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DETERMINATION BY THE FREE-FALL METHOD OF THE LONGITUDINAL STABILITY AND CONTROL CHARACTERISTICS OF A $\frac{1}{4}$-SCALE MODEL OF THE BELL XS-1 AIRPLANE AT TRANSONIC SPEEDS

By

James T. Matthews, Jr., and Charles W. Mathews

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
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SUMMARY

The free-fall investigations which are being conducted at the Langley Aeronautical Laboratory of the National Advisory Committee for Aeronautics have been extended to include tests to determine the longitudinal stability and control characteristics of airplane configurations at transonic speeds. This report presents the results of a test to determine the longitudinal stability and control characteristics of a $\frac{1}{4}$-scale model of the Bell XS-1 airplane. The elevator position of the model was automatically controlled by the normal acceleration in such a manner as to attempt to maintain a constant value of normal acceleration of about 0.45g. This value of normal acceleration corresponds to the lift coefficient obtained in level flight for the full-scale airplane at an average wing loading. There was no provision for roll stabilization on this model.

The model rolled for about 40 seconds after release; then it performed a gradual pull-out. The model had a violent short-period oscillation in the Mach number range from 0.72 to 0.81, which is believed due to the effect of roll on longitudinal stability.

The model did not exhibit the nose-down trim change indicated by wing-flow tests near a Mach number of 0.93. This trim change of the wing-flow model may have been caused in part by a negative change in pitching moment of the wing-fuselage combination. At the Mach number for this trim change the free-fall model required appreciably more down-elevator deflection for trim than was indicated by the wing-flow tests. The stabilizer of the free-fall model was set with $\frac{1}{2}^{\circ}$ positive incidence (leading edge up) as compared with 4° positive incidence for the wing-flow tests. Possibly in the case of the free-fall model the negative change in pitching moment was largely offset by a positive change in pitching moment due to loss in elevator effectiveness.

At the maximum Mach number of 0.98, the model drag coefficient was about 0.13 (based on wing area) and the lift-to-drag ratio was about 3

in the range of lift coefficients from 0.3 to 0.4. The model remained stable at lift coefficients encountered in this test, with the possible exception of the period of violent oscillations, and the variation of elevator deflection with speed was stable up to a Mach number of about 0.72.

On the basis of the results of the model test, it appears that an airplane of similar configuration could fly to a Mach number of 0.98 without encountering excessive normal acceleration as a result of longitudinal trim changes.

INTRODUCTION

The Langley Aeronautical Laboratory of the National Advisory Committee for Aeronautics is conducting a series of investigations by the free-fall method, as described in reference 1. All previous tests have been conducted to determine the transonic drag characteristics of various wings, bodies, and wing-body combinations. The free-fall method is being extended to include tests to determine the longitudinal stability and control characteristics of airplane configurations at transonic speeds. This report presents the results of a test to determine the longitudinal stability and control characteristics of a $\frac{1}{4}$-scale model of the Bell XS-1 airplane. The model was dropped with elevator control only, which was arranged to maintain the normal acceleration at about 0.45g. No provision was made for roll stabilization of the model. The results are presented as time histories of transverse and normal acceleration, longitudinal retardation, elevator deflection, and Mach number. Results are also presented which show the variation with Mach number of lift coefficient, drag coefficient, lift-to-drag ratio, and the slope of the curve of pitching-moment coefficient versus angle of attack.

APPARATUS AND METHOD

Test configuration.- The configuration tested was a $\frac{1}{4}$-scale model of the Bell XS-1 airplane whose full-scale physical characteristics are presented in table I. The general arrangement of the model is shown in figure 1, and the details and dimensions are shown in figure 2. The center of gravity of the model was at 25 percent of the mean aerodynamic chord, the stabilizer was set with $\frac{1}{2}^{\circ}$ positive incidence (leading edge up), and the elevator travel was 10.3° up and 4.5° down. The model weighed 1351 pounds and had a moment of inertia about a lateral axis through the center of gravity of 160 slug-feet^2. The model wing loading was 166 pounds per square foot.

An attempt was made to control the longitudinal trim of the model at a predetermined value of normal acceleration through the use of an automatic pilot. The value of normal acceleration selected was 0.45g, which, at the model wing loading, caused the model to fly at a lift coefficient corresponding to that required for level flight of the full-scale airplane at an average weight.

The automatic pilot was designed to operate the elevator in small steps upon a signal from a sensitive normal accelerometer. The automatic pilot was equipped with a device which produced a $1\frac{1}{2}$-second time-delay between elevator motion in one direction and the other. This time-delay was used to prevent any phase relationship between the elevator motion and the model motion which would produce dynamic instability.

Although no roll control was incorporated in the model, it was desired to have the model roll in order that the mean trajectory would be similar to a free-fall of a nonlifting body. The wing was found to have a slight built-in twist of $\frac{1}{2}^{\circ}$, but the twist was considered too large to produce the desired low rate of roll. In order to reduce the rate of roll somewhat, small wedges were installed on the trailing edge of the wing near the tips as shown in figure 2.

Instrumentation and measurements.- Measurements of the desired quantities were accomplished through use of the NACA radio-telemetering system and radar and phototheodolite equipment. The following quantities were recorded at two separate ground stations by the telemetering system:

(1) Static and total pressures measured by an airspeed head (described in reference 2) connected to aneroid cells and mounted on a boom two body diameters in front of the fuselage of the model.

(2) Normal and transverse accelerations and longitudinal retardation measured by three accelerometers alined with the respective axes of the model.

(3) Elevator position as measured by control-position pickup.

A time-history of the position of the model with respect to the ground axes was recorded during the first 40 seconds of the drop by radar and phototheodolite equipment. A survey of atmospheric conditions applying to the test was obtained from synchronized records of atmospheric pressure, temperature, and geometric altitude taken during the descent of the airplane from which the model was dropped. The direction and velocity of the horizontal component of the wind, in the range of altitudes for which data are presented, were obtained from radar and phototheodolite records of the path of the ascension of a free balloon.

DETERMINATION OF MACH NUMBER

Time-histories of the quantities used to determine the variation of Mach number M throughout the drop are presented in figure 3. The variation of Mach number with time was obtained from the radar and phototheodolite records in the following manner:

(1) The velocity of the model with respect to the ground was obtained by differentiating the flight path with respect to time.

