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TECHNICAL NOTE

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EFFECT OF GROUND PROXIMITY ON THE AERODYNAMIC CHARACTERISTICS OF ASPECT-RATIO-1 AIRFOILS WITH AND WITHOUT END PLATES

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EFFECT OF GROUND PROXIMITY ON THE AERODYNAMIC CHARACTERISTICS OF ASPECT-RATIO-1 AIRFOILS WITH AND WITHOUT END PLATES

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SUMMARY

An investigation has been made to determine the effect of ground proximity on the aerodynamic characteristics of aspect-ratio-1 airfoils. The investigation was made with the model moving over the water in a towing tank in order to eliminate the effects of wind-tunnel walls and of boundary layer on ground boards at small ground clearances.

The results indicated that, as the ground was approached, the airfoils experienced an increase in lift-curve slope and a reduction in induced drag; thus, lift-drag ratio was increased. As the ground was approached, the profile drag remained essentially constant for each airfoil. Near the ground, the addition of end plates to the airfoil resulted in a large increase in lift-drag ratio. The lift characteristics of the airfoils indicated stability of height at positive angles of attack and instability of height at negative angles; therefore, the operating range of angles of attack would be limited to positive values. At positive angles of attack, the static longitudinal stability was increased as the height above the ground was reduced.

Comparison of the experimental data with Wieselsberger's ground-effect theory (NACA Technical Memorandum 77) indicated generally good agreement between experiment and theory for the airfoils without end plates.

INTRODUCTION

The large thrust augmentation obtainable with annular-jet configurations in ground proximity has promoted considerable interest in ground-effect machines (GEM's) as possible transport vehicles. Although this thrust augmentation can be obtained in ground proximity during hovering, the inlet momentum drag of the air required to produce the jet results in relatively high drag at forward speeds and relatively low lift-drag ratios (see refs. 1 and 2). The inlet momentum drag will probably have to be reduced if reasonably high speeds and long ranges are to be achieved. This drag reduction may be accomplished by transferring some or all of the lift from the jet thrust and base lift to something approaching an airplane-type wing.

In order to obtain some data for use in predicting the performance of ground-effect machines at forward speeds with the annular jet and the inlet momentum drag completely eliminated, an investigation of the aerodynamic characteristics of airfoils in close proximity to the ground has been made in Langley tank no. 1. The investigation was made with the model moving over the water in the tank in order to eliminate the effects of wind-tunnel walls and boundary layer on ground boards at the small ground clearances desired. Inasmuch as most of the ground-effect machines built or contemplated at present have aspect ratios of 1 or less, the present investigation has been made on aspect-ratio-1 airfoils only. Lift, drag, and pitching-moment data were obtained on 22-percent-thick and 11-percent-thick airfoils. In addition, data were obtained on the 11-percent-thick airfoil with vertical end plates attached below the lower surface. A related investigation on wings in close proximity to the ground is presented in reference 3.

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SYMBOLS

The positive directions of the forces and moments are shown in figure 1.

A aspect ratio, $\frac{b^2}{S}$

b airfoil span, ft

c airfoil chord, ft

C_D drag coefficient, $\frac{D}{\frac{1}{2}\rho V^2 S}$

C_L lift coefficient, $\frac{L}{\frac{1}{2}\rho V^2 S}$

C_m pitching-moment coefficient, $\frac{M_Y}{\frac{1}{2}\rho V^2 Sc}$

ΔC_{Di} change in induced drag coefficient

D airfoil drag, lb

L airfoil lift, lb

h height of $c/4$ above ground plane, ft

h' height of trailing edge of airfoil above ground plane, ft

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M_Y airfoil pitching moment, ft-lb

S airfoil area, sq ft

V free-stream velocity, ft/sec

α angle of attack, deg

σ ground-influence coefficient

ρ mass density of air, slugs/cu ft

$(L/D)_\infty$ lift-drag ratio of airfoil out of ground effect

Subscript:

max maximum

MODEL AND APPARATUS

The airfoil sections tested and ordinates are shown in figure 1. The 22-percent-thick airfoil is the Glenn Martin 21 section (ref. 4) with the lower surface modified to have a flat bottom between the 30-percent-chord station and the trailing edge. The ordinates of the 11-percent-thick airfoil were obtained by dividing the 22-percent ordinates by 2. Both airfoils had a 48-inch chord and an aspect ratio of 1.

Vertical end plates were attached to the 11-percent-thick airfoil for some of the tests. These end plates were made of 1/16-inch-thick sheet metal. As shown in figure 1, the end plates were flush with the trailing edge and the bottom edges were parallel to the water surface. The end plates were changed for each angle of attack so that the bottom edges of the plates remained parallel to the water surface.

The investigation was made in Langley tank no. 1. A description of the tank and the apparatus used in the test is presented in reference 5. For these tests the airfoils were attached to the towing gear by a single streamline strut as shown in figure 2. Lift, drag, and pitching moment were measured by three external strain gages. The pitching moment was measured about a pivot point on the gear above the airfoil and then transferred to the moment center at the quarter chord on the lower surface (fig. 1). All tests were made at a forward speed of 72 feet per second, which corresponded to a Reynolds number of 1,840,000. Data were obtained through an angle-of-attack range from -6° to 18° at heights of the trailing edge of the airfoil above the water surface ranging from 0.015 chord to 2 chords. The height variation was obtained by changing the water level in the towing tank as well as by raising and lowering the airfoil through a limited range.

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RESULTS AND DISCUSSION

The results showing the effect of the ground on the aerodynamic characteristics of the aspect-ratio-1 airfoils are presented in figures 3 and 4. The variations of C_D, α, and C_m with C_L for the 22-percent-thick airfoil and for the 11-percent-thick airfoil with and without end plates are presented in figure 3 for a range of height-to-span ratios. The variation of C_L, C_D, and C_m with height of the trailing edge of the airfoil above the ground is presented in figure 4 for several angles of attack. Lines of constant height of the quarter-chord point are also shown in this figure.

Lift

The data of figure 3 show that, at small angles of attack, the lift-curve slope increased as the ground was approached. This increase in lift-curve slope was accompanied by a change in the angle of attack for zero lift. As the ground was approached, the angle of attack for zero lift became progressively less negative.

The lift for both the 11-percent-thick and 22-percent-thick airfoils near an angle of attack of 0° was essentially invariant with height of the airfoil above the ground. At positive angles of attack, the lift was increased as the ground was approached, whereas at negative angles of attack, the lift was decreased. These results suggest that the increase in lift at a given positive angle of attack, as the ground was approached, may be due to the ram air on the lower surface which increased the positive pressure on that surface. Pressure-distribution data presented in reference 6 for a wing with an aspect ratio of 5 indicate that the increase in lift at positive angles of attack was due to an increase in lower surface pressures; the upper surface pressures were essentially unaffected as the distance above the ground was changed.

The loss in lift as the ground was approached at a given negative angle of attack apparently was due to venturi action which increased the negative pressures on the lower surface as the ground was approached. The pressure-distribution data of reference 6 show the rapid increase in negative pressures on the lower surface near the airfoil leading edge as the ground was approached; whereas, again the upper surface pressures were essentially unaffected by changes in height above the ground at these negative angles.

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The additional lift obtained by the airfoil with end plates (compare figs. 3(b) and 3(c)) apparently was due to the reduction of flow out at the tips of the airfoil, which greatly increased the ram-pressure effect on the airfoil lower surface, especially at heights very near the ground.

Near an angle of attack of 0°, the lift coefficient for the 22-percent-thick airfoil (fig. 3(a)) was approximately twice that for the 11-percent-thick airfoil (fig. 3(b)). For the 11-percent-thick airfoil, the lift coefficient was only about 0.15. These low lift coefficients near an angle of attack of 0° and the fact that lift was essentially invariant with height at this attitude suggest the desirability of operating a ground-effect machine which has an airfoil-shaped body at positive angles of attack so that a reasonably high operating lift coefficient may be obtained. A further reason for operating a ground-effect machine only at positive angles of attack can clearly be seen in figure 4. These data graphically show that a reduction in height caused a loss in lift at negative angles of attack and an increase in lift at positive angles of attack. This lift characteristic would provide stability of height at positive angles of attack and because of the venturi action at negative angles of attack would limit the operating range of angles of attack to positive values.

Pitching Moment

The data of figure 3 show that the pitching moments became less negative at an angle of attack of 0° as the ground was approached. The pitching-moment data also show that, for positive angles of attack, the static longitudinal stability was increased as the height above the ground was reduced. This increase in stability apparently resulted from the ram pressure on the lower surface of the airfoil. As the ground was approached, the increase in lift due to the ram pressure was distributed more or less uniformly over the lower surface. (This effect is shown in ref. 6.) The center of this lift increment was, therefore, near the half-chord point and thus tended to move the center of total lift (aerodynamic center) aft and thereby increase the longitudinal stability. This effect was particularly noticeable for the airfoil with end plates (fig. 3(c)).

Drag

The data of figure 3 show the effects of the ground on drag. As the ground was approached, the induced drag was reduced although the profile drag remained essentially constant for each airfoil. Near the ground, the addition of end plates to the 11-percent-thick airfoil resulted in a large decrease in the induced drag. (Compare figs. 3(b) and 3(c).)

L1693

Lift-Drag Ratio

The results showing the effect of the ground on lift-drag ratios of the airfoils are presented in figures 5 and 6. Lift-drag ratios are plotted against lift coefficient in figure 5 for various heights of the trailing edge above the ground and in figure 6 for various heights of the quarter chord above the ground. The angle of attack for maximum L/D was about 2.5° for both the 22-percent-thick and 11-percent-thick airfoils. The addition of end plates increased the angle of attack for maximum L/D to about 3°. Maximum lift-drag ratios have been obtained from figures 5 and 6 and are plotted against height-to-span ratio in figure 7. A reduction in thickness from 22-percent to 11-percent chord increased the value of L/D approximately 45 percent at $\frac{h'}{b} = 2.00$ (no ground effect) and approximately 55 percent when the airfoil was in close proximity to the ground $\left(\frac{h'}{b} = 0.015\right)$. This increase was largely due to the lower profile drag of the thinner airfoil. The addition of end plates to the 11-percent-thick airfoil resulted in a large increase in L/D when the airfoil was in close proximity to the ground because of the increase in lift caused by the increase in ram pressure. The effect of end plates became negligible when the trailing edge was 15 percent of the span above the ground or when the quarter chord was 25 percent of the span above the ground.

