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RESEARCH MEMORANDUM

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HANDLING QUALITIES OF HIGH-SPEED AIRPLANES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

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RESEARCH MEMORANDUM

HANDLING QUALITIES OF HIGH-SPEED AIRPLANES

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The requirements for satisfactory handling qualities were first proposed by Gilruth in 1940. These requirements were based on flight tests of many airplanes up to 1940 and were further substantiated by flight tests of the World War II airplanes. The results of these tests led to the Army-Navy specifications for satisfactory handling characteristics. Since that time, however, there have been drastic changes in the speed range and configuration of the airplanes. It is desirable to compare the handling qualities of some of these newer aircraft with the requirements. In this paper, the attempt will not be to describe completely the handling characteristics of all the research airplanes but will be to describe objectionable characteristics and those which indicate review of the requirements. These handling qualities are discussed in an order similar to the specifications. The longitudinal case is described first.

One of the primary longitudinal characteristics is the elevator angle required to trim the airplane through the speed range. In figure 1, the variation of elevator angle required for trim with Mach number for the X-1 unswept-wing, the D-558-I unswept-wing, the D-558-II swept-wing, and the X-4 swept-wing tailless airplanes is presented. As shown, all the airplanes undergo a longitudinal trim change at transonic speeds. In addition, the variation with Mach numbers at supersonic speeds is unstable. These are trim changes and not instabilities since through this speed range the airplanes are extremely stable with change in lift coefficient at any given speed except as discussed subsequently. The elevator effectiveness is very low at these speeds and as a result, if the airplane is not trimmed absolutely correctly with the elevator, the rate of divergence is reasonably slow. It should be noted that the data for the X-1 and D-558-II were taken at two different stabilizer settings. The blank area in the D-558-II plot is caused by the fact that our flight plans to date have required stabilizer maneuvers in this speed range and hence elevator data are as yet unavailable. The maneuvering characteristics are discussed subsequently.

Much of these trim changes are primarily caused by changes in elevator effectiveness and vary with stabilizer incidence. In order to illustrate this point further, figure 2 gives the variation of elevator angle with Mach number at various stabilizer settings for both the X-1 airplane and the F-86A airplane. As can be seen in this figure, the variation of elevator angle with Mach number can be markedly changed by small changes in the stabilizer incidence. It should be noted that in the case of the X-1 the trim change can be varied from nose-down to nose-up by changing the stabilizer setting. The two extreme stabilizer settings in the case of the X-1 indicate the limiting conditions of elevator deflection. Obviously, in this region the elevator is not a good trimming device. Also shown is variation with Mach number of the stabilizer incidence required for trim with zero elevator angle, that is, an all-movable tail. As can be seen, this variation is very small.

The increase in stability coupled with the loss in elevator effectiveness in this speed range causes a great increase in the elevator required to maneuver. This is illustrated in figure 3 where the elevator per unit C_{N_A} and the stick force per g are plotted as functions of Mach number for the D-558-I, the X-1, the X-4, and the D-558-II airplanes. These data apply for moderate lift changes from straight flight. It is shown in this figure that above a Mach number of about 0.8 all these airplanes experience very large changes in elevator required for maneuvering. The stick force per g is extremely high, but even if boost were used to reduce the forces, the maneuvering characteristics would still be poor because of the large elevator angles required per unit C_{N_A}. These values are well in excess of the elevator deflection range of the airplanes which is of the order of 25° total travel.

In order to maneuver the airplanes to any reasonable degree in this speed range, we have had to use the adjustable stabilizer as a maneuvering control. The required stabilizer angles for maneuvering do increase with Mach number because of the stability change as can be seen in figure 4 where the increment of stabilizer incidence required for unit C_{N_A} is plotted as a function of Mach number for the D-558-II airplane. The stabilizer required is not extremely large when compared to the elevator deflection required. Also included in this plot are data from the Langley 8-foot high-speed tunnel which indicated the same trend as measured in flight. Maneuvering with an adjustable stabilizer is not satisfactory. The stabilizer is actuated by a switch on the control column. With high rates of deflection, that is, 2° or 3° per second, it is very difficult to position accurately the stabilizer and thereby maneuver the airplane properly. The rates used are of the order of 1° per second. With these rates, the stabilizer can be positioned precisely but cannot be maneuvered rapidly. Actually, for good control, it would be required to have a surface that is directly linked to the stick and the travel of which is proportional to stick displacement.

In the case of the X-1, by maneuvering the airplane with the stabilizer maximum lift has been reached at all Mach numbers up to a Mach number of 1.0 and high values of normal-force coefficients at speeds in excess of Mach number 1.0. No adverse stability and control characteristics were experienced below maximum lift but buffeting, which was encountered at the high lift coefficients, limited the maneuverability of the airplane. In the case of the D-558-II, the X-4, and the

F-86A, the situation is markedly different. With these airplanes, a change in stability occurs at lift coefficients well below maximum lift of the airplane and before buffeting becomes severe. This stability change, called pitch-up, was experienced at low speeds on the D-558-II airplane during tests several years ago. Since then the tests have been expanded over a greater speed range. Figure 5 presents a time history of elevator angle, angle of attack, and normal acceleration in a wind-up turn at a Mach number of 0.91 with the D-558-II airplane in which this type of instability occurred. It should be noted that, while the elevator motion remains smooth, the angle of attack takes an abrupt increase with an accompanying change in the normal acceleration. The average rate of this abrupt angle-of-attack increase is of the order of 20° per second as compared to the 1/2° per second rate through the controlled part of the maneuver which amounts to an increase in rate of change of angle of attack of some 40 times. In no case has it been possible to check this pitch-up without an increase in normal acceleration of at least 1 g.

