NASA Technical Memorandum 84565

Effect of Modifications on Aerodynamic Characteristics of a Single-Stage-to-Orbit Vehicle at Mach 5.9

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SUMMARY

Longitudinal and lateral-directional characteristics have been determined for a single-stage-to-orbit vehicle based on control-configured stability concepts. The configuration had a large body with a small 50° swept wing. Two vertical-fin arrangements were investigated: a large center-line vertical tail and small wing-tip fins. The movable outward surfaces of the wing-tip fins (controllers) were designed to provide yaw control. Tests were conducted in the Langley 20-Inch Mach 6 Tunnel over an angle-of-attack range from 0° to 40° at a Reynolds number of 2.5×10^6 based on fuselage length. Yaw-control effectiveness of the wing-tip-fin controllers was obtained at a sideslip angle of 0°.

With the center of gravity at 71.5 percent of fuselage length, the model had about the same longitudinal characteristics with either the center-line vertical tail or the wing-tip fins. Both configurations could be trimmed longitudinally over an angle-of-attack range from approximately 13° to 40° with zero or positive control deflection. Both configurations were directionally unstable over the angle-of-attack range but had positive effective dihedral at angles of attack greater than 8°. Significant yaw-control effectiveness was indicated when the wing-tip-fin controller was deflected outward 40°.

INTRODUCTION

For the past several years, NASA and industry have been studying advanced orbital transportation systems that could provide greater cost and performance advantages than the current shuttle system. These studies have dealt mainly with winged single-stage-to-orbit vehicles incorporating improved state-of-the-art technologies in structures, heat protection systems, rocket propulsion, and guidance and control schemes. Comprehensive overviews relating to many aspects of this study are discussed in references 1, 2, and 3.

In one phase of this study, NASA has focused its attention on two vertically launched single-stage-to-orbit vehicles designed for a payload mass of 65 000 lb. Both vehicles had large bodies for internal fuel and payload storage, 50° swept delta wings, a vertical tail, and a body flap. Using a computer-aided design process, the baseline vehicle was designed to have a positive level of longitudinal stability, whereas the second vehicle was designed for more relaxed stability criteria based on control-configured concepts recently used for transport and fighter aircraft. This design philosophy is discussed in reference 4, which also included wind-tunnel results for the two vehicles for a Mach number range from 0.3 to 4.63. Hypersonic characteristics of both vehicles are presented in reference 5 at a Mach number of 20.3. As indicated in reference 4, both vehicles yielded acceptable stability and performance; however, the control-configured vehicle had a lower gross lift-off weight. Therefore, attention was refocused on this vehicle, and several modifications were incorporated. The planform areas of the elevons and body flap were increased. Also, since the vertical tail was shielded by the body and wing at reentry angles of attack and was therefore ineffective, the tail was removed, and wing-tip fins were added for directional stability.

The purpose of this paper is to present the stability, control, and performance results on the single-stage-to-orbit control-configured vehicle at Mach 5.9. Two models were tested, one having a single center-line vertical tail and the other having wing-tip fins with movable controllers. Static longitudinal and lateral-directional stability characteristics were obtained on the 0.006-scale models over an angle-of-attack range from 0° to 40°. Also determined were the effects on yaw and roll of deflecting the wing-tip-fin controllers 20° and 40° at a sideslip angle of 0°. This investigation was conducted in the Langley 20-Inch Mach 6 Tunnel at a constant Reynolds number of 2.5×10^6 based on model fuselage length.

SYMBOLS

b reference wing span

C_A adjusted axial-force coefficient, $\frac{\text{Axial force}}{qS}$, $C_{A,T} - C_{A,B}$

$C_{A,B}$ base axial-force coefficient, $\left(\frac{p_B - p_\infty S_B}{qS}\right)$

$C_{A,T}$ total axial-force coefficient, $\frac{\text{Total axial force}}{qS}$

C_D drag coefficient, $\frac{\text{Drag force}}{qS}$

C_L lift coefficient, $\frac{\text{Lift force}}{qS}$

C_l rolling-moment coefficient, $\frac{\text{Rolling moment}}{qSb}$

C_{l_β} effective dihedral parameter, $\Delta C_l/\Delta\beta$, per deg

C_m pitching-moment coefficient, $\frac{\text{Pitching moment}}{qS\bar{c}}$

C_N normal-force coefficient, $\frac{\text{Normal force}}{qS}$

C_n yawing-moment coefficient, $\frac{\text{Yawing moment}}{qSb}$

C_{n_β} directional-stability parameter, $\Delta C_n/\Delta\beta$, per deg

$\left(C_{n_\beta}\right)_{dyn}$ dynamic directional-stability parameter, $C_{n_\beta} \cos\alpha - C_{l_\beta}\left(\frac{I_Z}{I_X}\right)\sin\alpha$, per deg

C_Y side-force coefficient, $\frac{\text{Side force}}{qS}$

C_{Y_β} rate of change of side-force coefficient with sideslip angle, $\Delta C_Y/\Delta\beta$, per deg

$\bar{c}$ wing mean aerodynamic chord

I_Z/I_X ratio of moments of inertia about yaw and roll axes

L/D lift-drag ratio

l fuselage reference length

M free-stream Mach number

q free-stream dynamic pressure

p pressure

R_l Reynolds number based on fuselage length

S wing total planform reference area

x longitudinal distance measured from theoretical nose of fuselage

α angle of attack, deg

β angle of sideslip, deg

δ_e elevon deflection angle, positive for trailing edge down, deg

δ_F body-flap deflection angle, positive for trailing edge down, deg

δ_{TF} tip-fin controller deflection, positive when controller is deflected outward, deg

Subscripts:

B base area of fuselage

cg center of gravity

cp center of pressure

∞ free-stream conditions

$0.715l$ moment center at 71.5 percent of fuselage reference length

DESCRIPTIONS OF MODELS

The two 0.006-scale models were modified versions of the control-configured vehicle tested previously (refs. 4 and 5). The modifications consisted of reshaping the upper portion of the fuselage to accommodate relocation of the payload bay and increasing the planform areas of the elevons and body flap. Both models were fabricated from aluminum and were geometrically similar except one model incorporated a single center-line vertical tail and the other had wing-tip fins. (See fig. 1.) The movable outer surfaces of the wing-tip fins were designed for outward deflections only. These movable controllers were machined from metal as wedgelike components simulating deflection angles of 20° and 40° and were attached to the wing-tip fin by small screws. Elevon deflections were set by using pre-bent brackets, whereas body-flap deflections were obtained by using separate interchangeable components for each deflection.

Models 1 and 2 were designated BWVF and BWTF, respectively, where model components are identified as follows:

B	fuselage
W	wing
V	vertical tail
T	tip fin
F	body flap

Full-scale dimensions of both vehicles are presented in table I. Photographs of each model mounted in the Langley 20-Inch Mach 6 Tunnel test section are shown in figure 2.

APPARATUS AND TESTS

Wind Tunnel

This investigation was conducted in the Langley 20-Inch Mach 6 Tunnel which is a blowdown type facility using air as the test medium. The tunnel has a two-dimensional contoured nozzle which is 2.27 m (89.4 in.) long and incorporates a test section measuring 0.52 by 0.508 m (20.5 by 20 in.). The sting-support system is remotely controlled and can provide an angle-of-attack range from -5° to 50° and a sideslip-angle range from 0° to -10°. Stagnation pressures can be varied from 0.2 MPa to 3.6 MPa (30 to 525 psia). To prevent liquefaction, the air can be preheated up to 567 K (560°F) by the use of an electrical resistance heater. Test run times of 1 minute are possible when the flow exhausts into a vacuum sphere and up to 20 minutes when an annular type air ejector is used. Additional details including Mach number calibrations are presented in reference 6.

Tests

All tests were conducted at a stagnation pressure of 0.689 MPa (100 psia) and a temperature of 453 K (355°F). The average free-stream Mach number was 5.93 at a unit Reynolds number of 6.24×10^6 per meter (1.9×10^6 per foot).

Force and moment data were measured by a sting-supported six-component strain-gage balance. Both models were tested over an angle-of-attack range from 0° to 40° in 5° increments at sideslip angles of 0° and -2°. Model attitudes were accurately set by using a small prism mounted flush in the fuselage which reflected light from a point source located near the test section onto a calibration board. Free-stream Mach number was determined by using an actuator-mounted pitot probe which was inserted into the airstream only at the beginning and ending of each blowdown run. This procedure precluded the possibility of interference effects on the model test data.

The estimated uncertainties in the measured data were based on ±0.5 percent of the balance design loads and are as follows:

C_N	±0.0115	C_l	±0.00016
C_A	±0.0029	C_n	±0.00027
C_m	±0.0027	C_Y	±0.0024

The accuracy of the angles of attack and sideslip is estimated to be ±0.15°; free-stream Mach number is estimated to be accurate to ±0.02. Base pressure was measured at one location for all tests and was used to adjust the axial-force coefficients to free-stream pressure acting on the base.

RESULTS AND DISCUSSION

Flight Profile

This vehicle was designed for vertical take-off and would employ rocket engine gimballing for attitude control during ascent. For entry, the vehicle would glide at an angle of attack of approximately 36° over the hypersonic regime down to a Mach number of 8. The angle of attack would then gradually be reduced to 10° at Mach 4 and maintained at this attitude until just prior to horizontal landing.

Longitudinal Aerodynamic Characteristics

The static longitudinal characteristics of model 1 are presented in figure 3 for a center-of-gravity (c.g.) location at 71.5 percent of the fuselage length. The control system (elevons and body flap) was capable of trimming the configuration over an angle-of-attack range from approximately 13° to 40° for various control deflections. These trim conditions were unstable up to approximately $\alpha = 30°$ and were then neutrally stable or stable at higher attitudes. As shown in figure 3(d), a stable trim condition occurred at about $\alpha = 40°$ with the body flap deflected 10°. Entry trajectory studies (ref. 7) indicated that the flight angle of attack would be 26° for a Mach number of 6. For this angle of attack, neutral stability could be achieved without control deflections if the center of gravity were shifted forward to 69.6 percent of the fuselage length. However, an unpublished weight analysis indicated that c.g. locations for the control-configured vehicle with the large vertical tail would be more rearward, at approximately 74 percent. Consequently, more forward c.g. locations would appear unrealistic at the present time for model 1. A maximum lift-drag ratio of 2.57 was obtained at $\alpha = 12.5°$ without control deflections. At $\alpha = 26°$, the L/D was about 1.75 with the body flap deflected 10°.

The longitudinal aerodynamic characteristics of model 2 are presented in figure 4 for various deflections of the tip-fin controllers at zero elevon and body-flap settings. A comparison of the longitudinal aerodynamic characteristics of model 1 and model 2 at zero control deflections shows negligible differences.

Consequently, the previous discussion of stability and control of model 1 is applicable to model 2 for the same flight conditions and c.g. location.

Tip-fin controller deflection had only a small effect on the pitching-moment coefficient (fig. 4(d)). When the right controller was deflected 40°, C_m at $\alpha = 26°$ changed by only -0.003, which is approximately equal to estimated balance accuracy. An even smaller increment in C_m was measured when both controllers were deflected 20°. The only appreciable effect of tip-fin controller deflection was on the maximum values of L/D which occurred at angles of attack from 12.5° to 15°, as shown in figure 4(g). At the operational angle of attack of 26°, the measured value of L/D was approximately 1.77 for the various controller deflections.

Lateral-Directional Aerodynamic Characteristics

The lateral-directional aerodynamic characteristics of models 1 and 2 are presented in figure 5 for zero deflections on all controls. The data were obtained at sideslip angles of 0° and -2°. Although both configurations were statically unstable at Mach 5.93, the results showed that removing the rather large center-line vertical tail and adding the smaller wing-tip fins actually slightly increased directional stability. At angles of attack greater than 8°, both models exhibited positive effective dihedral $\left(-C_{l_\beta}\right)$ with about the same levels of magnitude. Favorable (positive) values of $\left(C_{n_\beta}\right)_{dyn}$ were obtained only at higher angles of attack for both configurations. At the flight angle of attack of 26°, the dynamic directional-stability parameter was zero for the center-line vertical tail configuration and slightly positive for the wing-tip-fin configuration.

Lateral-Directional Control Characteristics

In figure 6, the effects of tip-fin controller deflection of the right wing-tip fin on roll-, yaw-, and side-force control parameters were determined at zero sideslip. At the operational angle of attack of 26°, the magnitudes of roll- and yaw-control parameters were quite small for a controller deflection of 20°. However, an increase in the deflection to 40° did result in significant roll- and yaw-control capability, especially yaw control. At flight conditions, the ratio of ΔC_n to ΔC_l of about 5.0 indicates that the wing-tip-fin controller is basically a yaw-control device. In-house calculations using the reaction-control system values from figure 1(b) of reference 7 indicate that the wing-tip-fin controller when deflected 40° can produce a yawing-moment increment equal to approximately 1.2 yaw jets, or it can provide a trim capability for a 1° perturbation in sideslip.

