[redacted]

Copy 76
RM H55L29a

NACA RM H55L29a

LIBRARY NACA - HSFS

NACA

RESEARCH MEMORANDUM

SOME RECENT RESEARCH ON THE HANDLING QUALITIES OF AIRPLANES

By Walter C. Williams and William H. Phillips

High-Speed Flight Station
Edwards, Calif.

CLASSIFICATION CHANGED
TO Unclassified
BY AUTHORITY OF DECL. NO. 123 Date
NOV 8 1957

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

February 21, 1956

[redacted]

LIBRARY NACA HSFS

 [redacted]

LIBRARY NACA - HSFS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

SOME RECENT RESEARCH ON THE HANDLING QUALITIES OF AIRPLANES

By Walter C. Williams and William H. Phillips

SUMMARY

Results of recent research on the handling qualities of airplanes are reviewed. Among the subjects considered are dynamic longitudinal stability, transonic trim changes, pitch-up due to decreasing airspeed, dynamic lateral stability, aileron control, rudder control, and mechanical characteristics of power control systems.

INTRODUCTION

The problem of interpreting the pilot's opinion of the handling of an airplane in engineering terms has been the subject of investigation for a number of years. Up to and through World War II there was little change in the requirements since, generally speaking, the airplanes were of the same type. In recent years, however, speed range of military airplanes has doubled and configurations have been drastically altered. It has been attempted, therefore, to continue research into the handling qualities of airplanes so that the requirements would meet the needs of the newer speed ranges and configurations.

Some of this work has been under way at the NACA High-Speed Flight Station using research airplanes as well as some of the more recent operational airplanes (three fighters and one medium bomber). The ranges of configurations covered included straight-wing airplanes, swept-wing airplanes having 35° to 60° of sweep, and delta-wing configurations which were tailless. In addition, both civilian and military test pilots as well as military operational pilots have been consulted. This paper does not attempt to specify directly new requirements since either the information does not cover a large enough number of airplanes or the investigations are not complete enough at this time to state requirements definitely. This paper is, therefore, an indication of the thinking of the National Advisory Committee for Aeronautics with regard to deficiencies or possible changes in the handling-qualities specifications.

[redacted]

LIBRARY NACA - HSFS

SYMBOLS

a_n	normal acceleration
b	wing span
$C_{1/2}$	cycles to damp to half amplitude
$C_{1/10}$	cycles to damp to one-tenth amplitude
C_N	normal-force coefficient
F_s	stick force
h_p	pressure altitude
i_t	stabilizer incidence
M	Mach number
P	period
p	rolling angular velocity
$\dot{p}$	rolling angular acceleration
p_{max}	maximum rolling velocity
$\dot{p}_{max}$	maximum rolling acceleration
t	time
$t_{1/2}$	time to damp to half amplitude
V	true airspeed
V_i	indicated airspeed
v_e	equivalent side velocity
α	angle of attack
δ_a	aileron angle
δ_e	elevator angle
ϕ	angle of roll
$\Delta\phi$	change in angle of roll

DISCUSSION

Longitudinal Stability and Control

Dynamic longitudinal stability.- In connection with dynamic longitudinal stability, periods and times to damp have been determined by

using the usual pulsing techniques. These data are shown in figure 1. The speeds are from subsonic to moderately high supersonic with an altitude range from 10,000 to 50,000 feet. Also illustrated in this figure is the present military specification which requires damping to one-half amplitude in one cycle as well as the older requirement of damping to one-tenth amplitude in one cycle. The corresponding scales are also shown. The pilots in this case did not feel that the damping was sufficient for satisfactory handling qualities, but as the damping approached the old requirement of one-tenth amplitude in one cycle the airplanes became more satisfactory. There is evidence from studies of tracking runs that damping of the order shown in conjunction with the characteristics of the usual powered control system adversely affects the gunnery. Extension of these data will be accomplished in the near future with the installation of artificial damping in one of these airplanes because it appears that the pilot prefers the short-period oscillation well damped. This study of the pitch damping requirements is a subject of intense investigation at this time because it has been found, as is pointed out subsequently, that there are other characteristics of the airplane that are seriously affected by pitch damping.

Longitudinal trim changes with speed.- Figure 2 shows three different types of variation of elevator or stabilizer angle and force with Mach number. All these airplanes have irreversible control systems with artificial feel. In none of these cases did the pilot object strenuously to the trim changes in the transonic region for the case of accelerating through this speed range. It is noted that the trim force changes are quite moderate, under 10 pounds. There was, however, a gradation of pilot opinion between the various airplanes. The pilots objected most to airplane A where there was a reversal of the elevator force and position with speed. They objected somewhat less to airplane B where the reversal was of smaller magnitude, in this case only 3 pounds. They preferred the characteristics of airplane C where increasing speed always calls for increasing push force, even though, between Mach numbers of 0.95 and 1.1, there is a change in force of the order of 10 pounds, which, however, is always in the stable direction. It appears, therefore, that if the trim changes are light (of the order of 10 pounds) the pilot will not object too strenuously; it is further apparent that he still desires trim characteristics such that increasing speed calls for increasing push force. In the older airplanes having similar force variations with speed but with a much higher level of changes, in some cases as high as 50 to 60 pounds, the pilot found such trim curves extremely undesirable. For the problem of cruising within the regions of trim changes, either where the trim variation is very flat or reversed, the problem is a little more involved. It was found that the pilot encountered some difficulty in actually setting up the trim speed in this region. However, once the speed was established, with practice he could fly reasonably steadily in this speed range. It did, however, require continuous attention and a moderate amount of control manipulation. For a long-range cruise it would be

rather tiring. For flight at high altitude (50,000 feet) it is possible that the entire flight speed range of the airplane is within the trim-change region. In discussions with military pilots it was found that they were working continuously to fly formation in this speed range.