To further illustrate this pitch-up and the manner of analysis, figure 6 presents the variation of elevator angle and normal-force coefficient with angle of attack. The point of instability is defined as the point at which there is an abrupt change in the variation of elevator angle with angle of attack. It should be noted that there is a change in lift-curve slope. This change in lift-curve slope actually makes it mandatory to consider the elevator-angle variation with angle of attack. If considered in the usual case with normal-force coefficient, the severity of the pitch-up could be misleading.

From a series of maneuvers such as these, the normal-force coefficient at which the airplanes pitch up or become unstable through the transonic Mach number range has been determined. The results of these measurements are shown in figure 7 which presents the variation with Mach number of the normal-force coefficient at which pitch-up occurs for the X-4 airplane, the D-558-II airplane, and the F-86A airplane. Also presented is the variation with Mach number of the lift coefficient required for level flight at 40,000 feet with wing loadings of 40, 80, and 120 pounds per square foot. In the case of the X-4, the boundary has only been described up to a Mach number of 0.86 since above this Mach number insufficient elevator control is available to reach the lift coefficients at which pitch-up occurs. In the case of the D-558-II, the boundary has been defined up to a Mach number of 0.95. At a Mach number of 0.95, the pitch-up occurs, as can be seen, at a normal-force coefficient of about 0.45. Above this Mach number and up to a Mach number of 1.30, the airplane has been maneuvered up to normal-force coefficients of 0.4 to 0.5 and has not encountered an instability which indicates, at least, that the C_{N_A} for pitch-up does not decrease further as the Mach number is increased. Whether such a boundary exists supersonically is not known at this time. In the case of the F-86A, the boundary has been definitely established as shown up to 0.95 Mach number. These tests, which were made at the Ames Laboratory, indicate that above this Mach number no pitch-up occurred to a lift coefficient of 0.7. The significance of these data is about as follows: The 40- to 80-pound wing loadings correspond to present-day fighter-type airplanes and the modern bombers would fall into the 80- to 120-pound category. It can be seen that, with the fighter-class wing loading and the D-558-II instability boundary, the maneuver margin under the instability boundary for maneuvering is extremely small which means that at a relatively low value of g the airplane will pitch up. The heavier loaded airplanes, as can be seen, actually encounter this pitch-up in straight flight, and in the case of airplanes which have large control forces, this could be extremely severe and dangerous. The pilot's opinion is that, a pitch-up of the nature of the D-558-II case would be intolerable in a tactical airplane. At the Ames Laboratory with the F-86A airplane, tests were made of the effects of vortex generators and boundary-layer fences. At a Mach number of 0.90 the vortex generators raised the normal-force coefficient at which pitch-up occurred approximately $0.1C_{N_A}$ with no apparent untoward effects on the characteristics of the airplane. The boundary-layer fences at the same Mach number increased the C_{N_A} at which pitch-up occurs 0.2; however, these fences were rather large and there were three per wing and, although no exact measurements were made, it was indicated that there was a large drag increase in connection with these fences. An additional outboard fence was tried on the D-558-II airplane. This fence was small and did not appear to change appreciably the C_{N_A} at which pitch-up occurred but it did appear to alleviate the pitch-up somewhat. The pilots report that they could control the pitch-up better with the fences installed.

The lateral and directional stability and control characteristics of these airplanes are now discussed. As far as the static directional stability is concerned, no serious problems have arisen with the possible exception of a characteristic of the XF-92A airplane in aileron rolls in approach condition. This was reported during the Air Force evaluation and the pilots described it as excessive adverse yaw. Figure 8 presents a time history of a rudder-fixed aileron roll in landing configuration at 195 miles per hour. Notice that while the sideslip does not exceed 6°, which is not excessive, the dihedral is very high and reduces the rate of roll to a very low value until the sideslip diminishes. Because the airplane rolls about the body axis at high angles of attack, the yaw develops rapidly with the angle of bank. A combination of high dihedral and low directional stability has given similar results in airplanes in the past. With the XF-92A there is also high side force which may add to the pilot's discomfort. When the NACA receives the airplane the problem will be studied with a view to solution.

With dynamic lateral and directional stability, difficulties have been experienced. The X-1 snaking oscillation has been described quite completely in the past. A solution has not been found but it must be remembered that calculations indicate the tail loads required to sustain the snaking were of the order of ±10 pounds.

With the X-4 airplane, an undamped oscillation about all three axes at a Mach number of 0.88 has been experienced. In figure 9 the time histories of normal acceleration, rolling velocity, control positions, and sideslip are shown. The pitching appears predominant to the pilot. The small undamped yawing oscillation at this speed induces a pitching oscillation at twice the frequency of the yawing oscillation. The pitching is apparently amplified because the natural frequency in pitch is twice that of yaw as shown in figure 10. These data were obtained from rudder kicks and stick impulses, and incidentally, in all maneuvers where there is yawing there is pitching at twice the frequency. Figure 11 shows that at 0.9 Mach number the yawing oscillation diverges, rolling becomes large, and the whole motion is intolerable. The violence is attested by the control motions which result from accelerations on the pilot. Lateral accelerations reach ±1 g. The irregularity of pitching is probably caused by the control motion.

Another very interesting dynamic lateral stability problem arose during the manufacturer's demonstration of the D-558-II airplane. As has been previously reported, the damping of the lateral oscillation at subsonic Mach numbers is very light. In the landing configuration the oscillation is completely undamped from about 200 to 250 miles per hour. In early attempts to reach maximum speed undamped lateral oscillations with accompanying rudder oscillation occurred. Interesting is the fact that power-on $C_{h_{\alpha}}$ of the rudder is positive and power-off is negative. An explanation is the wide expansion of the rocket exhaust at the low atmospheric pressures above 60,000 feet, which causes a family of shock waves in the rudder region. The rudder was locked and the speed range was extended to 1.87 Mach number. A large lateral oscillation occurred at the higher speeds and is shown in figure 12 where time histories of Mach number, normal acceleration, aileron angle, rolling velocity, and sideslip are given.

