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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1212

EFFECT OF REFLEX CAMBER ON THE AERODYNAMIC CHARACTERISTICS OF A HIGHLY TAPERED MODERATELY SWEPT-BACK WING AT REYNOLDS NUMBERS UP TO 8,000,000

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EFFECT OF REFLEX CAMBER ON THE AERODYNAMIC CHARACTERISTICS OF A HIGHLY TAPERED MODERATELY SWEPT-BACK WING AT REYNOLDS NUMBERS UP TO 8,000,000

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SUMMARY

Tests have been conducted at Reynolds numbers up to 8,000,000 to determine the effectiveness of a reflex-cambered mean line in shifting the low-drag range of a highly tapered, moderately swept-back wing without materially affecting the longitudi al stability. Two models were tested, one with symmetrical airfoil sections and the other with the same basic thickness forms but with a reflex-cambered mean line.

The results of these tests show the following effects of the reflex-cambered mean line: (1) the upper limit of the low-drag range was shifted from a lift coefficient of about 0.35 to about 0.65; (2) airplane trim was unaffected at zero lift but at low lift coefficients the neutral point was moved forward about 2 percent of the mean aerodynamic chord and at lift coefficients beyond the low-drag range the forward shift in the neutral point was more severe; (3) the wing stall was delayed but, once started, progressed more rapidly; and (4) the maximum lift coefficient, if the wings were trimmed, would be slightly increased.

INTRODUCTION

In selecting the airfoil sections to be employed in the design of a tailless airplane, an important consideration is the wing pitching moments which, for trim requirements, must remain moderate. Because of their low drag qualities, NACA 6-series airfoils are desirable for high-speed and long-range operations and, if symmetrical, have moderate pitching moments. The lift coefficients encompasing the cruising conditions are, however, generally above the low-drag range of practical symmetrical airfoils. Adding camber and reflexing the mean line offers a possibility of shifting the low-drag range of the wing to include higher lift coefficients without materially affecting the pitching moment. Tests were conducted in the Langley 19-foot

pressure tunnel of two highly tapered, moderately swept-back wings of identical plan form. One of the wings was of NACA 6-series symmetrical airfoil sections and the other wing incorporated the same basic airfoil sections but had cambered and reflexed mean lines. The Reynolds number range for these tests was from 3,000,000 to 8,000,000.

SYMBOLS

C_L lift coefficient (L/qS)

C_D drag coefficient (D/qS)

C_{D_o} profile-drag coefficient $\left(C_D - C_{D_i}\right)$ from force measurements; $\int_{\text{wake span}} \frac{c_{d_o} c}{S} dy$ from wake surveys

c_{d_o} section profile-drag coefficient based on section chord from measurements of flow in wake

C_m pitching-moment coefficient $(M'/qS\bar{c})$

α angle of attack of root chord corrected for air-flow misalinement and jet-boundary interference effects, degrees

R Reynolds number $(\rho V\bar{c}/\mu)$

M Mach number (V/V_c)

where

L lift

D drag

M' pitching moment about quarter-chord point of mean aerodynamic chord

C_{D_i} induced-drag coefficient

$$(0.0436C_L^2 + 0.0006C_L + 0.0003)$$

q dynamic pressure of free stream $\left(\frac{1}{2}\rho V^2\right)$

S wing area

c section chord

$\bar{c}$ mean aerodynamic chord (M.A.C.) $\left(\frac{2}{S}\int_0^{b/2} c^2 dy\right)$

ρ mass density of air

V airspeed

μ coefficient of viscosity

b wing span

y lateral coordinate

V_c speed of sound in air

MODELS

Both wing models were made of laminated mahogany lacquered and sanded to a smooth finish. The symmetrical wing had NACA 65(318)-019 airfoil sections at the center line and NACA 65,3-018 sections at the construction tip; these sections are described in reference 1. The modified wing incorporated the same basic thickness profiles as the original wing but used a reflex-cambered mean line. The mean line was similar to that of the NACA 65,3-618 airfoil with a 0.2-chord pitch control flap deflected upward to effect zero pitching moment at zero lift. The mean line for the modified wing was faired so that no break occurred at the 0.8-chord station. Ordinates for the root and construction tip sections are given in table I.

The wings were practically the same in geometry and the exact dimensions for each wing are given in figure 1. Figure 2 shows the symmetrical wing model installed in the test section. The wings were tested without flaps, control surfaces, landing gear, nacelles, or other protuberances.

APPARATUS AND TESTS

The tests were conducted in the Langley 19-foot pressure tunnel with the air compressed to a density of approximately 0.0052 slug per cubic foot. Values of dynamic pressure ranged from 20 to 145 pounds

per square foot with the resulting Mach numbers varying from 0.08 to 0.21. Tests were made over an angle-of-attack range from below zero lift to beyond the stall. Measurements of lift, drag, and pitching moment were obtained by means of a simultaneous-recording balance system. The profile drag was obtained both from force tests and from surveys which determined the loss in momentum of the wing wake. The stalling characteristics were determined by observing the action of strands of cotton thread attached to the upper surface of the wings on the rear 60 percent of the wing chord. Force tests and stall studies were also made with roughness applied to the leading edge of each wing. The roughness was obtained by application of No. 60 (0.011-inch mesh) carborundum grains to a thin layer of shellac over a surface length of 8 percent chord measured from the leading edge on both upper and lower surfaces. The grains covered 5 to 10 percent of the affected area.

RESULTS AND DISCUSSION

All data have been corrected for the tare and interference effects of model supports, for air-flow misalinement, and for jet-boundary interference effects. In order to obtain values of profile-drag coefficient from force measurements, the induced-drag coefficient was computed by the method described in reference 2, as follows:

$$C_{D_i} = 0.0436C_L^2 + 0.0006C_L + 0.0003$$

The values of the constants in the formula for C_{D_i} were computed because the charts given in reference 2 do not apply for the twist distribution and tip shape of this wing. The lift distribution was determined by the method of references 3 and 4.

Effect of Camber

Lift and stalling characteristics.- A comparison of the aerodynamic and stalling characteristics of the two wings can be obtained from figures 3 and 4. The lift-curve slopes for the two wings were approximately equal at lift coefficients below 0.2 and above 1.0. At values between these lift coefficients the rate of change of the slope for the symmetrical wing was essentially uniform whereas the slope for the cambered wing remained constant up to a lift coefficient of about 0.7, then decreased abruptly and remained constant almost to the stall. In reference 1 the data for the NACA 65,3-618 airfoil with the 0.20-chord flap deflected -10° are considered to approximate the characteristics of the cambered wing section whereas the data for the NACA 65,3-018 airfoil apply directly as the symmetrical-wing section characteristics. A

comparison of the data (reference 1) of each section with the data of the corresponding complete wing (fig. 3) indicates that the shape of the lift curves are similar. The maximum lift coefficients of the wings in the untrimmed condition were approximately the same.

The stall patterns (fig. 4) of the two wings were similar. As the angle of attack was increased, a cross flow started near the trailing edge of the center section of each wing. This flow increased in severity and spread outboard until it was directly perpendicular to the model center line. Any region where the direction of spanwise flow was forward of this perpendicular was then interpreted as being a stalled area. Addition of camber slightly delayed the cross flow and the beginning of stalled regions, but once started the stall progressed more rapidly. For both wings the initial stall occurred at the upper end of the low-drag range. Differences in stall progression can be directly correlated with the differences in section characteristics previously discussed. There was little tendency for the stall to be intermittent until after the attitude of maximum lift coefficient had been reached, at which time a swirling type of stall developed on both wings.

Drag characteristics.- Figure 5 presents the profile-drag coefficient of the two wings as measured by force tests and by momentum loss of the wing wake. The results from the two experimental methods were in close agreement. Adding camber to the wing airfoils shifted the upper limit of the low-drag range from $C_L = 0.35$ to 0.65. Also, the value of minimum drag coefficient was slightly lower, probably because of small differences in the surface condition of the wings, since the section drag data of reference 1 do not show this benefit. The drag values were higher for the cambered wing than for the symmetrical wing from $C_L = 0.80$ to the stall. This difference in drag is characteristic of the airfoil sections and is associated with the rates of stall progression.

A comparison of the section profile-drag coefficients at several values of lift coefficient is given in figure 6. Because of the cross-flow on the wing which developed to a noticeable degree at values of lift coefficient above 0.5 (fig. 4), the drag measured at a given spanwise station is not necessarily the drag corresponding to the section at that station but may correspond to a section farther inboard. The peaks indicated at $0.5\frac{b}{2}$ for the cambered wing were found (after the survey) to have resulted from narrow flat areas on the leading edge of the wing.

