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SIMULATOR STUDY OF COUPLED ROLL-SPIRAL MODE EFFECTS ON LATERAL-DIRECTIONAL HANDLING QUALITIES

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16. Abstract

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SUMMARY

A piloted fixed-base simulator study has been made to provide a preliminary determination of the effects of a coupled roll-spiral mode on lateral-directional handling qualities. The coupling of the roll and spiral modes is characterized as an unconventional lateral oscillatory mode and has only recently become of interest since conventional aircraft have not displayed this phenomenon. No attempt is made in the present study to establish any kind of handling-qualities criteria because of the limited scope of the investigation, including the limitations of fixed-base simulation.

The results indicate that when the conventional roll and spiral modes couple, the lateral-directional handling qualities are seriously degraded regardless of how the coupling was brought about, that is, regardless of which aerodynamic derivative or combination of derivatives caused the two modes to couple. When this coupling occurs, regardless of the cause of the coupling, the pilot sees a serious degradation in roll damping. The comments made by the pilots and the pilot ratings assigned to the various configurations evaluated seemed to correlate somewhat in terms of the frequency of the roll-spiral mode in that "acceptable" pilot ratings $\left(6\frac{1}{2} \text{ or less}\right)$ were more probable if the frequency of the coupled roll-spiral oscillatory mode was greater than 0.35 rad/sec, and indications were that this frequency should not be greater than approximately 1.0 rad/sec. There did not seem to be any definite trend regarding the magnitudes of the damping ratio of the coupled roll-spiral oscillatory mode or damping ratio of the Dutch roll mode required for satisfactory pilot ratings.

INTRODUCTION

Radically different types of aircraft can have modes of motion which are so different from those experienced by conventional aircraft that they cannot be evaluated prior to some form of simulation or actual flight tests. This, of course, causes extreme difficulty in the evaluation of possible problem areas during the development of new types of aircraft. One such problem which has occurred recently with such widely diverse types of aircraft as the supersonic transport, the V/STOL, and the piloted reentry vehicles is that an unconventional lateral oscillatory mode, which is brought about by the coupling of the conventional roll and spiral modes, may be experienced. Only very limited information is available concerning the effects of such roll-spiral coupling on the flight characteristics of airplanes since conventional aircraft have not displayed this phenomenon.

Reference 1 presents the results of a fixed-base-simulator study of the lateral-directional handling qualities of a hypothetical fighter airplane having roll-spiral coupling. The general conclusion drawn from that study was that an aircraft with roll-spiral coupling would have unacceptable handling qualities. The results of reference 1 are considered to be limited in application, however, since (1) only a fighter-type airplane at a high altitude, 30 000 ft (12 km), and a high airspeed (Mach number of 1.2) was considered and (2) the roll damping derivative C_{l_p} was, in general, the main parameter varied in order to cause the coupled mode.

Because of the lack of adequate information with which to predict the acceptability of the lateral-directional handling qualities of aircraft having roll-spiral coupling, the present study was made to provide a preliminary evaluation of the problem. This study consisted of a fixed-base simulator study in which the aerodynamic characteristics of the simulated aircraft were varied in such a way as to obtain a coupled roll-spiral mode in various ways and with varying specific characteristics. The simulator tests were made for two sets of initial conditions, a subsonic cruise condition and a landing-approach condition. No attempt was made to establish any kind of handling-qualities criteria; the aim of the present study was simply to generate information that will be of use in preflight evaluation of the flying qualities of an aircraft having a coupled roll-spiral mode within its normal flight envelope.

SYMBOLS

The units for the physical quantities used herein are presented in both the U.S. Customary Units and the International System of Units (SI). All aerodynamic coefficients and moments of inertia are referred to principal body axes.

a_n normal acceleration, g units (meters/sec^2)

a_y lateral acceleration, g units (meters/sec^2)

b wing span, feet (meters)

$\bar{c}$ mean aerodynamic chord, feet (meters)

C_l rolling-moment coefficient

C_m pitching-moment coefficient

C_n yawing-moment coefficient

C_X force coefficient along X-body axis

C_Y force coefficient along Y-body axis

C_Z force coefficient along Z-body axis

C_1, C_2, C_3, C_4, C_5 coefficients of characteristic equation

g acceleration due to gravity, ft/sec^2 (meters/sec^2)

h altitude, feet (meters)

I_X, I_Y, I_Z moments of inertia about X-, Y-, and Z-body axes, respectively, slug-ft^2 (kilogram-meters^2)

K_p pilot gain, δ_a/ϕ

m mass of airplane, slugs (kilograms)

p,q,r rolling, pitching, and yawing angular velocities, respectively, radians/second

P period, seconds

s Laplace operator

S wing area, ft^2 (meters^2)

t_R roll time constant, seconds

t_S spiral time constant, seconds

$t_{1/2}$ time to one-half amplitude, seconds

T	thrust, pounds (newtons)
u,v,w	components of airplane resultant velocity along X-, Y-, and Z-body axes, respectively, ft/sec (meters/second)
V	resultant velocity of airplane, ft/sec (meters/second)
α	angle of attack, deg or rad
β	angle of sideslip, deg or rad
δ_a	aileron deflection, positive for right roll command, deg or rad
δ_c	cockpit control deflection, inches (cm)
δ_e	elevator deflection, positive trailing-edge down, deg or rad
δ_r	rudder deflection, positive trailing-edge left, deg or rad
δ_s	stabilizer deflection, positive trailing-edge down, deg or rad
ϵ_{gs}	glide-slope error, deg
ϵ_{loc}	localizer error, deg
ζ_D	Dutch roll damping ratio
ζ_{RS}	roll-spiral mode damping ratio (open-loop)
ζ'_{RS}	roll-spiral mode damping ratio (closed-loop)
ζ_ϕ	damping ratio of numerator quadratic of ϕ/δ_a transfer function
θ	pitch angle, deg
ρ	air density, slugs/ft^3 (kilograms/meters^3)
ϕ	angle of roll, deg
ψ	angle of yaw, deg

ω_D undamped natural frequency of Dutch roll mode, radians/second

ω_{RS} undamped natural frequency of coupled roll-spiral mode, radians/second

ω_ϕ undamped natural frequency appearing in numerator quadratic of ϕ/δ_a transfer function, radians/second

$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$ $\quad C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$ $\quad C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$

$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a}$ $\quad C_{n_{\delta_a}} = \frac{\partial C_n}{\partial \delta_a}$ $\quad C_{Y_{\delta_a}} = \frac{\partial C_Y}{\partial \delta_a}$

$C_{l_{\delta_r}} = \frac{\partial C_l}{\partial \delta_r}$ $\quad C_{n_{\delta_r}} = \frac{\partial C_n}{\partial \delta_r}$ $\quad C_{Y_{\delta_r}} = \frac{\partial C_Y}{\partial \delta_r}$

$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}}$ $\quad C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}}$ $\quad C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V}}$

$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$ $\quad C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$ $\quad C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V}}$

$C_{m_{\delta_e}} = \frac{\partial C_m}{\partial \delta_e}$ $\quad C_{X_{\delta_e}} = \frac{\partial C_X}{\partial \delta_e}$ $\quad C_{Z_{\delta_e}} = \frac{\partial C_Z}{\partial \delta_e}$

$C_{m_{\delta_s}} = \frac{\partial C_m}{\partial \delta_s}$ $\quad C_{X_{\delta_s}} = \frac{\partial C_X}{\partial \delta_s}$ $\quad C_{Z_{\delta_s}} = \frac{\partial C_Z}{\partial \delta_s}$

$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}}$ $\quad C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$

A dot over a symbol represents a derivative with respect to time.

GENERAL DISCUSSION ON ROLL-SPIRAL COUPLING

From the lateral-force, rolling-moment, and yawing-moment equations of motion, the characteristic equation describing the lateral-directional open-loop flight motions of an aircraft is determined and is of the form

$$C_1 s^4 + C_2 s^3 + C_3 s^2 + C_4 s + C_5 = 0$$

This quartic equation usually can be factored as follows:

$$\left(s^2 + 2\zeta_D \omega_D s + \omega_D^2\right)\left(s + \frac{1}{t_R}\right)\left(s + \frac{1}{t_S}\right) = 0$$

The quadratic has a complex conjugate pair of roots and is called the Dutch roll mode. The two real roots are referred to as the roll and spiral aperiodic modes of motion, respectively. The roll-mode root usually has a dominant effect on the initial bank-angle response to aileron inputs, whereas the spiral-mode root usually has a dominant effect on the long-term bank-angle characteristics. Therefore, the magnitudes of the four roots of the characteristic equation affect the lateral-directional response of an aircraft, which in turn affects the pilot's assessment of the flying qualities of that aircraft.

As mentioned previously, it is anticipated that some of the V/STOL, supersonic transport, and piloted reentry configurations that have been proposed may experience an unconventional lateral oscillatory mode which is brought about by the coupling of the conventional roll and spiral modes. That is, for certain combinations of the aerodynamic stability derivatives of a given aircraft, the aforementioned characteristic equation will have two complex conjugate pairs of roots instead of the conventional one complex conjugate pair of roots and two real roots. When this occurs, the characteristic equation would have the factored form

$$\left(s^2 + 2\zeta_D\omega_D s + \omega_D{}^2\right)\left(s^2 + 2\zeta_{RS}\omega_{RS} s + \omega_{RS}{}^2\right) = 0$$

The first quadratic (subscript D) is the previously mentioned Dutch roll oscillation, and the second quadratic (subscript RS, roll-spiral) represents the second complex conjugate pair of roots and usually describes a long-period oscillation ($P > 20$ sec) which has sometimes been termed a lateral phugoid (ref. 1, for example). This second oscillation is brought about when (1) there is an unusually large or small value of a particular aerodynamic stability derivative or (2) there is a certain combination of several of the aircraft's static and dynamic aerodynamic stability derivatives.

When the aerodynamics are of such a nature that the roll and spiral modes couple, the resulting oscillation will affect the pilot's control of bank angle. The pilot normally controls bank with ailerons commanding a roll rate. However, when the coupled roll-spiral mode is experienced, the pilot may see the ailerons commanding either roll acceleration (low ω_{RS}) or roll attitude (high ω_{RS}). Figure 1 illustrates these three different types of response to a step aileron input.

The root-locus method is a graphical procedure that allows the variation in the roots of an equation to be shown, on a complex plane, as the coefficients of the equation change. (Fig. 2 shows the features of the complex plane as applied to dynamic systems.) Figure 3 presents a root-locus plot which illustrates a case in which the conventional roll and spiral modes couple and form a second oscillatory mode as the aircraft's stability derivatives are arbitrarily varied. Some of the results of this study are presented with the root-locus graphical technique and are discussed subsequently.

SIMULATOR

The simulator presented the pilot with the essential elements of flying under instrument conditions. The cockpit was equipped with a stick-type pitch and roll control, conventional rudder pedals, a single lever thrust controller, and flight instruments arranged in the standard basic "T." (See fig. 4.) The simulator did not incorporate cockpit motion and no external visual display was used. Control forces were provided by springs. The maximum travel of the controls, control breakout forces, and control-force gradients are presented in table I. A general-purpose analog computer was used with the simulator and was programed with the equations of motion for six degrees of freedom shown in the appendix. These equations represent motions along and about the airplane body axes.

TEST CONFIGURATIONS AND CONDITIONS

For the present study, a hypothetical light transport airplane was considered. The airplane was heavily loaded along the fuselage $\left(I_X < I_Y\right)$, and the mass and dimensional characteristics are presented in table II. The simulator tests were made in two phases: one for conditions representative of cruise flight and one for conditions representative of the landing approach. Specifically these conditions are

> Phase I – the airplane was considered to be initially at an altitude of 20 000 feet (6.1 km) and trimmed for straight and level flight at an angle of attack of 3.85° and a true airspeed of 400 knots.
>
> Phase II – the airplane was considered to be in the landing-approach configuration and initially at an altitude of 2000 feet (610 m) and trimmed for straight and level flight at an angle of attack of 15° and a true airspeed of 135 knots.

The lateral aerodynamic characteristics of the basic configurations are presented in table III. No longitudinal characteristics are presented because the longitudinal handling qualities of the basic configurations were adjusted until they were rated by the pilots to be very satisfactory $\left(\text{a pilot rating of } 2\frac{1}{2}\right)$ before the evaluation of the effects of roll-spiral coupling began. The aerodynamic characteristics of the other configurations were varied during the investigation as shown by the values of the aerodynamic stability derivatives listed in table IV. For the most part, the variations made in the lateral-directional aerodynamic derivatives during this study were arbitrary but were considered to be within a realistic range. Table IV also presents the dynamic stability characteristics of the various configurations evaluated during the two phases of simulated flight. The dynamic stability characteristics presented in tables III and IV were determined from calculations based on classical linearized equations of motion.

EVALUATION PROCEDURES

Since this study was concerned solely with the evaluation of the lateral-directional flying qualities, an attempt was first made to optimize the values of the longitudinal aerodynamic parameters required for satisfactory handling qualities of that axis. As a result, the longitudinal axis was assigned an overall pilot rating of $2\frac{1}{2}$ and was not considered to influence the pilots' evaluation of the lateral-directional handling qualities.

Each test configuration was established by varying the magnitudes of the necessary lateral-directional aerodynamic coefficients so that the required frequency and damping of both the Dutch roll mode and the roll-spiral coupled mode were achieved. (Whenever possible, the frequencies and damping ratios were varied from low values to high values in incremental steps.) The general handling qualities of the configurations were evaluated in level flight for both the phase I and phase II conditions, and for the phase II conditions, the configurations were also evaluated for the instrument landing system (ILS) approach task.

The pilots evaluated each test configuration separately but were not informed of the parameters being varied. An effort was made to set up the order of tests so that changes in consecutive conditions were gross enough to be clearly different. The pilots also reevaluated the basic configuration whenever desired in order to retain a reference. Two pilots participated in the simulation program; unfortunately, the number of test conditions that were "flown" by both pilots was much less than desired. Most of the conditions tested during phase I of the program were evaluated by pilot A, and most of the conditions during phase II were evaluated by pilot B. No complete listing of all of the pilot comments for each configuration evaluated is presented, but table IV indicates the pilots' major objections to each configuration.

General Flying Qualities

Standard flight test procedures and techniques (ref. 2) were used in the evaluation of the lateral-directional flying qualities of each test configuration and condition, and a pilot rating was assigned to each case, with appropriate pilot comments. See table V for the pilot rating system used. The lateral-directional characteristics evaluated are as follows:

(1) Control powers

(2) Response and sensitivity

(3) Roll damping

(4) Dutch roll oscillations

(5) Adverse-proverse yaw

(6) Spiral stability

(7) Heading control in turn entry and recovery

(8) Directional stability

(9) Dihedral effect

(10) Lateral oscillation characteristics

(11) Bank-angle control

Instrument Landing System Approach Task

The ILS approach was initiated with the airplane in the power-approach condition (power for level flight) at an altitude of 2000 feet (610 m), a true airspeed of 135 knots, and 8.5 nautical miles (15.8 km) from the runway. The cockpit indicator presented localizer and glide-slope deviation only, and the initial conditions placed the airplane offset to the left of the localizer and below the glide slope. The glide-slope angle used during the study was 2.7°. The pilot's initial task was to turn to intercept the localizer, and then when the glide slope was captured, the pilot attempted to maintain both the localizer and glide slope as closely as possible until the 200-foot (61 m) altitude termination point was reached.

RESULTS AND DISCUSSION

As stated previously, the present study was conducted to obtain a preliminary determination of the effects of the coupling of the roll and spiral modes on the lateral-directional handling qualities of a hypothetical light transport airplane. Also, although no attempt is made to establish any kind of handling-qualities criteria, the intent of this paper is to present information that will be of use in preflight evaluation of the flying qualities of an aircraft that has a coupled roll-spiral mode within its normal flight envelope. The results of the study are, for the most part, presented and discussed in relation to pilot ratings and opinions. It should be mentioned that although a complete pilot assessment of the lateral-directional flying qualities were made for each test condition, the pilot's evaluation of bank-angle control is given the most attention in the discussion since the coupling of the roll and spiral modes has a predominant effect on bank-angle control.

