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THE EFFECT OF BLUNT-TRAILING-EDGE MODIFICATIONS ON THE HIGH-SPEED STABILITY AND CONTROL CHARACTERISTICS OF A SWEPT-WING FIGHTER AIRPLANE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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THE EFFECT OF BLUNT-TRAILING-EDGE MODIFICATIONS ON THE HIGH-SPEED STABILITY AND CONTROL CHARACTERISTICS OF A SWEPT-WING FIGHTER AIRPLANE

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SUMMARY

An investigation was conducted on a 35° swept-wing fighter airplane to determine the effects of several blunt-trailing-edge modifications to the wing and tail on the high-speed stability and control characteristics and tracking performance. The results indicated significant improvement in the pitch-up characteristics for the blunt-aileron configuration at Mach numbers around 0.90. As a result of increased effectiveness of the blunt-trailing-edge aileron, the roll-off, customarily experienced with the unmodified airplane in wings-level flight between Mach numbers of about 0.9 and 1.0 was eliminated. The results also indicated that the increased effectiveness of the blunt aileron more than offset the large associated aileron hinge moment, resulting in significant improvement in the rolling performance at Mach numbers between 0.85 and 1.0. It appeared from these results that the tracking performance with the blunt-aileron configuration in the pitch-up and buffeting flight region at high Mach numbers was considerably improved over that of the unmodified airplane; however, the tracking errors of 8 to 15 mils were definitely unsatisfactory. A drag increment of about 0.0015 due to the blunt ailerons was noted at Mach numbers to about 0.85. The drag increment was 0 at Mach numbers above 0.90.

INTRODUCTION

Two of the problems experienced during flight tests of a 35° swept-wing fighter airplane are pitch-up and wing dropping or roll-off. The pitch-up, which has been shown in reference 1 to result primarily from premature flow separation on the outboard wing sections and from a consequent inboard (and forward) shift in the center of pressure of additional load on the wing-fuselage combination, is manifested by an abrupt, more or less uncontrollable stalling tendency. The roll-off, which, apparently, is due to both asymmetric flow separation on the wings and to a reversal in aileron effectiveness for small angles (ref. 2), is evident as a rapid change in lateral trim in the Mach number range from about 0.9 to 1.0.

Previous flight studies (refs. 2 to 4) of these two problems have included a number of modifications intended to reduce or eliminate the effects of flow separation. These studies indicated that at Mach numbers up to about 0.84, where separation occurred initially forward of the midchord, outboard on the wing, the pitch-up was virtually eliminated by the use of leading-edge extensions. (See ref. 3.) At higher Mach numbers ($M = 0.85$ to 0.94) where separation occurs initially near the trailing edge, outboard on the wing, leading-edge extensions, arrangements of vortex generators (ref. 2), and wing fences (ref. 4) were effective in delaying flow separation and the occurrence of the pitch-up by normal-force coefficients of about 0.1 to 0.2. In addition, the vortex-generator arrangement was also found to be effective in alleviating the roll-off.

Although the pitch-up and roll-off tendencies were reduced in these previous investigations, additional attention was directed toward control of the trailing-edge type of flow separation, since the instability experienced at high Mach numbers remained as severe as for the unmodified airplane. Wind-tunnel data (ref. 5) indicated that some improvement in both the pitch-up and the roll-off might be obtained by the relatively simple expedient of reducing the trailing-edge angle on the outboard wing sections by using blunt-trailing-edge ailerons.

The present report summarizes the results obtained during flight tests on a 35° swept-wing airplane equipped with blunt-trailing-edge ailerons similar to one of the configurations reported in reference 5. Information is included on the effect of this modification on the pitch-up and roll-off characteristics and on tracking performance. Some results are also presented for the test airplane with various other modifications, including a complete blunt-trailing-edge wing, blunt-trailing-edge ailerons and elevators, and blunt-trailing-edge ailerons combined with leading-edge extensions.

SYMBOLS

A_L acceleration along airplane body axis (positive when directed forward), g units

A_Z ratio of net aerodynamic force along airplane Z axis (positive when directed upward) to weight of airplane (A_Z of 1 = 1 g)

$\dot{A}_Z$ rate of change of normal-acceleration factor A_Z with time

b wing span, ft

b_a aileron span (one), ft

c wing thickness at aileron hinge line, in.

$\bar{c}$ wing mean aerodynamic chord, ft

$\bar{c}_a$ aileron average chord aft of hinge line, ft

C_C airplane chord-force coefficient, $\frac{WA_L}{qS}$

C_D airplane drag coefficient ($C_C \cos \alpha + C_N \sin \alpha$)

C_{h_a} aileron hinge-moment coefficient, $\frac{H_a}{qb_a\bar{c}_a^2}$

C_l airplane rolling-moment coefficient, $\frac{L}{qSb}$

$C_{m_{w+f}}$ wing-fuselage pitching-moment coefficient about quarter mean aerodynamic chord, $\frac{M_{w+f}}{qS\bar{c}}$

$C_{m_{tail}}$ pitching-moment coefficient due to horizontal tail

C_N airplane normal-force coefficient, $\frac{WA_Z}{qS}$

C.P. chordwise center of pressure of additional loading on wing-fuselage combination (forward movement considered positive), percent $\bar{c}$

$C_{l_{\delta_{a_T}}}$ aileron effectiveness parameter, $\frac{\partial C_l}{\partial \delta_{a_T}}$, per radian

F_a aileron stick force (right force positive), lb

F_e elevator stick force (pull force positive), lb

F_N net thrust, lb

g acceleration due to gravity, 32.2 ft/sec^2

h aileron trailing-edge thickness, in.

H_a	aileron hinge moment, ft-lb
L	airplane rolling moment, ft-lb
M	free-stream Mach number
M_{w+f}	wing-fuselage pitching moment referred to $\frac{\bar{c}}{4}$, ft-lb
p	airplane rolling velocity, radians/sec
$\frac{pb}{2V}$	wing-tip helix angle, radians
q	free-stream dynamic pressure, lb/sq ft
S	wing area, sq ft
t	time, sec
V	true airspeed, ft/sec
W	airplane weight, lb
α	airplane angle of attack, deg
δ_a	aileron angle (positive downward), deg
δ_{a_T}	total aileron angle, $\delta_{a_L} - \delta_{a_R}$, deg or radians
$\delta_{a_{av}}$	average aileron angle, $\frac{\delta_{a_L} + \delta_{a_R}}{2}$, deg
δ_e	elevator angle (positive downward), deg
$\ddot{\theta}$	airplane pitching acceleration, radians/sec^2
$\dot{\theta}$	airplane pitching velocity, radians/sec
σ_x	standard deviations of aim wander in yaw, mils
σ_y	standard deviations of aim wander in pitch, mils
Δ	before a symbol denotes change of that quantity from some arbitrary initial value

Subscripts

L	left
R	right
t	trim
max	maximum value

EQUIPMENT AND TESTS

Unmodified Airplane

The test airplane is a jet-powered fighter with swept-back wing and tail surfaces. Figure 1 is a photograph of the unmodified airplane in its flight-test configuration. The physical characteristics and a two-view drawing of the airplane are given in table I and figure 2, respectively. The test airplane was not equipped with the standard elevator bungee or bobweight.

Modifications

The basic modification consisted of reducing the trailing-edge angle outboard on the wing from about 13° to 8° by increasing the trailing-edge thickness of the ailerons to 0.4 that at the hinge line. This modification was identical to one of the model configurations reported in reference 5. A detail photograph of the left aileron modification and a sketch giving the dimensional details are presented in figures 3 and 4, respectively. In order to minimize the increase in aileron moment of inertia (thereby reducing the tendency toward single-degree flutter of the aileron), a light-weight plastic material, expanded polystyrene, with a specific weight of about 1.6 pounds per cubic foot was used. The plastic material was cemented to the upper and lower surfaces of the ailerons by a water-soluble glue. The ailerons were then rebalanced to their original 5-inch-pounds overbalance. The modification roughly doubled the aileron moments of inertia, the values increasing from about 1.0 to 2.0 slug-feet squared.

Most of the results presented herein are for the airplane equipped only with blunt-trailing-edge ailerons. This configuration will be referred to as the "blunt-aileron configuration." Some data were also obtained for the airplane with various other configurations in order to explore more fully the possibilities of the blunt-trailing-edge modifications. Another configuration tested comprised the blunt-trailing-edge ailerons described above and blunt-trailing-edge flaps. This configuration will be referred to as the "blunt-wing configuration." A third configuration consisted of blunt-trailing-edge ailerons and blunt-trailing-edge elevators with the trailing-edge thickness of the elevators equal to that at the hinge line. (Figure 5 presents a detail rear view of the elevator modification.) A fourth configuration comprised the blunt-trailing-edge ailerons and the leading-edge extensions described in reference 3.

Instrumentation

Standard NACA instruments and an 18-channel oscillograph were used to record all measured quantities. The horizontal-tail loads (from which the wing-fuselage pitching moments were determined) were measured by means of strain gages at three pin-joined attachment fittings which join the tail to the fuselage. The true Mach number was determined from the nose-boom airspeed system calibrated over the test Mach number range by the NACA radar-phototheodolite method as reported in reference 6. A U. S. Navy Mark 8 Mod 5 fixed sight and a 16-mm gun camera were used to evaluate the tracking performance of the modified airplane. Airplane drag was measured by the method described in reference 2. The angles of attack used in calculating the drag were not directly measured in the present tests but were obtained from lift-curve data obtained previously on the unmodified airplane.

Tests

Longitudinal-stability measurements were taken in essentially constant Mach number wind-up, or gradually tightening, turns. At the onset of pitch-up, the pilot was instructed to hold the controls fixed and the airplane was allowed to pitch up to the stall or limit normal-acceleration factor. Aileron effectiveness was determined both in terms of the variation of rolling-moment coefficient C_l with total aileron angle and the variation of wing-tip helix angle $pb/2V$ with total aileron angle. The former was obtained directly from measurements of the rolling acceleration at zero rolling velocity by the method described in reference 7. The latter was obtained from measurements of maximum rolling velocity and total aileron angle in rudder-fixed aileron rolls. Lateral trim characteristics were measured in terms of both aileron stick force and total aileron angle required to maintain lateral balance in steady straight flight with wings level up to a Mach number of 1.02. The tracking performance of the test airplane equipped with blunt ailerons was evaluated in the buffeting and pitch-up flight region at Mach numbers of 0.80

and 0.90. Standardized gunnery runs, as described in reference 8, were performed. A production F-86D was used as the target airplane.

The present tests were conducted at pressure altitudes between 35,000 and 40,000 feet. The stabilizer angle varied between $\pm 0.5^{\circ}$, and the automatic leading-edge slats remained closed during the longitudinal stability tests. The center of gravity was located at an average value of 22.5 percent of the mean aerodynamic chord.

Corrections and Accuracy

The wing-fuselage pitching-moment coefficients and elevator angles presented for normal-force coefficients in the pitch-up range were corrected for the effects of pitching acceleration. The correction to the tail load was computed as the additional load required at the tail to reduce the measured pitching acceleration to zero. This incremental load, converted to pitching-moment coefficient, was used with the elevator-effectiveness data of reference 1 to determine an approximate trim elevator angle. No corrections were applied to the elevator angles and stick forces presented in time-history form or to the elevator stick forces for airplane normal-force coefficients in the pitch-up range. Because of zero shifts in the tail-load data during the present tests, the wing-fuselage pitching-moment coefficients were adjusted to zero at zero normal-force coefficient. The values of aileron effectiveness $C_{l_{\delta_{a_T}}}$ presented herein were corrected for sideslip-angle effects by using measured values of sideslip and values of the effective dihedral parameter C_{l_β} given in reference 9. The aileron hinge-moment coefficients given in the present report are total values, which include both the effects of changes in aileron deflection and wing angle of attack. No corrections were applied for the induced effects due to rolling velocity.

The accuracy of the longitudinal stability and drag data are essentially the same as that reported in reference 4.

RESULTS AND DISCUSSION

Longitudinal Stability and Control

Previous flight investigations of the longitudinal stability and control of the test airplane have indicated that the degree of longitudinal instability or pitch-up that occurs is related to the location of initial flow separation on the wing. At low speeds and up to about 0.80 Mach number, initial flow separation occurs in the neighborhood of the leading edge, outboard on the wing, and results in a relatively mild pitch-up, which is often masked by a severe roll-off. A successful attempt to control this type of separation by the use of leading-edge chord extensions, outboard on the wing, is described in reference 3. At Mach numbers between 0.80 and 0.84, initial flow separation occurs just forward of the midchord, outboard on the wing, resulting in a moderately severe pitch-up. At Mach numbers from 0.86 to about 0.94, initial flow separation occurs near the trailing edge, outboard on the wing, resulting in a severe pitch-up. The present series of tests were conducted in an attempt to control this trailing-edge type of flow separation.

Blunt-aileron configuration.- The variation of wing-fuselage pitching-moment coefficient $C_{m_{W+F}}$, trim elevator angle δ_{e_t}, and stick-force factor F_e/q with airplane normal-force coefficient C_N at several values of Mach number is shown in figures 6(a) through 6(f) for the blunt-aileron configuration. The characteristics of the unmodified airplane are also included in figure 6 for comparison. These results show that there was improvement in the wing-fuselage pitching moments and, consequently, in the trim elevator angles and in the stick-force factors at all test Mach numbers up to 0.93. At a Mach number of 0.93 (fig. 6(f)), no significant improvement was obtained, possibly because at this high speed where flow separation is confined to smaller areas of the wing and where the pitch-up tends to become less severe, only small changes in the pitching-moment characteristics may be expected due to any wing modification. In the comparison of stick-force factors in figure 6(f), the more favorable variation for the unmodified airplane resulted primarily from the pilot pulling the control back after onset of the pitch-up instead of holding the controls relatively fixed, as was the case for the other examples presented for the lower Mach numbers. A further point of interest in figure 6 is that, in addition to the improvement in the pitch-up characteristics at Mach numbers of 0.90 and 0.91 (figs. 6(d) and 6(e), respectively), a significant improvement was also obtained at the lower Mach numbers. (See figs. 6(a) and 6(b).)

Since a question might arise as to whether the blunt-aileron modification affected the horizontal-tail stability contribution as well as the wing-fuselage contribution, the tail pitching-moment variations for both the unmodified and blunt-aileron configurations were estimated from the elevator angles and wing-fuselage pitching moments shown in figure 6, using the elevator effectiveness data presented in reference 1. The results, shown in figure 7 for Mach numbers of 0.70, 0.82, and 0.90, indicate that the tail pitching-moment variations were fairly linear with normal-force coefficient and were approximately the same for the unmodified airplane and for the modified airplane. The approximately linear tail pitching moments indicate that the primary cause of the pitch-up was a change in wing-fuselage stability, a conclusion that has already been pointed out in reference 1 for the unmodified airplane. The quantitatively similar variations in tail pitching moments for the unmodified airplane and for the modified airplane show that the blunt-aileron modification affected, primarily, the wing-fuselage pitching moments without significantly altering the downwash characteristics at the tail.

The pilots' evaluation of the pitch-up indicated that they did not appreciate the improvement at low Mach numbers (M = 0.70 to 0.82), although they did note that the severe roll-off customarily encountered at a Mach number of 0.70 with the unmodified airplane did not occur with the blunt-aileron configuration. At intermediate Mach numbers between about 0.82 and 0.86, the pilots did not note any significant improvement in the pitch-up characteristics. At Mach numbers between 0.87 and 0.93, however, the pilots noted that the present configuration was the best of any tested thus far. They felt they could control the airplane within the pitch-up flight region at these speeds, whereas they had little or no control with the unmodified airplane. Time histories of one of the pilot's attempts to maintain constant normal-acceleration factors just below and just above that for pitch-up at a Mach number of 0.90 are presented in figures 8(a) and 8(b), respectively. In figure 8(a), although small oscillatory control motions were required, a constant value of normal-acceleration factor of about 3 was maintained. In figure 8(b), although large, abrupt control motions were required, a fairly constant normal-acceleration factor of about 3.5 was maintained. It should be noted that this degree of controllability can by no means be interpreted as precise or satisfactory (as will be illustrated more clearly in the section on tracking performance); however, it does represent a marked improvement over that available with the unmodified airplane.

Blunt-wing configuration.- The longitudinal stability and control characteristics for the blunt-wing configuration are shown in figures 9(a) through 9(d) where they are compared with those for the unmodified airplane. These data show an improvement in the pitch-up characteristics at Mach numbers from 0.70 to 0.82. At Mach numbers from about 0.86 to 0.91, though the airplane normal-force coefficient for instability was increased somewhat, the pitch-up, when it occurred, was as abrupt or more so than that of the unmodified airplane. The pitching-moment curves in figure 9 show an interesting, marked stabilizing effect on the wing-fuselage combination due to blunting the wing trailing edge, particularly at Mach numbers above 0.82.

The pilot's comments on this configuration indicated that at low Mach numbers (M = 0.70 to 0.82), the pitch-up appeared about the same as that for the unmodified airplane. He also noted again the absence of an abrupt roll-off at a Mach number of 0.70. At Mach numbers above 0.85, although the pilot was aware of the higher normal-acceleration factor available before the airplane became unstable, he objected strongly to both the increased stability of the airplane (which required large pull forces on the stick just prior to the pitch-up) and to the severity of the instability when it occurred.

Blunt-aileron, blunt-elevator configuration.- To determine whether further improvement in control within the unstable flight region at high Mach numbers would be obtained if the control effectiveness were increased, limited tests were conducted on the test airplane equipped with both blunt ailerons and blunt elevators. The stability characteristics for this configuration are compared with those for the unmodified airplane in figures 10(a) and 10(b). An improvement in the pitch-up at the lower speeds ($M = 0.78$) may be noted again in figure 10(a). A comparison of the elevator angles and stick-force factors in figures 10(b) and 6(d) shows a noticeable increase in elevator effectiveness due to blunting the elevator trailing edge. However, no further improvement in the pitch-up characteristics was obtained due to this increase in effectiveness at a Mach number of 0.90.

The pilot's comments on this configuration indicated the pitch-up was slightly improved at a Mach number of 0.78, and that the same order of improvement as that noted for the blunt-aileron configuration was observed at a Mach number of 0.90. A slight buffet in steady straight flight at a Mach number of 0.90 was also observed by the pilot. This buffet was too slight to appear in the film records.

Blunt-aileron, extended-leading-edge configuration.- A modification comprising the leading-edge chord extension described in reference 3 and the blunt ailerons was made to determine whether the beneficial effects of these two modifications were cumulative. It was reasoned that the leading-edge extensions and blunt ailerons would control or reduce the leading-edge-type and trailing-edge-type separation, respectively, and that the combination might reduce the tendency toward flow separation in the neighborhood of the midchord. The variations of wing-fuselage pitching-moment coefficient, trim elevator angle, and stick-force factor with airplane normal-force coefficient for this configuration are presented in figure 11 where these variations are compared with those for the unmodified airplane. These results show a significant improvement in the pitch-up characteristics at the lower Mach numbers (figs. 11(a) and 11(b)). At intermediate Mach numbers (fig. 11(c)), there appears to be an appreciable improvement although, when compared to the results for the blunt ailerons alone (fig. 6(c)), the improvement is not so marked. At the higher Mach numbers (fig. 11(d)), the data show a delay in the occurrence of instability by a C_N of about 0.1, but the instability, when it occurs, is as severe as with the unmodified airplane.

The pilot's evaluation of the stability characteristics with this configuration indicated that the pitch-up was virtually eliminated at Mach numbers up to 0.82. At intermediate Mach numbers ($M = 0.82$ to 0.87), the pitch-up was considered mild, and at the higher Mach numbers, the pilot observed that the pitch-up was as severe as with the unmodified airplane.

Factors Influencing Pilot Evaluation of Pitch-Up

In general, the pilot evaluation of the pitch-up correlated fairly well with the stability and control comparisons shown in figures 6 through 11. However, in several cases, particularly for the blunt-aileron configuration, the improvement shown in the stability data alone did not seem, on the surface, sufficient to merit the degree of improvement noted by the pilots. Referring back to figure 6, it may be noted that following the pitching-moment breaks, the instability of both the wing-fuselage combination and of the airplane (given by the trim elevator angles) was less severe than that of the unmodified airplane. It follows that the uncontrolled airplane motions would be less severe and the required corrective control less abrupt than for the unmodified airplane. Since the pilots impression of the pitch-up is governed, perhaps primarily, by the degree of controllability he exercises over the airplane, and the controllability is, in turn, dependent on both the abruptness of the airplane motions at pitch-up and the available control effectiveness, some quantitative information on these two quantities appears desirable to correlate with pilot opinion. In the present case, information is only available on the motions of the airplane at pitch-up. (The increased control effectiveness with the blunt elevators was apparently too small to be observed either by the pilot or in the data.)

