UNCLASSIFIED CONFIDENTIAL

NACA RM A57L10

c2

NACA

RESEARCH MEMORANDUM

A FLIGHT STUDY OF LONGITUDINAL-CONTROL-SYSTEM DYNAMIC CHARACTERISTICS BY THE USE OF A VARIABLE-CONTROL-SYSTEM AIRPLANE

By Norman M. McFadden, Frank A. Pauli, and
Donovan R. Heinle

Ames Aeronautical Laboratory
Moffett Field, Calif.

CLASSIFICATION CHANGED

To UNCLASSIFIED

By authority of Nasa TPA 9 Date Effective 9-1-59

NB 12-3-59

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

March 3, 1958

CONFIDENTIAL

UNCLASSIFIED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

A FLIGHT STUDY OF LONGITUDINAL-CONTROL-SYSTEM DYNAMIC CHARACTERISTICS BY THE USE OF A VARIABLE-CONTROL-SYSTEM AIRPLANE

By Norman M. McFadden, Frank A. Pauli, and
Donovan R. Heinle

SUMMARY

Flight tests have been conducted with an airplane equipped to vary the longitudinal-control-system dynamic characteristics over a wide range. Control is obtained through a stabilizer force-command position-feedback longitudinal-control system. The break-out force, the sensitivity, and the control-system time constant can be varied over wide ranges.

For the flight conditions tested it was found that with the proper selection of control-system dynamic characteristics the static stick force per g (the steady-state gain) was relatively unimportant. Regardless of the static stick force per g or the flight conditions, the pilot would select control-system dynamic characteristics to yield more or less identical dynamic normal-acceleration responses of the airplane to stick force input. It was calculated that the control-system characteristics selected by the pilot would yield a normal acceleration response of about 0.09g in the first second in response to a 1-pound step in stick force input.

INTRODUCTION

In order to furnish adequate control for high-speed aircraft irreversible power controls have been used. With such controls various artificial-feel devices are employed to assist the pilot in applying the necessary control motions. In most cases these systems have been made to simulate as closely as possible the steady-state control forces with which the pilots are familiar and which provided satisfactory control for earlier and slower aircraft.

Since the dynamic-response and -feel characteristics of these control systems can be adjusted at will, there is now an opportunity to select these characteristics to optimize the performance of the complete pilot-control-aerodynamics system. Each of the elements of the over-all system is being studied in typical tasks encountered in flight. The dynamic response of the human being has been considered in many reports, references 1 and 2 among others. With the use of the variable-stability airplane technique, optimum short-period longitudinal aerodynamics have been investigated as discussed in reference 3 and optimum lateral-directional oscillatory characteristics have been investigated as discussed in reference 4. In each of these cases the study was made for a specific control system. Studies of control-system dynamic-response parameters are illustrated by references 5 and 6.

Combining the ability to vary control system and aerodynamic parameters in one flight-test vehicle makes possible the investigation of optimum combinations, from the flying-qualities point of view (mapping areas of varying pilot opinion and proficiency). It also appears possible to use conventional servomechanisms theory to try to understand the reasons for the pilots' opinions and techniques.

At the Ames Aeronautical Laboratory a jet fighter-type airplane was equipped with a longitudinal-control system wherein stabilizer position was commanded through a servo system by stick force. By use of this equipment the break-out force, system time constant, and system gain (i.e., stabilizer angle per unit stick force) could be varied over wide ranges. The original mechanical link between stick and stabilizer valve was left intact for safety reasons. Thus the stick position followed stabilizer motion through the normal system control valve; however, because of the slack (due to valve motion) this was not expected to compromise the primary force-command feature.

This report presents a study to determine acceptable dynamic-response characteristics of the longitudinal-control system in which the static gain (stick force per unit acceleration), break-out force, and time constant can be varied over wide ranges. A limited variation of airplane basic aerodynamic response characteristics was obtained by changing flight conditions. General flying qualities, tracking, and formation flying were used in evaluating the control system. The pilots were also instructed to consider three general problems which have been encountered in power control systems: (1) break-out forces large enough to be objectionable and to make small precise control applications difficult, (2) sensitivity which makes it difficult to avoid persistent small amplitude oscillations, and (3) pilot-induced oscillations of a divergent nature.

NOTATION

$\frac{F_s}{g}$ stick force per g, lb/g

g acceleration due to gravity, ft/sec^2

M Mach number, ratio of forward velocity to speed of sound

V volt

τ equivalent first-order time constant, sec (time to reach 63 percent of the steady-state value in a response to a step input)

TEST AIRPLANE

A YF-86D airplane (fig. 1) was used for this investigation. Longitudinal control of this airplane is achieved by means of an all-movable horizontal stabilizer. For the purposes of this research project, the operation of the longitudinal-control system was modified. Figure 2(a) is a mechanical hydraulic schematic diagram of the longitudinal-control system as originally designed by North American Aviation, Inc. It will be noted that the stabilizer is driven from a hydraulic actuator which consists of two pistons in series. Two mechanical valves are mounted on the body of the actuator. One piston and its valve is utilized for normal operation; the other piston and its valve is used for emergency operation. Only one piston and valve combination is in use at a time; the unused pair is hydraulically bypassed. Identical performance is achieved by either system. A mechanical linkage connects the pilot's control stick to a preloaded bungee. Both valves are then connected to the push rod so that they both follow the stick motion, although only one valve ports oil to its piston in a particular mode of operation. The actuator piston is connected to the airframe and the actuator body to the stabilizer in the conventional fashion, so that as the stabilizer moves in response to valve opening, the actuator body moves also with respect to the linkage from the control stick, and the valve is thereby closed. The gearing between control stick motion and stabilizer motion is 2.3° of stabilizer per inch of stick travel at the pilot's grip. This gives a static gain of 0.38 pound per g at the test condition of $M = 0.80$ and 35,000 feet altitude. Full stabilizer travel is 23° corresponding to 10 inches of stick travel. A stick travel of 0.2 inch corresponds to full opening of the valve; that is, if the actuator were locked, the pilot could move the stick only 0.2 inch before the valve lever hit its mechanical limit. Any additional force then exerted by the pilot would result in further stick motion only to the extent allowed by cable stretch.

For this investigation, the emergency valve was replaced by an electrically operated servo-control valve as shown in figure 2(b). The normal stabilizer drive system was left unchanged. During the research portions of the test flights, the stabilizer hydraulic control was switched to the emergency mode so that the servo valve drove the emergency portion of the actuator while the normal portion was hydraulically bypassed. The normal system was used for take-off and landing. Figure 3 is a functional block diagram which indicates how the stabilizer was operated during research tests in which a 400 cycles per second servo system was used. It will be noted that there is no mechanical feedback from the stabilizer to the servo valve so that the flow of oil to the actuator is dependent only on the electrical input to the valve. The strain gage on the pilot's stick generates an electrical signal, V_{out}, proportional to the force exerted by the pilot. This signal drives the stabilizer to a position which is measured by the follow-up pickoff (angular position transducer) which generates an electrical signal to balance out the strain-gage signal. Thus the stabilizer deflection is proportional to the signal existing at the input to the servo loop. This command signal will be directly proportional to stick force only when the modifying elements in the path between the strain gage and servo-loop input are at their "no effect" position. The dead zone which simulates a break-out force is electrically achieved by the use of biased diodes and performs as indicated below its block in figure 3. The break-out force is variable by the pilot in flight from 0 to a maximum value of 25 pounds. The time-constant function is provided by an RC network (preceded by a demodulator and followed by a modulator). The time constant of this network is variable by the pilot from 0 to 4 seconds. The static force gain control is variable from 1° per pound to 0.04° per pound. In deference to aerodynamic convention, the static gain of the system in degrees of stabilizer per pound of stick force is usually given in inverted form as pounds per degree. Since for tests at a particular flight condition the steady-state normal acceleration of the airplane is directly proportional to stabilizer deflection, the over-all gain is stated as pounds per g. Examination of figure 3 indicates the manner in which the stabilizer position follows stick force as modified by static force gain, break-out force, and time constant, all of which are adjustable by the pilot.

Attention should be called to the fact that the stick has been left mechanically connected to the push rod, bungee, and normal valve input lever (fig. 2(b)). This means that force applied to the stick will be opposed by the bungee and bob-weight. Also as noted previously, in absence of stabilizer motion, the stick displacement is limited by the travel of the normal valve input lever. When the control system is operated in the research mode, the position of the normal valve input lever has, of course, no effect on oil flow. When the stabilizer moves in response to the electric valve, it pulls the actuator body, including the normal valve, along with it. This then allows the stick to move. In fact, the stabilizer now drives the stick (except for the 0.2-inch mechanical clearance provided by the movement of the normal valve input lever between its limits). The over-all operation thus consists of three steps:

1. The pilot applies force to move the stick against the bungee force.

2. The strain-gage signal moves the stabilizer and tends to back the normal valve out of the way so that its input lever is not bottomed.

3. This operation continues until the stabilizer reaches the angle called for by the stick force input. At this time the stick has moved a distance equivalent to the stabilizer motion, with the uncertainty provided by the mechanical clearance of the normal system valve. The stick force is balanced by the bungee and bob-weight forces and possibly by an additional force on the normal system valve stops if the valve is bottomed.

Since the servo valve is very fast acting compared to the unmodified system, the stabilizer to stick linkage does not ordinarily bottom the normal valve and the only forces felt by the pilot are those due to the bungee. However, it should be noted that the possibility of bottoming the normal valve and thus introducing extraneous forces does exist if the pilot attempts to introduce extremely rapid motions at low settings of static stick force per g. Whether or not the normal valve is moved out of the way of the valve lever depends upon a number of factors, that is, the relative magnitude of the gain, break-out force, and time constant in the experimental system and in the normal system, as well as the rate of control application and the magnitude of the control motion. Although valve bottoming was not generally encountered during the research flights, the possibility should be kept in mind when considering the possible implications of results obtained at certain extreme control-system settings.

It is not felt that the bob-weight effect is important in the test system because the stick motion is controlled by the stabilizer motion. For small stick forces the break-out force of the normal system (about 7-1/2 lb) is large enough that any force produced by the bob-weight will not move the stick, but merely transfer some of the load from the bungee to the bob-weight. For large stick forces calling for large stabilizer motions, the motion of the stick is controlled primarily by the stabilizer and the bob-weight effect will not materially change the stick motions.

The performance characteristics of the servo system are shown in figure 4. The curve marked "basic system" is an experimental frequency response of the modified longitudinal-control system utilizing the electric valve with the "basic electronic system" (all the modifying factors in the stabilizer input channel at their "no effect" settings). When the time-constant control is used in the command channel there is a first-order lag added to the system. For values of the time constant in the command channel above about 0.5 both the amplitude ratio and the phase lag introduced will be appreciable in the low frequency range in which the system is normally operated. Thus the over-all response with fairly large values of time constant added to the command channel will very closely resemble that of a first-order system. For this reason it seems convenient to describe the system by the "equivalent first-order time constant" which is the time required for the output to build up to 63 percent of its final value in response to a step input. A transient-response test of the basic system showed an 8-percent overshoot and reached 63 percent of the final value in 0.15 second; hence, this basic system is considered to have an equivalent first-order time constant of 0.15 second and is so labeled in figure 4. Other curves of figure 4 show the actual response of the system for various values of the equivalent first-order time constant. The term "time constant" as used in this report will mean the equivalent first-order time constant as described above.

Since the addition of break-out force immediately makes the system nonlinear and a plot such as figure 4 is impossible without specifying the amplitude of the motions being imposed on the system, no attempt is made to specify the system in such a manner when break-out force is used.

