AN INVESTIGATION OF THE EFFECTS OF ROLL-SPIRAL COUPLING ON THE LATERAL-DIRECTIONAL HANDLING QUALITIES OF A STOL SUBSONIC TRANSPORT

By

Frederick Lyle Moore

Thesis submitted to the Graduate Faculty of the

Virginia Polytechnic Institute

in partial fulfillment for the degree of

MASTER OF SCIENCE

in

AEROSPACE ENGINEERING

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Frederick L. Moore

Abstract

For certain new types of aircraft, such as the supersonic transport and V/STOL configurations, an unusual lateral mode of motion is expected to be present. This mode of motion is found when the conventional roll and spiral modes of motion couple and form a second lateral oscillation in addition to the Dutch roll oscillation. The present thesis presents the results of an investigation on the effects of the roll-spiral coupled mode of motion on the lateral-directional handling characteristics of a hypothetical subsonic STOL transport aircraft. The investigation consisted of a general analysis and analytical calculations of the lateral dynamics for configurations of the transport having various types of roll-spiral oscillations. Also, a fixed-base simulator study was conducted in order to obtain pilot evaluation of the handling qualities of the various configurations under instrument flight rules (IFR) conditions. The results of simulator study indicated that the hypothetical transport could have acceptable qualities with a roll-spiral coupled oscillation present provided small lateral inputs are used.

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III. ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the National Aeronautics and Space Administration for permission to use the material in this thesis which was obtained from a research program at Langley Research Center.

He also wishes to thank Dr. Frederick H. Lutze of the Aerospace Engineering Department of the Virginia Polytechnic Institute for his assistance in preparing this thesis.

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VI. INTRODUCTION

Radically new designs for modern-day aircraft, such as supersonic transport and V/STOL configurations, produce unusual values of the conventional static and dynamic aerodynamic stability derivatives. These unique values for the stability derivatives in turn lead to unconventional dynamic modes of motion for which little or no previous experience is available. As a result of unconventional values of the stability derivatives, several present-day aircraft are expected to exhibit an unusual lateral-directional mode of motion consisting of a rather long period, lightly damped oscillation sometimes referred to as the lateral phugoid. Inasmuch as this mode of motion arises from coupling between the conventional roll and spiral modes of motion, the phenomenon will herein be referred to as roll-spiral coupled mode or roll-spiral oscillation.

Limited information is available concerning the characteristics of roll-spiral coupling due to non-existence of this mode of motion during normal operations of conventional aircraft. A fixed-base simulator study of the lateral-directional handling qualities of a high-speed fighter configuration having roll-spiral coupling was conducted in Reference 1. The general conclusion drawn from the investigation was that an aircraft with roll-spiral coupling would have unacceptable handling qualities. The results of Reference 1, however, are considered to be rather limited in application to more general configurations. In view 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 conducted to provide data which can be used for evaluation of configurations having this mode of motion during early stages of design.

The information contained herein presents the results of an investigation of the effects on lateral-directional handling qualities of a hypothetical subsonic STOL transport aircraft due to variations of the characteristics of the roll-spiral oscillation. The investigation consisted of (1) a general analytical study of roll-spiral coupling, and (2) a fixed-base simulator study to obtain quantitative pilot evaluation of the various configurations under IFR flight conditions.

VII. SYMBOLS AND NOMENCLATURE

The calculated stability and control results are presented with respect to the body axis system shown in Figure 1.

A,B,C,D,E	coefficients of lateral stability quartic
b	wing span, ft
$C_{1/2}$	cycles required for oscillation to damp to one-half amplitude
C_l	rolling moment coefficient
C_n	yawing moment coefficient
C_Y	side-force coefficient
$\bar{c}$	mean aerodynamic chord, ft

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$$

$$C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$$

$$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a}$$

$$C_{n_{\delta_a}} = \frac{\partial C_n}{\partial \delta_a}$$

$$C_{Y_{\delta_a}} = \frac{\partial C_Y}{\partial \delta_a}$$

$$C_{l_{\delta_r}} = \frac{\partial C_l}{\partial \delta_r}$$

$$C_{n_{\delta_r}} = \frac{\partial C_n}{\partial \delta_r}$$

$$C_{Y_{\delta_r}} = \frac{\partial C_Y}{\partial \delta_r}$$

$$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}}$$

$$C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}}$$

$$C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$$

$$C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$$

$$C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V}}$$

IFR instrument flight rules

I_X, I_Y, I_Z moments of inertia about X, Y, and Z axes, respectively, slug-ft^2

K_P static gain of pilot transfer function (ϕ/δ_a) $\frac{\text{deg bank angle}}{\text{deg aileron}}$

$$L_P = (q_o S b) \frac{b}{2V} \frac{C_{l_p}}{I_X} \qquad 1/\text{sec}$$

$$L_r = (q_o S b) \frac{b}{2V} \frac{C_{l_r}}{I_X} \qquad 1/\text{sec}$$

$L_\beta = (q_o Sb) \frac{C_{l_\beta}}{I_X}$ $1/sec^2$

$L_{\delta_a} = (q_o Sb) \frac{C_{l_{\delta_a}}}{I_X}$ $1/sec^2$

$L_{\delta_r} = (q_o Sb) \frac{C_{l_{\delta_r}}}{I_X}$ $1/sec^2$

m mass, slugs

$N_P = (q_o Sb) \frac{b}{2V} \frac{C_{n_p}}{I_X}$ 1/sec

$N_r = (q_o Sb) \frac{b}{2V} \frac{C_{n_r}}{I_Z}$ 1/sec

$N_\beta = (q_o\ Sb) \frac{C_{n_\beta}}{I_Z}$ $1/sec^2$

$N_{\delta_a} = (q_o Sb) \frac{C_{n_{\delta_a}}}{I_Z}$ $1/sec^2$

$N_{\delta_r} = (q_o Sb) \frac{C_{n_{\delta_a}}}{I_Z}$ $1/sec^2$

P period, sec

p roll rate, radians/sec

q_o dynamic pressure, $1/2\rho V^2$, lb/ft^2

r yaw rate, radians/sec

S wing area, ft^2

$T_{1/2}$ time of one-half amplitude, sec

T_2 time to double amplitude, sec

T_R roll time constant, sec

T_S spiral time constant, sec

V airspeed, knots or ft/sec

W weight, lbf

$$Y_P = (q_oS)\frac{b}{2V}\frac{C_{Y_p}}{mV}$$

$$Y_r = (q_oS)\frac{b}{2V}\frac{C_{Y_r}}{mV}$$

$$Y_\beta = (q_oS)\frac{C_{Y_\beta}}{mV} \qquad 1/\text{sec}$$

$$Y_{\delta_a} = (q_oS)\frac{C_{Y_{\delta_a}}}{mV} \qquad 1/\text{sec}$$

$$Y_{\delta_r} = (q_oS)\frac{C_{Y_{\delta_r}}}{mV} \qquad 1/\text{sec}$$

α angle of attack, deg

β angle of sideslip, deg

δ_a aileron deflection, deg

δ_p pedal deflection, in.

δ_r rudder deflection, deg

δ_s stick deflection, deg

ζ_d Dutch roll damping ratio

ζ_{RS} roll-spiral mode damping ratio

θ	angle of pitch, deg
ϕ	angle of roll, deg
$\lvert\phi/\beta\rvert_d$	magnitude of roll angle to sideslip angle ratio at the Dutch roll complex frequency
$\lvert\phi/\beta\rvert_{RS}$	magnitude of roll angle to sideslip angle ratio at the spiral-roll complex frequency
ψ	angle of heading, deg
ω_d	undamped natural frequency of Dutch roll mode, radians/sec
ω_{RS}	roll-spiral mode undamped natural frequency, radians/sec
ω_ϕ	undamped natural frequency appearing in numerator quadratic of ϕ/δ_a transfer function, radians/sec

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

VIII. ANALYSIS

A. Method of Analysis

The analysis was made for a hypothetical transport airplane having mass characteristics similar to present-day designs. The investigation considered only the effect of the roll-spiral oscillation on the lateral-directional handling qualities of the STOL transport. The values of the longitudinal stability characteristics chosen were considered satisfactory and representative of subsonic transports and remained unchanged throughout the analysis. Various values of the lateral aerodynamic stability derivatives were determined to provide several combinations of the frequency and damping for the roll-spiral and Dutch roll oscillations. Analytical studies were made using a digital computer to calculate time histories and stability characteristics of the lateral oscillations such as the period and time to half amplitude. A fixed-based simulator was used to evaluate the flying qualities of the transport in a quantitative manner using standard flight evaluation procedures under IFR conditions.

B. Description of Vehicle

As stated previously, the airplane configuration used in the present study was a hypothetical STOL subsonic transport. This test configuration was evaluated only at cruise conditions. The airplane was said to be heavily loaded along the fuselage ($I_X < I_Y$) and the mass and dimensional characteristics are presented in Table I. The basic aerodynamic stability derivatives and the dynamic stability characteristics of the hypothetical

STOL aircraft are presented in Table II. (Note that no longitudinal aerodynamic characteristics are presented. This is because, as previously mentioned, the longitudinal handling qualities of this aircraft were satisfactory before evaluation of the effects of roll-spiral coupling began.) Also, for the most part, the variation made in the lateral-directional aerodynamic derivatives during this study were taken as being within a realistic range.

C. Determination of Stability Derivatives

A general study was conducted to determine realistic values of the stability derivatives for which the basic configuration of the hypothetical aircraft, having the conventional lateral modes of motion, would display various types of roll-spiral oscillations. Several different combinations of the frequency and damping for the roll-spiral oscillation can be calculated using various values of the lateral aerodynamic stability derivatives C_{Y_β}, C_{n_β}, C_{l_β}, C_{n_p}, C_{l_p}, C_{n_r}, and C_{l_r}. A method was therefore developed to determine the required values of the stability derivatives that would produce the desired frequency and damping for the roll-spiral and Dutch roll oscillations. The method and equations used to predict the stability derivatives are presented in Appendix B.

D. Methods and Scope of Investigation

Calculations were made to determine the dynamic lateral stability and control characteristics of the various configurations of the subsonic STOL transport for the condition of cruise flight at an altitude of

20,000 feet. The calculations were made using the equations of motion given in Appendix A.

The dynamic lateral stability calculations consisted of determination of the period and damping of the lateral-directional modes of motion. In addition, the roll-to-sideslip ratio $|\phi/\beta|$ and the roll coupling parameters, ω_ϕ/ω_d and ω_ϕ/ω_{RS}, were calculated for the oscillatory modes. For adequate handling qualities, the value of roll-to-sideslip parameter ϕ/β for the Dutch roll mode varies between 0.5 to 1.5 for large subsonic jet transports as stated in Reference 4. Also, the optimum value for the roll coupling parameter ω_ϕ/ω_d is generally near unity. The importance of these handling quality parameters for an aircraft having a roll-spiral oscillation has not been established.

Since control of bank angle is generally the primary lateral piloting task, only the roll-control characteristics were calculated. Two methods were used in calculating the roll-control characteristics. The first method, using the equations of motion for six degrees of freedom, calculated the time history of the roll response due to a 2° aileron step input for the various configurations. The second method approximated the closed-loop (pilot in the system) bank angle control characteristics for variation in the pilot gain, K_P; that is, the pilot actuates the aileron stick proportional to the observed error in bank angle without lead or lag. This second method was accomplished by calculating the aircraft's open-loop (no pilot) stick to bank angle transfer function as discussed in Appendix C. In other words, the pilot gain was equal to the ϕ/δ_a transfer function.

In conjunction with these calculations, the graphical root locus technique was used to help visualize the effect of varying the pilot gain. This technique illustrates the path or locus of the various solutions of the transfer function on the complex plane. Presented in Figure 2 are the features of the complex plane as applied to dynamic systems. References 2 and 3 present a more detailed explanation of the root locus technique as applied to dynamic systems.

E. Description of Simulator

The simulator used in the investigation presented the pilot with the essential elements of flying under IFR conditions. The cockpit was equipped with a control stick, conventional rudder pedals, a single level thrust controller, and a flight instrument display panel (see Figures 3 and 4). The simulator did not incorporate cockpit motion and no external visual display was used. The control forces were provided by springs and thus were functions of control displacement only. The maximum travel of the controls, control breakout forces, and control forced gradients are listed in Table III. A general-purpose analog computer was used in conjunction with the simulator and was programmed with the nonlinear differential equations of motion for six degrees of freedom with linear aerodynamic inputs.