Phase I – Cruise Condition

Basic configuration.- The lateral-directional dynamic stability characteristics of the basic configuration are presented in table III. Both pilots assigned a pilot rating of 2 to the lateral-directional handling qualities of this basic configuration. The pilots stated that the lateral control characteristics were excellent, that the Dutch roll and adverse-proverse yaw characteristics were satisfactory, and that the heading control in a turn entry and recovery was good. Figure 5 presents a time history of the motion obtained for an aileron step input.

The only objectionable handling qualities of the basic configuration were:

(1) The spiral characteristics were less than good – although $t_{1/2} \approx 21$ seconds, the pilots felt that the spiral mode was too stable.

(2) The harmony between the longitudinal and lateral stick forces was less than desired – the pilots would have preferred a slight reduction in the lateral stick force or a slight increase in the longitudinal stick force.

No changes were made in these characteristics, however, since table V describes a rating of 2 as "good enough without improvement."

Effects of variations in aerodynamic derivatives on stability characteristics.- Reference 1 states that a coupled roll-spiral mode can exist if an aircraft has low roll damping C_{l_p} and low directional stability C_{n_β}, especially if the effective dihedral parameter C_{l_β} is large. In addition, reference 3 states that the magnitude of C_{n_p} must be considered. For example, it is stated in reference 3 that when C_{l_p} is at least that required for satisfactory "ideal" roll control $\left(t_R \leqq 1.2 \text{ sec}\right)$, the possibility of roll-spiral coupling would normally be confined to low C_{n_β} in combination with very high C_{l_β} and positive C_{n_p}.

The four aforementioned derivatives C_{l_β}, C_{n_β}, C_{l_p}, and C_{n_p} as well as two additional derivatives C_{n_r} and C_{l_r} were considered in the present study to establish the various conditions ω_D, ζ_D, ω_{RS}, and ζ_{RS} to be evaluated by the pilots. The conditions were chosen so that the frequencies and damping ratios would be varied from low values to high values, in incremental steps, whenever possible. An example of how the variation in these derivatives, one at a time, can affect the dynamic stability characteristics of the airplane used in the present study is shown in figure 6. The root-locus technique is used to present this information, and with only a brief glance at figure 6, the following effects of the stability derivatives are noted:

Parameter varied	Direction	Can cause roll-spiral coupling
C_{l_β}	More negative	Yes
C_{n_β}	Less positive	No
C_{l_p}	Less negative	Yes
C_{n_p}	More positive	Yes
C_{l_r}	Less positive	No
C_{n_r}	More negative	No[1]

[1]Although increasing the yaw damping will not cause the roll and spiral modes to couple on the airplane used in this study, very large values of C_{n_r} will cause all modes to become aperiodic.

Effects of coupled roll-spiral mode.- When the conventional roll and spiral modes couple, the lateral-directional handling qualities are seriously degraded regardless of how the coupling was brought about, that is, regardless of which aerodynamic derivative or combination of derivatives caused the two modes to couple. This result is illustrated by the fact that the pilot ratings given in table IV for all the modified configurations are markedly worse than those for the basic configurations. In fact they were $3\frac{1}{2}$ or greater, compared with a rating of 2 for the basic configuration (configuration I-1). Although sometimes there were many factors involved that made the handling qualities less than desired, one factor that the pilots always complained about was the apparent lack of roll damping; this point was always mentioned by the pilots regardless of the magnitude of C_{l_p} if the roll and spiral modes were coupled.

Various parameters were examined to determine whether there were any factors that could be correlated and thus provide a means for assessing the degree of degradation of the handling qualities that could be expected prior to flight tests of an aircraft. The parameters examined were ω_{RS}, ζ_{RS}, and ζ_D. Only ω_{RS} seemed to provide any broad correlation. The frequency of the coupled roll-spiral mode ω_{RS} varied from 0.10 to 1.39 rad/sec for the various conditions covered during the present study, and the pilot ratings along with their major objections to each condition are presented in table IV. Figure 7 presents a plot of ω_{RS} against pilot rating for the various conditions tested. (It can be noted from table IV that the damping of both the coupled roll-spiral mode and the Dutch roll mode was always positive.) The comments made by the pilots and the pilot ratings assigned to the various configurations indicated that "acceptable" ratings $\left(6\frac{1}{2}\right.$ or $\left.\text{less}\right)$ were more probable if ω_{RS} was greater than 0.35 rad/sec.

When the frequency of the coupled roll-spiral mode ω_{RS} was approximately 0.30 rad/sec or less, the pilots consistently stated

(1) The damping in roll was very low or nonexistent

(2) The airplane was overly responsive to lateral inputs

(3) The airplane exhibited high proverse yaw for lateral inputs

When the frequency of the coupled roll-spiral mode ω_{RS} was as much as 0.40 rad/sec but less than 1.0 rad/sec, the pilots generally stated

(1) The damping in roll was low or moderately low

(2) The spiral stability was much too strong

(3) There was no evidence of proverse-adverse yaw

When ω_{RS} was very high (approximately 1.0 rad/sec or greater), the pilot indicated disapproval because the spiral mode was much too stable and the roll control effectiveness was no longer sufficient to maneuver the airplane adequately. This set of circumstances $(\omega_{RS} > 1.0 \text{ rad/sec})$ was documented for only one condition, configuration I-8 where $\omega_{RS} = 1.39$ rad/sec; but when the pilot "flew" this configuration, he stated: "By applying the lateral control slowly, a maximum of 30° bank angle can be attained and held with full lateral control." This result was not surprising, however, since it is obvious that the higher the frequency of the oscillation the quicker the roll rate will become zero.

The damping of the coupled roll-spiral mode ζ_{RS} and the damping of the Dutch roll mode ζ_D varied from approximately 0.10 to 1.0 for the conditions covered in phase I of the present study (h = 20 000 ft (6.1 km) and V = 400 knots) and there did not seem to be any definite trend of pilot rating with the magnitude of ζ_{RS} or ζ_D.

Phase II – Landing-Approach Condition

Basic configuration.- Pilots A and B assigned pilot ratings of $2\frac{1}{2}$ and $3\frac{1}{2}$, respectively, to the lateral-directional handling qualities of this configuration (configuration II-1) for both the "air work" and the ILS approach. Both pilots stated that the roll control, in general, was good and that the roll damping and the damping of the Dutch roll oscillation were both good. The only adverse comments involved heading control and lateral stick force; the pilots stated that the amount of adverse yaw and the magnitude of the lateral stick force were higher than desired.

Effects of coupled roll-spiral mode.- As was the case for phase I, when the roll and spiral modes coupled, the lateral-directional handling qualities were seriously degraded regardless of how the coupling was brought about. This fact is illustrated by the pilot ratings presented in table IV which are almost uniformly markedly worse for the configurations with a coupled roll-spiral mode than for the basic configuration. As for phase I, the parameters ω_{RS}, ζ_{RS}, and ζ_D were examined to determine whether the same trends were present for phase II as for phase I. The results showed that again, only ω_{RS} seemed to provide even broad correlation with the degradation in the lateral-directional handling qualities.

The frequency of the coupled roll-spiral mode ω_{RS} varied from 0.10 to 0.60 rad/sec for the various conditions covered in phase II of the study. (See table IV.) Figure 8 presents a plot of ω_{RS} against pilot rating for the various configurations evaluated, and with the exception of five configurations, these results agree with the conclusion drawn from the results obtained during phase I; that is, no unacceptable pilot ratings were assigned to configurations having an ω_{RS} greater than 0.35 rad/sec. The only reason that can be offered as to why these five conditions $(\omega_{RS} > 0.35)$ were assigned unacceptable pilot ratings is that either ζ_D or ζ_{RS} was what might be considered to be relatively low for all five conditions. (See configurations II-11, II-15, II-18, II-19, and II-28 in table IV.)

As stated previously, for certain configurations "flown" during phase II, a landing approach was made under instrument conditions to determine whether the initial pilot assessment and rating would change for a more precise piloting task. Figure 9 shows time histories of the landing approach for three representative configurations. Figure 9(a) is an approach made with the basic configuration (configuration II-1). Pilot A assigned a rating of $2\frac{1}{2}$ and pilot B, a rating of $3\frac{1}{2}$ to the lateral-directional handling qualities of this configuration during the air work, and these ratings remained unchanged for the ILS approach task. Figure 9(b) presents an approach time history for configuration II-10, which represents a condition in which the roll and spiral modes have coupled, with $\omega_{RS} = 0.10$ rad/sec. This configuration was assigned a pilot rating of 9 and 10 by pilots A and B, respectively, during the air work, and both pilots assigned a rating of 10 to this configuration during the ILS approach. Comparison of figures 9(a) and 9(b) shows that configuration II-10 was uncontrollable, or at least uncontrollable to the extent that it could not be landed safely. Figure 9(c) presents an approach time history for configuration II-17, which represents a condition in which the roll and spiral modes have coupled, with $\omega_{RS} = 0.40$ rad/sec. This configuration was assigned a pilot rating of 4 and 6 by pilots A and B, respectively, during the air work and a pilot rating of 4 and 5, respectively, during the ILS approach. This time history (fig. 9(c)) shows that the pilot "flew" configuration II-17 on the approach more precisely than he did the configuration of figure 9(b) and slightly less precisely and with slightly more effort than he did the basic configuration of figure 9(a).

Although the fact is not necessarily reflected in the pilot ratings assigned to these three representative configurations, the difference in the pilot ratings assigned to a given configuration during the air work and the ratings assigned to the same configuration during the ILS approach task were fairly consistent; sometimes the ratings did not change and sometimes the ratings were as much as 1 pilot rating better or worse for the ILS approach. The piloting tasks used during the present study were therefore concluded to be adequate for evaluating the lateral-directional handling qualities of the various configurations investigated.

General Comments on the Effects of Turbulence

The scope of the present investigation did not include the effects of atmospheric turbulence, but some general comments on the possible effects of turbulence on an aircraft that possesses the unconventional dynamic stability characteristics discussed in the Introduction are reviewed. The following discussion applies only to the situation in which the roll and spiral modes are coupled.

When there is no atmospheric turbulence, as was the case in the present investigation, and a pilot elects to roll the aircraft to a predetermined bank angle, the pilot's initial lateral control input must be countered, in most cases, by an opposite control input because of the apparent lack of a sufficient amount of roll damping. Then generally, the pilot must make a series of smaller corrections in both directions in an attempt to stabilize the aircraft at the prescribed bank angle. The pilots believe that if the aircraft is being flown in turbulence, the pilot would not be able to provide the desired roll damping by making these small corrective inputs. It is believed that in turbulence, the lateral oscillations that are triggered by the lateral control inputs would be aggravated, and as a result, the pilot would tend to overcontrol during his manual damping process; thus, pilot-induced oscillations would occur. For such a set of circumstances, however, if the pilot released the controls, the pilot inputs to the oscillation would cease and the strong apparent spiral stability, which is found in the cases in which $\omega_{RS} > 0.35$ rad/sec, would return the airplane to a wings-level condition with the minimum of lateral oscillations. From these considerations, it is concluded that the already marginal configurations, without turbulence, could be degraded by a pilot rating of 1 or 2 if turbulence were added to the problem.

Validity of Fixed-Base Simulation Results

On a fixed-base simulator most pilot cues that the pilot would have on a motion simulator or an in-flight simulator are not present. On the basis of limited results available from programs which permit direct comparison, it appears that when a pilot's rating of the flying qualities of a given airplane are good, the results will be the same whether a fixed-base simulator or an in-flight simulator is used. As the characteristics and ratings become more marginal, however, the ratings obtained from the two methods will differ, the in-flight or motion simulator results being rated better than the fixed-base simulator results.

With these points in mind, it could be said that the fixed-base simulator results presented in the present report are conservative. That is, since most of the conditions tested received marginally acceptable or marginally unacceptable pilot ratings, if these same conditions existed for an in-flight simulator program or if these conditions existed on an actual aircraft, the marginally unacceptable conditions could very well become acceptable; furthermore, the acceptable conditions could conceivably become satisfactory.

Comments on Piloting Techniques Required When a Coupled Roll-Spiral Oscillatory Mode Is Experienced

As stated previously, when the roll and spiral modes couple and form a second oscillatory mode, in addition to the conventional Dutch roll oscillatory mode, the pilot's control of bank angle is seriously affected. (When the coupled roll-spiral mode is experienced, the pilot may see the ailerons commanding either roll acceleration or roll position, whereas he normally expects ailerons to command roll rate.)

Throughout the test program the pilots stated that in order for them to maintain control of the aircraft during roll maneuvers, for most of the configurations they were required (1) to use very small lateral control inputs when attempting to roll to a desired bank angle, and (2) to use no rudder inputs during these rolling maneuvers. In regard to the requirement of using small lateral control inputs for roll maneuvers one pilot stated: "When the roll and spiral modes have coupled, the response resulting from a lateral input appears to have low or zero roll damping causing the pilot to 'check' or reverse all lateral inputs in order to manually damp the rolling motion. The checking inputs required to stop the bank-angle change create an oscillation, or a series of oscillations, in roll. There is a definite limit to the size of these checking inputs without making the oscillations become divergent. Therefore, the only thing the pilot can do is forget a desired bank angle and simply get the oscillations stopped at any bank angle. Then – the pilot might be able to roll very slowly to the desired attitude." The same pilot also stated: "Any amount of spiral stability or instability is detrimental to precise bank-angle control since it caused inputs which increased the chances of exciting the oscillations in roll."

In an attempt to understand further why the pilots were required to use small lateral inputs during roll maneuvers, an analysis of the pilot-airplane combination was made with the root-locus technique to determine the closed-loop dynamic characteristics. For the present study, the dynamic representation of the pilot was a simplified version of the technique used in reference 4 in that the pilot was represented as being a pure gain; that is, the pilot actuates the lateral control proportionally to the error in bank angle. The method used may be of questionable validity for the wide range of lateral characteristics examined, but it does provide a reasonable approximation to the possible piloting difficulties in roll control.

Three representative configurations from phase I of this investigation are used to illustrate why the pilot is required to use small lateral control inputs during roll maneuvers. The configurations used were the basic configuration I-1 and configurations I-22 and I-17, and the results are presented in figure 10. A plot of the locus of closed-loop roots for variations in pilot gain of configuration I-1 is presented in figure 10(a) and indicates that either small or large lateral control inputs could be used for roll maneuvers since for all pilot gains, all modes remain in the stable portion of the complex plane and are well damped. The root locus for a variation in pilot gain for configuration I-22 is presented in figure 10(b). Configuration I-22 represents a condition in which the roll and spiral modes have coupled and formed a low-frequency oscillation $\left(\omega_{RS} = 0.10 \text{ rad/sec}\right)$. It is seen from figure 10(b) that if the pilot disturbs the aircraft in roll and uses anything other than small inputs, the coupled roll-spiral oscillatory mode will become unstable $\left(\zeta'_{RS}\right.$ becomes negative$\left.\right)$. Configuration I-17 represents a condition in which the roll and spiral modes have coupled and formed an oscillation with a frequency ω_{RS} of

0.40 rad/sec. Figure 10(c) presents the root locus for a variation in pilot gain for configuration I-17 and shows that although the oscillation does not become unstable as the pilot gain is increased, the higher the pilot gain the lower the damping of the oscillation ζ'_{RS} will be.

From these results it is concluded that when the roll and spiral modes couple and form a second oscillatory mode, in addition to the conventional Dutch roll mode, the pilots must use small lateral control inputs during roll maneuvers in order for the resulting oscillation to be as well damped as possible. It is possible however that this reasoning will not be true when ω_{RS} is greater than 1 rad/sec. As stated previously, when ω_{RS} is very high $\left(\omega_{RS} \geqq 1.0 \text{ rad/sec}\right)$, the pilot may give the configuration an unacceptable rating not only because of the strong apparent spiral stability but also because the aileron control effectiveness will appear to be low for the higher ω_{RS} values.

