Report 2259-1

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WIND TUNNEL INVESTIGATION OF AN ASPECT RATIO 10 TANDEM WING AIRCRAFT CONFIGURATION IN GROUND EFFECT PART I - LONGITUDINAL CHARACTERISTICS

by

Charles W. Harry and Lynn A. Trobaugh

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July 1966

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WIND TUNNEL INVESTIGATION OF AN ASPECT RATIO 10 TANDEM WING AIRCRAFT CONFIGURATION IN GROUND EFFECT PART I - LONGITUDINAL CHARACTERISTICS

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Bureau of Naval Weapons
Problem Assignment 1-34-52

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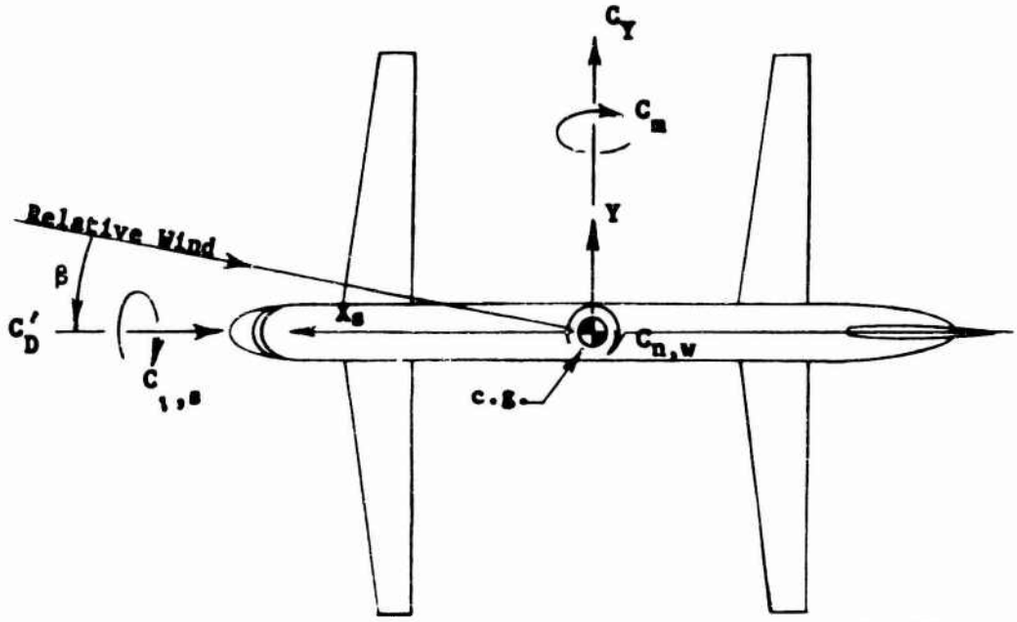
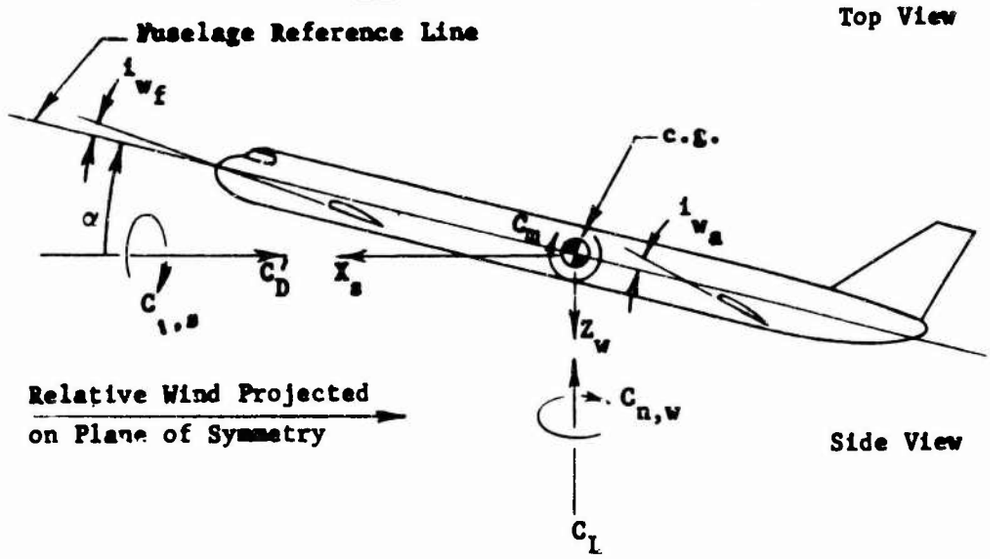
NOTATION

Positive directions of axes, forces, moments, and angular displacements are shown by arrows.



Top View



Side View

Axis	Force in pounds	Force Coefficient	Moment in pound-feet	Moment Coefficient
X_s	F'_D	$C'_D = F'_D/qS$	M_{X_s}	$C_{l,s} = M_{X_s}/qSb$
Y	F_Y	$C_Y = F_Y/qS$	M_Y	$C_m = M_Y/qS\bar{c}$
Z_w	F_L	$C_L = F_L/qS$	M_{Z_w}	$C_{n,w} = M_{Z_w}/qSb$

SYMBOLS

A	wing geometric aspect ratio (b^2/S)
A_e	wing effective aspect ratio $\left(\frac{1}{\pi}\frac{dC_L^2}{dC_D'}\right)$
b	wing span in feet
$\bar{c}$	mean geometric chord of wing in feet
C_D'	drag coefficient (D'/qS)
c.g.	center of gravity
C_L	lift coefficient (L/qS)
C_m	pitching moment coefficient $\left(\frac{\text{pitching moment}}{qS\bar{c}}\right)$
D'	aerodynamic drag in pounds
h	height in feet (measured vertically from the ground board to a point directly below the c.g. in the plane defined by the trailing edges of both wings)
i_w	wing incidence angle in degrees (wing reference line taken as bottom of Clark Y section)
Δi_w	difference in incidence angle on the forward and aft wing $\left(\Delta i_w = i_{w_a} - i_{w_f}\right)$
L	lift in pounds
r	distance in feet aft of the forward c.g. location to any other desired c.g. location
S	total wing area (two wings) in square feet
W	gross weight in pounds
α	angle of attack in degrees (angle between fuselage reference line and relative-wind vector)

Subscripts

a	aft c.g. location or aft wing
f	forward c.g. location or forward wing
m	mid c.g. location
max	maximum

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SUMMARY

Subsonic wind-tunnel test results of a tandem-wing aircraft model investigated in and out of ground effect are given. Test variables included model height above a ground board, model angle of attack, forward and aft wing incidence angles, and center-of-gravity location.

Ground effect, by increasing the lift of the wings and reducing their drag, provided a substantial increase in the lift/drag ratio of the model. For example, the lift/drag ratio of the model was increased by a factor of 2 as a result of ground proximity when the model was closest to the ground board.

Static longitudinal stability of the model is very sensitive to center-of-gravity location. Of the three center-of-gravity locations tested, only the forward and mid locations provided longitudinal stability. The mid center-of-gravity location is preferred because, at this position, the model could be trimmed with less difference in the fore and aft wing incidence angles. This resulted in slightly improved lift/drag ratio.

INTRODUCTION

The aerodynamicist has long been familiar with the high lift/drag ratios possible for aircraft cruising continuously in close proximity to the earth's surface in order to exploit the suppression of induced drag by ground effect. As presently envisioned, interface vehicles utilizing this effect appear practical only for large craft. Because of the dearth of experimental aerodynamic data on the ground-effect phenomenon, it was felt that a configuration study would be incomplete without some answers to questions which include stability and control.

Earlier DTMB tests of a wing-in-ground-effect (WIG), presented in Reference 1, indicated very good altitude or heave stability but poor pitch stability, making longitudinal control difficult. This led to the consideration of an equal-span, tandem-wing configuration as a solution to the WIG's longitudinal control problem. This model, referred to as a TWIG (tandem wing in ground effect), was tested in the DTMB 8- by 10-Foot Subsonic Wind Tunnel in the presence of a ground board to simulate ground effect. A wing with an aspect ratio of 10 was chosen

for the model because it was felt that this aspect ratio was optimum as far as structural feasibility and high lift/drag ratios were concerned. The model was also tested out of ground effect. Longitudinal aerodynamic characteristics of the TWIG model are presented in this report. A lateral stability study was also made and the results will be made available in a forthcoming report (Reference 2).

MODEL AND EQUIPMENT

A 1/40-scale model of a hypothetical TWIG configuration was designed and constructed at DTMB. The geometry and principal dimensions of the model are presented in Figure 1. A listing of the physical characteristics of the model is given in Table 1. The model represents a craft having a wing span of 200 feet.

The fuselage of the model consists of an aluminum box veneered with a 1/2-inch thickness of mahogany on the sides, top, and bottom. Carved mahogany nose and tail blocks were attached to the aluminum box to create a streamlined fuselage. A hinged mounting pad in the fuselage controlled by a jackscrew provided a method of varying the angle of attack of the model.

A Clark Y airfoil section was used for each of the two wings. Both wings were constructed of fiberglass with embedded steel spars to improve wing stiffness. The distance between the wings was chosen from the results of tandem wing tests in Reference 1. Each wing was mounted on a bracket which was constructed so that the incidence angle could be varied. The brackets were hinged so that rotation of the wing occurred about its trailing edge. Each mounting bracket had its own adjusting jackscrew so that the incidence angle of either wing could be varied independently. The wings and the vertical tail had no control surfaces.

A special, telescoping mounting strut was constructed for the test. When the strut with the model attached was installed in the tunnel, the model could be translated vertically through a distance of nine inches. The strut was also capable of being yawed through an angle of $\pm 25^{\circ}$. Details of the strut are shown in Figure 2.

For the ground-effect tests, a metal ground board was installed in the tunnel so that when the strut was fully extended, the model was closest to the ground board. Conversely, when the strut was retracted, the model was at a distance of about nine inches from the ground board. The model was mounted in an inverted position on the strut for the in-ground-effect tests and upright for the out-of-ground-effect tests.

TESTS

All tests were conducted in the DTMB 8- by 10-Foot Subsonic Wind Tunnel at a dynamic pressure of 50 pounds per square foot. For the TWIG model, this corresponds to a Reynolds number of approximately 654,000.

In-ground-effect tests of the TWIG model were conducted at heights of 1.8 to 9.0 inches, through an angle-of-attack range from -2° to +6°. Longitudinal force and moment data were recorded and reduced by digital computer. The large number of test variables involved prevented a complete investigation of all resultant matrix quantities. However, sufficient tests were conducted and data recorded to determine trends of interest.

The model support apparatus, Figure 2, caused a change in the height parameter h/b with the variation of fuselage angle of attack. The reference height h was determined at $\alpha = 0°$ as the vertical distance from the ground board to the plane of the trailing edges of the wings. Test data were first reduced to the forward center-of-gravity location. The following transfer equations were then employed in the computer program to calculate the data to the mid and aft center-of-gravity locations.

$$\frac{h_m}{b} = \frac{h_f - r_m \sin \alpha}{b}$$

$$\frac{h_a}{b} = \frac{h_f - r_a \sin \alpha}{b}$$

$$C_{m_m} = C_{m_f} + \frac{r_m}{\bar{c}} \left(C_L \cos \alpha + C_D' \sin \alpha \right)$$

$$C_{m_a} = C_{m_f} + \frac{r_a}{\bar{c}} \left(C_L \cos \alpha + C_D' \sin \alpha \right)$$

For the TWIG model, r_m and r_a have the values of 0.25 and 0.50 feet, respectively. Data for other center-of-gravity locations may be computed, if desired, merely by substituting the proper value of r into the above equations.

The in-ground-effect data were obtained by using a ground board to simulate the earth's surface. A pressure survey was conducted over the ground board to determine the boundary layer thickness in the vicinity of the model. The boundary layer thickness in this region was only about 0.75 inch, which is well below the minimum wing-to-ground-board clearance of 1.5 inches.

RESULTS

The nondimensional parameter, height/span (h/b), has proven useful in the study of ground-effect phenomena. Therefore, the data were prepared for presentation as follows: (a) longitudinal aerodynamic coefficients were plotted against height/span for each center-of-gravity position (forward, mid, and aft), (b) values of the coefficients were read from these plots for several values of height/span ratio (0.03 to 0.15) for each center-of-gravity position, and (c) plots were made using these values of the aerodynamic coefficients.

Longitudinal aerodynamic characteristics of the TWIG model with various equal wing incidence angles $\left(i_{w_f} = i_{w_a}\right)$ are presented in Figures 3 through 6. Curves for all three center-of-gravity locations are presented for each value of $\left(i_{w_f} = i_{w_a}\right)$ tested (namely, 0°, 2°, 4°, and 8°), except at the highest incidence angle (Figure 6), where the forward center-of-gravity location is omitted.

The TWIG performance parameters: $(L/D)_{max}$, C_L at $(L/D)_{max}$, and A_e/A are given in Figure 7. The experimental curves were obtained from the faired values of the data similar to the data shown in Figures 3 through 6. Several curves of A_e/A are shown. The predicted curve was obtained by correcting the TWIG drag polar for out-of-ground-effect flight to drag polars for in-ground-effect flight, at a number of h/b's, using correction factors from Reference 3. The values of A_e for the predicted and the experimental curves were computed from the equation:

$$A_e = \frac{1}{\pi}\left(\frac{dC_L^2}{dC_D'}\right)$$

where the slope $\frac{dC_L^2}{dC_D'}$ was determined graphically from plots of C_L^2 versus C_D' (Reference 4). The theoretical curve of A_e/A for this figure was obtained from Reference 3.

Figures 8 and 9 show the effectiveness of the forward and aft wings, respectively, as longitudinal control and/or trim devices. In Figure 8, the forward wing acts as a canard with i_{w_a} and α held equal to zero. Conversely, in Figure 9, the aft wing is used as an elevator with i_{w_f} and α held equal to zero. Both of these figures are for the mid center of gravity only.

Shown in Figure 10 is the effect of i_{w_a} on the lift performance of the TWIG. These curves are applicable to all three center-of-gravity locations, since α was held constant at zero for this series of tests. In each part of the figure, i_{w_f} was set at some new value and held there for the range of i_{w_a} tested.

Trim data for the TWIG model in-ground-effect is given in Figure 11. Because of insufficient data, it was necessary to extrapolate the existing data slightly to obtain trim points. Higher α's restricted the lowest h/b to values greater than 0.063 because of ground clearance. For this reason, in part (a) of Figure 11, the maximum α is 2°. Values of h/b lower than 0.05 are not given, since it was physically impossible to operate the model over a sufficiently large range of α's.

Figures 12 through 15 present data on the TWIG model out of ground effect. Figure 12 shows the longitudinal aerodynamic characteristics for $i_{w_f} = 0^\circ$, and i_{w_a} restricted to small angles. Pitching moment coefficients and lift coefficient curves for all three center-of-gravity locations are given in the same figure. The aft wing incidence angle was varied slightly to show the power of i_{w_a} in changing C_m.

Figure 13 is a presentation of the model data out of ground effect. This figure contains data for trimmed flight ($C_m = 0^c$, only). The symbols in the figure show what value of i_{w_a} is required for a given i_{w_f} to trim the model. A curve for each of the three center-of-gravity locations is presented. Should values of i_{w_f} other than those represented by the symbols be desired, they can be obtained by interpolating linearly between the symbols on a given center-of-gravity curve. In addition, values of i_{w_f} required for trim at center-of-gravity locations lying between those represented by the curves may be obtained by interpolating linearly between the center-of-gravity curves on a given i_{w_f} curve. Also given in Figure 13 are curves of the L/D ratios of the trimmed model flying out of ground effect.

Figure 14 was derived from the data of Figure 13. It shows how different wing incidence angles on the forward and aft wings affect the lift performance. In Figure 14, Δi_w was computed from the equation

$$\Delta i_w = i_{w_a} - i_{w_f}$$

Thus, positive values of Δi_w indicate that $i_{w_a} \geq i_{w_f}$ and, conversely, negative values of Δi_w indicate $i_{w_a} < i_{w_f}$.

Longitudinal aerodynamic characteristics of the TWIG model flying out of ground effect with the aft wing removed are presented in Figure 15. This figure is comparable to the tandem wing model configuration data of Figure 12. In Figure 15, data are presented to give some indication of the interference effects of the forward wing upon the aft wing.

The trim data of the TWIG model, both in and out of ground effect, are given in Figure 16. This figure is presented to summarize the in- and out-of-ground-effect data. In-ground-effect data were obtained from the linear interpolation of plots similar to Figures 3 through 6 to obtain values of the coefficients at trim conditions. Out-of-ground-effect data were obtained from plots presented earlier in this report.

Only data for the mid center-of-gravity location are given and only for $\alpha = 0°$.

Unless otherwise noted, the data presented in the above-mentioned figures are for the in-ground-effect case. Out-of-ground-effect flight would be required only for high sea states and for clearing large obstacles such as those that might be encountered in arriving at or departing from an inland airport.

DISCUSSION

The primary purpose of these tests was to determine the aerodynamic characteristics of a tandem wing configuration operating in and out of ground effect. The discussion is subdivided into these sections: Lift/Drag Characteristics, Longitudinal Stability, and Longitudinal Trim.

LIFT-DRAG CHARACTERISTICS

Figure 7 shows a comparison of the TWIG model wind-tunnel test results and the predicted in-ground-effect performance with the theory of Reference 3. As can be seen from the figure, the experimental and predicted results are in good agreement with theory, even though several simplifying assumptions are made by theory. It was found that the tandem-wing configuration behaved as though its aspect ratio $\left(A = \frac{b^2}{S}\right)$ were 5 instead of the individual wing aspect ratio of 10. The experimental and predicted curves of A_e/A were both computed using A = 5. The theoretical curve is independent of aspect ratio. If A = 10 had been used in computing the experimental and predicted curves, values of A_e/A for both curves would be only half of those which were obtained using A = 5. The theoretical curve would not be changed.

Values of C_L at $(L/D)_{max}$ for the TWIG model in ground effect are higher than desired. For example, at a practical h/b of 0.10 at the mid center-of-gravity location, the required value of C_L is about 0.55 (see Figures 11d and 16). Figure 7 shows that, at the mid center-of-gravity location, C_L for $(L/D)_{max}$ is high for all values of h_m/b, the lowest C_L value being 0.53 for $h_m/b = 0.15$ and the highest C_L value being 0.70 for $h_m/b = 0.03$. Furthermore, as can be seen in Figure 11, if i_{w_f} is set at a value greater than zero, the C_L for $(L/D)_{max}$ has even larger values than the curve of Figure 7. Further examination of

Figure 16 reveals that, as higher L/D ratios are sought, hence requiring lower values of h/b, the C_L value required for trimmed cruise flight at $(L/D)_{max}$ increases. As can be seen from Figure 16, high values of C_L for $(L/D)_{max}$ also occur with the model flying out of ground effect. Thus, it is not possible to conclude that these high C_L values are a characteristic of in-ground-effect flight. It is possible that lower values of C_L for $(L/D)_{max}$ may be obtained by using a thinner airfoil section.

High values of C_L present several problems. If high cruise velocities are desired (i.e., about 200 knots), wing loadings would be undesirably higher than currently accepted values. These high wing loadings would require that the take-off and landing speeds be a very high percentage of the cruise velocity unless the value of C_L at take-off and landing can be significantly increased with high-lift devices—an unlikely event, considering the ineffectiveness of flaps in ground effect. On the other hand, currently acceptable wing loadings can be obtained only by sacrificing high cruise velocity.

The effects of wing incidence angles on lift performance are shown in Figures 3 through 6 for the model flying in ground effect. A comparison of these figures reveals that, for a given center-of-gravity location, as i_{w_f} and i_{w_a} are increased equally, the slopes of the C_L versus C_D' curves decrease slightly. This would indicate that the aircraft should be flown at the lowest incidence angles possible so that the lowest possible value of C_L for $(L/D)_{max}$ may be used.

For trimmed cruising flight in ground effect, the value of $(L/D)_{max}$ is increased over the value of $(L/D)_{max}$ out of ground effect by a factor of about 2. For example, in Figure 16, the maximum value of L/D out of ground effect is about 16.5. In ground effect, for $h_m/b = 0.03$, the maximum value of L/D is 33.

The effects of center-of-gravity location on lift/drag characteristics with the model trimmed are shown in Figure 11. Effects of mutual

wing interference are evident in the reflex in the L/D curves of the figure. Interference effects become more pronounced at lower values of i_{w_f} and at the aft center-of-gravity location. Figure 11 also shows that higher L/D values are available at the aft center-of-gravity location. For a given h/b, values of L/D at a given C_L may be as much as 10 percent higher at the aft center-of-gravity location than at the forward center-of-gravity location.

LONGITUDINAL STABILITY

Conventional aircraft obtain longitudinal stability from the fact that the pitching moment contribution of the horizontal stabilizer (with its change of lift on a long moment arm) exceeds the change in pitching moment of the wing when the aircraft is disturbed from equilibrium. Out of ground effect, the TWIG obtains stability in the same manner. Hence, as with a conventional aircraft, as the center-of-gravity position of the TWIG is moved aft, the longitudinal stability of the model decreased (the moment arm to the aft lifting surface was reduced).

It was hoped that the stability of the tandem wing configuration for in-ground-effect flight would be augmented by the individual wing contribution from a change in lift as a result of the change in each wing's operational height for a pitch displacement of the model. That is, if the model were pitched nose up, the lift on the front wing would decrease as a result of the increase in its effective operational height. Simultaneously, there would be an increase in the lift of the aft wing as its height decreased. Thus, a restoring pitching moment is formed which, it was hoped, along with craft basic stability would result in a very stable configuration.

However, simultaneously the moment in ground effect is reduced because, even with the TWIG pitched nose up, the forward wing is still in proximity to the ground and, as a result, its downwash is restricted. This reduction in downwash results in a reduction of the aft wing contribution to longitudinal stability, since its change in angle of attack is reduced. Nevertheless, the TWIG configuration is substantially more stable in ground effect than out of ground effect.

Pitching moment data were obtained for three different center-of-gravity locations. The locations on the model are shown in Figure 1. The aft center-of-gravity location is stable only over a small operational range, but this range does occur at $(L/D)_{max}$. The forward and mid center-of-gravity locations are stable, with the mid center-of-gravity location possessing some regions of instability. However, only the mid center-of-gravity location could be trimmed with a small Δi_w, which led to superior L/D ratios.

One of the more desirable stability characteristics of any type of aircraft is that the pitching moment coefficient should vary linearly with C_L in the flight spectrum. Of the three center-of-gravity locations tested for the TWIG model, the forward center-of-gravity location most nearly results in linear C_m to C_L variation (i.e., a constant stability derivative, $\left(\frac{dC_m}{dC_L}\right)$; however, even it departs significantly from being completely linear. Figures 3 through 6 show a hump in the pitching moment coefficient curves above an h/b of 0.07, which is present at all three center-of-gravity locations. As i_{w_f} and i_{w_a} are increased equally, the hump occurs at higher C_L values and tends to flatten out at higher values of $i_{w_f} = i_{w_a}$. The hump in the curves appears to be caused by the mutual interference effects of tandem wings.

Figure 15 shows the pitching moment curves of the TWIG model with the aft wing removed. As can be seen from this figure, the curves are linear. However, when the aft wing is placed on the model and flown in ground effect, the pitching moment curves are no longer linear and the hump appears in the curves. Pitching moment curves are not linear for the out-of-ground-effect case either, as can be seen from Figure 12. The model is unstable out of ground effect for values of C_L below 0.6, the aft center of gravity being the most unstable. Above C_L values of 0.6, the model becomes stable. Such results suggest mutual wing interference as a cause of the non-linearity of the pitching moment curves.

Insufficient data were taken to present curves of $\frac{dC_m}{dC_L}$ for the model. However, the curves of Figures 3 through 5 may be used in

conjunction with the trim curves of Figure 11 to get an indication of stability with the model trimmed (small discrepancies in i_{w_f} should not change the slope of the C_m/C_L curve).

LONGITUDINAL TRIM

The extrapolated data of Figure 11 indicate that the model may be trimmed at any of the three center-of-gravity locations when flying in ground effect. However, for small values of i_{w_f}, trim at the forward center-of-gravity location may be accomplished only by using negative values of i_{w_a}. From a trim standpoint, the mid center-of-gravity location is preferred because it requires lower i_w's and Δi_w's to trim at operational values of L/D. The same applies to the out-of-ground-effect case, Figures 13 and 14. However, were it not for the instability of the aft center-of-gravity location, it would be preferred over the other two center-of-gravity locations, even though larger values of Δi_w are required for trim, because higher values of L/D are available.

Figures 8 and 9 show the effectiveness of the forward and aft wings as trim devices. In Figure 8, the forward wing is the trim device, and in Figure 9, the aft wing is used as the trim device. Both the forward and aft wings are equally effective as trim devices. It might be pointed out that the data of Figures 8 and 9 may be used to determine the amount of elevator power required for longitudinal control of the model. The wings can be assumed to be fixed at some incidence angle and the data in the figures correlated to the effects of a hinged control surface.

CONCLUSIONS

As a result of wind-tunnel tests on a TWIG model in and out of ground effect, it was concluded that:

1. Values of effective aspect ratio derived from the test results were in fairly good agreement with theory.

2. From the standpoint of longitudinal stability and trim, the mid center-of-gravity location is preferred over the other two locations. However, the mid center-of-gravity location is not completely satisfactory in that it becomes unstable at lower values of C_L. This trend of instability is especially true for the lower model heights investigated.