Pitch-up with decreasing speed.- In the past there has been much discussion of longitudinal instabilities during constant-speed accelerated maneuvers which involved nonlinearities in the variation of pitching moment with lift coefficient. Since that time, however, much has been learned to eliminate this problem through actual design procedures.

Another subject of research has been that of instabilities or pitch-ups during maneuvers made at constant g with decreasing speed, particularly for the case of decreasing speed from supersonic to subsonic speeds. Many airplanes studied in the past had constant-speed pitch-ups at transonic speeds. For the present discussion, airplanes are considered which had linear stability with lift through the range covered.

In order to study the problems associated with slowing down while holding constant g, measurements have been made on three airplanes of the longitudinal control deflections and forces as a function of Mach number and normal acceleration. In addition tests were made in which the pilot attempted to hold the normal acceleration constant in turns while slowing down at various rates. The control deflections and forces to hold 1g are shown in figure 2. The corresponding curves in an accelerated turn may be visualized by adding the increments due to increasing C_N or g shown in figure 3, which gives the variation of force per g and elevator control per unit C_N as a function of Mach number. As shown in this figure, airplane A exhibited a large loss in control effectiveness in the transonic range. The instability shown in the curve of δ_e as a function of M for 1g would therefore be accentuated at higher values of g. On the other hand, the loss in control effectiveness for airplane C is very slight, and when combined with the stable curve for 1g would result in nearly constant control deflection to hold some value of normal acceleration in a turn. (The characteristics of airplane B are intermediate between those of A and C.)

The variation of force per g with Mach number for the three airplanes is also shown in figure 3. The curves differ considerably from the position curves because of the characteristics of the individual feel devices. The characteristics are such, however, that a marked decrease in pull force would be required in airplane A when slowing down through the transonic range in a turn, whereas the force for airplane C would be about constant.

Time histories of the maneuvers at constant g made with these airplanes are now presented. It should be noted that changing the rate of

decrease of Mach number when decelerating from supersonic to subsonic speeds by making runs with afterburner on and off had little effect on the general conclusions to be drawn from these runs.

The maneuver made with airplane A (fig. 4) shows that the pilot had little difficulty in maintaining the average value of g throughout the maneuver. In entering the region of greatest trim change, however, the airplane was disturbed in pitch, and from then on, because of low damping in pitch, the pilot had difficulty in controlling the maneuver precisely.

Similar results are shown in the case of airplane B (fig. 5). This run was made at a somewhat higher value of g. A fairly abrupt stabilizer motion made on entering the unstable region may be seen. The resulting disturbance continued as the Mach number decreased further. In this case, precision of control was further adversely affected by large control friction and breakout forces.

The maneuver made with airplane C (fig. 6) shows, in contrast, a very steady and precise control of normal acceleration, with little change required in stabilizer position or force.

These data show that, for airplanes with adequate control power and positive stability with change in angle of attack, the pilot can control the average normal acceleration reasonably well in maneuvers in which the speed decreases from supersonic to subsonic. When there are large trim changes and low damping in pitch, however, precise control is difficult. Increases in pitch damping and improvements in the power control system are expected to alleviate these problems.

Most of the difficulties experienced in earlier airplanes with excessive pitch-up in reducing speed have occurred at low altitude, where the deceleration is greater and the normal acceleration due to a given change in angle of attack is increased. Also, these airplanes usually had conventional elevators which experience large increases in effectiveness as the speed is decreased from supersonic to subsonic. The provision of all-moving tails, which maintain more nearly constant effectiveness, has been found to alleviate these problems greatly. Nevertheless, the unsteadiness encountered in the present tests at high altitude would be expected to increase at lower altitude. The conclusion may be drawn, therefore, that efforts should be made to avoid as much as possible trim changes and variations in control effectiveness with Mach number in the transonic range.

Lateral Stability and Control

Lateral-directional oscillations.- The next subject to be discussed is lateral-directional stability and control, in particular, damping of

the lateral-directional oscillations. This particular requirement has probably been the source of more discussion and/or controversy than any of the other requirements. This is probably because it depends on many variables and leans extremely heavily on pilot opinion. The pilots, in this case, were required to fill out a form which covered maneuvers used in operations typical of cruise, instrument, and gunnery flying. As a basis for a start, figure 7 illustrates the present requirement that specifies the cycles to damp as a function of the parameter ϕ/v_e which is the ratio of bank angle to equivalent side velocity. The upper curve on this plot is the damping requirement as stated in the present Military Specifications for most configurations with controls fixed and free. The lower curve covers the case of artificial damping devices inoperative in the power-approach condition. As can be seen in this figure, there are airplanes that fall into the satisfactory zones but are considered unsatisfactory or marginal at best by the pilots. This is particularly true in the case of high values of ϕ/v_e. Actually, the curve reported in reference 1 calling for a very much higher degree of damping at the higher values of ϕ/v_e more nearly agrees with the pilot opinion. When these characteristics were looked at from many viewpoints with the use of other criteria, it was found that one of the primary sources of pilot satisfaction or dissatisfaction was the ratio of roll to yaw, as this curve indicates. It was found that the airplanes could actually be separated into two general regions depending on the value of the ratio of rolling rate to yawing rate. Figure 8 goes back to the original requirement of time to damp to one-half amplitude as a function of period for airplanes having values of roll-to-yaw ratios less than 4. These data show that this requirement would be quite adequate. It is indicated that for general flying, not the close flying of gunnery or bombing, the pilot would tolerate less damping where the period was high. However, in considering the case of roll-to-yaw ratios greater than 4, as shown in figure 9, it can be seen that, regardless of the damping, the airplanes are generally unsatisfactory. In obtaining data on a subject like this, of course, there are many influences. However, on the basis of these data and what might be called general pilot opinion on the flying of any particular airplane, high ratios of roll to yaw are very objectionable to the pilot since any correction in yaw or a side gust results in excessive rolling which causes changes in heading.