F. Pilot Evaluation Procedures

The hypothetical transport was considered to be flying in smooth air at an altitude of 20,000 feet, at a true airspeed of 400 knots, and

under IFR conditions. As stated previously, the longitudinal aerodynamic parameters were satisfactory and were considered not to influence the pilot's evaluation of the lateral-directional handling qualities. These handling qualities were evaluated by two pilots. The pilots rated the various configurations by the Cooper rating scale presented in Table IV. The pilots were allowed to fly the simulator in any manner they desired and were not time limited. The following maneuvers which were considered to be typical piloting tasks were also included:

1. Roll to 30° and 45° bank angles with slow and rapid control application.

2. Rollout on desired headings from 30° and 45° bank angles.

3. Make a 180° turn at a 30° bank angle.

4. Repeat task 3 while climbing and descending at 1,000 fpm.

The various aircraft configurations were presented in a random or arbitrary manner in order to prevent biased evaluations. The following is a list of the lateral-directional characteristics evaluated:

1. Control power

2. Response and sensitivity to control input

3. Roll damping

4. Dutch roll oscillations

5. Adverse-proverse yaw

6. Spiral stability

7. Heading response in turn entry and recovery

8. Directional stability

9. Dihedral effect

10. Lateral oscillation characteristics

11. Bank angle control

IX. RESULTS AND GENERAL DISCUSSION

A. General Analysis of Roll-Spiral Coupling

From the side-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:

$$AS^4 + BS^3 + CS^2 + DS + E = 0$$

This quartic equation 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; for conventional airplanes this mode is usually a lightly-damped oscillatory 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 response. Therefore, the magnitude of the four roots of the characteristic equation affect the lateral response of an aircraft, which in turn affects the pilot's assessment of the flying qualities of that aircraft.

As mentioned previously, it is suspected that some of the V/STOL, SST, 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 pair 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). Figure 5 presents a root locus plot to illustrate a case in which the conventional roll and spiral modes have coupled and formed a second oscillatory mode as the aircraft's stability derivatives are arbitrarily varied. This second oscillation is brought about when (1) there is an unusually large or small value of particular aerodynamic stability derivatives, such as low values of roll damping, C_{l_p}, or large positive values of yawing moment due to roll, C_{n_p}, (see Configurations 2 and 3 in Table II); and (2) there is a certain combination of several of the aircraft's static and dynamic aerodynamic stability derivatives.

B. Results and Discussion of Simulator Study

As stated previously, the present study was conducted to determine the effects of the coupling of the roll and spiral modes on the lateral-directional handling qualities of a hypothetical STOL transport airplane. Also, although no attempt is made to establish any kind of handling qualities criteria, it is the intent of this paper to present information that will be of use in evaluating 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. Two pilots participated in the simulation program; unfortunately, due to time limitations, the number of test conditions that were "flown" by both pilots were much less than desired. The majority of the conditions tested during the program were evaluated by pilot A. The individual Cooper pilot ratings and comments for each test condition are presented in Appendix D.

Basic Aircraft.- The lateral-directional dynamic stability characteristics of the basic aircraft in which there existed no roll-spiral coupled mode of motion are presented in Table II and indicated as Configuration 1. Both pilots assigned a Cooper rating of 2.0 to

the lateral-directional handling qualities of this basic configuration. The pilots stated that the lateral control characteristics were excellent, the Dutch roll and adverse-proverse yaw characteristics were negligible or nonexistent, and that the heading response in a turn entry and recovery was good.

The only objectionable comments made regarding the handling qualities of the basic configuration were: (1) the spiral characteristics were less than good. Although the $T_{1/2} \approx 21$ seconds, the pilots felt that the spiral mode was too stable; and (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 IV describes a rating of 2.0 as "good enough without improvement."

Effect of Frequency on the Roll-Spiral Coupled Mode.- The remaining configurations of the hypothetical transport consisted of various combinations of the frequency and damping of the Dutch roll and roll-spiral oscillations. The results of the pilot ratings and comments indicated that variation in the frequency of the roll-spiral coupled mode, ω_{RS} had the most effect on the lateral handling qualities. The frequency of the coupled roll-spiral mode ω_{RS} was varied from 0.10 to 1.39 during the present study. The damping of both the coupled roll-spiral mode and the Dutch roll mode was always positive, although the damping of each mode was also varied. Figure 6 presents a plot of ω_{RS}

against pilot rating for the various configurations tested. The comments made by the pilots and the pilot ratings assigned to the various configurations indicated that in order for the aircraft to have an "acceptable" rating (PR $\leq$ 6-1/2), the ω_{RS} should be greater than 0.35, and indications are that ω_{RS} should not be greater than approximately 1.0. Generally, the higher the damping of both the coupled roll-spiral mode and the Dutch roll mode the better the pilot ratings; however, there did not seem to be any definite trend regarding the damping of either mode.

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

(1) The damping in roll is very low or nonexistent.

(2) The aircraft is overly responsive to lateral inputs.

(3) The aircraft exhibits high proverse yaw for lateral inputs.

When the frequency of the coupled roll-spiral mode ω_{RS} was approximately 0.40 or greater, the pilots generally stated:

(1) The damping in roll is low or moderately low.

(2) The spiral stability is much too strong.

(3) There is no evidence of proverse/adverse yaw.

Effects of Damping on the Roll-Spiral Coupled Mode.- The damping of the coupled roll-spiral mode ζ_{RS} was varied from approximately 0.10 to 1.0 during the present study and, as stated previously, there did not seem to be any definite trend regarding ζ_{RS}. Figure 7 shows a plot of ζ_{RS} against the frequency of the coupled roll-spiral mode,

ω_{RS}, with the corresponding pilot ratings. It could be said, however, that for configurations having ω_{RS} greater than 0.35, an increase in ζ_{RS} appears to be beneficial indicated by the pilot ratings becoming better. It should also be mentioned that when the ζ_{RS} is high ($\zeta_{RS} > 0.50$), as is the case for other parameters, the pilots may be able to "handle" the aircraft better than when $\zeta_{RS} < 0.50$. Yet this will not necessarily be reflected in the pilot rating that he assigned to the configuration.

Effects of the Dutch Roll Mode.- The effect of the Dutch roll frequency ω_d was not studied during the analysis and was held at approximately the value for that of the basic configuration ($\omega_d \approx 2.0$). The Dutch roll damping ζ_d, however, was varied from 0.05 to approximately 1.0 during the present study for various combinations of ω_{RS} and ζ_{RS}. Figure 8 shows a plot of ζ_d against ω_{RS} with the corresponding pilot ratings. As can be seen, no definite trend is established. It only stands to reason that when the roll and spiral modes couple and form a second oscillatory mode, in addition to the conventional Dutch roll mode, that the better the Dutch roll damping, the easier it will be for the pilot to cope with the adverse effects caused by the coupled roll-spiral mode.

Two final pilot comments which applied to all of the configurations having the roll-spiral coupled mode were the following: (1) The simulator had to be flown with small lateral inputs and all pilot ratings are subject to this, and (2) for the majority of the configurations evaluated, 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.

C. Additional Analysis

With the results of the simulator study, an attempt was made to understand further (1) the difference between the roll characteristics for a configuration having a low frequency roll-spiral oscillation ($\omega_{RS} < 0.20$) and one having a high frequency roll-spiral oscillation ($\omega_{RS} > 0.40$); and (2) the reason why the pilots were required to use small lateral inputs during roll maneuvers. In regard to the roll characteristics, time histories of the roll rate for the various configurations studied with a 2° aileron step input were calculated and the following results were found. For the configurations having the low frequency roll-spiral oscillations, the pilot sees the ailerons commanding roll acceleration as shown in Figure 9. This type of roll rate response is the main reason for the aircraft to be overly responsive to lateral inputs, and adds to the difficulty in roll control. Figure 10 shows a typical configuration having a high frequency roll-spiral coupled mode and that the ailerons now command roll attitude. This type of roll rate is more acceptable than the acceleration command; however, for a very high frequency roll-spiral oscillation such as Configuration 8, the pilot was only able to roll the aircraft to a 30° bank angle with full aileron input.

For all of the configurations having the coupled roll-spiral mode, the pilot ratings were based on small lateral inputs; therefore an analysis of the closed-loop aileron control characteristics for the hypothetical transport was made using the root locus technique. The dynamic representation of the pilot was approximated as being a pure gain, K_p; that is, the pilot actuates the aileron control proportional to the observed error in bank angle, without adding lead or lag to the system. This method used may be of questionable validity for the wide range of lateral characteristics examined, but it does provide a reasonable estimation to the reasons for piloting difficulties in roll control.

Three representative configurations from the simulator study are used to illustrate why the pilots were required to use small lateral control inputs during roll maneuvers. The configurations used were 1, 22, and 17, and the results are presented in Figure 11. A plot of the root locus of the closed-loop bank angle transfer function for variation in pilot gain of Configuration 1 is presented in Figure 11(a). The root locus plot indicates that either small or large control inputs could be used for roll maneuvers since, for all pilot gains, all modes remain in the stability portion of the complex plane and are well damped. The root locus for a variation in pilot gain for Configuration 22 is presented in Figure 11(b). Configuration 22 represents a condition where the roll and spiral modes coupled and formed a low frequency oscillation, $\omega_{RS} = 0.10$. It is seen from Figure 11(b) that if the pilot

disturbs the aircraft in roll and uses anything other than very small inputs, the coupled roll-spiral oscillatory mode will become unstable (ζ_{RS} becomes negative). Configuration 17 represents a condition where the roll and spiral modes have coupled and formed an oscillation with a frequency ω_{RS} of 0.40. Figure 11(c) presents the root locus for a variation in pilot gain for Configuration 17 and it is shown that although the oscillation does not become unstable as the pilot gain is increased, it is indicated that 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.

X. CONCLUDING REMARKS

The following remarks are made summarizing the results obtained during a fixed-base simulation program conducted to determine the coupled roll-spiral mode effects on the lateral-directional handling qualities of a hypothetical STOL subsonic transport.

The comments made by the pilots, and the pilot ratings assigned to the various configurations, indicated that in order for the aircraft to have an "acceptable" rating (PR $\leq$ 6-1/2), the frequency of the coupled roll-spiral oscillatory mode, ω_{RS}, should be greater than 0.35, and indications are that ω_{RS} should not be greater than approximately 1.0.

Generally, the higher the damping ratio of the coupled roll-spiral oscillatory mode ζ_{RS} and the damping ratio of the conventional Dutch roll mode ζ_d, the better the possibility is of having acceptable handling qualities. However, there did not seem to be any definite trend regarding the 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 resulting oscillation 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 easier if the rudder was not used.

The fixed-base simulator results of this investigation are believed to be conservative. That is, since the majority of the conditions evaluated resulted in the pilots assigning marginally acceptable or marginally unacceptable Cooper ratings to them, it is believed that if these conditions were evaluated during an in-flight simulation program, or if these conditions existed on an actual aircraft, where all the necessary pilot cues are present, the marginally unacceptable conditions could very well become acceptable; furthermore, the acceptable conditions could conceivably become satisfactory.

XI. REFERENCES

1. Newell, F. D.: Ground Simulator Evaluations of Coupled Roll-Spiral Mode Effects on Aircraft Handling Qualities. AFFDL-TR-65-39 (CAL Report No. TC-1921-F-1), March 1965.
2. Seckel, Edward: Stability and Control of Airplane and Helicopters. Academic Press, Inc., C. 1964.
3. Distefano, J. J., III, Stufferud, A. R., and Williams, I. J.: Feedback and Control Systems. Schaum Publishing Company, 1967.
4. Grantham, W. D., and Deal, P. L.: A Piloted Fixed-Base Simulator Study of Low-Speed Flight Characteristics of an Arrow-Wing Supersonic Transport Design. NASA TN D-4277, 1968.
5. Stapleford, R. L., Johnston, D. E., Teper, G. L., and Weir, D. H.: Development of Satisfactory Lateral-Directional Handling Qualities in the Landing Approach. Systems Technology, Inc., NASA CR-239, July 1965.