The following quantities were measured with standard NACA instruments: airspeed, altitude, and angular velocity about all three axes. Stabilizer position, stick position, stick force, angle of attack, and sideslip angle were recorded on an oscillograph. The records of the various instruments were synchronized by a 0.1-second timer trace on all records.

TESTS

In conducting the flight tests the pilots were instructed to select the best available and the maximum and minimum usable values of the control-system time constant for specific values of static stick force per g and break-out force. The control system was evaluated by checking the over-all response and controllability in flight maneuvers involving tracking a distant target, rapid entry into turns, and rapid return to straight and level flight following small deviations. In addition spot checks of the time constants determined in the above maneuvers were made in formation flight.

For the initial series of tests a Mach number of 0.80 and an altitude of 35,000 feet were chosen to give a condition of relatively poor longitudinal aerodynamic characteristics. The undamped natural frequency was 0.63 cps and the damping ratio was 0.21, defined in reference 3 as unacceptable. Later flight tests were made at an altitude of 5,000 feet and a Mach number of 0.35 to improve the dynamic characteristics. This flight condition yielded an undamped natural frequency of 0.57 cps and a damping ratio of 0.36. Figure 5 locates these points on a plot showing pilot opinion of handling qualities determined in reference 3. The change in flight conditions brought the aerodynamics from the unacceptable to the acceptable region of the plot.

RESULTS AND DISCUSSION

By varying the control-system time constant the pilots found that at low values of the time constant the system was very sensitive with a tendency to overcontrol. There were small persistent oscillations present which the pilot was unable to damp out. As the time constant was increased beyond a certain point the controllability diminished, excessive lag developed, and large forces were required to maneuver rapidly. The best available time-constant settings were between these two limiting conditions.

Mach Number of 0.80 at 35,000 Feet Altitude

The first flight conditions to be discussed will be those at 35,000 feet altitude at a Mach number of 0.80. At this flight condition the control characteristics of the airplane were considered to be marginal, a natural frequency of 0.63 cps and a damping ratio of 0.21. Figure 5 shows that the work of reference 3 would also indicate this condition to be unacceptable from the control standpoint. The time constants between stick-force application and stabilizer response which were selected by the pilot are presented in figure 6 as a function of stick force per g and in figure 7 as a function of break-out force. Three values of time constant are shown - the maximum acceptable, the best available, and the minimum acceptable.

Best available time constant.- The best available values of time constant will be considered first. It was found that the pilot could not adequately compensate for the undesirable aerodynamic characteristics of the airframe with the variables provided in this study. On the basis of the rating system of reference 7, shown in figure 8, the best combination he could select at this flight condition was rated 4, that is, acceptable but with unpleasant characteristics.

Figures 6 and 7 show that in these flight conditions the pilot chose surprisingly large time constants. This was particularly true at the lower values of stick force per g and break-out force. At 4 pounds per g and zero break-out force the pilot chose a time constant of about 2 seconds and would tolerate values ranging from 0.9 to 3.5 seconds. As the stick force per g or break-out force was increased, the selected time constant became lower.

The pilot reported that an increase in the time constant felt like an increase in damping in the control system. This feeling of damping comes from the fact that when rapid control movements are initiated, an increase in the control-system time constant requires an increase in the control force necessary to move the control at the same rate. This increased force required for the same rate of stick motion is interpreted by the pilot as an increase in damping in the control system.

Figure 9 shows the calculated normal-acceleration response of the airplane to a step input in stick force for two values of the control-system time constant. These calculations were made on the assumption that the aircraft response is a second-order system and the control system is a first-order system. With the low time constant there is a rapid response with considerable overshoot. As the time constant increases, the response to the stick-force inputs is slower with no overshoot. This does not serve to increase the damping of the airframe itself, which is still poorly damped to inputs from external disturbances, but it does give apparent damping to control force inputs in that it does not allow rapid stabilizer motions.

Minimum acceptable time constant.- The minimum acceptable time-constant boundary corresponded to a sensitivity problem - small continuous oscillations were encountered which were difficult or impossible for the pilot to control. Figure 10 shows several time histories of the stick force, the stabilizer motion, and the airplane normal acceleration during 1g tracking runs. In figures 10(a) and 10(b) there is a regular and persistent oscillation that definitely seems to be an instability of the combined system, including the pilot's response. This is the short-period oscillation that the pilots found to be objectionable. Figure 10(c) shows for comparison a similar run for a time constant near the best available for this flight condition. The pilot still found it necessary to use persistent control application but it was no longer a regular oscillation and he was able to control the acceleration better.

On one entry into an abrupt turn in formation flight with a time constant of 0.15 second and a stick force of 4 pounds per g, an oscillation of about 1g was encountered which was difficult for the pilot to damp out. A time history of this particular run is presented in figure 11. In this instance the oscillation seems to be driven by the rather large and rapidly applied stick forces which the pilot was not able to phase properly to stop the oscillation. At higher dynamic pressures where the airframe natural frequency is higher, the response to stabilizer motion would be greater and the pilot would have even greater difficulty in properly phasing his applied stick forces and such an oscillation could possibly build up to disastrous proportions.

The pilot also noticed what he called "feedback" in the control system when flying at low values of time constant, stick force per g, and break-out force. When moving the controls rapidly they would feel extraneous forces in the stick which seem to be associated with bottoming of the normal system valve. The addition of small amounts of either time constant or break-out force would minimize this condition.

Maximum acceptable time constant.- As the time constants were increased above the best available setting, the "apparent damping" of the control system would increase and the response of the airplane to stick forces would become sluggish. The maximum time-constant boundary corresponded to the point at which the pilot felt that the response of the airplane was too slow and the forces required for initiating a maneuver were too large. The pilot described the effect of large time constants as "making the plane feel like flying the DC-3."

Stick force per g and break-out force.- The pilot found that the values of static stick force per g were relatively unimportant as long as a suitable time constant could be selected. It only seemed necessary to keep the maximum forces for the maneuver within reasonable bounds. Also, as long as the break-out force was kept below about 2 pounds its actual value seemed to make little difference to the pilot since he could compensate for variations in both break-out force and static stick force per g by selecting a time constant that would result in satisfactory aircraft response.

Mach Number of 0.35 at 5,000 Feet Altitude

The results presented thus far have been for the airplane with a fairly high natural frequency and low damping (natural frequency of 0.63 cps and a damping ratio of 0.21). To determine if the previous selections of large time constants were an effort to counterbalance these poor airframe dynamic characteristics, more limited tests were conducted at a Mach number of 0.35 at an altitude of 5,000 feet. Here the aircraft undamped natural frequency was 0.57 cps and the damping ratio was 0.36, which, according to figure 5, should be acceptable.

At this flight condition it was again possible to find values of the control-system time constant that were either low enough to cause a sensitivity problem or high enough to make the response of the airplane sluggish. The results are shown in figure 12. The control-system dynamics selected by the pilot definitely appear to vary with the airframe dynamics. There is a tendency to select lower time constants than those in the tests at the higher altitude. This suggests that in the previous flight condition the pilot was attempting to compensate for poor airframe dynamics by choosing different control-system characteristics.

Normal-Acceleration Response

It has been shown that the pilot modifies his selection of the control-system time constant as stick force per g, break-out force, and airframe dynamics are changed. In an attempt to establish the parameter that the pilot is trying to optimize by his selection of desirable control-system time constants, it is desirable to consider the over-all response of the airplane. Since there is no doubt that the pilot is responsive to normal acceleration, it seems reasonable to examine the normal-acceleration response of the airplane to stick-force inputs under these conditions.

The aircraft was assumed to be a second-order system and the control system to be first order. The normal-acceleration response to a step input in stick force was calculated for the values of control-system time constant that the pilot selected as the maximum, the minimum, and the best available for both flight conditions. Figure 13 shows the calculated responses for a static stick force per g of 4 pounds and zero break-out force. The comparison of the initial acceleration response for the two flight conditions shows good agreement.

Figure 14 presents the calculated initial response of normal acceleration for various values of static stick force per g. From these data it would appear that the pilot uses the initial response of the airplane to stick force as a criterion for selecting the desirable control-system dynamics, regardless of the static stick force per g or the airframe dynamic characteristics.

Figure 14 indicates that the pilot prefers a dynamic airplane response of about 0.09g per pound the first second after a force application. If the response reaches about 0.15g per pound at one second, it is considered too fast and the control system is described as "too sensitive." When the response decreases to about 0.05g per pound at one second, the response of the plane is too sluggish and too much control force is required for rapid maneuvers. It should be noted that there are no curves presented in figures 14(a) and 14(b) for the minimum acceptable time constant at the highest values of static stick force per g because, with the present system, it was not possible to reduce the control-system time constant to a minimum acceptable value.

These same data are examined in a different light in figure 15. The calculated amplitude ratio of the normal-acceleration response of the airplane (assuming that the aircraft was a second-order system and using the measured control-system dynamic characteristics) to stick-force input is shown as a function of frequency for the time constants from the faired curves of figures 6(a) and 12 for stick forces of 4, 8, and 12 pounds per g. It is noteworthy that for the best available time constants the amplitude ratio at the airframe short-period frequency is relatively constant at about 0.11g per pound (or a stick force per g of about 9.1) for all values of static stick force per g at both flight conditions. Again for the maximum and minimum time constants the amplitude ratios are relatively constant at the airframe natural frequency. Thus it appears that the pilot in choosing the time constants of the control system has, in fact, selected constant values of the dynamic stick force per g (inverse of the amplitude ratio of the normal-acceleration response to stick force) at the airplane natural frequency, regardless of the static value of the stick force per g.

The above data are for the zero break-out force case only. In calculating the amplitude ratios it was necessary to assume a linear transfer function for the control system. The addition of break-out force immediately makes the control response to stick force nonlinear and requires the use of some sort of "average transfer function" for the response of the control system. Rather than establish this average transfer function, which at best would be only approximate at the one amplitude of input, the analysis was made using the measured control-system transfer function with no break-out force present, and the dynamic stick force per g at the airplane natural frequency was determined in the same manner as the data presented above. The control-system time constants used were obtained from the faired curves of figure 6 for static stick forces of 4, 8, and 12 pounds per g. The results are presented in figure 16 as functions of break-out force.

It is seen that regardless of the static stick force per g at any one break-out force, the pilot selects control-system dynamics to give relative constant values of dynamic stick force per g at the airplane natural frequency. As the break-out force increases the value of this dynamic stick force per g at the airplane natural frequency decreases.

Two criteria have been presented for the optimum control-system dynamic characteristics which seem to be valid for the flight conditions of the present tests. Unfortunately these two criteria are not compatible as the airplane dynamic characteristics are changed from the test conditions; that is, to maintain a constant dynamic stick force per g at the airplane natural frequency requires a smaller control-system time constant as the frequency is increased, while it requires a larger control-system time constant to maintain a constant initial normal-acceleration response to a step in stick-force input as the frequency increases.

From a consideration of the pilot's control applications it would appear that the dynamic stick force per g at the airplane natural-frequency criterion may be important in cases of low damping of the airframe where a major portion of the pilot's effort is expended trying to damp the short-period oscillation. If the damping is high so that the pilot is not required to expend a major portion of his control effort at one frequency, the dynamic stick force per g at the short-period frequency probably would no longer be important. In this case the initial normal-acceleration response to a step in stick force may well be the important criterion.