Lateral control.- The lateral-control requirements and changes made thereto along with the increase in speeds of the airplanes have always, up to now, resulted in increasing roll velocities and increasing rolling accelerations. During the past year or two, however, the rates have become high enough to be in resonance with the pitch and/or yaw frequencies of the airplanes so that a serious roll-coupling problem on a number of airplanes has resulted. Calculations have shown that the value of the roll rate as well as the angle of bank reached has, of course, very serious effects upon the degree of roll coupling that exists, or at least on the motions resulting from roll coupling. It is indicated that a reduction

in either roll rate or angle of bank reached during a roll, or both, will have very beneficial effects on the roll coupling to the point that it could be relegated to a very restricted portion of the flight envelope; it might be added that these calculations also showed that increasing the damping in pitch had a very beneficial effect on the roll coupling. In any event it appeared to be of urgent importance to reexamine carefully the roll requirements, both at high and low speeds. A number of flight and analog investigations bearing on this problem have been carried out at the NACA High-Speed Flight Station and at the Langley Aeronautical Laboratory. The findings from these investigations are summarized in figures 10 to 12. This, incidentally, is one of the problems discussed quite thoroughly with military pilots.

Figure 10 presents a summary of the aileron control characteristics for a typical airplane at a Mach number of 0.8 and altitude of 30,000 feet. Maximum rolling velocity and time to roll to 90° are plotted as a function of total aileron deflection.

The solid line indicates the minimum time required to pass through 90° bank angle. It is apparent that above an aileron deflection of 20° a region of diminishing returns is present. Note that this airplane would barely meet the present specifications of 100° change in bank angle in one second with maximum aileron deflection. This curve does show the difficulty of making a test to prove this requirement since the time measurement requires very high accuracy because of the small slope of t with δ_a. It also shows that the designer may have to double the aileron power to gain 1/10 second in time to reach a given bank angle.

Another manner in which the aileron capabilities have been evaluated is by not only including the time to accelerate and roll through a given bank angle but also to include the time required to become reasonably stabilized at the desired bank angle. This time designated t^* is of considerable significance when making offensive or tracking maneuvers. The dashed curve represents the average time required by pilots to complete rolls from a 45° bank turn to 45° in the opposite direction. It would appear that the time t^* decreases with aileron deflection until about 21° of total aileron is used; above this deflection the time required increases fairly rapidly. This was primarily attributable to overshoot. The aileron deflection for minimum t^* agreed very well with the pilots' opinions of the optimum aileron required for the 90° maneuver. The peak roll velocity attained for optimum conditions in this maneuver would be about 2 radians per second and it is evident that the ultimate roll rate is fairly well developed in 90°. It should also be mentioned that studies of this type covered a Mach number range of 0.7 to 1.2 for this airplane and the t^* curves and accompanying pilot impressions did not appreciably change over the entire speed range.

In figure 11 is shown one type of analysis of aileron requirements based on this investigation. Maximum roll velocity is plotted as

ordinate and maximum roll acceleration as abscissa. These quantities were obtained from 90° maneuvers of the type summarized in figure 10. The approximate test envelope is shown by the dashed line. If in figure 10 the regions of t that are less and greater than 1.75 seconds are arbitrarily separated, the flight envelope of figure 11 is divided as shown into three regions: a region of perhaps too slow response for general use, a region in which combinations of roll acceleration and roll velocity produced satisfactory results, and a region of roll velocity and acceleration that was obviously too much for the average pilot to cope with. As a point of interest the center of the satisfactory range is defined fairly well by a value of $p_{max} = 2$ radians per second and a value of $\dot{p}_{max} = 5$ radians per second squared.

A flight and analog investigation of the aileron power required for visual tracking in pursuit-type attack and evasive maneuvers has been completed at the Langley Aeronautical Laboratory. The flight investigation was necessarily restricted to subsonic speeds. A similar flight study is under way at the NACA High-Speed Flight Station and will include work at supersonic speeds.

The analog-computer investigation consisted of a determination of the theoretical values of rolling velocity and rolling acceleration required of an attacking airplane in order to follow a target airplane during various turn entry maneuvers. Some results of this investigation are plotted in figure 12. These results show that in the target maneuvers involving 90° bank, the rolling velocity and rolling acceleration required of the attacking airplane decrease rather rapidly as the range increases. When the target makes a 180° roll, however, the rolling velocity and rolling acceleration required of the tracking airplane are considerably greater and do not decrease rapidly with increasing range. The values of rolling velocity and rolling acceleration obtained from these analog-computer studies are in good agreement with those obtained from flight tests under similar conditions. It therefore appears that the rolling requirements of an attacking airplane can be determined on a rational basis by means of analog-computer studies of this type. Also, the analog computer allows studies of a much wider range of conditions with closer control of the variables than is possible in flight tests. Extension of these calculations to supersonic speeds and to cases in which the attacker is overtaking the target is now in progress. Results obtained so far for a Mach number of 1.4 show that values of rolling velocity about 50 percent greater than those plotted in figure 12 are required in order to follow similar target maneuvers.

Interviews with military pilots indicated that as far as high-speed control was concerned they felt the present airplanes had more aileron control than they would ever use. They found it hard to recall any case where they had hit the stops in using ailerons at high speeds. They generally felt that the deflection could be cut down without serious

effect. They felt, further, generally speaking, that not over 180° of bank angle would be required in any tactical maneuver. There were a few holdouts but the general concensus was that if the airplane were satisfactory within this bank-angle range the tactical mission would not be restricted. Since it has been established that, for high-speed flight, aileron power was greater than required, the low-speed case should then be considered; that is, the take-off and landing as well as whatever low-speed maneuvering may be required in flight.

Rudder-fixed rolls were made at V_i = 160 knots with landing gear down with two airplanes. The roll specification for low-speed flight calls for an average $pb/2V$ of 0.05 for the first 30° of bank.

