RM L56F06

NACA

RESEARCH MEMORANDUM

A FLIGHT INVESTIGATION OF THE HANDLING CHARACTERISTICS OF A FIGHTER AIRPLANE CONTROLLED THROUGH A RATE TYPE OF AUTOMATIC CONTROL SYSTEM

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

September 14, 1956
Declassified December 3, 1958

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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A FLIGHT INVESTIGATION OF THE HANDLING CHARACTERISTICS OF A FIGHTER AIRPLANE CONTROLLED THROUGH A RATE TYPE OF AUTOMATIC CONTROL SYSTEM

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SUMMARY

A flight investigation was made to obtain experimental information on the handling qualities of a fighter airplane which a pilot controlled by supplying signals to a rate type of automatic control system. A control stick which was similar to a conventional type of control stick was used to introduce signals into the automatic control system.

The handling qualities were investigated in pull-ups, aileron rolls, aerobatics, rough-air flying, and precision tasks such as air-to-air tracking, ground strafing, and landings. The pilots were of the opinion that the handling characteristics of the airplane with the rate control system were good, being generally equal to and in some respects better than those of the airplane alone which had good handling qualities. In air-to-air tracking and ground strafing runs, the pilot was able to do about equally well when using either the rate control or the conventional control system. The pilots were also of the opinion that a combination of a rate control system for maneuvering and an attitude stabilization system for nonmaneuvering flight would be a versatile system having applications for many flight operations. Flight tests of a combination of these systems were not made and the pilots' opinion is based on separate tests of attitude and rate control systems.

INTRODUCTION

The National Advisory Committee for Aeronautics is conducting a flight research program using a fighter airplane equipped with various types of automatic control systems. With these control systems, the human pilot controls and maneuvers the airplane by supplying signals to the automatic control system and the automatic control system operates to reduce to zero any error which may exist between the actual response of the airplane and the pilots' commanded response. Furthermore, with these control systems, no continuous proportional relationship exists between the pilots' controller deflections and the control-surface deflections of the airplane. The objects of the flight program are to obtain experimental information on the handling qualities of an airplane when it is controlled through various types of control systems and to attempt to determine what advantages might result from the use of these systems. Reference 1 reports results obtained for an attitude type of control system. Reported herein are results obtained for a so-called "rate" type of control system; that is, a system in which a human pilot's input signal produces a proportional change in airplane pitching or rolling angular velocity. For control-free, or hands-off, operation this system tends to maintain the angular velocities of the airplane at zero.

Some of the data presented in this paper have been presented previously in reference 2. A more complete discussion of these data is given in the present paper.

SYMBOLS

a_n	normal acceleration, g units
a_y	lateral acceleration, g units
F_{c_l}	pilot control force, lateral, lb
F_{c_p}	pilot control force, fore and aft, lb
h_p	pressure altitude, ft
K_f	servo-actuator-feedback gain, volts per radian of servo drum rotation (subscripts a, e, and r refer to aileron, elevator, and rudder, respectively)
K_{a_y}	pendulum gain, volts/g
$K_{\dot{\theta}}$	pitch-rate-gyro gain, volts/radian/sec
$K_{\dot{\phi}}$	roll-rate-gyro gain, volts/radian/sec
$K_{\dot{\psi}}$	yaw-rate-gyro gain, volts/radian/sec

M	Mach number
p	rolling velocity, radians/sec
r	yawing velocity, radians/sec
V_i	indicated airspeed, knots
x_{c_l}	automatic-control-system stick movement, lateral, in.
x_{c_p}	automatic-control-system stick movement, fore and aft, in.
x_{s_l}	conventional stick movement, lateral, in.
x_{s_p}	conventional stick movement, fore and aft, in.
β	angle of sideslip, deg
$\Delta\beta$	change in angle of sideslip, deg
δ_{a_l}	left aileron deflection, deg
δ_{a_r}	right aileron deflection, deg
δ_{a_T}	total aileron deflection, deg
δ_{c_l}	automatic-control-system stick deflection, lateral, deg
δ_{c_p}	automatic-control-system stick deflection, fore and aft, deg
δ_e	elevator deflection, deg
δ_r	rudder deflection, deg
θ	angle of pitch, deg
ϕ	angle of bank, deg
ψ	angle of yaw, deg
ω	circular frequency, radians/sec

A dot placed over a symbol indicates differentiation with respect to time.

DESCRIPTION OF AIRPLANE AND AUTOMATIC CONTROL SYSTEM

Airplane

The airplane used was a fighter type with an unswept wing and a turbojet engine and was of conventional configuration. A photograph of the airplane is presented in figure 1 and a two-view drawing of the airplane is shown in figure 2. General dimensions and characteristics of the airplane are listed in table I. The wing-tip fuel tanks were on the airplane for all flights but no fuel was carried in them. A hydraulic booster system, which provides a boost ratio of approximately 37:1, is incorporated in the aileron control system of the airplane and a spring tab is used in the elevator control system. The rudder control system is of the conventional manual type.

Some transient and frequency response data for the airplane are presented and discussed later in the report.

Automatic Control System

The rate automatic control system used was a modification of a General Electric G-3 automatic pilot. The standard G-3 automatic pilot is of the attitude type and a description of its components is given in reference 3. Major modifications made to the G-3 automatic pilot in converting it to a rate-type automatic control system were: the vertical and directional gyros were removed and rate gyros were added to the pitch and roll channels; a means of canceling servo-follow-up signals were added to the roll channel; the standard G-3 controller was replaced by a control stick very similar to a conventional manual-control stick both as to location and motions; and the means of introducing signals into the servo amplifiers from the automatic-control-system controller were changed so that controller signals are introduced directly into the servo amplifier. (The standard G-3 controller signals are operated on by an effective first-order lag before reaching the servo amplifier.)

Pitch, roll, and yaw channels.- Block diagrams of the pitch, roll, and yaw channels of the automatic control system in the maneuvering mode of operation are presented in figure 3. Figure 3(a) applies to the pitch channel and figure 3(b) applies to the roll and yaw channels.

In pitch, for steady-state conditions the airplane's pitching angular velocity as measured by the pitch rate gyro is proportional to the longitudinal stick deflection of the automatic control system. The servo follow-up and tachometer signals provide stability for the system. The follow-up canceler system is a positional servomechanism having a time constant of approximately 1 second. The inputs to the canceler are the servo follow-up and tachometer signals. For steady-state conditions, the output of the canceler is equal in magnitude and opposite in sign to the servo-follow-up signal. Since the output of the canceler is an input to the servo system, steady-state servo follow-up signals are effectively canceled and the only signal which balances a pilots' input signal comes from the rate gyro. A given pilots' stick deflection will produce therefore (within the capabilities of the airplane) the same steady-state pitching velocity at any airspeed. Since the follow-up canceler system has a time constant of approximately 1 second, the stabilizing effect of the servo follow-up and tachometer signals for rapid airplane motions is retained.

In the pitch channel the servo-follow-up gain, the pitch-rate-gyro gain, the control-stick sensitivity, and the time constant of the follow-up canceler system are adjustable. No adjustment of the servo-tachometer signal is available but rather a constant ratio of servo-tachometer gain to servo-follow-up gain is maintained.

In operation, the roll channel, lower part of figure 3(b), is the same as the pitch channel. Also the same gains and time constants are adjustable in the roll channel as in the pitch channel. The ratio of the servo-tachometer gain to servo-follow-up gain is higher in the roll channel than it is in the pitch and yaw channels.

A block diagram of the yaw channel of the automatic control system is shown in the upper part of figure 3(b). In the yaw channel a rate gyro provides increased damping in yaw to the airplane, and a pendulum is used to maintain the lateral acceleration acting on the airplane at zero. The yaw channel is identical to that used with the attitude automatic pilot described in reference 1.

Automatic-control-system controller.- The automatic-control-system stick used was the same as that used with the attitude automatic pilot described in reference 1. Figure 4 shows a photograph of the automatic-control-system-stick installation. The maximum stick throws were about ±20° longitudinally and ±15° laterally. The stick sensitivities (ratio of electrical signal output to stick deflection) could be varied but all of the flight data presented in this report were obtained with the same sensitivities. The electrical signal varied linearly with stick deflection for small deflections. Some nonlinearity was present for near maximum deflections. Within the stick sensitivities used, full lateral stick deflection produced (within the capabilities of the airplane) a rolling velocity of about 150° per second and full longitudinal stick deflection produced a pitching velocity of about 15° per second. There was no mechanical connection between the automatic-control-system stick and the airplane control system; therefore, motions of the airplane control surfaces were not transmitted to the stick.

A stick-force feel system consisting of springs which provided a force approximately proportional to stick deflection was used with the rate automatic control system. Several springs having different spring rates were used but almost all of the data presented in this paper were obtained when using the same springs. Figure 5(a) shows the variation of longitudinal stick force with stick deflection provided by these springs, and figure 5(b) shows a similar plot for lateral stick motions. The data presented in figure 5 were obtained as the control stick was moved slowly. About 1 to 2 pounds of friction was present for both longitudinal and lateral stick motions, and spring preload was used in an effort to overcome the friction and thus to provide stick centering.

Other automatic-control-system components.- Standard G-3 automatic pilot electrical servo actuators were used. Frequency-response and speed-torque data for the automatic-control-system servo loop are presented in reference 1. The mechanical installation of the servo actuators was the same as that used in the tests of the attitude control system reported in reference 1.

Time histories of the response characteristics of the canceler system in the roll channel of the automatic control system for near step voltage inputs are presented in figure 6. Two magnitudes of input voltage were used. Inspection of figure 6 shows the response of the canceler system to be nonlinear in that velocity limiting and a time delay are present. The time constants (although not simple time constants) of the canceler systems in all three channels of the automatic control system could be varied. The data presented in figure 6 are for the smallest roll-canceler time constant available and is the value used in flight. The time constant of the pitch canceler system was about the same as the roll-channel time constant, whereas that of the yaw channel was about three times larger for comparable inputs.

A summary of the signal gradients, time constants, and mechanical gearings for the automatic control system is presented in table II. Although many of these could be varied, all flight data presented in this report were obtained with the values listed in the table. Information for some of the other automatic-control-system components not previously discussed is listed in the following table:

Automatic-control-system component	Natural frequency, cps	Damping ratio	Range
Roll rate gyro	50	0.4	±2.62 radians/sec
Pitch or yaw rate gyro	20	0.6	±1.05 radians/sec
*Pendulum	Not known	0.5	±0.07g

*Pendulum date taken from reference 4.

The pendulum was located about 5 feet forward of the airplane center of gravity in the nose-wheel well.

INSTRUMENTATION

NACA recording instruments which measured the following quantities were installed in the airplane:

Normal, longitudinal, and transverse accelerations
Pitching, rolling, and yawing velocities and accelerations
Airspeed and altitude
Elevator, aileron, and rudder positions
Elevator, aileron, and rudder servo positions
Angle of attack and sideslip angle
Pitch and bank attitude angles
Longitudinal and lateral automatic-control-system stick positions
Longitudinal and lateral automatic-control-system stick forces

The airspeed head, which was used to measure airspeed and altitude, was mounted on a boom which extended out of the nose of the airplane (see fig. 1). No calibration was made of the airspeed installation and therefore the airspeed and altitude data presented in this paper have not been corrected for position error. It is estimated that the error in the measured static pressure due to the fuselage pressure field is about 2 percent of the impact pressure at low angles of attack. The airplane angle of attack and sideslip angle were measured with vanes which also were mounted on the nose boom.

In order to obtain a record of the tracking errors, a 16-millimeter camera was used to photograph the gunsight image and a reflected image of the target airplane.

TESTS, RESULTS, AND DISCUSSION

The response characteristics and handling qualities of the airplane—automatic-control-system combination were determined in various maneuvers such as abrupt rolls, turns, and abrupt and gradual pull-ups. Also, the system was evaluated in various flight operations such as air-to-air tracking, ground strafing, rough-air flying, and landings. In order to have a basis for comparison, the flight operations also were performed with the airplane controlled through the conventional control system.

Response Characteristics in Pitch

Transient response.- Transient responses of the airplane in pitch for near step automatic-control-system stick deflections are presented in figure 7. A chain fastened to the instrument panel of the airplane and to the top of the control stick served as a stop for the step inputs. Since the pilot's force and the restraining force on the stick were not applied at the same point, the recorded stick forces (presented in fig. 7) were not necessarily equal to the force output of the feel system. However, since the pilot's hand and the restraint were close together, this effect was small as a comparison of the feel system calibration (fig. 5(a)) and the deflection and forces of figure 7 indicates. For the maneuver made at a Mach number of 0.6 and an altitude of 30,000 feet (fig. 7(d)), the force gradient was about 2/3 as large as for the other maneuvers of figure 7. For all four flight conditions, the response and damping characteristics are good. Although different magnitudes of inputs were used the steady-state relationship between pitching velocity and stick position is essentially the same. Also, it should be noted that even though quite large ranges of airspeed and altitude were covered, the same values of automatic-control-system gains were used for all flight conditions. However, the flexibility of the control cables between the elevator servo and the elevator effectively increased the servo-follow-up gain with increase in dynamic pressure. As expected, the response time decreases with increasing dynamic pressure and at the flight condition for the highest dynamic pressure ($M = 0.7$; $h_p = 10,000$ ft) the response time (based on time to reach 90 percent of steady-state pitching velocity) is about 0.5 second. In the pilot's opinion the response and damping characteristics in rapid pull-ups, such as presented in figure 7, were quite satisfactory.

