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REVIEW AND INVESTIGATION OF UNSATISFACTORY CONTROL CHARACTERISTICS INVOLVING INSTABILITY OF PILOT-AIRPLANE COMBINATION AND METHODS FOR PREDICTING THESE DIFFICULTIES FROM GROUND TESTS

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SUMMARY

A number of examples are presented of control difficulties which appear to result from a tendency for dynamic instability of the combination of pilot, control system, and airplane. The unsatisfactory characteristics involved have been encountered most frequently with hydraulic-power control systems, although several cases have also been experienced with conventional control systems. Tests of a bomber and a fighter airplane with experimental power control systems have been made to study this problem further.

The results of the investigation show that control difficulties of the type considered have always been associated with a marked phase difference between the pilot's control force and the associated control-surface deflection. The presence of static friction in the control valves of hydraulic-power control systems was found to be the explanation for unsatisfactory characteristics in several airplanes equipped with such systems. Definite limits or simple rules for the tolerable amount of valve friction appear to be difficult to establish because of the large number of variables which may influence the problem.

A method of analysis of the stability of an airplane under control of the pilot is presented which provides a physical explanation of the problem and appears to predict qualitatively the difficulties encountered in flight. A method of making ground tests of a control system, with the use of a simple simulator to represent the airplane response characteristics, was also investigated. This method is suggested for detecting undesirable control characteristics of the type under consideration before actual flight tests of a new airplane are attempted.

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[1] Supersedes recently declassified NACA Research Memorandum L53F17a by William H. Phillips, B. Porter Brown, and James T. Matthews, Jr., 1953.

INTRODUCTION

The National Advisory Committee for Aeronautics flying-qualities requirements (ref. 1) outline the stability and control characteristics which should be provided in order for an airplane to have desirable qualities from the pilots' standpoint. Most of these requirements are stated in terms of control forces and deflections in steady flight conditions or in terms of dynamic-stability characteristics with controls free. These requirements have generally proved adequate to define the characteristics that are important to the pilot. However, some problems of dynamic stability have been encountered which are not covered in the existing requirements.

These problems have been recognized in the form of instability of the airplane-pilot combination which made precise control of the airplane difficult. Situations of this type were encountered several times during tests by the NACA of airplanes equipped with various experimental manual control systems. Experience with such systems has shown that unsatisfactory control by the pilot can exist even though all the requirements of reference 1 may be satisfied. During evaluation tests of hydraulic-power control systems, these problems have again been encountered. With power controls, however, the cause of the trouble has frequently been difficult to determine because on the ground the power control system may apparently exhibit excellent following characteristics with no appreciable time lag, dead spot, or backlash. In flight, however, the combination of pilot, power control system, and airplane may be completely unsatisfactory from the standpoint of control. A series of tests has been made to obtain a better understanding of these problems and to establish methods which may be used in the early stages of a design to determine whether a system will be satisfactory or unsatisfactory.

The purpose of this paper is to summarize the past experience with unsatisfactory control characteristics involving the pilot-airplane combination and to present the results of tests made to study this problem in connection with power control systems. In addition, methods of analysis are suggested which offer promise of predicting these unsatisfactory conditions.

SYMBOLS

F_s	stick force, lb
$\dot{\theta}$	pitching velocity, radians/sec
δ_e	elevator deflection, deg

δ_s stick deflection, deg

g acceleration of gravity (32.2 ft/sec^2)

ω frequency, radians/sec

PREVIOUS EXPERIENCE

Conventional Control Systems

The term "conventional control systems" refers to control systems with a direct mechanical linkage between the pilot and the control surface, as contrasted to hydraulic-power control systems. Arrangements involving bobweights, servotabs, and so forth, are considered to be conventional control systems.

The type of dynamic instability involving the pilot-airplane combination has been most frequently encountered with hydraulic-power control systems, whereas conventional control systems ordinarily have been free of this difficulty. Several instances have occurred in the past, however, on conventional control systems in which similar difficulties were experienced. In most cases, these control systems were experimental types. The instances in which difficulties occurred have been presented for the individual airplanes involved, but no effort has previously been made to bring together these instances in order to obtain an overall picture of the problem. Examination of these cases has shown that the causes, manifestations, and cures of the control difficulties not covered by reference 1 are extremely varied and therefore difficult to classify in terms of additional requirements. All the cases do, however, exhibit a common instability of the pilot-airplane combination. Although no attempt is made to explain completely each case of this type, a review of these cases appears desirable in order to show the nature of the problems involved.

An example of a case in which the pilot encountered difficulty in attempting to maintain exactly a constant airspeed is shown in figure 1. This figure shows the variation of elevator position and normal acceleration which occurred on a scout-bomber airplane (ref. 2) as the pilot held the airspeed at 207 miles per hour. The pilot had the impression that static longitudinal instability of the airplane caused this difficulty. This impression was incorrect, however, as proved by the fact that, at the end of the record shown, the pilot released the stick and the airplane flew steadily at a speed of 215 miles per hour for several minutes. In this case, the control system was entirely conventional. The difficulty, however, was attributed to a combination of flexibility in the elevator control system and friction in the elevator hinge. Under these conditions small movements of the stick could be made without moving the elevator, but once the elevator started to move it would overshoot the desired position. The exact elevator angle required to maintain the airspeed of 207 miles per hour was never attained and therefore continual adjustments had to be made by the pilot.

This example illustrates how a nonlinear characteristic of the control system at small deflections may cause a type of instability of the pilot-airplane combination when precise control of the airplane, such as maintaining exact speed, is attempted. This nonlinearity did not result in any difficulty in maneuvers such as pull-ups, where larger control movements were required.

Another type of control-feel problem has been encountered with airplanes incorporating control systems involving closely balanced control surfaces and bobweights. In contrast to previously discussed cases with nonlinear characteristics, these control systems did not exhibit any marked nonlinear effects. In these cases, therefore, when troubles were experienced they could occur in maneuvers involving large control deflections as well as in maneuvers involving small deflections. Such difficulties were noticed during tests of an experimental control system in a fighter airplane (ref. 3). The purpose of this investigation was to evaluate an all-movable tail as a means of longitudinal control. In this system, the tail was very closely balanced aerodynamically and was controlled through a servotab. A bobweight was used to provide a stable stick-force variation with acceleration and, in conjunction with the trim tab, a stable variation with speed. It was found that the stick-free oscillations of the airplane damped out satisfactorily. In steady turns the variation of stick force with acceleration was also satisfactory. The variations of stick force and elevator angle with speed were low but were considered to be sufficient.

In spite of the airplane meeting all these requirements, the control felt uncertain and oversensitive to the pilots and was therefore unacceptable. In this case the unsatisfactory characteristics were caused by the fact that the pilot was not provided with forces in phase with the stick deflection in rapid maneuvers. The control demanded continuous attention to avoid small stick movements and, because of the low-stick-fixed stability, small inadvertent movements of the stick resulted in annoying motions of the airplane. The system in this airplane was made satisfactory by connecting the stick directly to the all-movable tail and converting the servotabs to geared unbalancing tabs (ref. 4). These modifications did not alter the stick-fixed stability, but they did provide the pilot with some "feel" for small rapid stick movements.

A second result was observed during flights made in this program. Originally, the control system was designed to provide an unusually low value of friction, about ±0.2 pound. The pilots complained, however, that the very low friction actually increased the difficulty of flying smoothly because small inadvertent stick movements would be made as a result of any slight airplane motions such as those due to rough air.

In the later stages of the program, the elevator control friction was increased to about ±2.0 pounds. This value is still relatively low by comparison with the friction in many airplanes. The increased friction eliminated the inadvertent stick movements and thereby improved the control characteristics of the airplane.

Tests of another fighter airplane in which control sensitivity troubles were encountered with a conventional elevator rather than an all-movable tail are reported in reference 5. This experimental system also involved a closely balanced control surface with a bobweight and possessed fairly linear characteristics. Tests showed that this system exhibited poor control-free dynamic stability and the pilots considered the system to be unsatisfactory because the airplane felt oversensitive. In addition, the bobweight provided undesirable control-feel characteristics when flying through rough air. The difficulties in this airplane were greatly alleviated through the use of a mechanical device which increased the control forces only for rapid stick movements.

The serious nature of the foregoing control-feel problems was recognized and some empirical rules for avoiding these difficulties (ref. 6) were formulated and inserted in the existing flying-qualities requirements. The possibility of analyzing these problems as an instability of the airplane-pilot combination was not investigated, however.

Power-Operated Control Systems

Figure 2 presents data that were obtained in a jet fighter airplane equipped with a hydraulic slide-valve control booster on the ailerons. Figure 2 shows time histories of rolling velocity, control force, and deflection as the pilot attempted to maintain laterally level flight. The difficulty encountered is evidenced by the oscillations in force, deflection, and rolling velocity. Note that the control force is almost 180° out of phase with the rolling velocity. This result indicates that the pilot attempted to oppose the buildup of rolling velocity; but, because of the characteristics of the booster system, he actually produced a continuous oscillation. The amplitude of the variation of angle of bank in this oscillation is about $\pm 1.8^{\circ}$. The airplane in this example was a service jet fighter airplane. The control difficulty shown in figure 2 was recognized by most pilots who flew the airplane but was not considered sufficiently serious to be unsatisfactory, probably because the angles of bank involved in the oscillation were not large enough to affect the flight path appreciably.

Similar troubles were reported on an early model of a tailless jet fighter airplane also equipped with a hydraulic slide-valve servomechanism, but in this case the difficulties were in the elevator control system and the characteristics were considered very unsatisfactory by the pilots. The more serious nature of the trouble may probably be attributed to the fact that the elevator control system, rather than the aileron control system, was involved. If, for example, the airplane developed an oscillation in pitch of the magnitude of the lateral oscillation referred to previously (±1.8°), the airplane would undergo changes in normal acceleration of about ±1 g in high-speed flight. Such an oscillation would be unsatisfactory. The elevator control system is apparently much more sensitive to this type of difficulty than the aileron control system. For this airplane the problem was the ability to trim and to fly the airplane smoothly in certain conditions of steady flight. In trying to approach and maintain accurately a desired flight path, the pilot would attempt to move the controls to perform the desired maneuver; but, in order to achieve this result, he would have to make a series of small corrections with the controls which on some occasions resulted in rather large changes in acceleration. On some attempts the desired final condition was never attained. One pilot reported that the difficulties were aggravated if he attempted to be more exact in maintaining the given attitude and altitude.

In both of the foregoing examples with powered controls the airplanes possessed static stability, and the control-free dynamic stability with power controls operating was acceptable. Again, the instability reported was a result of the combination of pilot, control system, and airplane.

TESTS TO INVESTIGATE FEEL CHARACTERISTICS OF POWER CONTROL SYSTEMS

Tests of a Bomber Airplane

At the time the experimental tailless fighter airplane was undergoing tests by the manufacturer, an attempt was made by the NACA to gain further insight into the nature of the problems introduced by power control systems. The first investigation was made by utilizing a bomber airplane which had been equipped by the NACA with an experimental power control system and mechanical feel device on the elevator. This system is described in detail in references 7 and 8. The system utilized a two-stage hydraulic servomechanism in which the position of a variable displacement pump was controlled by a small slide-valve booster which required very small input forces (of the order of 1.0 ounce at the pilot's control wheel). When this system was tested either with a finite boost ratio or as an irreversible system in conjunction with a mechanical feel device, none of the control difficulties which have been described in the previous section were encountered. In fact, since the servomechanism was attached directly to the control column, the control characteristics of the original airplane were improved considerably by the reduction in control-system friction which was formerly excessive. Because the forces required to displace the control valves on the previously described hydraulic control systems were believed to be considerably larger than the corresponding force for the system of the bomber airplane, control-valve friction was suspected as a cause of these difficulties. The manner in which control-valve friction affects the force characteristics of an idealized hydraulic-power control system is illustrated in figure 3. The figure shows the variation of stick force, valve position, and elevator angle with time when it is assumed that no feel device is in the system so that the only forces required to move the stick are those required to overcome valve friction. Examination of figure 3 shows that the valve does not respond to the pull force until the valve friction is exceeded. Then the valve opens and causes the elevator to move up at a constant rate. If, at this point, the pilot wished to reverse the elevator motion, he would instinctively push on the stick. The elevator, however, would continue to move up until the push force again exceeded the valve friction and made the valve open in the opposite direction. Throughout the entire oscillation in the figure, the stick force is 180° out of phase with the resulting elevator motion.

An important distinction exists between the effects of valve friction and the effects of the ordinary type of control-system friction. Valve friction tends to keep the control moving, whereas ordinary friction tends to hold the control fixed. The allowable magnitude of valve friction would therefore be expected to be different from that for normal control-system friction.

In order to investigate the effect of control-valve friction on the bomber airplane, this friction was artificially increased through the use of a spring clamp attached to the valve operating rod. The valve-position recorder produced an additional friction force that was sufficiently large to be considered during the tests.

It was thought that the tolerable amount of valve friction might be related to the force variation with normal acceleration. For this reason, tests were made with several values of valve friction and force gradient. The force gradients used for the substantially no-valve-friction case were 5.0, 10.5, and 15.0 pounds per degree of stick deflection, whereas the gradients used with 1.0 pound of friction were 10.5, 15.0, and 22.5. The highest friction, 2.5 pounds, was tested with force gradients of 15.0, 22.5, and 35.0 pounds per degree of stick deflection. These combinations of friction and force gradient were chosen so that three distinct conditions could be studied. The results would show the effect of increasing the force gradient for a constant friction and also the effect of increasing the friction at a constant force gradient. In addition, the tests would show the effect of increasing the friction while the ratio of friction to force gradient is relatively constant. Because valve friction is a nonlinear phenomenon, tests were made to study the control characteristics both in maneuvers requiring small precise control movements and in maneuvers involving larger control movements. In order to study the characteristics for small control movements, data were obtained during runs in which the pilot intentionally exceeded the trim speed of approximately 220 miles per hour by 10 miles per hour and then attempted to regain the trim speed. Figure 4 shows the data obtained with substantially no valve friction for three force gradients. Figure 5 shows the same tests made with 1 pound of valve friction measured at the control stick, whereas figure 6 presents the data for $2\frac{1}{2}$ pounds of friction. It will be noted that valve position is not shown in figures 4 and 5 because the recorder was disconnected in order to obtain friction values of 0 and 1 pound. The recorder contributed about 1/2 pound of friction when connected. The valve position is shown in figure 6, and the friction produced by the valve-position recorder is included in the quoted $2\frac{1}{2}$ pounds.

The amount of elevator angle required to produce the intentional 10-mile-per-hour speed change was about $\frac{1}{6}^\circ$. The force required of the pilot to produce $\frac{1}{6}^\circ$ of elevator angle varied with the force-gradient setting of the feel device. The highest gradient required about $5\frac{1}{2}$ pounds, whereas the lowest gradient necessitated only about 0.8 pound.

The records show that, for a given force gradient, an increase in the friction resulted in more difficulty in controlling the airplane, as evidenced by the increase in the oscillations of normal acceleration as the pilot attempted to control the airspeed. A comparison of the records for friction equal to 0 and 1 pound shows that there was apparently very little difference, but it should be pointed out that rough air was present in both sets of runs which produced changes in normal acceleration that tend to obscure the differences between the two friction conditions. The pilots reported that actually there was a considerable reduction in the ease of control when the friction was increased to 1 pound. Friction values larger than those used in the runs presented were investigated, but the tests showed that, when the friction exceeded $2\frac{1}{2}$ pounds, the difficulties in controlling the airplane did not increase proportionally. These high frictions, however, did increase the amount of work required of the pilot.

Figures 4 to 6 show that, from the standpoint of the oscillations in acceleration imposed upon the airplane in holding a trim speed, increasing the force gradient for any of the friction values did not improve the handling characteristics appreciably. Inspection of the force records, however, shows that for a given friction an increase in force gradient resulted in more work required of the pilot. For this reason, the pilots believed that an increase in gradient was detrimental rather than helpful in controlling the airplane. It should be noted here that for these tests the airplane possessed good stick-fixed stability (2.5 in. of stick motion per g) which was probably an important factor in preventing any severe oscillations in acceleration.

All the aforementioned tests on the bomber airplane were made to investigate the problems associated with small control movements such as would be required for precise flying. Some abrupt pull-up maneuvers were also made in which large control displacements were necessary. Figure 7 presents a time history of such a pull-up which was made with 1 pound of valve friction at 250 miles per hour. No difficulties were encountered in accurately holding a desired value of acceleration because the valve friction was such a small percentage of the force required in the pull-up. In the case illustrated in figure 7, the force gradient was about 50 pounds per g. The data in figure 7 were obtained in approximately the same flight condition as presented in figure 5(b).

The results of these tests indicate that specification of an allowable amount of valve friction in terms of the force per g of an airplane would not be logical. Even a small amount of valve friction in the bomber airplane, which had a large force gradient, was considered undesirable by the pilots. The data show, however, that for a large airplane, with relatively slow response to control motion and large control motion per g in maneuvers, further increases in valve friction did not proportionally increase the difficulties in the attainment of precise control. Increase of either the friction or the force gradient was considered undesirable for precision flying because these changes increased the work required of the pilot.

Tests of an Experimental Fighter Airplane

The results of tests on the bomber airplane did not give much information on the difficulties experienced with fighter airplanes. For this reason, a fighter airplane which had been equipped by the manufacturer with irreversible power controls was obtained for further research. For the sake of brevity this airplane will be referred to as fighter A. This airplane differed from the bomber airplane mainly in having much lower longitudinal stability in maneuvers, lower stick-force gradients, and the faster response to control which is typical of smaller airplanes. The details of the power control systems in this airplane are described in reference 9. This airplane was well suited to a study of the problems associated with power controls inasmuch as the pilot could engage in flight either the normal manual control system or the power control system. The power control system consisted of a conventional hydraulic slide-valve servomechanism. The airplane was also equipped with mechanical feel devices with provision for supplying stick force as a function of stick deflection and impact pressure. The mechanical feel devices could also be controlled from the cockpit separately from the power control system. Although all three controls could be power operated, the discussion herein is confined to the elevator control system which proved to be most critical from the standpoint of obtaining satisfactory characteristics.

When fighter A was first obtained for flight tests the valve friction measured at the pilot's stick was found to be about ±4 pounds. The experience gained from the tests on the bomber airplane indicated that this value was probably high; consequently, every effort was made to reduce the friction without excessive modifications to the system. It was found that the adjustment and cleanness of the valve linkages affected the friction considerably. The lowest value of friction obtainable, however, was about ±3/4 pound measured at the stick. As in the tests on the bomber airplane, a friction clamp was added to vary the friction for various flights.

In order to study the effects of valve friction in maneuvers requiring very small control movements, tests similar to those on the bomber airplane were conducted, in which the pilot deliberately exceeded a trim speed by about 10 miles per hour and then tried to return to the trim speed. The elevator movement required to produce this 10-mile-per-hour change in trim speed at 300 miles per hour was shown by static stability measurements to be about 0.1° and the corresponding stick force to be negligible. The data obtained with the manual control are shown in figure 8(a), whereas the data obtained with the power control are shown in figure 8(b).

Contrary to expectations the pilot reported that this maneuver could be performed about as well with the power controls as with manual control. The resulting variations of normal acceleration with time for each type of control shown in figures 8(a) and 8(b) are very similar and tend to substantiate the pilot's report. The stick-force variation with time, however, shows very poor phasing with the elevator motion and a very nonlinear force variation with deflection. There were two factors which were found to contribute to the pilot's ability to perform this maneuver about as well with either control. First, the elevator could be controlled manually through a very small deflection range in which the stick forces were less than the stick forces required to break through the valve friction, because the elevator power control and bell-crank system was somewhat flexible. Second, it was found that, with the power control operating, the elevator could be moved at slow rates without actually breaking through the valve friction. This phenomenon was believed to be due to the rubber O-ring hydraulic seals in the valve being sufficiently flexible to allow some motion of the valve piston without the piston actually sliding in the seal. Since the airplane had very low static stability (static margin about 3 percent of the mean aerodynamic chord), the pilot could make fine corrections to the flight path without breaking through the valve friction. Although it would have been desirable to have made other flights with increased static stability, it was found to be unfeasible since all the ballast that could conveniently be installed ahead of the center of gravity had already been employed to offset the weight of the test equipment and power-control installation.

