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WING INCLUDING A COMPARISON WITH WIND-TUNNEL RESULTS

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## SUMMARY

The ground effect on an aircraft with a low-aspect-ratio Ogee wing was determined in flight and was compared with results for similar configurations determined in three wind tunnels. The maximum flight increments in lift coefficient and elevon angle for trim in ground proximity ($\Delta C_L = 0.18$ and $\Delta\delta_e = 4^\circ$ trailing edge down) agreed with the values measured in all the wind tunnels. These ground effect increments did not affect the pilot's ability to make successful landings.

## INTRODUCTION

Preliminary simulation tests of large low-aspect-ratio aircraft indicate that ground effects can drastically affect the pilot's landing performance. To study ground effects and their influence on landing characteristics, the flight test program on an existing low-aspect-ratio wing aircraft (ref. 1) was extended to supply data concerning ground effect. The extent to which wind-tunnel data on ground effect can be used to predict landing characteristics was also examined through a comprehensive wind-tunnel program in conjunction with the flight program.

The flight investigation was made at the Ames Research Center with a Douglas F5D-1 aircraft which had been modified to incorporate an Ogee wing planform. At the same time wind-tunnel tests were conducted in the Ames 40- by 80-foot wind tunnel and the Lockheed 8- by 12-foot wind tunnel with ground boards, and in the Langley 7- by 10-foot wind tunnel, with a moving and a stationary ground belt.

The flight-measured ground effect characteristics of the test aircraft are described in this report and the various wind-tunnel data are compared with the flight data. Data for the tests in the Lockheed tunnel were obtained from reference 2. The Ames 40- by 80-foot wind tunnel and the Langley 7- by 10-foot wind tunnel data are unpublished and currently on file at the respective research centers.

## NOTATION

$C_D$ drag coefficient, drag/qS

$C_{D_{trim}}$ drag coefficient at trim

| | |
|---|---|
| $C_L$ | lift coefficient, lift/qS |
| $C_{L_{trim}}$ | lift coefficient at trim |
| $\bar{c}$ | mean aerodynamic chord, ft |
| h | distance from mean aerodynamic chord to the ground at $\alpha = 0$, ft |
| q | dynamic pressure, lb/sq ft |
| R | Reynolds number based on mean aerodynamic chord |
| S | wing area, sq ft |
| $\alpha$ | angle of attack, deg |
| $\delta_e$ | elevon angle, deg |
| $\delta_{e_{trim}}$ | elevon angle for trim |
| $\partial C_m/\partial \delta_e$ | change in pitching moment per change in elevon angle |

## DESCRIPTION AND TESTS

### Test Airplane

The aircraft used for these flight tests was the low-aspect-ratio delta-wing Douglas F5D-1 which had been modified as described in reference 1 to incorporate an Ogee planform. Figure 1 is a photograph of the aircraft in flight, and figure 2 is a two-view sketch. Pertinent dimensions of the aircraft are presented in table I, and the flight-measured aerodynamic characteristics of this modified aircraft are presented in reference 1. During these tests the weight of the aircraft varied from 21,000 to 24,000 pounds and the center of gravity was located at 32 percent of the mean aerodynamic chord of the Ogee wing.

### Flight Instrumentation

Prior to the flight tests, instruments were installed for recording simultaneous measurements of airspeed, altitude, normal and longitudinal acceleration, angles of attack and sideslip, control positions, angular velocities, and tail-pipe total pressure. To minimize the errors in the airspeed and angle-of-attack measurements, the sensing instruments were mounted on a nose boom 10 feet long. This installation was not calibrated but a similar installation indicated the errors due to the presence of the aircraft to be small. The effect of the proximity of the ground on the static pressure source of the airspeed system is unknown, so the ground reference static pressure measured at the tower and corrected to field altitude was used during these tests.

A Lockheed Location Orientation Recording Instrument (LORI) was mounted vertically on the lower surface of the fuselage. This system (described in ref. 3) measured aircraft height above the runway, rate of change in height, ground speed, and pitch angle.

The accuracy of the flight instrumentation, based on a dynamic pressure of 100 $lb/ft^2$, is estimated to be 0.01 for lift coefficient and 0.0015 for drag coefficient.

## Flight Tests

To measure the ground effect on the aircraft during flight, a series of runs was made along the runway at various fixed heights and at constant airspeeds of 200, 175, 150, and 125 knots. The Reynolds number varied from $49\times10^6$ to $30.5\times10^6$. These runs were made at main wheel heights from 1/2 foot to 35 feet. A photograph taken during one run is shown in figure 3. The pilot had no visual aids to help him maintain a fixed height; however, the data indicated they were unnecessary since the pilot maintained less than ±1/2 foot variation at the lower heights and ±1-1/2 feet at the higher heights. The flight-measured parameters were converted to lift and drag characteristics by the method described in reference 4.

During the flight tests the LORI measurements defined the distance from the wheels to the ground, and this distance was converted to a mean aerodynamic chord height (h) by adjusting for the normal distance from the wheels to the fuselage reference plane. This procedure introduced a discrepancy in $h/\bar{c}$ that increased with angle of attack ($h/\bar{c} = 0.28$ at main wheel ground contact at $\alpha = 0$). This procedure is similar, however, to that used during the wind-tunnel tests so that flight and wind-tunnel data are comparable.

## Wind-Tunnel Models

The actual aircraft was used as the model in the full-scale tests conducted in the Ames 40- by 80-foot wind tunnel. For these tests the aircraft was mounted from the landing gear, as shown in figure 4, and the inlet ducts were sealed and faired. For the tests in the Lockheed 8- by 12-foot wind tunnel and the Langley 7- by 10-foot wind tunnel, the original 0.15 scale model of the F5D-1 was used. It was loaned by the Bureau of Naval Weapons, U. S. Navy, and modified by Lockheed to conform with the Ogee wing planform of the aircraft used in the flight tests. In the Lockheed tunnel, the model was mounted on struts attached to the model ahead and inboard of the gear (fig. 5). In the Langley tests, the model was sting mounted (fig. 6) and was tested with both a moving ground belt and a stationary ground belt. In the Lockheed and Langley tests, the inlets and fuselage exit were unsealed.

### Wind-Tunnel Tests

In each wind tunnel a set of lift, drag, and pitching-moment data was obtained at several heights above the ground plane. The number of heights tested varied from two in the Lockheed tunnel to seven in the Langley tunnel. In addition to the basic data for elevon angle of zero, data were obtained for three other elevon deflections (one down and two up deflections) to obtain elevon effectiveness. In the Lockheed tunnel out of ground effect data were obtained with the ground plane removed while in the Ames and Langley tunnels the greatest heights were considered to be out of ground effect. It is assumed that the data from each wind tunnel have been fully corrected for the necessary wall, flow angularity, and tare effects.

## RESULTS AND DISCUSSION

### Basic Data

The flight-measured data are presented in figure 7 in the form of variations in angle of attack, drag coefficient, and trim elevon angle with lift coefficient. Each data point represents a stabilized point during a low-level run; the points have been grouped according to constant height parameters, $(h/\bar{c})$. Figures 8, 9, and 10 present data obtained in the Ames 40- by 80-foot wind tunnel, the Lockheed 8- by 12-foot wind tunnel, and the Langley 7- by 10-foot wind tunnel, respectively.

So these data could be presented in the same form, the pitching moments measured in the wind-tunnel tests were converted to equivalent elevon angles and are plotted in figures 8, 9, and 10. This equivalent elevon angle was obtained by dividing the pitching moment by the elevon effectiveness determined in the same facility. In the Lockheed tests, only the outboard elevons were deflected while elevon effectiveness was measured; whereas in the flight tests and the other two wind tunnels both the inboard and outboard elevons were moved in unison. Consequently, the Lockheed data for elevon effectiveness and lift due to elevon deflection have been increased by 32 percent (ratio of elevon areas and moment arms) to account for the inboard elevon deflection and to allow correlation with the other tests.

The data from the tests in the 7- by 10-foot wind tunnel showed no differences with a fixed ground belt and with the moving ground belt; hence, only the data with the belt stationary are shown. During these tests, the sting-mounted model oscillated occasionally; to prevent the landing gear from contacting the belt during these oscillations, the gear was removed during the low-height tests. However, the data shown were obtained during stable conditions. The data on figure 8 are for the configuration with the gear removed and the drag data have been corrected to include the drag of the gear. Data obtained with the gear on and off indicated negligible effect of the gear on the lift or moment data.

All four sets of data (figs. 7-10) indicate the same general influence on the aerodynamic properties associated with operation near the ground. There is a definite increase in lift-curve slope and in the nose-down pitching moment, as indicated by the increase in elevon angle required for trim. The changes in drag coefficient, however, are not so clearly defined and the trends vary slightly between the four tests.

The elevon effectiveness is also influenced by the proximity of the ground. The magnitude of this effect as measured in the three wind tunnels is shown in figure 11 at angles of attack of $10^\circ$ and $15^\circ$. These data show an increase in elevon effectiveness as the height was decreased and an agreement between the wind tunnels. The Ames 40- by 80-foot wind-tunnel data do not indicate as large an effect of ground proximity as the other two tunnels; elevon effectiveness was higher and the ground effect greater at the lower angle of attack. The data measured in the Lockheed tunnel have been corrected to account for the inboard elevon effect, as noted earlier.