3. Largest values of L/D occurred at the aft center of gravity for a trimmed model.

4. Mutual wing interference appears to be a contributing factor in causing the non-linearity and regions of instability in the pitching-moment-coefficient curves, both in and out of ground effect.

5. With zero angle of attack and a trimmed model, $(L/D)_{max}$ was increased from 16.5 out of ground effect to 33 at an h_m/b of 0.3 in ground effect. This represents an increase by factor of 2.

6. Values of C_L for trimmed, cruise flight at $(L/D)_{max}$ in ground effect are undesirably high, starting at $C_L = 0.53$ at $h_m/b = 0.15$ and increasing to $C_L = 0.70$ at $h_m/b = 0.03$. Such high C_L values for cruising flight are not compatible with practical wing loadings or practical take-off and landing speeds. Lower C_L values for $(L/D)_{max}$ might be achieved by using a thinner airfoil section.

7. Out of ground effect, the model is unstable at all three center-of-gravity locations for values of C_L below 0.6. As C_L is increased above 0.6, the model becomes stable except for the aft center-of-gravity location which, at best, becomes neutrally stable.

8. The model can be trimmed for any of the three center-of-gravity locations by varying the incidence angle of the aft wing. However, the model can be trimmed with small values of Δi_w only at the mid center-of-gravity location.

9. The drag and lift/drag results presented were not adjusted for Reynolds number effects or for effects of appendages, roughness, and other factors which might differ between the model and a full-scale aircraft. The results therefore indicate trends but do not directly indicate the absolute performance levels which might apply to full-scale aircraft.

Aerodynamics Laboratory
David Taylor Model Basin
Washington, D. C.
July 1966

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Table 1

Physical Characteristics of a 1/40-Scale Model TWIG

Wing (Forward and aft are identical)

Airfoil section	Clark Y
Root chord in feet	0.667
Tip chord in feet	0.333
Taper ratio	0.5
Twist in degrees	0
Mean geometric chord in feet	0.50
Span in feet	5.0
Area in square feet	2.50
Aspect ratio	10
Sweep in degrees (1/4 chord)	1.91

Vertical Tail

Airfoil section	NACA 0012
Root chord in feet	1.000
Tip chord in feet	0.333
Taper ratio	0.333
Mean geometric chord in feet	0.721
Area in square feet	0.57
Sweep in degrees (1/4 chord)	45

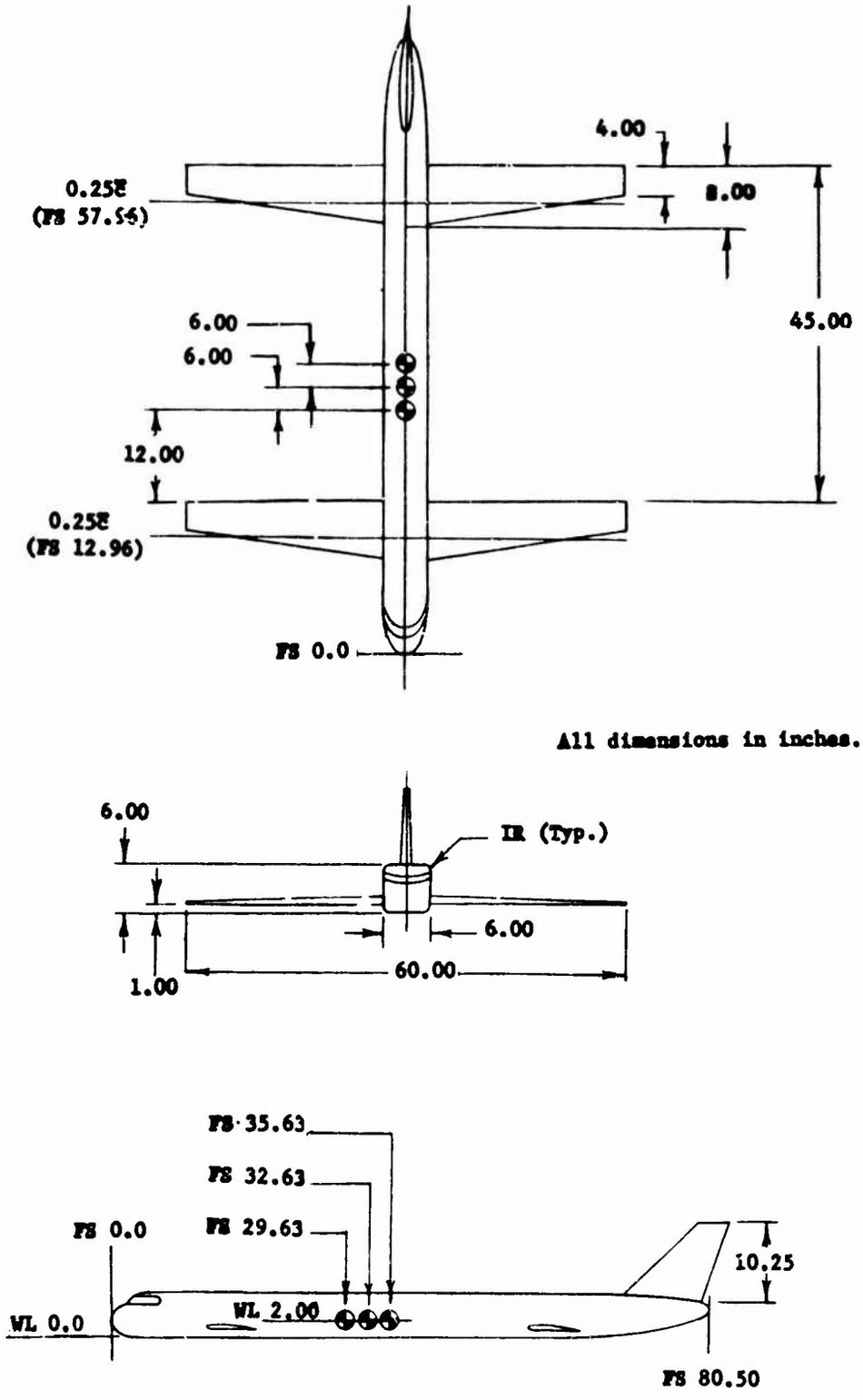

Figure 1 - Principal Dimensions of a 1/40-Scale Model Tandem Wing In Ground Effect

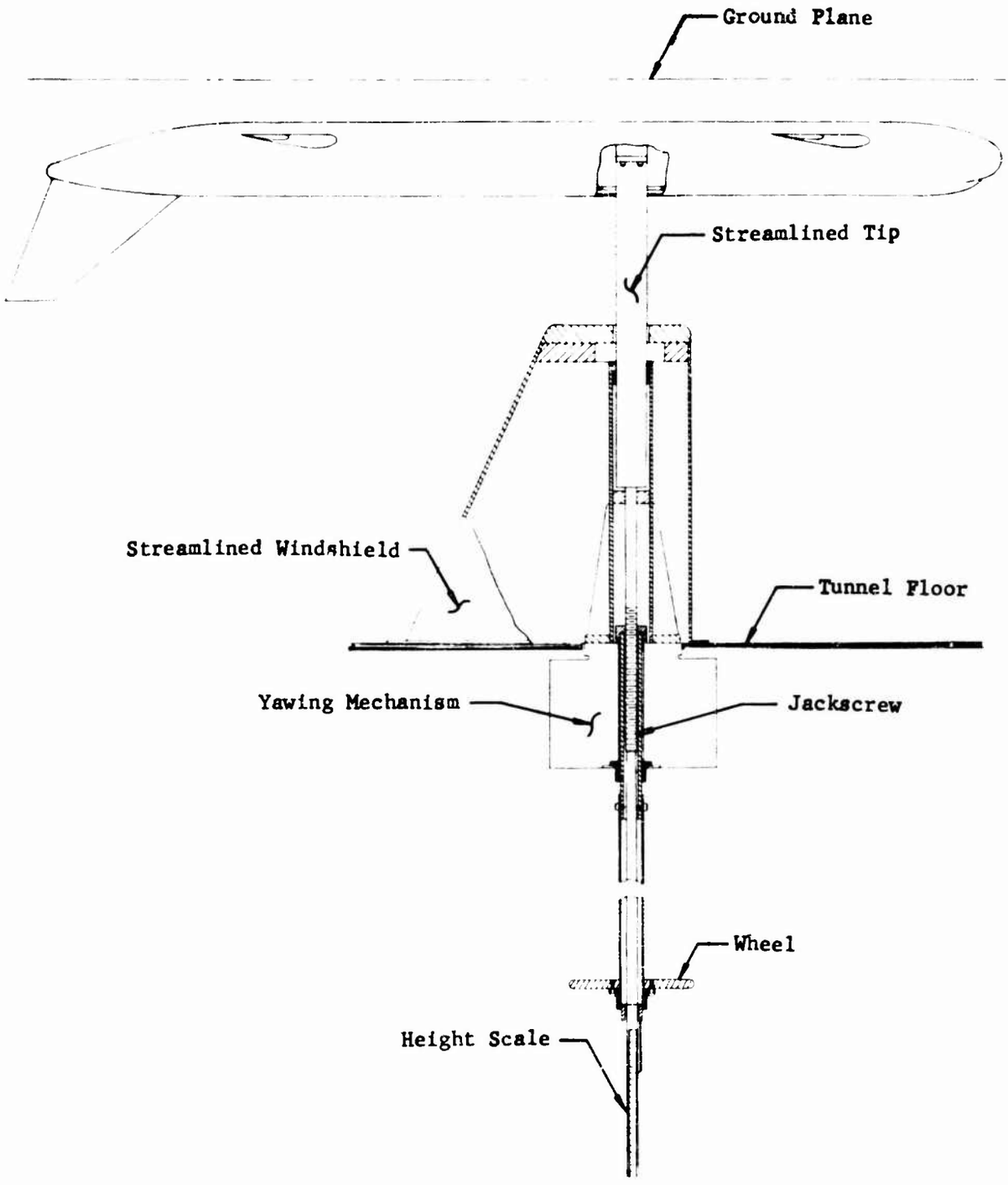

Figure 2 - Side View of Tunnel Installation Showing Inverted Model and Telescoping Strut

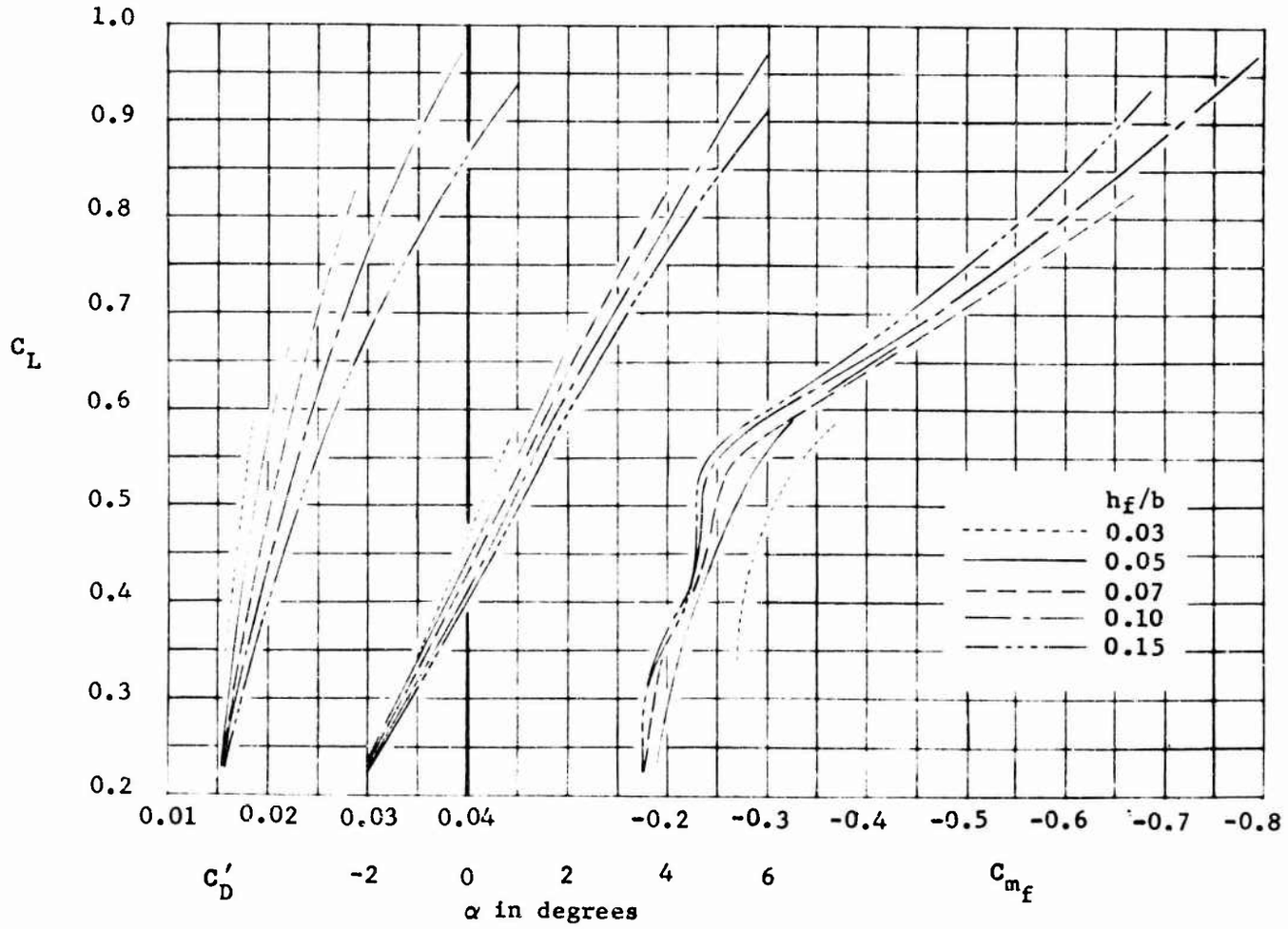

Figure 3 - Longitudinal Aerodynamic Characteristics of the TWIG Model With $i_{w_f} = i_{w_a} = 0°$

(a) Forward c.g.

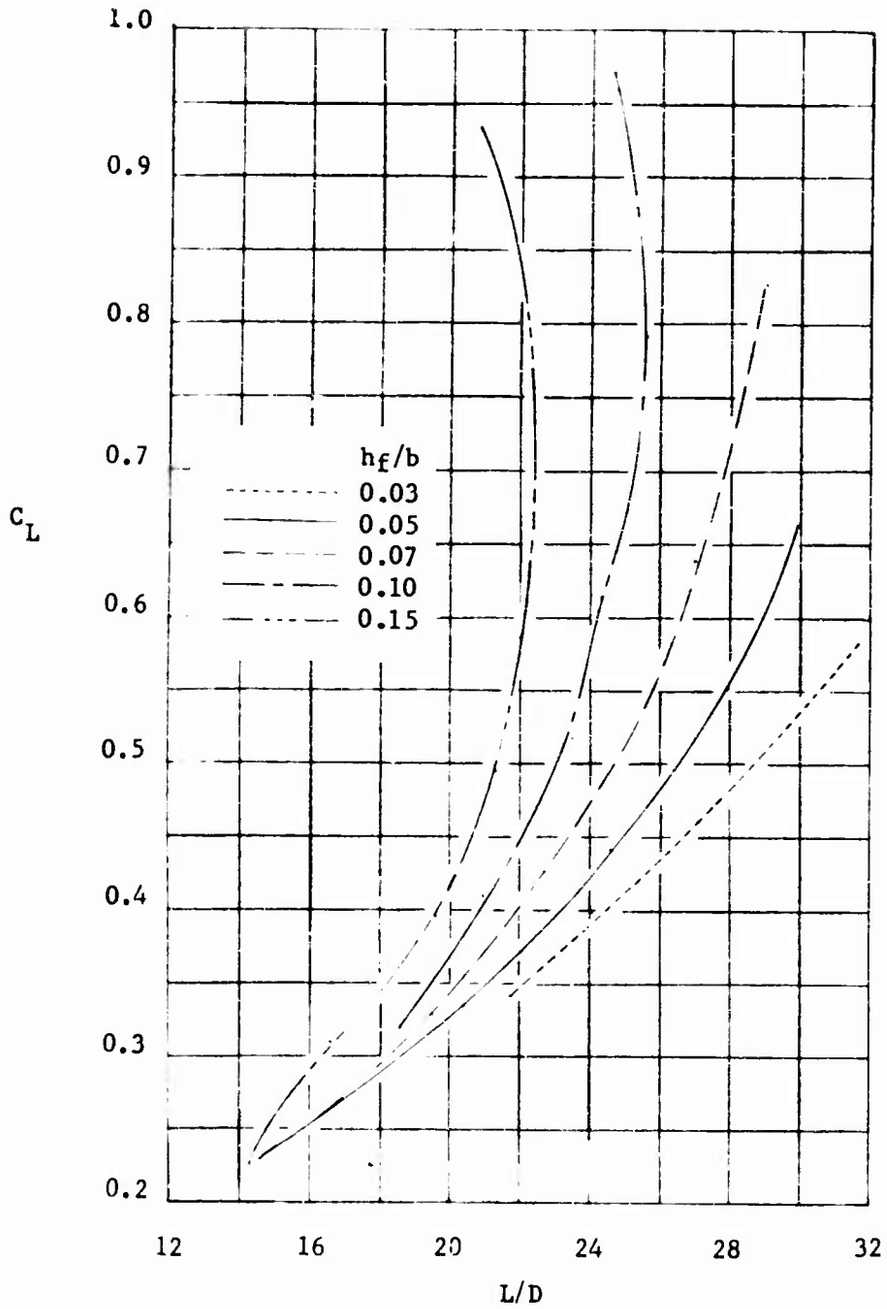

Figure 3 (Continued)

(a) Concluded

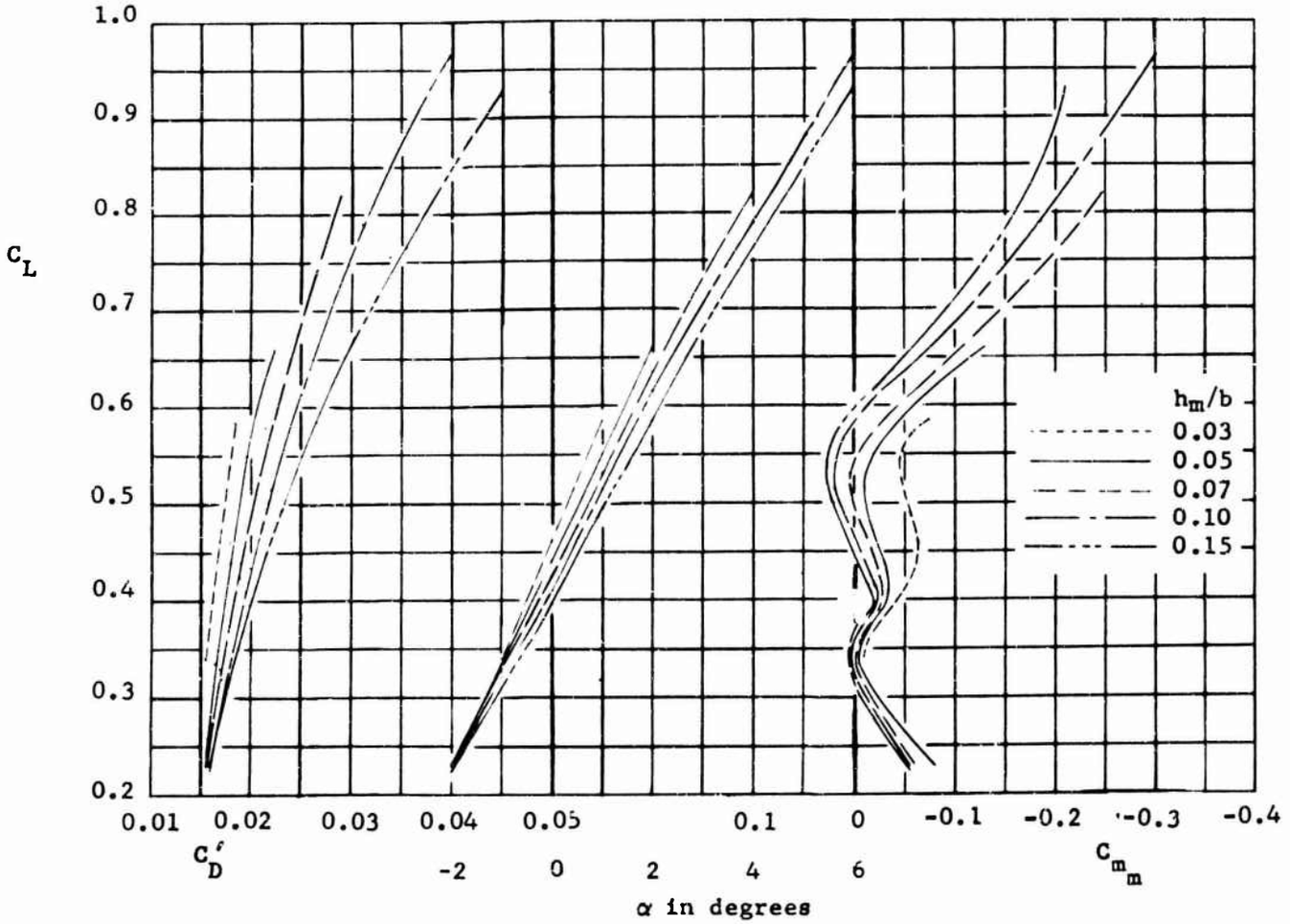

Figure 3 (Continued)

(b) Mid c.g.

