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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF THE LONGITUDINAL STABILITY AND CONTROL CHARACTERISTICS OF THE DOUGLAS D-558-I AIRPLANE (BUAERO NO. 37972) AT MACH NUMBERS UP TO 0.89

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

Results and analysis pertaining to the longitudinal stability and control characteristics of the Douglas D-558-I airplane (BuAero No. 37972) are presented. The results were obtained during shallow dives and wind-up turns at altitudes between 37,000 and 27,000 feet and at Mach numbers between 0.60 and 0.89.

The results indicate that large and rapid changes in elevator deflection and force were required for balance at Mach numbers above 0.84. At Mach numbers above about 0.84, a sharp decrease in the relative elevator-stabilizer effectiveness was shown and analysis indicated that a major part of the observed trim changes was explained by this decrease. Values of change in elevator deflection required to produce a unit change in the normal-force coefficient C_{N_A} and of change in wheel force per unit normal acceleration g increased smoothly up to values of 57° per unit change in C_{N_A} and 120 pounds per g, respectively, at a Mach number of 0.89. The increase in the apparent stick-fixed stability parameter $\frac{d\delta_e}{dC_{N_A}}$ was attributed to a decrease of relative elevator effectiveness together with an increase of the stability of the airplane by a factor of 4 between Mach numbers of 0.75 and 0.89.

INTRODUCTION

The National Advisory Committee for Aeronautics is engaged in a flight research program in the transonic speed range utilizing the Douglas D-558-I airplanes. These airplanes were procured by the Bureau of Aeronautics of the Department of the Navy for use by the NACA in high-speed flight.

Some measurements of longitudinal stability and control characteristics were made with airplane BuAero No. 37971 and the results of these measurements were reported in references 1 and 2. The data presented in reference 2 indicated that small changes in stabilizer incidence caused very marked changes in the longitudinal trim characteristics. When airplane BuAero No. 37972 became available, a more detailed investigation of the effects of stabilizer incidence was made extending the range of conditions reported in reference 2.

SYMBOLS

M_i indicated Mach number

M corrected Mach number

H pressure altitude, feet

A_Z normal acceleration factor (ratio of net aerodynamic force along Z-axis to weight of airplane)

W airplane weight, pounds

q dynamic pressure, pounds per square foot

S wing area, square feet

C_{N_A} airplane normal-force coefficient $\left(\frac{WA_Z}{qS}\right)$

i_t stabilizer incidence with respect to fuselage center line, degrees

δ_e elevator angle with respect to stabilizer, degrees

δ_a total aileron angle, degrees

α angle of attack, degrees

F_e elevator wheel force, pounds

β sideslip angle, degrees

τ relative elevator-stabilizer effectiveness $\left(\frac{di_t}{d\delta_e}\right)$

C_m pitching-moment coefficient

$\frac{d\delta_e}{dC_{N_A}}$ apparent stick-fixed stability parameter

$\frac{dF_e}{dg}$ apparent stick-free stability parameter

$\frac{dC_m}{dC_L}$ stability parameter

C_L lift coefficient

Subscripts:

A airplane

W-F wing-fuselage

T tail

AIRPLANE

The Douglas D-558-I research airplane is a single-place low-wing monoplane powered by a General Electric TG-180 turbojet engine. Detailed specifications of the airplane are given in table I and a three-view drawing and photographs of the airplane are presented as figures 1 and 2, respectively. As flown in the tests reported herein, the airplane weighed 10,610 pounds (take-off condition, without tip tanks) and the center of gravity was at 23.34 percent of the mean aerodynamic chord. Negligible movement of the center of gravity occurs as fuel is consumed.

INSTRUMENTATION

Synchronized NACA instruments were used to record time histories of indicated airspeed; static pressure; normal, longitudinal, and transverse accelerations; rolling angular velocity; aileron, elevator, and rudder control force and position; stabilizer incidence; and sideslip angle. The elevator position was measured in the fuselage at the elevator actuating arm. The airspeed head and the yaw vane were mounted on booms 1 chord ahead of the right and left wing tips, respectively.

The airspeed system of the airplane was calibrated by the low-altitude fly-by method at Mach numbers between 0.28 and 0.80 and it was found that in this range the blocking at the airspeed head was constant at 1 percent of the impact pressure. The calibration was extended to Mach numbers near 0.90 during the course of the flights reported herein by use of the radar method of reference 3. The results obtained are in reasonable agreement with similar results presented in reference 2 and are plotted in figure 3. During the flights considered herein, only one static-pressure source was provided for both the pilot and the research instruments with the result that the lag was excessive. The equivalent sea-level time lag of the system was determined by ground tests to be about 0.27 second. This value corresponds to a time lag of about 0.8 second at altitudes from 30,000 to 35,000 feet where a large part of the data presented herein were obtained. All results presented in this paper are corrected for both the blocking and the lag; however, due to the large magnitude of the lag corrections, the Mach number values above 0.85 are considered to be uncertain within about ±0.02.

TESTS, RESULTS, AND DISCUSSION

The results were obtained during shallow dives, pull-outs, and wind-up turns at altitudes between 37,000 and 27,000 feet and at Mach numbers between 0.60 and 0.89. Time histories typical of the results obtained are shown in figures 4 and 5. Figure 4 presents data obtained with a stabilizer setting of 1.6° during a shallow dive from 37,000 feet with a $3\frac{1}{2}$g pull-out at about 30,000 feet. The data in figure 5 were obtained in a dive from about 37,000 feet with a stabilizer setting of 3.3°. At about 48 seconds (fig. 5) as the pilot attempted to pull out, the elevator angle and stick force necessary to execute the maneuver became excessive and the stabilizer had to be used for recovery from the dive. The time history for this run was not extended beyond 48 seconds because the subsequent data were not satisfactory for analysis. Both runs reached a maximum Mach number of about 0.89, and it is evident from the figures that large changes in longitudinal trim occur at Mach numbers above about 0.84.

Longitudinal Stability Characteristics in Straight Flight

The variation of elevator angle δ_e with Mach number for several stabilizer settings is presented in figure 6. The points shown on this figure were derived from the data presented in figures 4 and 5 and from similar data not presented herein. The data from figure 6 were corrected to a normal-force coefficient of 0.2 by adding (or subtracting) to the flight-test values of elevator angle the increments due to the difference ΔC_{N_A} between the flight values of C_{N_A} and a value of C_{N_A} of 0.2. These elevator-angle increments were determined by multiplying the values of ΔC_{N_A} by the flight-determined rate of change of elevator angle with normal-force coefficient. The maximum error introduced by using gradients determined in curved flight to correct the straight-flight data was computed to be about 0.2°. The faired curves adjusted to a normal-force coefficient of 0.2 are presented in figure 7. It is interesting to note in this figure that, for a stabilizer incidence of 1.6°, the elevator-angle variation indicates a moderate nose-up tendency and for a stabilizer setting of 3.3° a relatively severe diving tendency is indicated as the Mach number is increased above 0.84. It is also apparent from this figure that the trim changes noted for the higher stabilizer settings have reached peak values at about 0.88 and 0.89 Mach numbers and that further increase in speed results in reduced values of up-elevator deflections and pull forces required for trim. The significant change in the airplane trim characteristics that occurs as the stabilizer setting is increased from 1.6° to 3.3° can be explained partly by the data in figure 8 which show the variation in the relative elevator-stabilizer effectiveness τ with Mach number. The data indicate a rapid decrease in the relative effectiveness as the Mach number exceeds about 0.84. The data also show two values of effectiveness at Mach numbers greater than 0.86, the higher values being associated with elevator angles close to neutral and the lower values with moderate values of up-elevator deflection. (It is pointed out that this variation does not conform to the usual observation of a lower effectiveness at small control deflections. It is possible that elevator distortion may have contributed to some error in analyzing the results since elevator twist was not measured during these tests.) It is indicated that the variation with Mach number of the elevator angle required for trim above Mach number of 0.75 may be largely dependent upon the variation of relative effectiveness. In order to determine how much of the trim change was due to loss in relative effectiveness, figure 9 was prepared. In this figure the variation of elevator position with Mach number presented in figure 7 was corrected to a constant effectiveness. This correction was made by multiplying the elevator angle at each Mach number by the ratio of the corresponding value of relative effectiveness to the relative effectiveness at a Mach number of 0.75. As can be seen in the figure, the variation of elevator position with Mach number for the various stabilizer settings is practically the same when this correction is applied. The small basic moment change with Mach number in the nose-up direction indicated in figure 9 modified the trim changes favorably at the higher stabilizer settings, and increased the trim changes at the lower stabilizer settings. It can be said, however, that the loss in relative elevator effectiveness accounted for the greater portion of the observed trim changes.

