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TECHNICAL NOTE

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AERODYNAMIC CHARACTERISTICS OF LOW-ASPECT-RATIO WINGS IN CLOSE PROXIMITY TO THE GROUND

By Marvin P. Fink and James L. Lastinger

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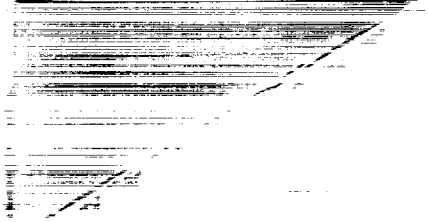

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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AERODYNAMIC CHARACTERISTICS OF LOW-ASPECT-RATIO WINGS IN CLOSE PROXIMITY TO THE GROUND

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SUMMARY

A wind-tunnel investigation has been conducted to determine the effect of ground proximity on the aerodynamic characteristics of thick highly cambered rectangular wings with aspect ratios of 1, 2, 4, and 6. The results showed that, for these aspect ratios, as the ground was approached all wings experienced increases in lift-curve slope and reductions in induced drag which resulted in increases in lift-drag ratio. Although an increase in lift-curve slope was obtained for all aspect ratios as the ground was approached, the lift coefficient at an angle of attack of 0° for any given aspect ratio remained nearly constant. The experimental results were in general agreement with Wieselsberger's ground-effect theory (NACA Technical Memorandum 77).

As the wings approached the ground, there was an increase in static longitudinal stability at positive angles of attack. When operating in ground effect, all the wings had stability of height at positive angles of attack and instability of height at negative angles of attack. Wing-tip fairings on the wings with aspect ratios of 1 and 2 produced small increases in lift-drag ratio in ground effect. End plates extending only below the chord plane on the wing with an aspect ratio of 1 provided increases in lift coefficient and in lift-drag ratio in ground effect.

INTRODUCTION

The advent of the ground-effect machine as a possible transport vehicle has promoted considerable interest in the machine as a large overwater transport. A ground-effect machine, to be competitive with other carrier vehicles, would have to travel at velocities where an aerodynamic shape would be required from drag considerations. The question then arises as to whether a vehicle cruising at these velocities could utilize the aerodynamic lift of a wing more efficiently than the ground air cushion for support. It might therefore be of interest to fly an airfoil-shaped vehicle or a wing very close to the ground. Previous

research (refs. 1 to 4) has shown that a considerable increase in the lift-drag ratio may be obtained by a wing flying in close proximity to the ground; however, the aspect ratios studied in these investigations (aspect ratios of 5 and 6) were higher than might be considered practical for a large vehicle flying close to the ocean surface.

In order to obtain information on the effect of the ground on wings of low aspect ratio, a wind-tunnel investigation was conducted on a series of rectangular wings having aspect ratios of 1, 2, 4, and 6 at several ground heights. The wings had a 22-percent-thick, highly cambered airfoil section with a flat bottom. The large amount of camber was used to produce high lift at angles of attack near zero, and the extreme thickness could provide greater cargo space.

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SYMBOLS

A	aspect ratio, b^2/S
A_e	effective aspect ratio in ground effect
$A_{e,\infty}$	effective aspect ratio for wings out of ground effect
b	wing span, ft
c	airfoil chord, ft
C_D	drag coefficient, D/qS
$C_{D,min}$	minimum drag coefficient
C_L	lift coefficient, L/qS
C_{L_α}	lift-curve slope
C_m	pitching-moment coefficient, M_Y/qSc
D	wing drag, lb
h	height of $c/4$ above ground plane, ft (fig. 1)
h'	height of trailing edge of wing above ground plane, ft
L	wing lift, lb
L/D	wing lift-drag ratio

M_Y	pitching moment, ft-lb
q	free-stream dynamic pressure, $\frac{1}{2}\rho V^2$, lb/sq ft
S	wing area, sq ft
V	free-stream velocity, ft/sec
α	angle of attack, deg
ρ	mass density of air, slugs/cu ft

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APPARATUS AND TESTS

Model

The models used in the investigation had rectangular planforms and aspect ratios of 1, 2, 4, and 6. The principal dimensions of the models and a table of airfoil ordinates are given in figure 1. All wings had a chord of 12 inches and a Glenn Martin 21 airfoil section (ref. 5) modified to provide a flat bottom wing from the 0.30c station to the trailing edge. Wing-tip fairings and end plates (fig. 2) were attached to the wings with aspect ratios of 1 and 2 for some tests. With these tip fairings, the aspect ratios were increased to 1.4 and 2.4. The additional wing area was taken into consideration in computing the coefficients. The end plates, which were made of 0.030-inch-thick sheet metal attached to the wing tip, extended 1 inch below and were parallel to the lower surface of the wing and were trimmed to the airfoil on top for the out-of-ground-effect test. For the ground-effect tests the angle of attack and height-chord ratio were set, and then the end plates of the test and image wings were set with their bottom edges parallel and as close as possible without touching. Three-component strain-gage balances were mounted internally in the models to measure the lift, drag, and pitching moment. A different balance was used in the $A = 1$ and $A = 2$ wings from the one used for the $A = 4$ and $A = 6$ wings. The balances were selected with drag sensitivities so that the measured drag forces on the various wings would be commensurate with the wing size.

Tests

The ground-effect tests were conducted in the wind tunnel by the image-wing method since this method does not present the boundary-layer problems associated with the wing and ground-board methods. (See ref. 6.) The image-wing technique involves the use of an identical model mounted

inverted with respect to the test model as shown in figure 3. The additional wing is, in effect, an image or reflection of the test wing with the distance between the two wings being equal to twice the ground height represented. Tests made with the image-wing method have, in the past, produced results which correlate well with results of tests in which a model was actually moved over a still surface.

Force measurements were taken with an internally mounted strain-gage balance on the upper model only. Tests were made with the image wing in place throughout an angle-of-attack range from -8° to 12° and at values of h/c from 0.042 to 1.000. Tests were also made over an angle-of-attack range from -10° to 20° with the image wing removed to represent the $h/c = \infty$ case. Based on the wing chord, the test Reynolds number was approximately 490,000. Several tests were made with the wing-tip fairings on the $A = 1$ and $A = 2$ wings at the lower values of h/c.

RESULTS AND DISCUSSION

Effect of Aspect Ratio

The longitudinal aerodynamic characteristics of the wings out of ground effect presented in figure 4 show effects of aspect ratio similar to those obtained in previous investigations. (For example, see ref. 7.) There was a reduction in lift-curve slope and increases in both profile-drag and induced-drag coefficients as the aspect ratio was decreased, and for positive angles of attack there was an increase in longitudinal stability associated with a decrease in aspect ratio. One point of interest shown by the data of figure 4 is that, since all these wings have about the same angle of attack for zero lift, the wings with the lower aspect ratios have the lower values of C_L at $\alpha = 0^\circ$ because of their lower lift-curve slope. It would therefore appear that the lower aspect ratio wings are inherently limited to lower operating lift coefficients.

The results showing the effect of the ground on the aerodynamic characteristics of the wings with aspect ratios of 1, 2, 4, and 6 are presented in figures 5 and 6. The same data are presented in both figures; however, in figure 5 the variation of C_D, α, C_m, and L/D with C_L at various height-chord ratios is presented whereas in figure 6 the variation of C_m, C_D, C_L, and L/D with h/c at various angles of attack is presented. The data of figure 5 show that for all the aspect ratios the lift-curve slope increases as the ground is approached. This increase in lift-curve slope, however, is accompanied by an increase in the angle of attack for zero lift. The lift coefficient

at an angle of attack of 0° is approximately the same for all values of h/c. This characteristic is significant in connection with the application to ground-effect machines which operate near zero angle of attack, for it means that a very highly cambered wing will probably be needed to obtain a reasonably high operating lift coefficient.

The variation of lift coefficient with height above the ground shown in figure 6 is a factor that should be considered in the selection of the operating angle of attack of a ground-effect machine in forward flight. The data indicate that a reduction in height causes a loss in lift at negative angles of attack, little or no change at zero angle of attack, and an increase in lift at positive angles of attack. At positive angles of attack the machine would therefore have a stability of height which would not be present at zero and negative angles of attack. (At negative angles, of course, there would be height instability.) This variation of height stability with angle of attack indicates that a positive angle of attack will be desirable for cruising flight. The data of figure 6 show a reduction in negative pitching moment at zero angle of attack as the ground is approached. The pitching-moment data of figure 5 show that, for positive angles of attack, the static longitudinal stability is increased as the height above the ground is reduced.

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The summary of the lift-curve slopes at $\alpha = 0^\circ$ presented in figure 7 shows the effect of height to be more pronounced for the lower height-chord ratios. At a height of one chord the wings appear to be essentially out of the influence of the ground.

The data of figure 5 show the effects of the ground on drag, that is, a reduction in induced drag and essentially no change in profile drag as the ground is approached. At the lower ground heights, the induced drag is reduced to very low values, especially for the $A = 4$ and $A = 6$ wings. This drag reduction is reflected in the L/D plots of figure 5 which show large increases in L/D as the ground is approached. These plots also show that maximum lift-drag ratio is obtained at progressively higher lift coefficients as h/c is reduced.

The data shown in figure 5 for $h/c = 0.042$ and $\alpha = 2^\circ$ are replotted in figure 8 together with similar data for $h/c = \infty$. Also shown in figure 8 is a dashed line representing a possible upper limit in L/D for the various aspect ratios. This upper limit was obtained by taking the value of the lift coefficient at $\alpha = 2^\circ$ and $h/c = 0.042$ for each aspect ratio and dividing it by the minimum drag coefficient of the wing. The assumption in this procedure is that the highest possible L/D is obtained when the induced drag is reduced to zero and only the profile drag remains. The curves of figure 8 indicate not only that there is a reduction in the potential lift-drag ratio when the aspect ratio is reduced, but also that the beneficial ground effect actually obtained with the lower aspect ratios appears to be a smaller percentage of the potential gain possible.

Ground height in terms of wing chord has been used for convenience in this investigation since the wing chord of the models was held constant as aspect ratio was reduced; therefore, a given value of h/c represented the same absolute height above the ground for all aspect ratios. The theoretical treatment by Wieselsberger presented in reference 2, however, was developed using the height-span ratio rather than the height-chord ratio as the correlating parameter. A plot similar to that shown in figure 8, but with the data presented in terms of h/b rather than h/c is shown in figure 9. These data do not show the pronounced advantage of the higher aspect ratio wings indicated by figure 8. In fact, the $A = 1$ and $A = 2$ wings seem to realize about as great a proportion of their potential beneficial ground effect as the $A = 4$ and $A = 6$ wings.

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The theory of reference 2 indicates that the percentage increase in L/D or effective aspect ratio produced by operating in ground effect at a given value of h/b is the same regardless of aspect ratio. Figure 10 shows the theoretical variation with h/b of the ratio of the effective aspect ratio in ground effect to that out of ground effect $(A_e/A_{e,\infty})$. The dashed portion of the curve represents the range of h/b for which the author of reference 2 felt the theory was inapplicable. Also shown in figure 10 are values obtained from analysis of the data of figure 5. The agreement between theory and experiment appears to be generally good in the range of h/b values (0.03 to 0.25) for which the theory is considered valid. At values of h/b lower than 0.03, the theory underestimates the beneficial ground effect.

In view of the relatively high values of minimum drag coefficient produced by the thick airfoil section used in this investigation, it would seem that a substantial improvement in L/D could be obtained by using a thinner section. Reference 7, for example, shows much lower values of minimum drag coefficient for wings having Clark Y airfoil sections. Data showing the effect of the ground on an $A = 5$ rectangular wing with a Clark Y-H airfoil section are presented in reference 4. The Clark Y-H section is about 12 percent thick and has a reflexed trailing edge. In order to indicate the improvement in L/D that could be obtained by using a thinner wing than that used in the present investigation, data from reference 4 are presented in figure 11 and compared with data obtained by interpolation from the plots of figure 5. Since the trailing edge of the wing was used as the reference height point in reference 4, the data from the present investigation were also put in terms of h'/c for this comparison. Figure 11 shows that the reduction in wing thickness produces the expected improvement in maximum lift-drag ratio and that the improvement was greater in ground effect than out of ground effect. Because of the reduction in camber accompanying the reduction in thickness, the maximum lift-drag ratio occurs at lower lift coefficients for the thin wing, but the range of superiority of the thin wing in ground effect extends to fairly high lift coefficients. The

thick, highly cambered wing of the present investigation provides high values of L/D only at the very high lift coefficients. A possible advantage of the thick wing is the lower angle of attack for a given lift coefficient. For example, at a lift coefficient of 1.2 and h'/c of 0.025, both wings provide a value of L/D of a little over 40 but the angles of attack for the thick and thin wings are 2° and 8°, respectively. Thus, the thick wing may be used to an advantage where the operating angle of attack must be kept low while flying at a high lift coefficient.

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Effect of Wing-Tip Modifications

Wing-tip fairings.- The data of reference 7 show that certain wing-tip fairings were beneficial in reducing the profile drag of low-aspect-ratio wings. In an effort to obtain lower profile drag and higher values of L/D with the A = 1 and A = 2 wings used in this study, tests were made with the wing-tip fairings shown in figure 2. The effect of these fairings on the aerodynamic characteristics of the wings out of ground effect is presented in figure 12(a). These data show that the minimum drag was decreased by the fairings, but since there was also a reduction in lift coefficient at a given angle of attack, only a small improvement in L/D was obtained. The data of figure 12(b) obtained from tests in ground effect at $\alpha = 2^{\circ}$ indicate that the fairings provided a modest improvement in L/D for both wings at the lower values of h/c.

End plates.- End plates extending below the wing only (see fig. 2) were tested on the wing with an aspect ratio of 1 over an angle-of-attack range from 0° to 4° with the trailing edge of the wing held at a constant height above the ground (h'/c = 0.042). An end plate extending below the wing only was chosen because it was of interest to see the effect of preventing the ram air on the lower surface from flowing around the wing tips. The data obtained in these tests are presented in figure 13. The results indicate that addition of the end plates produced a substantial improvement in L/D over the test angle-of-attack range. This increase in L/D was caused by a large increase in lift coefficient at a given angle of attack and was great enough to more than offset the increase in drag coefficient caused by addition of the end plates. The large increase in lift coefficient produced by the end plates is considered especially significant in view of the desirability in some cases of having as high a lift coefficient as possible at the low angles of attack at which a ground-effect machine of this type would normally be operated. It should be pointed out, however, that increasing the aspect ratio from 1 to 2 would provide greater overall aerodynamic benefits than adding the end plates. The data of figures 5(a) and (b) and figure 13 indicate that the increase in aspect ratio would produce almost as much lift increase as the end plates and would provide much higher values of L/D.

SUMMARY OF RESULTS

The results of a wind-tunnel investigation to determine the effect of ground proximity on thick highly cambered wings with aspect ratios of 1, 2, 4, and 6 over a range of angles of attack from -8° to 12° and height-chord ratios from 0.042 to 1.000 may be summarized as follows:

1. As the ground was approached, all wings experienced increases in lift-curve slope and reductions in induced drag which resulted in large increases in lift-drag ratio.

2. Although an increase in lift-curve slope was obtained for all aspect ratios as the ground was approached, the lift coefficient at an angle of attack of 0° for any given aspect ratio remained nearly constant.

3. The results of the investigation were in general agreement with Wieselsberger's ground-effect theory (NACA Technical Memorandum 77).

4. As the ground was approached, there was an increase in static longitudinal stability at positive angles of attack. In addition, when operating in ground effect, all the wings had stability of height at positive angles of attack and instability of height at negative angles of attack.