It should be noted that at the time the airplane exceeded $M = 1.4$ or 1.5 and was pushed over to about 0.2g, a lateral oscillation began. The pilot used aileron control and initially was able to control the oscillation although he did not stop it. He later got out of phase with the motion and the oscillation diverged. Again the airplane oscillated in pitch with a frequency twice that of yaw but was not resonant. As the airplane slowed down to below a Mach number of 1.4 and the normal acceleration was increased above 0.2g the oscillation began to damp.

In order to isolate the effects of Mach number and lift coefficient, the NACA flew a similar flight but at higher normal acceleration which is shown in figure 13. The main difference of the two flights is the higher g and lower maximum speed on the NACA flight. The motion was much less violent but again 1.4 Mach number appeared to bound the oscillation. As was predicted and as shown in figure 14, the directional stability C_{n_β} is decreasing with Mach number increase. Also shown is a test point from the Langley 4- by 4-foot supersonic pressure tunnel. An explanation for the oscillation lies in the diminishing directional stability of the airplane.

Another transonic problem is the wing heaviness. Figure 15 presents the variation of aileron required to fly with the wings level with Mach number for the X-1 and F-86A airplanes. Notice that the wing heaviness is extremely sensitive to sideslip. If aileron is required at zero sideslip for trim, the lateral trim change will be approximately proportional to the loss in effectiveness. This phenomenon has also been experienced on the D-558-I and to a small degree on the D-558-II. Preliminary work on the D-558-I showed that vortex generators will relieve wing heaviness. Further investigation by the Ames Laboratory on the F-86A shows that vortex generators greatly reduce sensitivity to sideslip.

Lateral control effectiveness warrants further consideration. Figure 16 presents maximum rolling rates and the maximum helix angles against Mach number for the X-1, the X-4, and the D-558-II as measured in abrupt rudder-fixed aileron rolls. The X-4 data were taken at 30,000 feet and the X-1 and D-558-II at 40,000 feet. The pb/2V values shown are not high and in all cases are less than the Air Force requirements of 0.09. The rolling velocities, however, approached 300° per second while the requirements state that 220° need never be exceeded. These are very fast rolls. With these high rates, rolling accelerations are important. Figure 17 presents a time history of an X-4 roll at 31,000 feet at 0.81 Mach number. From the variation of rolling velocity and bank angle with time it is seen that the maximum rolling velocity is not reached until after 200° of rotation. Such a maneuver does not describe aileron requirements realistically. The time to reach 90° is probably more indicative of aileron usefulness than maximum rolling rate or helix angle. In addition, the design speed and altitude range must be considered. In figure 18, time to reach an angle of bank of 90° for various aileron angles are shown for the X-4 and the D-558-I airplanes. Above 15° of aileron deflection, little is gained because of the finite time required for the pilot to deflect the ailerons. Experience indicates that the minimum of 1 second to reach 90° is adequate. The airplanes presented are considered to have good aileron control characteristics in the approach condition even though pb/2V is only about 0.04 to 0.06 because of the higher approach speeds and short spans.

In summary, the foregoing characteristics are reviewed from a pilot's viewpoint with regard to their seriousness. These fall into four natural categories. Category I includes characteristics that are dangerous and impose serious limitations on the operation of the airplane. Category II includes characteristics that are not dangerous but impose serious limitations on the use of the airplane. Category III includes characteristics that are not dangerous and do not impose serious limitations on the airplanes but are very objectionable. Category IV has in it the characteristics that indicate change in the handling-qualities requirements.

In the first category is the static longitudinal instability at moderate lift coefficients with swept wing. Any nonlinearities in variation of elevator angle with g or angle of attack as encountered in the pitch-up of the swept-wing airplanes can be very dangerous. Static instability has not been tolerated in the past and should not be now tolerated in tactical airplanes.

Also in the first category, the X-4 oscillations about three axes are determined as having their origin in very low to zero damping in yaw and by the fact that the ratios of natural frequencies and coupled oscillations are similar. Largely because of these oscillations it was considered unreasonable to extend the speed beyond the maximum Mach number reached, nearly 0.93.

Also in the first category is the supersonic undamped motion of the D-558-II apparently arising from the low directional stability. The low directional stability presents a real problem and probably will limit the maximum speed attainable until some improvement is made.

In the second category which is a serious limitation in the use of the airplanes but not of a particularly dangerous nature is the loss of elevator control at transonic and supersonic speeds. The unsatisfactory elevator control requires that the stabilizer be used to maneuver. However, for good control the stabilizer should be linked to the control stick and there is no reason to question that the stick force per g and maneuvering parameters shouldn't be of the same order of magnitude as in the specifications.

The third category includes characteristics that are very objectionable but do not endanger the airplane or do not impose serious limitations on their usefulness. The XF-92A case indicates that, though adverse yaw is within requirements, an airplane with high dihedral that is flown at high angles of attack may have objectionable characteristics in roll. High side force may add to the objection.

Transonic snaking, as with the X-1, is in the third category and is difficult to diagnose because of the very low force inputs necessary to sustain it. This snaking on some occasions is hardly noticeable.

Again in the third category is wing heaviness which is more serious than snaking. At transonic speeds wing heaviness is very sensitive to sideslip but apparently can be largely eliminated with the use of vortex generators. In a tactical airplane extreme wing heaviness may become intolerable.