Although control difficulties were not apparent in the type of runs requiring a small change in airspeed, the pilots reported that another more serious problem was encountered in rapid maneuvers. On several occasions large variations in normal acceleration were inadvertently produced when rapid maneuvers were made or when flying through rough air. During early flights with the airplane, oscillations which reached amplitudes as large as -3g and 5g were encountered inadvertently, and control of the airplane was regained only by disengaging the power control system. No records were obtained of these inadvertent maneuvers, but in attempted rapid turns and pull-ups less violent oscillations were encountered more consistently. A typical time history of this type of maneuver is shown in figure 9(a) for the power-control condition, and the manual-control condition for comparison is shown in figure 9(b). In both cases, the pilot attempted a rapid turn to $3\frac{1}{2}$g. With the power control an oscillation of about 1- to 2-second period resulted (see fig. 9(a)) in which the acceleration varied between 2g and 4g. During this oscillation, the elevator angle was almost exactly in phase with the control-stick position. The possibility that the oscillation was caused by lag in the positioning ability of the power control system is therefore considered unlikely. On the other hand, figure 9(a) shows that the stick force during the oscillations was almost 180° out of phase with the stick position, even though the average stick force during the maneuver was in phase with the stick position. This result is in accordance with the simplified explanation of the effects of valve friction given previously in figure 3. The illogical force variations produced by the valve friction are thought to be the main cause of the tendency of the pilot to overcontrol and set up an oscillation.

As the pilots gained skill in flying the airplane, the number of instances of difficulty in performing a given maneuver decreased. In order to give the pilot a problem that would distract his attention from simply stabilizing the airplane and in order to provide a reference point, a formation flight was made in which fighter A was flown in formation with another fighter airplane which will be designated as fighter B. Both fighter airplanes were flown as the lead and as the following airplane. In each case fighter A was flown with the power control and with the normal manual control. The results are presented in figure 10 as time histories of the normal acceleration for each airplane for each of the four conditions. The variation of normal acceleration is shown in each part of figure 10 as a solid line for fighter A and a dashed line for fighter B. In figures 10(a) and 10(b) small accelerations are present with both airplanes when flown with manual control in the wing or following positions. A comparison of figures 10(a) and 10(c) shows a definite increase in the difficulty encountered by the pilot of fighter A with the power control system. In figure 10(d) even when fighter A with power controls operating was leading, small oscillations were present. In this case, however, the pilot of fighter B was almost able to duplicate the oscillations.

As in the case of the bomber airplane, various combinations of stick-force gradients and valve friction were tried in fighter A. The force per g was varied by changing the gradient of the artificial feel system. In the range of values tried, however, the pilots' comments indicated no appreciable change in the handling qualities. Variations of force per g from 1.5 pounds per g to 6 pounds per g were tried and various values of valve friction from ±3/4 pound to ±4 pounds at the stick were investigated. Because the friction came partly from the O-ring seals on the valve, it was affected, as mentioned previously, by the cleanness of the parts, as well as by the amount of lubrication present. For these reasons the values of friction obtained were not always consistent; this characteristic will be mentioned in more detail in a subsequent section.

Various schemes were tried to help alleviate this problem of valve friction and thereby improve the characteristics of the power control system of fighter A without major changes to the system. The addition of preloaded centering springs to the control valve proved to be the only scheme tried which improved the characteristics measurably. The preload of the centering springs was strong enough to overcome the valve friction and return the valve piston to neutral. This spring produced a breakout force at the stick slightly larger than that due to the valve friction force. It was found that the effect of this breakout force was considered by the pilots to be much less objectionable than the effect of valve friction which gave an equal value of breakout force.

The breakout force due to the preloaded centering springs resulted in a tendency for the stick to stay in a displaced position. It therefore adversely affected the ability of the airplane to return to a trimmed condition in a manner similar to the effects of normal control-system friction. It did not, however, result in any tendency to cause unstable oscillations of the pilot-airplane combination.

In order to compare the characteristics with and without the valve centering springs, records were obtained while the pilot attempted steady 3g turns. These data are presented in the form of time histories of stick force, elevator angle, and normal acceleration for the airplane with the normal manual control, the power control, and the power control with centering springs on the valve. Figure 11(a) gives the data for the manual control and shows that the control was applied rapidly and smoothly. Figure 11(b) shows the same maneuver being attempted when the power control with no centering springs was used. In this case an initial control was applied rapidly and resulted in an overshoot of the acceleration, and the pilot spent the remainder of the time trying to stabilize the airplane. Figure 11(c) shows the maneuver being done by using the power control with centering springs. In this case the pilot has much less difficulty though some oscillations were encountered.

The results of the tests of fighter A with a power control system further emphasize the difficulty of estabilishing any simple criterion for the allowable magnitude of valve friction. The values of valve friction tested were much larger in comparison with the value of force per g than those tested on the bomber airplane. As a result, serious oscillations were encountered in maneuvers. It might have been expected that even more serious difficulty would have occurred in maneuvers which required small corrections to the flight path, whereas actually surprisingly little difficulty was encountered in this case. These characteristics were traced to detailed peculiarities of the control system, which resulted in the ability to obtain very small control movements without breaking through the valve friction. With another airplane, these peculiarities might not exist, or other design details might be present which have equally important effects. The preloaded valve centering springs furnish an example of a design feature which may have a large influence on the control characteristics of the system.

QUALITATIVE DISCUSSION OF TEST RESULTS

Factors Involved in Avoiding Control Difficulties Due to Instability of Pilot-Airplane Combination

A review of the foregoing examples of control difficulties due to instability of the pilot-airplane combination indicates that these difficulties are of a rather complicated nature. It is unlikely that a set of quantitative rules similar to the existing handling-qualities specifications could be set up to specify the requirements for avoiding all such difficulties. One feature is apparent, however, in all the examples presented previously in which control difficulties have occurred; that is, a marked phase difference exists between the pilot's control force and the associated control-surface deflection. The presence of valve friction in a hydraulic-power control system has been shown to cause roughly a 180° phase lag between the control force and the resulting control motion. This phase lag exists only at small deflections and is reduced at larger deflections by the presence of restoring forces on the control stick. In all cases the difficulties associated with this type of friction have been encountered at small control deflections. In the case where the airplane involved had large static stability, these small control deflections were necessary in making small precise corrections to the flight path; but, in the case where the airplane had small static stability, small deflections were used in normal maneuvers.

The problems encountered with lightly balanced control surfaces in conjunction with bobweights involve the opposite condition in which, at the frequencies of control movement normally used in maneuvering, the control deflection leads the control force by a relatively large amount. In these cases satisfactory conditions were obtained by increasing the control force in phase with the control-stick deflection in order to reduce this phase shift.

As a general rule, therefore, the statement may be made that control difficulties of the type under consideration will not be encountered provided the control deflection is approximately in phase with the control force throughout the range of amplitudes and frequencies used by the pilot in controlling the airplane. This rule is recognized as an idealized condition which cannot be obtained in practice because certain friction and inertia effects are inevitable. Furthermore, the rule should not be interpreted as an exact condition to strive for because some damping of the control motion, which would tend to cause a phase difference between the control force and deflection, is probably desirable. Nevertheless, examination of flight records obtained with satisfactory conventional control systems indicates that this rule is very closely satisfied by comparison with the unsatisfactory cases discussed in this report. In designing an actual control system, the designer, of course, wishes to know whether a certain amount of deviation from the qualitative rule stated previously will be sufficient to result in unsatisfactory characteristics. In subsequent sections of this report analytical and experimental methods are presented for making an approximate check of individual cases to indicate whether satisfactory results will be obtained.

Effect of Nonlinear Characteristics

Caused by Friction or Preload

A characteristic frequently measured in evaluating a control system is the breakout force, that is, the force required to start the control stick moving from a trimmed position. Breakout forces, however, may arise from a number of different sources. In the preceding discussion, cases have been referred to in which these forces result from static friction on the control stick, static friction on the valve of a power control system, preloaded centering springs on the control stick, and preloaded centering springs on the valve. These various sources of breakout force do not have equivalent effects on the control characteristics. Further discussions of the effects of these nonlinear characteristics, based on experience obtained in flight tests, therefore appear desirable.

The effects of static friction on the control stick are considered first. Limits for the allowable amount of friction of this type for various classes of airplanes have been fairly well established and are given in the military handling-qualities specifications. A very small amount of static friction has been shown to be desirable, probably because it gives the pilot some knowledge of the fact that he is making small movements of the control stick. If this small amount of friction were absent, these movements might be made unintentionally as a result of airplane vibrations or accelerations. The amount of friction required for this purpose, however, is very small (approximately 1/2 pound). This value is less than usually exists even on the most frictionless control systems. Larger amounts of static friction are generally considered undesirable although large values do not appear to lead to instability of the pilot-airplane combination provided that control-system flexibility also is not present. One effect of static friction is to prevent a definite relationship between the control forces and control deflection when the control stick is at rest. Friction, therefore, leads to some difficulty in attaining a trimmed condition. In addition, large amounts of friction unnecessarily increase the work required by the pilot in maneuvering or in making small corrections to offset disturbances caused by rough air.

The second type of nonlinearity which is considered is the effect of static friction on the valve of a power control system. This type of friction has been shown in some cases to cause instability of the pilot-airplane combination. No simple rules regarding limits for this type of friction have been established. There appears to be no question, however, that much smaller values of this type of friction (as measured at the control stick) are permissible than the allowable limits for normal control-system friction. One undesirable effect of this type of friction is to prevent a definite relationship between the control force and the control deflection either when the control stick is at rest or moving at a constant rate. The presence of control friction in the valve of a power control system makes it difficult to define the phase relationship between the control force and the control motion when the stick is oscillated. Theoretically, the control force is defined for any prescribed control-stick motion in which the rate is not constant, but small variations in the wave form of the control-stick motion may require quite different control-force variations. Such a characteristic would be expected to lead to difficulty in precision flying even if it did not result in actual instability.

The third type of nonlinearity considered is that introduced by a preloaded centering spring on the control stick. Experience with this type of force variation has not been extensive but certain conclusions may be reached regarding its effects. This type of device is usually employed in order to reduce the adverse effects of static friction, and it has always been tested in conjunction with a certain amount of static friction (ref. 10). The control characteristics associated with a preloaded centering device appear to be desirable for cases in which long periods of steady flight are required because the device definitely holds the control stick at the desired trim position. The allowable limits for the forces introduced by this type of device appear to be considerably larger than those given in the handling-qualities requirements for static control friction. This type of force variation does not prevent an exact relationship between the control force and the control deflection. Furthermore, it tends to maintain the control force in phase with the control-surface deflection, an effect which has been shown to be desirable.

The fourth type of nonlinearity considered is the effect of a preloaded centering device on the valve of a power control system. This device has been shown to reduce the adverse effects of static friction on the valve. As far as the effects on control forces are concerned, however, this device is approximately equivalent to static friction on the control stick because it introduces a constant force which tends to oppose the motion of the control stick whether it is moving away from neutral or towards neutral. The limitations on the forces introduced by this type of device should therefore be similar to those established for static control friction. A practical limitation in the use of this device is that it must be adjusted to center the valve at exactly the point of zero flow of hydraulic fluid; otherwise the control stick will have a tendency to move slowly and a force equivalent to that required to overcome the preload will have to be exerted to hold the control stick fixed. If any leakage exists in the hydraulic-control system when loads are applied to the control surface, a similar undesirable effect will be produced.

An example was previously presented (fig. 1) in which flexibility of the control system in conjunction with friction at the elevator hinge caused a type of instability of the pilot-airplane combination. This condition is particularly undesirable because it prevents an exact relationship between either the stick force or the stick position and the control-surface deflection. In the usual case, when the stick is moved, backlash and flexibility in various links of the control system are taken up in turn and the friction introduced by the various bearings is added progressively until the control-stick motion is felt at the control surface. Such effects are obviously difficult to predict. For this reason, an attempt has been made to establish a method of analysis which includes such effects by utilizing measured frequency-response characteristics of the actual control system. This method is described in the following section of the report.

ANALYSIS OF STABILITY OF CONTROLLED AIRPLANE

The following analysis is presented in order to give a possible physical explanation of the control characteristics of fighter A equipped with the experimental power control system. Because of the arbitrary nature of the assumptions made in the analysis, the results are not regarded as being particularly accurate. The method should be tried in other cases before conclusions are reached regarding its usefulness for design purposes.

The pilot is visualized as controlling the airplane as shown by the block diagram of figure 12. The stability of such a feedback system is frequently determined by means of Nyquist's criterion. In order to apply this criterion, the frequency-response characteristics of each component of the system are used to plot the open-loop transfer function on the complex plane. Relatively simple rules may then be applied which allow the stability of the system to be predicted (ref. 11).

Although a frequency-response type of analysis is strictly accurate only for linear systems, it has been shown in reference 12 that it may be applied to obtain an approximate idea of the stability of systems in which some of the components have nonlinear characteristics. In this case, the frequency-response characteristics must be determined at a series of amplitudes, inasmuch as the degree of stability may depend on the amplitude of the motion.

The analysis was made for the control system of fighter A in order to try to correlate the analytical results with the actual flight results. The methods used in determining the characteristics of each of the blocks in figure 12 are now discussed.

Human-Pilot Characteristics

The characteristics of a human pilot are known to be too complicated to be represented completely by any simple mathematical expression or physical analog. For some purposes, however, it may be possible to approximate human response in this way for some specific type of operation. Although human response characteristics are generally nonlinear, the data of reference 13 show that they may be considered more nearly linear when the pilot is controlling a randomly varying quantity. Such a random variation has been shown in reference 14 to occur when the pilot is attempting to control a marginally stable system.

If the response characteristics of the pilot are considered linear, they may be simulated by an autopilot having suitable characteristics. The important quantities which must be determined for this autopilot are the inputs to which it is sensitive, the gain constants involved, and the lag characteristics.

Selection of the quantity or quantities which the human pilot senses in controlling the airplane is arbitrary and must be based mainly on the reasonableness of the results obtained. In the present analysis, the assumption was made that the pilot was sensitive to pitching velocity. The human pilot may also sense angle of pitch or normal acceleration. If these quantities are assumed to be the only quantities sensed, however, and if a reasonable lag is assumed in the pilot response, the pilot's actions would lead to instability even in the case of a manual control system for reasonably large values of gain constant. A time lag of 0.2 second in the pilot's response was assumed in accordance with results of reference 14 and other data on human-pilot response characteristics.

A point to be specified for the human-pilot characteristics is whether he controls the airplane by application of stick force or stick deflection. Movement of the control stick must in all cases result from application of stick force. If the stick movement required is large, however, the pilot may sense the position of the control stick by feeling the position of his arm. He may then apply forces necessary to control the stick position as desired. This action is analogous to that of a mechanical autopilot which includes a tight-position loop around the output servomotor. On the other hand, the human pilot may control the airplane by applications of force without regard for the resulting control-stick movement. This action is analogous to that of a so-called force-type autopilot in which the servomotor torque is regulated in accordance with the controlling quantities. Flight data appear to substantiate the belief that in most cases the human pilot prefers to control the airplane primarily through applications of force. This method relieves the pilot of the additional task of providing the equivalent of a tight-position loop on his output. Furthermore, in high-speed flight the control motion is normally very small, whereas the control forces bear a logical relation to the response of the airplane. The belief that the pilot tends to control the airplane through application of force is further substantiated by the data already presented in which serious instability of the pilot-airplane combination resulted when the force characteristics of the power-control system became illogical even though the position-following characteristics were very good. The possibility remains, however, that the pilot may, at will, use either method or a combination of both in order to obtain the most satisfactory control of the airplane.

In determining the gain constant used by the pilot, it was assumed that the pilot would use the same control effort to oppose an undesired pitching velocity as he would use to produce this pitching velocity in a steady turn or pull-up. Although this assumption is arbitrary, it was found to be approximately true in flight data obtained for conditions such as those shown in figure 11(b) where the pilot was attempting control in a marginally stable condition. The steady-force gradient was about 3 pounds per g, corresponding to a value of 49 pounds per radian per second of pitching velocity at an airspeed of 300 miles per hour. The resulting frequency-response characteristics assumed for the human pilot are shown in figure 13. Although the amplitude ratio is shown to be constant, the results of reference 14 have shown that the human pilot is unable to apply a consistent controlling action at frequencies much greater than 1 cycle per second ($\omega = 6.28$ radians per second). In practice the human pilot's response would be sharply attentuated at frequencies greater than this value. No effort has been made to approximate the human-pilot characteristics in this high-frequency range because both the flight and analytical data show that the instability of the pilot-airplane combination, if present, generally involves frequencies less than 1 cycle per second.

Control-System Characteristics

Control-system characteristics were measured by oscillating the control stick sinusoidally with a mechanical driving mechanism and recording the resulting control forces and control positions. Data were obtained through a range of frequencies of 0 to 10 radians per second at various amplitudes and with various combinations of force gradient and valve friction. Typical data obtained in this manner are shown in figure 14. During these tests the elevator-angle variation was approximately sinusoidal, although its amplitude changed somewhat as a function of frequency. Efforts were made to operate the control stick manually in order to obtain a more nearly constant amplitude of elevator motion. Oscillating the control stick manually to produce a reasonably accurate sinusoidal variation of the elevator, however, proved to be very difficult in many cases. This difficulty is a further indication of the control problems resulting from illogical control-force characteristics.

During the ground oscillation tests the elevator was not loaded to simulate aerodynamic hinge moments. Flight data showed, however, that at an airspeed of 300 miles per hour the ratio of elevator movement to control-stick movement was only about one-half that measured on the ground because of stretch in the control system. (The hydraulic actuator of the power control system was located near the cockpit.) The ratio of elevator angle to control force measured on the ground was therefore multiplied by one-half in order to apply it to conditions existing in flight.

Frequency-response data for the manual control system were obtained in a similar manner. For the ground tests the control forces were supplied by the feel device; whereas, in flight they came from the aerodynamic forces on the elevator. The feel device, however, is considered to represent adequately the effect of the aerodynamic forces on the elevator because in both conditions the force is primarily a spring-restoring moment.

The frequency response for the manual control system is shown in figure 15 for an amplitude of elevator motion of $\pm 1\frac{1}{2}^{\circ}$. Figure 15 also shows the frequency-response characteristics obtained with the power-control system at amplitudes of elevator motion for approximately $\pm 0.1^{\circ}$ to $\pm 3\frac{1}{2}^{\circ}$ and with values of valve friction from about ±1 pound to ±7 pounds. The phase-angle curves shown in figure 15 are faired values with an estimated accuracy of about $\pm 5^{\circ}$ in the low range and increasing to about $\pm 20^{\circ}$ in the high range. Although the curves of amplitude ratio and phase angle for various conditions do not appear to vary systematically with either valve friction or amplitude, analytical studies of similar power control systems indicate that these apparently inconsistent variations may arise as a result of the effect of valve friction. All the curves shown were obtained with the feel system engaged with the exception of the case with ±7 pounds of friction and $\pm 1\frac{1}{2}^{\circ}$ amplitude. This case does not correspond to a condition tested in flight but is included to show the frequency-response characteristics of the control system with an extreme amount of valve friction and no spring-restoring force. As mentioned previously, the values of valve friction were somewhat inconsistent. For this reason, all values of valve friction mentioned are average values.

Airplane Characteristics

The transfer function for fighter A relating pitching velocity to elevator deflection is shown in figure 16 for an airspeed of 300 miles per hour and an altitude of 10,000 feet. This transfer function was estimated theoretically by assuming the airspeed to be constant. Some of the aerodynamic parameters necessary to calculate the transfer function were obtained from wind-tunnel data; whereas, the elevator effectiveness and static stability were chosen to give response characteristics which would agree with those measured in flight.

Results of Analysis

The amplitude ratios and phase angles of the various components shown in the block diagram of figure 12 were combined, and the open-loop transfer-function locus of the pilot-control-airplane combination was plotted on the complex plane. Figure 17(a) shows the stability with the manual control compared to that with the power control with values of valve friction of ±1 pound, ±4 pounds, and ±7 pounds all at $\pm 1\frac{1}{2}^{\circ}$ of elevator motion. The criterion for stability for this simple single-loop system is that the locus does not encompass the critical point $-1 + j0$.