One of these airplanes had an average $pb/2V$ of 0.036 for the first 30° of bank and the pilots feel the lateral control to be entirely adequate for low-speed flight.

The other had an average $pb/2V$ for the first 30° of bank angle which was about 60 percent of the required minimum of 0.05 (about 0.03). This is brought about by a reduction in aileron effectiveness at the high angle of attack (11°) and adverse sideslip coupled with relatively high dihedral effect. Some pilots consider this airplane to have marginal lateral control power for landing.

Actually, it appears that, for the most part, present-day airplanes have sufficient lateral control power; however, consideration has to be given to cross-wind landings and take-offs and need for counteracting wakes of other airplanes during the close-pattern landings which appear to be a military requirement. It is felt that the present low-speed lateral-control requirement is perhaps unrealistic in that it could not be met on current airplanes which the pilots felt were satisfactory.

Rudder control.- Among other studies has been the use of rudder during high-speed maneuvers. It appears for the high-speed roll case that the pilot has a very difficult time coordinating any maneuver with the use of rudder because of the high roll rates. Also, because the airplane rolls about an axis inclined to the flight path with the cockpit usually well forward in the airplane, it is possible for the ball-bank indicator, which is one way of the pilot's knowing what sideslip is occurring, to give him fallacious indications with the result that perhaps the control introduced based on reading of the ball would be in the wrong direction. The pilot, of course, is undergoing the same acceleration forces. However, this does not mean that the rudder is not useful to the pilot in supersonic flight. It has been found that some pilots use the rudder quite a bit either to help damp high-speed lateral oscillations or to account for lateral trim changes that may occur in transonic or supersonic flight.

Control-System Characteristics

Research on power control systems has been continued using both theoretical methods and ground simulator studies in an attempt to formulate requirements for satisfactory characteristics. It is realized that because of the large number of variables affecting the characteristics of a power control system, a simple requirement for control friction or breakout force will not be adequate to rule out all unsatisfactory conditions.

A study is being conducted, using a ground simulator known as the pitch chair, to determine the boundaries between satisfactory and unsatisfactory regions in terms of such control-system parameters as valve friction, flexibility, backlash, and so forth.

Figure 13 illustrates some of the results obtained in this study. This figure shows a sketch of the control system which is being used. Provisions are made to add static friction to the control stick, static friction at the valve, and flexibility between the control stick and the valve. It should be noted that in this case the control feel device, which is a simple spring, is located at the control stick ahead of the region where flexibility is present. The curves in the lower left-hand part of the figure show the case for a rigid control system. At very low values of friction, less than 1/2 pound, conditions are considered to be tolerable though not entirely satisfactory because small movements of the airplane can cause the pilot to apply inadvertent control motions as a result of inertia of his hand and arm. Increasing values of valve friction in this case are acceptable provided the stick friction remains greater than the valve friction. This is true because the stick friction will then serve to center the valve and prevent the power control system from motoring in the absence of the pilot's inputs. However, when the combined values of stick friction and valve friction exceed approximately 3 pounds, the pilots considered the characteristics to be unsatisfactory because of the difficulty of making small control corrections when the breakout force exceeded 3 pounds.

The right-hand part of figure 13 shows similar results for the case in which flexibility is present between the control stick and the valve. In this case any amount of valve friction exceeding about 4 ounces at the control stick led to very unsatisfactory control characteristics. The introduction of flexibility ahead of the feel device, however, gave results more nearly similar to those in the left-hand part of the figure.

CONCLUSIONS

A few tentative conclusions can be drawn from the investigations which have been discussed. It appears that increased damping in pitch

should be provided in modern airplanes. This damping could be artificial since airplanes meeting the present requirements without artificial damping, although unsatisfactory, are not considered dangerous. Increases in damping in pitch will not only improve dynamic longitudinal stability but will improve longitudinal characteristics in maneuvers made with large speed losses as well as alleviate the roll-coupling problem. The exact degree of longitudinal damping desired is the subject of study at present and it is not possible to state the exact requirement.

It appears that trim changes involved in force changes of less than 10 pounds will not be extremely undesirable to the pilot; however, the more nearly the case of true stability with speed, that is, increase in push force for increase in speed, the more desirable the airplane will be. In the case of speed losses during maneuvers from supersonic to subsonic speeds it appears that one of the primary factors involved is the trim changes with speed coupled with low damping, so if effort is made to satisfy this case there will be improvement in the maneuvering characteristics. It is difficult at this time to state any definite requirement.

For a case of dynamic lateral stability the pilots are not satisfied with airplanes having high roll-to-yaw ratios and the results indicate that any airplane having a roll-to-yaw ratio greater than 4 will be considered undesirable by the pilot.

For the high-speed case, the lateral-control requirements can probably be relaxed - in fact, appreciably reduced. Study should be made of the mission the airplane is expected to perform. For the present it appears that the low-speed requirements are very stringent and some relaxation could be tolerated.

For a rigid power boost system some valve friction can be tolerated if there is greater stick friction. The combination of the two should not exceed 3 pounds. For a system having flexibility, the requirements for valve friction are very stringent if the feel system is at the stick. Placing the feel system at the valve results in requirements similar to those for the rigid case.

High-Speed Flight Station,
National Advisory Committee for Aeronautics,
Edwards, Calif., November 2, 1955.

REFERENCE

1. Liddell, Charles J., Jr., Creer, Brent Y., and Van Dyke, Rudolph D., Jr.: A Flight Study of Requirements for Satisfactory Lateral Oscillatory Characteristics of Fighter Aircraft. NACA RM A51E16, 1951.