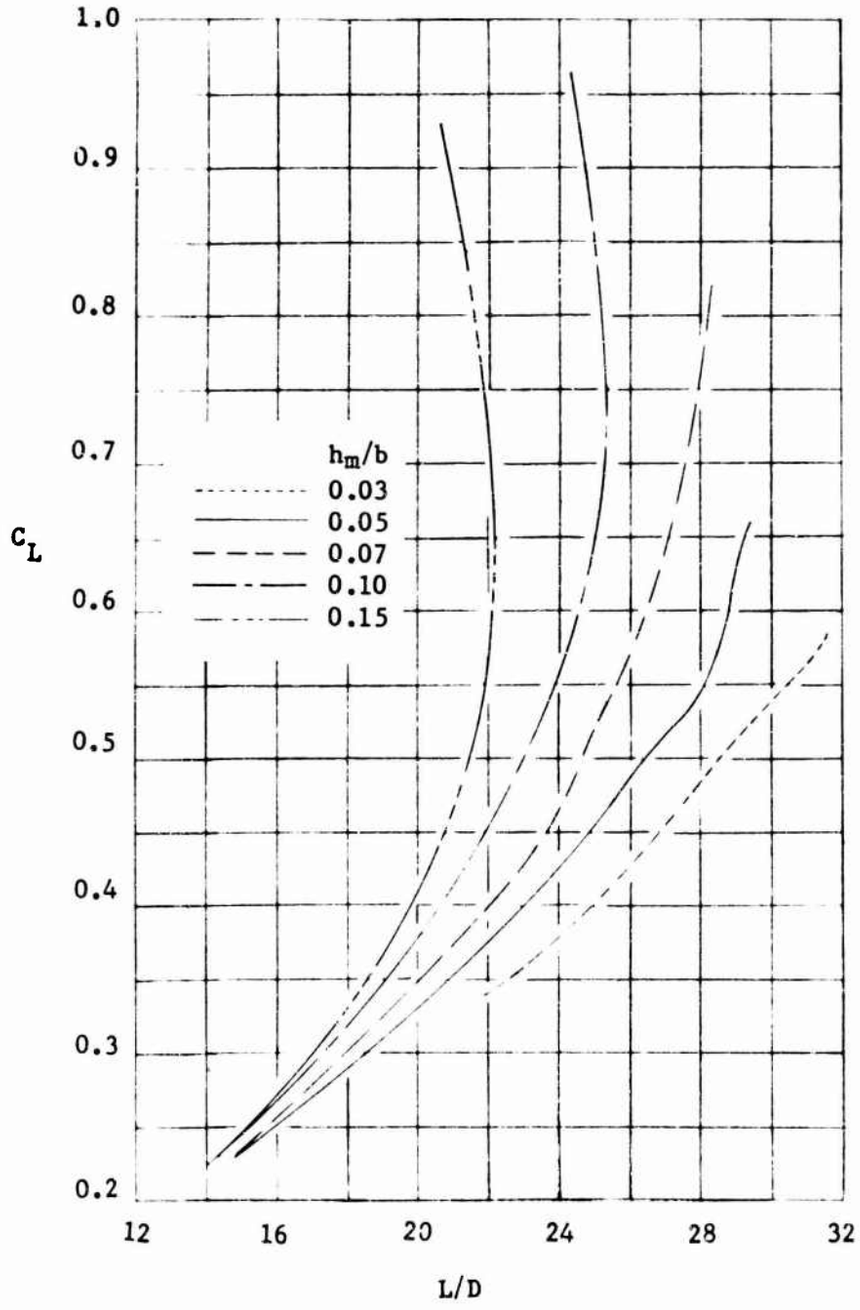

Figure 3 (Continued)

(b) Concluded

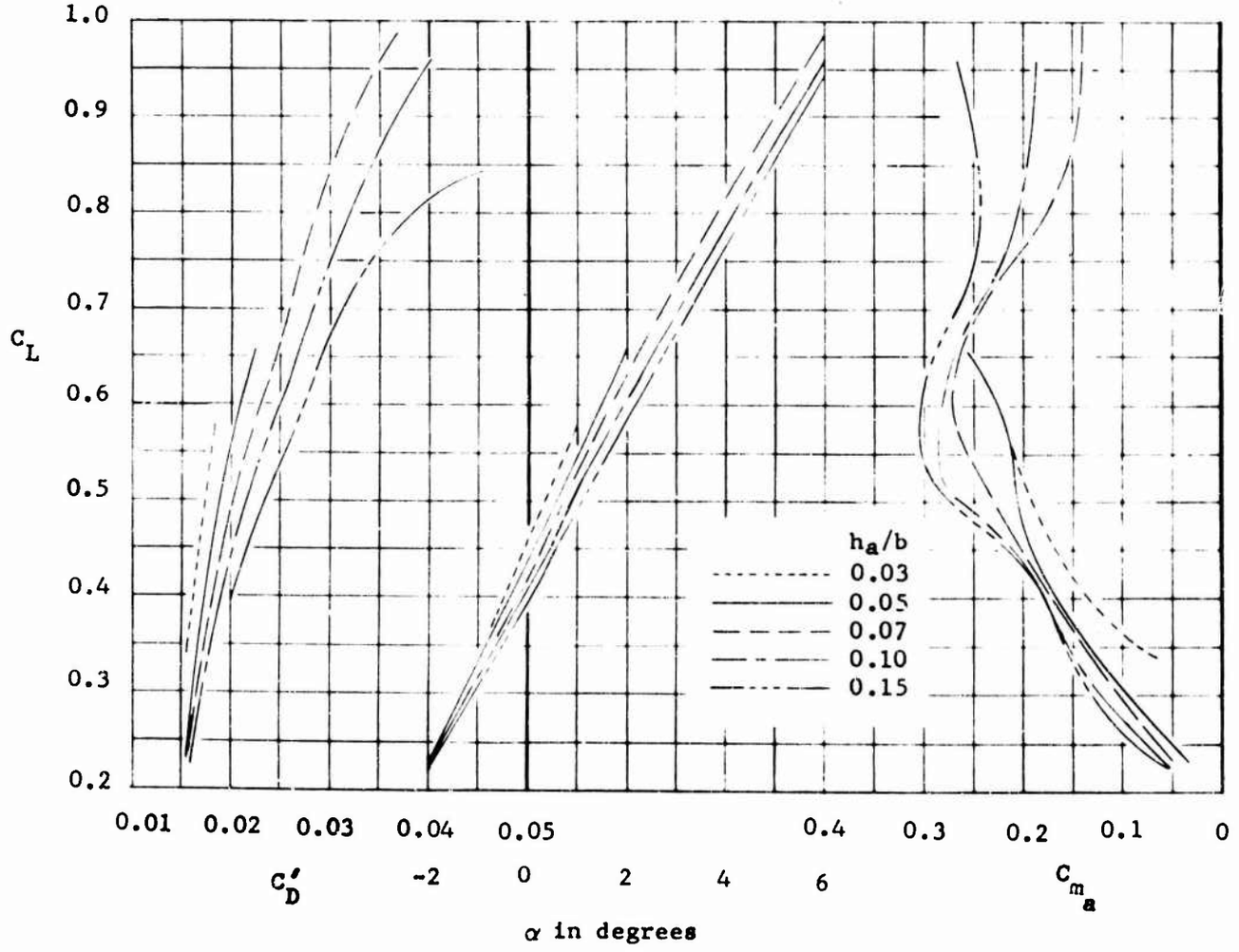

Figure 3 (Continued)

(c) Aft c.g.

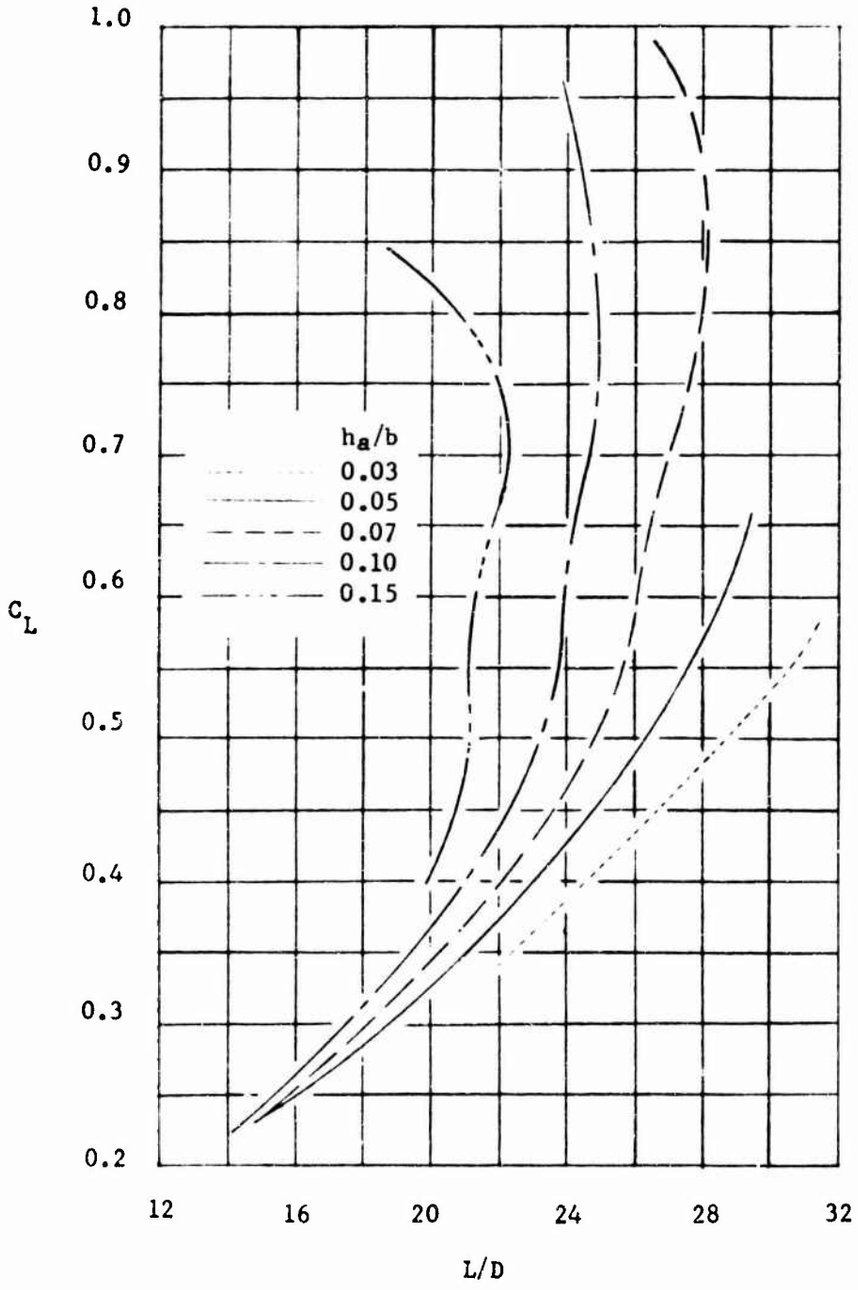

Figure 3 (Concluded)

(c) Concluded

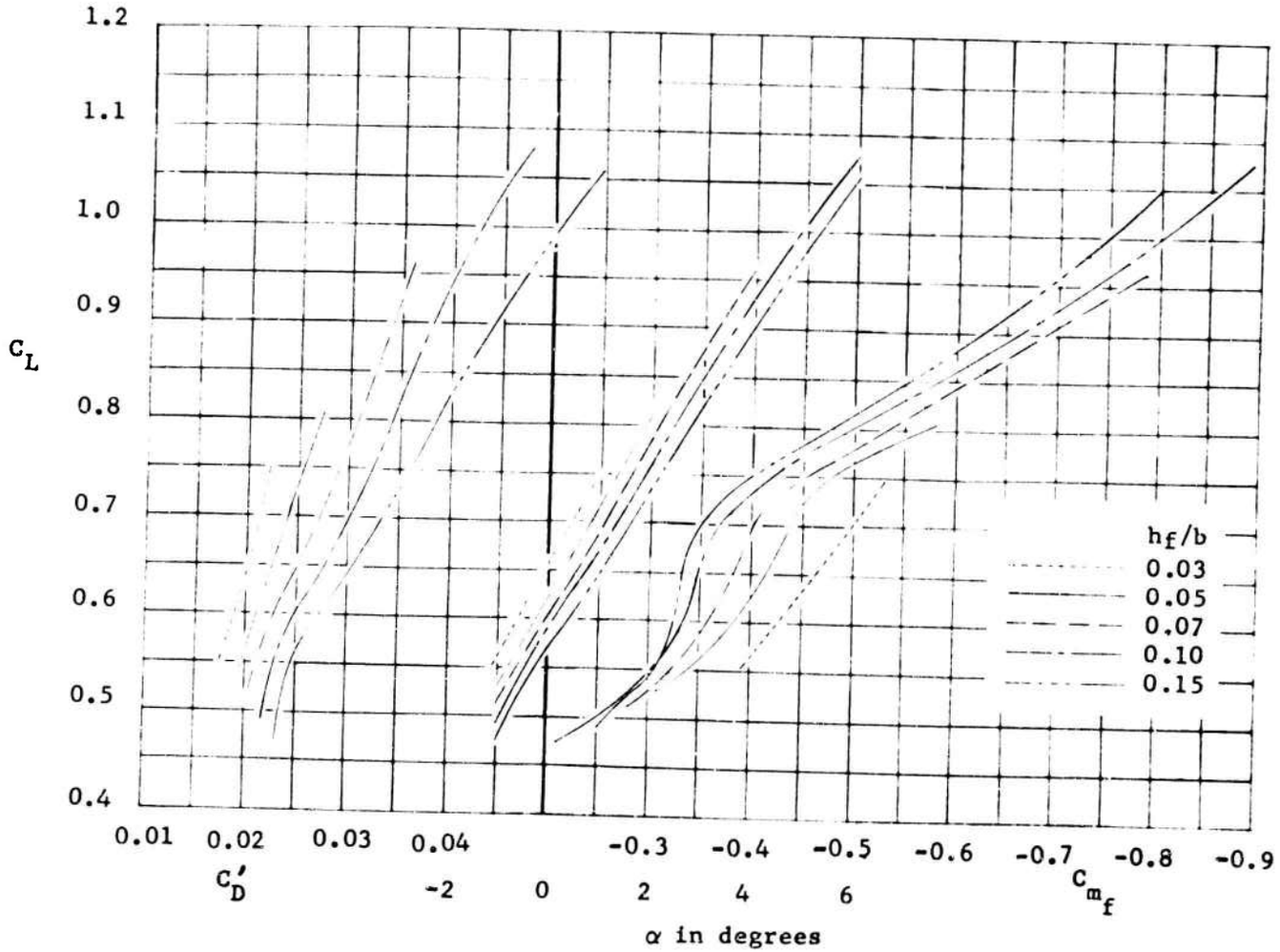

Figure 4 - Longitudinal Aerodynamic Characteristics of the TWIG Model With $i_{w_f} = i_{w_a} = 2°$

(a) Forward c.g.

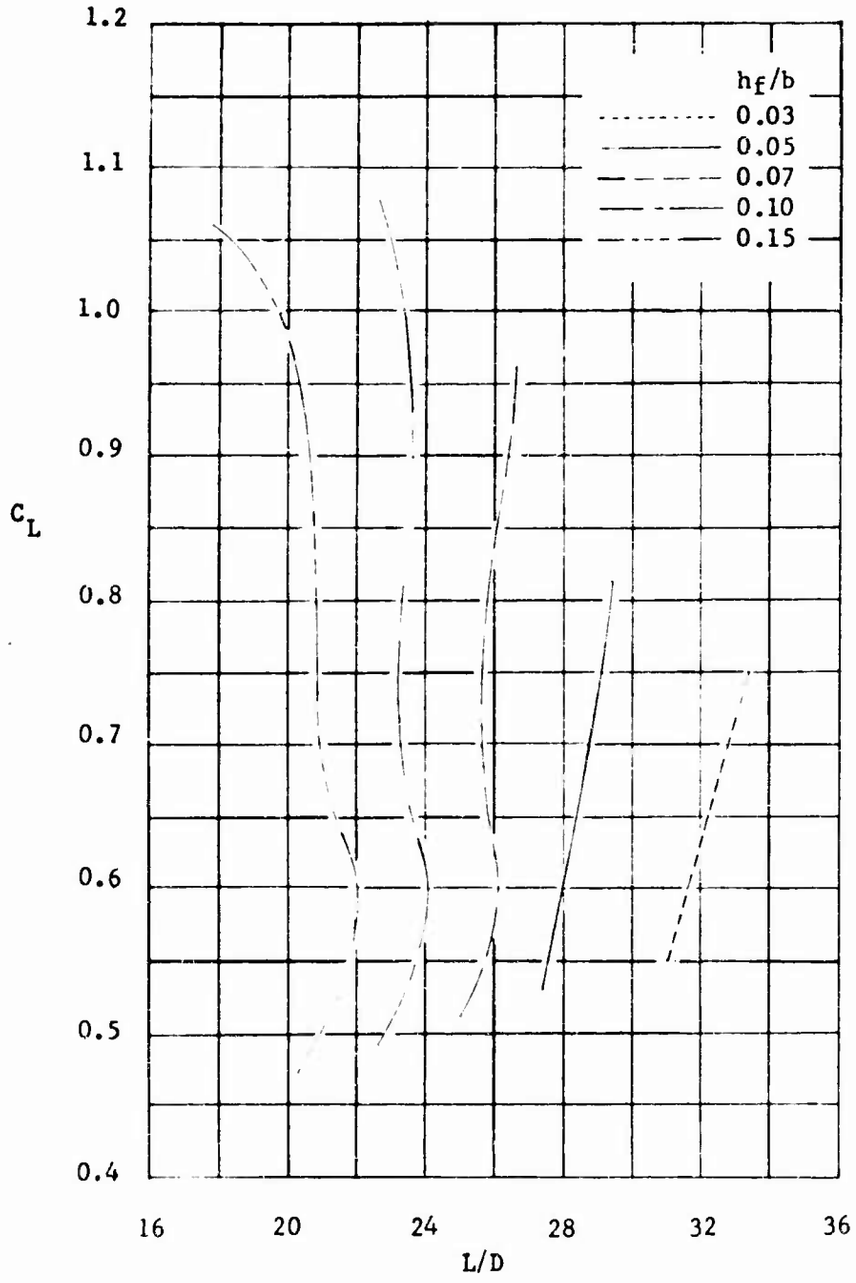

Figure 4 (Continued)

(a) Concluded

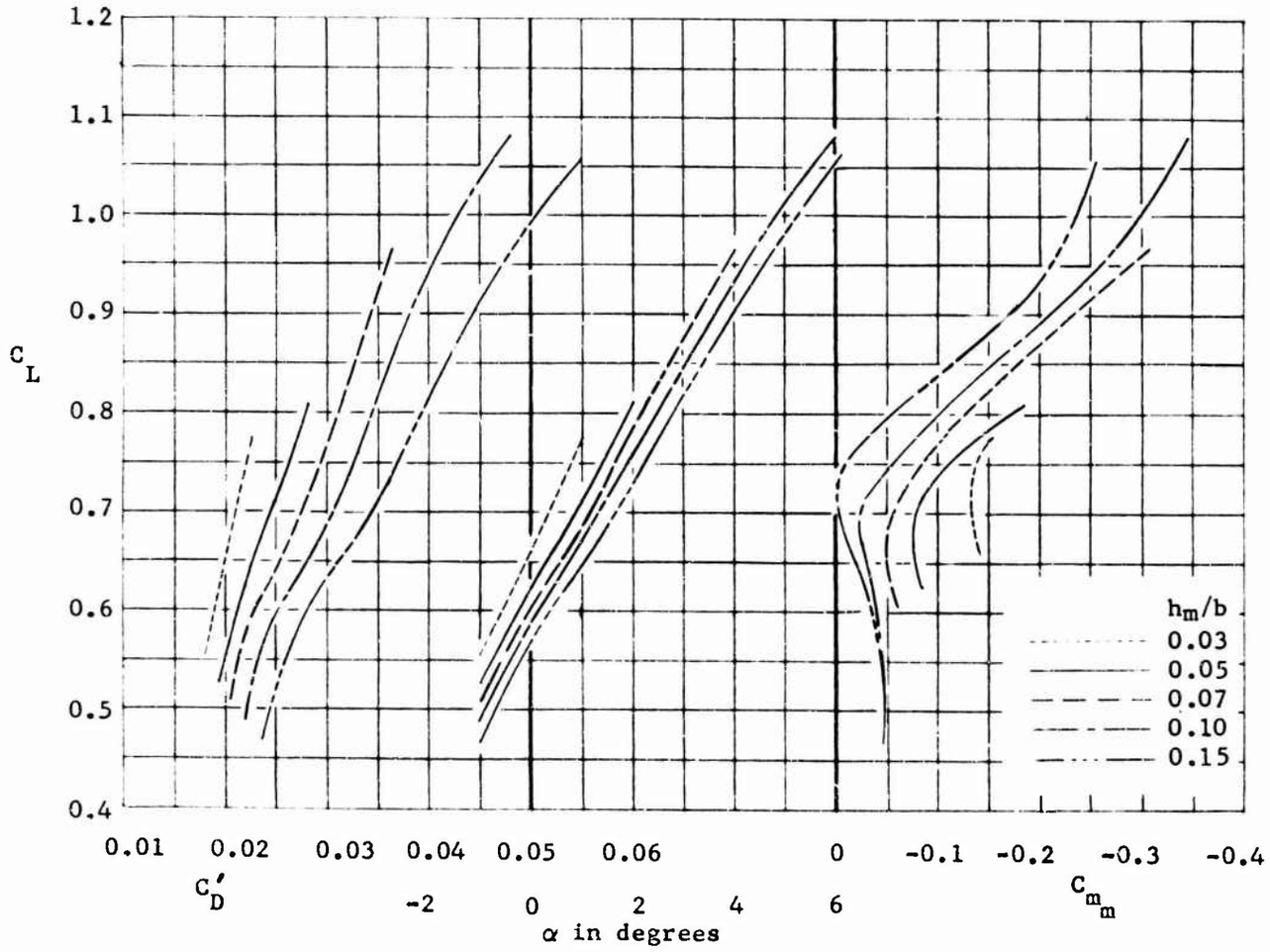

Figure 4 (Continued)

(b) Mid c.g.

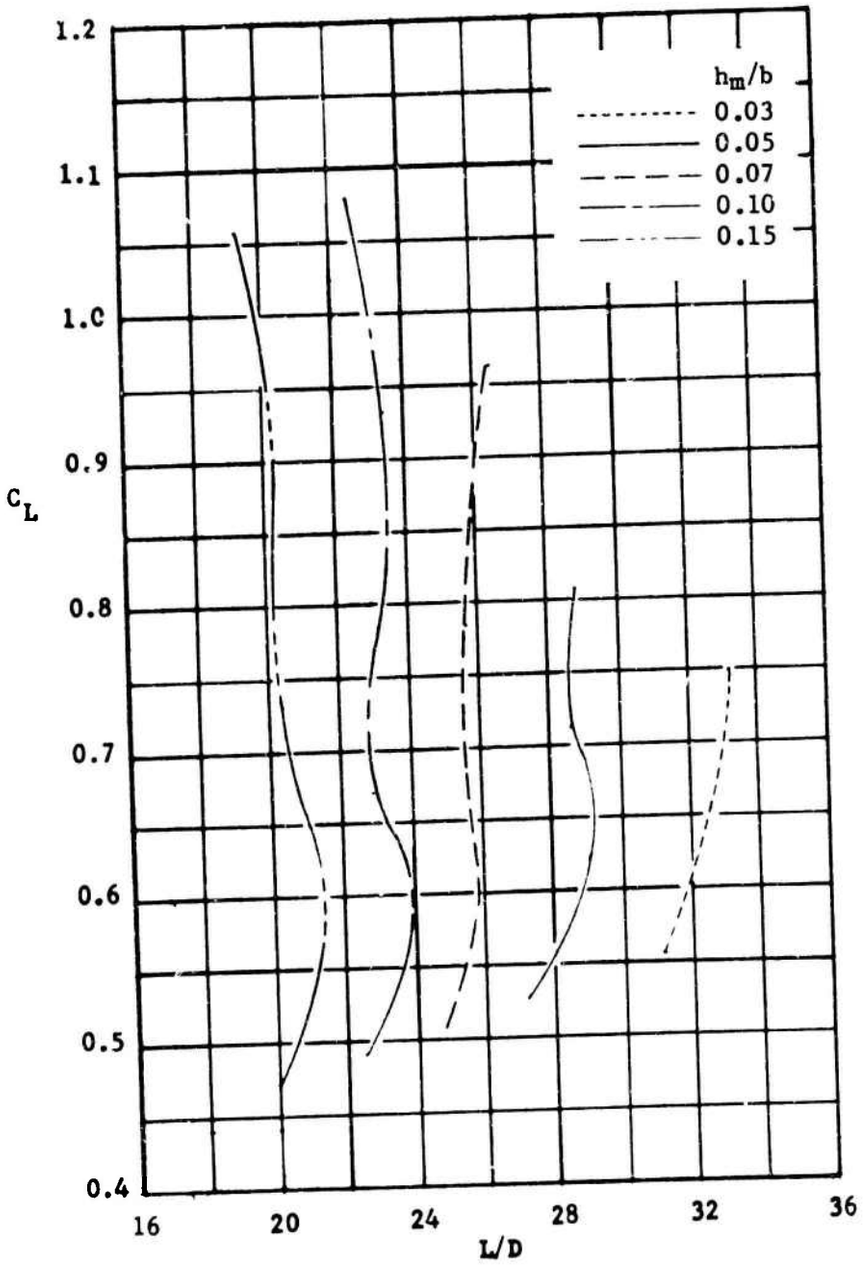

Figure 4 (Continued)

(b) Concluded

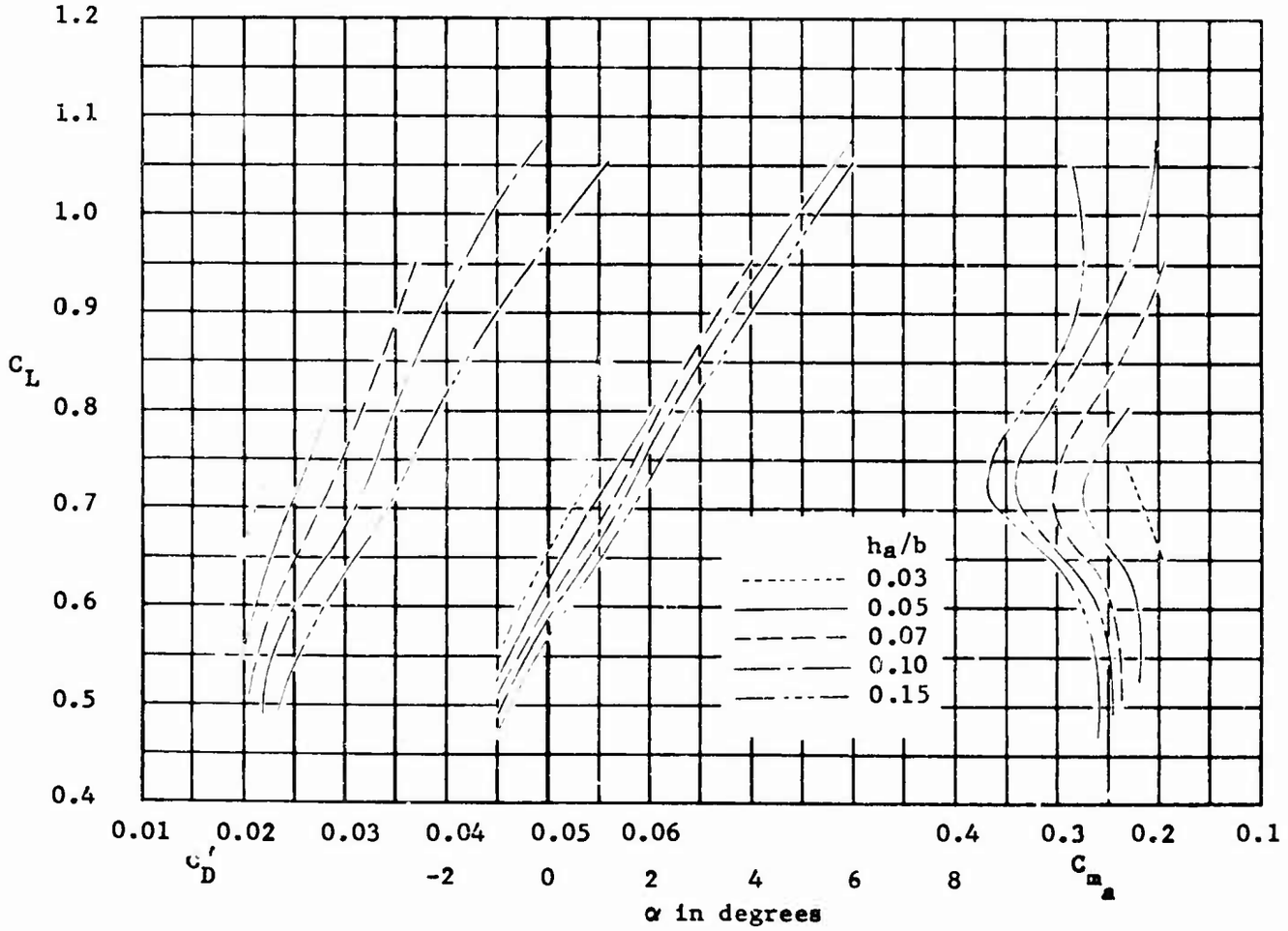

Figure 4 (Continued)

(c) Aft c.g.