Pitching-moment characteristics.- From figure 3 it is seen that adding reflex camber to the wing did not change the trim at zero lift since the values of pitching-moment coefficient were identical for the

two wings. In the low-drag range of lift coefficient, adding camber moved the neutral point ahead about 2 percent of the mean aerodynamic chord. At the upper extremes of the low-drag range of each wing there was a forward shift in the neutral point which often occurs with wings of swept-back plan form operating at moderate lift coefficients. This shift was much more noticeable for the cambered wing than for the symmetrical wing and was associated with the previously discussed behavior of the lift and drag curves and the stall progression. Near maximum lift the pitching-moment coefficient was more positive for the cambered wing than for the symmetrical wing by an amount that varied both with lift coefficient and Reynolds number. In order to trim each wing at its maximum lift coefficient by deflecting a trailing-edge control surface, a greater increment in lift coefficient would be added for the cambered wing than for the symmetrical wing. The resulting maximum lift coefficient would, therefore, be slightly higher for the cambered wing.

Effect of Roughness

The aerodynamic characteristics of both wings with and without leading-edge roughness and at four Reynolds numbers are presented in figure 7. Stalling characteristics of the wings with roughness are presented in figure 8.

Lift and stalling characteristics.- The application of leading-edge roughness decreased the value of $dC_L/d\alpha(C_L = 0)$ for both the symmetrical and the cambered wing from 0.085 to 0.078 and 0.082 to 0.077, respectively. The average decrement in maximum lift was 0.30 for the symmetrical wing and 0.26 for the cambered wing. The addition of leading-edge roughness to each wing did not change its stall pattern although the rate of stall progression accelerated, with a resultant decrease of 4° or 5° in the angle of attack for maximum lift. The stalled regions again developed more rapidly on the cambered wing.

Drag characteristics.- Any drag benefits shown by adding camber to the airfoil disappeared when roughness was applied. At values of lift coefficient below 0.3 the values of drag coefficient for the two wings were identical. The comparative values of drag coefficient for $C_L > 0.3$ were less for the symmetrical wing than for the cambered wing. This effect of roughness illustrates the need for maintaining a smooth surface condition in order that the benefit of a cambered mean line may be utilized.

Pitching-moment characteristics.- At low values of lift coefficient, the application of leading-edge roughness caused a forward shift in the neutral point of 1 to 2 percent of the mean aerodynamic chord. At high values of lift coefficient the neutral-point locations were approximately the same with the wings rough as with the wings

smooth, but the loss in maximum lift coefficient resulting from roughness increased the rate of change of neutral point with lift coefficient.

Variation of Aerodynamic Characteristics with Reynolds Number

Lift characteristics.- The variation of maximum lift coefficient with Reynolds number is given in figure 9. With the wing smooth the maximum lift coefficient increased with increasing Reynolds number. This increase was more pronounced for the symmetrical wing than for the cambered wing in the Reynolds number range of 3,000,000 to 5,000,000. The results shown in figure 7 indicate that at low values of lift coefficient the lift-curve slope is independent of Reynolds number. At the high values of lift coefficient an increase in slope with increasing Reynolds number is evidenced. With the wings rough, the maximum lift coefficient of both wings was essentially independent of Reynolds number. (See fig. 9.)

Drag characteristics.- Figure 10 presents the variation of profile-drag coefficient with Reynolds number for the approximate design conditions of high-speed ($C_L = 0.2$) and cruising ($C_L = 0.7$) flight. With the wings smooth, the profile-drag coefficient at $C_L = 0.2$ increased with increasing Reynolds number. An increase in tunnel air-stream turbulence with Reynolds number is believed to be partly responsible for this effect. Roughness applied to the leading edge of the wings initiated turbulent flow over the wing surfaces and then the drag coefficient showed little change with increasing Reynolds number. From previous discussion and the curves shown, the addition of camber to the symmetrical wing appeared to have little effect on the wing drag in the high-speed condition. In the cruising condition with the wings smooth the cambered wing still partly retained the low-drag qualities and thus maintained much lower values of drag coefficient than did the symmetrical wing. Applying wing roughness to both wings reversed the situation decidedly as pointed out previously and also resulted in appreciable decreases in drag with increase in Reynolds number.

Pitching-moment characteristics.- With the wings both smooth and rough, increasing the Reynolds number did not noticeably affect the pitching moment of the wings at low values of lift coefficient. At any given lift coefficient near the stall, the positive values of the pitching-moment coefficient decreased with increasing Reynolds number.

CONCLUSIONS

From tests of two highly tapered moderately swept-back wing models to determine the effect of changing the airfoil section from symmetrical profiles to reflex-cambered profiles, the following conclusions were indicated:

1. The upper limit of the low-drag region of the aerodynamically smooth wings was shifted from a lift coefficient of about 0.35 to 0.65, which allowed for a reduction in the drag in the cruising condition. With leading-edge roughness on the wings, the drag in the range of lift coefficient above 0.3 was decidedly more for the cambered wing.

2. The value of pitching-moment coefficient at zero lift did not change but the neutral point moved ahead 2 percent of the mean aerodynamic chord. The forward shift in neutral point which was observed at values of lift coefficient above the low-drag range of the wings was more severe for the cambered wing. Application of roughness had a destabilizing influence on both wings.

3. The lift-curve slope for both wings decreased at the upper end of the low-drag range. This decrease was more definite and pronounced for the cambered wing.

4. Stalled areas developed on both wings at the upper end of the low-drag range. The value of the maximum lift coefficient, if the wings were trimmed, would be slightly higher for the cambered wing even though the stall progression was more rapid.

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National Advisory Committee for Aeronautics
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1. Abbott, Ira H., von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA ACR No. L5C05, 1945.

2. Anderson, Raymond F.: Determination of the Characteristics of Tapered Wings. NACA Rep. No. 572, 1936.

3. Cohen, Doris: A Method for Determining the Camber and Twist of a Surface to Support a Given Distribution of Lift. NACA TN No. 855, 1942.

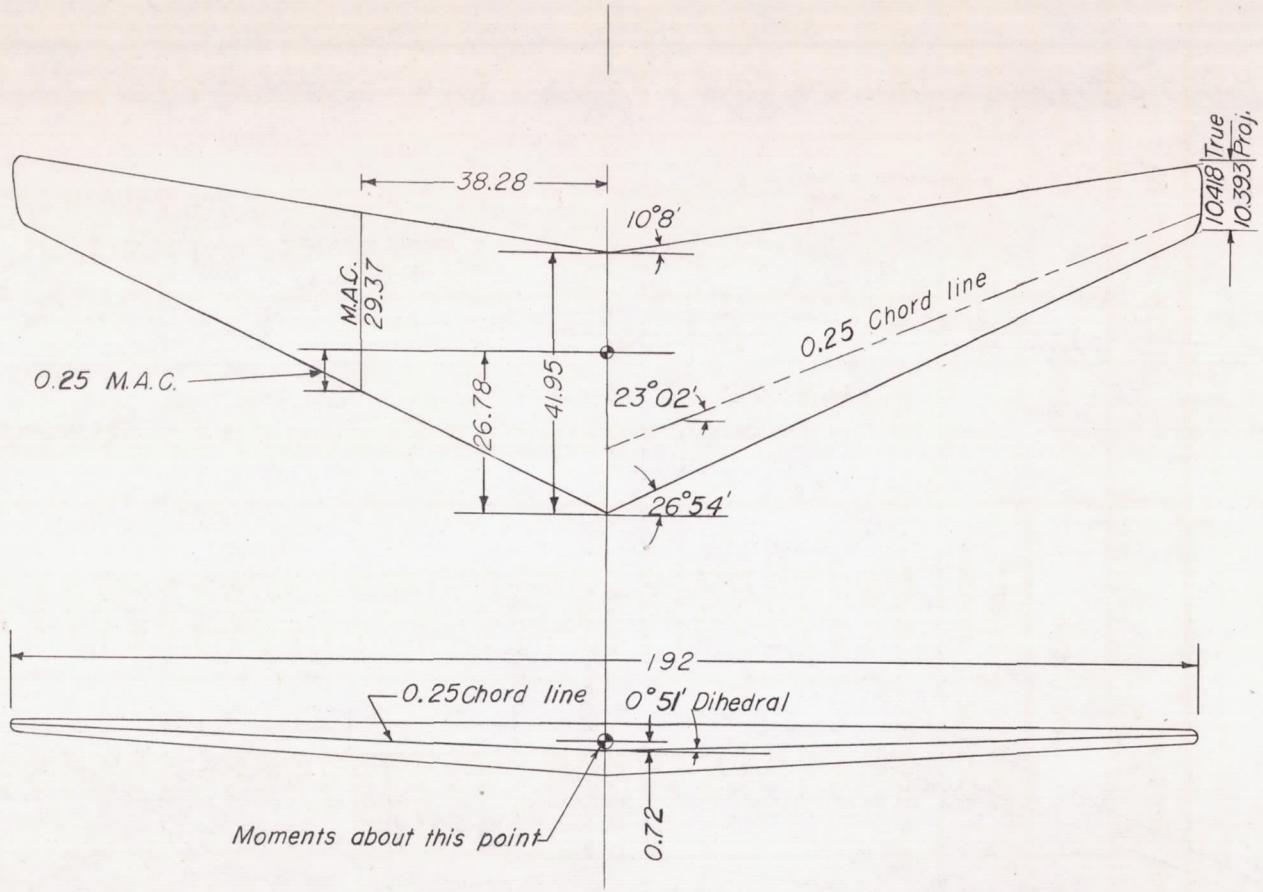
4. Cohen, Doris: Theoretical Distribution of Load Over a Swept-Back Wing. NACA ARR, Oct. 1942.