The variation of stick force shown in figure 7 follows the variation of elevator position with Mach number quite closely and analysis indicated that most of the stick-force change with Mach number was due to changes in control-surface setting and the increase in dynamic pressure between Mach numbers of 0.75 and 0.89.

Longitudinal Stability Characteristics in Accelerated Flight

The basic stability characteristics obtained in accelerated flight are presented in figure 10. This figure shows the variation of elevator deflection with normal-force coefficient, and stick force with normal acceleration for several values of Mach number. The slopes $\frac{d\delta_e}{dC_{N_A}}$ and $\frac{dF_e}{dg}$ were determined from the curves in figure 10 and from other data not included herein and are shown in figure 11 as a function of Mach number. The stabilizer incidence and pressure altitude of each point are identified on the figure. Although there is some scatter in the data, which may in part be caused by changes in stabilizer incidence and altitude, the data are adequately faired by the curves shown. The values of both $\frac{d\delta_e}{dC_{N_A}}$ and $\frac{dF_e}{dg}$ increase very rapidly above a Mach number of about 0.85, and at the maximum test Mach number of 0.89, values of 57° per unit C_{N_A} and 120 pounds per g were reached for $\frac{d\delta_e}{dC_{N_A}}$ and $\frac{dF_e}{dg}$, respectively. The large increase in these parameters indicates either a loss in relative elevator effectiveness τ, or a large increase in airplane stability, or a combination of these two effects. The data in figure 8 show a large loss in relative effectiveness between Mach numbers of 0.75 and 0.89. For a constant value of airplane stability, however, this factor would account for only 25 percent of the observed increase in $\frac{d\delta_e}{dC_{N_A}}$. In order to separate the effects of loss in relative effectiveness and of changes in airplane stability on the apparent stability, it was necessary to resort to wind-tunnel data. The data used are presented in references 4, 5, and 6. From this source, the variation with Mach number of the stability of the entire airplane $\left(dC_m/dC_L\right)_A$ and of the stability of the wing-fuselage combination $\left(dC_m/dC_L\right)_{W-F}$ was determined. These results are presented in figure 12. It can be seen in this figure that the stability of the airplane at a Mach number of 0.89 has increased to about four times its low-speed value. The change in stability of the wing-fuselage combination accounted for about 25 percent of the change in airplane stability; the remainder of the change in stability can be attributed to changes in the contribution of the horizontal tail to the stability of the airplane. In order to check the validity of the wind-tunnel data, the variation of $\frac{d\delta_e}{dC_{N_A}}$ was computed over a Mach number range of 0.75 to 0.89 by using the variations with Mach number of the airplane stability parameter $\left(\frac{dC_m}{dC_L}\right)_A$ and the tail lift-curve slope $\left(\frac{dC_L}{d\alpha}\right)_T$ from wind-tunnel data, and the flight-measured variation of the relative elevator effectiveness. In computing values of $\frac{d\delta_e}{dC_{N_A}}$ above a Mach number of 0.86, average values of the relative effectiveness τ were used. The results of these calculations are presented in figure 13. Comparison with the flight-measured characteristics also presented in this figure shows good agreement.

From the foregoing, it may be concluded that the 16-fold increase in the apparent stick-fixed stability parameter $\frac{d\delta_e}{dC_{N_A}}$ was the combined result of the relative elevator effectiveness dropping off to about one-fourth its low-speed value and the airplane stability increasing by a factor of 4 over the Mach number range considered.

CONCLUSIONS

Results and analysis pertaining to the longitudinal stability and control characteristics of the Douglas D-558-I airplane (BuAero No. 37972) obtained up to Mach numbers of 0.89 indicated the following conclusions:

1. At Mach numbers above about 0.84, large and rapid changes in elevator deflection and force required for trim occurred. For stabilizer incidences where up elevator was required for trim at low Mach numbers, a relatively severe diving tendency was encountered, and for stabilizer settings where elevator deflections near zero were required, a moderate pitch-up tendency was observed.

2. The relative elevator-stabilizer effectiveness decreased rather sharply above a Mach number of about 0.84. The data also indicated two values of effectiveness at Mach numbers greater than 0.86, the higher values associated with elevator angles near 0° and the lower values with moderate values of up elevator deflection.

3. Analysis indicated that a major part of the observed trim changes was caused by the measured loss of relative elevator effectiveness. It was shown that, if no loss in elevator effectiveness had occurred, the large trim changes that were encountered would have been almost completely eliminated. The basic nose-up moment change with Mach number, however, reduced the trim changes for up elevator deflections and increased the trim changes for down elevator deflections.

4. The values of change in elevator deflection required to produce a unit change in normal-force coefficient and of change in wheel force required per unit normal acceleration increased smoothly at an increasing rate above a Mach number of about 0.75 to reach values of 57° per unit change in C_{N_A} and 120 pounds per g at a Mach number of 0.89.

5. Analysis indicated that the 16-fold increase in the apparent stick-fixed stability factor $\frac{d\delta_e}{dC_{N_A}}$ was the combined result of the relative elevator effectiveness decreasing by a factor of approximately 4 and the airplane stability increasing by a factor of 4 between Mach numbers of 0.75 and 0.89. Most of the increase in airplane stability was due to the horizontal-tail contribution.

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TABLE I

PHYSICAL CHARACTERISTICS OF DOUGLAS D-558-1 AIRPLANE

Wing:	
Area, sq ft	150.7
Span, ft	25
Taper ratio	0.54
Aspect ratio	4.17
Root section	NACA 65-110
Tip section	NACA 65-110
Sweepback of 50-percent-chord line	0
Geometric dihedral, deg	4.0
Incidence at root chord, deg	2.0
Geometric twist	0
Mean aerodynamic chord, ft	6.21
Ailerons:	
Area aft hinge line (both ailerons), sq ft	7.94
Mean aerodynamic chord, ft	0.772
Span (one side), ft	5.19
Hinge-line location (percent c_w)	85
Horizontal tail:	
Area, sq ft	35.98
Span, ft	12.25
Aspect ratio	4.17
Taper ratio	0.55
Tail length, from $0.25c_w$ to elevator hinge line, ft	16.34
Elevators:	
Area aft of hinge line (both sides), sq ft	8.6
Span (one side), ft	5.91
Hinge location, percent horizontal-tail chord	75
Mean aerodynamic chord, ft	0.75
Vertical tail surface:	
Area, sq ft	25.68
Span, ft	5.55
Aspect ratio	1.20
Taper ratio	0.56
Fin offset	0
Tail length, from $0.25c_w$ to rudder hinge line, ft	17.38
Dorsal-fin area, sq ft	9.08

TABLE I

PHYSICAL CHARACTERISTICS OF DOUGLAS D-558-1 AIRPLANE - Concluded

Rudder:	
Area aft of hinge line, sq ft	7.92
Span, ft	5.67
Mean aerodynamic chord, ft	1.44
Fuselage:	
Fuselage length, ft	35.04
Fuselage depth (maximum), ft	4.0
Fuselage width (maximum), ft	4.0