CONCLUDING REMARKS

Aerodynamic characteristics of a single-stage-to-orbit vehicle based on control-configured concepts have been obtained at Mach 5.9 in the Langley 20-Inch Mach 6 Tunnel. The configuration had a large body for internal fuel and payload and a small 50° swept wing. Two vertical-fin arrangements were investigated: a large center-line vertical tail and small wing-tip fins. Longitudinal and lateral-directional characteristics were obtained over an angle-of-attack range from 0° to 40°.

With the center of gravity at 71.5 percent of the fuselage length, the aerodynamic control system provided longitudinal trim conditions for both configurations over an angle-of-attack range approximately 13° to 40°. These trim conditions were unstable up to approximately an angle of attack $\alpha = 30°$ and were then neutrally stable or stable at higher attitudes. A stable trim condition was achieved at $\alpha = 40°$ with the body flap deflected 10°. Both configurations had positive effective dihedral at angles of attack greater than 8°. Directional instability occurred over the entire angle-of-attack range because of the rearward center-of-gravity location. At the flight angle of attack of 26°, the dynamic stability parameter $\left(C_{n_\beta}\right)_{dyn}$ was zero for the vertical tail configuration and only slightly positive for the wing-tip-fin configuration. Large outward deflections of the wing-tip-fin controller were effective for yaw control.

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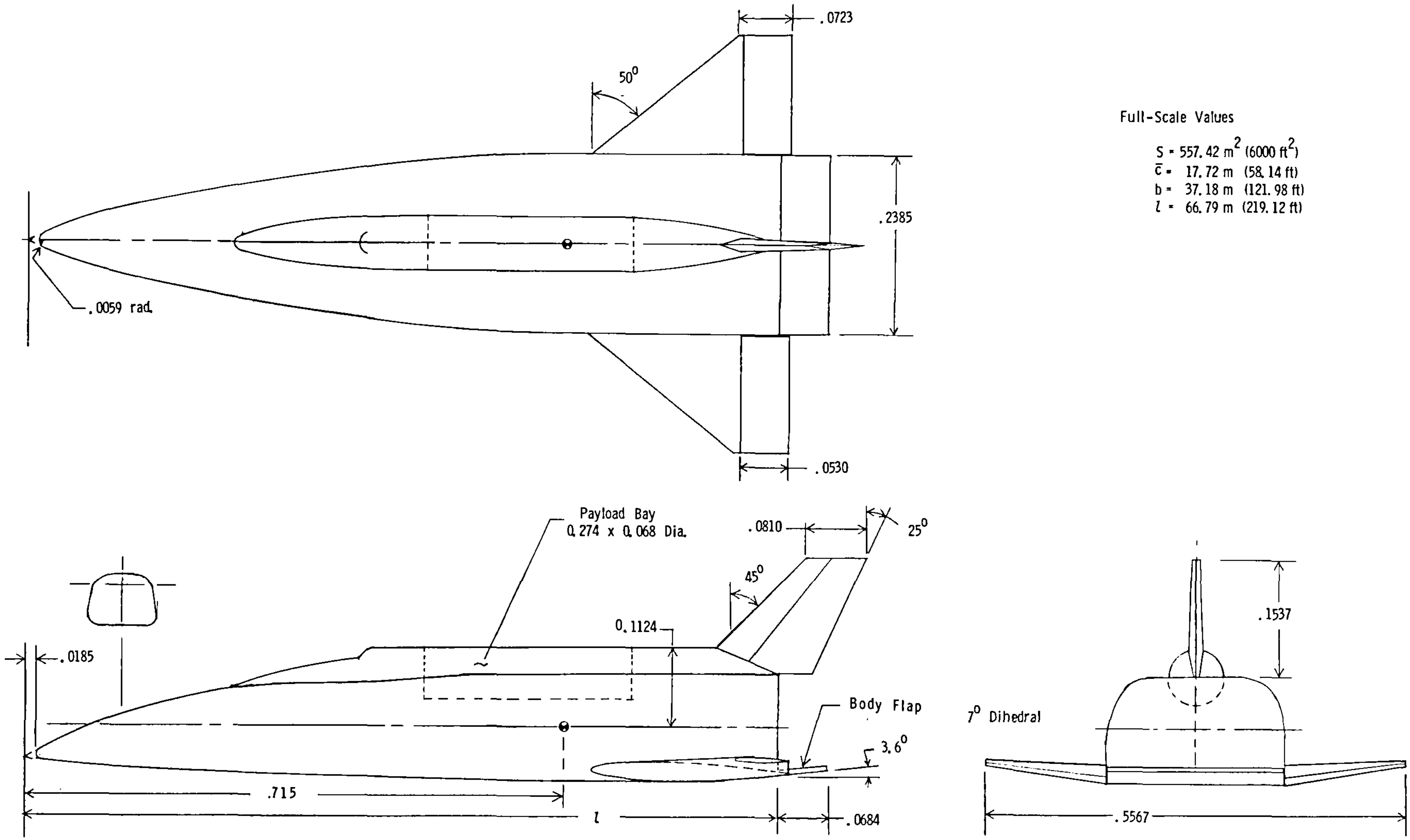
TABLE I.- GEOMETRIC DETAILS OF FULL-SCALE VEHICLES

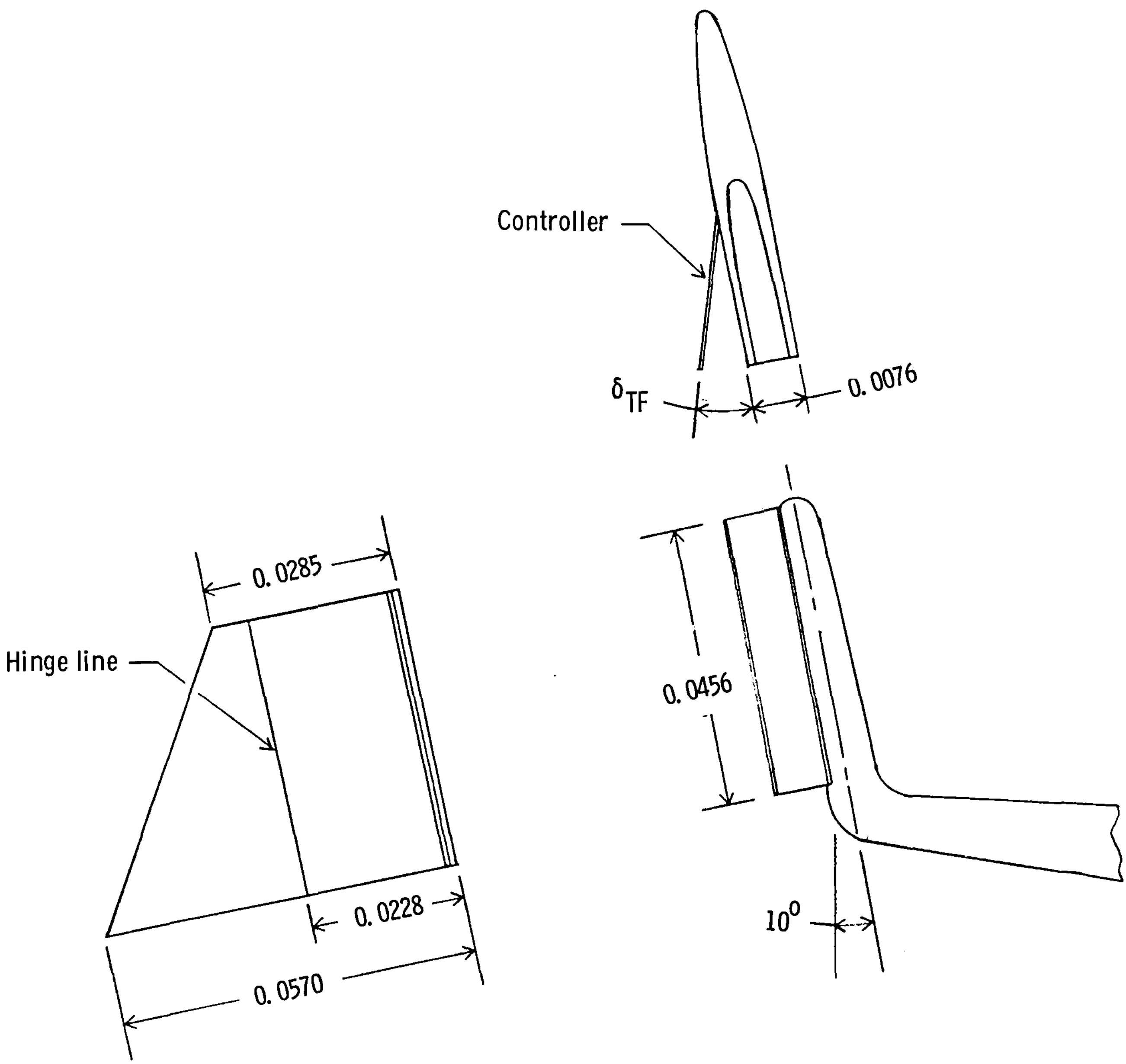
	Model 1 (BWVF)	Model 2 (BWTF)
Body:		
Length, m (ft)	66.79 (219.12)	66.79 (219.12)
Maximum width, m (ft)	15.93 (52.26)	15.93 (52.26)
Base area, m^2 (ft^2)	142.61 (1535)	142.61 (1535)
Fineness ratio[a]	4.955	4.955
Planform area, m^2 (ft^2)	815.21 (8774.9)	815.21 (8774.9)
Wing:		
Total area, m^2 (ft^2)	557.42 (6000)	557.42 (6000)
Span, m (ft)	37.18 (121.98)	37.18 (121.98)
Root chord at center line, m (ft)	26.07 (85.53)	26.07 (85.53)
Tip chord, m (ft)	4.82 (15.84)	4.82 (15.84)
Mean aerodynamic chord, m (ft)	17.72 (58.14)	17.72 (58.14)
Aspect ratio	2.48	2.48
Dihedral angle, deg	7	7
Incidence angle, deg	1.5	1.5
Leading-edge sweep, deg	50	50
Trailing-edge sweep, deg	0	0
Airfoil section at root	NACA 0008-64	NACA 0008-64
Airfoil section at tip	NACA 0012-64	NACA 0012-64
Elevon chord, m (ft)	3.54 (11.61)	3.54 (11.61)
Elevon span per side, m (ft)	10.63 (34.86)	10.63 (34.86)
Elevon total area, m^2 (ft^2)	75.2 (809.4)	75.2 (809.4)
Vertical tail:		
Root chord, m (ft)	10.88 (35.71)	
Tip chord, m (ft)	5.41 (17.74)	
Area, m^2 (ft^2)	83.61 (900)	
Span, m (ft)	10.27 (33.68)	
Leading-edge sweep, deg	45	
Trailing-edge sweep, deg	25	
Airfoil section	Wedge	
Body flap:		
Chord, m (ft)	4.57 (15)	4.57 (15)
Span, m (ft)	15.93 (52.26)	15.93 (52.26)
Area, m^2 (ft^2)	72.83 (783.9)	72.83 (783.9)
Tip fin:		
Root chord, m (ft)		3.81 (12.5)
Tip chord, m (ft)		1.90 (6.25)
Span, m (ft)		3.05 (10.0)
Area, m^2 (ft^2)		8.71 (93.75)
Toe-in angle, deg		2.33
Cant angle, deg		10
Controller chord, m (ft)		1.52 (4.99)
Controller span, m (ft)		3.04 (9.99)
Controller area, m^2 (ft^2)		4.64 (49.92)

[a] Values of fineness ratio are obtained by dividing the fuselage length by the diameter of a circle whose area equals the fuselage base area.