XII. VITA

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XIII. APPENDIX

A. Equations of Motion

The general analysis of the roll-spiral coupled mode of motion and the method of determining aerodynamic stability derivatives were based on the following lateral equations of motion which are given in Laplace transform and in prime notation.

$$\begin{bmatrix} (S - Y_\beta) & (-\sin\alpha_o - \frac{g}{sv}\cos\theta_o - Y_p) & (\cos\alpha_o - Y_r - \frac{g}{sv}\sin\theta_o) \\ (-L'_\beta) & (S - L'_p) & (-L'_r) \\ (-N'_\beta) & (-N'_p) & (S - N'_r) \end{bmatrix} \begin{Bmatrix} \beta \\ P \\ r \end{Bmatrix} = \begin{Bmatrix} Y_\delta \\ L'_\delta \\ N'_\delta \end{Bmatrix} \delta$$

where δ can be δ_a or δ_r.

$$N'_i = \frac{I}{K}\left(N_i + \frac{I_{XZ}}{I_Z} L_i\right)$$

$$L'_i = \frac{I}{K}\left(L_i + \frac{I_{XZ}}{I_X} N_i\right)$$

$$K = 1 - \frac{I_{XZ}^2}{I_X I_Z}, \quad i = p, r, \beta, \delta_a, \delta_r$$

From these equations of motion, the characteristic equation describing the lateral open-loop (no pilot) flight motions of an aircraft is determined. This is accomplished by setting the determinant of the square matrix equal to zero and is of the following form:

$$AS^4 + BS^3 + CS^2 + DS + E = 0$$

where

$$A = 1$$

$$B = -Y_B - L'_p - N'_r$$

$$C = N'_\beta \cos \alpha_o - L'_\beta \sin \alpha_o + L'_p N'_r$$

$$-L'_r N'_p + Y_\beta \left(L'_p + N'_r \right) - Y_r N'_\beta - Y_p L'_\beta$$

$$D = \cos \alpha_o \left(L'_\beta N'_p - L'_p N'_\beta \right) + \sin \alpha_o \left(L'_\beta N'_r - L'_r N'_\beta \right) - Y_\beta \left(L'_p N'_r - L'_r N'_p \right)$$

$$- \frac{g}{v} \left(L'_\beta \cos \theta_o + N'_\beta \sin \theta_o \right) + Y_r \left(L'_p N'_\beta - N'_p L'_\beta \right) + Y_p \left(L'_\beta N'_r - N'_\beta L'_r \right)$$

$$E = \frac{g}{v} \left(L'_\beta N'_r - L'_r N'_\beta \right) \cos \theta_o + \left(L'_p N'_\beta - L'_\beta N'_p \right) \sin \theta_o$$

B. Method of Determining Aerodynamic Stability Derivatives

In the study of the roll-spiral coupled mode of motion, it was required to know the values of the aerodynamic stability derivatives, C_{Y_β}, C_{l_β}, C_{n_β}, C_{n_p}, C_{l_p}, C_{n_r}, and C_{l_r} which would produce various combinations of frequency and damping for the roll-spiral and Dutch roll oscillatory modes. The following method was used to determine the values of these derivatives.

For this method the characteristic equation of the lateral equation of motion was rewritten for the stability axis system in which $\alpha_o = 0$. Also, the following assumptions were made:

$$\theta_o = 0$$

$$Y_p = Y_r = 0$$

Therefore, the coefficients of the characteristic equation become:

$$A = 1$$

$$B = -Y_\beta - N'_r - L'_p$$

$$C = N'_\beta - L'_r N'_p + Y_\beta \left(L'_p + N'_r \right) + L'_p N'_r$$

$$D = L'_\beta N'_p - L'_p N'_\beta - Y_\beta \left(L'_p N'_r - L'_r N'_p \right) - \frac{g}{v} L'_\beta$$

$$E = \frac{g}{v} \left(L'_\beta N'_r - L'_r N'_\beta \right)$$

Since the modes of motion consist of two oscillations, namely, the Dutch roll and roll-spiral coupled modes, the solution to the characteristic equations is of this form:

$$(S^2 + 2\zeta_d\omega_d S + \omega_d^2)(S^2 + 2\zeta_{RS}\omega_{RS}S + \omega_{RS}^2) = 0$$

Multiplying out:

$$S^4 + (2\zeta_{RS}\omega_{RS} + 2\zeta_d\omega_d) S^3 + (\omega_{RS}^2 + 4\zeta_{RS}\zeta_d\omega_{RS}\omega_d + \omega_d^2) S^2$$
$$+ (2\zeta_d\omega_d\omega_{RS}^2 + 2\zeta_{RS}\omega_{RS}\omega_d^2) S + \omega_d^2\omega_{RS}^2 = 0$$

Setting the coefficients of the characteristic equation equal:

$$A = 1$$

$$B = (2\zeta_{RS}\omega_{RS} + 2\zeta_d\omega_d) = (-Y_\beta - N_r' - L_p')$$

$$C = (\omega_{RS}^2 + 4\zeta_{RS}\zeta_d\,\omega_{RS}\omega_d + \omega_d^2) = (N_\beta' - L_r'N_p' + Y_\beta L_p' + Y_\beta N_r' + L_p'N_r')$$

$$D = (2\zeta_d\omega_d\omega_{RS}^2 + 2\zeta_{RS}\omega_{RS}\omega_d^2) = (L_\beta'N_p' - L_p'N_\beta' - Y_\beta L_p'N_r' + Y_\beta L_r'N_p' - \frac{g}{v} L_\beta')$$

$$E = (\omega_d^2\omega_{RS}^2) = \frac{g}{v}(L_\beta'N_r' - L_r'N_\beta')$$

By specifying the frequency and damping of the Dutch roll and roll-spiral coupled modes of motion, we have four nonlinear equations and seven unknown stability derivatives. By assuming that any three of the lateral stability derivatives are known, the other four derivatives can be determined. For example, Y_β, N_β', and L_β' are assumed to be known.

Let $Y_\beta = X$

$N'_\beta = Y$

$L'_\beta = Z$

then

$$B = -X - N'_r - L'_p$$

$$C = Y - L'_r N'_p + X\left(L'_p + N'_r\right) + L'_p N'_r$$

$$D = ZN'_p - YL'_p - X\left(L'_p N'_r - L'_r N'_p\right) - \frac{g}{v} Z$$

$$E = \frac{g}{v}\left(ZN'_r - YL'_r\right)$$

Where B, C, D, E are known by specifying desired values for the frequency and damping of the two lateral oscillations

Let $C1 = B + X$

$C2 = C - Y$

$C3 = D + \frac{g}{v} Z$

$C4 = E \frac{v}{g}$

$$C1 = -N'_r - L'_p \tag{1}$$

$$C2 = L'_r N'_p + XL'_p + XN'_r + L'_p N'_r \tag{2}$$

$$C3 = ZN'_p - YL'_p - XL'_p N'_r + XL'_r N'_p \tag{3}$$

$$C4 = ZN'_r - YL'_r \tag{4}$$

$$L'_p = -(C1 + N'_r) \tag{1-a}$$

$$L'_r = \frac{ZN'_r - C4}{Y} \tag{4-a}$$

Substitute (1-a) and (4-a) into (2) and solve for N'_p

$$N'_p = \frac{Y\,(X\,C1 + C2 + C1\,N'_r + N'^2_r)}{(C4 - Z\,N'_r)} \tag{2-a}$$

Substitute (1-a), (4-a), and (2-a) into (3) and solve for N'_r

$$N'_r = \frac{C2C4X + C1C4X^2 + C3C4 - C1XYZ - C2YZ - C1C4Y}{C3Z + C4Y + C1X^2Z + C2XZ} \tag{3-a}$$

Using equations (3-a), (1-a), (4-a), and (2-a), the values for the stability derivatives, N'_r, L'_p, L'_r, and N'_p, can be determined for any combination of frequency and damping of the lateral oscillations. It is pointed out that for particular combinations of the frequency and damping, the values of the stability derivatives may be very unrealistic. Also, after the aerodynamic stability derivatives were determined, these derivatives were transferred back to the body axis system which was used in programming the simulator.

C. ϕ/δ_a Transfer Function

The hypothetical transport's stick to bank angle transfer function was determined from Reference 5 and is as follows:

The roll rate angular velocity is

$$P = \dot{\phi} - r \sin \theta_o$$

or

$$\dot{\phi} = P + r \tan \theta_o$$

in Laplace transform style

$$S\phi = P + r \tan \theta_o$$

therefore the stick to bank angle transfer function is

$$\frac{\phi}{\delta_a} = \left(\frac{P}{\delta_a} + \frac{r}{\delta_a} \tan \theta_o\right)/S$$

where

$$\frac{P}{\delta_a} = \frac{N_{p\delta_a}}{\Delta} \quad \text{roll rate transfer function}$$

$$\frac{r}{\delta_a} = \frac{N_{r\delta_a}}{\Delta} \quad \text{yaw rate transfer function}$$

The roll and yaw rate transfer function are determined from the equation of motion and are equal to:

$$N_{p_{\delta_a}} = \begin{vmatrix} (S - Y_\beta) & Y_{\delta_a} & (\cos \alpha_o - Y_r - \frac{g}{Sv} \sin \theta_o) \\ (-L'_\beta) & L_{\delta_a} & (-L'_r) \\ (-N'_\beta) & N_{\delta_a} & (S - N'_r) \end{vmatrix} \frac{1}{\Delta}$$

$$N_{r_{\delta_a}} = \begin{vmatrix} (S - Y_\beta) & (- \sin \alpha_o - \frac{g}{Sv} \cos \theta_o - Y_p) & Y_{\delta_a} \\ (-L'_\beta) & (S - L'_p) & L_{\delta_a} \\ (-N'_\beta) & (-N'_p) & N_{\delta_a} \end{vmatrix} \frac{1}{\Delta}$$

Δ = Characteristic equation of motion for the dynamic system

The transfer function for the bank angle due to a unit step aileron input is

$$\frac{\phi}{\delta_a} = \frac{N\phi_{\delta_a}}{\Delta} = \frac{N_{p\delta_a} + N_{r\delta_a} \tan \theta_o}{S\Delta}$$

where

$$N\phi_{\delta_a} = C_1 S^2 + C_2 S + C_3$$

$$C_1 = L'_{\delta_a} + N'_{\delta_a} \tan \theta_o$$

$$C_2 = L'_\beta Y_{\delta_a} - L'_{\delta_a} (Y_\beta + N'_r)$$

$$+L'_r N'_{\delta_a} + Y_{\delta_a} N'_\beta \tan \theta_o + N'_p L'_{\delta_a}$$

$$-N'_{\delta_a} (Y_\beta + L'_p)$$

$$C_3 = -Y_{\delta_a} (N'_r L'_\beta - N'_\beta L'_r)$$

$$+L'_{\delta_a} (N'_\beta \cos \alpha_o - N'_\beta Y_r + N'_r Y_\beta)$$

$$-N'_{\delta_a} (Y_\beta L'_r + L'_\beta \cos \alpha_o - L'_\beta Y_r)$$

$$+Y_{\delta_a} \tan \theta_o (L'_\beta N'_p - N'_\beta L'_p)$$

$$-L'_{\delta_a} \tan \theta_o (Y_\beta N'_p - N'_\beta \sin \alpha_o - N'_\beta Y_p)$$

$$+N'_{\delta_a} \tan \theta_o (L'_p Y_\beta - L'_\beta \sin \alpha_o - L'_\beta Y_p)$$

D. Pilot Comments and Cooper Ratings For Each Configuration

Configuration 1 (basic).- Pilots A and B assigned the configuration a 2.0 Cooper rating and made the following comments:

1. Roll control is excellent.

2. Roll damping is excellent; the roll rate stops immediately upon stick release.

3. The adverse-proverse yaw is negligible. The leading response and turn entry are good.

4. There is no apparent Dutch roll.

5. The spiral stability is fair; may be a little too stable.

6. The tendency to sideslip during maneuvers is excellent (very small).

7. Would like to see a slight reduction in lateral stick force, or as a second choice, a slight increase in the longitudinal stick force.

Configuration 2.- Pilot A assigned the configuration a 4.0 Cooper rating and Pilot B assigned a Cooper rating of 6.0. They made the following comments:

1. Roll damping is very low.

2. Strong checking technique is required to acquire desired bank angle. Also, a precise bank angle is very difficult to hold, once achieved.

3. Spiral stability is strongly positive.

Configuration 3.- Pilot B assigned this configuration a 7.0 Cooper rating and made the following comments:

1. Roll damping is very low.

2. A desired bank angle is difficult to acquire and maintain.

3. Spiral stability is very strong.

4. Proverse yaw is strong.

5. There is no apparent Dutch roll.

Configuration 4.- Pilot A assigned this configuration a 6.0 Cooper rating and Pilot B assigned a Cooper rating of 7.0. They made the following comments:

1. Roll damping is very low.

2. The spiral stability is strongly positive and the proverse yaw is high.

3. Desired bank angles are almost impossible to acquire and maintain. A bank angle can be maintained close to the desired value only by the pilot furnishing his own roll damping (pilot damps the bank angle by continuously putting in small lateral inputs). For large lateral inputs, large roll oscillations in roll develop, but with small lateral inputs, the bank angle is fairly controllable.