TABLE I.- ORDINATES FOR REFLEX-CAMBERED AIRFOIL

[Stations and ordinates in percent chord]

Root Section			Tip Section		
Station	Ordinate		Station	Ordinate	
	Upper surface	Lower surface		Upper surface	Lower surface
0.3	1.65	-0.69	0.3	1.562	-0.657
.6	2.05	-1.05	.6	1.937	-.991
1.0	2.45	-1.41	1.0	2.324	-1.339
2.0	3.26	-1.99	2.0	3.085	-1.887
3	3.92	-2.42	3	3.711	-2.288
4	4.49	-2.79	4	4.259	-2.645
5	5.02	-3.13	5	4.752	-2.962
6	5.49	-3.43	6	5.194	-3.250
8	6.33	-3.97	8	5.995	-3.758
10	7.06	-4.43	10	6.683	-4.198
15	8.51	-5.39	15	8.056	-5.107
20	9.60	-6.15	20	9.092	-5.827
25	10.43	-6.79	25	9.873	-6.429
30	10.97	-7.27	30	10.392	-6.882
35	11.28	-7.57	35	10.676	-7.169
39.5	11.32	-7.70	39.5	10.717	-7.289
45	11.09	-7.66	45	10.498	-7.258
50	10.61	-7.45	50	10.047	-7.058
55	9.88	-7.06	55	9.358	-6.681
60	8.94	-6.52	60	8.463	-6.173
65	7.80	-5.83	65	7.389	-5.522
70	6.56	-5.04	70	6.212	-4.775
75	5.25	-4.16	75	4.972	-3.938
80	3.91	-3.26	80	3.700	-3.089
85	2.58	-2.35	85	2.444	-2.229
90	1.36	-1.48	90	1.285	-1.403
93	.73	-.97	93	[a].690	[a]-.932
95	.39	-.67	95	[a].367	[a]-.633
96	.26	-.51	96	[a].244	[a]-.482
97	.14	-.37	97	[a].135	[a]-.346
98	.08	-.23	98	[a].073	[a]-.222
99	.04	-.13	99	[a].036	[a]-.122
100	.04	-.04	100	[a]0	[a]0

[a]In order to facilitate model construction, the ordinates for the rear 10-percent chord of the tip section were increased above these basic values to provide a 0.1346-percent-chord trailing-edge radius



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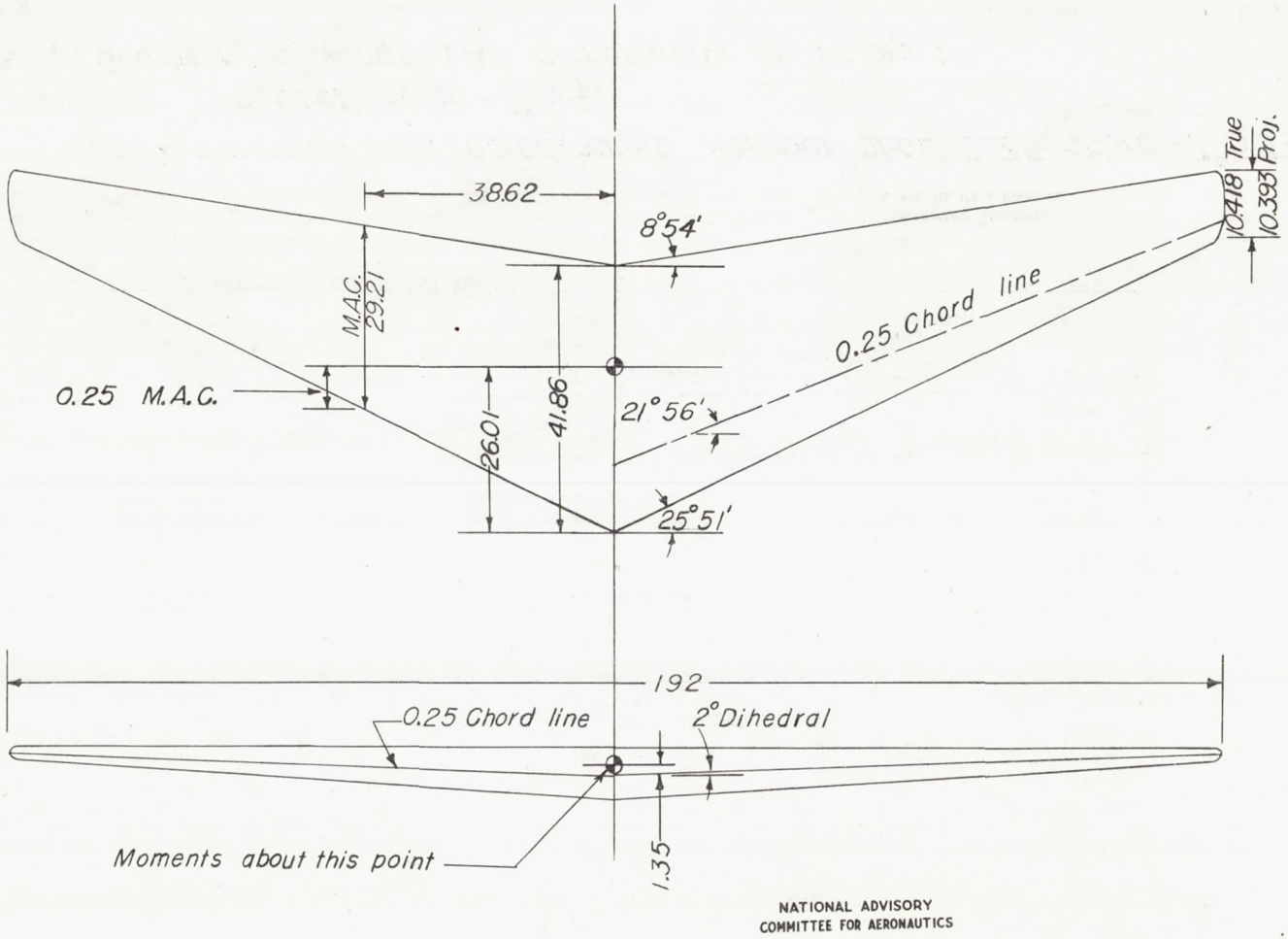
(a) Symmetrical wing; aerodynamic washout about 0.25 chord = 3°53'; aspect ratio = 7.34.

Figure 1.- Geometry of wings. (All dimensions in inches.)



(b) Cambered wing; aerodynamic washout about 0.25 chord = 4°; aspect ratio = 7.36.

Figure 1.- Concluded.