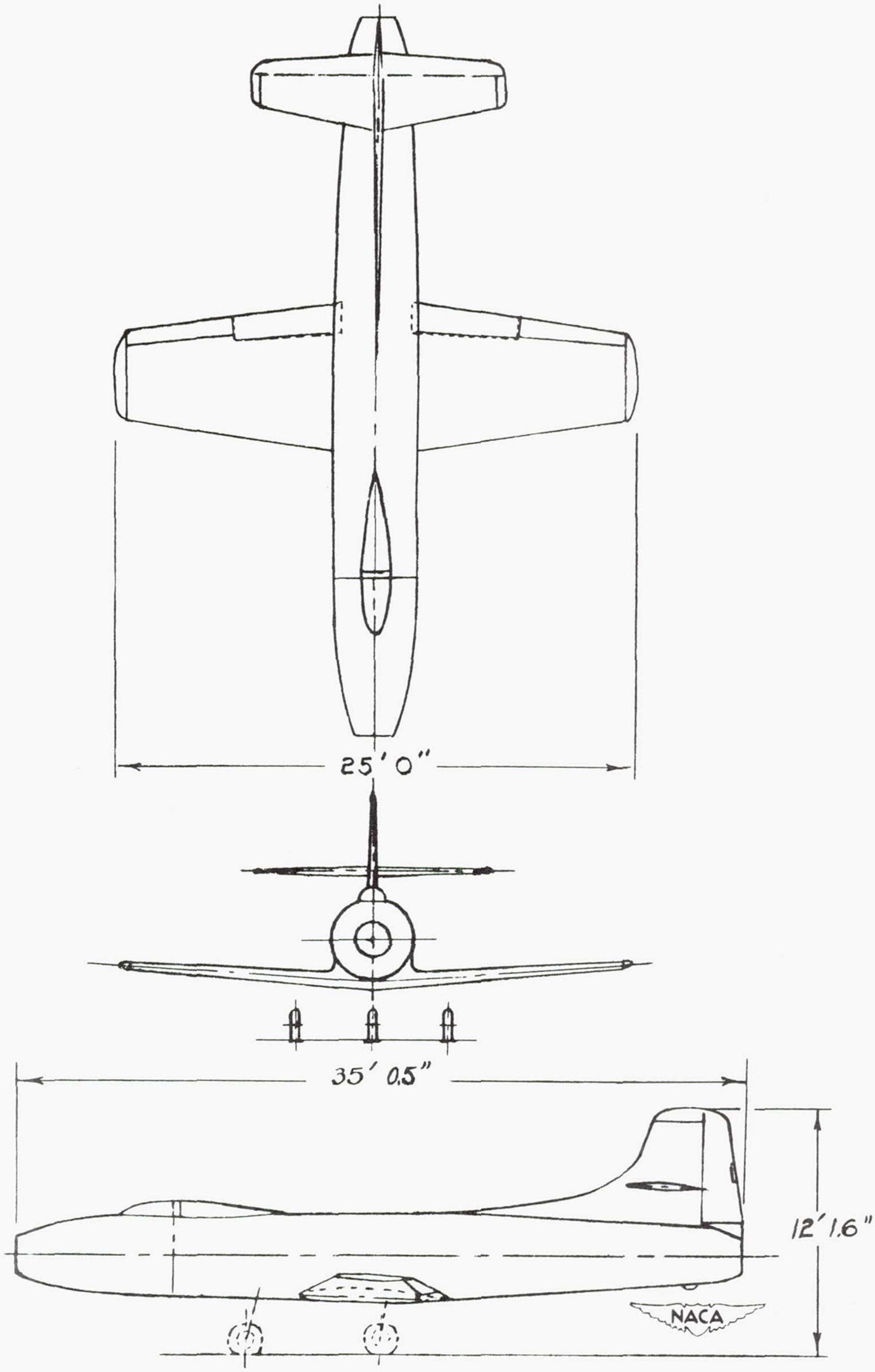
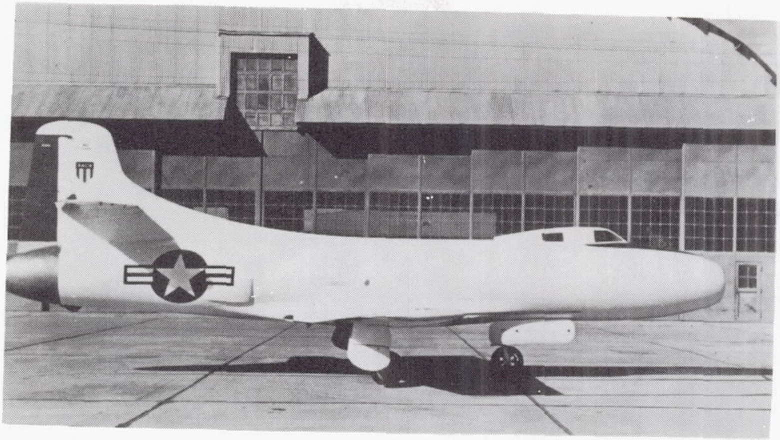
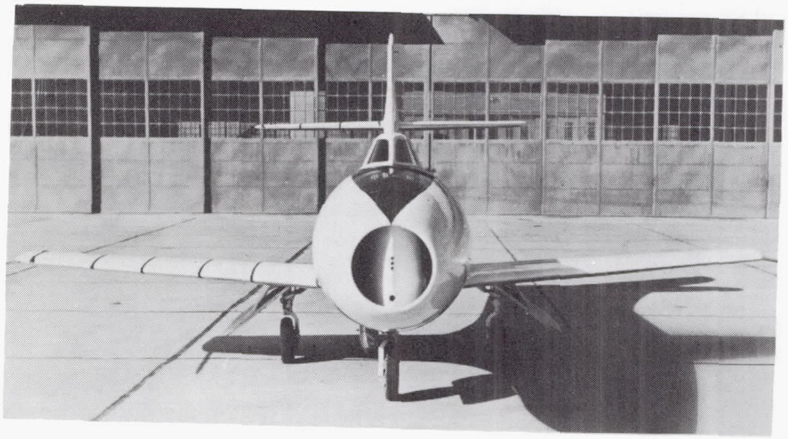


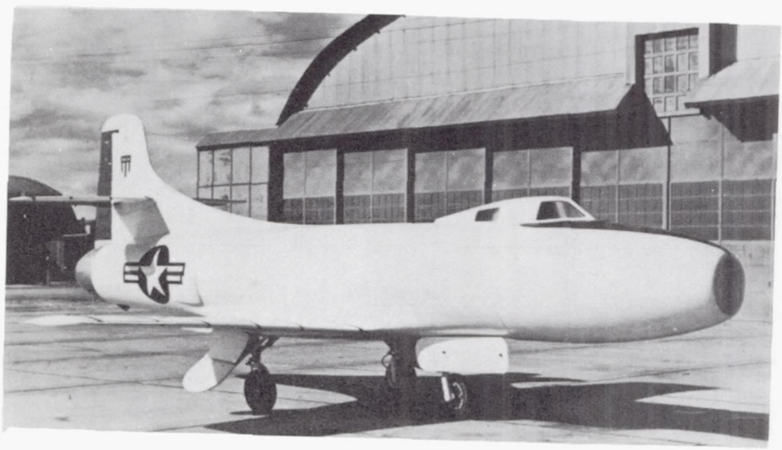
Figure 1.- Three-view drawing of the Douglas D-558-I airplane.



(a) Side view.



(b) Front view.



(c) Three-quarter view.

Figure 2.- Photographs of Douglas D-558-I airplane.

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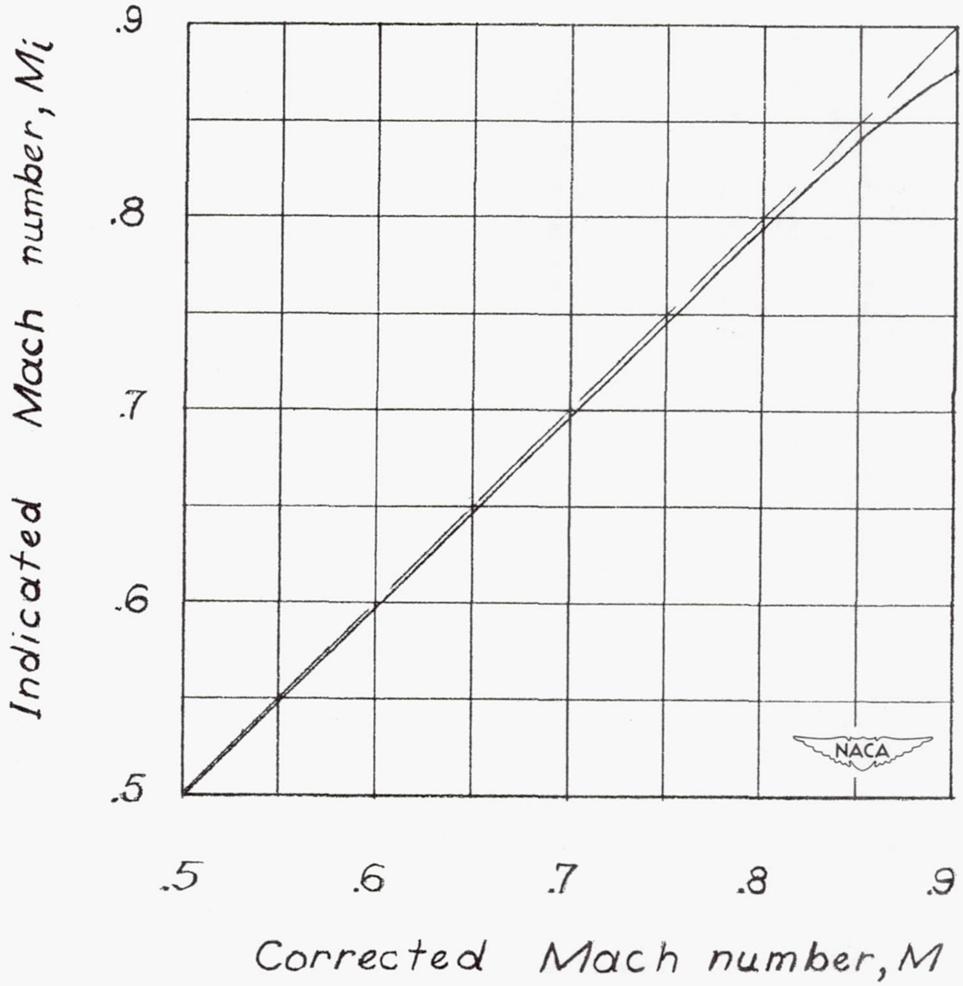


Figure 3.- Airspeed calibration for Douglas D-558-I airplane (BuAero. no. 37972). System consists of Kollsman D-1 head mounted 1 chord ahead of the right wing tip.