4. Due to the high proverse yaw, it is very difficult to "roll-out" on the desired heading.

Configuration 5.- Pilots A and B assigned the configuration a 10.0 Cooper rating and made the following comments:

1. The aircraft is completely uncontrollable.

2. The roll damping appears to be nonexistent and the proverse yaw is very high.

Configuration 6.- Pilots A and B assigned this configuration a 7.5 Cooper rating and made the following comments:

1. A desired bank angle is difficult to acquire and maintain due to the low roll damping and strong spiral stability.

2. A desired heading is impossible to roll-out on precisely because of the high proverse yaw.

3. The Dutch roll oscillation is easily excited with lateral control inputs, but the Dutch roll damping appears to be good.

4. The aircraft can be controlled only by keeping the lateral control inputs small. The aircraft would probably be uncontrollable in heavy turbulence.

Configuration 7.- Pilot A assigned this configuration a 4.0 Cooper rating and Pilot B assigned a Cooper rating of 4.5. They made the following comments:

1. The roll damping is low. It is not difficult to acquire a desired bank angle, but it is difficult to maintain due to a long period oscillation about the desired angle.

2. Spiral stability is strongly positive and the proverse yaw is high.

3. The Dutch roll characteristics are pretty bad, the damping is fair, but the period of the oscillation is too long.

Configuration 8.- Pilot A assigned this configuration a Cooper rating of 9.5 and made the following comments:

1. The aircraft is uncontrollable.

2. With full lateral control input, the pilot can only command a 30° bank angle. This bank angle can be held with full lateral input if the control has been applied slowly in order to achieve it in the first place. When the control stick is centered, the lateral phugoid is triggered which is of high frequency. With a rapid lateral control input, the pilot cannot reach a desired bank angle because the oscillation (roll-spiral coupled mode which was called lateral phugoid mode above) is excited immediately.

Configuration 9.- Pilot A assigned this configuration a 5.0 Cooper rating and made the following comments:

1. The roll damping is moderately low, which requires a lot of control activity in order to remain close to a desired bank angle.

2. The dihedral effect is very strong which is coupled with a long period (low frequency) lateral oscillation.

3. Pilot can roll to a predetermined heading with few corrections being necessary.

Configuration 10.- Pilot A assigned this configuration a 4.5 Cooper rating and made the following comments:

1. The pilot can achieve a near desired bank angle. Although he is oscillating around the desired bank angle, he can maintain this angle within the oscillations and the smaller the lateral inputs the smaller the oscillations. He has to maintain a given control input in order to maintain a desired bank angle, the roll rate washes out very quickly.

2. The roll damping appears to be fair, but the dihedral effect is very strong.

3. He can roll to a desired heading. Then, if a roll-out is desired, the stick may be centered and the dihedral effect will roll the wings level in an oscillatory manner. If a wings-level condition is desired quickly, opposite lateral control is required; however, overshoot generally results.

Configuration 11.- Pilot A assigned this configuration a 6.5 Cooper rating and made the following comments:

1. The roll damping is very low. A near desired bank angle can be achieved with very slow lateral control inputs; even the smallest lateral input triggers a lateral oscillation.

2. Very little sideslip is generated with lateral control inputs.

3. This configuration is overly responsive in roll.

Configuration 12.- Pilot A assigned this configuration a 4.5 Cooper rating and made the following comments:

1. The roll damping is very low. The pilot can achieve a desired bank angle with small lateral control inputs; large lateral inputs result in large overshoots which trigger a lateral oscillation.

2. The best procedure for returning the wings to level after achieving a desired heading is to simply release the control pressure that was required to maintain the desired bank angle.

3. Very little sideslip is generated with lateral inputs, and there is little evidence of a Dutch roll mode.

Configuration 13.- Pilot A assigned a Cooper rating of 4.5 to this configuration and made the following comments:

1. Roll damping is very low.

2. The spiral stability is much too positive.

3. There is little evidence of a Dutch roll mode.

4. The pilot must use small lateral inputs during maneuvers to keep from triggering a lateral oscillation.

Configuration 14.- Pilot A assigned this configuration a 5.0 Cooper rating and made the following comments:

1. Roll damping is very low.

2. A lateral oscillation is quite easily triggered during any kind of rolling maneuvers.

Configuration 15.- Pilot A assigned a Cooper rating of 5.0 to this configuration and made the following comments:

1. Due to the low roll damping and the strong positive spiral stability, it is difficult to acquire and maintain a desired bank angle.

2. When attempting to roll to a desired bank angle, a lateral oscillation is triggered; however, if small control inputs are used, this lateral oscillation is not a big problem.

3. It is possible to roll out to a desired heading.

4. There is no evidence of any proverse or adverse yaw.

5. The major objection to this configuration is the low roll damping.

Configuration 16.- Pilot A assigned this configuration a 4.0 Cooper rating and made the following comments:

1. The pilot can achieve and maintain any desired bank angle with considerable effort. The roll damping is low and the spiral stability is strongly positive which adds to the pilot's work load in maintaining a desired bank angle.

2. There is a very slight amount of adverse yaw.

3. Lateral-control response and sensitivity are slightly high.

Configuration 17.- Pilot A assigned this configuration a 3.5 Cooper rating and made the following comments:

1. The roll damping is less than good.

2. The spiral stability is moderately stable.

3. Desired bank angle can be achieved with many lateral inputs, and can roll-out to a predetermined heading from any bank angle.

4. A lateral oscillation is experienced during roll maneuvers, but this oscillation seems to be well damped.

5. There is little or no adverse or proverse yaw associated with lateral control inputs.

Configuration 18.- Pilot A assigned this configuration a 4.5 Cooper rating and made the following comments:

1. The roll damping is low.

2. A desired bank angle is very difficult to achieve and maintain due to the poor roll damping and the strong spiral stability.

3. A lateral oscillation is triggered during roll maneuvers, but this oscillation seems to be moderately damped.

4. The pilot can roll to a desired heading from any bank angle.

5. The aircraft is overly responsive in roll.

6. There is no evidence of adverse or proverse sideslip.

Configuration 19.- Pilot A assigned a 4.0 Cooper rating to this configuration and made the following comments:

1. The roll damping is low and the spiral mode is too stable.

2. Response and sensitivity in roll is too high.

3. Small lateral control inputs are required, with many small corrections, to achieve and maintain a desired bank angle; these many small corrections are needed because of the low roll damping and strong spiral stability.

4. The greater the lateral input, the greater the lateral oscillation is.

5. The major objections are the low roll damping and the fact that the lateral oscillation is present.

Configuration 20.- Pilot A assigned this configuration a 4.0 Cooper rating and made the following comments:

1. The roll damping is slightly low and the spiral stability is slightly strong.

2. Pilot can roll to a desired bank angle with several small corrections being required and had to supply own damping by several control reversals.

3. Very little sideslip is produced with small to moderate lateral control inputs.

4. A lateral oscillation is triggered during roll maneuvers, but this oscillation seems to be highly damped.

5. Pilot can roll out to a desired heading.

Configuration 21.- Pilot A assigned a 7.0 Cooper rating to this configuration and made the following comments:

1. The roll damping is very low; it is almost impossible to roll to a desired bank angle. Extremely small lateral control inputs are required for any resemblance of control of the aircraft.

2. The aircraft is overly responsive in roll and a lateral oscillation is triggered during roll maneuvers. The lateral oscillation appears to be fairly well damped, but it has such low frequency it is hard to counter. The oscillation can be damped with many control inputs, but it cannot be completely stopped.

3. There is a moderate amount of proverse yaw with small control inputs.

Configuration 22.- Pilot A assigned this configuration a 6.0 Cooper rating and made the following comments:

1. The roll damping is low. If a lateral control input is made and not countered with opposite control input, the bank angle is divergent; there appears to be no natural damping.

2. With considerable pilot effort, a near desired bank angle can be achieved.

3. It is practically impossible to roll out on a desired heading.

4. The response of the aircraft is too high.

5. There is a moderate amount of proverse sideslip.

Configuration 23.- Pilot A assigned this configuration a 6.0 Cooper rating and made the following comments:

1. The roll damping is low. It is very difficult to roll to a desired bank angle. Also, in order to maintain a desired bank angle, constant corrections are required. It is impossible to control bank angle unless very small lateral control inputs are made.

2. It is very difficult to roll out to a desired heading.

3. The aircraft is overly responsive in roll.

4. There is a moderate amount of proverse sideslip.

Configuration 24.- Pilot A assigned a 4.5 Cooper rating to this configuration and made the following comments:

1. The roll damping is slightly low. There is fairly strong spiral stability. A desired bank angle can be achieved and maintained without too much pilot effort, although numerous corrections are required to supply needed roll damping.

2. The aircraft is overly responsive in roll.

3. A pre-selected heading can be achieved.

4. Little or no sideslip is generated with lateral control inputs.

5. The major objection is that the roll damping is low.

Configuration 25.- Pilot A assigned this configuration a 4.5 Cooper rating and made the following comments:

1. The roll damping is low and the spiral stability is strongly positive.

2. A desired bank angle can be achieved and maintained, but requires many lateral control corrections.

3. Roll outs on desired headings can be made from 30° and 45° bank angles.

4. The aircraft is overly responsive.

5. There is no adverse yaw.

Configuration 26.- Pilot A assigned a 5.0 Cooper rating to this configuration and made the following comments:

1. Roll damping is low.

2. For small lateral inputs, the roll rate washes out while for longer lateral inputs, the roll rate appears to be self-substaining.

3. The major objection to this configuration is that the roll damping is very low.

Configuration 27.- Pilot A assigned this configuration a 5.0 Cooper rating and made the following comments:

1. Roll damping is low.

2. For small lateral inputs, the roll rate washes out very quickly.

Configuration 28.- Pilot A assigned this configuration a 4.5 Cooper rating and made the following comments:

1. Although the natural roll damping is higher than some of the previous configurations, it is still too low. Numerous small corrections are needed to achieve and maintain a desired bank angle.

2. There is slightly high proverse yaw with lateral control inputs.

3. A pre-selected heading can be readily achieved.

TABLE I. MASS AND DIMENSIONAL CHARACTERISTICS OF THE HYPOTHETICAL STOL TRANSPORT AIRCRAFT

Weight, lb	50,000
Wing area, sq ft	561
Wing span, ft	60
Mean aerodynamic chord, ft	9.4
I_X, slug-ft sq	78,000
I_Y, slug-ft sq	260,000
I_Z, slug-ft sq	325,000
I_{XZ}, slug-ft sq	0