5. The use of wing-tip fairings on the wings with aspect ratios of 1 and 2 produced small increases in the values of lift-drag ratio in ground effect.

6. The use of end plates extending only below the wing chord plane provided increases in lift-drag ratio and lift coefficient for the wing with an aspect ratio of 1 very close to the ground.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., May 19, 1961.

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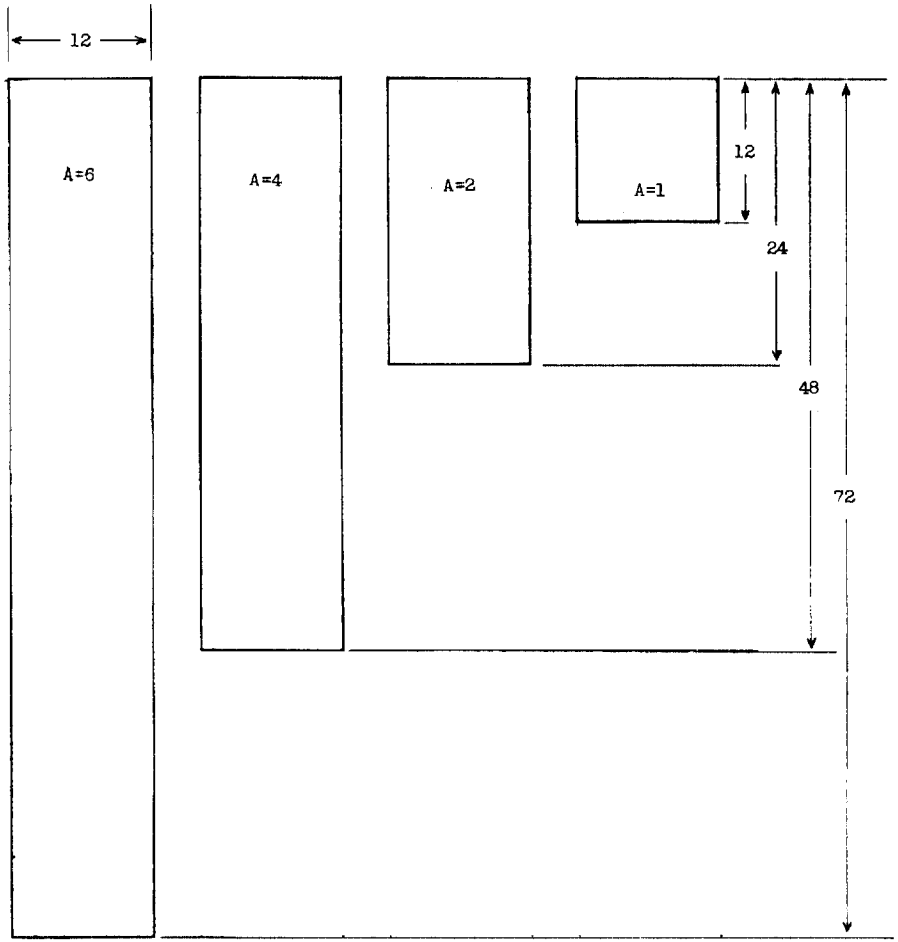
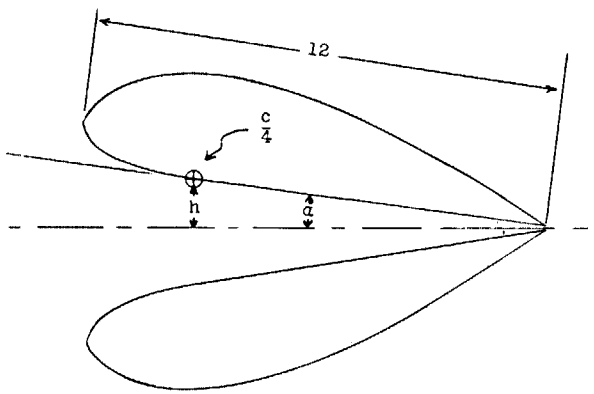


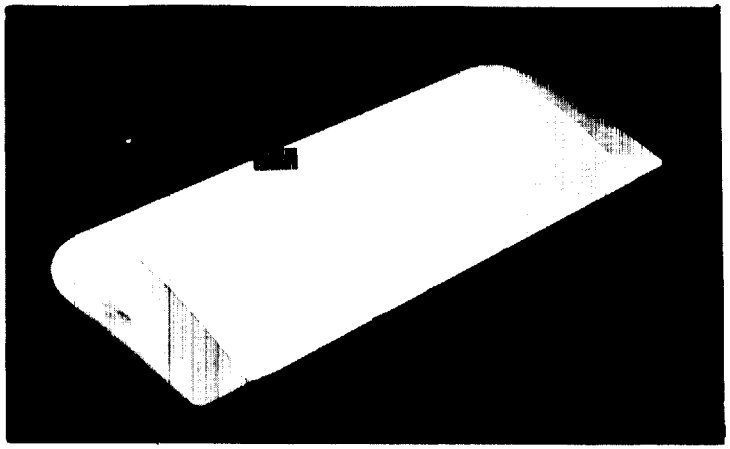


Airfoil coordinates

Station	Upper	Lower
0	8.86	8.86
1.25	12.21	6.03
2.50	13.81	4.79
5	15.98	3.33
7.50	17.65	2.35
10	18.92	1.72
15	20.72	0.75
20	21.68	0.28
30	22.13	0.00
40	21.13	0.00
50	19.20	0.00
60	16.64	0.00
70	13.35	0.00
80	9.43	0.00
90	5.00	0.00
95	2.57	0.00
100	0.00	0.00

Station and ordinates are in percent of airfoil chord

Figure 1.- Wing planforms and airfoil ordinates. All dimensions, unless otherwise noted, are in inches.



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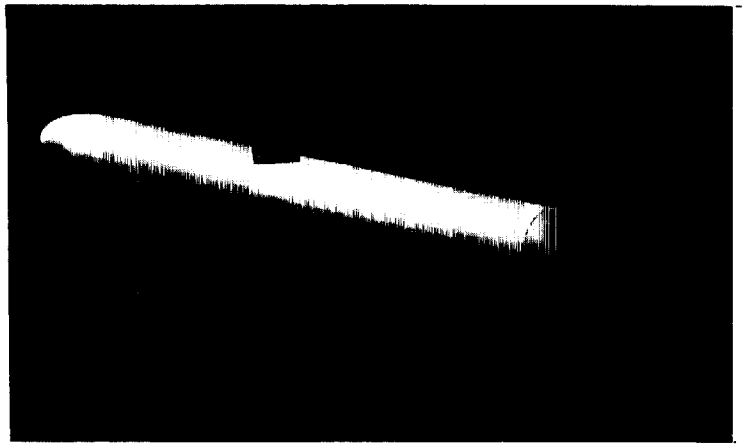

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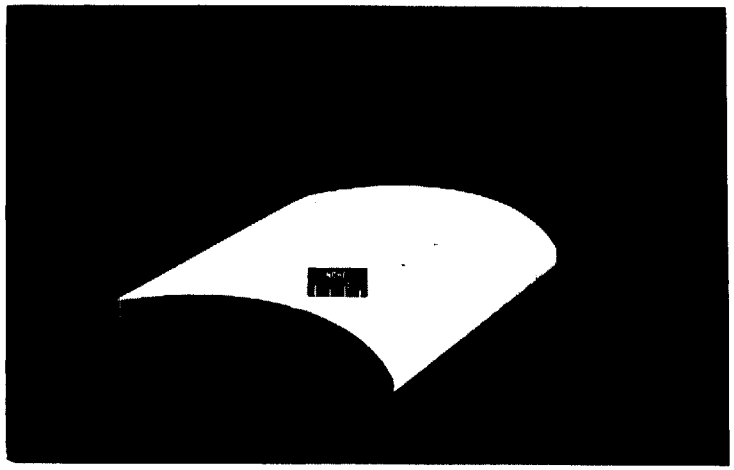
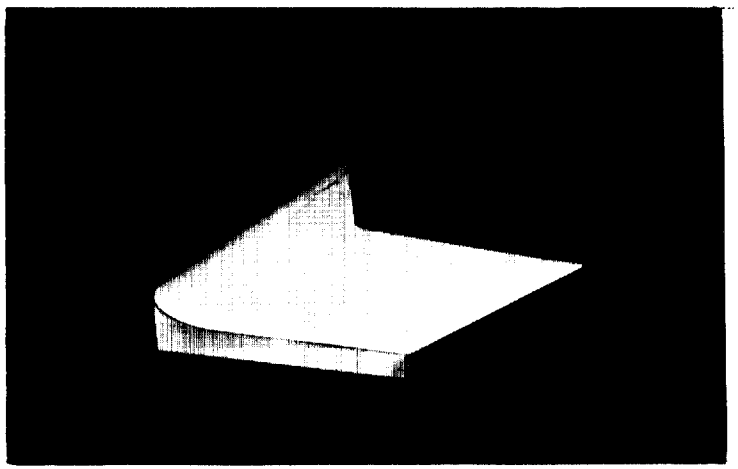
Faired wing tips





End plates

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Figure 2.- Wings with tip fairings and end plates.

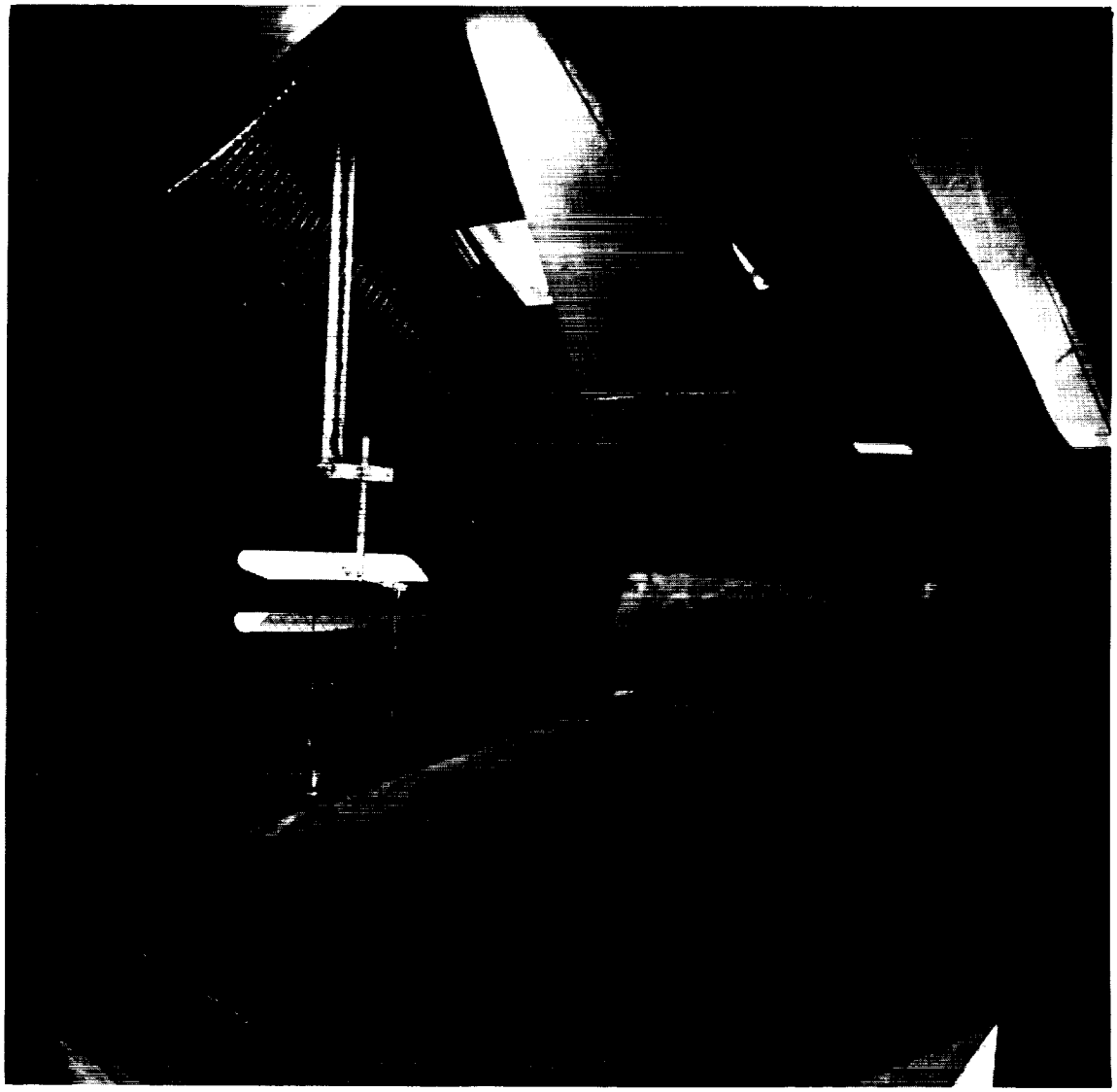

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Figure 3.- Photograph of a model and image in the tunnel.