The fourth and last category includes the characteristics that have been found to indicate a review of the handling-qualities requirements. All the airplanes undergo large trim changes transonically. These changes are not particularly objectionable so long as there is sufficient longitudinal control to trim out the unbalanced moments. With the stabilizer as the control the trim changes are small. The variation of elevator angle with speed has been unstable in some cases. This has not been particularly objectionable and does not imply the true stability of the airplane since the airplanes are very stable with lift. This is one point that perhaps should be reviewed or changed in the requirements.

The roll requirement is another that perhaps should be reviewed. The rolling criterion of 1 second to 90° with consideration of design speeds and altitudes is proposed as being a more representative requirement for high-speed airplanes. The rates of roll attainable with these airplanes are excessive and are reached at large angles of bank. The high aileron angles are not useful except to attain these high rolling velocities.

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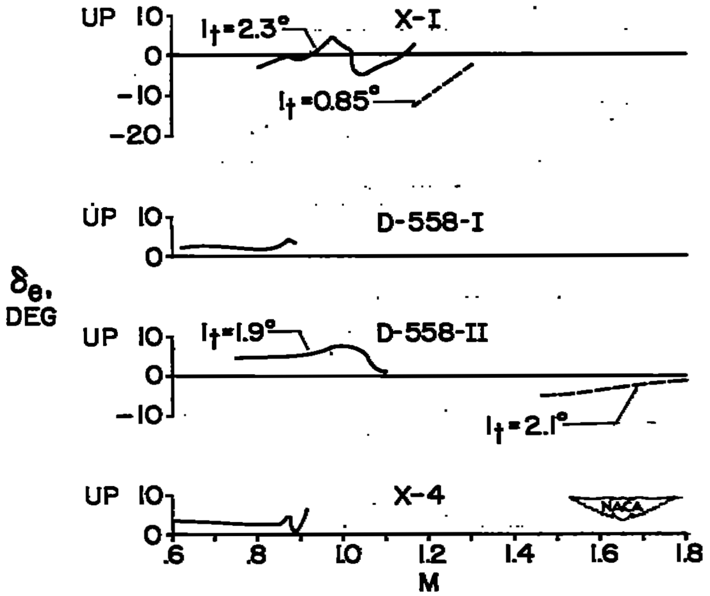

Figure 1.- Variation of elevator angle required for trim with Mach number for the X-1 and D-558-I unswept-wing and the D-558-II and X-4 swept-wing tailless airplanes.

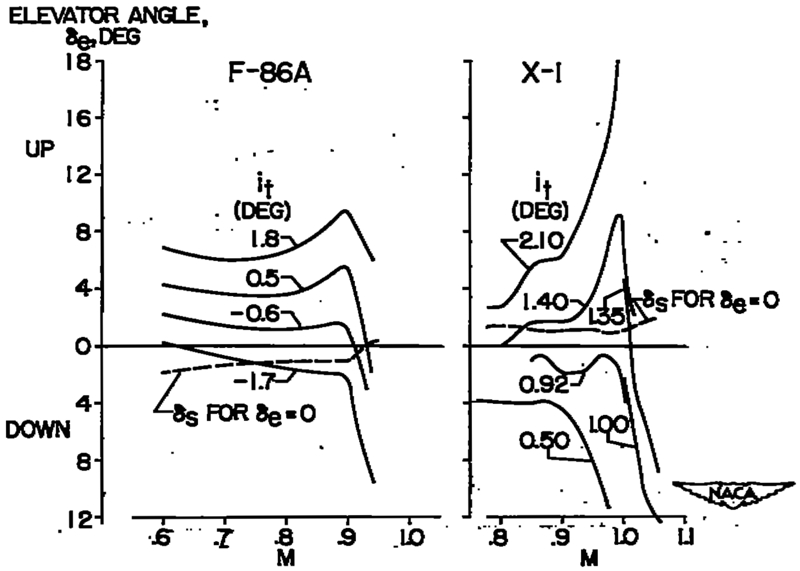

Figure 2.- Variation of elevator angle with Mach number at various stabilizer settings for both the X-1 airplane and the F-86A airplane.

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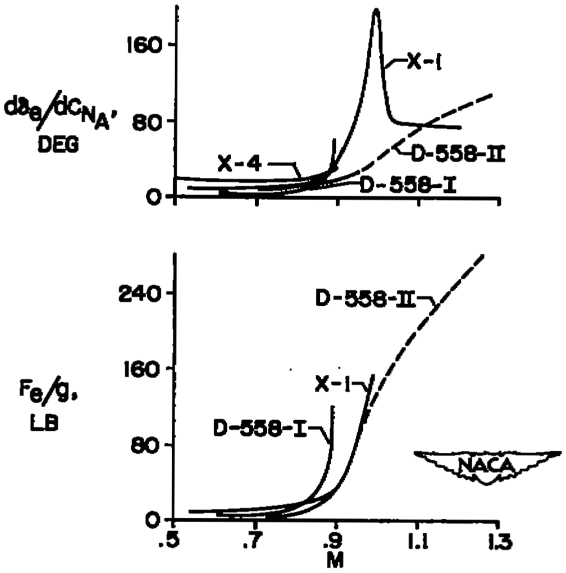

Figure 3.- Elevator angle per unit C_{N_A} and stick force per g plotted as functions of Mach number.