LIBRARY NACA - HSFS

PITCH DAMPING OF SEVERAL AIRPLANES
hp = 10,000 TO 50,000 FEET

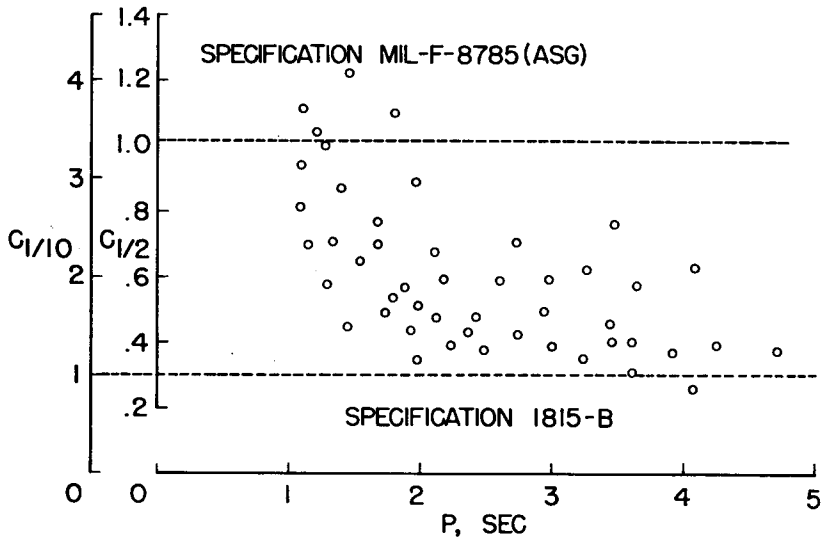

Figure 1

LONGITUDINAL TRIM CHARACTERISTICS OF SEVERAL AIRPLANES

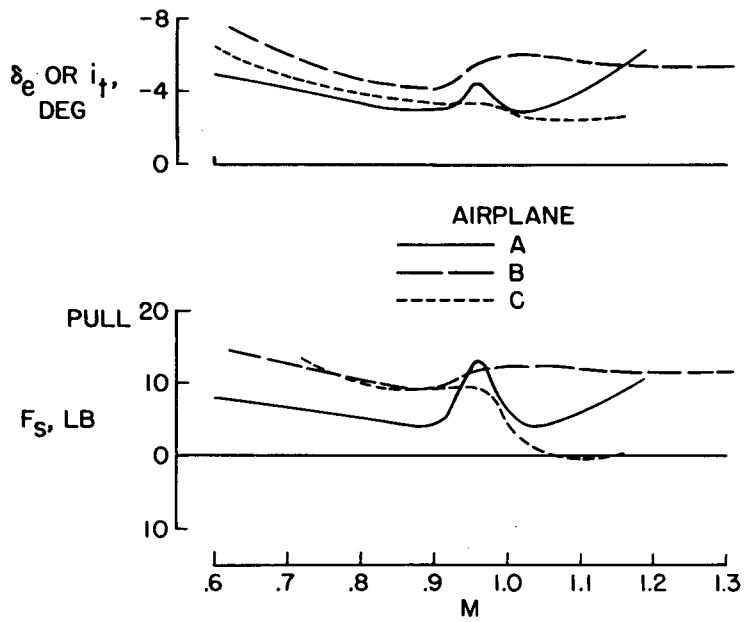

Figure 2