TABLE II. NONDIMENSIONAL STABILITY DERIVATIVES AND LATERAL DIRECTIONAL CHARACTERISTICS

Conf.	C_{n_β}	C_{l_β}	C_{n_p}	C_{l_p}	C_{n_r}	C_{l_r}	ω_d	ζ_d	$T_{1/2}$	P	$\lvert\phi/\beta\rvert_d$	ω_ϕ/ω_d	ω_{RS}	ζ_{RS}	$T_{1/2}$	P	$\lvert\phi/\beta\rvert_{RS}$	ω_ϕ/ω_{RS}	Pilot Rating A	Pilot Rating B
1 (Basic)	+0.12	-0.06	+0.04	-0.50	-1.00	+0.10	1.93	0.38	0.94	3.52	1.37	0.97							2.5	2.0
2			+0.04	-0.10			1.95	0.34	1.04	3.43	1.54	0.95	0.31	0.97	2.33	91.02	72.70	6.11	4.0	6.0
3			+0.80	-0.50			2.30	0.79	0.38	4.47	1.54	0.81	0.26	0.96	2.79	86.68	10.40	7.22		7.0
4			+1.00				2.55	0.79	0.34	4.01	1.32	0.73	0.24	0.25	11.93	27.53	11.10	7.93	6.0	7.0
5					-0.20	0.0	2.11	0.71	0.46	4.20	1.66	0.88	0.14	0.34	14.37	46.99	18.40	13.06	10.0	10.0
6					-0.80		2.55	0.74	0.37	3.64	1.38	0.73	0.24	0.25	11.72	27.58	11.20	7.93	7.5	7.5
7					-3.00		3.76	0.88	0.21	3.57	1.02	0.50	0.31	0.24	9.19	20.94	8.50	6.13	4.0	4.5
8	+0.05	-0.80	+0.04	-0.40	-2.00	+0.10	2.55	0.46	0.59	2.73	1.56	0.49	1.39	0.93	0.54	11.89	68.10	0.89	9.5	
9	+0.05	-0.08	+0.30		-2.00		2.68	0.89	0.29	5.08	2.56	0.48	0.41	0.19	9.00	15.51	11.20	3.12	5.0	
10	+0.12	-1.00	+0.04		-1.00		3.35	0.31	0.66	1.97	10.90	0.55	0.83	0.90	0.93	17.12	99.50	2.21	4.5	
11		-0.06	+0.16	-0.09	-1.84	+0.52	2.00	0.70	0.50	4.40	1.39	0.94	0.30	0.33	7.10	22.14	29.20	6.27	6.5	
12			+0.12	-0.06	-2.03	-0.09			0.50	4.41	2.26	0.94	0.50	0.30	4.55	13.16	29.60	3.75	4.5	
13			+0.11	-0.05	-2.19	-1.08			0.50	4.42	5.62	0.94	0.70	0.30	3.24	9.38	29.80	2.67	4.5	
14			+0.11	-0.02	-2.38	-2.39			0.50	4.44	11.90	0.95	0.90	0.31	2.49	7.27	30.00	2.07	5.0	
15			+0.14	-0.04	-1.95	+0.27			0.50	4.40	1.43	0.94	0.40	0.11	15.87	15.78	30.50	4.70	5.0	
16			+0.13	-0.10	-1.94	+0.26			0.50	4.40	1.60	0.94		0.51	3.41	18.21	28.30	4.70	4.0	
17			+0.12	-0.16	-1.93	+0.25			0.50	4.40	1.76	0.94		0.91	1.91	36.90	25.80	4.70	3.5	
18			+0.06	-0.01	-0.23	-0.59		0.05	7.10	3.14	2.50	0.93		0.22	7.76	16.12	276.70	4.64	4.5	
19			+0.05	-0.06	-0.22	-0.60		0.05	7.07	3.14	2.45	0.93		0.62	2.80	20.02	220.60	4.64	4.0	
20			+0.04	-0.11	-0.20	-0.61		0.05	7.04	3.14	2.37	0.93		0.92	1.79	39.71	186.80	4.64	4.0	
21			+0.40	-0.22	-0.10	+0.01	1.97	0.30	1.16	3.34	1.77	0.94	0.10	0.87	7.83	126.88	61.60	78.28	7.0	
22			+0.57	-0.30	-0.69	+0.30	1.97	0.62	0.56	4.07	1.76	0.94		0.73	9.27	90.16	32.40	18.23	6.0	
23			+0.70	-0.37	-1.31	+0.60	1.94	0.94	0.38	9.16	1.79	0.96		0.93	7.21	165.34	20.60	18.12	6.0	
24			+0.07	-0.03	-0.35	-0.53	2.00	0.10	3.51	3.16	2.44	0.93	0.40	0.32	5.37	16.60	175.30	4.64	4.5	
25			+0.10	-0.05	-0.87	-0.28		0.30	1.16	3.29	2.21	0.93		0.32	5.39	16.58	67.40	4.66	4.5	
26			+0.12	-0.06	-1.40	-0.01		0.50	0.69	3.63	1.91	0.94		0.32	5.47	16.55	41.00	4.68	5.0	
27			+0.13	-0.08	-2.23	+0.41		0.80	0.43	5.25	1.25	0.94		0.30	5.74	16.45	25.80	4.71	5.0	
28			+1.00	-0.60	-0.80	0.0	2.40	0.83	0.35	4.68	1.52	0.78	0.25	0.93	3.00	68.29	9.17	7.50	4.5	

TABLE III. SIMULATOR CONTROL CHARACTERISTICS

Control	Maximum Travel	Breakout Force	Force Deflection
Stick (pitch)	±5 in.	$1.0^{\#} \rightarrow 1.5^{\#}$	2.0 #/in.
Stick (roll)	±3.3 in.	$< 1.0^{\#}$	2.0 #/in.
Pedal	3.3 in.	$\approx 5.0^{\#}$	8.0 #/in.

TABLE IV. PILOT RATING SYSTEM

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

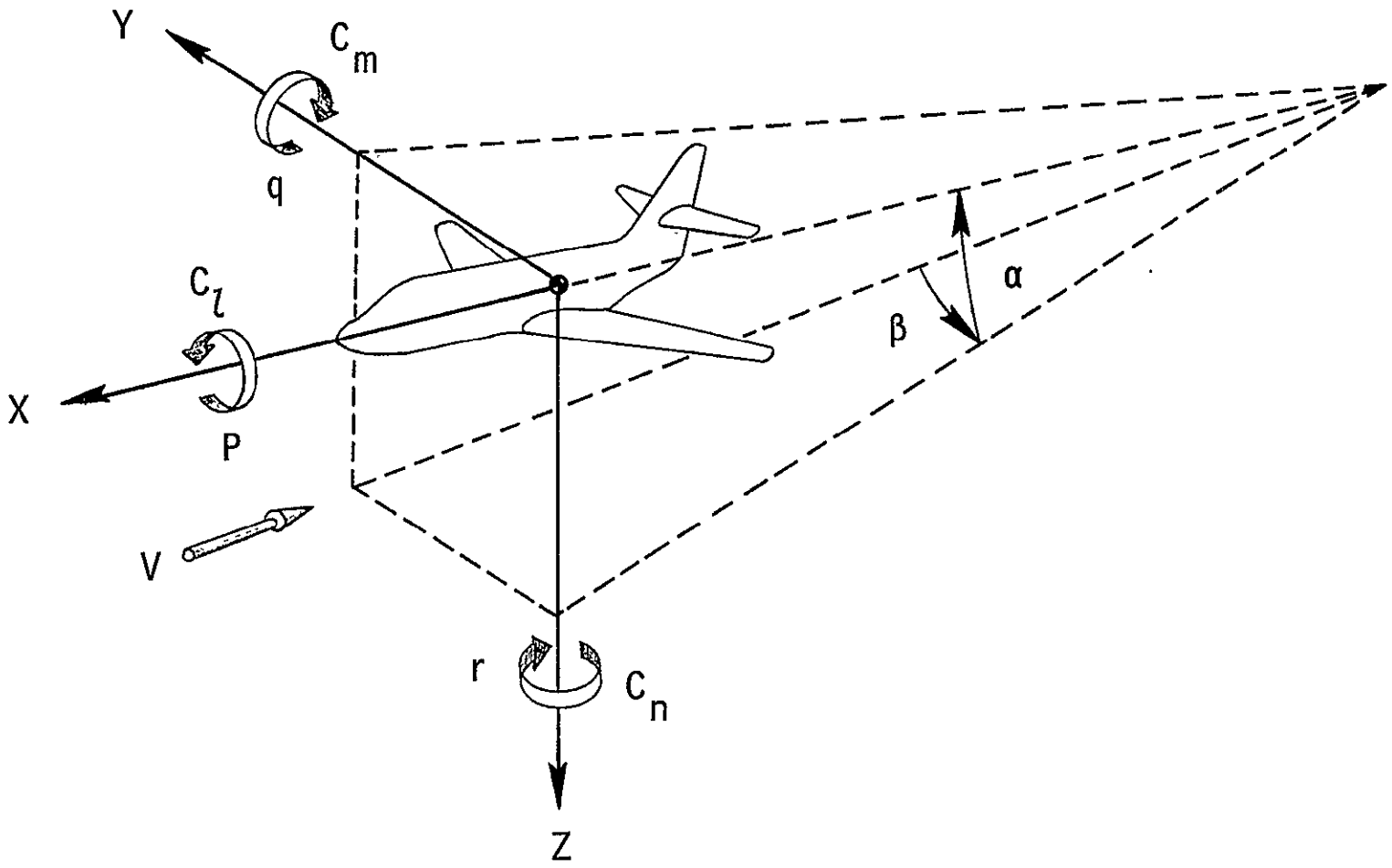


Figure 1.- The body axis system.

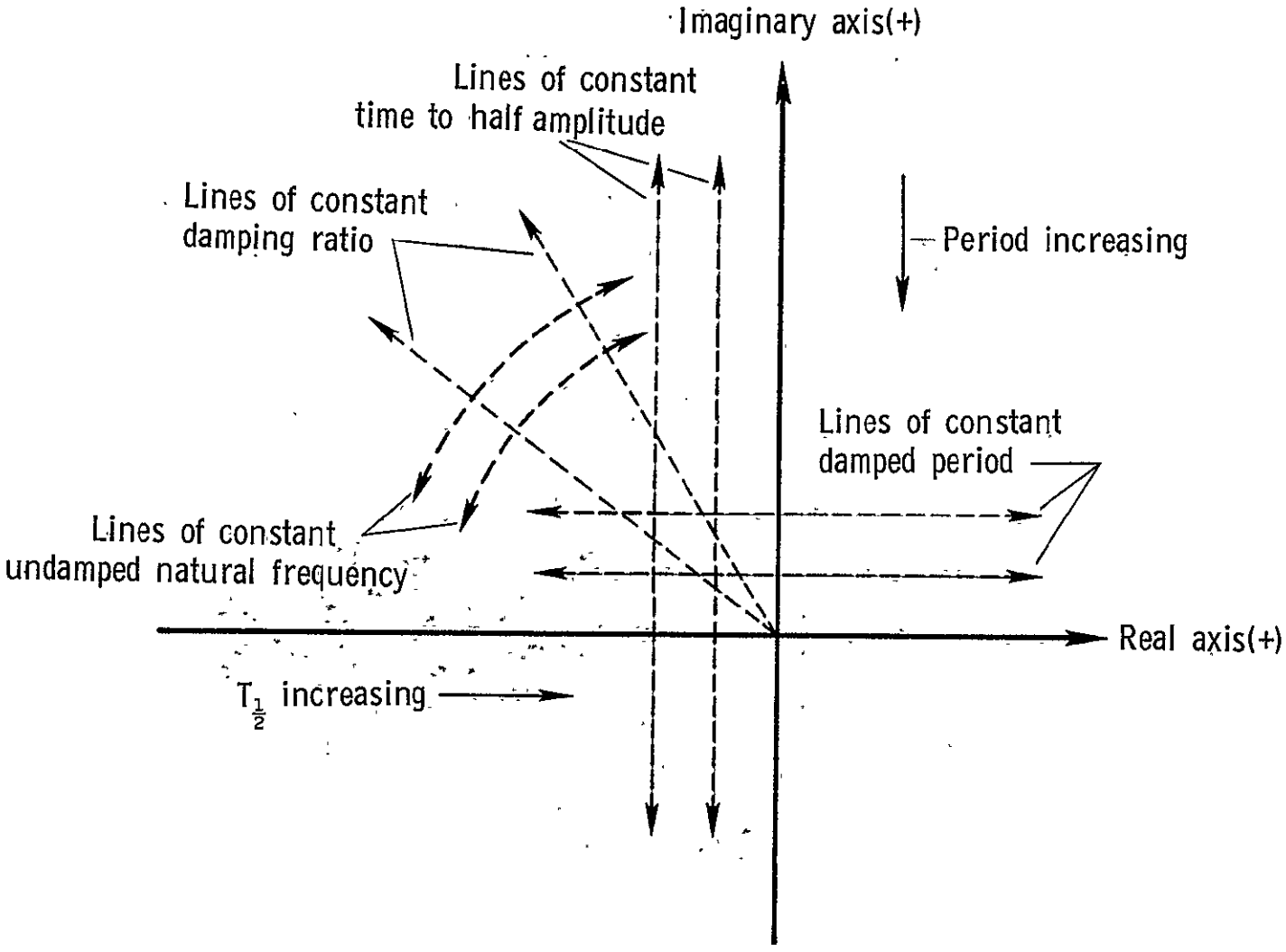


Figure 2.- Features of the complex plane.