For most of the configurations evaluated during the present investigation, the pilots chose not to use the rudder during roll maneuvers. The pilots stated that although sideslip was generated in using ailerons alone during roll maneuvers, the control task was much easier if the rudder was not used. One pilot stated: "The rudder acts as a powerful roll control and it simply doesn't make sense to try to use two controls simultaneously for the same thing. It is very difficult to anticipate the roll resulting from an aileron input alone, and when you overlay the strong roll control afforded by the rudder, you have an impossible control situation."

CONCLUDING REMARKS

The results obtained during a fixed-base simulator program conducted as a preliminary determination of the effects of a coupled roll spiral mode on lateral-directional handling qualities may be summarized as follows:

When the conventional roll and spiral modes couple, the lateral-directional handling qualities are seriously degraded regardless of how the coupling was brought about, that is, regardless of which aerodynamic derivative or combination of derivatives caused the two modes to couple.

The comments made by the pilots and the pilot ratings assigned to the various configurations correlated somewhat in terms of the frequency of the roll-spiral mode in that "acceptable" pilot ratings $\left(6\frac{1}{2} \text{ or less}\right)$ were more probable if the frequency of the coupled roll-spiral oscillatory mode was greater than 0.35 rad/sec, and indications were that this frequency should probably not be greater than approximately 1.0 rad/sec.

Generally, the higher the damping ratio of the coupled roll-spiral oscillatory mode and the damping ratio of the conventional Dutch roll mode, the better the possibility is of having acceptable handling qualities. However, there did not seem to be any definite correlation regarding the required magnitudes of the damping ratio of either mode.

When the roll and spiral modes couple and form a second oscillatory mode the pilot must use small lateral control inputs during roll maneuvers in order for the ensuing motion to be as well damped as possible.

Although sideslip was generated in using ailerons alone during roll maneuvers, the pilots found the control task to be much more difficult if the rudder was used in an attempt to achieve coordination.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 2, 1969.

APPENDIX

EQUATIONS OF MOTION AND ASSOCIATED FORMULAS

The equations of motion used for this simulation project are

$$\dot{p} = \frac{I_Y - I_Z}{I_X} qr + \frac{\rho V^2 Sb}{2I_X}\left(C_{l_\beta}\beta + C_{l_{\delta_a}}\delta_a + C_{l_{\delta_r}}\delta_r\right) + \frac{\rho V S b^2}{4I_X}\left(C_{l_p}p + C_{l_r}r\right)$$

$$\dot{q} = \frac{I_Z - I_X}{I_Y} pr + \frac{\rho V^2 S\bar{c}}{2I_Y}\left(C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e + C_{m_{\delta_s}}\delta_s\right) + \frac{\rho V S\bar{c}^2}{4I_Y} C_{m_q}q$$

$$\dot{r} = \frac{I_X - I_Y}{I_Z} pq + \frac{\rho V^2 Sb}{2I_Z}\left(C_{n_\beta}\beta + C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r\right) + \frac{\rho V S b^2}{4I_Z}\left(C_{n_p}p + C_{n_r}r\right)$$

$$\dot{v} = g \cos \theta \sin \phi + wp - ur + \frac{\rho V^2 S}{2m}\left(C_{Y_\beta}\beta + C_{Y_{\delta_a}}\delta_a + C_{Y_{\delta_r}}\delta_r\right) + \frac{\rho V S b}{4m}\left(C_{Y_p}p + C_{Y_r}r\right)$$

$$\dot{u} = -g \sin \theta + vr - wq + \frac{\rho V^2 S}{2m}\left(C_X + C_{X_{\delta_e}}\delta_e + C_{X_{\delta_s}}\delta_s\right) + \frac{T}{m}$$

$$\dot{w} = g \cos \theta \cos \phi + uq - vp + \frac{\rho V^2 S}{2m}\left(C_Z + C_{Z_{\delta_e}}\delta_e + C_{Z_{\delta_s}}\delta_s\right)$$

The following formulas were also used:

$$V = \left(u^2 + v^2 + w^2\right)^{1/2}$$

$$\alpha = \tan^{-1} \frac{w}{u}$$

$$\beta = \sin^{-1} \frac{v}{V}$$

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$$\dot{\theta} = q \cos \phi - r \sin \phi$$

$$\dot{\phi} = p + q \tan \theta \sin \phi + r \tan \theta \cos \phi$$

$$\dot{\psi} = \frac{r \cos \phi + q \sin \phi}{\cos \theta}$$

$$\dot{h} = u \sin \theta - v \cos \theta \sin \phi - w \cos \theta \cos \phi$$

$$a_n = - \frac{\dot{w} - uq + vp - g \cos \theta \cos \phi}{g}$$

$$a_y = \frac{\dot{v} - wp + ur - g \cos \theta \sin \phi}{g}$$

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4. Stapleford, Robert L.; and Tennant, J. Alford: Analysis of Several Handling Quality Topics Pertinent to Advanced Manned Aircraft. Section III – Lateral-Phugoid Mode Effects on Airplane Handling Qualities. AFFDL-TR-67-2, June 1967.

TABLE I.- SIMULATOR CONTROL CHARACTERISTICS

Control	Maximum travel		Breakout force		Force per deflection		Gearings from cockpit control to control surface		
	in.	cm	lbf	N	lbf/in.	N/cm		deg/in.	deg/cm
Stick (pitch)	±5	±12.7	1.0 to 1.5	4.45 to 6.66	2	3.5	δ_e/δ_c	-12	-4.7
Stick (roll)	±3.3	±8.4	<1.0	<4.45	2	3.5	δ_a/δ_c*	9	3.5
Pedal	3.3	8.4	5.0	2.22	8	14	δ_r/δ_c	-4.5	-1.8

*δ_a/δ_c for phase II was 12 deg/in. (4.7 deg/cm).

TABLE II.- MASS AND DIMENSIONAL CHARACTERISTICS

OF HYPOTHETICAL AIRPLANE

Weight, lbf (N)	50 000 (222 400)
Wing area, ft^2 (m^2)	561 (52.1)
Wing span, ft (m)	60 (18.3)
Mean aerodynamic chord, ft (m)	9.4 (2.9)
I_X, slug-ft^2 (kg-m^2)	78 000 (105 690)
I_Y, slug-ft^2 (kg-m^2)	260 000 (352 300)
I_Z, slug-ft^2 (kg-m^2)	325 000 (440 375)

TABLE III.- LATERAL-DIRECTIONAL AERODYNAMIC INPUTS AND DYNAMIC STABILITY CHARACTERISTICS OF THE BASIC CONFIGURATIONS

	Phase I	Phase II
Aerodynamic inputs:		
C_{l_β}, per radian	-0.0573	-0.0573
$C_{l_{\delta_a}}$, per radian	0.0573	0.0573
$C_{l_{\delta_r}}$, per radian	0.0015	0.0015
C_{l_p}, per radian	-0.5000	-0.5000
C_{l_r}, per radian	0.1000	0.1000
C_{n_β}, per radian	0.1146	0.1146
$C_{n_{\delta_a}}$, per radian	0	0
$C_{n_{\delta_r}}$, per radian	-0.0401	-0.0401
C_{n_p}, per radian	0.0400	0
C_{n_r}, per radian	-1.0000	-0.7000
C_{Y_β}, per radian	-0.2865	-0.2865
$C_{Y_{\delta_a}}$, per radian	0.0229	0.0229
$C_{Y_{\delta_r}}$, per radian	0.0573	0.0573
C_{Y_p}, per radian	0.2000	0.2000
C_{Y_r}, per radian	0.3000	0.3000
Dynamic stability characteristics:		
Roll mode:		
t_R, sec	0.38	0.62
$t_{1/2}$, sec	0.26	0.43
Spiral mode:		
t_S, sec	30	38
$t_{1/2}$, sec	21	27
Dutch roll:		
ω_D, rad/sec	1.93	0.98
ζ_D	0.38	0.37
$\left\lvert\frac{\phi}{\beta}\right\rvert$	1.27	0.80
$\left[\frac{\omega_\phi}{\omega_D}\right]^2$	0.94	0.80

TABLE IV.- AERODYNAMIC INPUTS, DYNAMIC STABILITY CHARACTERISTICS, AND THE PILOTS' RATINGS AND MAJOR OBJECTIONS FOR EACH CONFIGURATION SIMULATED

Configuration	Aerodynamic inputs per radian						Dynamic stability characteristics								Pilot rating		Pilots' primary objections	$\frac{\phi}{\delta_a}(s)$ numerator	
	C_{l_β}	C_{n_β}	C_{l_p}	C_{n_p}	C_{l_r}	C_{n_r}	ω_D	ζ_D	$(\phi/\beta)_D$	$[\omega_\phi/\omega_D]^2$	ω_{RS}	ζ_{RS}	$(\phi/\beta)_{RS}$	$[\omega_\phi/\omega_{RS}]^2$	Pilot A	Pilot B		ω_ϕ	ζ_ϕ
Phase I																			
I-1	-0.0573	0.1146	-0.5000	0.0400	0.1000	-1.0000	1.93	0.38	1.27	0.94					2	2		1.87	0.37
I-2	-.0573	.1146	-.1000	.0400	.1000	-1.0000	1.95	.34	1.84	.91	0.31	0.97	72.70	37.28	4	6	(a), (d)	1.87	.37
I-3	-.0573	.1146	-.5000	.8000	.1000	-1.0000	2.30	.79	1.54	.66	.26	.96	10.40	52.10		7	(a), (c), (d)	1.87	.39
I-4	-.0573	.1146	-.5000	1.0000	.1000	-1.0000	2.55	.79	1.32	.54	.24	.25	11.10	62.91	6	7	(a), (c), (d)	1.87	.39
I-5	-.0573	.1146	-.5000	1.0000	.0000	-.2000	2.11	.71	1.66	.77	.14	.34	18.40	170.60	10	10	(a), (b), (c)	1.86	.11
I-6	-.0573	.1146	-.5000	1.0000	.0000	-.8000	2.55	.47	1.38	.53	.24	.25	11.20	62.81	$7\frac{1}{2}$	$7\frac{1}{2}$	(a), (c), (d)	1.87	.32
I-7	-.0573	.1146	-.5000	1.0000	.0000	-3.0000	3.76	.88	1.02	.25	.31	.24	8.50	37.59	4	$4\frac{1}{2}$	(a), (c), (d)	1.90	1.09
I-8	-.8022	.0516	-.4000	.0400	.1000	-2.0000	2.55	.46	1.56	.24	1.39	.93	68.10	.79	$9\frac{1}{2}$		(b)	1.24	1.07
I-9	-.0802	.0516	-.4000	.3000	.1000	-2.0000	2.68	.89	2.56	.23	.41	.19	11.20	9.71	5		(a), (d)	1.28	1.06
I-10	-1.0028	.1146	-.4000	.0400	.1000	-1.0000	3.35	.31	10.90	.30	.83	.90	99.50	4.90	$4\frac{1}{2}$		(d)	1.85	.36
I-11	-.0573	.1146	-.0902	.1638	.5220	-1.8420	2.00	.70	1.39	.89	.30	.33	29.20	39.27	$6\frac{1}{2}$		(a), (b)	1.88	.67
I-12	-.0573	.1146	-.0643	.1184	-.0937	-2.0281	2.00	.70	2.26	.89	.50	.30	29.60	14.10	$4\frac{1}{2}$		(a), (d)	1.88	.73
I-13	-.0573	.1146	-.0461	.1083	-1.0751	-2.1904	1.99	.70	5.62	.89	.70	.30	29.80	7.15	$4\frac{1}{2}$		(a), (d)	1.88	.79
I-14	-.0573	.1146	-.0206	.1069	-2.3946	-2.3848	1.98	.70	11.90	.90	.90	.31	30.00	4.29	5		(a), (d)	1.88	.86
I-15	-.0573	.1146	-.0442	.1379	.2686	-1.9511	2.00	.70	1.43	.89	.40	.11	30.50	22.07	5		(a), (d)	1.88	.70
I-16	-.0573	.1146	-.1037	.1272	.2600	-1.9426	2.00	.70	1.60	.89	.40	.51	28.30	22.07	4		(a), (d)	1.88	.70
I-17	-.0573	.1146	-.1645	.1190	.2489	-1.9292	2.00	.70	1.76	.89	.40	.91	25.80	22.08	$3\frac{1}{2}$		(a)	1.88	.70
I-18	-.0573	.1146	-.0038	.0621	-.5910	-.2322	2.00	.05	2.50	.86	.40	.22	276.70	21.50	$4\frac{1}{2}$		(a), (b), (d)	1.85	.10
I-19	-.0573	.1146	-.0645	.0501	-.6024	-.2185	2.00	.05	2.45	.86	.40	.62	220.60	21.50	4		(a), (b), (d)	1.85	.09
I-20	-.0573	.1146	-.1114	.0435	-.6134	-.2032	2.00	.05	2.37	.86	.40	.92	186.80	21.50	4		(a), (d)	1.85	.08
I-21	-.0573	.1146	-.2161	.3998	.0047	-.1002	1.97	.30	1.77	.88	.10	.87	61.60	334.20	7		(a), (b)	1.85	.06
I-22	-.0573	.1146	-.2960	.5700	.3009	-.6933	1.97	.62	1.76	.89	.10	.73	32.40	332.50	6		(a), (b)	1.86	.27
I-23	-.0573	.1146	-.3690	.7000	.6101	-1.3124	1.94	.94	1.79	.93	.10	.93	20.60	328.30	6		(a), (b), (c)	1.87	.49
I-24	-.0573	.1146	-.0250	.0679	-.5312	-.3543	2.00	.10	2.44	.86	.40	.32	175.30	21.54	$4\frac{1}{2}$		(a), (b), (d)	1.86	.14
I-25	-.0573	.1146	-.0465	.0986	-.2758	-.8657	2.00	.30	2.21	.87	.40	.32	67.40	21.71	$4\frac{1}{2}$		(a), (b), (d)	1.86	.32
I-26	-.0573	.1146	-.0629	.1203	-.0108	-1.3963	2.00	.50	1.91	.88	.40	.32	41.00	21.89	5		(a), (d)	1.87	.51
I-27	-.0573	.1146	-.0771	.1346	.4061	-2.2308	2.00	.80	1.25	.89	.40	.30	25.80	22.17	5		(a), (d)	1.89	.80
I-28	-.0573	.1146	-.6000	1.0000	.0000	-.8000	2.40	.83	1.52	.61	.25	.93	9.20	56.21	$4\frac{1}{2}$		(a), (c)	1.87	.32
I-29	-.0573	.1146	-1.0000	1.0000	.0000	-.8000	1.42	.54	.98	1.72					4		(c)	1.86	.32
I-30	-.0573	.1146	-1.0000	1.0000	.0000	-2.0000	(e)	(e)	(e)	(e)	(e)	(e)	(e)	(e)	4		(b)	1.88	.74
I-31	-.0573	.1146	-1.0000	1.0000	.0000	-.5000	1.41	.40	.95	1.74					$4\frac{1}{2}$		(b), (c)	1.86	.21

See footnote at end of table, p. 25.