The theoretical treatment of ground effect presented by Wieselsberger in reference 7 indicates a method for predicting the reduction in induced drag for a wing at various heights of the quarter chord of the wing above the ground. According to reference 7, the reduction in induced drag of a monoplane in ground effect is given by the equation

$$\Delta C_{Di} = -\sigma \frac{C_L{}^2}{\pi A}$$

where σ is defined as the ground influence coefficient. At values of h/b between 0.033 and 0.25, σ may be obtained from the following formula:

$$\sigma = \frac{1 - 1.32 \frac{h}{b}}{1.05 + 7.4 \frac{h}{b}}$$

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where h in the present investigation is equal to one-half the quantity h defined in reference 7. The variation of σ with h/b (for h as defined in the present investigation) is shown in figure 8.

The results of the present investigation are compared with theory in figure 9, where the ratio of maximum L/D in ground effect to maximum L/D out of ground effect is plotted against height-to-span ratio at the airfoil quarter chord. At maximum values of the lift-drag ratio, the theory of reference 7 reduces to the following formula (for finite aspect ratio):

$$\frac{(L/D)_{max}}{(L/D)_{\infty,max}} = \frac{1}{\sqrt{1 - \sigma}}$$

The theory is plotted as a solid line. The dashed portion of the curve represents the range of values of h/b for which the author of reference 7 considered the theory inapplicable $\left(0.033 < \frac{h}{b} < 0.25\right)$. The agreement between experiment and theory appears to be generally good for the airfoils without end plates.

Data for the aspect-ratio-1 wing of reference 3 are shown in figure 9 for comparison with data from the present investigation. Data from the two investigations of aspect-ratio-1 airfoils without end plates appear to be in generally good agreement. Although only limited data were available for the model with end plates from reference 3, the effect of end plates on lift-drag ratio was considerably less than that of the model with end plates from the present investigation. The reason for this lack of agreement between the two sets of data is not known. The wind-tunnel data of reference 3, however, were obtained at a much lower Reynolds number than the present investigation, and the end plates were applied in a somewhat different manner.

CONCLUSIONS

The results of an investigation of the effect of ground proximity on the aerodynamic characteristics of aspect-ratio-1 airfoils led to the following conclusions:

1. As the ground was approached, the airfoils experienced an increase in lift-curve slope and a reduction in induced drag; thus, an increase in lift-drag ratio resulted. The agreement between experiment and Wieselsberger's ground-effect theory appears to be generally good for the airfoils without end plates.

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2. Near the ground, the addition of end plates to the airfoil resulted in further increase in lift-curve slope and reduction in induced drag which resulted in a large increase in lift-drag ratio.

3. As the ground was approached, the profile drag remained essentially constant for each airfoil.

4. At positive angles of attack, the static longitudinal stability was increased as the height above the ground was reduced.

5. The lift characteristics of the airfoils indicated stability of height at positive angles of attack and instability of height at negative angles. These characteristics would limit the operating range of angles of attack to positive values.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., August 11, 1961.

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2. Kuhn, Richard E., Carter, Arthur W., and Schade, Robert O.: Over-Water Aspects of Ground-Effect Vehicles. Paper No. 60-14, Inst. Aero. Sci., Jan. 1960.

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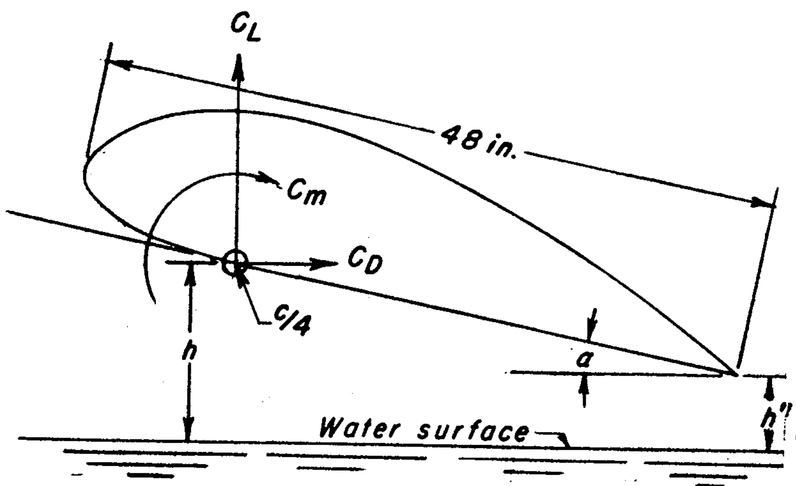
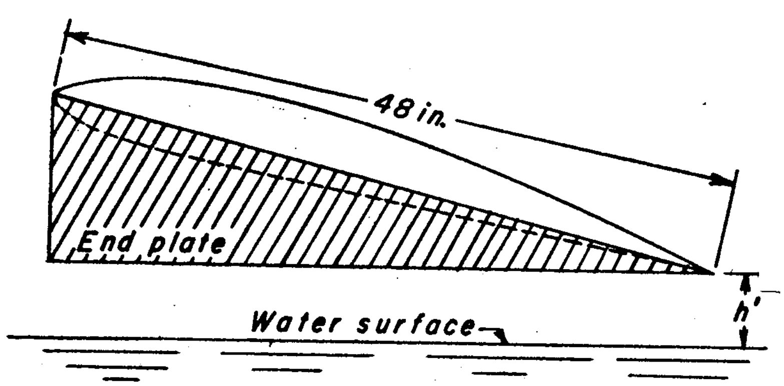


Station, percent chord	Airfoil ordinates percent chord	
	Upper	Lower
0	8.86	8.86
1.25	12.21	6.03
2.5	13.81	4.79
5	15.98	3.33
7.5	17.65	2.35
10	18.92	1.72
15	20.72	.75
20	21.68	.28
30	22.13	0
40	21.13	0
50	19.20	0
60	16.64	0
70	13.35	0
80	9.43	0
90	5.00	0
95	2.57	0
100	0	0

(a) 22-percent-thick airfoil.

L-1693



Station, percent chord	Airfoil ordinates, percent chord	
	Upper	Lower
0	4.43	4.43
1.25	6.10	3.02
2.5	6.90	2.40
5	7.99	1.66
7.5	8.82	1.18
10	9.46	.86
15	10.36	.38
20	10.84	.14
30	11.06	0
40	10.56	0
50	9.60	0
60	8.32	0
70	6.68	0
80	4.72	0
90	2.50	0
95	1.28	0
100	0	0

(b) 11-percent-thick airfoil with end plates.

Figure 1.- Airfoil sections, ordinates and principal dimensions.

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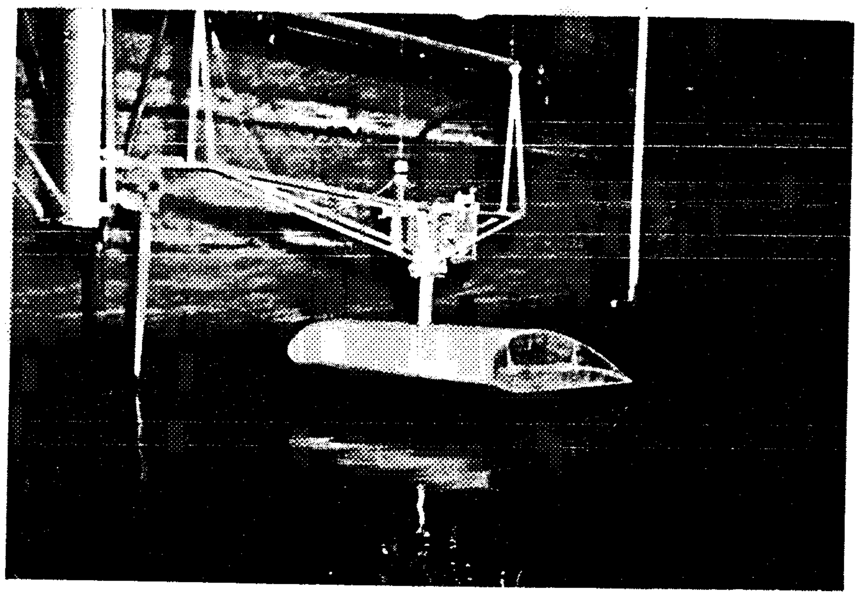
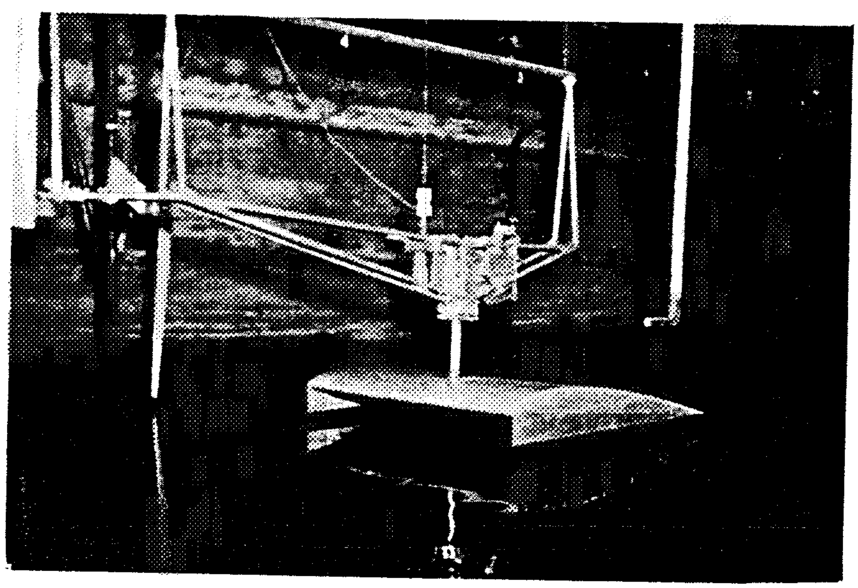
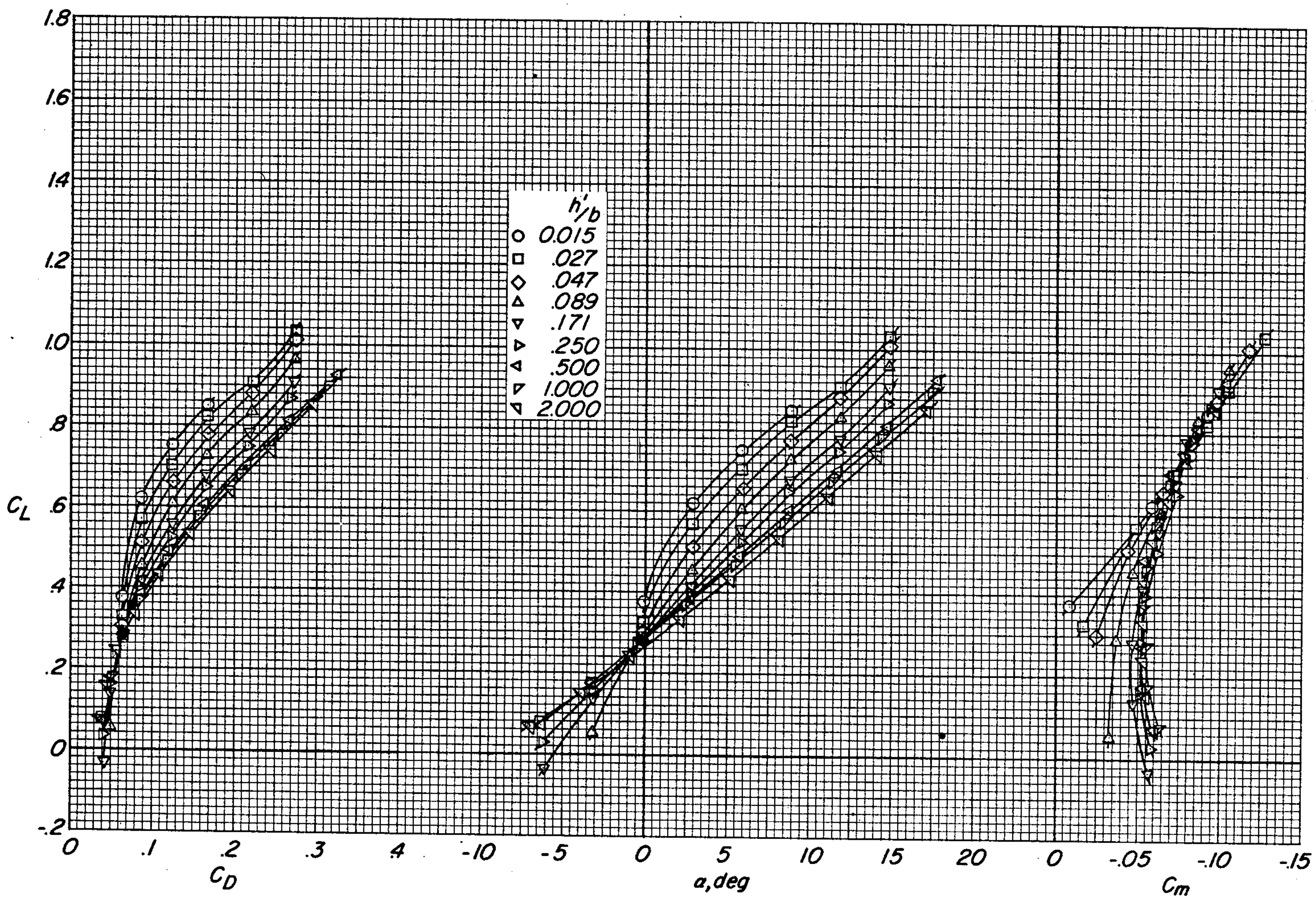