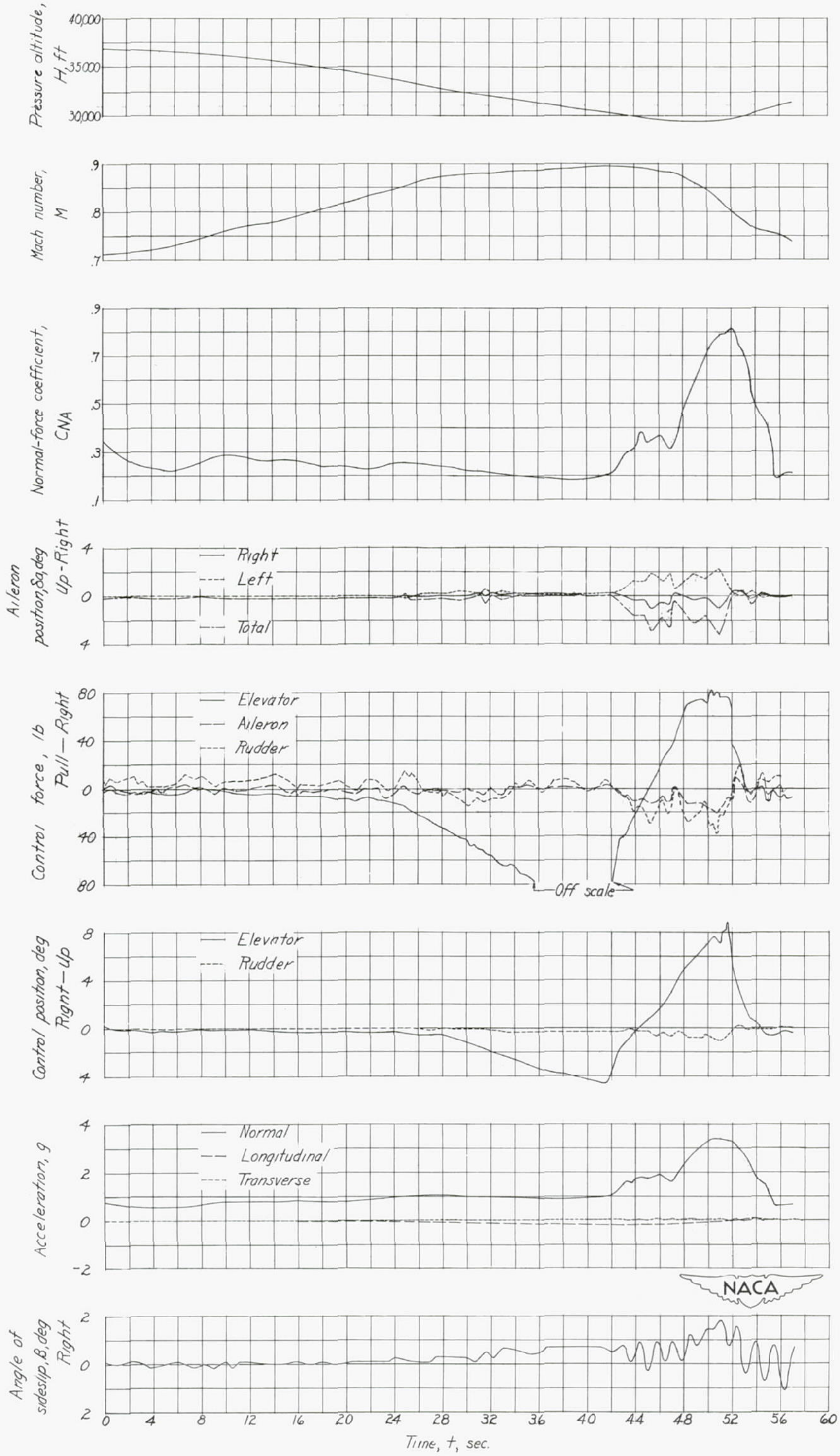


Figure 4.- Time history of a shallow dive and pull-out. Stabilizer incidence of 1.6°.

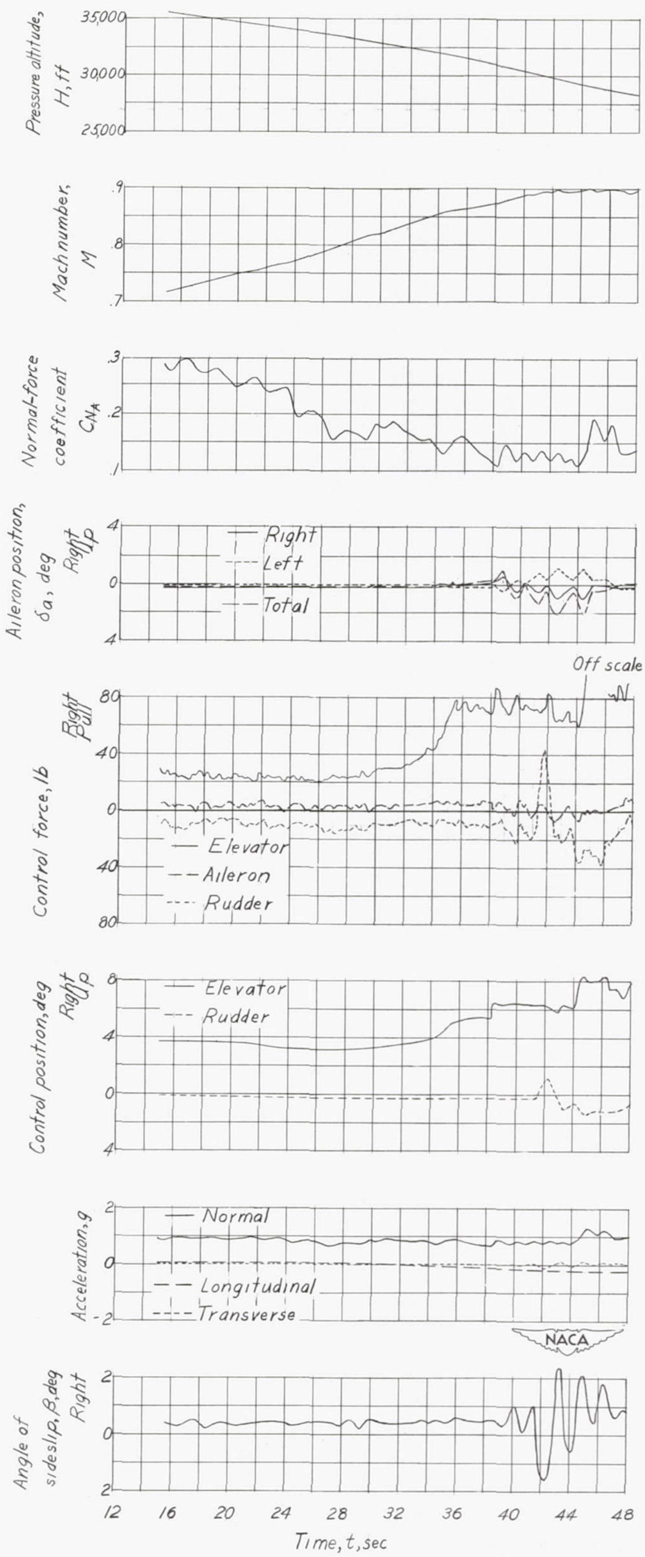


Figure 5.- Time history of a shallow dive. Stabilizer incidence of 3.3°.