LIBRARY NACA - HSFS

LONGITUDINAL CHARACTERISTICS IN ACCELERATED MANEUVERS

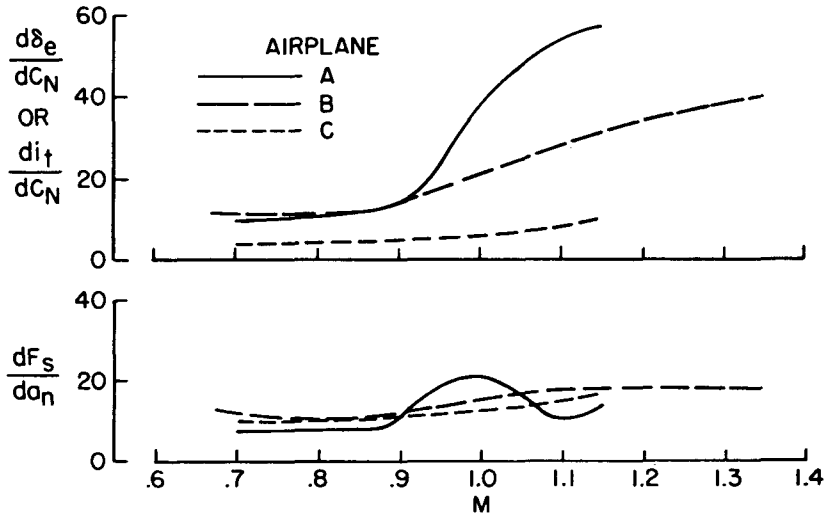

Figure 3

EFFECT OF CONSTANT g DECELERATION
AIRPLANE A

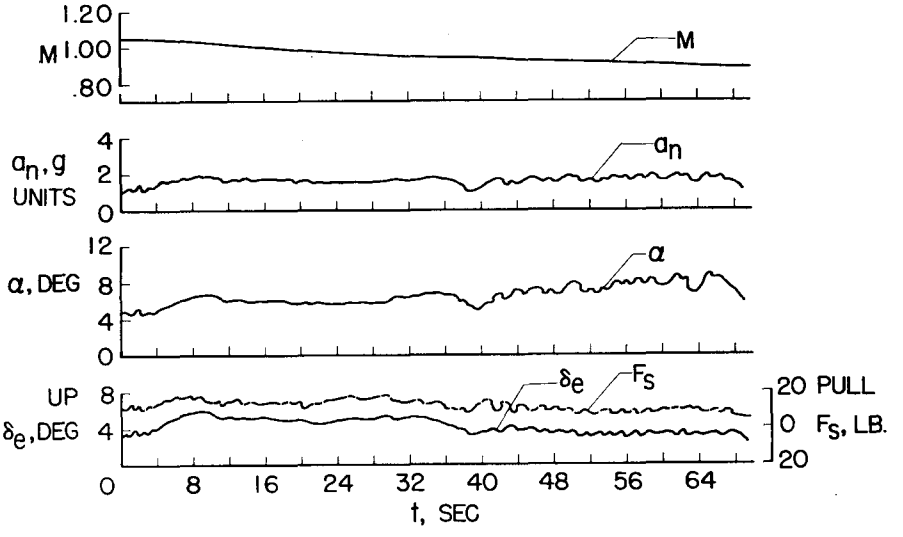

Figure 4