While it has been convenient for the purposes of this investigation to express the desirable aircraft response in the form of a dynamic stick force per g at the aircraft natural frequency, comparison of the results of this investigation with those made some time ago on a similar problem is in order. Reference 8 presents a discussion aimed at defining the time response of the aircraft to stick-force inputs. The results of that investigation were expressed in the form of the ratio of the maximum stick force to the maximum normal acceleration in pulse maneuvers as a function of the time duration of the stick-force pulse input. The results of the present investigation have been recast into this form and are presented in figure 17 for the control-system time constants selected for a stick force per g of 4 pounds and no break-out force. It is seen that the best available time constant agrees favorably with the data from reference 8.

CONCLUDING REMARKS

Flight tests have been conducted on an airplane in which the dynamic characteristics of the longitudinal control system could be varied over a wide range. The stabilizer was driven by a stick-force signal through an electric-hydraulic servo system with the stick connected to the stabilizer through the standby mechanical-hydraulic control-system linkages. Tests were conducted at two flight conditions to obtain a small variation in the airframe dynamics.

At the flight test condition of a Mach number of 0.80 at 35,000 feet altitude, the test airplane had relatively poor dynamic characteristics with a short-period natural frequency of 0.63 cycles per second and a damping ratio of 0.21. Under this condition the pilot was unable to find a combination of control-system variables that he felt produced a control-system-airframe combination with good characteristics by their rating standard (ref. 7). However, by the choice of fairly large values of control-system time constant with small values of break-out force, he rated the system satisfactory for normal operation even though the airframe dynamics are considered poor by previous standards (ref. 3).

At the other test condition, of a Mach number of 0.35 at 5,000 feet altitude, the airframe had the better dynamic characteristics of a natural frequency of 0.57 cycles per second and a damping ratio of 0.36. Under these conditions the pilot felt that control was much better and selected lower values of control-system time constant, indicating that in the previous tests he was tending to compensate for poor airframe dynamics by his choice of control-system dynamics.

From an examination of the over-all system response in these two test flight conditions the dynamic normal-acceleration response of the airplane to stick force appeared to be the critical factor in the pilot's choice of control-system dynamics. In both flight conditions the pilot's choice of control-system time constant was such that the initial normal-acceleration response calculated for the first second matched quite closely, regardless of the static stick force per g or the airframe dynamics. It was calculated that, with the control-system time constants selected by the pilots, the initial normal-acceleration response of the airplane would be about 0.09g per pound of stick force in the first second.

The static stick force per g did not seem to be of much concern when matched with the proper control-system dynamics as long as the maximum control forces were kept in line for the particular maneuvers being done.

Selecting control-system time constants that were too low resulted in sensitivity problems and in one case resulted in rather large amplitude oscillations in formation flight. With excessively large control-system time constants, the system became sluggish and excessively large stick forces were required for rapid maneuvers.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Dec. 10, 1957

REFERENCES

1. Anon.: Final Report. Human Dynamic Study. Rep. No. GER-4750, Goodyear Aircraft Corp., Apr. 8, 1952.

2. Krendel, Ezra S., and Barnes, George H.: Interim Report on Human Frequency Response Studies. WADC TR 54-370, June 1954.

3. Harper, Robert P., Jr.: Flight Evaluations of Various Longitudinal Handling Qualities in a Variable-Stability Jet Fighter. WADC TR 55-299, July 1955.

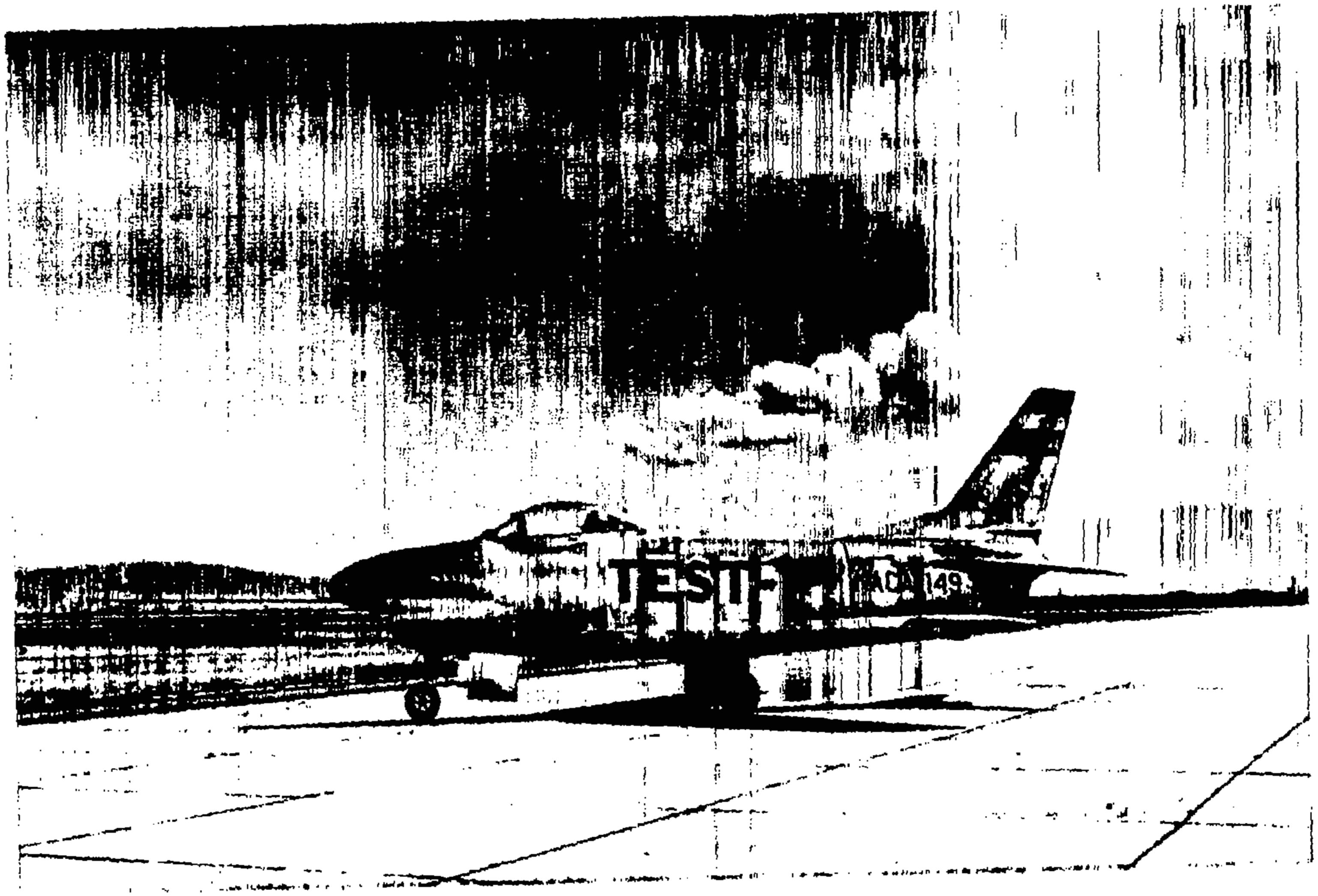
4. Kauffman, William M., and Drinkwater, Fred J., III: Variable-Stability Airplanes in Lateral-Stability Research. Aero. Engr. Rev., vol. 14, no. 8, Aug. 1955, pp. 29-35. (Also IAS preprint 520)

5. Phillips, William H., Brown, B. Porter, and Matthews, James T., Jr.: Review and Investigation of Unsatisfactory Control Characteristics Involving Instability of Pilot-Airplane Combination and Methods for Predicting These Difficulties From Ground Tests. NACA TN 4064, 1957. (Supersedes NACA RM L53F17a)

6. Brown, B. Porter: Ground Tests of the Elevator Power Control System and Feel Device in a Boeing B-47A Airplane. NACA RM L54G09, 1954.

7. Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Engr. Rev., vol. 16, no. 3, Mar. 1957, pp. 47-51, 56. (Also IAS preprint 683)

8. Phillips, William H.: An Investigation of Additional Requirements for Satisfactory Elevator Control Characteristics. NACA TN 1060, 1946.



A-18247

Figure 1.- Test airplane.

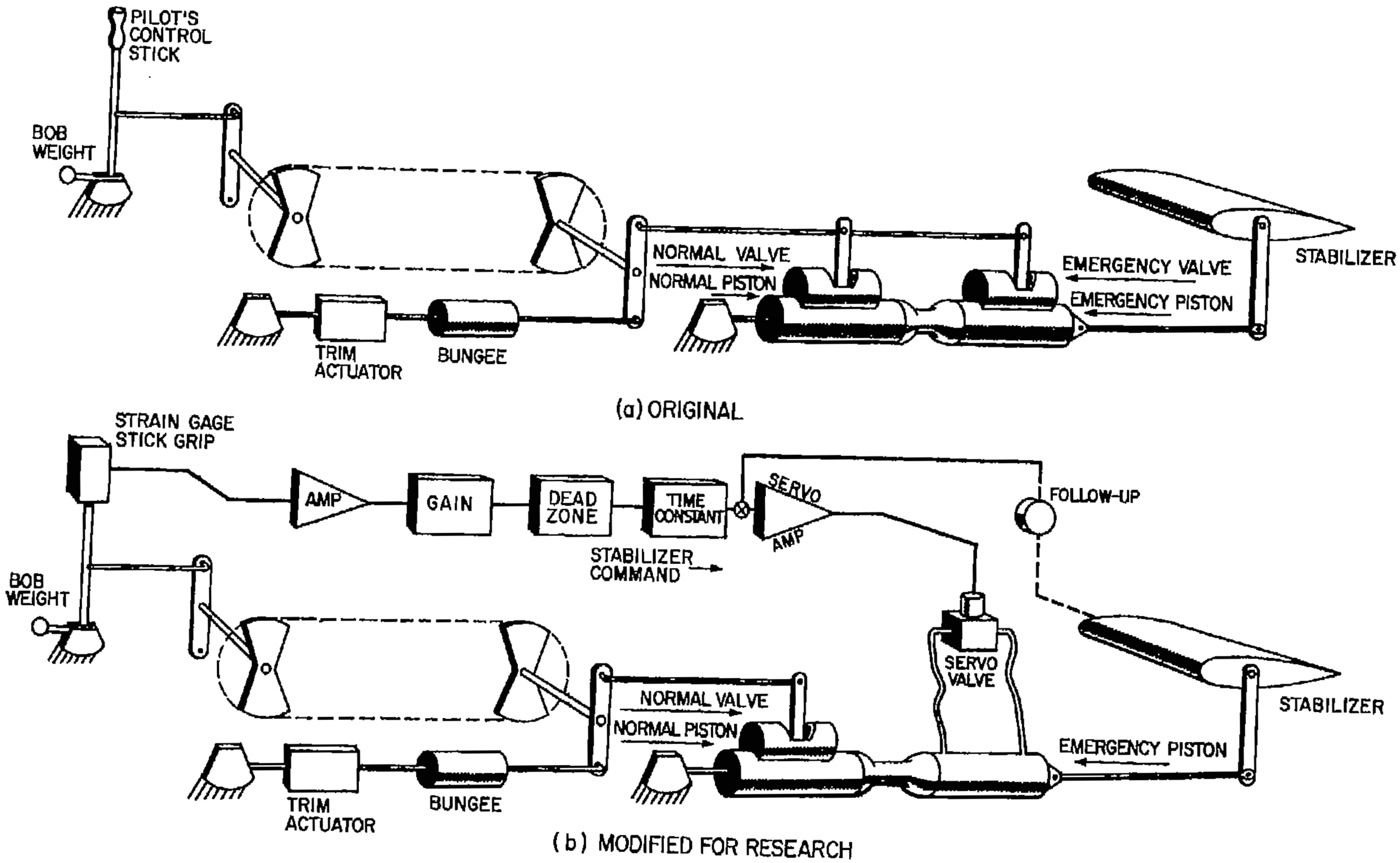


Figure 2.- Stabilizer drive mechanism.