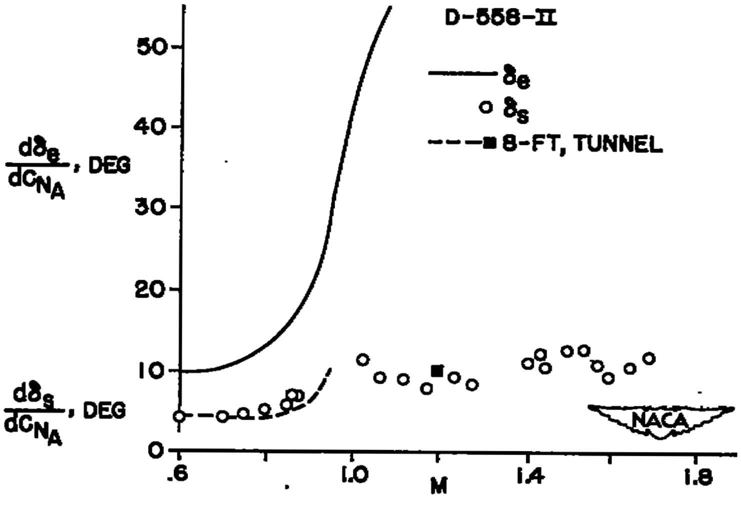

Figure 4.- Elevator angle per unit C_{N_A} and stabilizer angle per unit C_{N_A} plotted as functions of Mach number for the D-558-II airplane.

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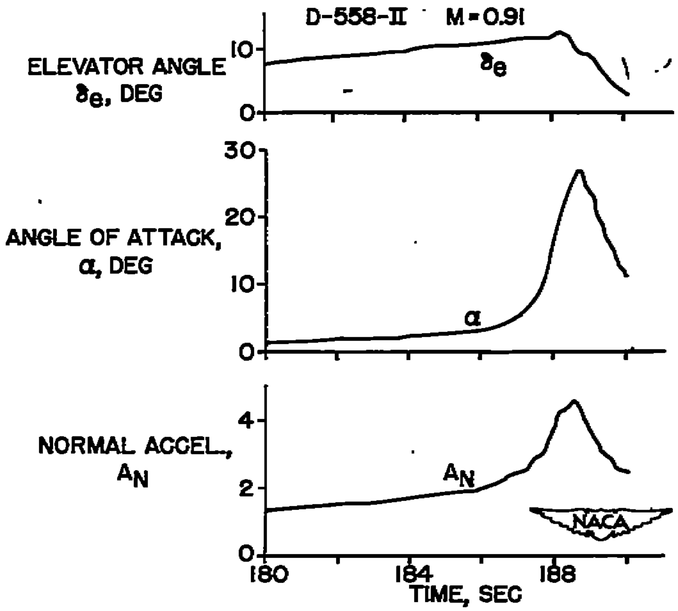

Figure 5.- Time history of elevator angle, angle of attack, and normal acceleration in a wind-up turn.

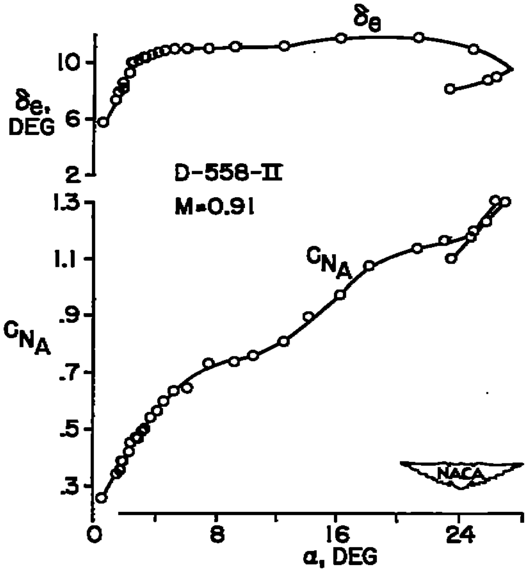

Figure 6.- Variation of elevator angle and normal-force coefficient with angle of attack.

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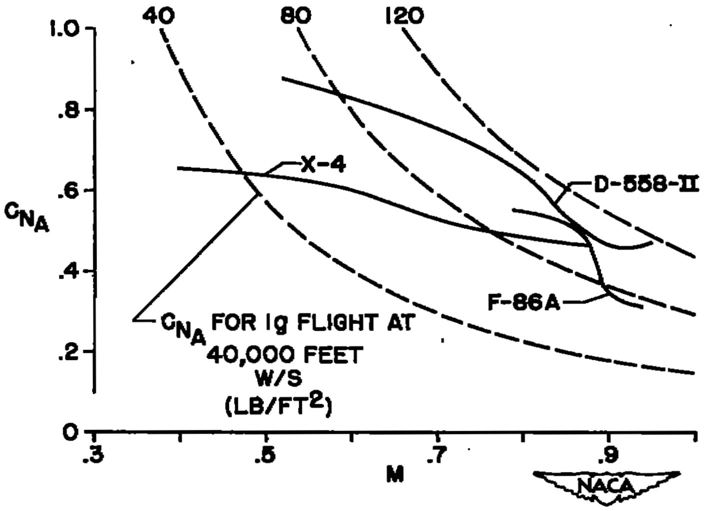

Figure 7.- Variation with Mach number of the normal-force coefficient at which pitch-up occurs for the X-4, the D-558-II, and F-86 airplanes.

