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SUMMARY

Tests have been conducted in the Langley 8-Foot Transonic Pressure Tunnel to obtain wind-tunnel data for comparison with static stability and control parameters from the Space Shuttle Orbiter approach and landing flight tests. The longitudinal-stability, elevon-effectiveness, lateral-directional stability, and aileron-effectiveness derivatives have been determined from the wind-tunnel data and compared with the flight-test results. The comparison covers a range of angles of attack from approximately 2° to 10° at subsonic Mach numbers of 0.41 to 0.56.

In general, the comparison showed that the wind-tunnel and flight-test results agreed quite well. This indicates the stability and control characteristics predicted with the wind-tunnel results appear to be adequate for entry-vehicle design for subsonic Mach numbers in the angle-of-attack range of the comparison.

INTRODUCTION

The Space Shuttle Orbiter approach and landing test (ALT) program has been completed, and aerodynamic flight-test data (refs. 1 and 2) have become available for analysis and for comparison with wind-tunnel data. Comparison of wind-tunnel data with the ALT results offers an opportunity to assess the validity of using wind-tunnel results in predicting the stability and control characteristics for the full-scale orbiter in the subsonic speed regime. To obtain the wind-tunnel values of static longitudinal and lateral-directional stability and control derivatives at conditions closely approximating those of the ALT flights, a 0.02-scale model of the orbiter with remotely driven elevons, ailerons, rudder, and body flap was tested in the Langley 8-Foot Transonic Pressure Tunnel.

Because of the nature of the ALT flight program, all of the data obtained are for a Mach number range from 0.41 to 0.56 and are for an angle-of-attack range from approximately 2° to 10°. Longitudinal and lateral-directional stability and elevon and aileron control effectiveness have been obtained in the wind tunnel where the flight values of the angle of attack, Mach number, trimmed elevon deflection, body-flap deflection, and speed-brake position were duplicated as closely as possible. With these data a comparison has been made of the stability and control characteristics determined from the ALT flights and the Space Shuttle Orbiter design data book (ref. 3), and the results are presented herein.

SYMBOLS

Both the longitudinal and the lateral-directional data are referred to the body system of axes. The origin of the axis was located to correspond to the position of the moment reference center shown in figure 1.

b	reference wing span, m
C_l	rolling-moment coefficient, Rolling moment/$q_\infty Sb$
C_{l_β}	effective-dihedral parameter, $\Delta C_l/\Delta\beta$, $\beta = 0^\circ$ and 1°, per degree
$C_{l_{\delta_a}}$	roll-control effectiveness, $\Delta C_l/\Delta\delta_a$, per degree
C_m	pitching-moment coefficient, Pitching moment/$q_\infty S\bar{c}$
C_{m_α}	$= \Delta C_m/\Delta\alpha$, per degree
$C_{m_{\delta_e}}$	$= \Delta C_m/\Delta\delta_e$, per degree
C_N	normal-force coefficient, Normal force/$q_\infty S$
C_{N_α}	$= \Delta C_N/\Delta\alpha$, per degree
$C_{N_{\delta_e}}$	$= \Delta C_N/\Delta\delta_e$, per degree
C_n	yawing-moment coefficient, Yawing moment/$q_\infty Sb$
C_{n_β}	directional-stability parameter, $\Delta C_n/\Delta\beta$ ($\beta = 0^\circ$ and 1°), per degree
$C_{n_{\delta_a}}$	yawing-moment due to aileron deflection, $\Delta C_n/\Delta\delta_a$, per degree
C_Y	side-force coefficient, Side force/$q_\infty S$
C_{Y_β}	side-force parameter, $\Delta C_Y/\Delta\beta$ ($\beta = 0^\circ$ and 1°), per degree
$C_{Y_{\delta_a}}$	$= \Delta C_Y/\Delta\delta_a$, per degree
$\bar{c}$	mean aerodynamic chord, m
l	body length, m
M	free-stream Mach number
q_∞	free-stream dynamic pressure, N/m^2
S	reference area, m^2
α	angle of attack, deg
β	angle of sideslip, deg

δ_a aileron deflection angle, (Left elevon - right elevon)/2, deg

δ_{BF} body-flap deflection, positive for trailing edge down, deg

δ_e elevon deflection, positive for trailing edge down, (Left elevon + right elevon)/2 deg

δ_{SB} speed-brake deflection, deg

VEHICLE DEFINITION AND TEST CONDITIONS

Drawings of the 0.02-scale model used in the wind-tunnel tests and Orbiter 101 used in the flight tests are presented in figures 1 and 2. A photograph of Orbiter 101 in flight is presented in figure 3. The 0.02-scale wind-tunnel model and Orbiter 101 have identical lines except for installation of a nose probe for the flight tests. The model was constructed with the capability to remotely set the elevons, ailerons, body flap, and rudder. This remote capability allowed easy duplication of flight values of elevon, body-flap, aileron, rudder, and speed-brake deflections. In both the flight and wind-tunnel tests, data were obtained at trimmed elevon deflections for speed-brake settings of 3.5° and 43°. A list of the wind-tunnel test conditions is presented in table I.

TABLE I.- WIND-TUNNEL TEST CONDITIONS

α, deg	M	δ_{SB}, deg	δ_{BF}, deg	δ_e, deg
Longitudinal data				
10.1	0.41	3.5	-0.5	2.9
6.0	.56	3.5	↓	1.8
4.2	.52	3.5	↓	2.2
2.4	.51	43.0	↓	4.4
Lateral-directional data				
10.1	0.41	3.5	-0.5	2.9
6.9	.49	↓	↓	2.2
3.8	.53	↓	↓	2.2
3.6	.56	↓	↓	1.4
2.9	.53	43.0	↓	4.4

The Reynolds number based on model length for the wind-tunnel tests varied from 7 to 9 × 10^6 compared with 350 to 625 × 10^6 for the flight test. A description of the Langley 8-Foot Transonic Pressure Tunnel is given in reference 4. For all of the wind-tunnel tests, boundary-layer transition strips 0.16 cm wide were applied to the model. The strips consisted of sparsely distributed carborundum grains, those with No. 100 grains located 1.27 cm (measured streamwise) from the leading edge of all lifting surfaces and those with No. 120 grains located 3.05 cm aft of the nose. The size of the carborundum grains was determined with the sizing methods of reference 5. The estimated accuracy of the wind-tunnel data is presented in table II.

TABLE II.- ACCURACY OF WIND-TUNNEL DATA

Parameter	Accuracy
C_N	±0.0060
C_m	±.0012
C_l	±.0025
C_n	±.0025
C_Y	±.0022

RESULTS AND DISCUSSION

A comparison of the stability and control derivatives measured in the wind tunnel with those measured by both the Air Force and NASA in ALT flights 4 and 5 (refs. 1 and 2) as well as those presented in the orbiter aerodynamic design data book (ref. 3) are presented in figures 4 to 7. The basic wind-tunnel data are presented in the appendix. The values from reference 3 are from averaging a large volume of data obtained prior to the ALT flights. These values have been corrected for aeroelastic effects. The results of the wind-tunnel tests, which have not been corrected for aeroelastic effects, provide a direct comparison of wind-tunnel and flight-test data measured for the same configuration (i.e., elevon, rudder, speed-brake, and body-flap deflection). Each of the flight-test data points represents a specific Mach number and angle of attack. A band of uncertainty labeled "Variations" (defined in ref. 3) is presented in the comparison figures. These variations are determined from wind-tunnel and flight-test data from previous aircraft that have basic similarities with the Space Shuttle. (See ref. 2.)

Longitudinal Stability and Control

Comparisons of the longitudinal-stability and control data are presented in figures 4 and 5. The longitudinal-stability data presented in figure 4 show the orbiter to be slightly stable with the reference center of gravity ($0.65l$) for both the flight and wind-tunnel results. The comparisons also show that the longitudinal stability determined from the wind-tunnel tests falls within the accuracy band (ref. 1) presented for the ALT flight data, indicating good agreement between the wind-tunnel data and both sets of flight data. The values of C_{m_α} and the variations obtained from reference 3 for

Mach numbers of 0.4 and 0.6 are also presented. In general, the data-book values (ref. 3) indicate a lower level of stability over the test angle-of-attack range than either the flight or wind-tunnel results. In all cases, both the wind-tunnel and flight-test values of C_{m_α} fall within the variation band.

There are three sets of flight-test values of C_{N_α} presented in the comparison in figure 4. Reference 1 provided C_{N_α} data that were extracted with both a primary and a back-up accelerometer, whereas only one set of data is presented from reference 2. Both references 1 and 2 describe some specific data-measurement problems that affected the accuracy of extracting certain derivatives. Reference 1 indicates that this accuracy problem does affect C_{N_α} and, therefore, both the primary- and the backup-accelerometer data are presented with no conclusion as to which is more accurate. The comparison of the wind-tunnel results with the flight-test data does not reinforce the accuracy of either set of flight-test data. The only conclusion that can be drawn about C_{N_α} is that the wind-tunnel data agree with the data-book values of reference 3 and that the flight-test data do differ from the data-book values but do not fall outside of the variation band. This is entirely consistent with the design philosophy because variations are a best guess of the uncertainties of using wind-tunnel data to predict flight characteristics.

Comparisons of the pitching-moment coefficients due to elevon deflection $C_{m_{\delta_e}}$ and normal-force coefficients due to elevon deflection $C_{N_{\delta_e}}$ measured in the wind tunnel and extracted from the ALT flight-test data are presented in figure 5. Generally the comparison shows very good agreement between the values of $C_{m_{\delta_e}}$ determined from flight, the wind tunnel, and the data book (ref. 3). As with the comparison of C_{N_α} values, there is considerable scatter in the flight-test data, and because of this scatter no real conclusion can be drawn about its accuracy. There are no variations presented in reference 3 for $C_{N_{\delta_e}}$.

Lateral-Directional Stability and Control

The lateral-directional stability parameters C_{n_β}, C_{l_β}, and C_{Y_β} determined from the wind-tunnel tests are compared with the flight-test results from both references 1 and 2 in figure 6. The comparison shows excellent agreement between wind-tunnel and flight-test values of the effective-dihedral parameter C_{l_β} but shows differences of approximately 15 percent for the directional-stability parameter C_{n_β}. The side-force parameter C_{Y_β} shows about the same agreement between the flight-test and wind-tunnel results as for C_{n_β}. The flight-test and wind-tunnel values of C_{n_β} and C_{Y_β} generally agree with the data-book values of reference 3, but for some cases for C_{l_β}, the data-book values are 15 percent higher than both the flight-test and wind-tunnel results. All of the flight-test and wind-tunnel lateral-directional data fall within the variations established in reference 3.

Presented in figure 7 are comparisons for the roll-control effectiveness $C_{l_{\delta_a}}$ and the yawing moment due to aileron deflection $C_{n_{\delta_a}}$ which show that both sets of flight-test values, wind-tunnel results, and aerodynamic design data-book predictions agree quite well. Since $C_{Y_{\delta_a}}$ is determined from the lateral acceleration, which is a difficult parameter to measure in flight, the flight-test values of $C_{Y_{\delta_a}}$ from references 1 and 2 show considerable scatter in the flight-test results. The aerodynamic data-book values agree better with the wind-tunnel results than with the flight-test values. At angles of attack of 3.8° and 10.1° the flight-test data for $C_{Y_{\delta_a}}$ fall outside of the variation band, but the accuracy band of the flight-test data indicates it could fall within the variation band. Therefore, these results present no difficulty.

CONCLUDING REMARKS

The results of a comparison of the wind-tunnel-measured stability and control derivatives and those determined from the Space Shuttle Orbiter approach and landing flight tests have shown that:

1. In general, except for the normal-force derivatives C_{N_α} and the side-force due to aileron deflection derivatives $C_{Y_{\delta_a}}$ for which there are known accuracy problems for the flight-test data, the wind-tunnel test results and the flight-test data agree quite well.

2. The general good agreement between the data determined from the wind-tunnel tests and the flight tests indicates that the stability and control characteristics predicted with the wind-tunnel results appear to be adequate at subsonic Mach numbers for entry-vehicle design for the low-angle-of-attack range of the comparisons.

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WIND-TUNNEL-TEST RESULTS

The results of tests to obtain data for comparison with the ALT flight-test data are presented in figures 8 to 11. The longitudinal-stability and elevon-effectiveness data are presented in figures 8 and 9. The results of figure 8 show that at the moment reference center of the data ($0.65l$) the orbiter is slightly stable over the test angle-of-attack range. The elevon-effectiveness data presented in figure 9 show that for all Mach numbers tested, the variation of pitching-moment coefficient with elevon deflections is linear.

The lateral-directional stability data are presented in figure 10. These data show that for all test Mach numbers and angles of attack C_{n_β} is positive and, therefore, the vehicle is directionally stable. The C_{l_β} is negative, which indicates positive effective dihedral. The offset in the rolling-moment coefficient at zero sideslip is due to an assymmetry in the elevon position at zero deflection. Measurements made after the tests showed that at zero elevon deflection, there was actually a difference in elevon position corresponding to an aileron deflection of -0.5°.