TABLE IV.- AERODYNAMIC INPUTS, DYNAMIC STABILITY CHARACTERISTICS, AND THE PILOTS' RATINGS AND MAJOR OBJECTIONS FOR EACH CONFIGURATION SIMULATED – Concluded

Configuration	Aerodynamic inputs per radian						Dynamic stability characteristics								Pilot rating		Pilots' primary objections	$\frac{\phi}{\delta_a}(s)$ numerator	
	C_{l_β}	C_{n_β}	C_{l_p}	C_{n_p}	C_{l_r}	C_{n_r}	ω_D	ζ_D	$(\phi/\beta)_D$	$\left[\omega_\phi/\omega_D\right]^2$	ω_{RS}	ζ_{RS}	$(\phi/\beta)_{RS}$	$\left[\omega_\phi/\omega_{RS}\right]^2$	Pilot A	Pilot B		ω_ϕ	ζ_ϕ
Phase II																			
II-1	-0.0573	0.1146	-0.5000	0.0000	0.1000	-0.7000	0.98	0.37	0.80	0.80					$2\frac{1}{2}$	$3\frac{1}{2}$		0.88	0.35
II-2	-.0573	.1146	-.0435	.1863	.2697	-.5696	1.00	.30	1.20	.77	0.10	0.30	11.29	77.54	7	8	(a), (c)	.88	.31
II-3	-.0573	.1146	-.1574	.4113	.2695	-.5701	1.00	.50	1.20	.77	.10	.30	9.52	77.45		7	(a), (c)	.88	.34
II-4	-.0573	.1146	-.3269	.7460	.2722	-.5765	1.00	.80	1.19	.78	.10	.31	7.26	77.83		8	(a), (c)	.88	.39
II-5	-.0573	.1146	-.2048	.4720	.3538	-.9187	1.00	.70	1.13	.78	.20	.30	6.17	19.55		6	(a), (c)	.88	.51
II-6	-.0573	.1146	-.1354	.2941	.2220	-1.3504	1.00	.70	1.20	.79	.40	.30	5.38	4.91		5	(a), (c), (d)	.89	.69
II-7	-.0573	.1146	-.1158	.2473	-.2374	-1.5747	1.00	.70	3.44	.80	.60	.30	5.25	2.17		5	(a), (c), (d)	.89	.79
II-8	-.0573	.1146	-.2309	.5844	.3337	-.6913	1.00	.70	1.16	.78	.10	.10	7.74	78.08		7	(a)	.88	.42
II-9	-.0573	.1146	-.2960	.6712	.2279	-.4913	1.00	.70	1.20	.77	.10	.40	8.07	77.71	$7\frac{1}{2}$	9	(a), (c)	.88	.34
II-10	-.0573	.1146	-.4235	.8828	-.0080	-.0313	1.00	.70	1.25	.76	.10	.70	8.98	76.53	9	10	(a), (c)	.87	.14
II-11	-.0573	.1146	-.0005	.1632	-.1912	-.4871	1.00	.10	1.75	.77	.40	.31	25.64	4.80		8	(a), (c), (d)	.88	.27
II-12	-.0573	.1146	-.0578	.2315	-.0791	-.7234	1.00	.30	1.62	.77	.40	.31	12.61	4.83	5	6	(a), (d)	.88	.39
II-13	-.0573	.1146	-.1038	.2771	.0565	-1.0070	1.00	.50	1.45	.78	.40	.30	7.61	4.87		6	(a), (d)	.88	.53
II-14	-.0573	.1146	-.1446	.2893	.3186	-1.5496	1.00	.80	1.01	.80	.40	.30	4.69	4.94		$4\frac{1}{2}$	(a), (d)	.89	.78
II-15	-.0573	.1146	-.0878	.3143	.2418	-1.3589	1.00	.70	1.07	.79	.40	.10	5.56	4.91		7	(a), (c), (d)	.89	.70
II-16	-.0573	.1146	-.1853	.2782	.1977	-1.3327	1.00	.70	1.31	.79	.40	.50	5.15	4.91		4	(a), (d)	.89	.68
II-17	-.0573	.1146	-.3083	.2931	.1005	-1.2003	1.00	.70	1.42	.79	.40	.90	4.33	4.91	4	6	(d)	.89	.62
II-18	-.0573	.1146	-.0023	.1183	-.2131	-.4562	1.00	.05	1.74	.79	.40	.40	27.33	4.80		8	(a), (c), (d)	.88	.25
II-19	-.0573	.1146	-.0480	.0298	-.1899	-.5507	1.00	.05	1.60	.77	.40	.70	25.04	4.81		7	(a), (c), (d)	.88	.28
II-20	-.0006	.0046	-.2947	.1064	-.6662	-.9481	1.00	.91	2.09	.06	.10	.41	.74	5.34		10	(c)	.23	1.81
II-21	-.0573	.1146	-.2000	.2941	.2220	-1.3504	1.00	.72	1.25	.76	.39	.52	4.93	5.21		$4\frac{1}{2}$	(d)	.89	.69
II-22	-.0573	.1146	-.3000	.2941	.2220	-1.3504	1.00	.78	1.34	.81	.39	.89	3.90	5.31		$3\frac{1}{2}$	(d)	.89	.69
II-23	-.0573	.1146	-.2000	.2315	-.0791	-.7234	1.02	.38	1.45	.74	.37	.76	9.20	5.52		$4\frac{1}{2}$	(a), (c), (d)	.88	.39
II-24	-.0573	.1146	-.5000	1.0000	.0000	-.7000	1.33	.83	.96	.44	.26	.31	3.41	1.12		8	(c), (d)	.88	.48
II-25	-.0573	.1146	-.5000	1.0000	.0000	-.2000	1.05	.84	1.20	.70	.18	.51	4.79	24.07		$9\frac{1}{2}$	(a), (b), (c)	.88	.24
II-26	-.0573	.1146	-.5000	1.0000	.0000	-3.0000	2.19	.94	.96	.17	.33	.27	2.73	7.57		5	(c), (d)	.91	3.05
II-27	-.0573	.1146	-.0435	.1863	.2697	-1.0000	.94	.47	1.21	.88	.31	.23	6.87	8.13		7	(a), (c), (d)	.88	.51
II-28	-.0573	.1146	-.0435	.1863	.2697	-2.0000	.96	.96	1.01	.88	.53	.03	3.83	2.82		8	(a), (c), (d)	.90	.98

[a]Low roll damping.

[b]Poor roll response characteristics (too low or too high).

[c]Poor aileron yaw characteristics.

[d]Strong spiral stability.

[e]All modes are aperiodic.

TABLE V.- PILOT RATING SYSTEM

<table>
<tr><td rowspan="6">CONTROLLABLE
Capable of being controlled or managed in context of mission, with available pilot attention.</td><td rowspan="6">ACCEPTABLE
May have deficiencies which warrant improvement, but adequate for mission.
Pilot compensation, if required to achieve acceptable performance, is feasible.</td><td rowspan="3">SATISFACTORY
Meets all requirements and expectations, good enough without improvement.
Clearly adequate for mission.</td><td>Excellent, highly desirable.</td><td>1</td></tr>
<tr><td>Good, pleasant, well behaved.</td><td>2</td></tr>
<tr><td>Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.</td><td>3</td></tr>
<tr><td rowspan="3">UNSATISFACTORY
Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.</td><td>Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.</td><td>4</td></tr>
<tr><td>Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.</td><td>5</td></tr>
<tr><td>Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.</td><td>6</td></tr>
<tr><td></td><td colspan="2" rowspan="3">UNACCEPTABLE
Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.</td><td>Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.</td><td>7</td></tr>
<tr><td></td><td>Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.</td><td>8</td></tr>
<tr><td></td><td>Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.</td><td>9</td></tr>
<tr><td colspan="3">UNCONTROLLABLE
Control will be lost during some portion of mission.</td><td>Uncontrollable in mission.</td><td>10</td></tr>
</table>

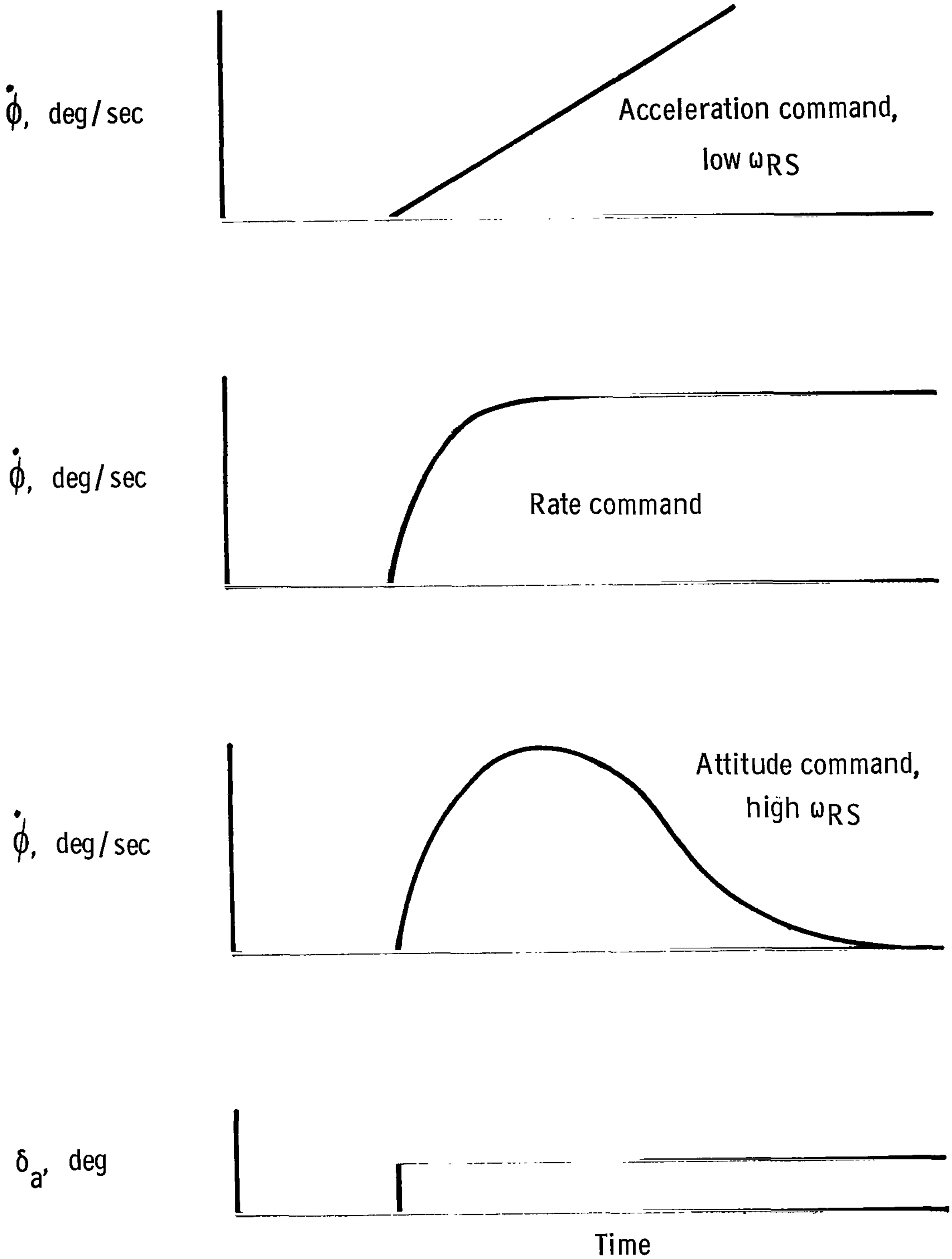


Figure 1.- Roll-rate response to an aileron step input.

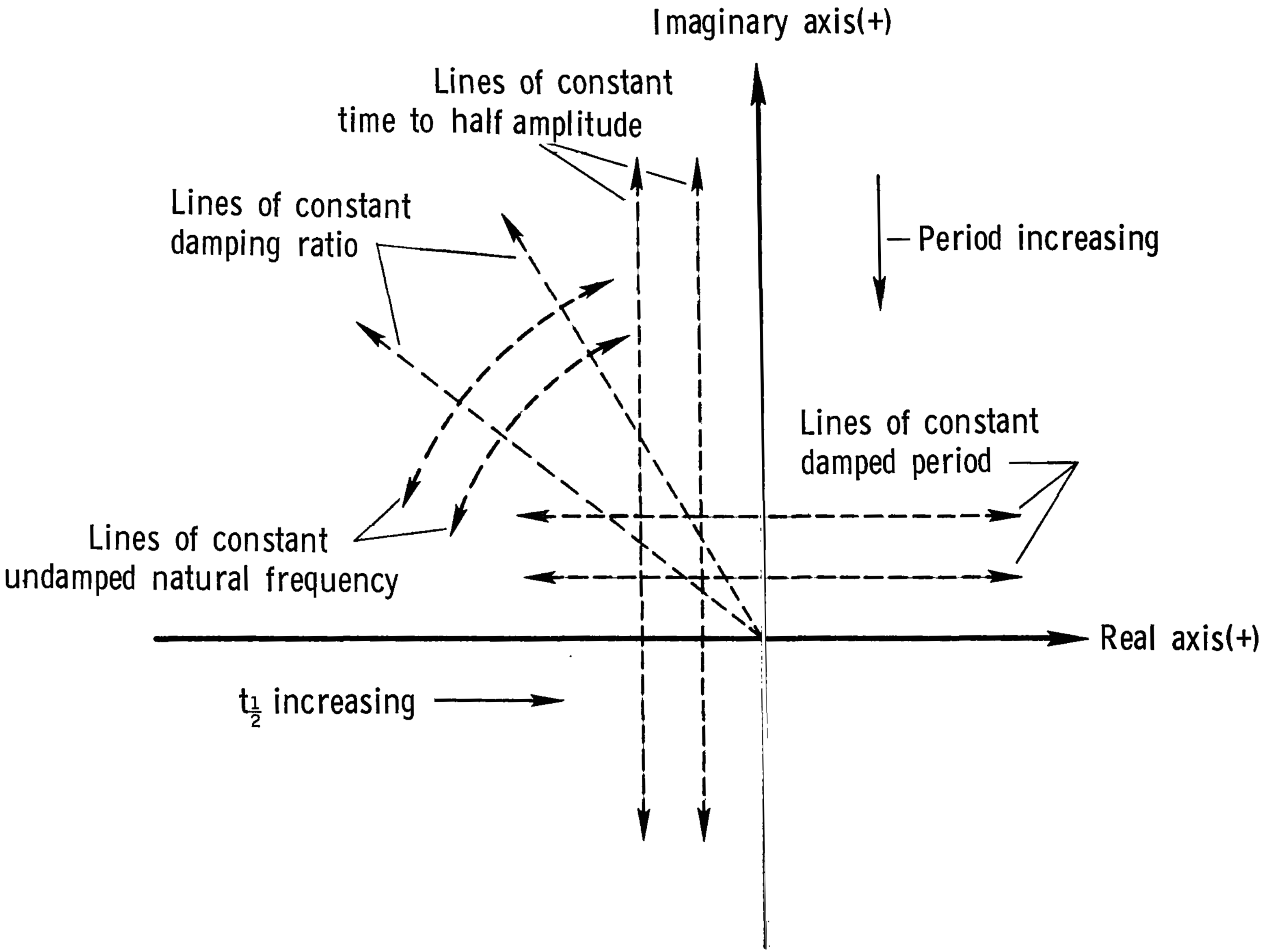


Figure 2.- Features of the complex plane.