(a) 22-percent-thick airfoil.



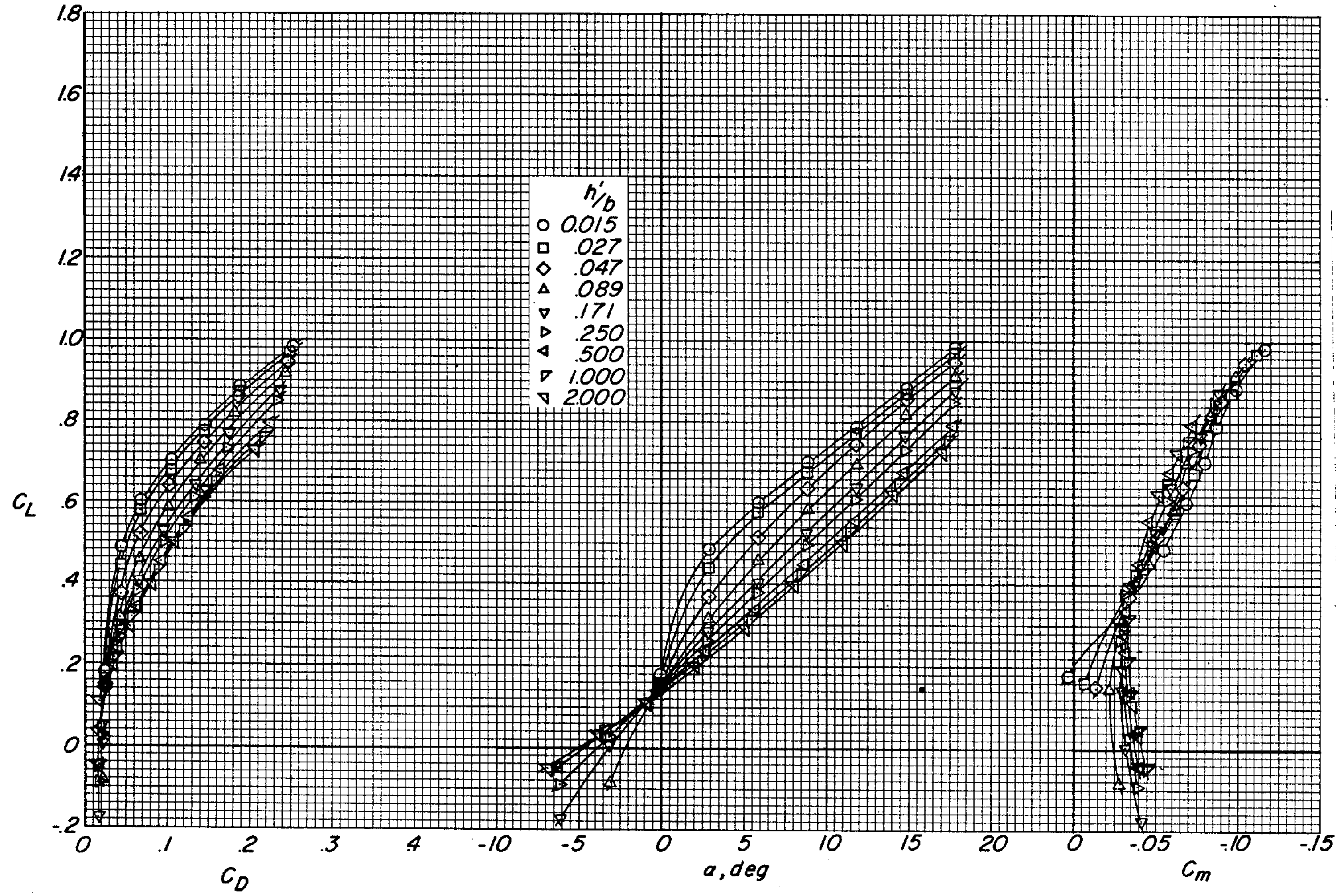
(b) 11-percent-thick airfoil with end plates. L-61-5064

Figure 2.- Photographs of airfoils and setup on towing carriage in Langley tank no. 1.



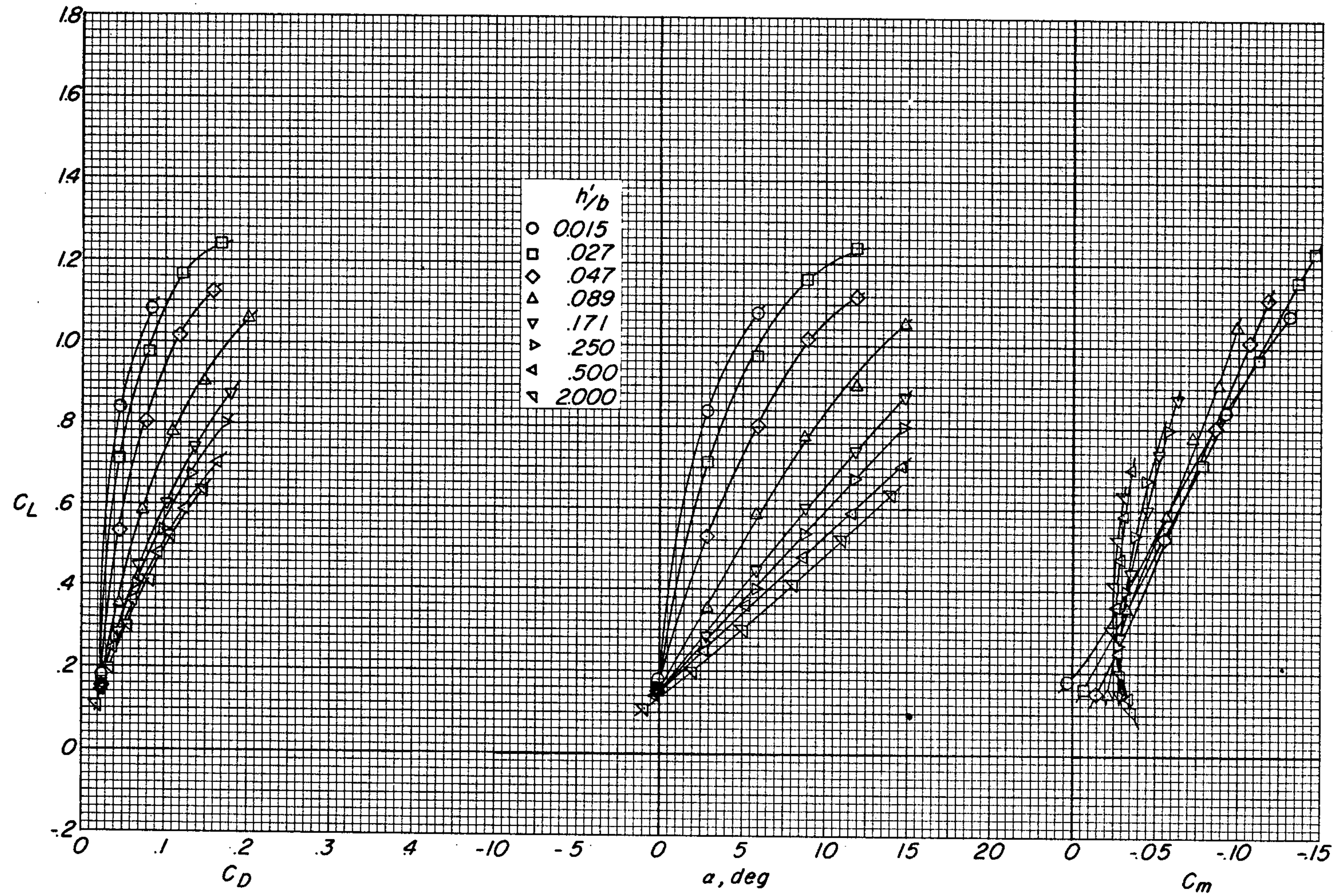
(a) 22-percent-thick airfoil.