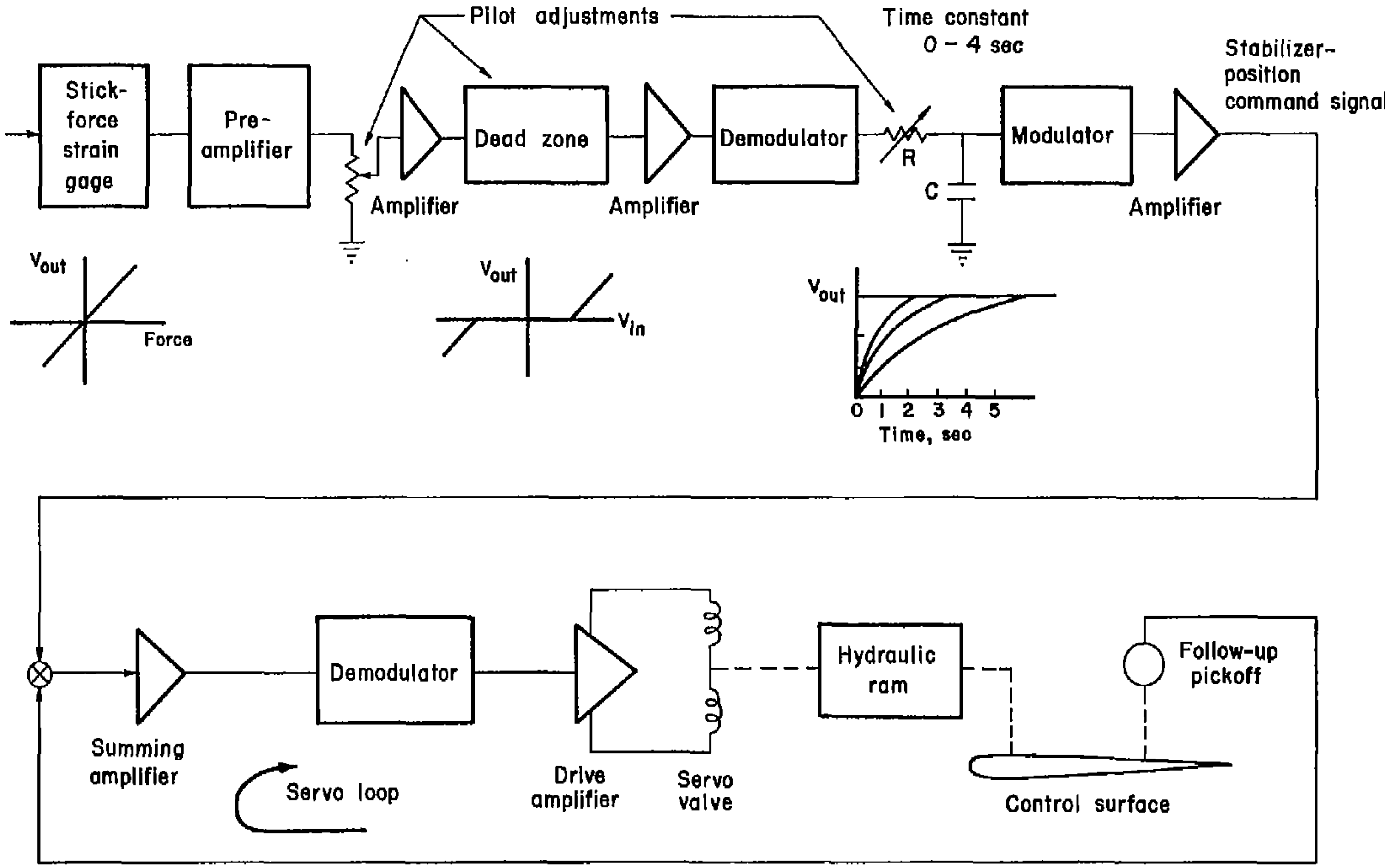


Figure 3.- Functional block diagram of modified longitudinal-control system.

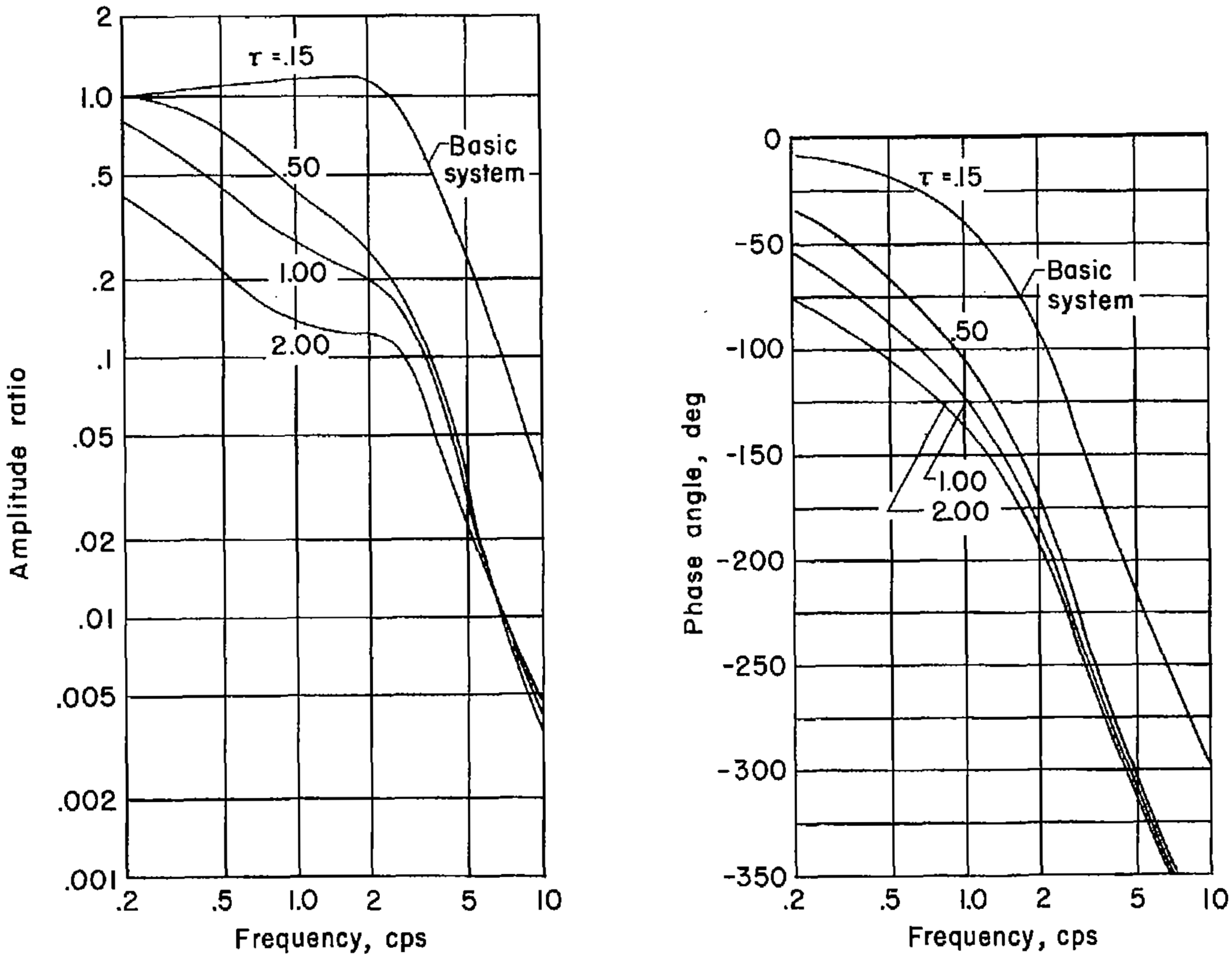


Figure 4.- Measured frequency response of control-system stabilizer to stick-force input; break-out force = 0.