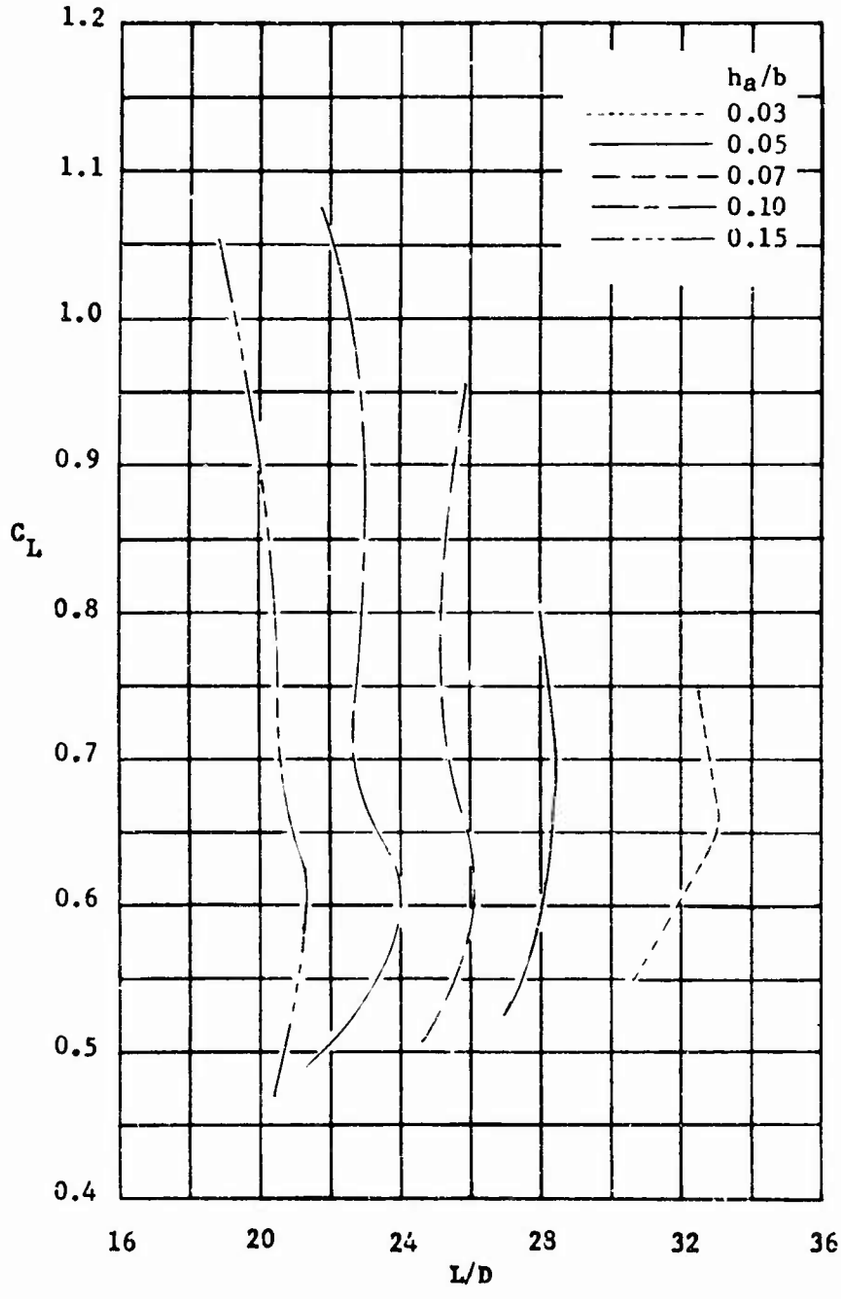

Figure 4 (Concluded)

(c) Concluded

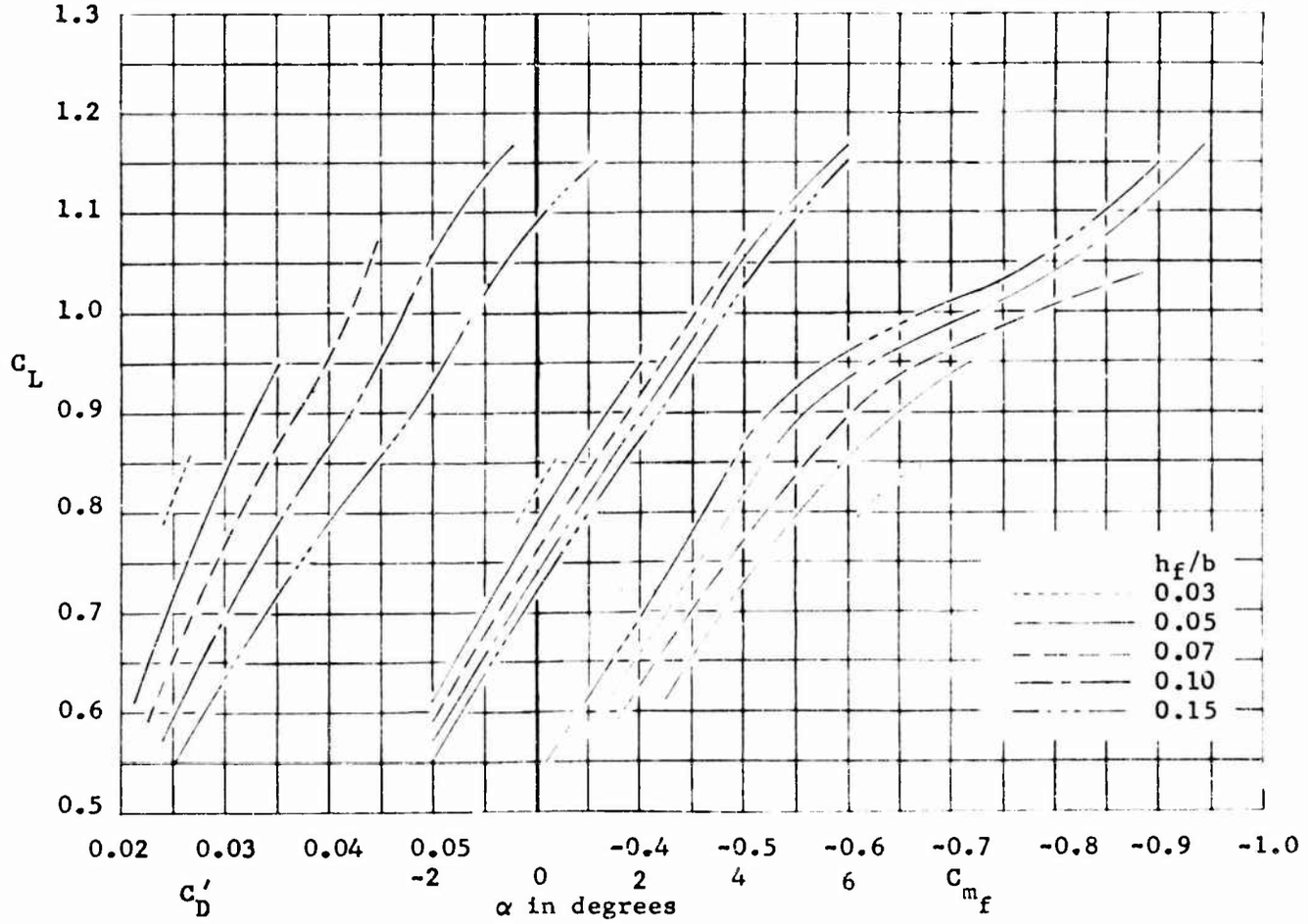

Figure 5 - Longitudinal Aerodynamic Characteristics of the TWIG Model With $i_{w_f} = i_{w_a} = 4°$

(a) Forward c.g.

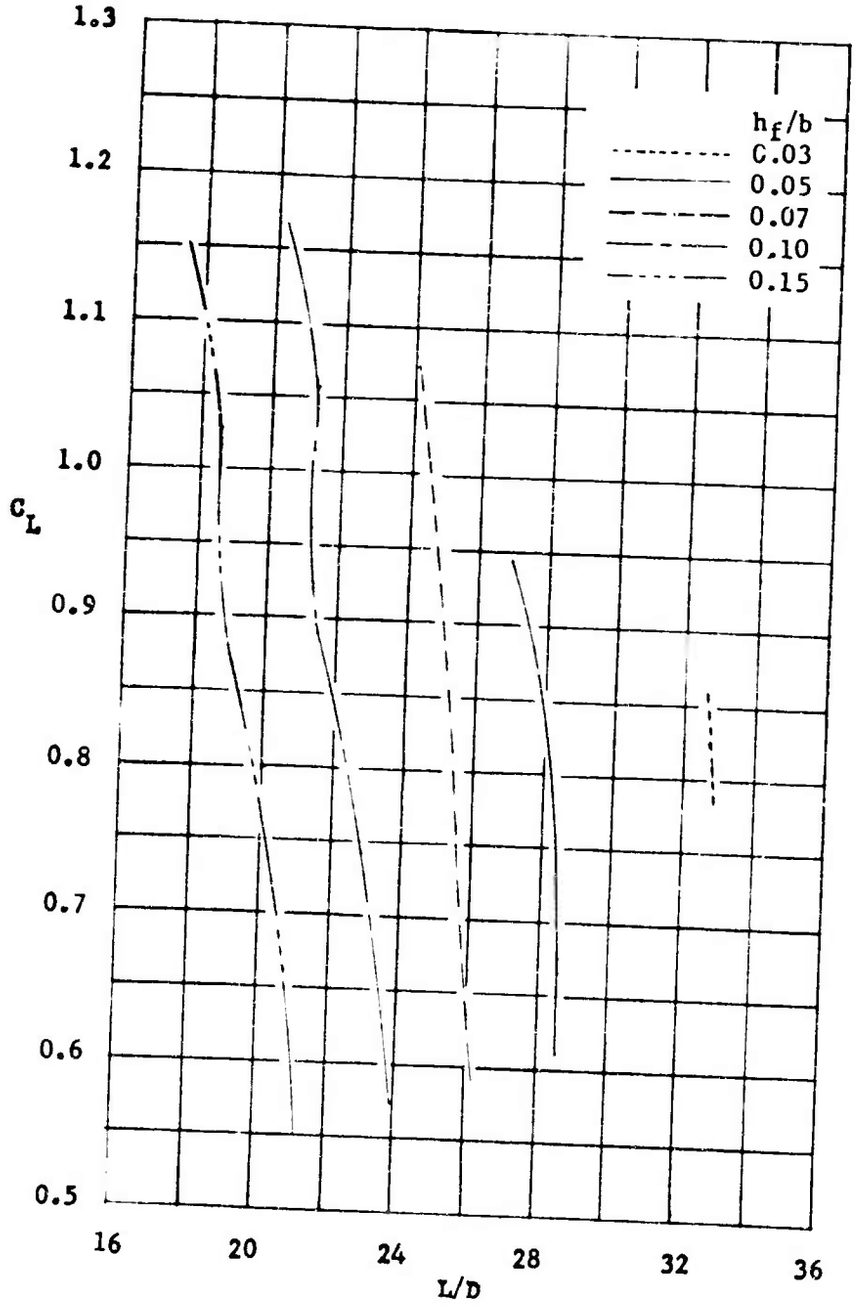

Figure 5 (Continued)

(a) Concluded

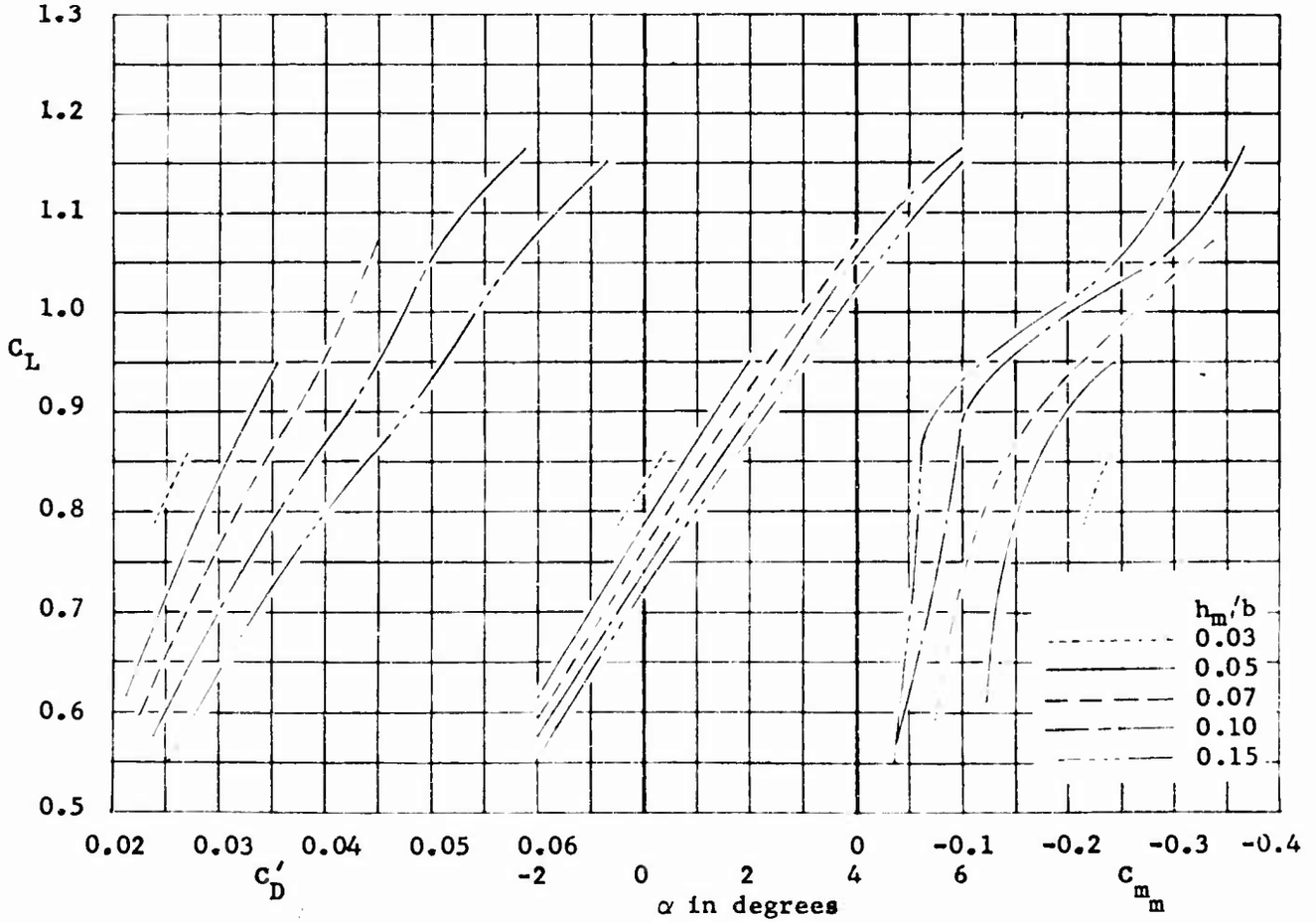

Figure 5 (Continued)

(b) Mid c.g.

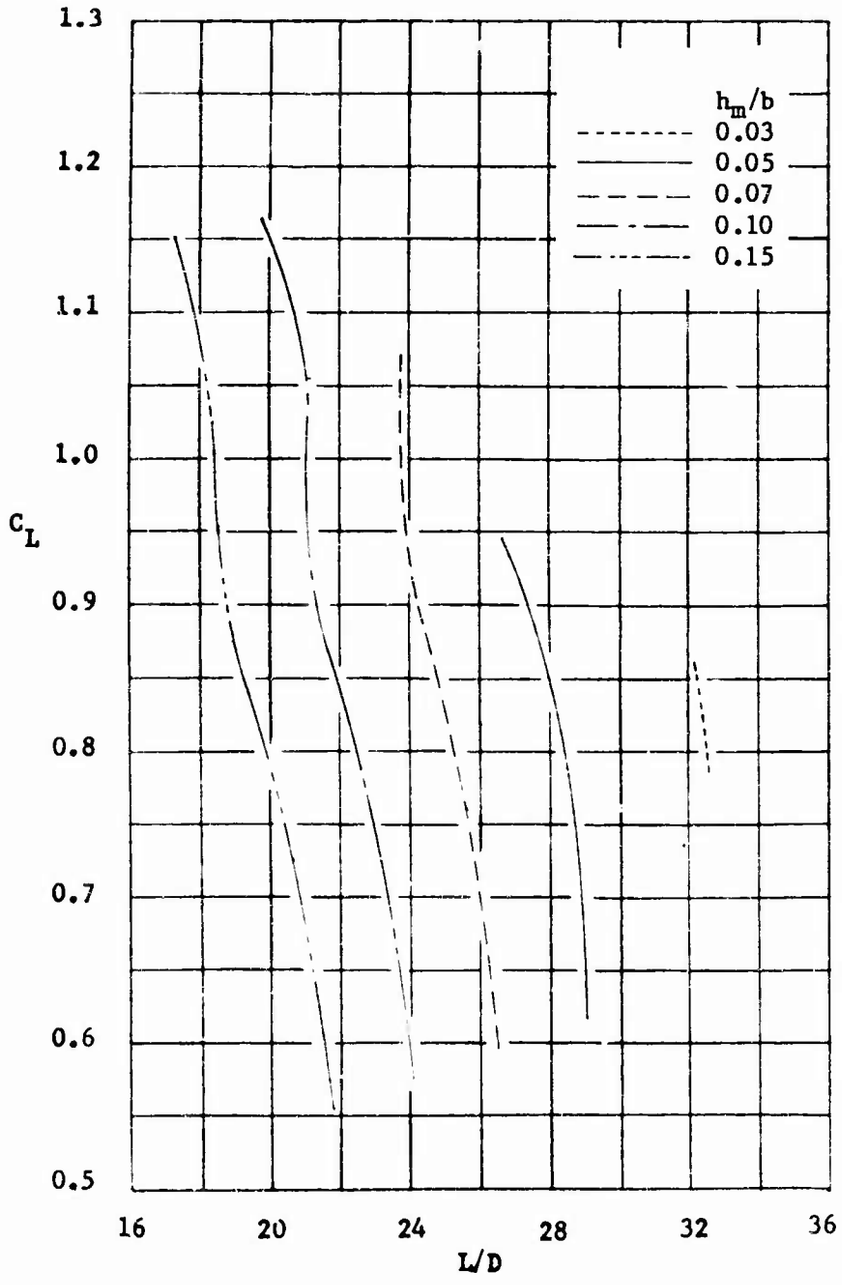

Figure 5 (Continued)

(b) Concluded

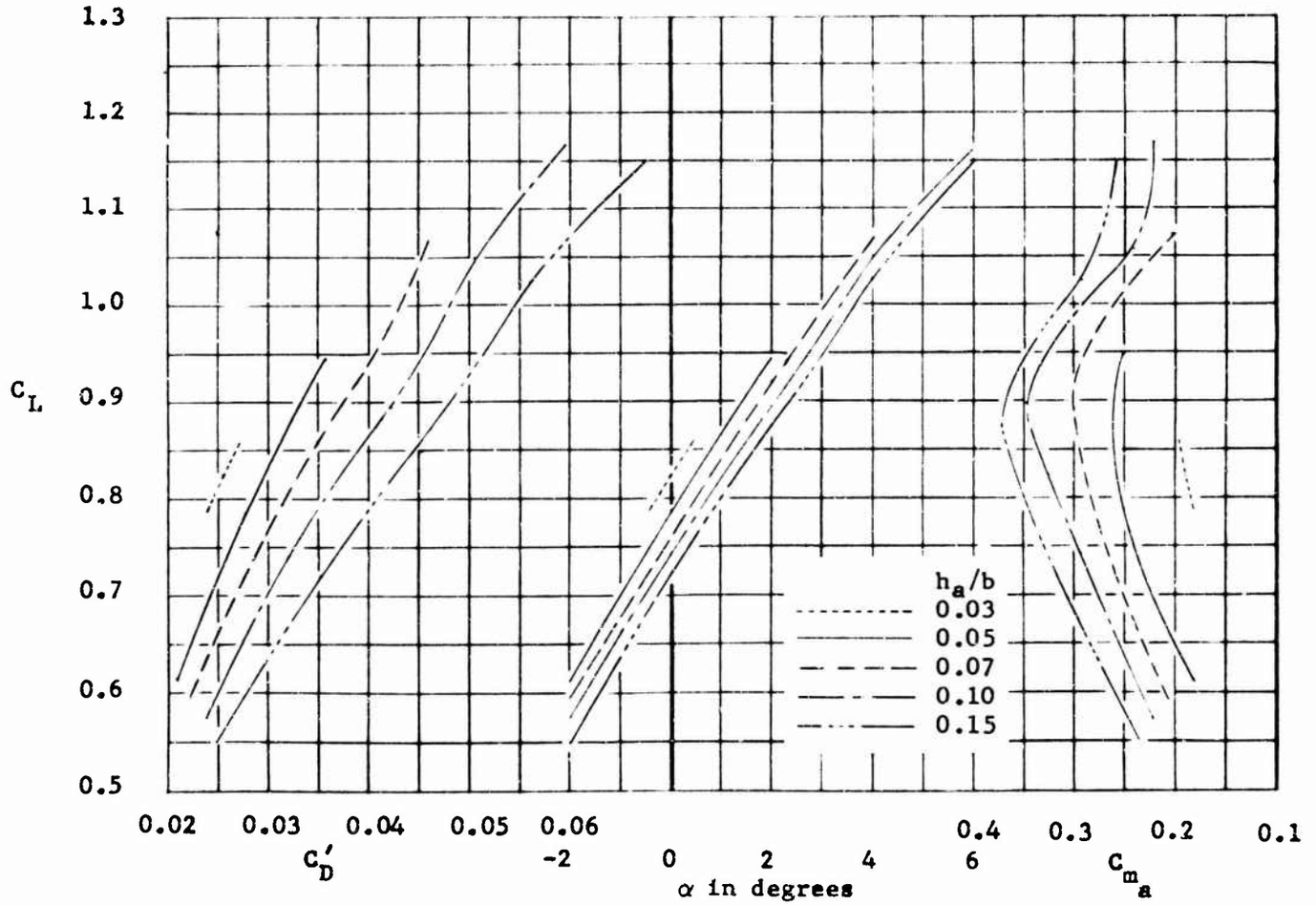

Figure 5 (Continued)

(c) Aft c.g.