It can be seen from figure 17(a) that the manual control is the only one that does not circle the critical point and that, as the valve friction increases, the corresponding locus crosses the real axis at greater values. The pilot's opinion verifies this trend of increasing difficulty as the valve friction increases. The case of $\pm 1\frac{1}{2}^{\circ}$ amplitude and ±7 pounds of friction, without the feel device, was not tested in flight, but figure 17(a) indicates that this condition would be more unstable than any of the other conditions.

Figure 17(b) shows relative stability as the amplitude of the elevator motion is changed. When an elevator motion on the order of $\frac{1}{10}^{\circ}$ is required for a given maneuver, the combination is stable as indicated by the solid line close to the origin. The reason for the stability in the case of $\frac{1}{10}^{\circ}$ amplitude is believed to be the ability to displace the valve slightly by deforming the seals without having to overcome the valve friction. As the elevator motion is increased, the stability decreases as shown by the loci for $\pm 1\frac{1}{2}^{\circ}$ and $\pm 3\frac{1}{2}^{\circ}$. These results are borne out by the flight test results presented previously in which the pilot had increasing difficulty controlling the airplane as the amplitude of elevator motion used during the oscillations encountered in a maneuver increased. The frequency of free oscillations of the system can be estimated from figure 17 for cases in which the transfer locus passes close to the point $-1 + j0$. The case with $\delta_e = \pm 1\frac{1}{2}^{\circ}$, friction ±4 pounds, corresponds to the flight condition of figure 11(b). The frequency of the oscillation shown in figure 17 is about 1/2 cycle per second. This result is in qualitative agreement with the flight results for which the frequency of the induced oscillation varies from about 1/2 to 1 cycle per second.

The preceding analysis is not regarded as being particularly accurate, because of the nonlinear characteristics of the power control system and because of the previously mentioned uncertainty in the ability to approximate the characteristics of a human pilot by a mathematical expression. The analysis is presented mainly to provide a physical explanation of the control difficulties encountered in flight. In spite of the uncertainties of the analysis, however, the difference between the phase-lag characteristics of the manual and power control systems is so great (fig. 15) that relatively large changes in the assumptions regarding the characteristics of the human pilot would not greatly change the overall conclusions.

It is believed that this type of analysis would be an aid in predicting the relative merits of various types of power controls and modifications to the power control selected for any given airplane. If this analysis is made before the power control system is constructed, a reasonable approximation to the frequency-response characteristics of the system could probably be made by analytical methods. If the control system is already in existence, a more accurate prediction of its flight characteristics may be obtained from ground tests of the type described in the following section.

GROUND TESTS OF CONTROL SYSTEM WITH SIMULATED AIRPLANE RESPONSE

In order to provide a more accurate method for determining whether a given control system will operate satisfactorily before actually flying an airplane, a method was tested using a simple simulator to represent the airplane response characteristics. A schematic drawing of the device is shown in figure 18. The simulator consisted simply of a projector mounted on pivots and equipped with springs and damping so that its period and damping characteristics simulated those of the short-period longitudinal motion of the airplane. The device was then connected by means of a spring to the elevator of the airplane and the projector produced a spot of light on a screen next to the pilot's cockpit. If the pilot abruptly deflected the elevator, the spot of light would move approximately in accordance with the development of normal acceleration that would be expected in flight. The most important mechanical consideration in designing this device was to insure that the projector was free to oscillate with a minimum of friction. For this reason plate knife edges were used as the pivots. Damping was supplied by a piston with large clearance immersed in a can of heavy oil. For purposes of recording the results obtained, the position of the projector was measured by an Autosyn pickup which contributed a negligible amount of friction.

The tests consisted of having several pilots attempt to position the spot of light from the projector between two marks on the screen by moving the control stick. These marks were spaced to simulate the elevator deflection required to produce a change of normal acceleration of 1 g on the airplane at an indicated airspeed of 300 miles per hour. Since the pilots experienced no appreciable difficulty in flying the airplane with the normal manual control, the first run in each case was made with the manual control and the second, with the power control. In both cases the artificial feel device was used to simulate the stick force required. Figure 19 shows a typical record made by a pilot with very little flight experience in fighter A. This figure shows the pilot had no difficulty in quickly positioning the light spot with manual control; whereas with power controls he first overshot the desired position and then produced a residual oscillation which was difficult to damp out. The pilot who had considerable experience flying fighter A both with manual and power controls experienced the same difficulty but to a lesser degree.

Tests were also made where the spring connecting the projector to the elevator was replaced with a rigid link to remove the lag introduced by the airplane. Other tests were made without the artificial feel system engaged but with the projector connected by means of a spring to the elevator. Time histories are shown in figure 20 and the results obtained for the direct linkage and spring linkage with and without feel device for both the manual control and power control systems are compared.

With manual control the pilot had very little difficulty positioning the spot of light either with or without the lag in airplane response included. With the power control system even without any lag of airplane motion the pilot experienced difficulty in producing a rapid step motion of the spot of light. With the airplane lag included and no feel, the resulting motion was actually unstable. Adding the control feel device reduced the violence of this instability somewhat.

Pilots who flew the airplane and also attempted control with the ground simulator believed that the simulator presented a very similar control problem to that encountered in flight. This conclusion is borne out by the similarity of oscillations obtained with the simulator and those encountered in flight. Further evidence that the simulator represented the airplane is shown by the fact that a pilot experienced in flying the airplane was able to control the simulator more easily than pilots who were inexperienced in flying the airplane. Control difficulties such as those illustrated in figure 20 were not at all apparent when the control was operated by the pilot on the ground without a sensitive device to indicate to him the elevator motion or the simulated airplane response. In this case, the control-stick motion appeared to follow the desires of the pilot perfectly, and there would have been no reason to suspect that control difficulties would be encountered in flight.

In cases where the actual control system is available for test the use of the simulator technique is believed to provide a more accurate indication of the probable control characteristics of the system than the theoretical analysis described in the preceding section. The simulator requires no assumptions as to the method of control used by the pilot and no approximations to the characteristics of the power-control system. The question might be raised, for example, in connection with the analytical results, as to how a pilot can control an airplane at all when the airplane-pilot combination is predicted to be unstable. The simulator results indicate that unstable oscillations may actually be obtained but that as soon as an oscillation starts the pilot attempts another method of control in which he regulates stick position rather than stick force. This method of control is quite difficult, however, under conditions where only a small stick motion may be required to maneuver. The difference in stick motion between fighter A and the bomber airplane probably accounts for the more serious difficulties caused by valve friction in the case of fighter A. It is believed, however, that in any case a pilot would object to the power-control characteristics if he could not obtain satisfactory control by the simpler method of force application.

CONCLUSIONS

A number of examples have been presented of control difficulties not completely covered by existing handling-qualities requirements. These control difficulties are hard for pilots to diagnose and are frequently described by terms such as "control sensitivity." These difficulties appear to result from a tendency for dynamic instability of the combination of the pilot, control system, and airplane. Tests of a bomber and a fighter airplane with experimental power control systems have been made to study this problem further. The following conclusions may be stated:

1. Control difficulties of the type considered have always been associated with a marked phase difference between the pilot's control force and the associated control-surface deflection.

2. The presence of static friction in the control valves of hydraulic-power control systems was found to be the explanation for several cases of control difficulty in airplanes equipped with such systems. The valve friction may cause a phase lag between the pilot's control force and the associated control-surface deflection approaching 180° at small control deflections.

3. Results of tests utilizing a bomber airplane and a fighter airplane (fighter A) equipped with power controls indicate that definite limits or simple rules for the tolerable amount of valve friction would be difficult to establish because of the large number of variables which may influence the problem. The control characteristics of these airplanes were strongly influenced by small design details of the power control systems. In general, however, a given value of valve friction (as measured at the control stick) appeared to be much more detrimental than a similar amount of static control-system friction.

4. The elevator control system was found to be much more critical from the standpoint of obtaining satisfactory characteristics of the power control system than the aileron or rudder control systems.

5. The only device which was tried that appreciably improved the handling qualities of an airplane with unsatisfactory characteristics due to valve friction was the addition of preloaded valve centering springs sufficiently strong to overcome the valve friction. These springs had an undesirable effect on control centering tendency, however, similar in nature to the effect of static control-system friction.

6. A method of analysis of the stability of the airplane under control of the human pilot has been presented which provides a physical explanation of the problem and appears to predict qualitative trends of the difficulties encountered in flight.

7. Ground tests of a control system using a simple simulator to represent the airplane response characteristics appear to be a satisfactory method for detecting undesirable control characteristics of the type under consideration before making actual flight tests.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 10, 1953.

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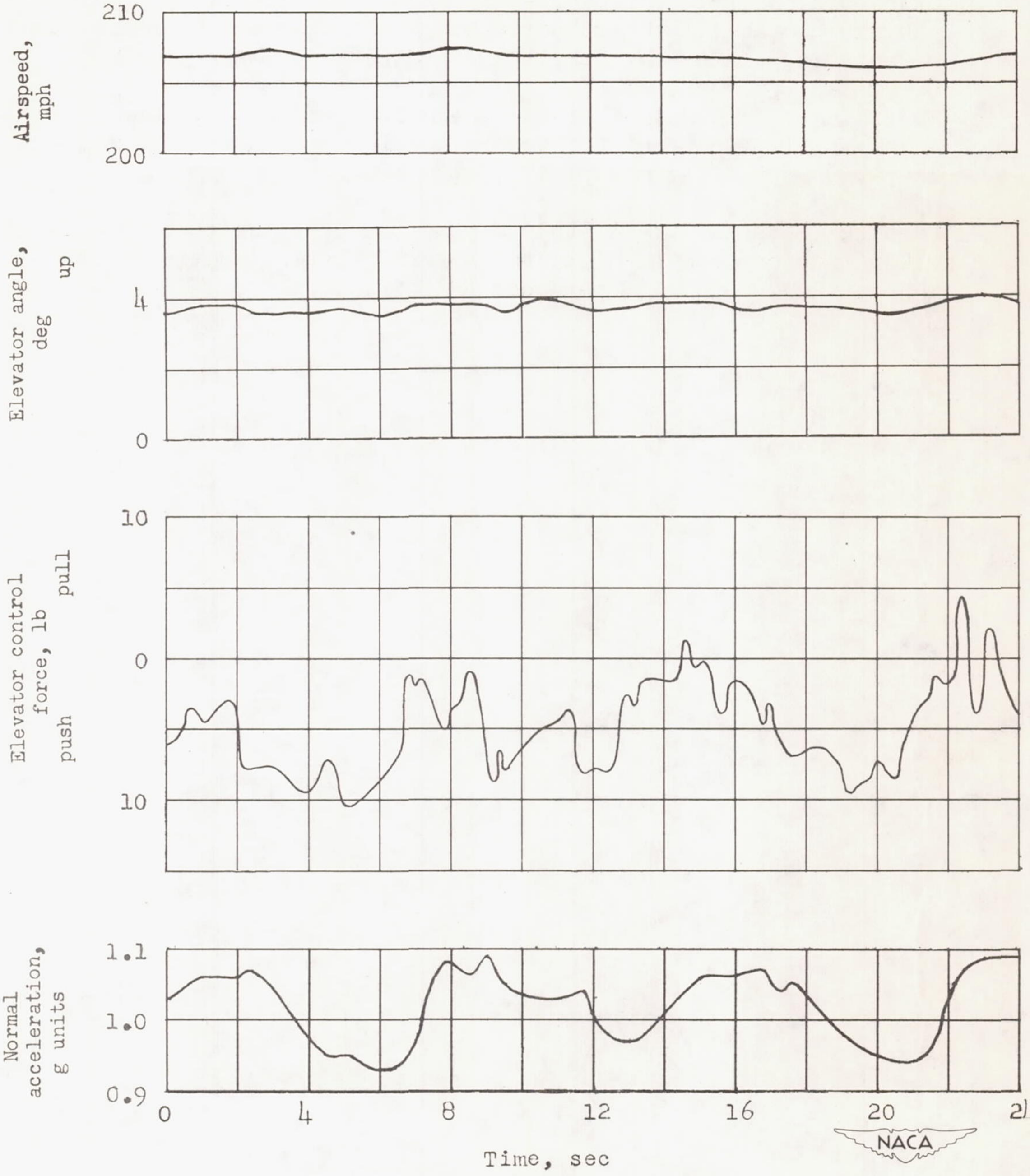


Figure 1.- Time histories of straight flight in a scout-bomber airplane. Note control-force variation used by pilot in holding a speed of 207 miles per hour.

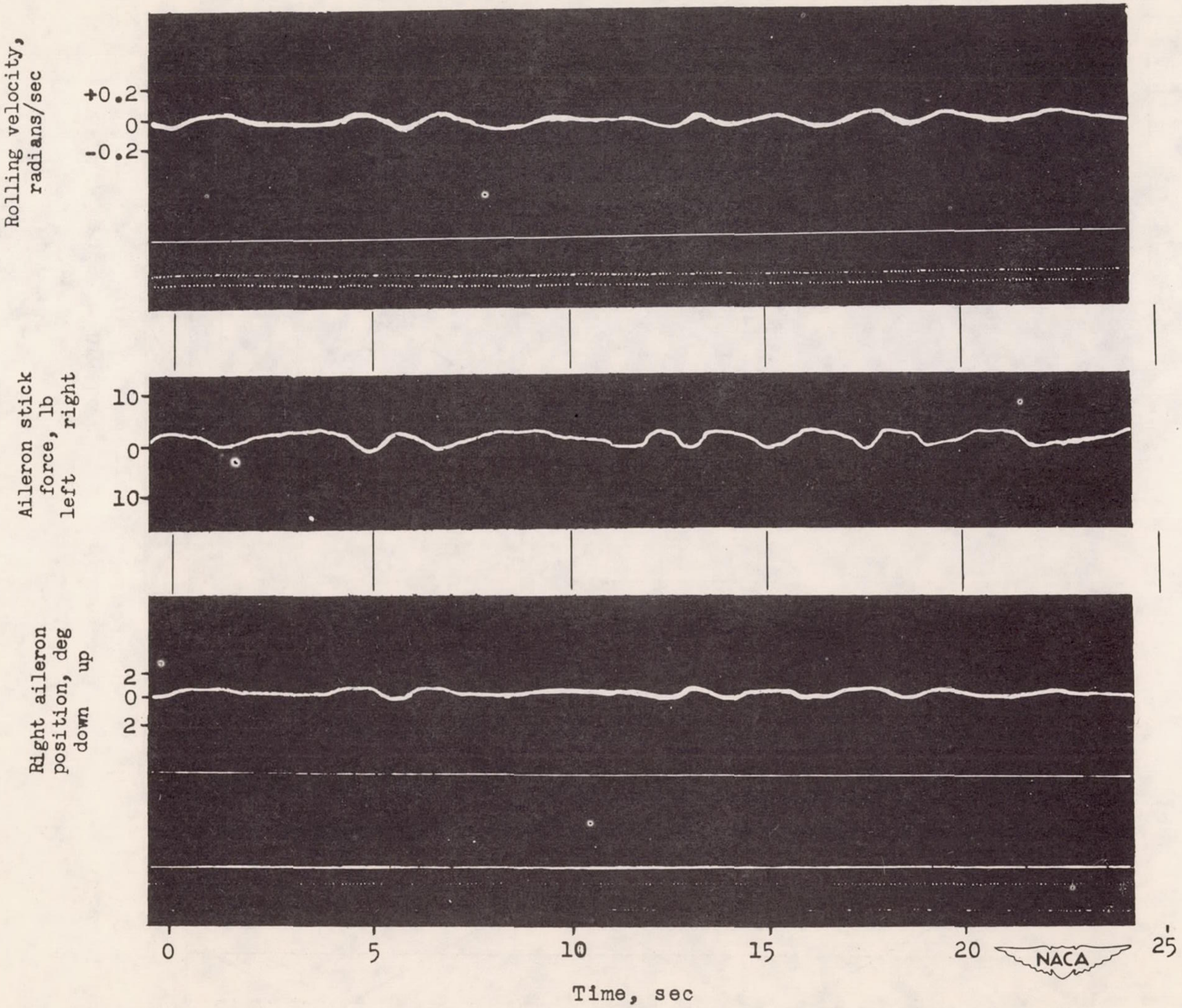


Figure 2.- Time histories of attempted laterally level flight in a jet fighter airplane with aileron boost.

