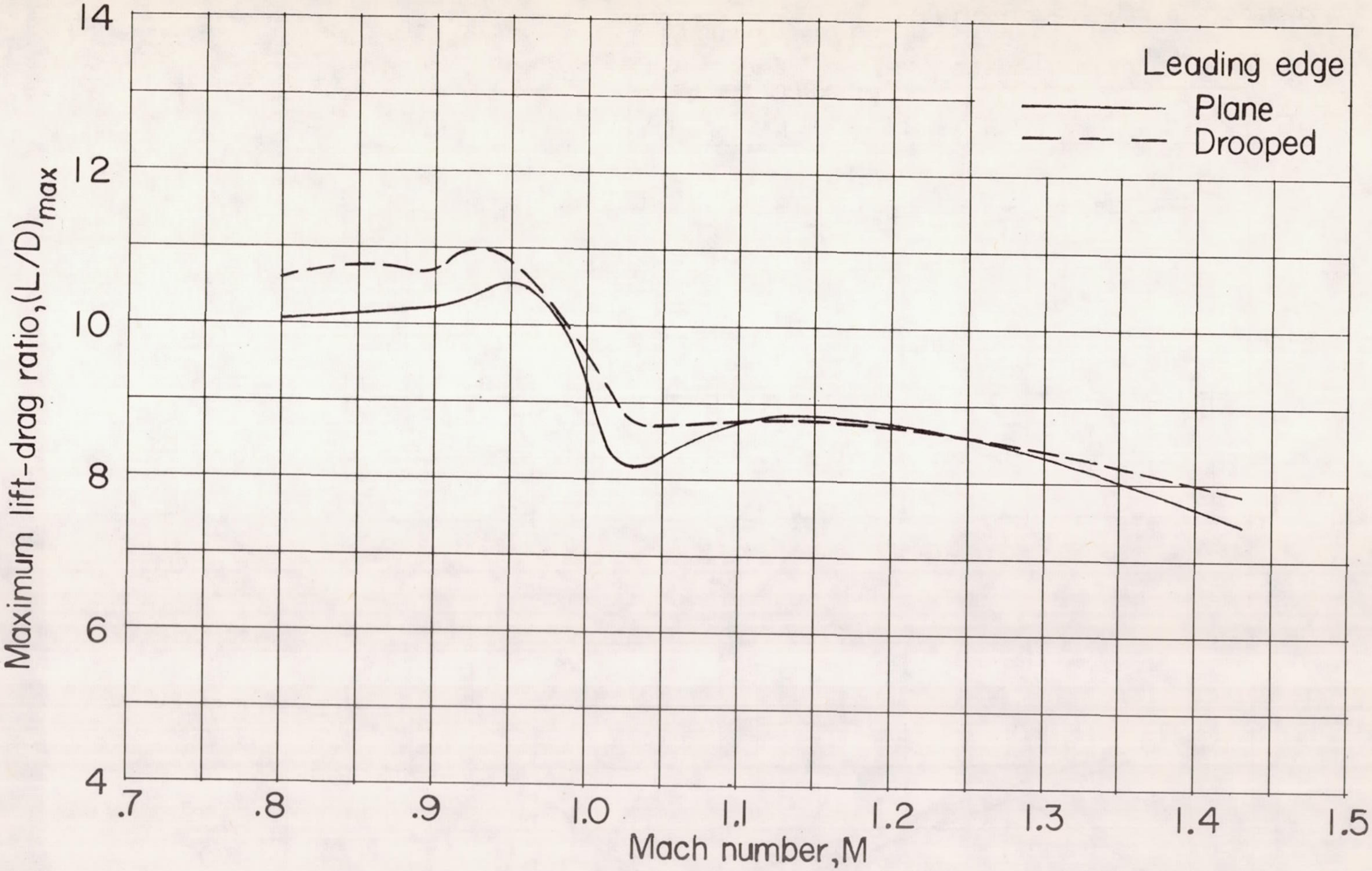

Figure 12.- Effect of leading-edge droop on maximum lift-drag ratio for 0.02t/c wing—elliptical-body configuration.