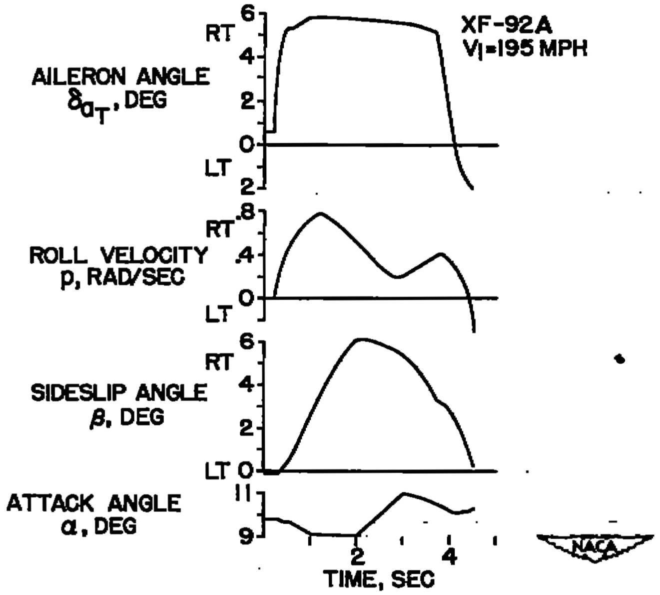

Figure 8.- Time history of a rudder-fixed aileron roll in a landing configuration at 195 miles per hour.

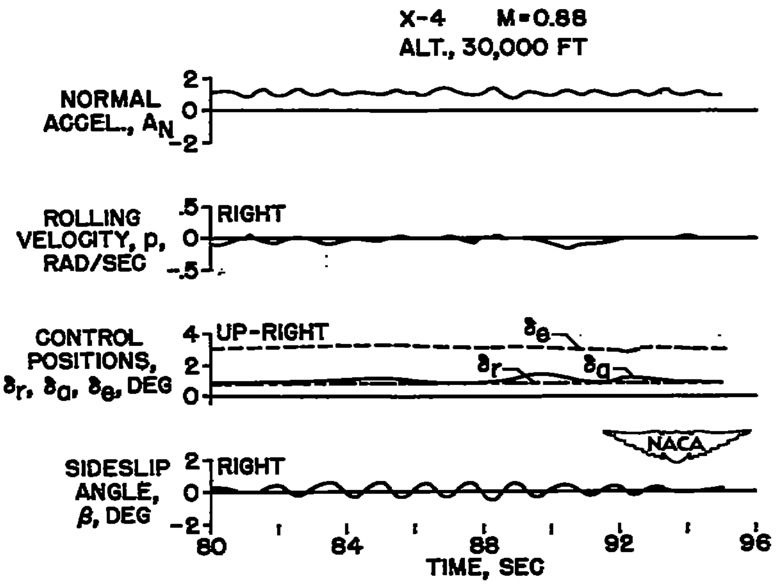

Figure 9.- Time histories of normal acceleration, rolling velocity, control positions, and sideslip for X-4 airplane at M = 0.88.

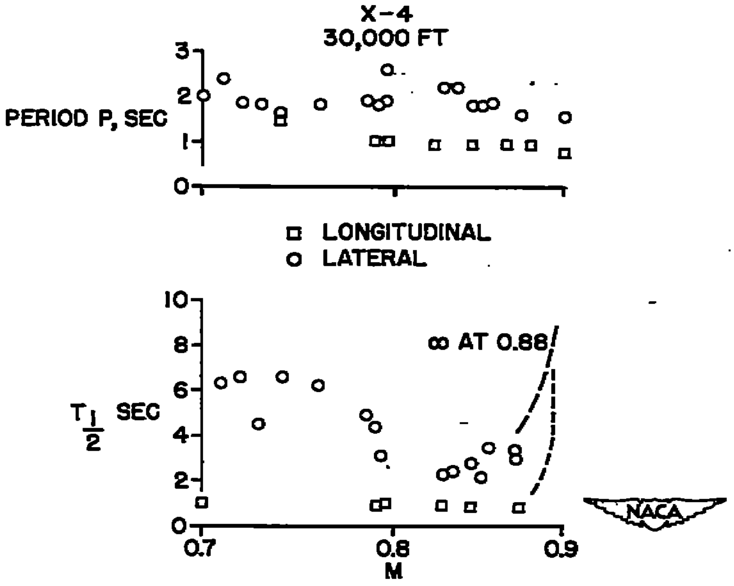

Figure 10.- Period and time to damp to one-half amplitude plotted against Mach number.

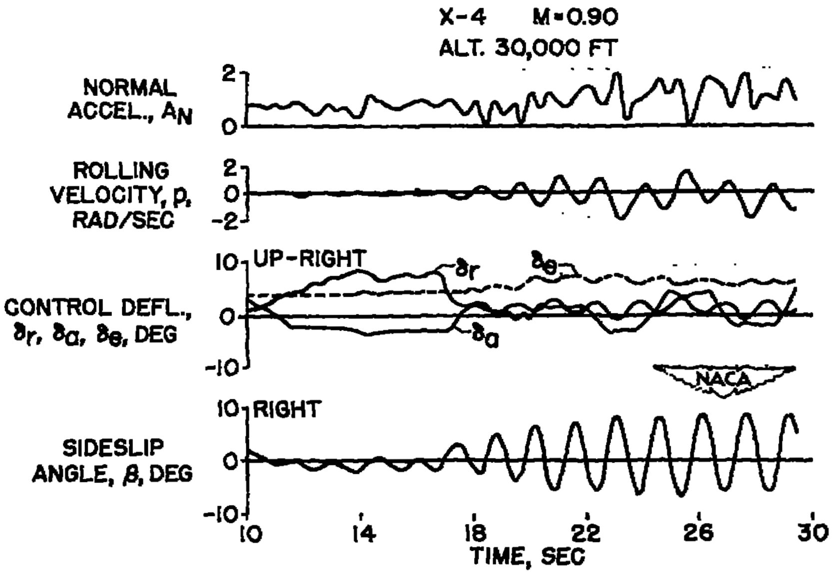

Figure 11.- Time histories of normal acceleration, rolling velocity, control deflection, and sideslip for X-4 airplane at M = 0.90.