The aileron-control effectiveness data are presented in figure 11. These results show that the rolling-moment coefficient C_l and the yawing-moment coefficient C_n vary linearly with aileron deflection for small deflections where the comparison derivatives were determined. The offset in rolling-moment coefficient at zero aileron deflection is also caused by the -0.5° error in the zero position of the elevons as previously discussed.

REFERENCES

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4. Schaefer, William T., Jr.: Characteristics of Major Active Wind Tunnels at the Langley Research Center. NASA TM X-1130, 1965.

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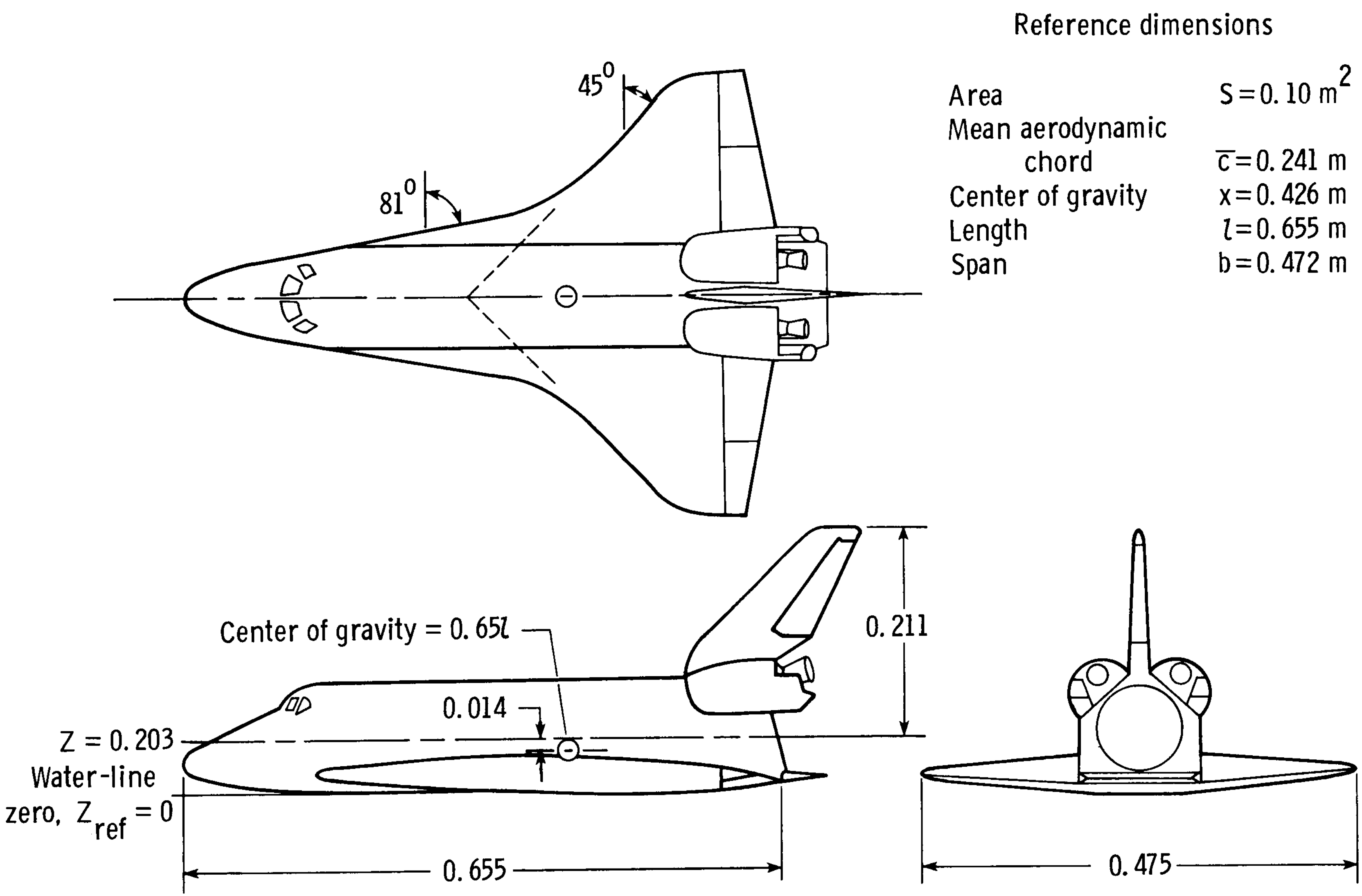
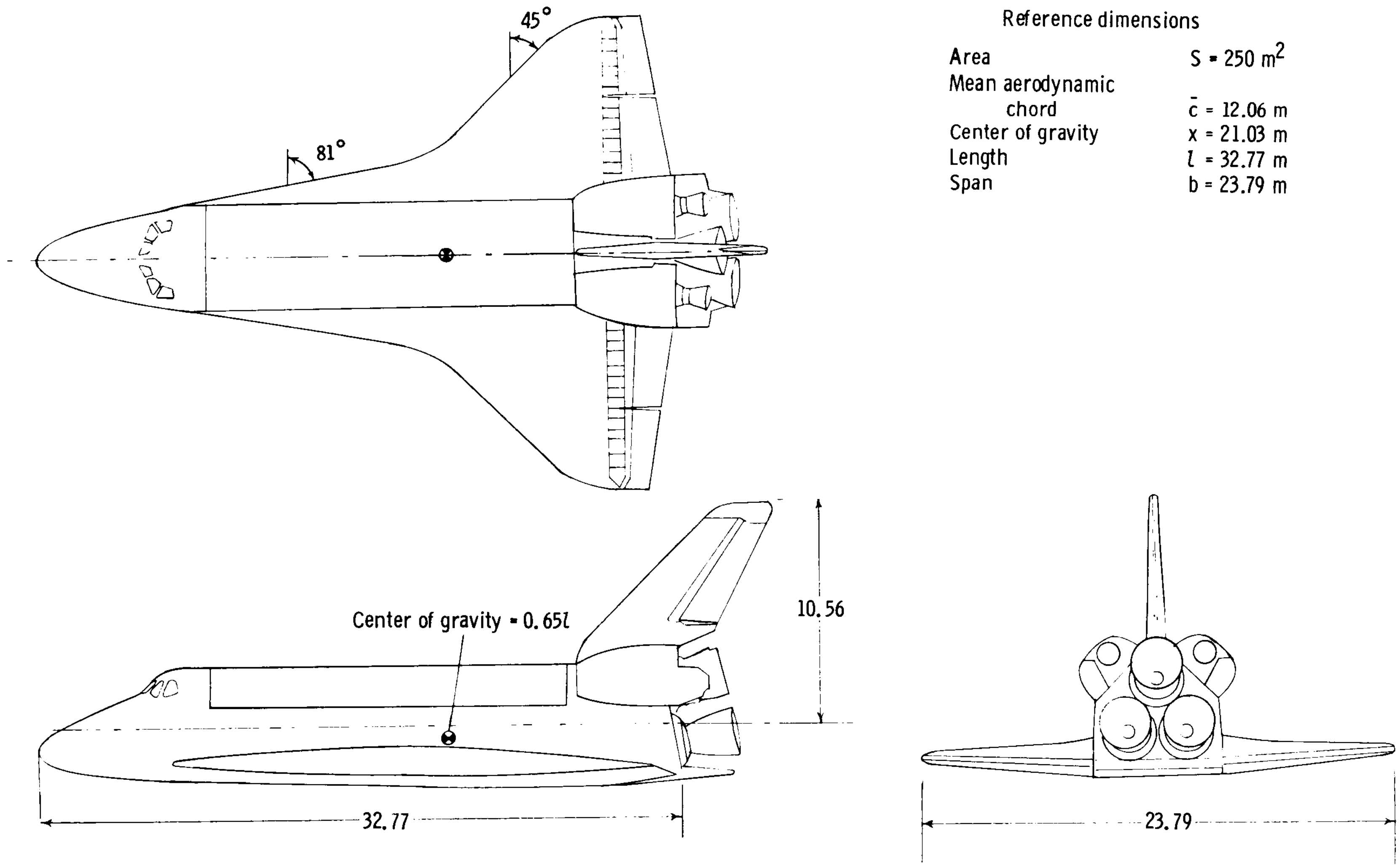


Figure 1.- Sketch of the 0.02-scale wind-tunnel model. All dimensions in meters unless otherwise noted.



Reference dimensions

Area	$S = 250\ m^2$
Mean aerodynamic chord	$\bar{c} = 12.06$ m
Center of gravity	$x = 21.03$ m
Length	$l = 32.77$ m
Span	$b = 23.79$ m

Figure 2.- Sketch of Orbiter 101. All dimensions given in meters unless otherwise noted.

L-78-414

Figure 3.- Orbiter 101 in flight.

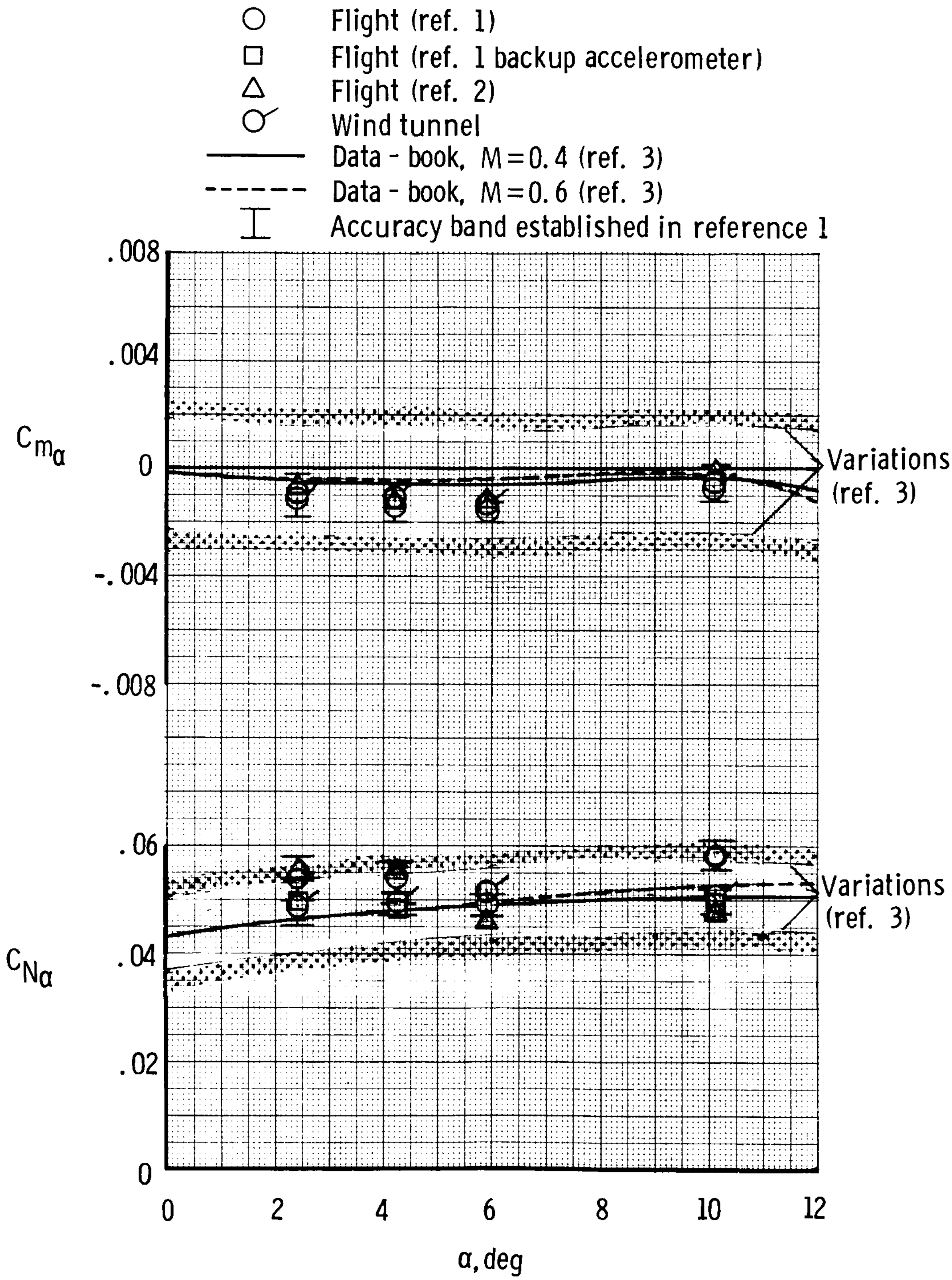


Figure 4.- Comparison of wind-tunnel and flight-test values of C_{m_α} and $C_{N\alpha}$. See table I for δ_e, δ_{SB}, and δ_{BF}.