Figure 3.- Aerodynamic characteristics of aspect-ratio-1 airfoil at various height-to-span ratios.



(b) 11-percent-thick airfoil.

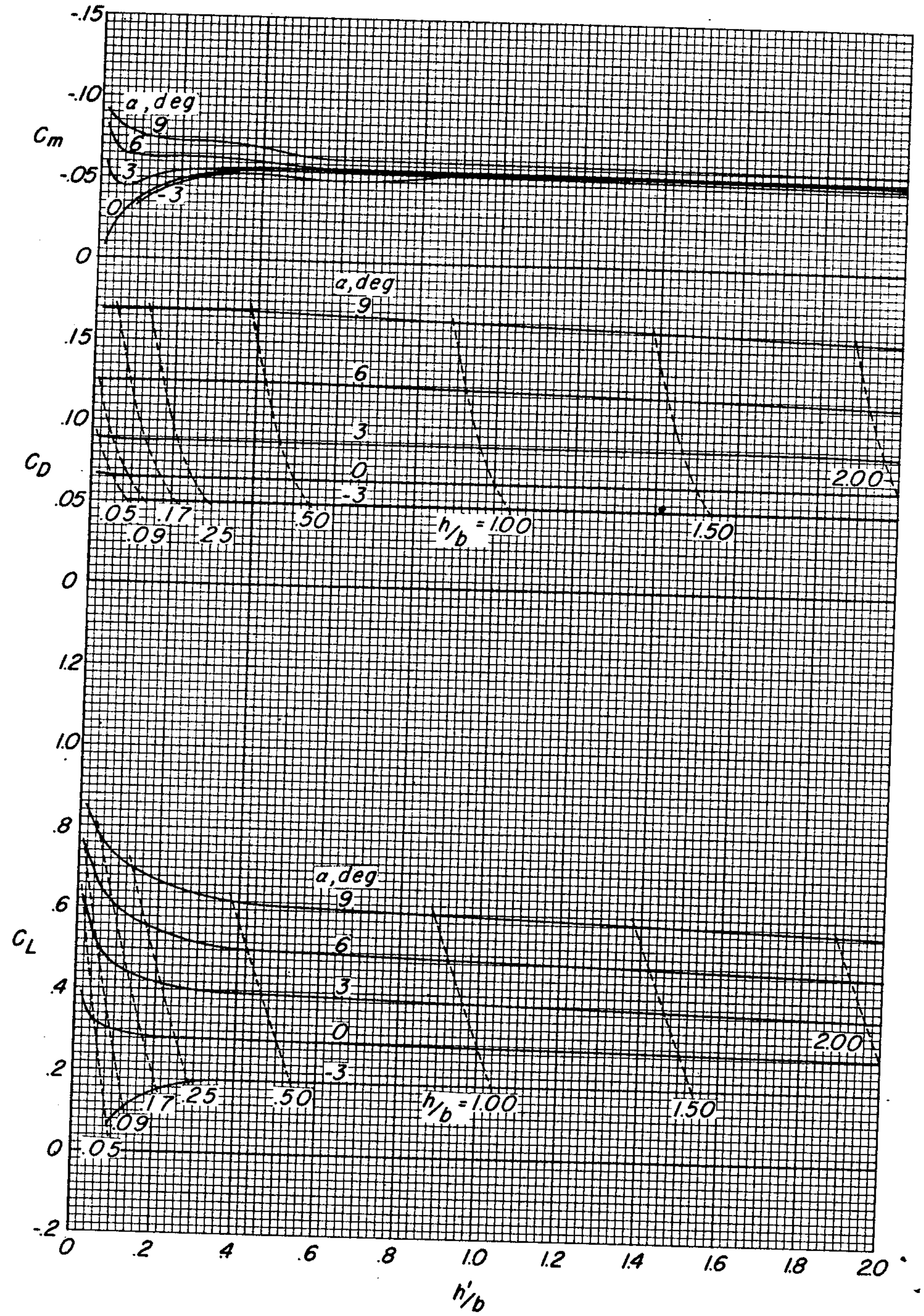
Figure 3.- Continued.



(c) 11-percent-thick airfoil with end plates.

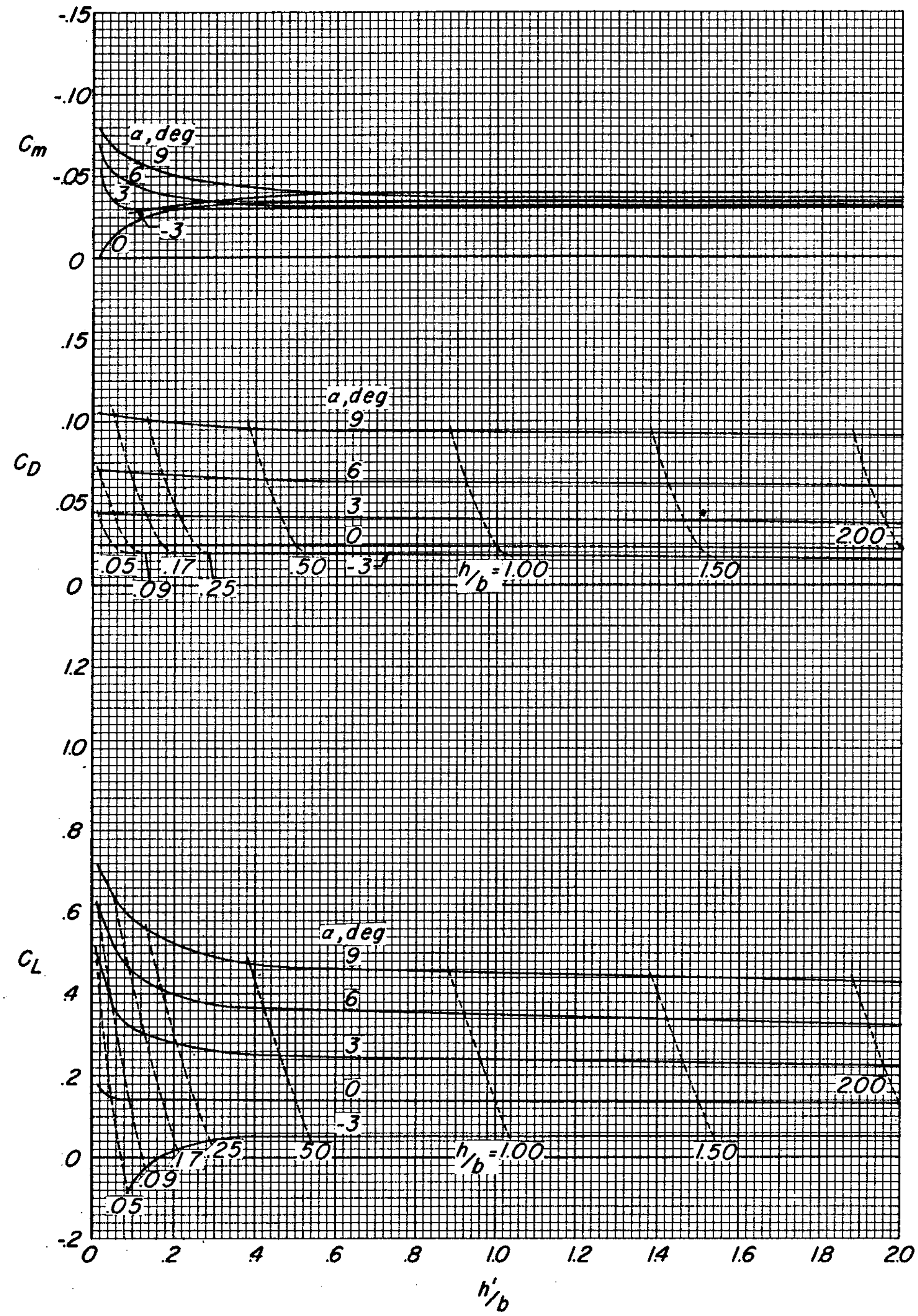
Figure 3.- Concluded.

L-1693



(a) 22-percent-thick airfoil.

Figure 4.- Variation of aerodynamic characteristics with height-to-span ratio for aspect-ratio-1 airfoil.



(b) 11-percent-thick airfoil.

Figure 4.- Continued.