Time histories of wind-up turns to the pitch-up for the blunt-aileron configuration and for the unmodified airplane at a Mach number of about 0.90 are presented in figures 12(a) and 12(b), respectively. The considerably milder pitch-up for the former configuration is evident in both the more gradual increase in normal acceleration and the lower pitching accelerations developed during pitch-up. The variation with Mach number of the maximum rates of change of normal-acceleration factor and pitching velocity during pitch-up is shown in figures 13(a) and 13(b), respectively. The elevator angles during build-up to the maximum values shown in figure 13 remained fixed at approximately the values existing at the onset of the pitch-up.[1] Both the maximum normal-acceleration rates and the maximum pitching accelerations developed during pitch-up with the blunt-aileron configuration are only about 60 percent of those experienced with the unmodified airplane. Peak values occur at about 0.90 Mach number, indicating the pitch-up is most severe at this speed. It is interesting to observe in figure 13 the fairly close correlation between pilots' evaluation of the pitch-up and the values of $\dot{A}_{Z_{max}}$ and $\ddot{\theta}_{max}$ experienced at a Mach number of about 0.90. For values of $\dot{A}_{Z_{max}}$ and $\ddot{\theta}_{max}$ of about 1.6 and 0.4, respectively, as was the case for the

[1]The pilots' normal reaction in a pitch-up would be to apply corrective control to check the maneuver. However, for these tests, the pilot was instructed to hold the elevator control fixed at onset of the pitch-up, allowing the airplane to pitch up either to the stall or the maximum allowable load factor.

blunt-aileron and for the blunt-aileron, blunt-elevator configurations, the pilot considered the airplane fairly controllable. For the unmodified airplane and for the blunt-wing and for the blunt-aileron, extended-leading-edge configurations, when values of $\dot{A}_{Z_{max}}$ and $\ddot{\theta}_{max}$ of about 2.8 and 0.6, respectively, were experienced at a Mach number of 0.90, the pilot considered the airplane uncontrollable during the pitch-up.

The reason for the pilots' favorable impression of the pitch-up at high speeds with the blunt-aileron configuration may be illustrated in another way, using a basic quantity, the variation of the wing-fuselage center of pressure of additional loading. Figure 14 presents time histories of the incremental center of pressure of additional loading on the wing-fuselage combination and of the incremental elevator angles required to balance these center-of-pressure variations at a Mach number of 0.90. The incremental center-of-pressure variations given in figure 14 were determined from the $C_{m_{W+F}}$ and C_N time histories presented in figure 12. A destabilizing variation in the incremental center of pressure of about 4 percent of the wing mean aerodynamic chord occurred for the blunt-aileron configuration during the first second following the onset of pitch-up, while a destabilizing variation of more than 8-percent $\bar{c}$ occurred in the same time interval for the unmodified airplane. The corresponding corrective elevator control required is only 3° as compared to $7\text{-}1/2^{\circ}$. These results indicate the pilot would have considerably more control or somewhat less trouble in preventing an undesirably large "overshoot" in normal-acceleration factor with the airplane equipped with blunt ailerons than he would with the unmodified airplane.

Flow Characteristics

The data have indicated a considerably milder pitch-up for the blunt-aileron configuration at a Mach number of about 0.9 due to the more gradual movement of the wing-fuselage center of pressure, both with time and with airplane normal-force coefficient during pitch-up. It might be expected that the aileron floating angles or tuft studies would indicate that this was due to a more gradual progression of the separated flow over the wing. The average aileron floating angles shown in figure 15 at several Mach numbers show no significant improvement over those for the unmodified airplane. However, since, at the higher speeds and normal-force coefficients, the flow over both upper and lower surfaces, outboard on the wing, was separated (ref. 10), it is possible that the separation was reduced over both upper and lower surfaces, thereby increasing the lift outboard without necessarily reducing the aileron hinge moments. Flow-separation patterns, as indicated by tufts in the wing boundary layer forward of the ailerons,[2] also showed no marked difference from those for the unmodified airplane shown in reference 4 and reproduced

[2]No tufts were located over the ailerons of the modified airplane.

herein as figure 16. The only difference appeared to be a slight reduction in the extent of separated flow located at about midspan at a C_N of 0.52 and at a Mach number of 0.91.

Lateral Stability and Control

It was mentioned earlier that another serious problem experienced with the test airplane is that of an abrupt lateral trim change or roll-off in the Mach number range from 0.9 to 1.0. One of the reasons advanced in reference 2 for the roll-off was the low or negative aileron effectiveness experienced in this speed range for small aileron deflections. By blunting the aileron trailing edge, reducing the trailing-edge angle from about 13° to 8°, it was hoped to improve the aileron effectiveness, and, consequently, the roll-off, at transonic speeds. Figure 17 presents the variation of the aileron effectiveness parameters $C_{l_{\delta_{a_T}}}$ and $\frac{\partial(pb/2V)}{\partial\delta_{a_T}}$ with Mach number for the blunt-aileron configuration. Results for the unmodified airplane and from the wind-tunnel data of reference 5 are also included in figure 17 for comparison. The comparison shows a marked improvement in effectiveness not only at transonic speeds but also at the lower speeds. A rapid decrease in aileron effectiveness above a Mach number of 0.90 was experienced with both the modified and unmodified airplanes. However, the effectiveness for the blunt-aileron configuration remained at moderate positive values as compared to small negative values for the unmodified airplane between Mach numbers of 0.94 and 0.98.

The results in figure 18, which show the aileron stick force and total aileron angle required to maintain wings-level flight, indicate that the increased effectiveness shown in figure 17 was adequate to virtually eliminate the roll-off. Except for a very slight right-wing heaviness indicated by the total aileron angle above a Mach number of 0.90 (compared to extreme left-wing heaviness for the unmodified airplane), no trim change occurred throughout the test Mach number range. The pilot commented that no roll-off was experienced up to the highest test Mach number of 1.02.

During abrupt aileron maneuvers, the pilot noted the aileron stick forces increased considerably, when the Mach number exceeded 0.90, indicating the aileron hinge moments were increasing rapidly at these higher speeds. The variation of left-aileron hinge-moment coefficient gradient $\partial C_h/\partial\delta_{a_L}$ with Mach number is shown in figure 19 for the blunt-aileron configuration. These results show more than a three-fold increase as the Mach number was increased from 0.90 to 1.02. This large increase in hinge moment did not penalize the airplane rolling performance appreciably, because the increased effectiveness (fig. 17) more than compensated for the reduced aileron angles available at the higher speeds.[3] This is illustrated in figure 20 where values of $(pb/2V)_{max}$ estimated from the flight data of the present tests and from the wind-tunnel data of reference 5 are presented. The flight results are presented for both 40,000 feet and 10,000 feet for the blunt-aileron configuration. The wind-tunnel data are presented for 10,000 feet for both the unmodified and the modified models. Both the flight data and the wind-tunnel data are presented for an aileron boost output of 17,000 inch-pounds. The comparison at 10,000 feet indicates a marked improvement in the rolling performance at Mach numbers between 0.90 and 1.00 and only a slight penalty at Mach numbers between 0.70 and 0.83. It should be noted that no corrections for wing twist were applied to the results estimated from flight data.

Tracking Performance

It was noted previously that the pilot considered the airplane equipped with blunt ailerons fairly controllable within the pitch-up region at the higher flight speeds, whereas he considered the unmodified airplane uncontrollable. To obtain a more precise measurement of this improved controllability, standard gunnery runs were made within the buffeting and pitch-up flight regions at 0.80 and 0.90 Mach number.

Standard deviations of aim wander within buffeting and pitch-up flight regions at Mach numbers of 0.80 and 0.90 are shown in figure 21. The standard deviations for the unmodified airplane obtained from reference 8 are also indicated in figure 21. The data in figure 21 indicate tracking errors for the unmodified airplane in stable flight (no buffeting or pitch-up) of about 2 mils. The tracking errors for the modified airplane at a Mach number of 0.80, where moderate buffeting and mild pitch-up were experienced, were approximately 8 mils. Within the pitch-up and buffeting flight region at a Mach number of 0.90, the standard deviation of the aim wander in pitch was about 15 mils. Although no tests were conducted specifically to determine tracking performance of the unmodified airplane within the pitch-up flight region at a Mach number of 0.90, it is indicated in reference 8 that inadvertent entry into the pitch-up region resulted in transient gross errors of 100 mils or more. It may be concluded that the present results represent a considerable improvement in controllability at high Mach numbers at normal-acceleration factors above the pitch-up. However, the degree of improvement was not adequate to provide satisfactory tracking performance within buffeting and pitch-up flight regions at Mach numbers of 0.80 and 0.90.

[3]Although no comparative flight data were available, it is believed the aileron hinge moments, and, consequently, stick forces, were considerably increased by the blunt-aileron modification, resulting in reduced aileron angles available at high speeds relative to those available with the unmodified airplane.

Drag

The effect of the various wing modifications tested in the present series of tests on the airplane drag coefficient at an airplane normal-force coefficient of 0.15 is shown in figure 22. The blunt-aileron modification adds a drag increment of about 0.0015 at Mach numbers up to about 0.85. At maximum level-flight Mach number of about 0.90 and up to the maximum test Mach number of about 1.0, the drag penalty due to blunting the ailerons is reduced to zero. The wind-tunnel results of reference 5 for a similar blunt-aileron model configuration indicated a drag increment of about 0.001 at 0.85 Mach number and a drag decrement of about 0.002 at 1.0 Mach number. The drag increment for the blunt-aileron, extended-leading-edge configuration at Mach numbers to 0.90 was about 0.003. The highest drag increment of 0.006, measured with the blunt-wing configuration at Mach numbers to about 0.85, was reduced almost to zero at a Mach number of 0.93.

CONCLUSIONS

An investigation to determine the effects of several blunt-trailing-edge modifications to the wing and tail on the longitudinal and lateral stability and control and tracking performance of a 35° swept-wing airplane has indicated the following:

1. Marked improvement of the pitch-up characteristics at Mach numbers around 0.90 was obtained with the blunt-aileron configuration. The pilots considered the modified airplane fairly controllable at normal-acceleration factors above that for pitch-up; whereas they considered the unmodified airplane virtually uncontrollable in the same flight region.

2. The improved controllability for the airplane equipped with blunt ailerons resulted from the less severe airplane instability, and, consequently, the more gradual motions of the airplane during pitch-up.

3. Movement of the center of pressure of additional loading on the wing-fuselage combination at a Mach number of 0.90 indicated a more gradual progression of flow separation following onset of pitch-up for the blunt-aileron configuration. Neither aileron up-float angles nor tuft studies verified this improvement in flow characteristics.

4. The increased aileron effectiveness at transonic speeds due to the blunt-aileron modification eliminated the roll-off customarily experienced with the unmodified airplane in wings-level flight between Mach numbers of 0.9 and 1.0.

5. The increased aileron effectiveness more than offset the large aileron hinge moments associated with the blunt-aileron configuration, resulting in marked improvement in rolling performance at Mach numbers between about 0.9 and 1.0.

6. Although no specific comparison was available, it appeared the tracking performance of the airplane with blunt ailerons was considerably better than that of the unmodified airplane at normal-acceleration factors above those for pitch-up at high speeds. However, the measured tracking errors of 8 to 15 mils were not considered satisfactory compared to 2 mils measured in stable flight regions.

7. The increment in airplane drag coefficient at a normal-force coefficient of 0.15 due to the blunt-aileron modification was about 0.0015 at Mach numbers to 0.85. Between the maximum level-flight Mach number of 0.90 and the test limit of about 1.0, the drag was approximately the same as for the unmodified airplane.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Mar. 31, 1954

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TABLE I.- DESCRIPTION OF TEST AIRPLANE

Wing	
Total wing area (including flaps, slats, and 49.92 sq ft covered by fuselage), sq ft	287.90
Span, ft	37.12
Aspect ratio	4.79
Taper ratio	0.51
Mean aerodynamic chord (wing station 98.7 in.), ft	8.08
Dihedral angle, deg	3.0
Sweepback of 0.25-chord line	35°14'
Sweepback of leading edge	37°44'
Geometric twist, deg	2.0
Root airfoil section (normal to 0.25-chord line)	NACA 0012-64 (modified)
Tip airfoil section (normal to 0.25-chord line)	NACA 0011-64 (modified)
Ailerons	
Total area, sq ft	37.20
Span, ft	9.18
Chord (average), ft	2.03
Horizontal tail	
Total area (including 1.20 sq ft covered by vertical tail), sq ft	34.99
Span, ft	12.75
Aspect ratio	4.65
Taper ratio	0.45
Dihedral angle, deg	10.0
Mean aerodynamic chord (horizontal-tail station 33.54 in.), ft	2.89
Sweepback of 0.25-chord line	34°35'
Airfoil section (parallel to center line)	NACA 0010-64
Maximum stabilizer deflection	1° up , 10° down
Elevator	
Area (including tabs and excluding balance area forward of hinge line), sq ft	10.13
Span, each, ft	5.77
Maximum elevator deflection	35° up, 17.5° down
Boost	Hydraulic
Horizontal-tail length, ft	18.25
Pitching moment of inertia, slug-ft^2	17,480

NACA

A-15004

Figure 1.- The unmodified airplane.

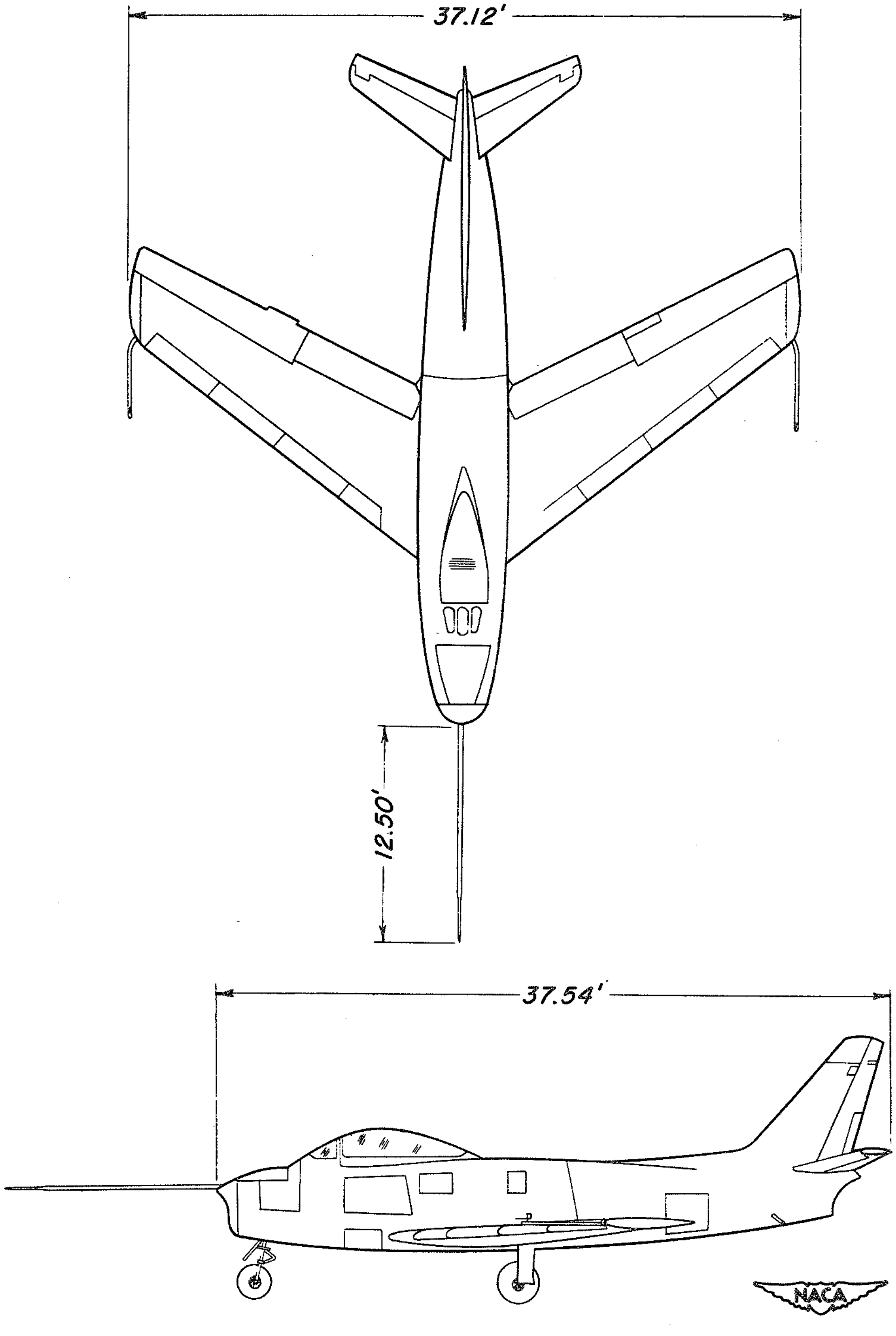

Figure 2.- Two-view drawing of the unmodified airplane.

[redacted]

A-18142

Figure 3.- Detail of blunt-trailing-edge modification on aileron.

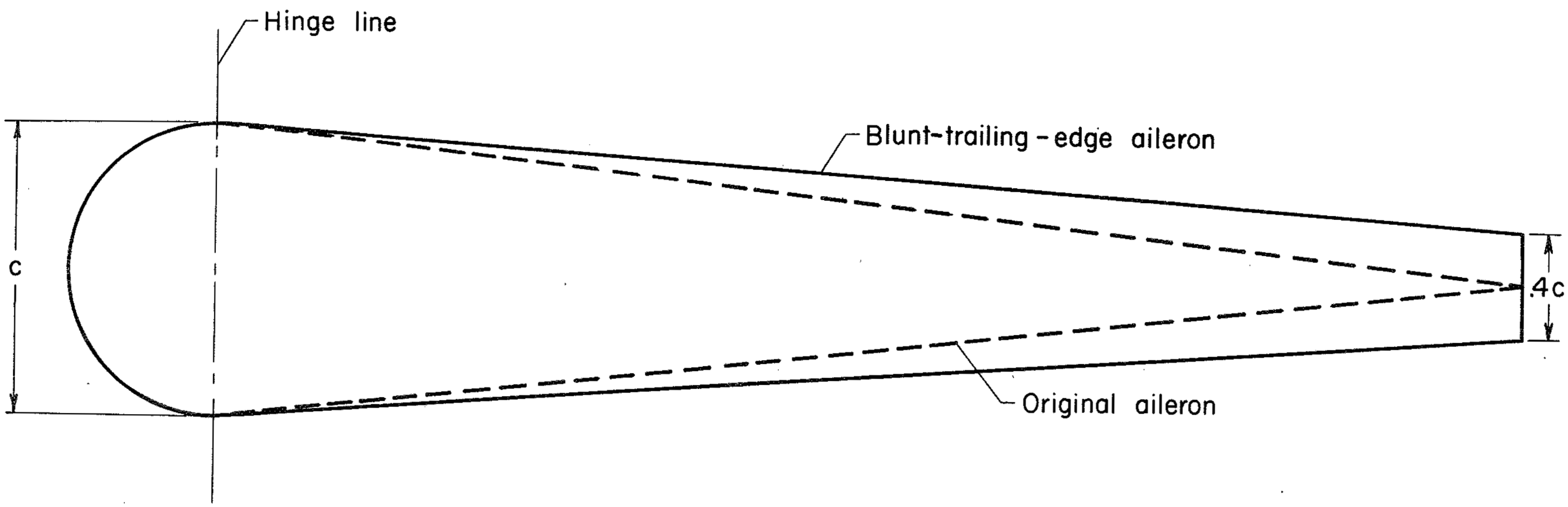

Figure 4.- Sketch of blunt-trailing-edge modification on aileron.