(2) True airspeed was obtained by a vector summation of this ground velocity and the horizontal wind velocity at coincident altitudes.

(3) The true airspeed was then combined with the corresponding absolute temperature, as determined from the atmospheric survey, to obtain the Mach number.

The radar and phototheodolite data could not be applied to the determination of Mach number after 40 seconds from release of the model because the radar-range tracking operator was unable to track the model after that time. (See fig. 3.) The scatter in the radar data is larger than usual for this equipment, due in part to the loss of tracking correction pictures. These pictures are usually taken by a long-range camera mounted on the tracking unit and ordinarily enable corrections to be made for small errors in tracking. These pictures were not obtained for this test because of haze conditions.

The Mach number variation with time was also obtained directly from the telemetered variations of static pressure p and total pressure H through use of the relation

$$M = \sqrt{\frac{\left(\frac{H}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{\gamma - 1}{2}}}$$

where the ratio of specific heats γ was taken as 1.4. The comparison, shown in figure 3, of this Mach number with the Mach number obtained from the radar data shows an appreciable discrepancy at the higher Mach numbers of the test. The Mach number obtained from the above relation, however, shows good agreement with the radar Mach number when the telemetered total pressure is combined with static pressure determined from the atmospheric survey. The discrepancy in Mach number, therefore, evidently results from an error in the telemetered static pressure. This error does not vary linearly with the magnitude of the static pressure, which is the type of error usually associated with telemeter instrumentation, and therefore is assumed to be a position error at the static head. The magnitude and sign of this error are of the type and on the order of that caused by subsonic blocking. The variation of this error in static head with Mach number as determined by direct comparison of the telemetered static pressure with the static pressure from the atmospheric survey is shown in figure 4. This calibration was used to correct the telemetered static pressure after 40 seconds from release. The corrected static pressure shown in figure 3 is, therefore, the atmospheric survey static pressure up to 40 seconds and the telemeter static pressure corrected from figure 4 after 40 seconds from release. The Mach number variation with time based on this corrected static pressure is believed accurate to within ±0.02M. All results presented in this report are based on this corrected Mach number variation.

REDUCTION OF DATA

Values of model weight W, wing area S, normal acceleration n (in g units), static pressure p, and Mach number M were used to determine the normal-force coefficient C_N through use of the relation,

$$C_N = \frac{Wn}{Sp \frac{\gamma}{2} M^2}$$

The chord-force coefficient C_C was calculated from the same relation using the longitudinal retardation.

The lift coefficient C_L, drag coefficient C_D, and the lift-to-drag ratio L/D were calculated by resolving the normal- and chord-force coefficients along the wind axes. The angle of attack was calculated from the variations of lift-curve slope and angle for zero lift with Mach number obtained from the wind-tunnel results presented in reference 3. Because the wind-tunnel results were not obtained beyond a Mach number of 0.925, the values of these parameters at a Mach number of 0.925 were assumed to apply at higher Mach numbers. The error incurred by this assumption is small since the angles of attack were small. Because of the low angles of attack involved, the difference between C_L and C_N and between C_D and C_C were small above a Mach number of 0.85. The variation of pitching-moment coefficient with angle of attack $\frac{dC_M}{d\alpha}$ was calculated by use of the equation,

$$\frac{dC_M}{d\alpha} = -\frac{(2\pi f)^2 I}{\frac{\gamma}{2} M^2 p S \bar{c}}$$

In this equation, f is the frequency of the oscillation of the model in pitch, I is the moment of inertia of the model about its lateral axis, and $\bar{c}$ is the mean aerodynamic chord (M.A.C.). This relation neglects the variation of frequency with aerodynamic damping and with the additional degree of freedom (vertical motion). The error caused by neglecting these two effects, however, was calculated and found to be less than 0.5 percent for this case.

RESULTS AND DISCUSSION

Figure 5 presents the variation with time of elevator deflection, normal and transverse acceleration, longitudinal retardation, and Mach number. The accuracy of the accelerations and elevator deflections is believed to be as follows: (1) normal acceleration within ±0.04g, (2) longitudinal retardation and transverse acceleration within ±0.01g, and (3) elevator deflection within ±0.3°.

At release, the elevator of the model went to the full-up position because of the low airspeed and high wing loading which necessitated a high lift coefficient to obtain the desired normal acceleration. The elevator had a stable variation with Mach number up to a Mach number of about 0.72 (decrease in elevator deflection with increase in M). It was observed by the tracking unit operators that the model rolled steadily up to approximately the time the maximum Mach number of 0.98 was attained. The model then ceased to roll and performed a gradual pull-out. The model had a violent short-period oscillation in pitch in the Mach number range of about 0.72 to 0.81, which was also reflected in yaw. This oscillation is believed to result from the effect of roll on the longitudinal stability of the model. An investigation into the effects of roll on longitudinal and directional stability indicates that the mass effects of an airplane due to roll decrease its stability. (See reference 4.) The destabilizing effect increases as the rate of roll approaches the natural circular frequency of the airplane in either pitch or yaw. The rate of roll was not measured during this test but was observed to be high (roughly 1 revolution per second) for the period where the violent oscillation occurred. In the Mach number range of this violent oscillation wind-tunnel data show that the longitudinal stability of the XS-1 configuration is low at all lift coefficients up to the stall. During this oscillation the model apparently diverged to positive and negative stalls. The maximum lift coefficients reached were 0.685 and −0.63, respectively. There was a similar oscillation in yaw, which was associated with the oscillation in pitch, with the side-force coefficients varying from maximum values of about 0.10 right to about 0.137 left. These side-force coefficients correspond to about $7\frac{1}{2}^{\circ}$ of left sideslip and $8\frac{1}{2}^{\circ}$ of right sideslip when the variation of side force with angle of sideslip taken from wind-tunnel results of tests of the XS-1 airplane at low Mach numbers is assumed to apply at higher Mach numbers.

It is believed but not definitely established that the model rolled with the wing twist. The cause of cessation of roll has not been determined. After the model ceased to roll, it had a small directional oscillation of approximately $\pm\frac{1}{2}^{\circ}$ amplitude about an average left sideslip of $1\frac{1}{2}^{\circ}$.