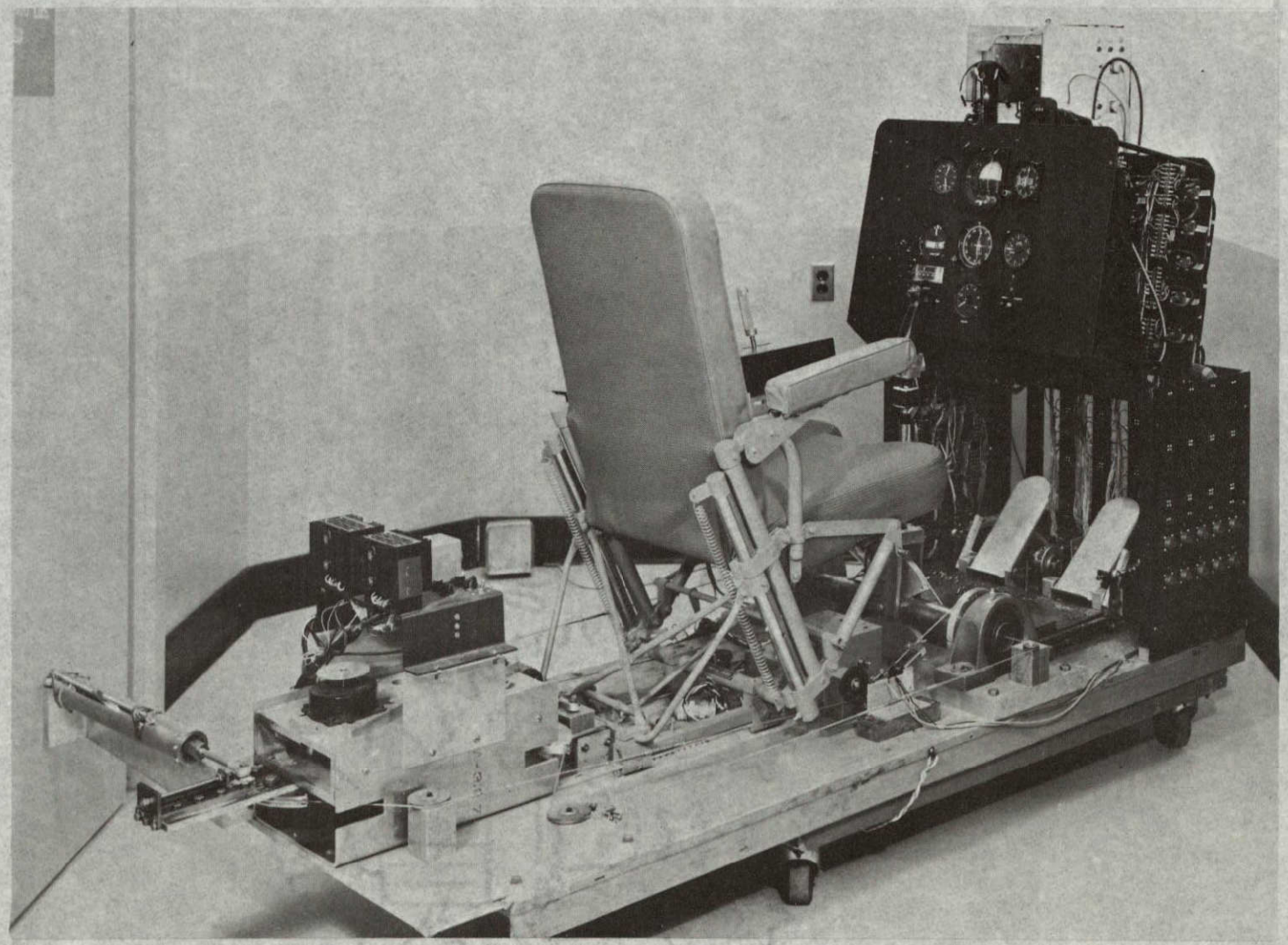


Figure 3.- Photograph of fixed-base simulator.

NOT REPRODUCIBLE

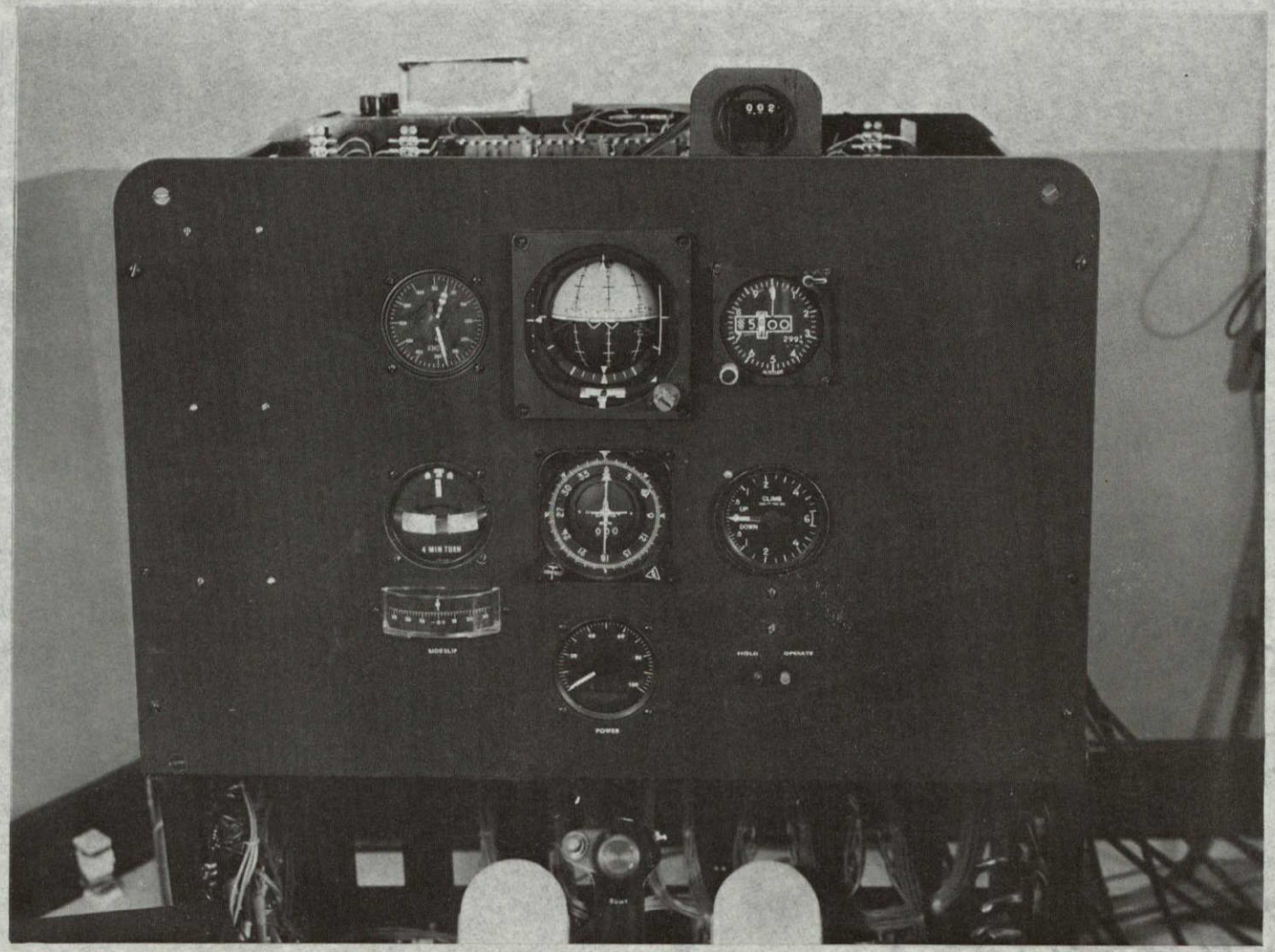


Figure 4.- Photograph of instrument display.

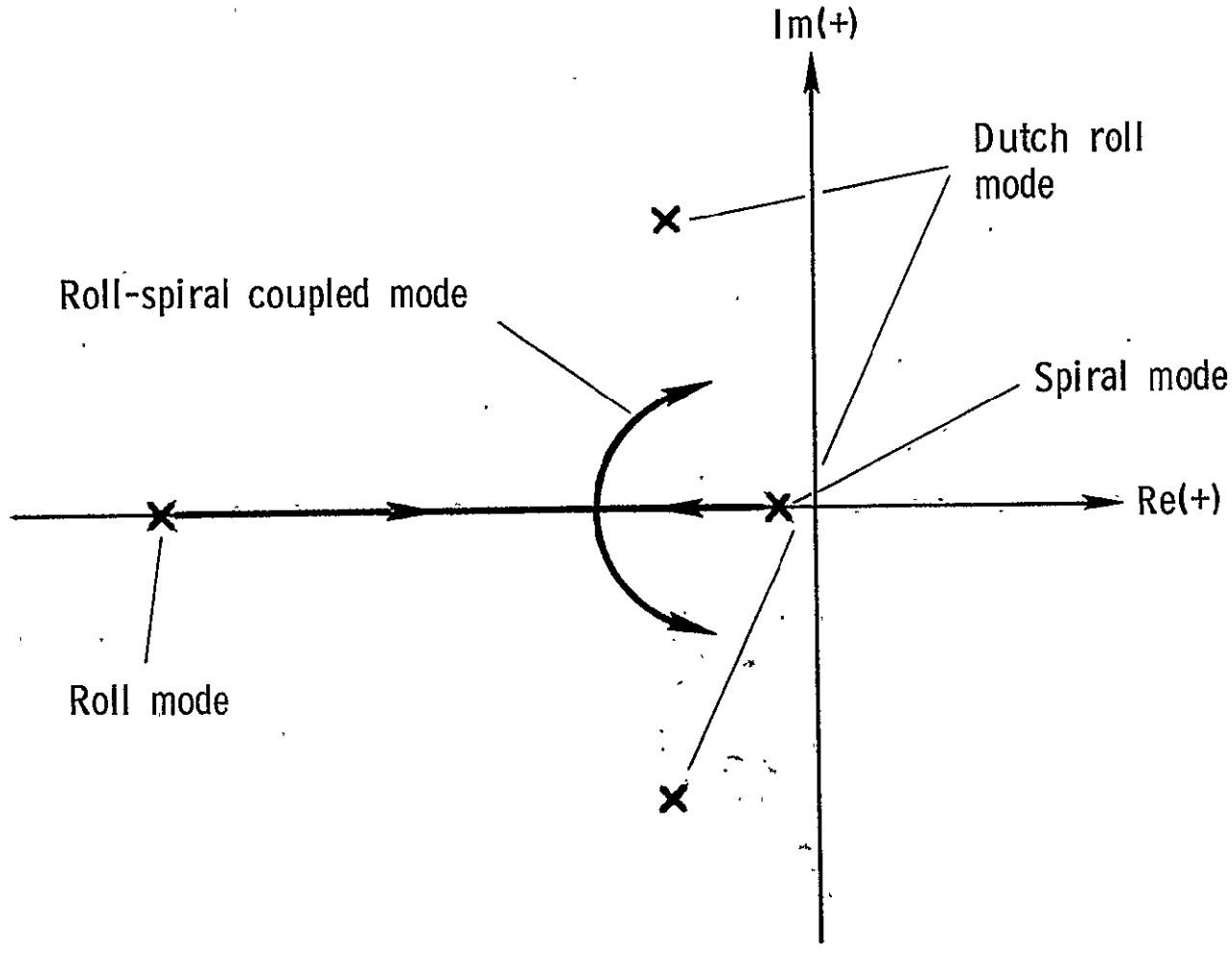


Figure 5.- The formation of the roll-spiral coupled mode.