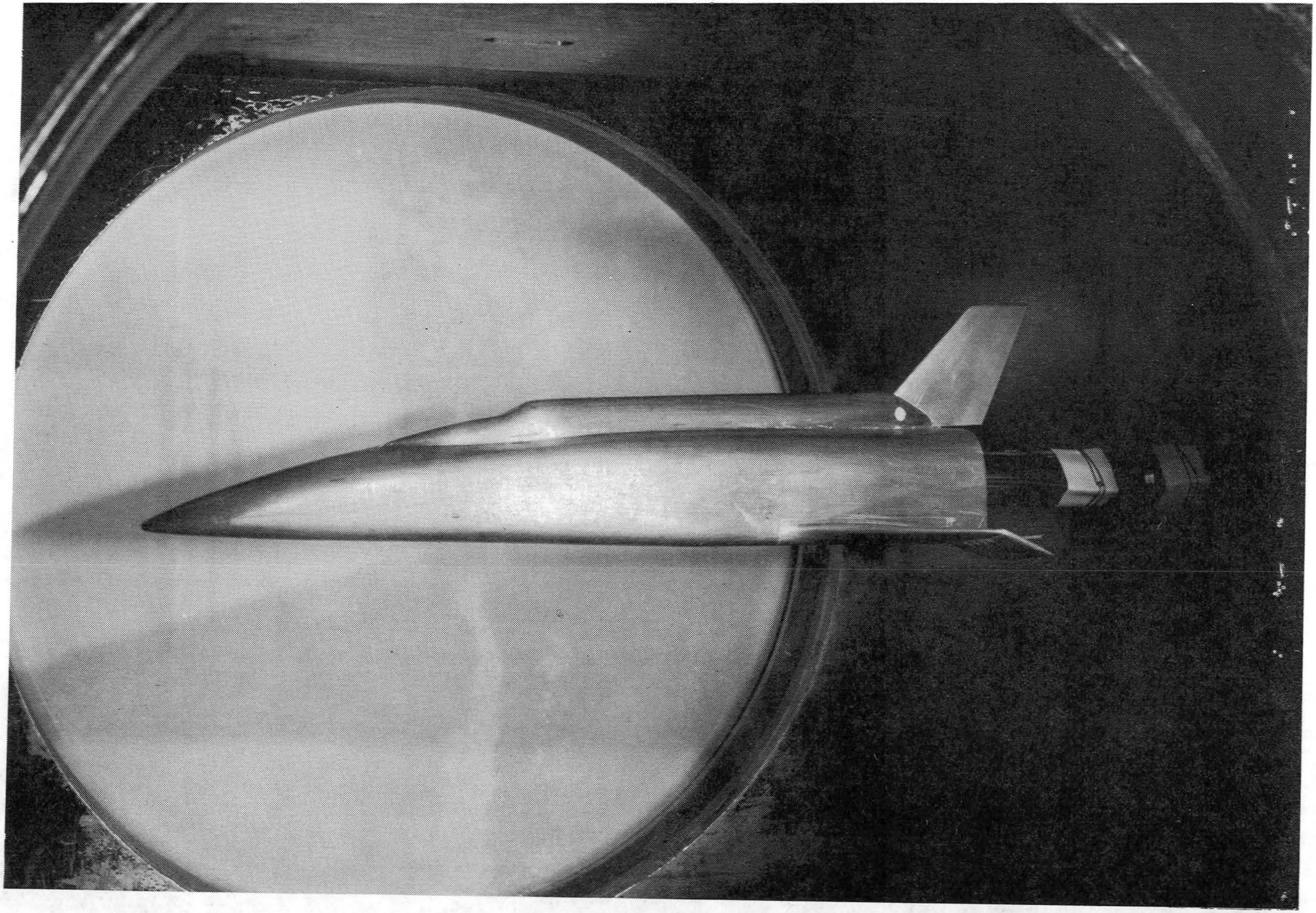
(a) Model 1.

Figure 1.- Model details. Dimensions are normalized by reference fuselage length, l.



(b) Tip-fin details for model 2.

Figure 1.- Concluded.



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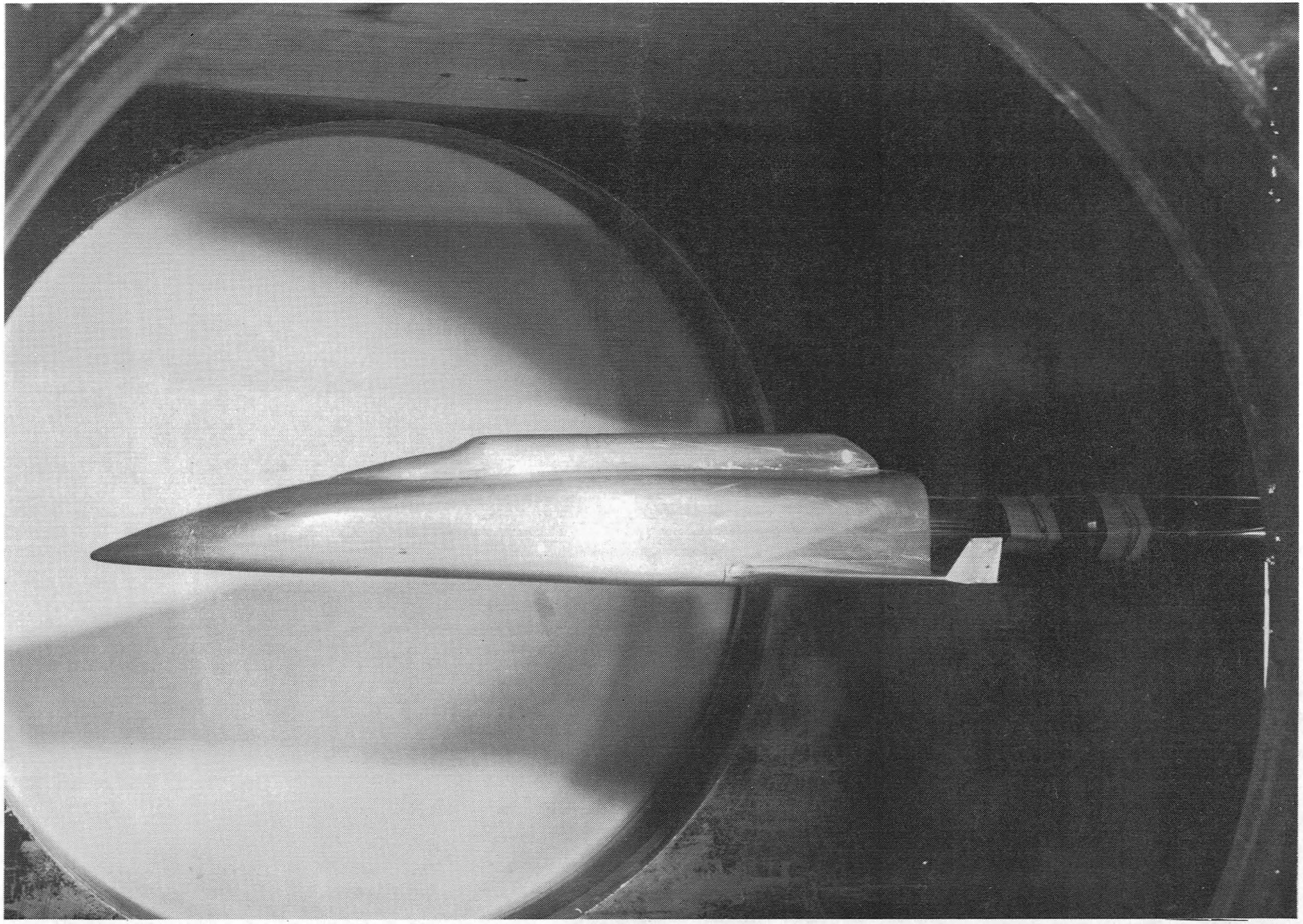
(a) Model 1.

Figure 2.- Model-sting arrangements in test section of Langley 20-Inch Mach 6 Tunnel.



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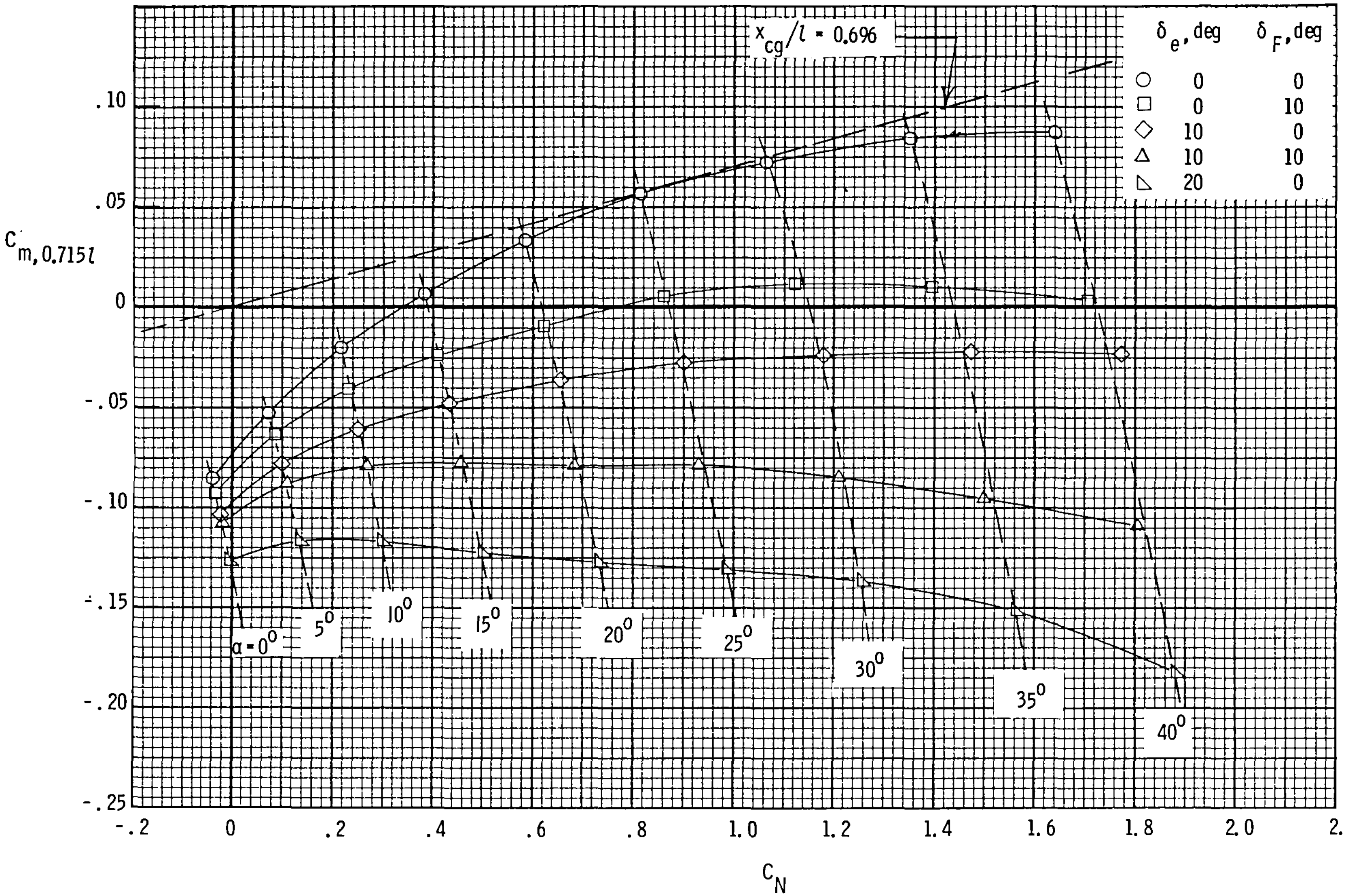
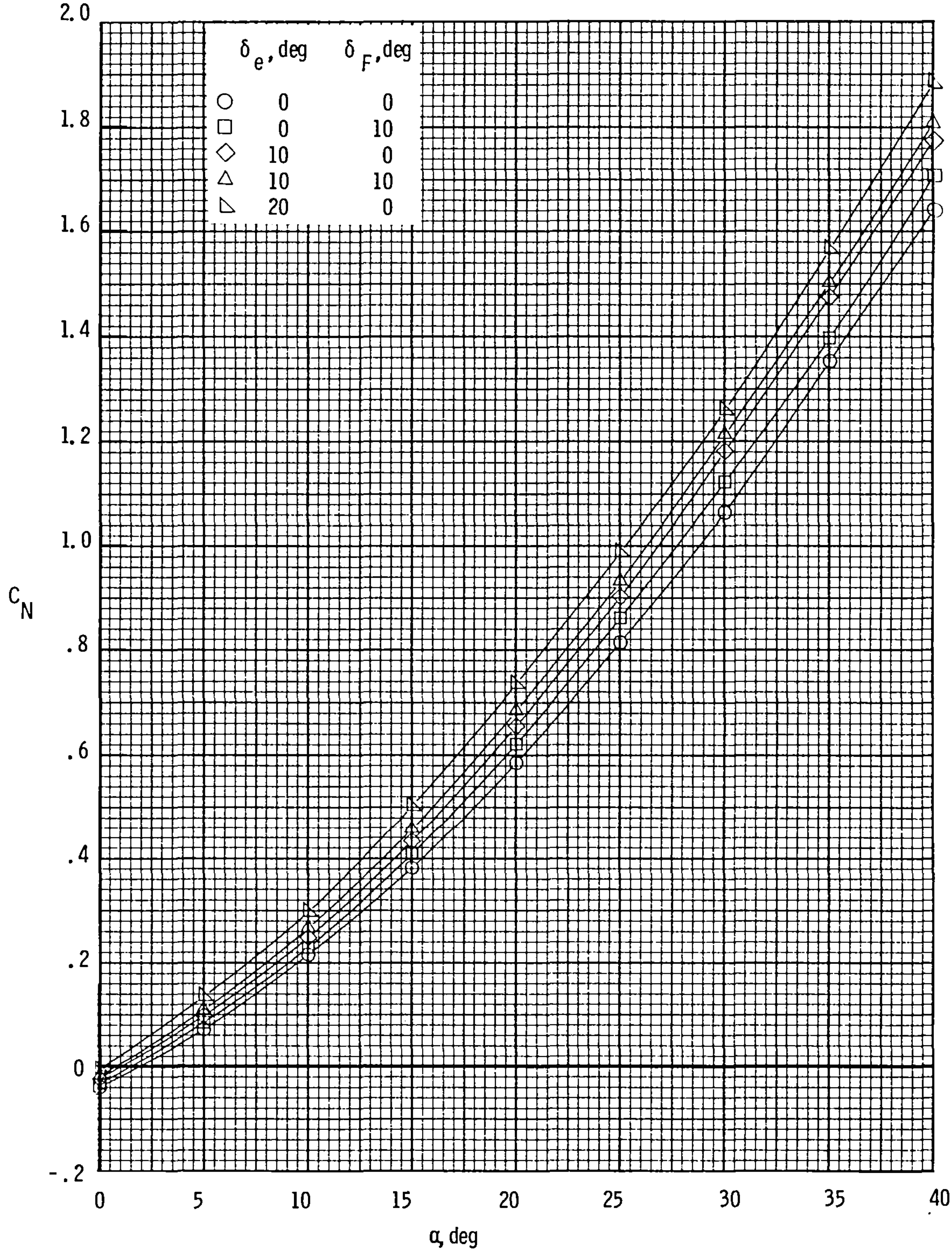
(b) Model 2.