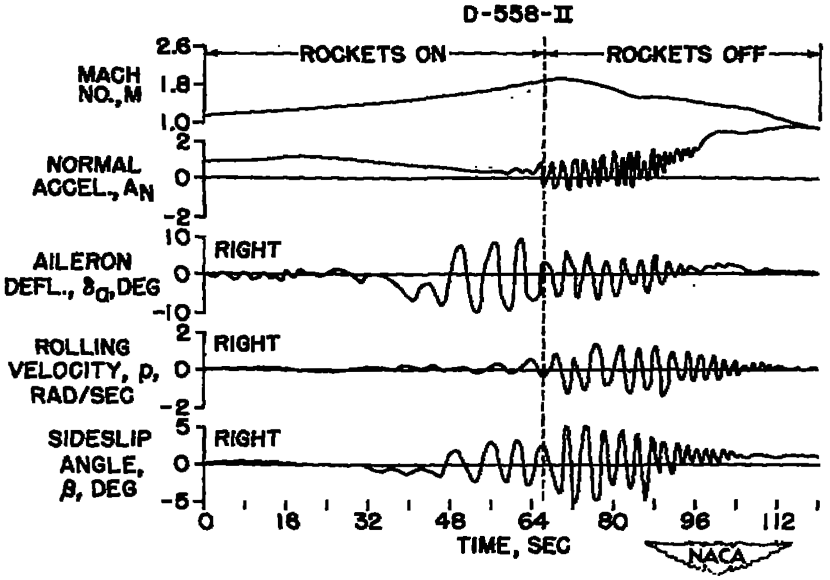

Figure 12.- Time histories from manufacturer's demonstration flight of D-558-II airplane.

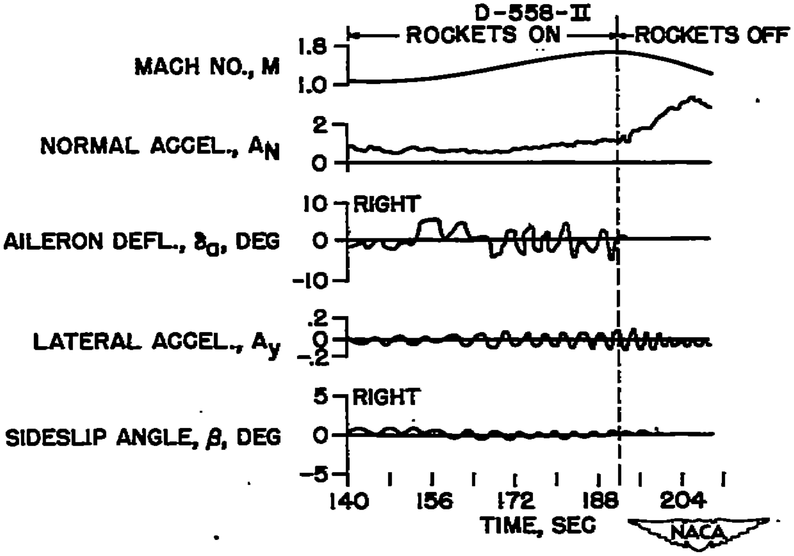

Figure 13.- Time histories from NACA flight of D-558-II airplane.

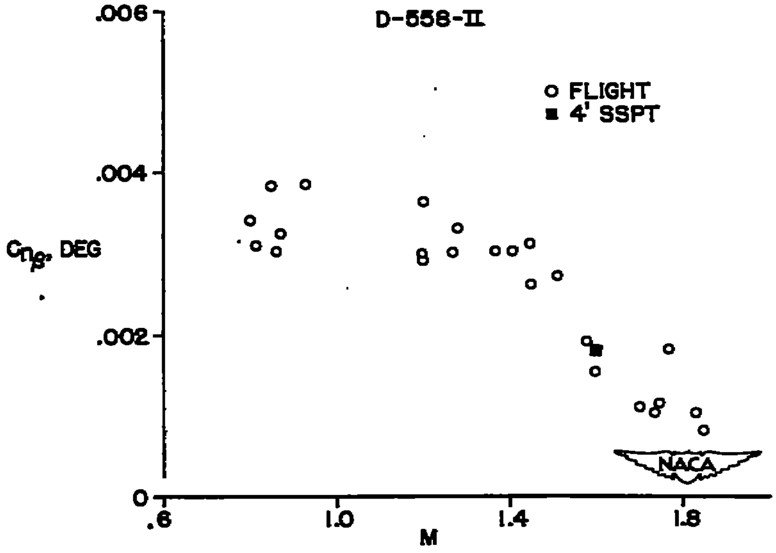

Figure 14.- Directional stability parameter C_{n_β} plotted against Mach number for D-558-II airplane.

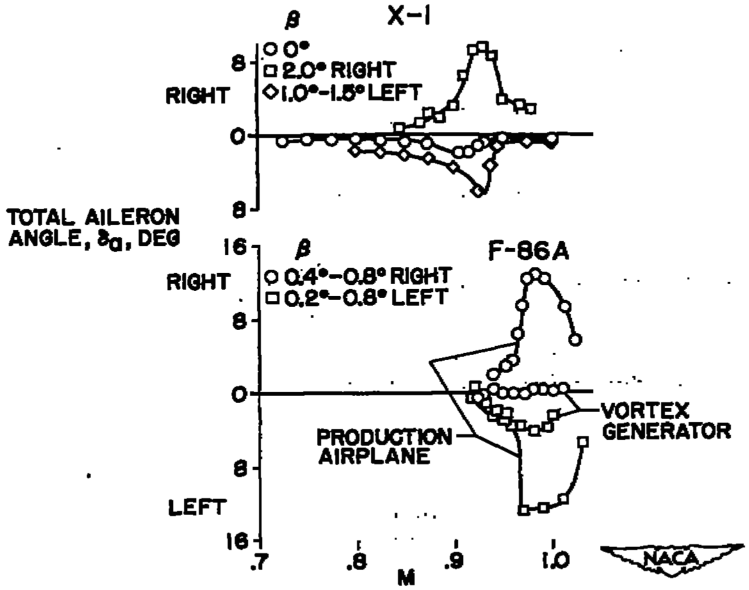

Figure 15.- Variation with Mach number of aileron required for level flight for the X-1 and F-86A airplanes.