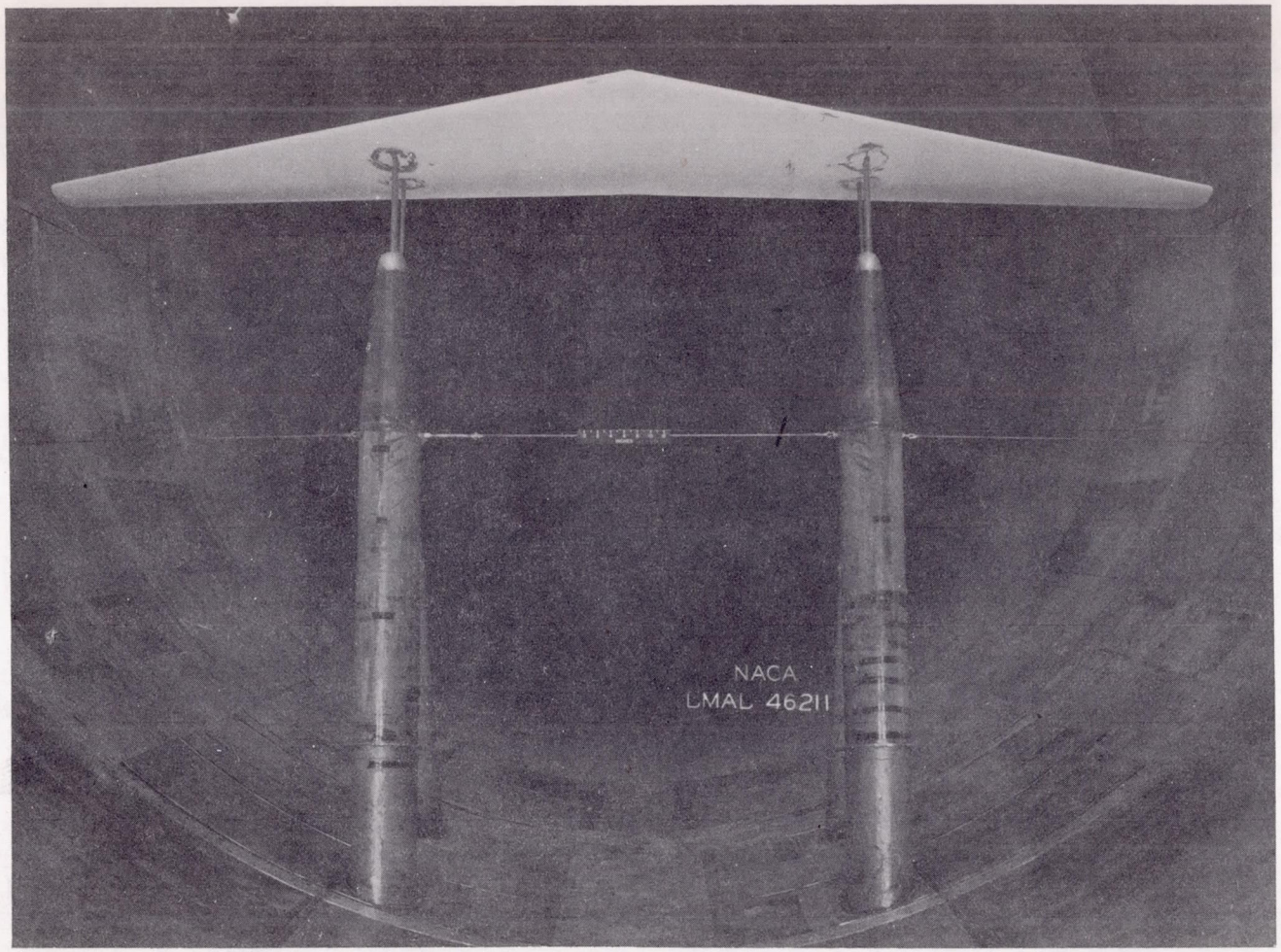


Figure 2.- Symmetrical wing mounted for testing in the Langley 19-foot pressure tunnel.

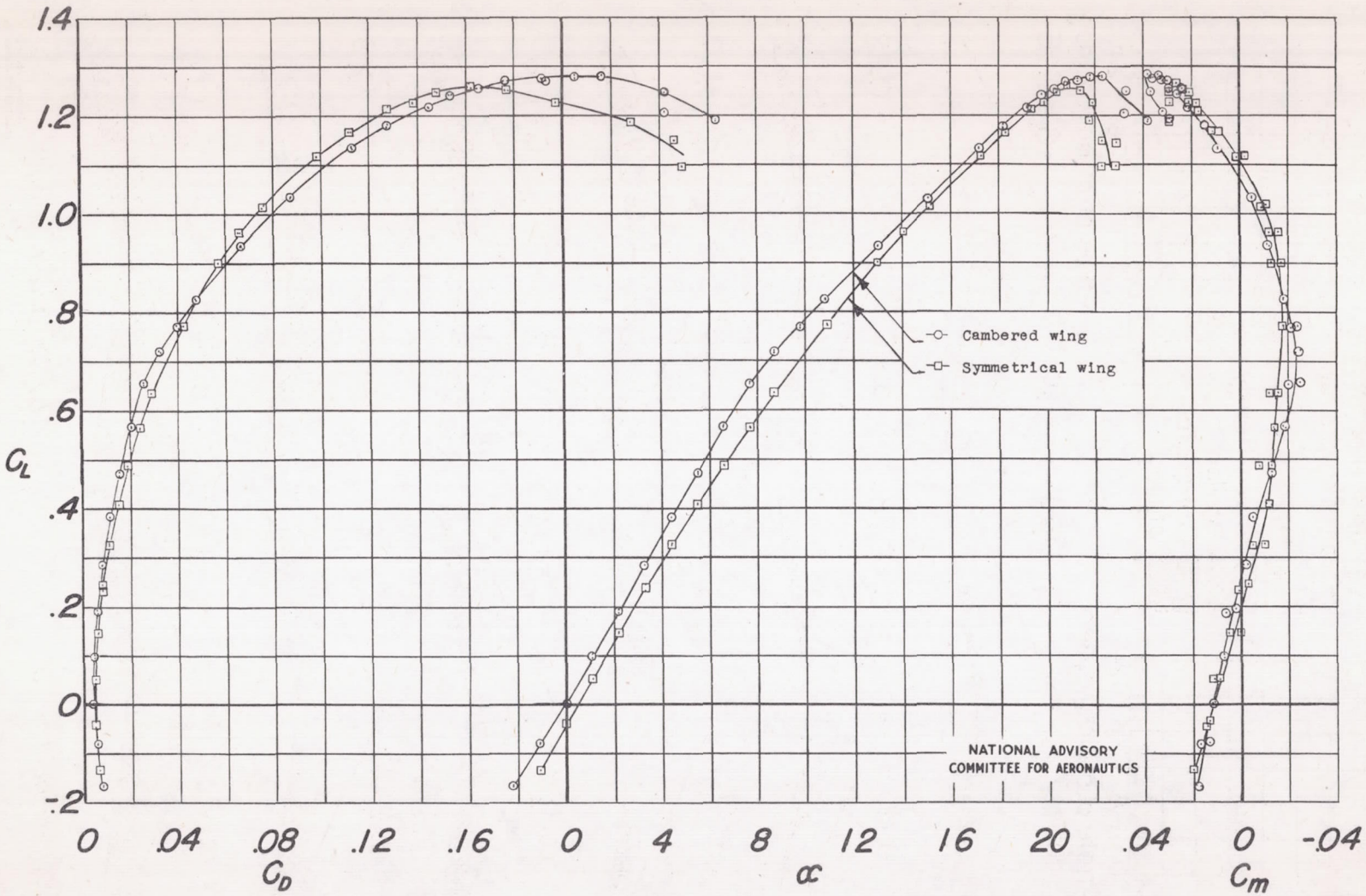
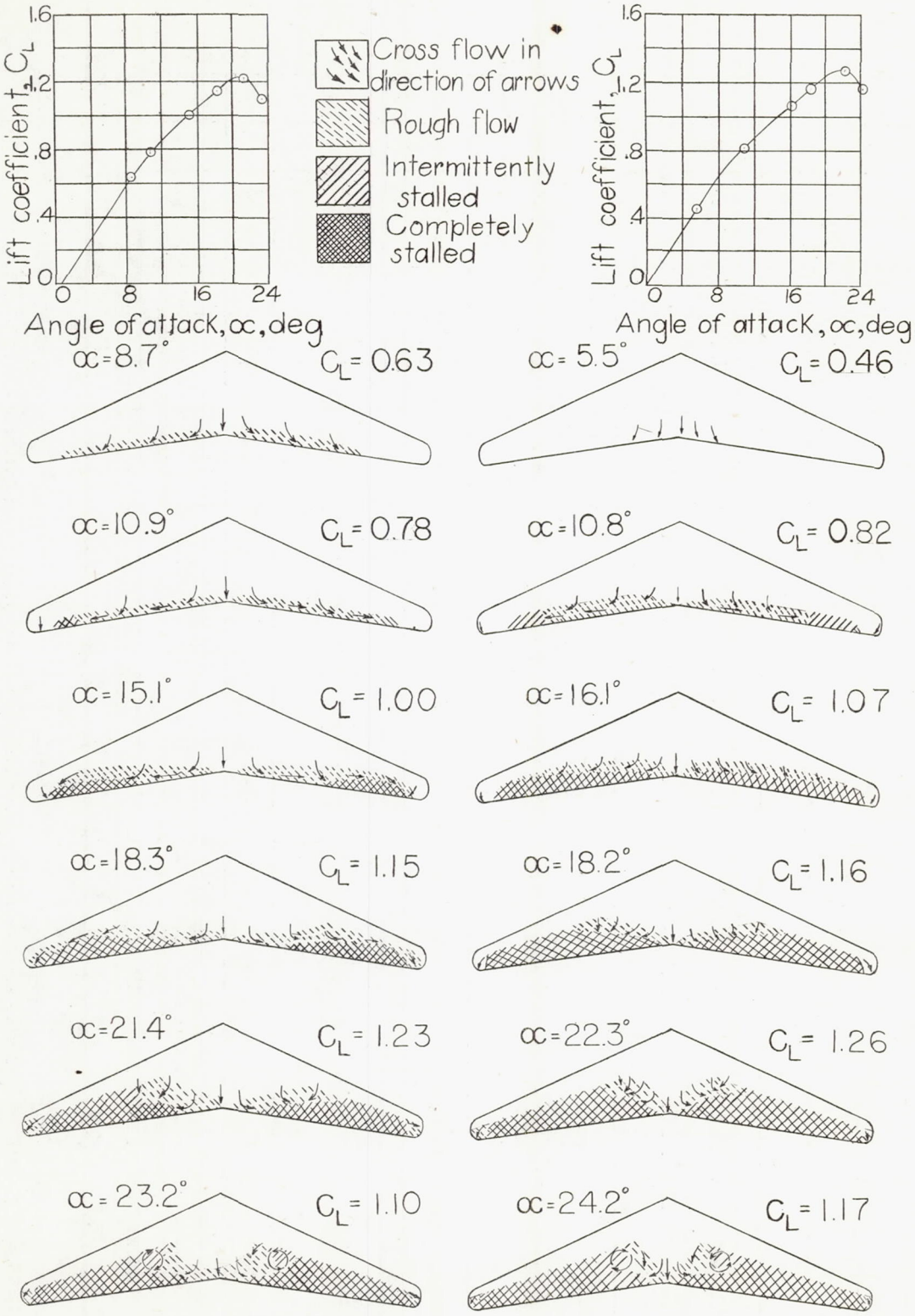