Figure 2.- Concluded.



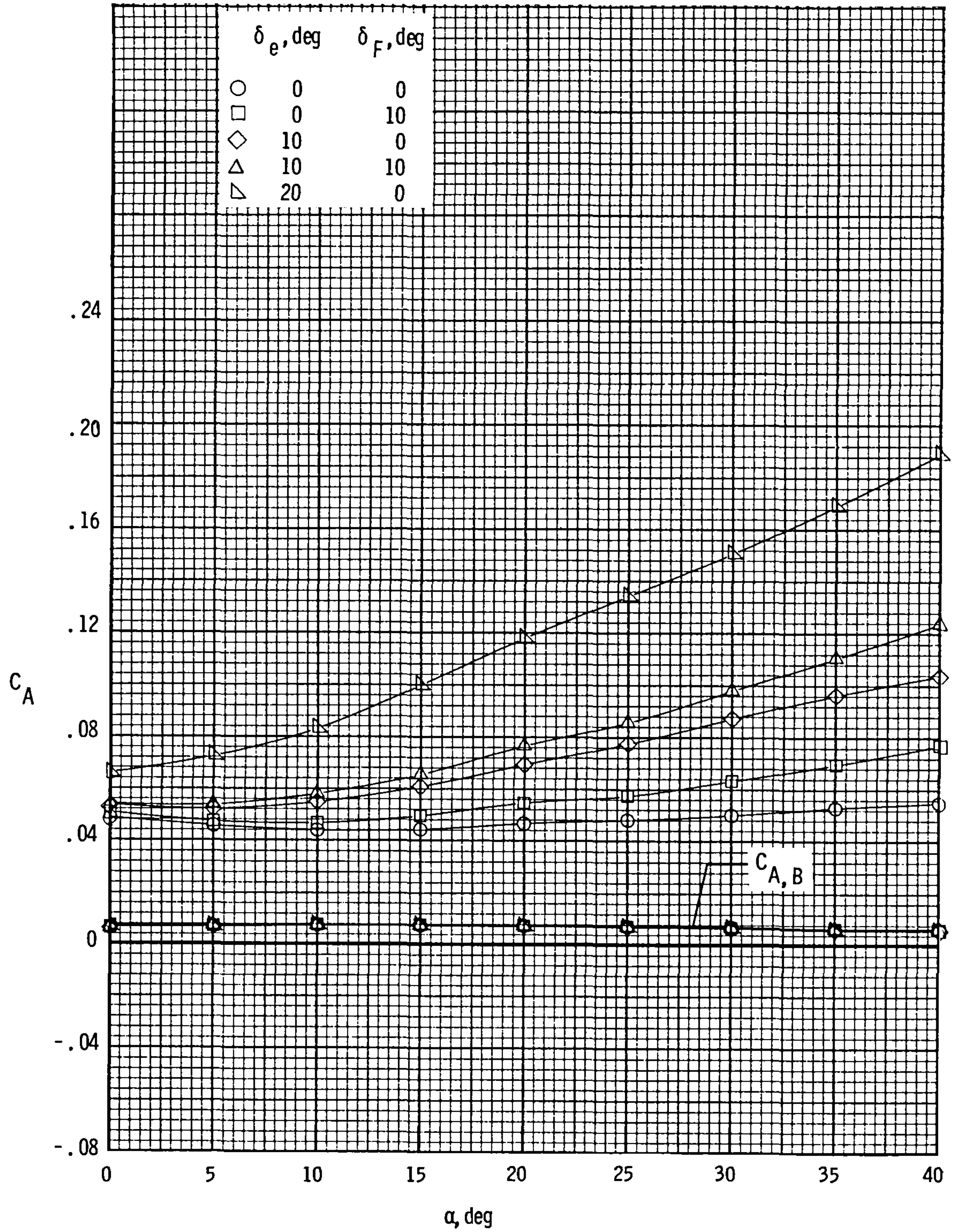
(a) C_m plotted against C_N.

Figure 3.- Effects of elevon and body-flap deflections on static longitudinal aerodynamic characteristics of model 1. $M = 5.93$; $R_l = 2.5 \times 10^6$.



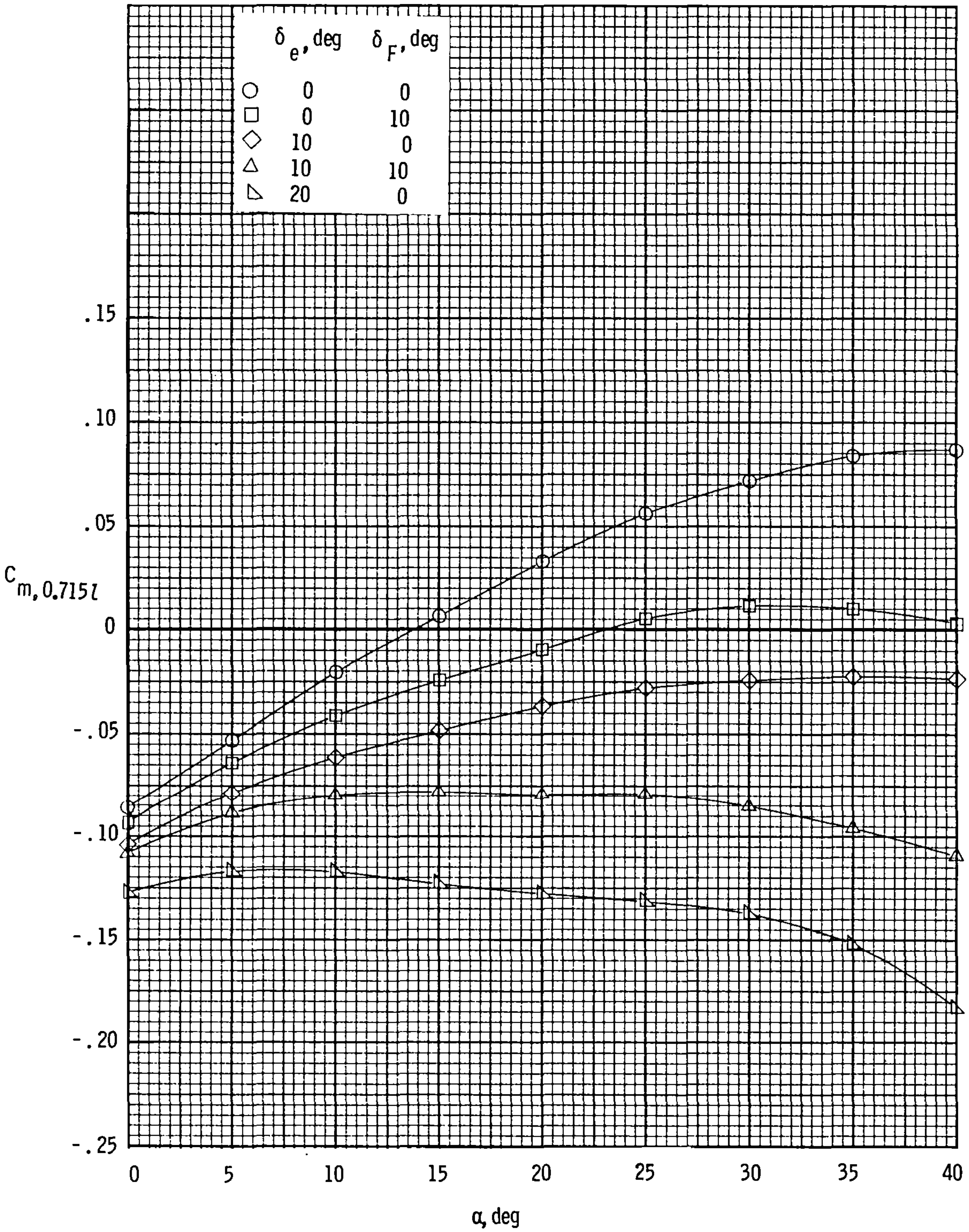
(b) C_N plotted against α.

Figure 3.- Continued.



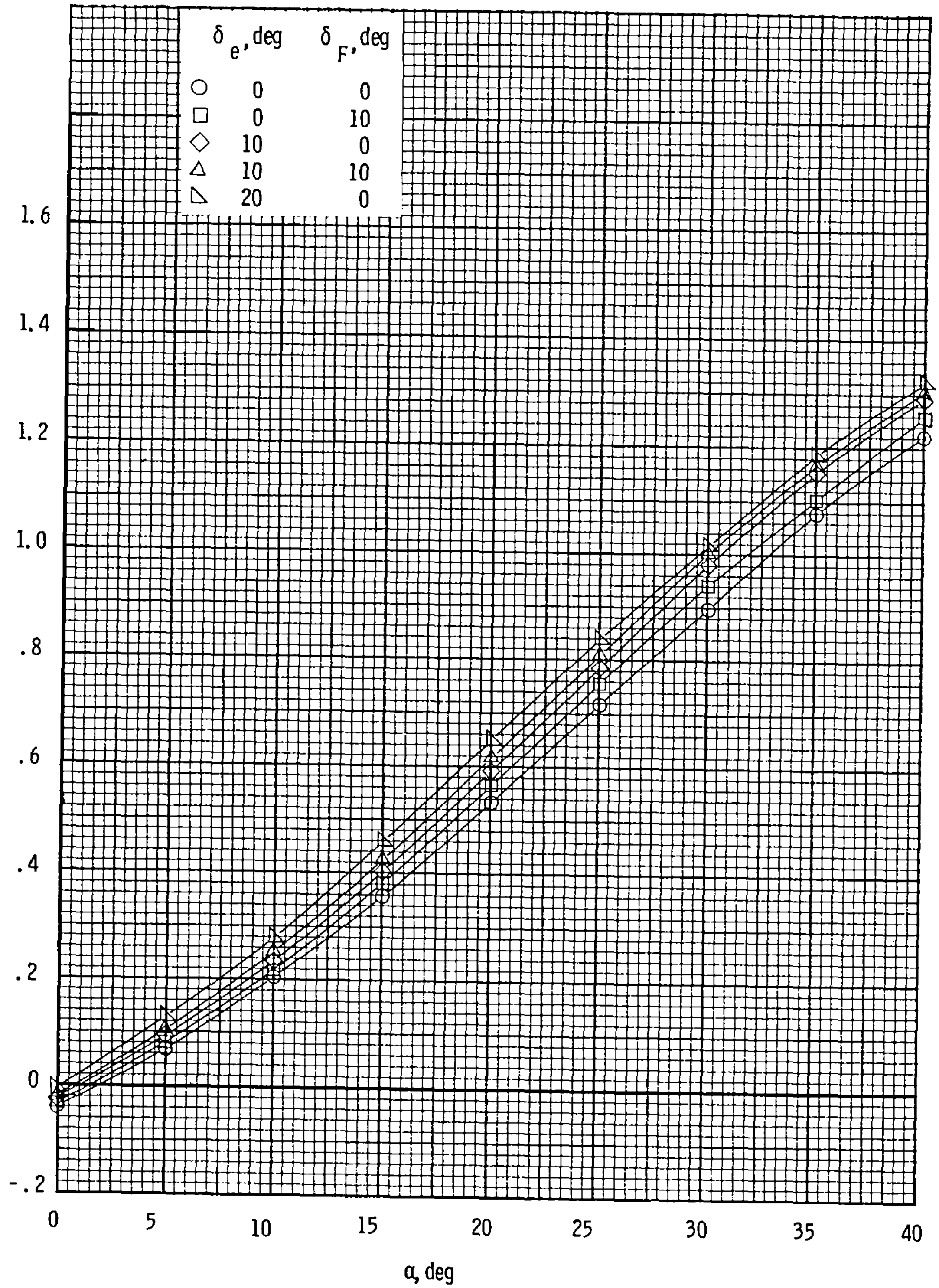
(c) C_A and $C_{A,B}$ plotted against α.