## Comparison of Flight and Wind-Tunnel Data

The lift and drag characteristics measured in the wind tunnels have been corrected to the trim condition and compared with the flight data. These comparisons are presented in figures 12, 13, and 14 for lift, drag, and elevon angle required for trim, respectively. These comparisons indicate a fair agreement between flight and wind-tunnel data. During the reduction of the flight data it was found that the angle measured by the angle-of-attack sensor was influenced by the nearness of the ground. This effect was most noticeable at the lowest height and high angles of attack. Consequently, the data presented in figures 12, 13, and 14 for an $h/\bar{c}$ of 0.33 have been corrected for this effect using the pitch attitude data obtained with the LORI camera and upwash data measured in the Ames 40- by 80-foot wind tunnel. This correction varied linearly with angle of attack and was minus $2^\circ$ at an indicated angle of attack of $14^\circ$.

Various factors might influence the correlation among all these data; however, it is impossible to determine their relative significance. Therefore, this report will only list some of the factors affecting the correlation of these data. The drag data will be influenced by the fact that the 40- by 80-foot wind-tunnel data were obtained with the inlets sealed and faired, while in the other two tunnel programs the inlets were open. The flight-drag data might be affected by an uncertainty in the nozzle coefficient used in determining thrust, because a recent calibration for the probe-engine combination used was not available. The differences between the flight and wind-tunnel results for the elevon required for trim are of the same magnitude shown earlier in flight tests on the Ogee wing and reported in reference 1. This increment in elevon angle is equivalent to an uncertainty in locating the aircraft center of gravity of about 2 percent of the mean aerodynamic chord. The difference between the Ames 40- by 80-foot wind-tunnel data and the Lockheed low speed tunnel and the Langley 7- by 10-foot wind-tunnel data may be due to strut interference differences.

The flight data are summarized in figure 15. The changes in lift coefficient and pitching moment, illustrated by the change in elevon angle required for trim, are shown as a function of the height parameter $(h/\bar{c})$ for two values of angle of attack. These data indicate that at an approach angle of attack of 15°, a change in lift coefficient of about 0.18 and a pitching-moment change equivalent to 4° of up elevon angle is experienced during a landing approach and touchdown. It should be pointed out that this magnitude of ground effect was barely noticed by the pilot and had no effect on the pilot's ability to perform landings.

## Comparison With Theory

The method of reference 5 has been used to calculate the changes in lift curve slope and location of the aerodynamic center due to ground effect. This method is based on slender wing theory which limits its application to wings of very small aspect ratio. While the 1.70 aspect ratio of the wing in these tests undoubtedly exceeds the limitations of the theory, nevertheless, it was felt to be of interest to compare the method with the measured characteristics presented herein. To accommodate the limitations of the theory, the wing plan-form shown in figure 16 was adjusted as indicated. The comparisons of the calculated and measured changes in characteristics due to ground proximity are presented in the following table. The $h/\bar{c}$ for the theoretical calculations is 0.30, while the measured data are for values of $h/\bar{c}$ of 0.33 or 0.34, depending upon the tunnel. Since the theory is for low angles of attack, the

| Change in - | Calculated | Ames 40 × 80 | Lockheed wind tunnel | Langley 7 × 10 | Flight |
|---|---|---|---|---|---|
| Lift curve slope | 0.017 | 0.012 | 0.020 | 0.018 | 0.011 |
| Location of aerodynamic center | $.038\bar{c}$ | $.027\bar{c}$ | $.033\bar{c}$ | $.025\bar{c}$ | [a] $.026\bar{c}$ |

[a] To compute the shift in aerodynamic center from flight data the elevon effectiveness as measured in the Ames 40- by 80-foot wind tunnel was used.

slopes for the lift curves were measured near $\alpha = 6^\circ$. This comparison shows reasonable agreement except for the change in lift curve slope measured in flight and in the Ames 40- by 80-foot wind tunnel; also, the calculated results indicate a more rearward shift in the location of the aerodynamic center than was measured. The calculated and wind tunnel results are for the untrimmed condition, while the flight data are for the trimmed condition.

## CONCLUDING REMARKS

Flight and wind-tunnel tests to determine the ground effect on an aircraft with a low-aspect-ratio Ogee wing indicated fair degree of agreement. The magnitude of this ground effect was exhibited by (at wheels touchdown) a trimmed lift increment of about 0.18 in $C_L$ and a nose-down pitching moment requiring $4^{\circ}$ of up elevon angle for trim at an aircraft angle of attack of $15^{\circ}$. This ground effect was barely noticed by the pilot and had negligible effect on the pilot's ability to perform landings.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., March 22, 1966

## REFERENCES

1. Rolls, L. Stewart; Koenig, David G.; and Drinkwater, Fred J., III: Flight Investigation of the Aerodynamic Properties of an Ogee Wing. NASA TN D-3071, 1965.

2. Bennett, G. B.: Low Speed Wind Tunnel Test of a 0.15 Scale Douglas F5D With NASA Ogee Wing Planform. Rep. LFL L-92 II, Lockheed Aircraft Corp., Sept. 2, 1964.

3. Sullo, A. A.; Dick, R. E.; and Duke, J. O.: Lockheed Location Orientation Recording Instrument. Rep. 16256, Lockheed Aircraft Corp., 1962.

4. Rolls, L. Stewart; and Wingrove, Rodney C.: An Investigation of the Drag Characteristics of a Tailless Delta-Wing Airplane in Flight, Including Comparison With Wind-Tunnel Data. NASA MEMO 10-8-58A, 1958.

5. Gersten, Klaus: Calculation of the Aerodynamic Characteristics of Wings of Finite Span Near the Ground. Royal Aircraft Establishment Library Trans. 1054, Dec. 1963.

TABLE 1. DIMENSIONAL DATA FOR THE F5D-1 AIRPLANE WITH AN OGEE PLANFORM WING

| | |
|---|---|
| Wing | |
| Area, sq ft | 661 |
| Span, ft | 33.5 |
| Aspect ratio | 1.70 |
| Mean aerodynamic chord, ft | 22.59 |
| Incidence at root, deg | 0 |
| Geometric twist, deg | 0 |
| Sweep | |
| Leading edge at root, deg | 77 |
| Leading edge, minimum, deg | 55.8 |
| Elevon | |
| Area aft of hinge line (one side), sq ft | 24.26 |
| Span, ft | 11.79 |
| Inboard elevon | |
| Area aft of hinge line (one side), sq ft | 9.04 |
| Span, ft | 2.58 |
| Vertical tail | |
| Area, sq ft | 69.87 |
| Span, ft | 9.46 |
| Sweep of 25-percent chord line, deg | 48.22 |
| Rudder | |
| Area aft of hinge line, sq ft | 9.29 |
| Span, ft | 6.29 |
| Fuselage | |
| Length, ft | 46.83 |
| Maximum depth, ft | 4.75 |
| Maximum width, ft | 4.75 |


A-33500-3

Figure 1.- Photograph of the test aircraft in flight.