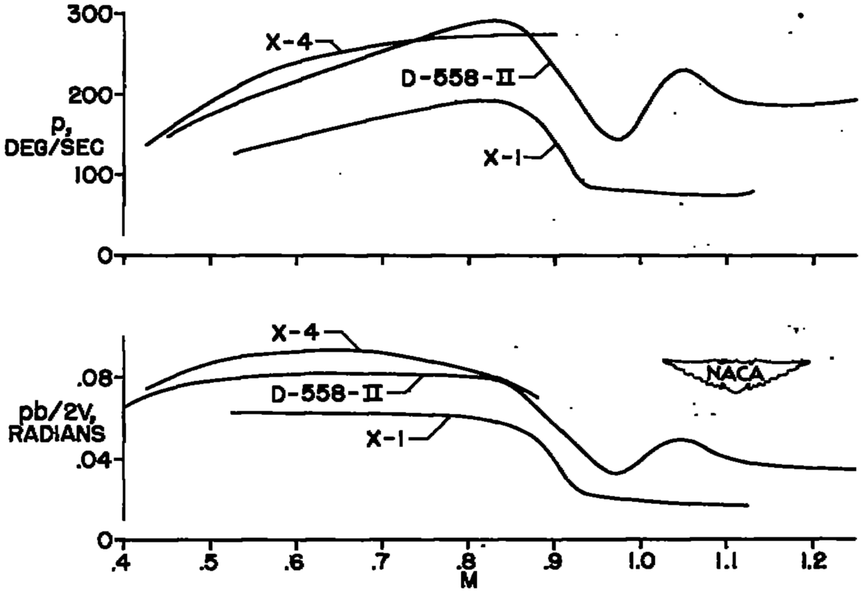

Figure 16.- Maximum rolling rates and maximum helix angles plotted against Mach number for the X-1, the X-4, and the D-558-II airplanes as measured in abrupt rudder-fixed aileron rolls.

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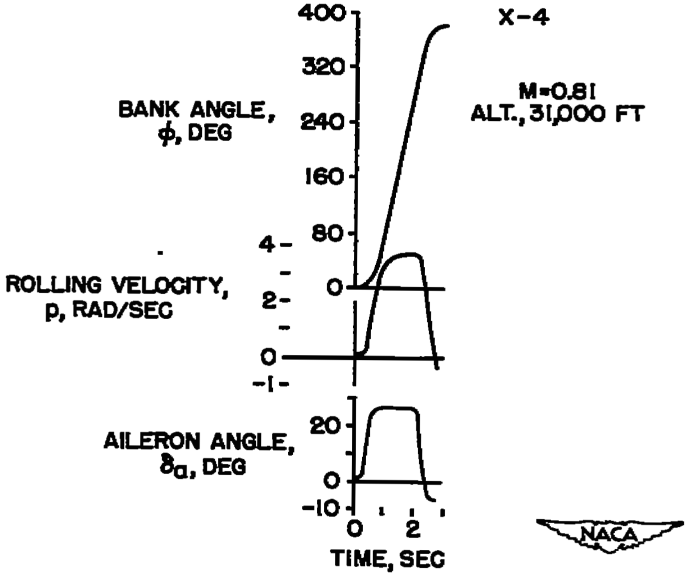

Figure 17.- Time history of angle of bank, rolling velocity, and aileron angle for an X-4 roll at 31,000 feet and at a Mach number of 0.81.

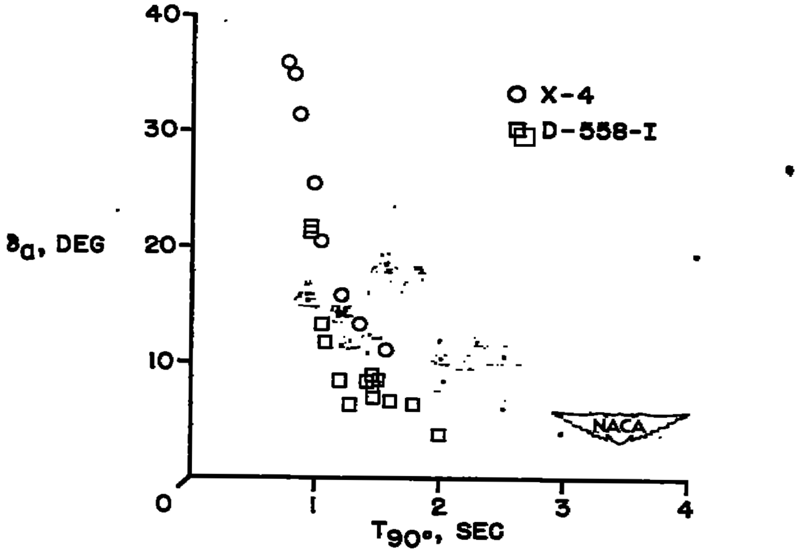

Figure 18.- Time to reach an angle of bank of 90° for various aileron angles for the X-4 and D-558-I airplanes.

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