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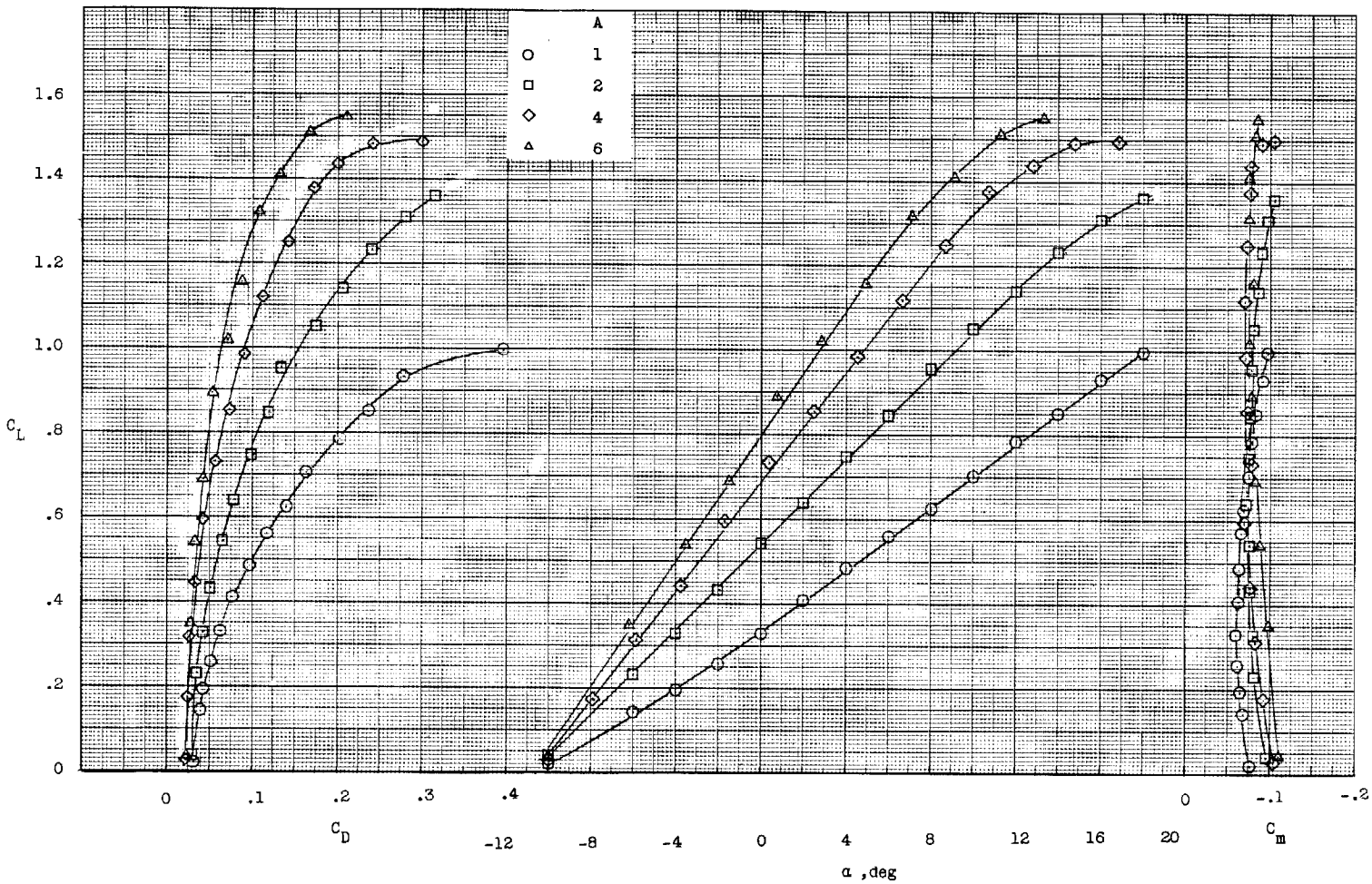
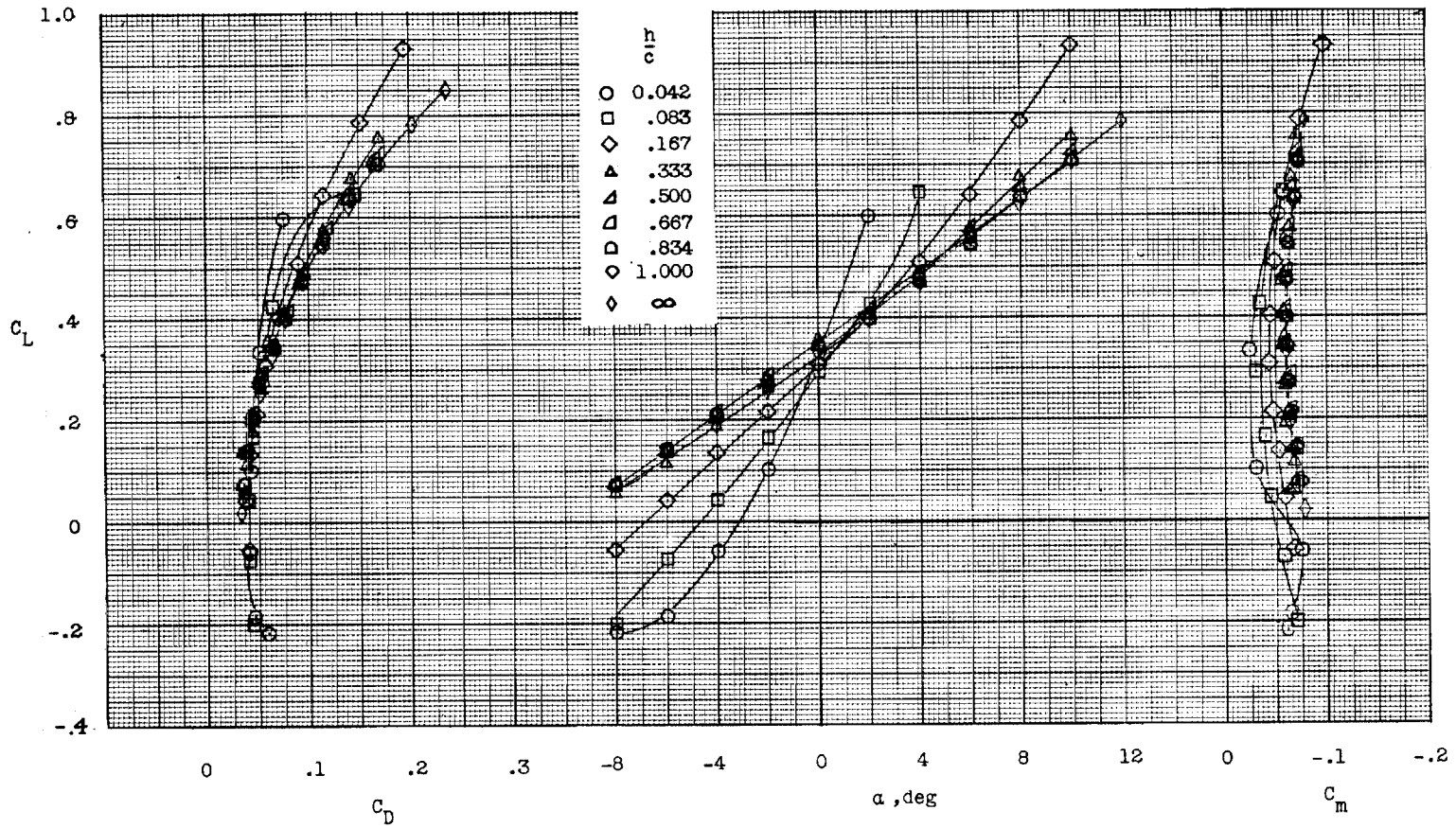
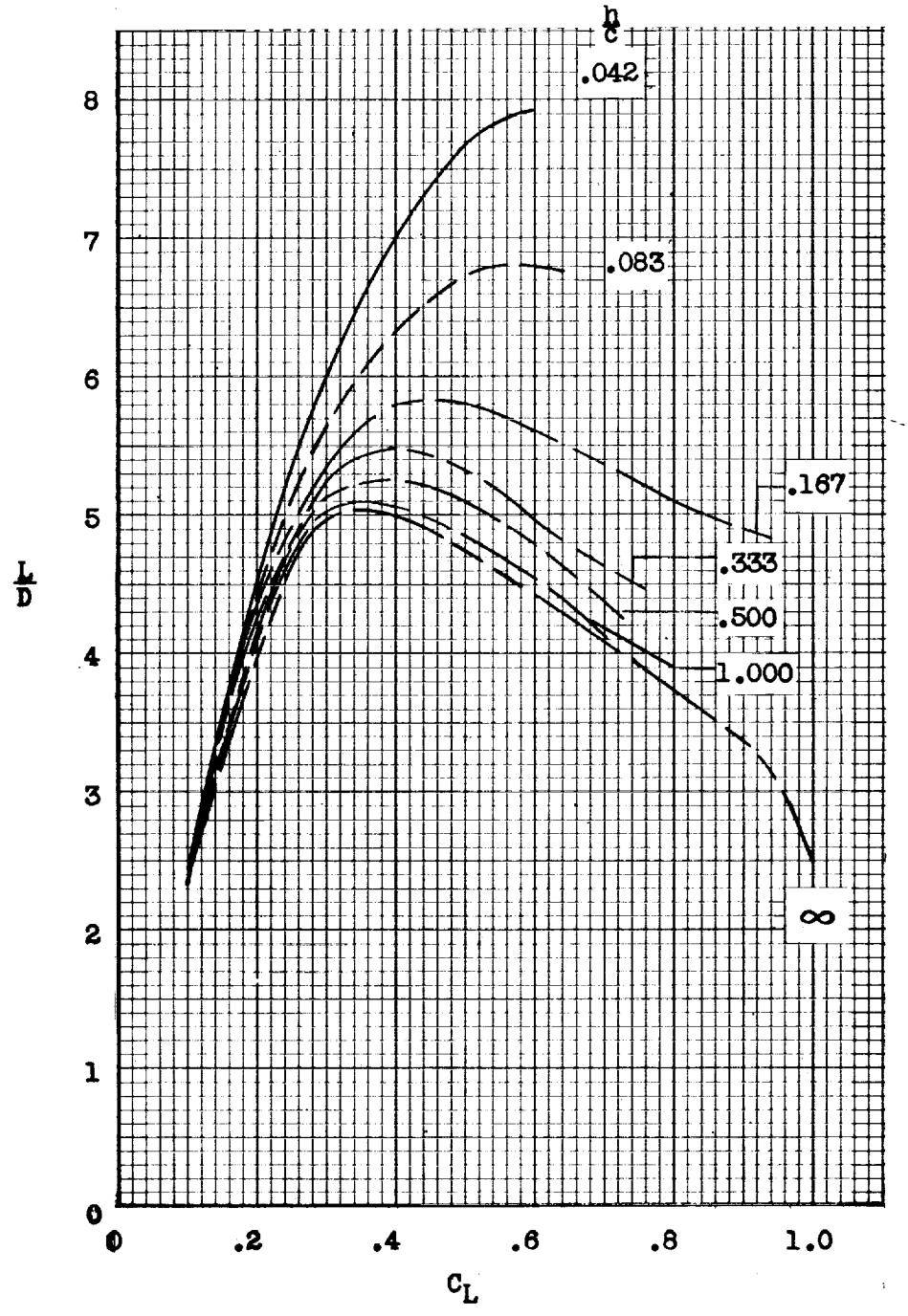


Figure 4.- Aerodynamic characteristics of wings with aspect ratios of 1, 2, 4, and 6 out of ground effect. $\frac{h}{c} = \infty$.



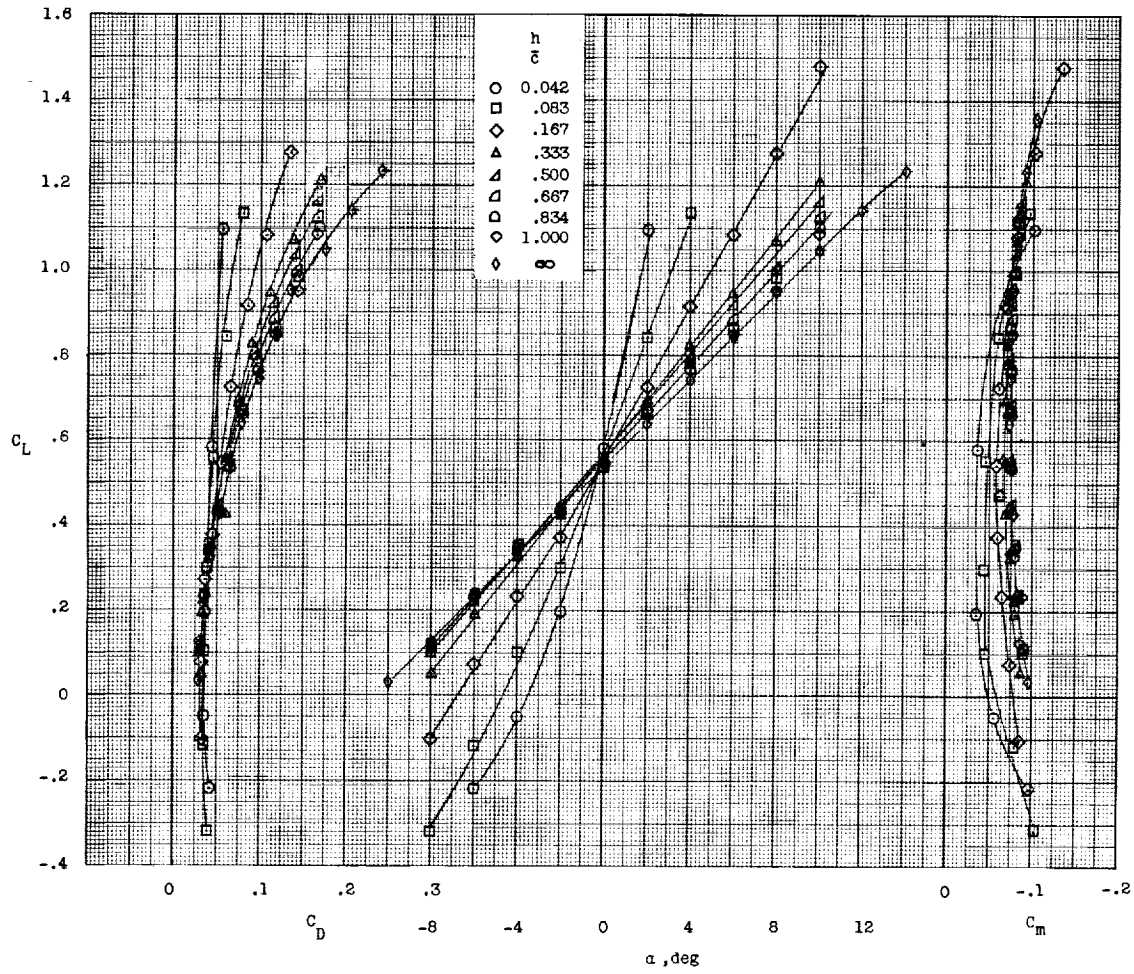
(a) A = 1.

Figure 5.- Aerodynamic characteristics for wings with aspect ratios of 1, 2, 4, and 6 at various height-chord ratios.



(a) A = 1. Concluded.

Figure 5.- Continued.



(b) A = 2.

Figure 5.- Continued.