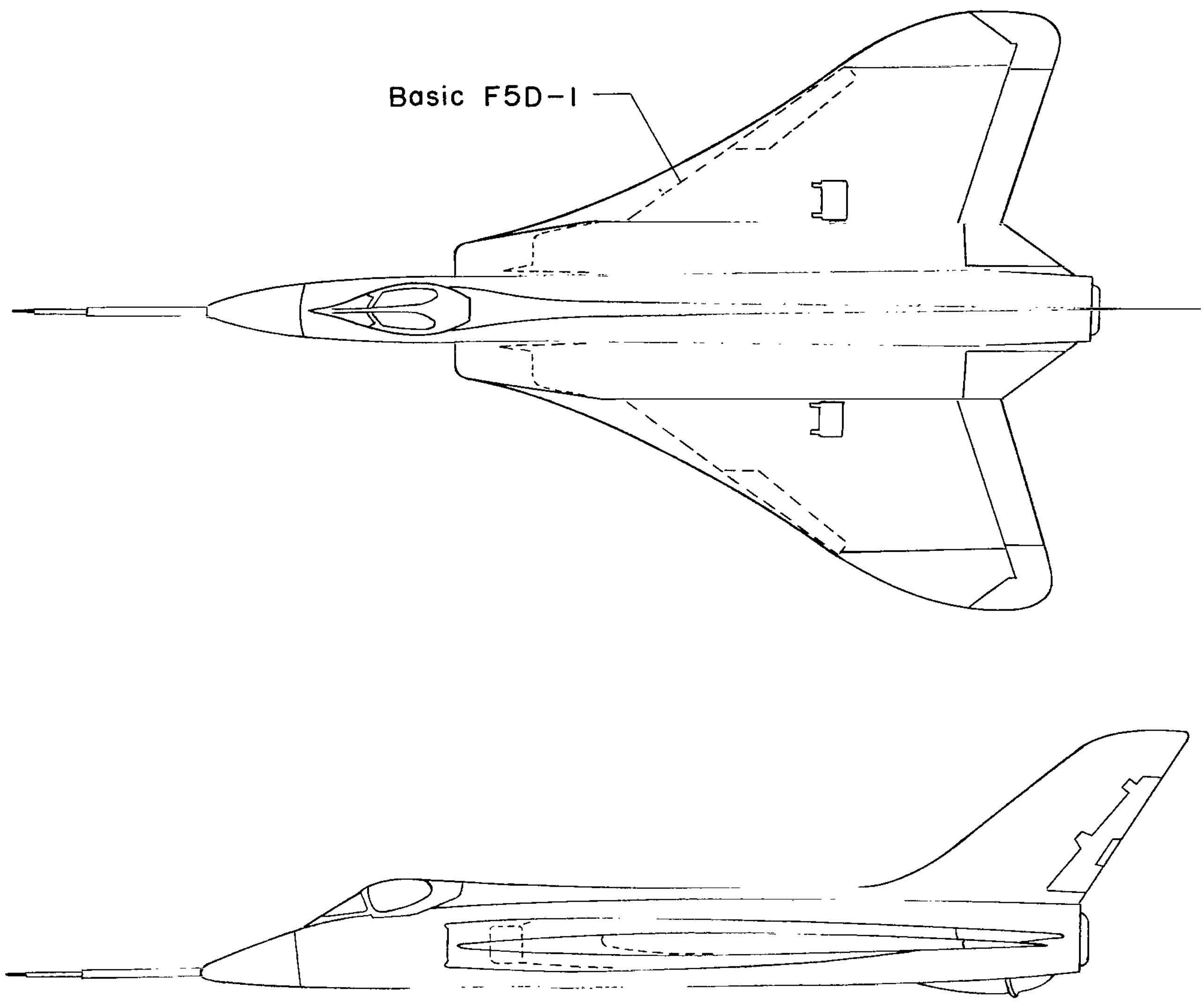
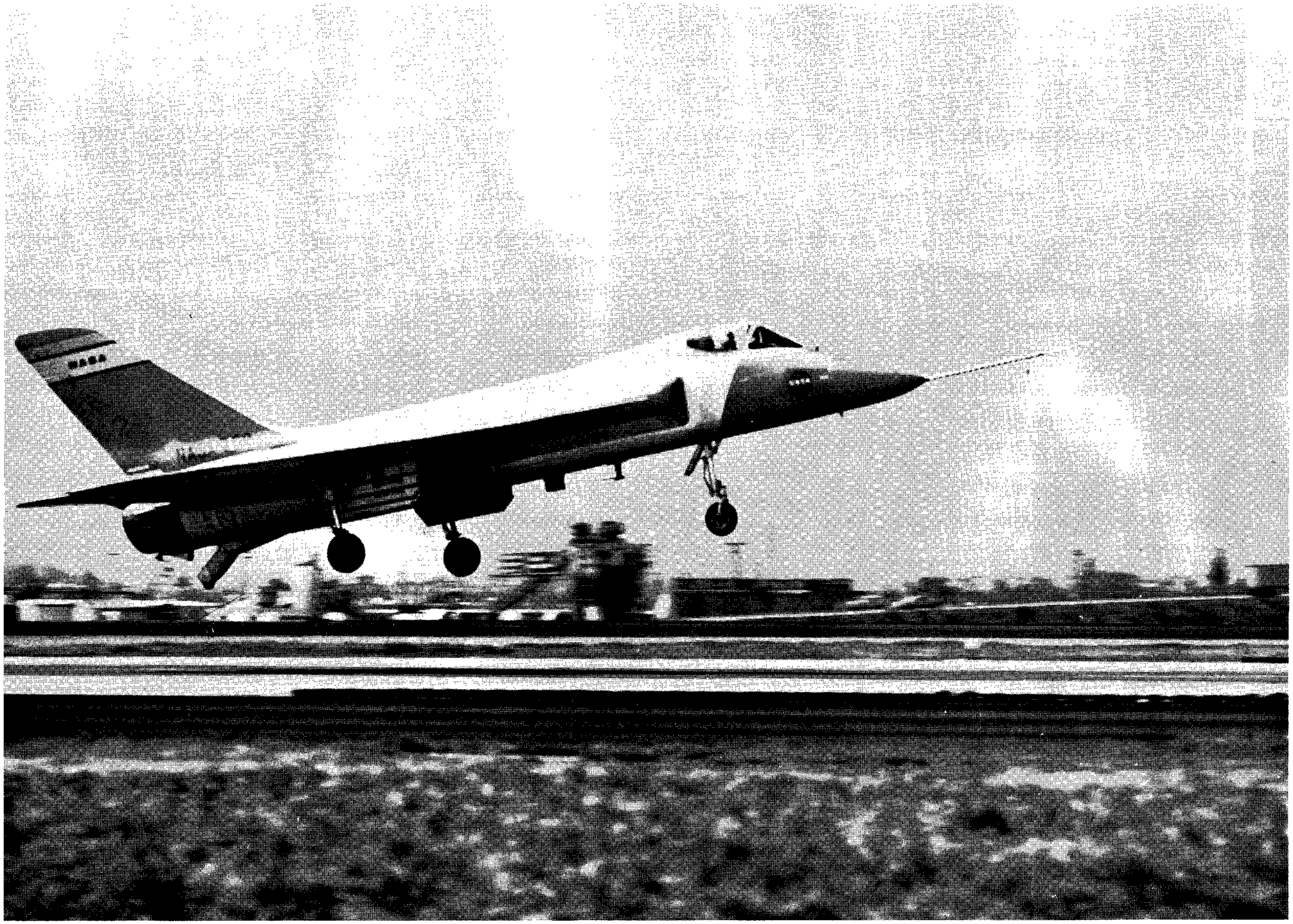



Figure 2.- Two-view sketch of test airplane.



A-35650-2

Figure 3.- F5D airplane during a low, level run along the runway.

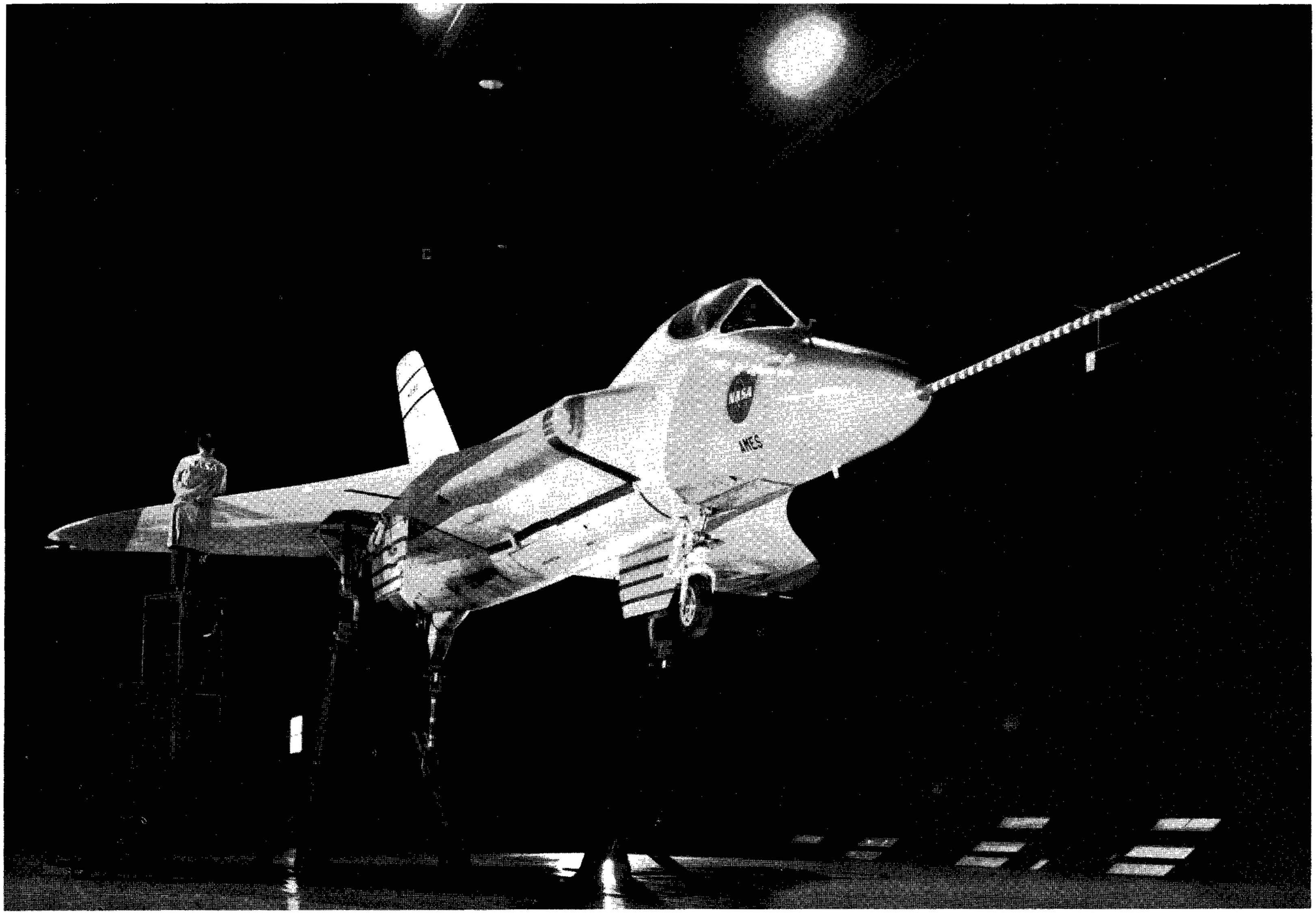



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Figure 4.- F5D airplane mounted in the Ames 40- by 80-foot wind tunnel.