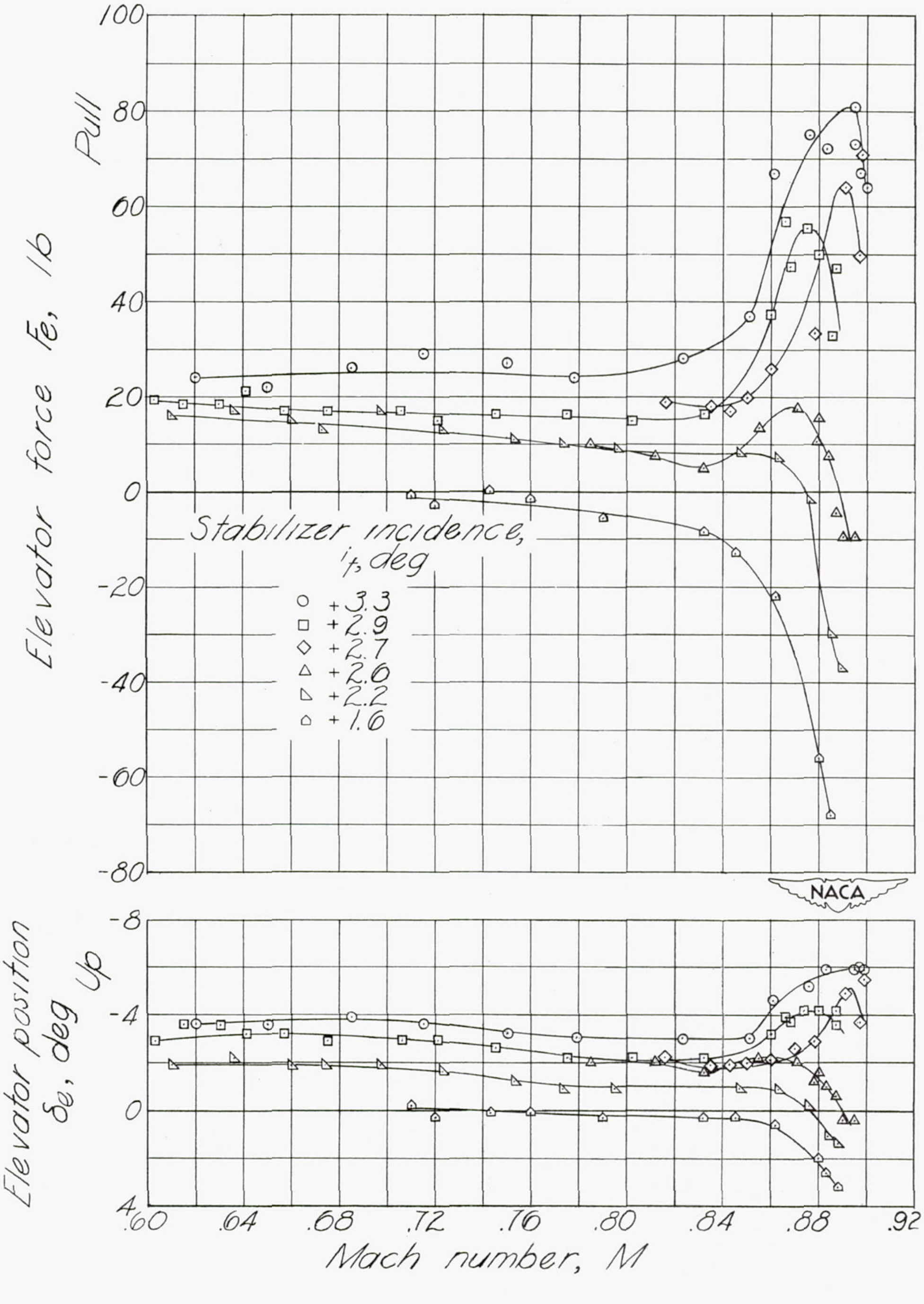


Figure 6.- Variation with Mach number of the elevator deflection and wheel force required to balance the airplane at several values of stabilizer incidence in shallow dives from 37,000 to 27,000 feet.

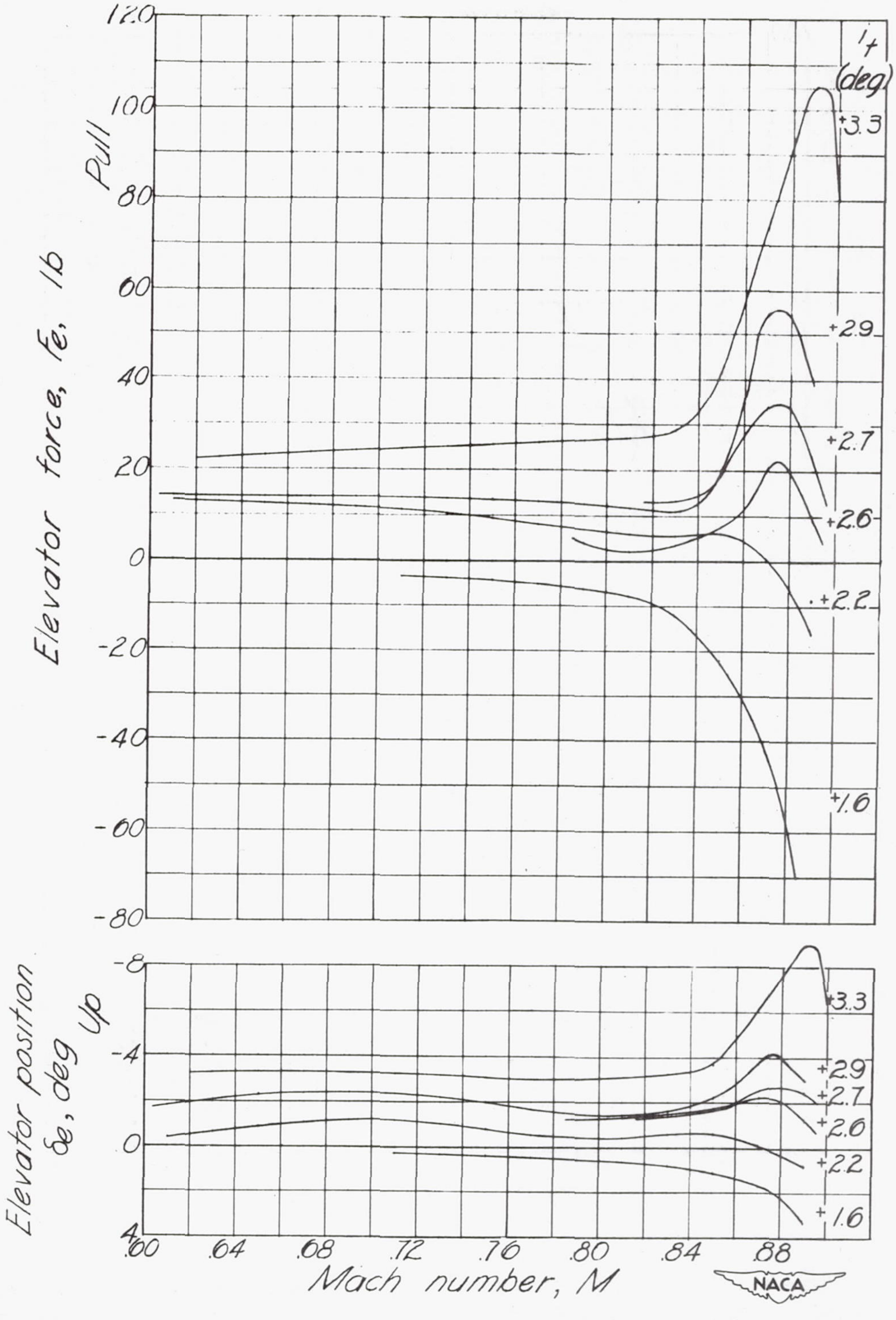


Figure 7.- Faired variation with Mach number of the elevator deflection and wheel force required for balance at a normal-force coefficient of 0.2 for several values of stabilizer incidence in dives from 37,000 to 27,000 feet.