Slightly above a Mach number of 0.9, as indicated by the recorded accelerations, the elevator should have gone to its full-down position and remained there throughout the remainder of the drop. The elevator, however, varied about 1° from the full-down position. This movement of the elevator is believed to be caused by the increased dynamic pressure at the lower altitudes, which enabled the elevator hinge moment to overcome the preload in a spring used to hold the elevator deflected whenever the hinge moment was in the up direction. With the elevator near full-down, the model trimmed around 1.75g normal acceleration in the higher Mach number range ($M \approx 0.90$ to 0.98), but the normal acceleration tended to decrease as the Mach number decreased. The normal acceleration increased slightly at times when the elevator varied from its full-down position.

The automatic pilot controlled the mean normal acceleration of the model (neglecting oscillations), within reasonable limits of the desired 0.45g. The automatic control was lost at a Mach number of 0.9 because of the limitation of down-elevator travel.

The model did not exhibit the nose-down trim change, at a Mach number of about 0.93, indicated from the results of references 3 and 5. When the Mach number for this trim change was attained, the free-fall model required appreciably more down-elevator deflection for trim than the wing-flow tests. The reason was probably due to the difference in stabilizer incidences. The free-fall model had $\frac{1}{2}^{\circ}$ positive incidence (leading edge up) as compared with 4° positive incidence of the wing-flow test. In the case of the free-fall model, it is possible that a loss in elevator effectiveness in this Mach number range caused a positive pitching moment which largely offset the negative pitching moment as shown in reference 3 for the wing-fuselage combination.

The variations of lift coefficient, drag coefficient, and lift-to-drag ratio with Mach number are presented in figure 6. At the maximum Mach number obtained (0.98), the model drag coefficient was about 0.13 (based on wing area) and the lift-to-drag ratio was about 3 for the range of lift coefficients between 0.3 and 0.4. Figure 7 presents a comparison of the variation of drag coefficient with Mach number for the present tests and the results of reference 3. The drag-coefficient data from the free-fall test are in excellent agreement with those obtained from the wind-tunnel tests.

The variation of the static-longitudinal-stability parameter $\frac{dC_M}{d\alpha}$ with Mach number is presented in figure 8. The solid curve presented is from the results of reference 3, and the test points are from the present test. The static longitudinal stability of the model increased from a

Mach number of 0.85 to a maximum at about 0.9 $\left(\frac{dC_M}{d\alpha}\text{ became more negative}\right)$. The stability then decreased as the maximum Mach number of 0.98 was approached. The model remained stable at all lift coefficients tested with the possible exception of the period of violent oscillations.

CONCLUSIONS

The results of the free-fall investigation of a $\frac{1}{4}$-scale model of the Bell XS-1 airplane indicate that an airplane of similar configuration can fly in straight flight up to a Mach number of 0.98 without encountering excessive accelerations in pitch as a result of longitudinal trim changes.

The model did not exhibit the nose-down trim change indicated by the wing-flow test to occur near a Mach number of 0.93. This trim change of the wing-flow model was thought to result from loss of elevator effectiveness and a change in pitching moment of the wing-fuselage combination. With the stabilizer incidence fixed and the elevator automatically controlled to maintain the normal acceleration at 0.45g, the free-fall model required appreciably more down elevator for trim than the wing-flow test. It is possible that a loss in elevator effectiveness in this Mach number range caused a positive pitching moment which largely offset the negative pitching moment of the wing-fuselage combination.

The model was not roll-stabilized, but it was observed by the tracking unit operators to roll until the approximate attainment of the maximum Mach number of 0.98, when it ceased to roll and performed a gradual pull-out. The model exhibited a violent short-period oscillation in pitch and yaw between a Mach number of 0.72 and 0.81. This oscillation is believed to result from an effect of roll on longitudinal stability.

At the maximum Mach number of 0.98, the model drag coefficient was about 0.13 and the lift-to-drag ratio was about 3 in the range of lift coefficients between 0.3 and 0.4. The model remained stable at the lift coefficients encountered in the test, with the possible exception of the period of violent oscillations, and the elevator deflection had a stable variation with speed up to a Mach number of 0.72. An analysis of the data in the Mach number range from 0.85 to 0.98 indicates that the maximum stability occurred at a Mach number of about 0.9.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

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TABLE I

PHYSICAL CHARACTERISTICS OF THE

BELL XS-1 TRANSONIC RESEARCH AIRPLANE

Power:	
Four rocket units each capable of delivering 1500 pounds thrust, grouped in rear of fuselage.	
Wing loading:	
Take-off, lb/sq ft	103
Landing, lb/sq ft	40
Design center-of-gravity position, percent M.A.C.	0.25
Wing:	
Area, sq ft	130
Span, ft	28
Mean aerodynamic chord, in.	57.71
Aspect ratio	6
Root and tip sections	65-110(a = 1.0)
Incidence (root chord to thrust line), deg	2.5
Incidence (tip chord to thrust line), deg	1.5
Horizontal tail:	
Total area, sq ft	25.0
Span, ft	11.4
Aspect ratio	5
Root-mean-square chord of elevator, ft	0.464
Vertical tail:	
Total area, sq ft	27.1
Aspect ratio	1.81
Height, ft	7.0
Moment of inertia, (gross weight, 8410 lb; c.g. = 25.9):	
I_X, slug-ft^2	1981
I_Y, slug-ft^2	9182
I_Z, slug-ft^2	10,519