Inspection of the stick force and normal-acceleration time histories of figure 7 shows that the stick force per unit acceleration decreases with increase in airspeed when a simple spring feel system is used with the rate automatic-control system. The stick force per unit acceleration was about 6.5 pounds per g at an indicated airspeed of 150 knots and an altitude of 10,000 feet (fig. 7(a)) and 1.7 pounds per g at a Mach number of 0.7 and an altitude of 10,000 feet (fig. 7(c)). The reduction in force per g occurs because the system was designed so that a given stick force produces the same steady pitching velocity at any airspeed. In the pilot's opinion the stick force per g provided by a simple spring feel system was satisfactory for the range of speed and altitude conditions covered in the present tests (Maximum Mach number = 0.8, Maximum altitude = 30,000 feet). However with airplanes having larger speed and altitude ranges, the feel-system spring rate or the stick sensitivity might have to be varied as a function of true airspeed or Mach number if a satisfactory force per g is to be provided.

As reported in reference 1, a damper feel system giving a force proportional to the rate of stick deflection was found to be desirable with an attitude control system, whereas a spring feel system was used in the present investigation of a rate control system. Although the two feel systems are quite different, when integrated with their respective airplane—automatic-control-system combinations, they produce almost equivalent airplane responses to pilot-applied forces; that is, a constant stick force produces a constant airplane angular velocity. In terms of normal-acceleration response the pilot must apply a constant force to perform a constant acceleration pull-up.

It should be noted that the airplane with the rate control system had neutral stick-fixed and stick-free speed stability; that is, the airplane could be balanced at any speed with the controller stick in neutral. Although a small amount of speed stability is generally considered desirable, many high-speed airplanes with normal control systems are only slightly stable stick-fixed and some are slightly unstable. Since a rate control system with servo-follow-up canceling has, in effect, attitude stabilization to gusts or other outside disturbances, speed stability is probably not as important for the rate control system as for conventional control systems. The three pilots who flew with the system did not consider the lack of speed stability to be an important factor for the flight operations reported herein.

Frequency response.- In order to supplement the transient response data, frequency analyses were made of transient responses to determine the frequency responses of the airplane alone and the airplane—automatic-control-system combination. Several features of the rate control system can be seen more clearly by comparing the responses on a frequency basis rather than on a transient basis. A rolling-sphere harmonic analyzer was used to make the frequency analyses. A description of this machine and a discussion of the analysis procedure is given in reference 5. For the airplane alone, additional frequency-response data were obtained by oscillating the stick sinusoidally at various frequencies.

Frequency-response data for both the airplane alone and the airplane—automatic-control-system combination are presented in figure 8 for a Mach number of 0.6 and an altitude of 10,000 feet. Pitching angular velocity and normal acceleration are the output quantities analyzed and conventional stick movement and automatic-control-system stick movement and force are the input quantities. The conventional control stick of the airplane and the automatic-control-system stick were of different lengths and in order to provide a direct comparison the stick-motion data of figure 8 are presented in linear rather than angular units. A comparison of the pitching-velocity responses to stick-displacement inputs shows that the peak in the amplitude ratio for the airplane alone is practically eliminated by the automatic control system and also that the static sensitivity is about two times larger with the conventional control system than with the rate control system (0.14 radian/sec/in. and 0.062 radian/sec/in., respectively). With a conventional control system with a constant ratio of elevator displacement to stick displacement, the static sensitivity between airplane pitching angular velocity and stick deflection varies directly as true airspeed (at least for subsonic speeds) and with the rate system this static sensitivity is independent of speed. At high subsonic speeds a conventional control system will tend therefore to be more sensitive than a rate control system. Furthermore with a conventional control system where a proportional relation exists between control stick and elevator deflections, the mechanical advantage between the stick and the elevator is largely dictated by the elevator deflections required to balance the airplane in 1 g flight, such as in landing. The mechanical advantage between the stick and the elevator required for low-speed flight may be too low for flight at high subsonic speeds where only small elevator motions are required for maneuvering. On the other hand, with the rate control system used, the controller stick is neutral for 1 g flight and the sensitivity of the controller stick is not dictated by 1 g balance requirements. Thus the rate system provides, in effect, features of mechanical advantage changing between the stick and the elevator and automatic trimming. An additional feature of the rate system is the stability augmentation provided by the pitch rate feedback as indicated by the smaller peak amplitude ratio. Although the stability augmentation feature is not of great importance for the airplane used in this investigation, it would be important for aircraft which lack sufficient aerodynamic damping to provide satisfactory dynamic longitudinal stability characteristics.

There were no major differences in the magnitudes of the phase angles over the frequency range covered. This indicates that the speed of response is about the same for the two systems. The response was considered to be good by the pilots who flew the airplane with the rate system.

The normal-acceleration responses to stick-displacement inputs for the airplane alone and the airplane—automatic-control-system combination are shown in figure 8(b). As in the pitching-angular-velocity responses the major difference between the two systems is the favorably reduced sensitivity of normal acceleration to stick displacement at the higher speeds for the airplane—automatic-control-system combination. The reduction in sensitivity is a direct result of the reduced pitching-velocity sensitivity since for steady-state conditions, the normal acceleration is proportional to pitching velocity. Since the commanded quantity in this system is pitching velocity, the steady-state normal-acceleration response is not independent of flight condition, the stick displacement and force per unit normal acceleration decreasing with increasing speed as a result of the linear variation of normal acceleration per unit pitching velocity with airspeed.

The frequency response relating normal acceleration to stick force for the airplane—automatic-control-system combination is presented in figure 8(c). It can be seen that the amplitude ratio decreases rapidly with increasing frequency or conversely the force per unit normal acceleration increases with increasing frequency. From a flying-qualities standpoint this means that the force per g in rapid pull-ups is greater than in steady pull-ups. Past research (see, for example, ref. 6) has indicated that this is a desirable characteristic and the Military Flying Qualities Specifications (ref. 7) require that the force per g in rapid pull-ups should not be less than in steady pull-ups. Complete frequency-response data for the normal-acceleration—stick-force response of the airplane alone are not available. However, the stick force per g is about 10 pounds per g at $M = 0.6$, $h_p = 10{,}000$ feet, and a center-of-gravity location of about 28 percent of the mean aerodynamic chord. This is quite high compared to the $2\frac{1}{2}$ pounds per g of the airplane—automatic-control-system combination. It should be noted that with the rate control system the steady force per g does not vary with changes in the center-of-gravity location of the airplane.

The reason for the offset or jog in the phase angles of the airplane—automatic-control-system responses at about 6 radians per second is not definitely known. Calculations indicate it may be caused by the canceler, but it may also be associated with nonlinearities in the system.

Response Characteristics in Roll

Transient response.- Time histories showing the response characteristics of the airplane in roll for near step automatic-control-system stick deflections are presented in figure 9. The data are for four different flight conditions as listed in the figure. The same values of automatic-control-system gains were used in all cases. The maneuvers were started from left banked turns, and this is the reason a yawing velocity to the left is present at zero time for all runs. As can be seen in figure 9, at all flight conditions the response is rapid and well damped and the static sensitivity $\dot{\phi}/\delta_{c_l}$ is nearly constant. As expected, the response time decreases with increasing dynamic pressure.

The sideslip data presented in figure 9 are incremental values measured from zero time. The absolute values of the sideslip angle at zero time are not known but they are believed to be less than 2°. Sideslip angles of appreciable magnitude were reached in the roll made at a Mach number of 0.6 and an altitude of 30,000 feet (see fig. 9(d)). The rudder deflection which occurred immediately following the stick motion is in all cases to the right and this rudder deflection produces a yawing moment which tends to balance the yawing moment due to rolling velocity. The right rudder deflection results from the effect of the rolling acceleration on the pendulum in the yaw channel of the automatic control system (since the pendulum is below the center of gravity of the airplane, a rolling acceleration to the right is equivalent to a linear acceleration to the left). As the rolls progress, the rudder in all cases returns toward neutral and the right sideslip angles increase. The reason the rudder returns toward neutral is that the yawing velocity to the right increases and the yaw rate gyro generates a signal calling for left rudder deflection. In steady turns the yaw-rate-gyro signal is canceled, but the cancelation must be accomplished at a slow rate (in order to retain adequate damping of Dutch roll oscillations) and during rapid rolls and turn entries the canceler rate dictated by this requirement is not compatible with good rudder coordination. A damper with rate-of-sideslip sensing might allow better turn coordination than the yawing velocity damper. In the pilots' opinion the response characteristics of the airplane in rapid rolls were in general satisfactory. However, better regulation of the sideslip angle in rolls at low speed would be desirable. The jerkiness or oversensitivity of lateral control for small, rapid, or irregular control motions which the pilots found objectionable in the attitude control system of reference 1 was not present in the rate system except at high dynamic pressures. At the high dynamic pressures, the pilots found the airplane rolling response to be slightly oversensitive for small rapid controller deflection. The control sensitivity probably resulted from a combination of the low control-force gradient and the short response time of the airplane (high rolling accelerations) for these flight conditions.

Frequency response.- Frequency analyses were made of transient responses, such as presented in figure 9, in order to obtain frequency-response data. Figure 10 presents frequency-response data in terms of rolling-velocity outputs and stick-displacement inputs for both the airplane—automatic-control-system combination and the airplane alone. The data were obtained at a Mach number of 0.6 and an altitude of 30,000 feet. Examination of figure 10 shows that at this flight condition the static sensitivity is about the same for the airplane—automatic-control-system combination and the airplane alone. For the airplane alone the static sensitivity is of course proportional to the airspeed and for the automatic control system the static sensitivity is independent of flight condition. The airplane—automatic-control-system combination also had somewhat higher damping than the airplane alone as indicated by the reduction of the resonant peak in the amplitude ratios.

The phase-angle curve for the airplane alone has a tendency toward leading phase angles at a frequency of about 2.5 radians per second. This is indicative of a lightly damped Dutch roll mode of motion. The continued increase in phase lags of the airplane—automatic-control-system combination at frequencies where the phase lag of the airplane alone has ceased to increase is associated with the servo actuator. In the pilots' opinion the lateral control characteristics were satisfactory with either the conventional or automatic control systems.

Dynamic Lateral Stability

Time histories of the short-period lateral oscillation for the airplane alone and for the airplane with the yaw channel of the automatic control system in operation are shown in figure 11. The oscillations were induced by the pilot by deflecting the rudder pedal and then releasing it. When the yaw channel of the automatic control system was being used the pilot overpowered the servo actuator when deflecting the rudder. The maneuvers shown in figure 11 were made at a Mach number of 0.60 and an altitude of 30,000 feet. A comparison of the two maneuvers shows the yaw channel of the automatic control system to be very effective in increasing the damping of the lateral oscillation. Also, no measurable residual oscillations resulted from use of the yaw channel. Although the damping of the lateral oscillation was satisfactory, rudder coordination during rapid turn entries was not adequate as has already been noted.

General Maneuvering Characteristics

The characteristics of the airplane-automatic control system were further evaluated by performing various aerobatics. Among the maneuvers performed were a loop, Immelmann turn, and barrel rolls.

Figure 12 shows a time history of various airplane response quantities and control inputs during a loop and Immelmann turn. This maneuver was started at an indicated airspeed of 245 knots and an altitude of 25,600 feet. The loop was made quite gradually with the maximum normal acceleration being about 3.8g. The indicated airspeed varied between about 95 knots and 340 knots (maximum Mach number of 0.75). The minimum airspeed occurred near the top of the loop (at times of about 48 sec.), and the normal acceleration was small at the low speeds, being only about 0.2g.

The loop which was completed in 76 seconds was followed by an Immelmann turn. The 180° left roll during the Immelmann turn was made at low speed, about 110 knots. The rolling response was satisfactory. A maximum sideslip angle of about 7° occurred during the roll.

A time history of a barrel roll made at a Mach number of 0.60 and an altitude of 20,000 feet is shown in figure 13. This maneuver was started during a pull out which accounts for the normal acceleration being about 1.5g at the start of the record. The stick was deflected rapidly to the right in this maneuver and a rolling velocity greater than 2.0 radians per second (which was the range of the rolling-velocity recorder) was reached. The maximum changes in sideslip angle were about 3° right and left.

For all of these aerobatics the airplane was easily controlled with no apparent uncontrolled-for motions occurring. In the pilot's opinion, the handling qualities of the airplane were satisfactory and more desirable than those present when using the conventional control system. The major difference in favor of the automatic control system was the lighter control forces which reduced the pilot effort. Also the overall handling qualities were at least as good as those of the basic airplane and in some respects better. It should be pointed out that the airplane used in this investigation had good flying qualities (except for low Dutch roll damping and high longitudinal control forces) and therefore the automatic control system could not be expected to provide any large improvement in the overall flying qualities.

Rough-Air Flying, Tracking, and Landing Characteristics

Rough-air characteristics.- Simulated cross-country flying was done in moderately rough air at a Mach number of 0.6 and an altitude of 5,000 feet when both the conventional control system with the yaw channel of the automatic control system in operation and the automatic control system were used. For this flying, the pilot maintained straight and level flight with the precision ordinarily used in cross-country flying. Inspection of the flight records for the two runs showed that there was little difference in the motion of the airplane. With the automatic control system there was some high frequency, low amplitude, aileron motion which had little effect on the bank angle. The pitch attitude was quite steady with both systems. For this flying the pilot preferred the rate control system to the conventional control system although any advantage of the rate system was not marked and the pilot's opinion is based on very limited experience. The lighter control forces of the rate system allowed the pilot to maintain straight and level flight within a given tolerance with less effort. Also, the increased damping made the airplane more stable in the rough air. Although, theoretically, attitude stabilization to gust disturbances is provided by the servo-follow-up canceling in the rate system used in the present investigation, difficulty in trimming the rate command signals to zero and, possibly, a lack of sensitivity of the rate gyros to very small angular velocities tends to mask the attitude stabilization feature. The pilot was of the opinion that an attitude and heading stabilization system such as reported in reference 1 was preferable to the rate control system not only for cross-country flying in rough air but for all flight operations that require little or no maneuvering. This was the general opinion of the three pilots who flew the airplane with the rate system and the attitude system of reference 1. This indicates that a combination of a rate control system for maneuvering and an attitude stabilization system for nonmaneuvering flight would be a versatile system having application for many flight operations.