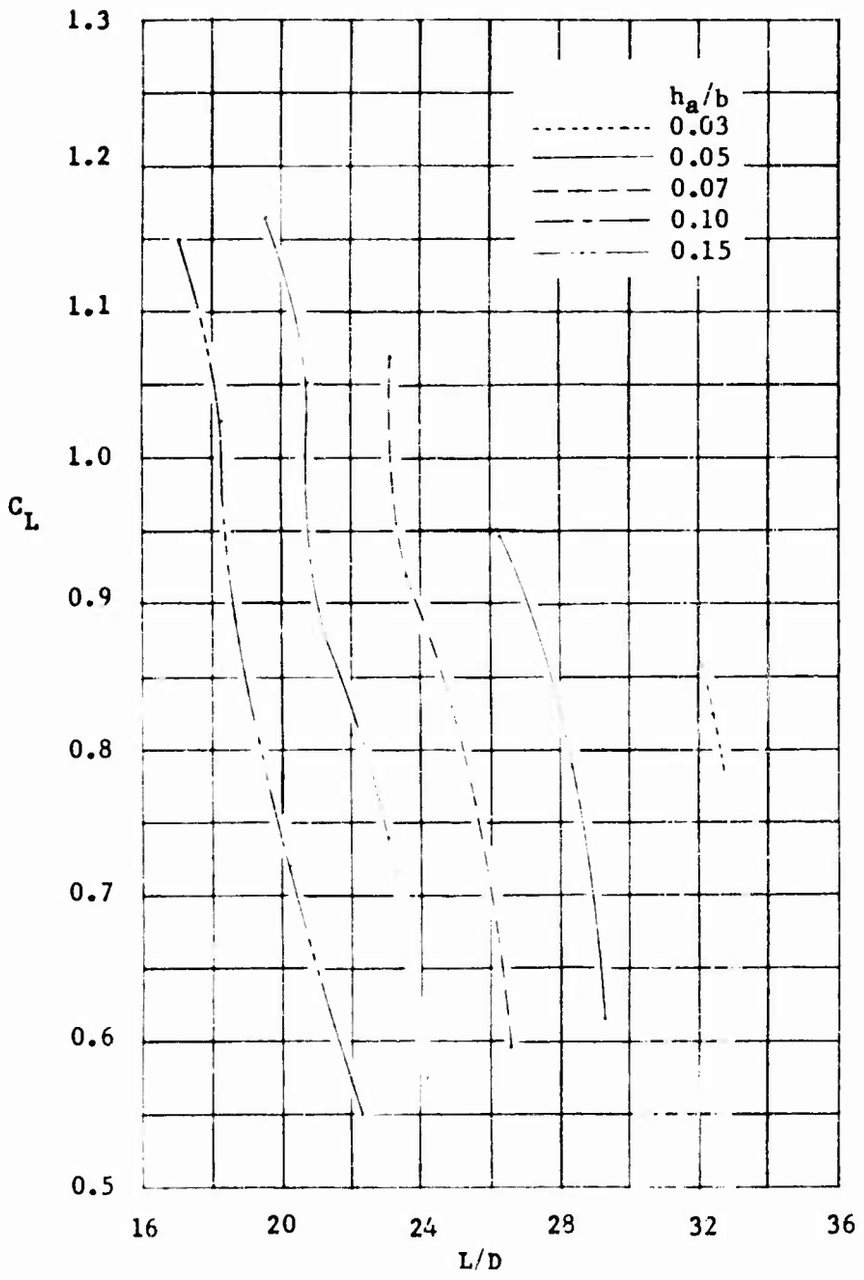

Figure 5 (Concluded)

(c) Concluded

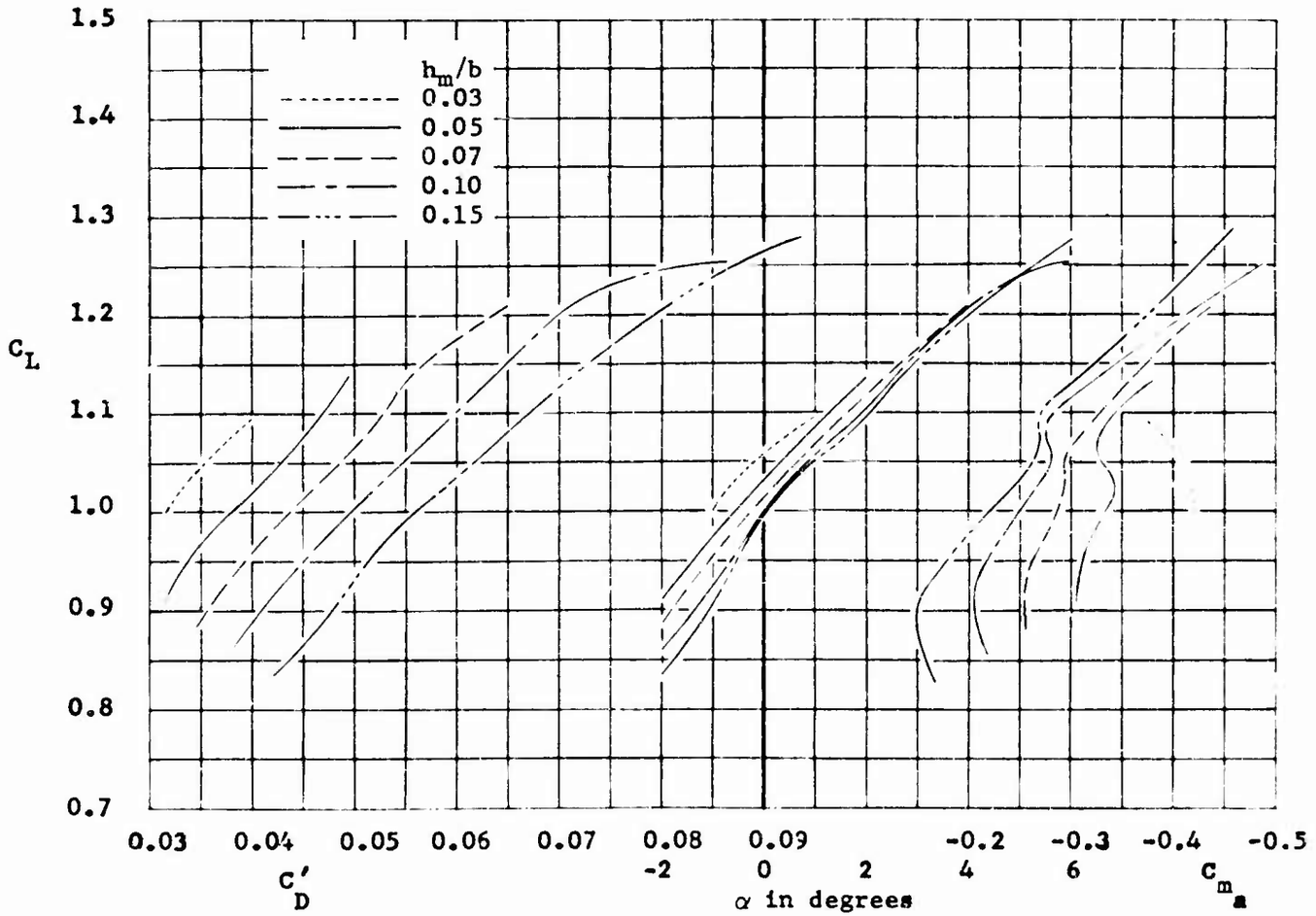

Figure 6 - Longitudinal Aerodynamic Characteristics of the TWIG Model With $i_{w_f} = i_{w_a} = 8°$

(a) Mid c.g.

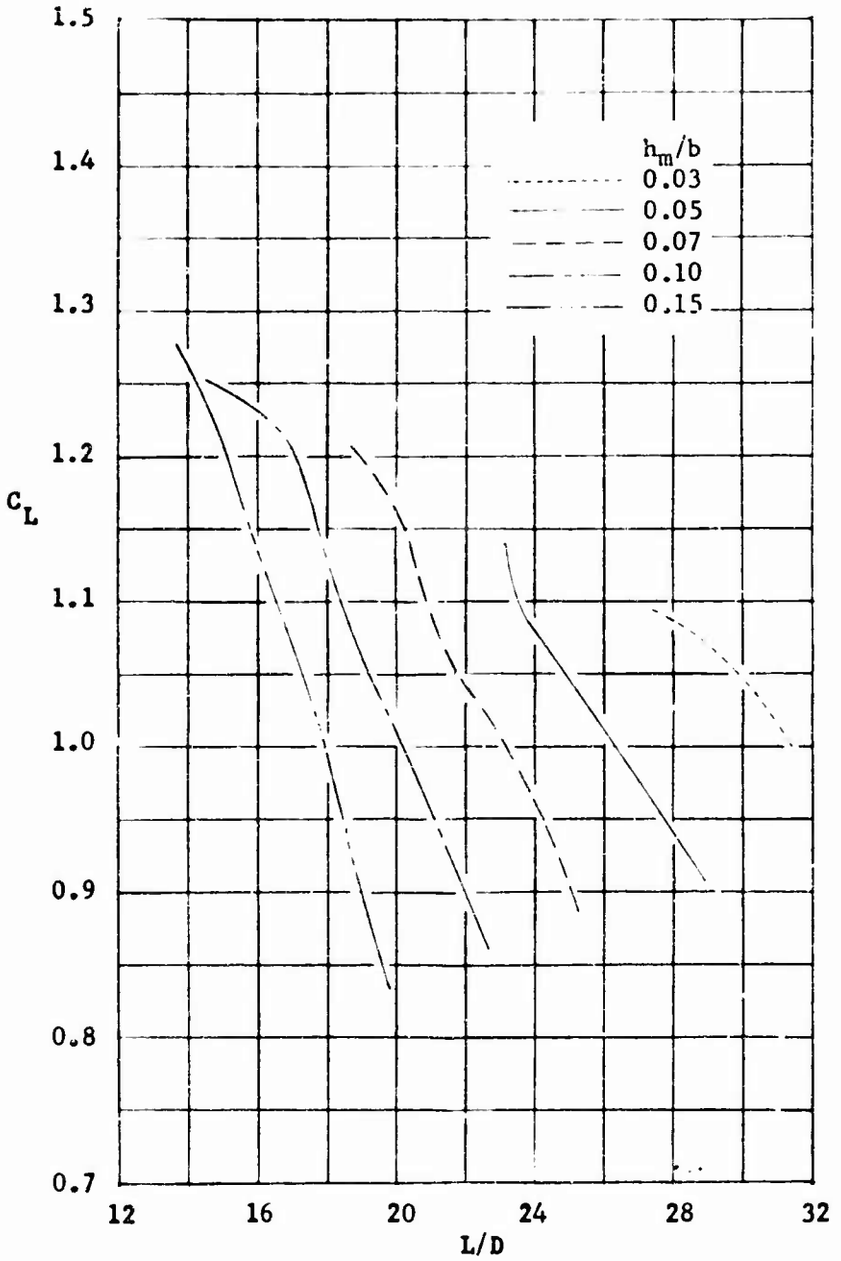

Figure 6 (Continued)

(a) Concluded

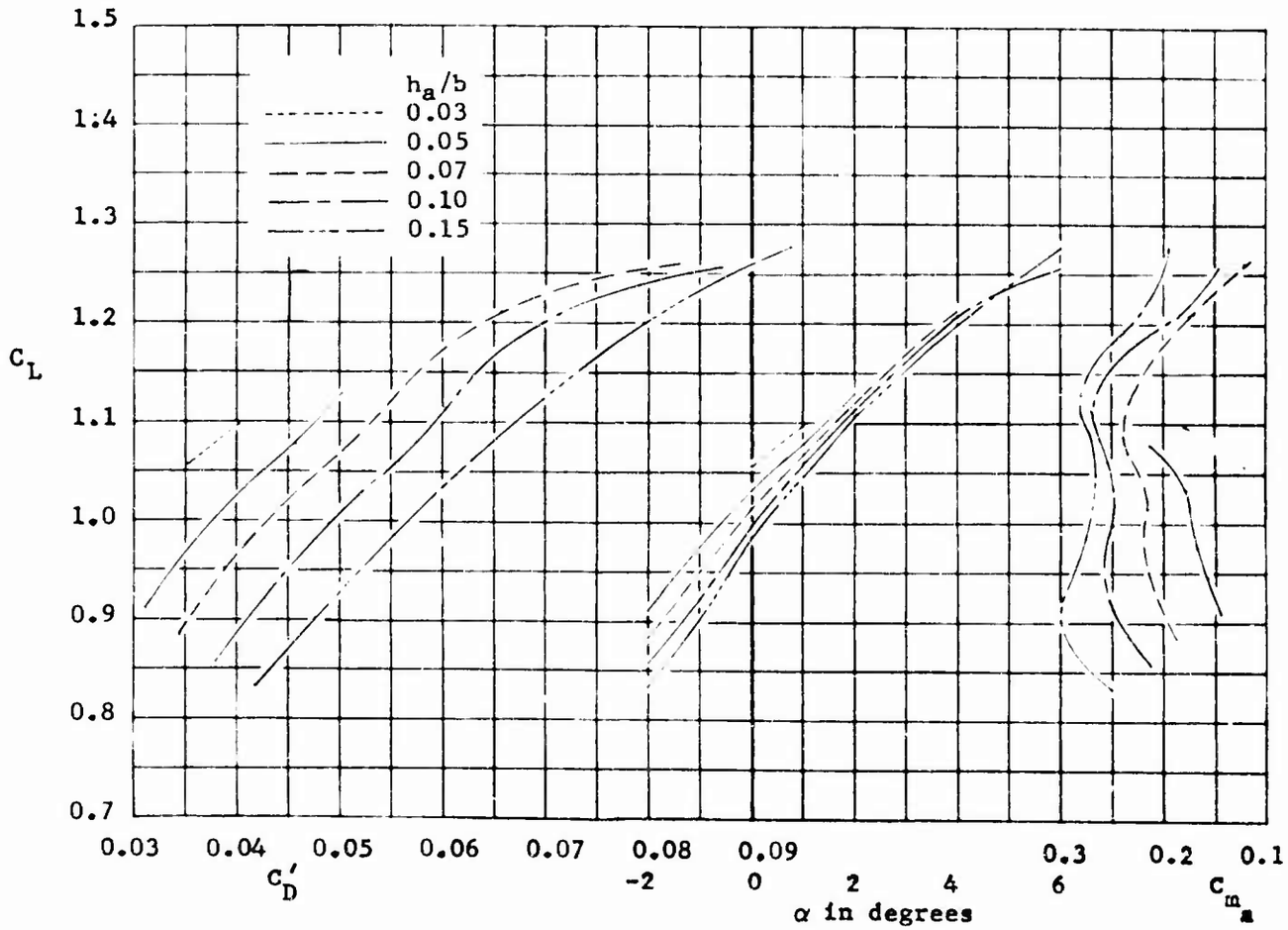

Figure 6 (Continued)

(b) Aft c.g.

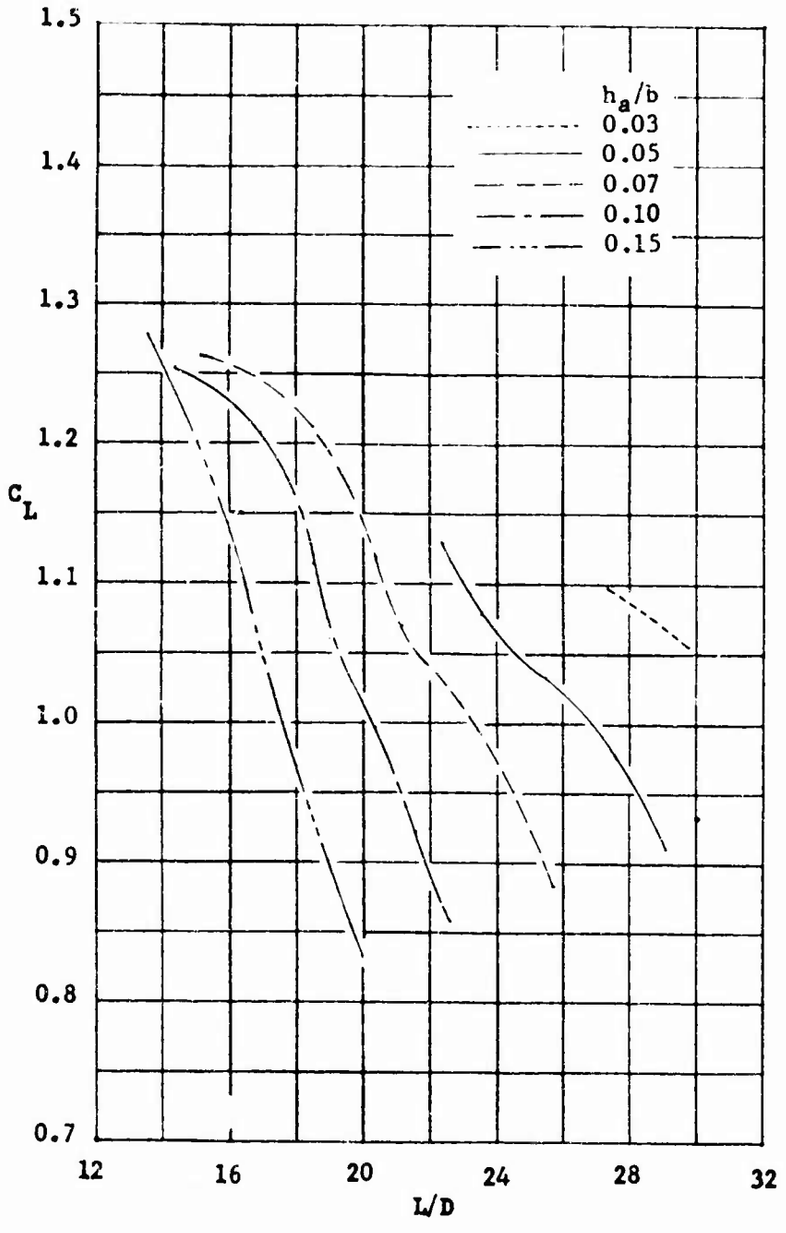

Figure 6 (Concluded)

(b) Concluded

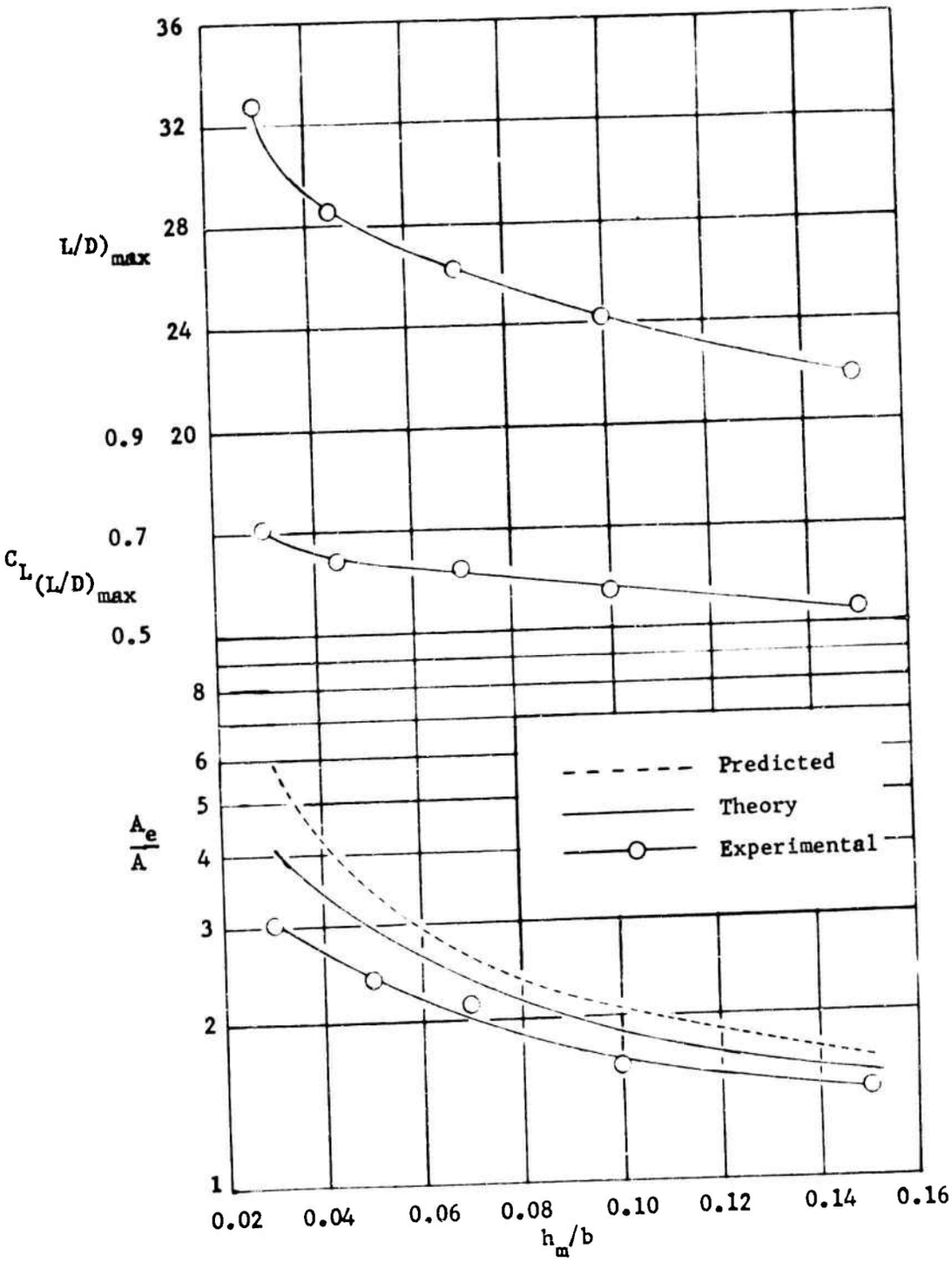

Figure 7 - Performance Parameters of Trimmed TWIG Model at Mid c.g. $\alpha = 0^{\circ}$

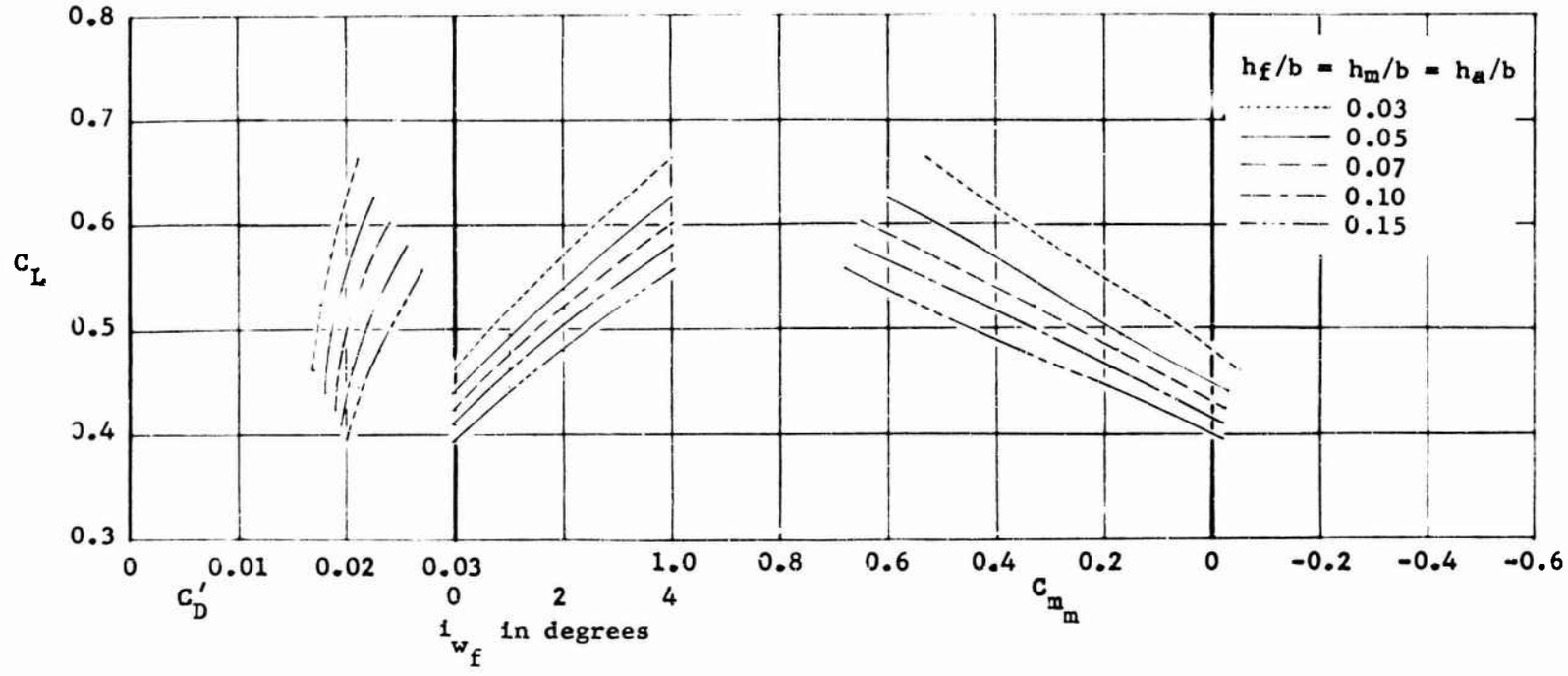

Figure 8 - Forward Wing Effectiveness of the TWIG Model With a Mid c.g. Location and $i_{w_a} = \alpha = 0°$