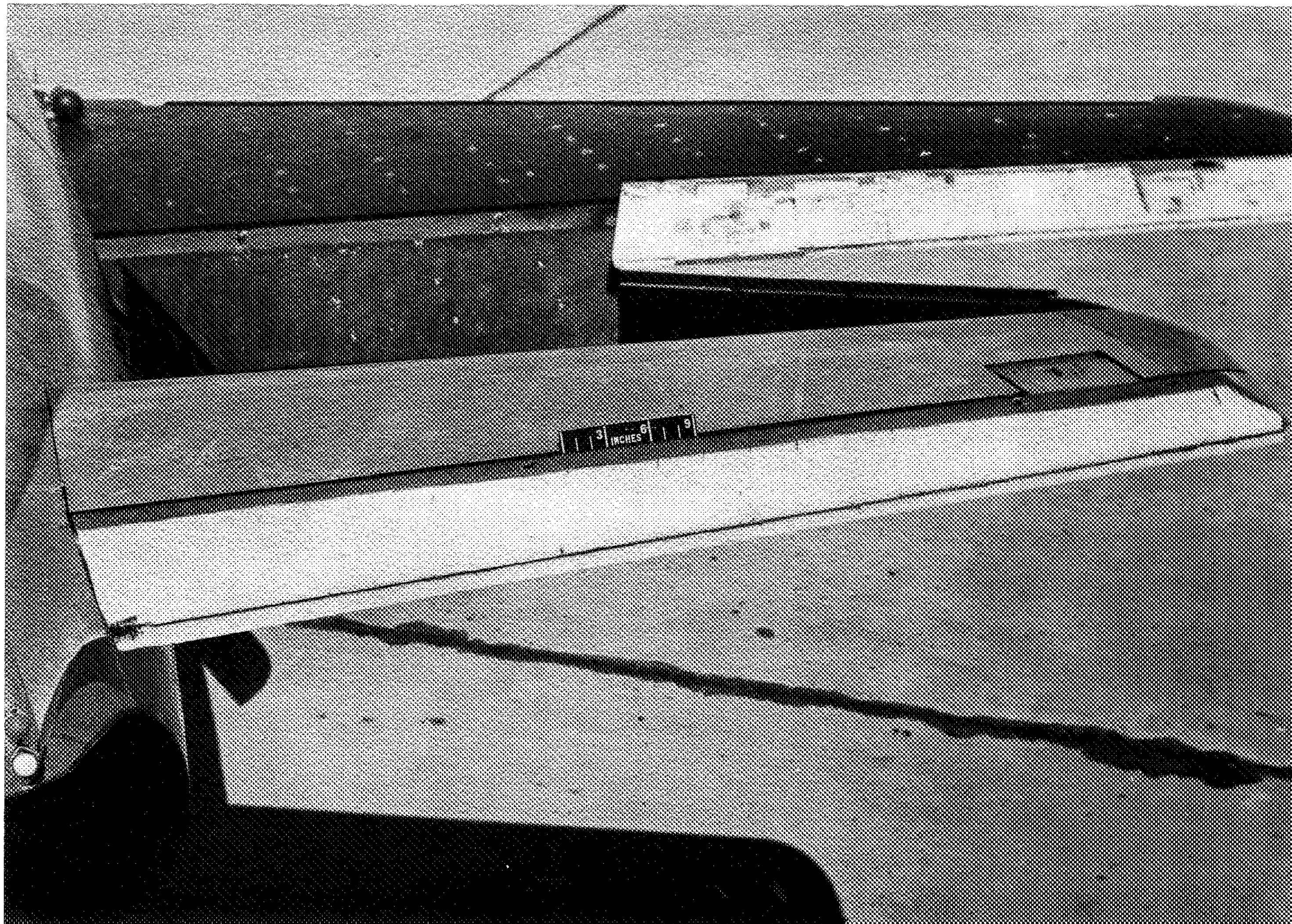

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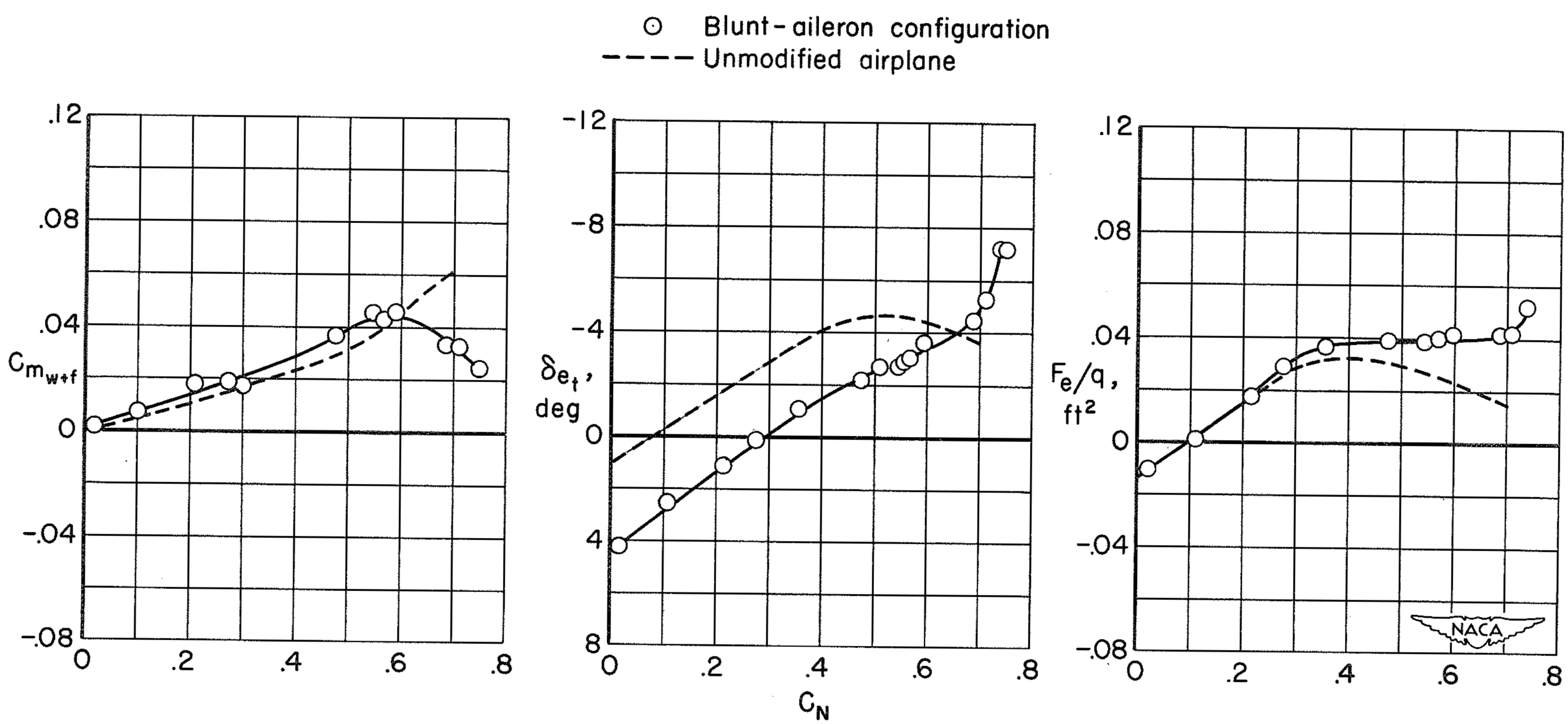
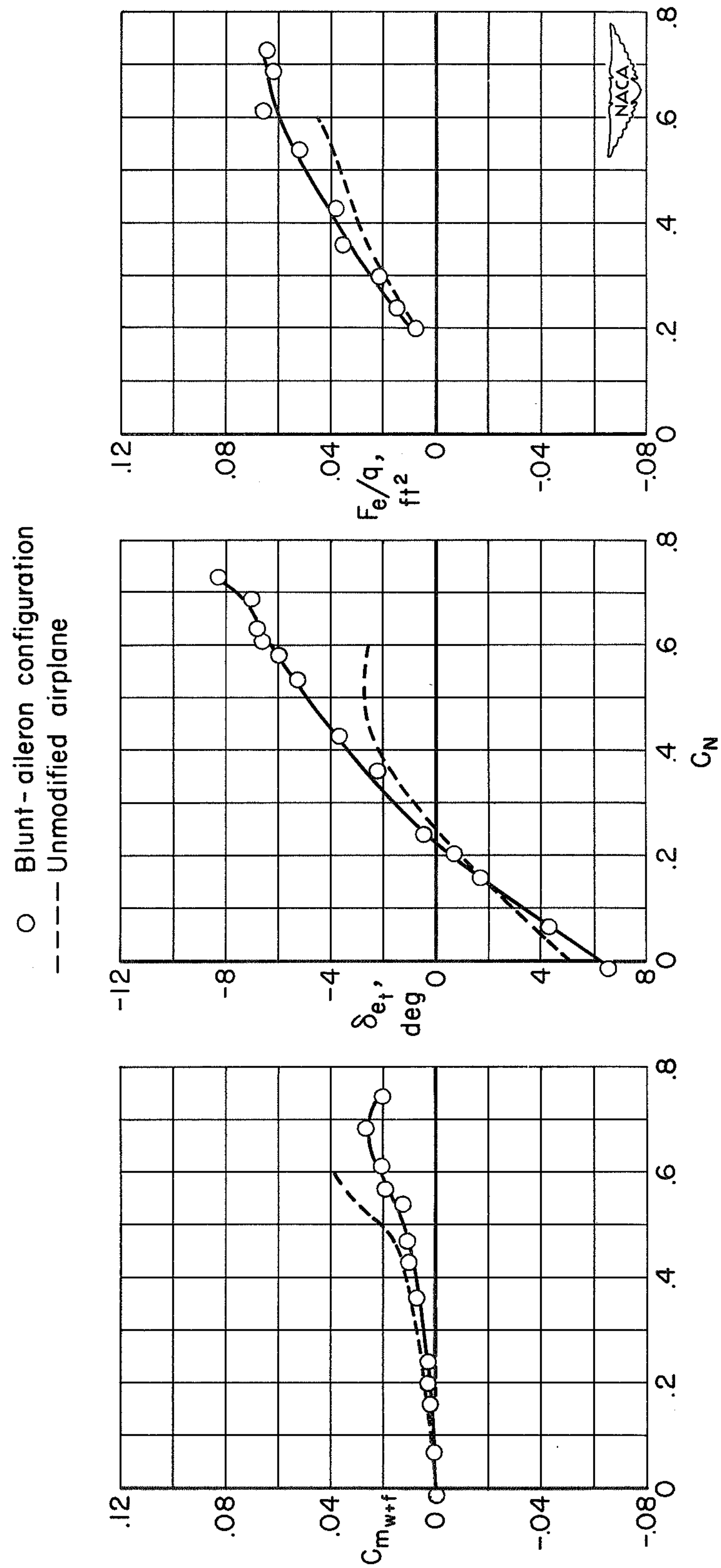
Figure 5.- Detail of blunt-trailing-edge-elevator modification.



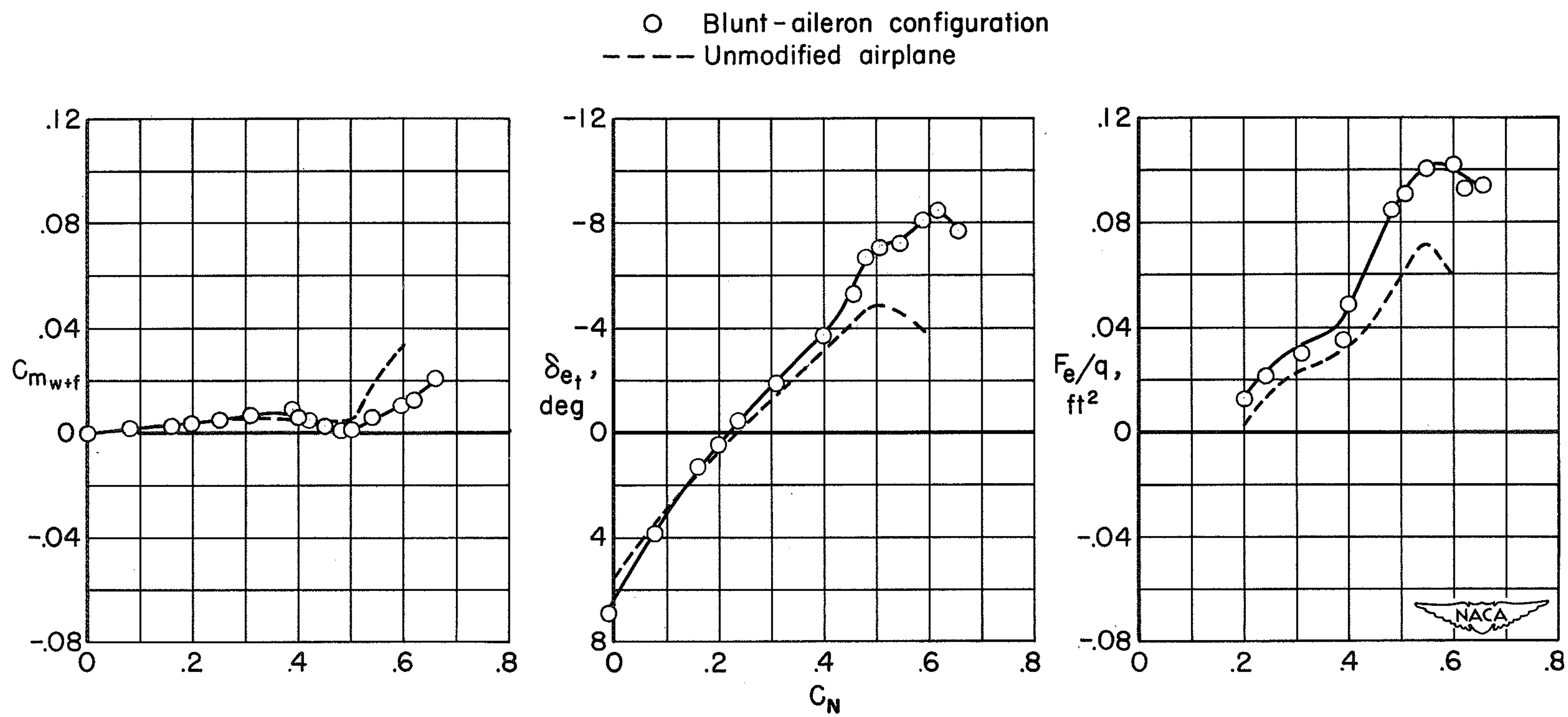
(a) M = 0.70

Figure 6.- Variation of wing-fuselage pitching-moment coefficient, trim elevator angle, and stick-force factor with airplane normal-force coefficient at several Mach numbers for the blunt-aileron configuration.



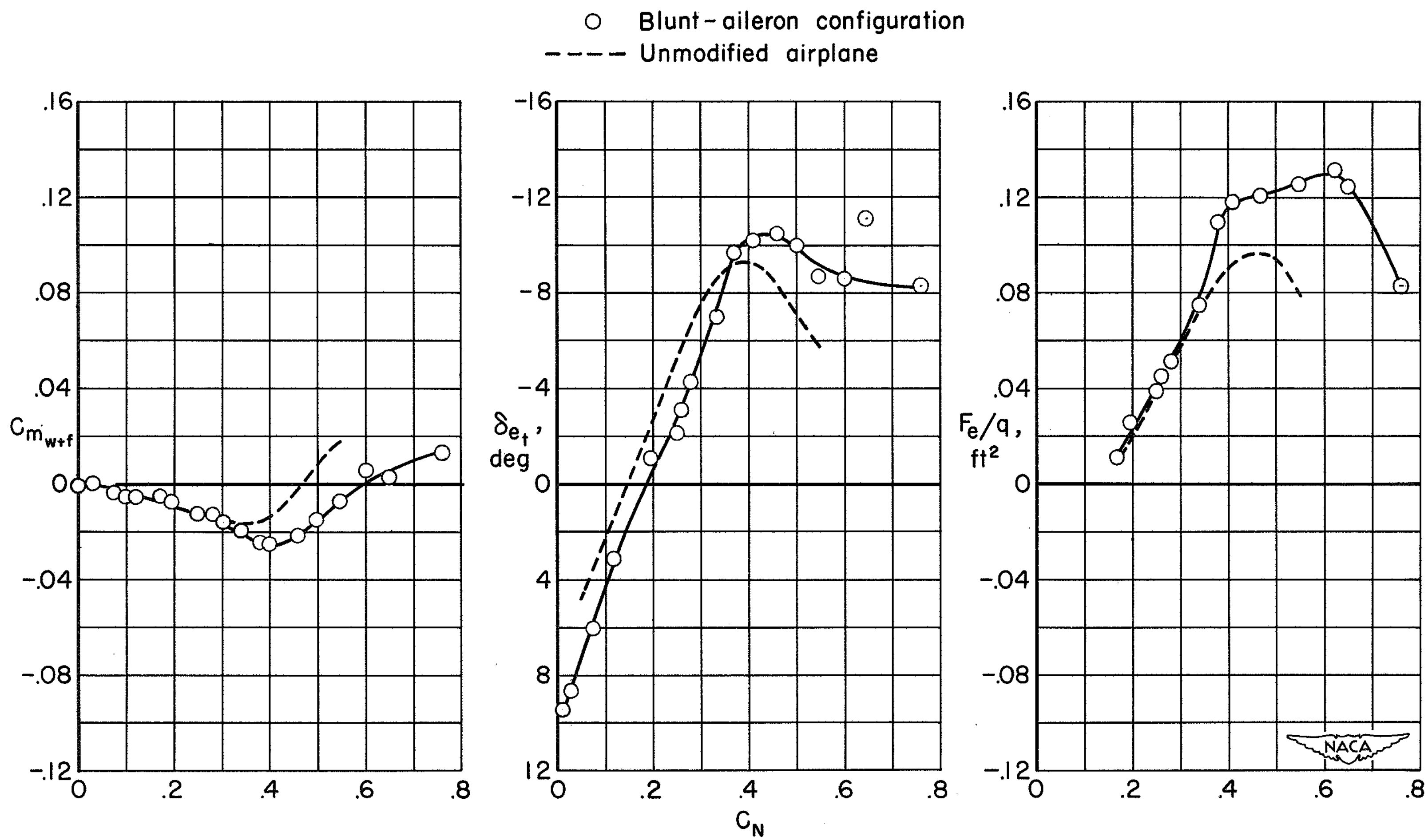
(b) M = 0.82

Figure 6.- Continued.



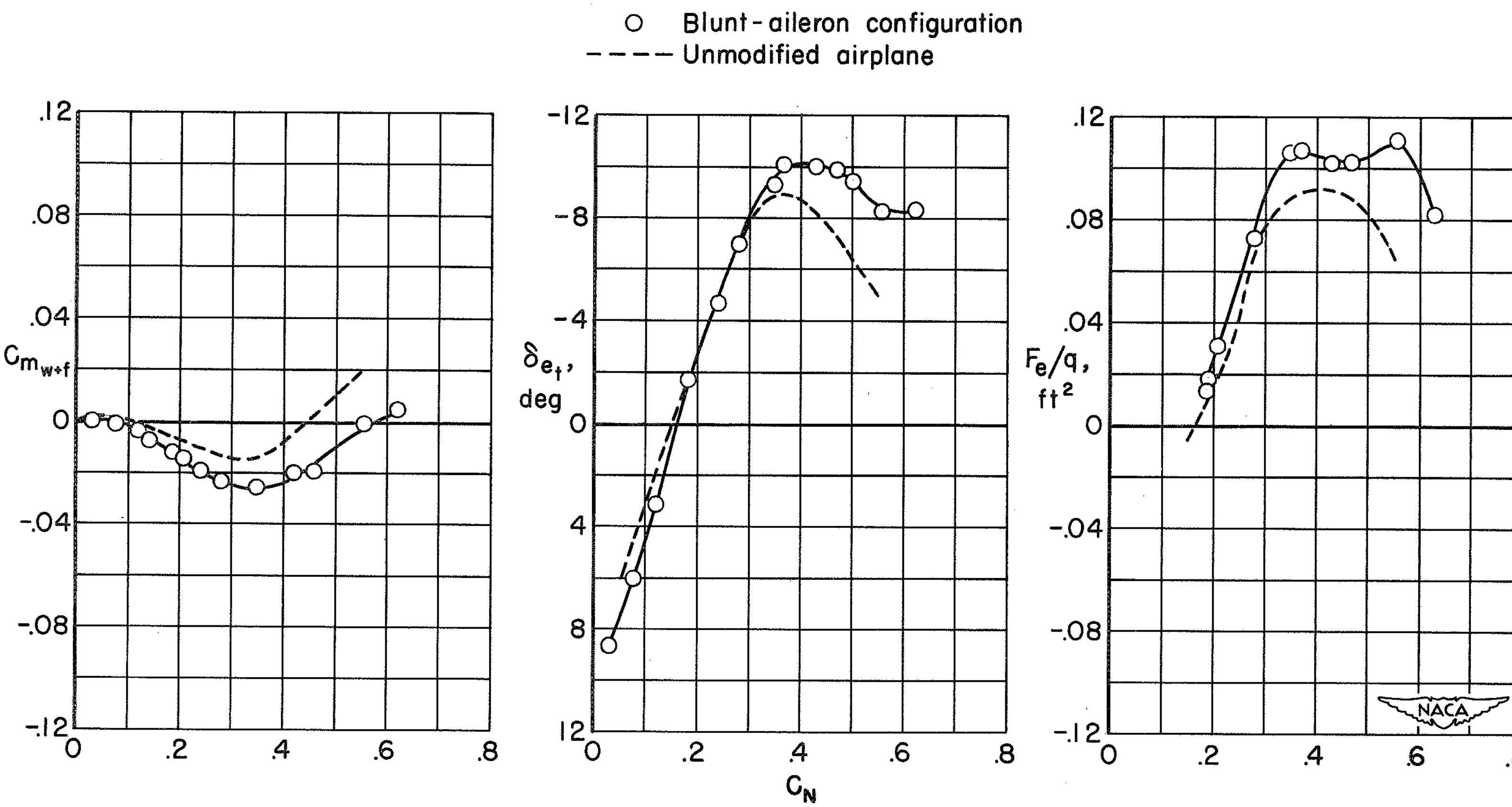
(c) M = 0.85

Figure 6.- Continued.