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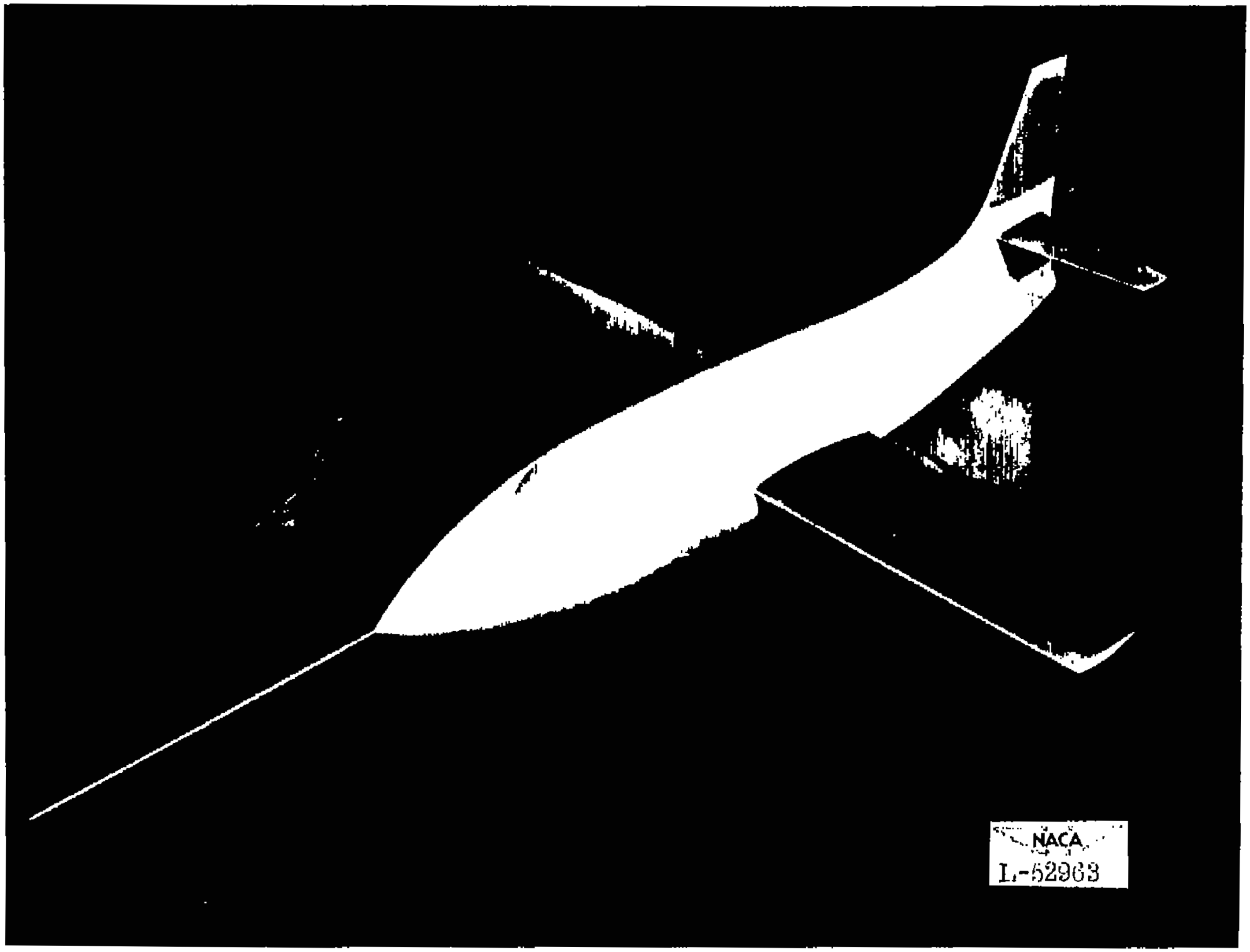

Figure 1.- Three-quarter front view of $\frac{1}{4}$-scale model of the Bell XS-1 airplane used in free-fall test.

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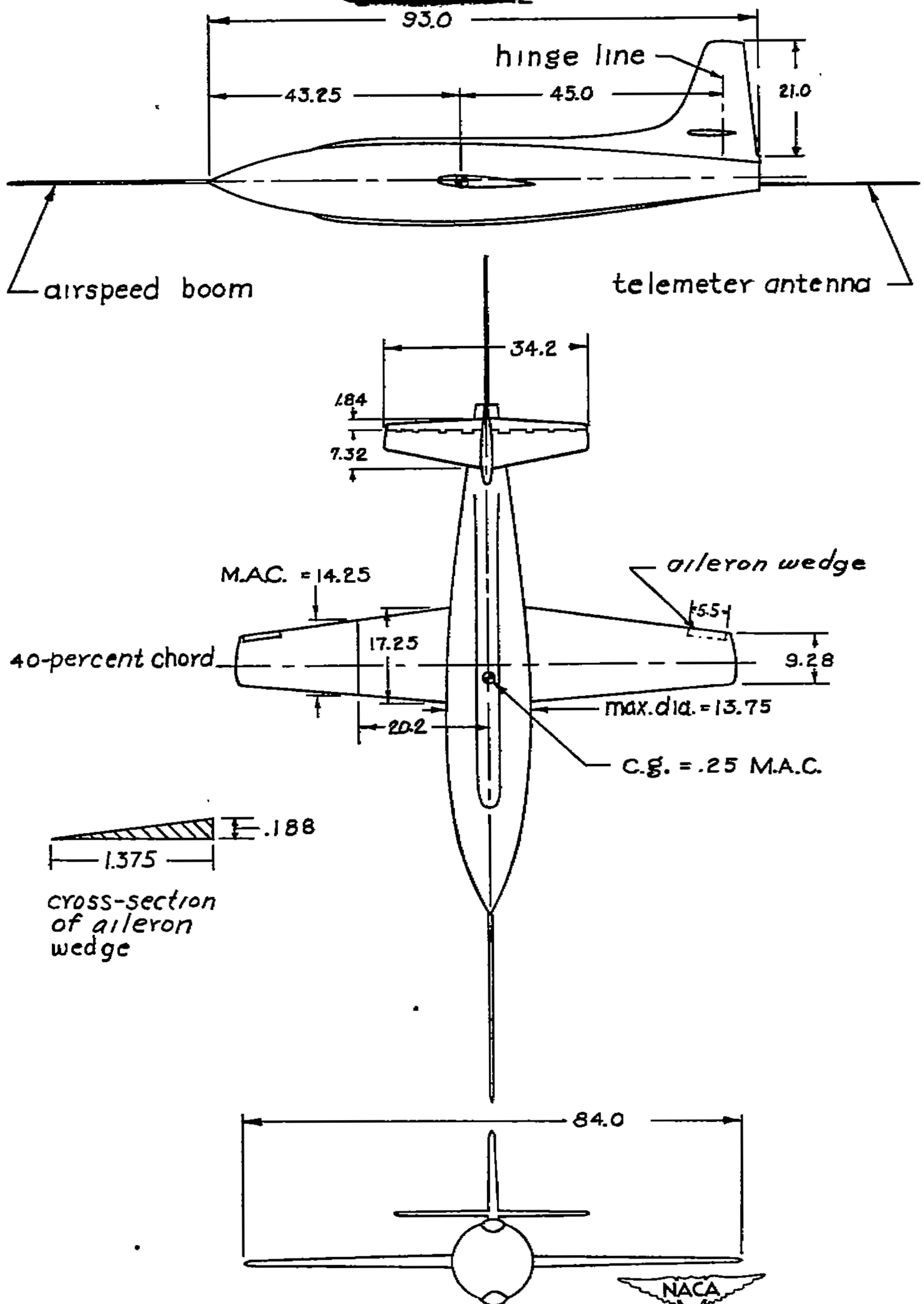