Figure 3.- Continued.



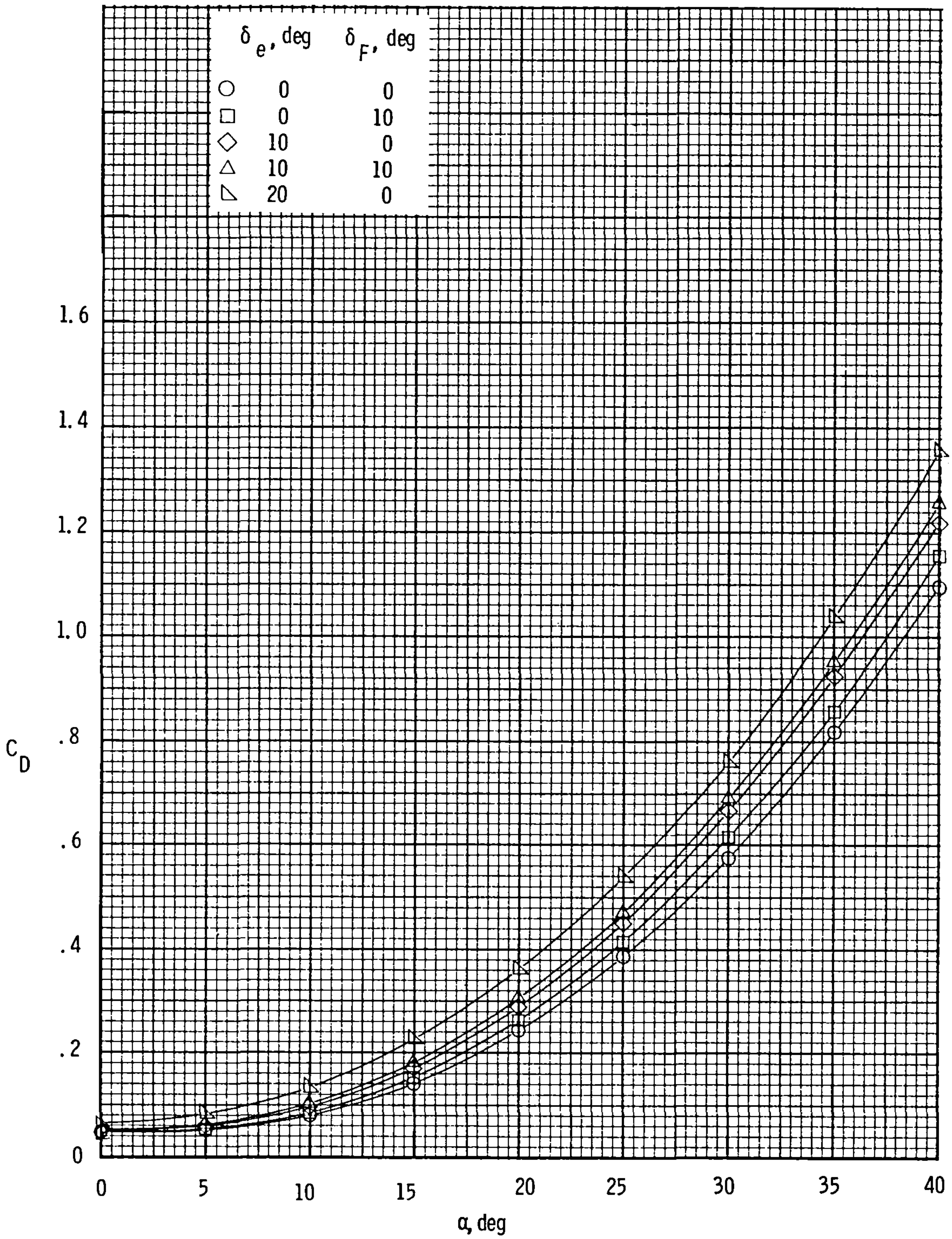
(d) C_m plotted against α.

Figure 3.- Continued.



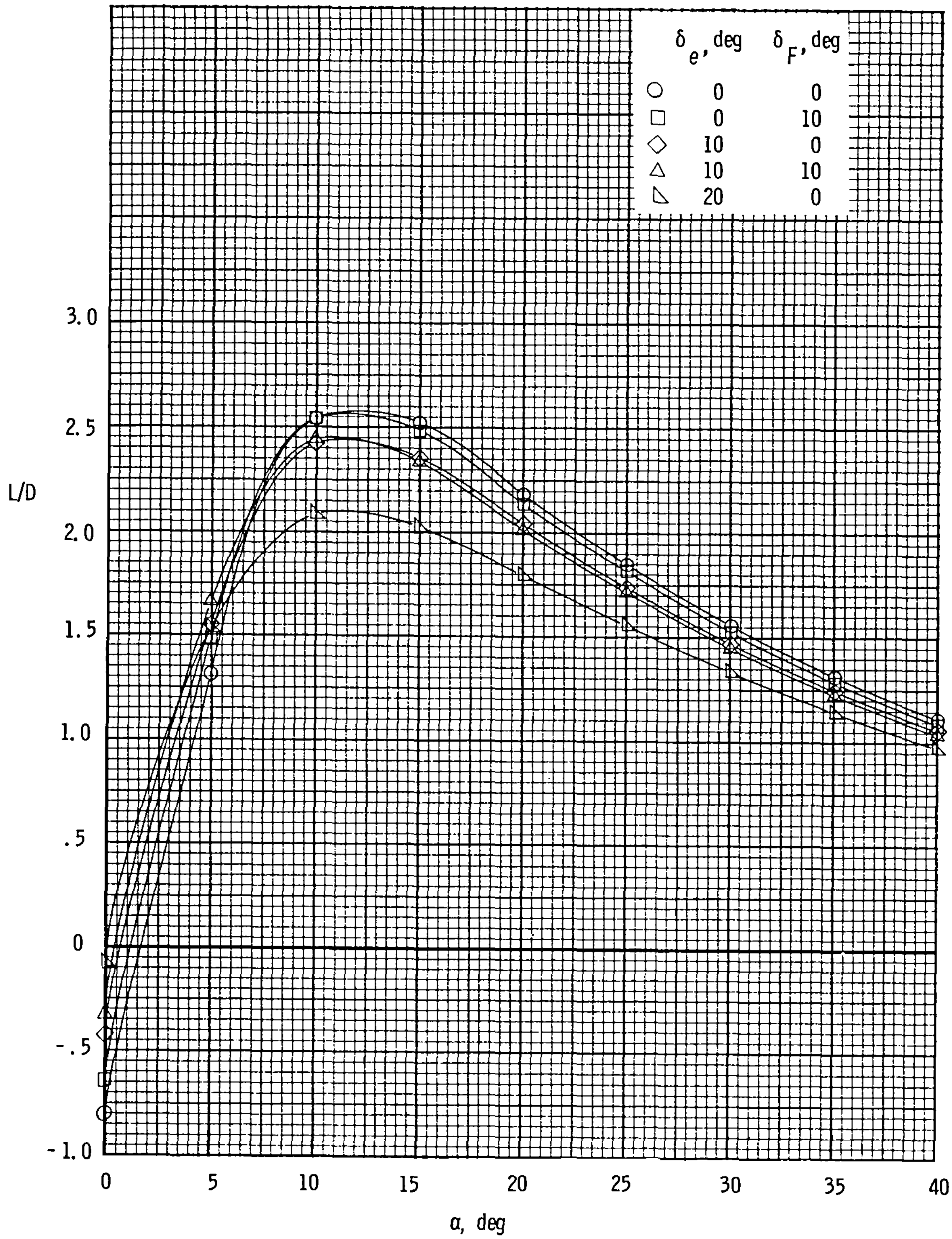
(e) C_L plotted against α.

Figure 3.- Continued.



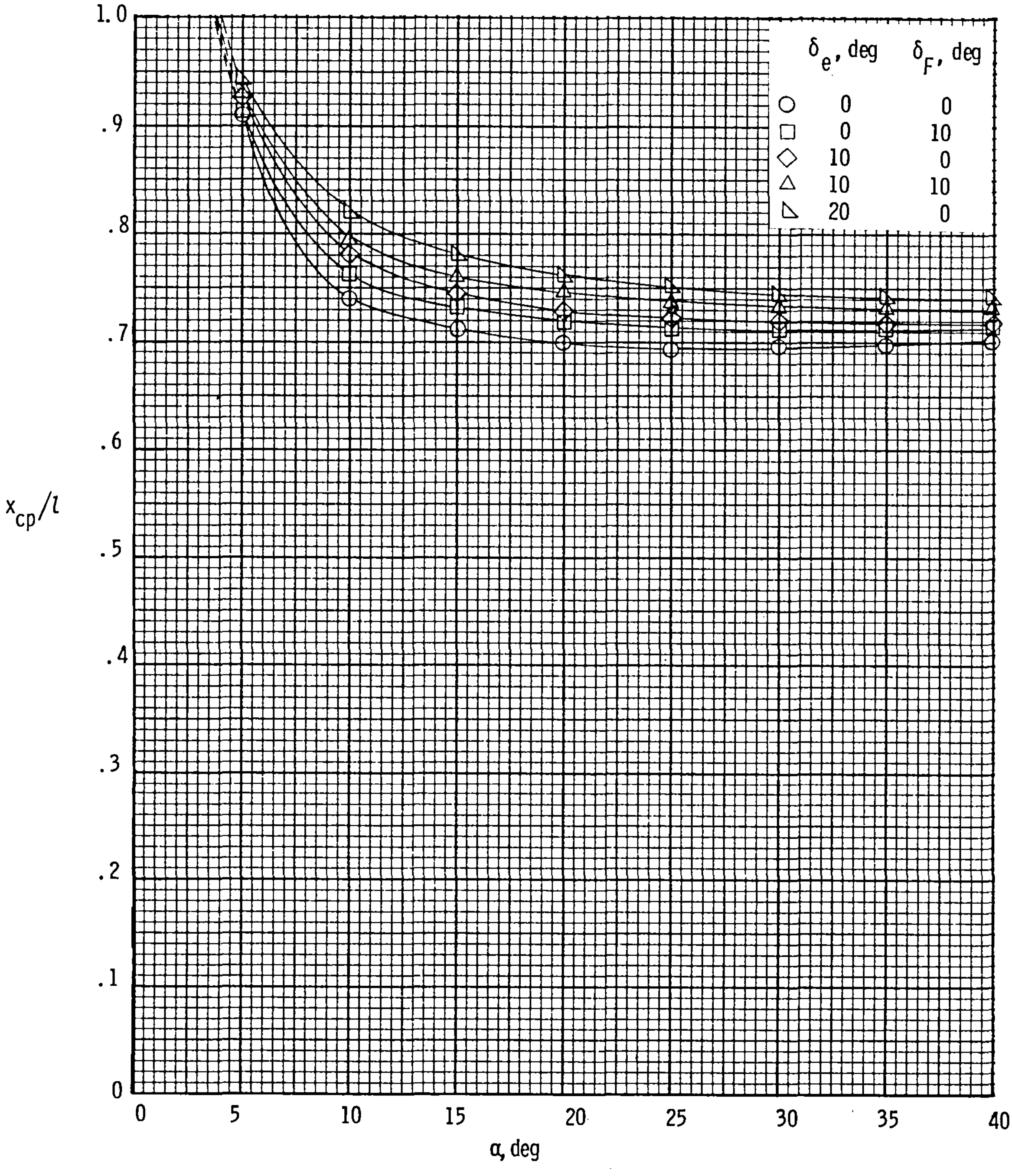
(f) C_D plotted against α.

Figure 3.- Continued.