Tracking.- Tracking runs on a target airplane and ground-strafing runs in rough air were made to evaluate quantitatively the automatic control system when the pilot was performing precision tasks. In order to have a basis for comparison, similar runs were made with the pilot controlling the airplane with the conventional control system. All of the air-to-air tracking runs were made at a Mach number of about 0.6, an altitude of 30,000 feet, and a range of about 500 yards. The strafing runs were also made at a Mach number of 0.6. For all tracking runs made with the conventional control system, the yaw channel of the automatic control system was in operation.

Table III shows a comparison of the tracking errors in various maneuvers when the conventional control system and the automatic control system were used. In either air-to-air tracking or in ground strafing, there are no significant differences in the pilot's tracking ability with the two systems.

Landing.- A time history of a landing with the automatic control system is shown in figure 14(a). For comparison, a similar landing with the conventional control system is shown in figure 14(b). A power-on sinking type of approach was used for these landings. No difficulty was experienced in making the landing with the automatic control system. The automatic trimming was not objectionable to the pilot. In the landing made with the automatic control system the cross-wind was small. Some form of rudder control would, no doubt, be necessary for landings in cross-winds of appreciable magnitude.

CONCLUSIONS

A flight investigation was made to obtain experimental information on the handling qualities of a fighter airplane which the pilot controlled by supplying signals to a rate type of automatic control system. An automatic-control-system stick which was similar to a conventional control stick was used by the pilot to introduce signals into the automatic control system. The main conclusions reached as a result of this flight program are as follows:

1. For flight operations involving both rapid maneuvering (such as required in a fighter airplane) and mild maneuvering, the pilots generally preferred the rate-type automatic control system to the conventional control system. This preference was due primarily to the lighter maneuvering forces required for the rate system and to a lesser extent to the increased damping provided by the rate system.

2. Pilots were able to perform precision tasks such as strafing or air-to-air tracking about as well with the rate control system as with the conventional control system.

3. The pilots were of the opinion that a combination of a rate control system for maneuvering and an attitude stabilization system for nonmaneuvering flight would be a versatile system having applications for many flight operations. Flight tests of a combination of these systems

were not made and the pilot's opinion is based on separate tests of attitude and rate control systems.

4. For flight conditions ranging from landings at sea level to Mach numbers from 0.7 to 0.8 at altitudes up to 30,000 feet, a simple spring feel system, that is, one which provided a constant stick force per unit angular velocity with no variation with speed or altitude, gave adequate control force characteristics. Since this type of feel system gives a stick force per unit normal acceleration which is inversely proportional to true airspeed, some means of varying the longitudinal-stick-force gradient might be necessary for airplanes with larger speed ranges.

5. For flight conditions ranging from landings at sea level to Mach numbers from 0.7 to 0.8 at altitudes up to 30,000 feet, acceptable although not necessarily optimum response characteristics were obtained without changing the gains of the automatic control system.

6. Some of the inherent features of the rate control system used are automatic trimming for 1 g flight, stability augmentation, and the equivalent of mechanical advantage changing between the stick and the control surfaces which provides a uniform angular velocity response to stick deflections for all flight conditions.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 24, 1956.

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2. Sjoberg, S. A.: A Flight Investigation of the Handling Characteristics of a Fighter Airplane Controlled Through Automatic-Pilot Control Systems. NACA RM L55F01b, 1955.

3. Anon.: Handbook of Operation and Service Instructions for G-3 Automatic Pilot (General Electric). Rep. AN 05-45FB-1, BuAer and Air Materiel Command, June 15, 1951.

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5. Eggleston, John M., and Mathews, Charles W.: Application of Several Methods for Determining Transfer Functions and Frequency Response of Aircraft From Flight Data. NACA Rep. 1204, 1954. (Supersedes NACA TN 2997.)

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

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TABLE I

GENERAL DIMENSIONS AND CHARACTERISTICS OF AIRPLANE

Wing:	
Span (with tip tanks), ft	37.99
Span (without tip tanks), ft	35.25
Area (without tip tanks), sq ft	250
Airfoil section	NACA 64_1A012
Aspect ratio (without tip tanks)	4.97
Taper ratio	0.46
Incidence, deg	0
Dihedral, deg	4
Twist, deg	0
Sweep of 27-percent-chord line, deg	0
Mean aerodynamic chord (M.A.C.), in.	89.45
Total aileron area, sq ft	18.44
Aileron travel, deg	19 up 14 down
Horizontal tail:	
Span, ft	17.21
Area (including elevator), sq ft	66.20
Elevator area, sq ft	19.20
Elevator travel, deg	18 up 15 down
Tail length, 25-percent M.A.C. of wing to elevator hinge line, ft	18.45
Vertical tail:	
Area (not including dorsal fin), sq ft	36.02
Rudder area, sq ft	8.54
Rudder travel, deg	±26
Miscellaneous:	
Length (excluding nose boom), ft	38.13
Weight, take-off (tip tanks empty), lb	14,460
Center-of-gravity position, take-off, percent M.A.C.	26.5
Center-of-gravity position, landing (1,000 lb of fuel), percent M.A.C.	28.4
Engine	J42-P-8

TABLE II

SIGNAL GRADIENTS, TIME CONSTANTS, AND GEARINGS FOR THE AUTOMATIC CONTROL SYSTEM

Servo follow-up signal gradients:	
K_{f_a}, volts/radian	7.0
K_{f_e}, volts/radian	7.0
K_{f_r}, volts/radian	5.7
Ratio of servo-tachometer—servo-follow-up signal gradients for -	
Aileron servo, sec	0.08
Elevator servo, sec	0.04
Rudder servo, sec	0.04
Time constants of servo follow-up canceler system (time to reach 63 percent of steady-state response for step inputs of about 4 volts) for -	
Aileron, sec	0.6
Elevator, sec	0.6
Rudder, sec	1.8
Rate-gyro signal gradients:	
$K_{\dot{\phi}}$, volts/radian/sec	5.3
$K_{\dot{\theta}}$, volts/radian/sec	11.6
$K_{\dot{\psi}}$, volts/radian/sec	20.1
Pendulum signal gradient:	
K_{a_y}, volts/g	16.4
Ratio of control-surface displacement to servo drum rotation (ground measurements with no load on surfaces) for -	
Total aileron/Aileron servo, radian/radian	0.6
Elevator/Elevator servo, radian/radian	0.2
Rudder/Rudder servo, radian/radian	0.23
Automatic-pilot-controller signal gradients (through neutral):	
Fore and aft	0.18 volt/deg 0.69 volt/in.
Lateral	0.76 volt/deg 2.9 volts/in.

TABLE III

STANDARD DEVIATIONS OF TRACKING ERRORS WITH RATE AUTOMATIC CONTROL SYSTEM AND CONVENTIONAL CONTROL SYSTEM

Maneuver	Mach number	Altitude, ft	Pitch error, mils, for -		Yaw error, mils, for -	
			Rate automatic control system	Conventional control system	Rate automatic control system	Conventional control system
Nonmaneuvering tail chase	0.6	30,000	1.9	2.2	2.2	1.7
Turns, 30° to 60° bank angles	0.6	30,000	3.7	3.6	3.7	3.8
Pull-ups and push-downs, 2.5g to 0.25g	0.6	30,000	5.1	4.4	3.8	3.1
Strafing	0.6	2,500 to 300	5.6	4.4	5.4	5.2

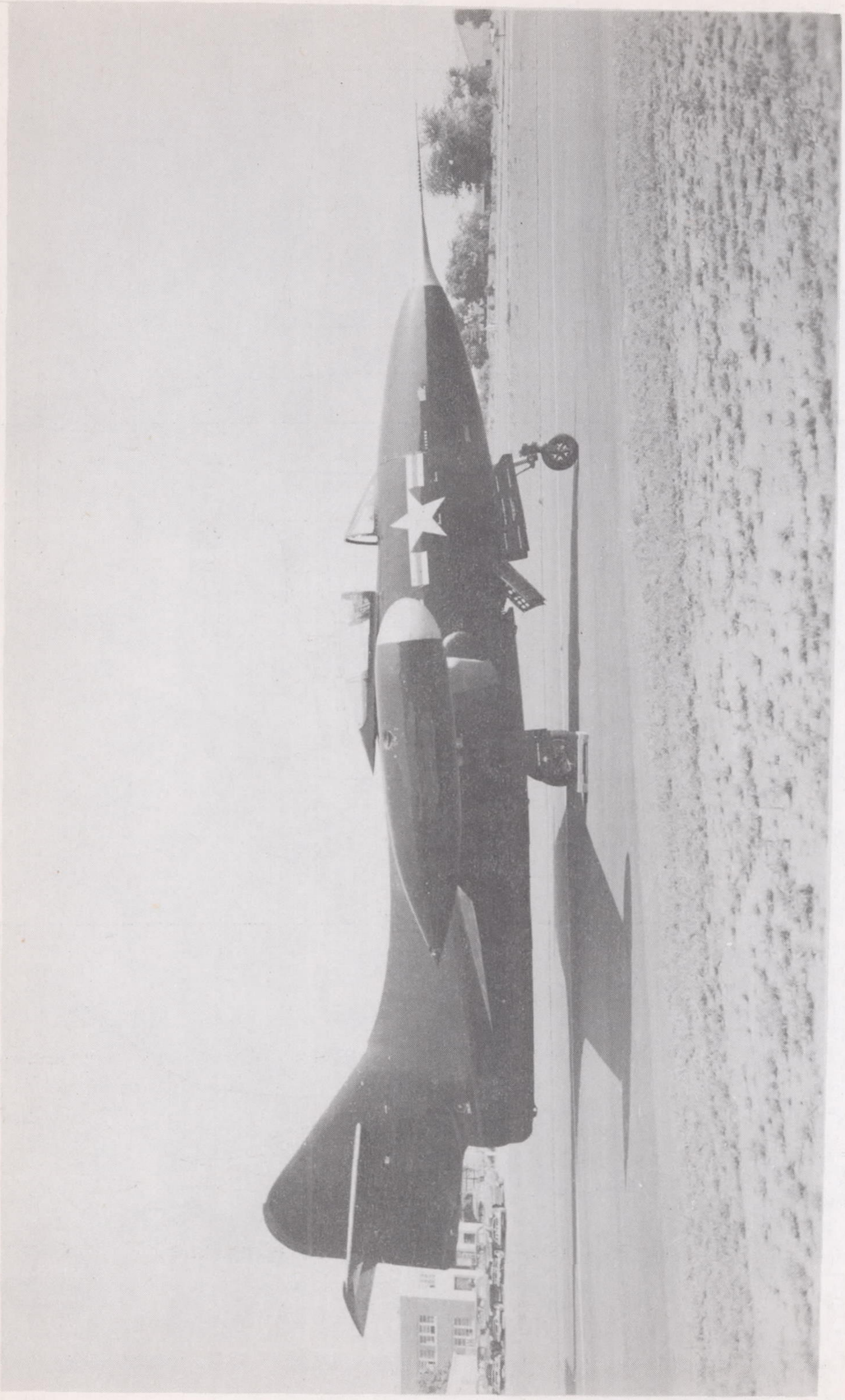

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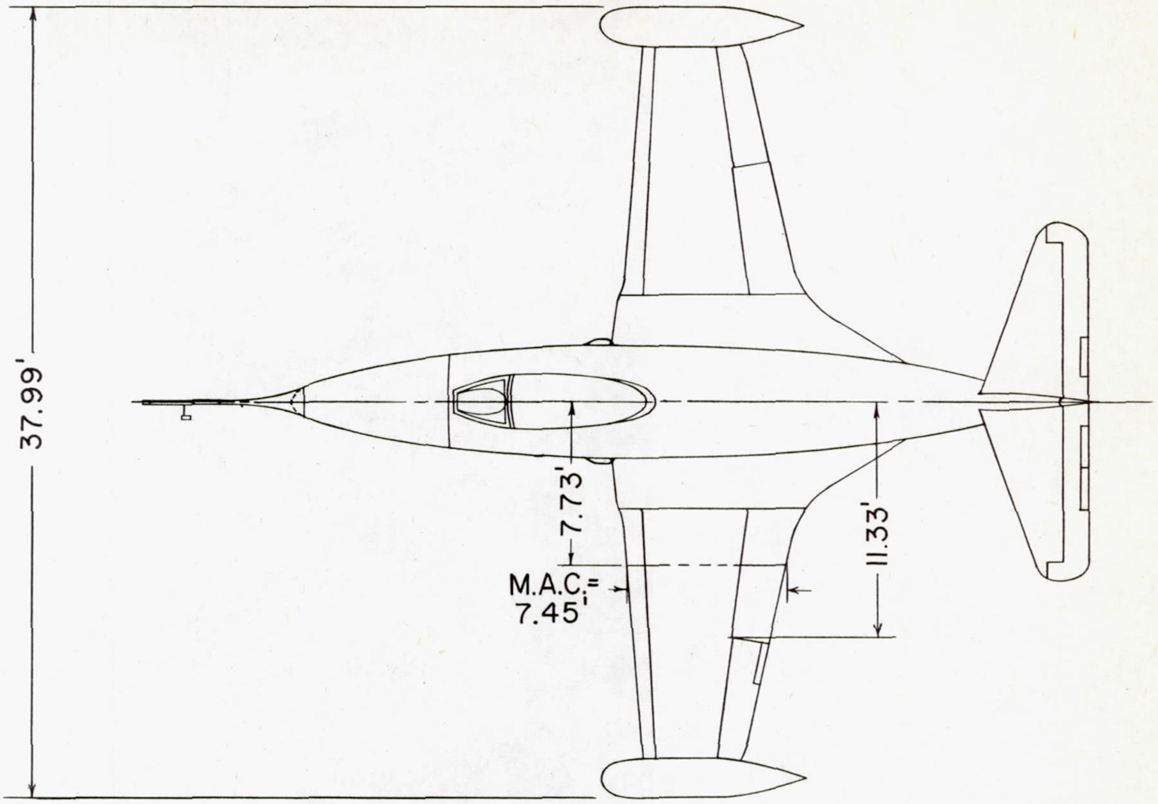
Figure 1.- Airplane used in investigation.