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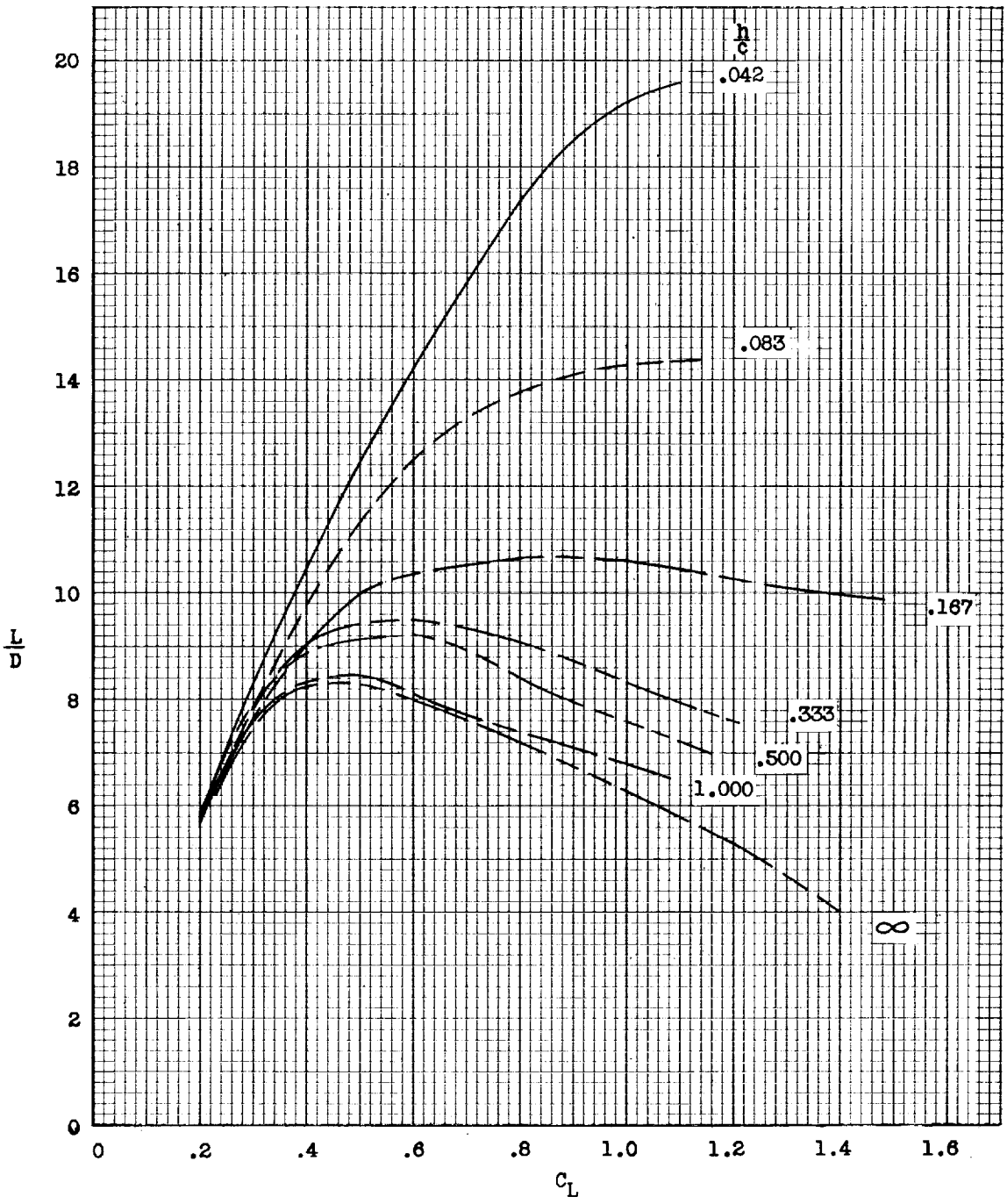
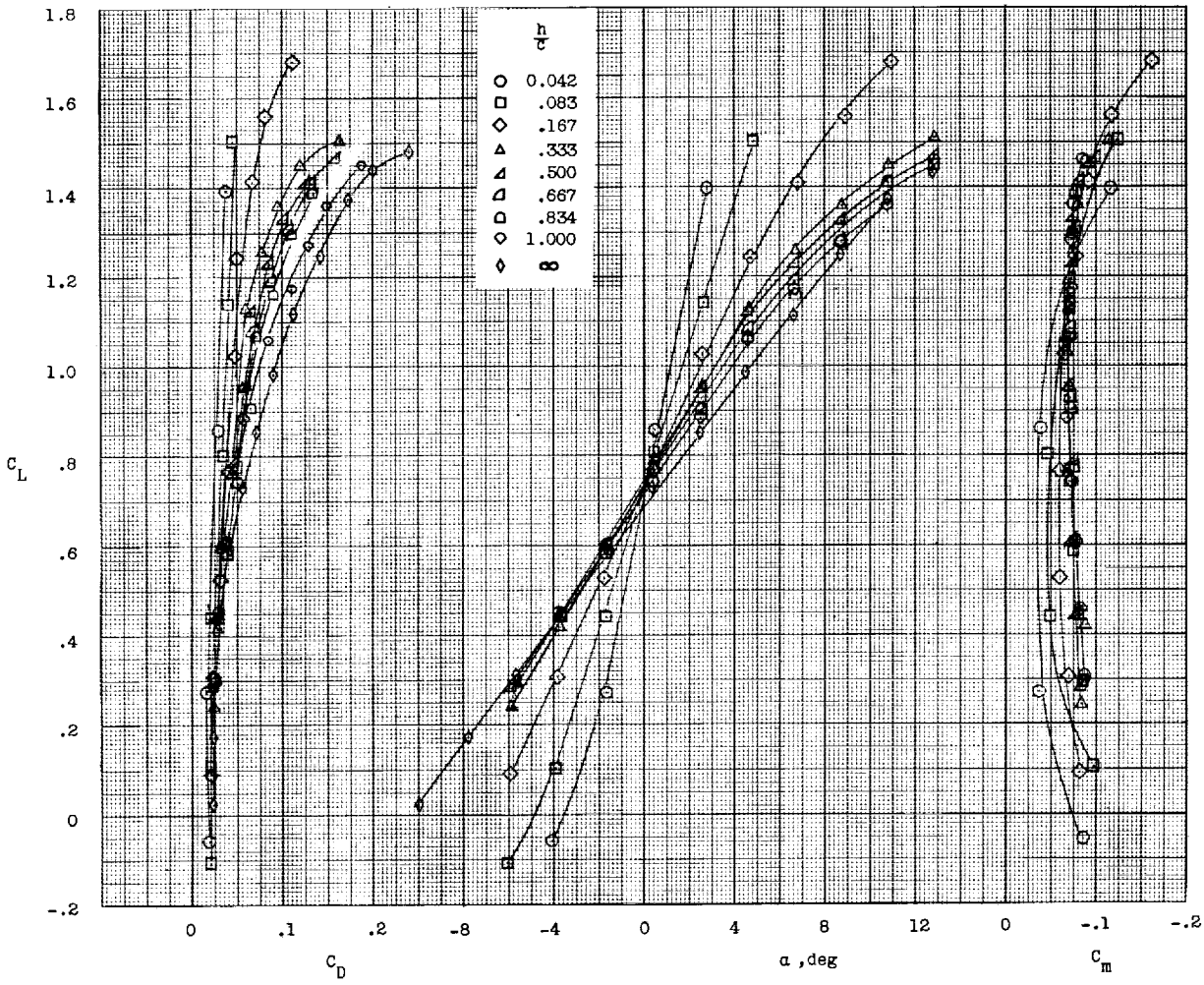


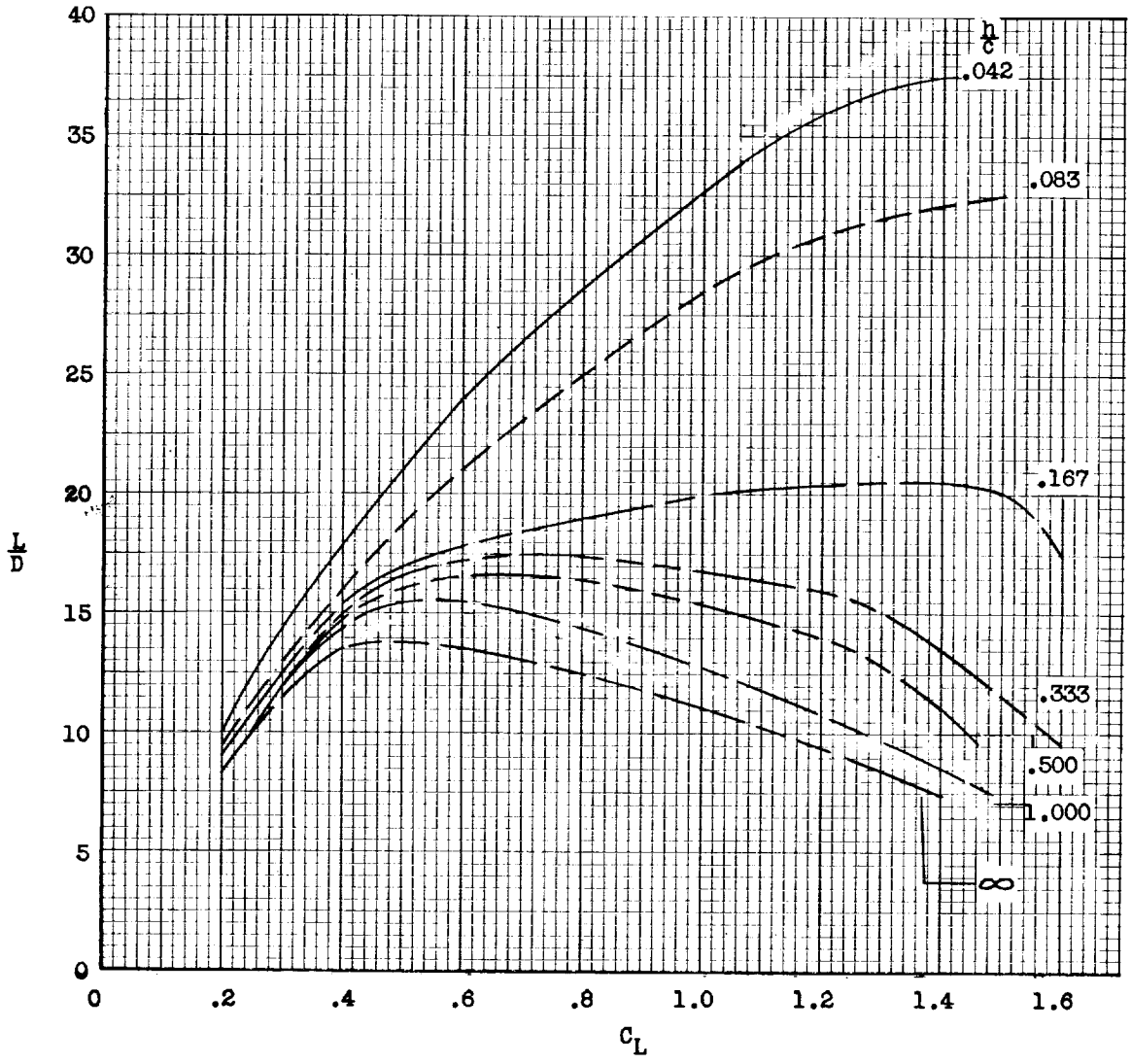
(b) A = 2. Concluded.

Figure 5.- Continued.



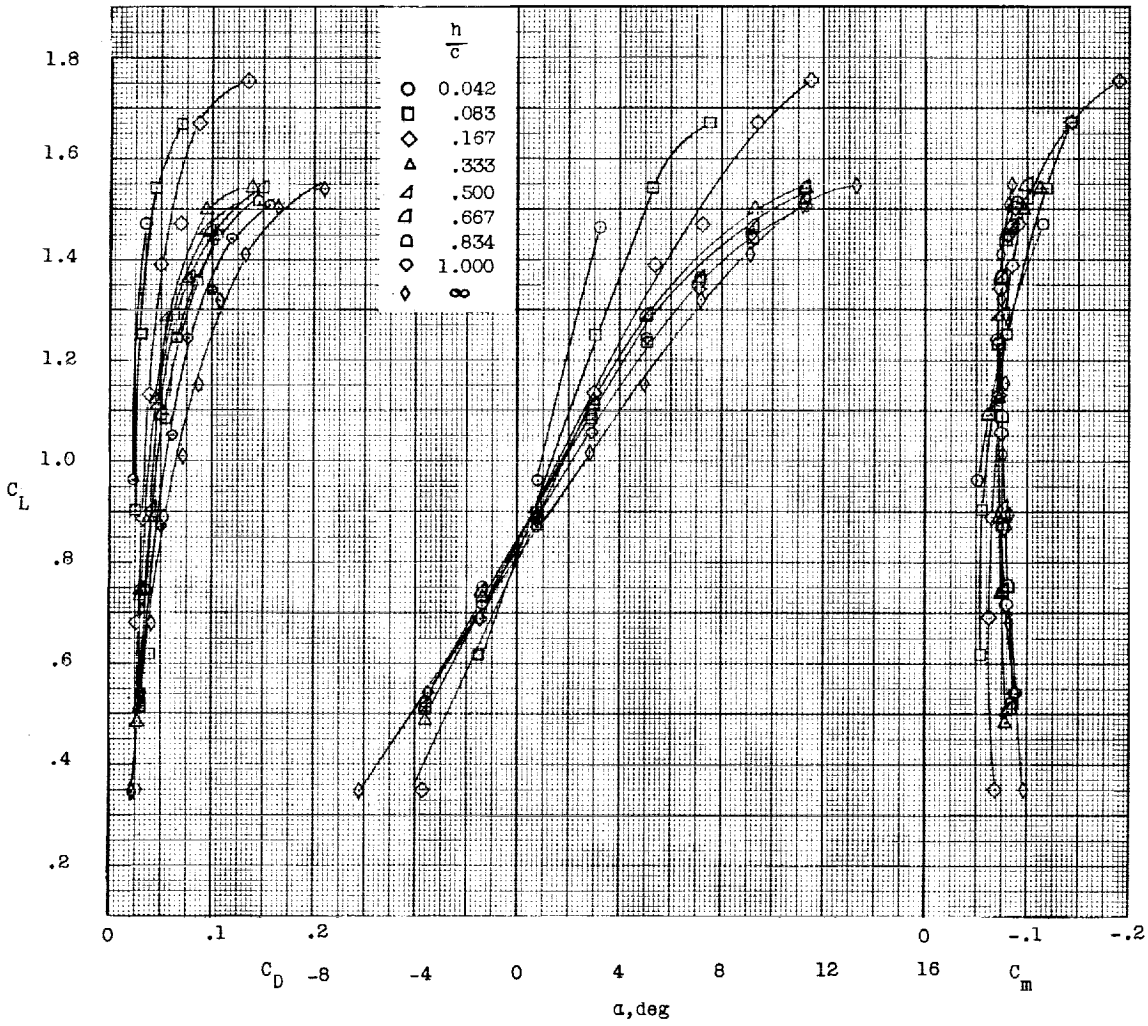
(c) A = 4.

Figure 5.- Continued.



(c) A = 4. Concluded.

Figure 5.- Continued.



(d) A = 6.

Figure 5.- Continued.