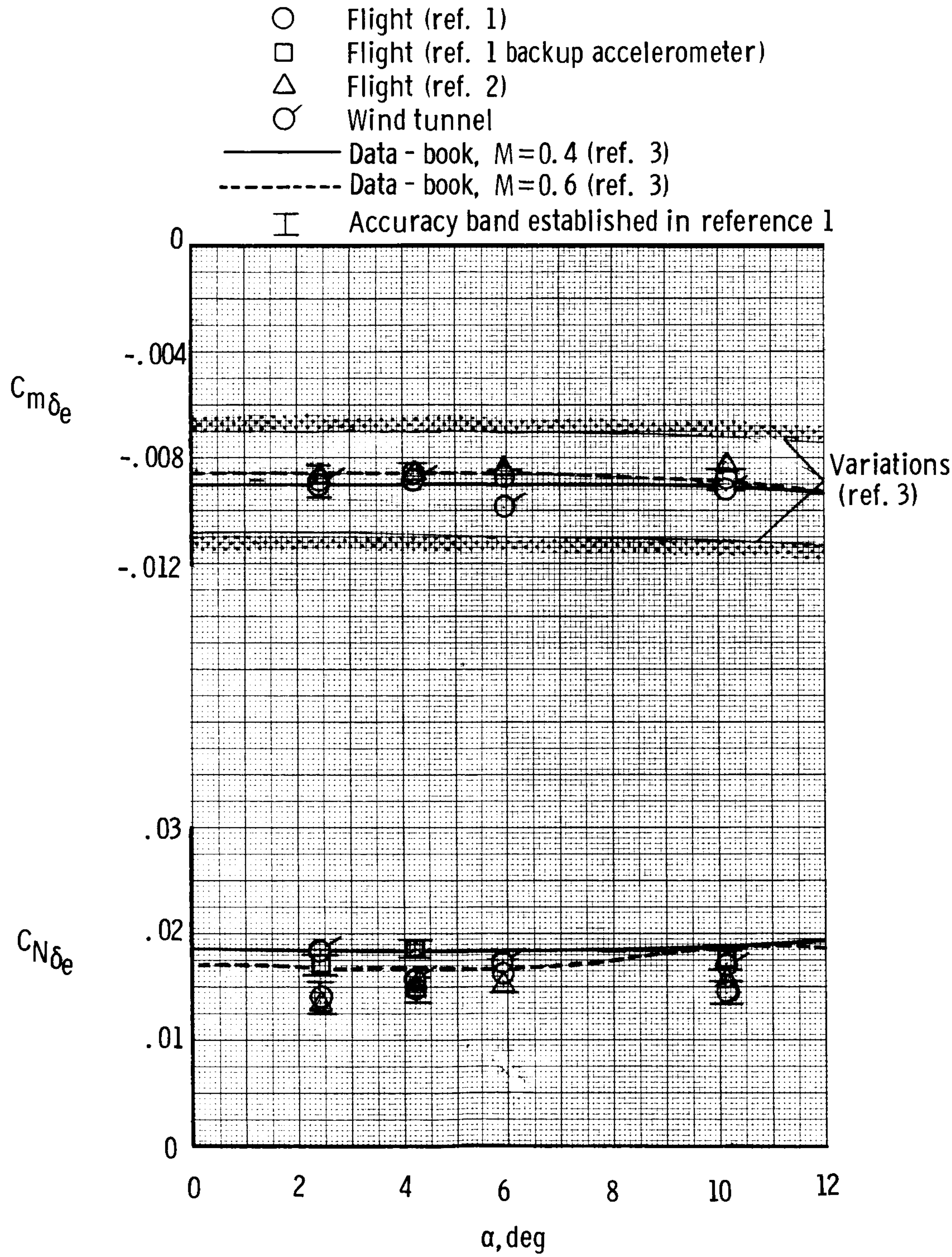


Figure 5.- Comparison of wind-tunnel and flight-test values of the elevon effectiveness. See table I for δ_e, δ_{SB}, and δ_{BF}.

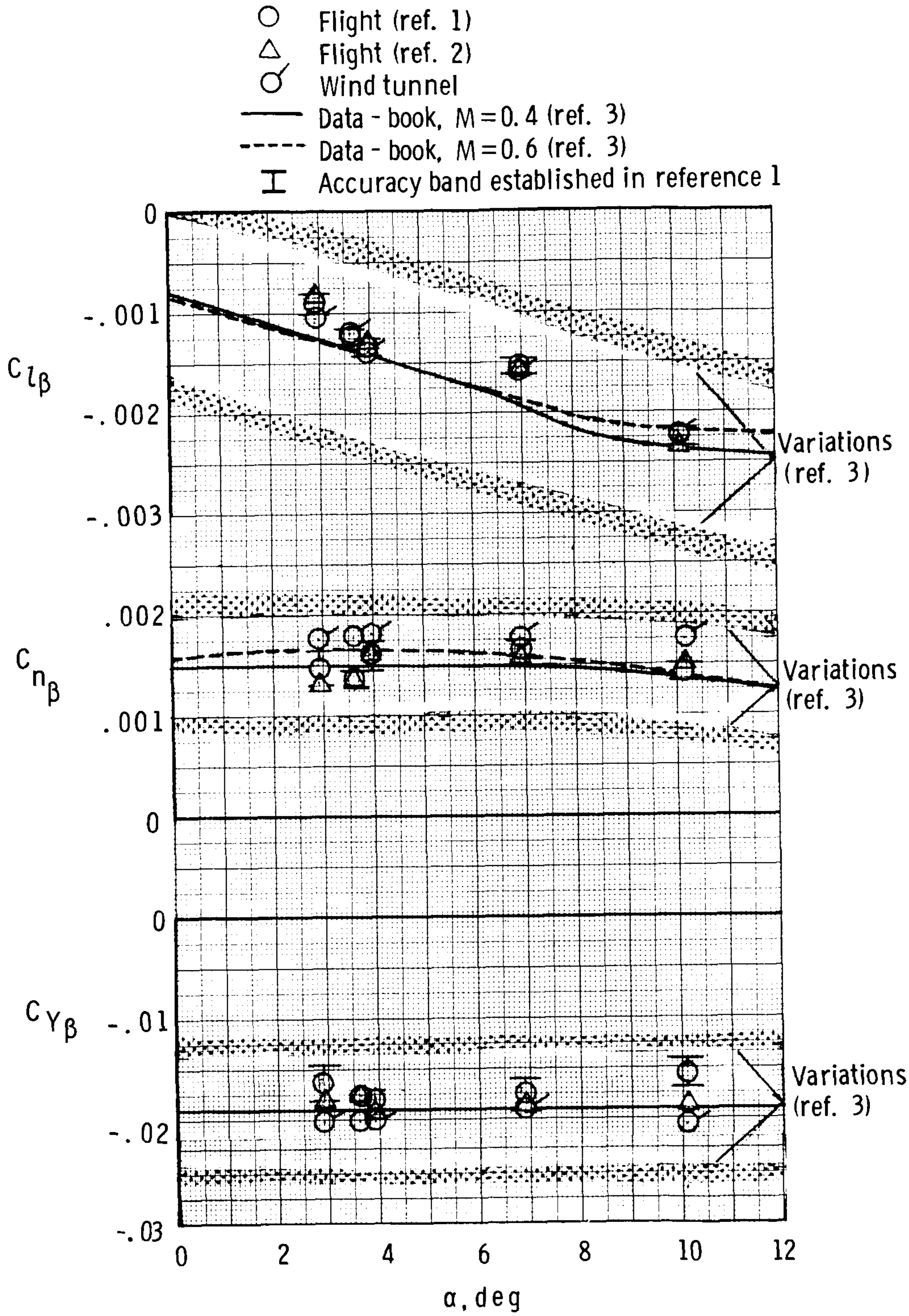


Figure 6.- Comparison of wind-tunnel and flight-test values of the lateral-directional stability parameter. See table I for δ_e, δ_{SB}, and δ_{BF}.

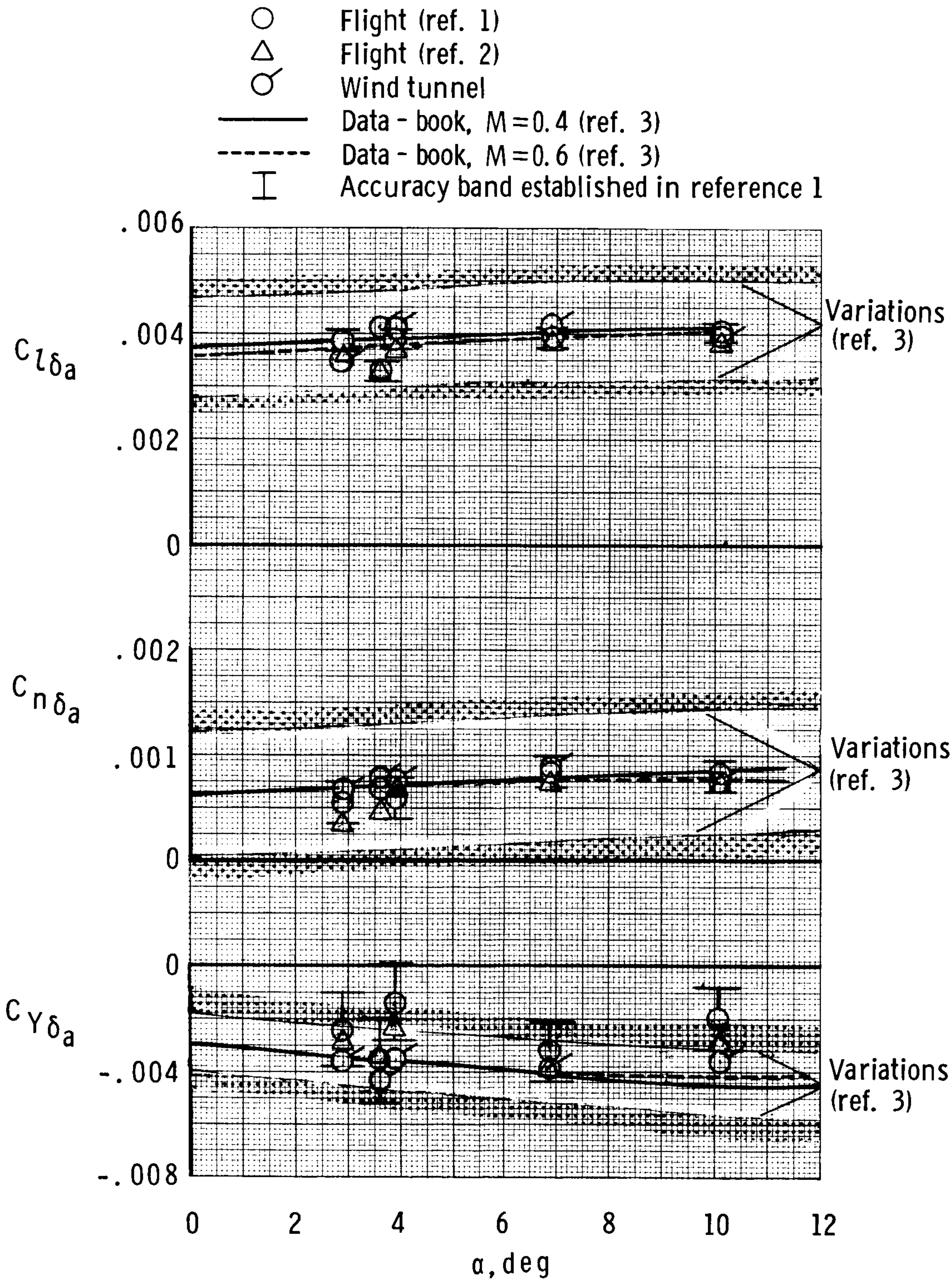
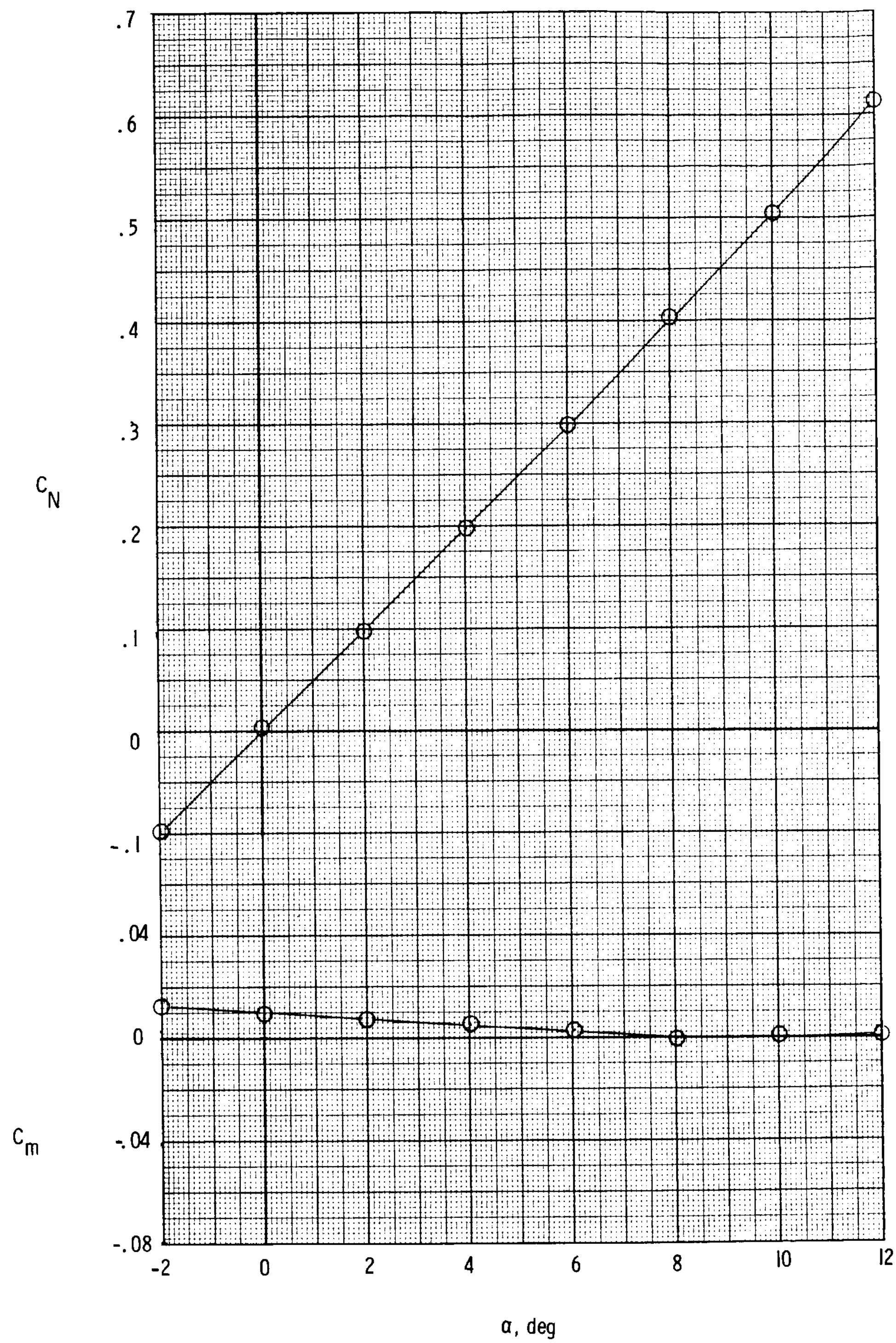
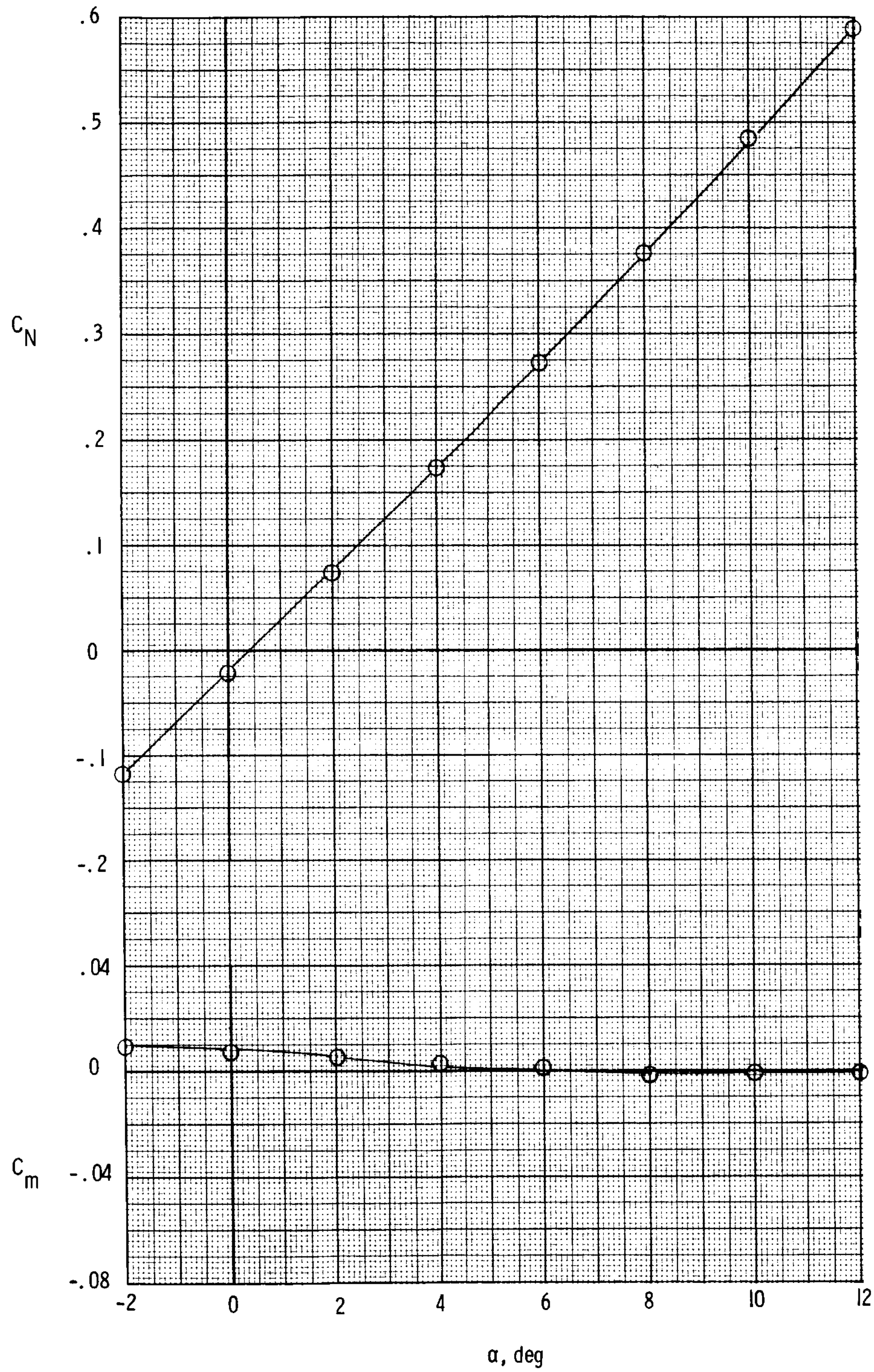