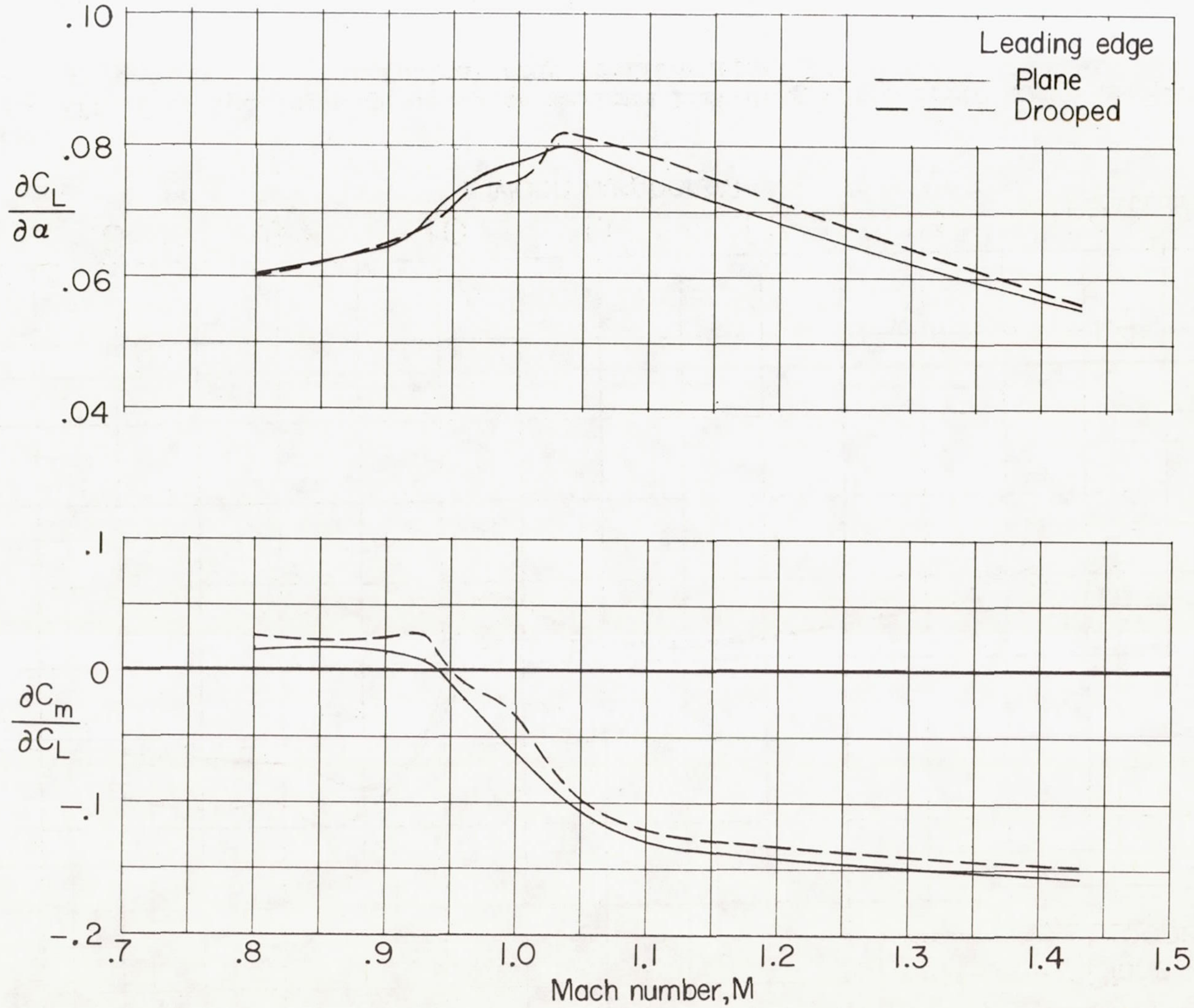

Figure 13.- Effect of leading-edge droop on lift-curve and pitching-moment-curve slopes taken at $C_L = 0$ for 0.02t/c wing—elliptical-body configuration.