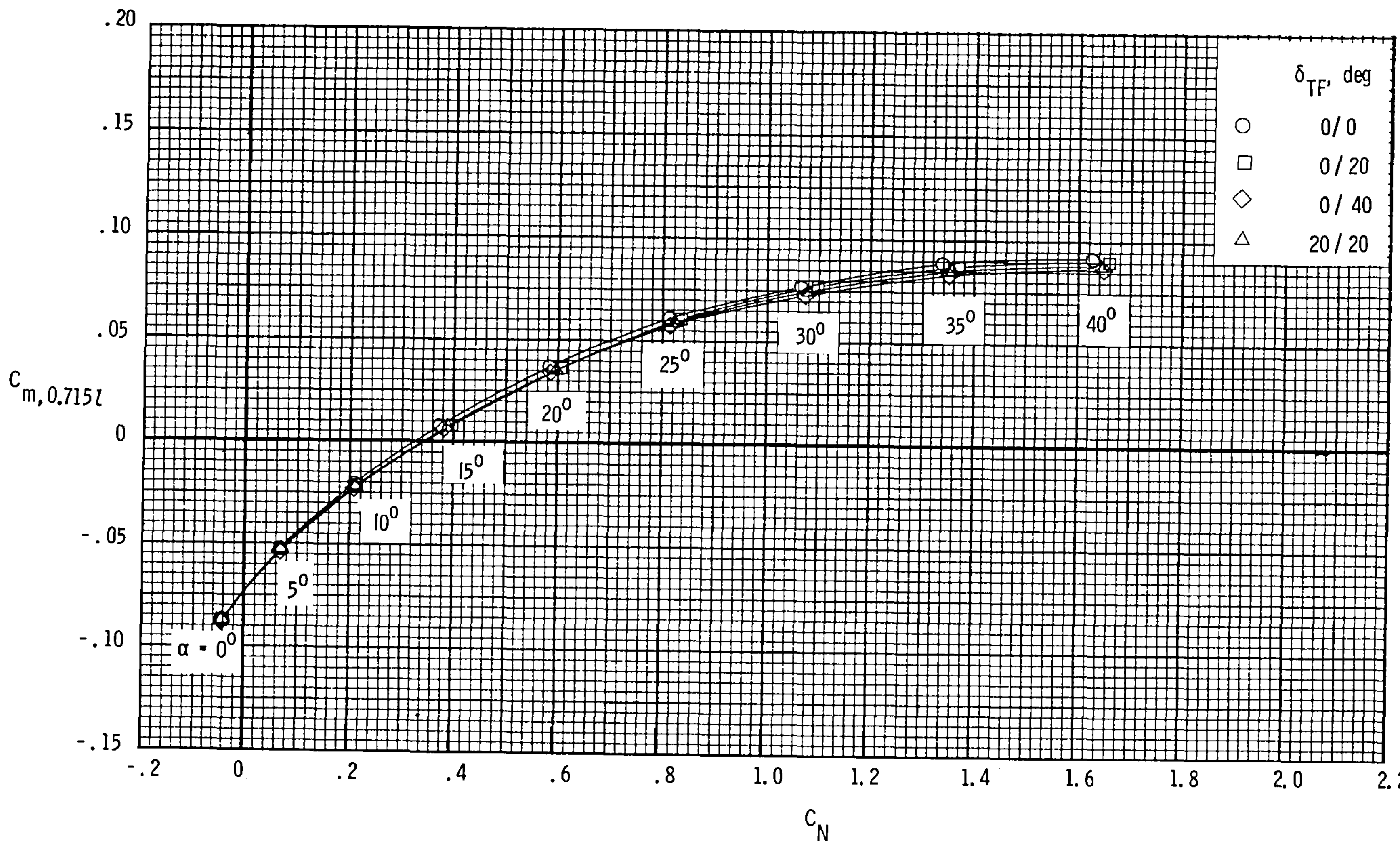
(g) L/D plotted against α.

Figure 3.- Continued.



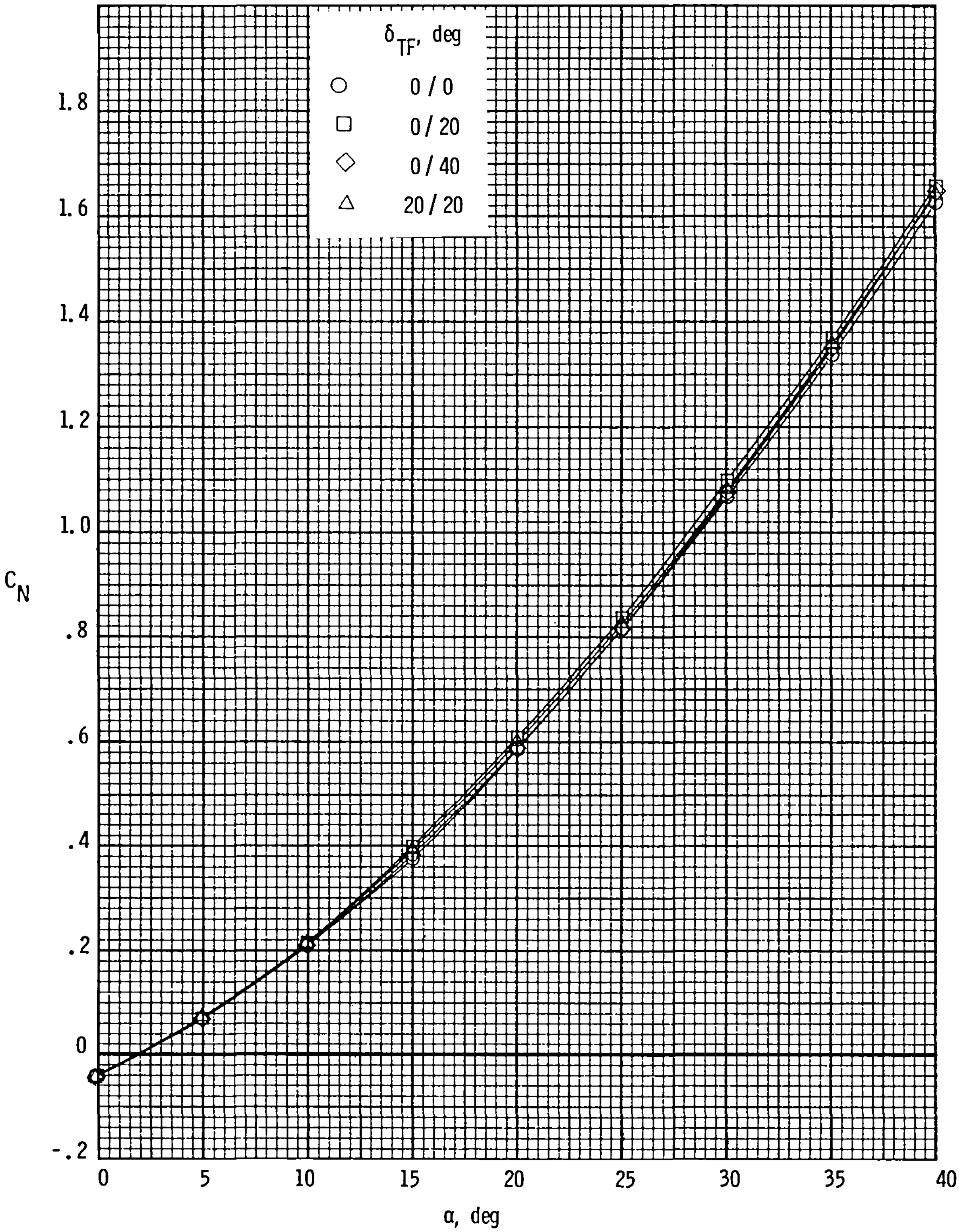
(h) x_{cp}/l plotted against α.

Figure 3.- Concluded.



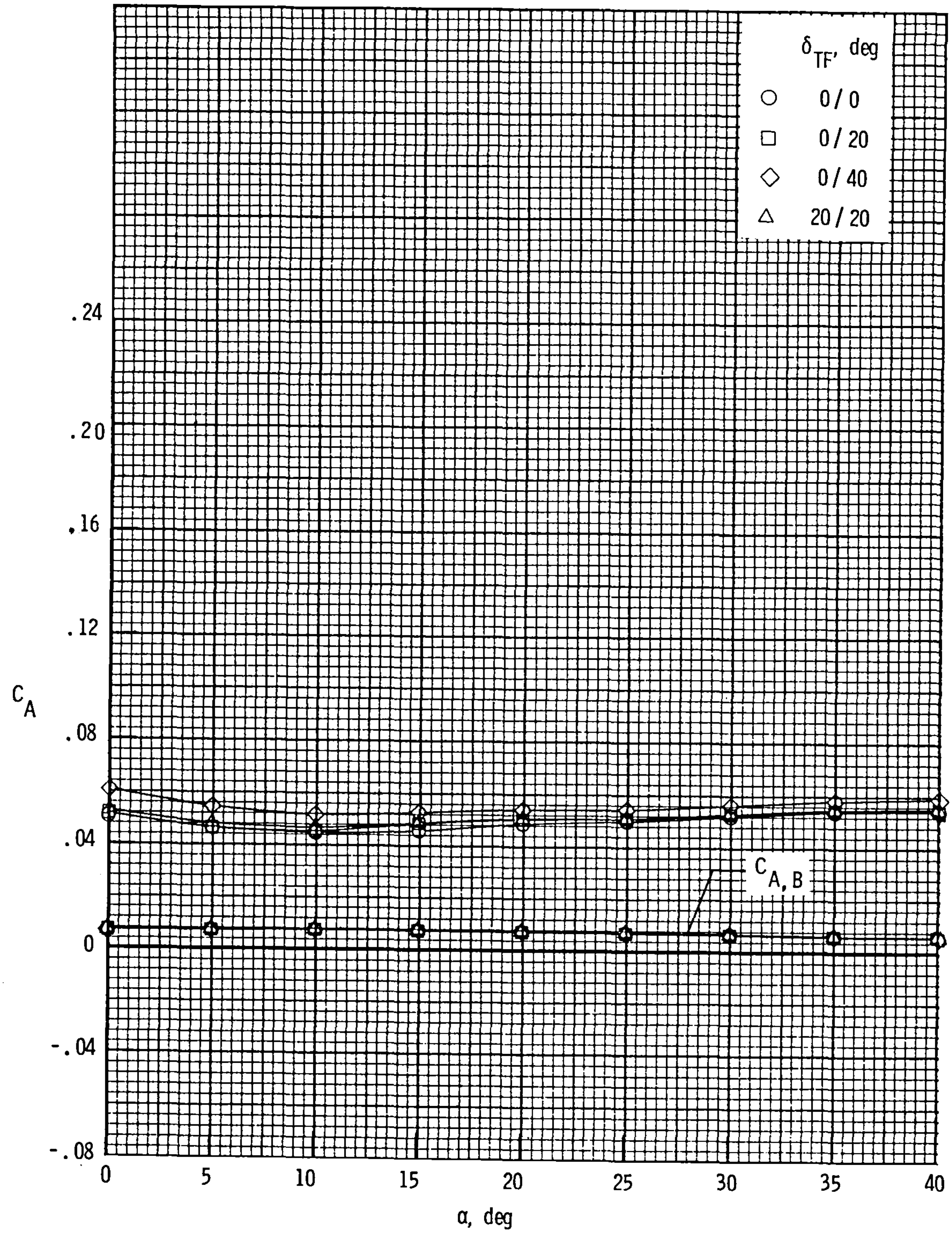
(a) C_m plotted against C_N.

Figure 4.- Effects of tip-fin controller deflection on longitudinal aerodynamic characteristics of model 2. $\delta_e = \delta_F = 0°$; $M = 5.93$; $R_l = 2.5 \times 10^6$.



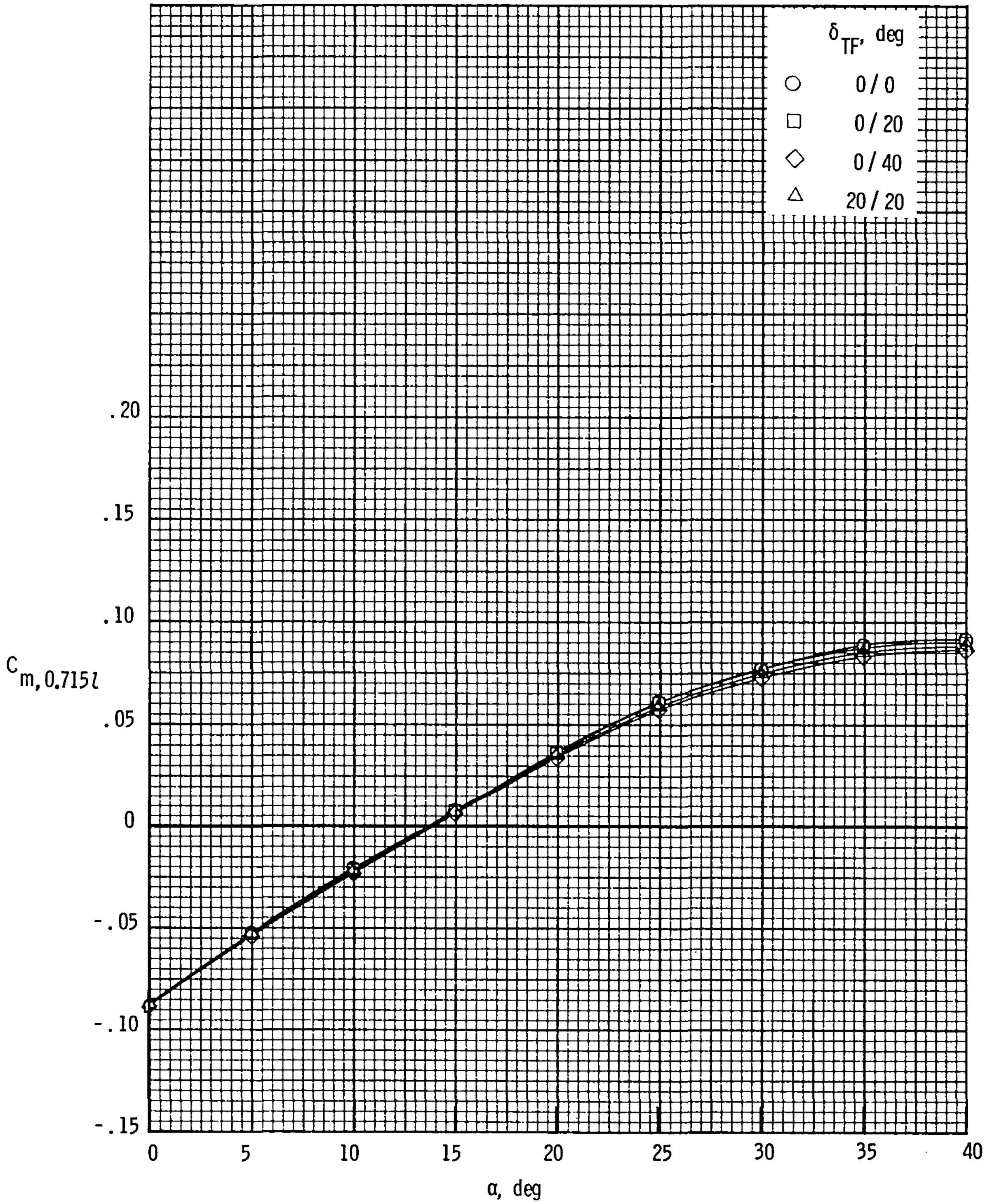
(b) C_N plotted against α.