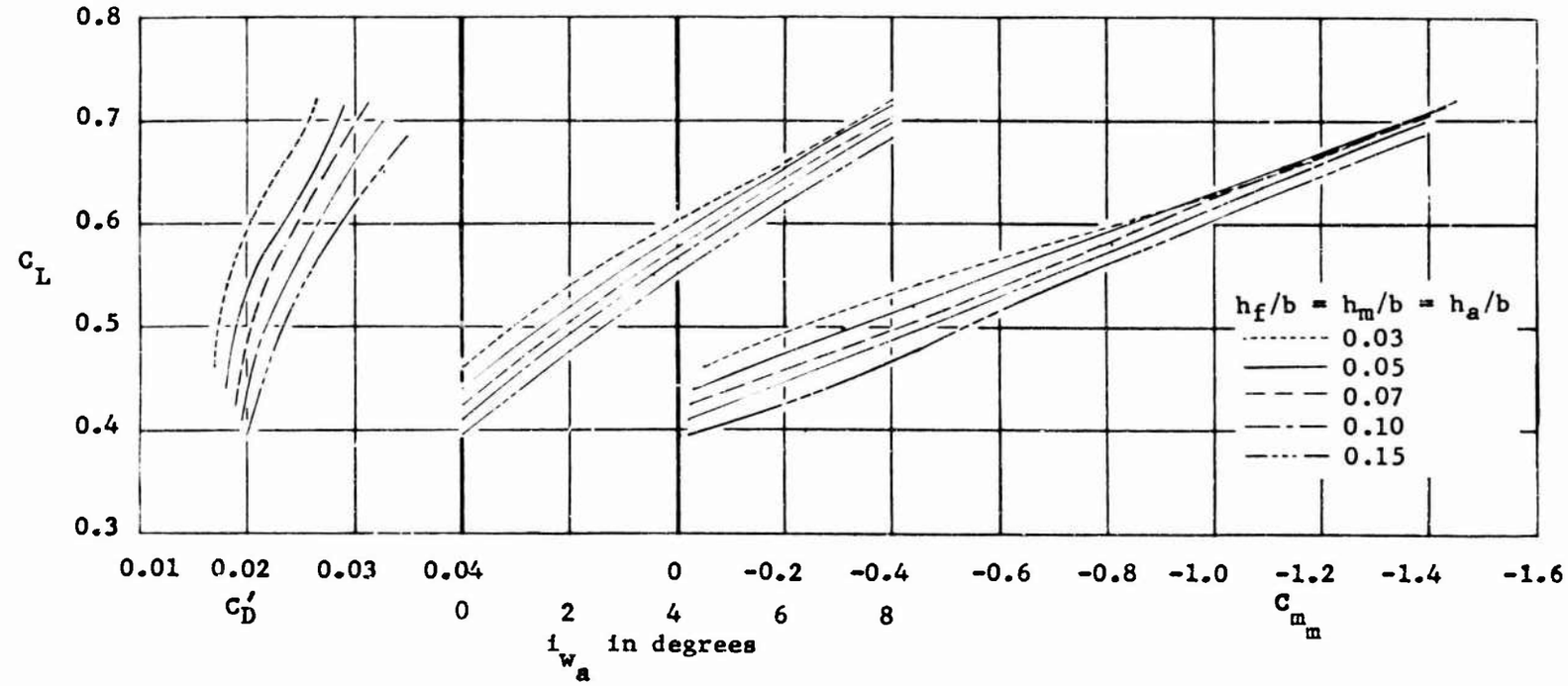

Figure 9 - Aft Wing Effectiveness of the TWIG Model With a Mid c.g. Location and $i_{w_f} = \alpha = 0°$

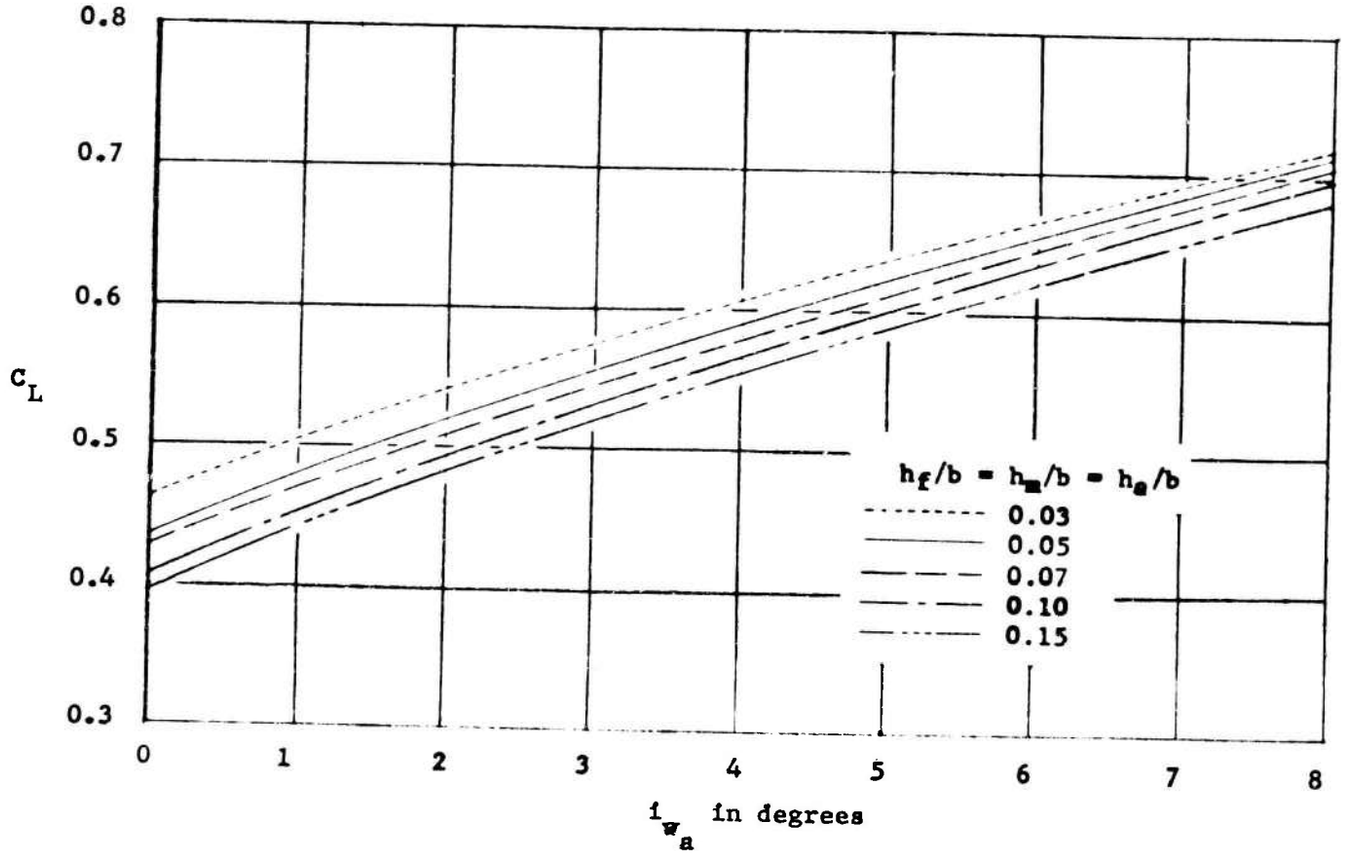

Figure 10 - Effect of i_{w_a} on the TWIG Model Lift Performance With $\alpha = 0°$

(a) $i_{w_f} = 0°$

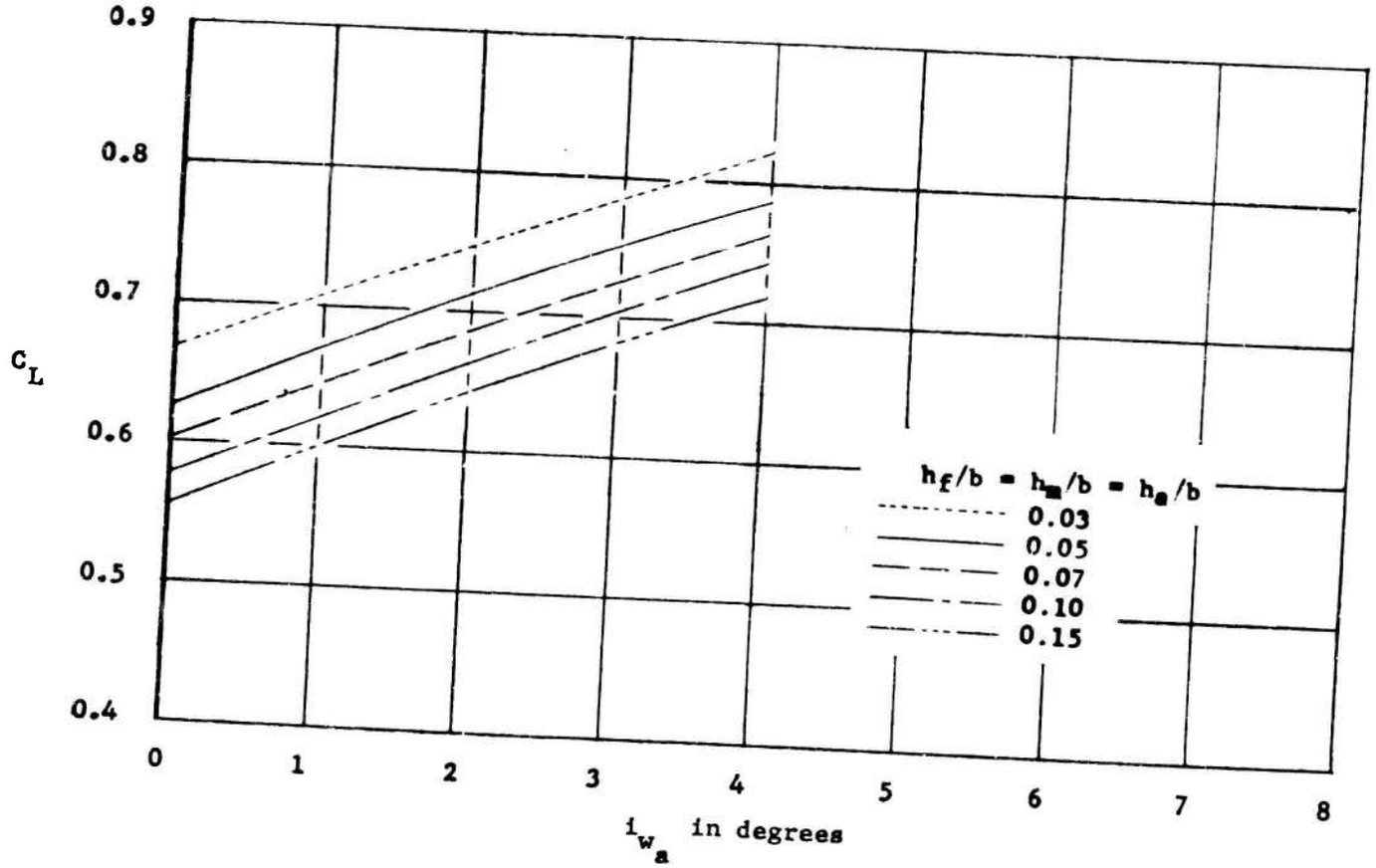

Figure 10 (Continued)

(b) $i_{w_f} = 4°$

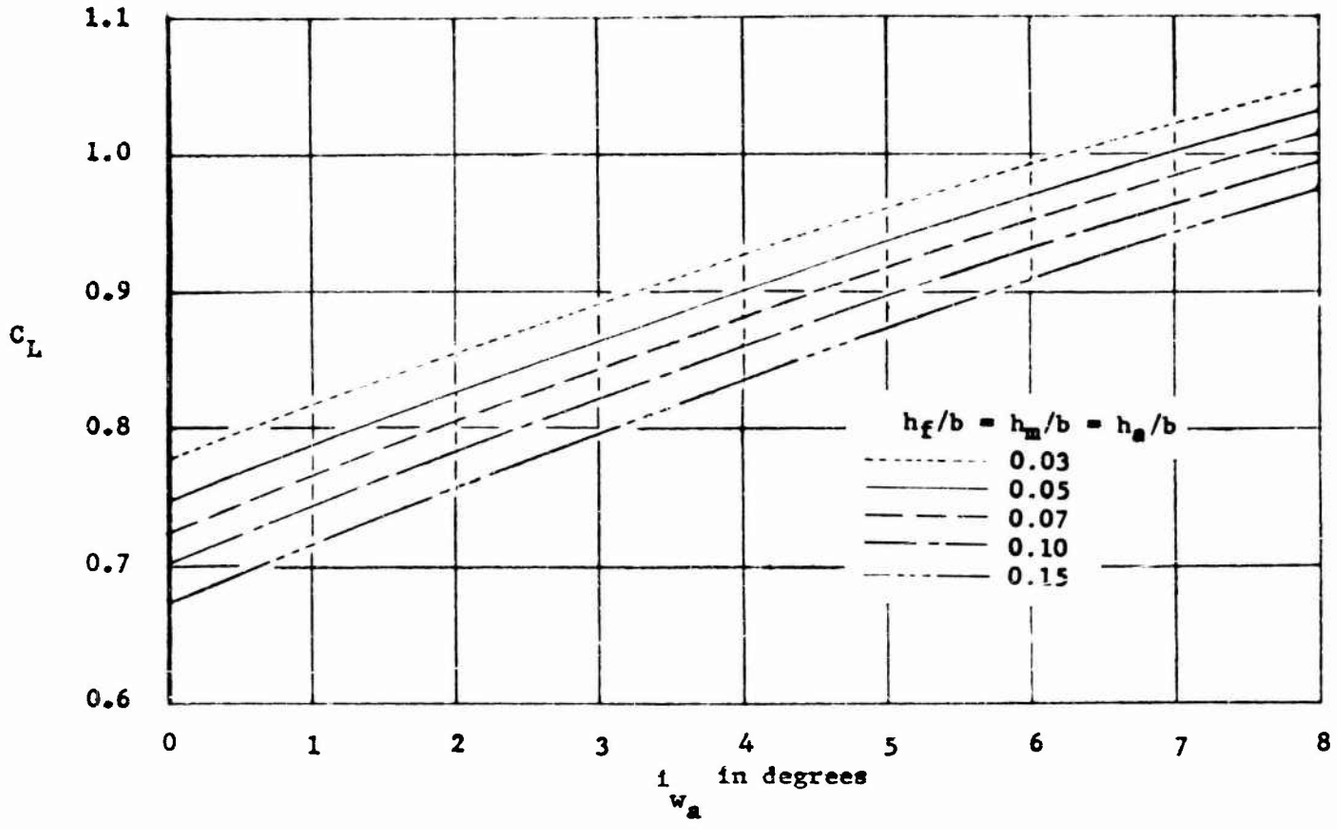

Figure 10 (Concluded)

(b) $i_{w_f} = 8°$

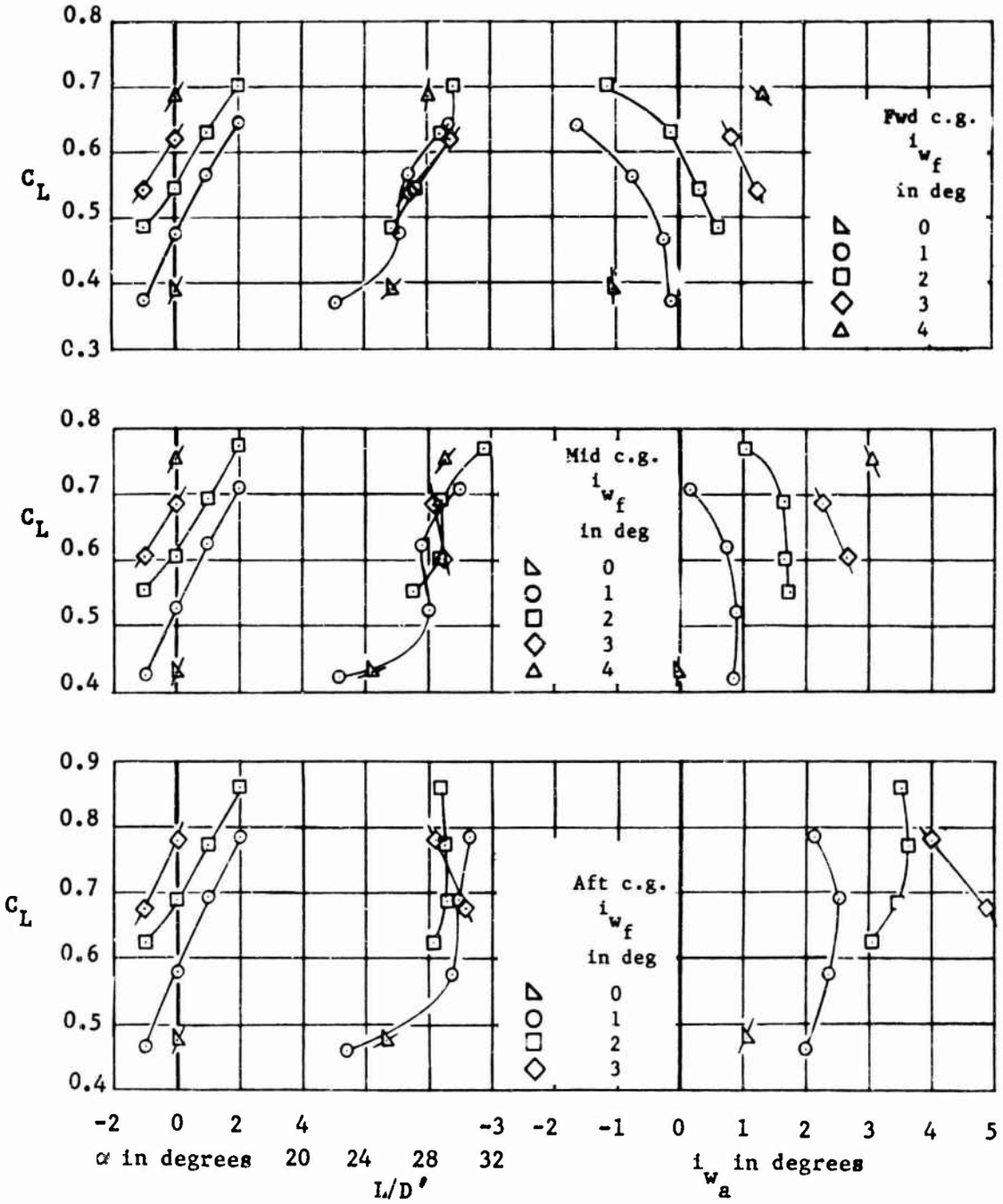

Figure 11 - Required i_{w_a} for Trim of the TWIG Model In Ground Effect

(a) h/b = 0.05

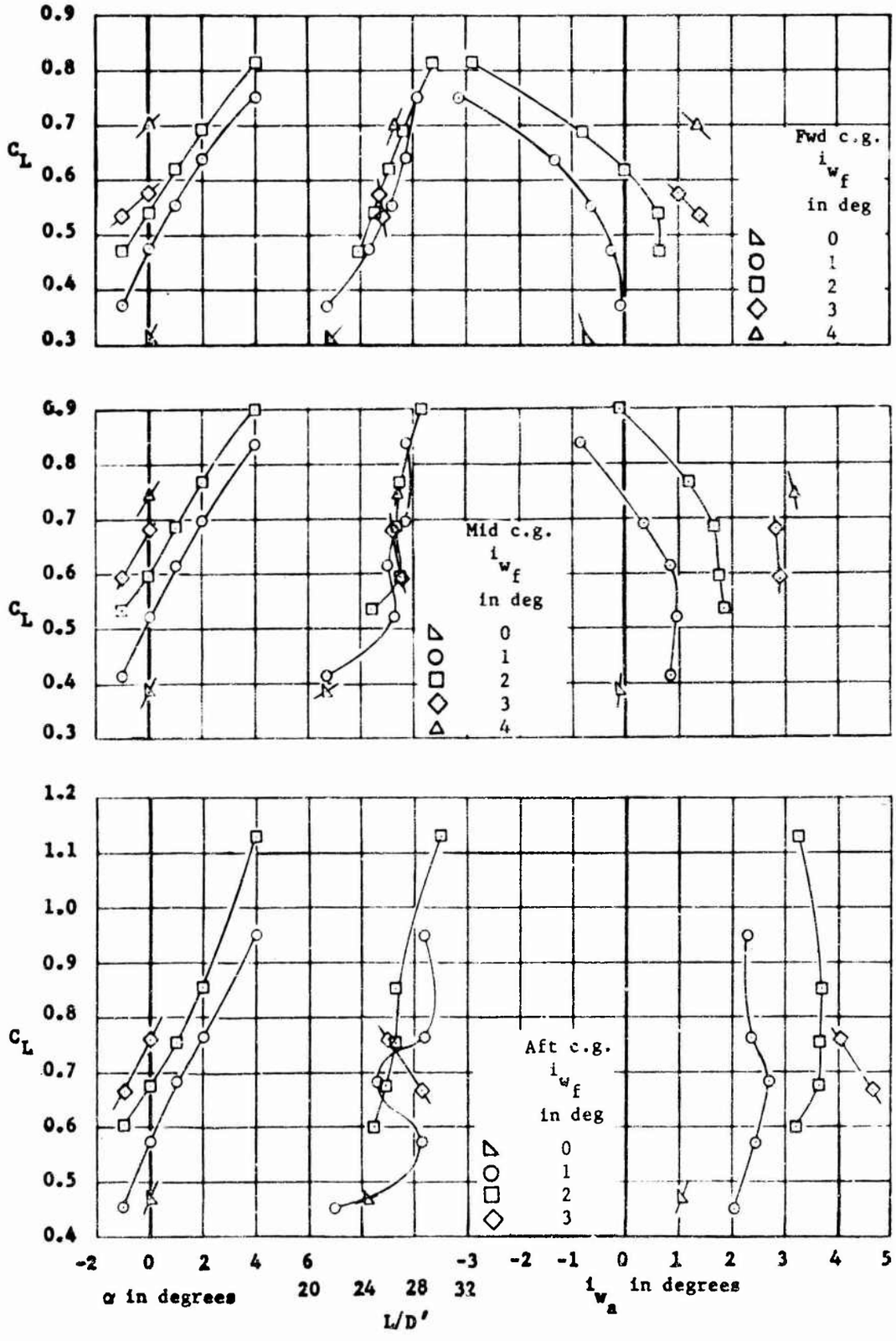

Figure 11 (Continued)
(b) h/b = 0.063

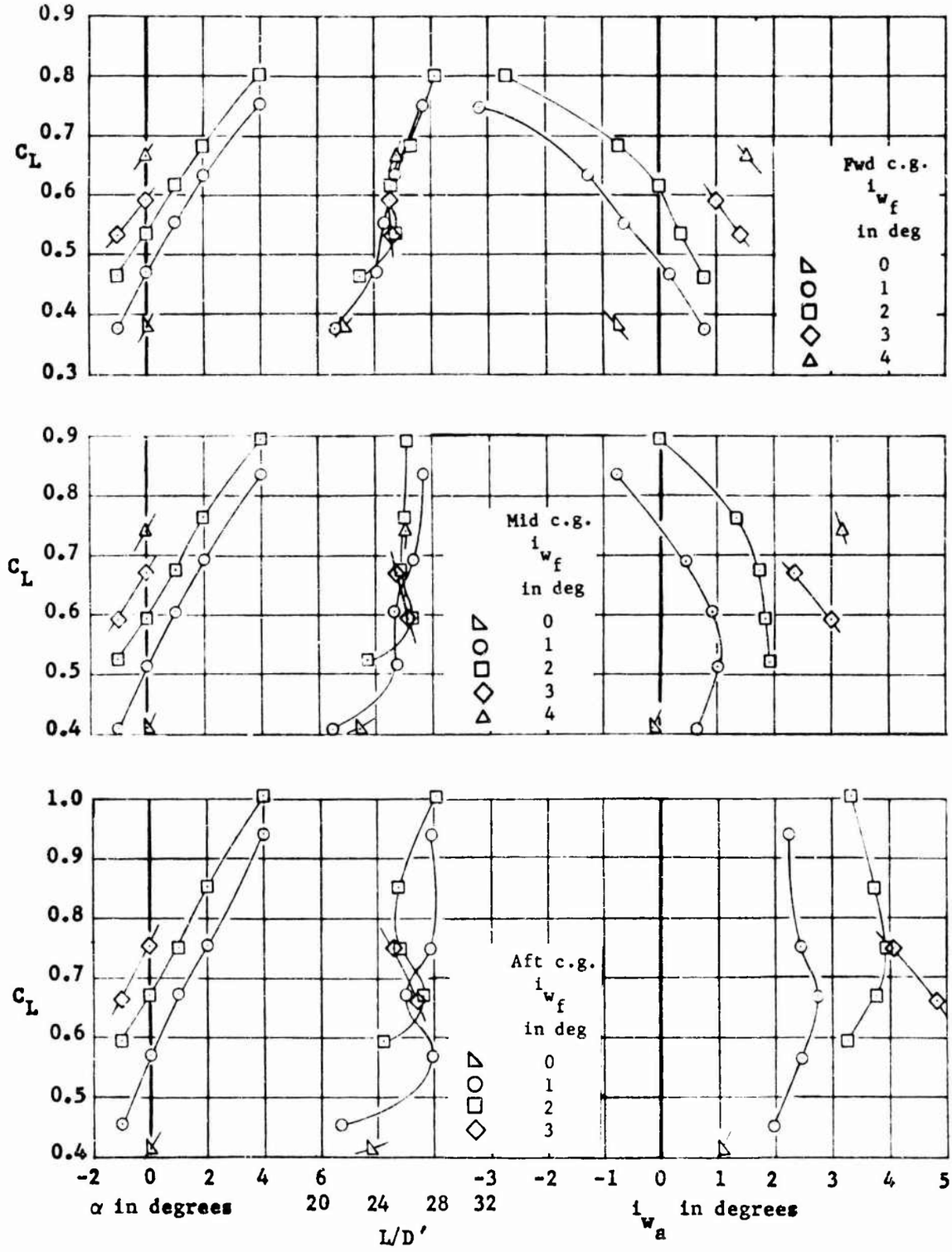

Figure 11 (Continued)