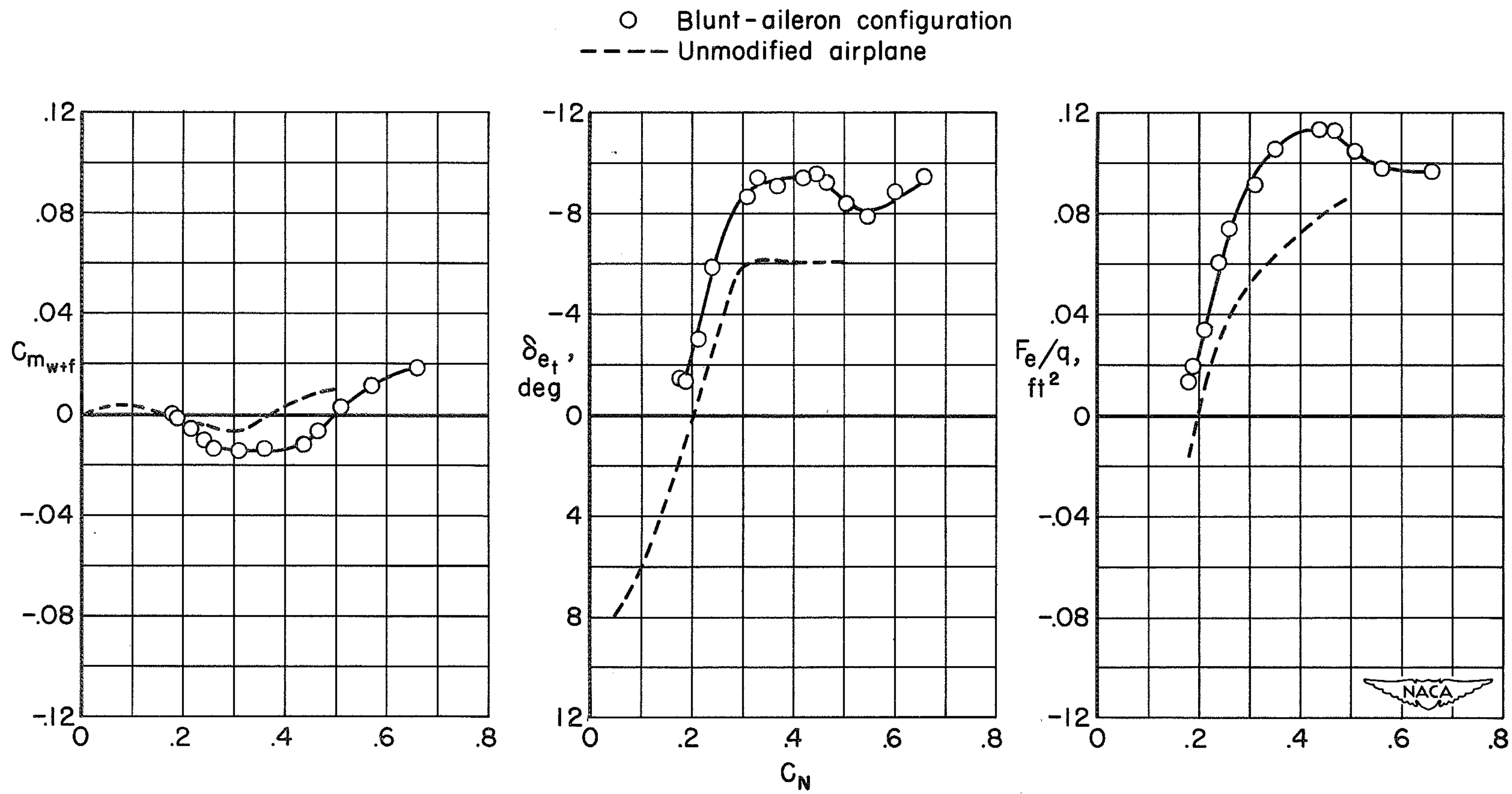
(d) M = 0.90

Figure 6.- Continued.



(e) M = 0.91

Figure 6.- Continued.



(f) M = 0.93

Figure 6.- Concluded.

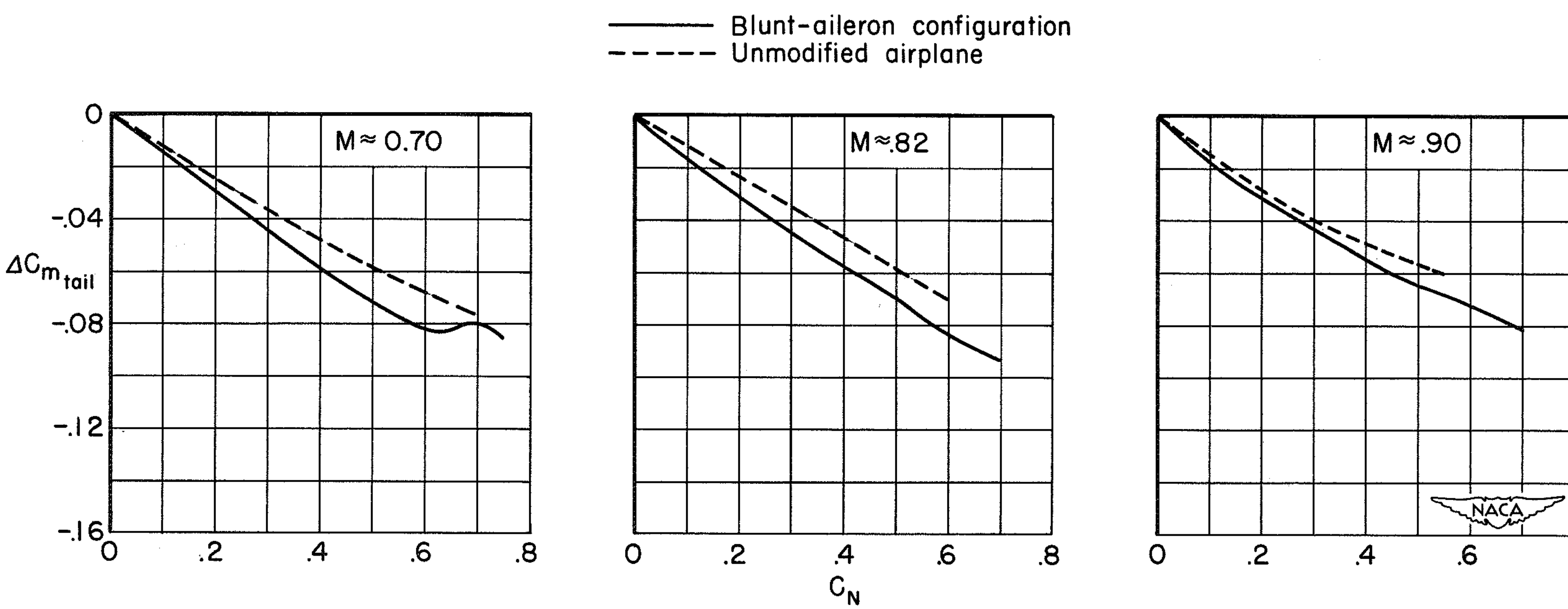
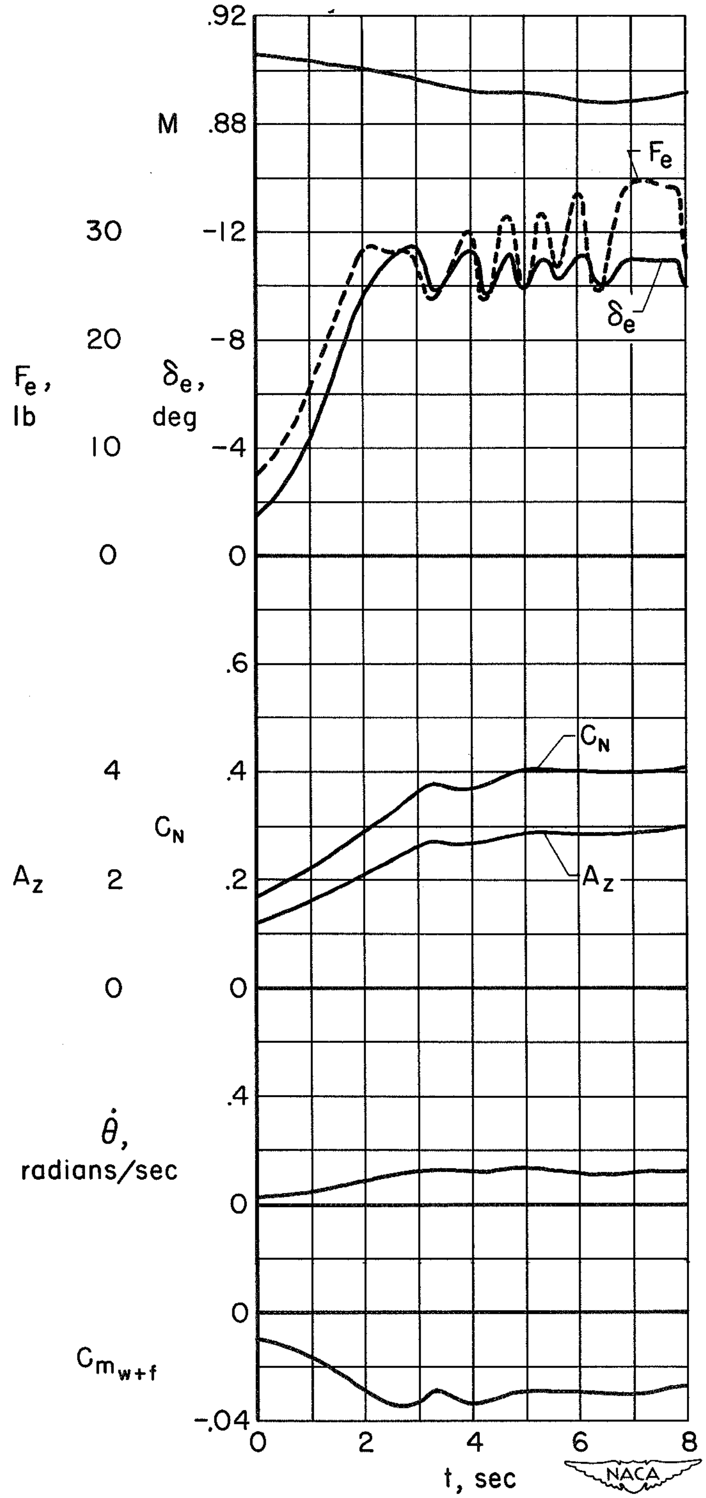


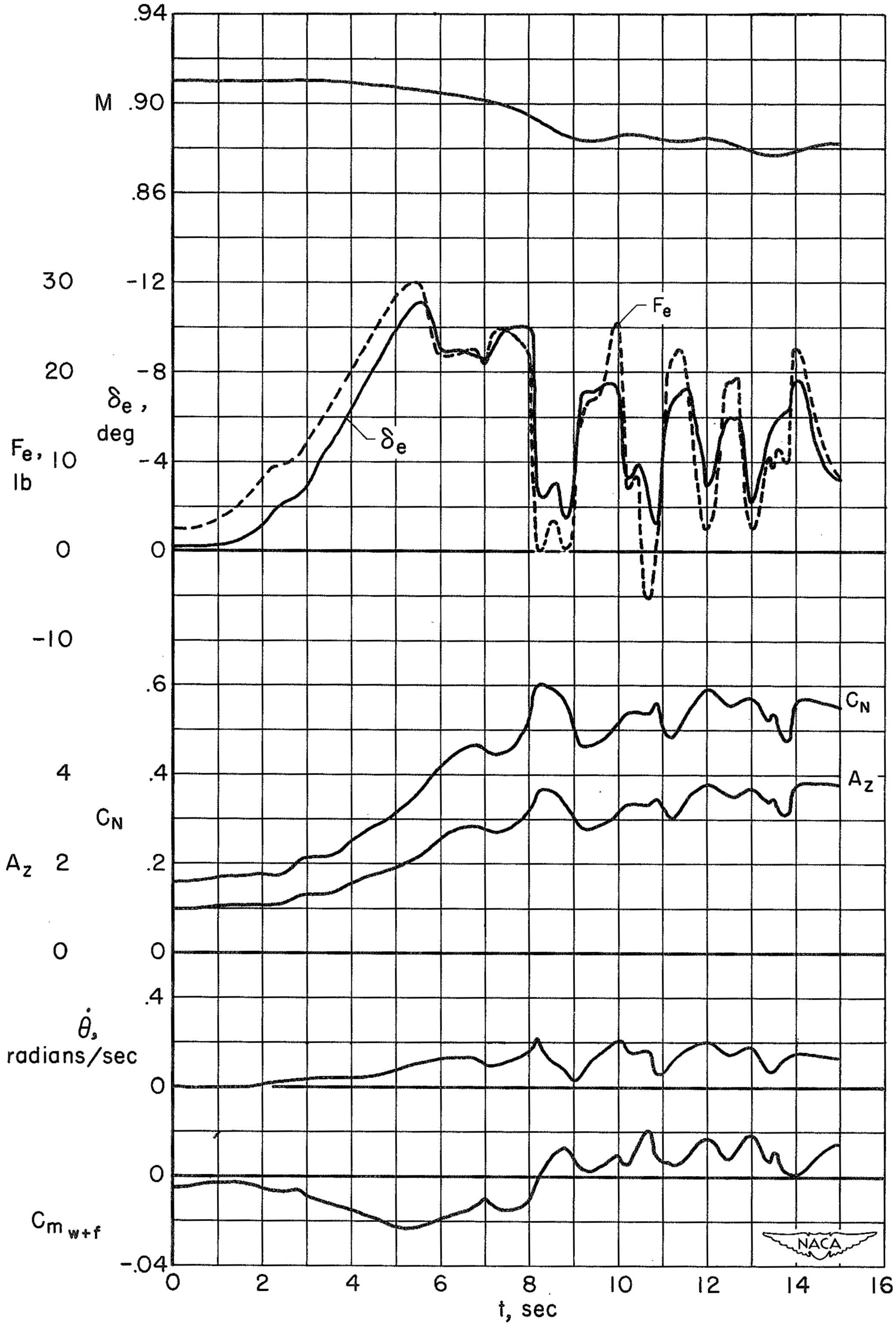
Figure 7.- Comparison of incremental horizontal-tail pitching-moment coefficients estimated from data in figure 6.



(a) Just below pitch-up.

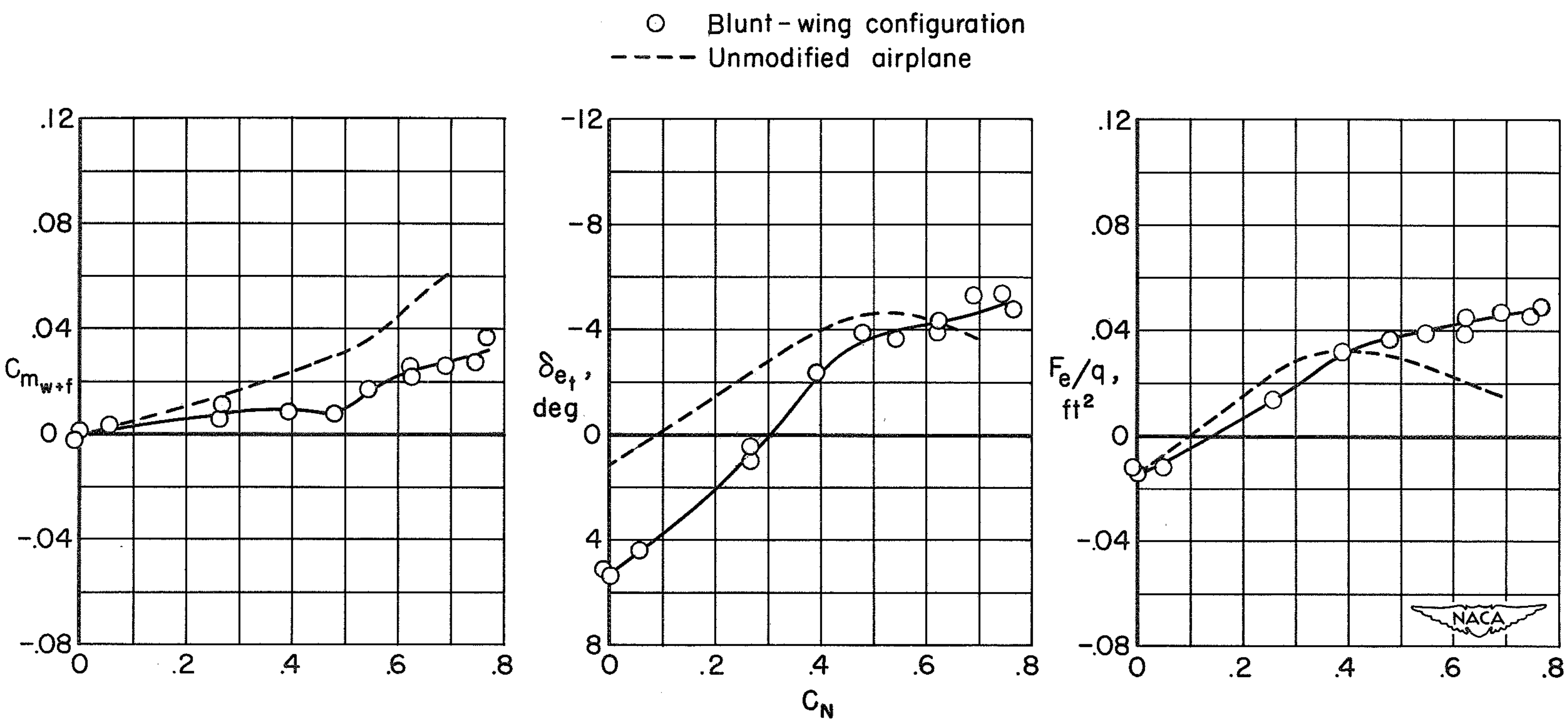
Figure 8.- Time histories of pilot-attempted, constant, normal-acceleration-factor turns just below and just above the pitch-up at a Mach number of about 0.90 for the blunt-aileron configuration.

[redacted]



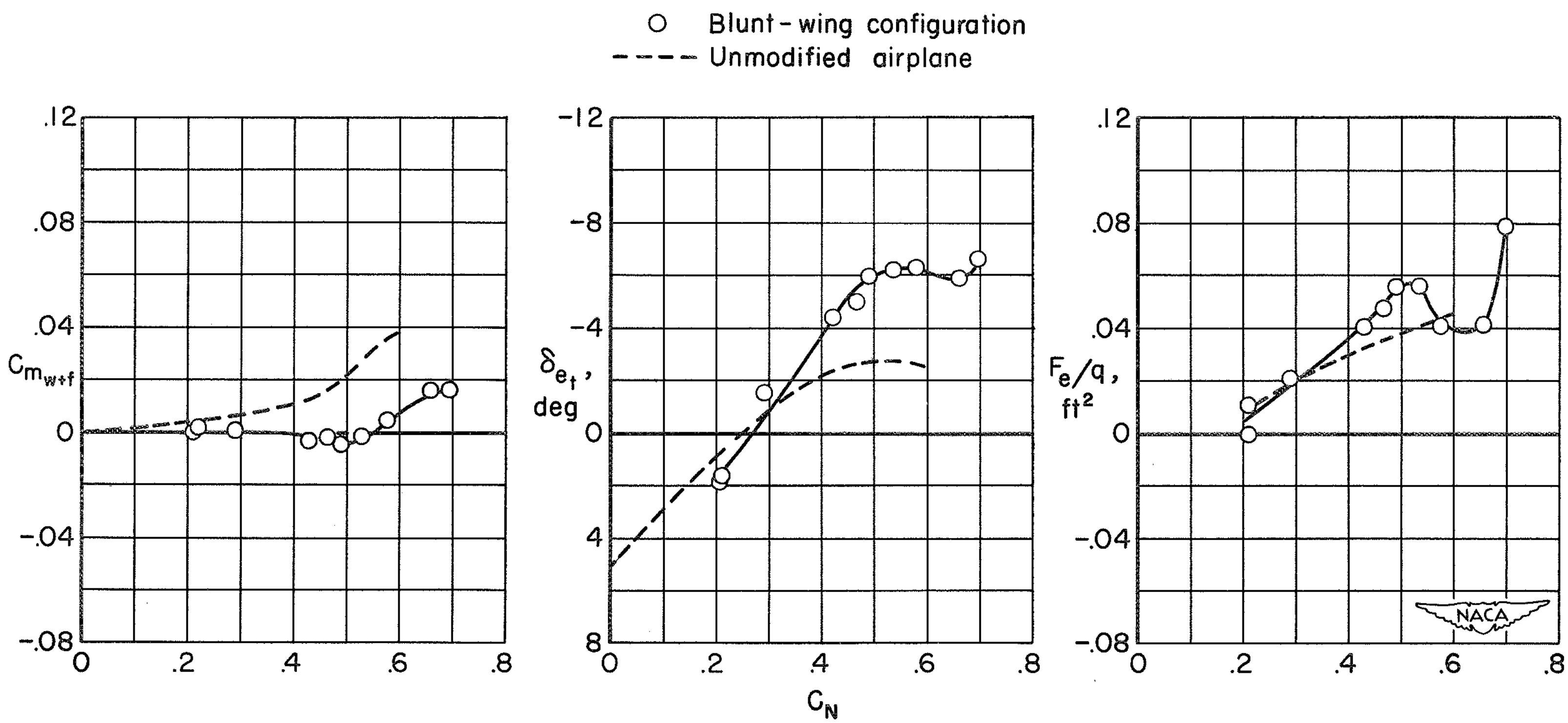
(b) Just above pitch-up.