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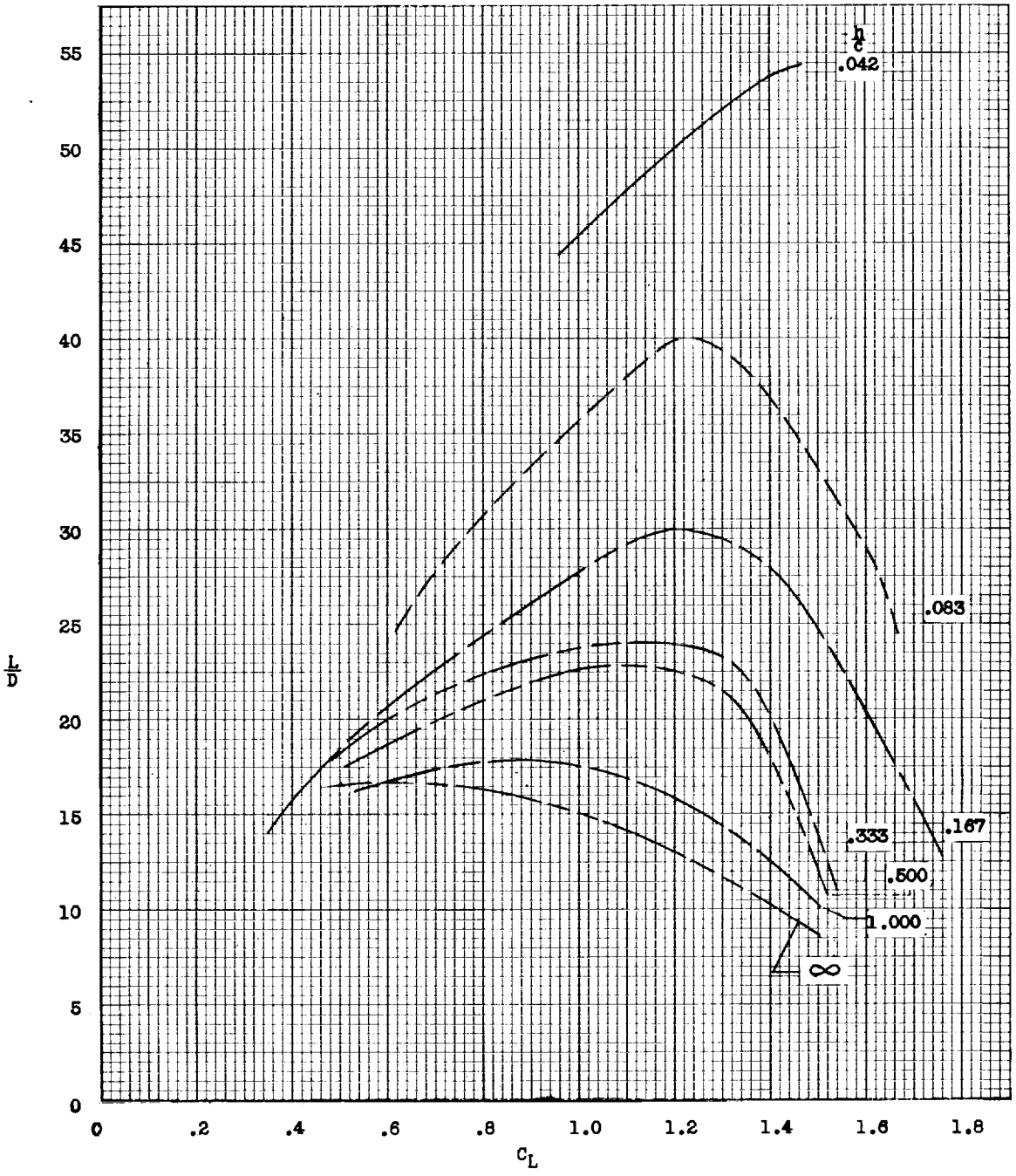
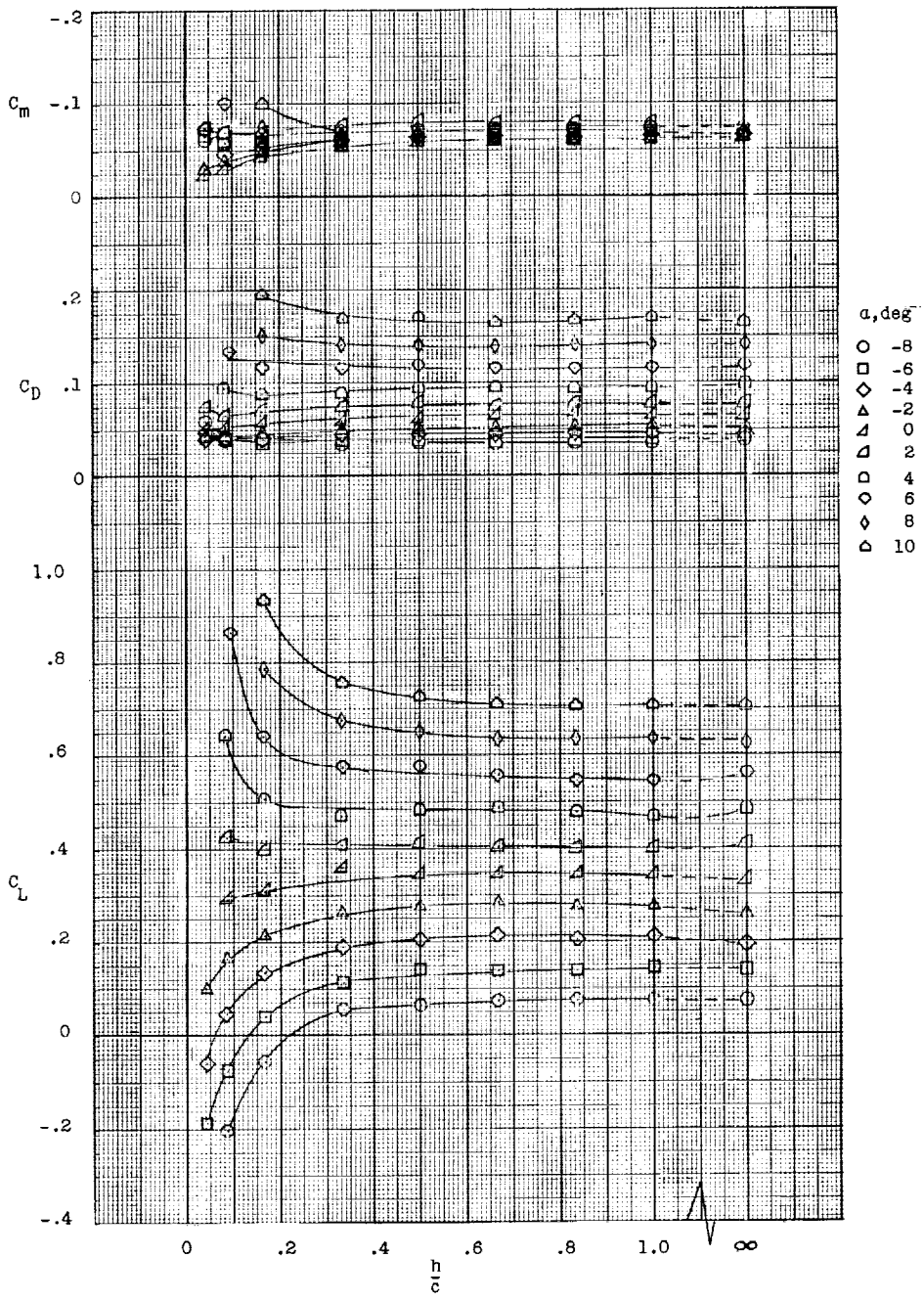


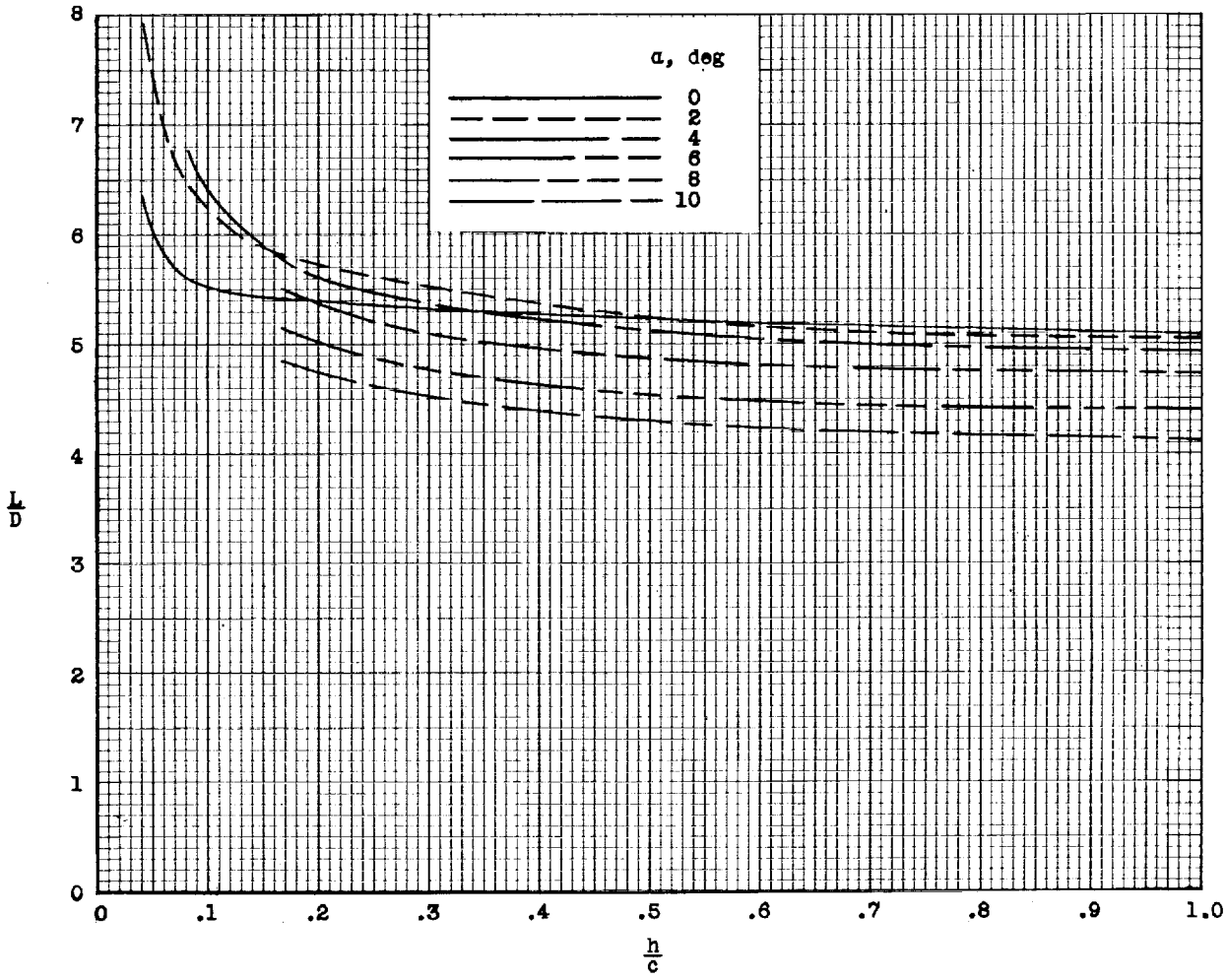
(d) A = 6. Concluded.

Figure 5.- Concluded.



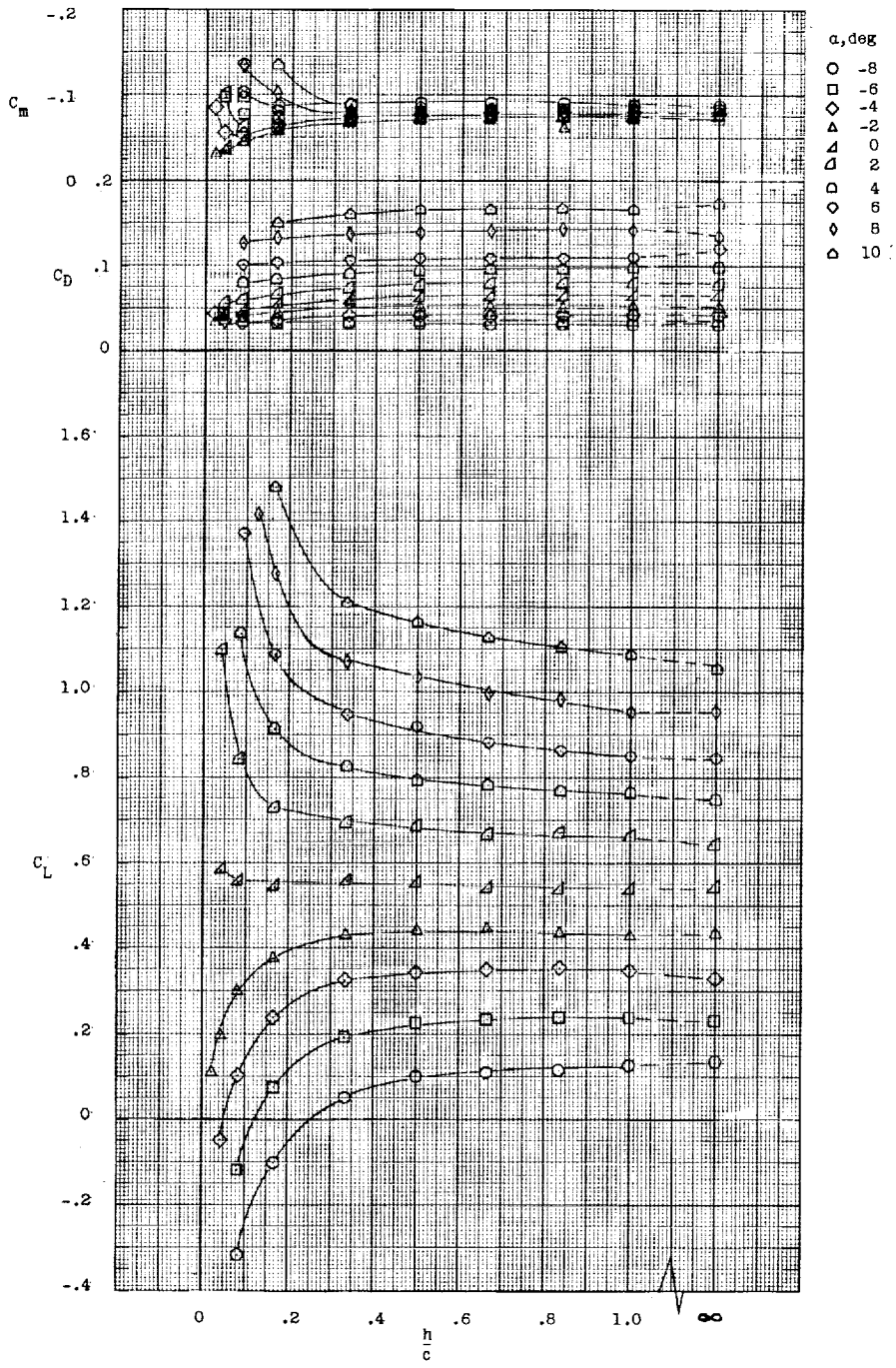
(a) A = 1.

Figure 6.- Aerodynamic characteristics for wings with aspect ratios of 1, 2, 4, and 6 at various angles of attack.



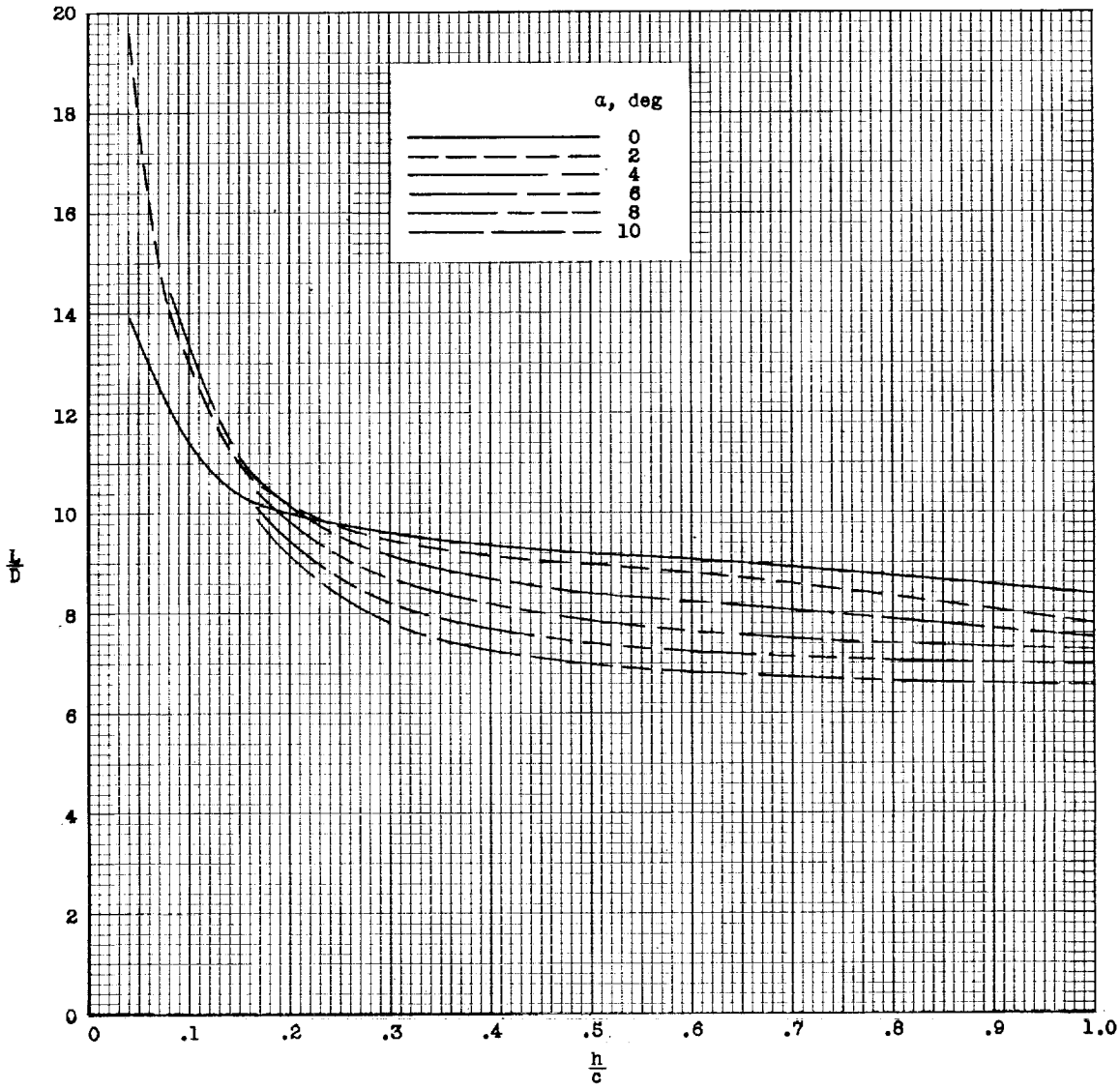
(a) A = 1. Concluded.