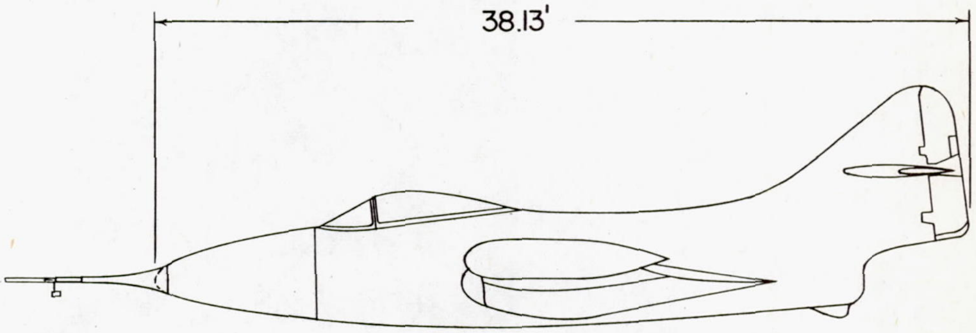
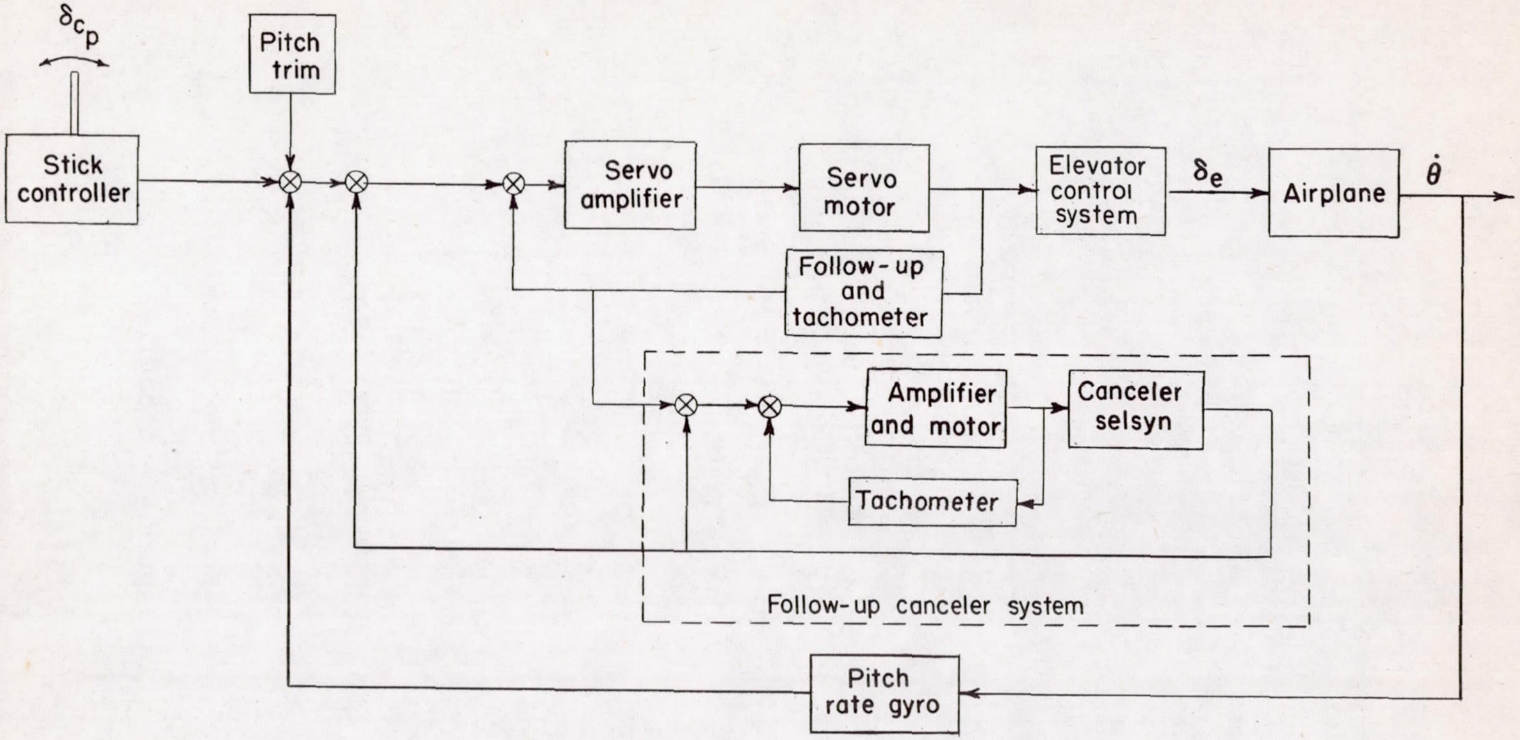
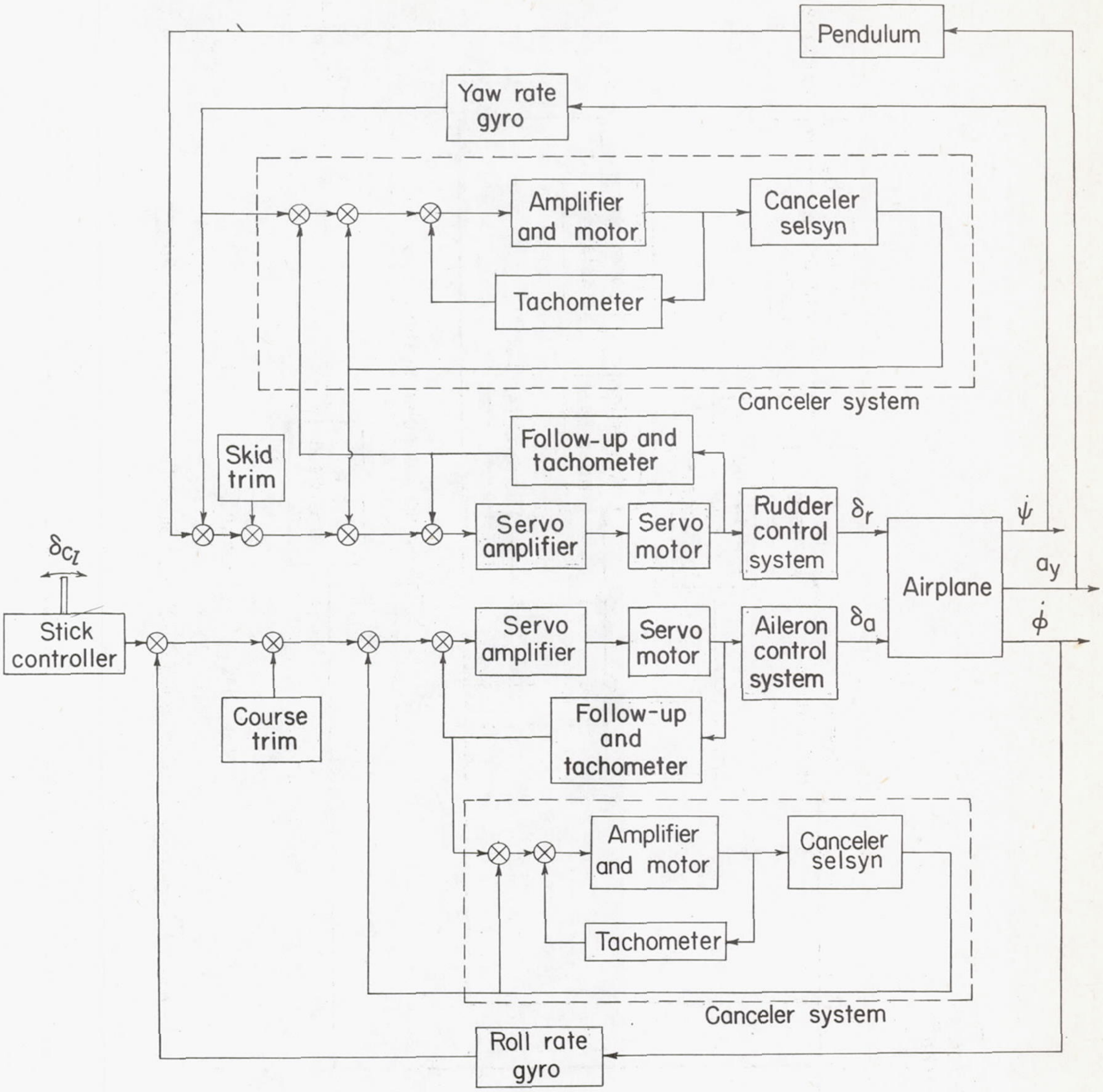


Figure 2.- Two-view drawing of airplane.



(a) Pitch channel.

Figure 3.- Block diagrams of automatic control system.



(b) Roll and yaw channels.

Figure 3.- Concluded.