Figure 7.- Comparison of wind-tunnel and flight-test values of the aileron-control effectiveness. See table I for δ_e, δ_{SB}, and δ_{BF}.



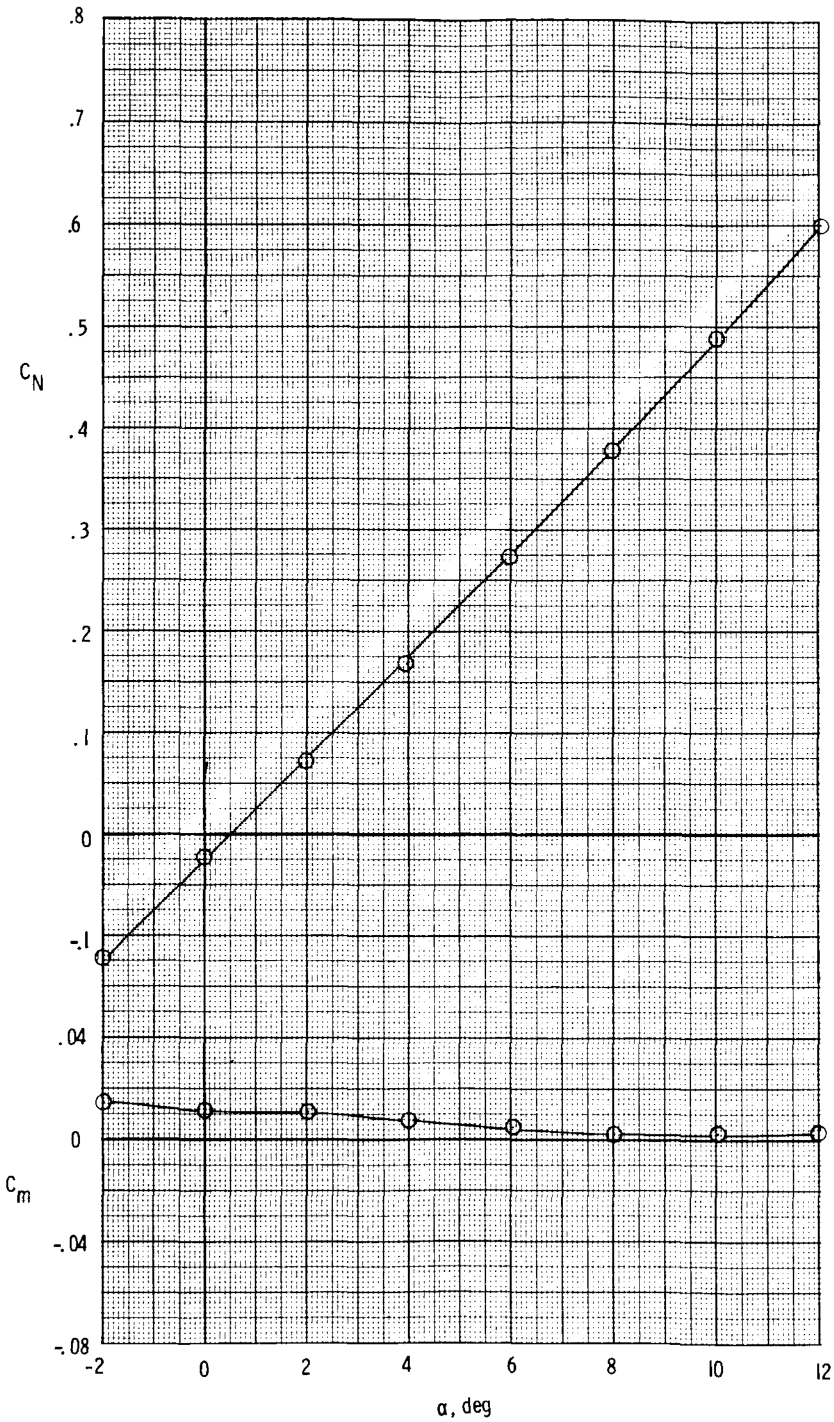
(a) M = 0.51; $\delta_{SB} = 43^{\circ}$; $\delta_e = 4.4^{\circ}$.

Figure 8.- Basic longitudinal wind-tunnel data. $\delta_{BF} = -0.5^{\circ}$.



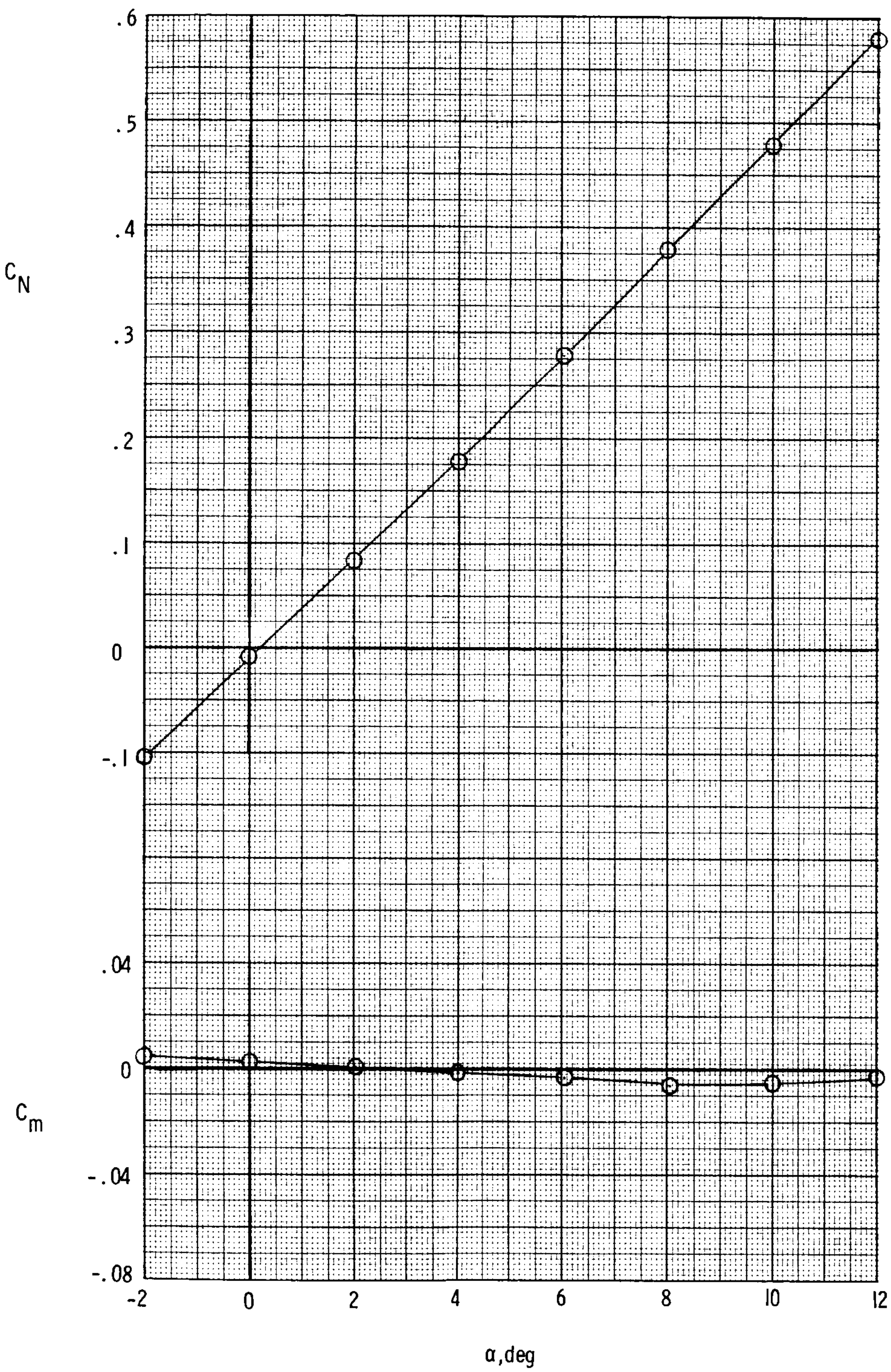
(b) $M = 0.52$; $\delta_{SB} = 3.5^{\circ}$; $\delta_e = 2.2^{\circ}$.