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Figure 2.- Three-view drawing of $\frac{1}{4}$-scale model of the Bell XS-1 airplane used in free-fall test. All dimensions in inches.

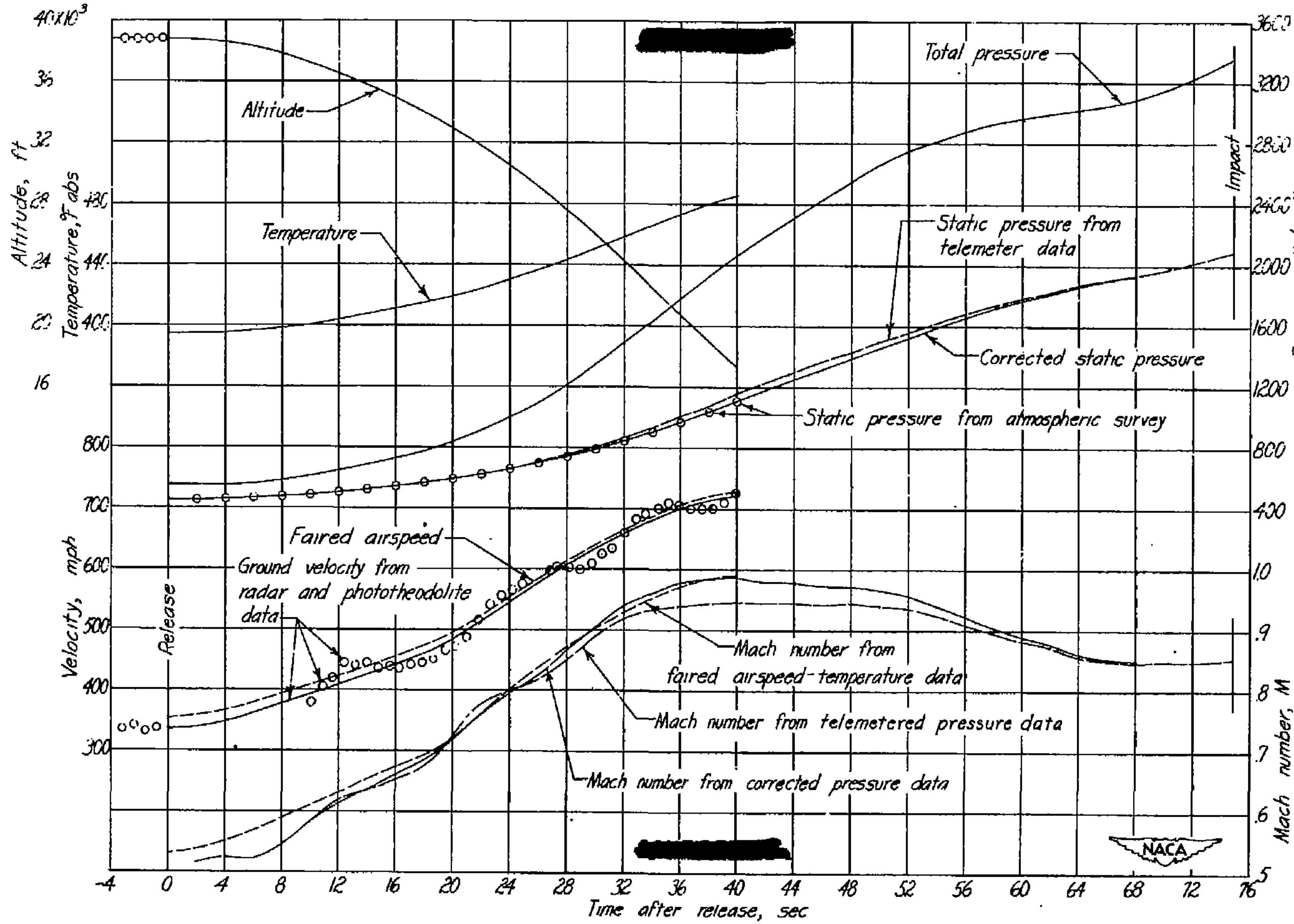

Figure 3.- Time histories of quantities used in the determination of the Mach number for a $\frac{1}{4}$-scale model of the Bell XS-1.