Figure 4.- Continued.



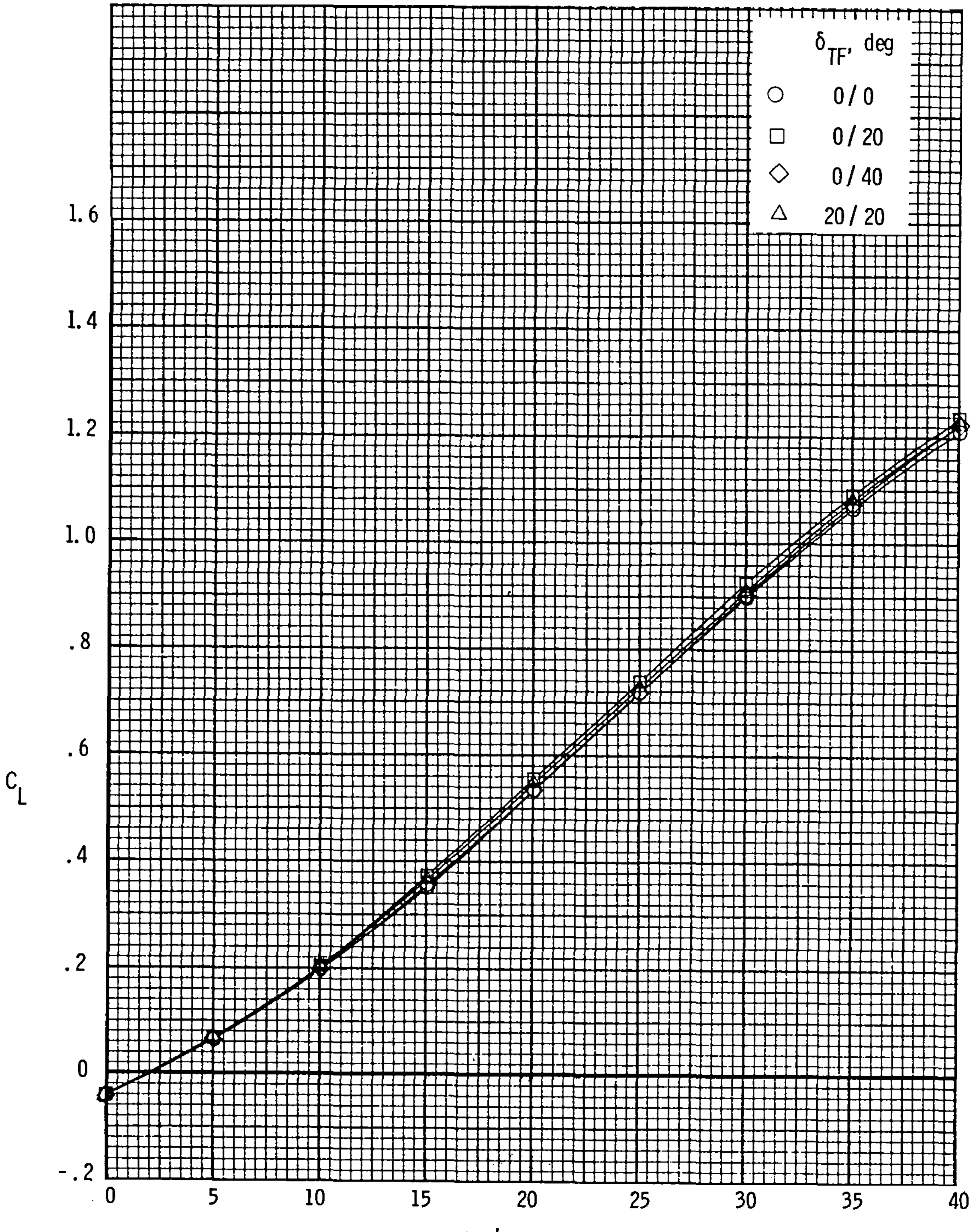
(c) C_A and $C_{A,B}$ plotted against α.

Figure 4.- Continued.



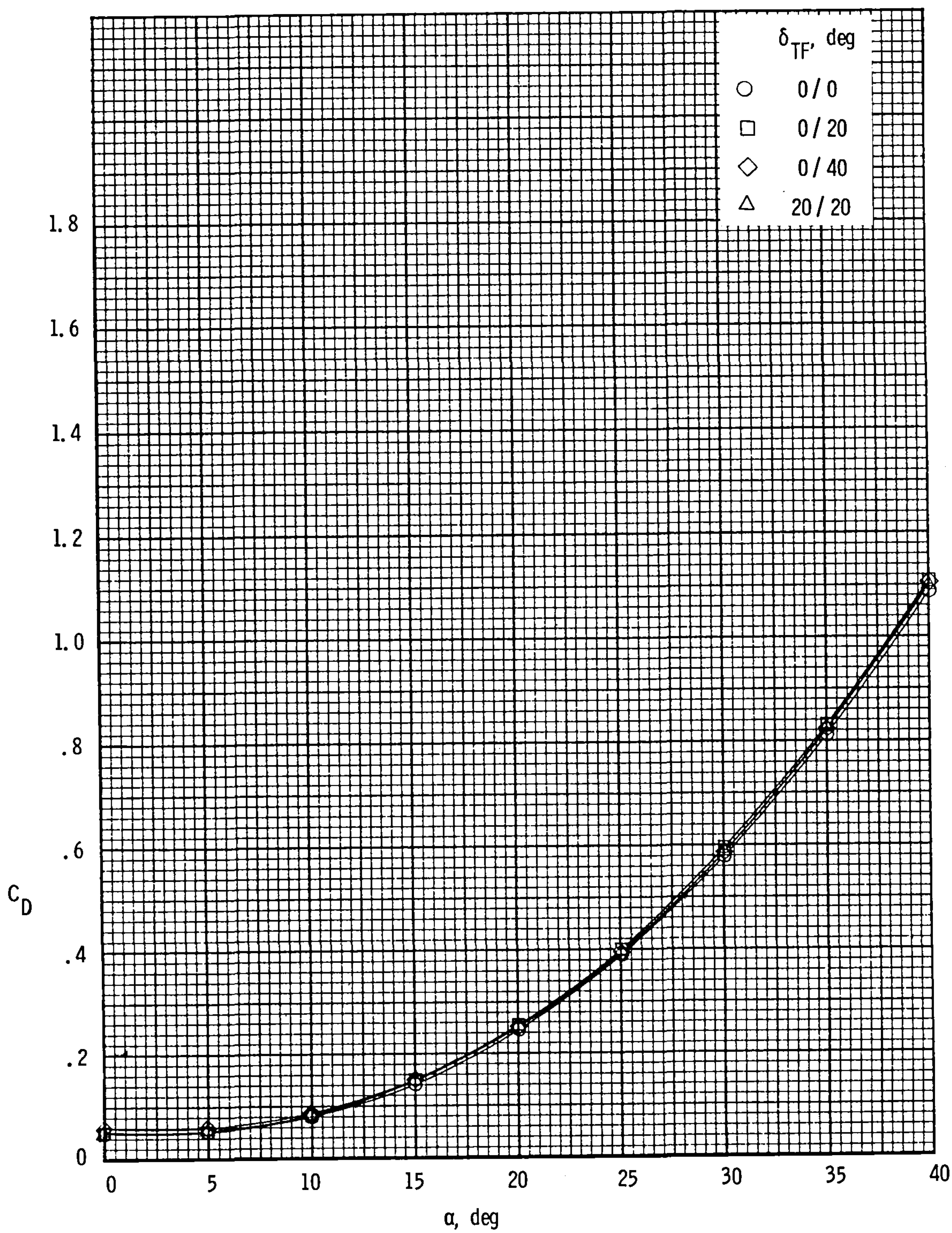
(d) C_m plotted against α.

Figure 4.- Continued.



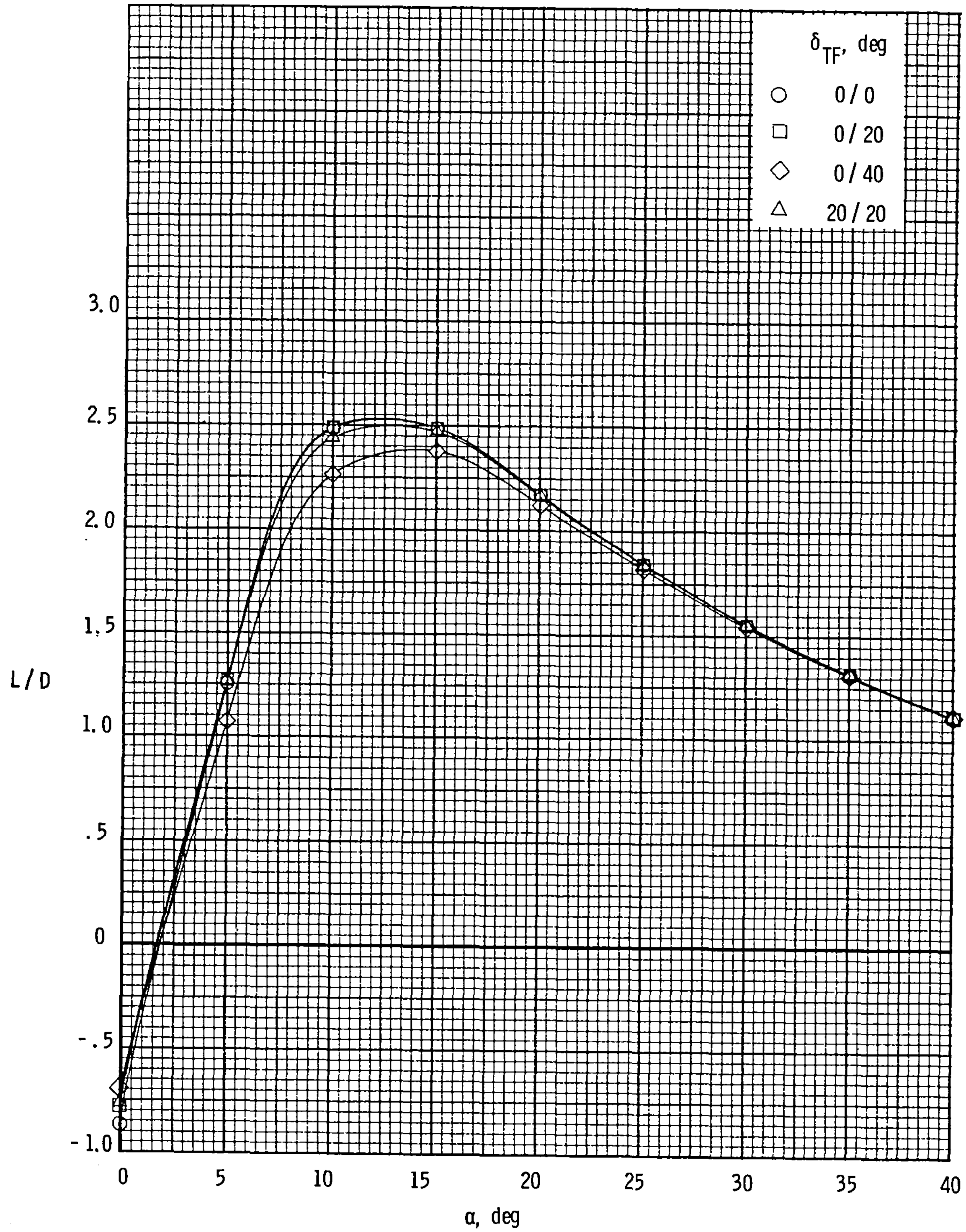
(e) C_L plotted against α.