Figure 3.- Effect of airfoil modifications on aerodynamic characteristics; $R \approx 4,860,000$; $M = 0.13$.



(a) Symmetrical wing. (b) Cambered wing.

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Figure 4.- Stalling characteristics of wings; $R \approx 4{,}680{,}000$; $M = 0.13$.

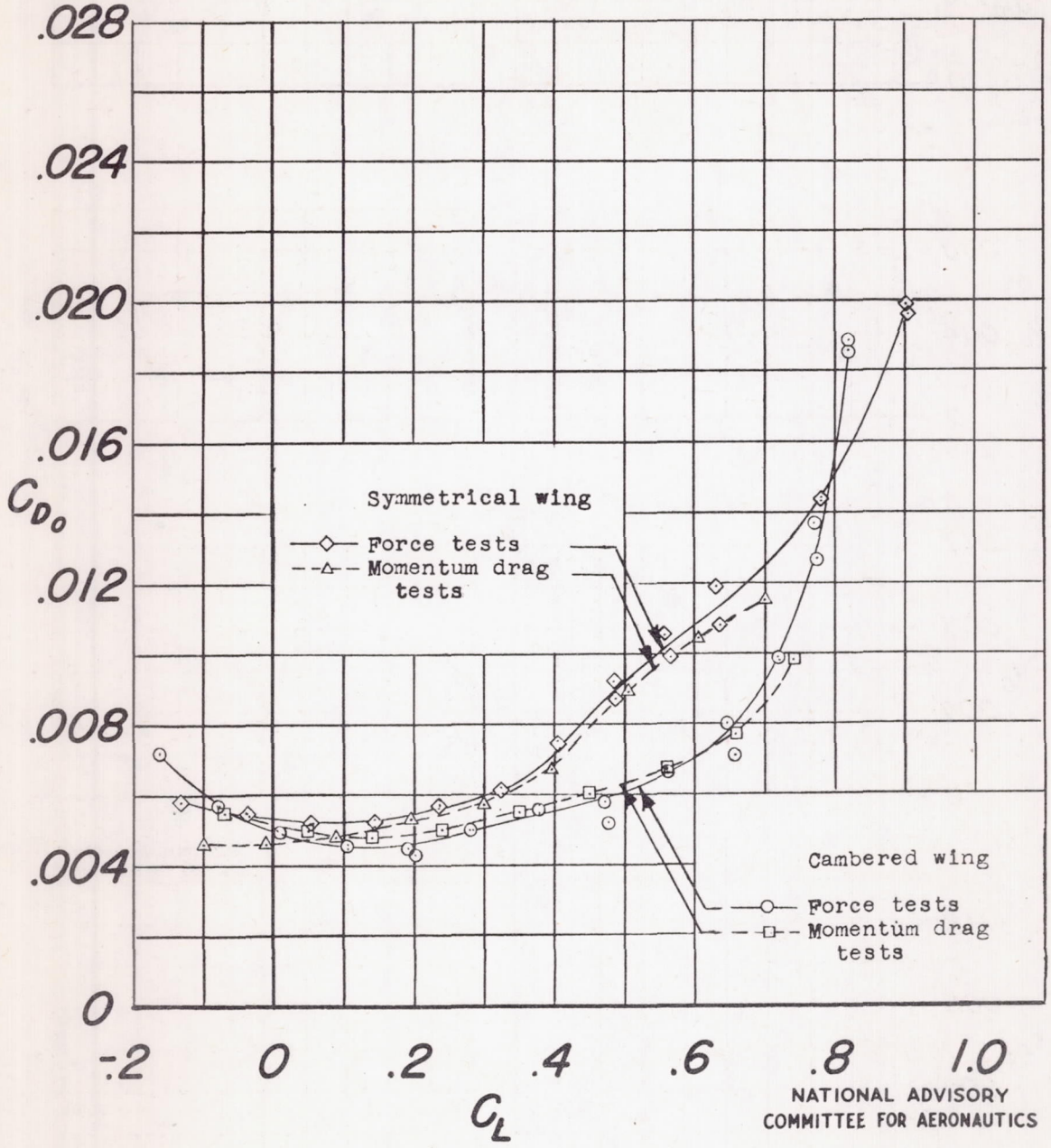
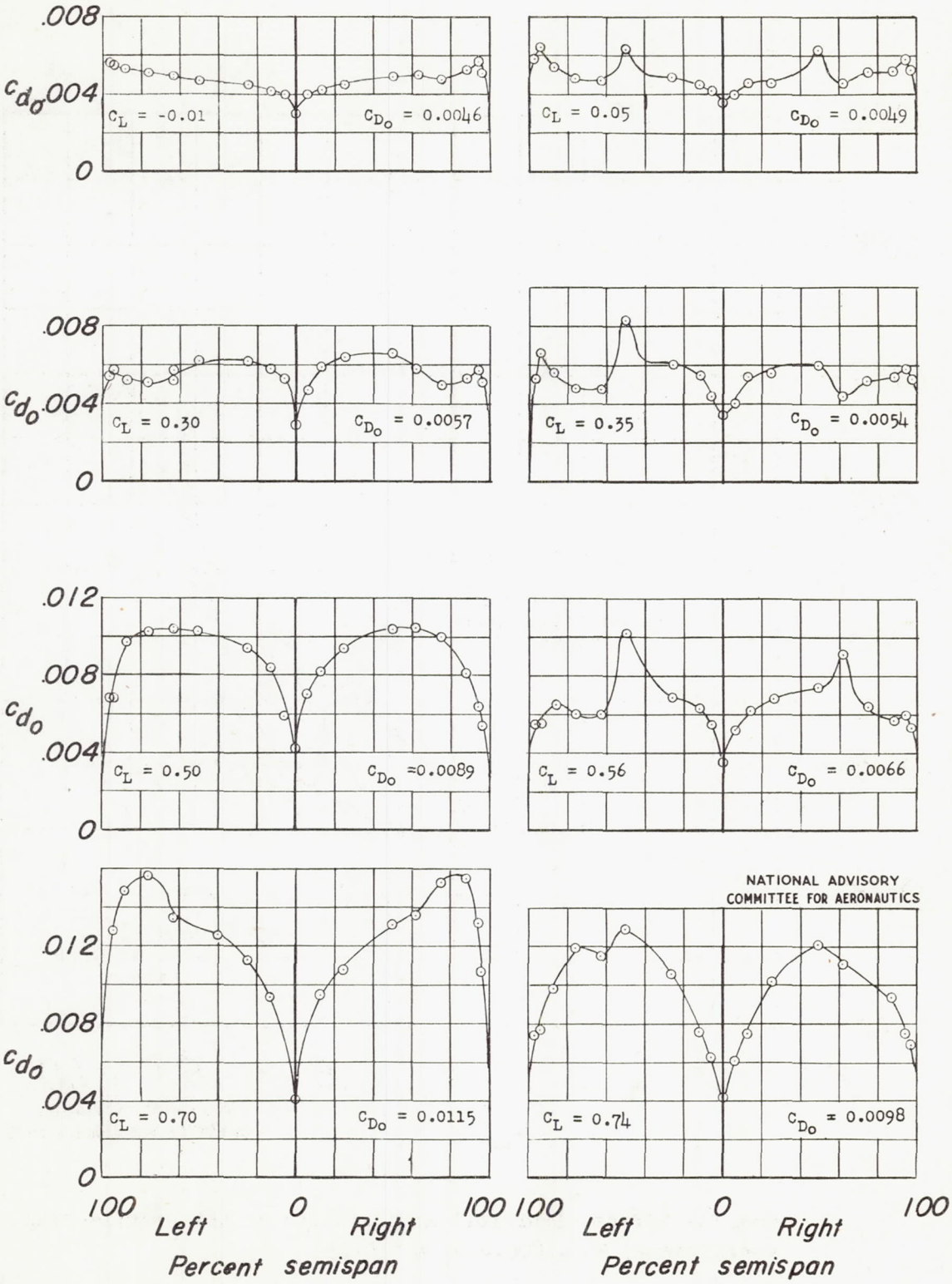
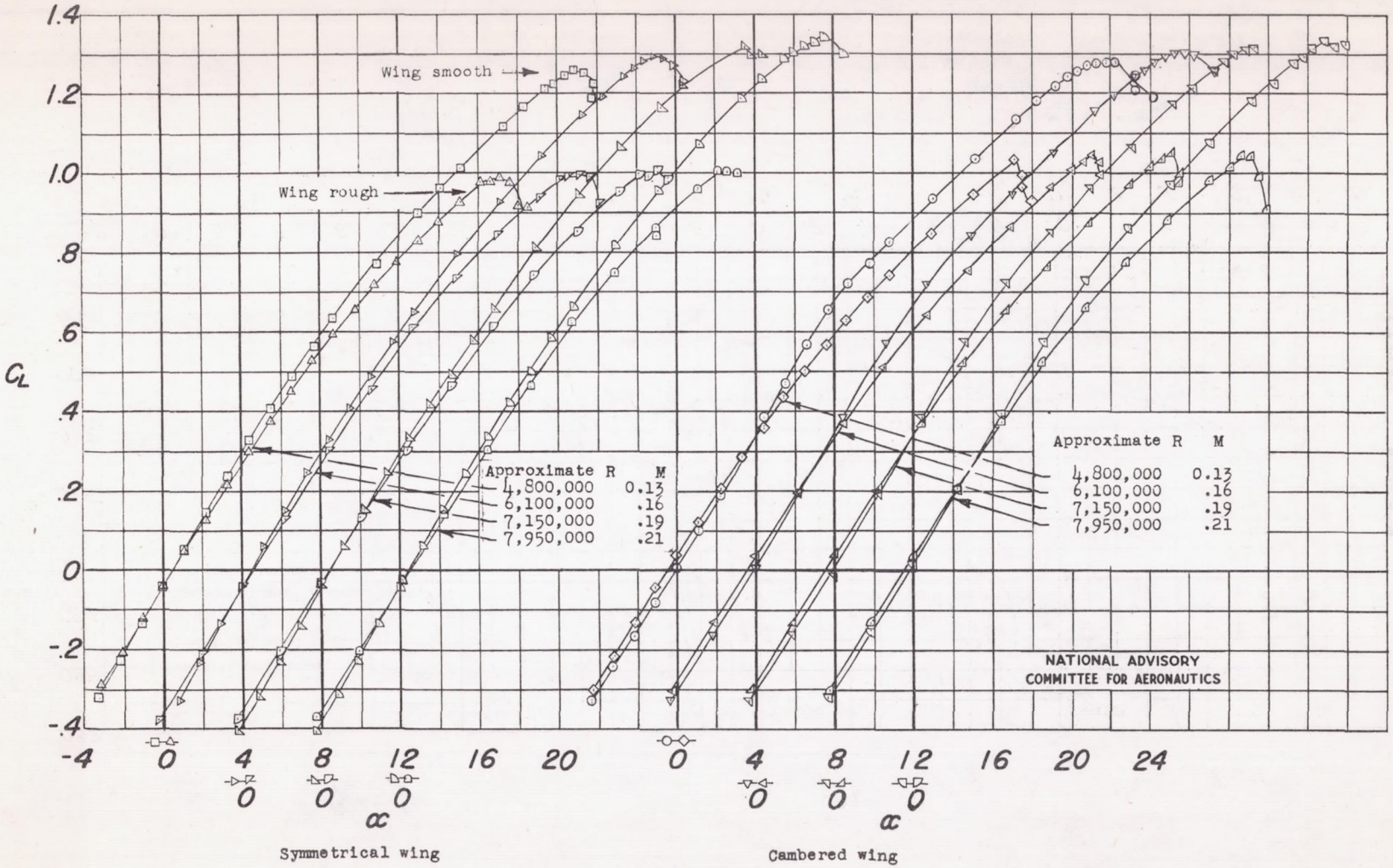


Figure 5.- Effect of airfoil modifications on the profile-drag coefficient; R ≈ 4,800,000; M = 0.13.



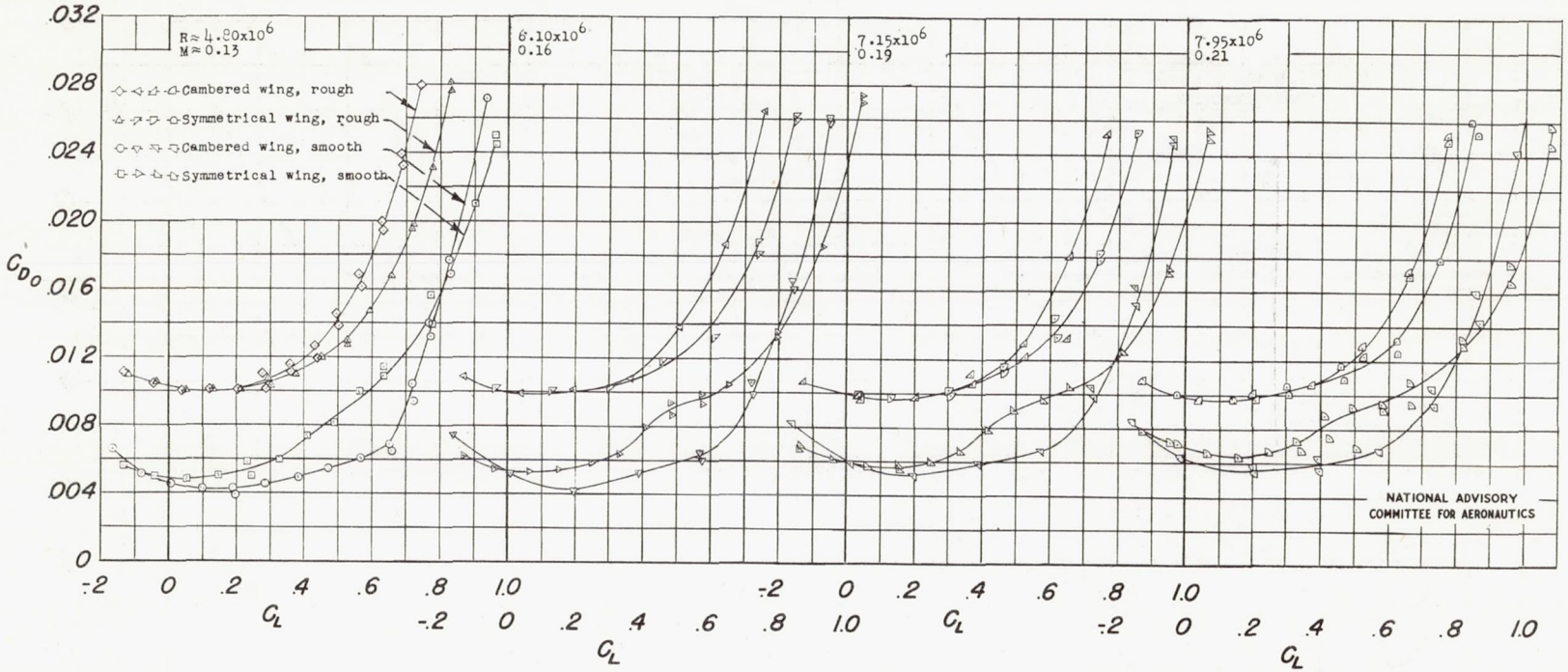
(a) Symmetrical wing. (b) Cambered wing.