Figure 8.- Concluded.



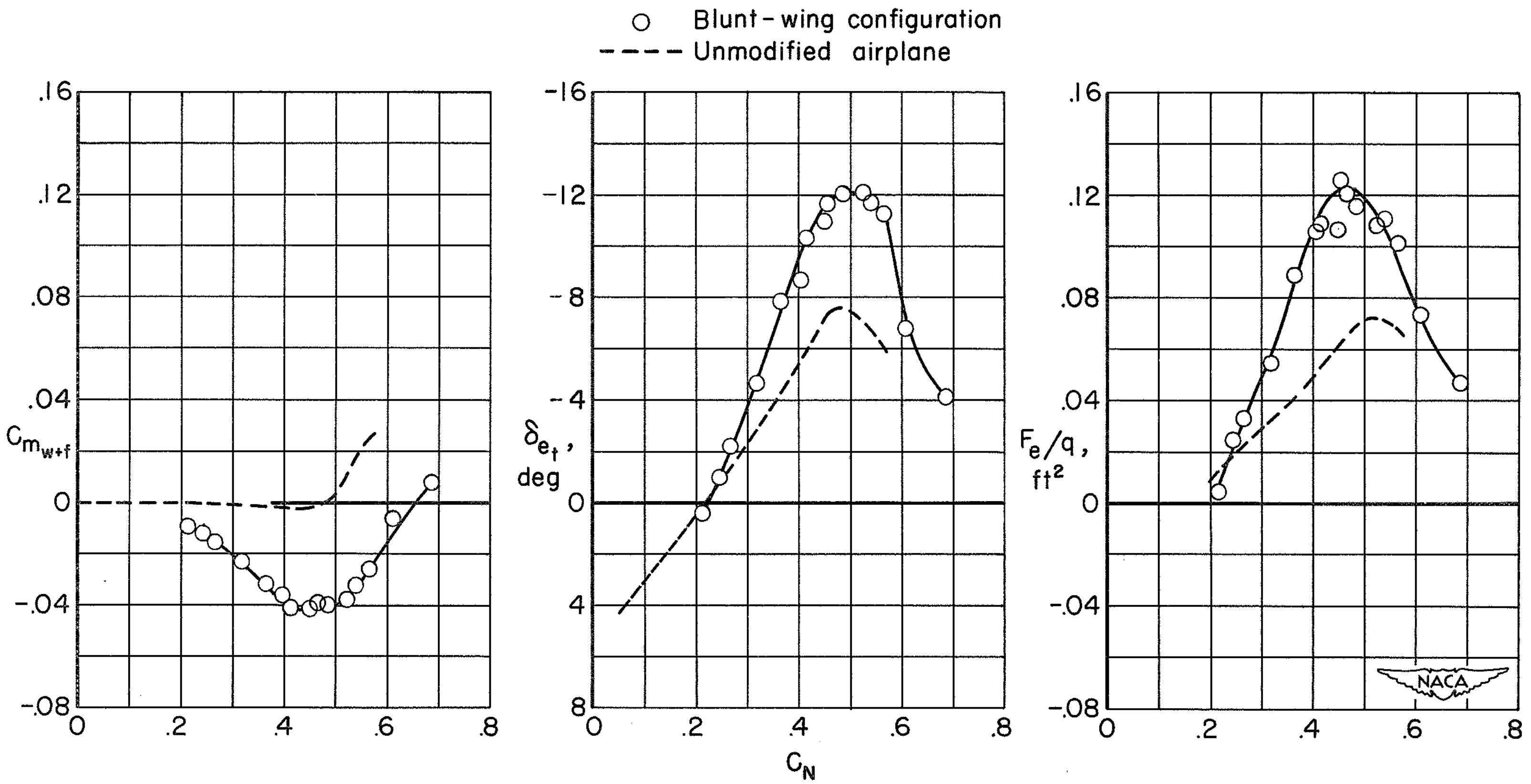
(a) M = 0.70

Figure 9.- Variation of wing-fuselage pitching-moment coefficient, trim elevator angle, and stick-force factor with airplane normal-force coefficient at several values of Mach number for the blunt-wing configuration.



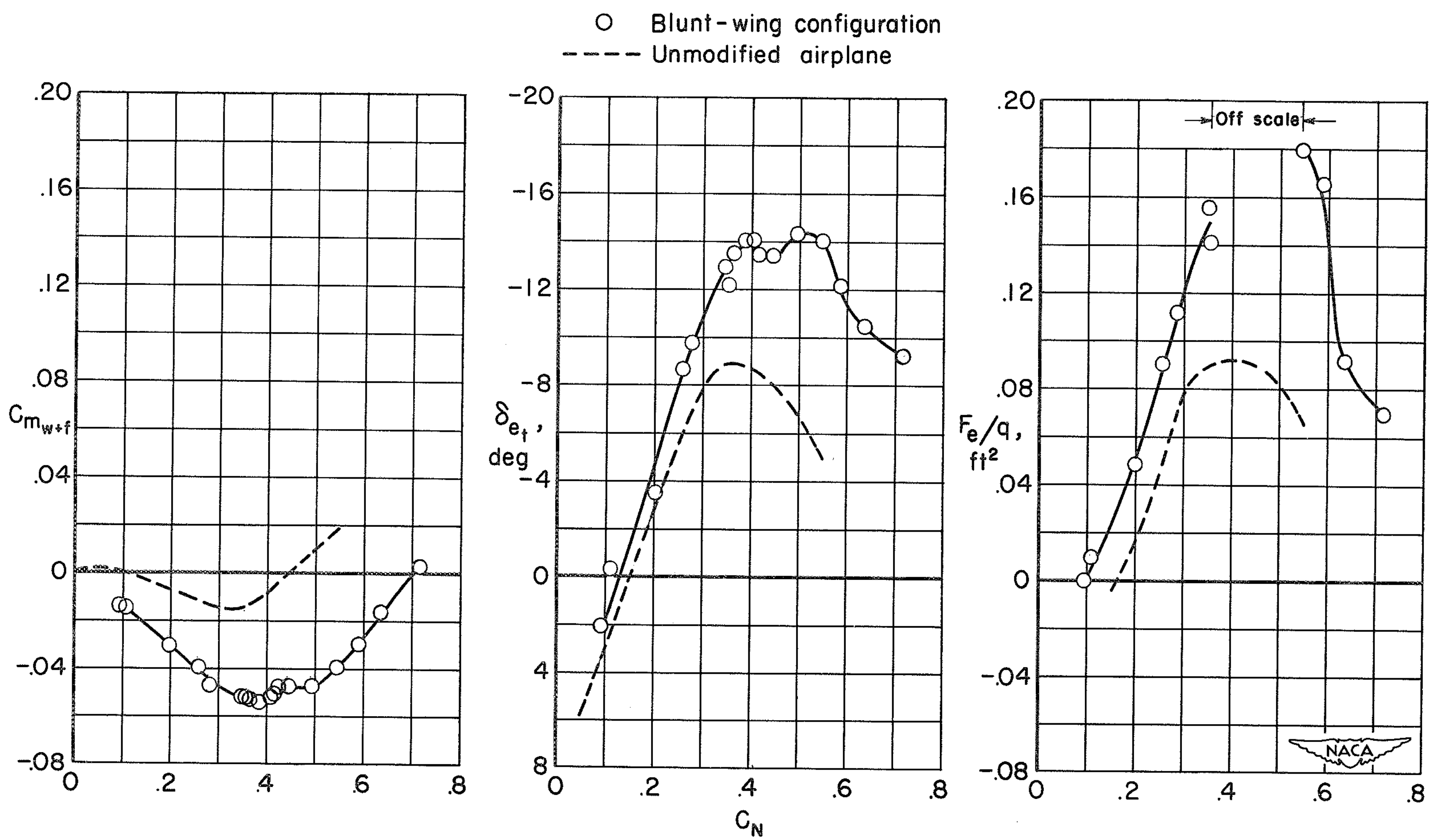
(b) M = 0.82

Figure 9.- Continued.



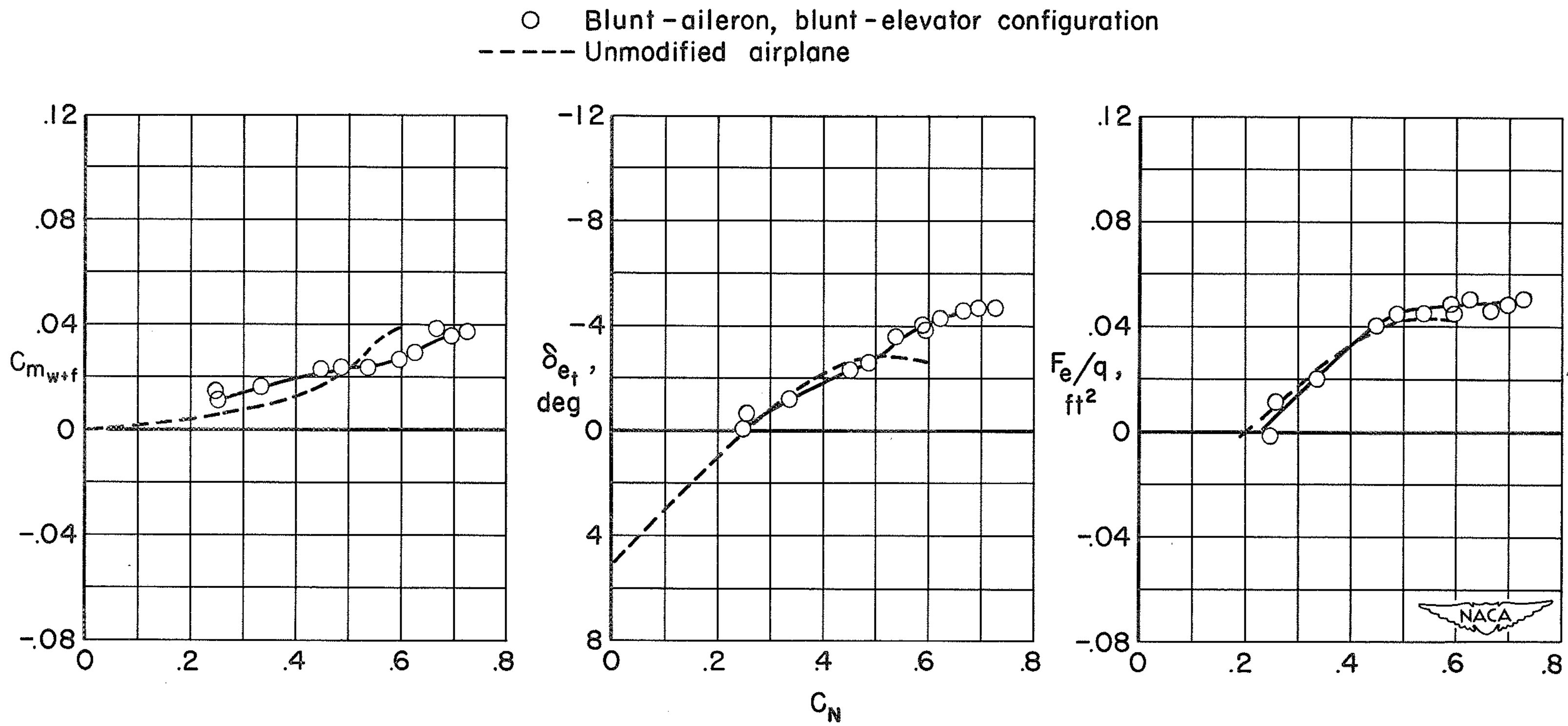
(c) M = 0.86

Figure 9.- Continued.



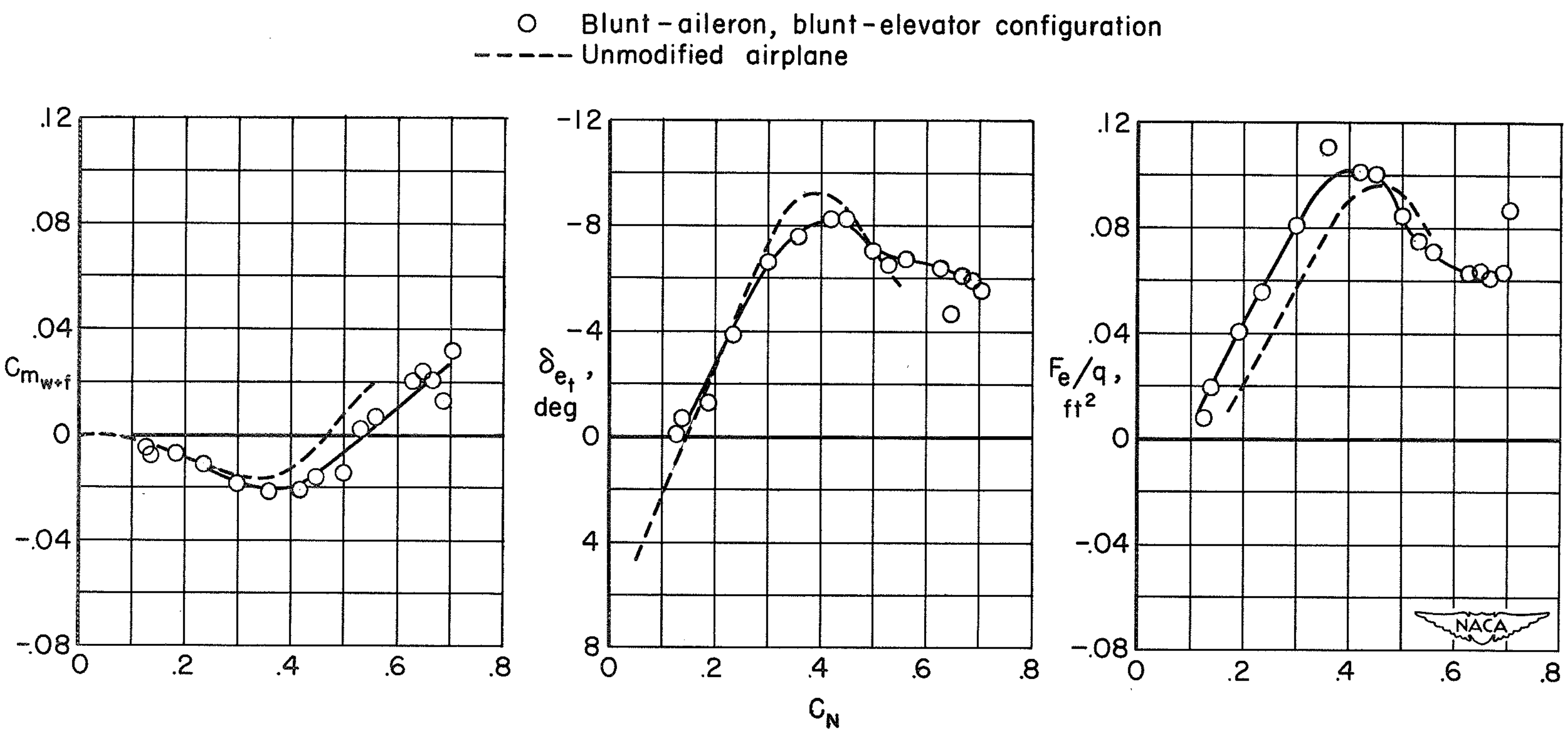
(d) M = 0.91

Figure 9.- Concluded.



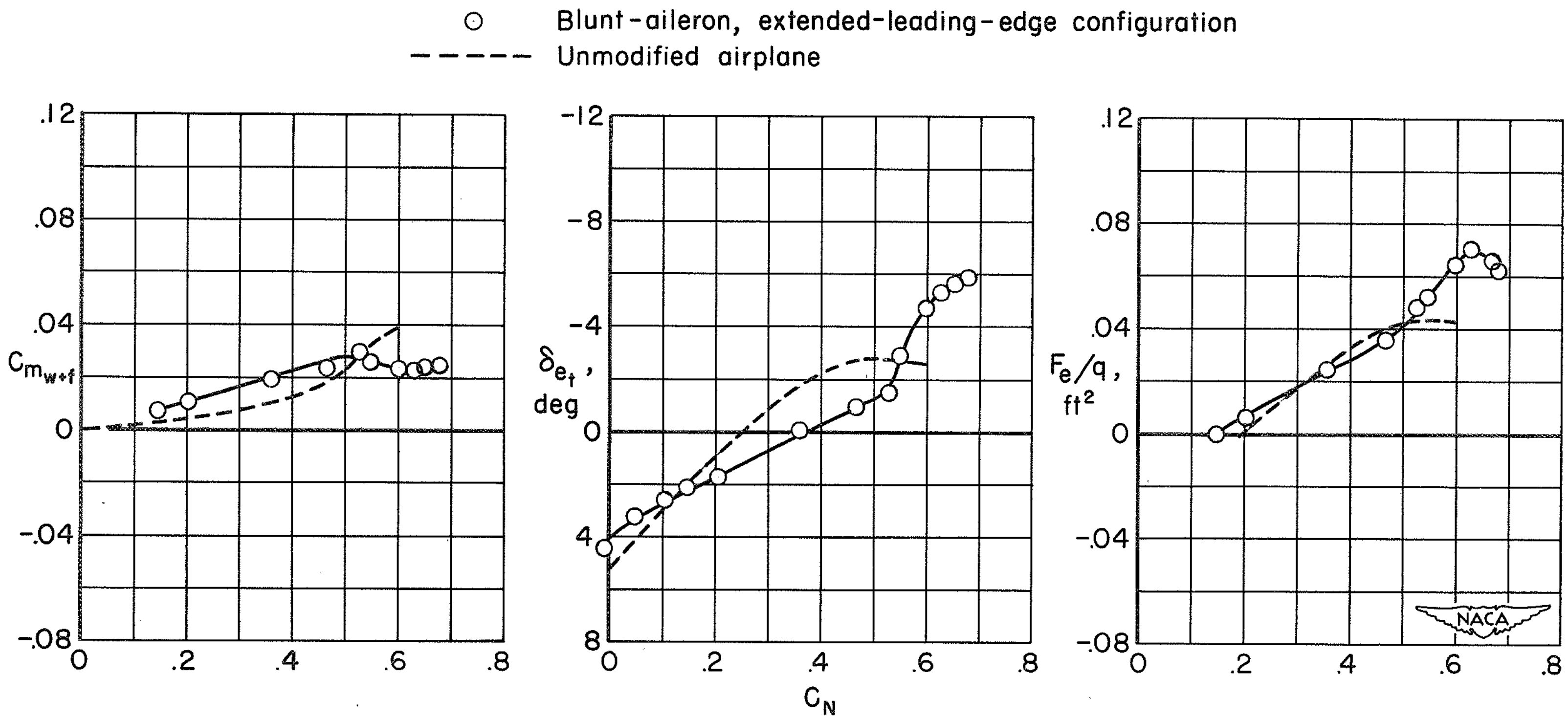
(a) M = 0.78

Figure 10.- Variation of wing-fuselage pitching-moment coefficient, trim elevator angle, and stick-force factor with airplane normal-force coefficient at several Mach numbers for the blunt-aileron, blunt-elevator configuration.