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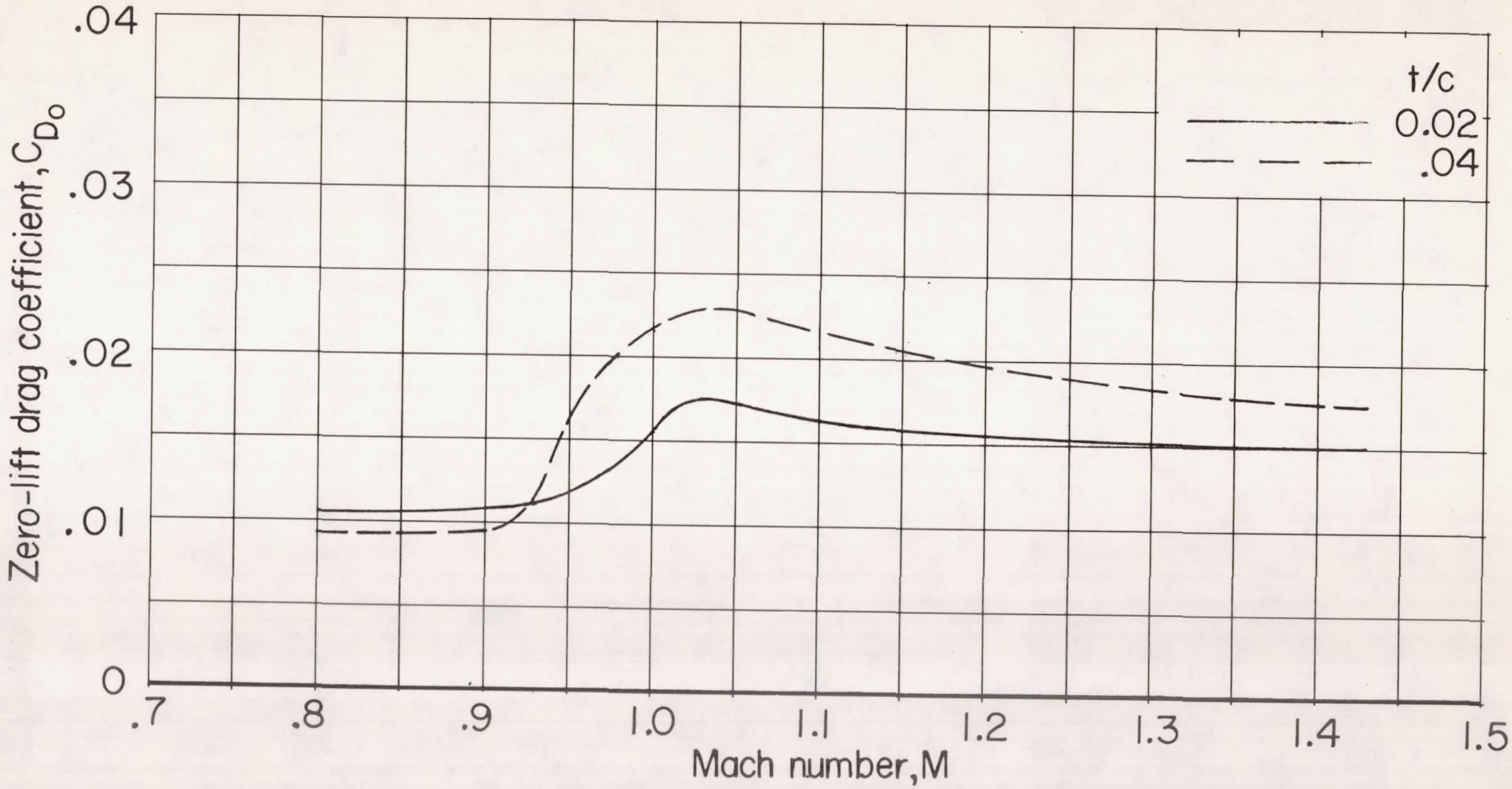

Figure 14.- Effect of wing thickness on zero-lift drag for basic-body configuration.

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