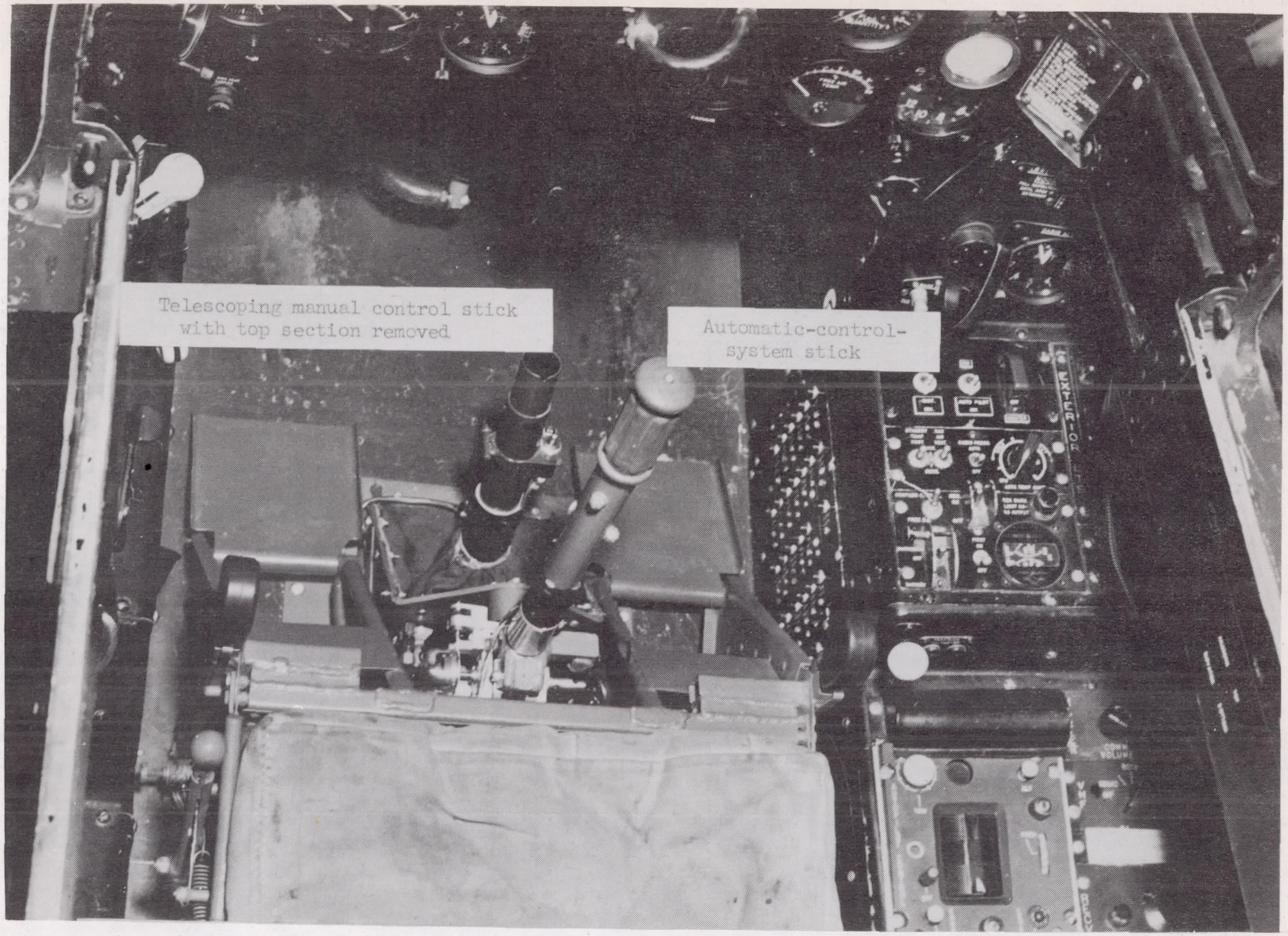


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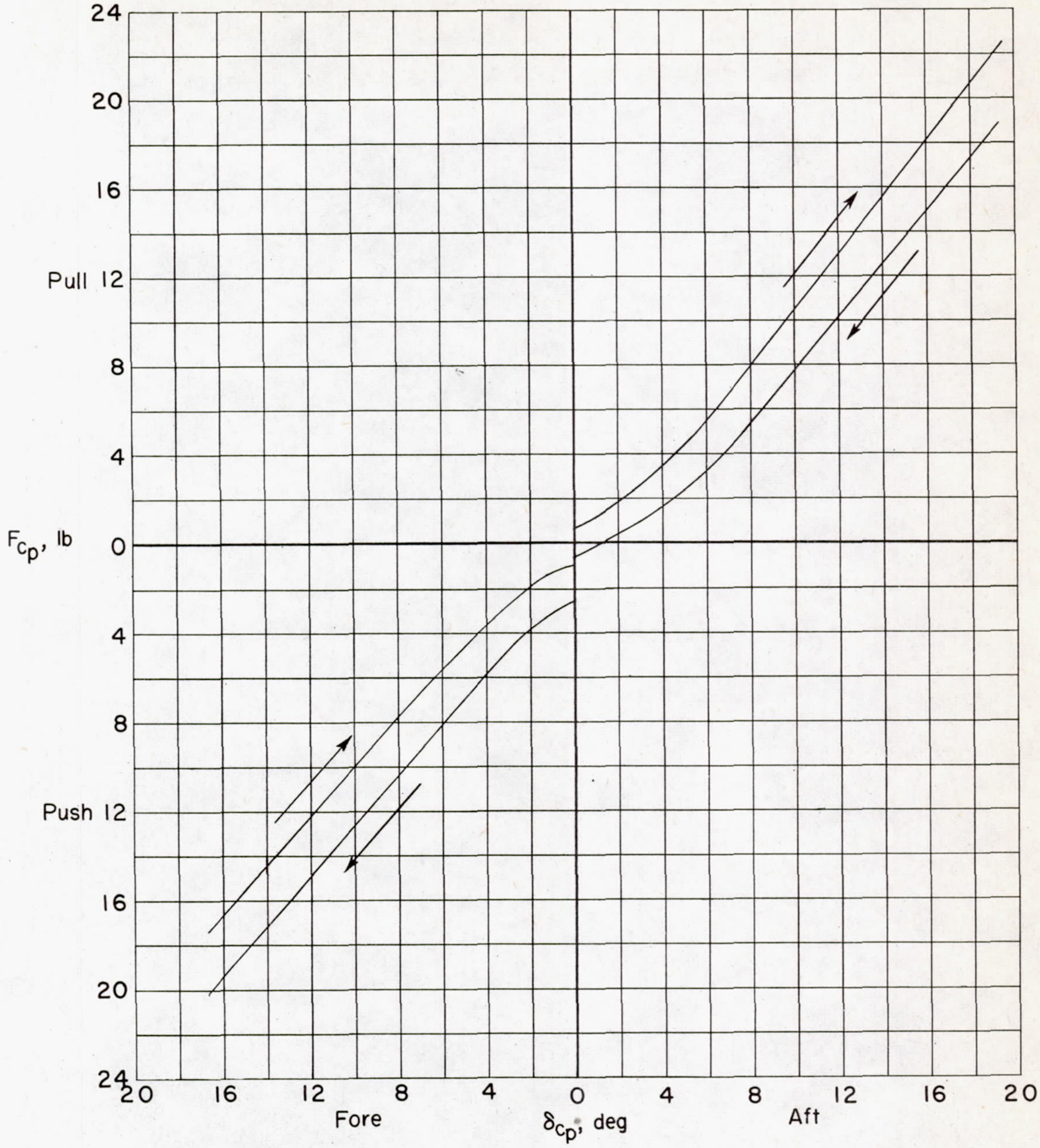
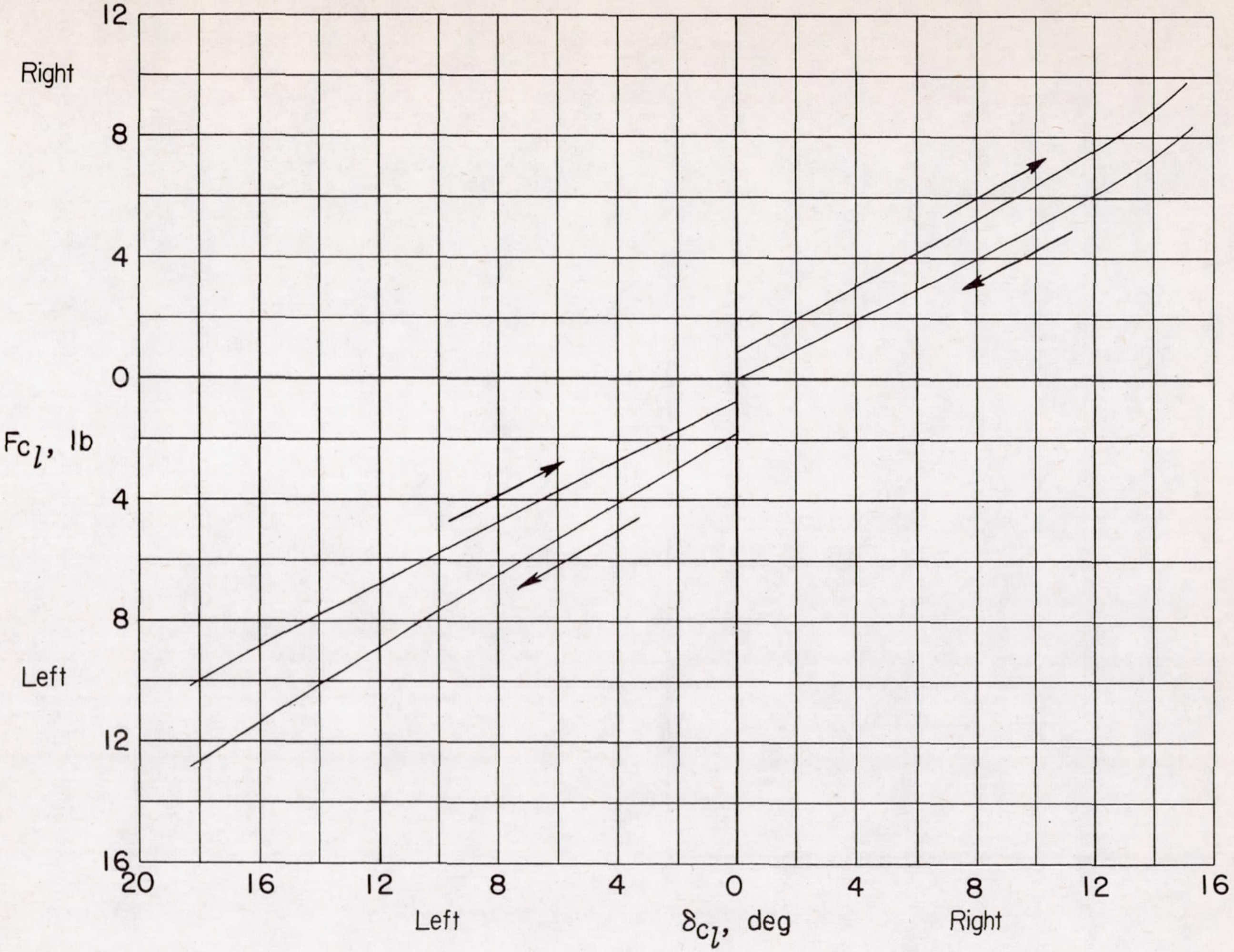
Figure 4.- Top view of cockpit showing automatic-control-system stick installation.



(a) Longitudinal.

Figure 5.- Variation of automatic-control-system stick force with stick position.



(b) Lateral.

Figure 5.- Concluded.

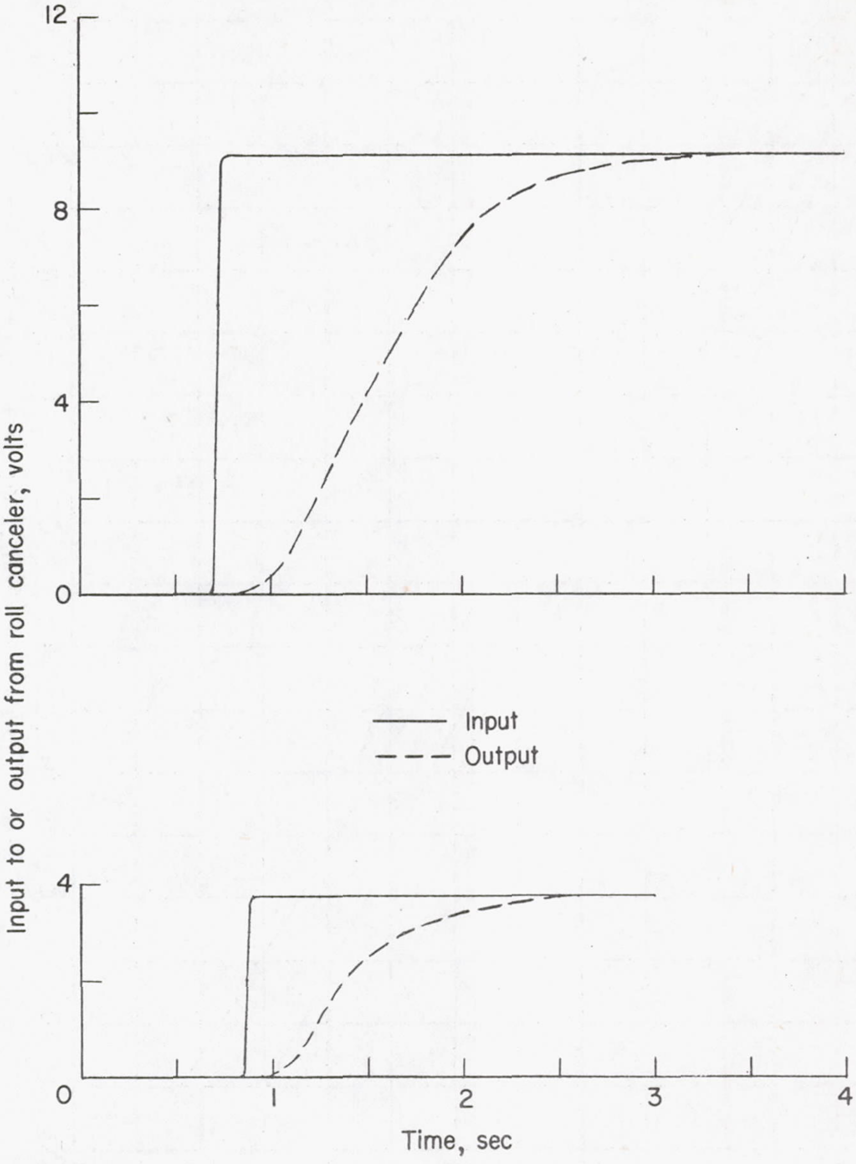
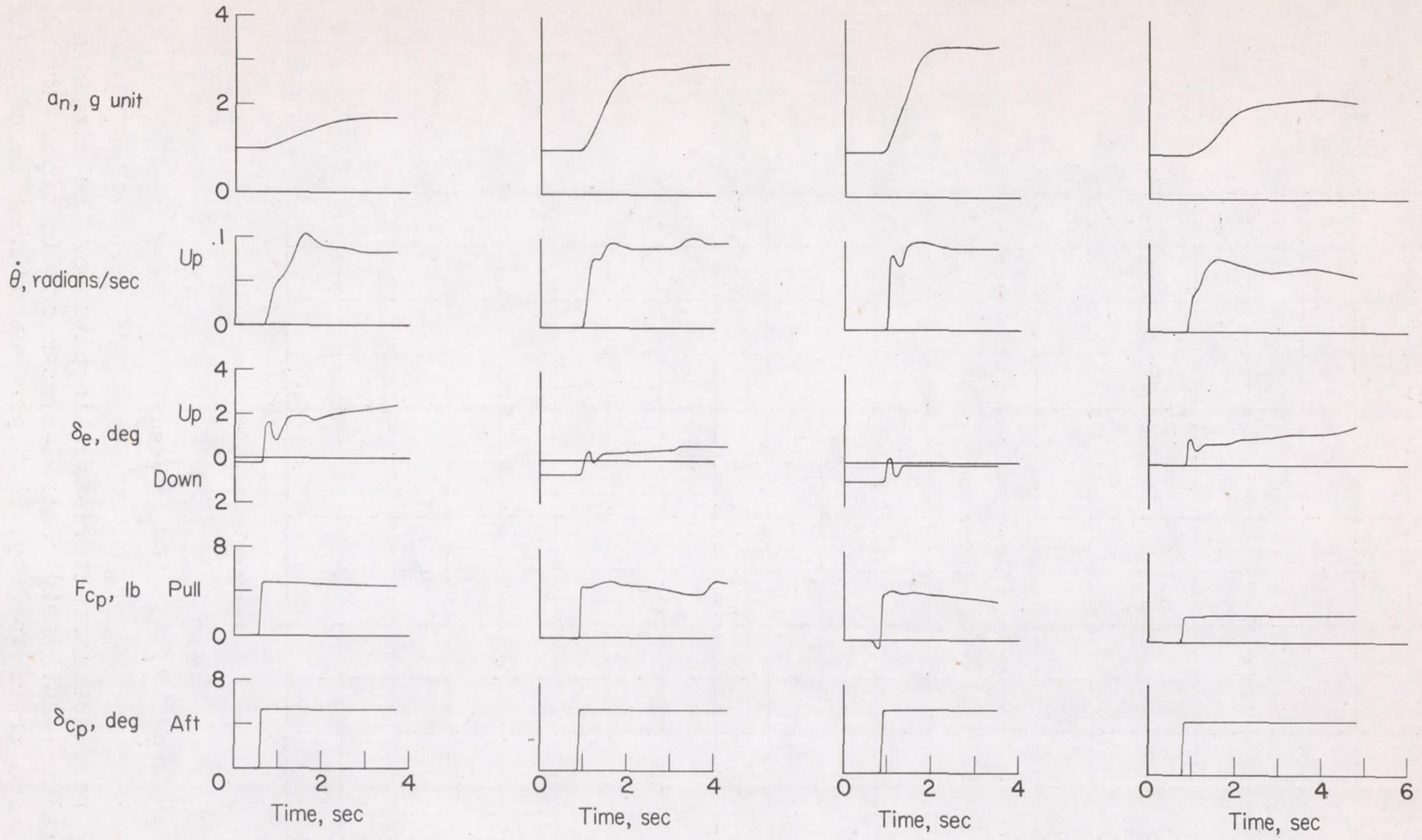


Figure 6.- Transient-response characteristics of roll-canceler system for two amplitudes of input.