Figure 8.- Continued.



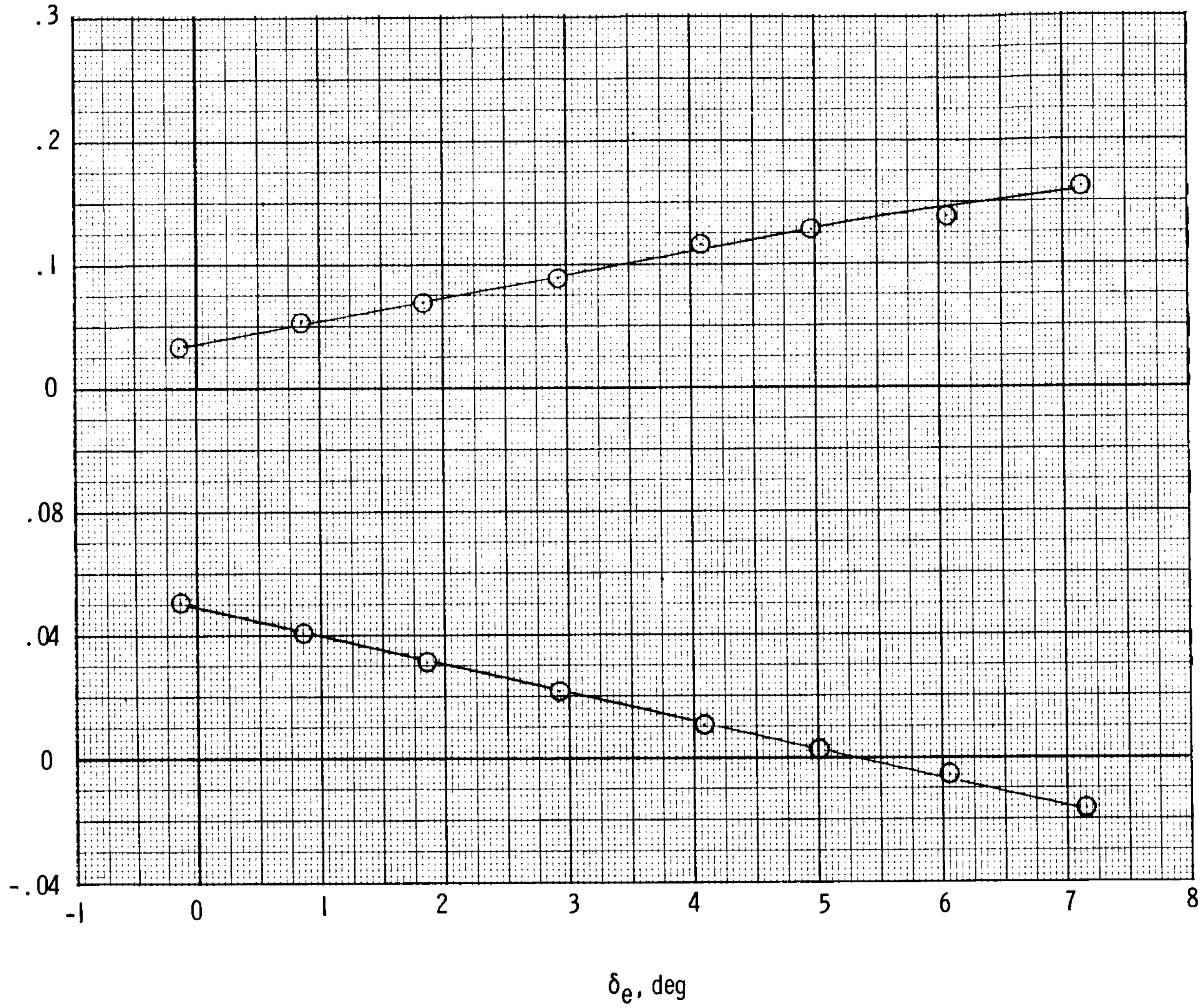
(c) $M = 0.56$; $\delta_{SB} = 3.5^{\circ}$; $\delta_e = 1.8^{\circ}$.

Figure 8.- Continued.



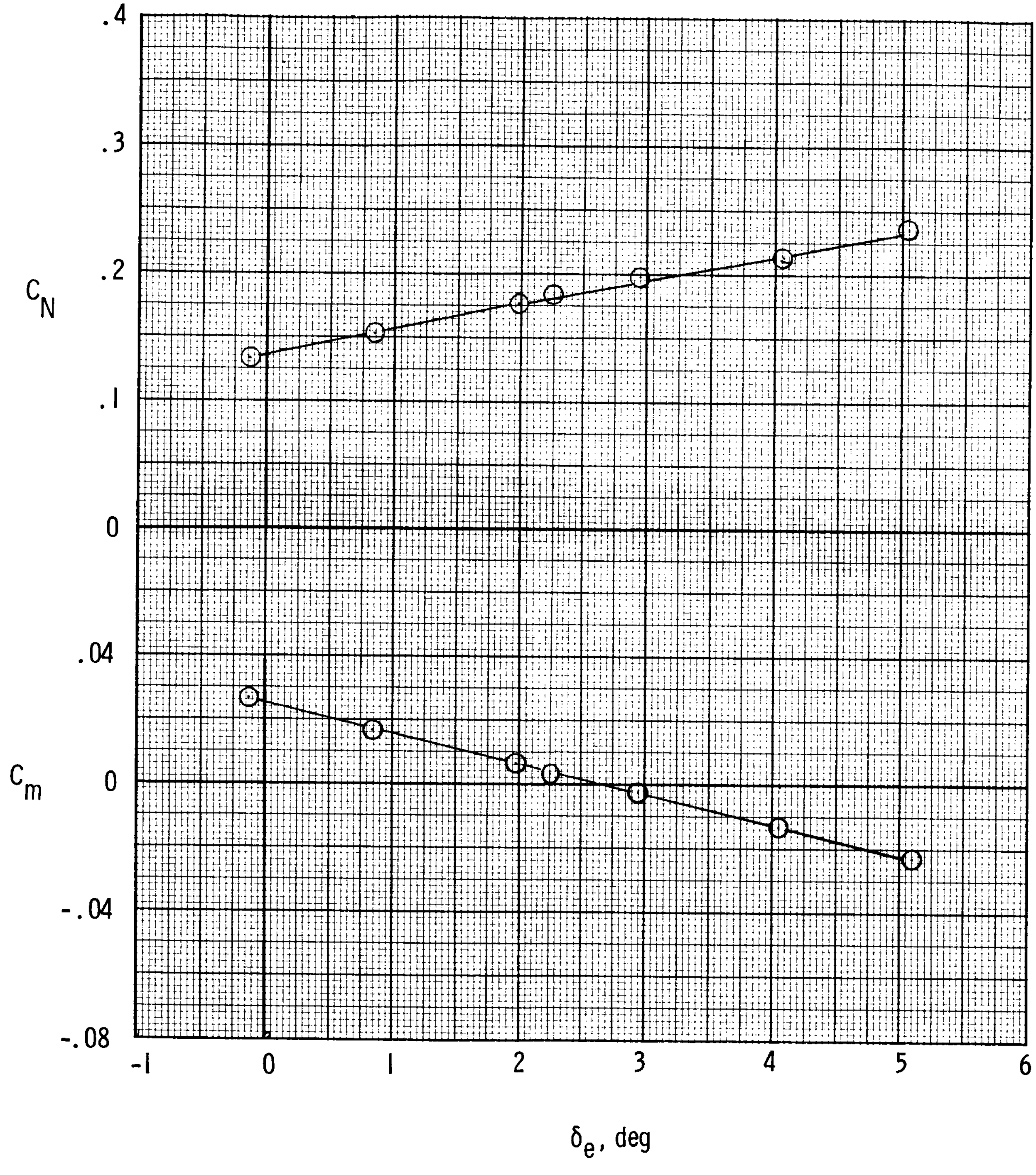
(d) M = 0.41; $\delta_{SB} = 3.5^{\circ}$; $\delta_e = 2.9^{\circ}$.

Figure 8.- Concluded.



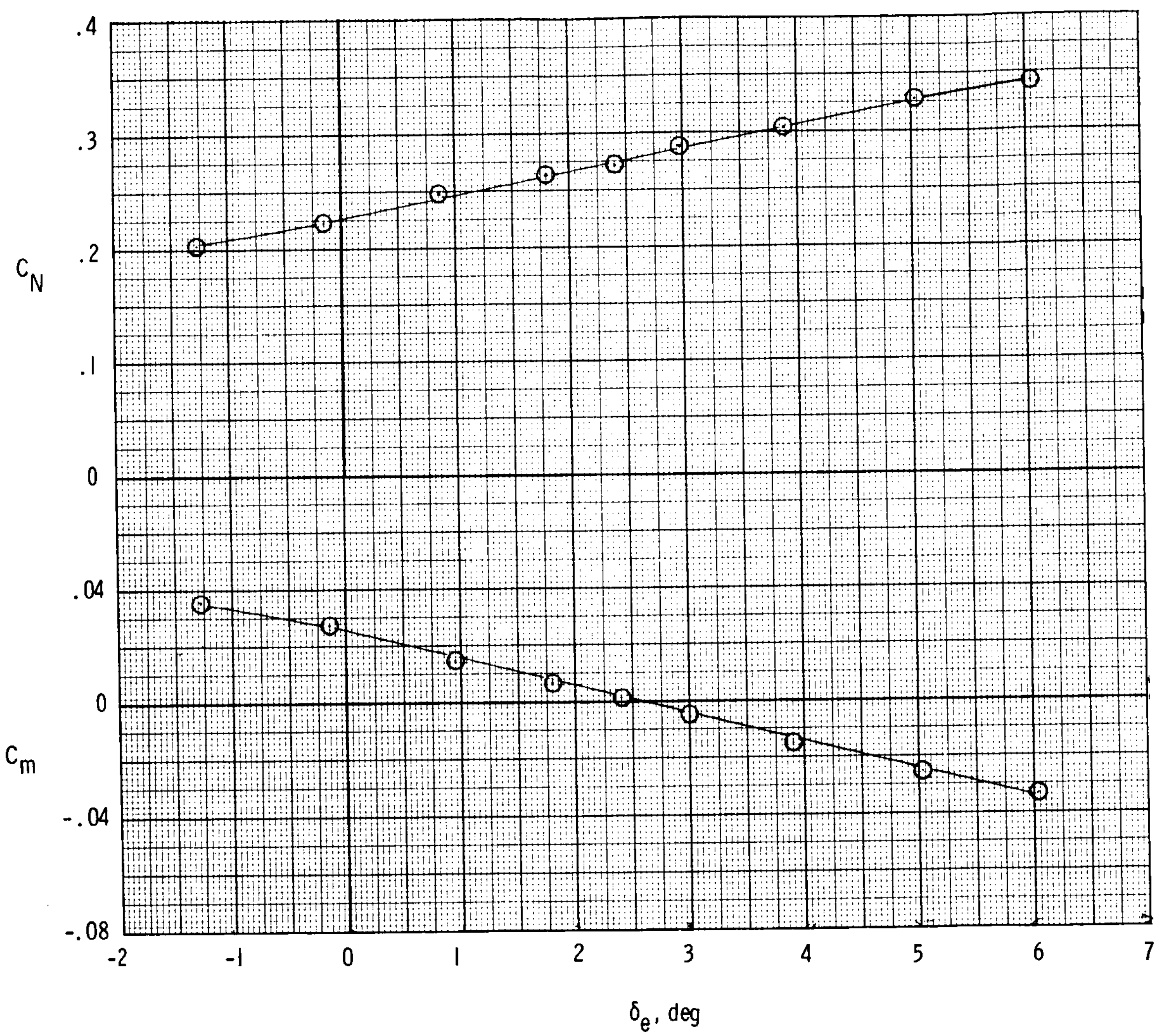
(a) M = 0.51; $\alpha = 2.4^\circ$, $\delta_{SB} = 43^\circ$.

Figure 9.- Elevon-effectiveness data. $\delta_{BF} = -0.5^\circ$.