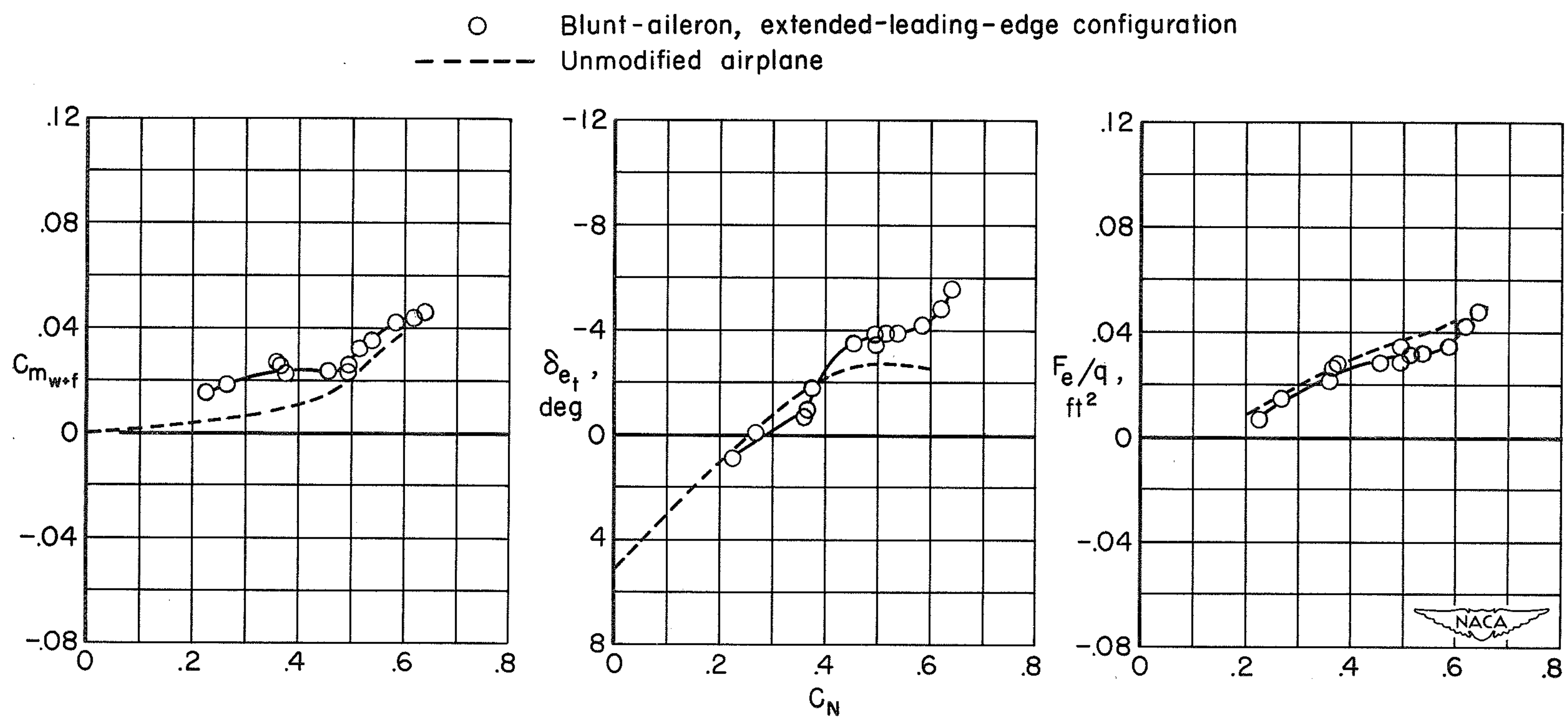
(b) M = 0.90

Figure 10.- Concluded.



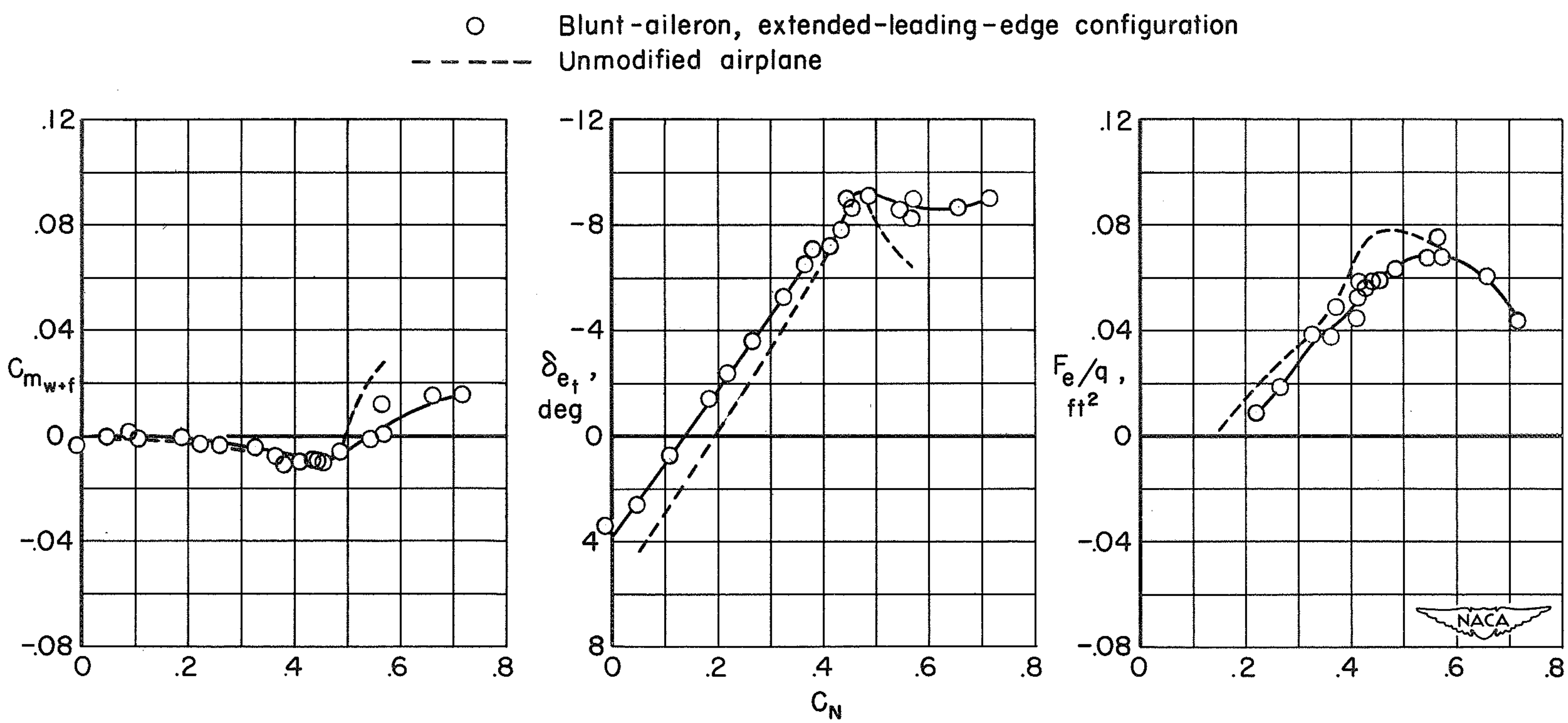
(a) M = 0.78

Figure 11.- Variation of wing-fuselage pitching-moment coefficient, trim elevator angle, and stick-force factor with airplane normal-force coefficient at several Mach numbers for the blunt-aileron, extended-leading-edge configuration.



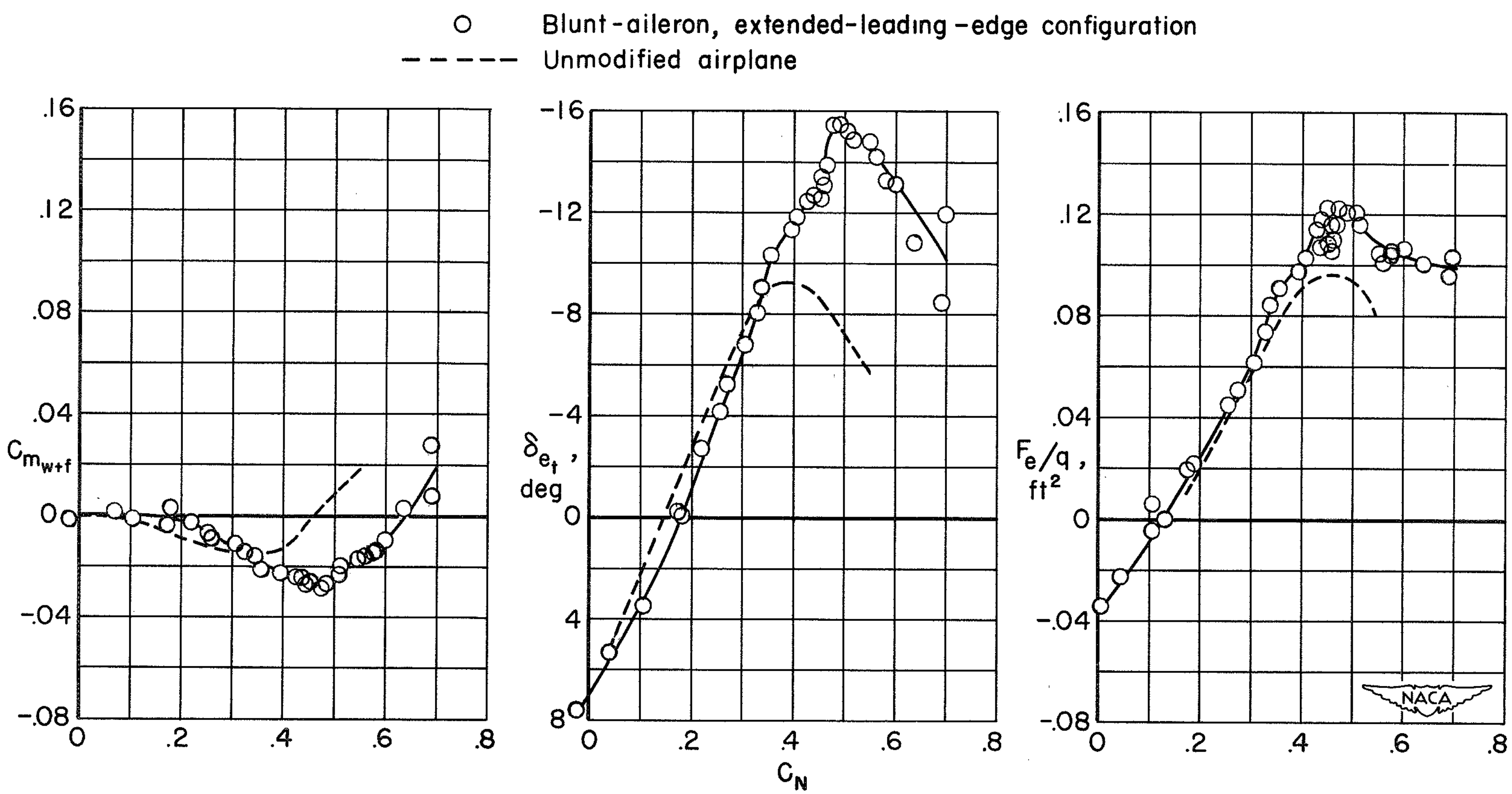
(b) M = 0.82

Figure 11.- Continued.



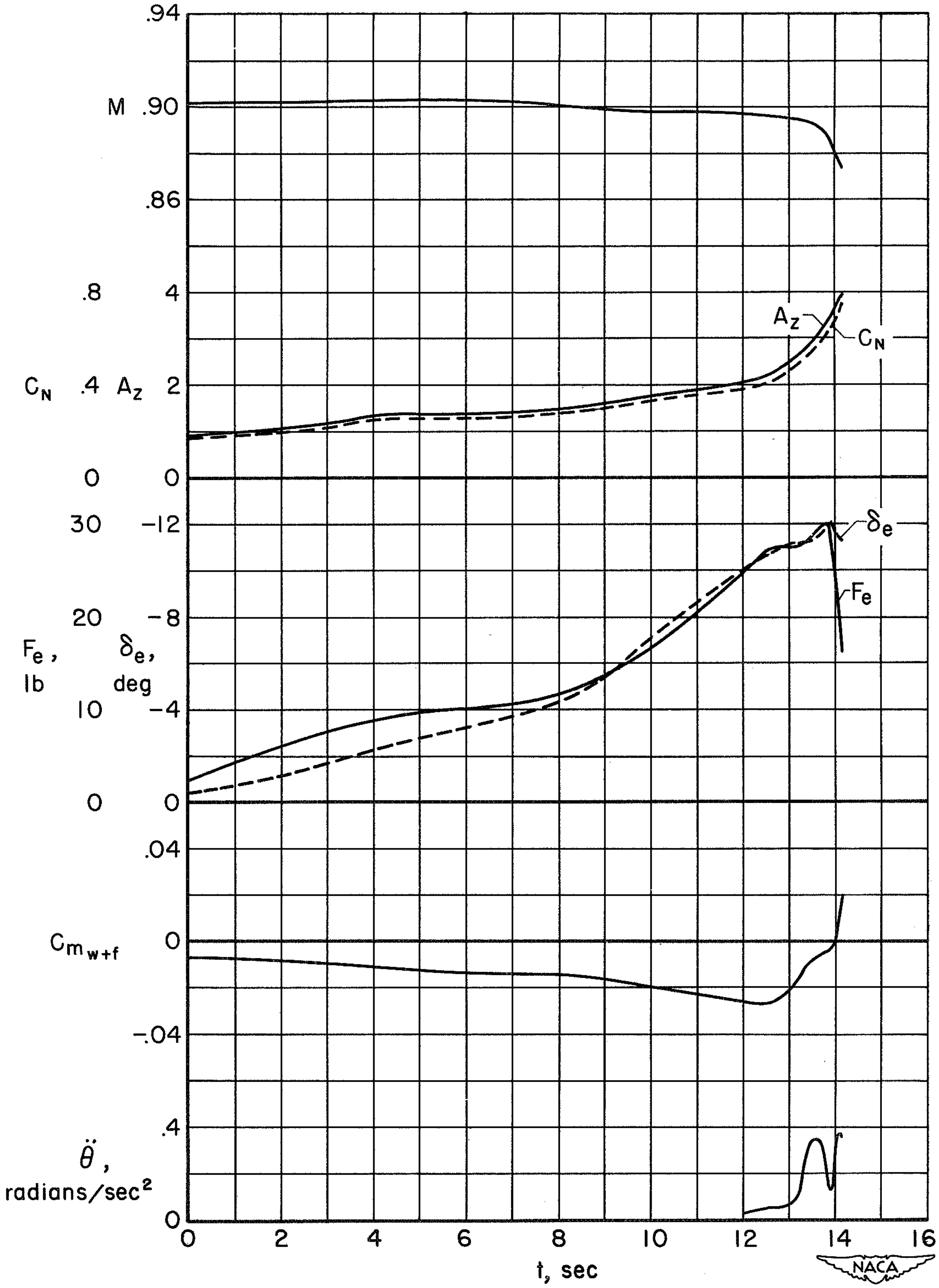
(c) M = 0.87

Figure 11.- Continued.



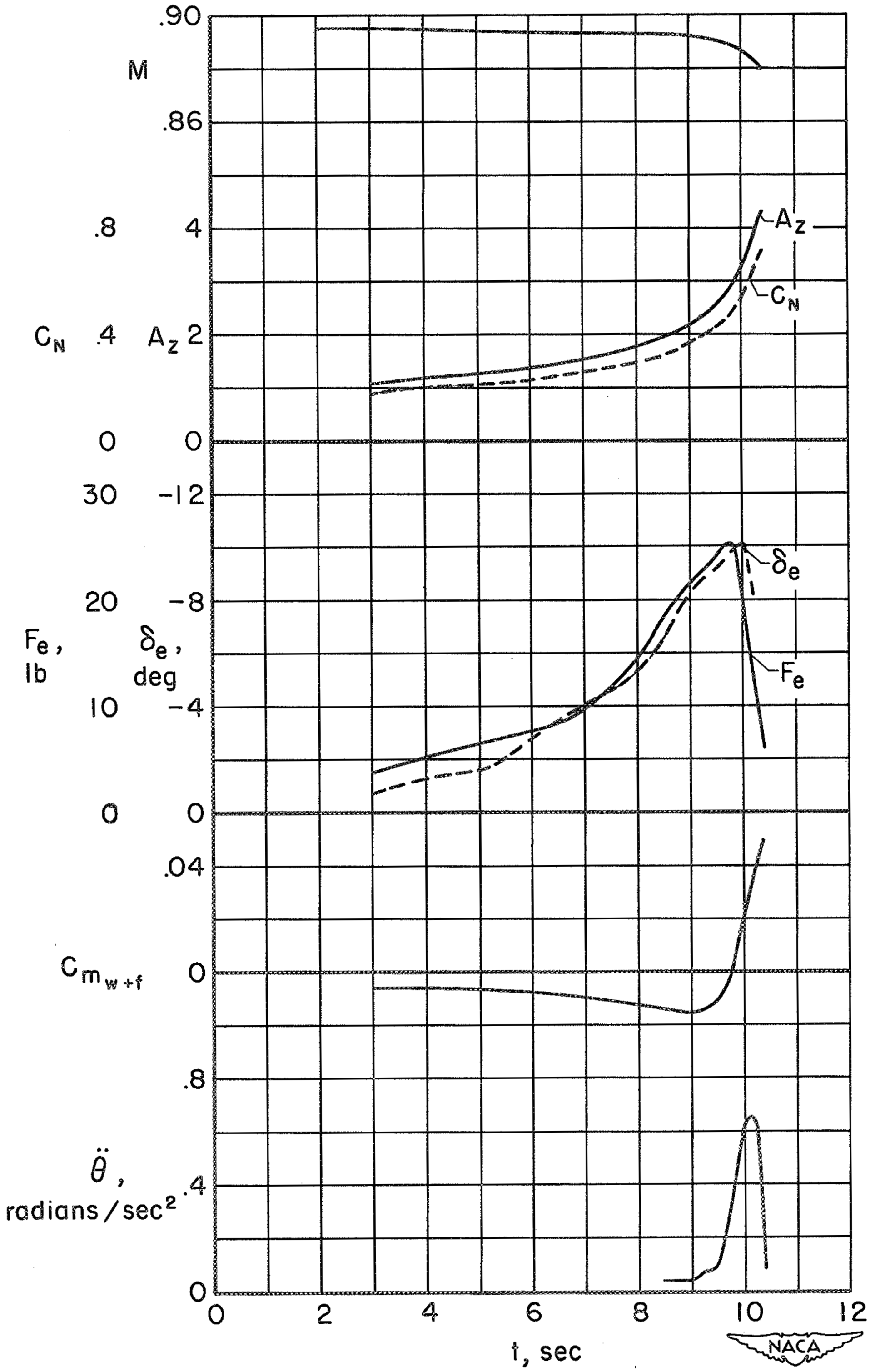
(d) M = 0.90

Figure 11.- Concluded.