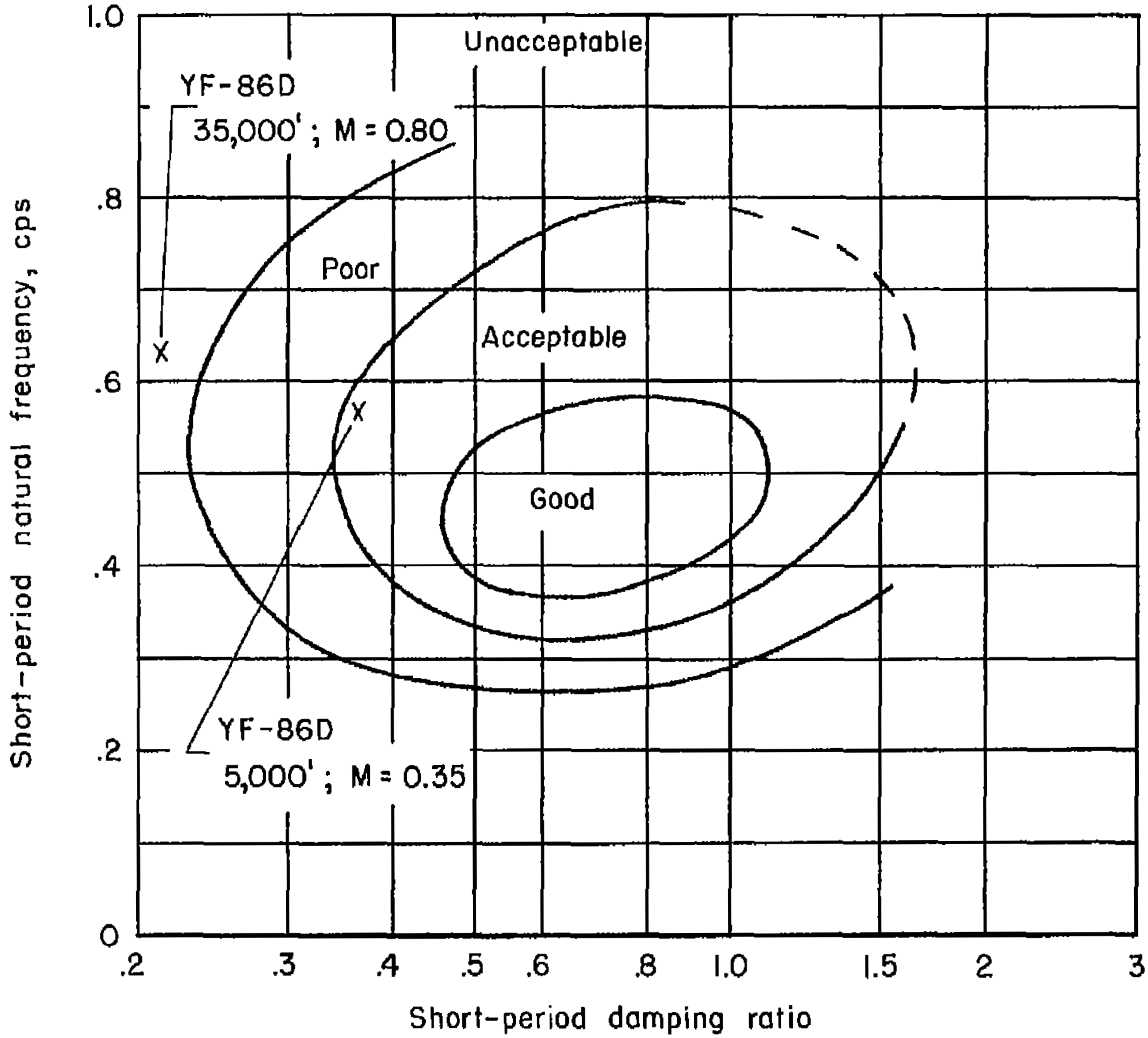
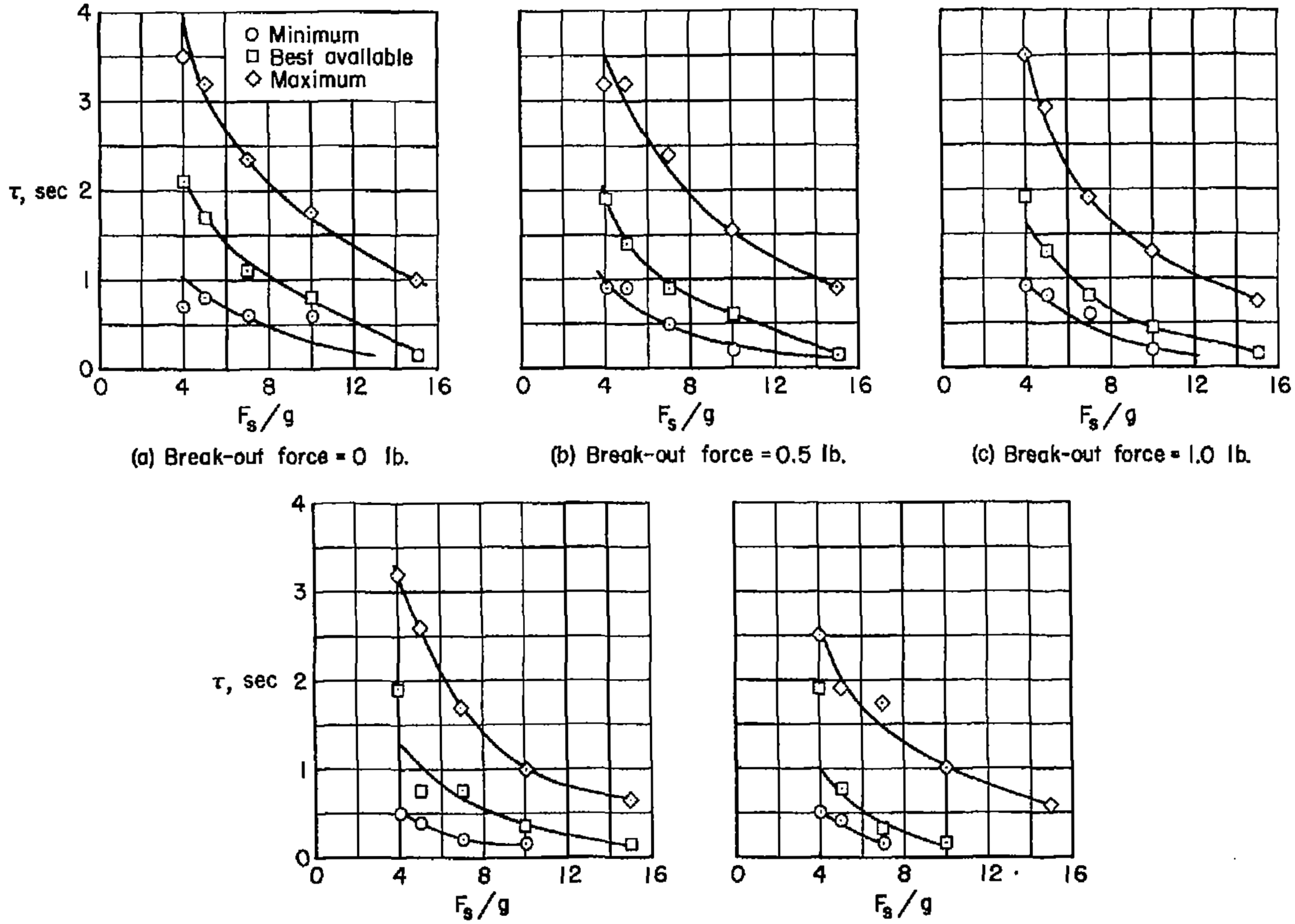


Figure 5.- Boundaries of airframe short-period frequency and damping ratio for acceptable handling qualities (ref. 3).



(a) Break-out force = 0 lb.

(b) Break-out force = 0.5 lb.

(c) Break-out force = 1.0 lb.

(d) Break-out force = 2.0 lb.

(e) Break-out force = 5.0 lb.

Figure 6.- Control-system time constants selected by the pilot as a function of stick force per g; altitude = 35,000 feet, Mach number = 0.80.

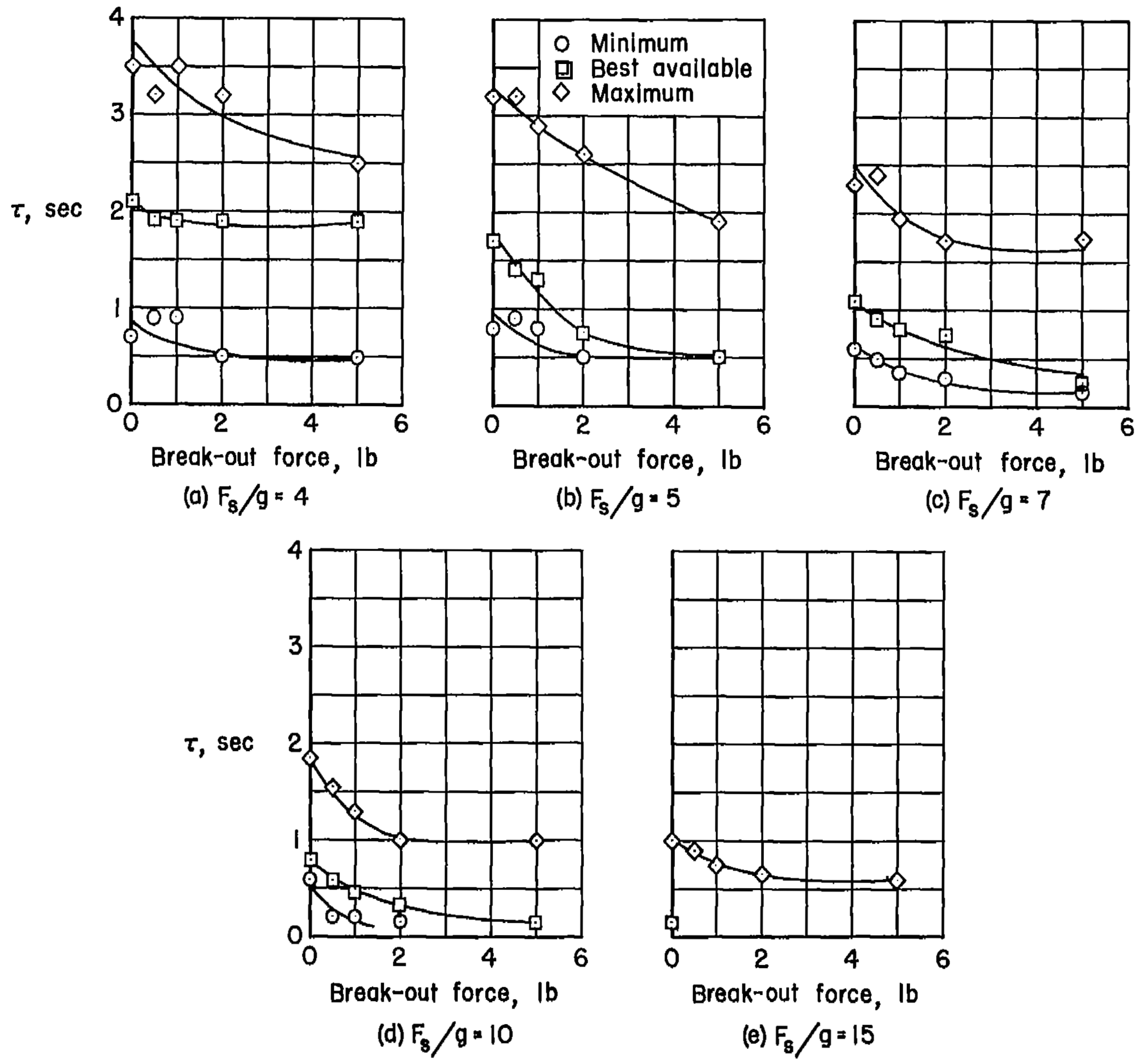


Figure 7.- Control-system time constants selected by the pilot as a function of break-out force; altitude = 35,000, Mach number = 0.80.

PROPOSED PILOT OPINION RATING SYSTEM FOR UNIVERSAL USE

	ADJECTIVE RATING	NUMERICAL RATING	DESCRIPTION	PRIMARY MISSION ACCOMPLISHED?	CAN BE LANDED
NORMAL OPERATION	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
EMERGENCY OPERATION	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
NO OPERATION	Unacceptable	7	Unacceptable even for emergency condition *	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Unprintable	10	x!◎ ~~~ ~~!! Did not get back to report	What mission?	

*(Failure of a stability augmenter)

A-22255-3

Figure 8.- Pilot-opinion rating system from reference 7.