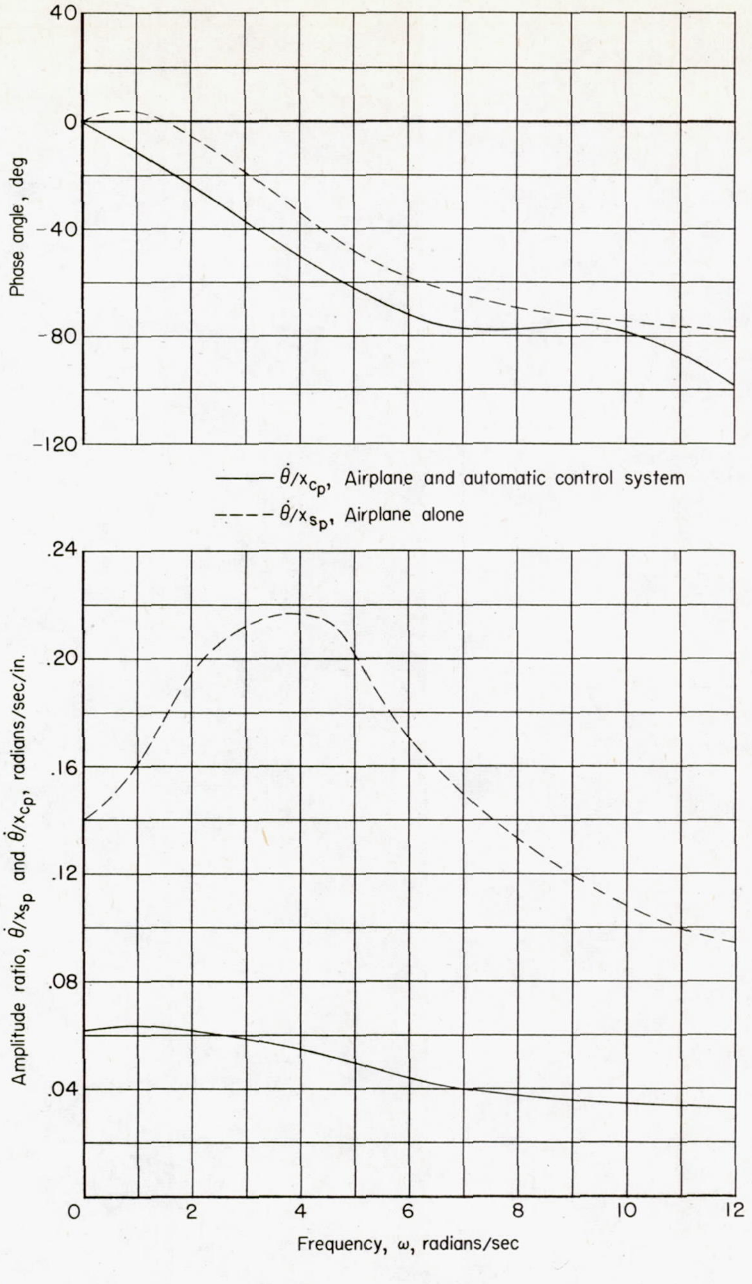
(a) V_i = 150 knots;
h_p = 10,000 feet.

(b) M = 0.6;
h_p = 10,000 feet.

(c) M = 0.7;
h_p = 10,000 feet.

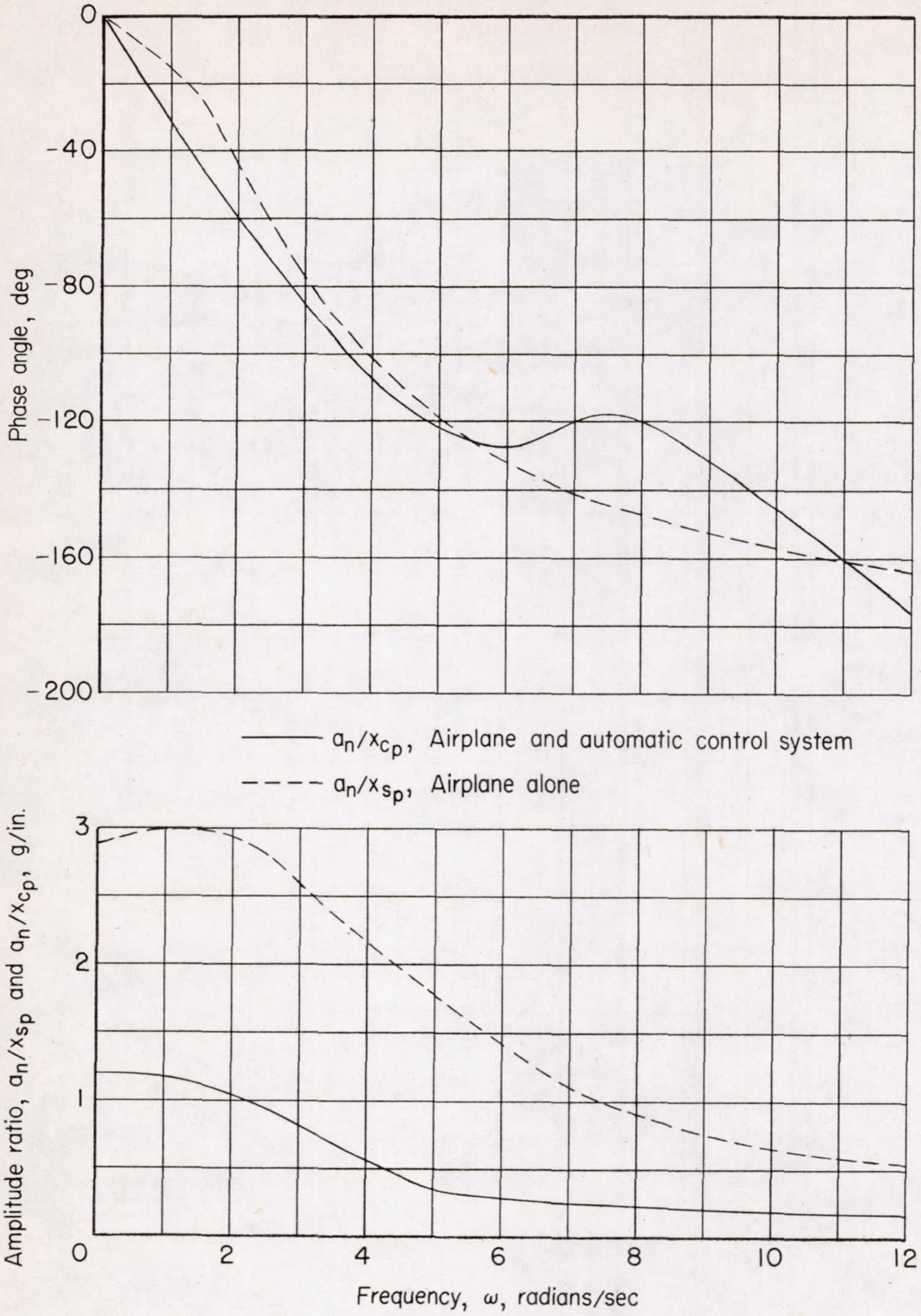
(d) M = 0.6;
h_p = 30,000 feet.

Figure 7.- Transient-response characteristics in pitch of airplane—automatic-control-system combination. Airplane in clean condition; power for level flight; center of gravity approximately 27.5 percent of mean aerodynamic chord; $K_{\dot{\theta}}$ = 11.6 volts/radian/sec; K_{f_e} = 7.0 volts/radian.



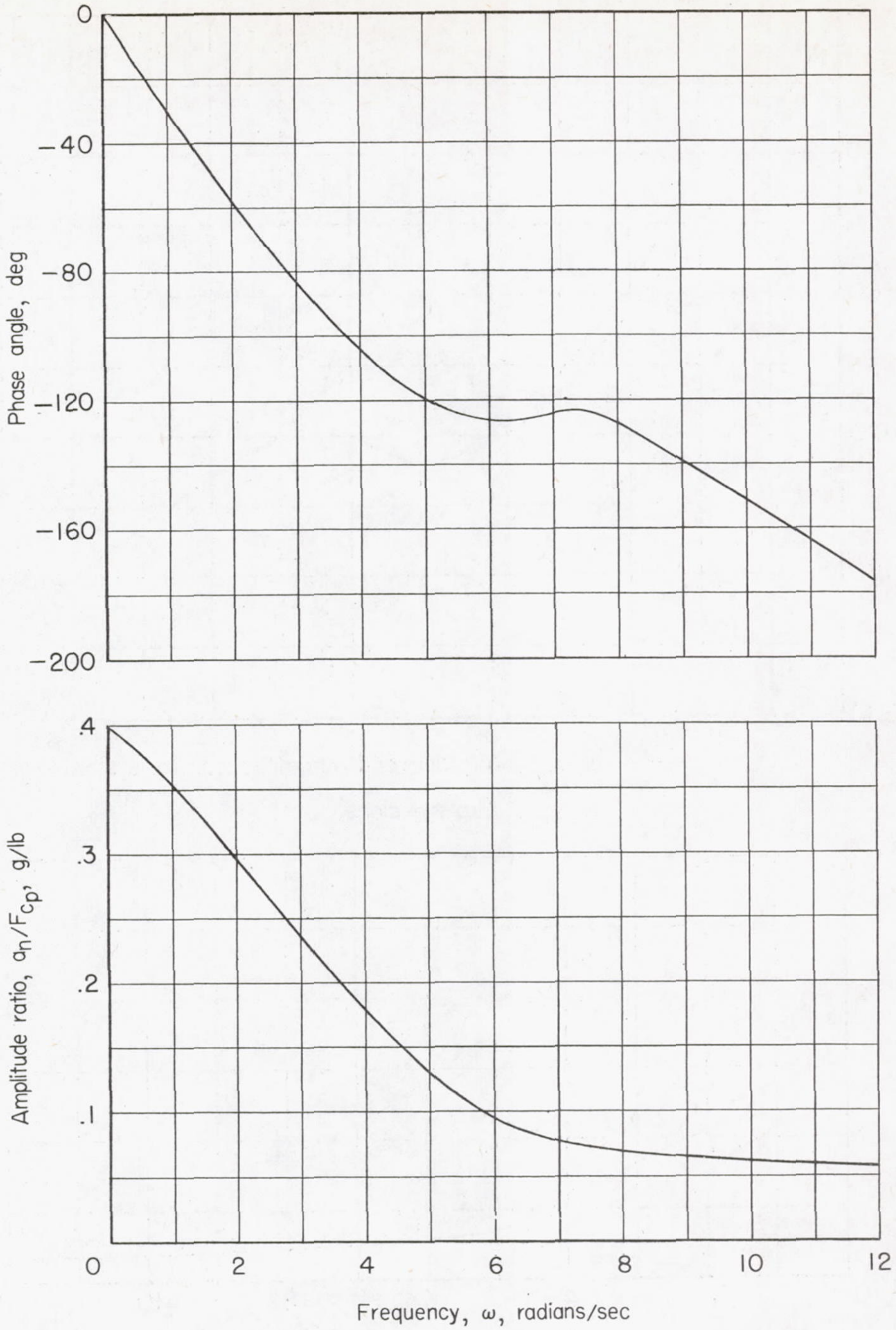
(a) $\dot{\theta}/x_{c_p}$ and $\dot{\theta}/x_{s_p}$.

Figure 8.- Frequency-response characteristics in pitch of the airplane alone and the airplane—automatic-control-system combination. $M = 0.6$; $h_p = 10,000$ feet; center of gravity, 27.5 percent of mean aerodynamic chord; $K_{\dot{\theta}} = 11.6$ volts/radian/sec; $K_{f_e} = 7.0$ volts/radian.