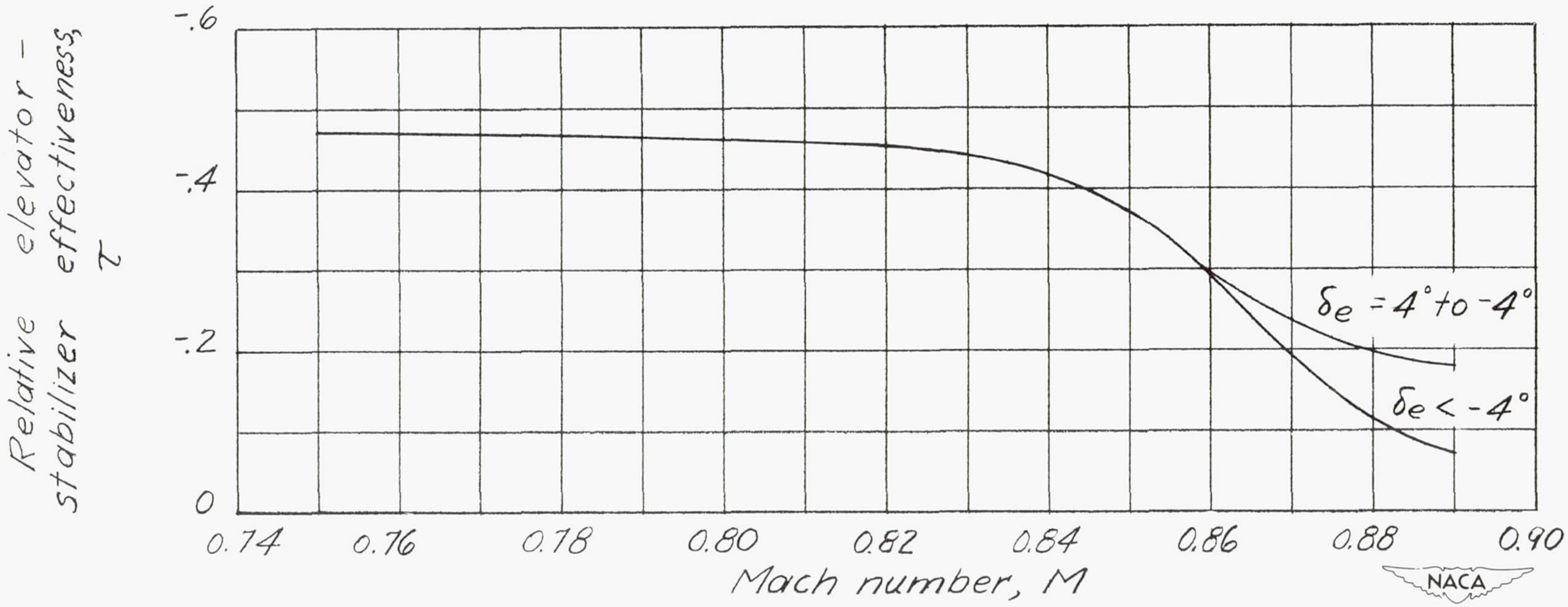


Figure 8.- Variation of relative elevator-stabilizer effectiveness with Mach number.

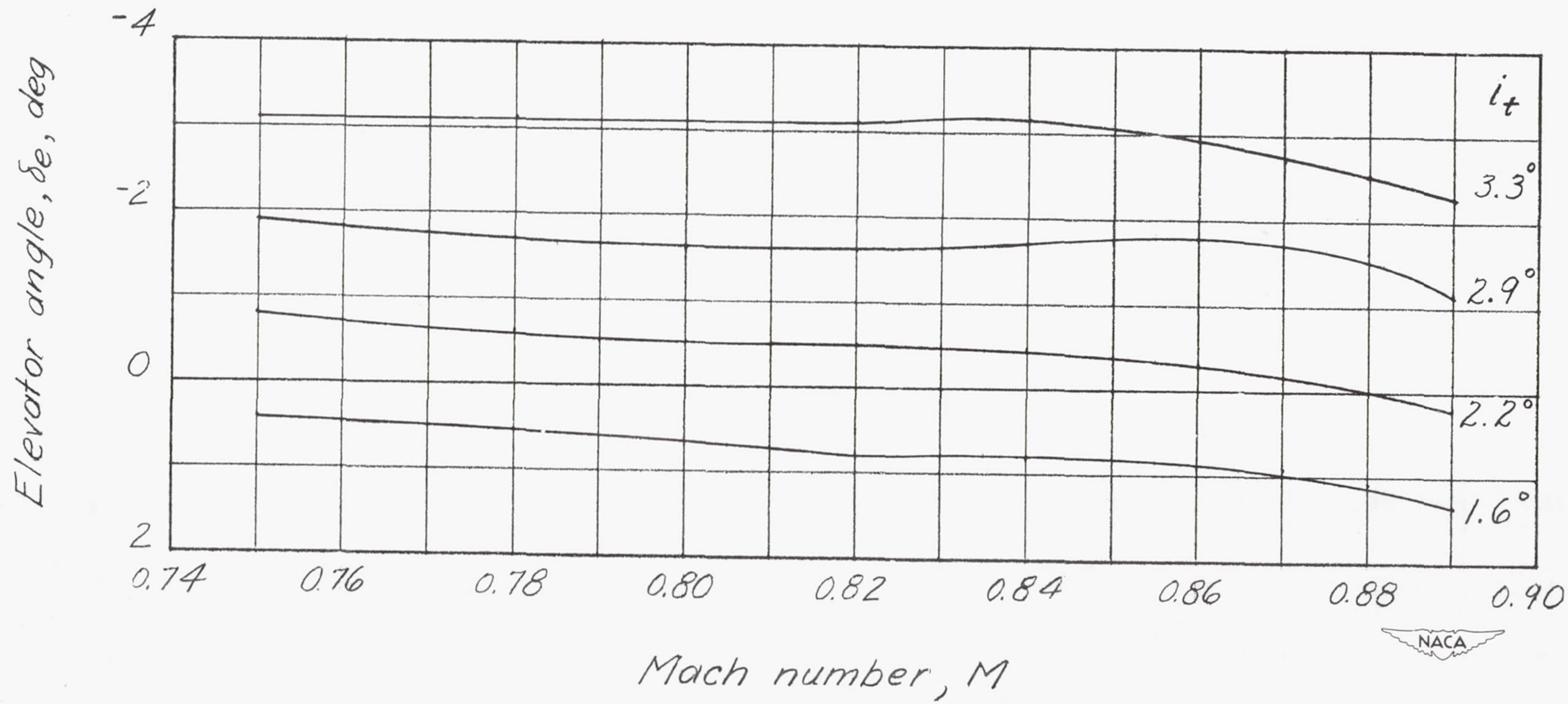
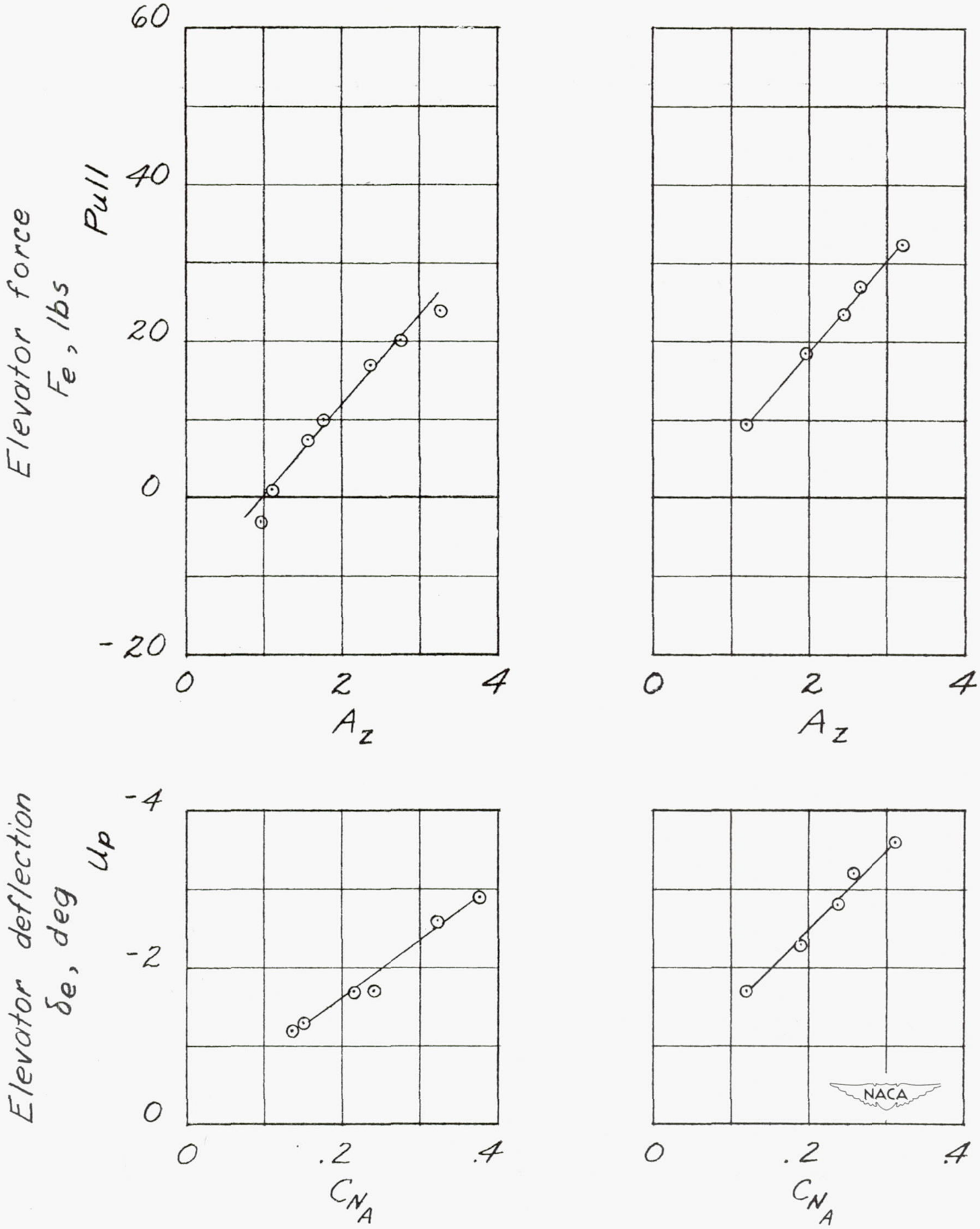