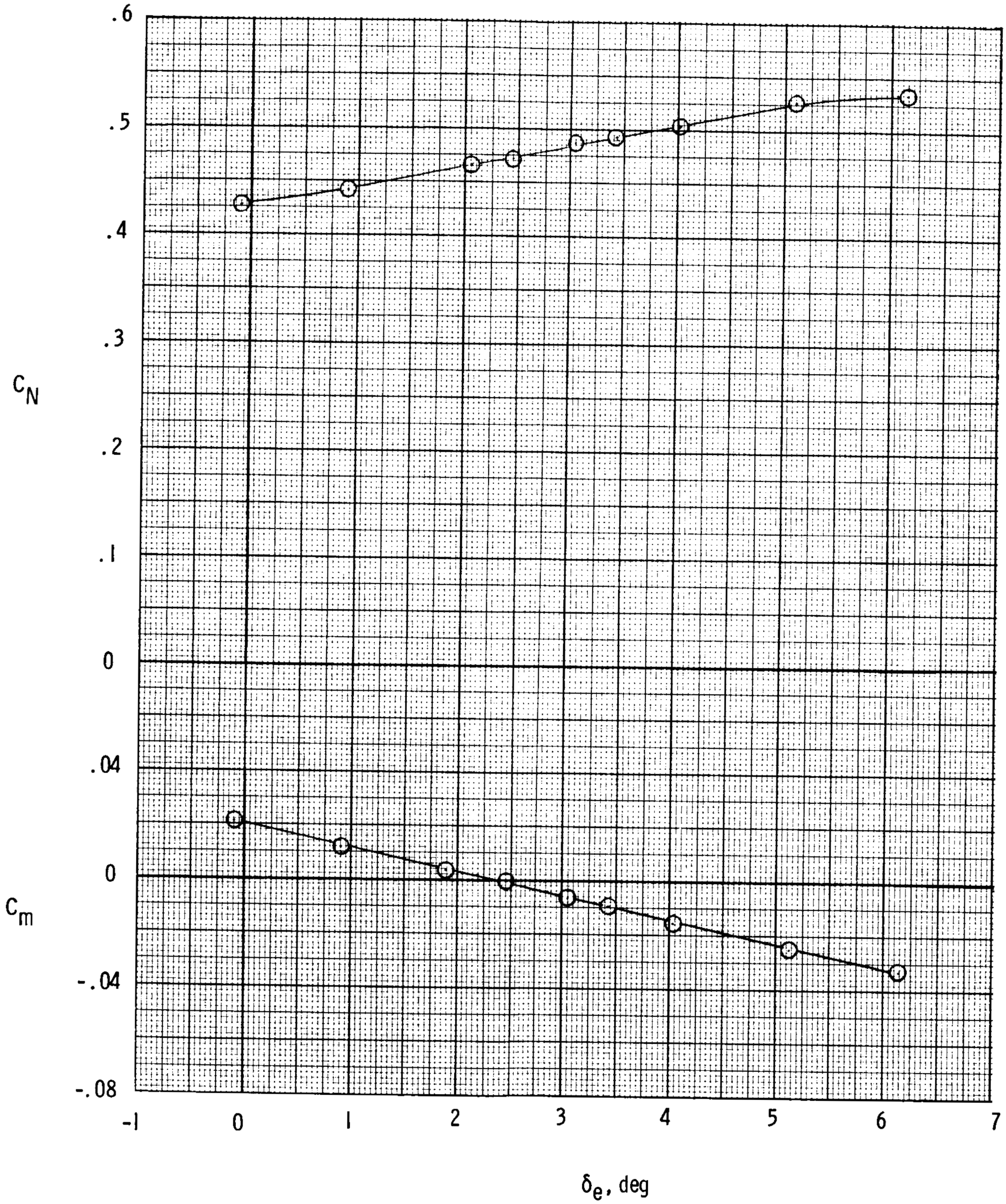
(b) $M = 0.52$; $\alpha = 4.2^{\circ}$; $\delta_{SB} = 3.5^{\circ}$.

Figure 9.- Continued.



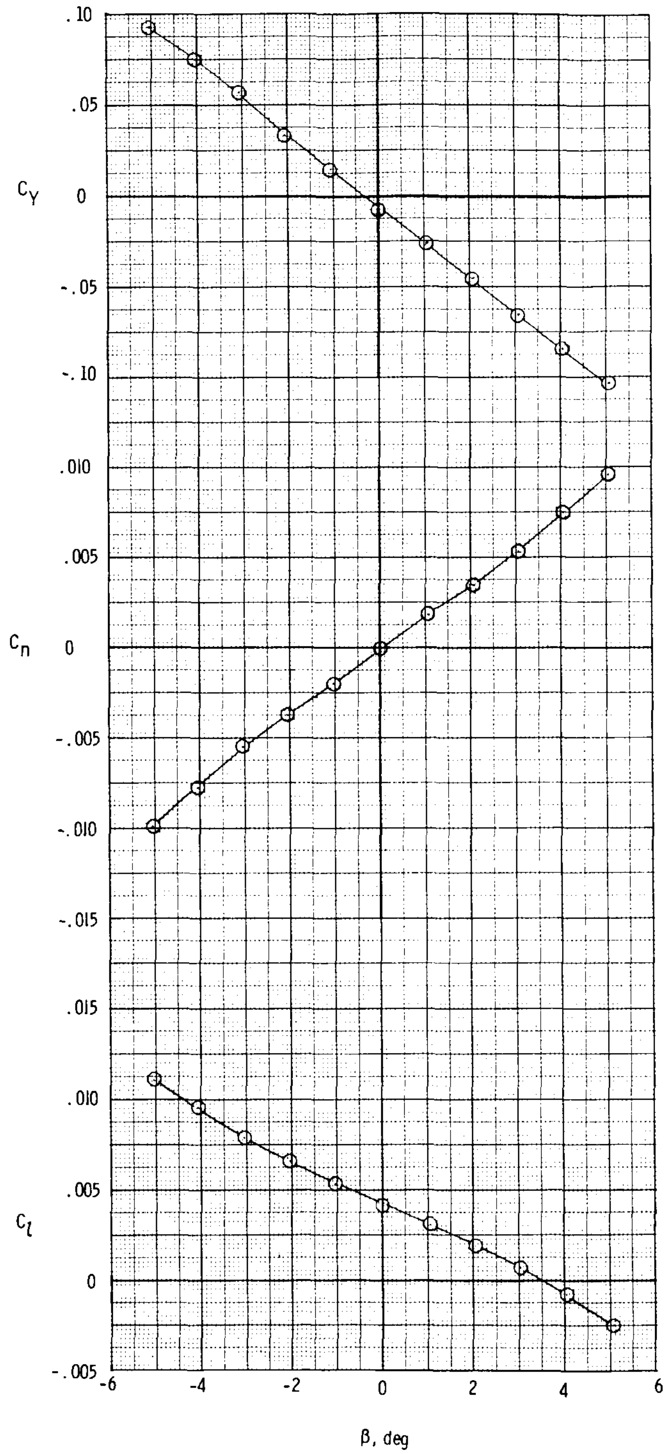
(c) M = 0.56; $\alpha = 5.9^{\circ}$; $\delta_{SB} = 3.5^{\circ}$.

Figure 9.- Continued.



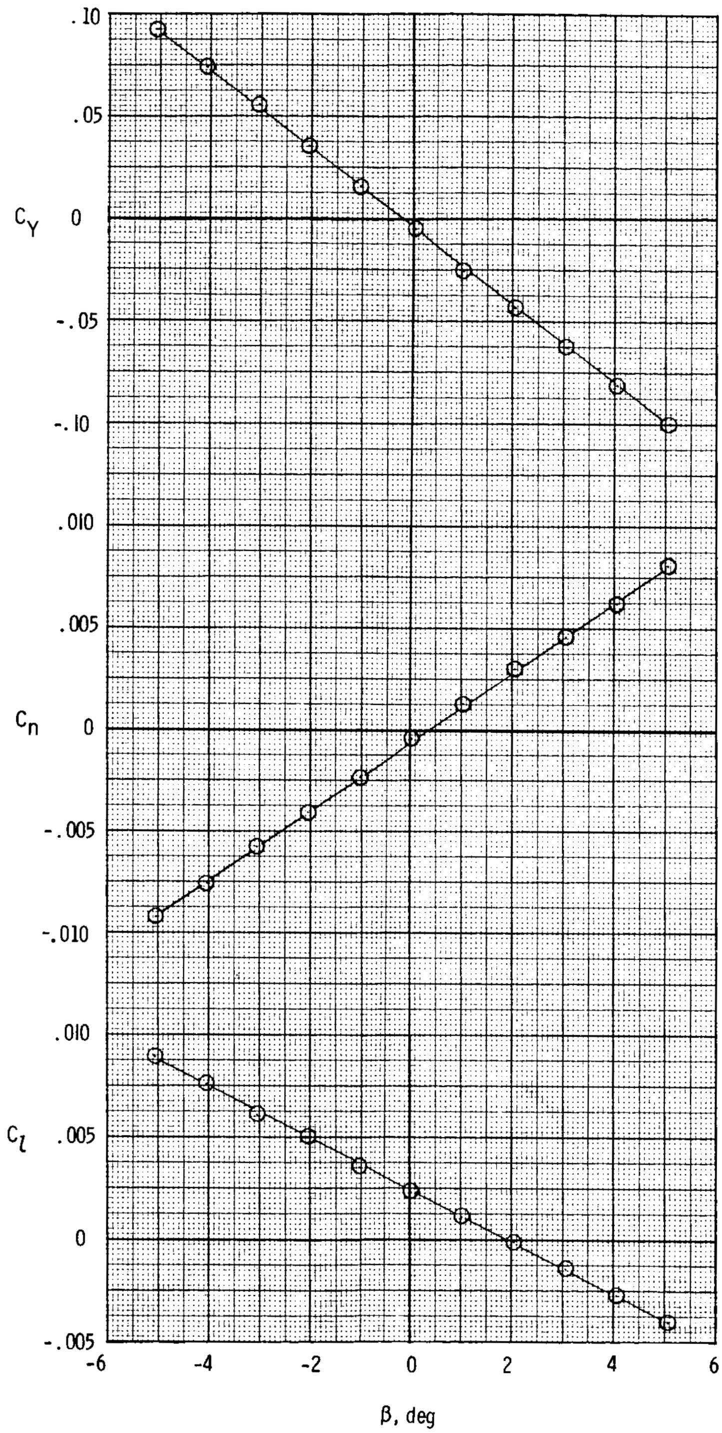
(d) M = 0.41; $\alpha = 10.1^\circ$; $\delta_{SB} = 3.5^\circ$.

Figure 9.- Concluded.



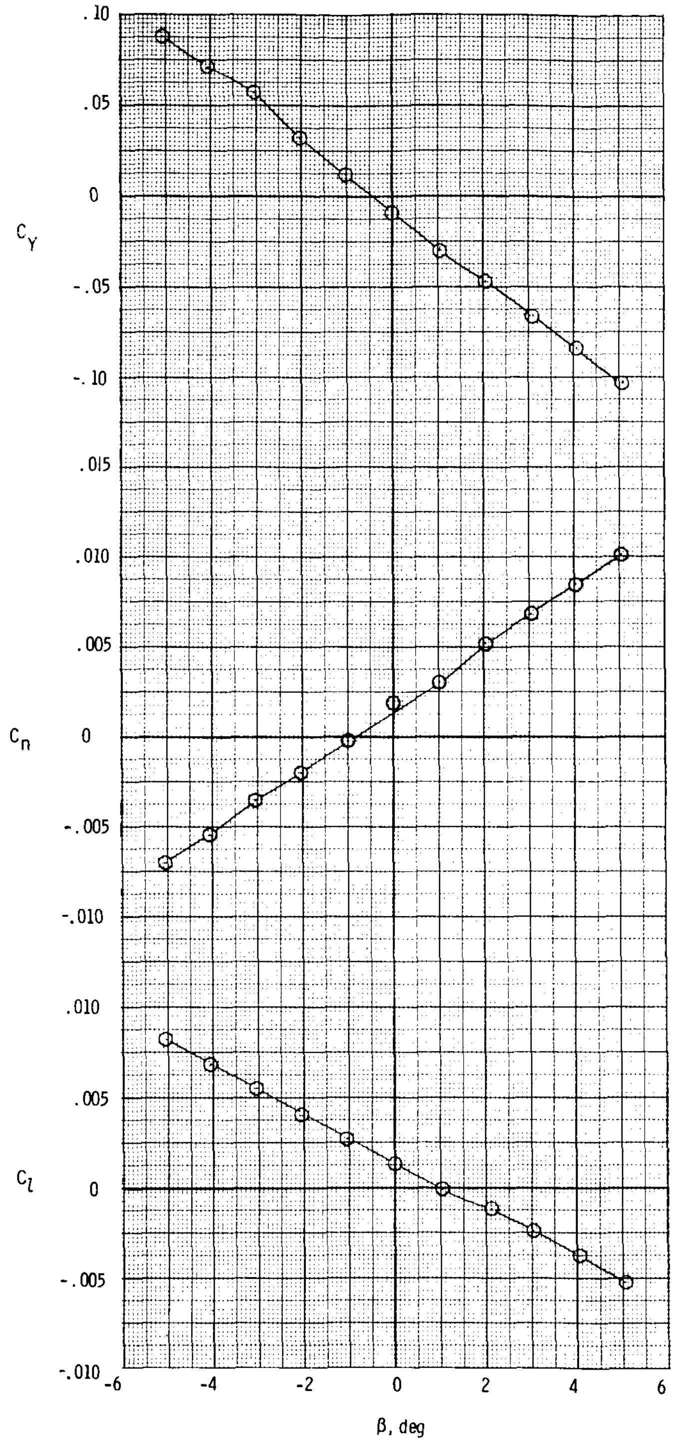
(a) $M = 0.53$; $\alpha = 2.9^{\circ}$; $\delta_e = 4.40$; $\delta_{SB} = 43^{\circ}$.