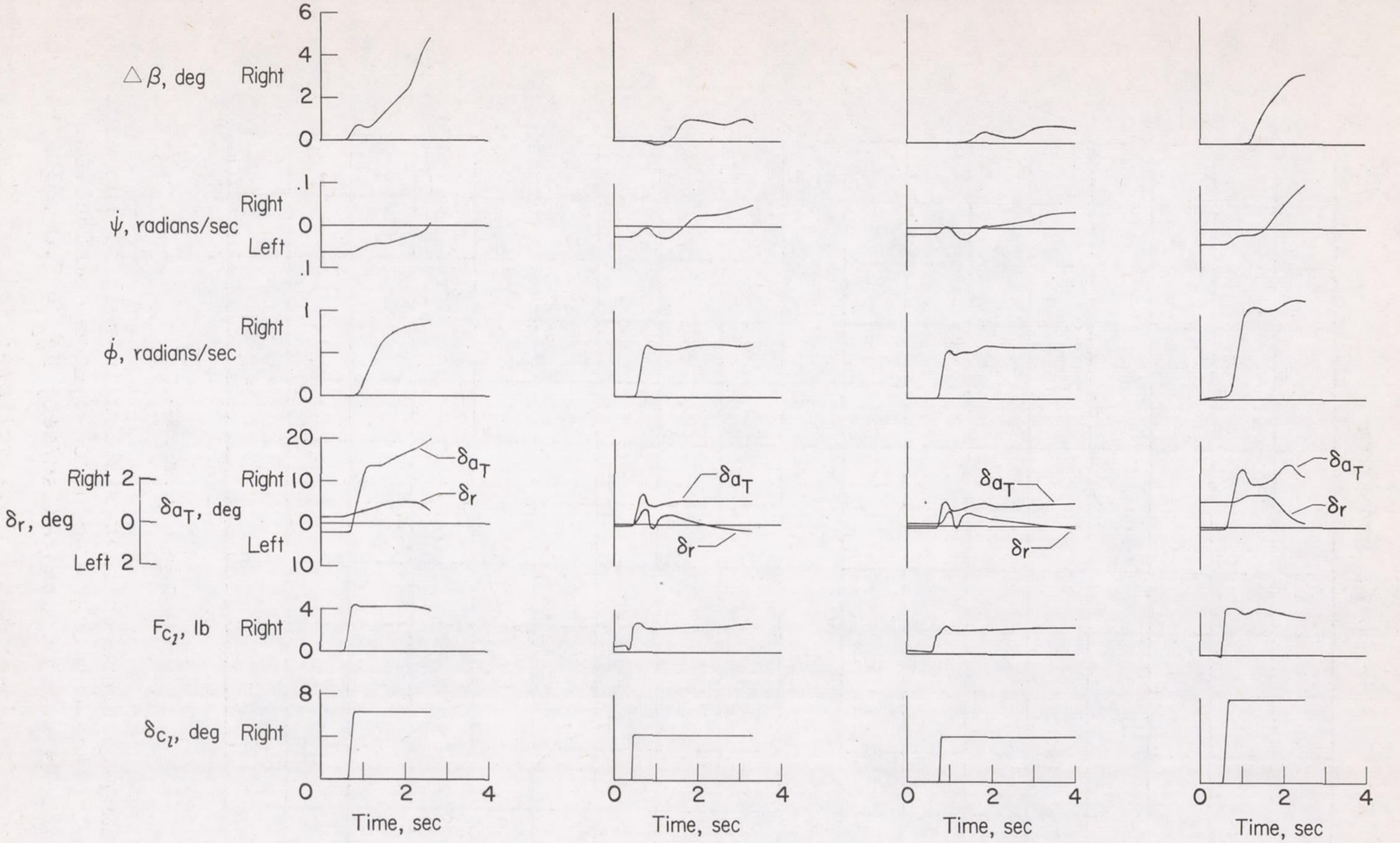
(b) a_n/x_{c_p} and a_n/x_{s_p}.

Figure 8.- Continued.



(c) a_n/F_{c_p}.

Figure 8.- Concluded.



(a) V_i = 150 knots; h_p = 10,000 feet.

(b) M = 0.6; h_p = 10,000 feet.

(c) M = 0.7; h_p = 10,000 feet.

(d) M = 0.6; h_p = 30,000 feet.

Figure 9.- Transient-response characteristics in roll of the airplane—automatic-control-system combination. Rolls started from left banked turns. $K_{\dot{\phi}}$ = 5.3 volts/radian/sec; K_{f_a} = 7.0 volts/radian; $K_{\dot{\psi}}$ = 20.1 volts/radian/sec; K_{a_y} = 16.4 volts/g; K_{f_r} = 5.7 volts/radian.

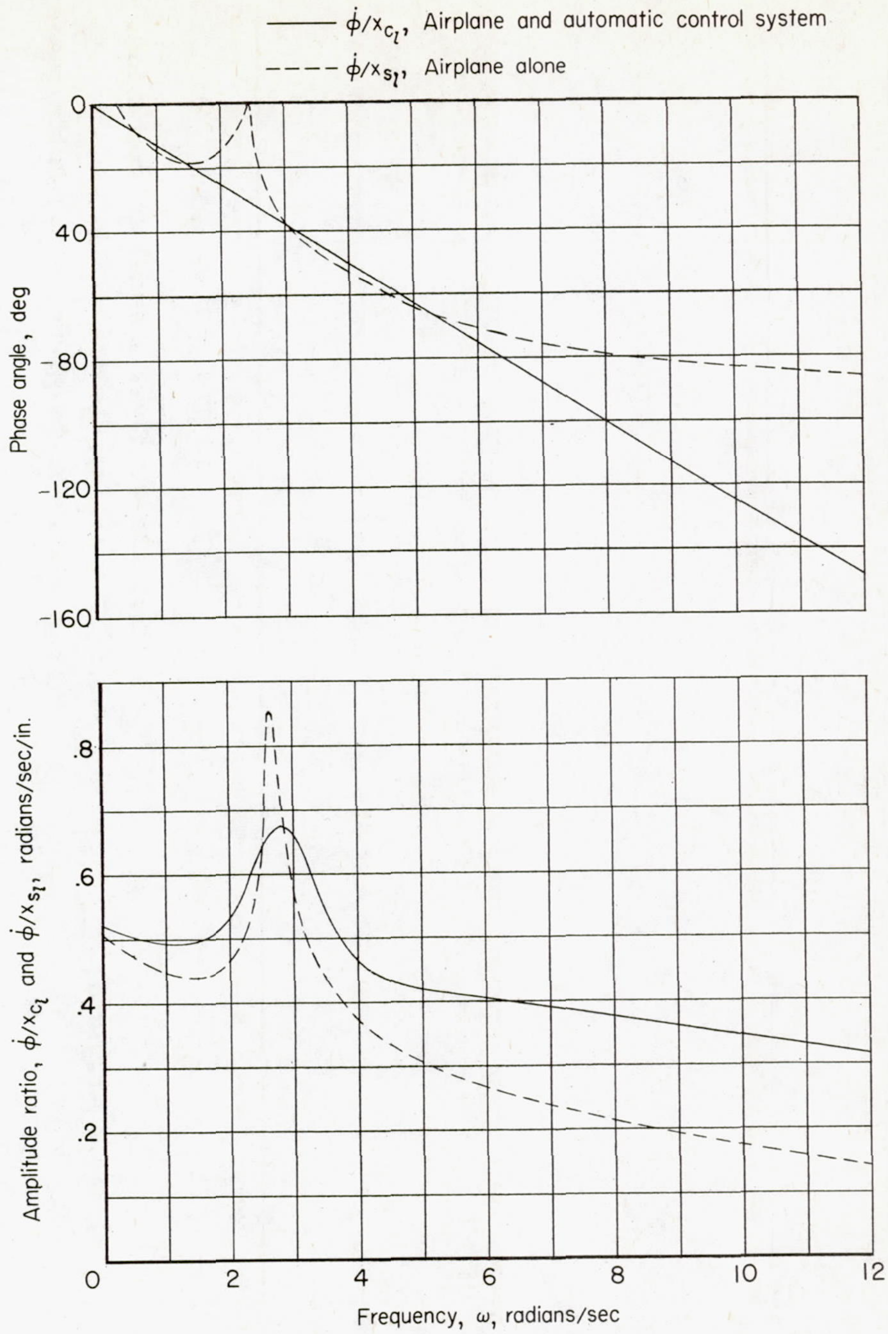
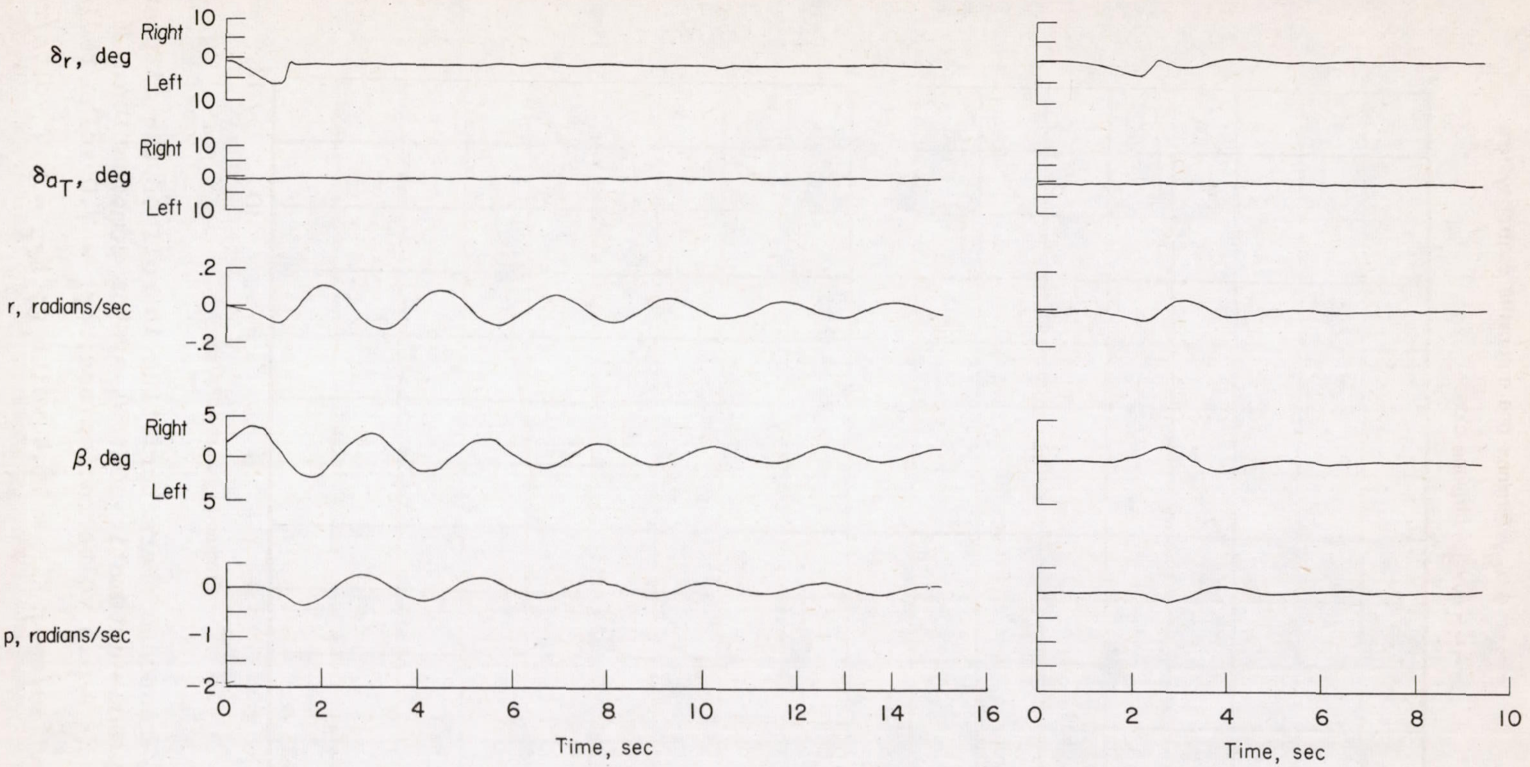


Figure 10.- Frequency-response characteristics in roll of the airplane alone and the airplane—automatic-control-system combination. $M = 0.6$; $h_p = 30{,}000$ feet; $K_{\dot{\phi}} = 5.3$ volts/radian/sec; $K_{f_a} = 7.0$ volts/radian; $K_{\dot{\psi}} = 20.1$ volts/radian/sec; $K_{a_y} = 16.4$ volts/g; $K_{f_r} = 5.7$ volts/radian.



(a) Basic airplane.

(b) Airplane with yaw channel in operation.
$K_{\dot{\psi}}$ = 20.1 volts/radian/sec;
K_{a_y} = 16.4 volts/g; K_{f_r} = 5.7 volts/radian.

Figure 11.- Time histories of rudder kicks at $M = 0.60$ and $h_p = 30{,}000$ feet.

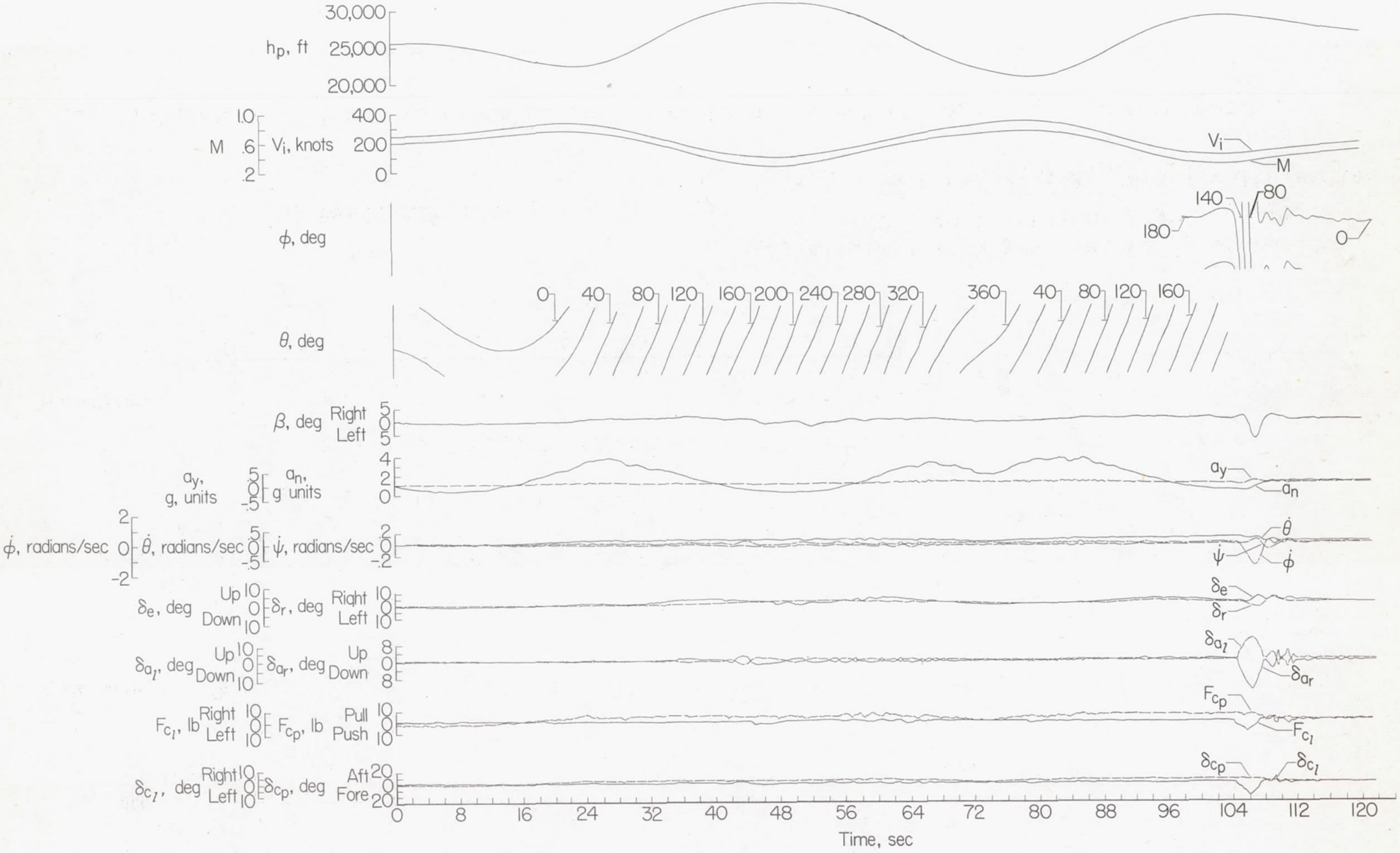


Figure 12.- Time history of a loop followed by an Immelmann turn. Airplane controlled through automatic control system. $K_{\dot{\theta}}$ = 11.6 volts/radian/sec; K_{f_e} = 7.0 volts/radian; $K_{\dot{\phi}}$ = 5.3 volts/radian/sec; K_{f_a} = 7.0 volts/radian; $K_{\dot{\psi}}$ = 20.1 volts/radian/sec; K_{a_y} = 16.4 volts/g; K_{f_r} = 5.7 volts/radian.