Figure 4.- Continued.



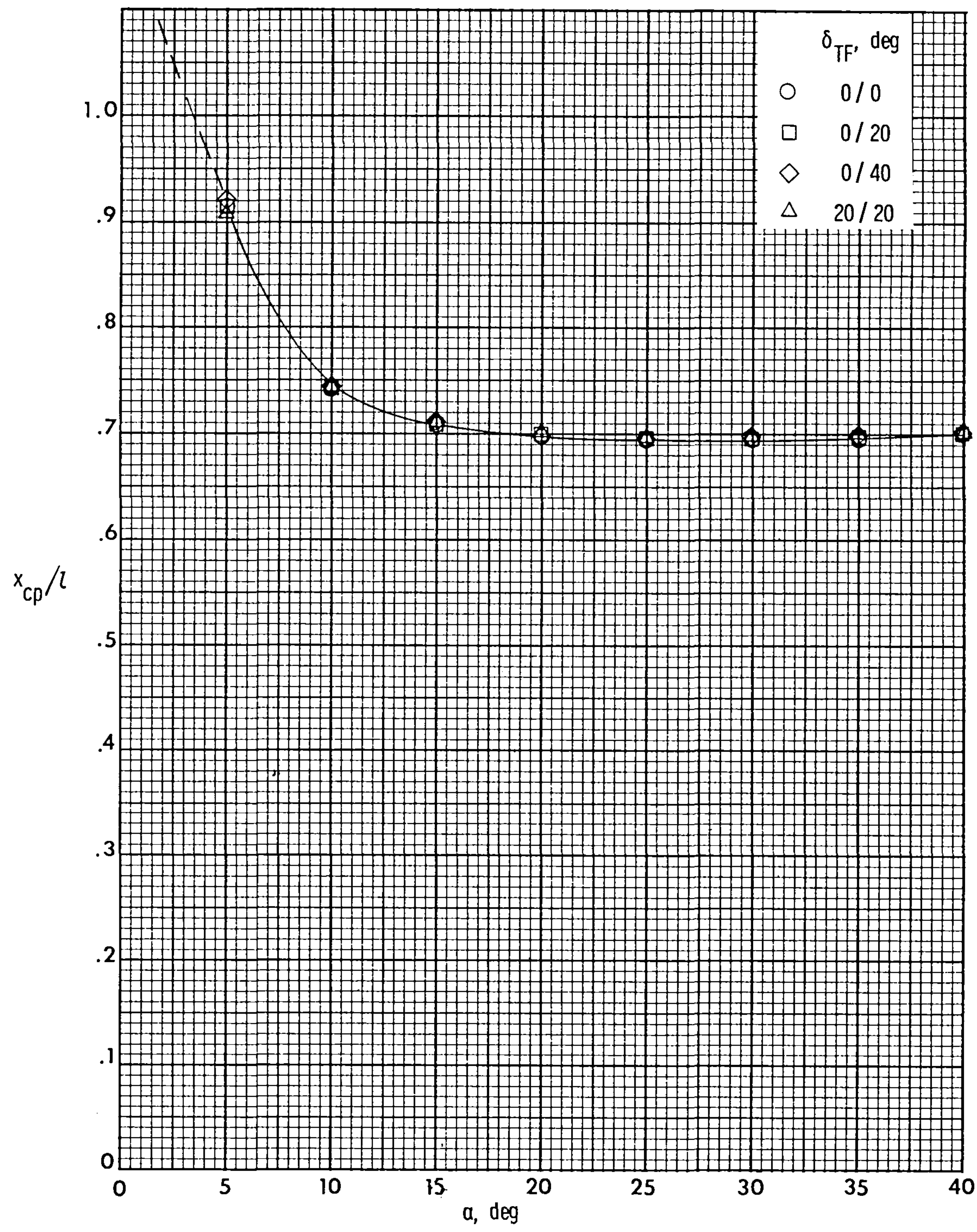
(f) C_D plotted against α.

Figure 4.- Continued.



(g) L/D plotted against α.

Figure 4.- Continued.



(h) x_{cp}/l plotted against α.

Figure 4.- Concluded.

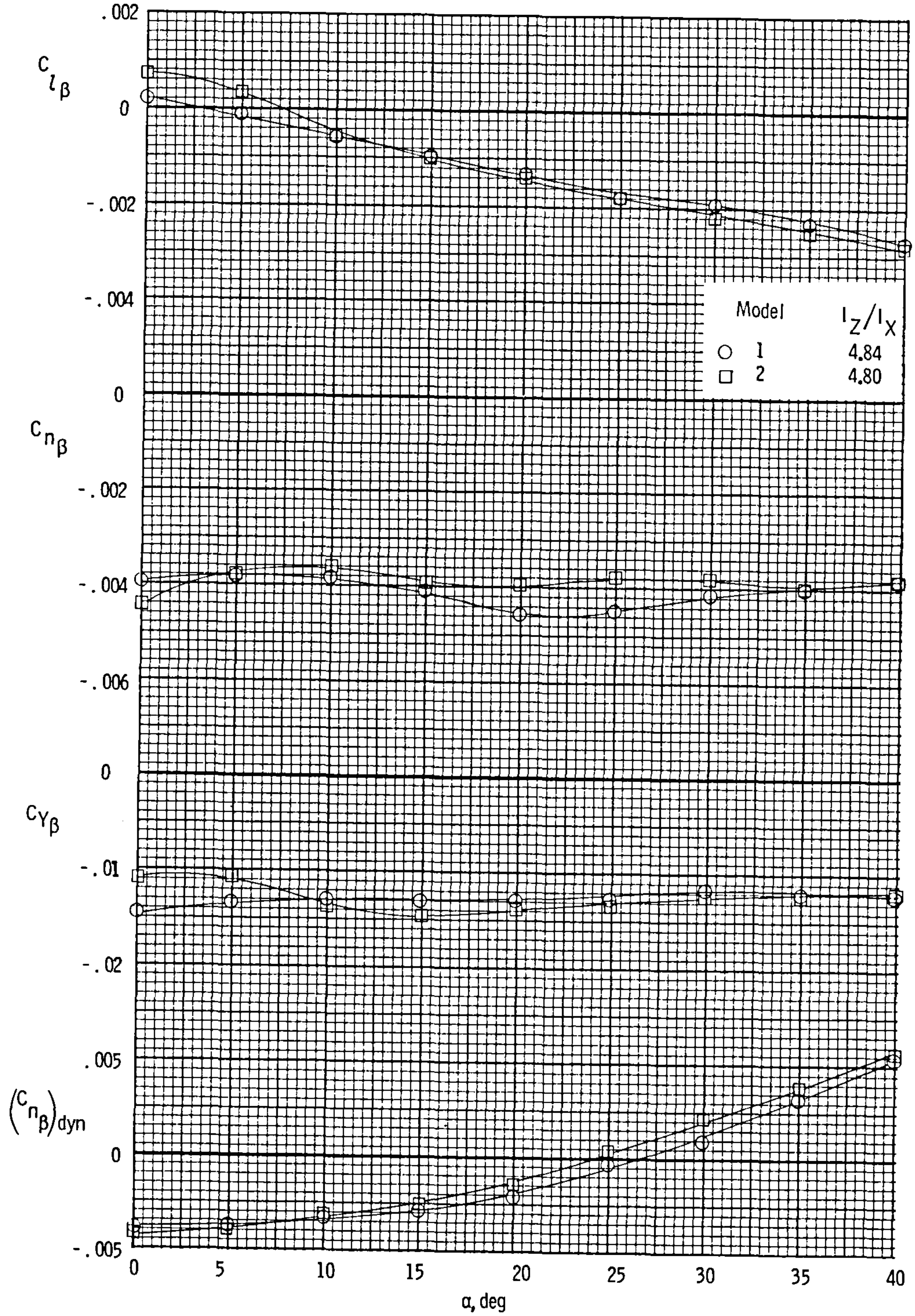


Figure 5.- Lateral-directional aerodynamic characteristics of models 1 and 2. $\delta_e = \delta_F = \delta_{TF} = 0°$; $M = 5.93$; $R_l = 2.5 \times 10^6$.

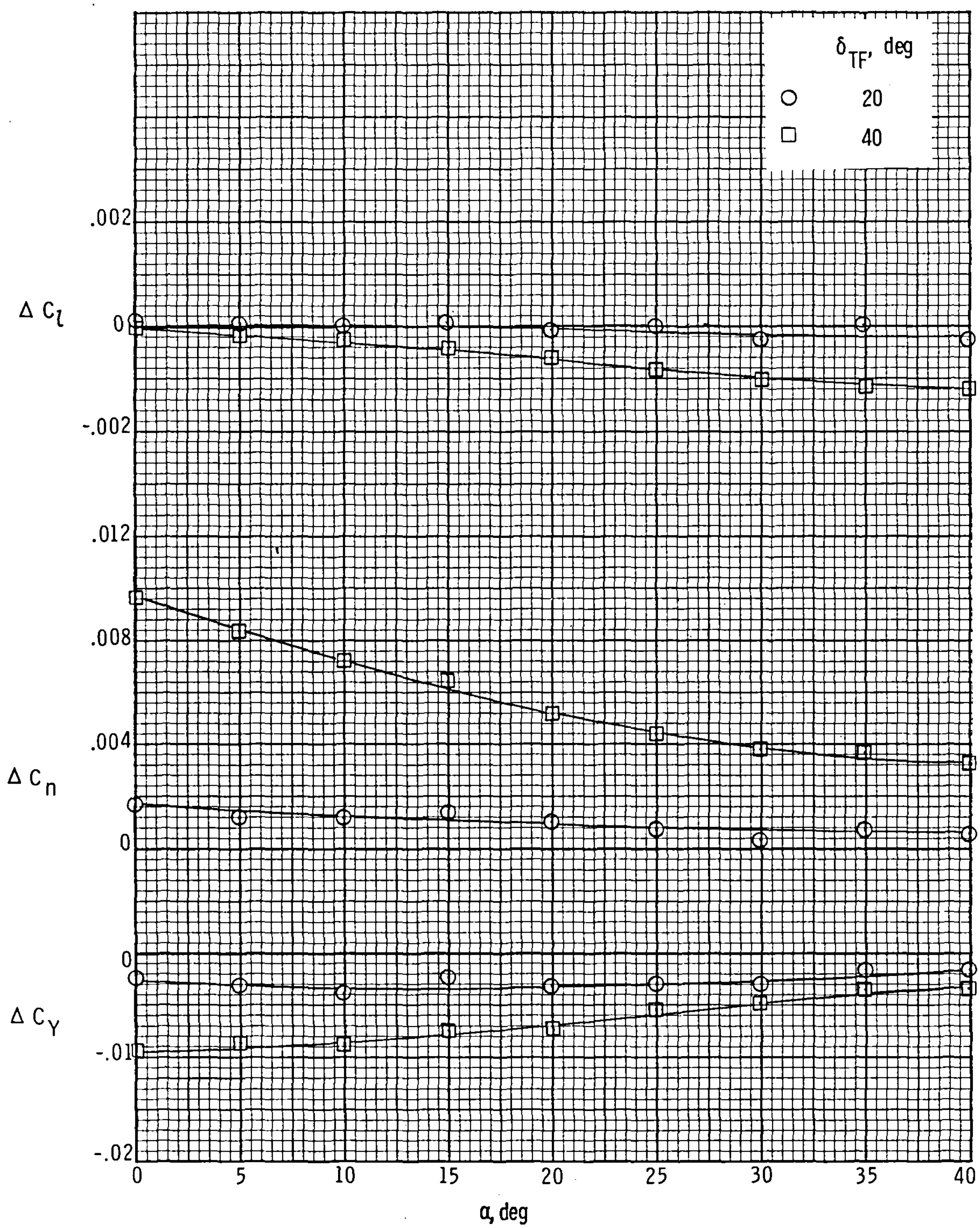


Figure 6.- Effects of tip-fin controller deflection of right wing-tip fin on lateral-directional control parameters of model 2. $\beta = \delta_e = \delta_F = 0°$; $M = 5.93$; $R_l = 2.5 \times 10^6$.

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16. Abstract

Hypersonic stability, control, and performance characteristics have been determined on a single-stage-to-orbit vehicle based on control-configured stability concepts. The configuration (0.006-scale model) had a large body with a small 50° swept wing. Two vertical-fin arrangements were investigated which consisted of a large center-line vertical tail and small wing-tip fins. The wing-tip fins had movable surfaces called controllers which could be deflected outward. Longitudinal and lateral-directional characteristics were obtained over an angle-of-attack range from 0° to 40°. The effects of tip-fin controller deflection on roll- and yaw-control characteristics at a sideslip angle of 0° were obtained. This investigation was conducted in the Langley 20-Inch Mach 6 Tunnel.

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