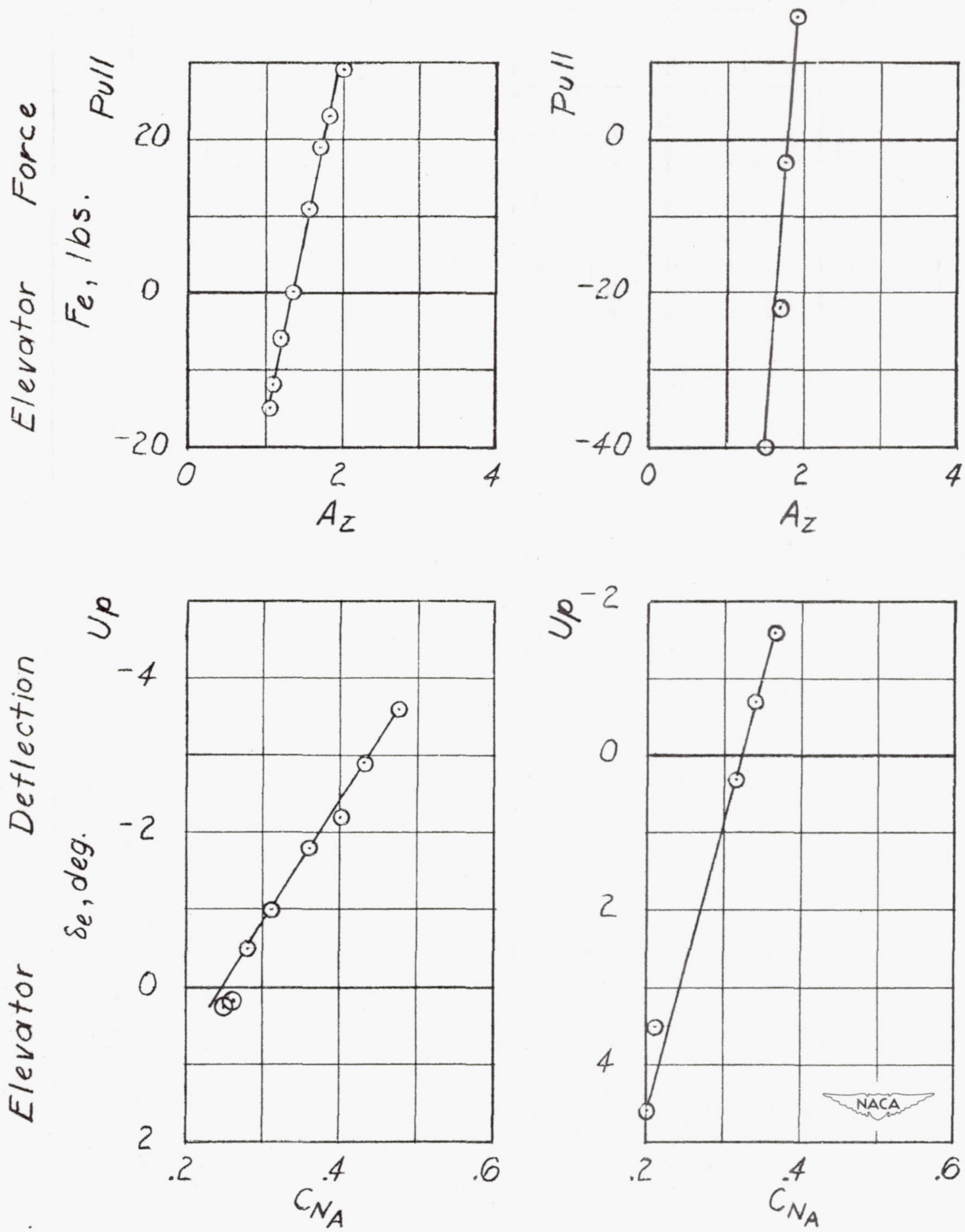
Figure 9.- Stick-fixed balance characteristics for a constant value of elevator effectiveness at several stabilizer settings.



(a) M = 0.70; $i_t = 2.4^\circ$.

(b) M = 0.815; $i_t = 2.6^\circ$.

Figure 10.- Variation of elevator deflection with normal-force coefficient and wheel force with normal acceleration for several values of Mach number.



(c) M = 0.860; i_t = 1.6°. (d) M = 0.893; i_t = 1.6°.

Figure 10.- Concluded.