Figure 10.- Lateral-directional stability data. $\delta_{BF} = -0.5^{\circ}$.



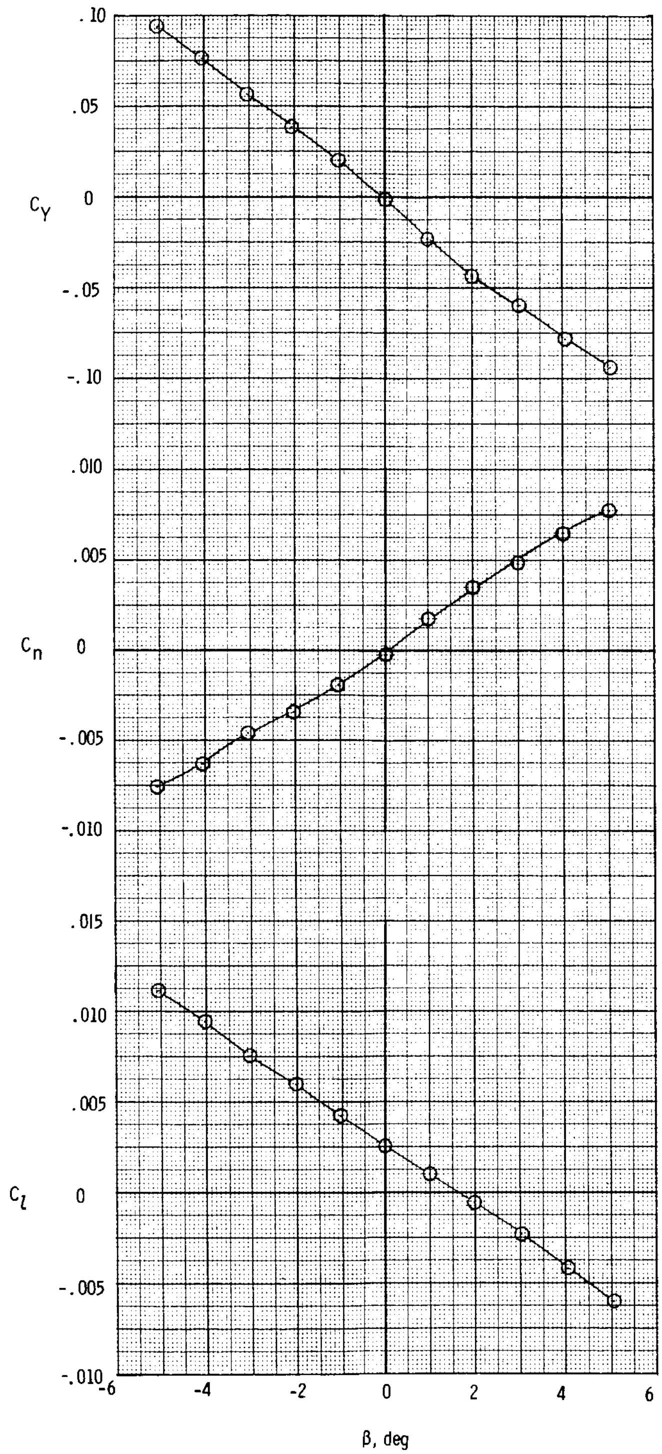
(b) M = 0.56; $\alpha = 3.6^{\circ}$; $\delta_e = 1.85^{\circ}$; $\delta_{SB} = 3.5$.

Figure 10.- Continued.



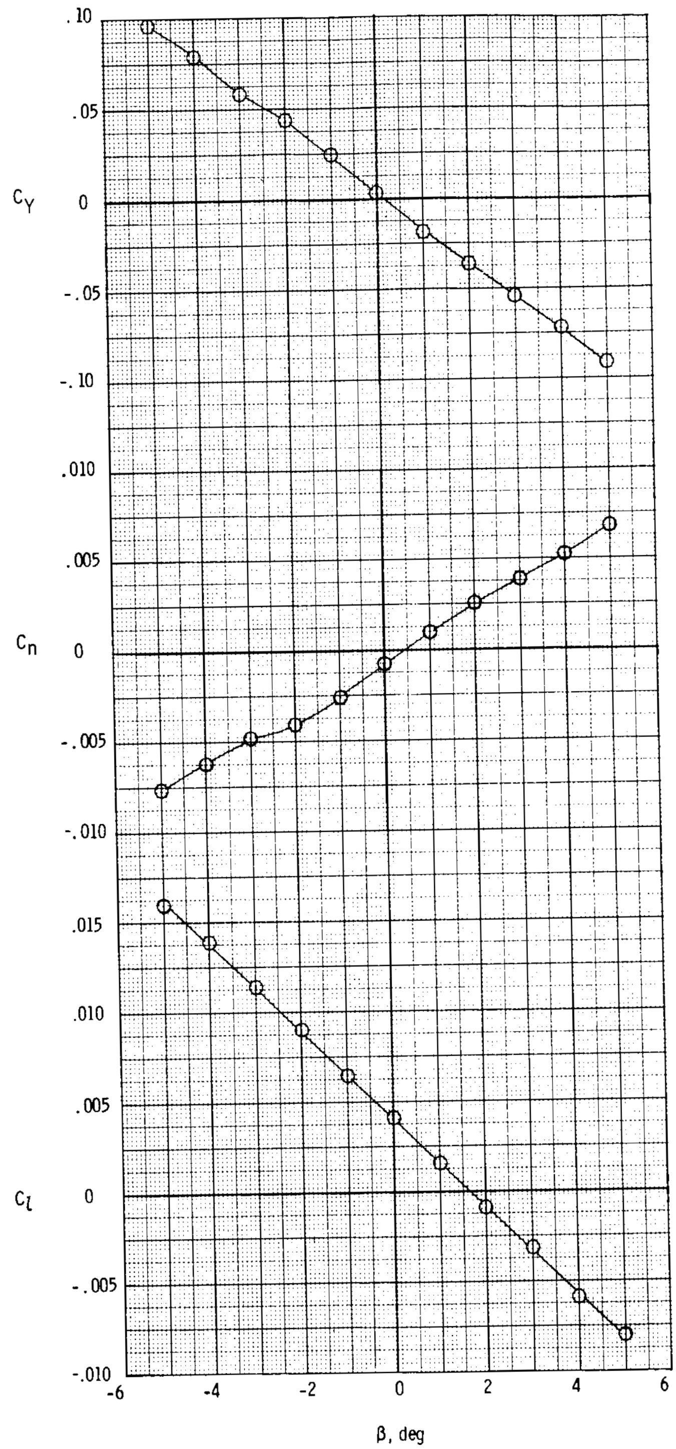
(c) $M = 0.53$; $\alpha = 3.9^{\circ}$; $\delta_e = 2.16^{\circ}$; $\delta_{SB} = 3.5^{\circ}$.

Figure 10.- Continued.



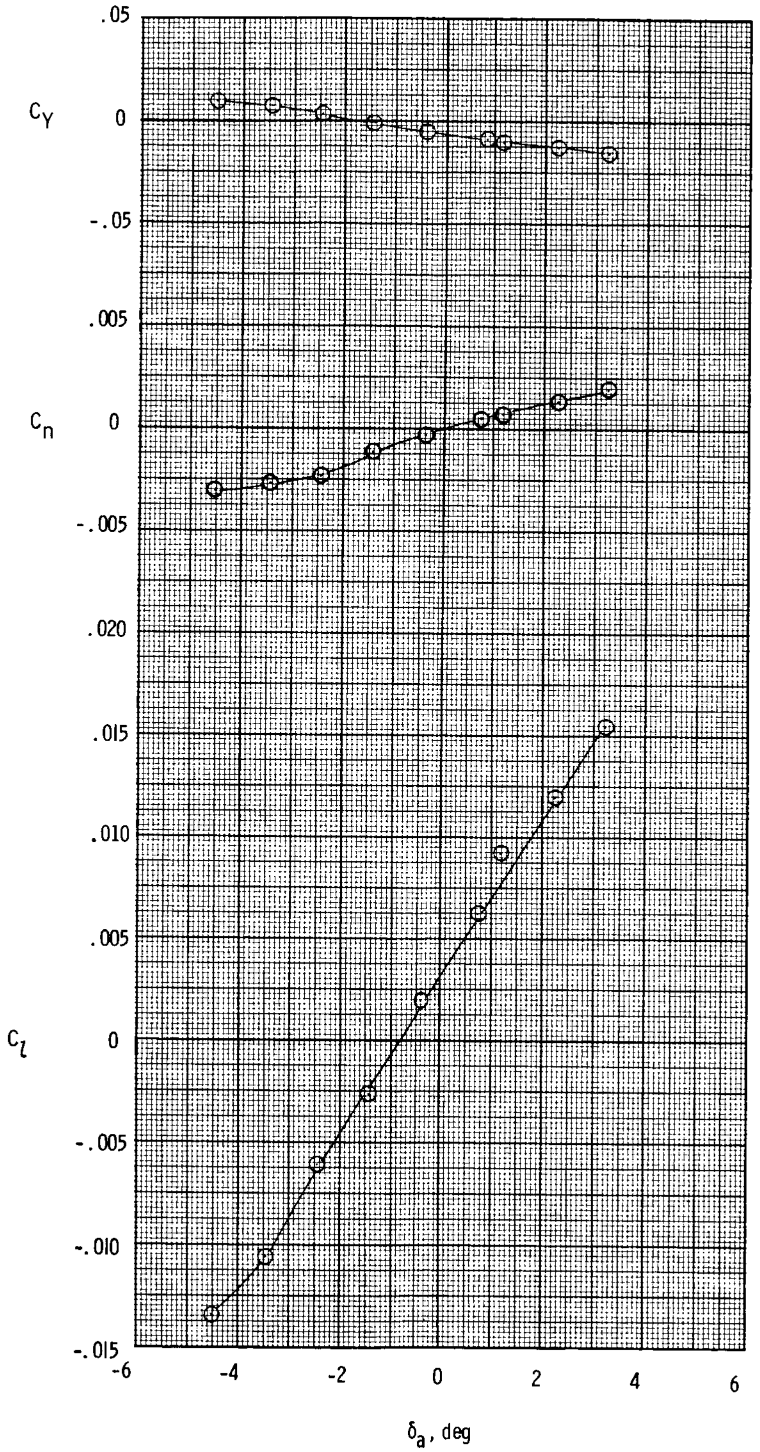
(d) $M = 0.49$; $\alpha = 6.9$; $\delta_e = 2.15$; $\delta_{SB} = 3.5$.

Figure 10.- Continued.



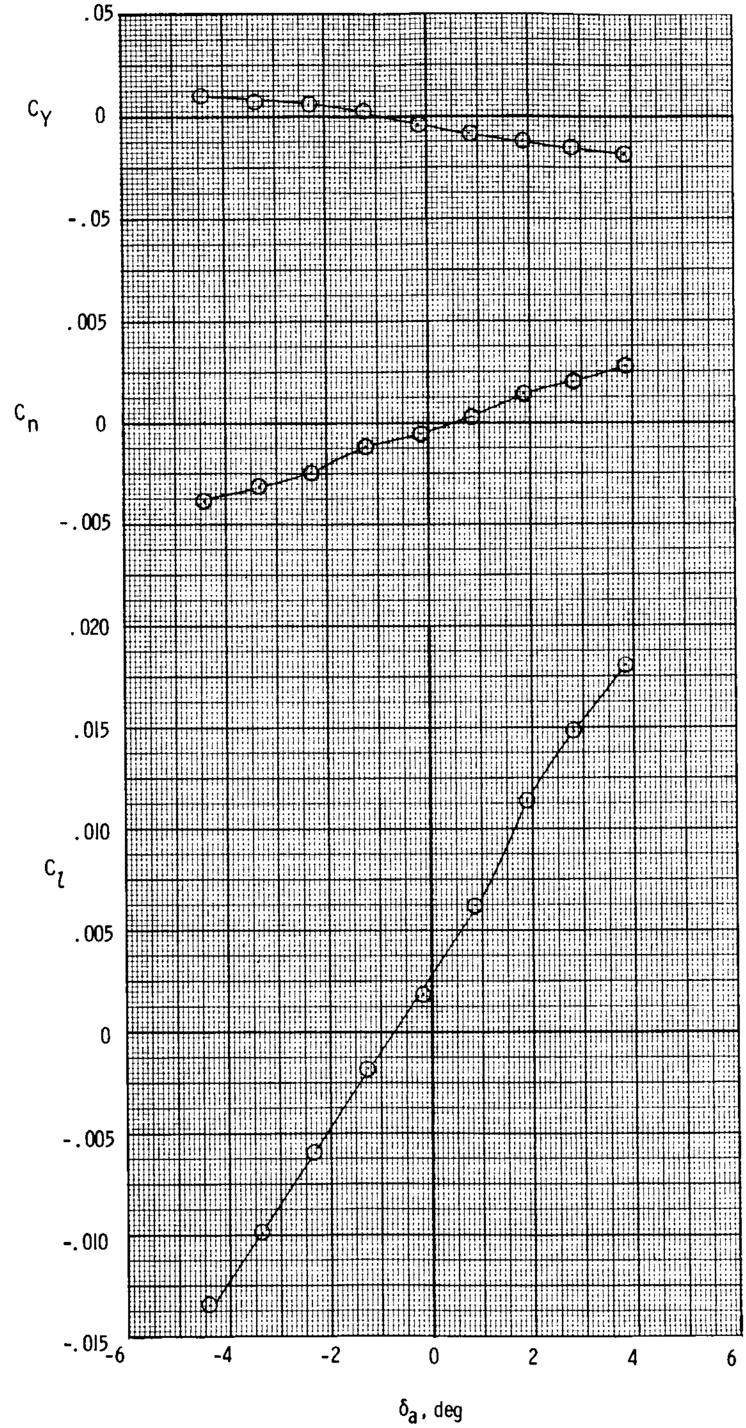
(e) $M = 0.41$; $\alpha = 10.1^{\circ}$; $\delta_e = 2.90^{\circ}$; $\delta_{SB} = 3.5^{\circ}$.