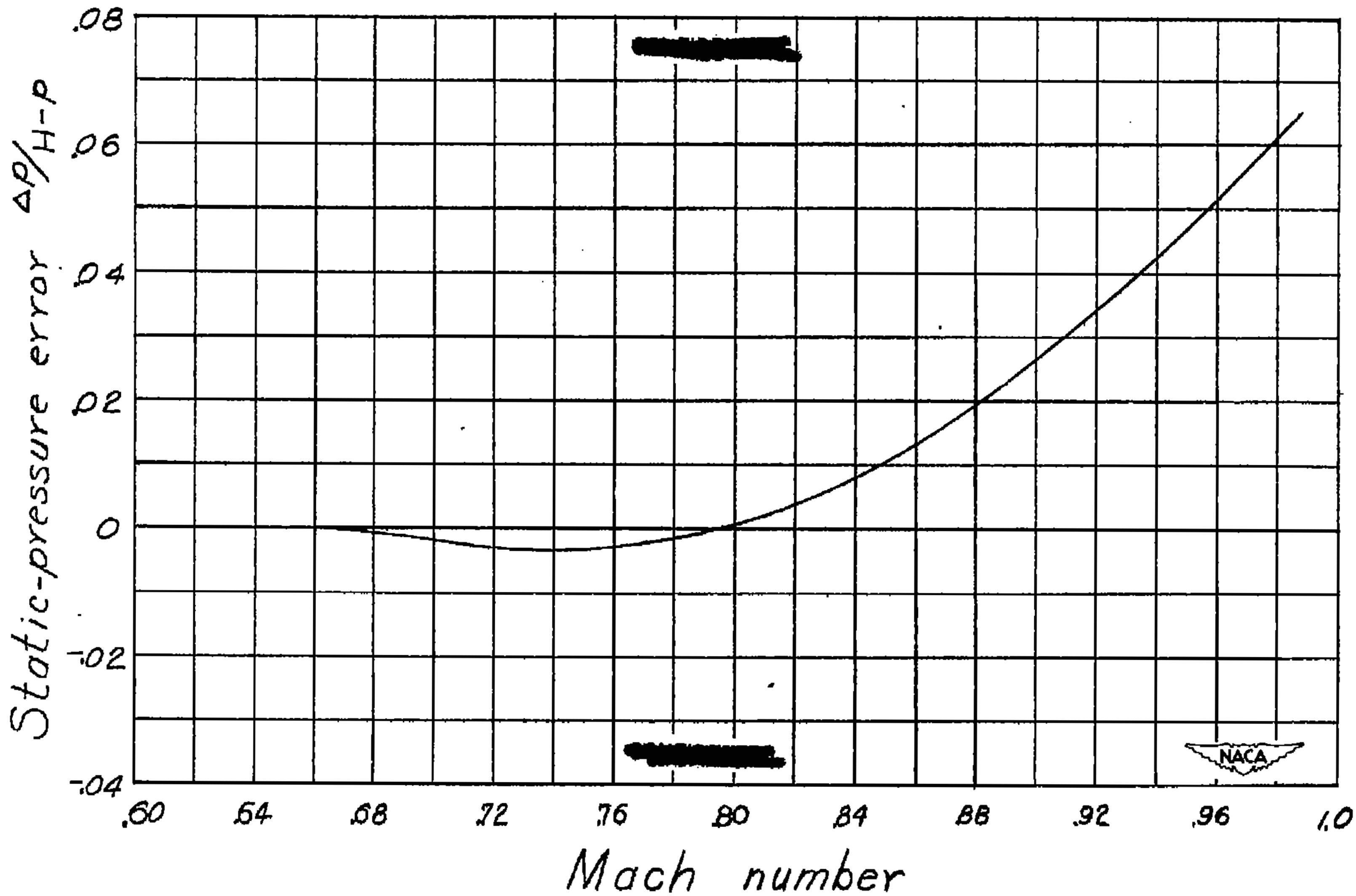

Figure 4.- Variation with Mach number of static-pressure error of airspeed boom for $\frac{1}{4}$-scale model of the Bell XS-1 airplane.

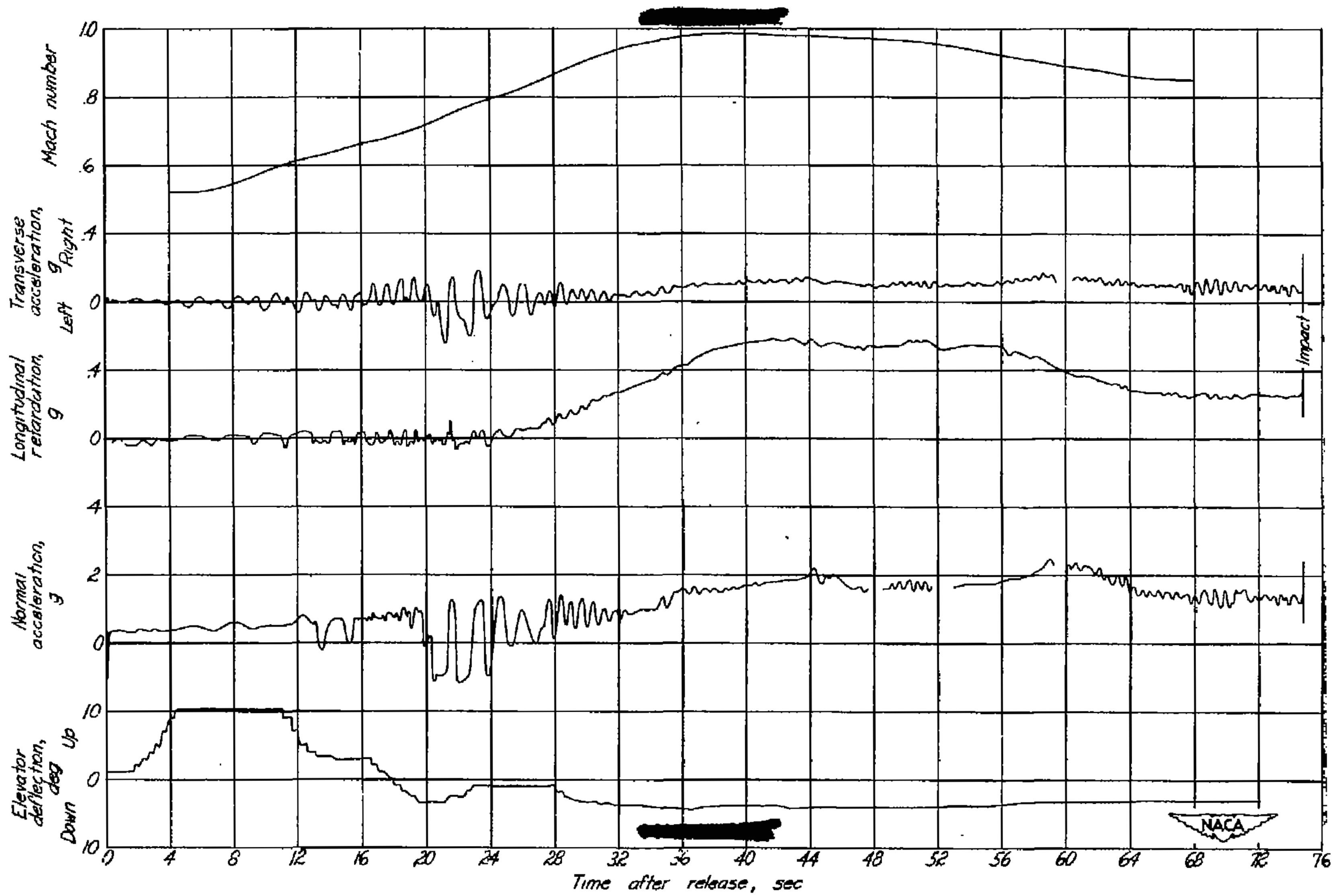

Figure 5.- Time history of free fall of $\frac{1}{4}$-scale model of the Bell XS-1 airplane.