Figure 6.- Continued.



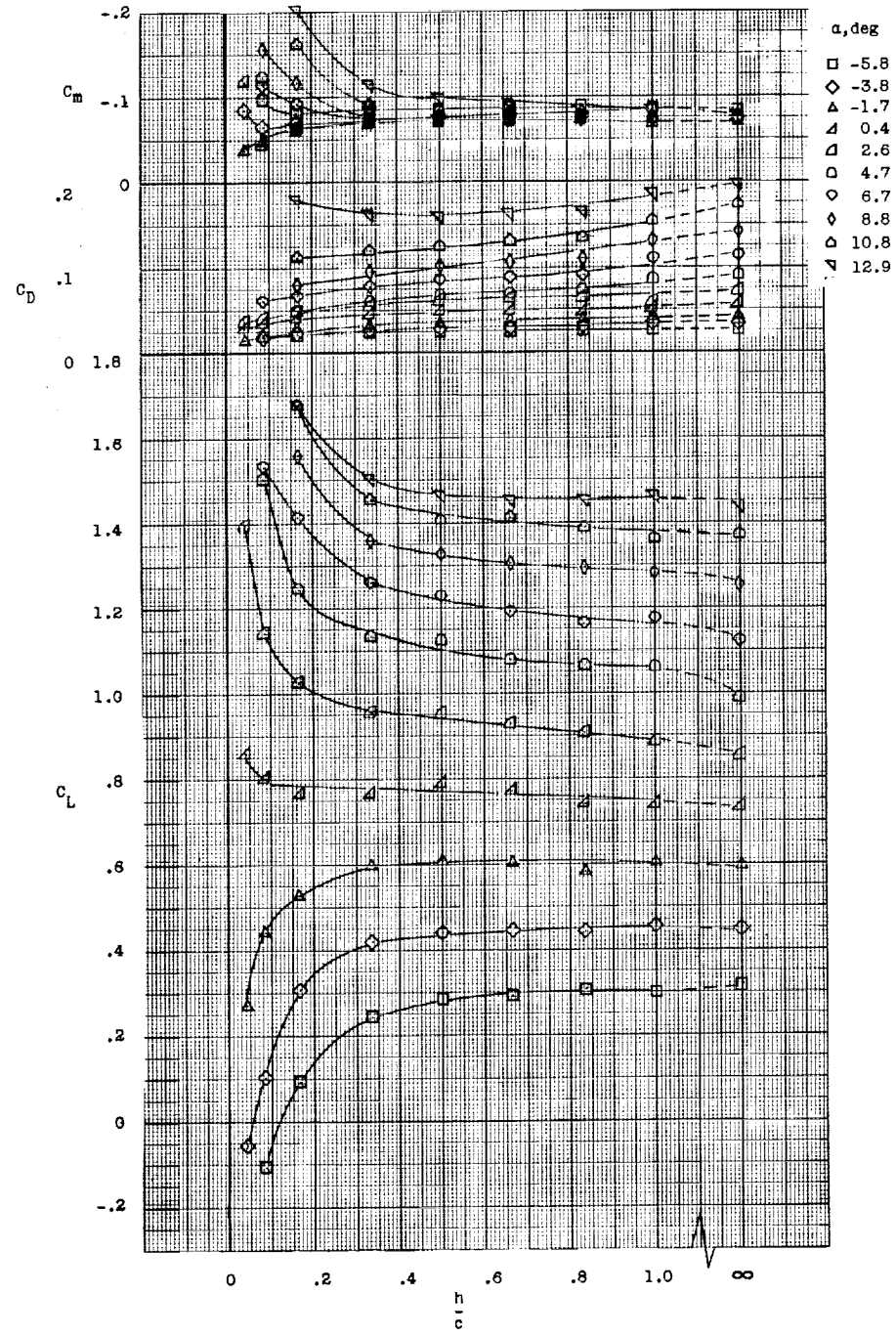
(b) A = 2.

Figure 6.- Continued.



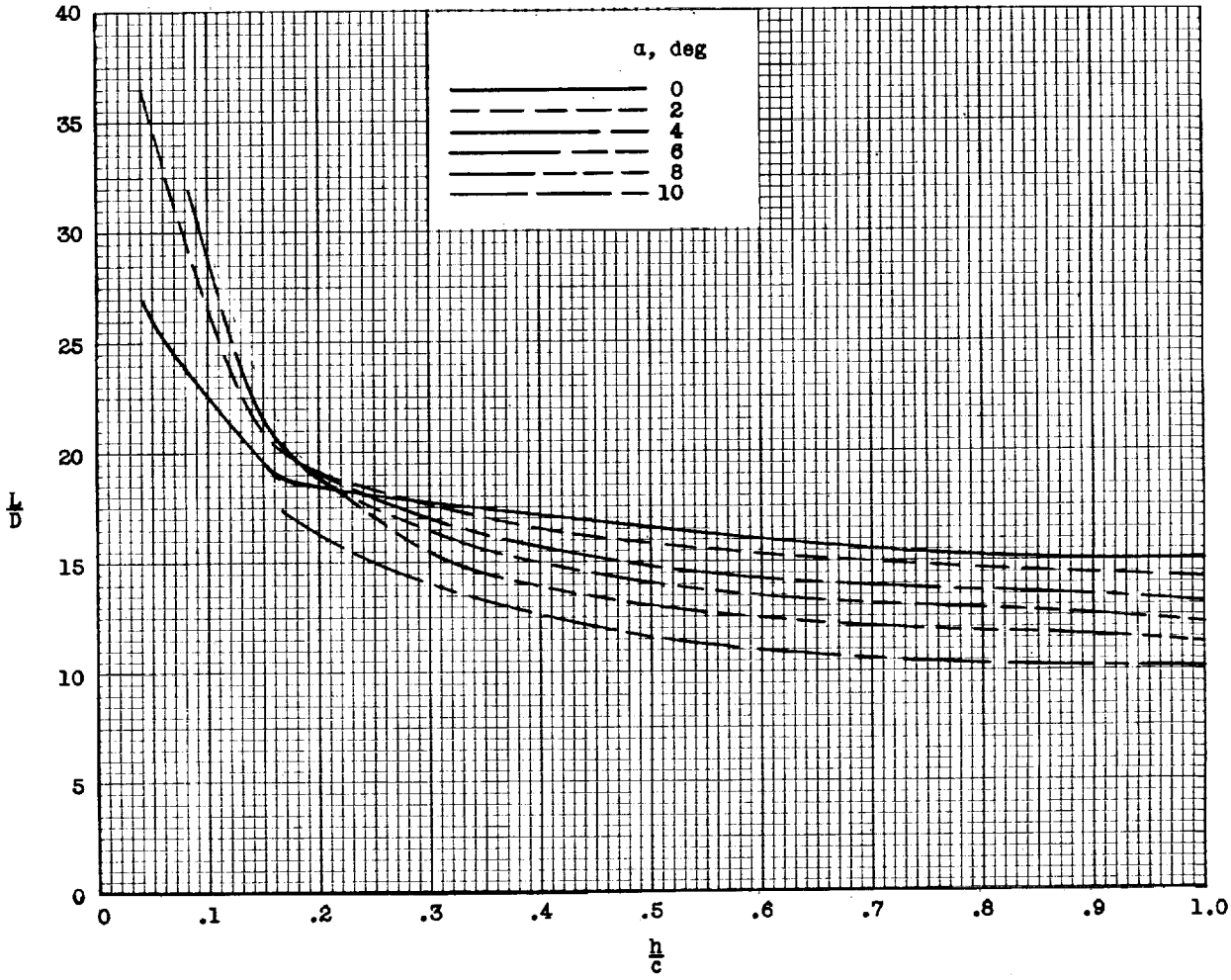
(b) A = 2. Concluded.

Figure 6.- Continued.



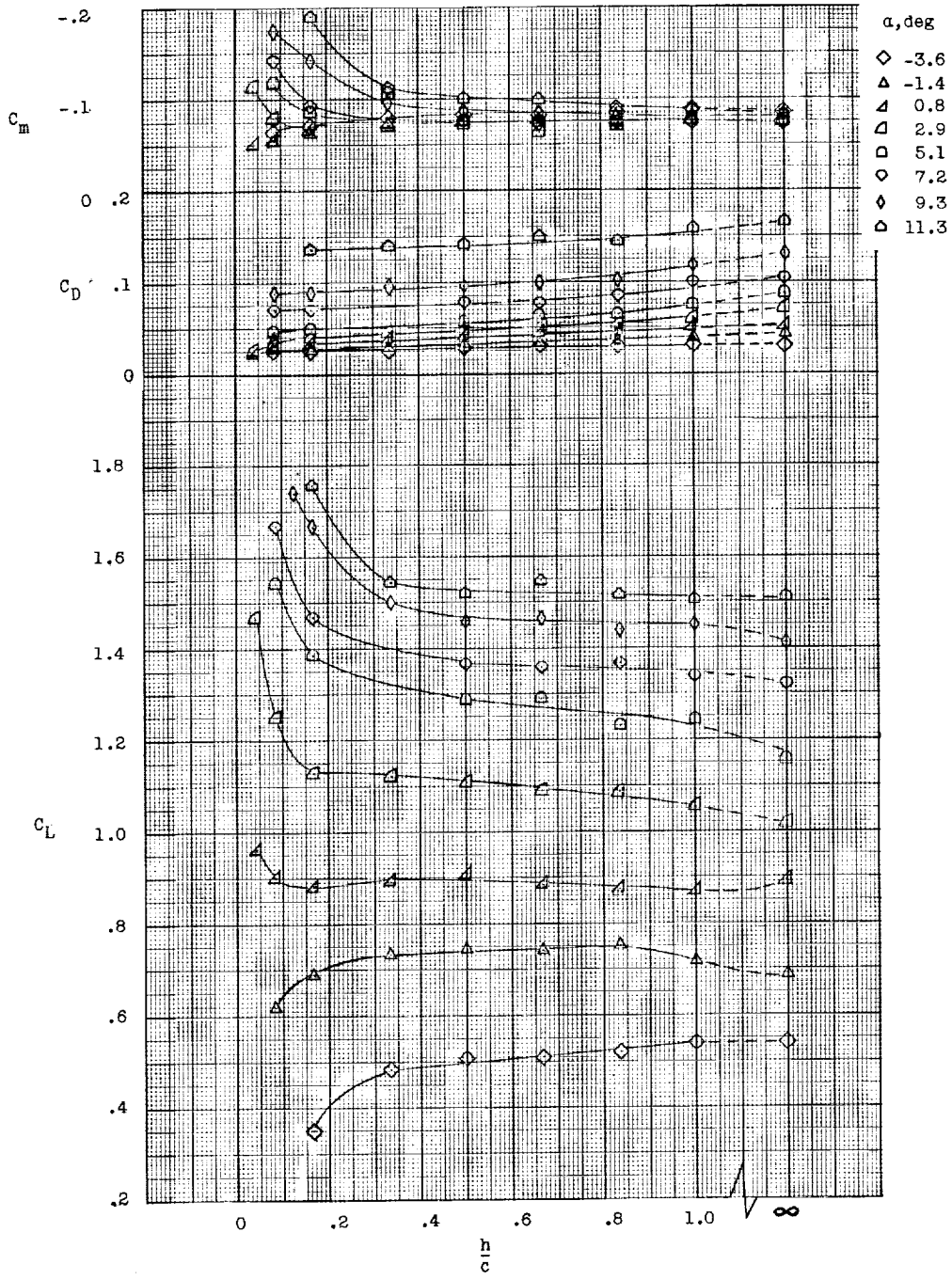
(c) A = 4.

Figure 6.- Continued.



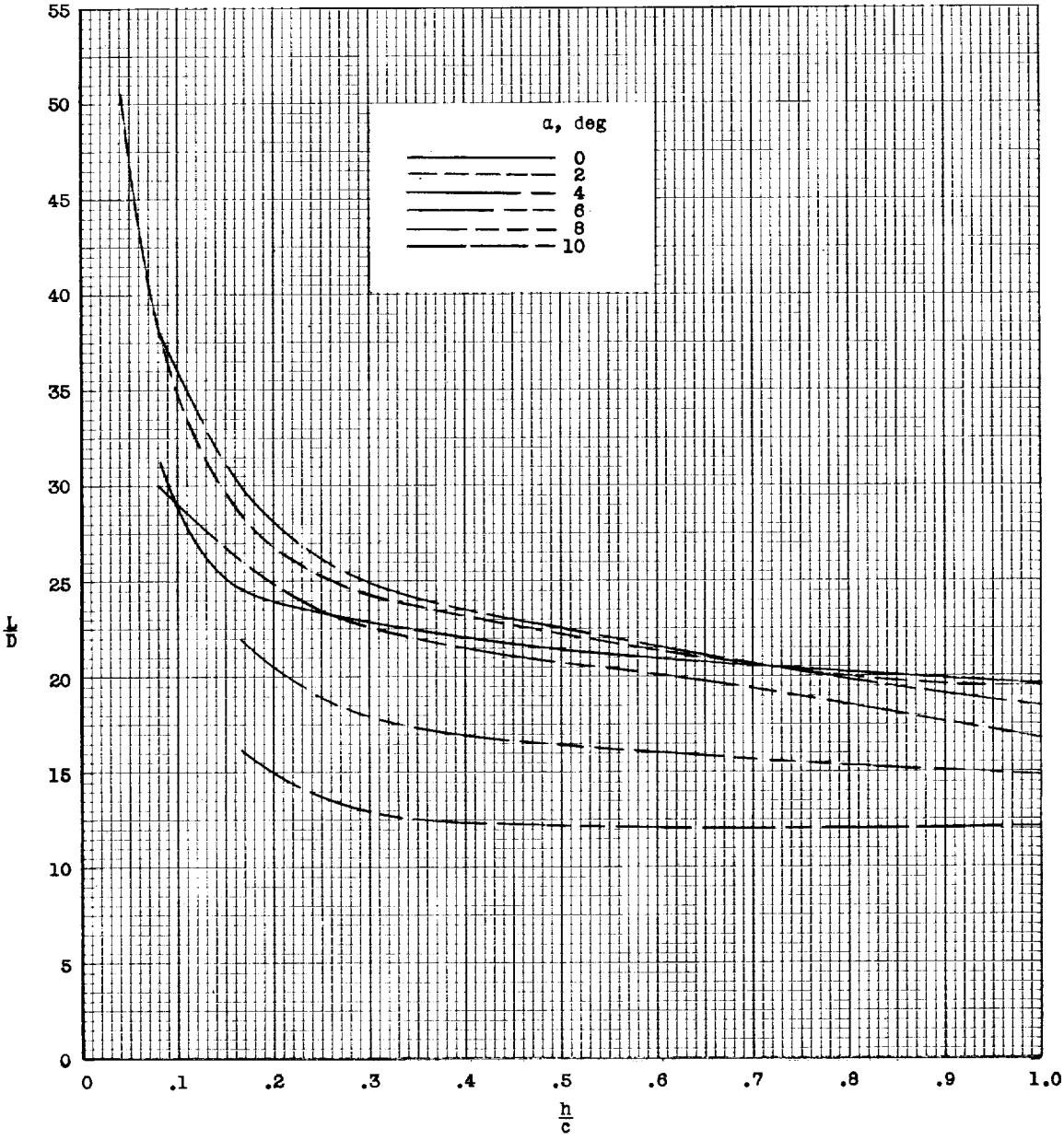
(c) A = 4. Concluded.