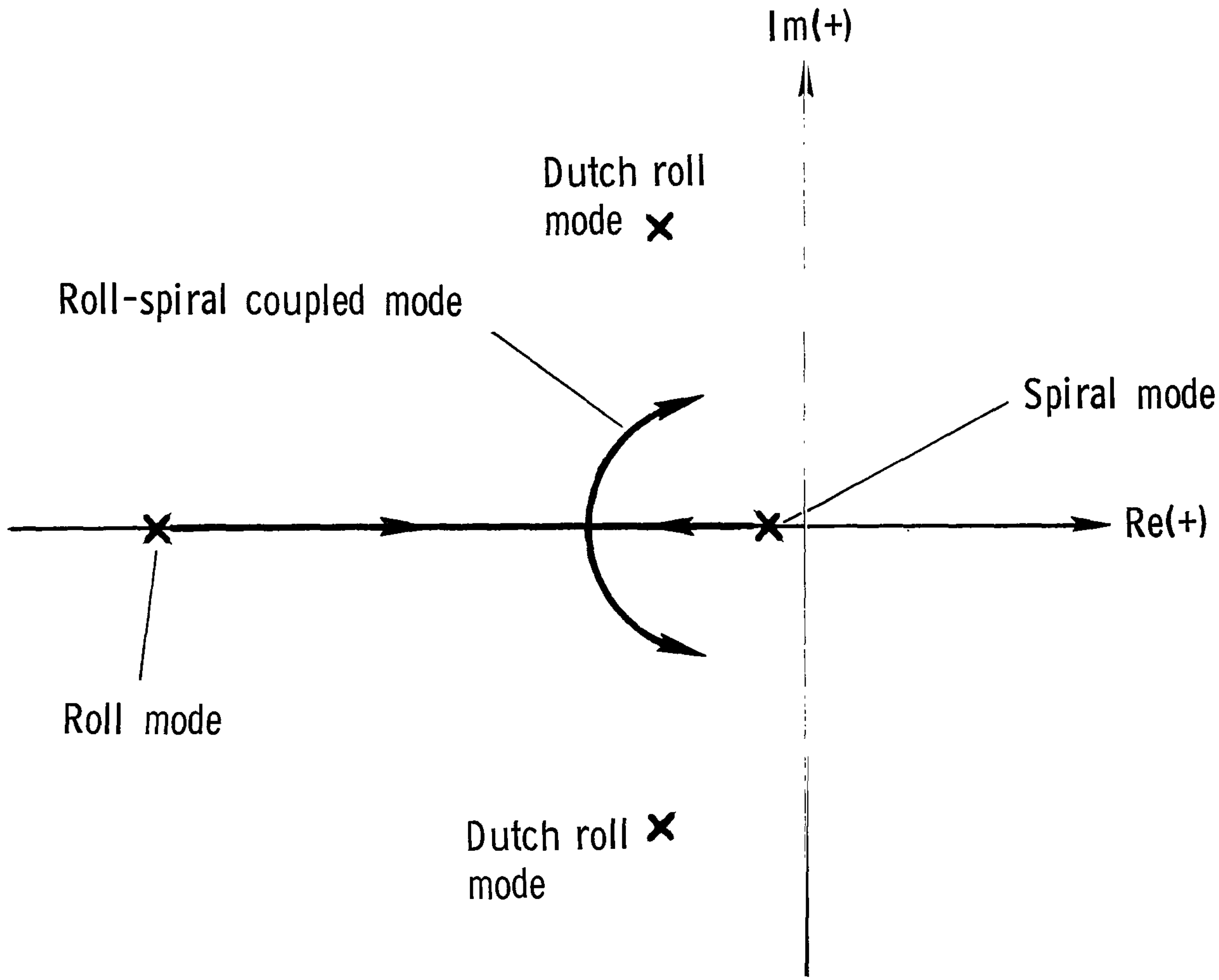


Figure 3.- Formation of the roll-spiral coupled mode.

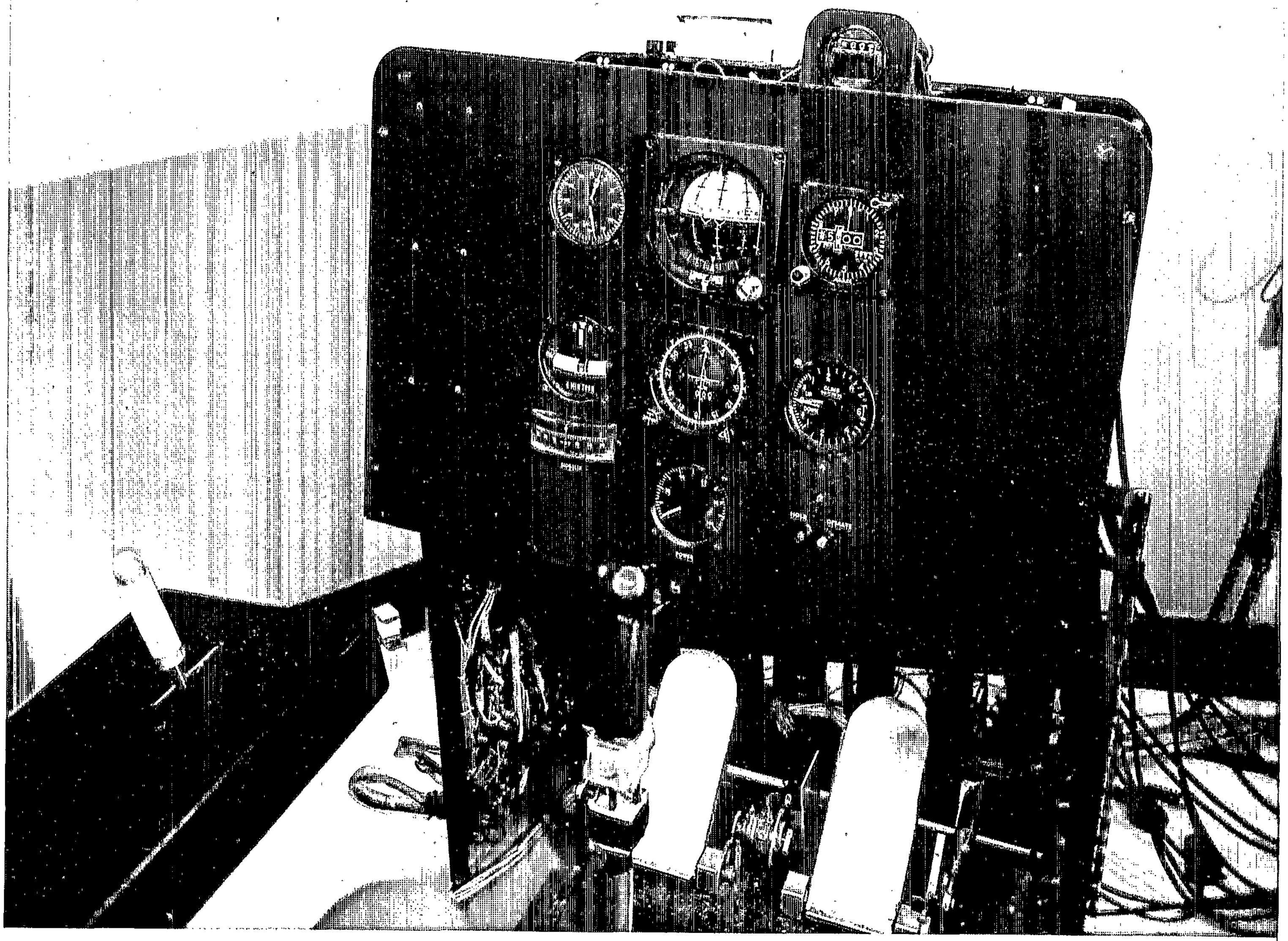


Figure 4.- Photograph of pilot's instrument display.

L-68-7632

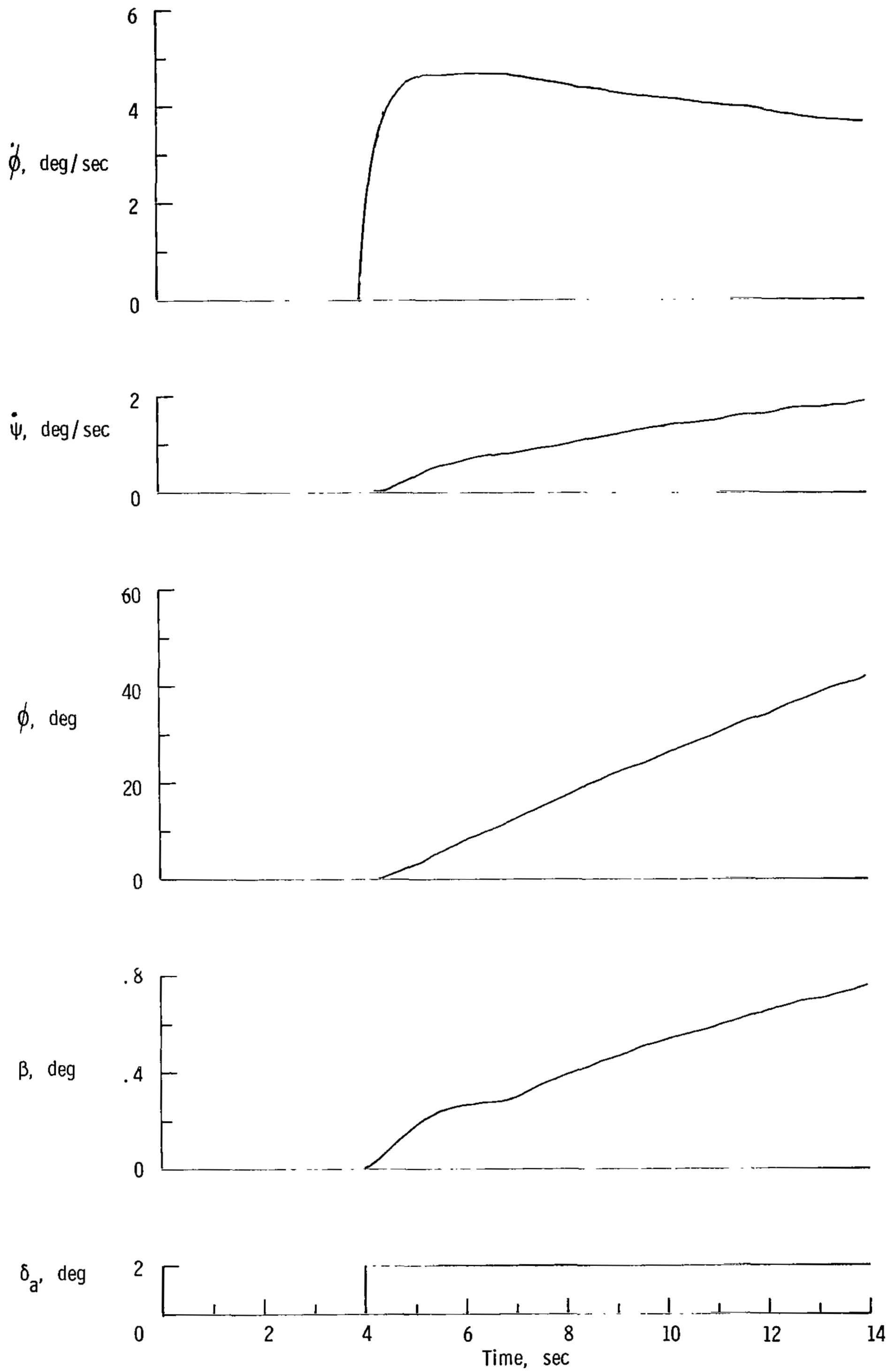
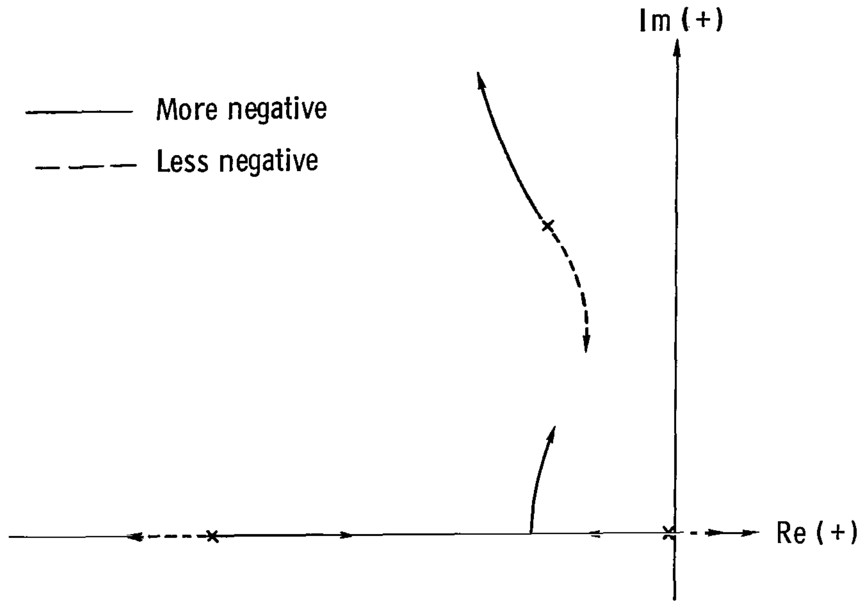
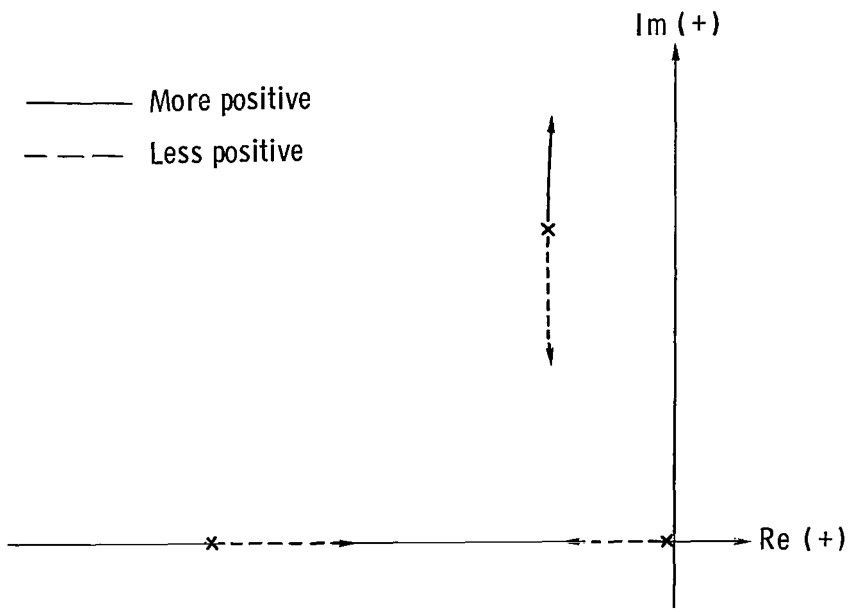


Figure 5.- Time history of motion obtained for an aileron step input with configuration I-1.

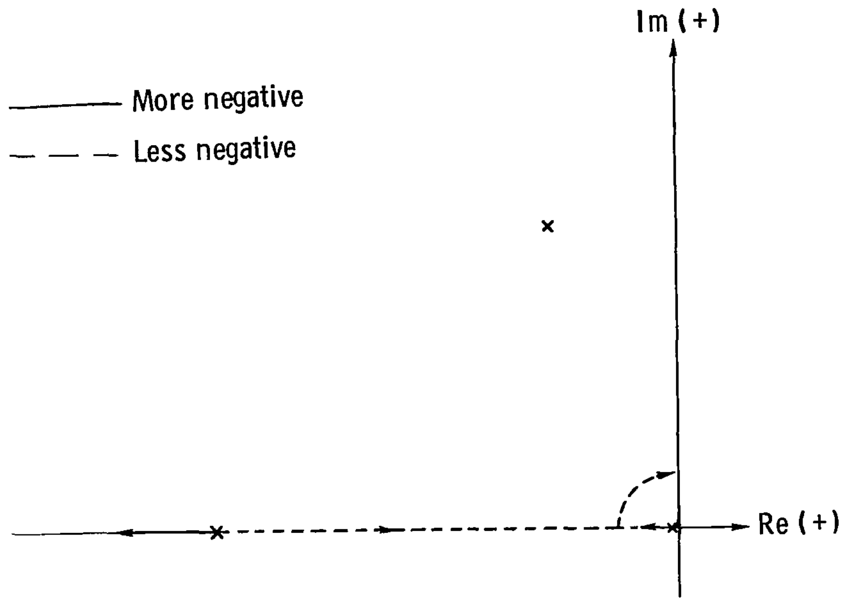


(a) Variation of C_{l_β}.