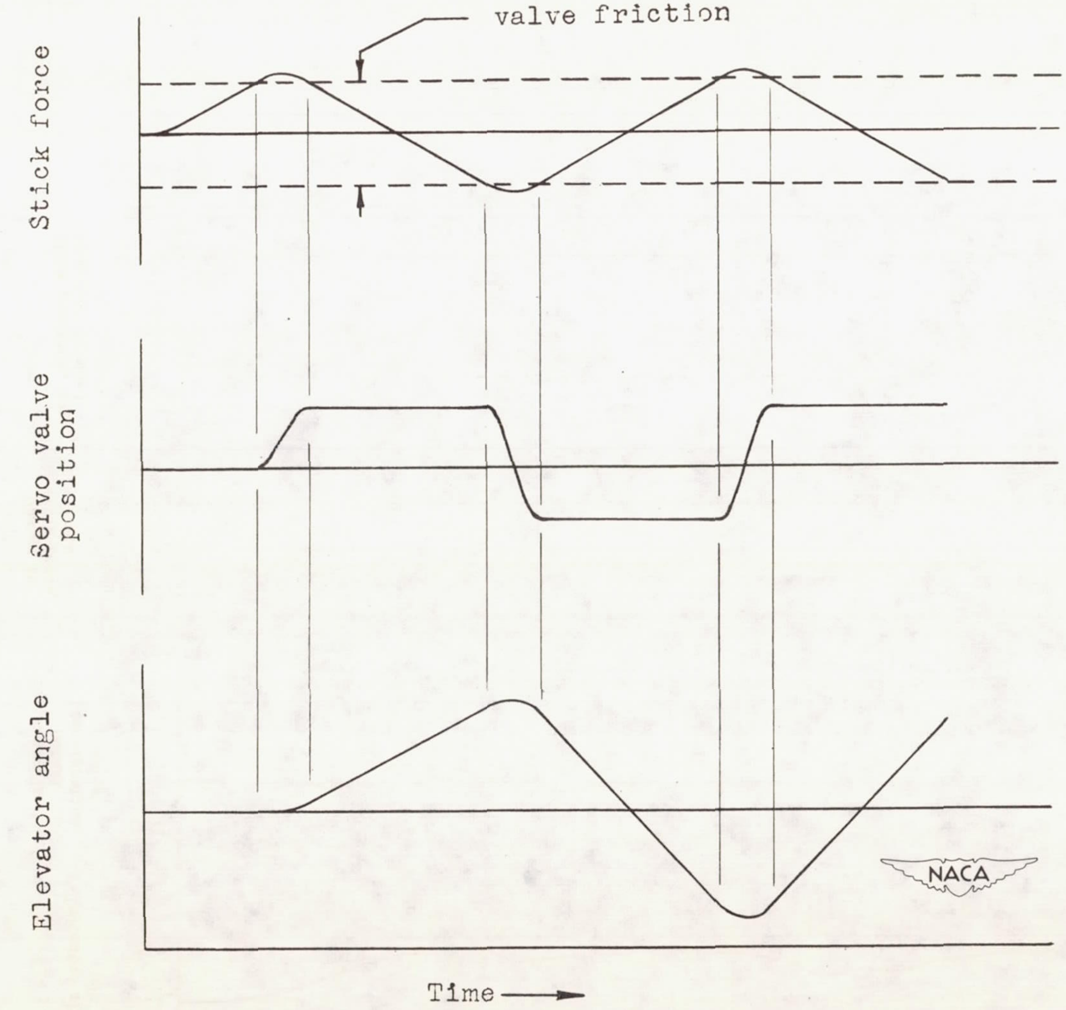
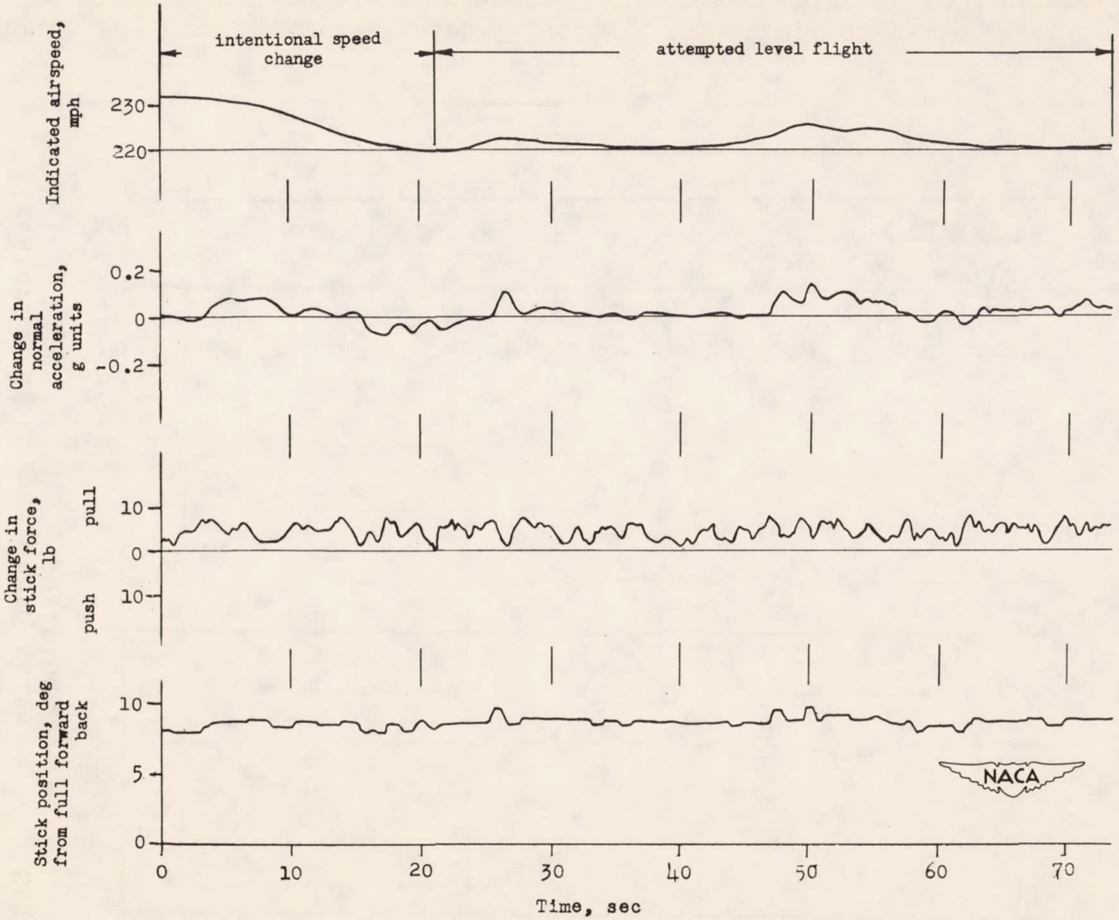
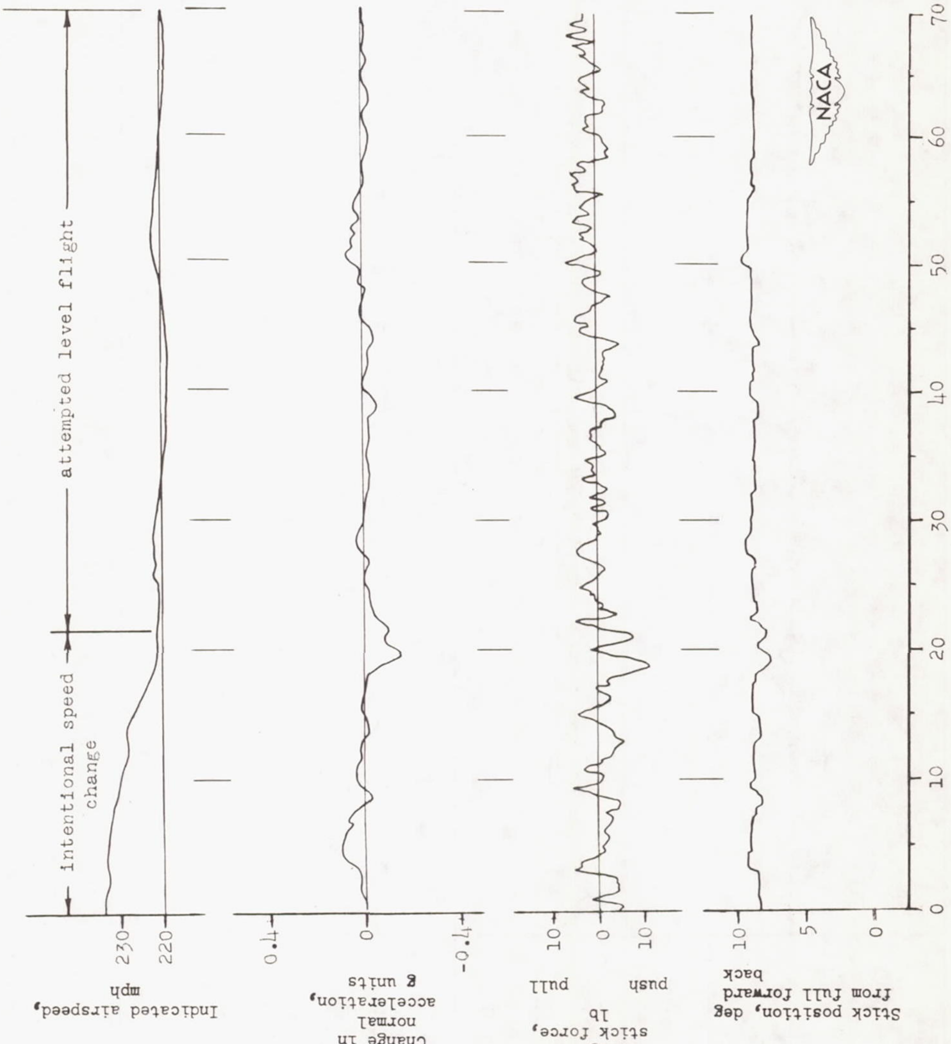


Figure 3.- Time histories which illustrate the effect of valve friction on stick force and elevator angle. Note phase shift of 180° between force and the resulting elevator motion.



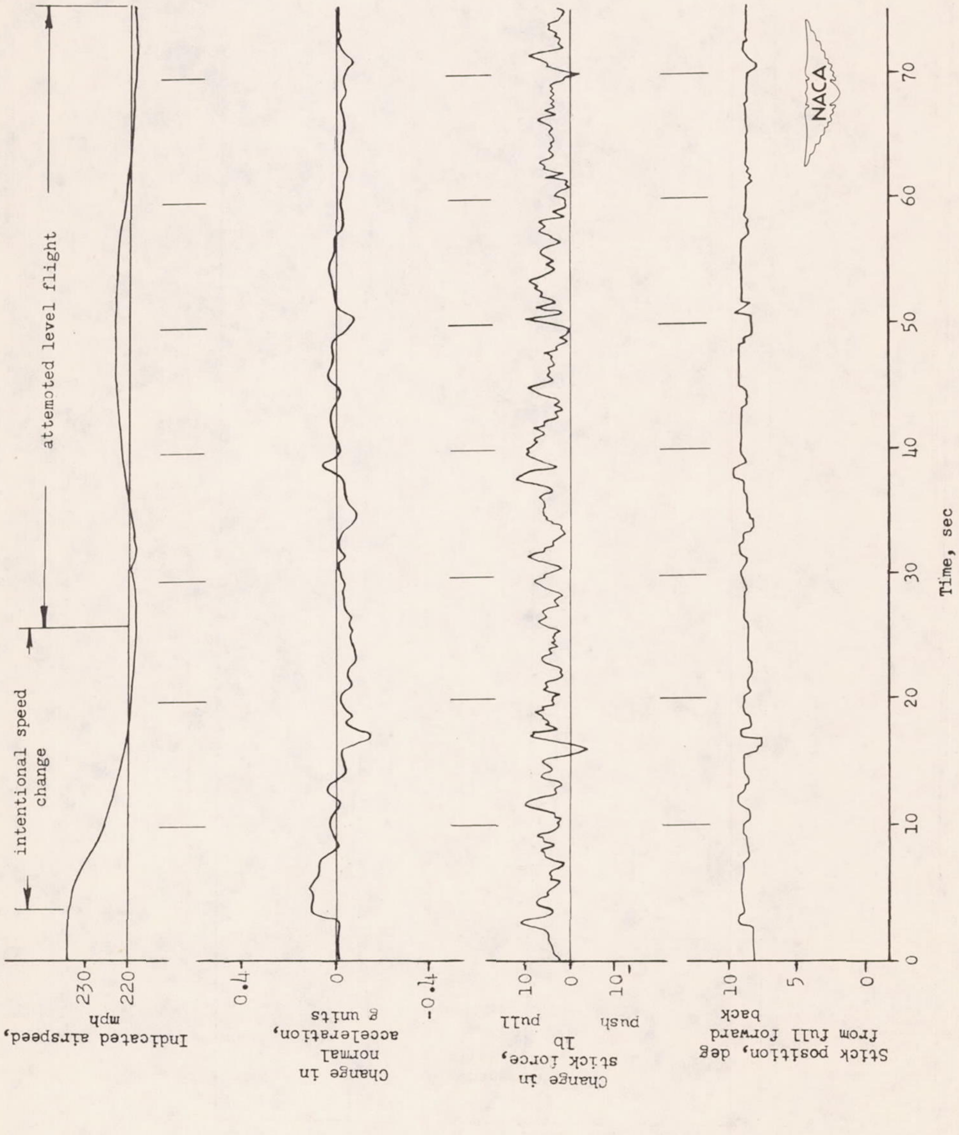
(a) $\frac{F_s}{\delta_s} = 5.0$ lb/deg.

Figure 4.- Time histories showing attempted precise flight with substantially no valve friction for three force gradients. Bomber airplane.



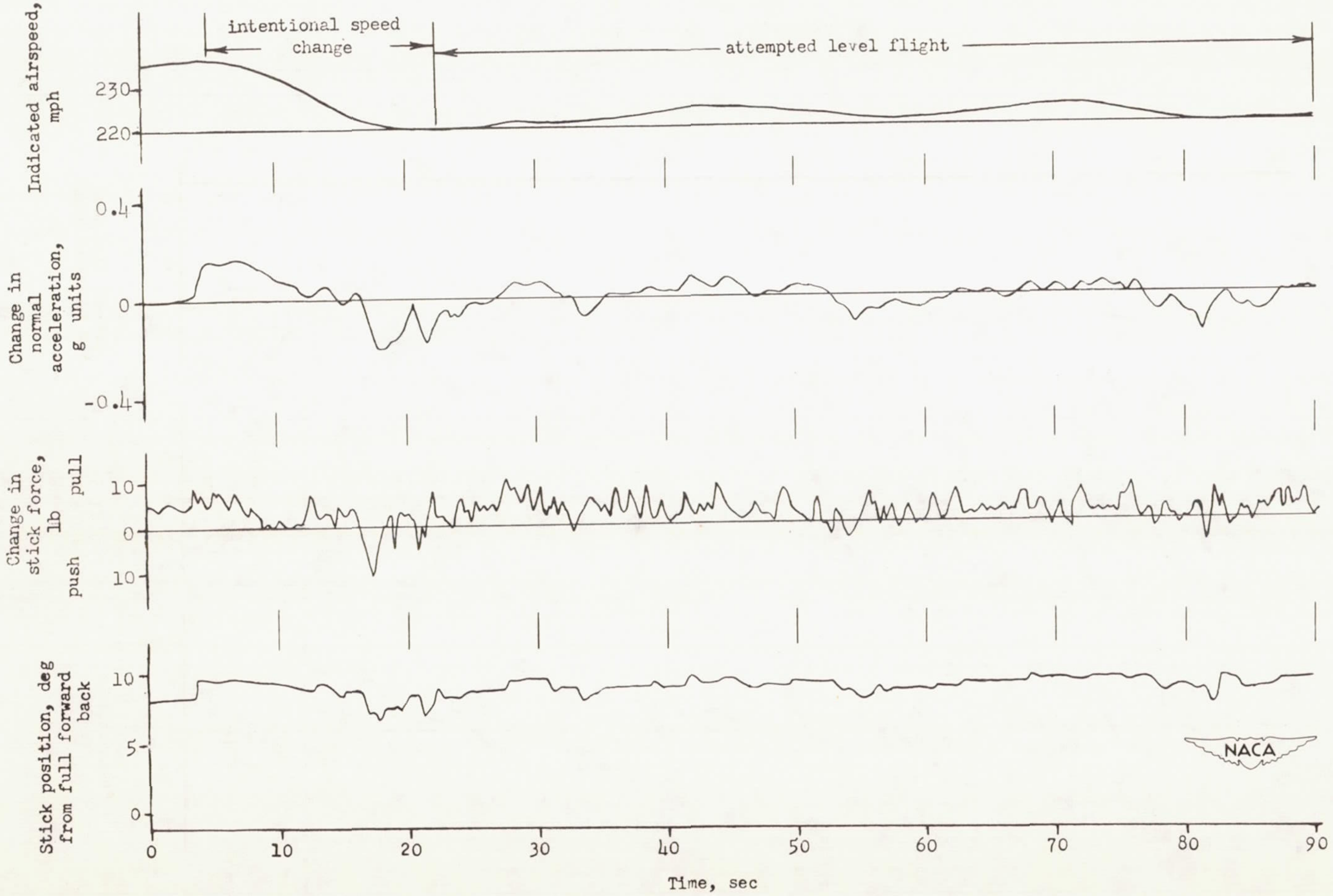
(b) $\frac{F_s}{\delta_s} = 10.5$ lb/deg.

Figure 4.- Continued.



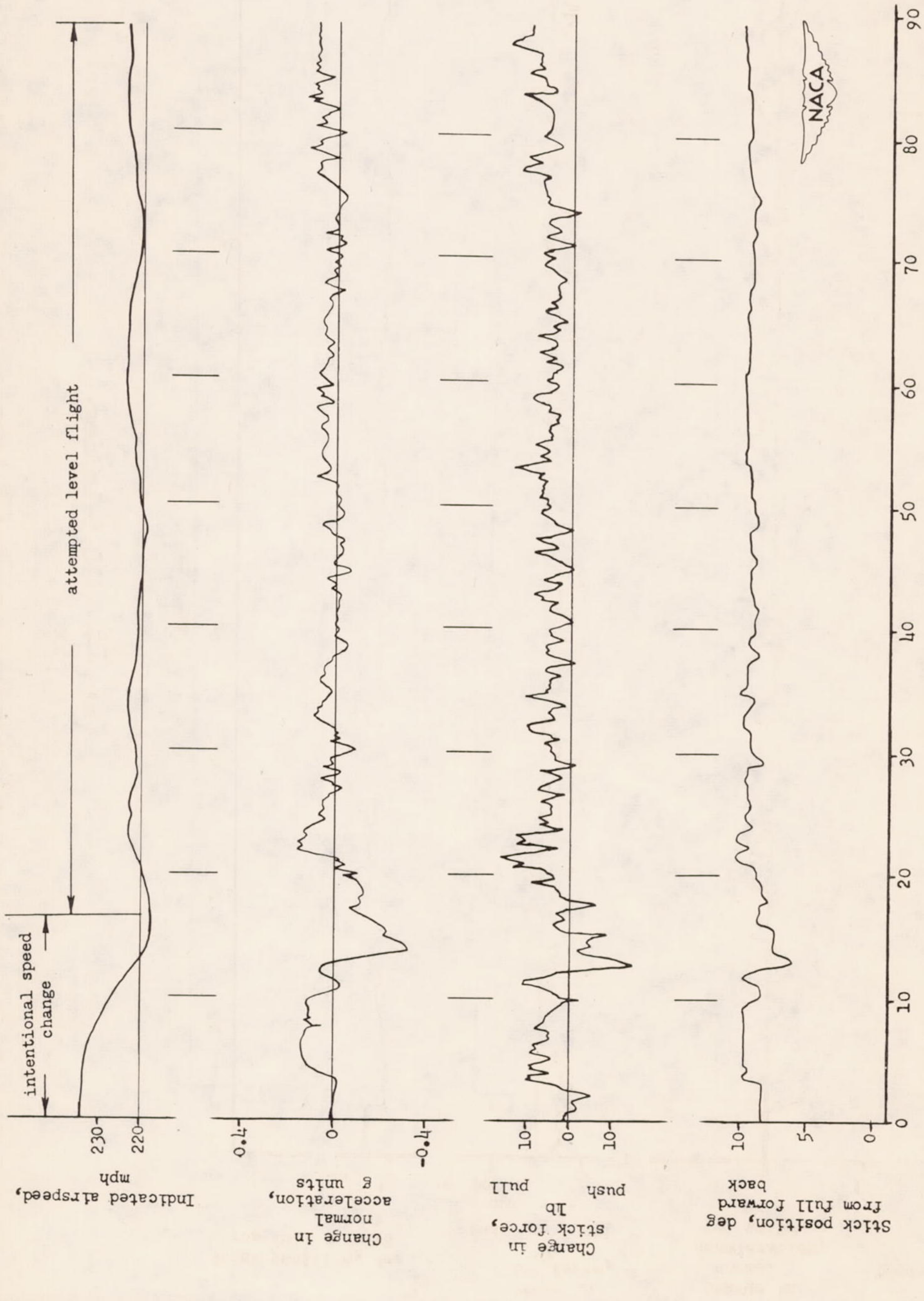
(c) $\frac{F_s}{\delta_s} = 15.0$ lb/deg.

Figure 4.- Concluded.



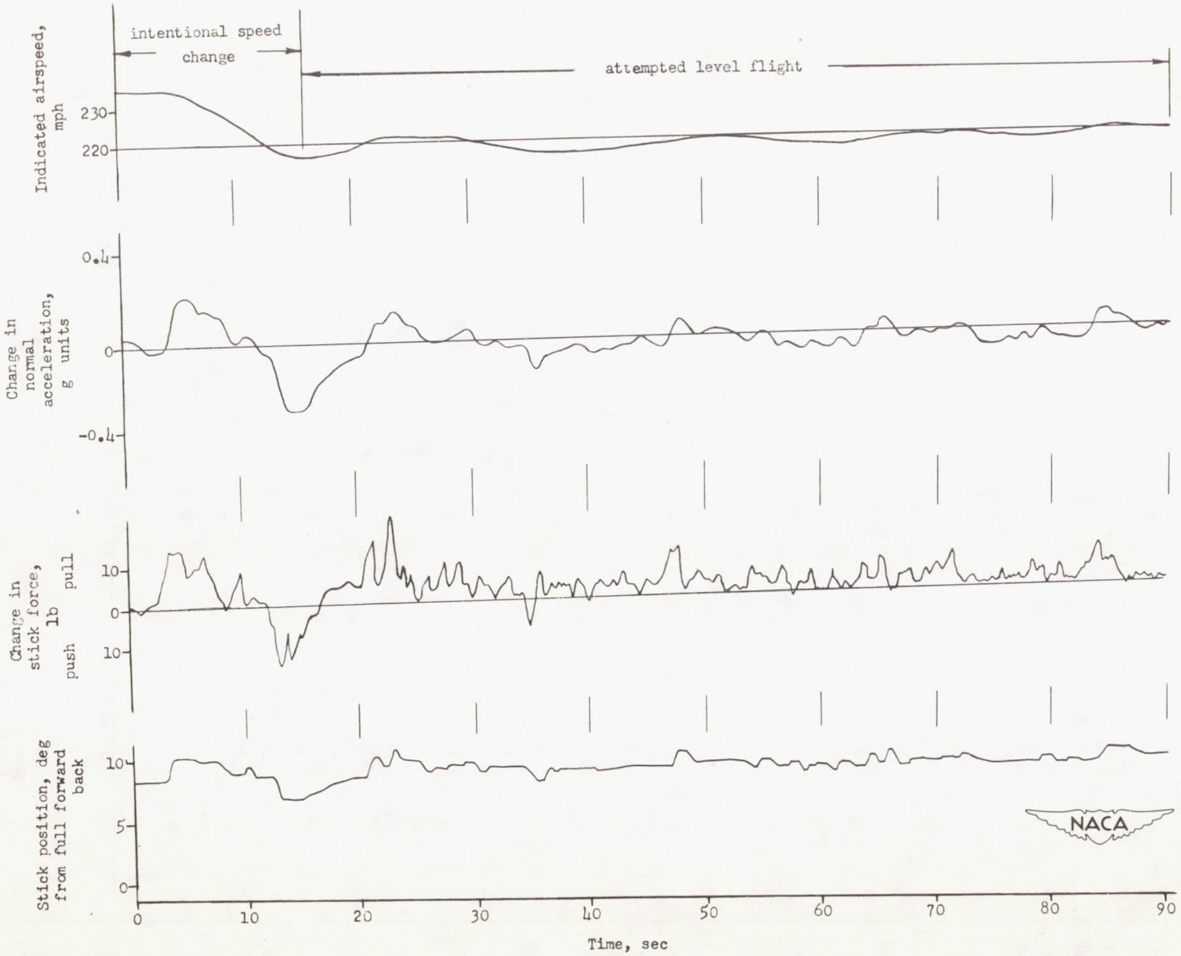
(a) $\frac{F_s}{\delta_s} = 10.5$ lb/deg.