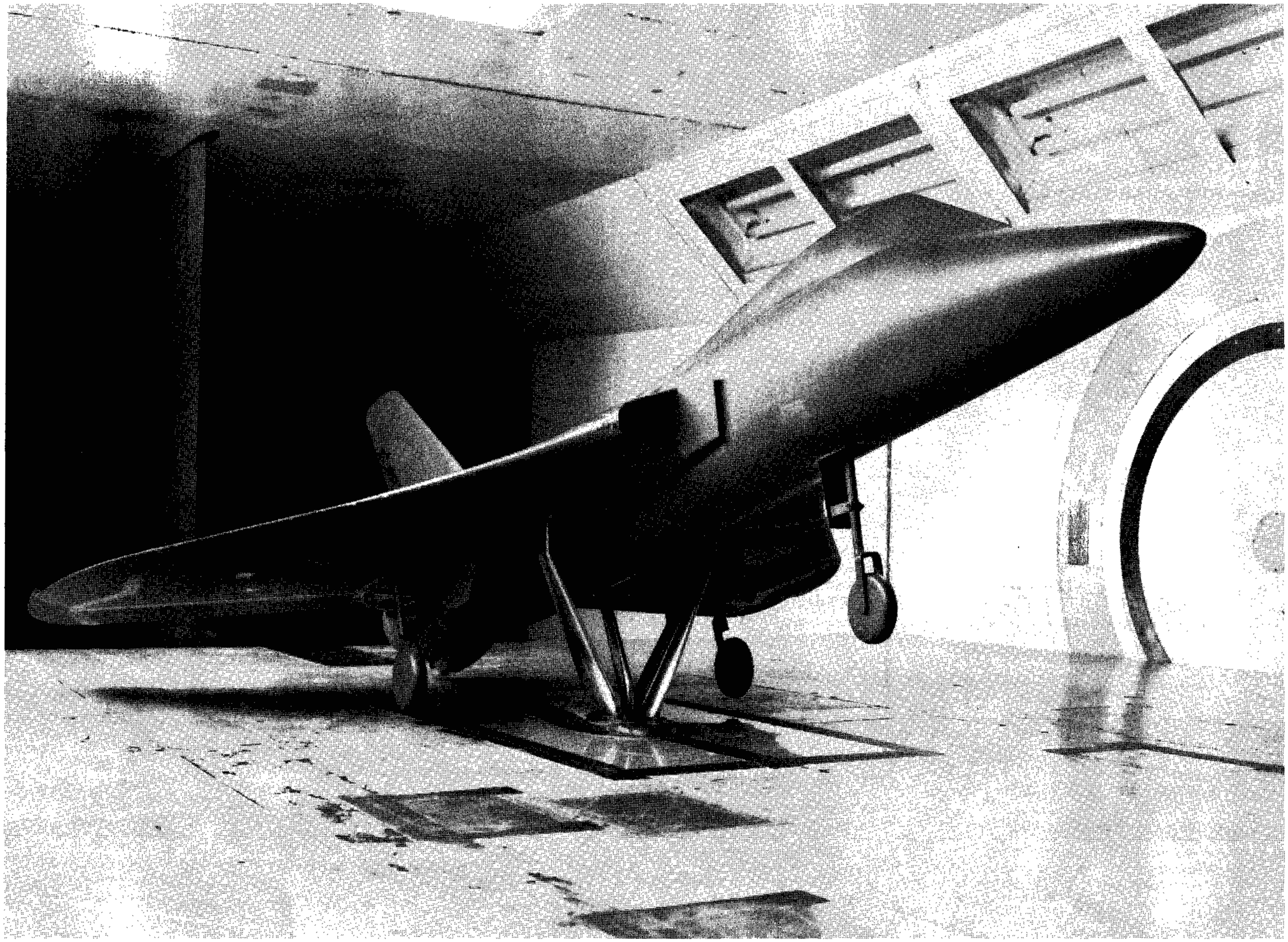

Figure 5.- Model mounted in Lockheed tunnel (model shown prior to installation of Ogee planform).

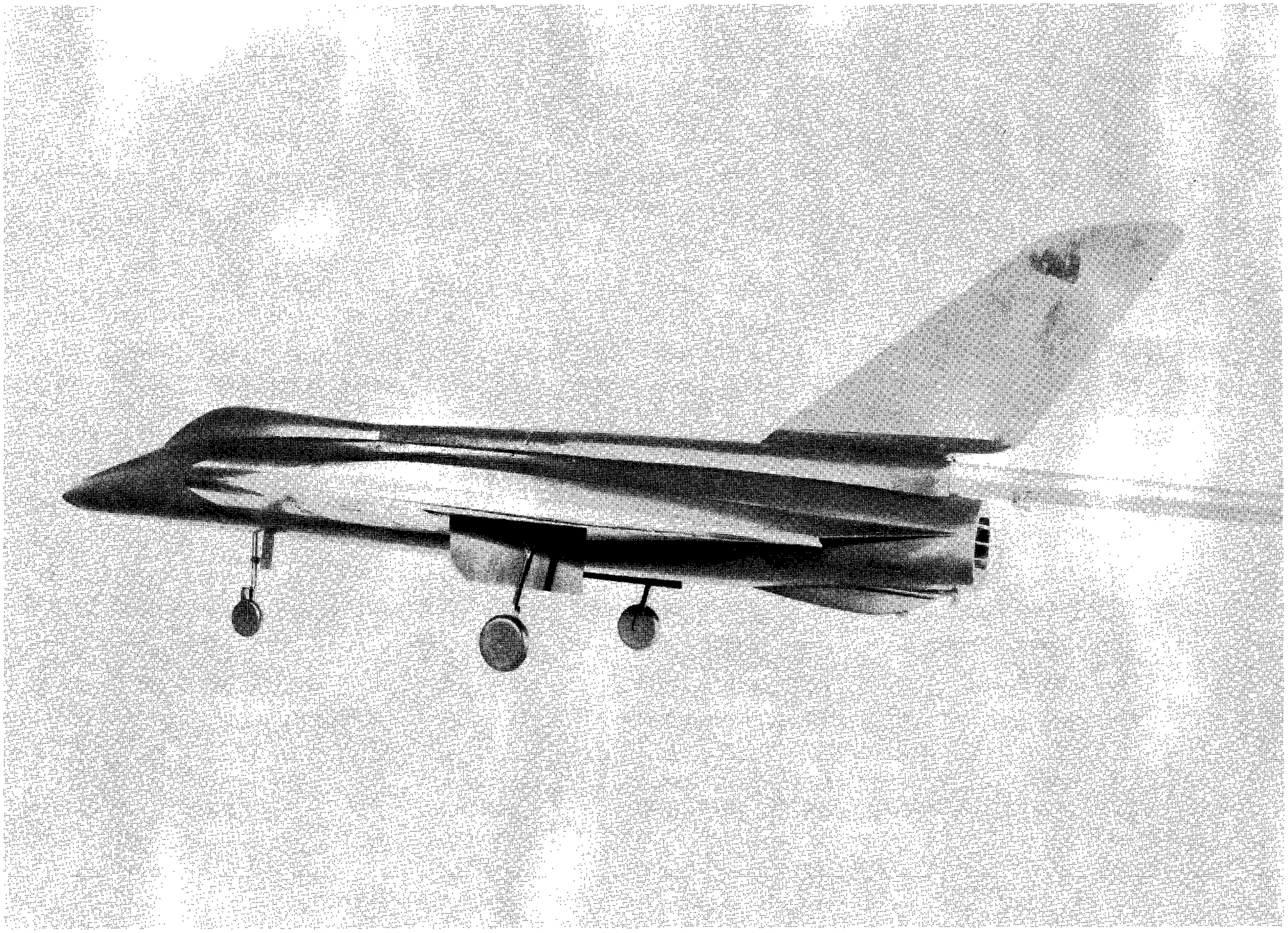

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Figure 6.- Model as tested in Langley tunnel.