(c) h/b = 0.07

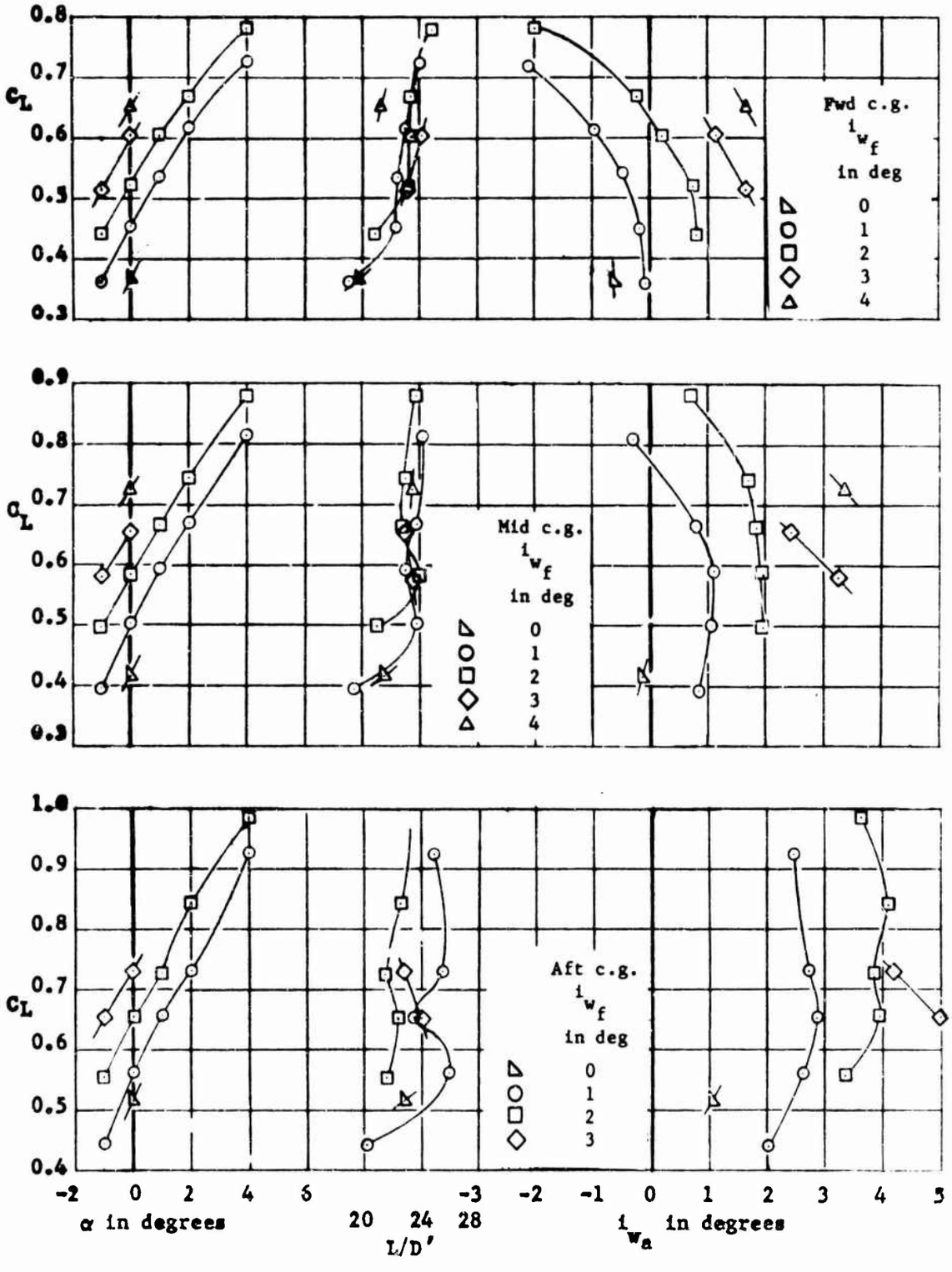

Figure 11 (Continued)

(d) h/b = 0.10

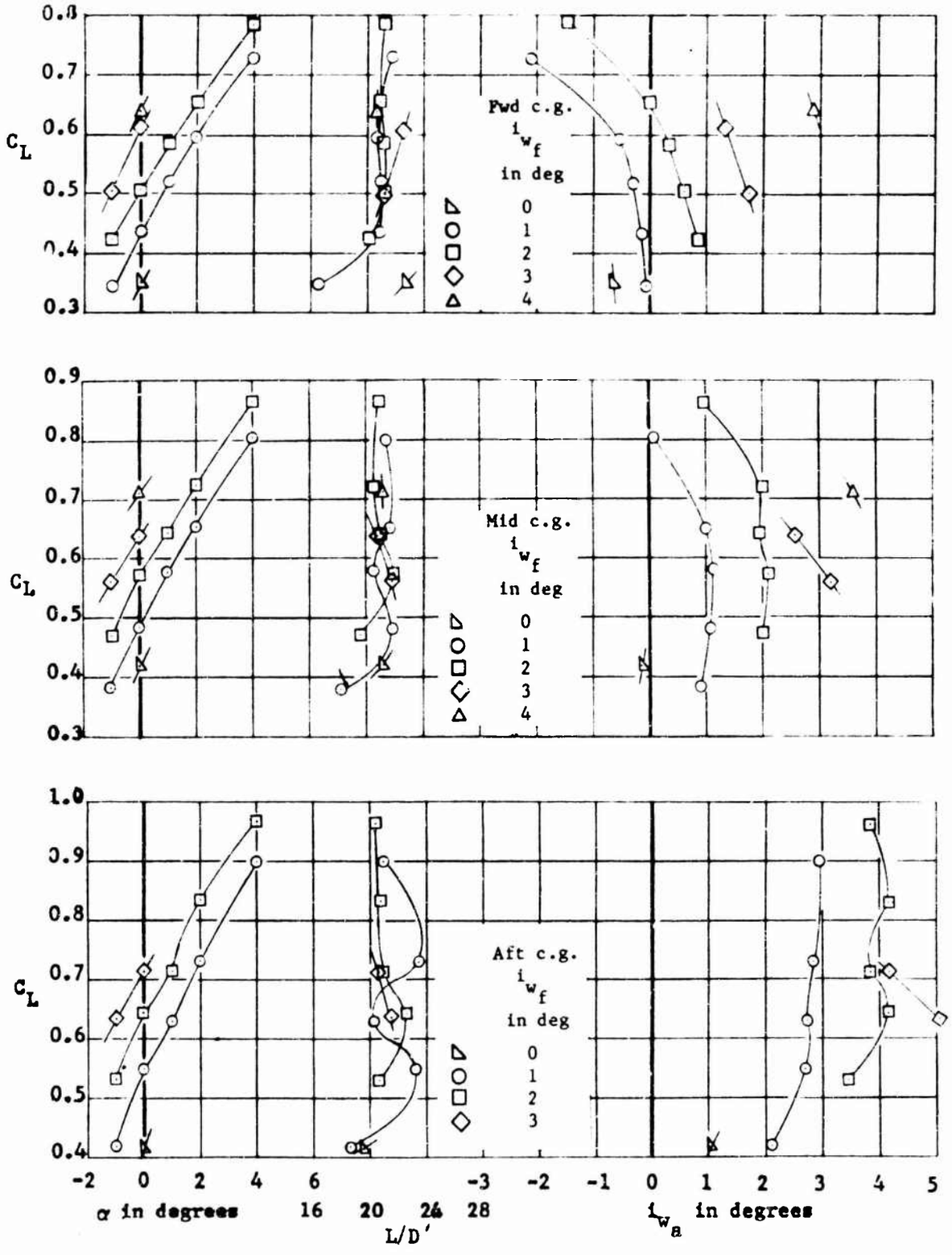

Figure 11 (Concluded)

(e) h/b = 0.15

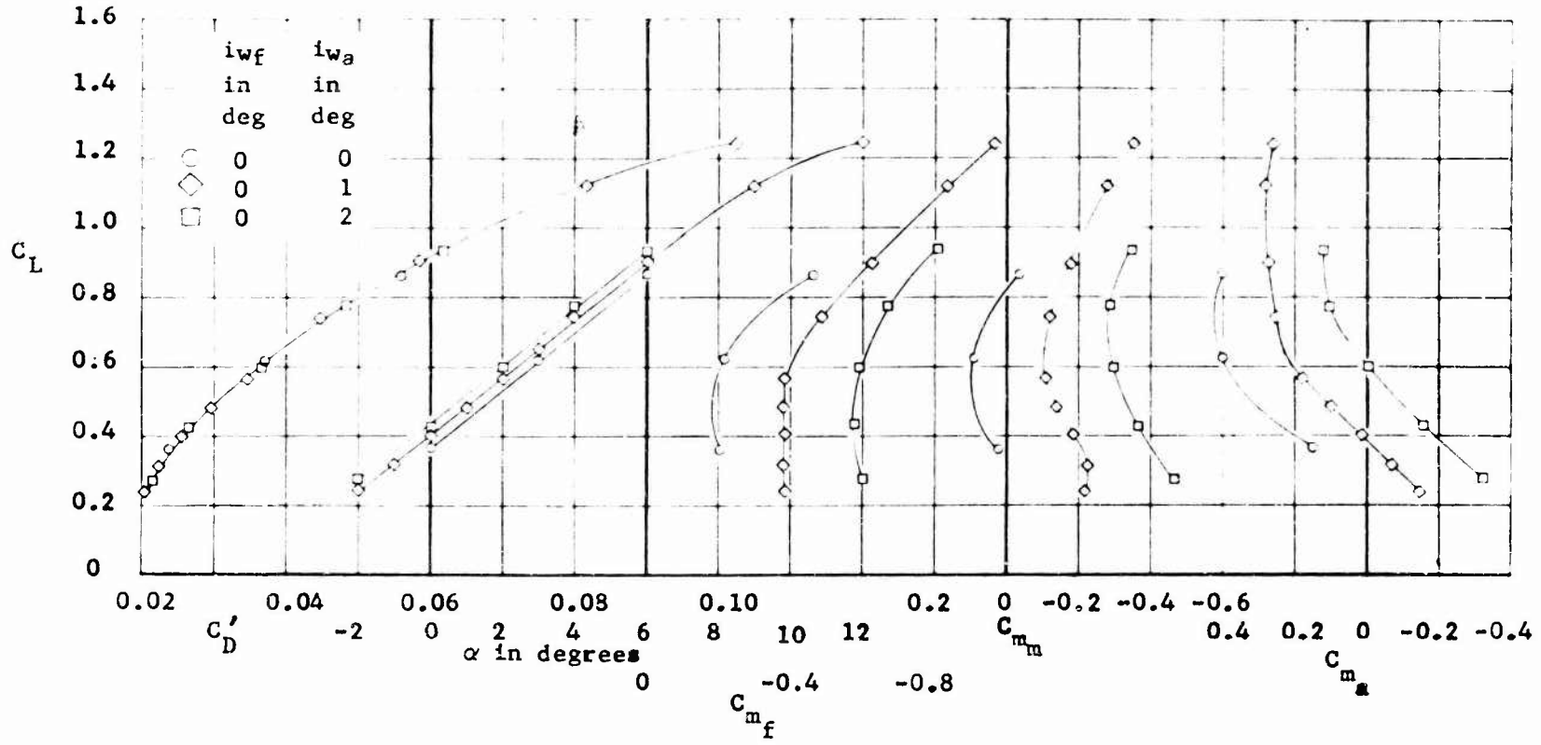

Figure 12 - Longitudinal Aerodynamic Characteristics of the TWIG Model Out of Ground Effect (h/b = ∞)

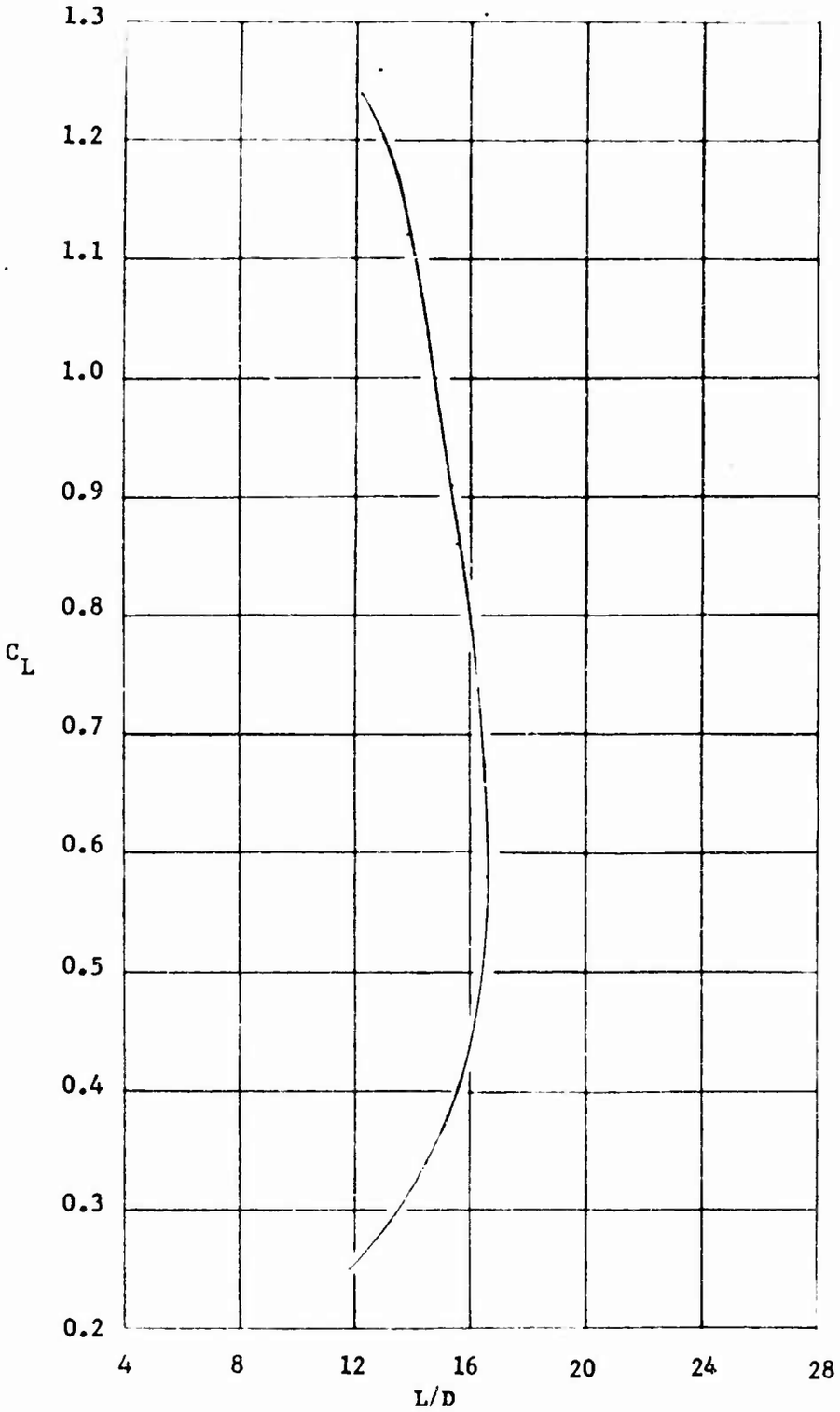

Figure 12 (Concluded)

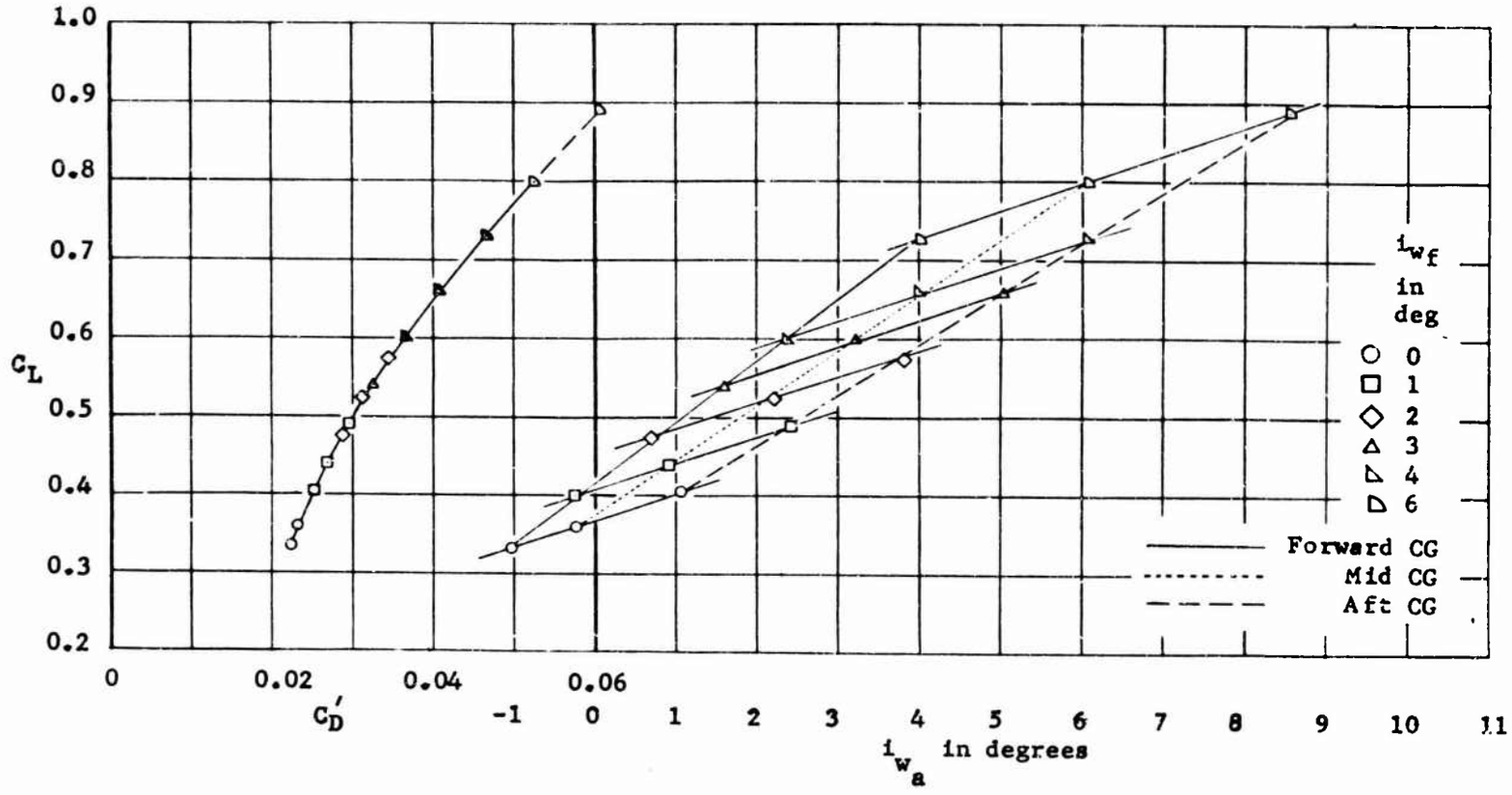

Figure 13 - Required i_{w_a} for Trim of the TWIG Model Out of Ground Effect

(a) $\alpha = 0°$

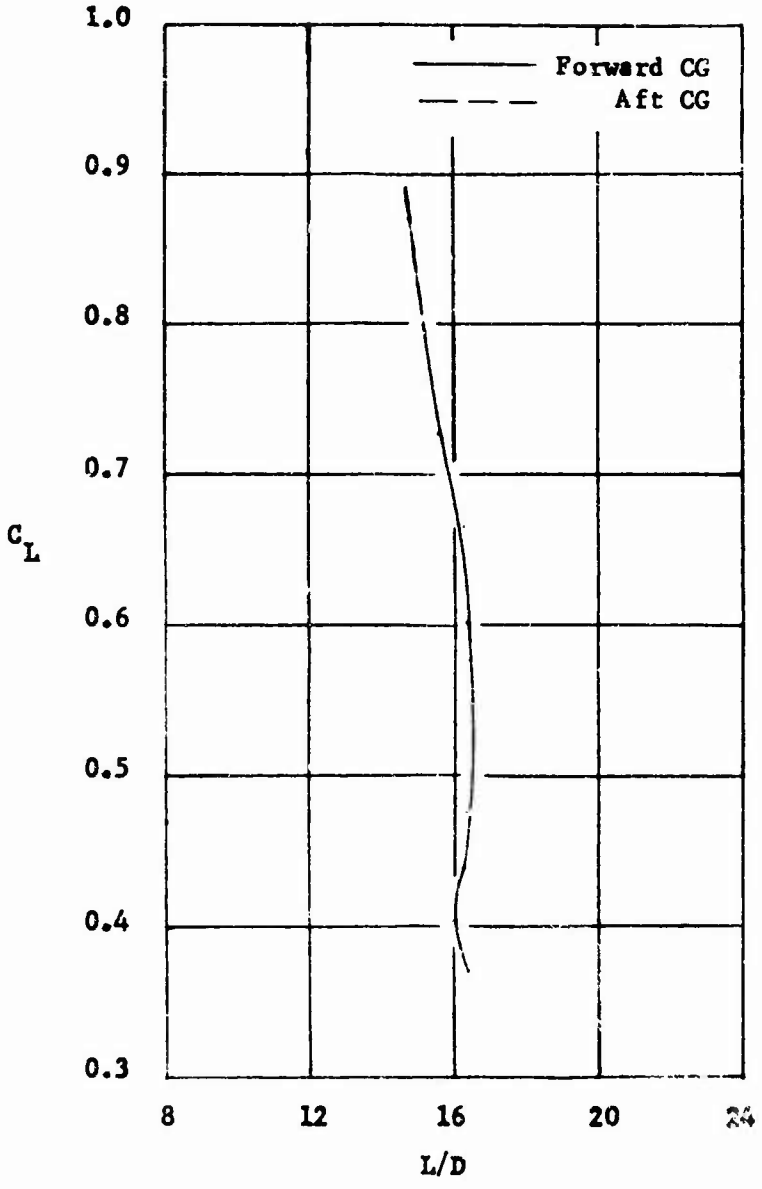

Figure 13 (Continued

(a) Concluded

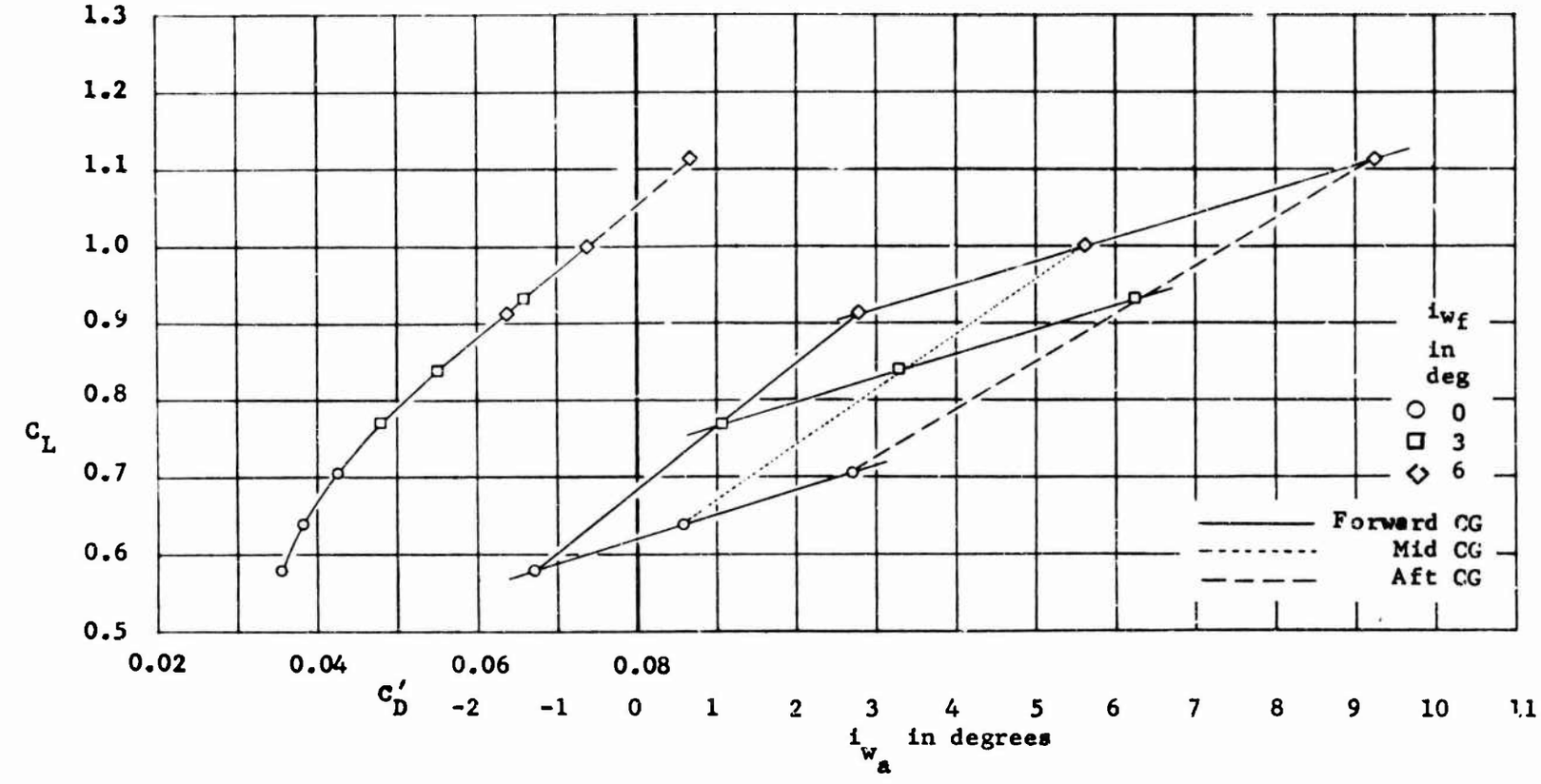

Figure 13 (Continued)