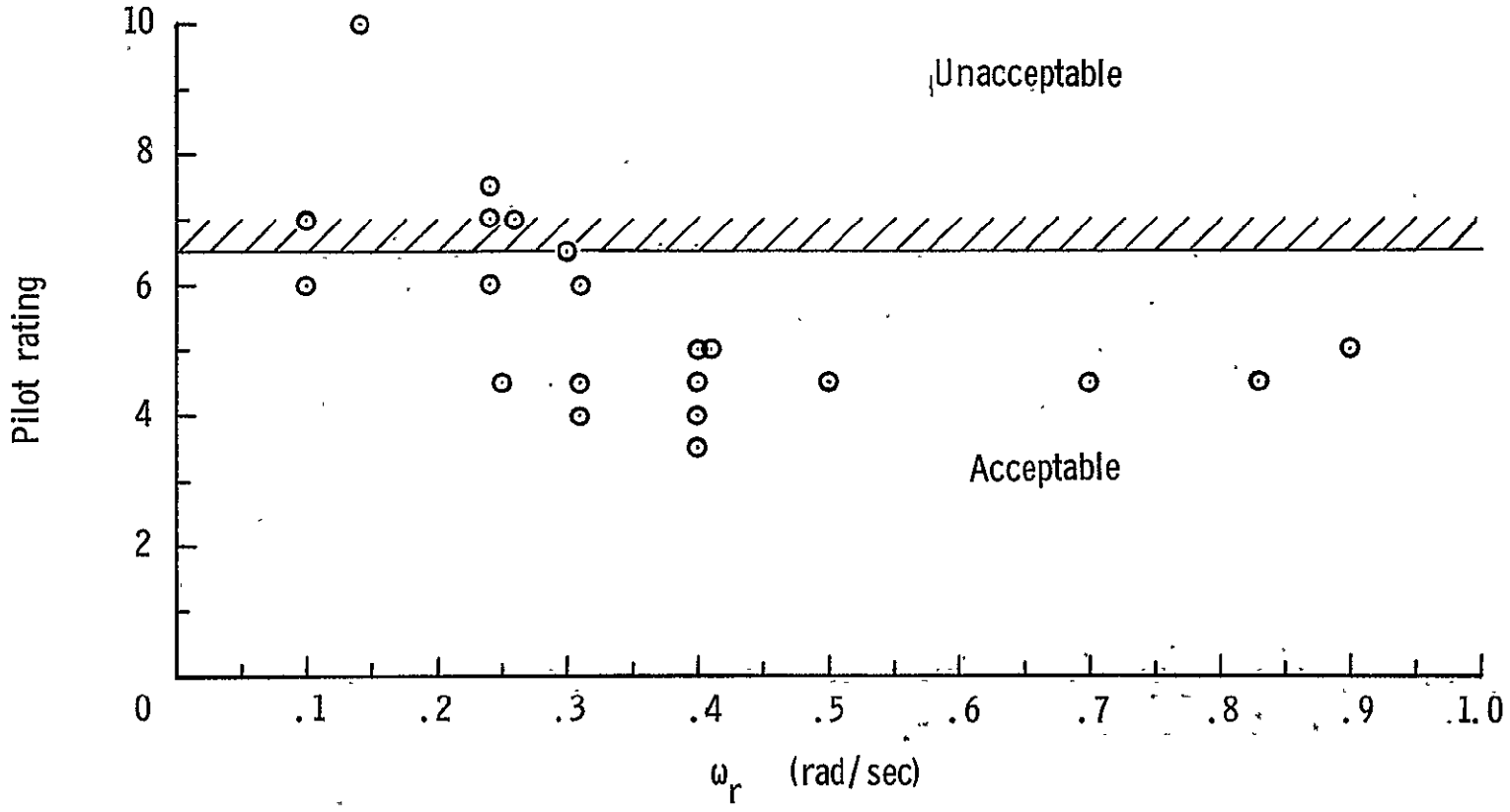


Figure 6.- Effect of frequency of the roll-spiral oscillation on pilot rating.

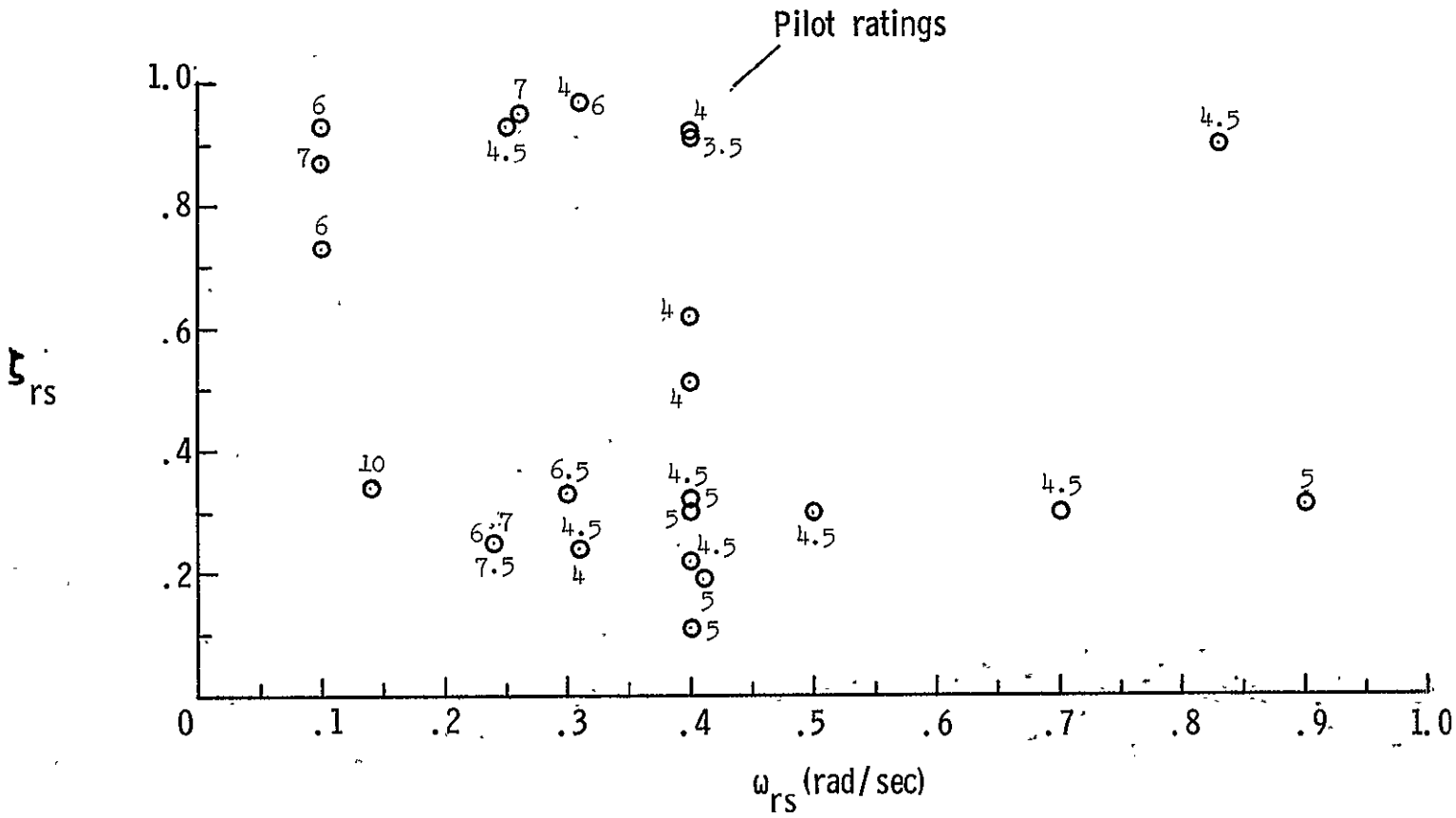


Figure 7.- Variation of the frequency and damping of the roll-spiral coupled mode with pilot rating.

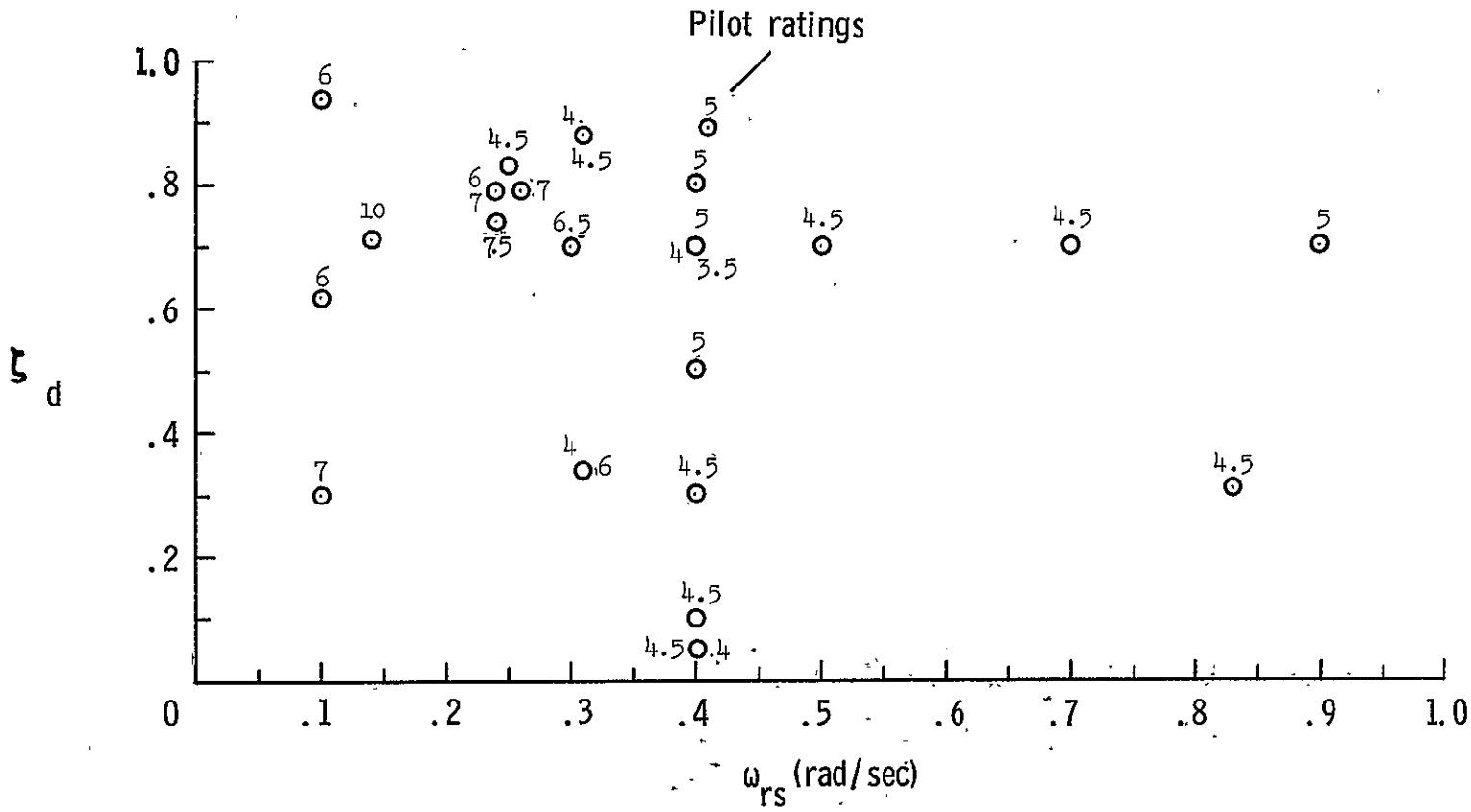


Figure 8.- Variation of the frequency of the roll-spiral coupled mode, ω_{rs}, and Dutch roll damping, ζ_d, with pilot rating.

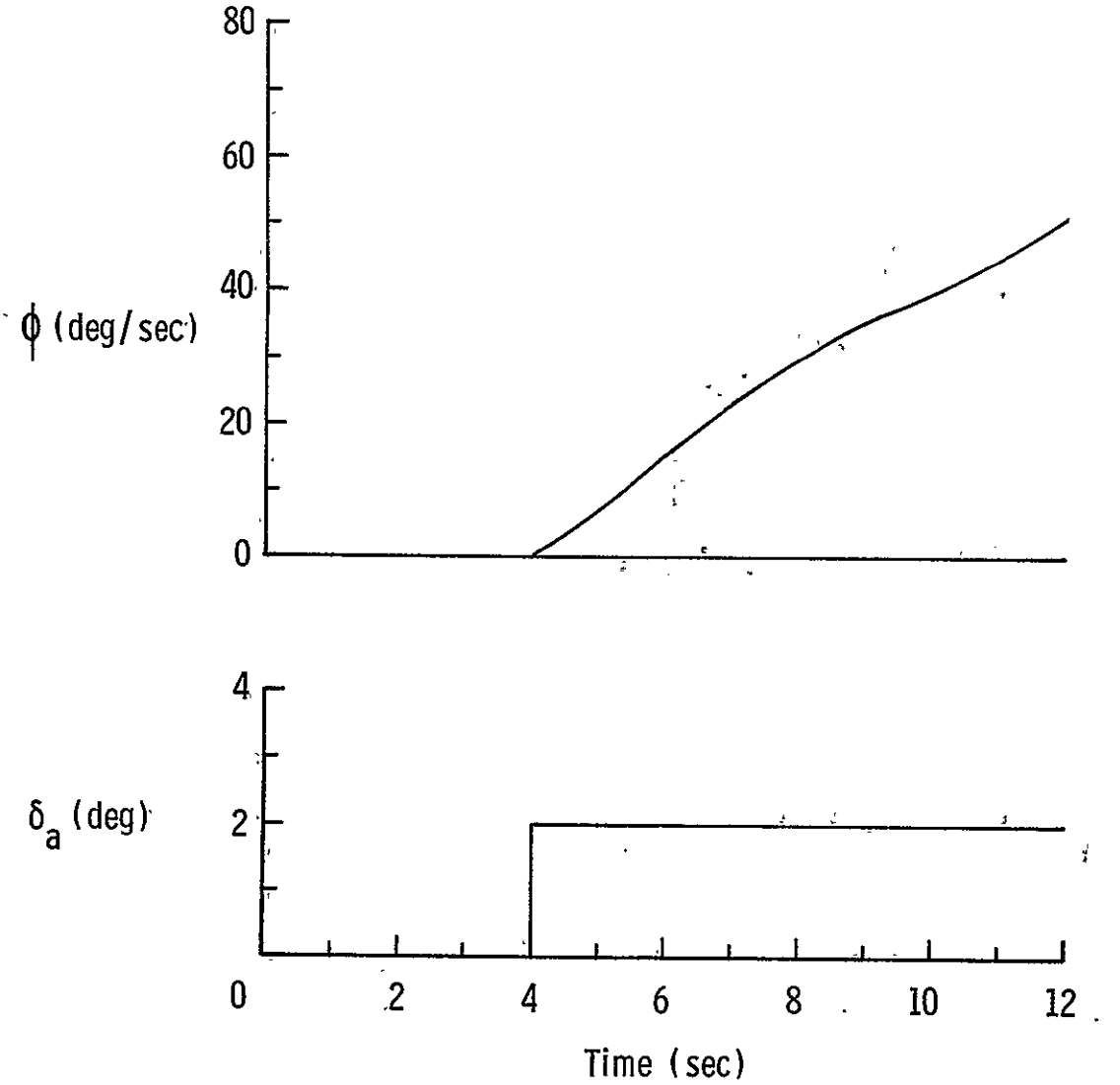


Figure 9.- Roll-rate response to a step aileron input for low frequency roll-spiral oscillation.