L-1693

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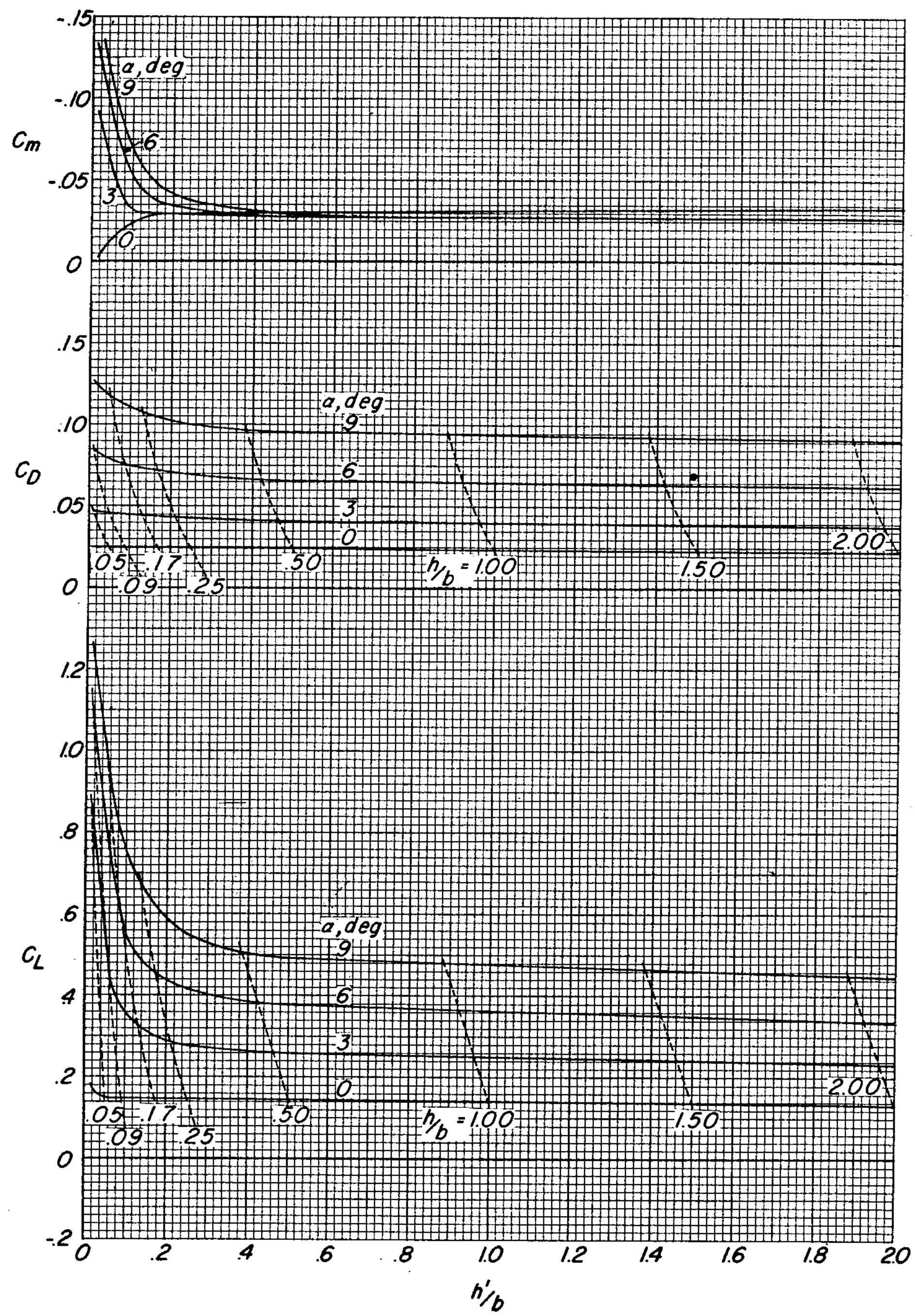
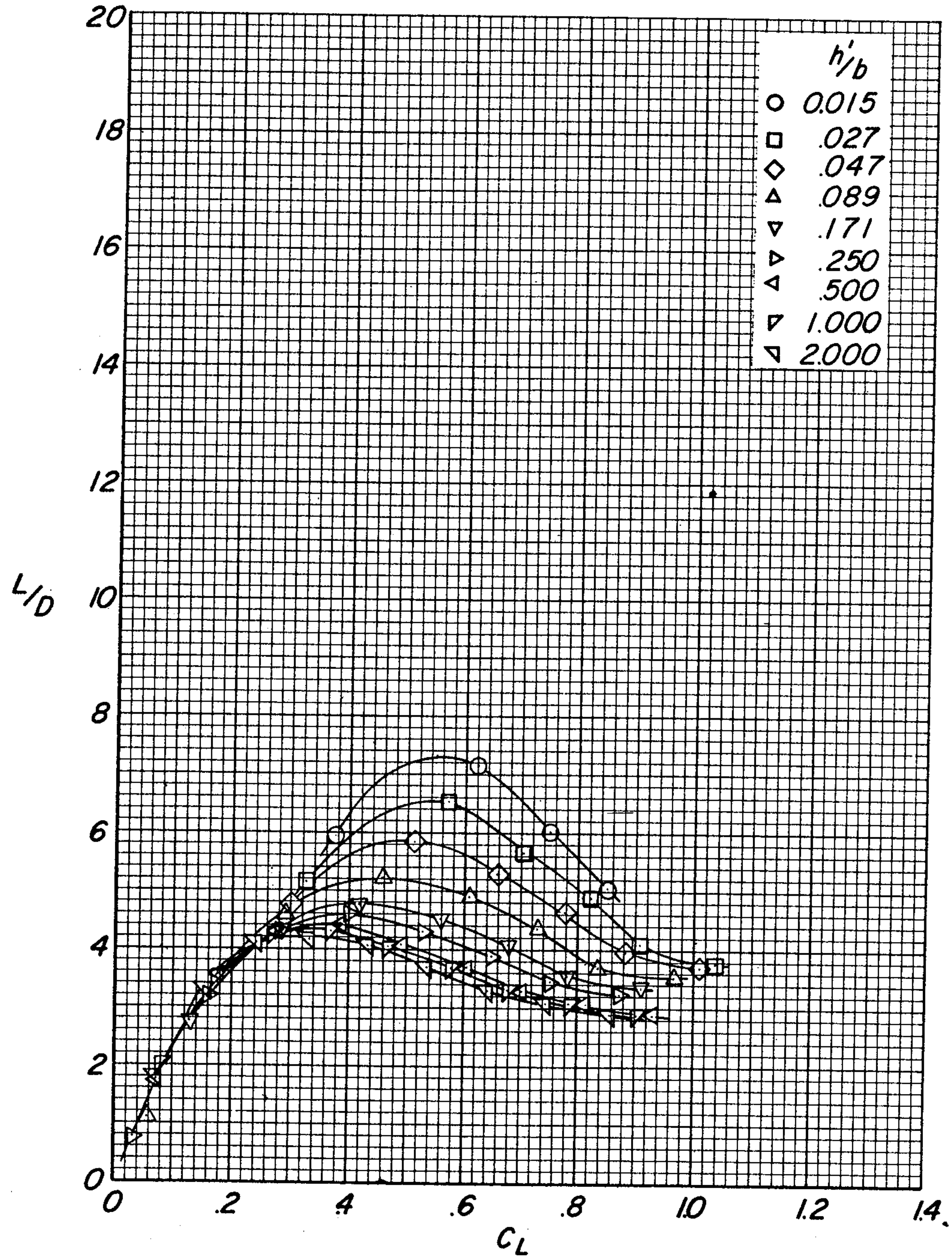
L-1693



(c) 11-percent-thick airfoil with end plates.

Figure 4.- Concluded.



(a) 22-percent-thick airfoil.

Figure 5.- Variation of lift-drag ratio with lift coefficient for aspect-ratio-1 airfoil at various heights of the airfoil trailing edge above the ground.

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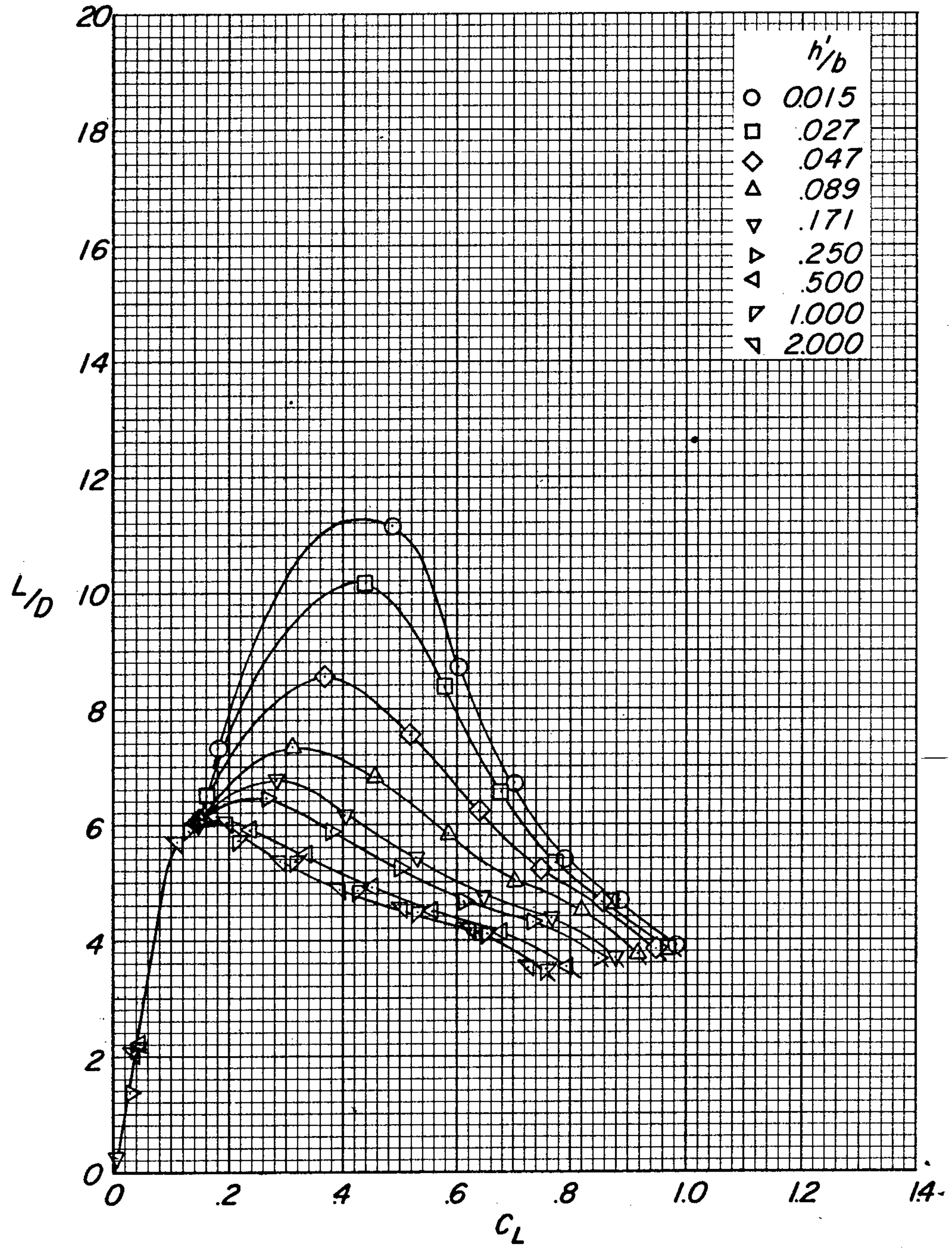
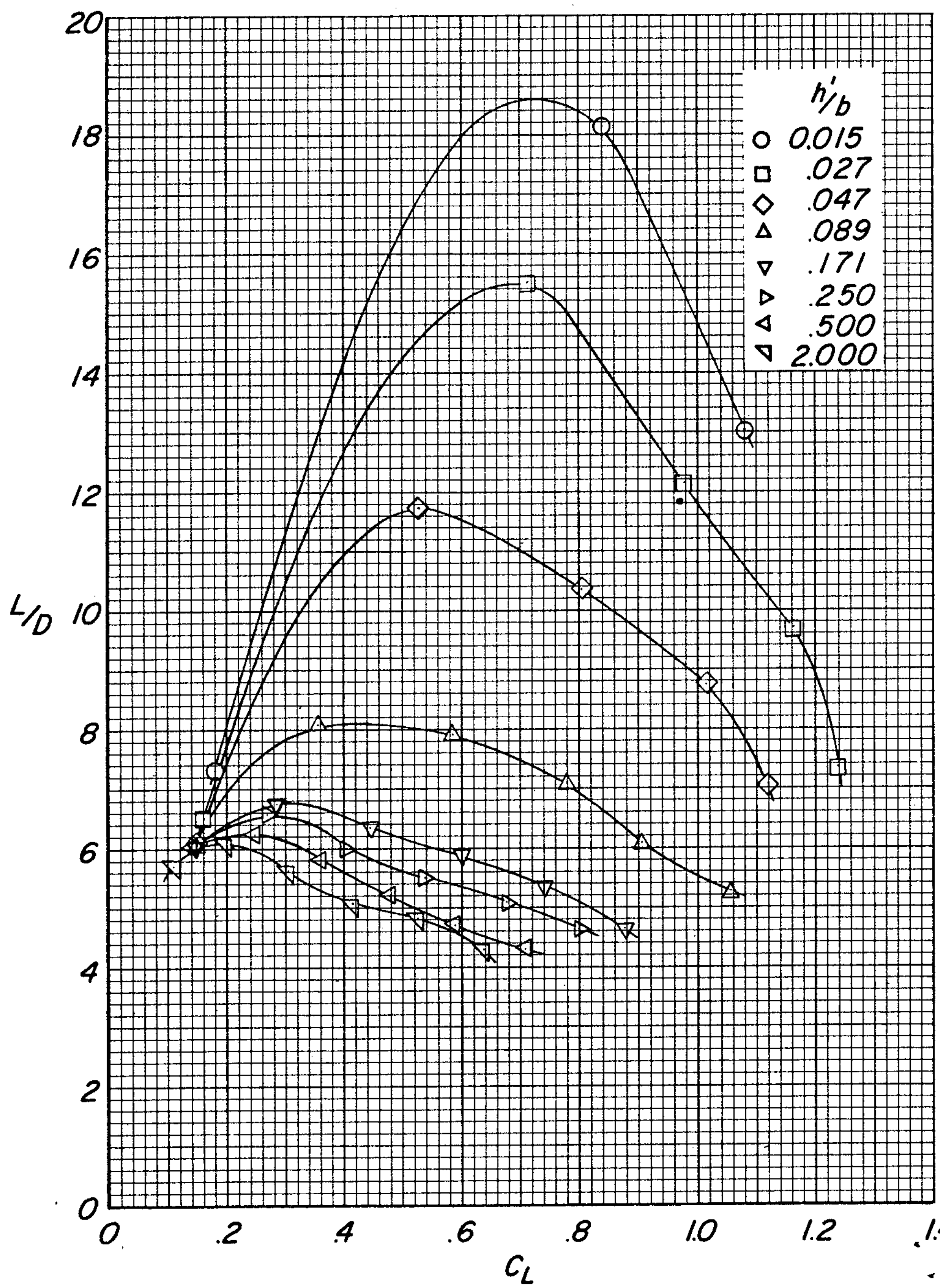