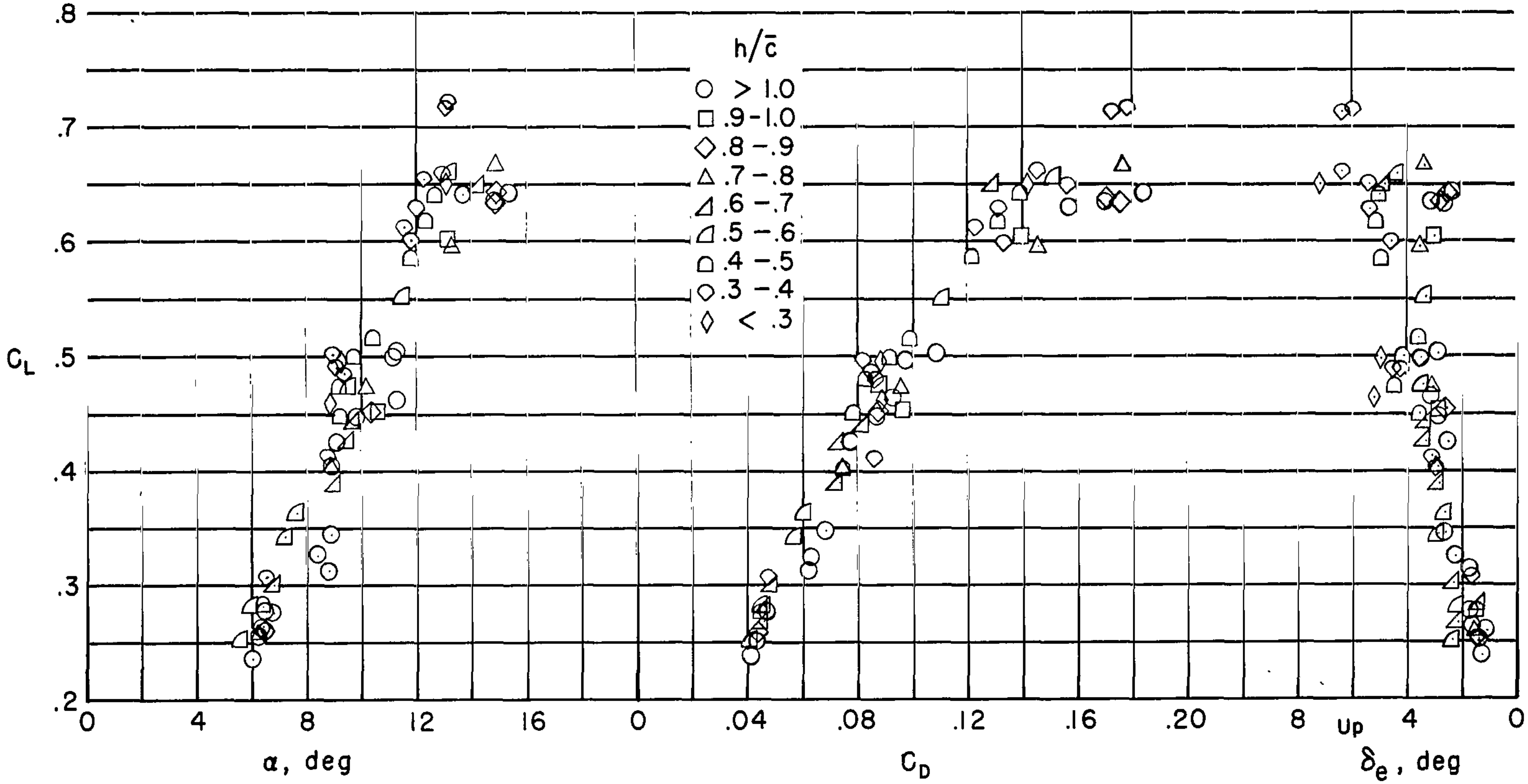



Figure 7.- Flight data at various heights above ground.

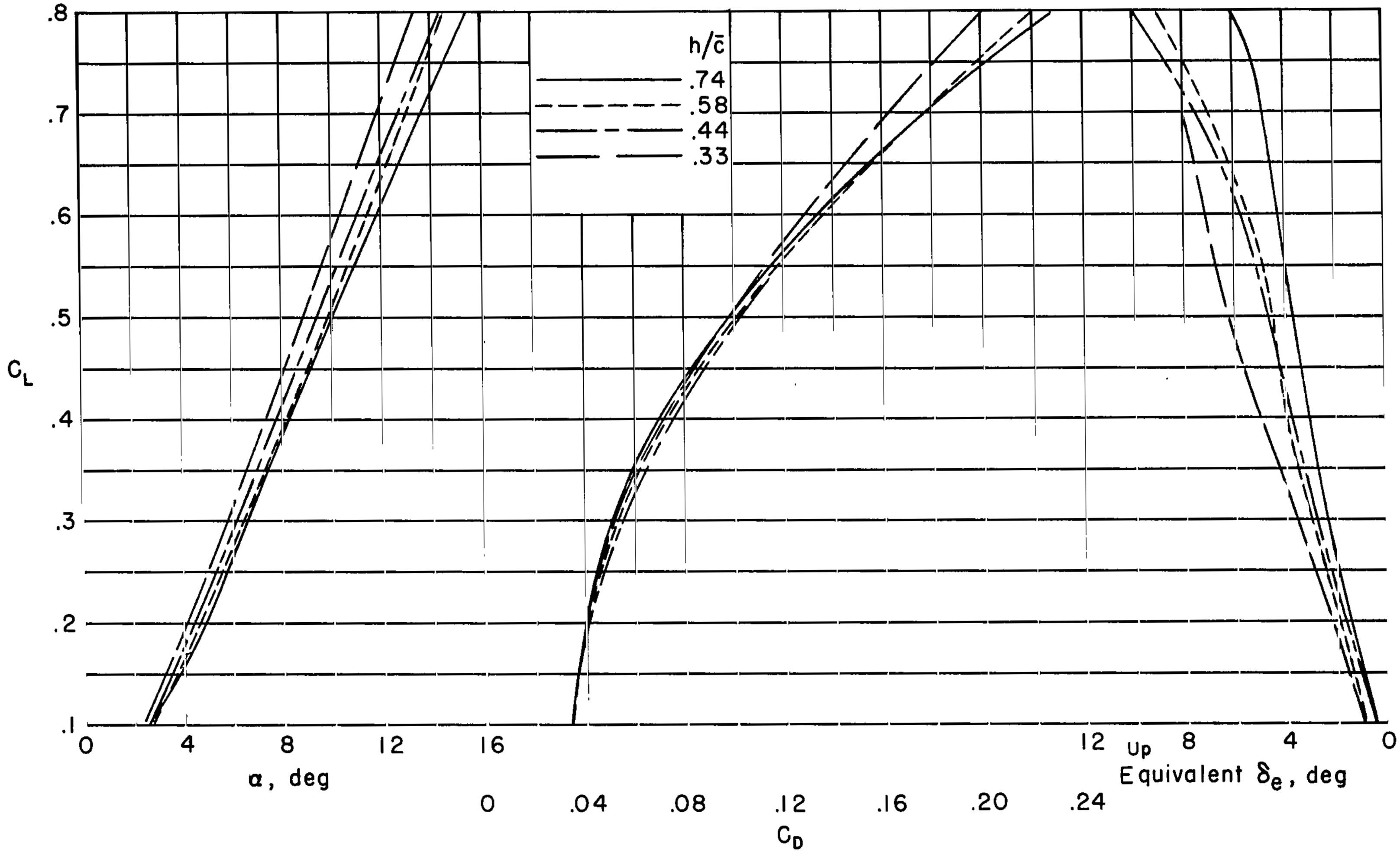



Figure 8.- Basic data from test of airplane in Ames 40- by 80-foot wind tunnel; $q = 35$ lb per ft$^2$, $R = 24 \times 10^6$.

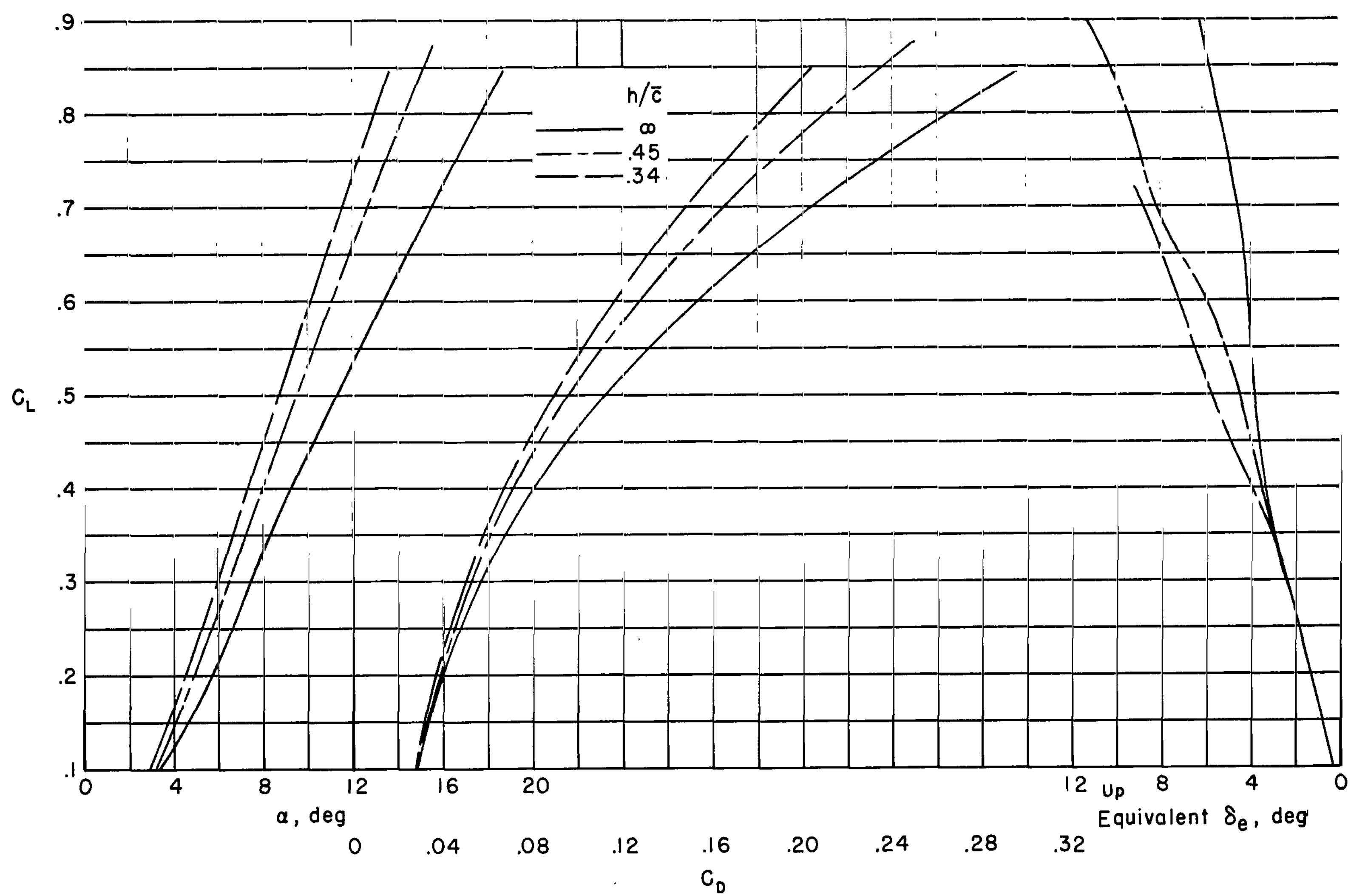



Figure 9.- Basic data from test of a 0.15 scale model in Lockheed 8- by 12-foot subsonic tunnel; $q = 60$ lb per ft$^2$, $R = 4.4 \times 10^6$.