Figure 5.- Time histories showing attempted precise flight with 1 pound of valve friction for three force gradients. Bomber airplane.



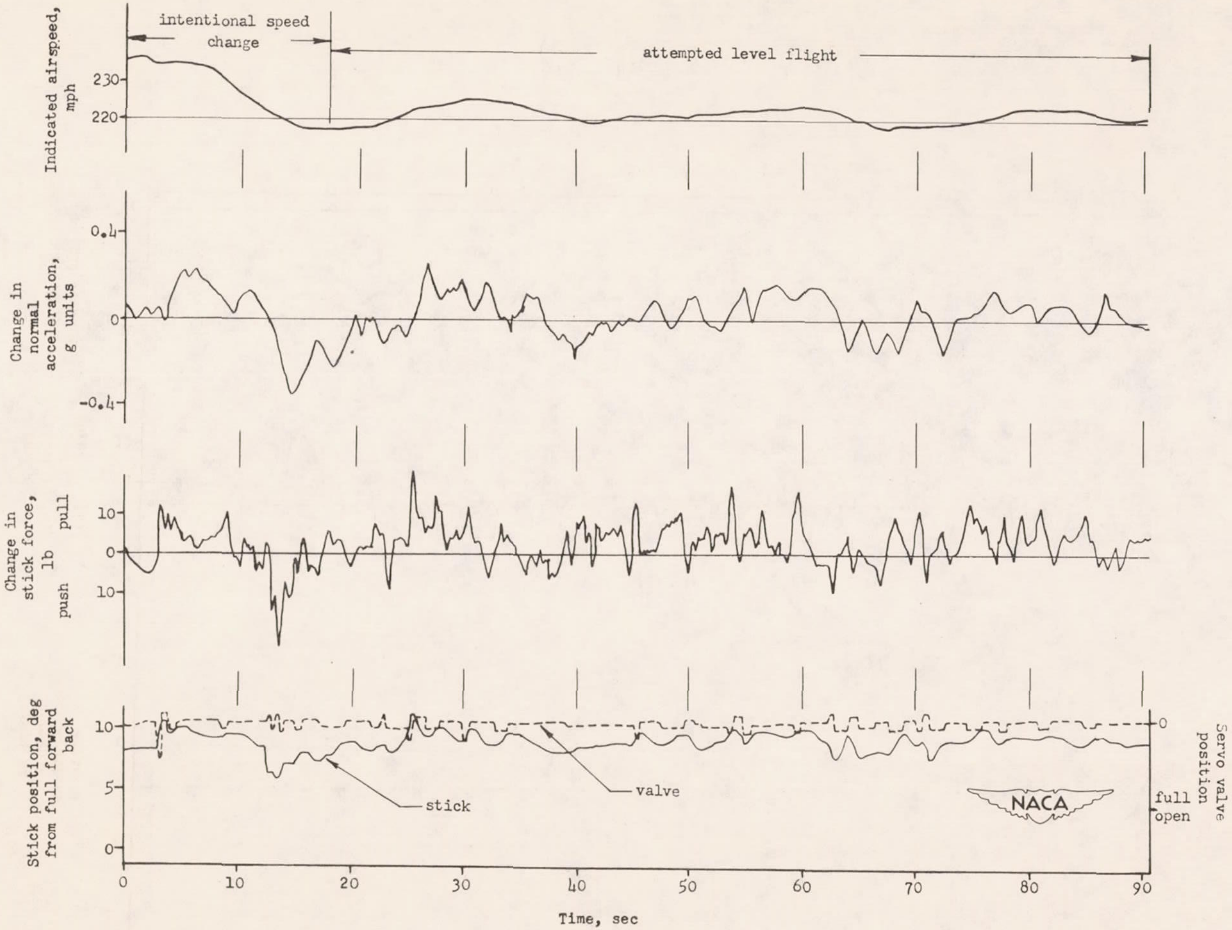
(b) $\frac{F_s}{\delta_s} = 15.0$ lb/deg.

Figure 5.- Continued.



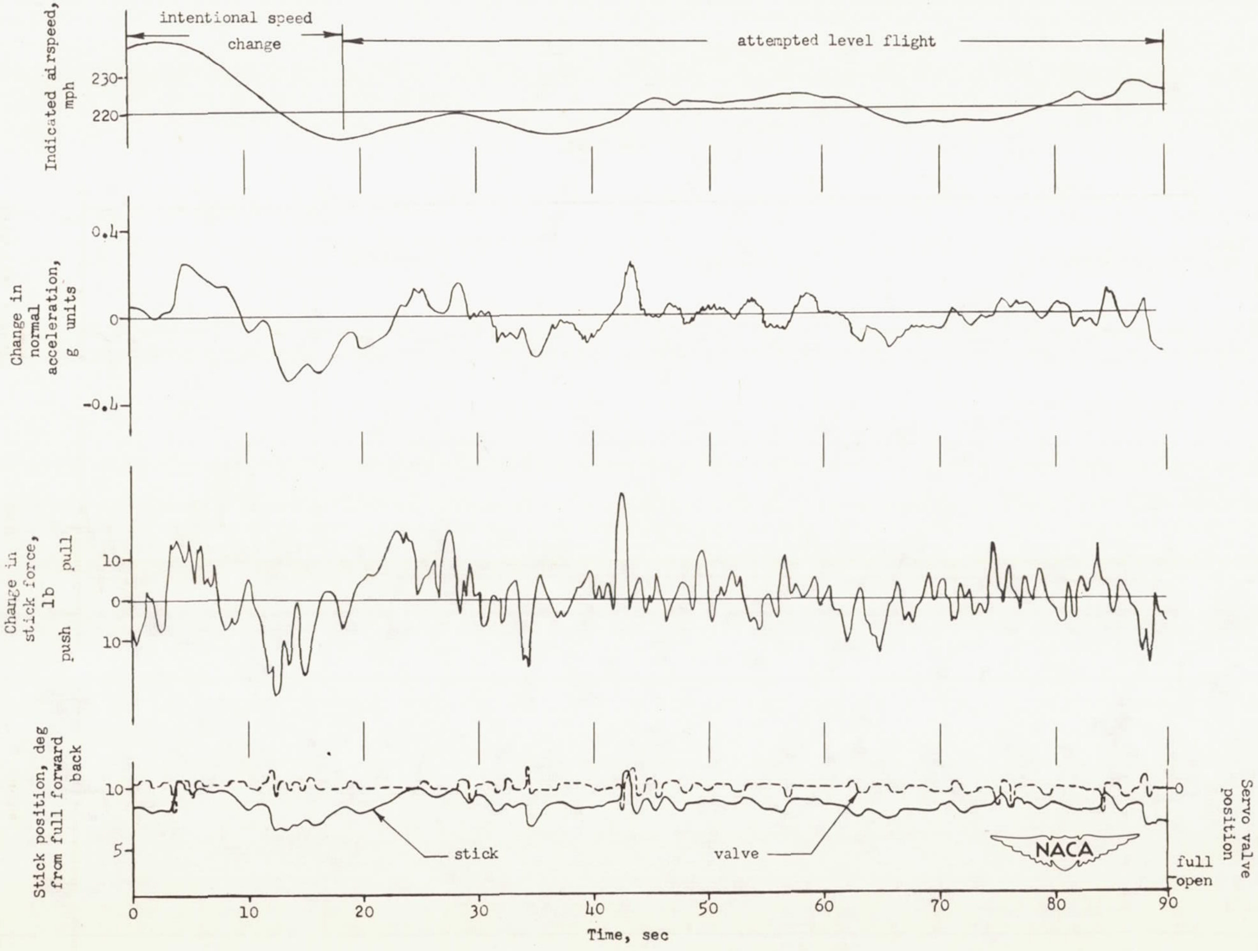
(c) $\frac{F_s}{\delta_s} = 22.5$ lb/deg.

Figure 5.- Concluded.



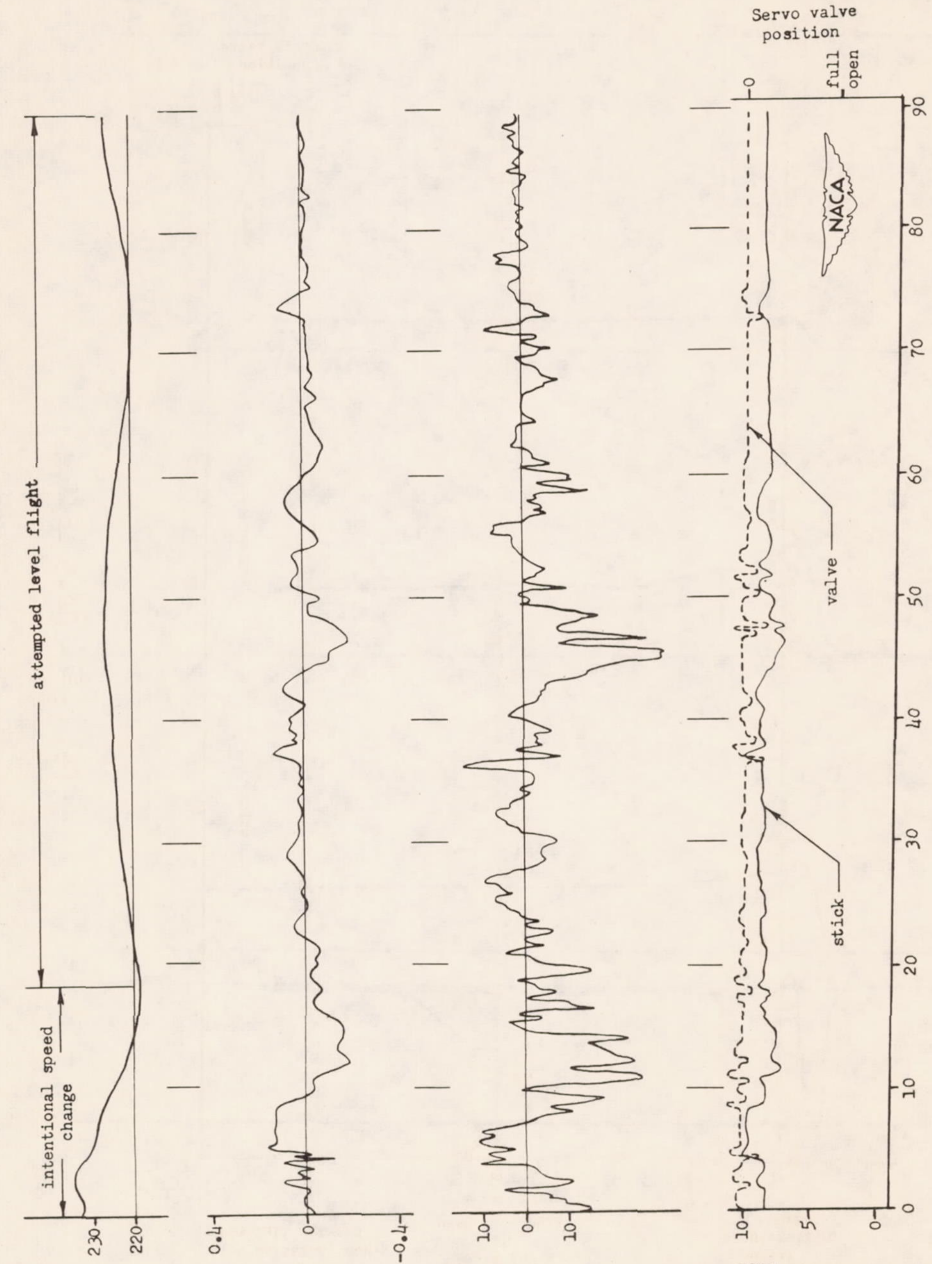
(a) $\frac{F_s}{\delta_s} = 15.0$ lb/deg.

Figure 6.- Time histories showing attempted precise flight with $2\frac{1}{2}$ pounds of valve friction for three force gradients. Bomber airplane.



(b) $\frac{F_s}{\delta_s} = 22.5$ lb/deg.

Figure 6.- Continued.



(c) $\frac{F_s}{\delta_s} = 35.0$ lb/deg.

Figure 6.- Concluded.

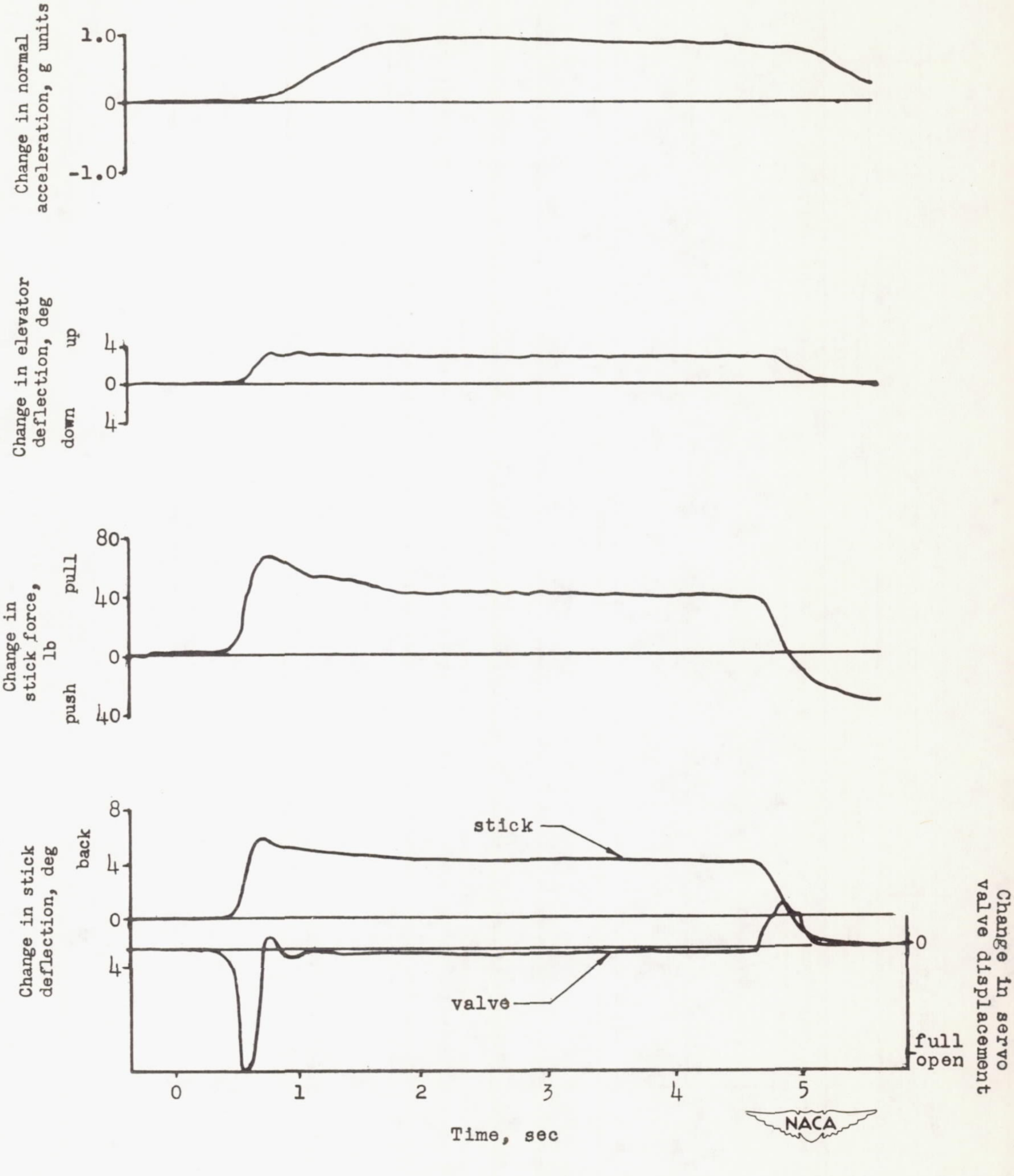
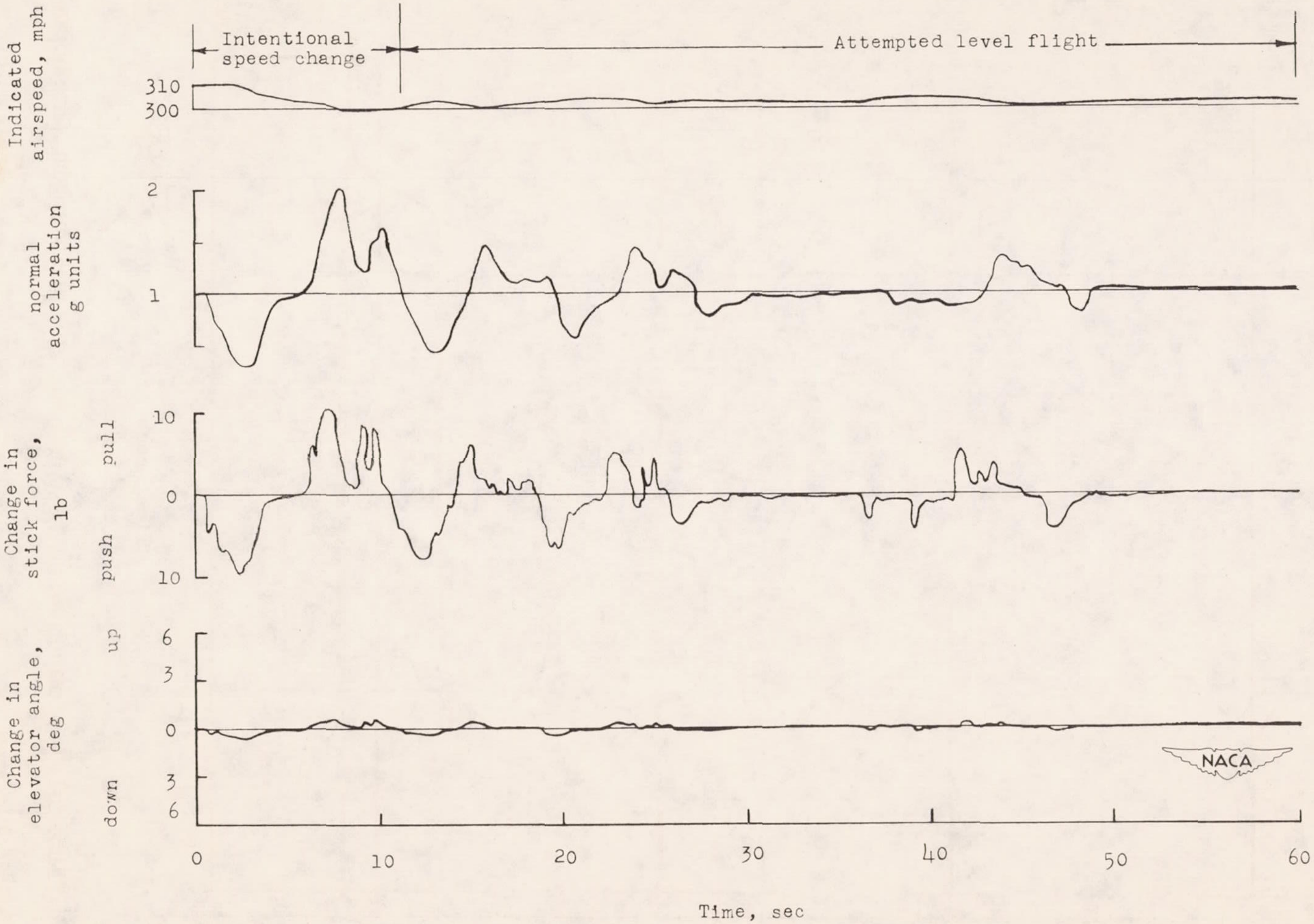
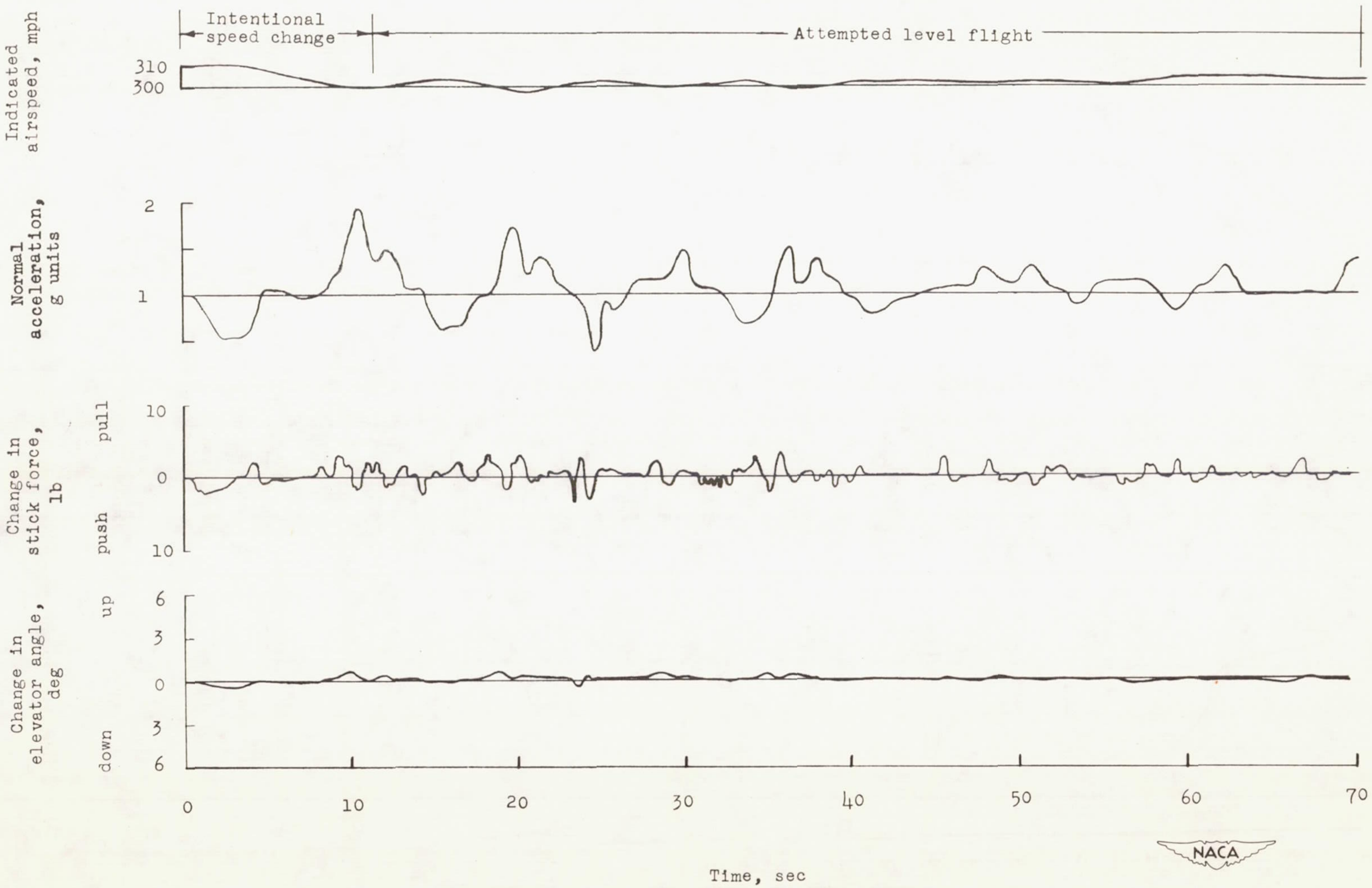