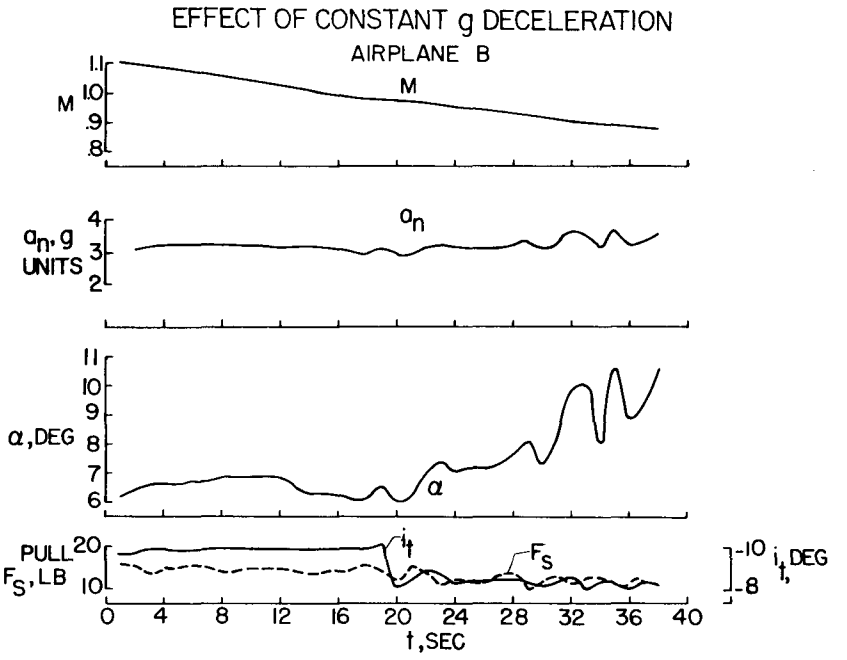

Figure 5

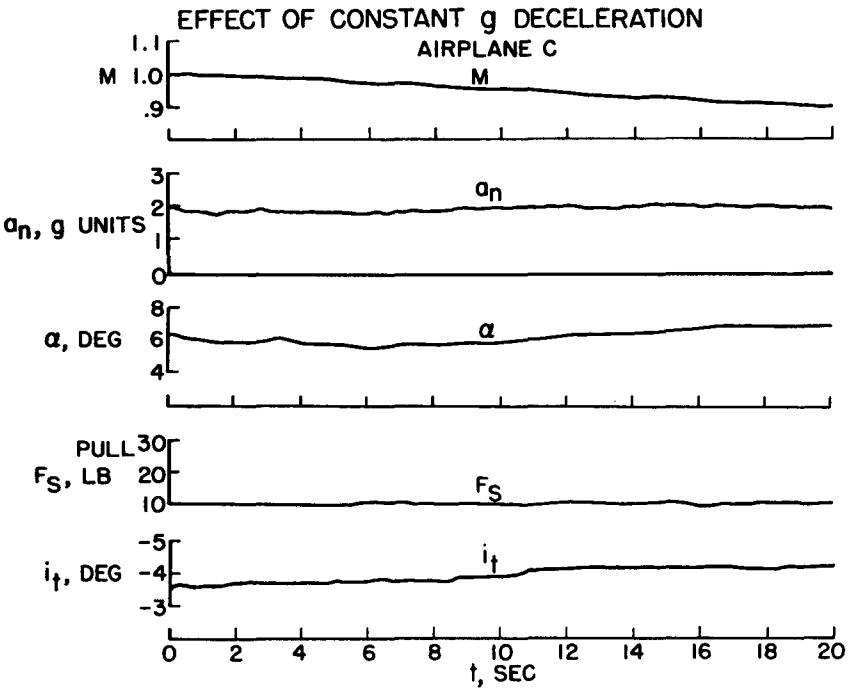

Figure 6

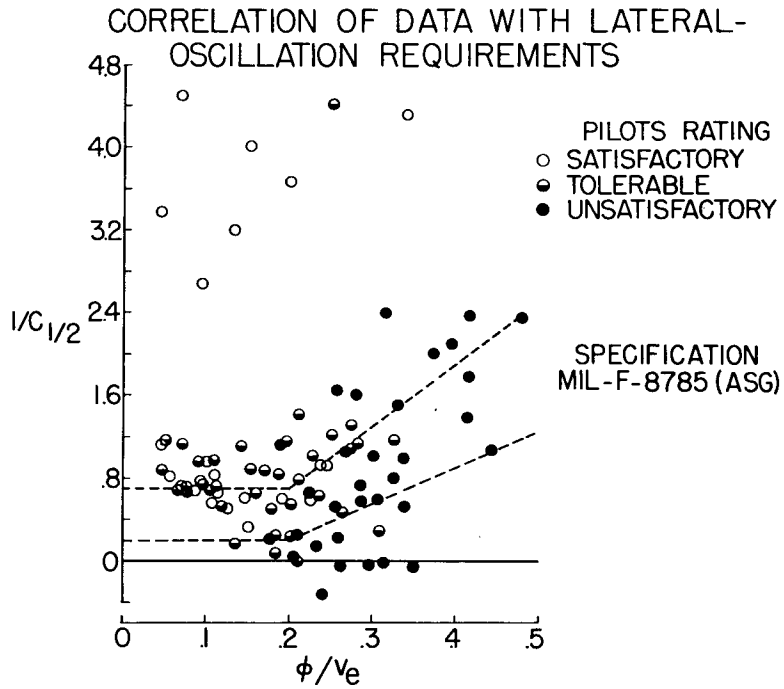

Figure 7

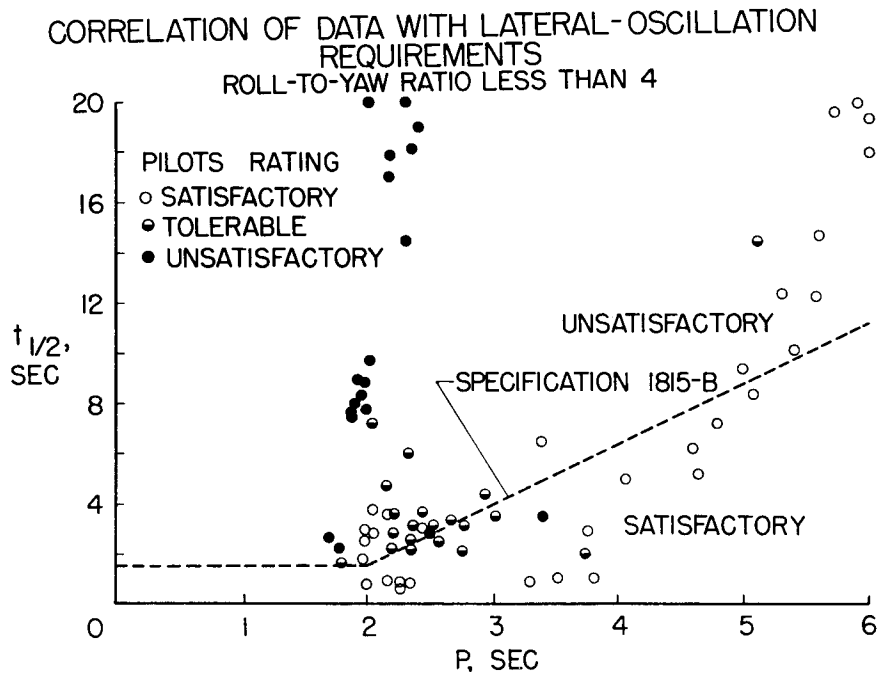

Figure 8

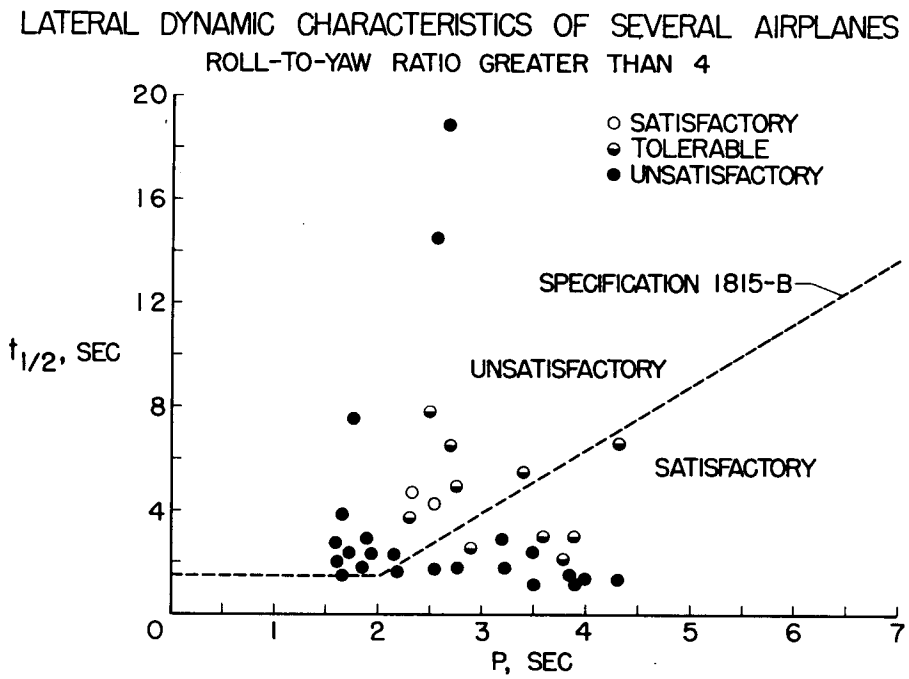

Figure 9