Figure 6.- Continued.



(d) A = 6.

Figure 6.- Continued.



(d) A = 6. Concluded.

Figure 6.- Concluded.

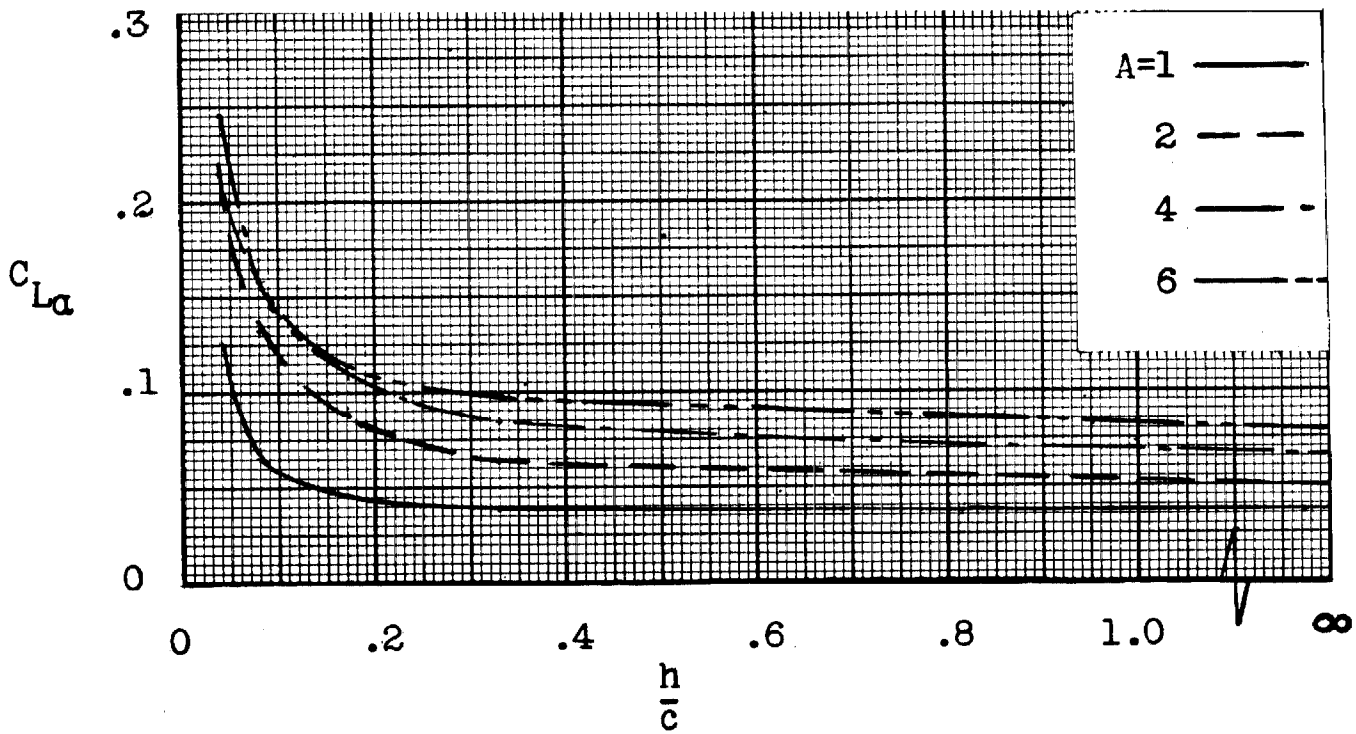


Figure 7.- Variation of lift-curve slope with height-chord ratio for wings with aspect ratios of 1, 2, 4, and 6. $\alpha = 0^{\circ}$.

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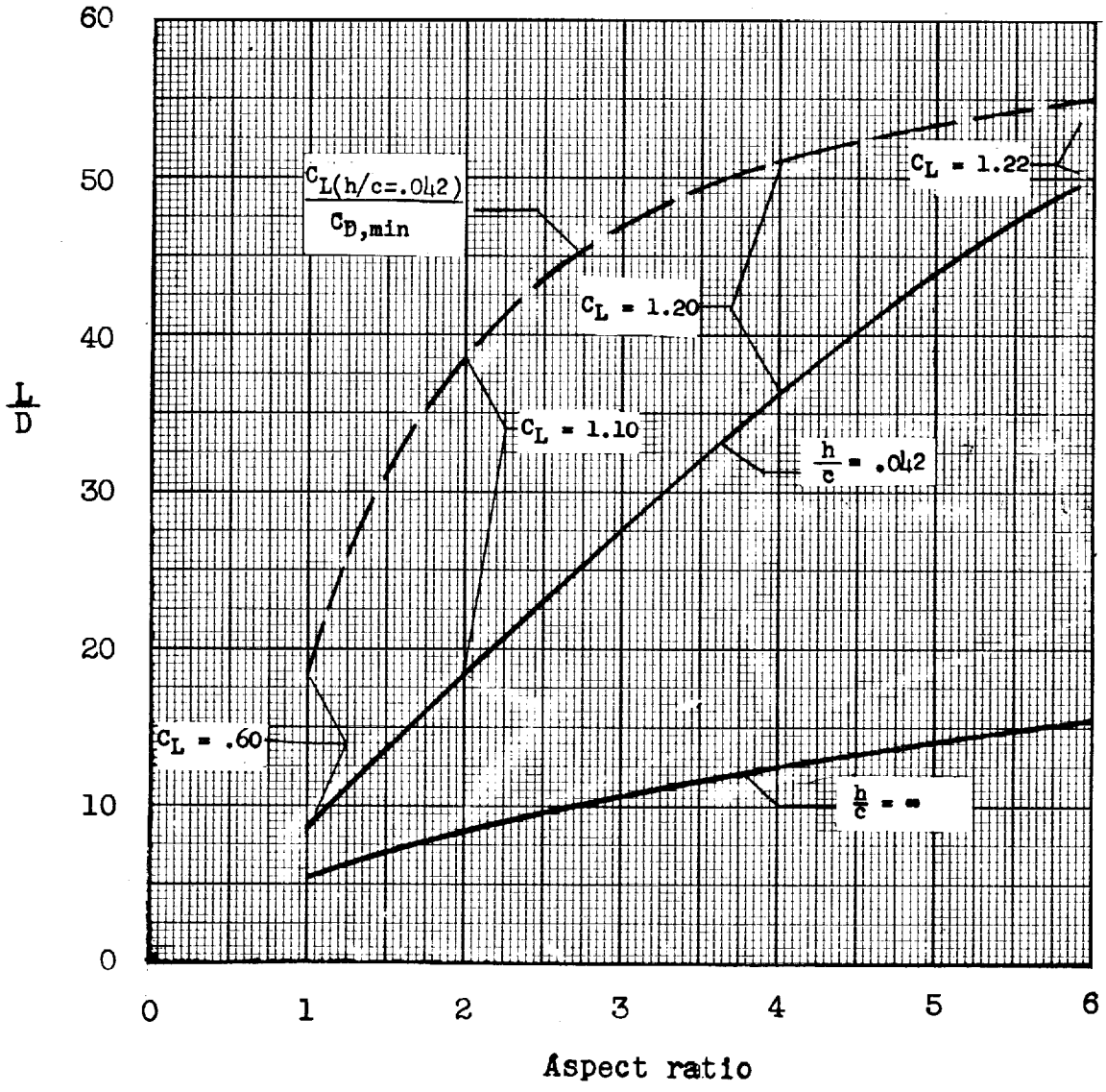

Figure 8.- Variation of lift-drag ratio with aspect ratio based on wing height-chord ratio. $\alpha = 2^{\circ}$.

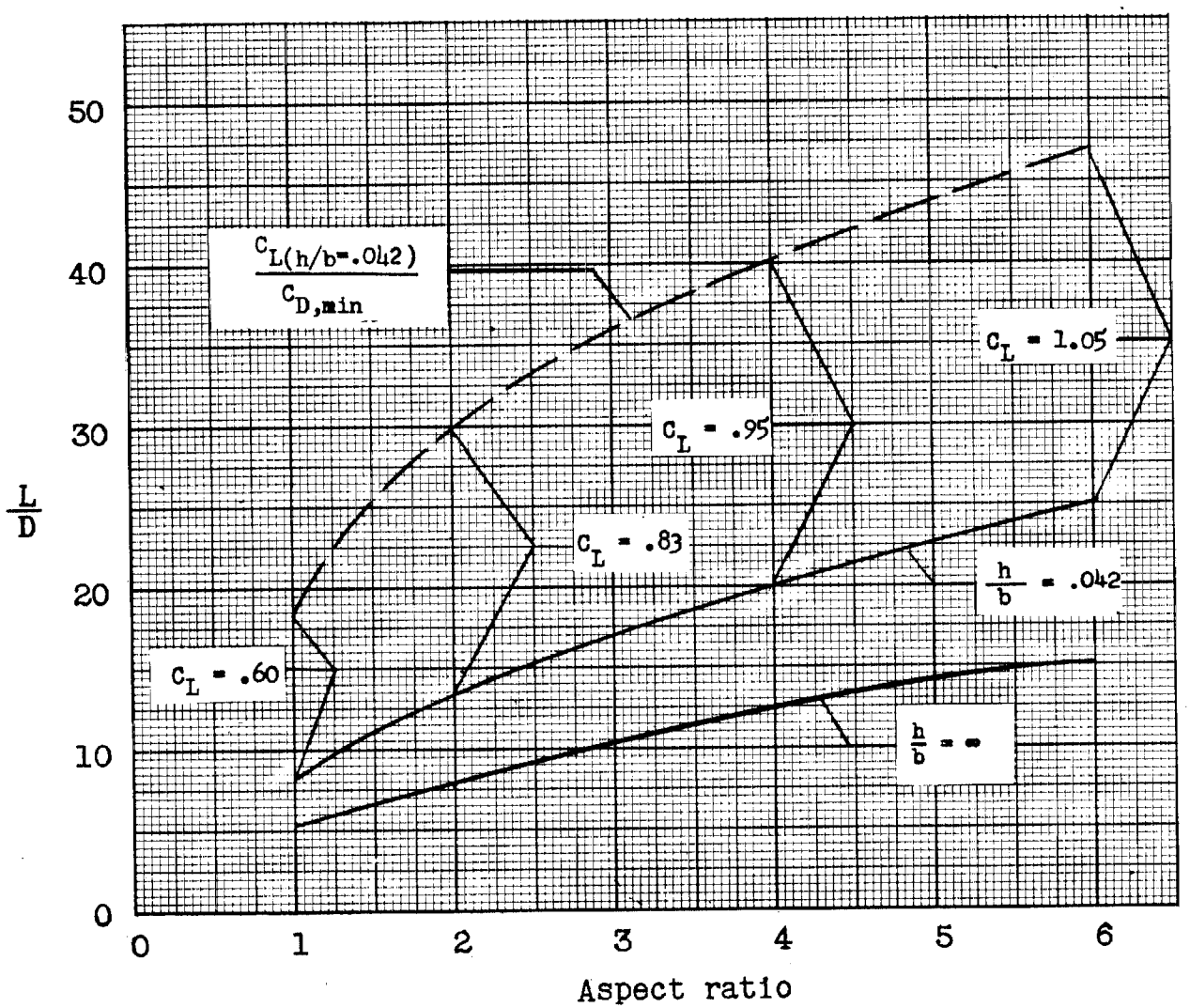

Figure 9.- Variation of lift-drag ratio with aspect ratio based on wing height-span ratio. $\alpha = 2^{\circ}$.

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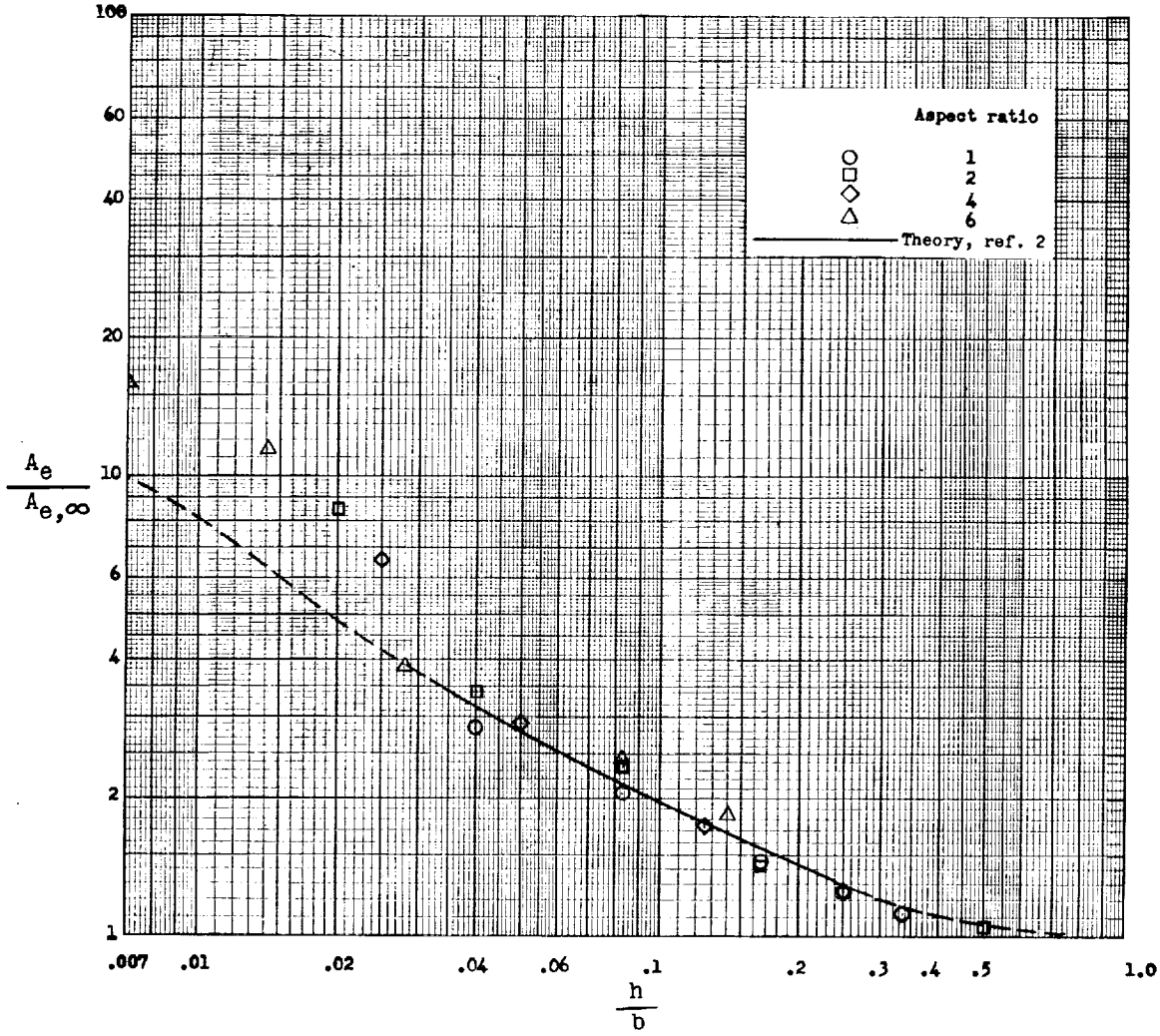


Figure 10.- Comparison of the theoretical and experimental effect of ground proximity on the ratio of effective aspect ratio in ground effect to that out of ground effect.