Figure 7.- Time histories showing typical abrupt pull-up in the bomber airplane with 1 pound of friction in the servovalve. $\frac{F_s}{g} = 50$ lb; 250 mph.



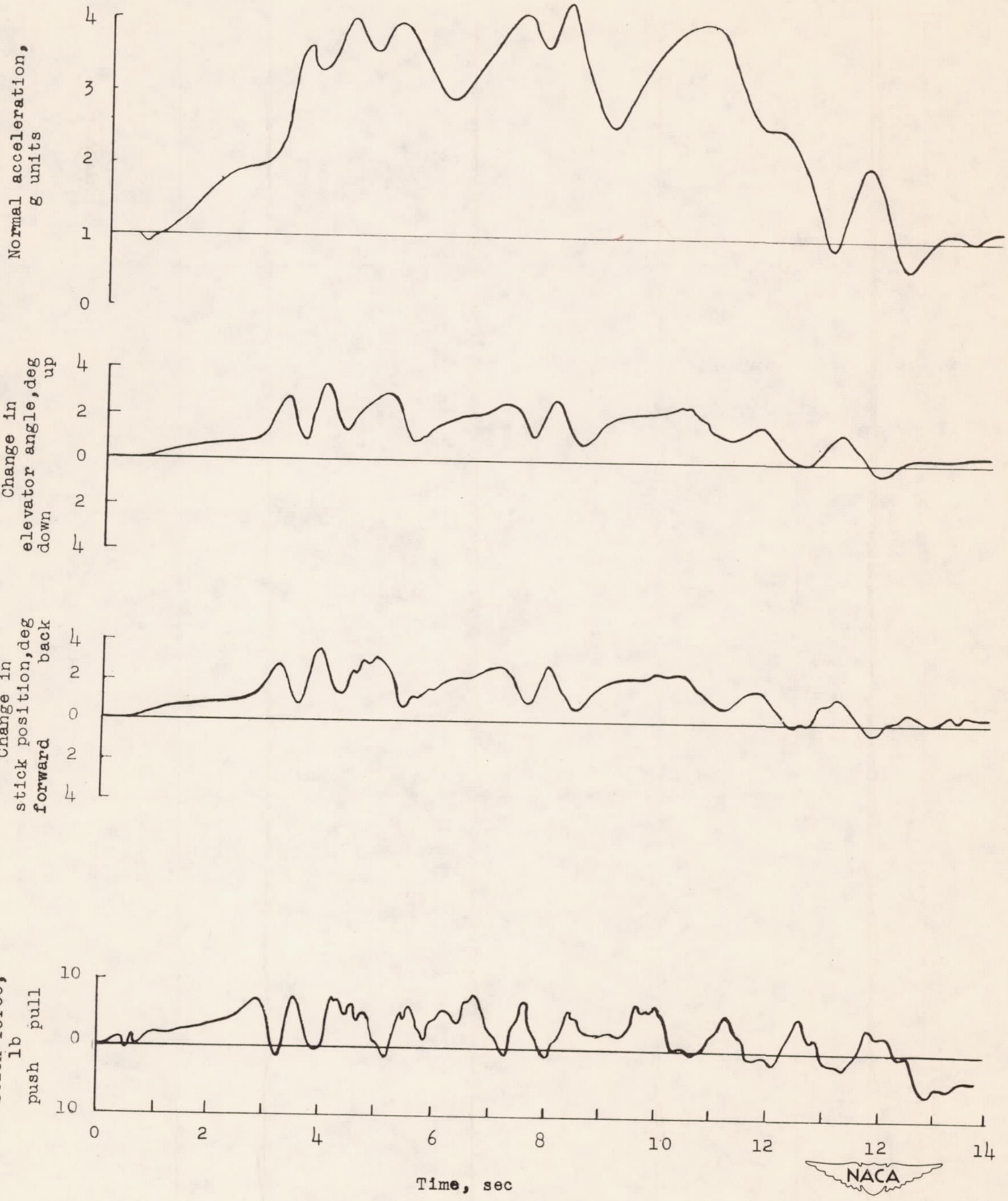
(a) Manual control.

Figure 8.- Time history showing attempted precise flight. Fighter A.



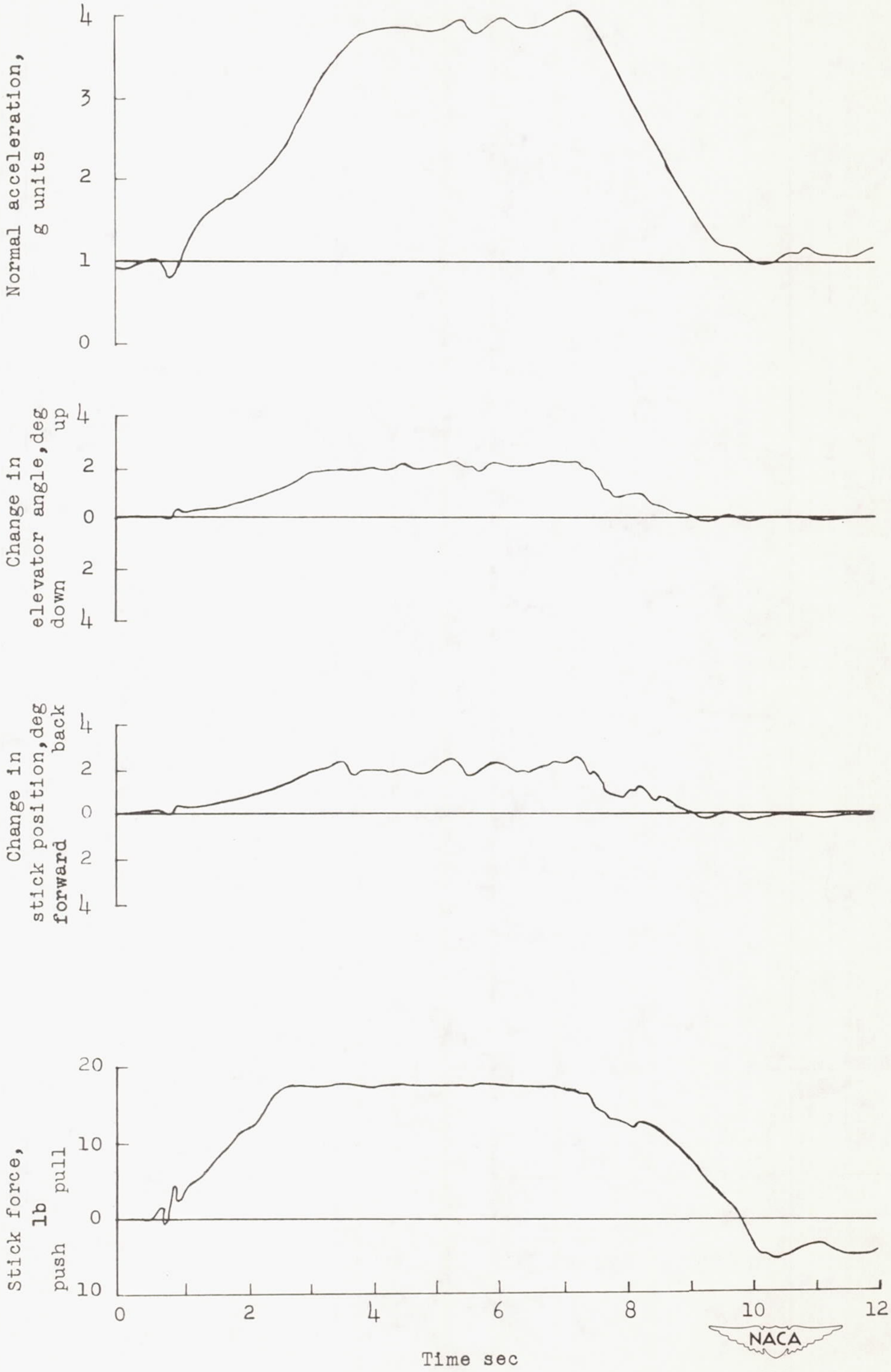
(b) Power control.

Figure 8.- Concluded.



(a) Power control.

Figure 9.- Time history showing an abrupt $3\frac{1}{2}$g pull-up. Fighter A.



(b) Manual control.

Figure 9.- Concluded.

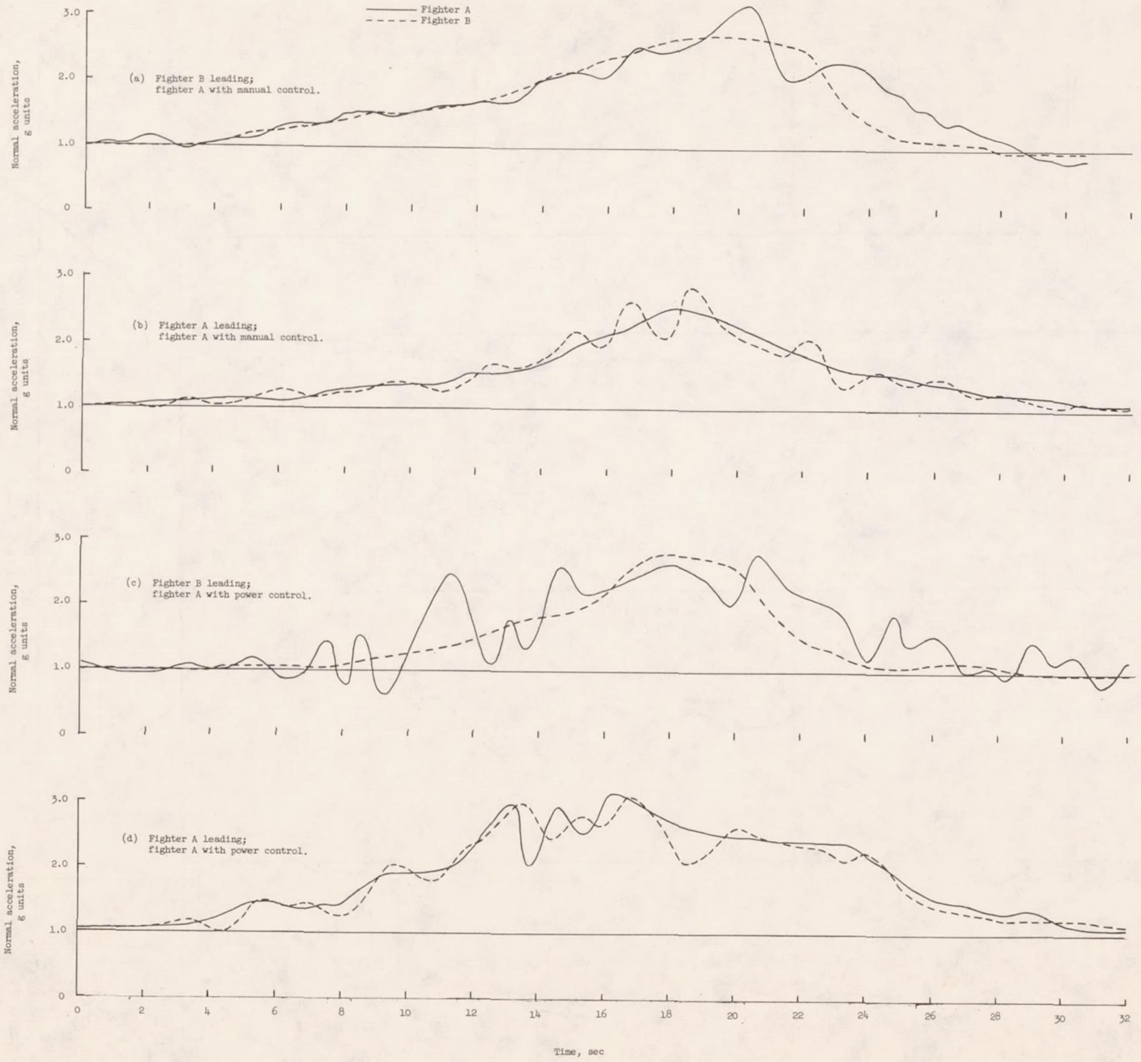
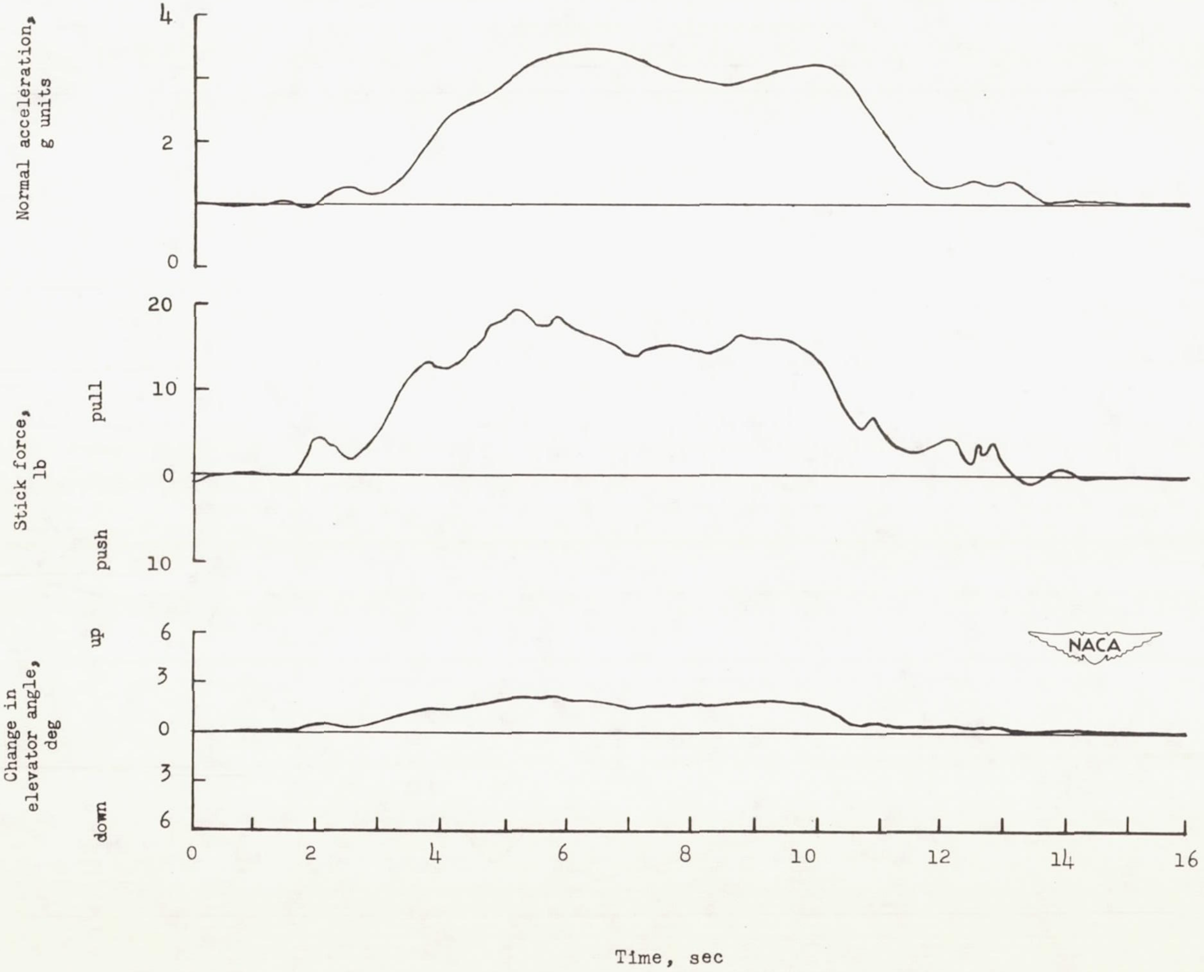
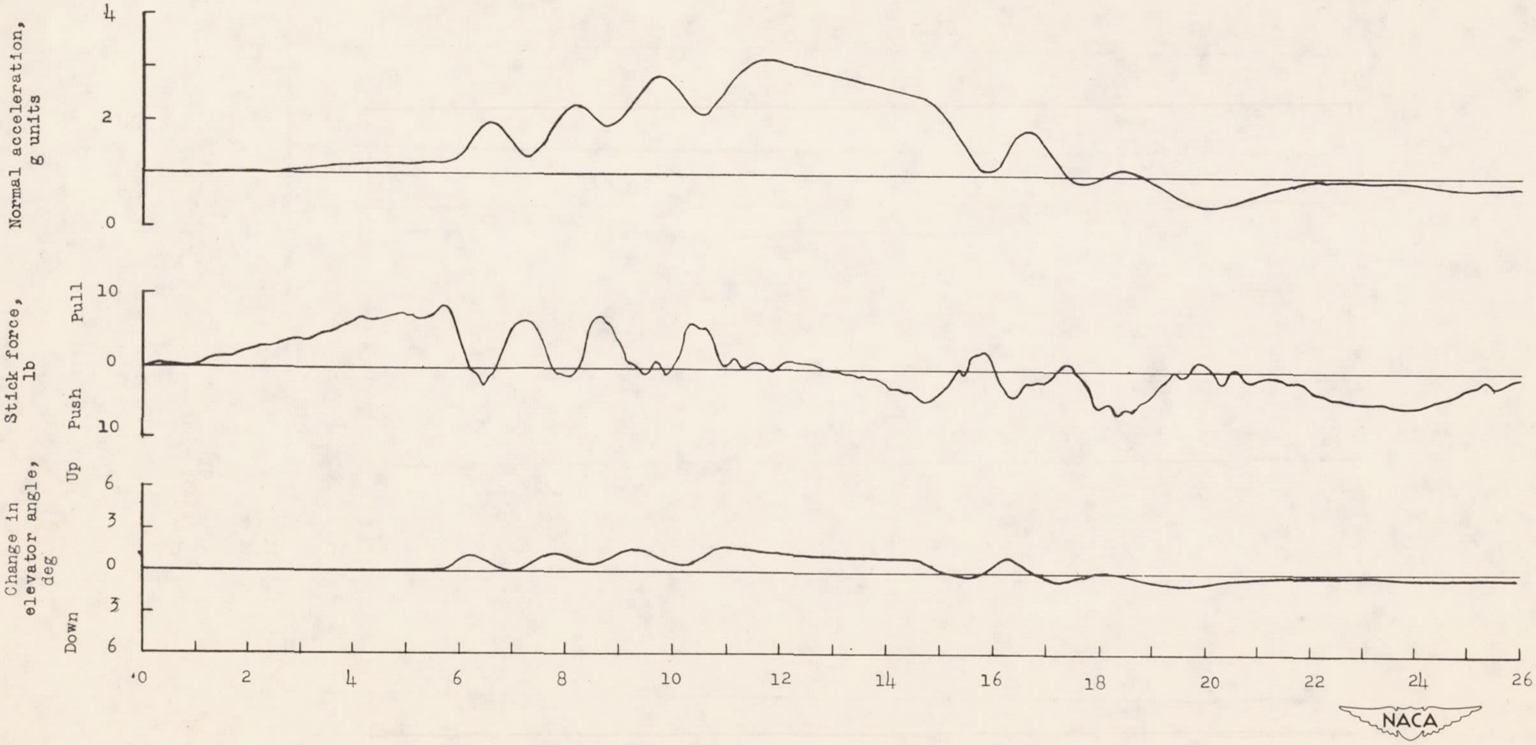