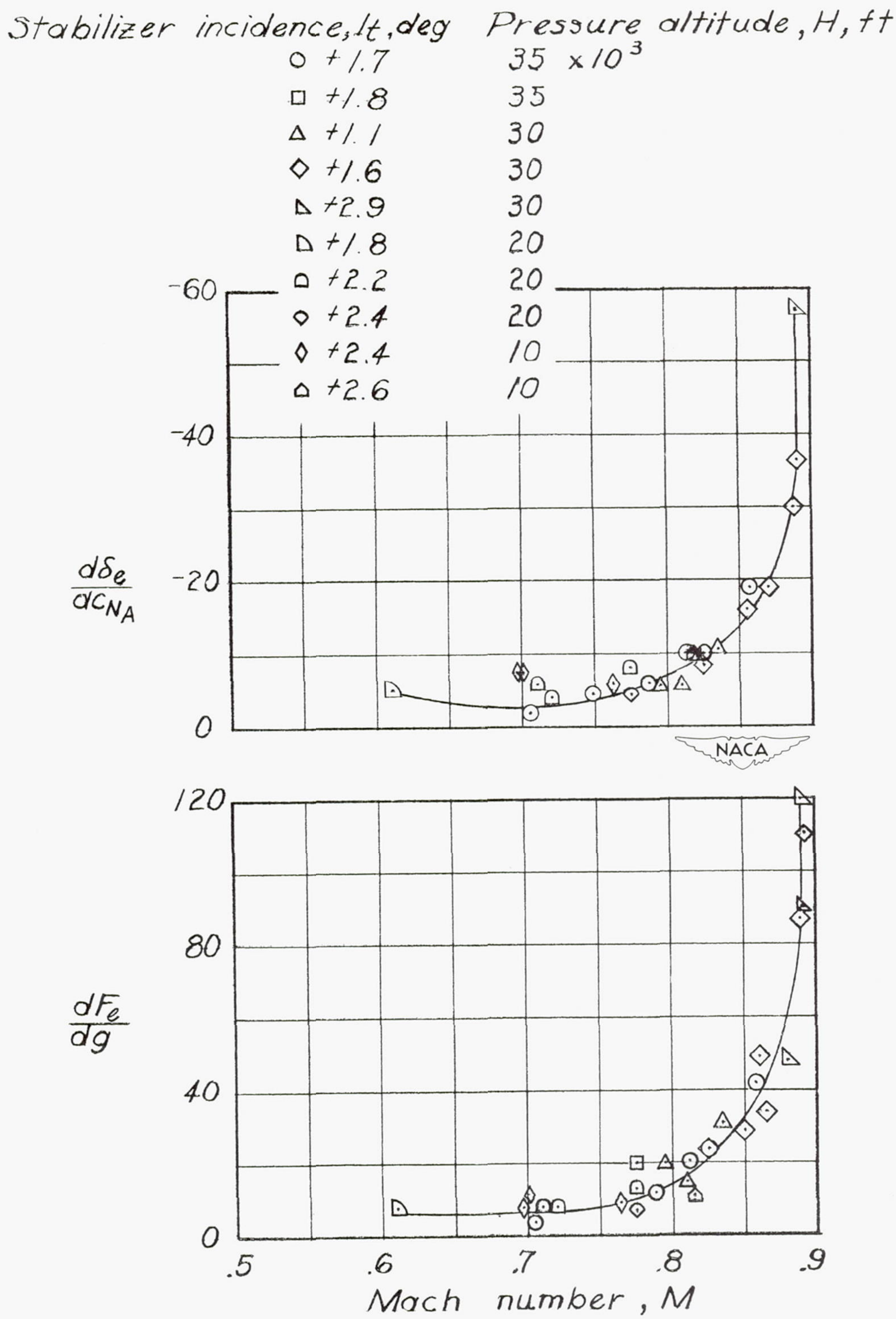
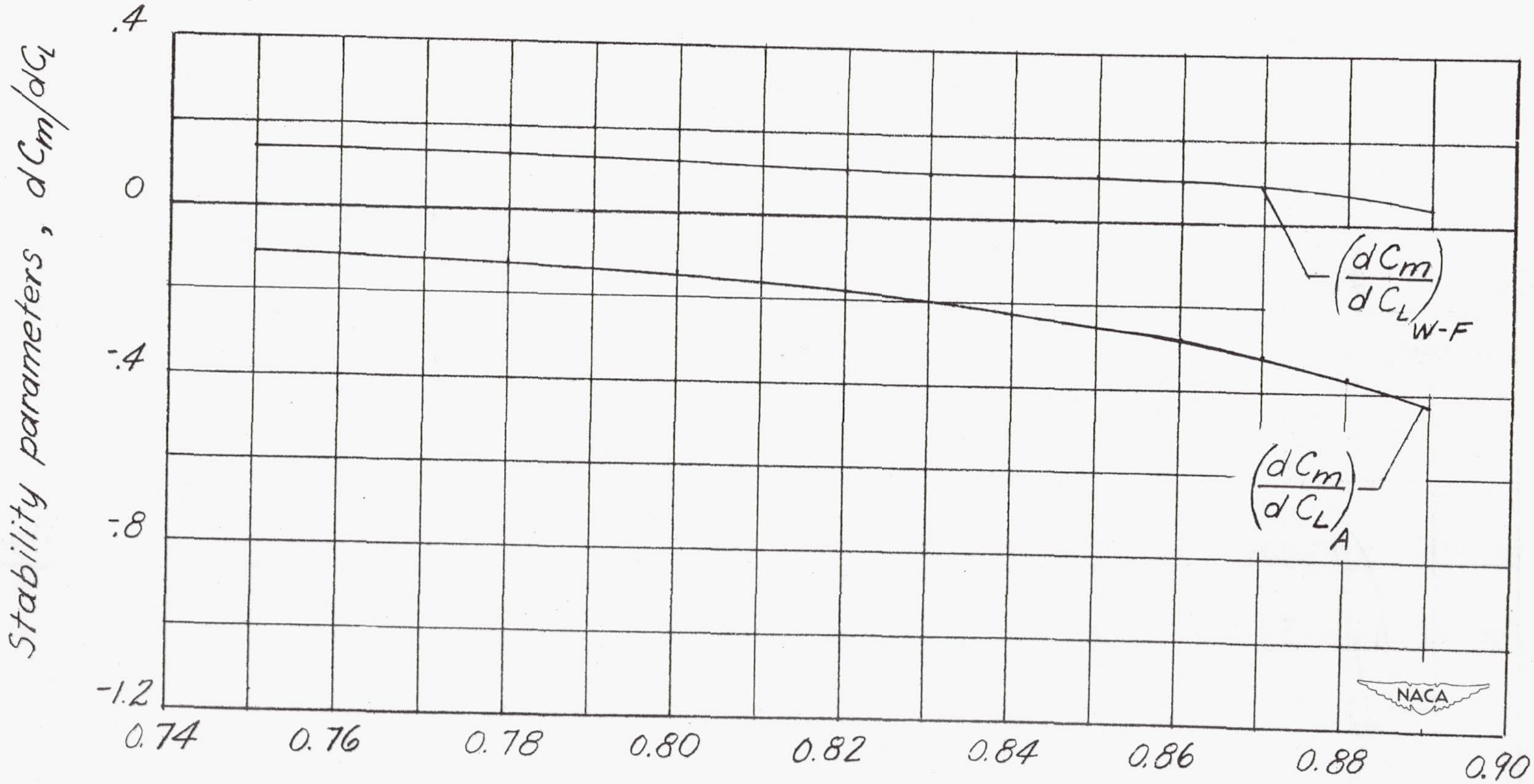


Figure 11.- Variation with Mach number of the change in elevator deflection required to produce a unit change in normal-force coefficient and the change in wheel force required per unit normal acceleration.



Mach number, M

Figure 12.- Variation of the airplane and the wing-fuselage stability parameters with Mach number.

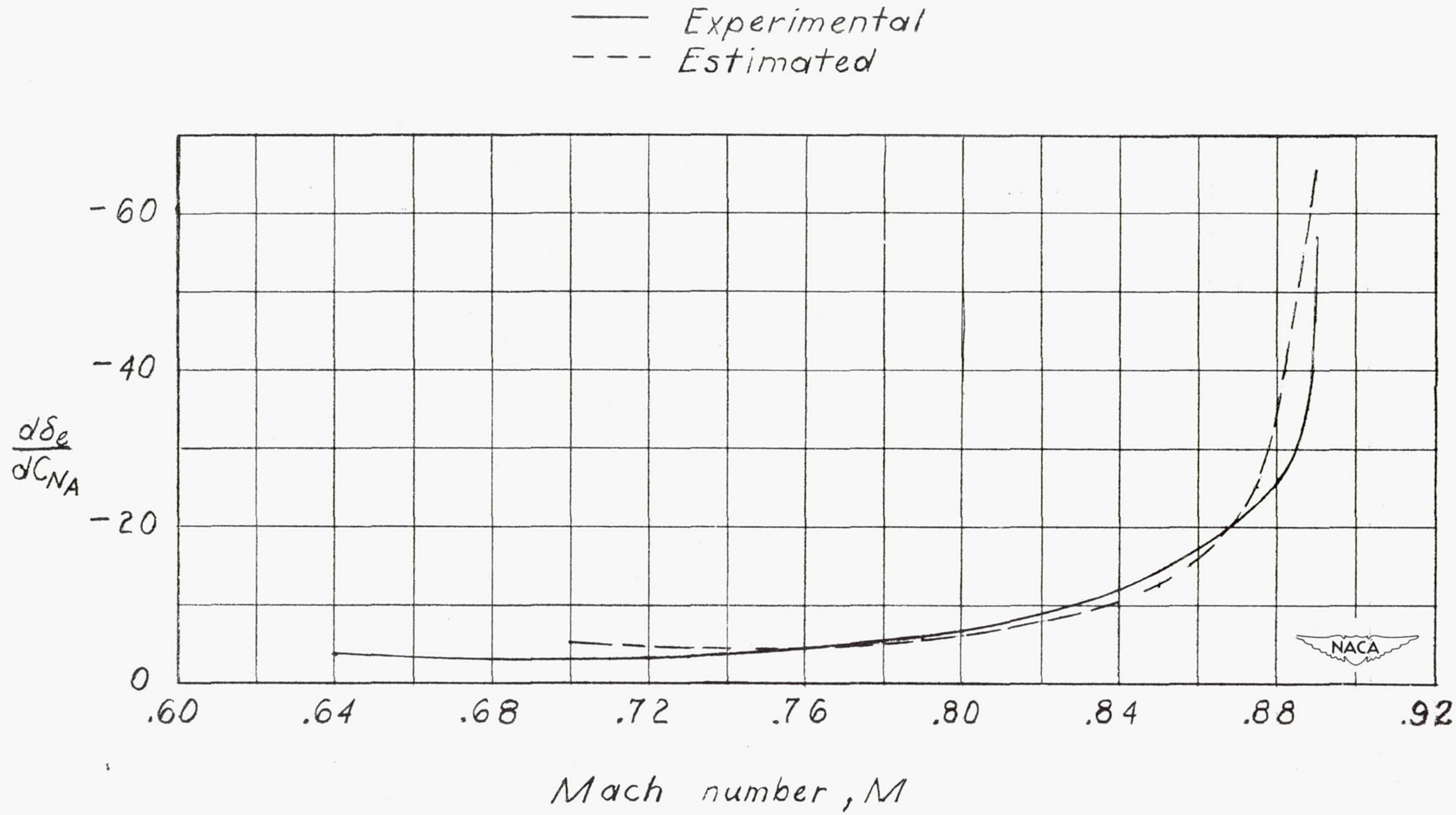


Figure 13.- Comparison between the estimated and experimental variation with Mach number of the change in elevator deflection required per unit change in airplane normal-force coefficient.