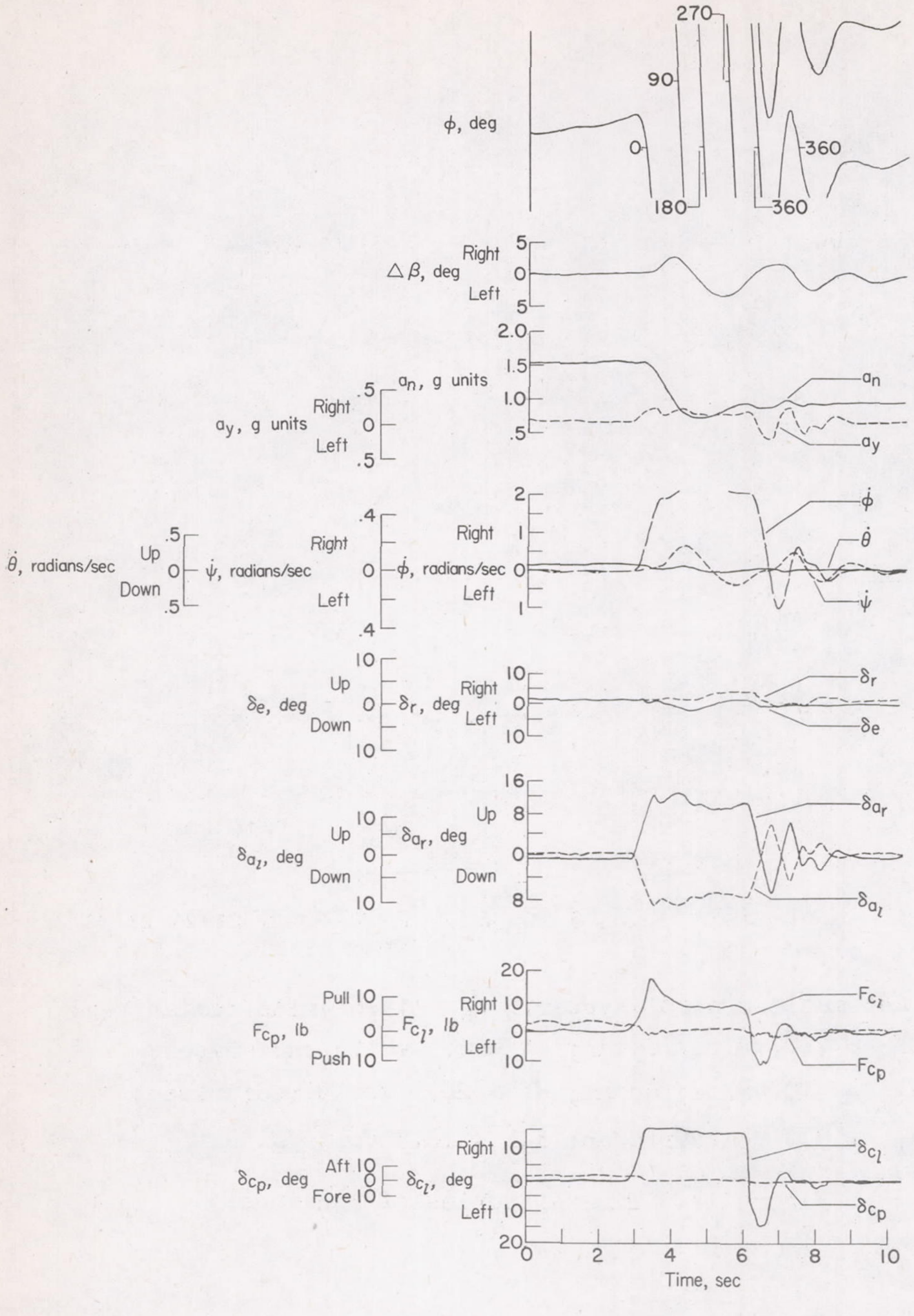
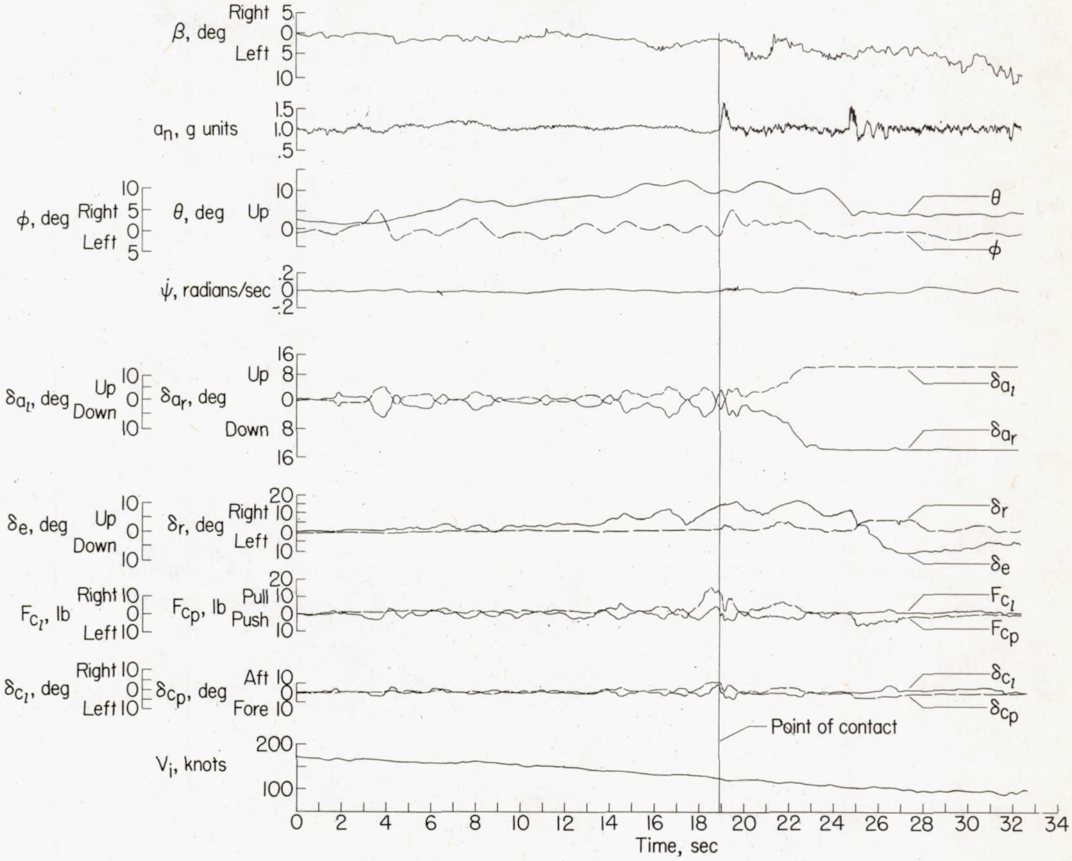
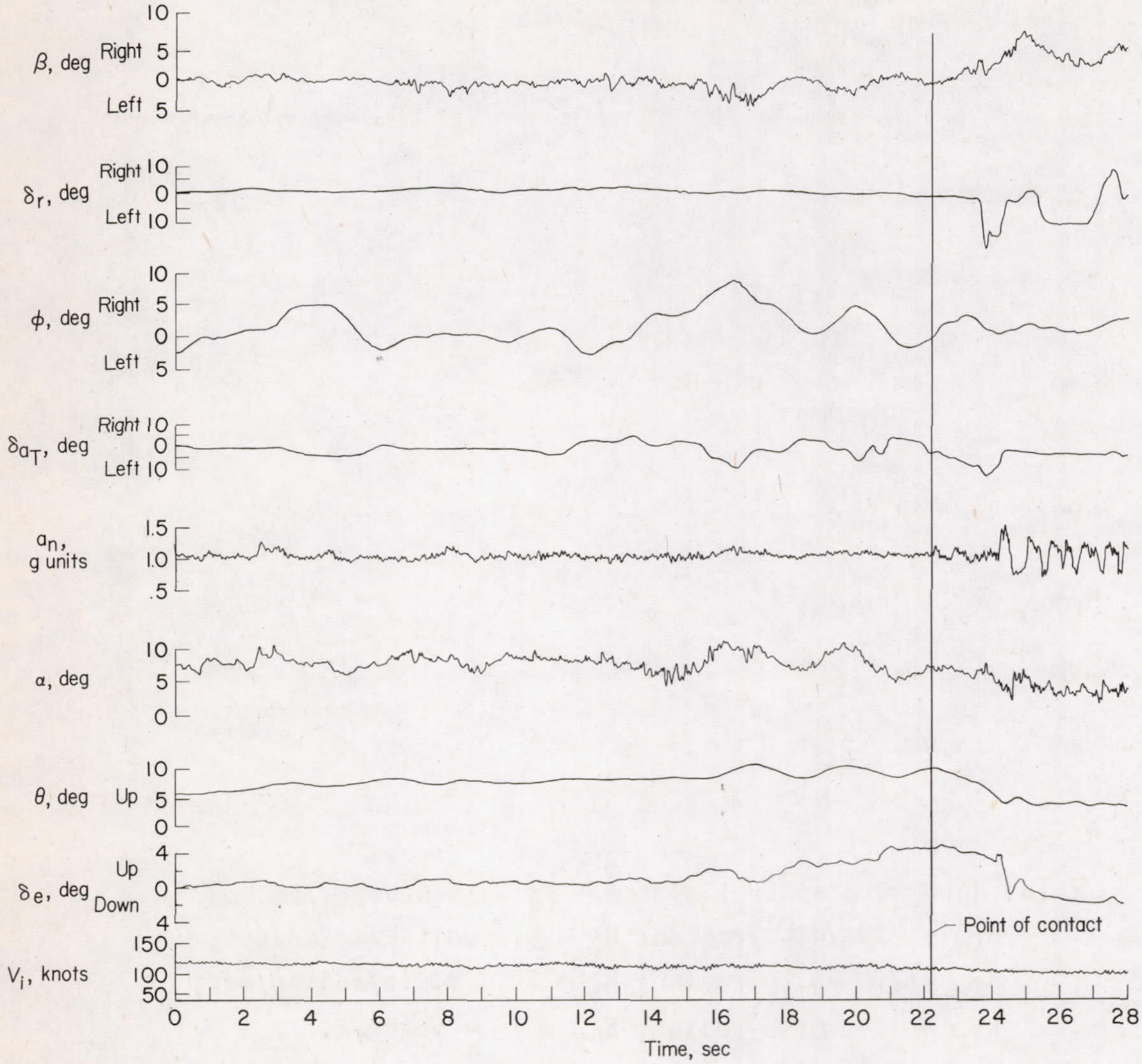


Figure 13.- Time history of a rapid barrel roll made with automatic control system: M = 0.6; h_p = 20,000 feet; $K_{\dot{\theta}}$ = 11.6 volts/radian/sec; K_{f_e} = 7.0 volts/radian; $K_{\dot{\phi}}$ = 5.3 volts/radian/sec; K_{f_a} = 7.0 volts/radian; $K_{\dot{\psi}}$ = 20.1 volts/radian/sec; K_{a_y} = 16.4 volts/g; K_{f_r} = 5.7 volts/radian.



(a) Automatic control system. $K_{\dot{\theta}}$ = 11.6 volts/radian/sec;
K_{f_e} = 7.0 volts/radian; $K_{\dot{\phi}}$ = 5.3 volts/radian/sec;
K_{f_a} = 7.0 volts/radian; $K_{\dot{\psi}}$ = 20.1 volts/radian/sec;
K_{f_r} = 5.7 volts/radian; K_{a_y} = 16.4 volts/g.

Figure 14.- Time histories of landings.



(b) Conventional control system.

Figure 14.- Concluded.

NACA - Langley Field, Va.