Figure 10.- Time history showing the variations in normal acceleration for fighter A and fighter B during formation flight.



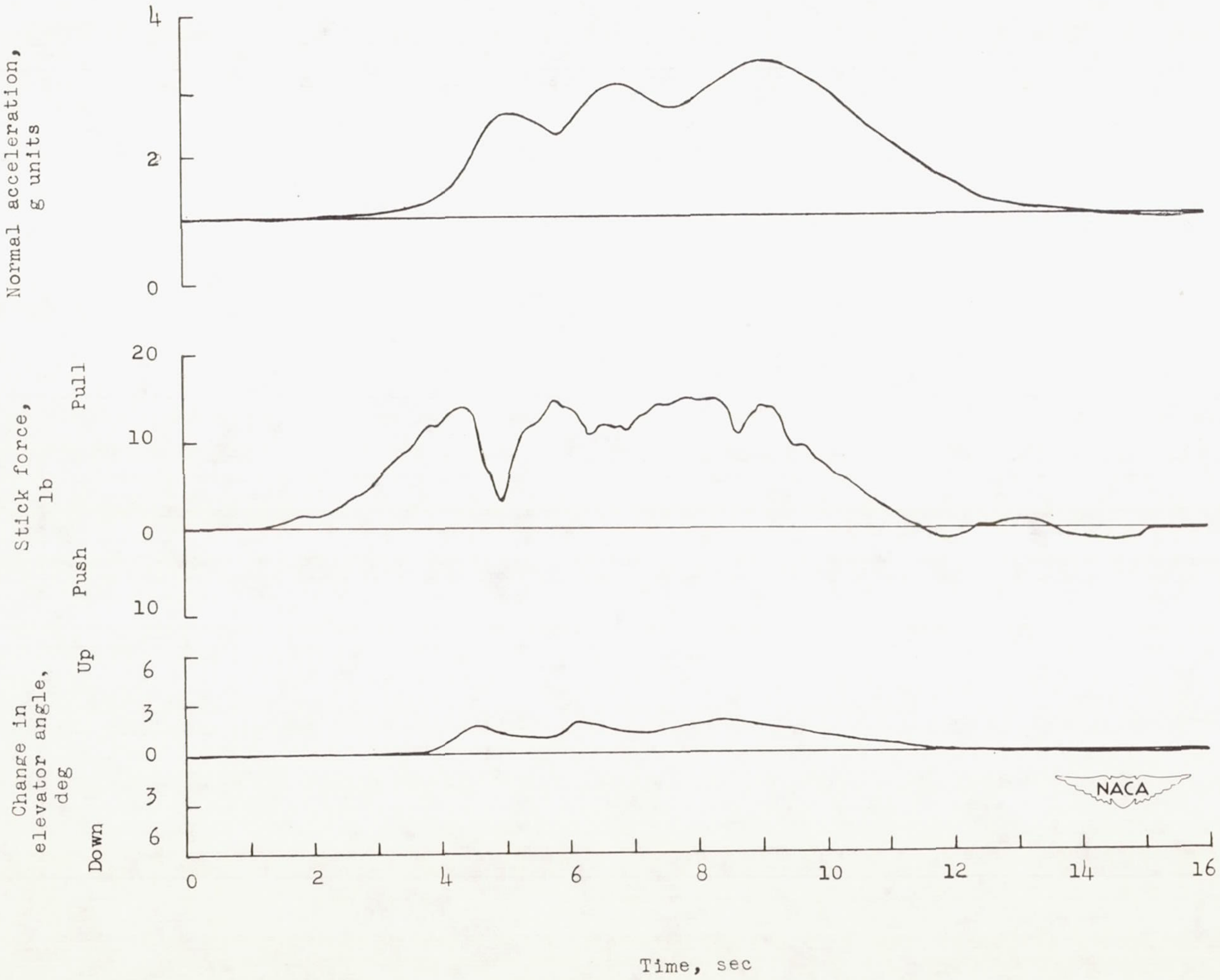
(a) Manual control.

Figure 11.- Time history showing a rapid 3g turn. Fighter A.



(b) Power control without centering springs on control valve.

Figure 11.- Continued.



(c) Power control with centering springs on control valve.

Figure 11.- Concluded.

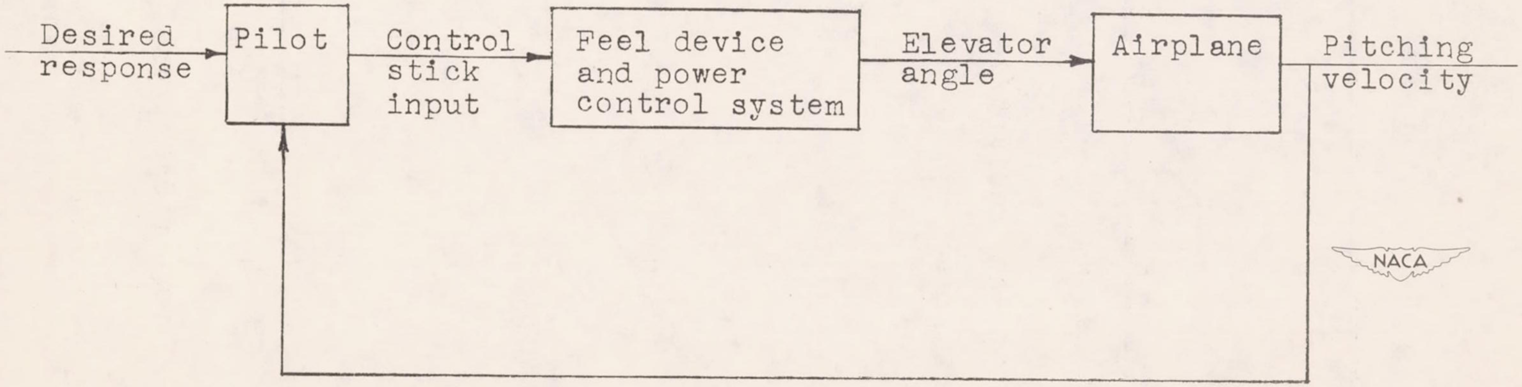
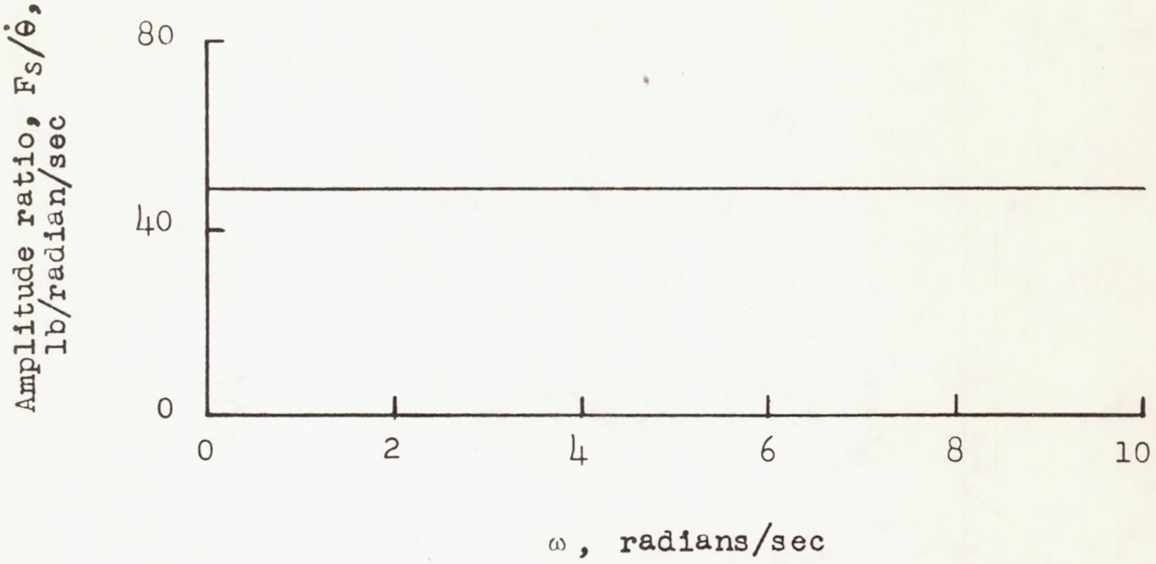


Figure 12.- Block diagram illustrating method of control of airplane.



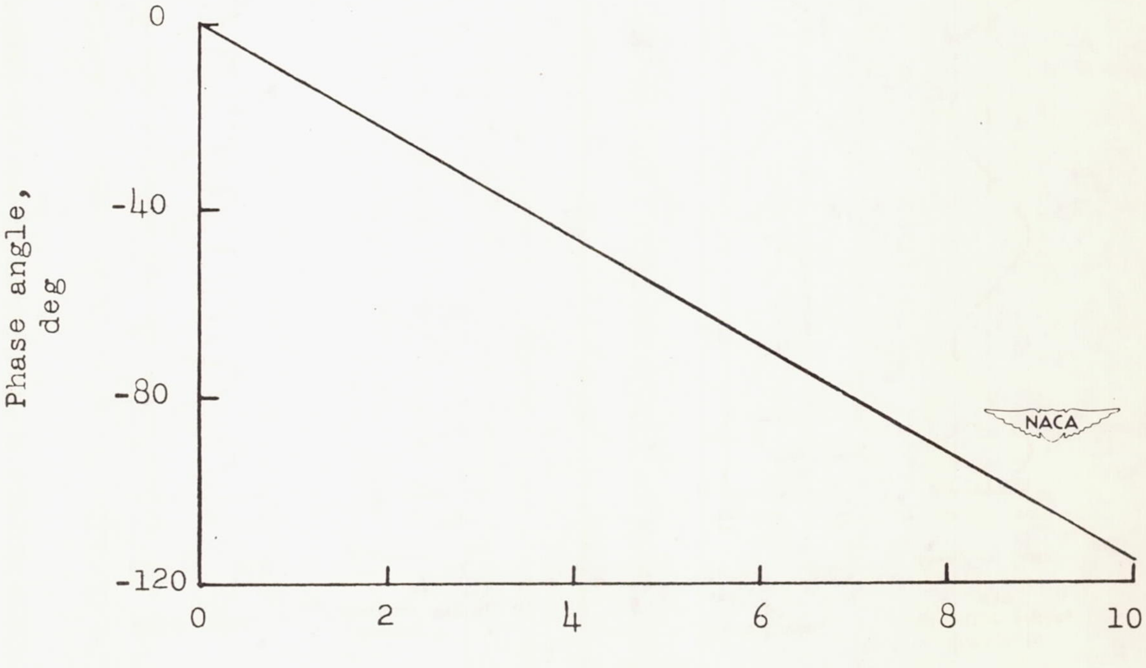


Figure 13.- Assumed frequency-response characteristics of the pilot.

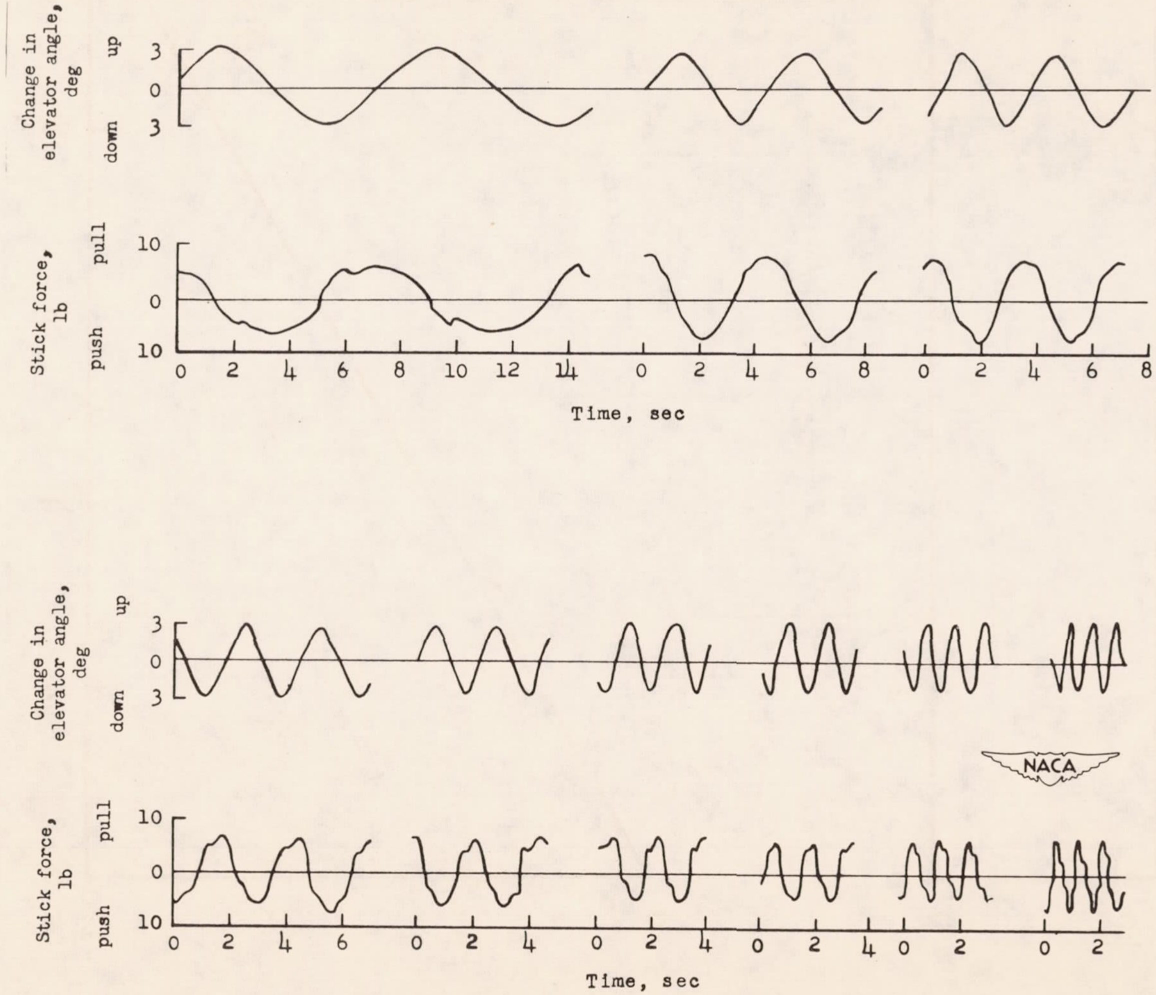


Figure 14.- Typical time history from which the frequency response characteristics of the power control system were obtained. Fighter A.

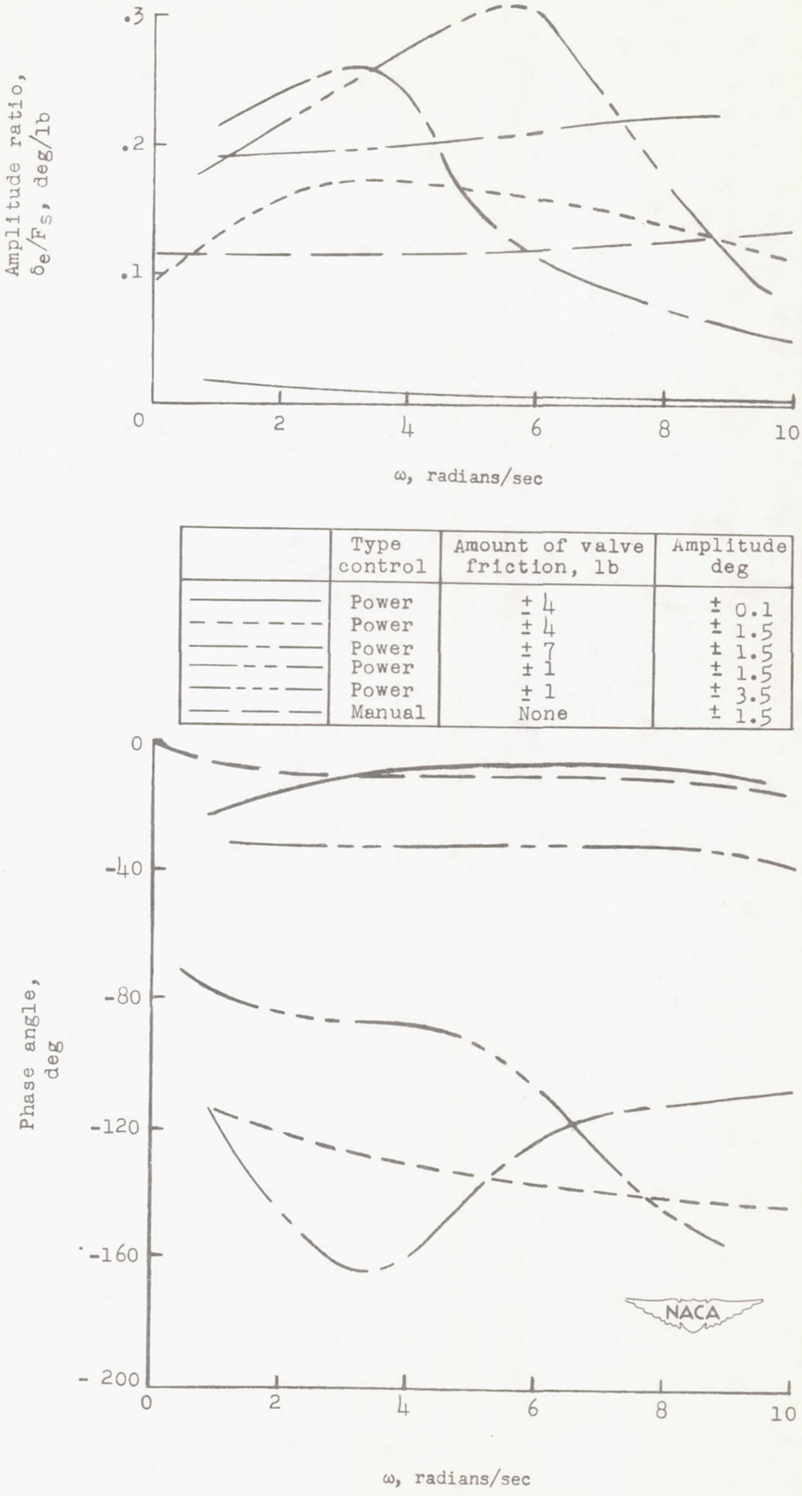


Figure 15.- Measured frequency responses for the manual and power control systems for different amplitudes and amounts of control valve friction. Fighter A.