(b) 11-percent-thick airfoil.

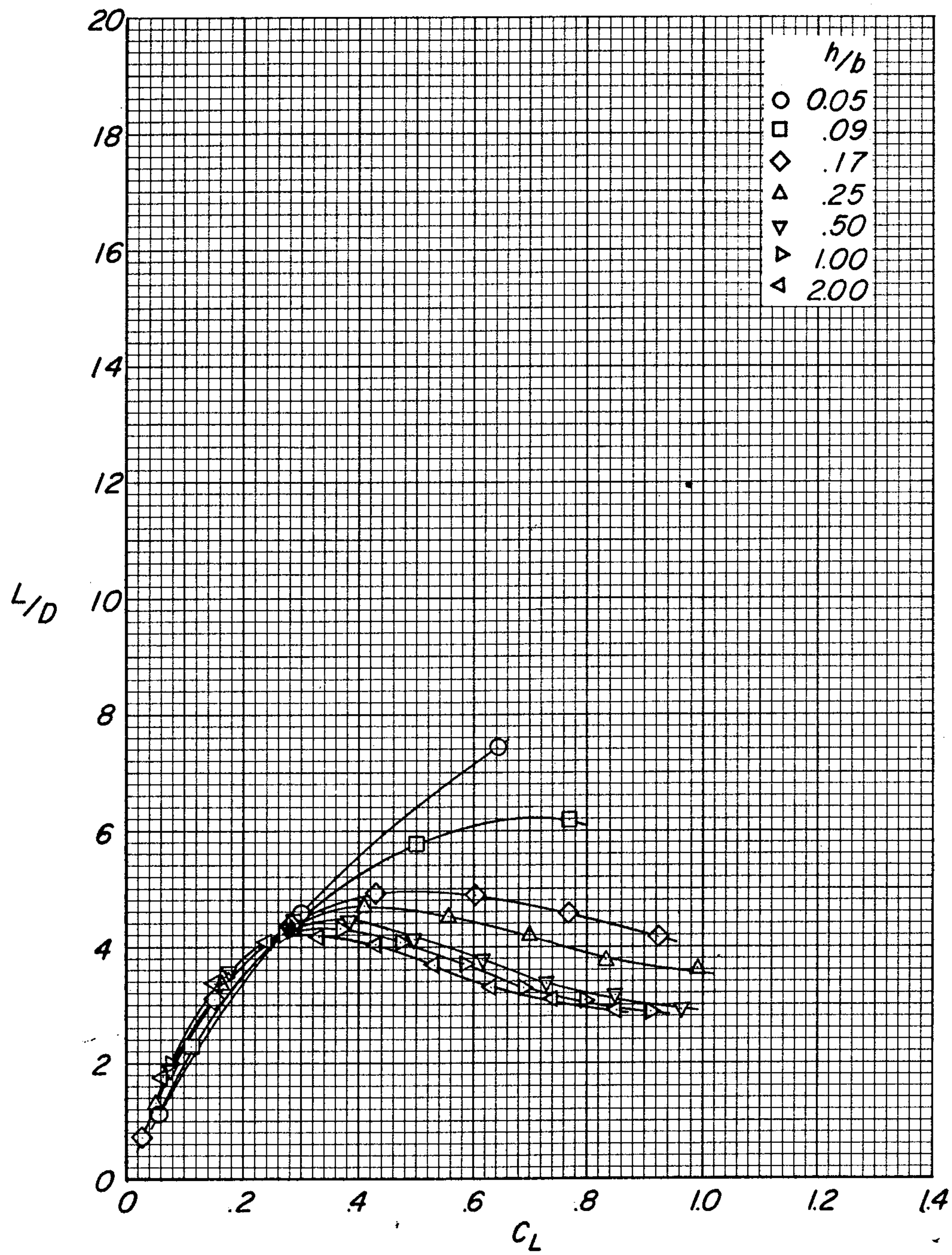
Figure 5.- Continued.



(c) 11-percent-thick airfoil with end plates.

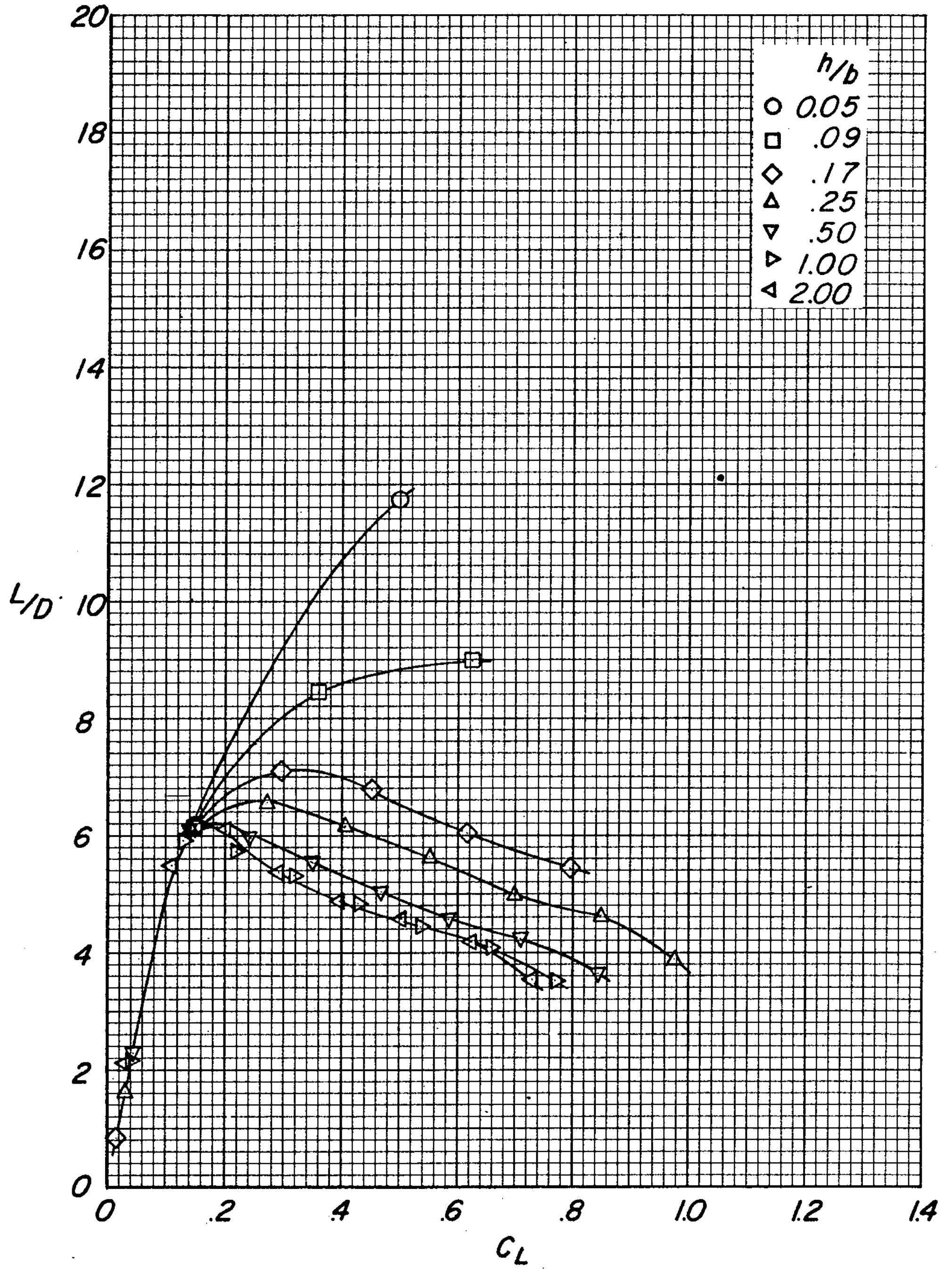
Figure 5.- Concluded.