Figure 6.- Variation of section profile-drag coefficient along span; R ≈ 4,760,000; M = 0.13.



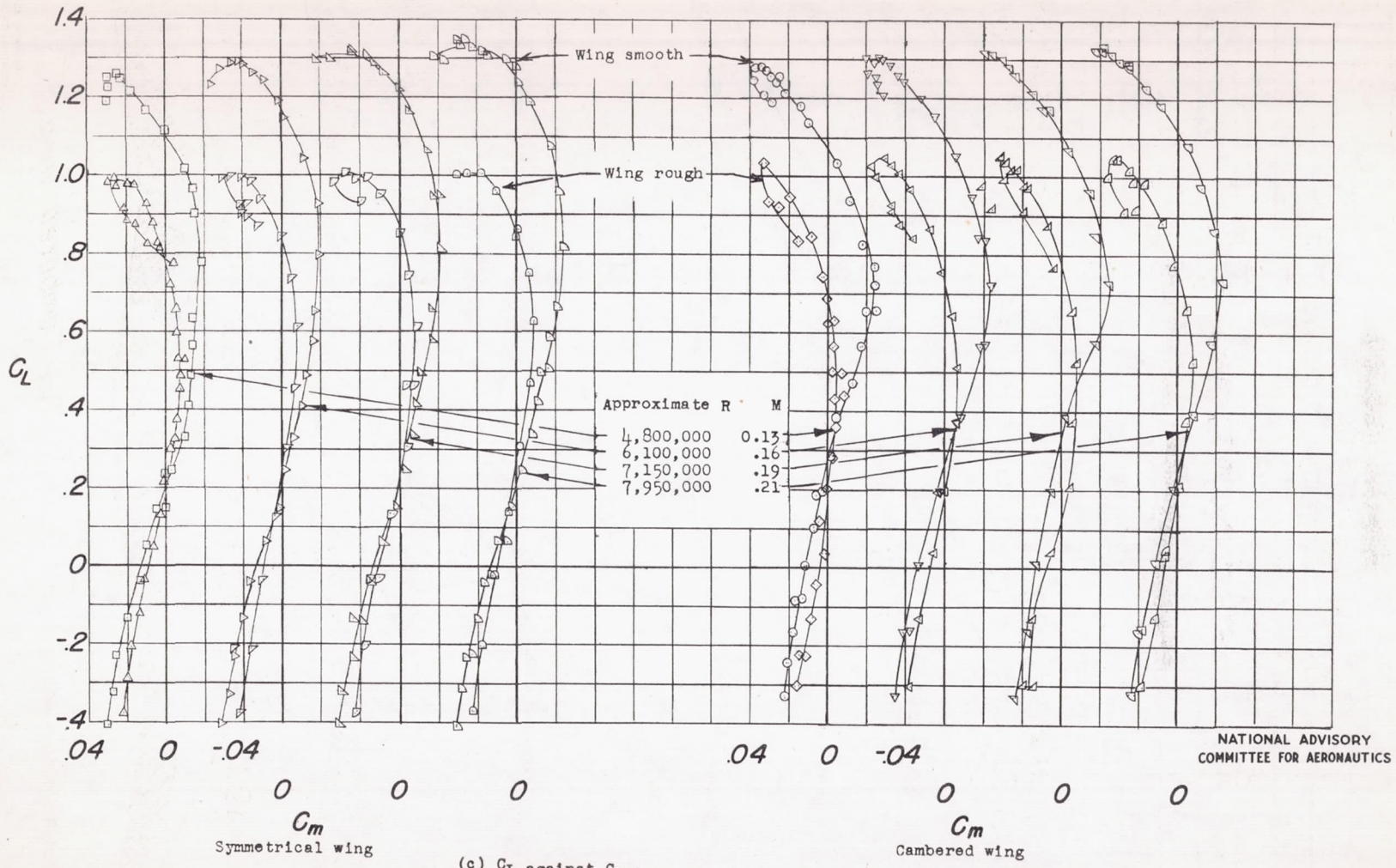
(a) C_L against α.

Figure 7.- Variation of aerodynamic characteristics with Reynolds number with and without leading-edge roughness.



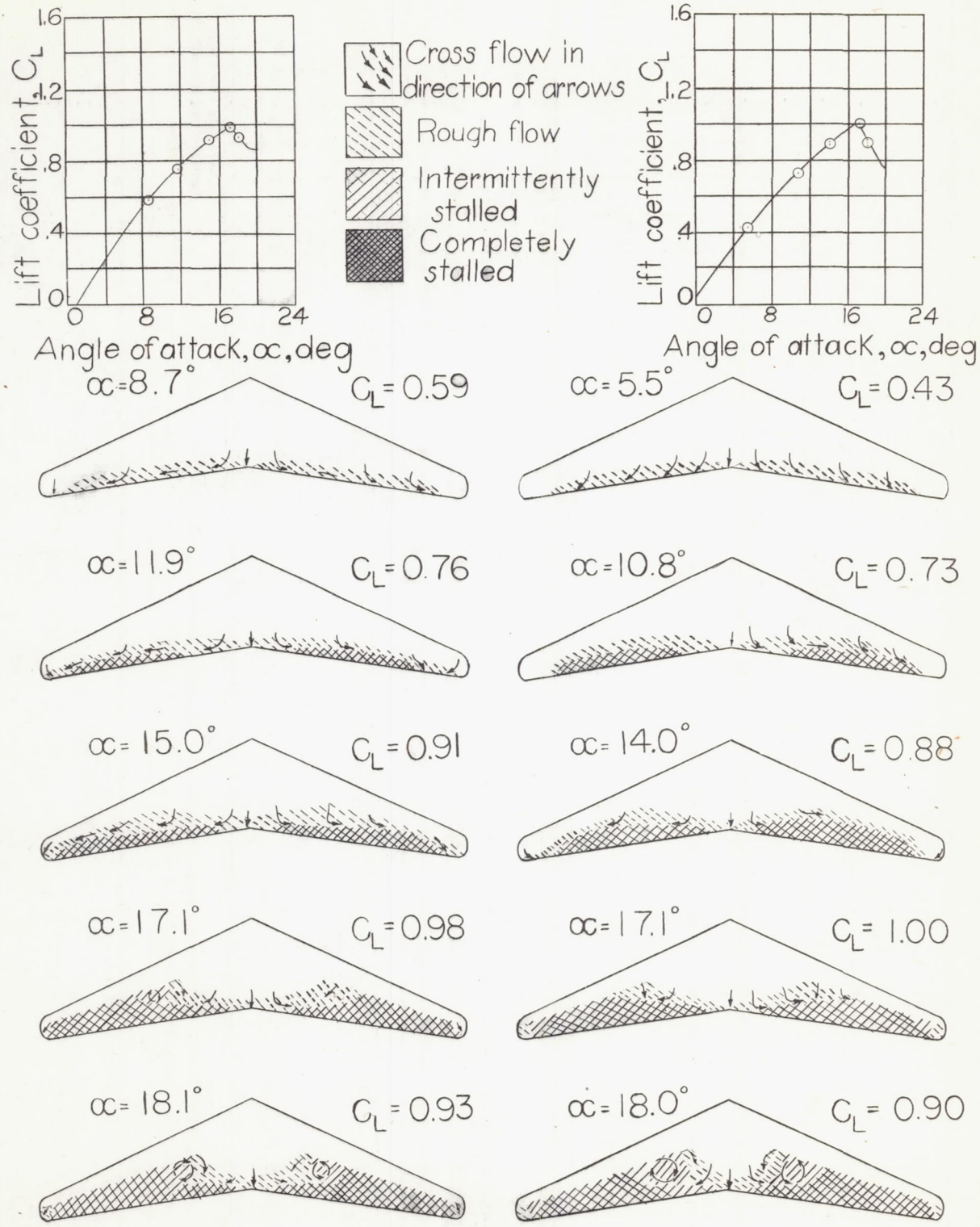
(b) C_{D_o} against C_L.