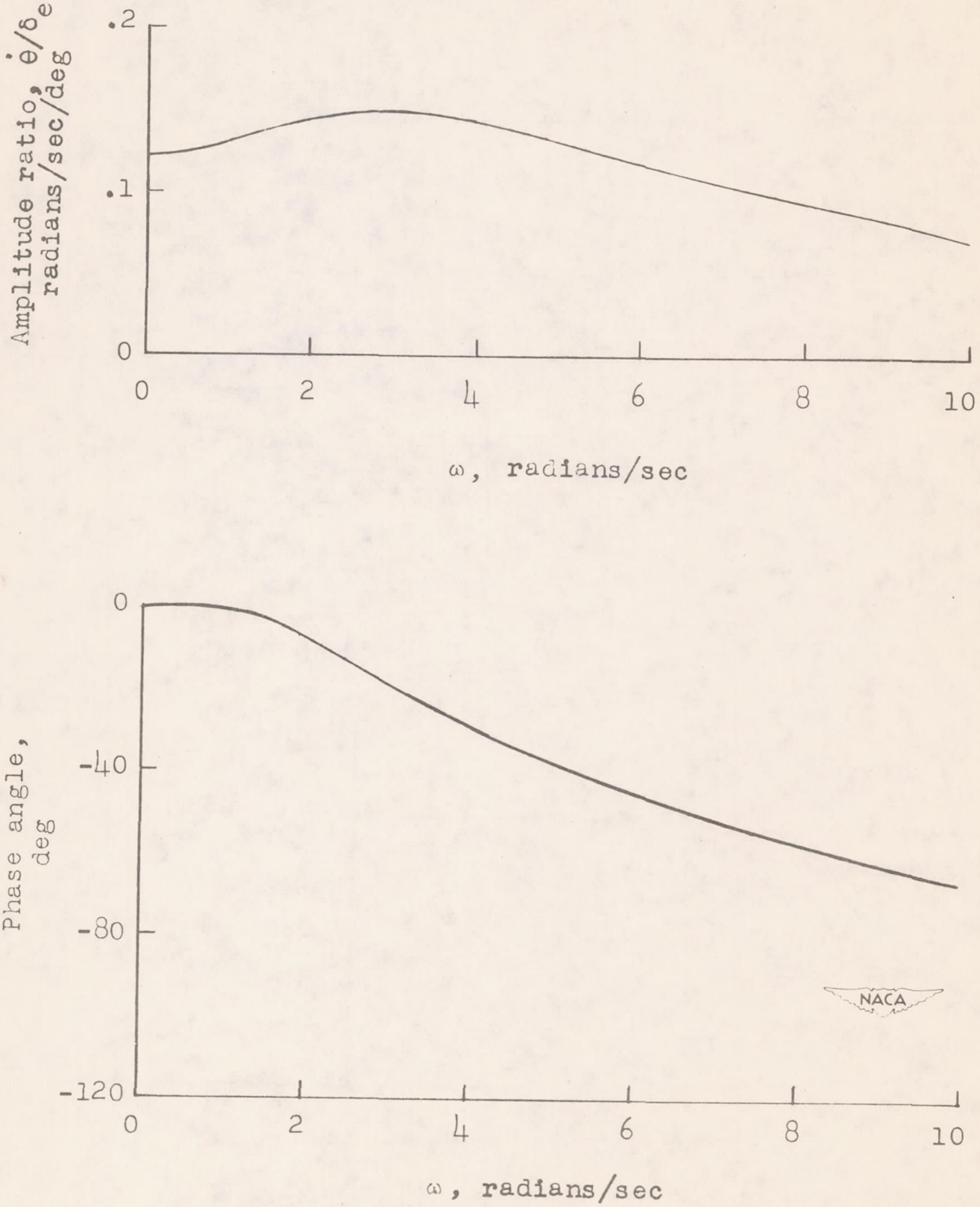
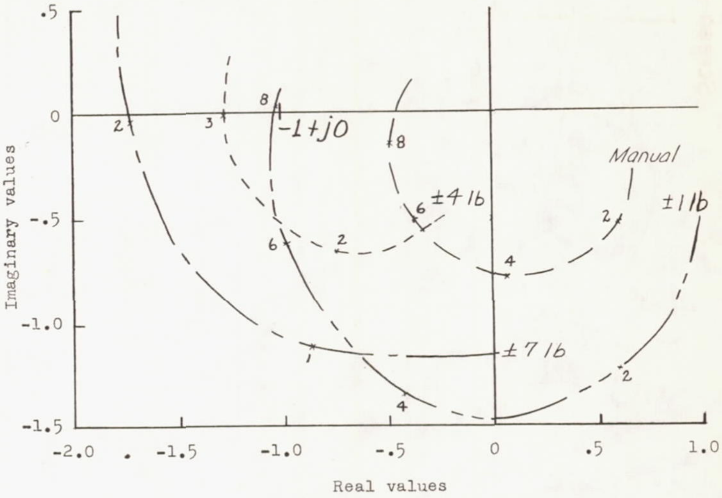
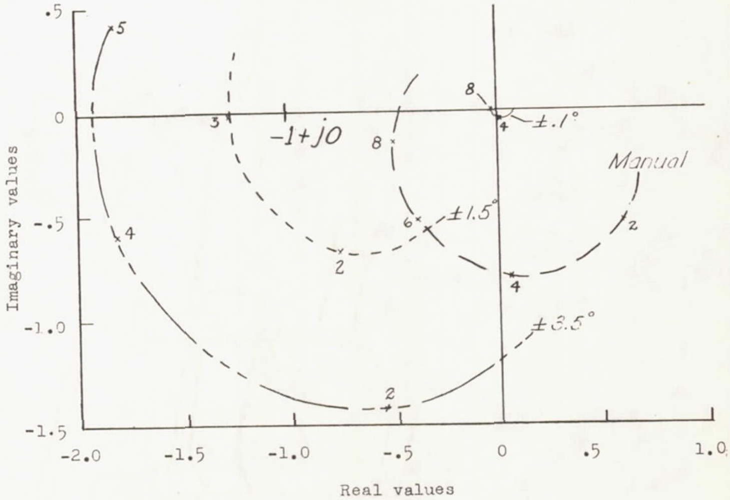


Figure 16.- Calculated frequency response of pitching velocity to elevator angle for fighter A at an airspeed of 300 miles per hour and an altitude of 10,000 feet.



(a) Variation with amount of friction.

	Type control	Amount of valve friction, lb	Amplitude, deg
———————	Power	± 4	± 0.1
– – – – – –	Power	± 4	± 1.5
——— – ———	Power	± 7	± 1.5
——— - - ———	Power	± 1	± 1.5
- - - - - - ———	Power	± 1	± 3.5
——— ——— ———	Manual	None	± 1.5



(b) Variation with amplitude.

Figure 17.- Nyquist diagram for the pilot-airplane control system combinations using the normal manual control and the power control system. (Note that frequencies are in radians per second.)

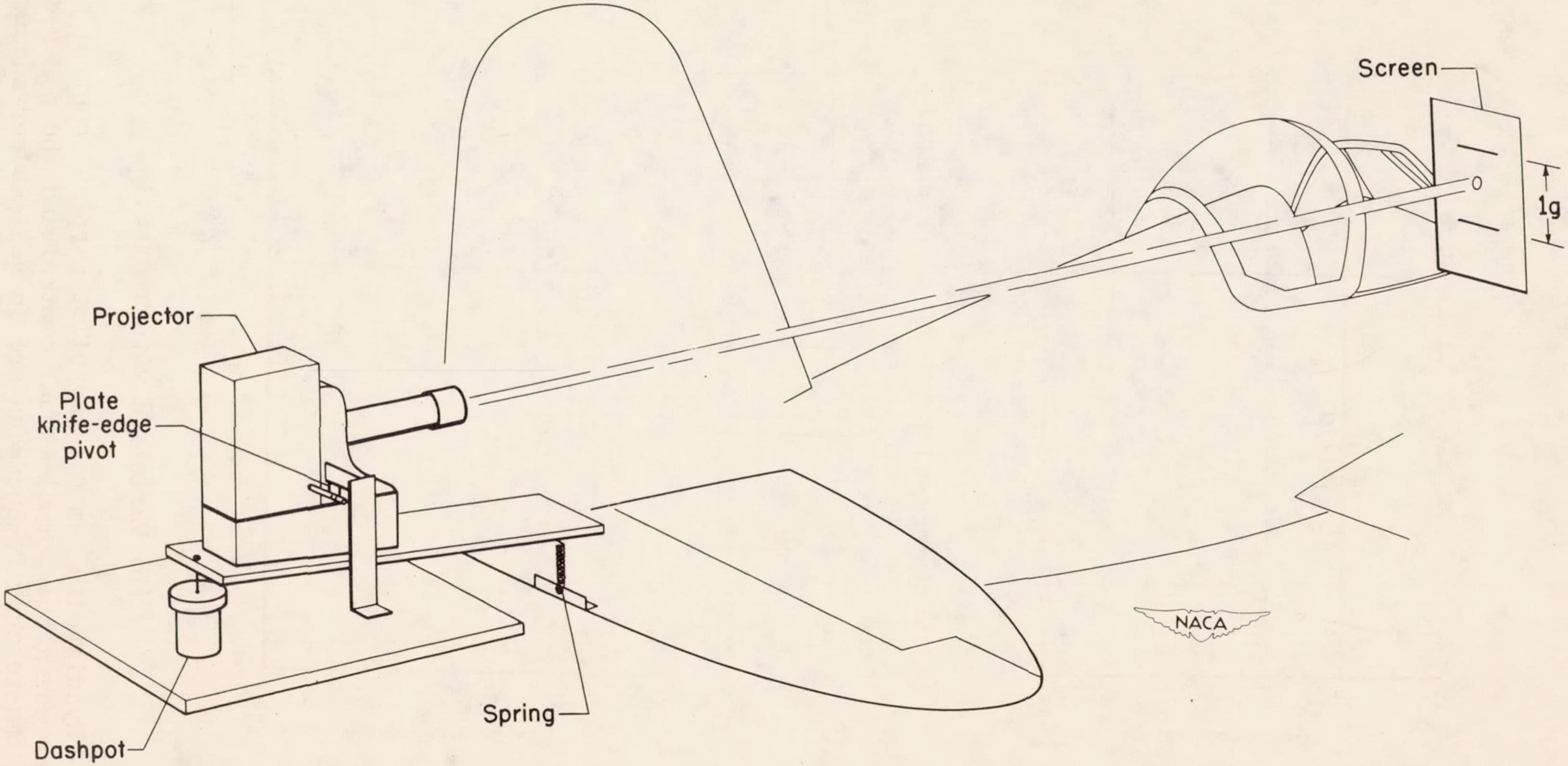


Figure 18.- Schematic drawing of ground simulator as used with fighter A.

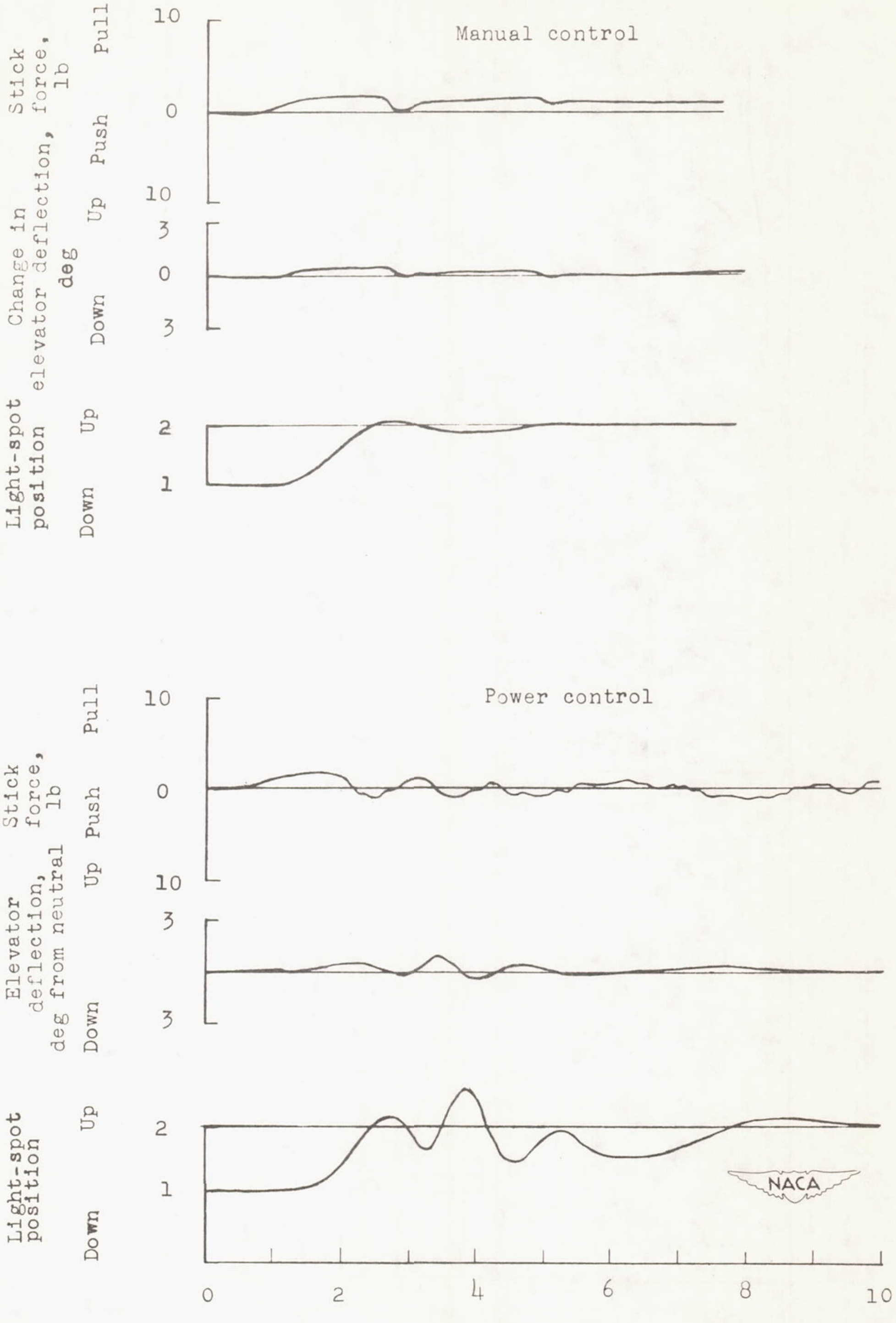


Figure 19.- Time history showing pilot attempting to position the spot of light from the simulator with manual and power controls.

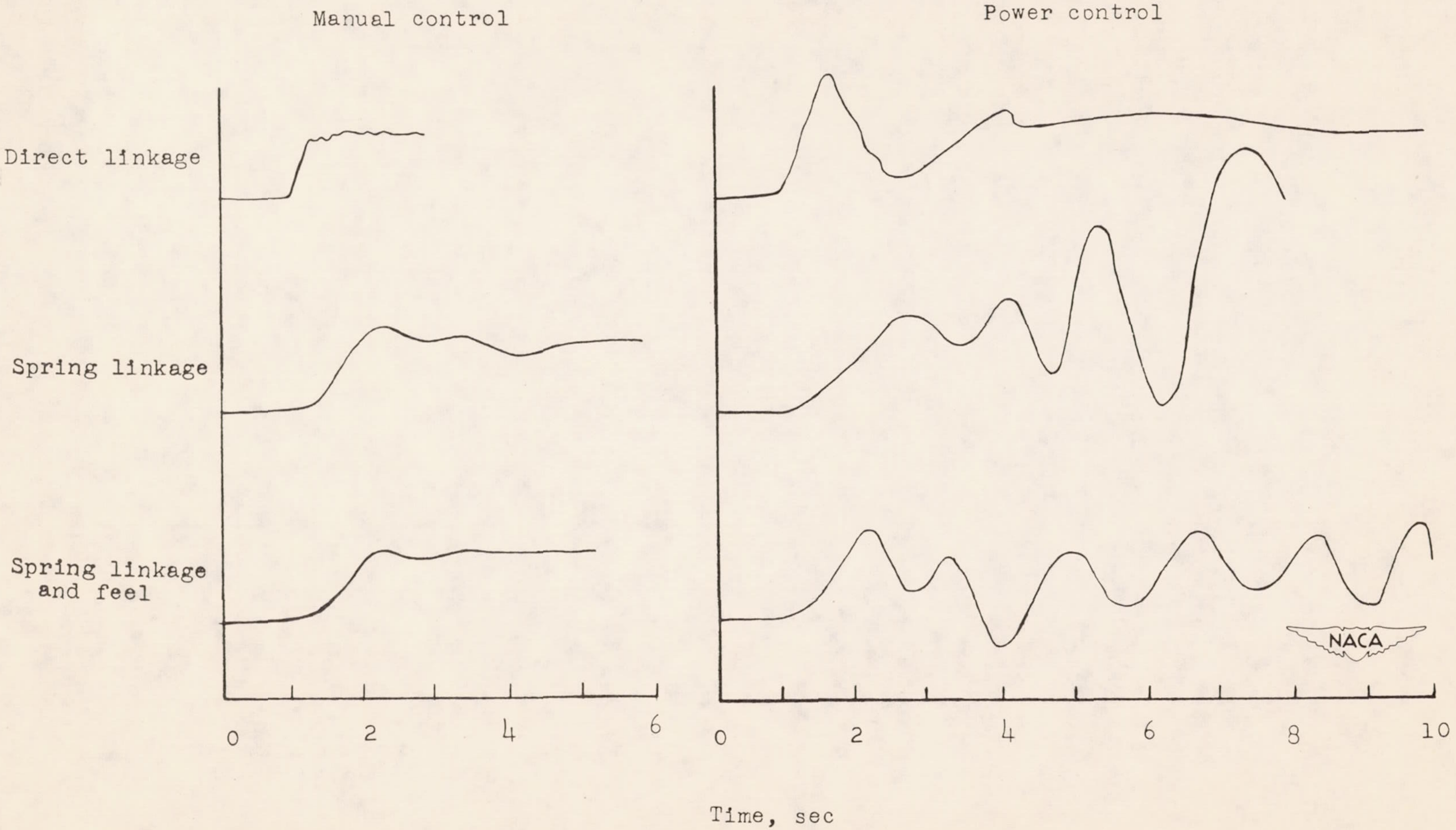


Figure 20.- Time history showing pilot's ability to position the simulator dot with direct linkage, with spring-alone linkage, and with spring linkage and the artificial feel system engaged.

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