L-1693



(a) 22-percent-thick airfoil.

Figure 6.- Variation of lift-drag ratio with lift coefficient for aspect-ratio-1 airfoil at various heights of the airfoil quarter-chord line above the ground.



(b) 11-percent-thick airfoil.

Figure 6.- Continued.

L-1693

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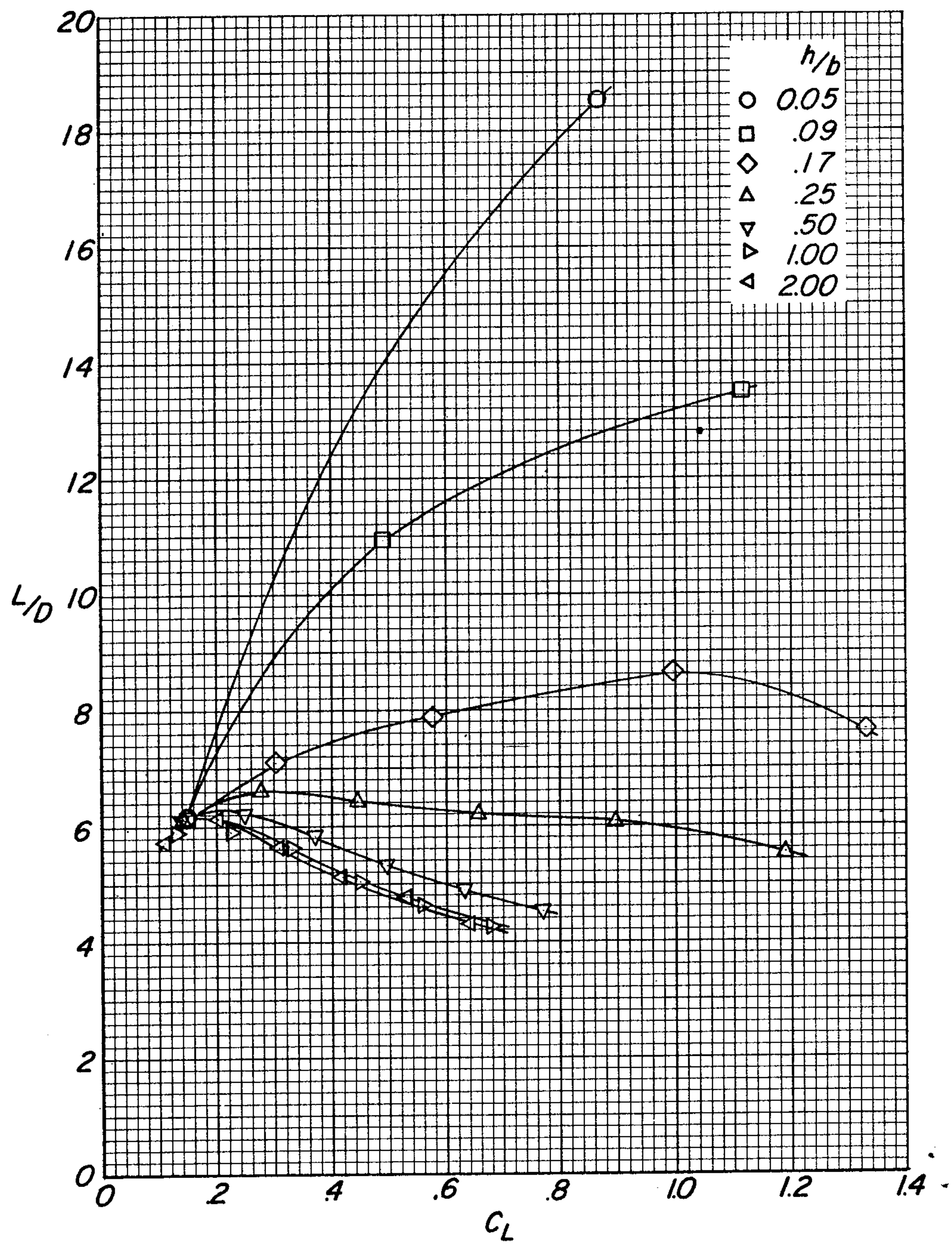
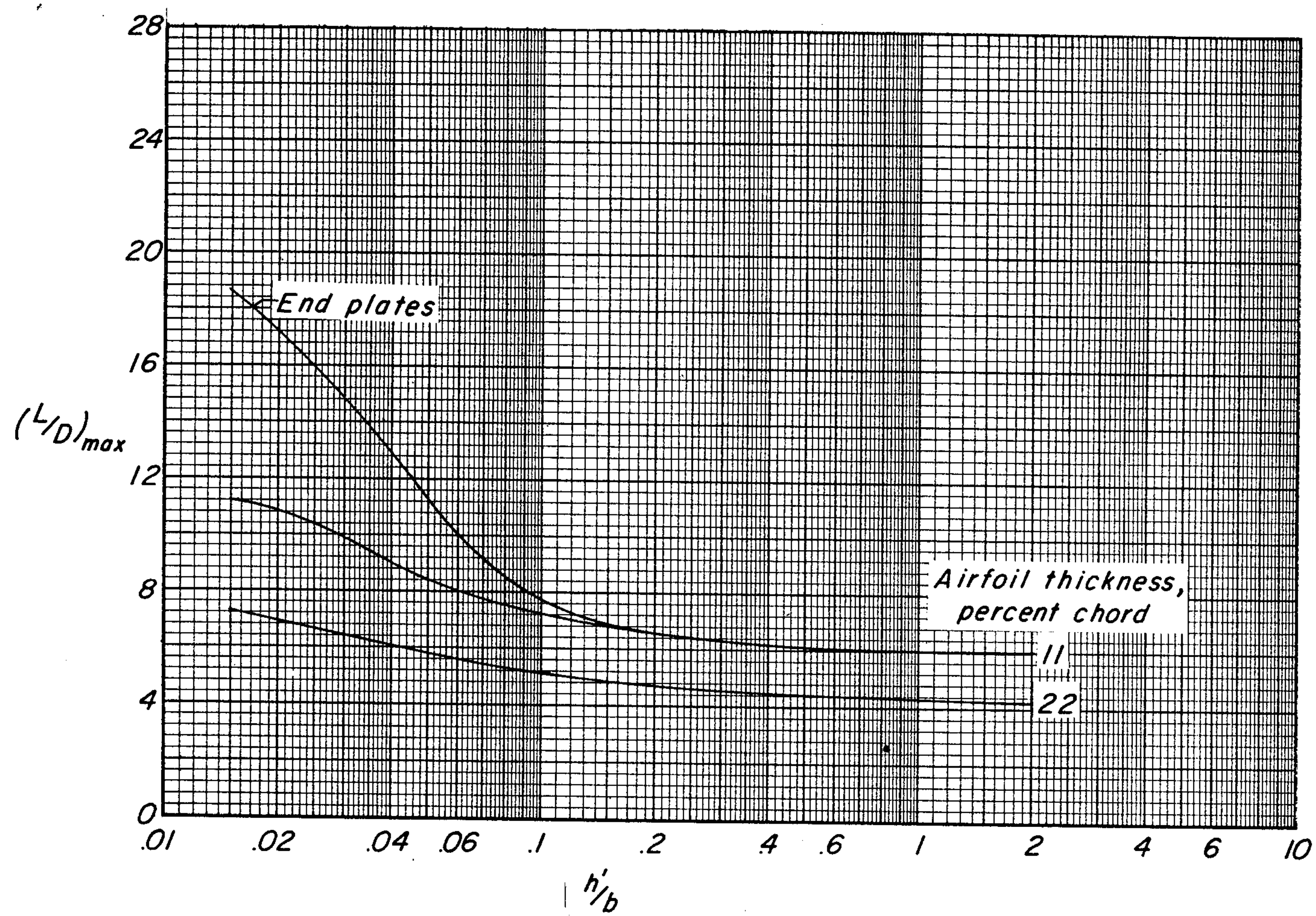