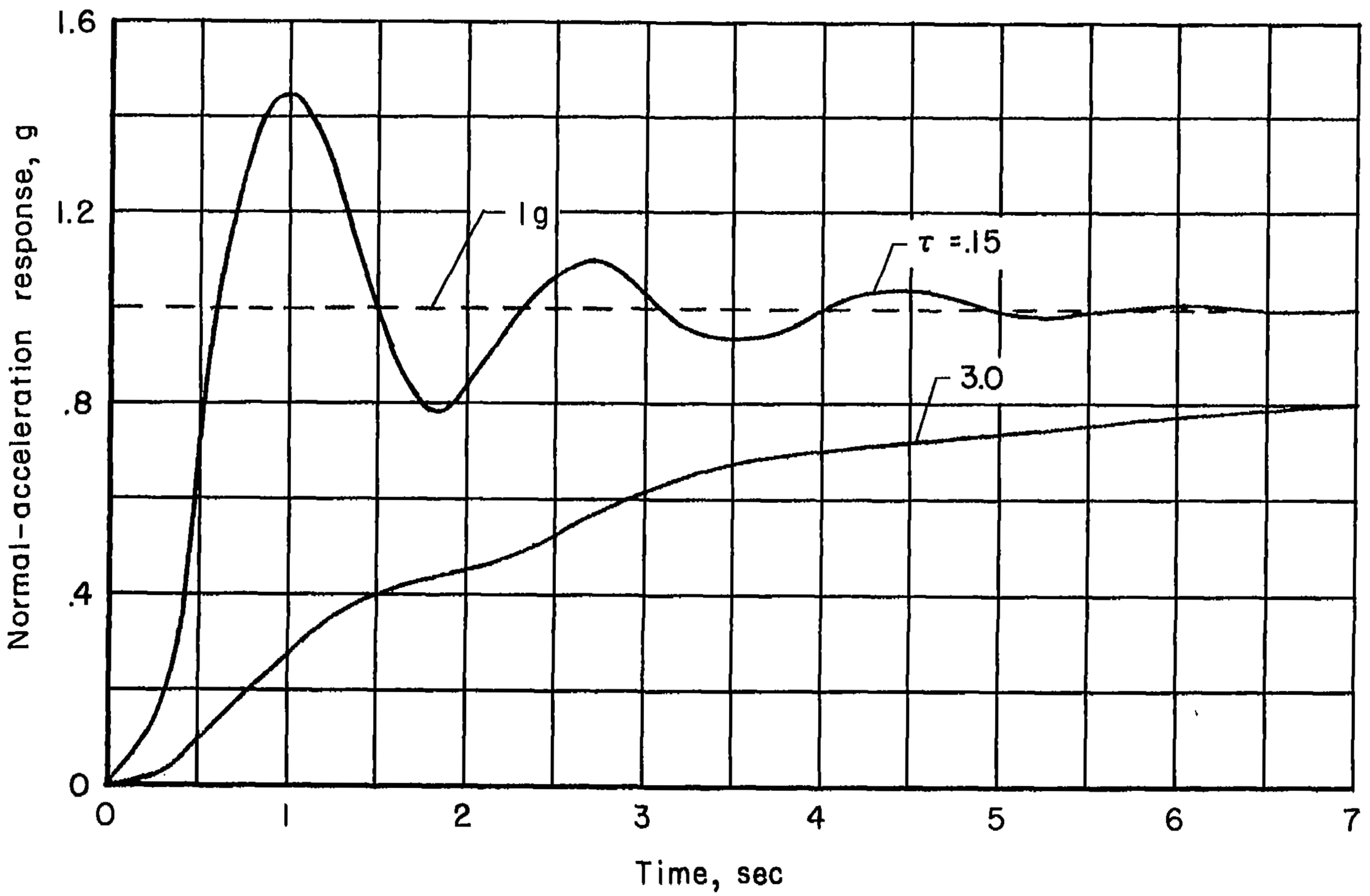
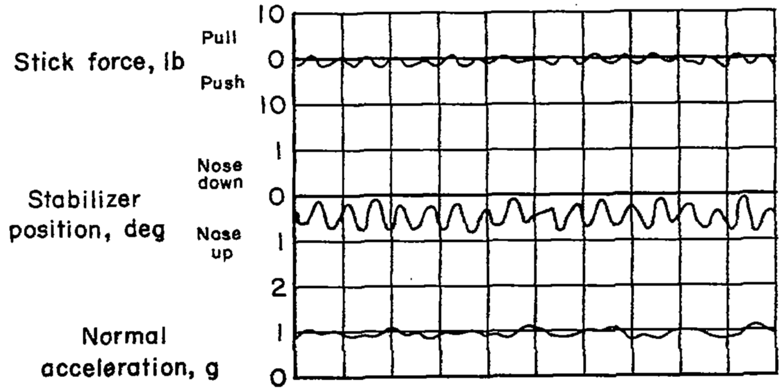
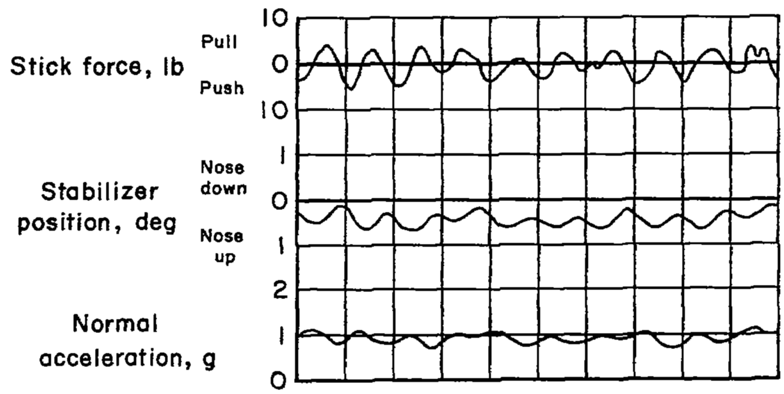


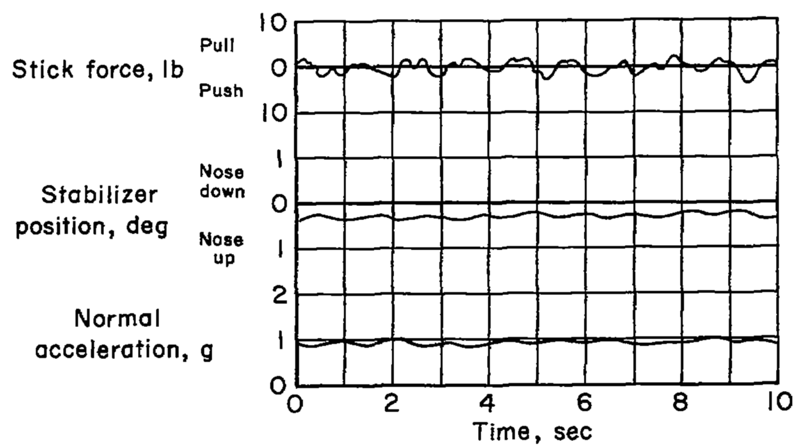
Figure 9.- Normal-acceleration response to a 1g command step in stick force; altitude = 35,000 feet, Mach number = 0.80.



(a) τ = 0.15 second



(b) τ = 1.10 seconds



(c) τ = 1.80 seconds

Figure 10.- Time history of tracking run; altitude = 35,000 feet, Mach number = 0.80, break-out force = 0, F_s/g = 4 pounds.

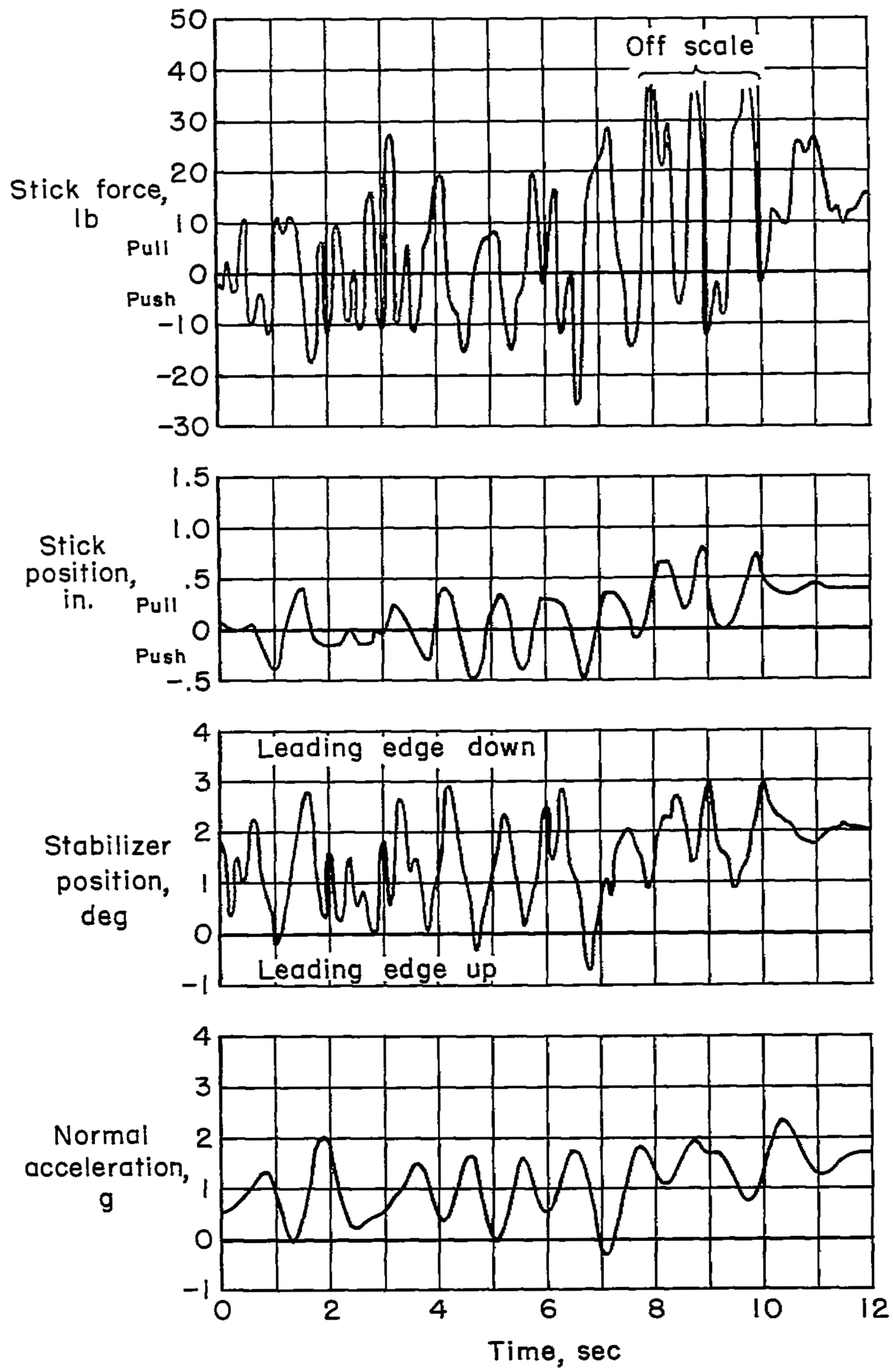


Figure 11.- Time history of pilot-induced oscillation (entry into a turn in formation); $F_s/g = 4$ pounds, $\tau = 0.15$, break-out force = 0, Mach number = 0.80, altitude = 35,000 feet.

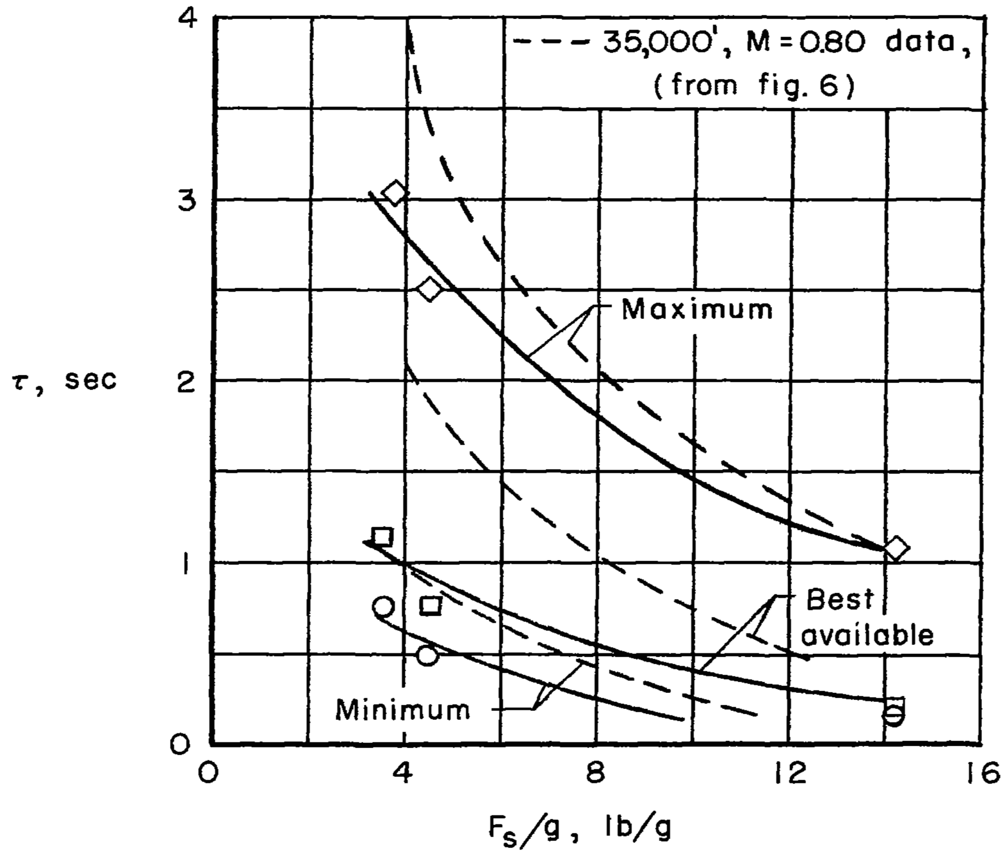


Figure 12.- Control-system time constants as a function of stick force per g; altitude = 5,000 feet, M = 0.35, break-out force = 0.