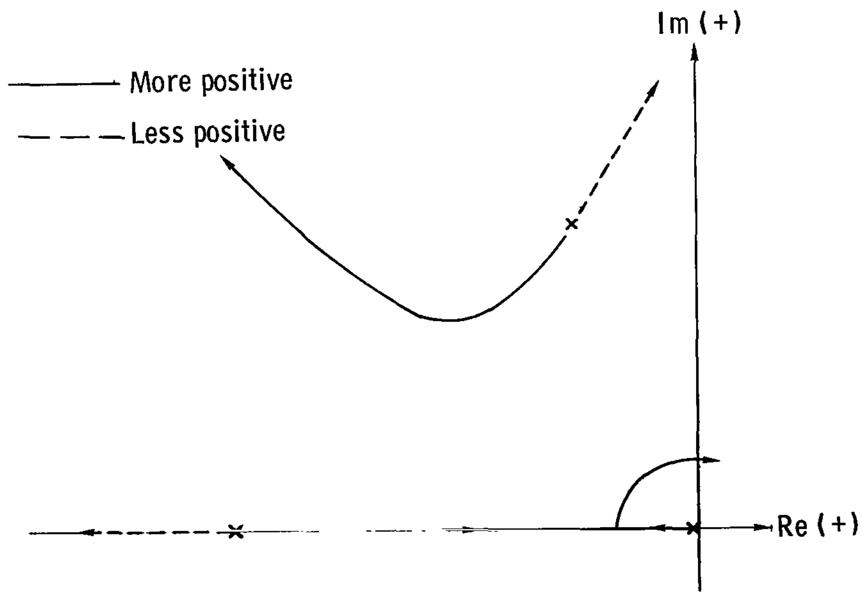


(b) Variation of C_{n_β}.

Figure 6.- Root-locus sketches for variations of the six aerodynamic derivatives investigated.

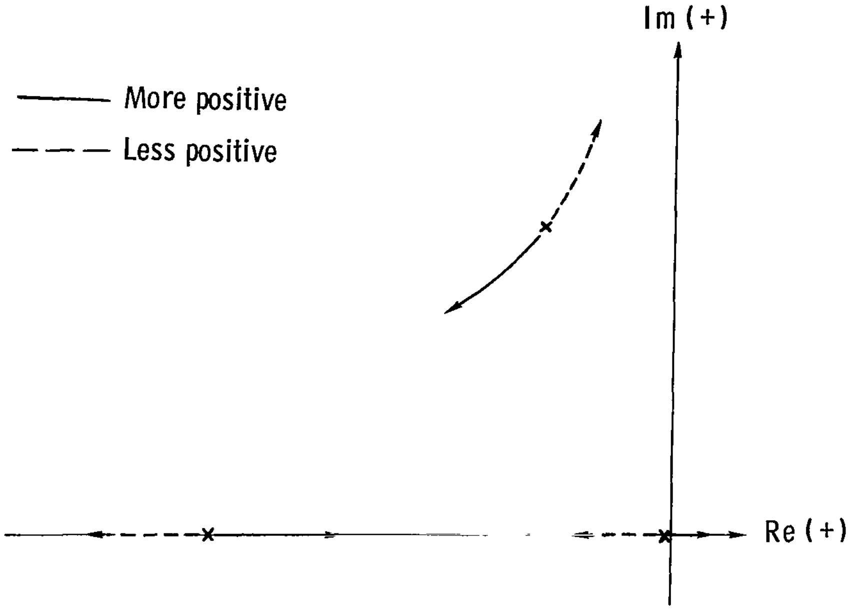


(c) Variation of C_{l_p}.

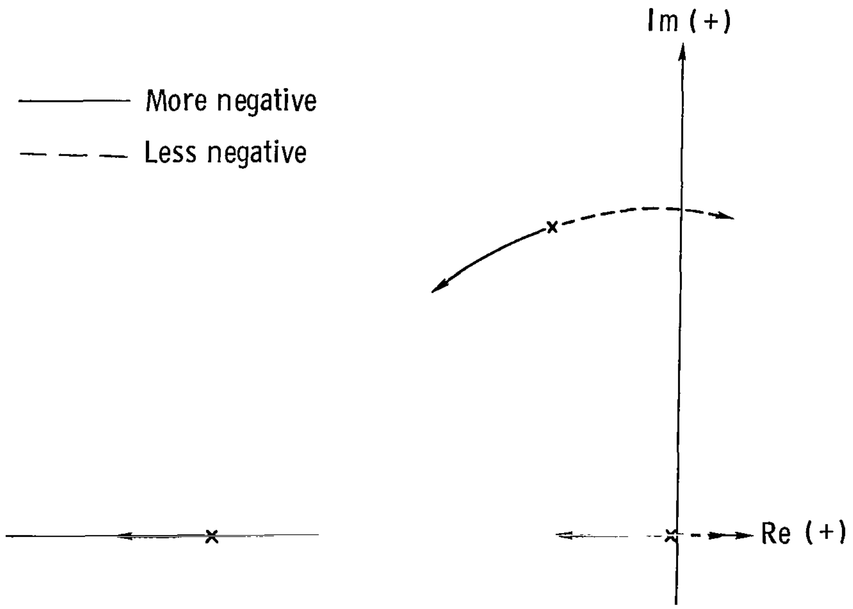


(d) Variation of C_{n_p}.

Figure 6.- Continued.



(e) Variation of C_{l_r}.



(f) Variation of C_{n_r}.

Figure 6.- Concluded.

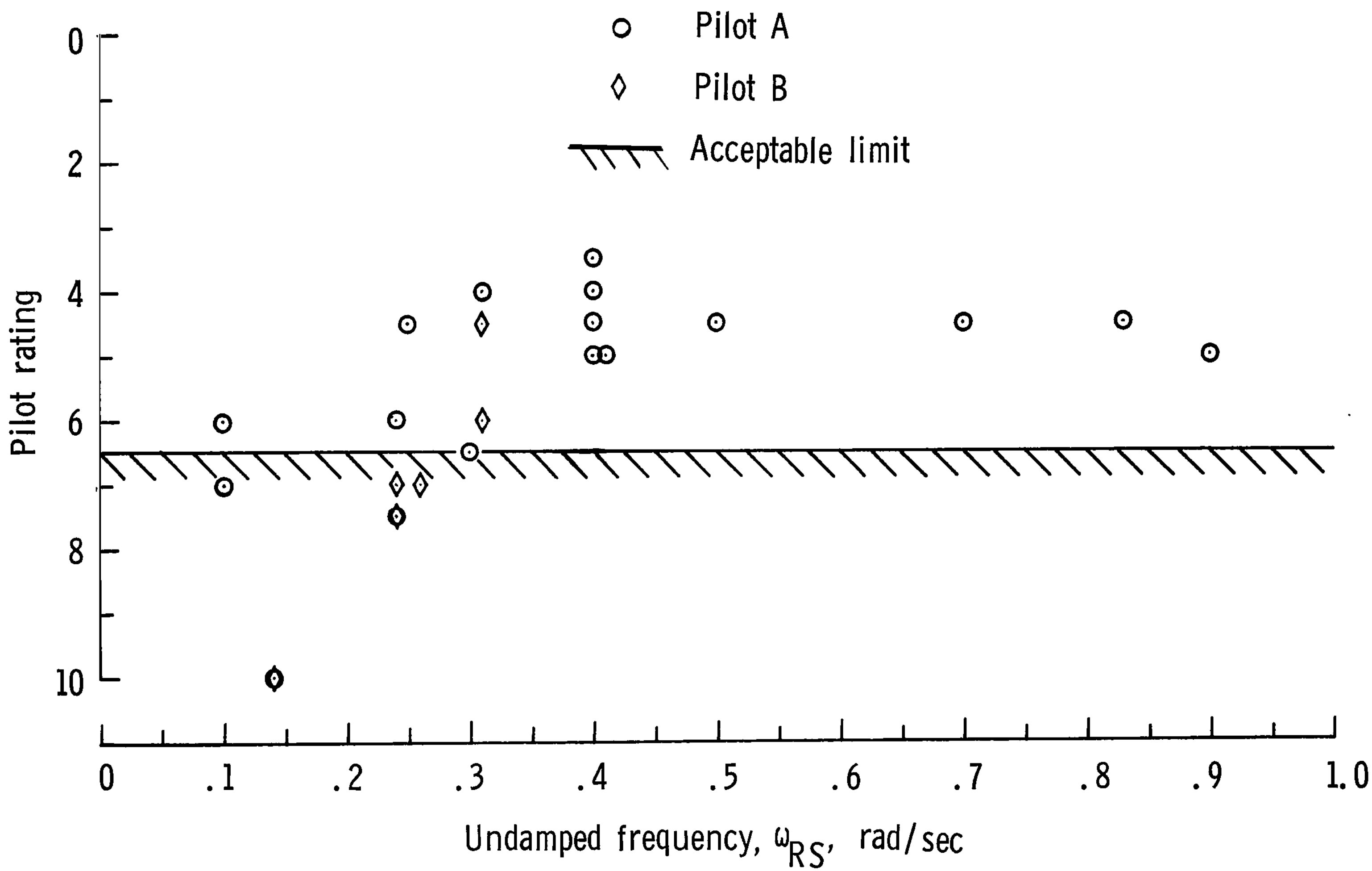


Figure 7.- Variation of pilot rating with ω_{RS} for phase I.

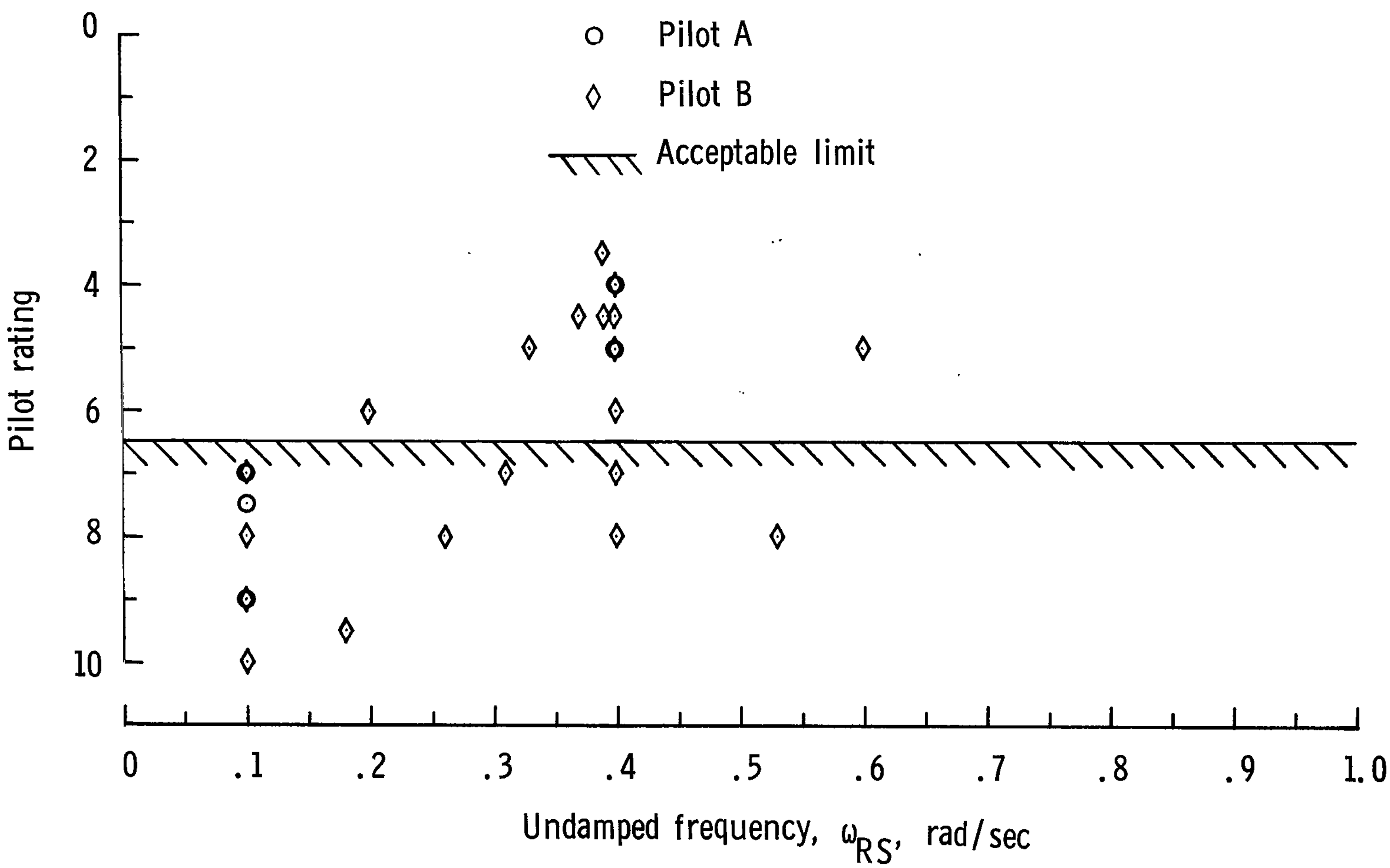
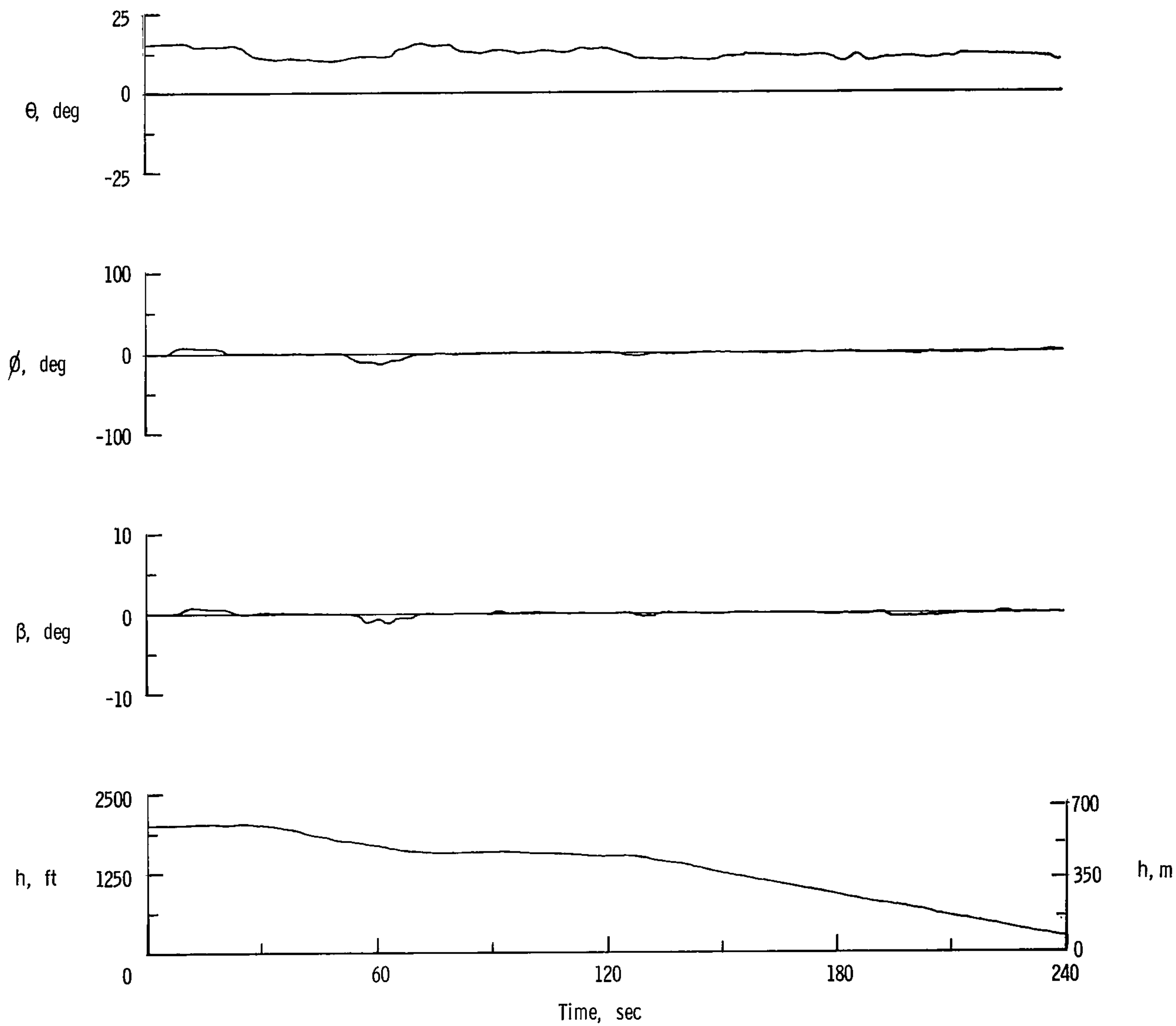
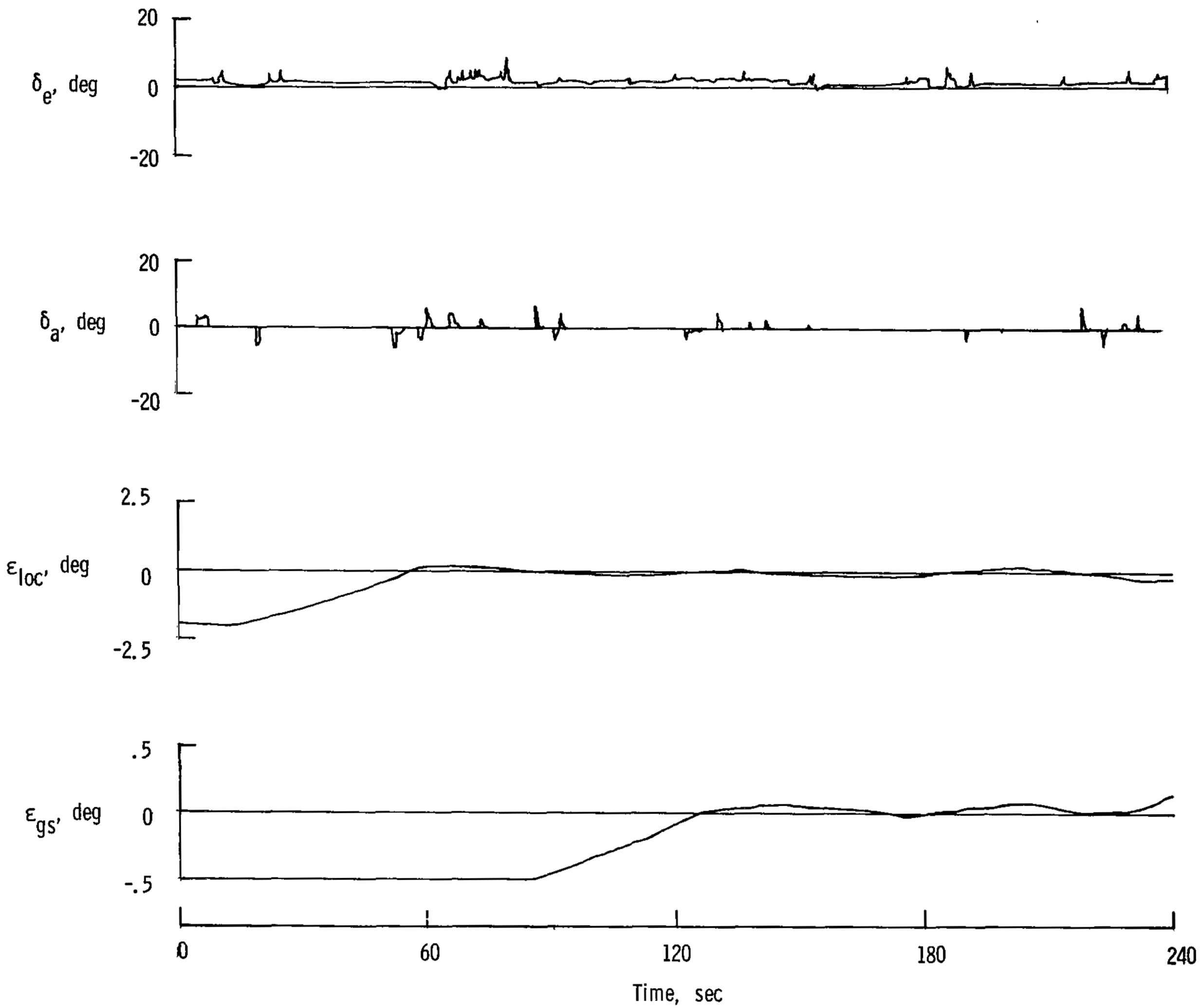