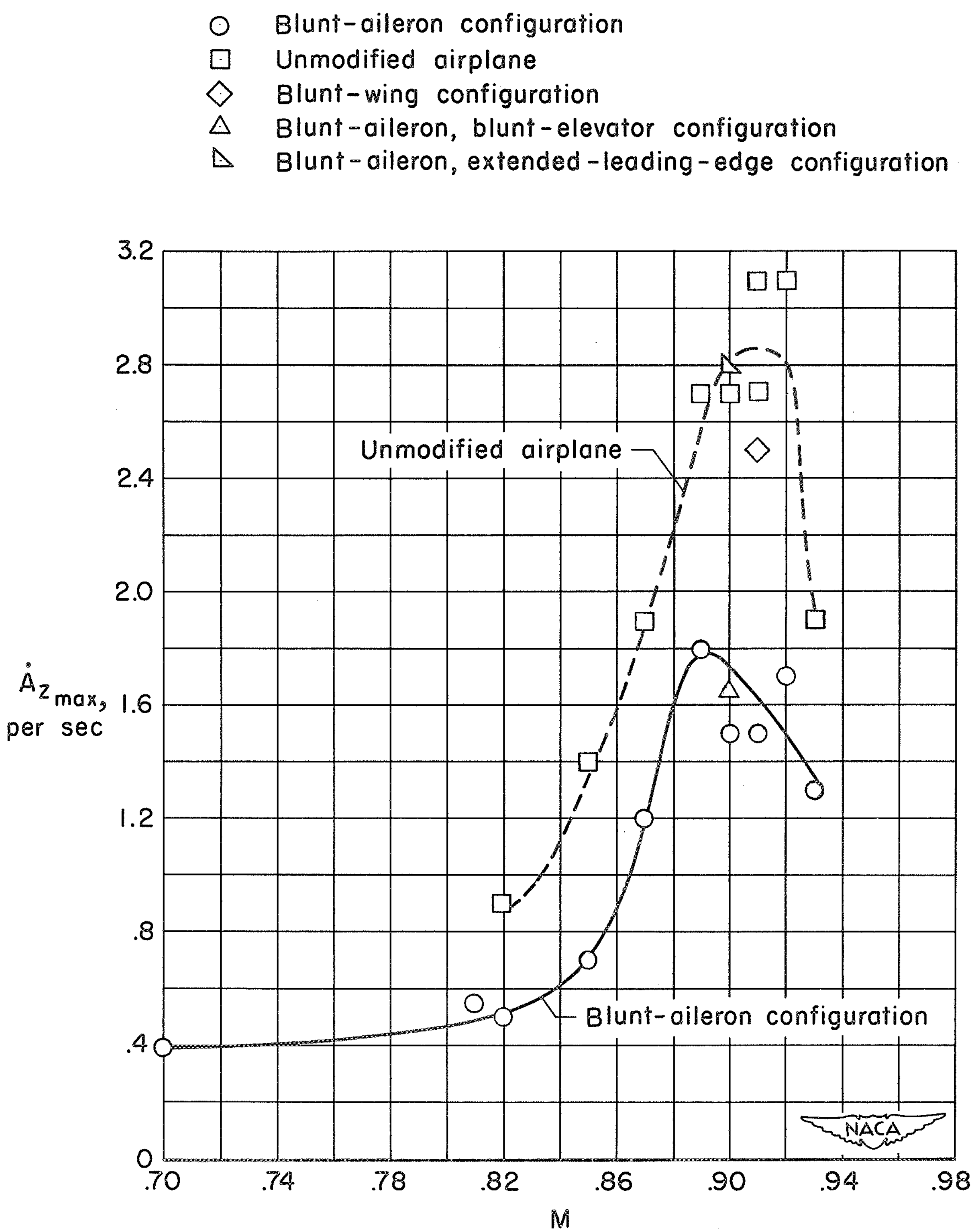
(a) Blunt-aileron configuration.

Figure 12.- Comparative time histories of wind-up turns to the pitch-up for the blunt-aileron configuration and for the unmodified airplane at a Mach number of 0.90.



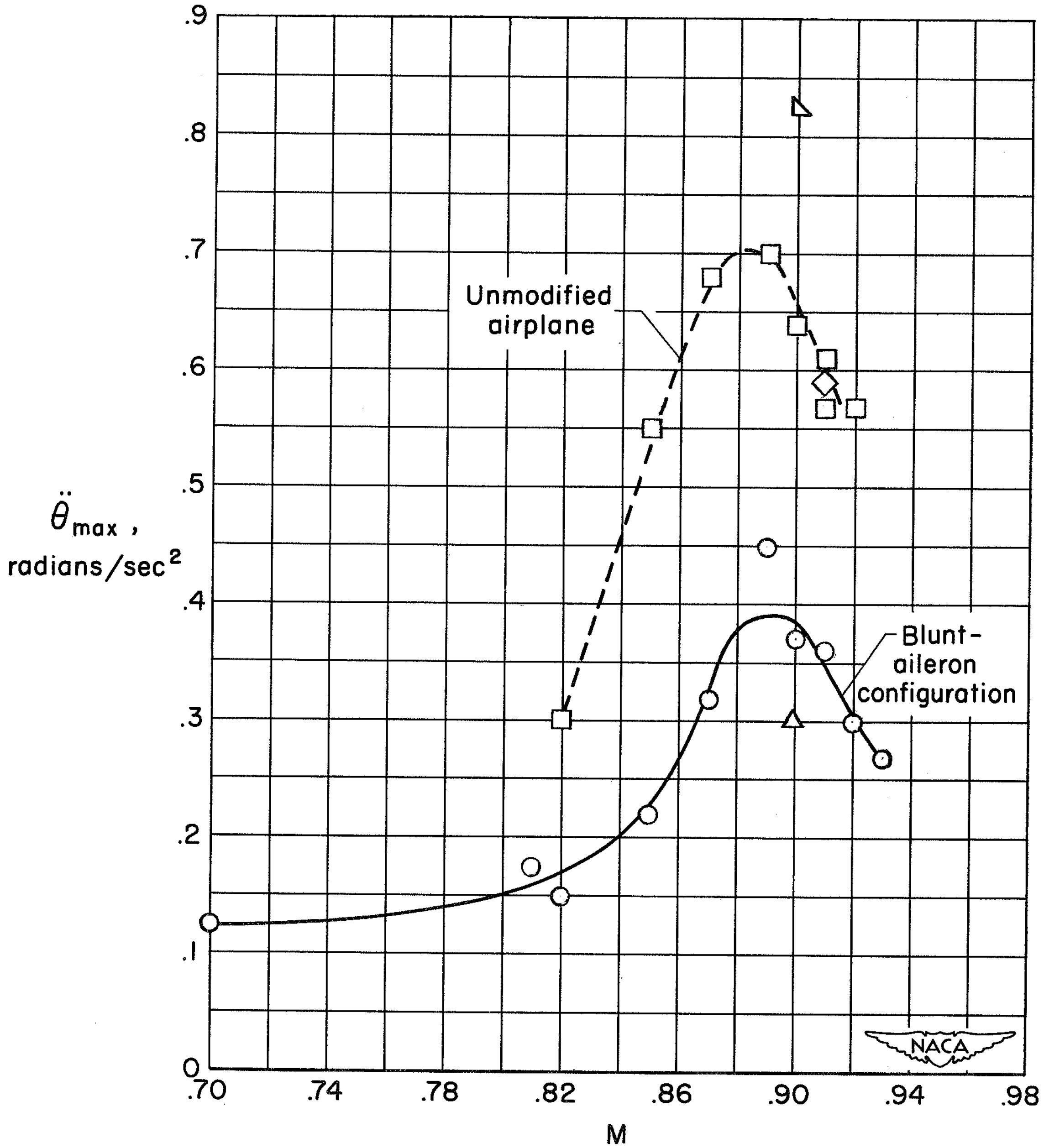
(b) Unmodified airplane.

Figure 12.- Concluded.



(a) Normal-acceleration rate.

Figure 13.- Variation with Mach number of the maximum rate of change of normal-acceleration factor and pitching velocity during pitch up.



(b) Pitching-velocity rate.

Figure 13.- Concluded.

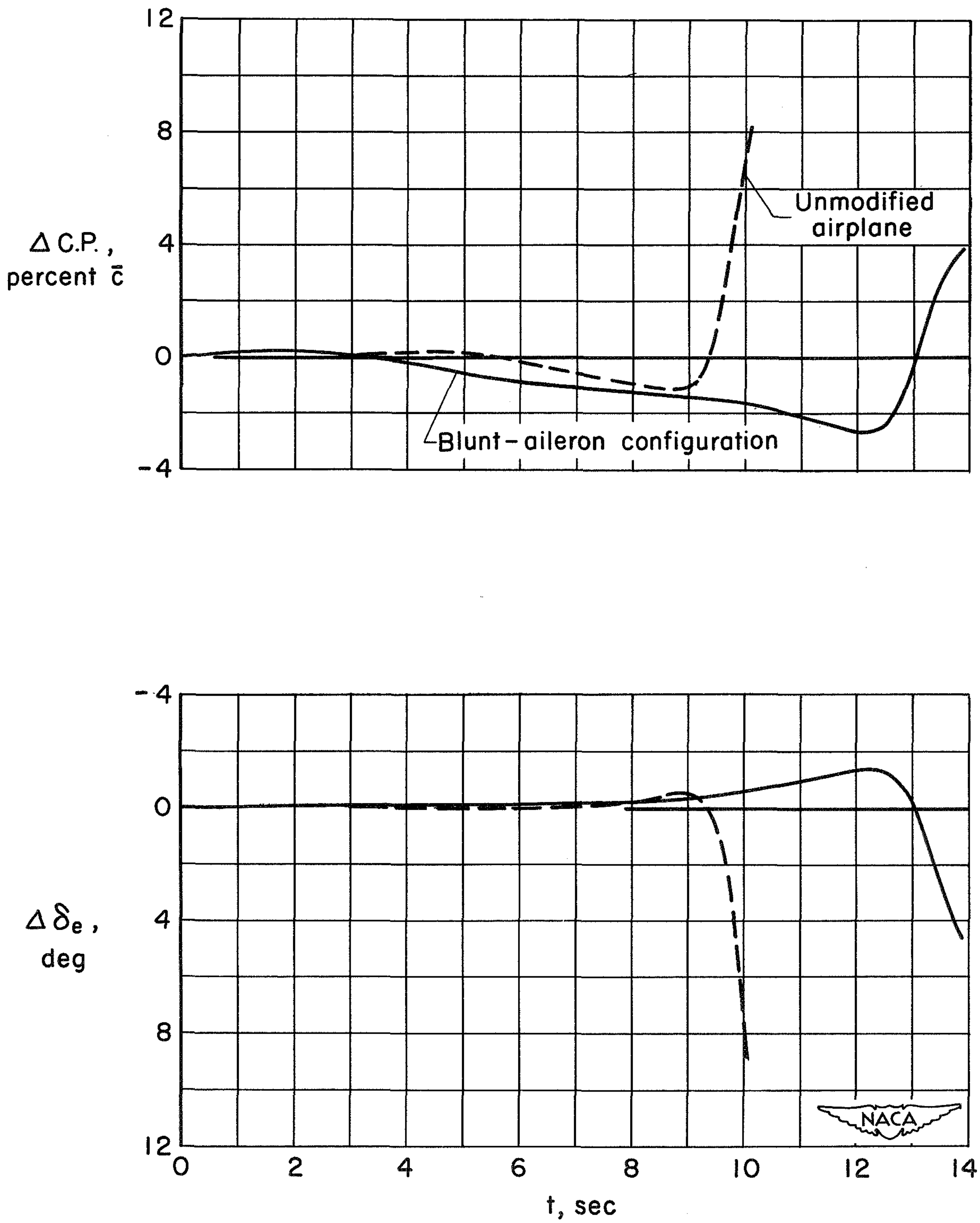


Figure 14.- Comparative time histories of incremental wing-fuselage centers of pressure of additional loading and of the incremental elevator angles required for balance at a Mach number of 0.90.

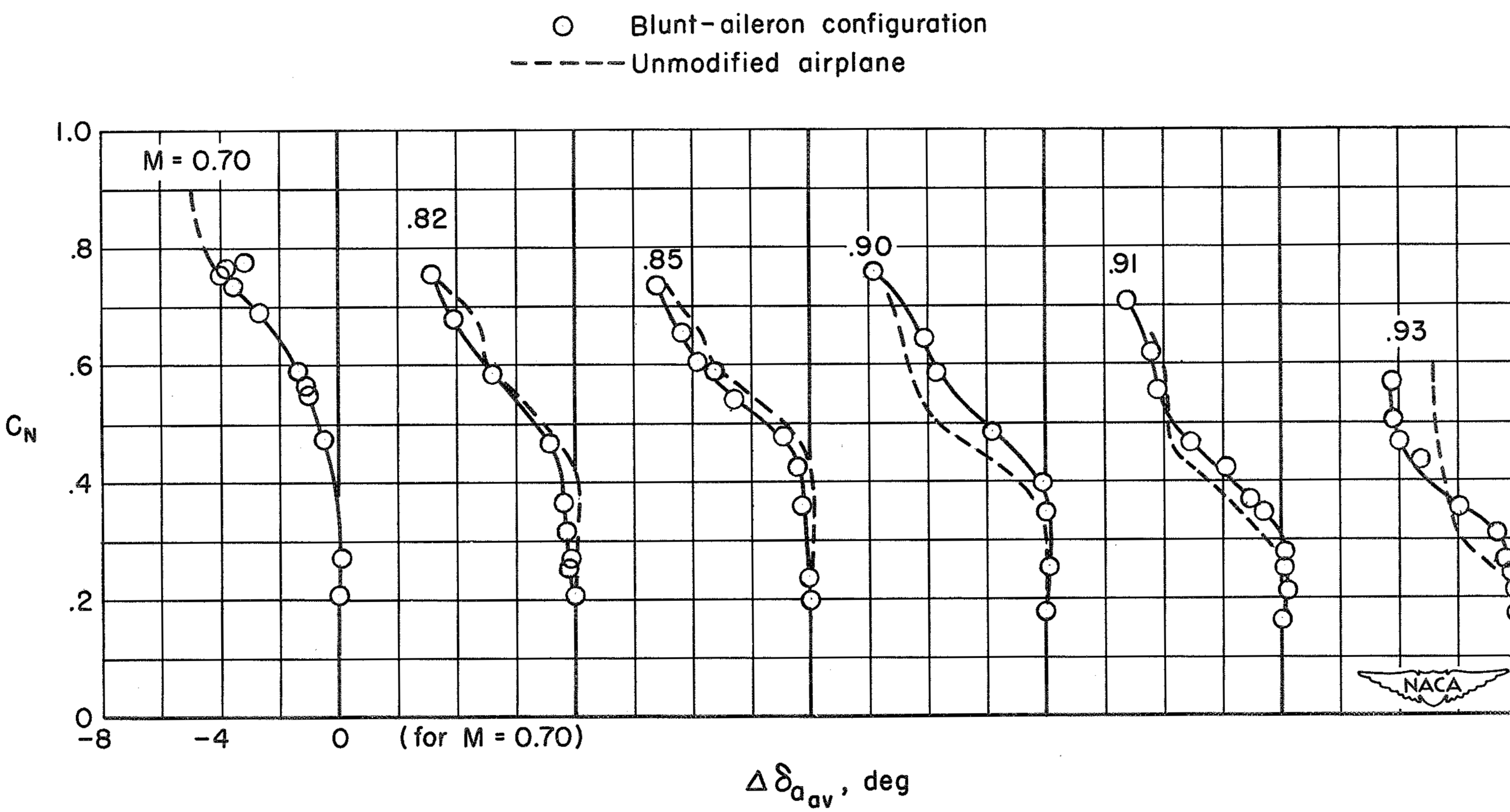
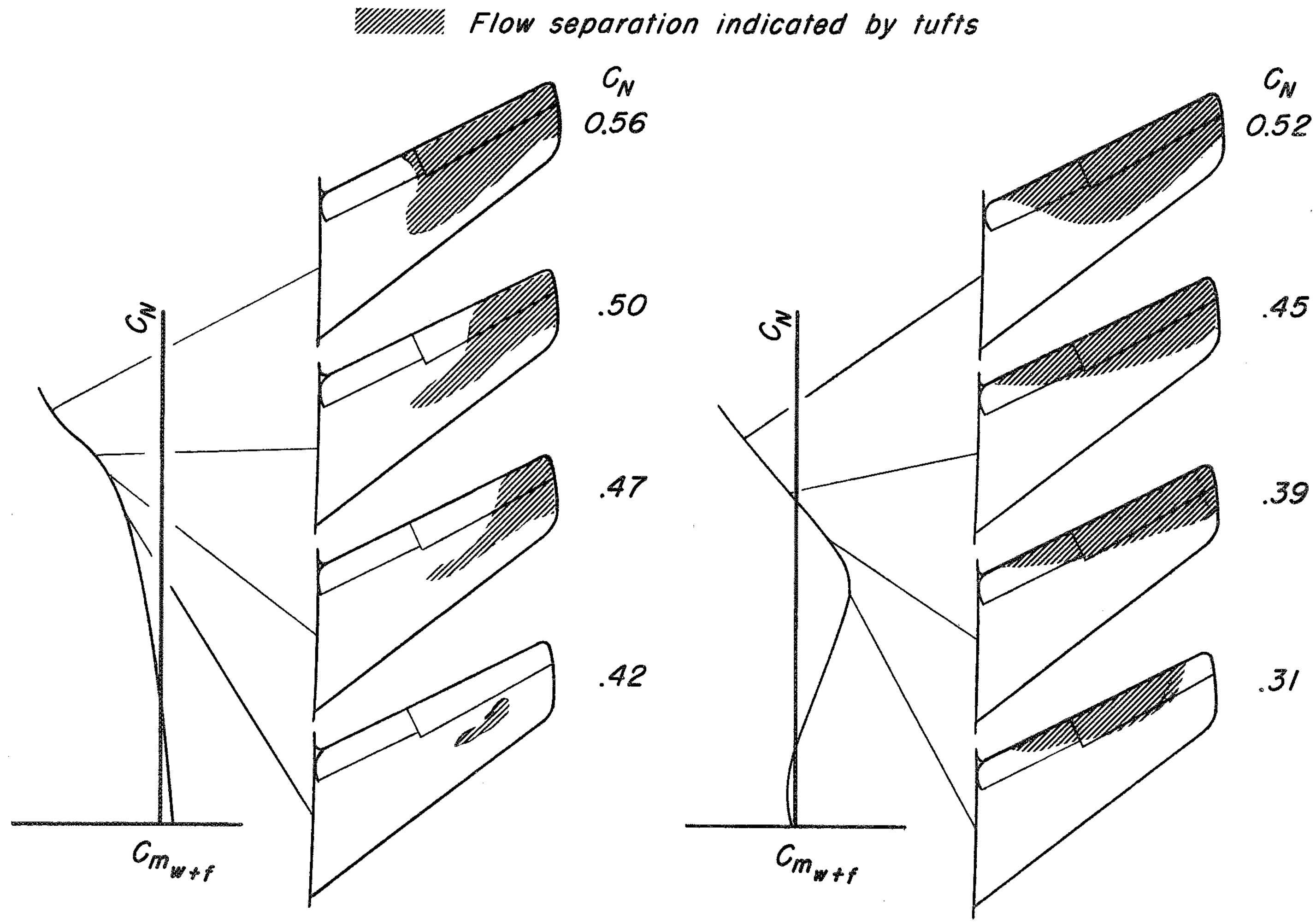


Figure 15.- Variation with airplane normal-force coefficient of the average aileron floating angle at several values of Mach number.



(a) M = 0.82

(b) M = 0.91

Figure 16.- Flow-separation patterns on unmodified wing of the test airplane as seen in motion pictures of tufts in the wing boundary layer.