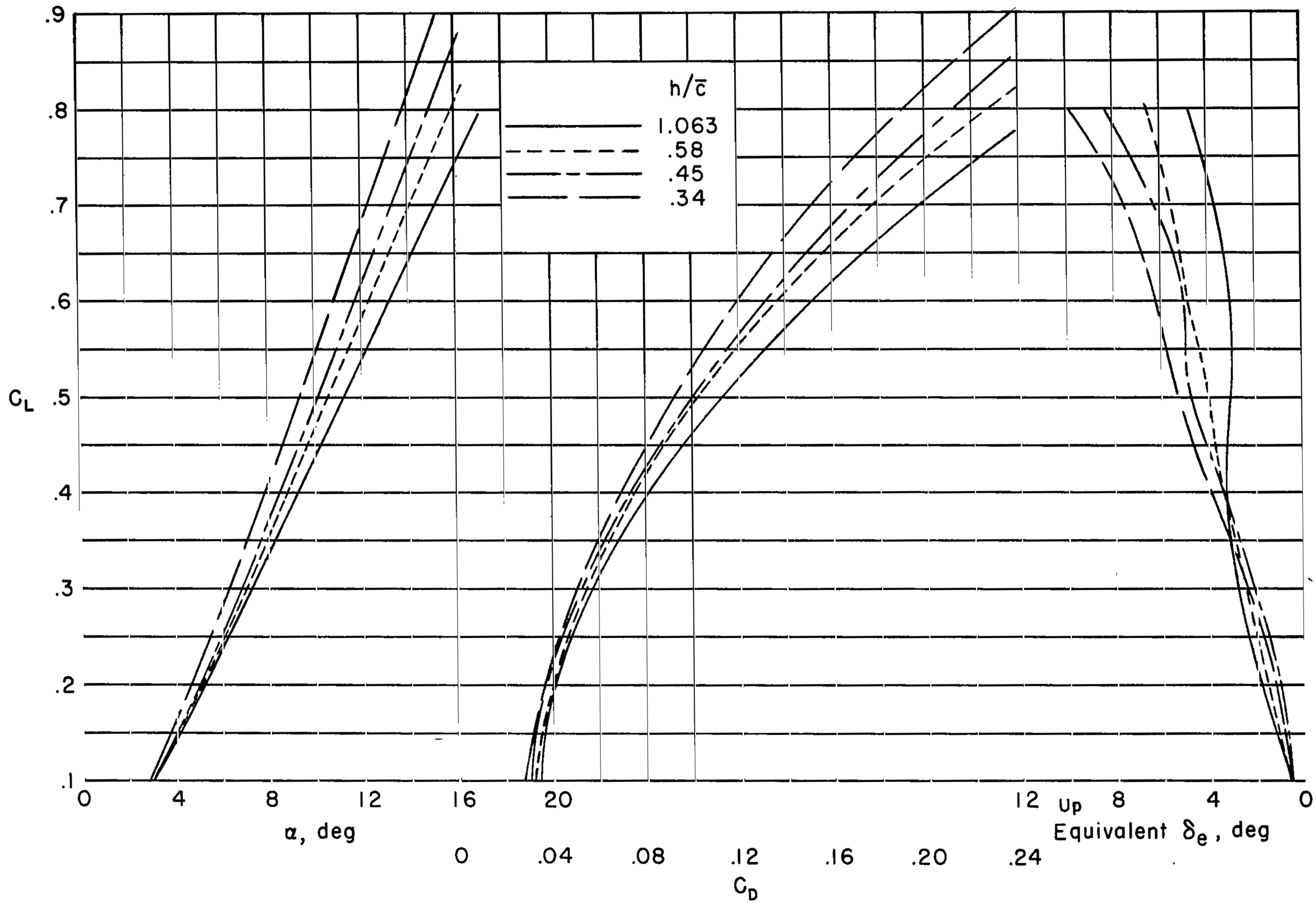



Figure 10.- Basic data from test of a 0.15 scale model in Langley 7- by 10-foot wind tunnel; $q = 9.0$ lb per ft$^2$, $R = 1.7 \times 10^6$.