Figure 8.- Variation of pilot rating with ω_{RS} for phase II.



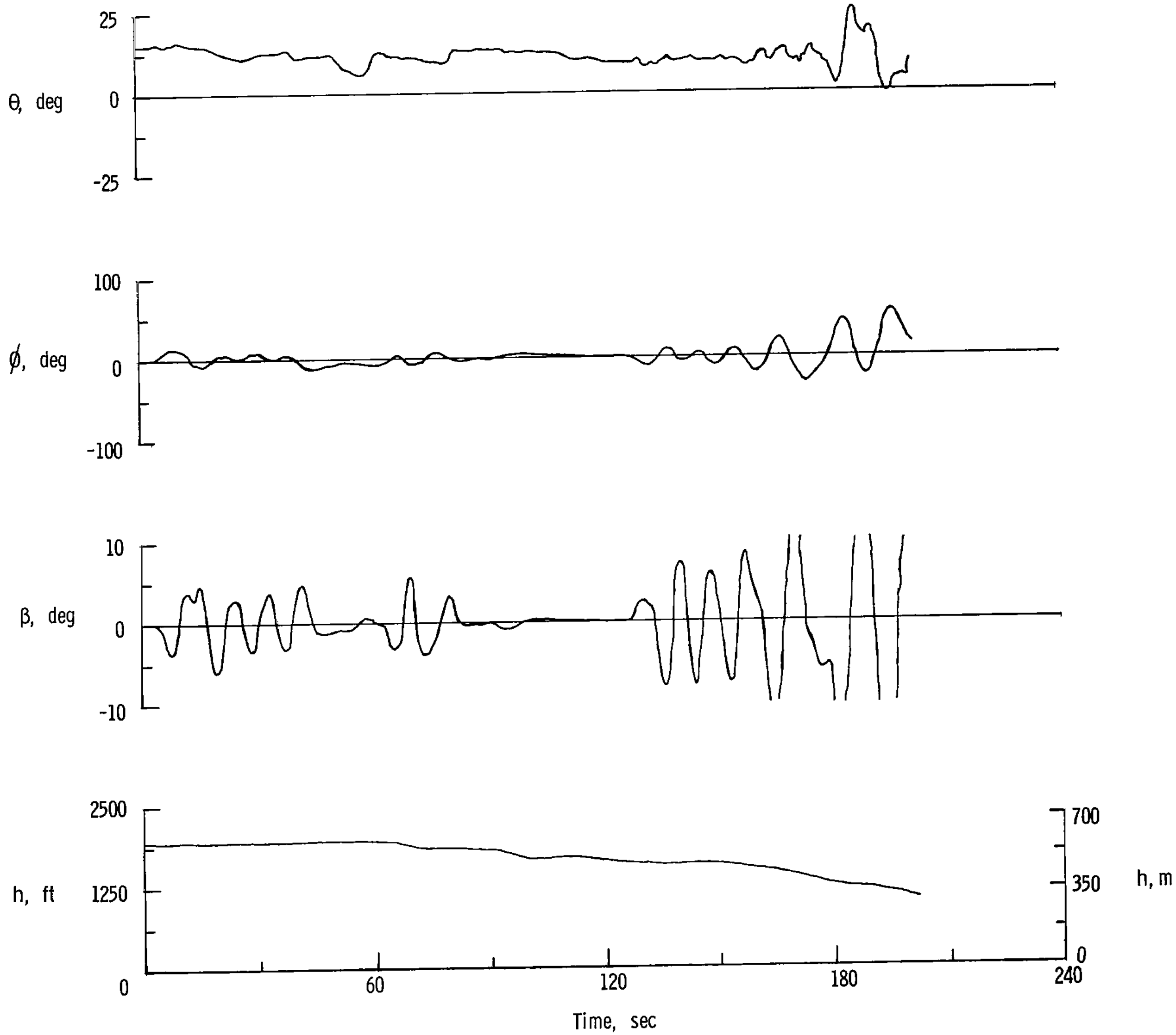
(a) Configuration II-1.

Figure 9.- Typical approaches of configurations II-1, II-10, and II-17.



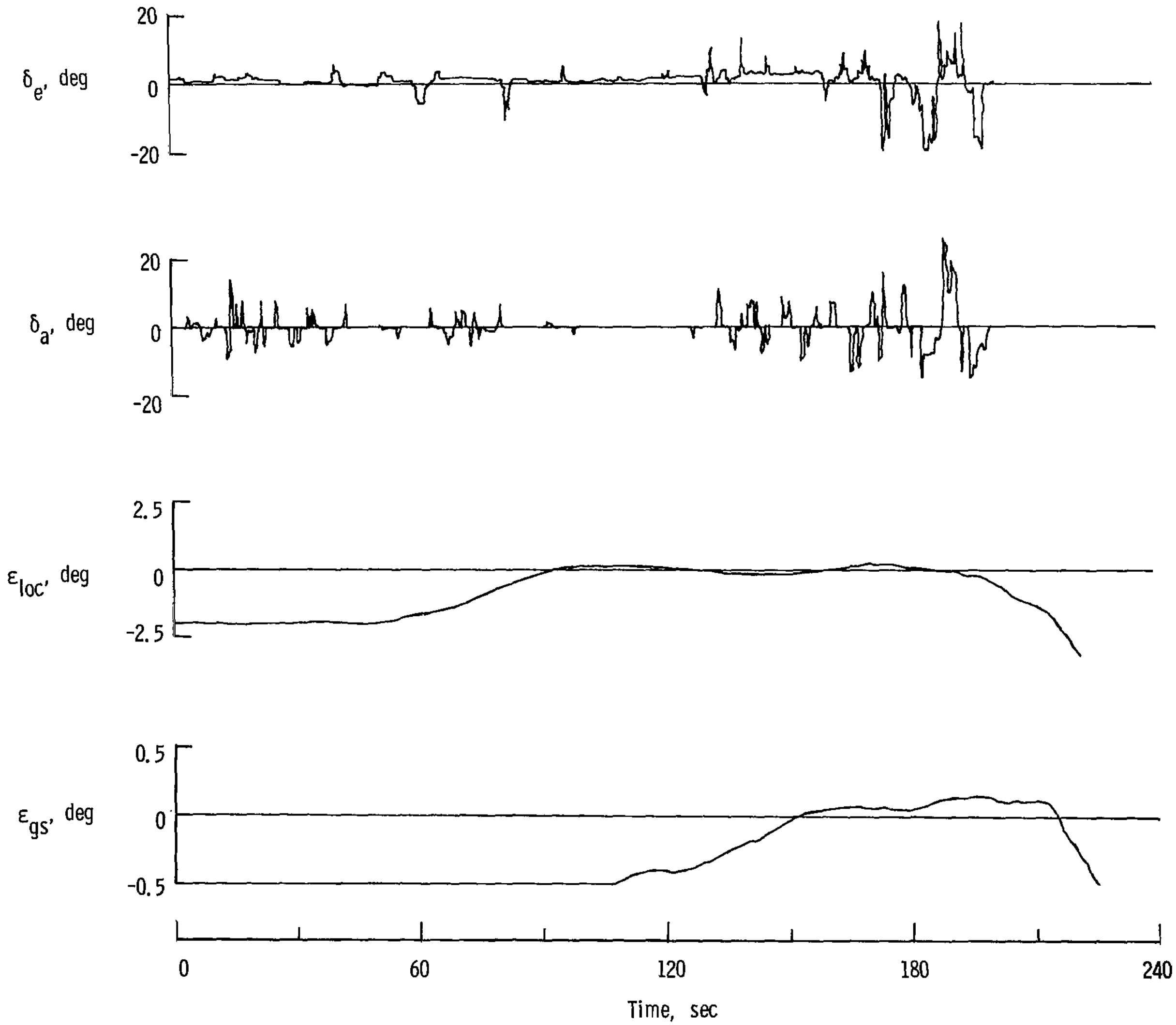
(a) Concluded.

Figure 9.- Continued.



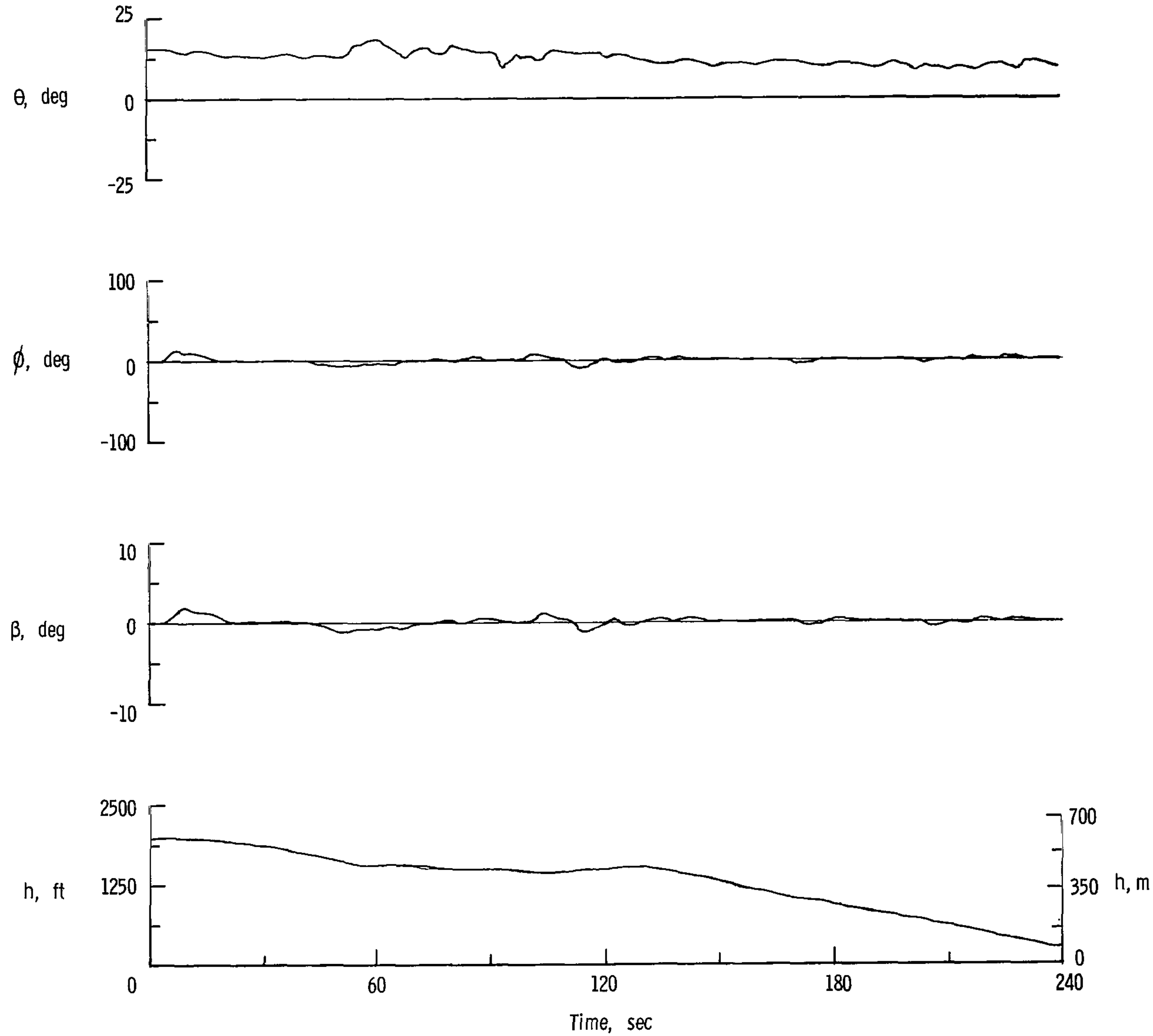
(b) Configuration II-10.