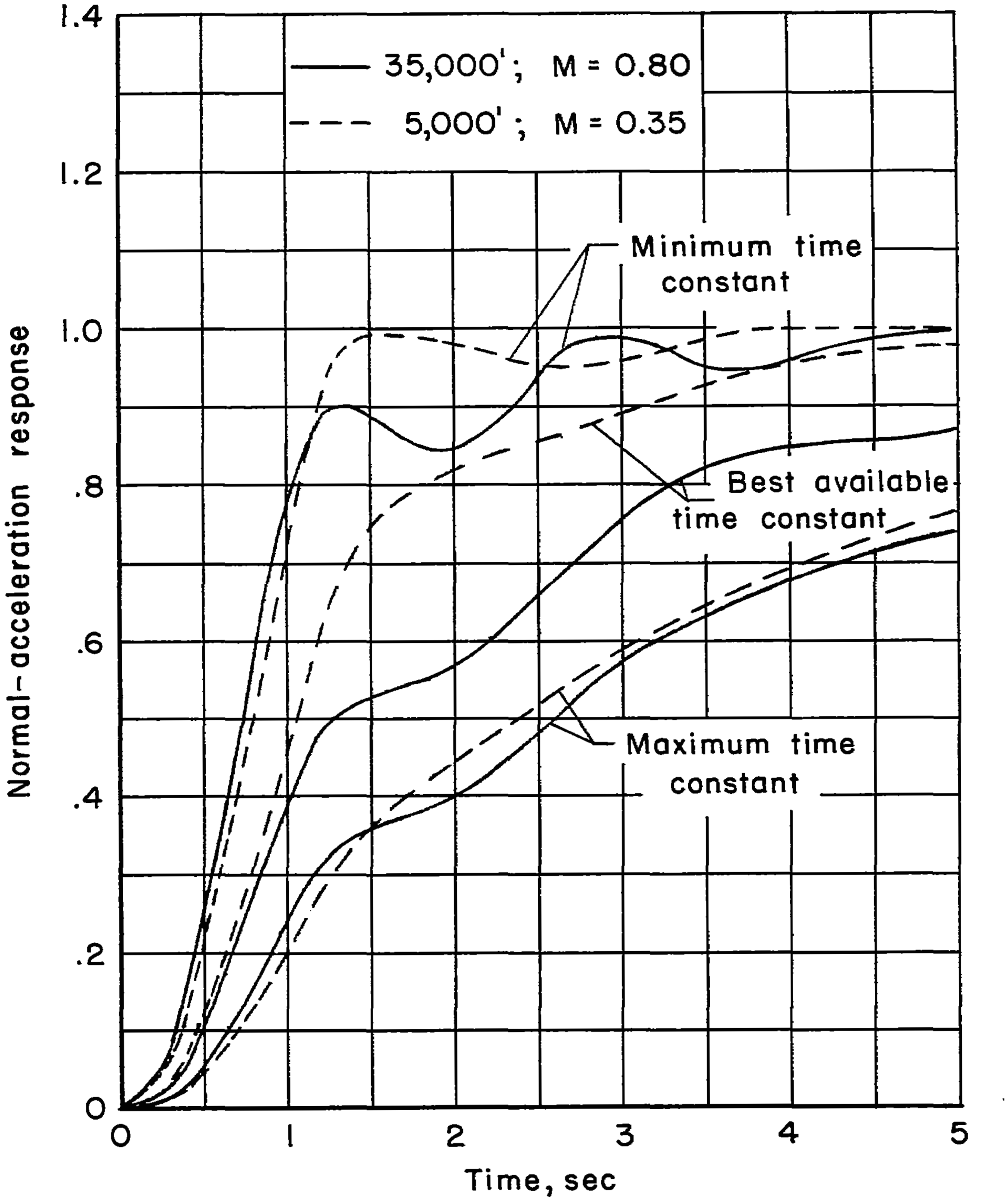
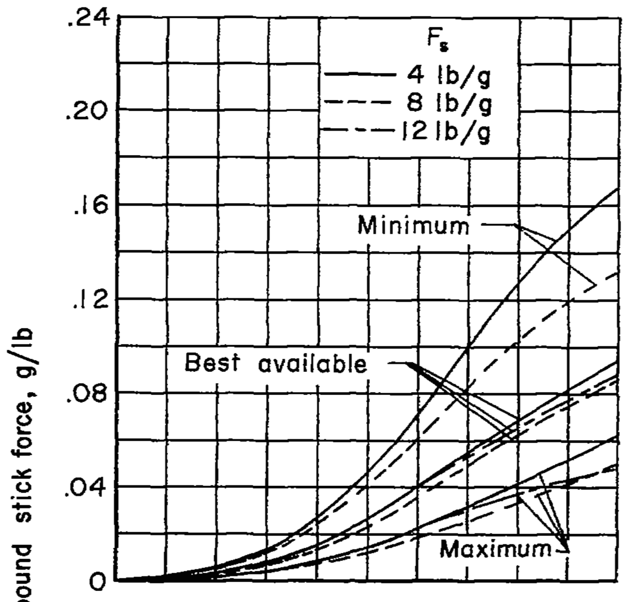
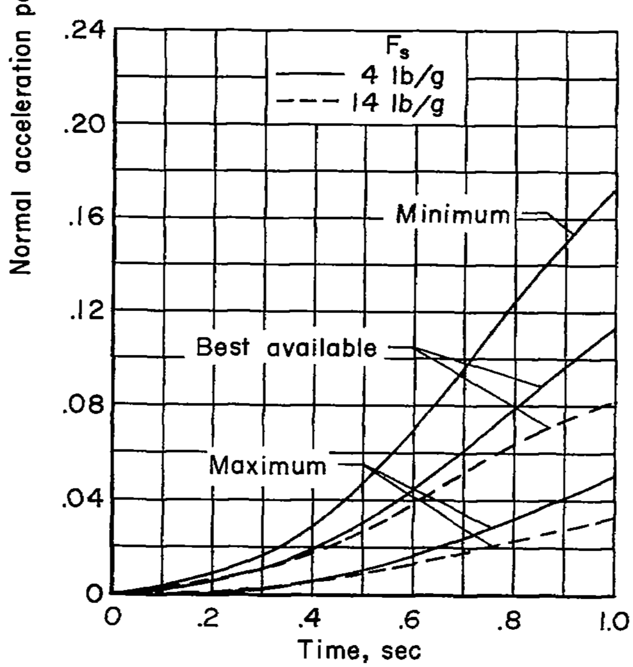


Figure 13.- Calculated normal-acceleration response to a 1g command step in stick force; break-out force = 0, F_s/g = 4 pounds.