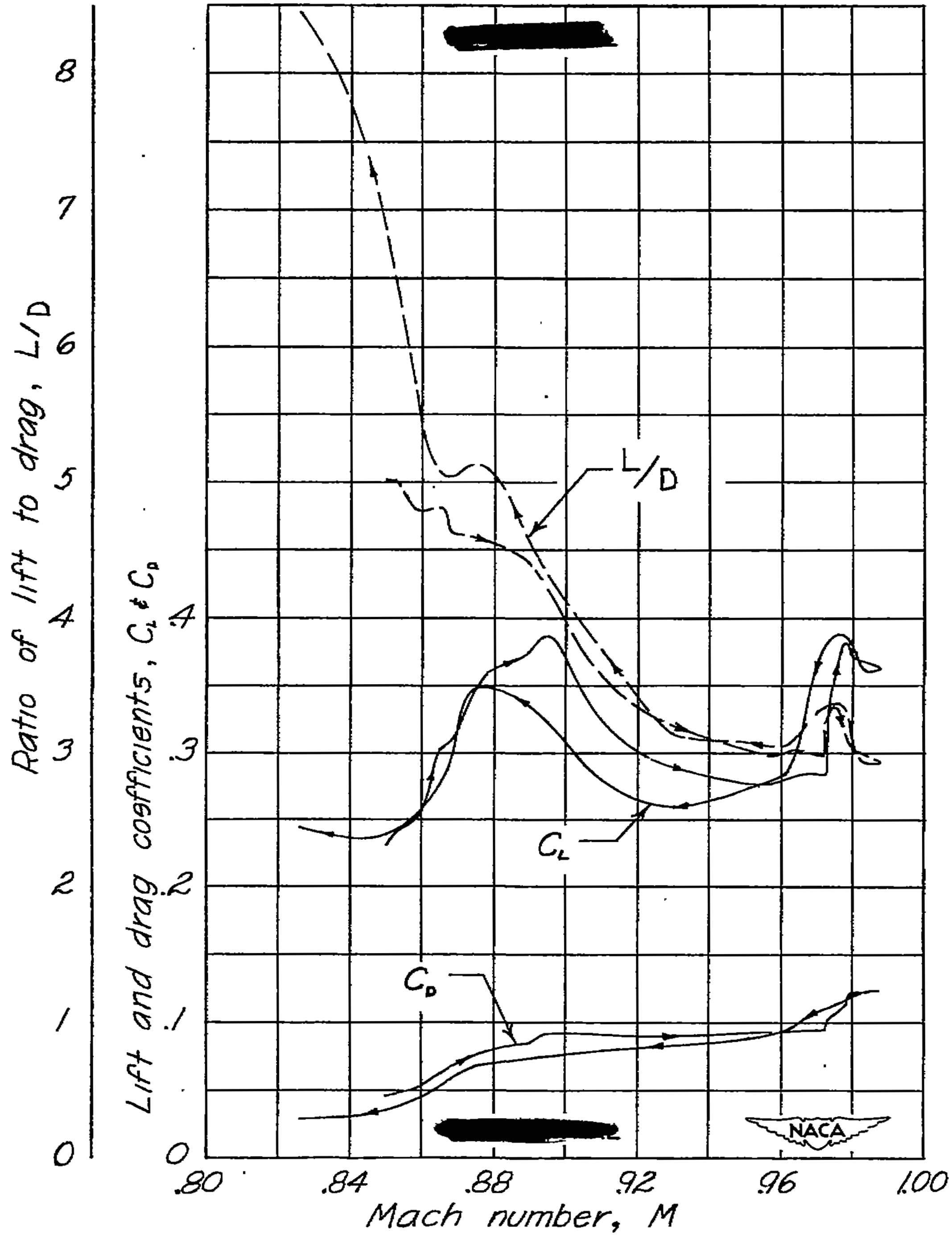

Figure 6.- Variation with Mach number of lift coefficient, drag coefficient, and lift-to-drag ratio of a $\frac{1}{4}$-scale model of the Bell XS-1 airplane.