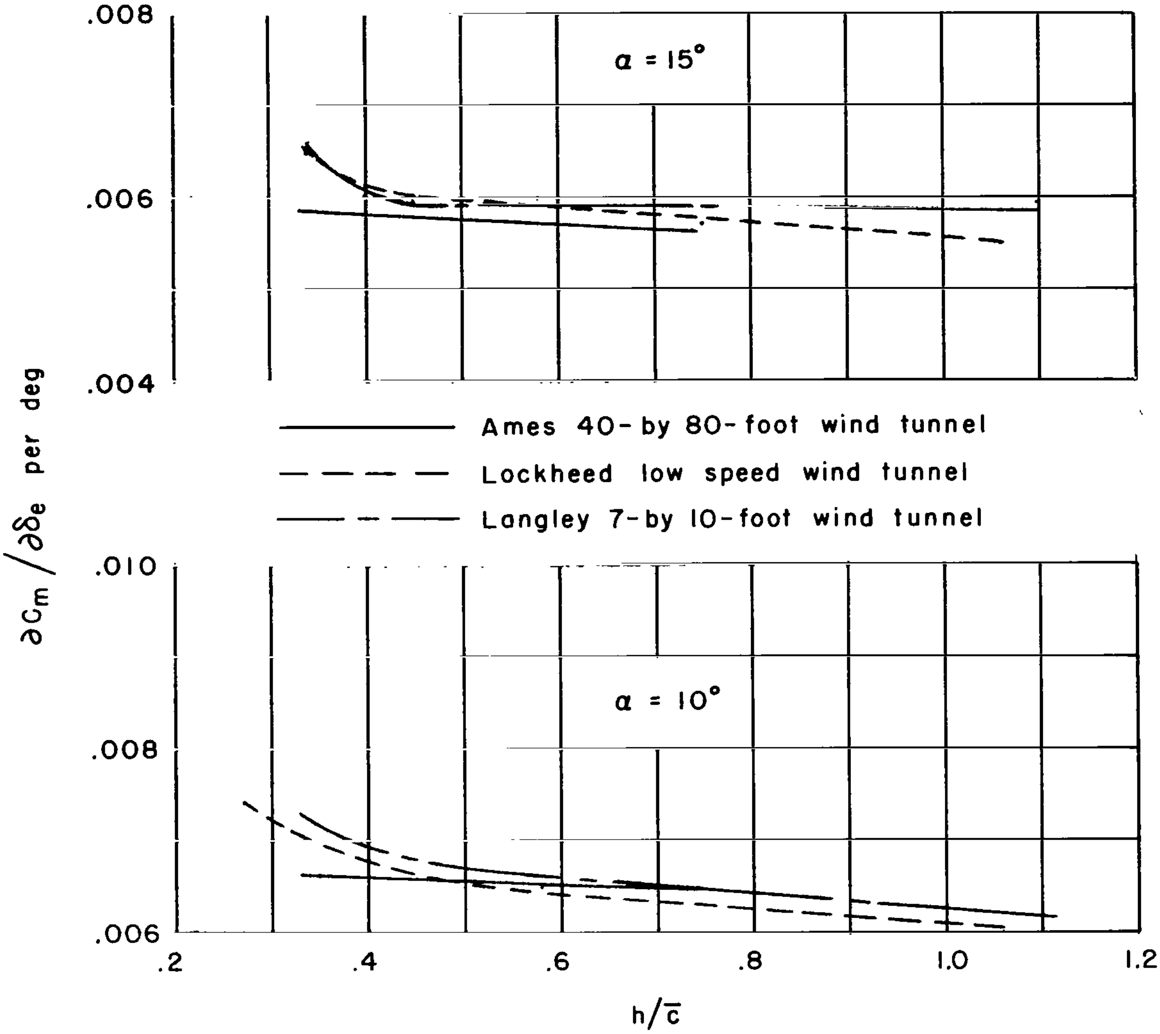
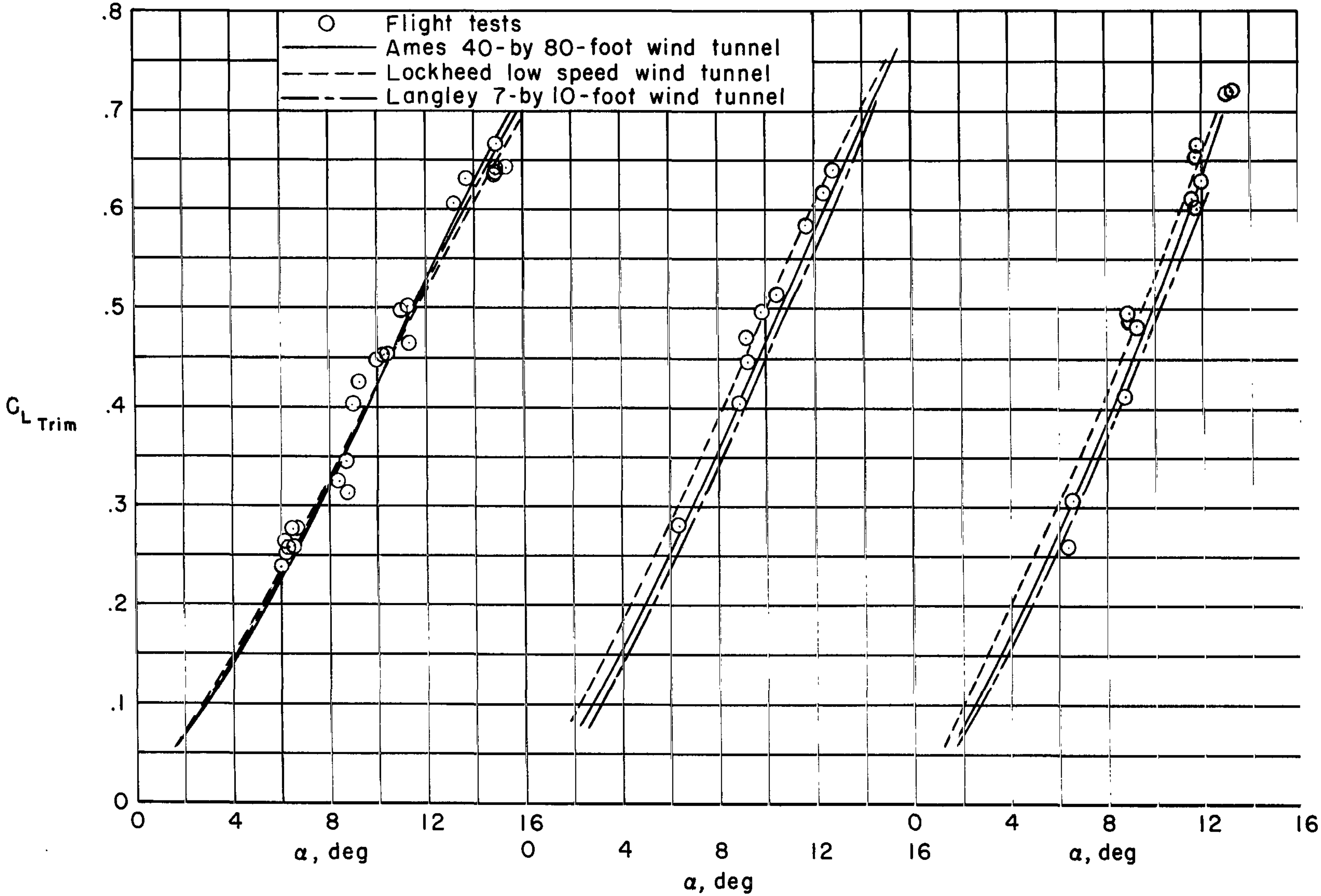
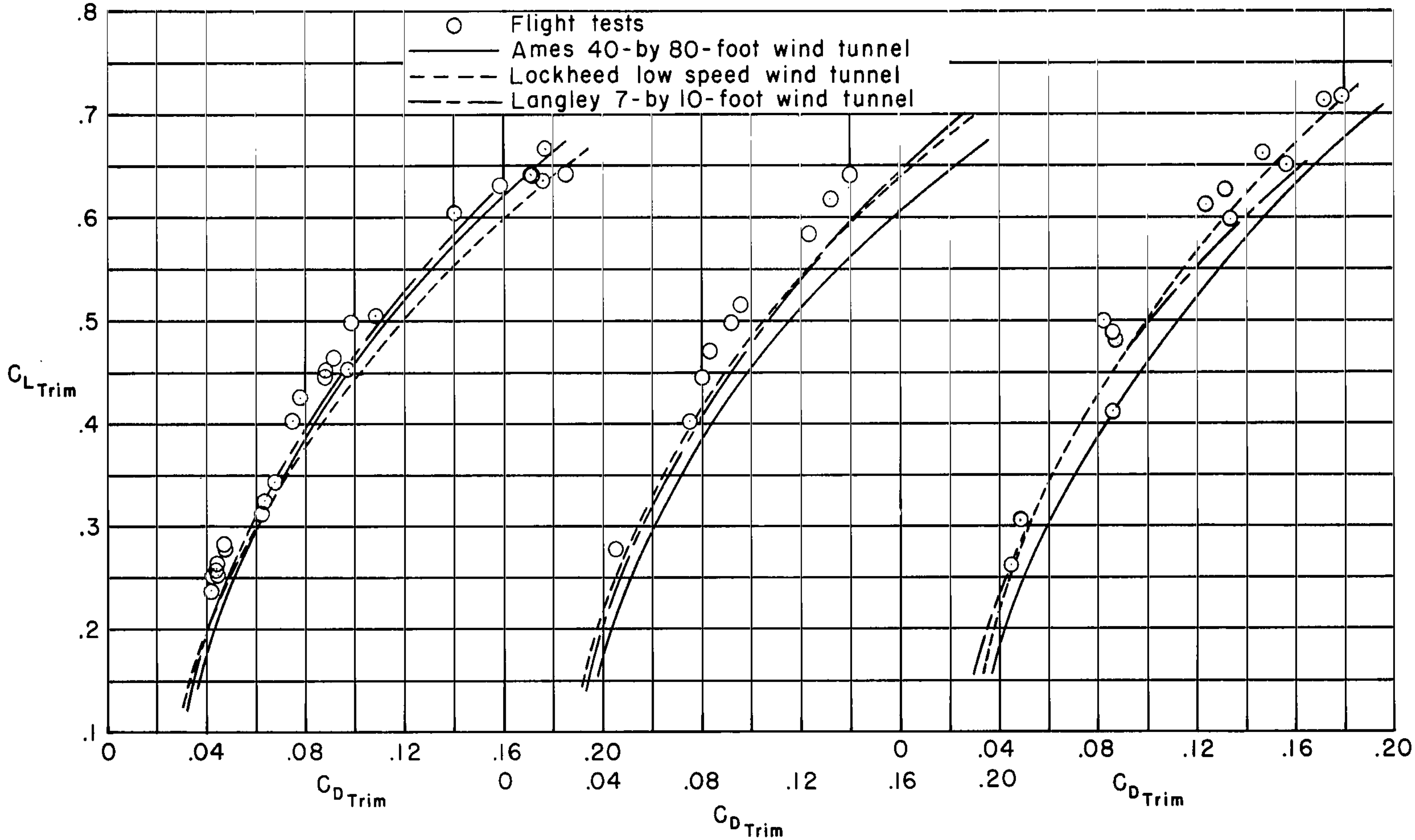



Figure 11.- Variation of elevon effectiveness with height for two values of angle of attack.