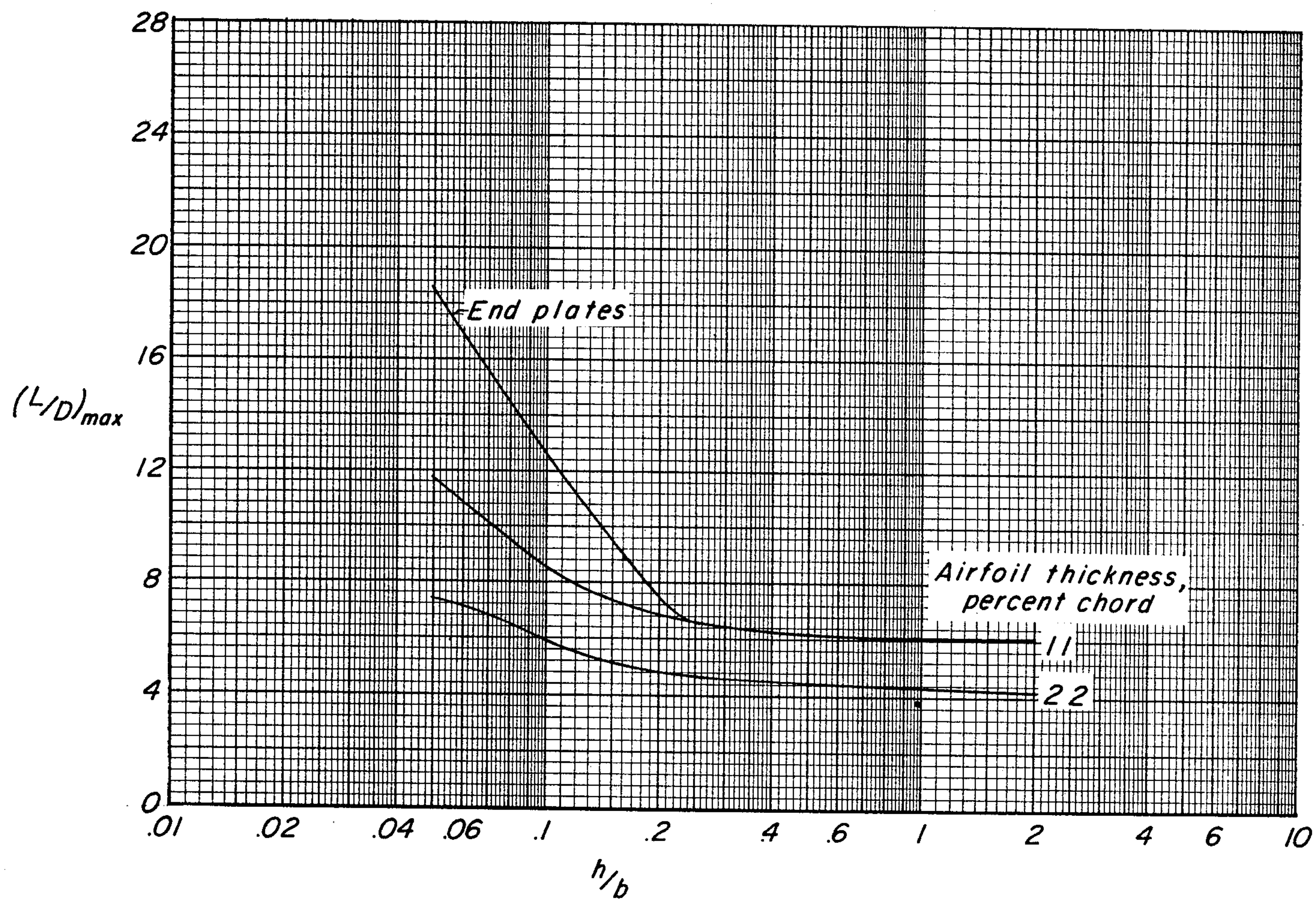
(c) 11-percent-thick airfoil with end plates.

Figure 6.- Concluded.



(a) Height-to-span ratio at airfoil trailing edge.

Figure 7.- Effect of thickness and end plates on maximum lift-drag ratios of aspect-ratio-1 airfoil.



(b) Height-to-span ratio at airfoil quarter-chord line.

Figure 7.- Concluded.

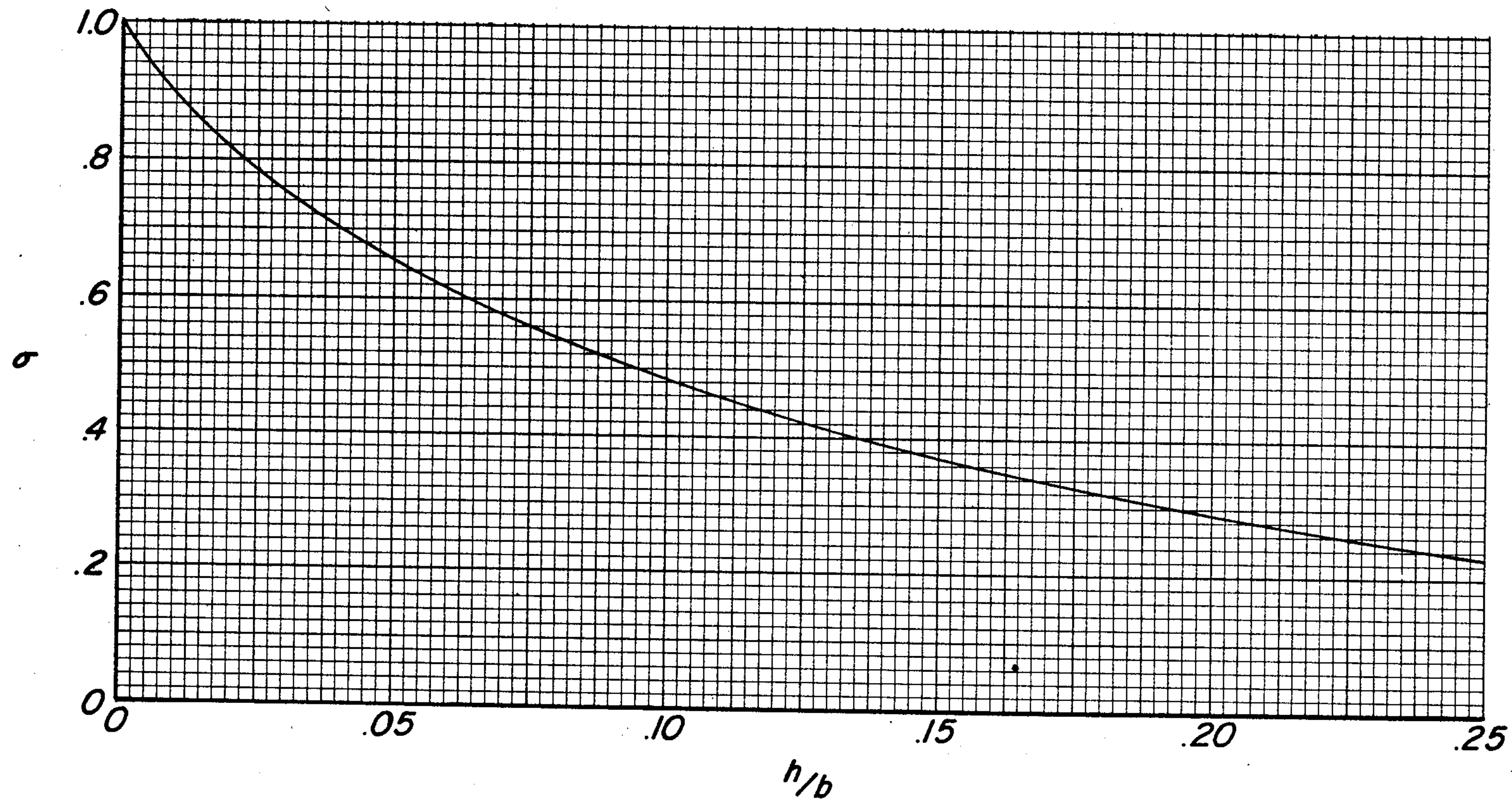


Figure 8.- Variation of ground-influence coefficient with height above the ground. (See ref. 7.)

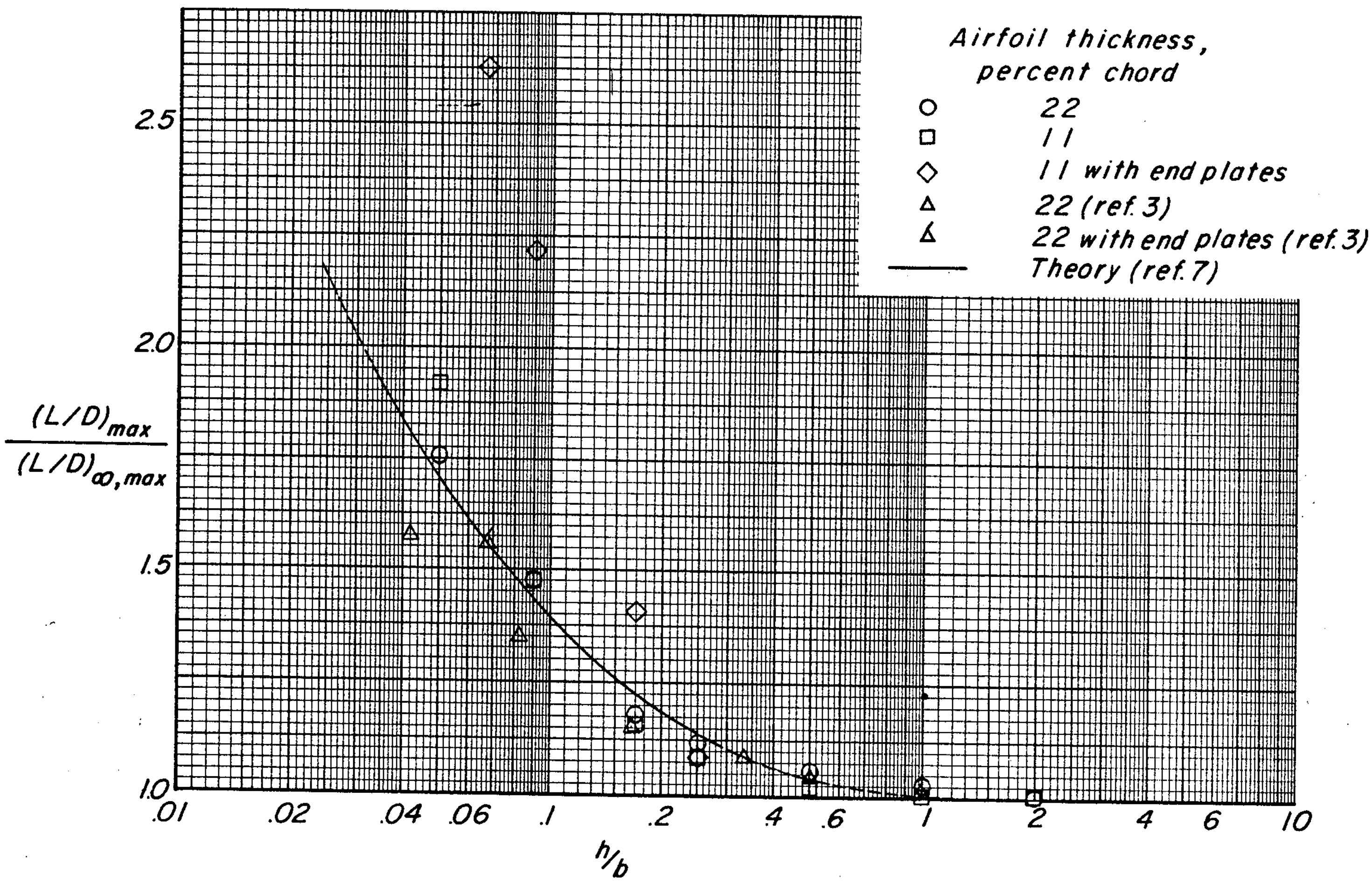


Figure 9.- Comparison of the theoretical and experimental effect of ground proximity on the ratio of the maximum lift-drag ratio in ground effect to that out of ground effect.

NASA-Langley, 1961 L-1693