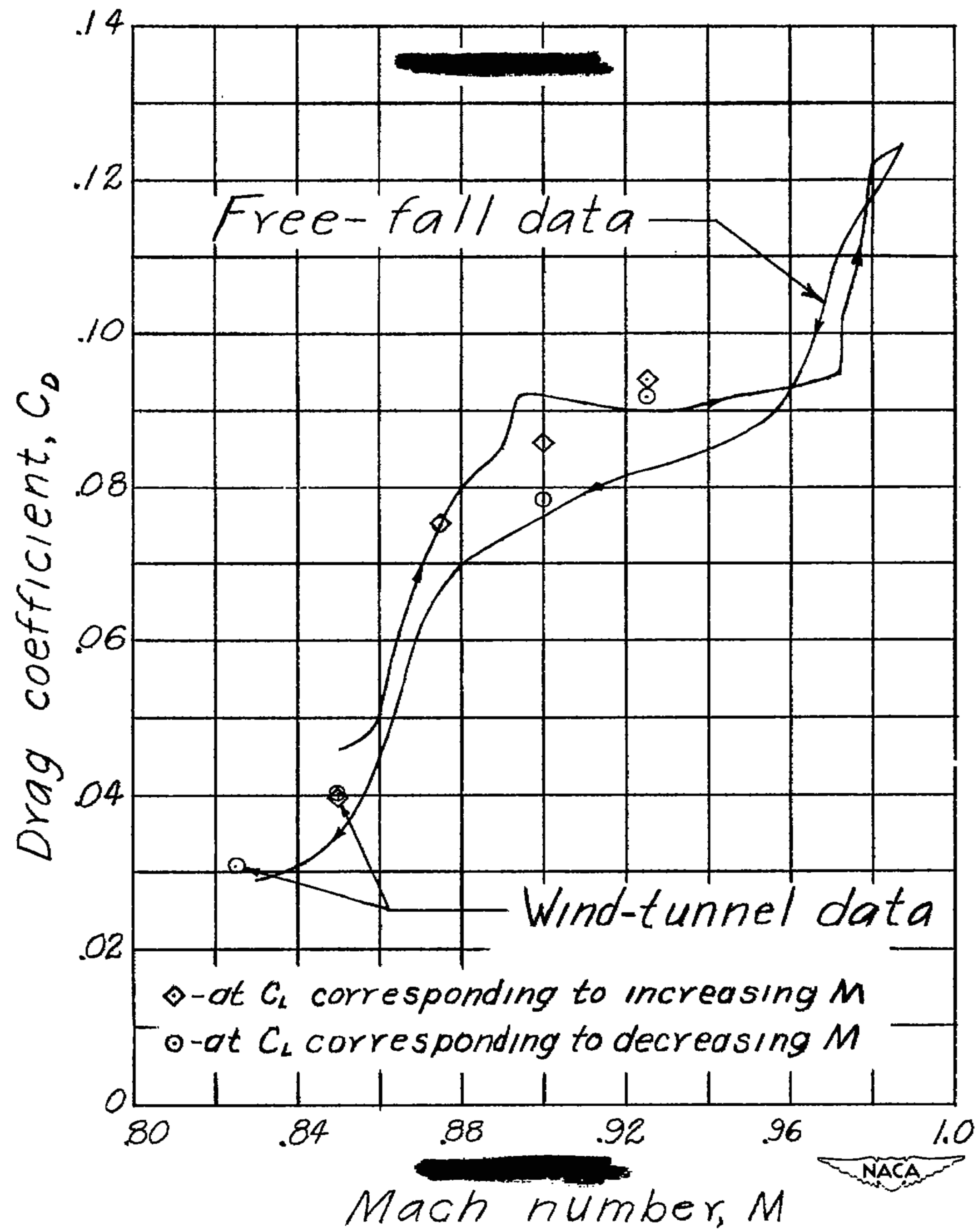

Figure 7.- Comparison of results of free-fall tests of a $\frac{1}{4}$-scale model of the Bell XS-1 airplane and wind-tunnel tests of a similar configuration; variation of drag coefficient with Mach number.

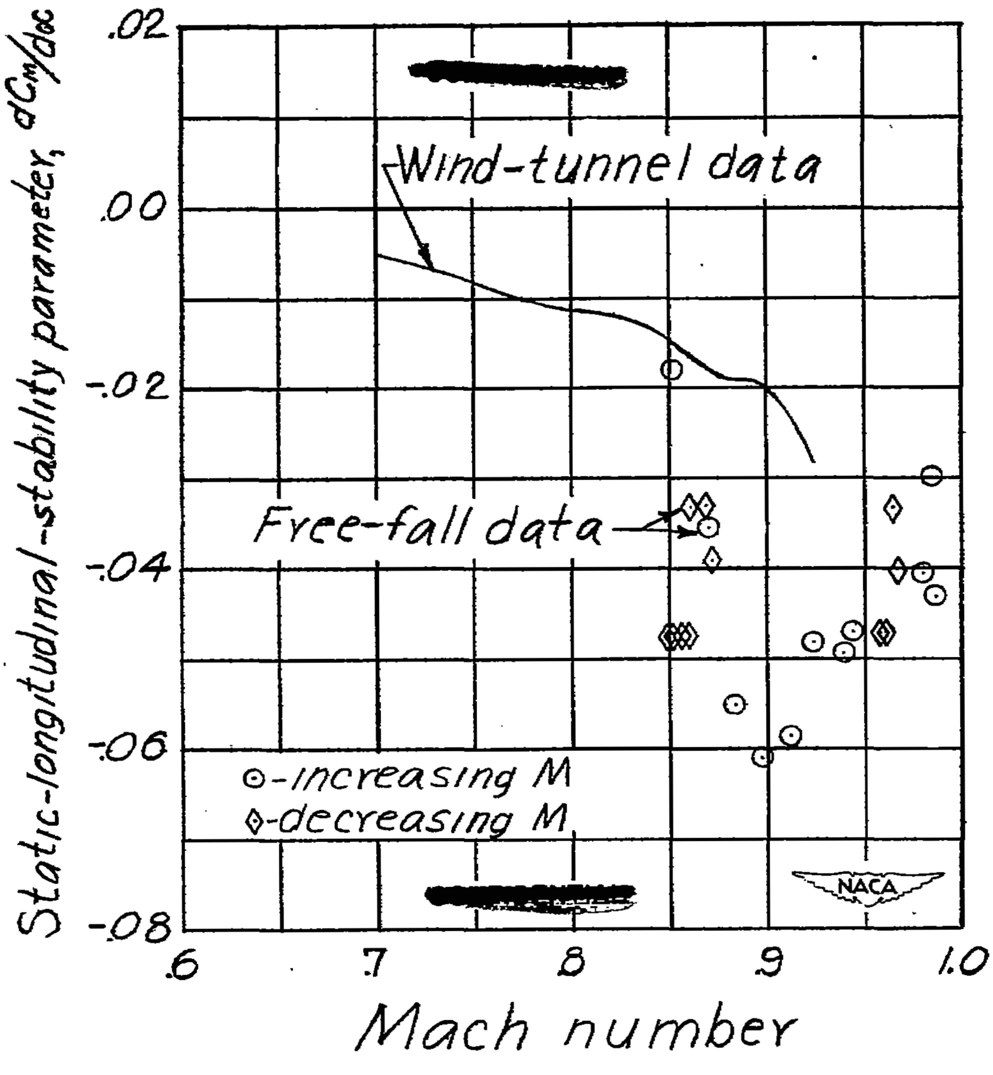

Figure 8.- Static-longitudinal-stability parameter $dC_m/d\alpha$ for a $\frac{1}{4}$-scale model of the Bell XS-1 airplane.