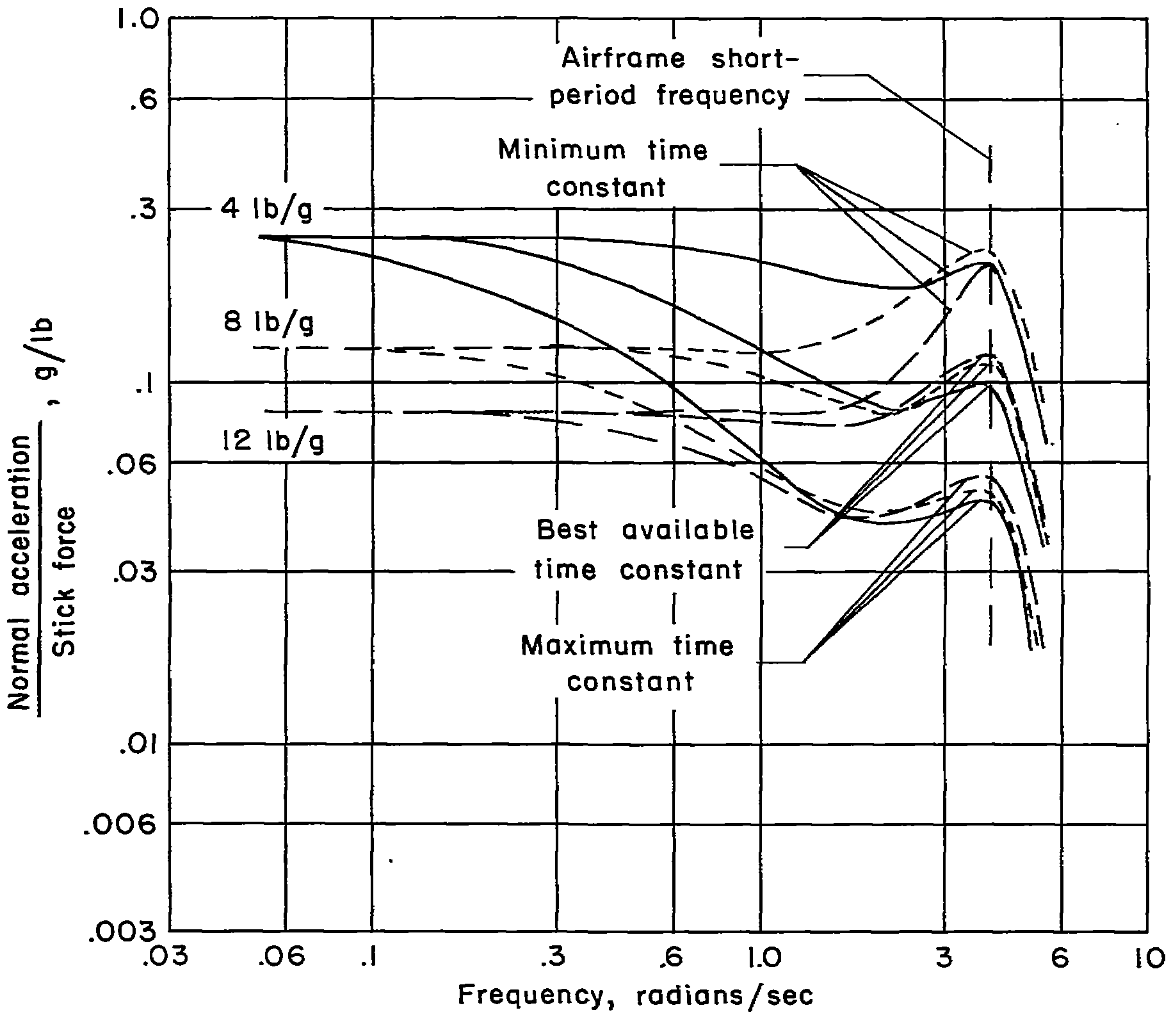


(a) Altitude = 35,000 feet, M = 0.80



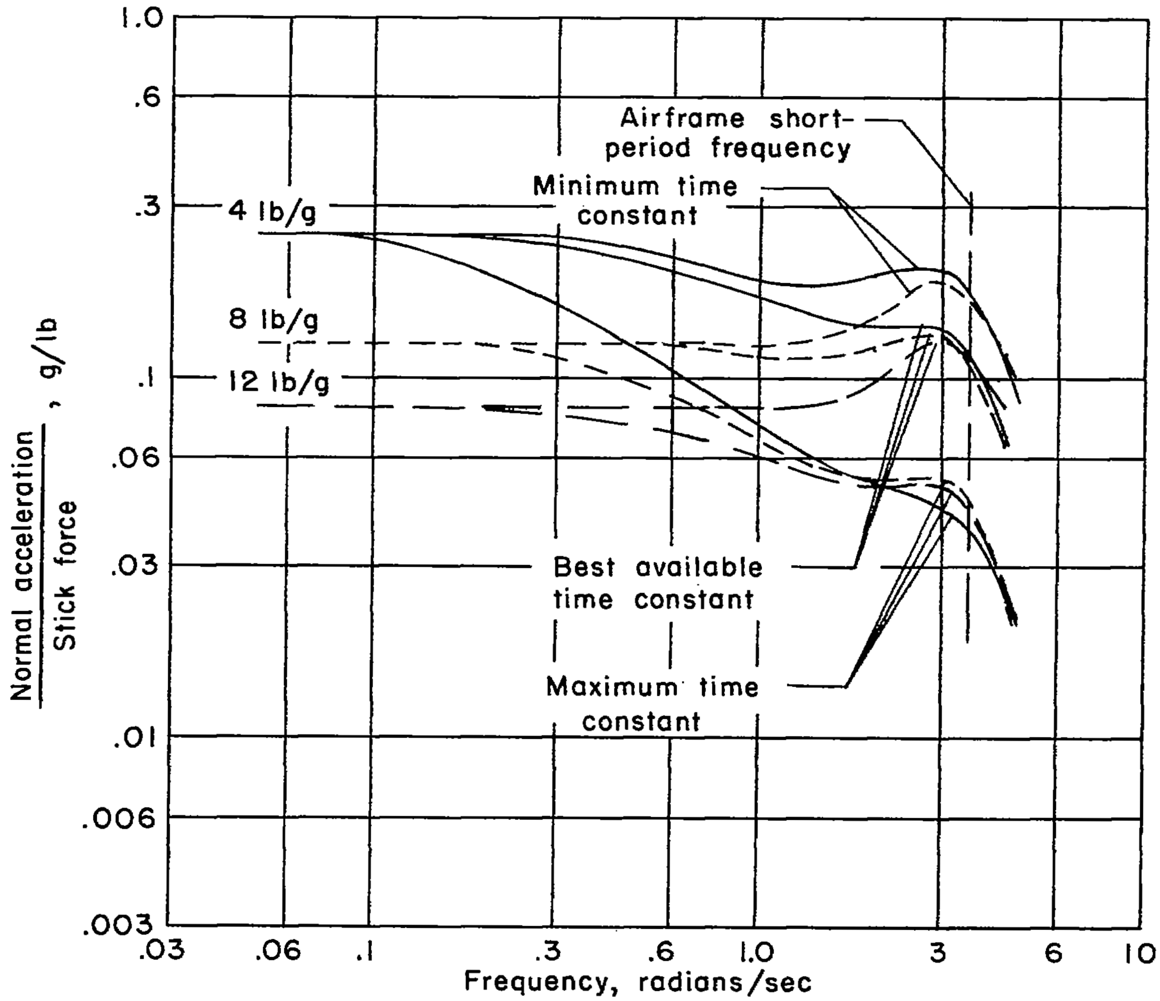
(b) Altitude = 5,000 feet, M = 0.35

Figure 14.- Calculated initial normal-acceleration response of control-system and airframe to a step in stick force for time constants selected by the pilot; break-out force = 0.



(a) Altitude = 35,000 feet, M = 0.80

Figure 15.- Amplitude ratio of combined control-system airframe response; break-out force = 0.



(b) Altitude = 5,000 feet, M = 0.35

Figure 15.- Concluded.

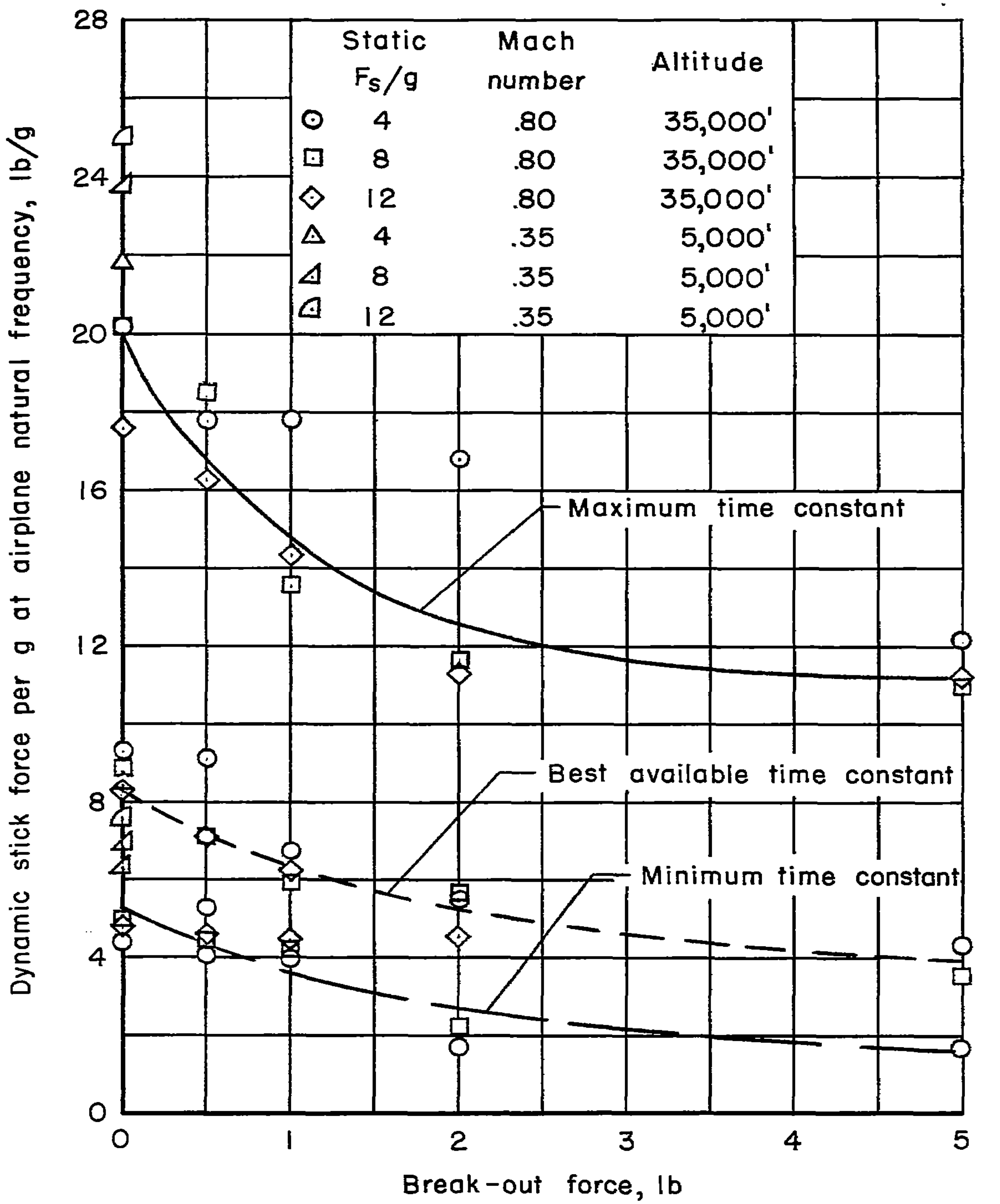


Figure 16.- Calculated dynamic stick force per g at natural frequency with pilot selected control-system dynamic characteristics.

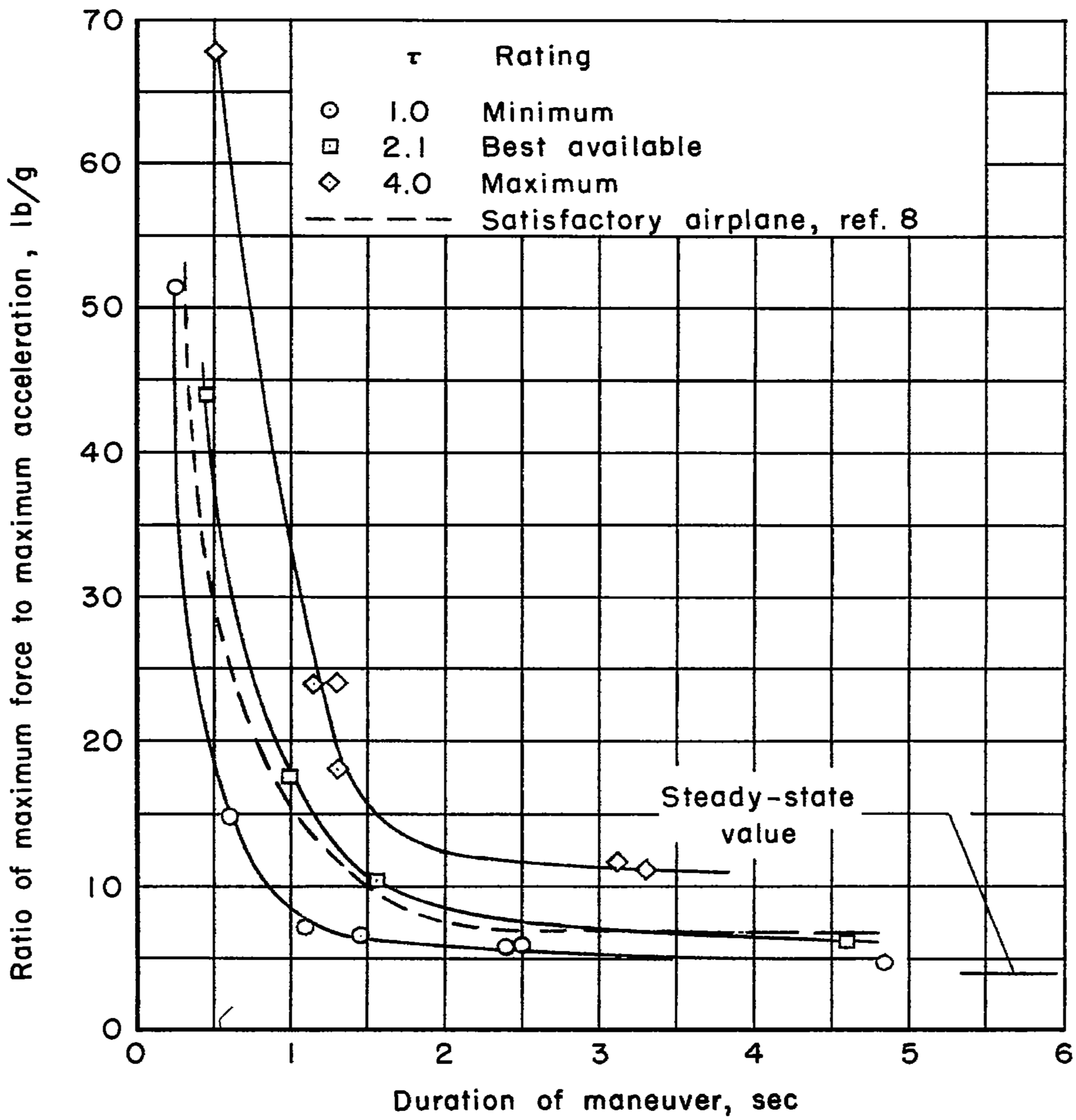


Figure 17.- Ratio of maximum stick-force increments to maximum acceleration increments in pulse maneuvers; altitude = 35,000 feet, Mach number = 0.80.

NACA - Langley Field, Va.