Figure 10.- Concluded.



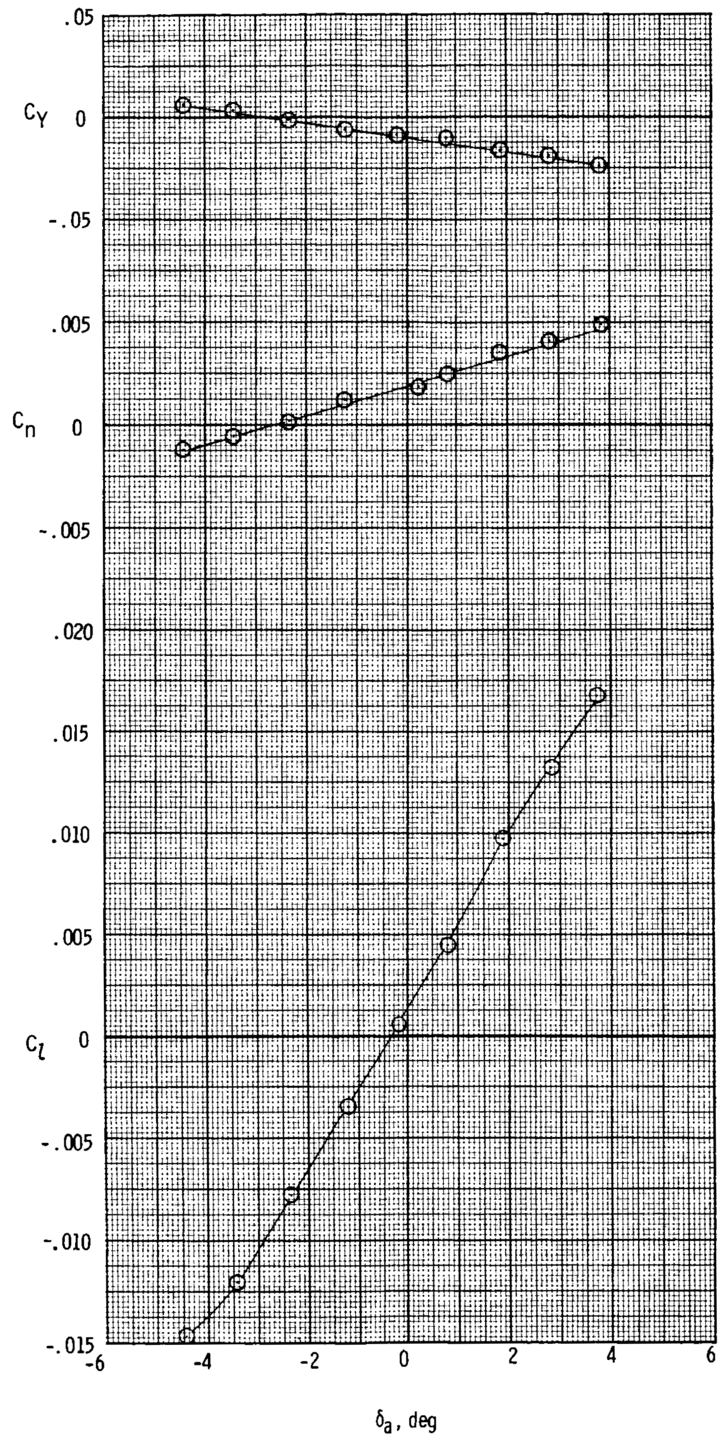
(a) $M = 0.53$; $\alpha = 2.9^\circ$; $\delta_e = 4.40$; $\delta_{SB} = 43^\circ$.

Figure 11.- Aileron-control effectiveness data. $\delta_{BF} = -0.5^\circ$.



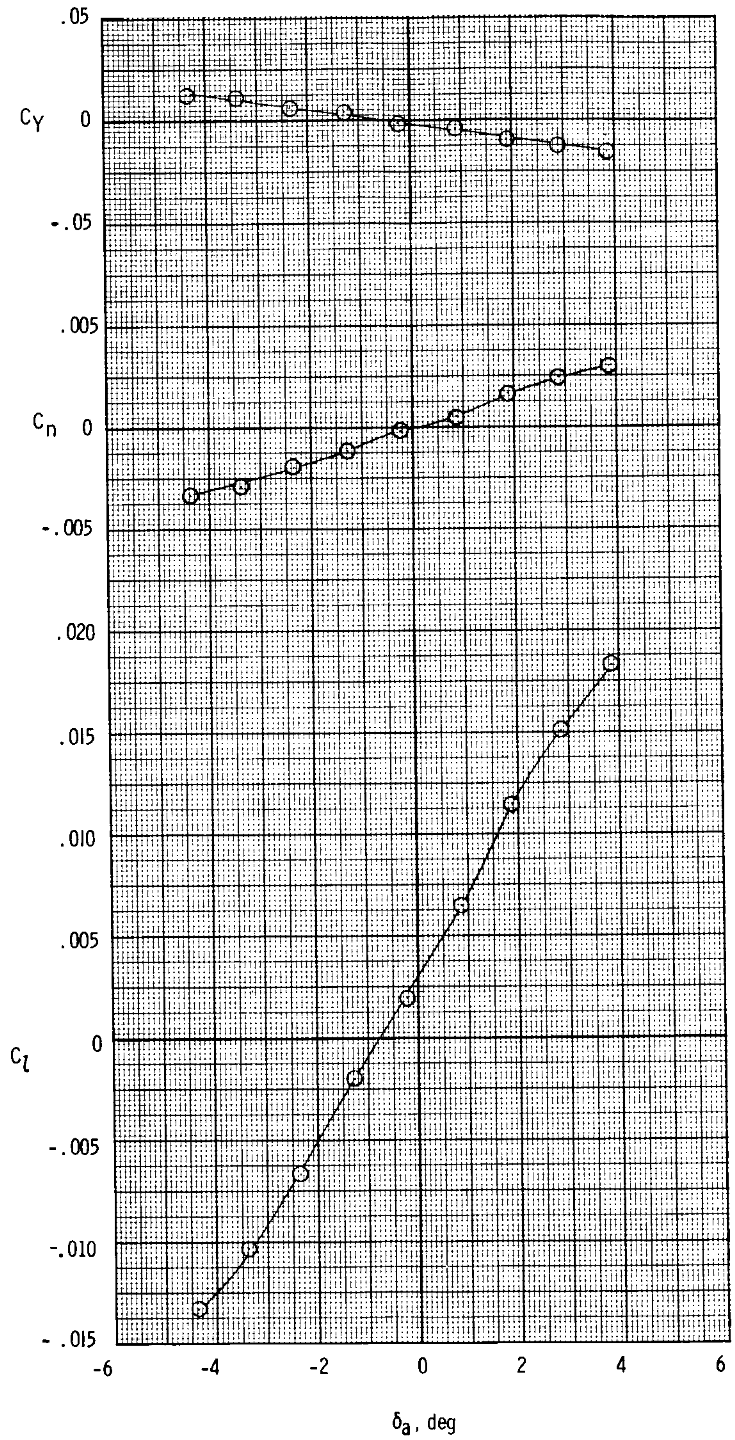
(b) M = 0.56; α = 3.6; δ_e = 1.85; δ_{SB} = 3.5°.

Figure 11.- Continued.



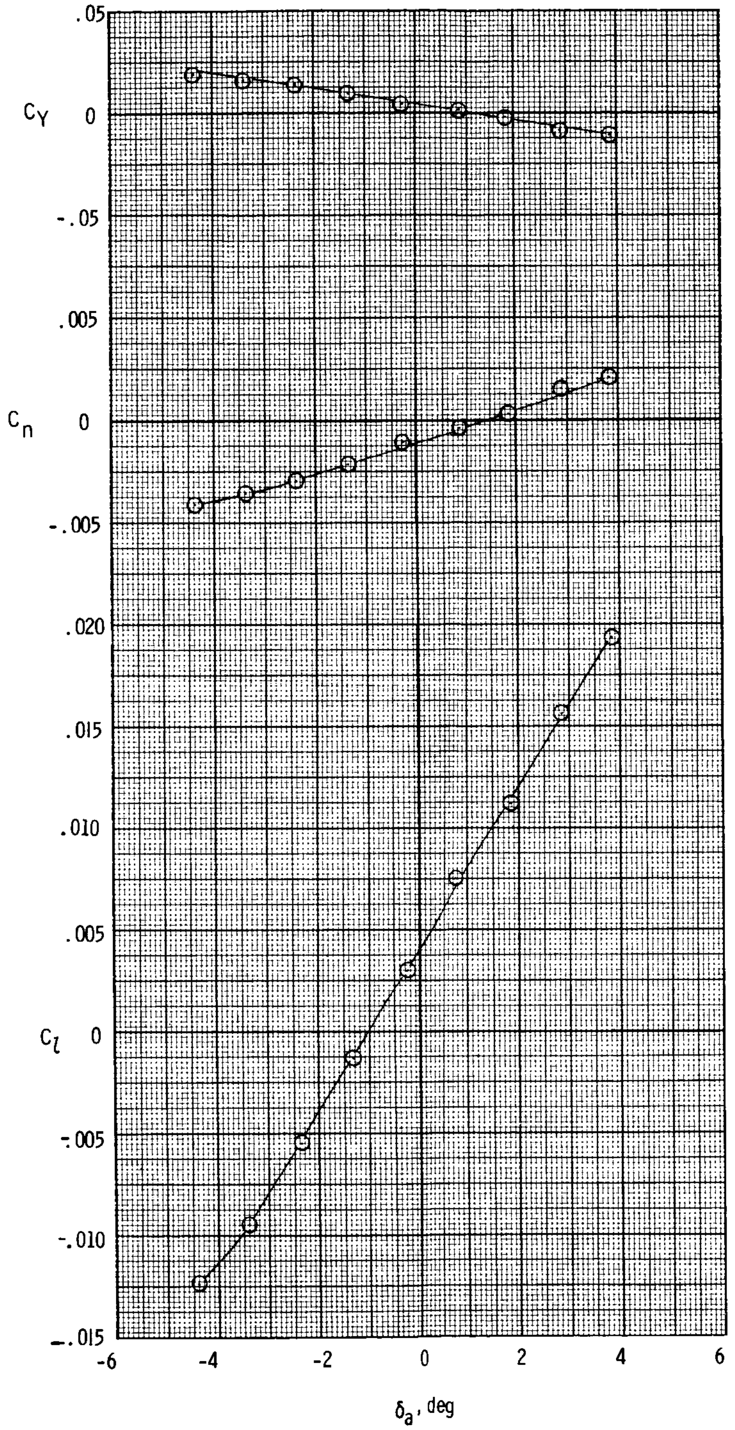
(c) $M = 0.53$; $\alpha = 3.9^\circ$; $\delta_e = 2.16^\circ$; $\delta_{SB} = 3.5$.

Figure 11.- Continued.



(d) $M = 0.49$; $\alpha = 6.9^{\circ}$; $\delta_e = 2.16^{\circ}$; $\delta_{SB} = 3.5^{\circ}$.

Figure 11.- Continued.



(e) $M = 0.41$; $\alpha = 10.1^{\circ}$; $\delta_e = 2.90^{\circ}$; $\delta_{SB} = 3.5^{\circ}$.

Figure 11.- Concluded.

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15. Supplementary Notes

16. Abstract

Tests have been conducted in the Langley 8-Foot Transonic Pressure Tunnel to obtain wind-tunnel data for comparison with static stability and control parameters measured on the Space Shuttle Orbiter approach and landing flight tests. The longitudinal-stability, elevon-effectiveness, lateral-directional stability, and aileron-effectiveness derivatives have been determined from the wind-tunnel data and compared with the flight-test results. The comparison covers a range of angles of attack from approximately 2° to 10° at subsonic Mach numbers of 0.41 to 0.56. In general the wind-tunnel results agreed well with the flight-test results, indicating the wind-tunnel data is applicable to the design of entry vehicles for subsonic speeds over the angle-of-attack range studied.

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