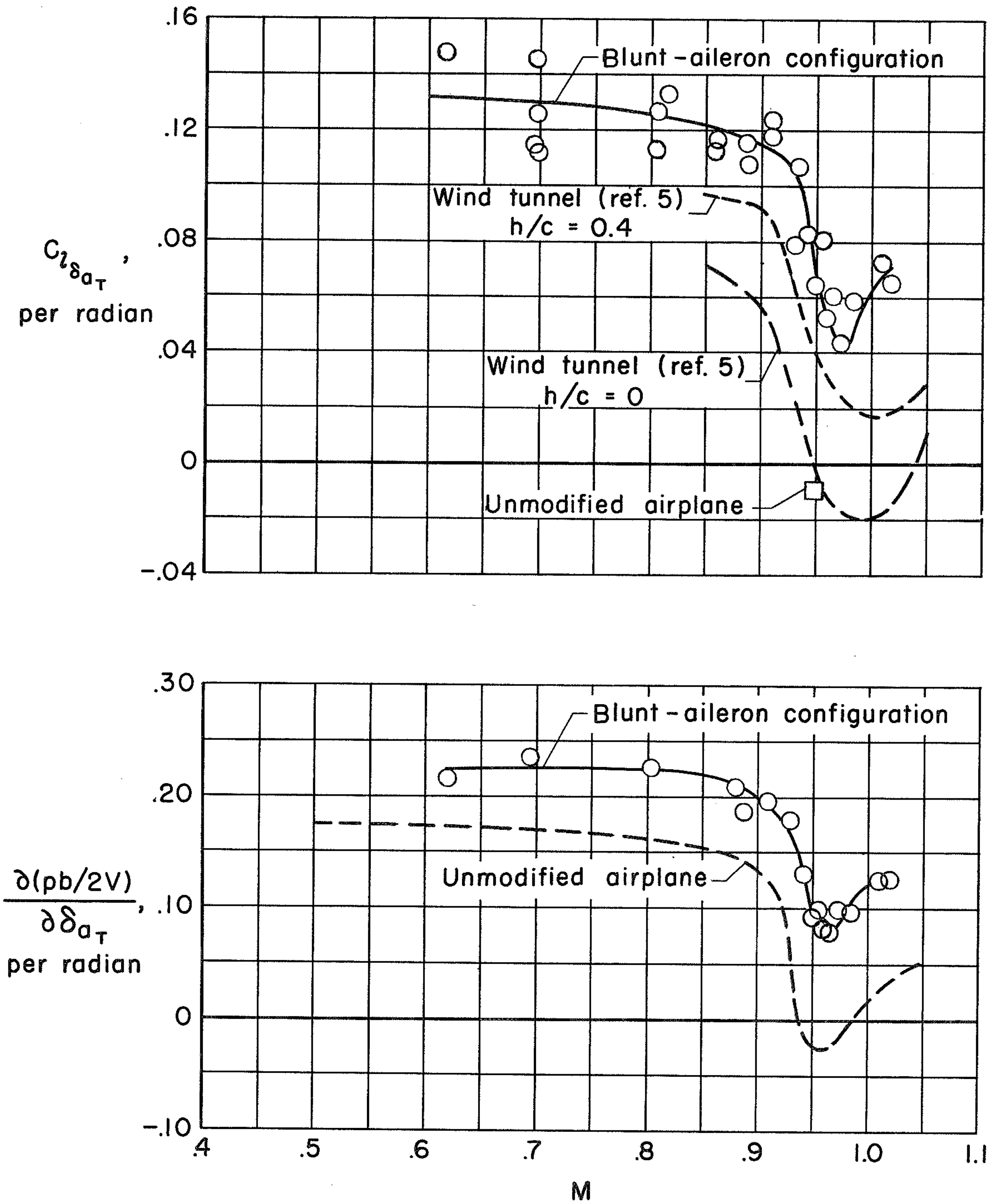
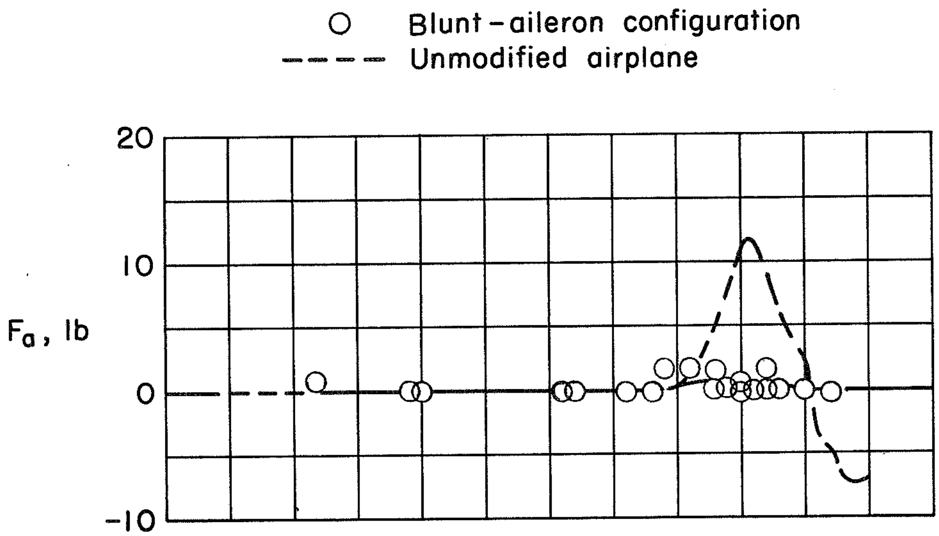
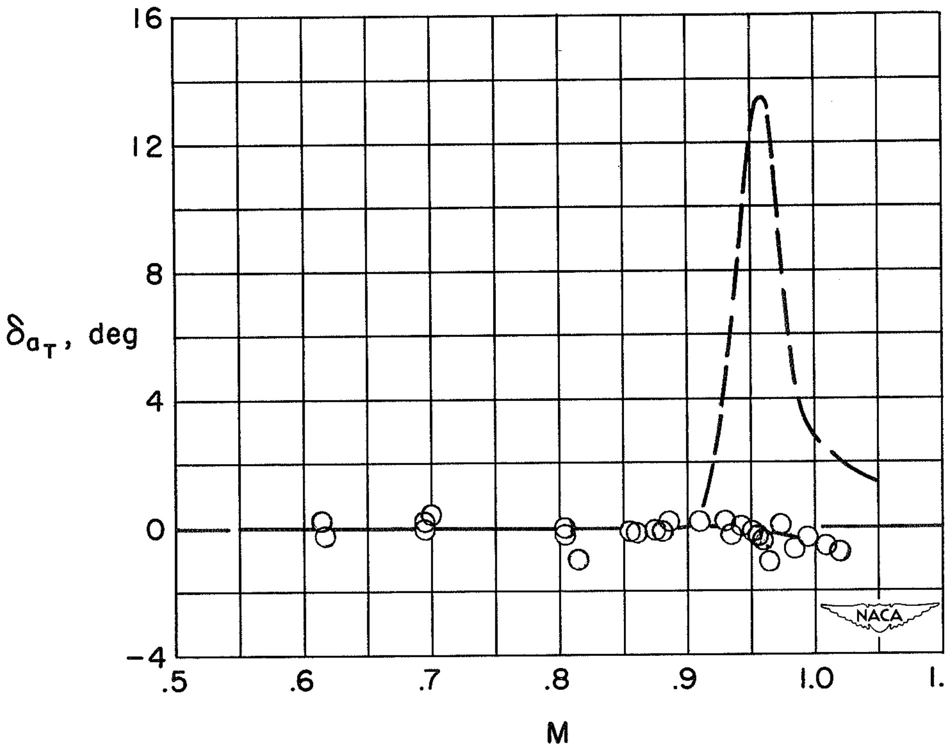


Figure 17.- Variation of aileron effectiveness parameters $C_{l_{\delta_{a_T}}}$ and $\partial(pb/2V)/\partial\delta_{a_T}$ with Mach number.



(a) Aileron stick force.



(b) Total aileron angle.

Figure 18.- Variation with Mach number of aileron stick force and total aileron angle to maintain wings-level flight.

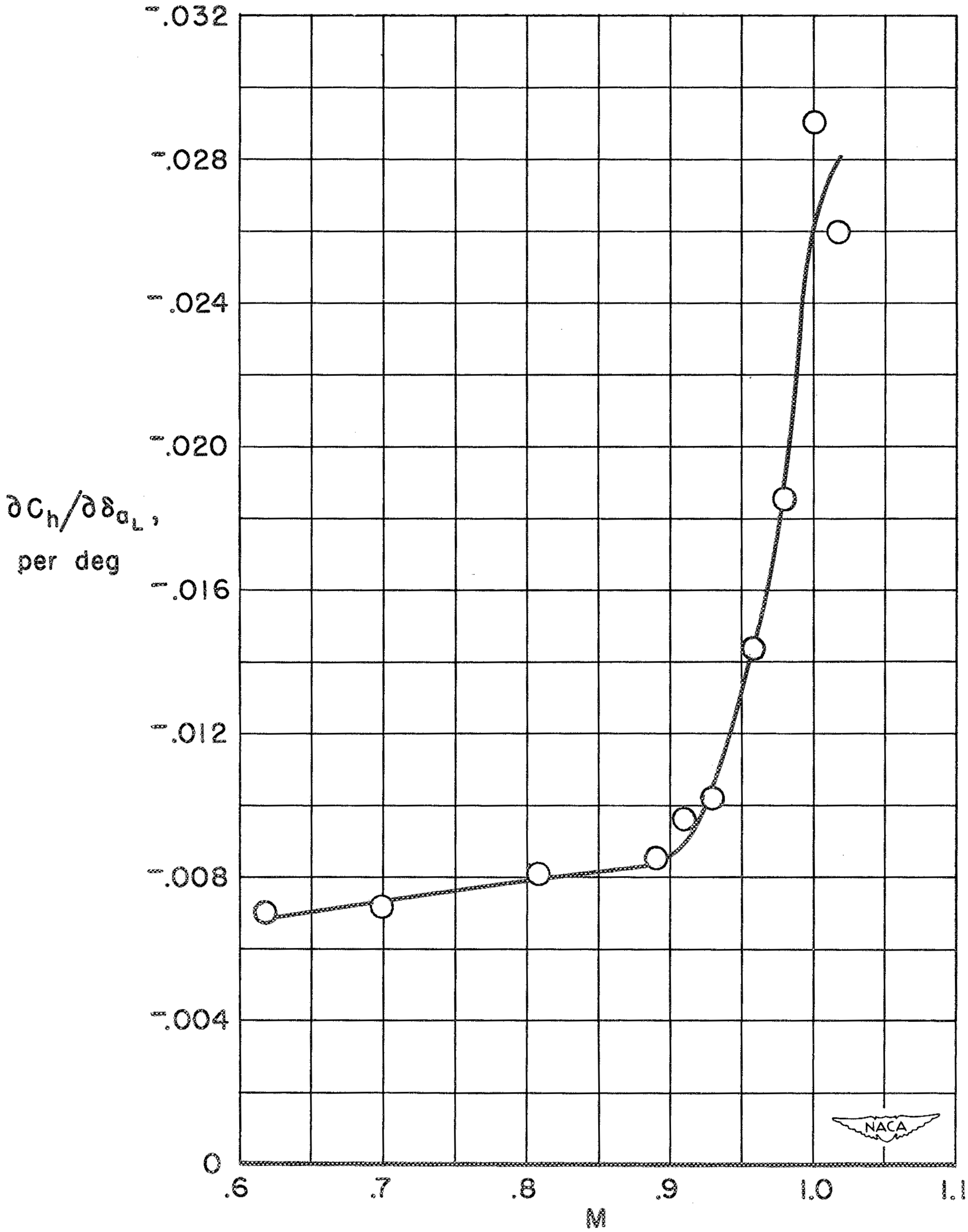


Figure 19.- Variation of the left aileron hinge-moment-coefficient gradient with Mach number for the blunt-aileron configuration.

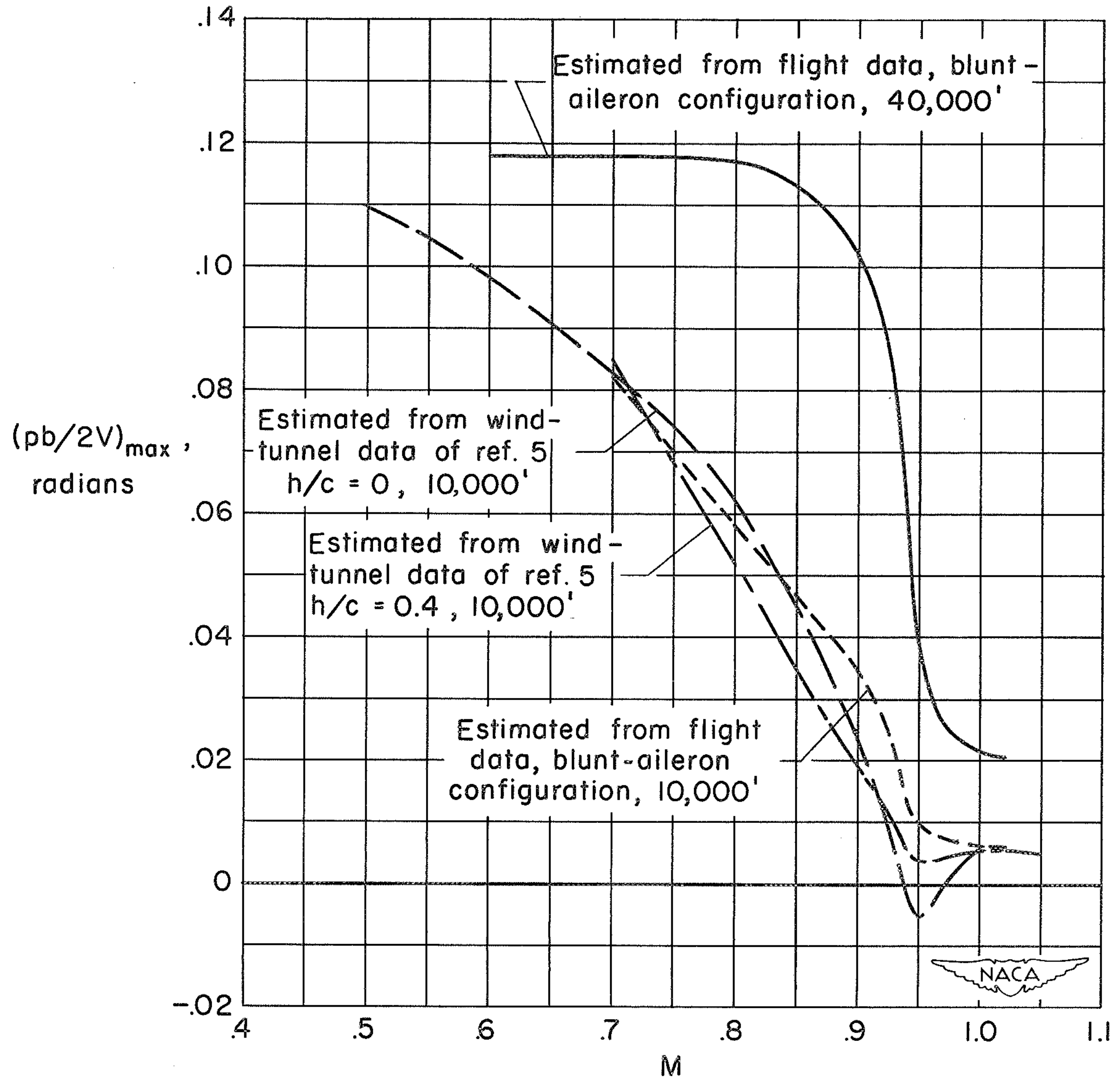


Figure 20.- Maximum wing-tip helix angles estimated from flight data and from wind-tunnel data.

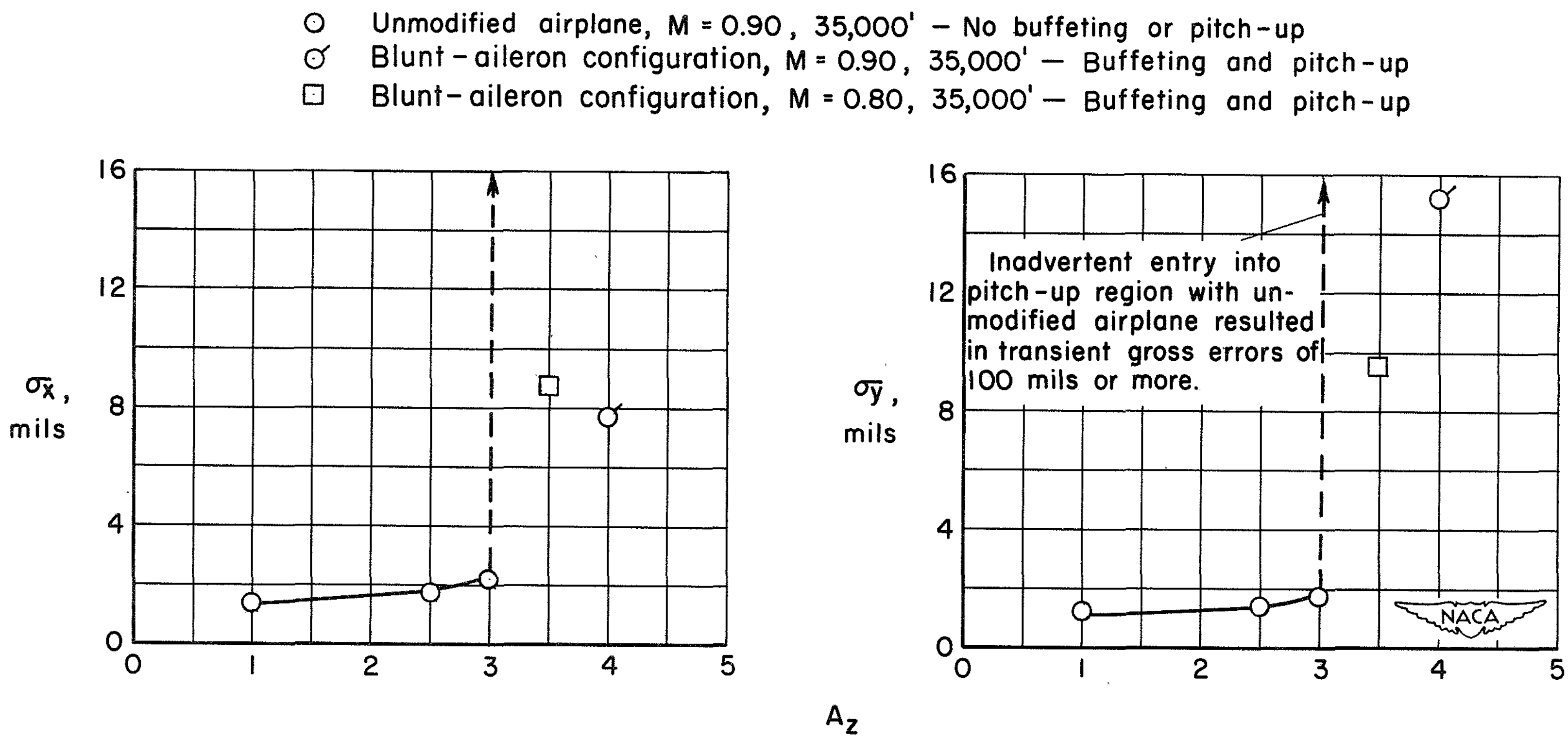


Figure 21.- Standard deviations of aim wander for the unmodified airplane and for the blunt-aileron configuration at several Mach numbers at 35,000 feet.

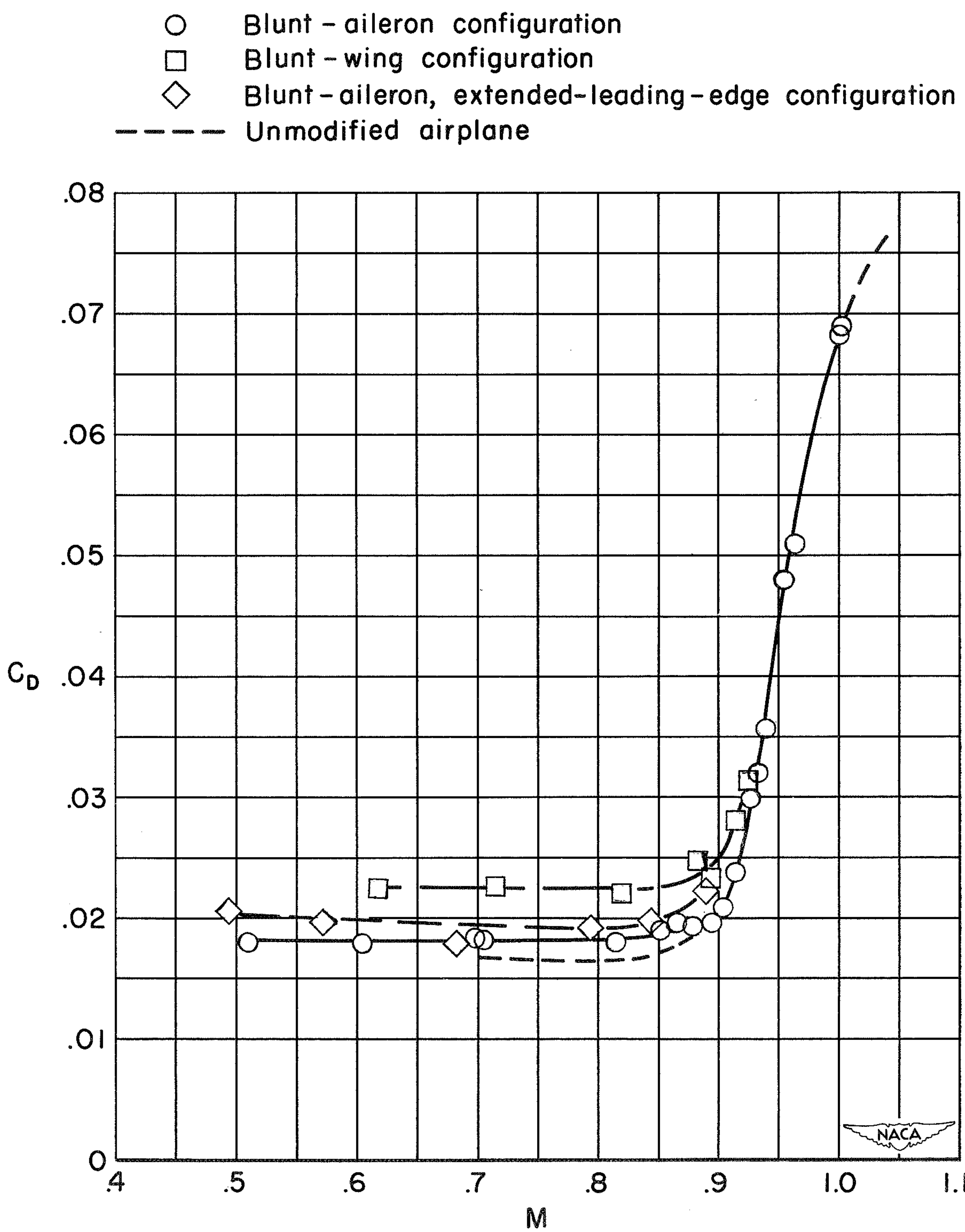


Figure 22.- The effect of various wing modifications on the airplane drag coefficient at an airplane normal-force coefficient of 0.15.

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