(b) $\alpha = 3°$

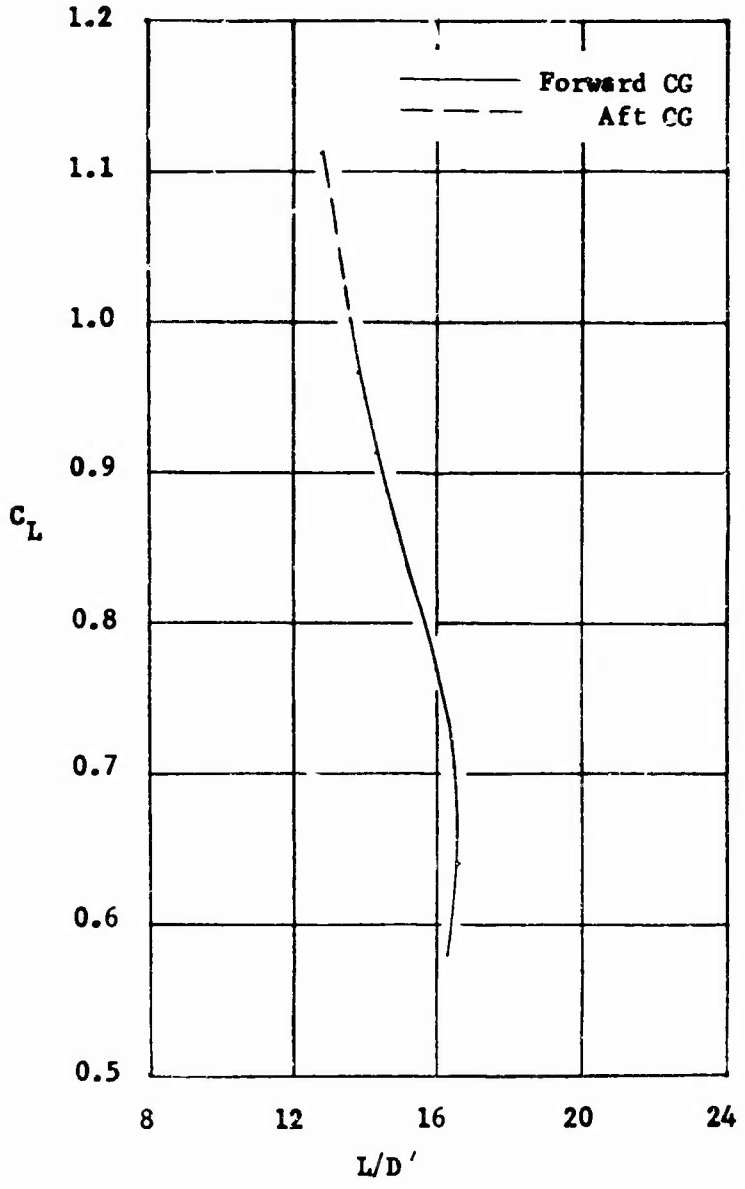

Figure 13 (Continued)

(b) Concluded

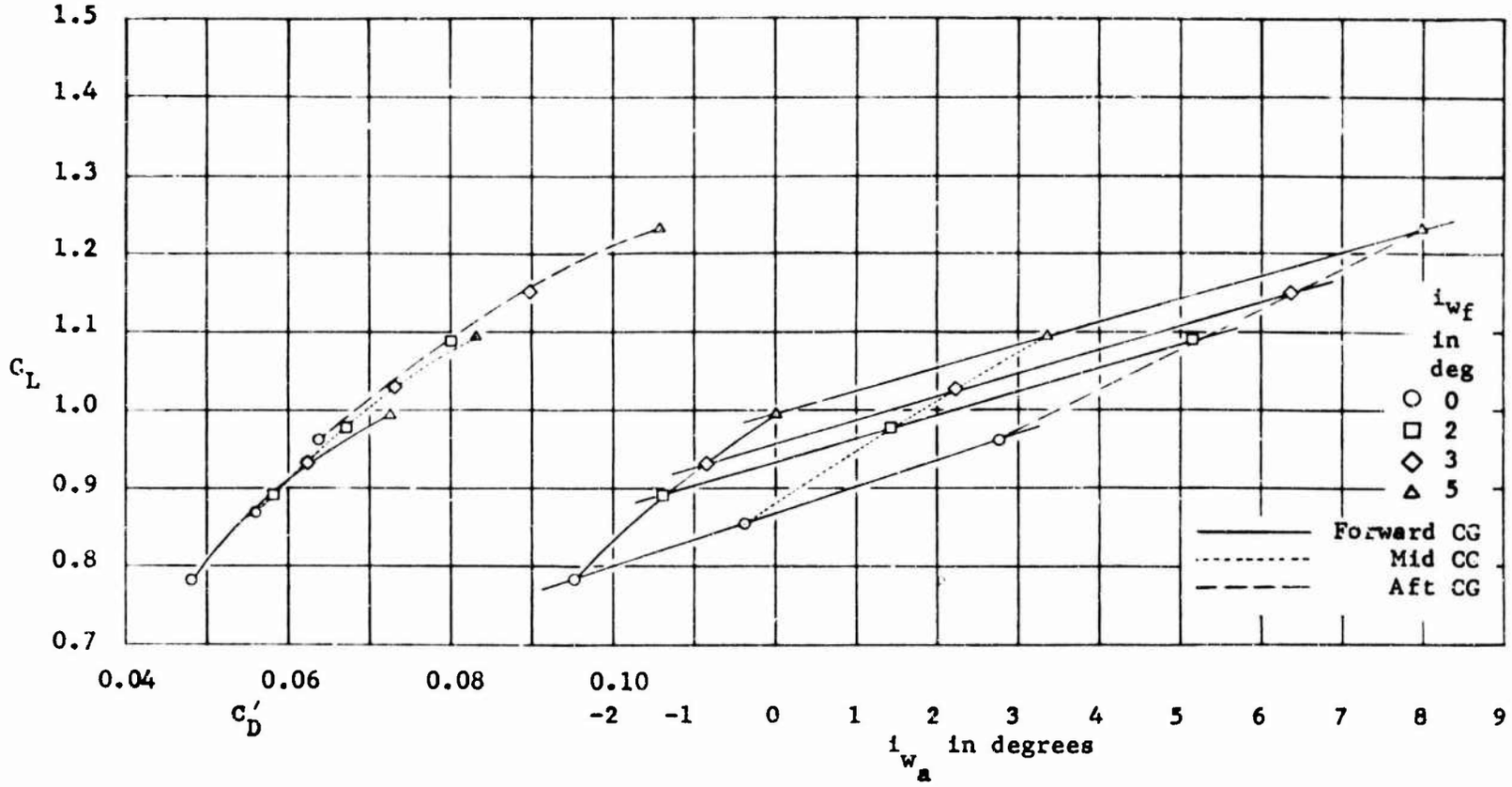

Figure 13 (Continued)

(c) $\alpha = 6°$

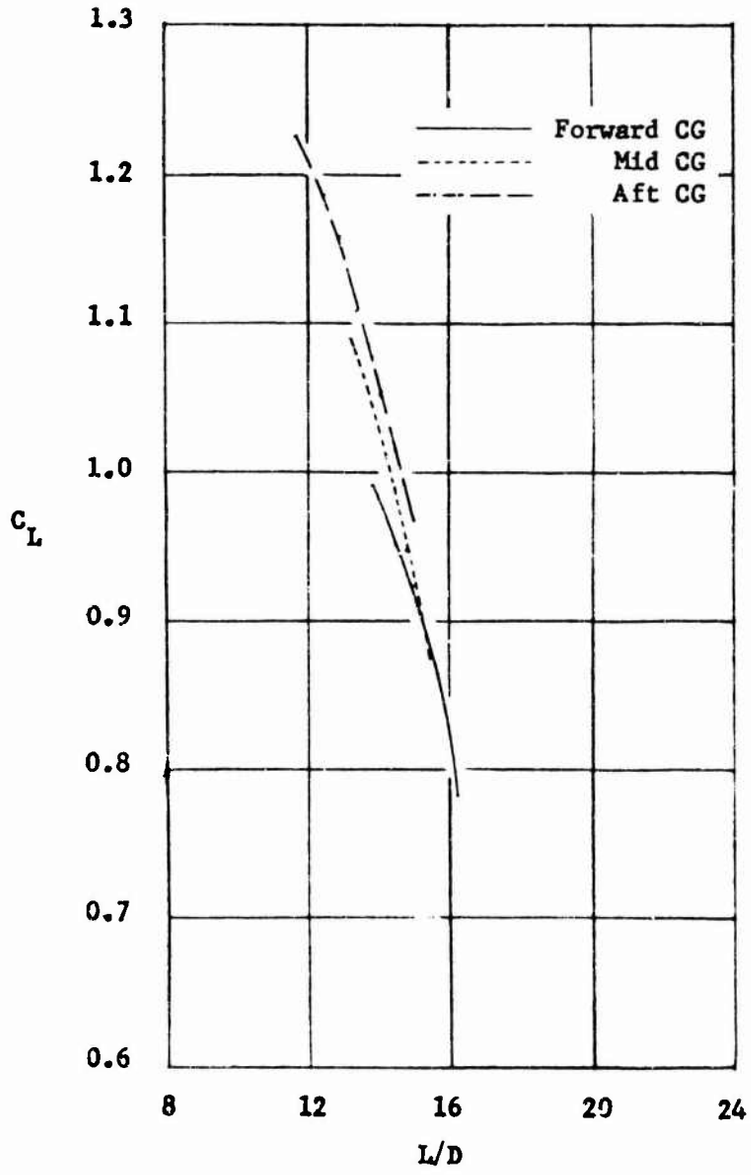

Figure 13 (Concluded)

(c) Concluded

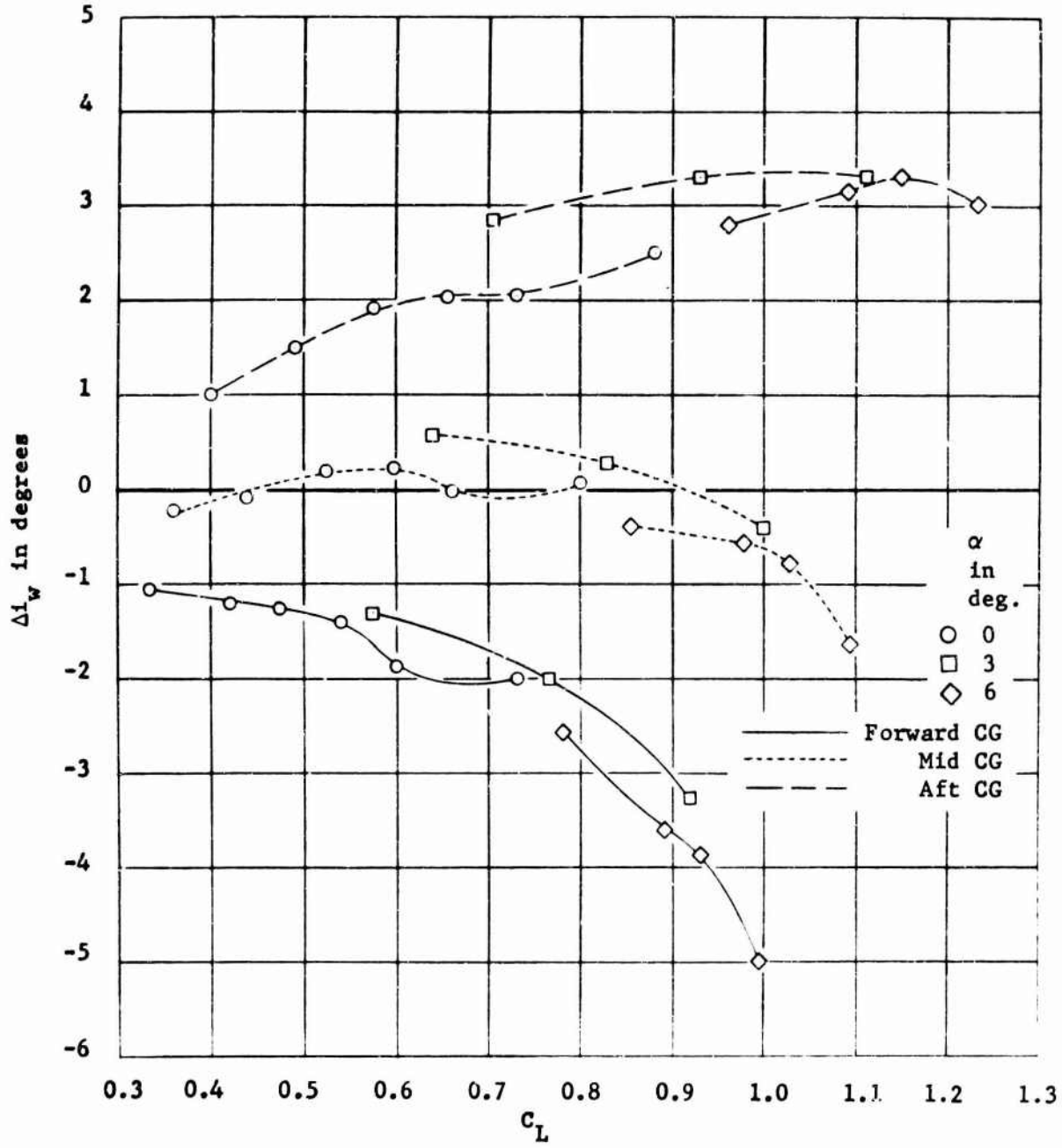

Figure 14 - Difference in Wing Incidence Angles Required for Trim of the TWIG Model Out of Ground Effect

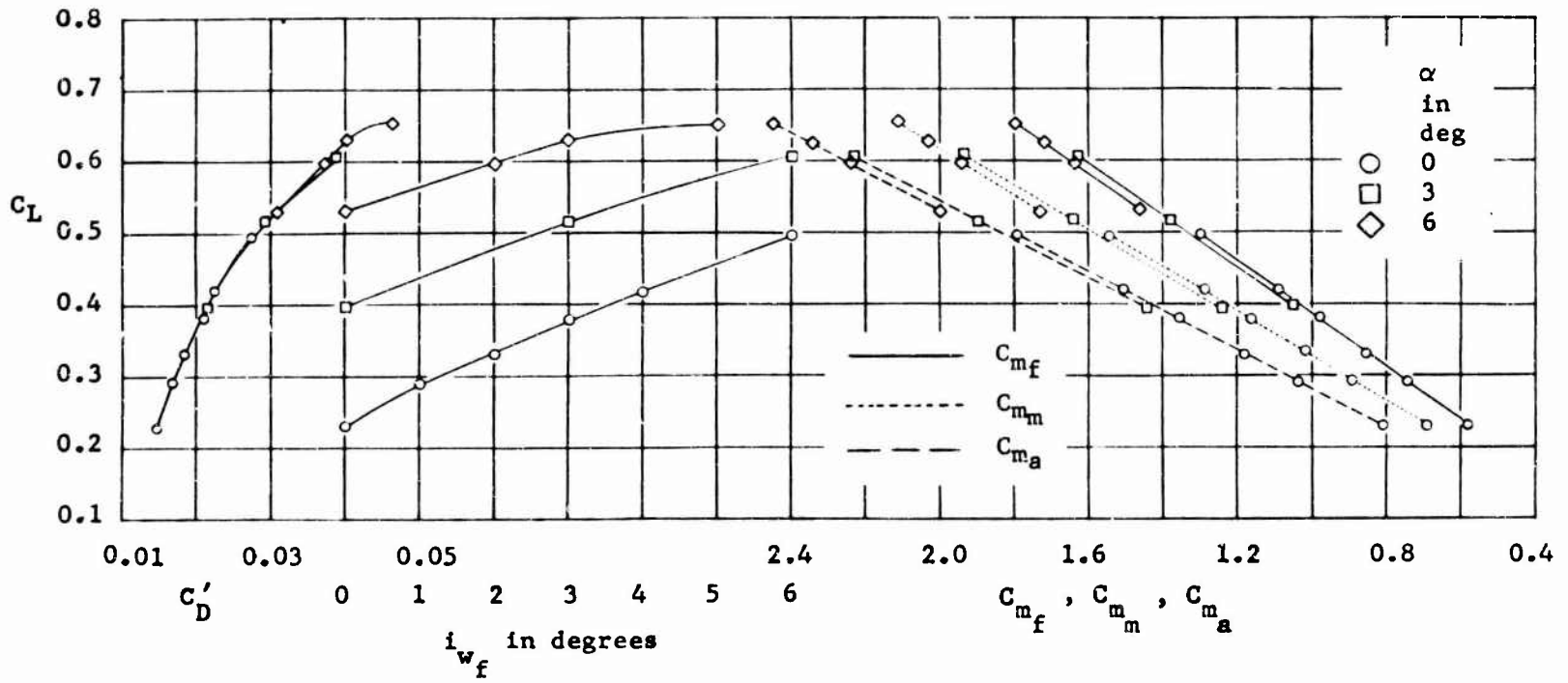

Figure 15 - Longitudinal Aerodynamic Characteristics of the TWIC Model Out of Ground Effect With the Aft Wing Removed

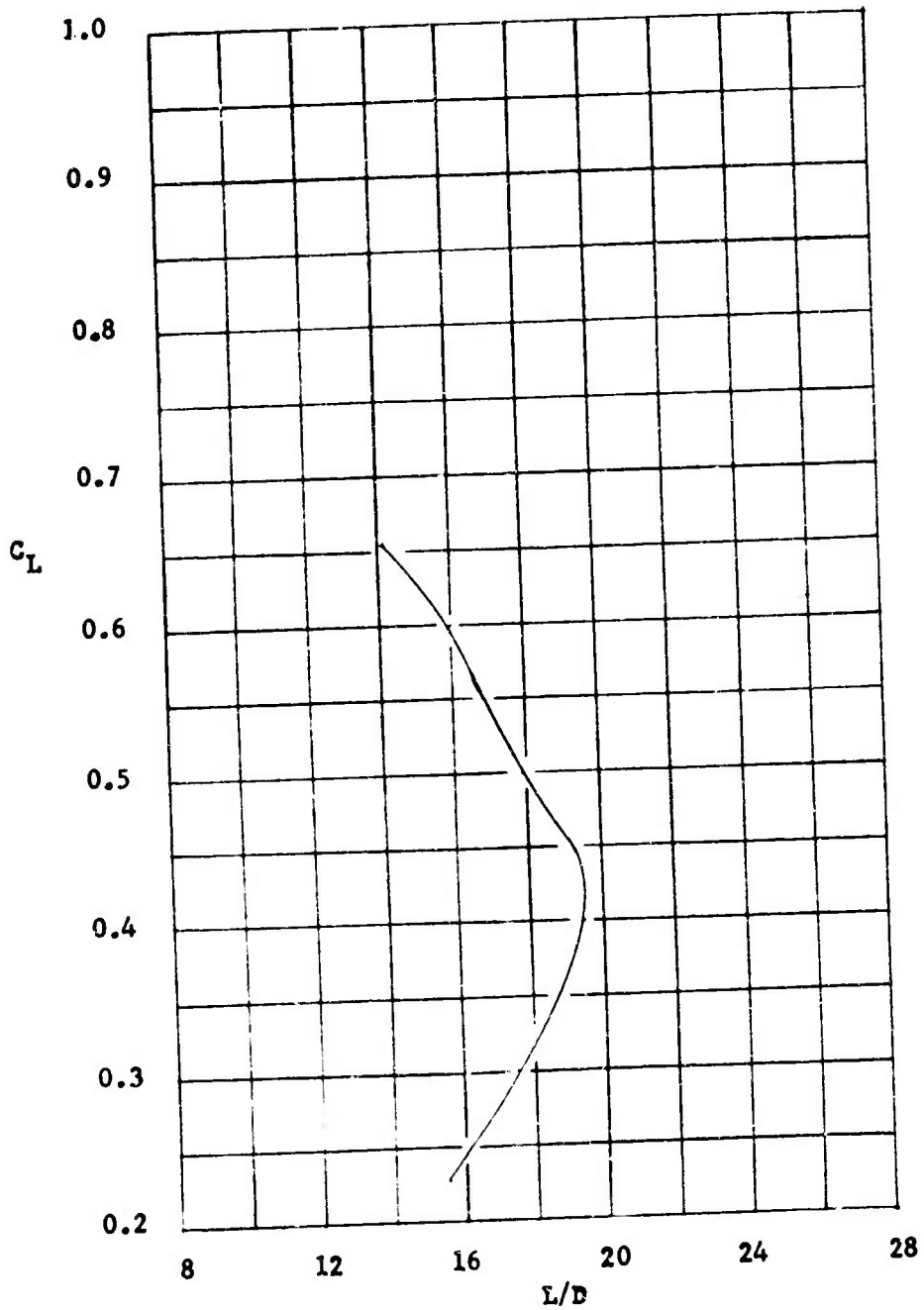

Figure 15 (Concluded)

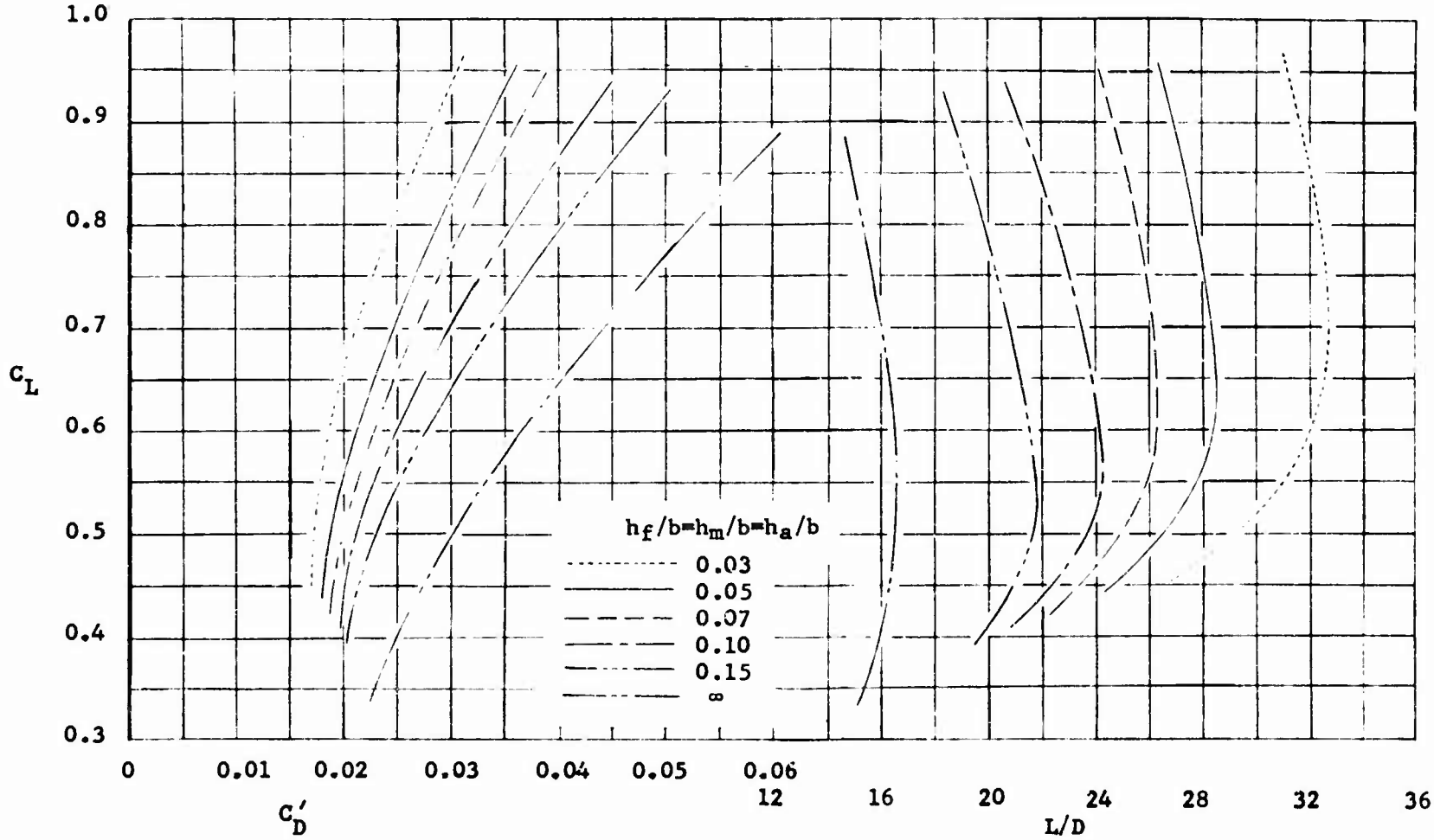

Figure 16 - Summary of TWIG Model Trim Data In and Out of Ground Effect. $\alpha = 0°$

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PART I — LONGITUDINAL CHARACTERISTICS

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13 ABSTRACT

Subsonic wind-tunnel test results of a tandem wing aircraft configuration are given. Conventional longitudinal tests out of ground effect, and similar tests in ground effect, employing the ground board test technique, were conducted on the configuration. Test variables included height above the surface, forward and aft wing incidence angles, angle of attack, and center-of-gravity location.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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Subsonic Wind Tunnel Tests						
Tandem Wings						
Wing Incidence						
Longitudinal Stability						
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