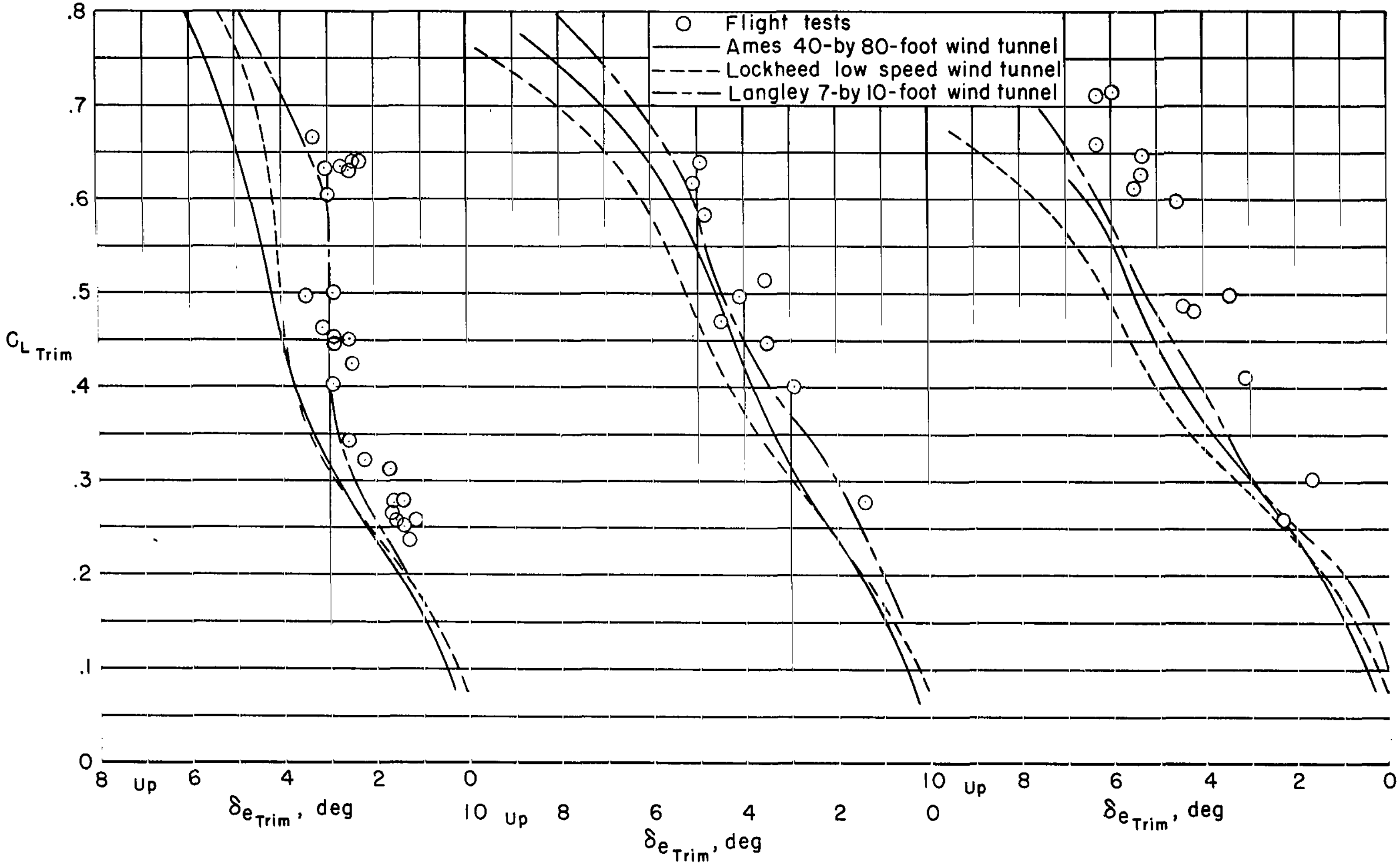

(a) $h/\bar{c} > 0.75$ (b) $h/\bar{c} \approx 0.44$ (c) $h/\bar{c} \approx 0.33$

Figure 12.- Lift characteristics at several heights above ground.




(a) $h/\bar{c} > 0.75$ (b) $h/\bar{c} \approx 0.44$ (c) $h/\bar{c} \approx 0.33$

Figure 13.- Drag characteristics at several heights above ground.




(a) $h/\bar{c} > 0.75$

(b) $h/\bar{c} \approx 0.44$

(c) $h/\bar{c} \approx 0.33$

Figure 14.- Trim characteristics at several heights above ground.

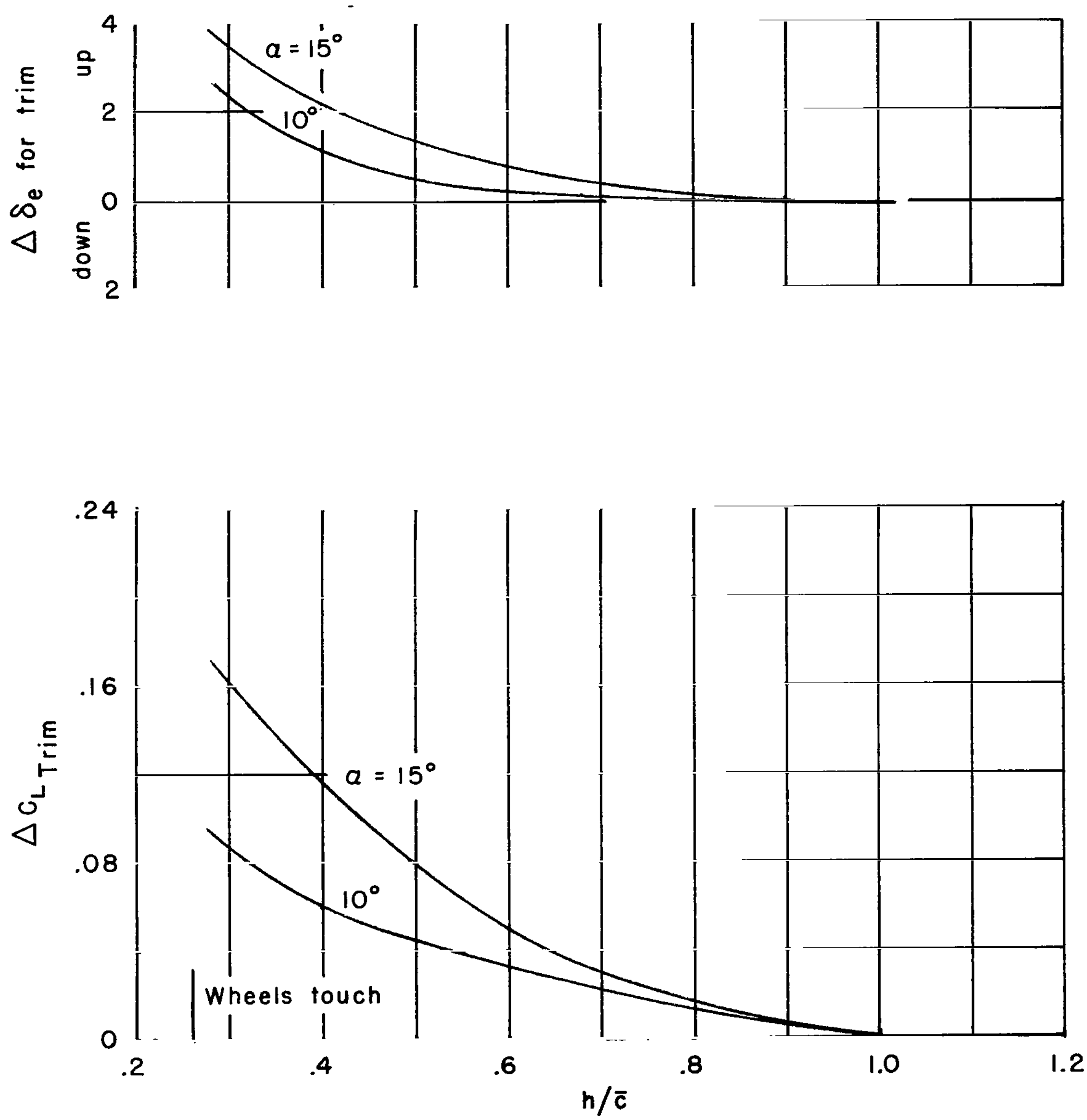



Figure 15.- The flight-measured variation of incremental lift and elevon deflection for trim with height above ground.

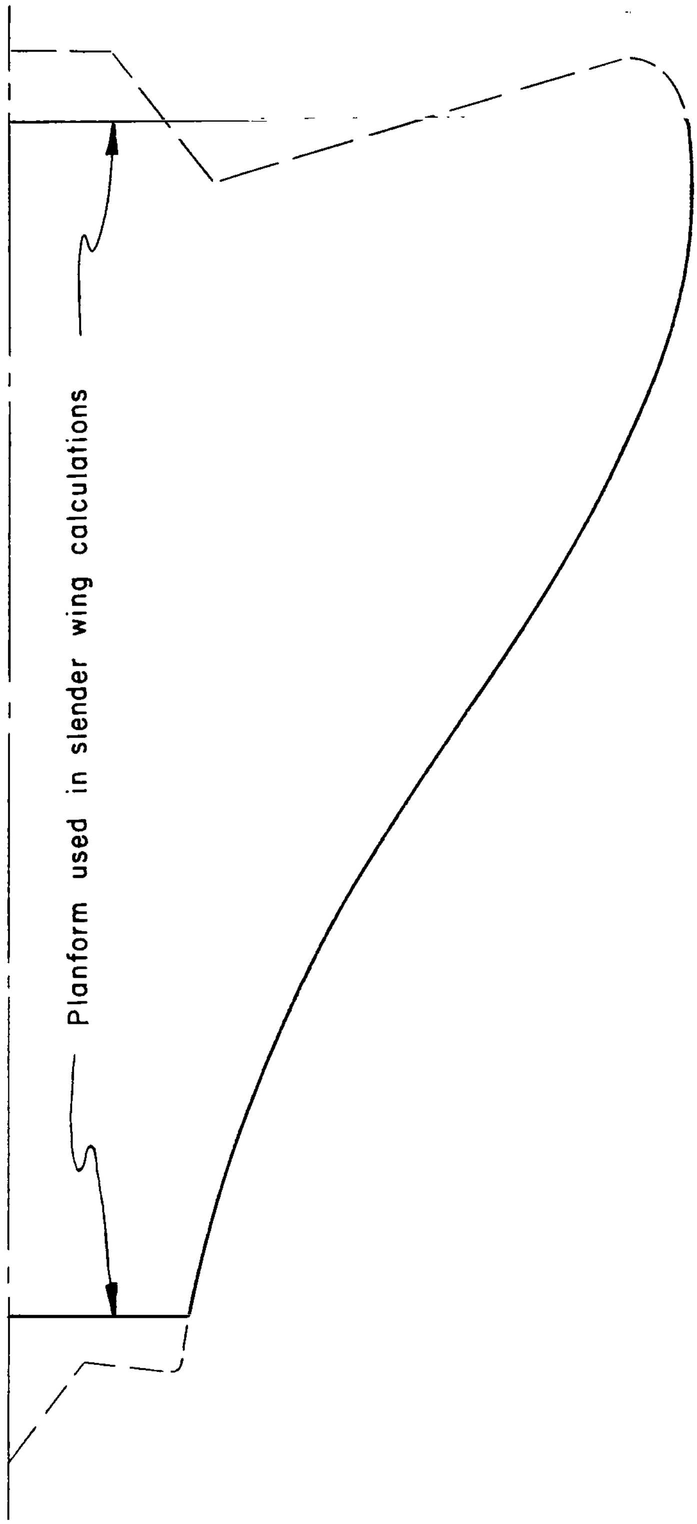



Figure 16.- Changes made to planform to facilitate the theoretical calculation of lift and moment.



NASA-Langley, 1966 A-2286

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