Figure 9.- Continued.



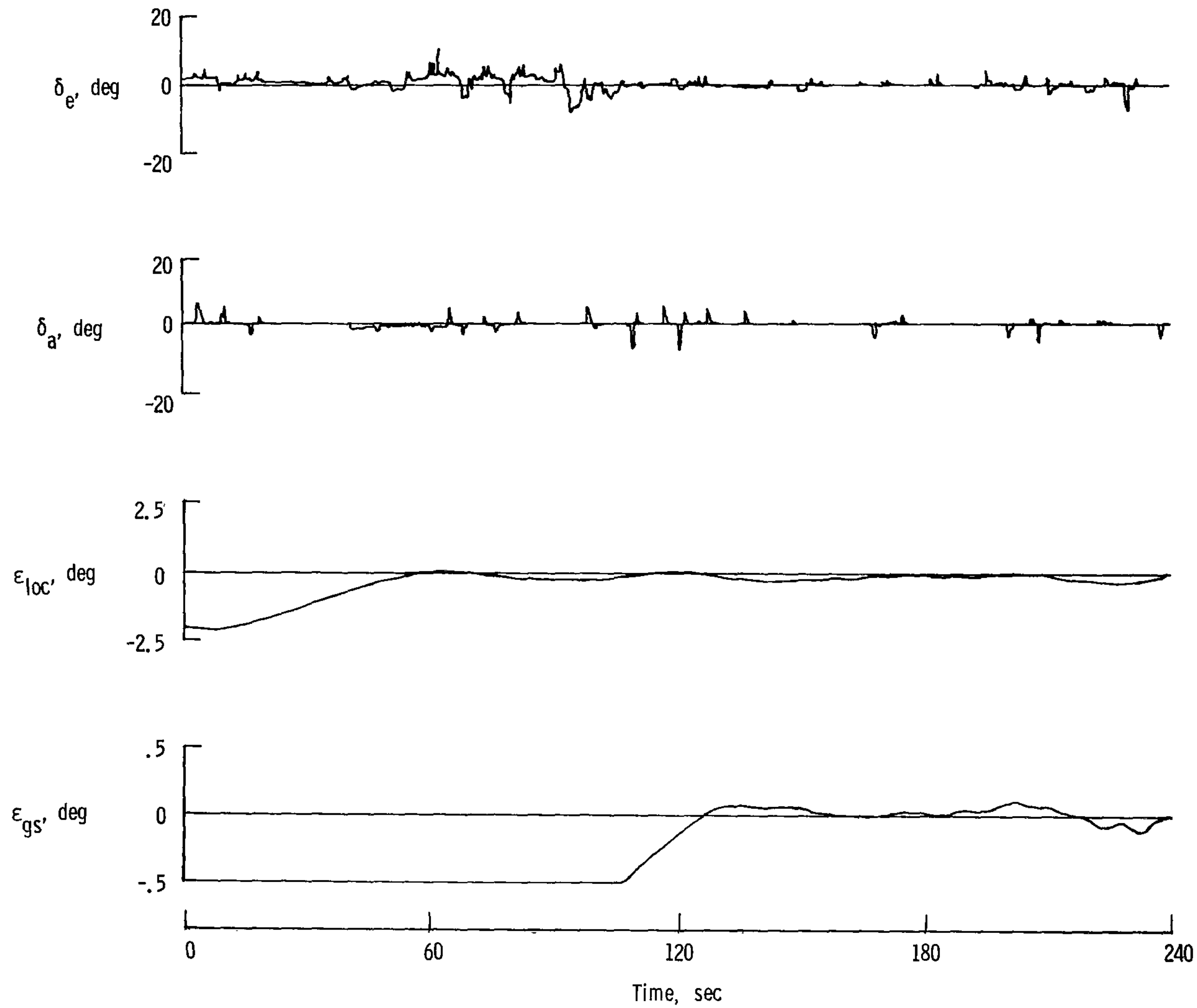
(b) Concluded.

Figure 9.- Continued.



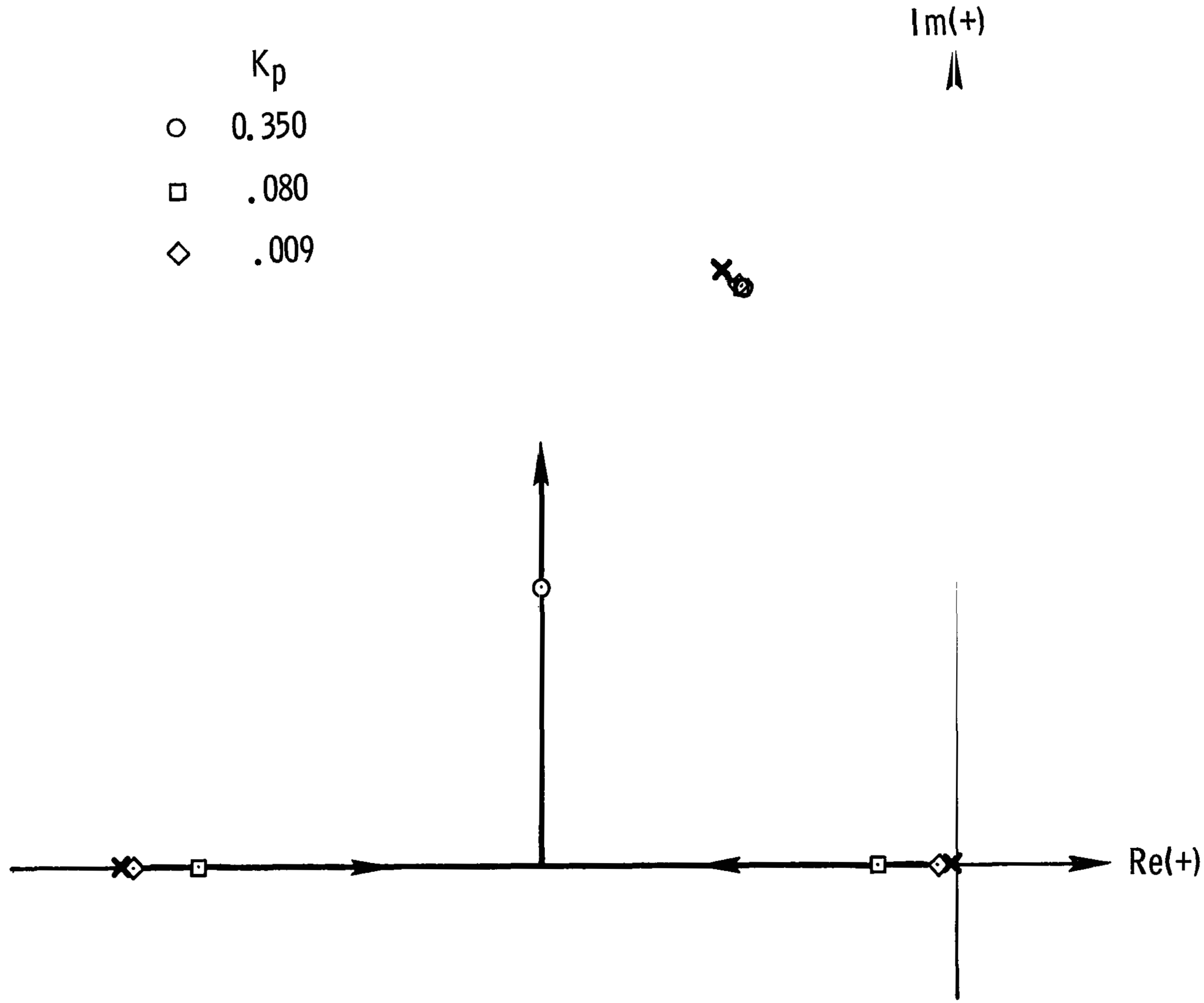
(c) Configuration II-17.

Figure 9.- Continued.



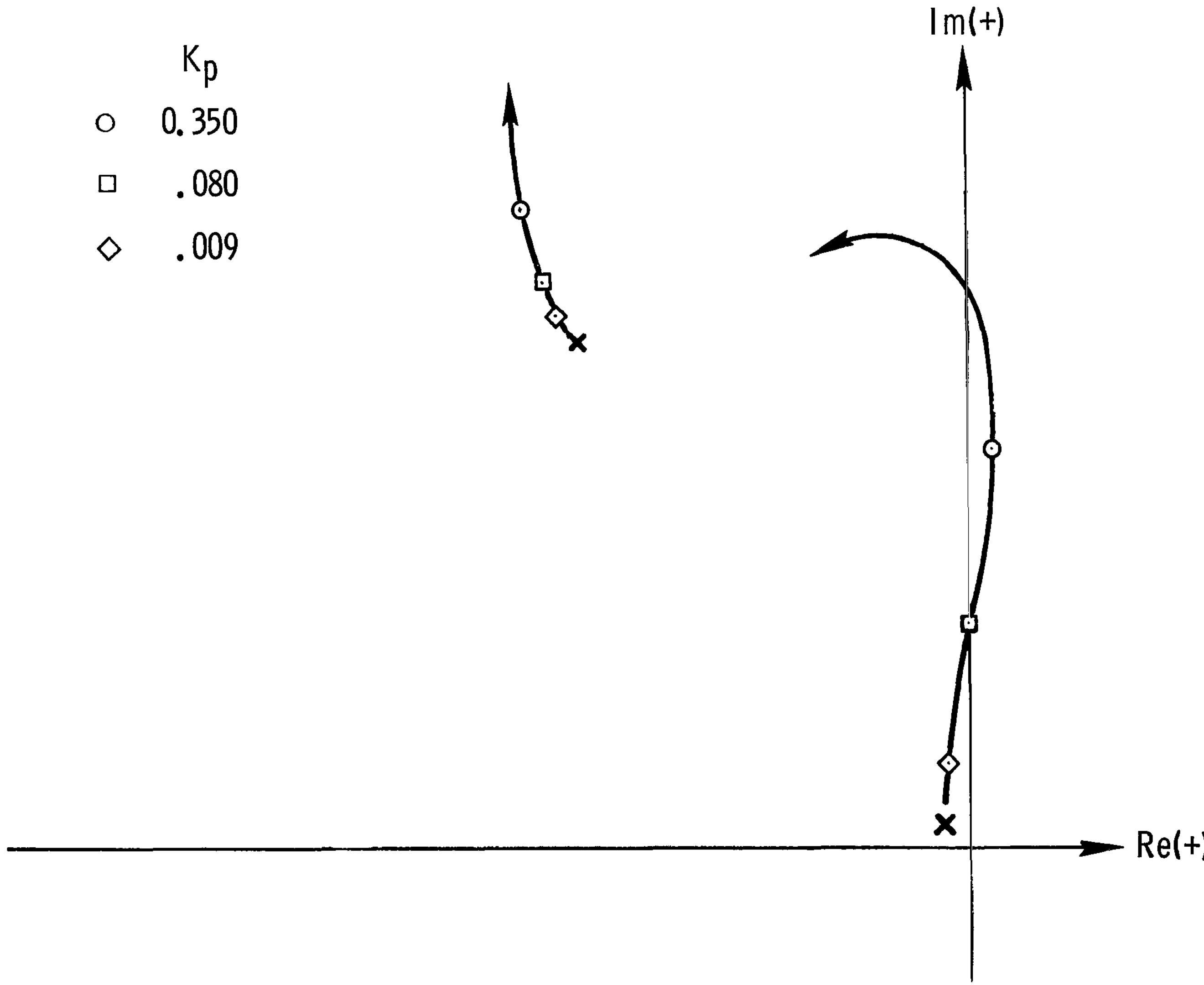
(c) Concluded.

Figure 9.- Concluded.



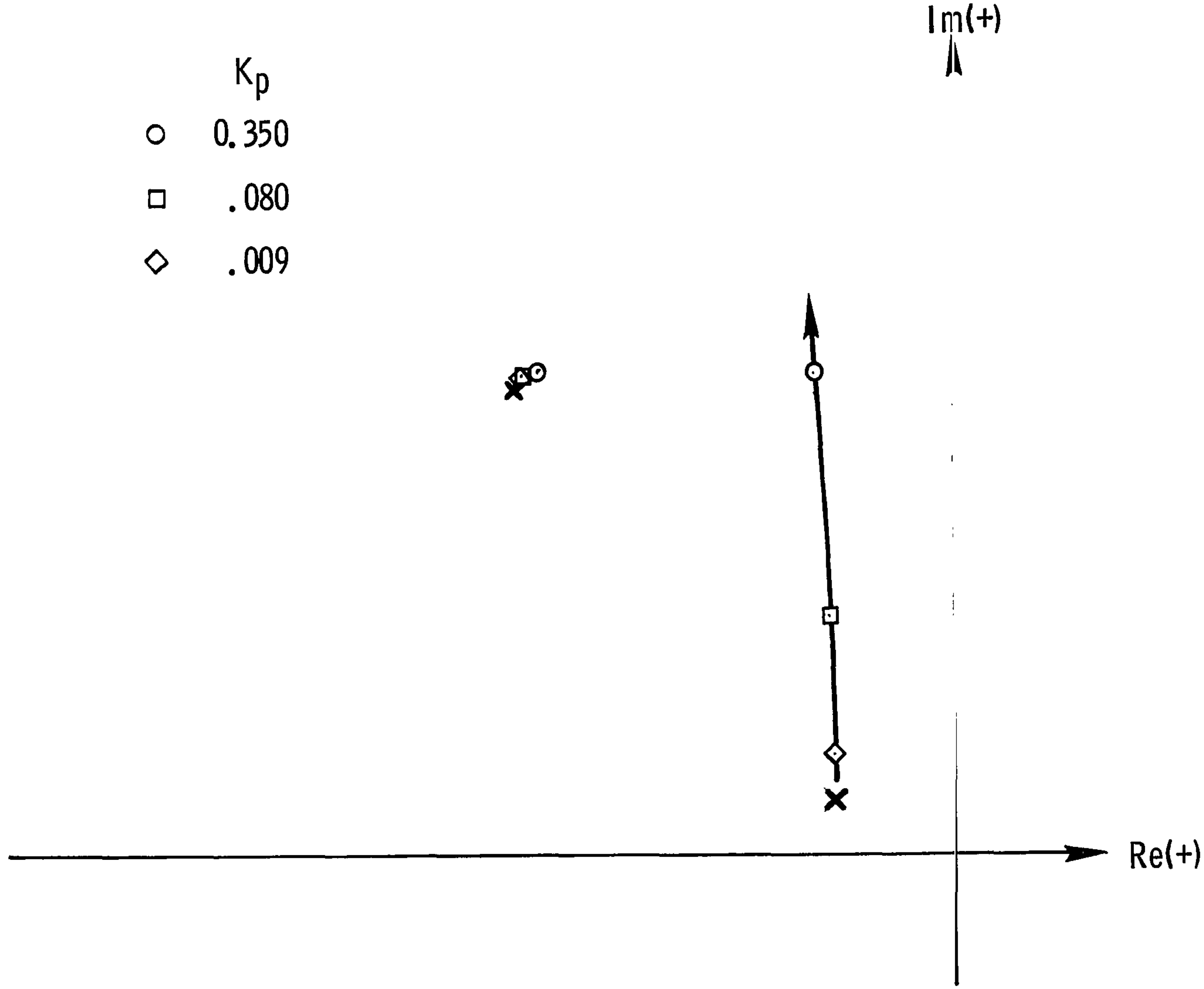
(a) Configuration I-1.

Figure 10.- Root-locus sketches of the closed-loop bank-angle transfer function for variation in pilot gain.



(b) Configuration 1-22.

Figure 10.- Continued.



(c) Configuration I-17.

Figure 10.- Concluded.

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