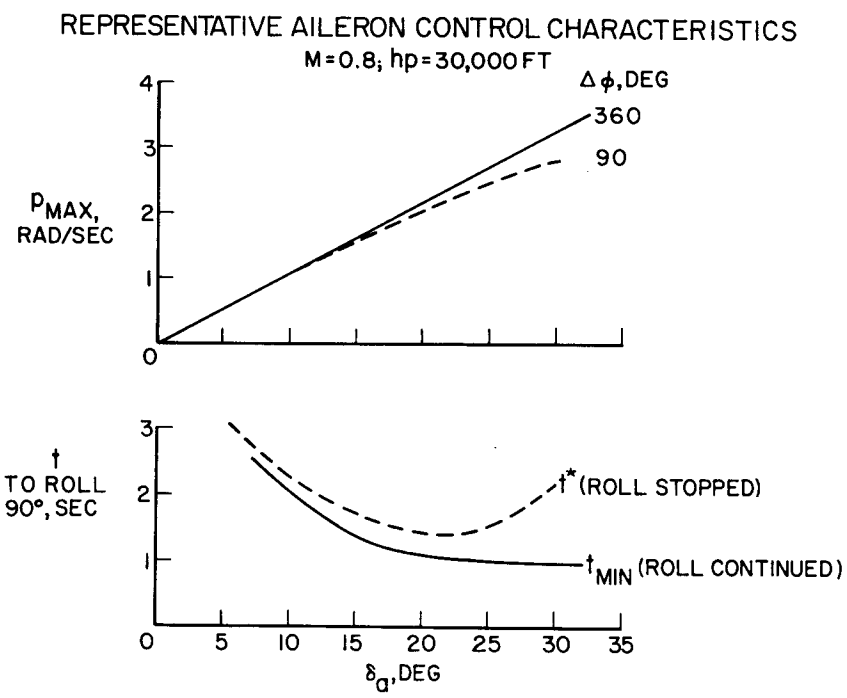

Figure 10

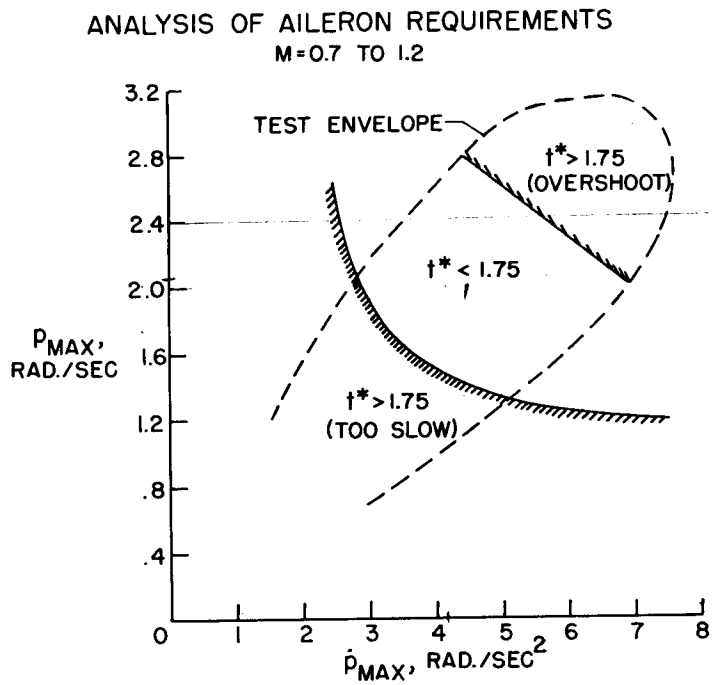

Figure 11

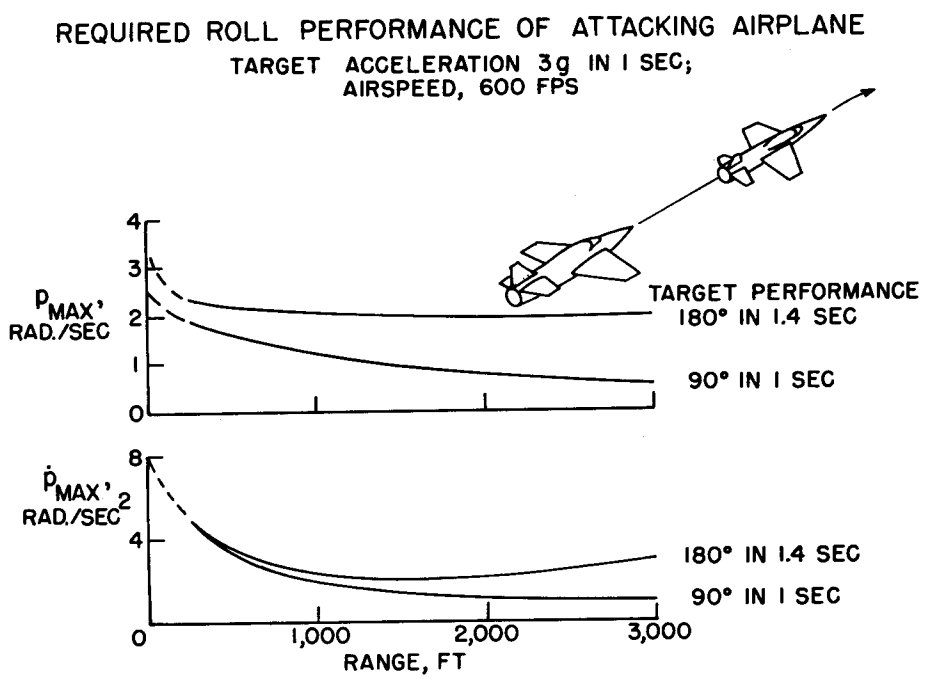

Figure 12

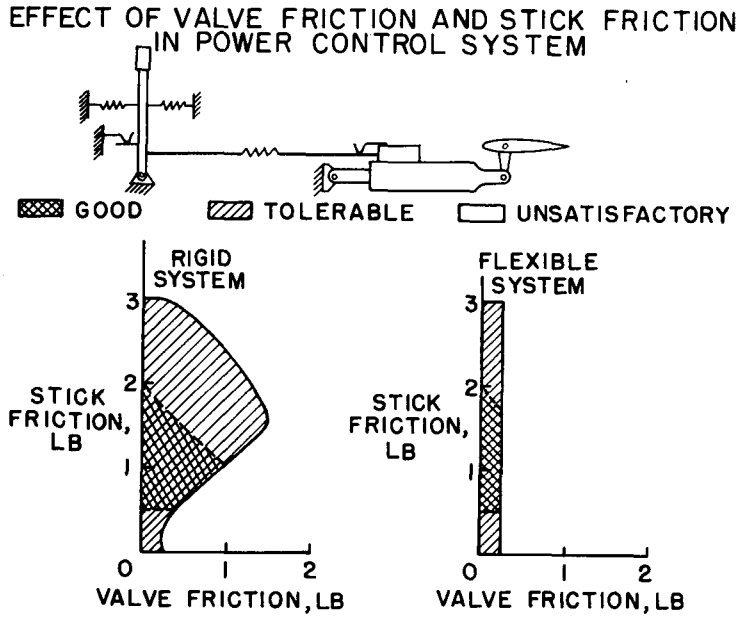

Figure 13

NACA - Langley Field, Va.