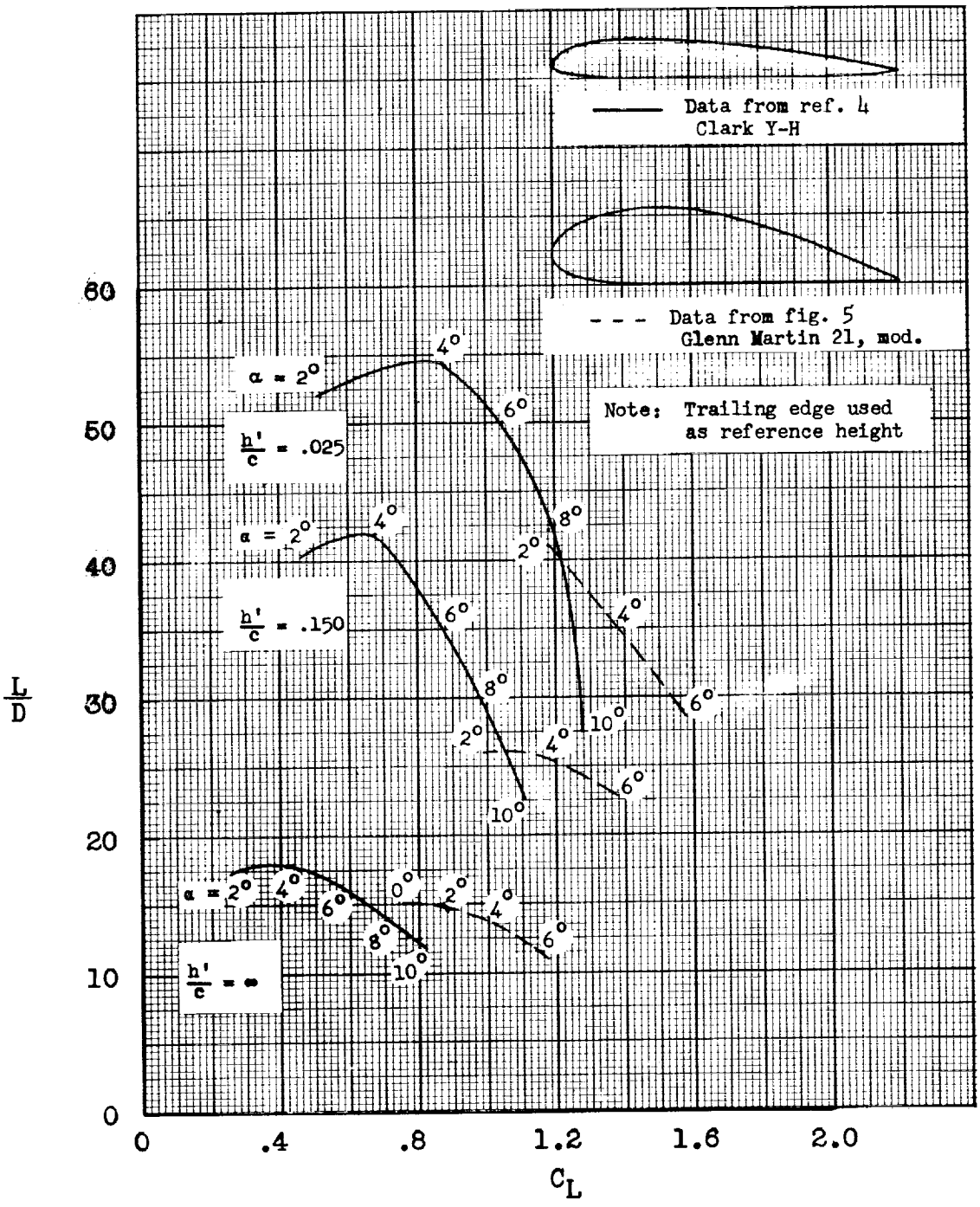
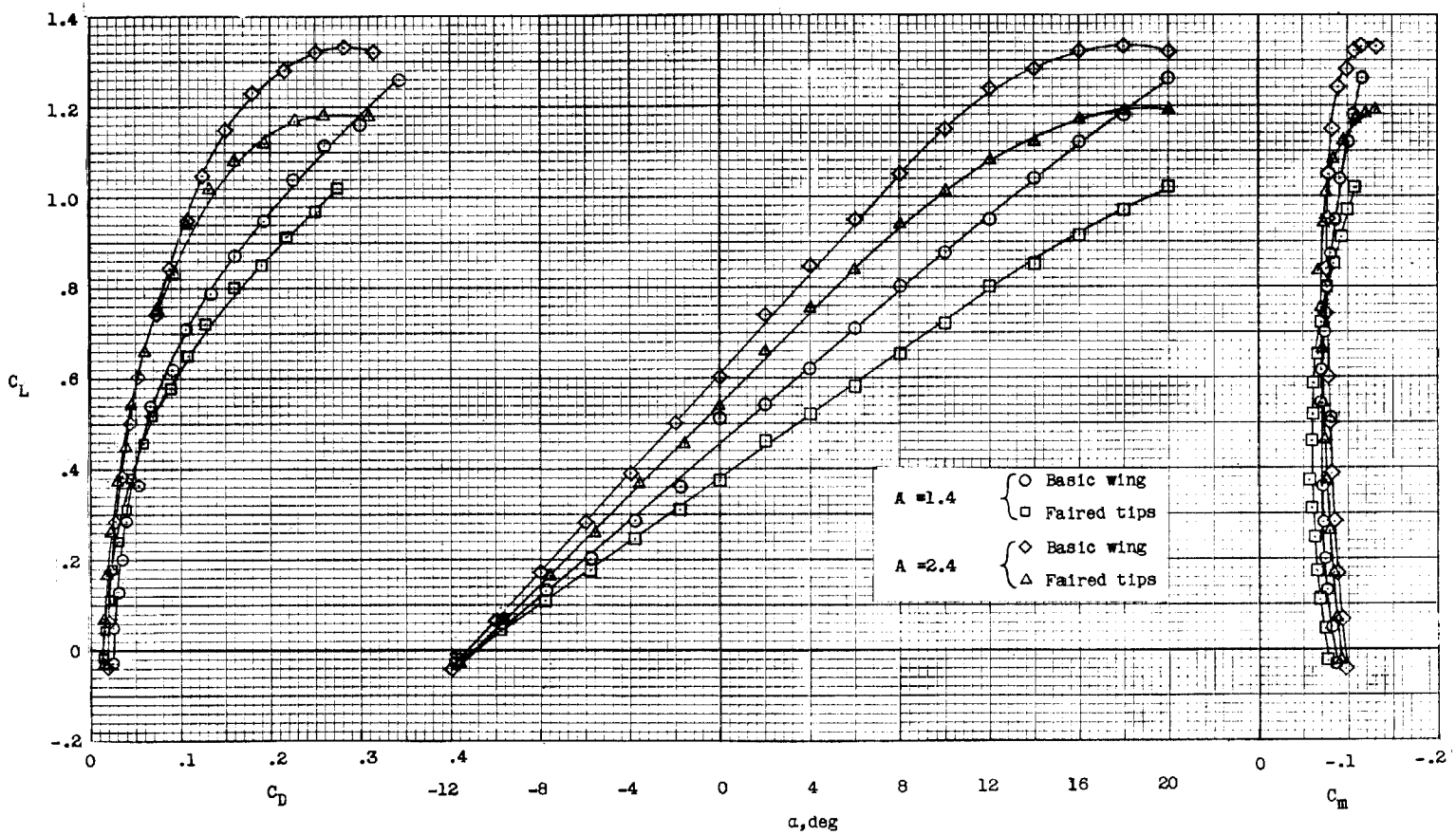
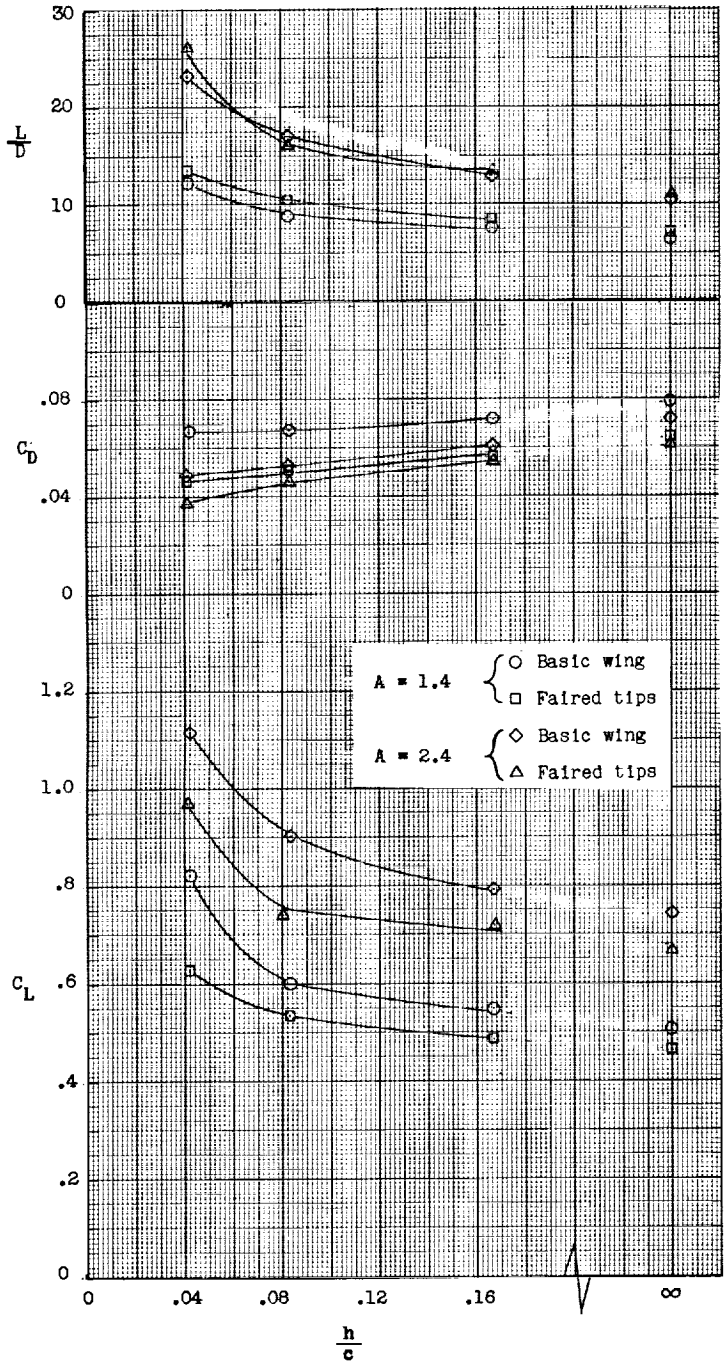


Figure 11.- Effect of ground height on two wings of aspect ratio 5 and different section thickness. Trailing edges held at constant height above ground.



(a) Out of ground effect.

Figure 12.- Aerodynamic characteristics of wing with and without tip modifications for two aspect ratios.



(b) In ground effect. $\alpha = 2.0^{\circ}$.

Figure 12.- Concluded.

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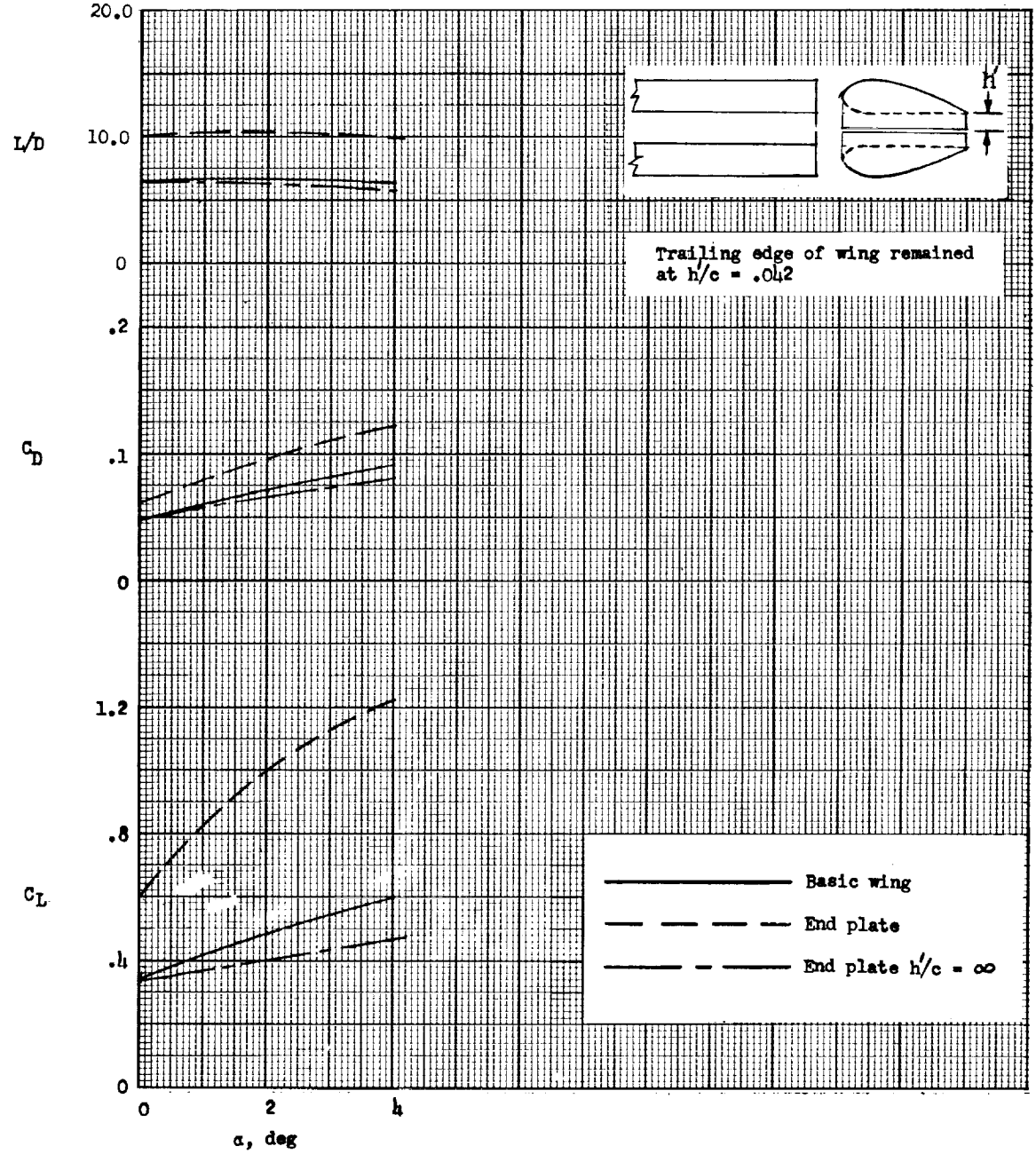

Figure 13.- Effect of end plates on wing with aspect ratio of 1. h'/c = 0.042.