Figure 7.- Continued.



(c) C_L against C_M

Figure 7.- Concluded.



(a) Symmetrical wing. (b) Cambered wing.

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Figure 8.- Stalling characteristics of wings with leading-edge roughness. $R \approx 4,730,000$; $M = 0.13$.

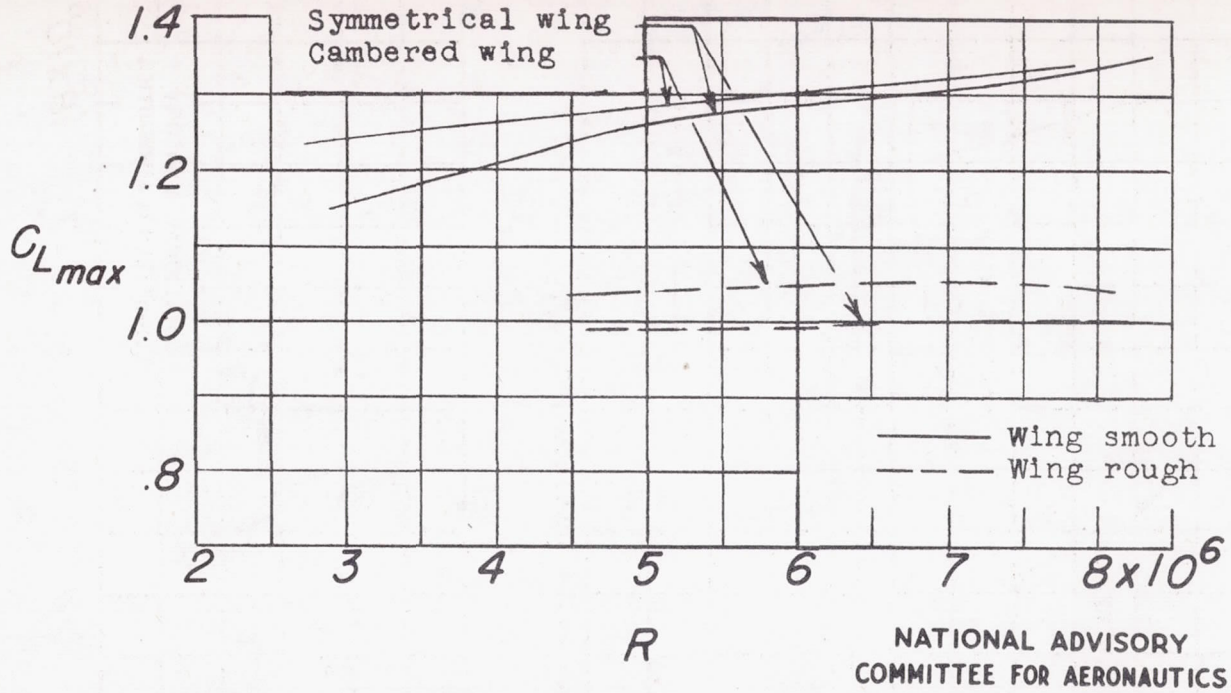
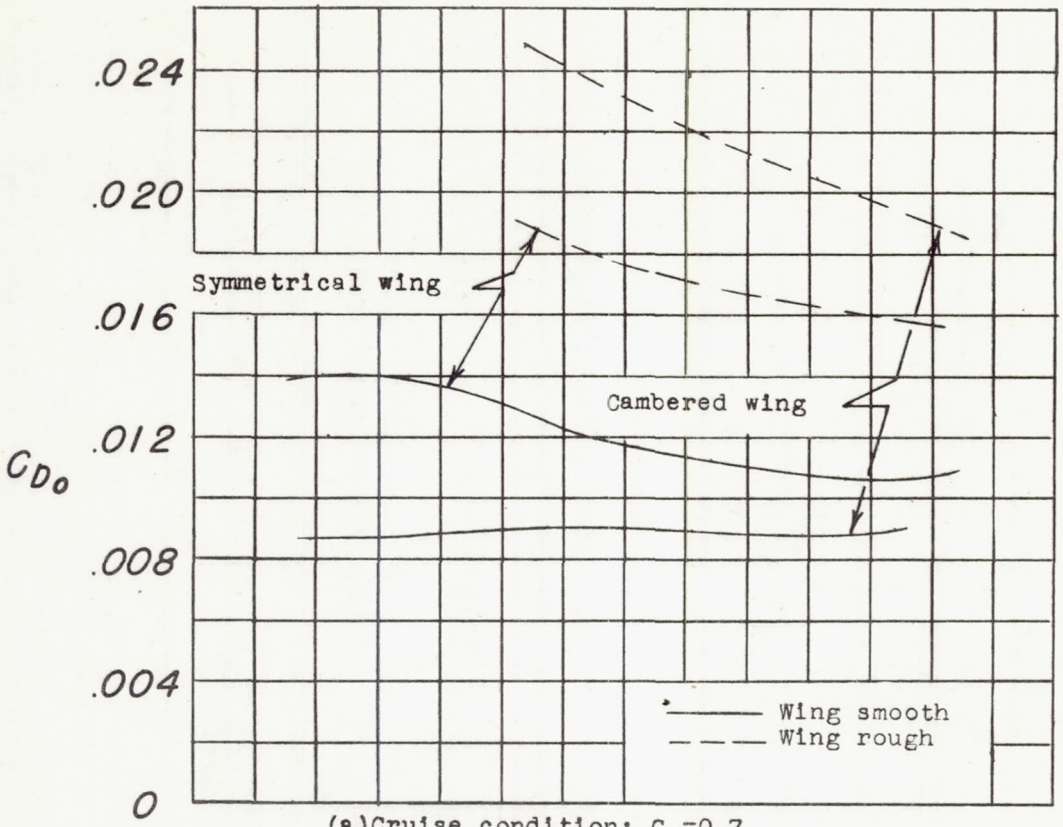
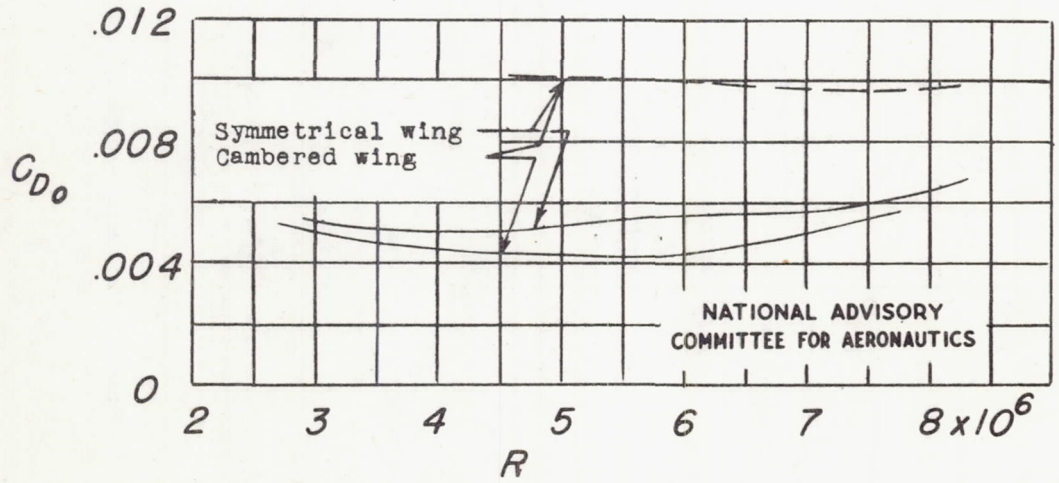


Figure 9.- Effect of Reynolds number on maximum lift coefficient with and without leading-edge roughness.



(a)Cruise condition; C_L=0.7.



(b) High speed condition; C_L = 0.2.

Figure 10.- Effect of Reynolds number on C_{D_o} at high speed and cruise condition with and without leading-edge roughness.