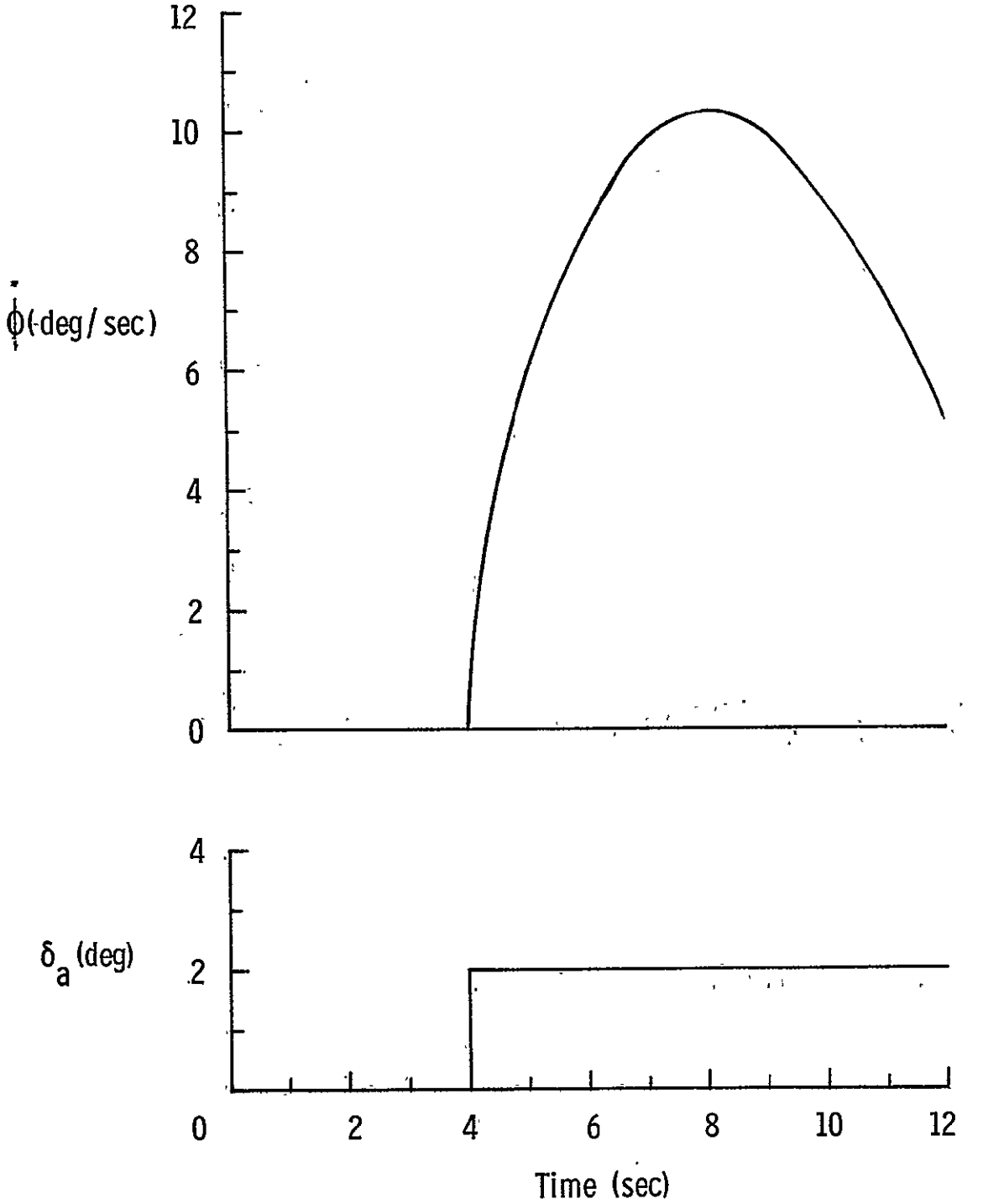
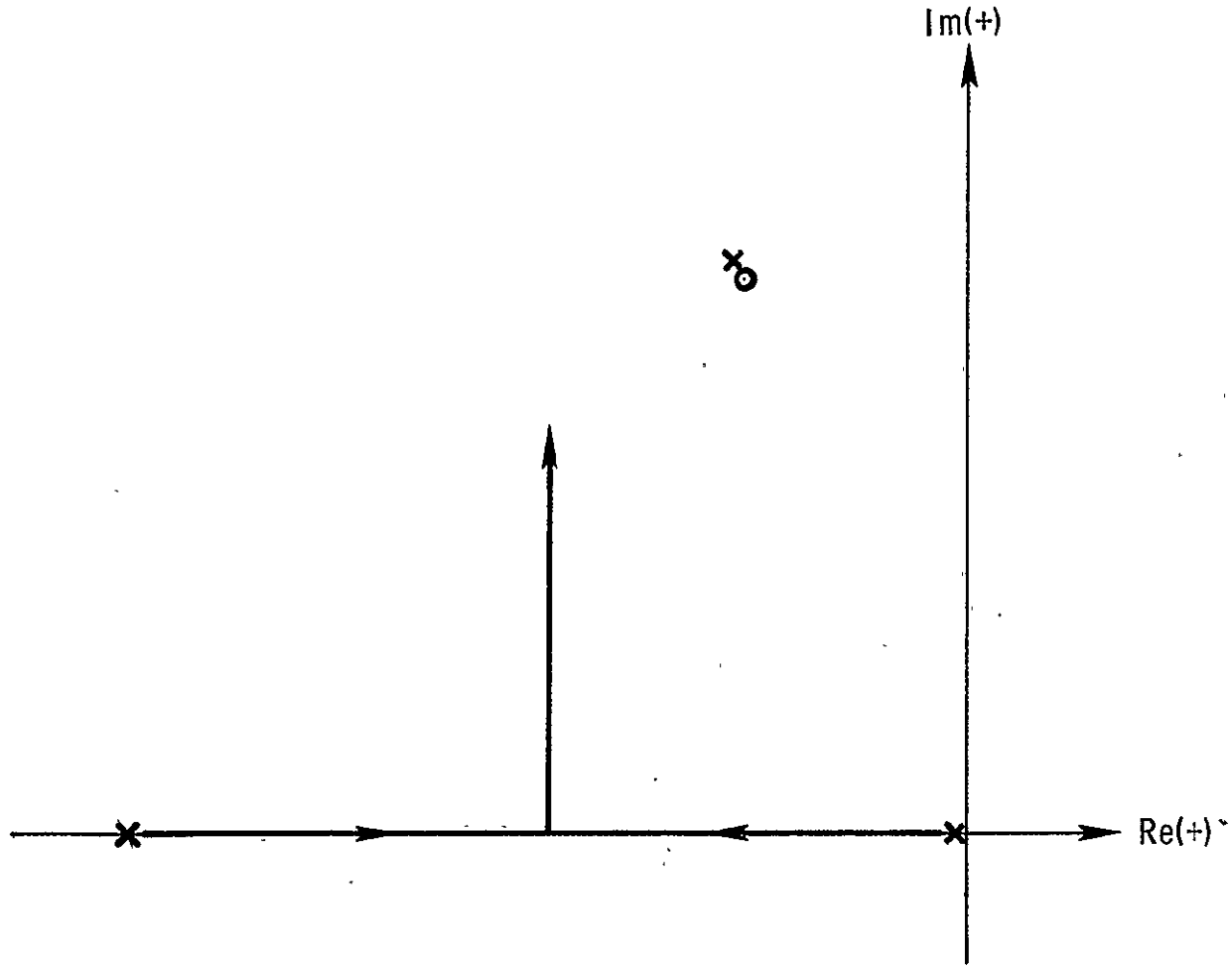
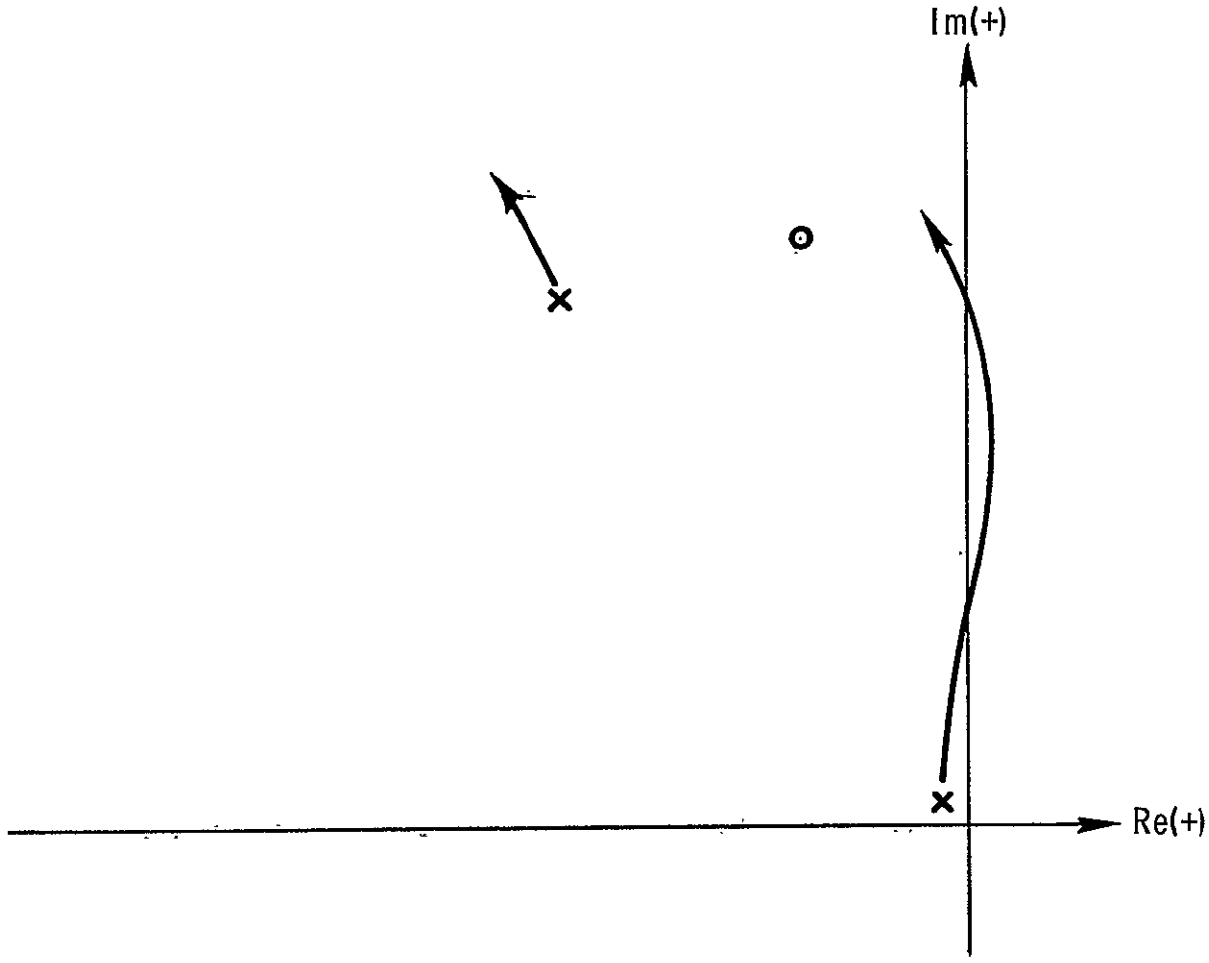


Figure 10.- Roll-rate response to a step aileron input for high frequency roll-spiral oscillation.



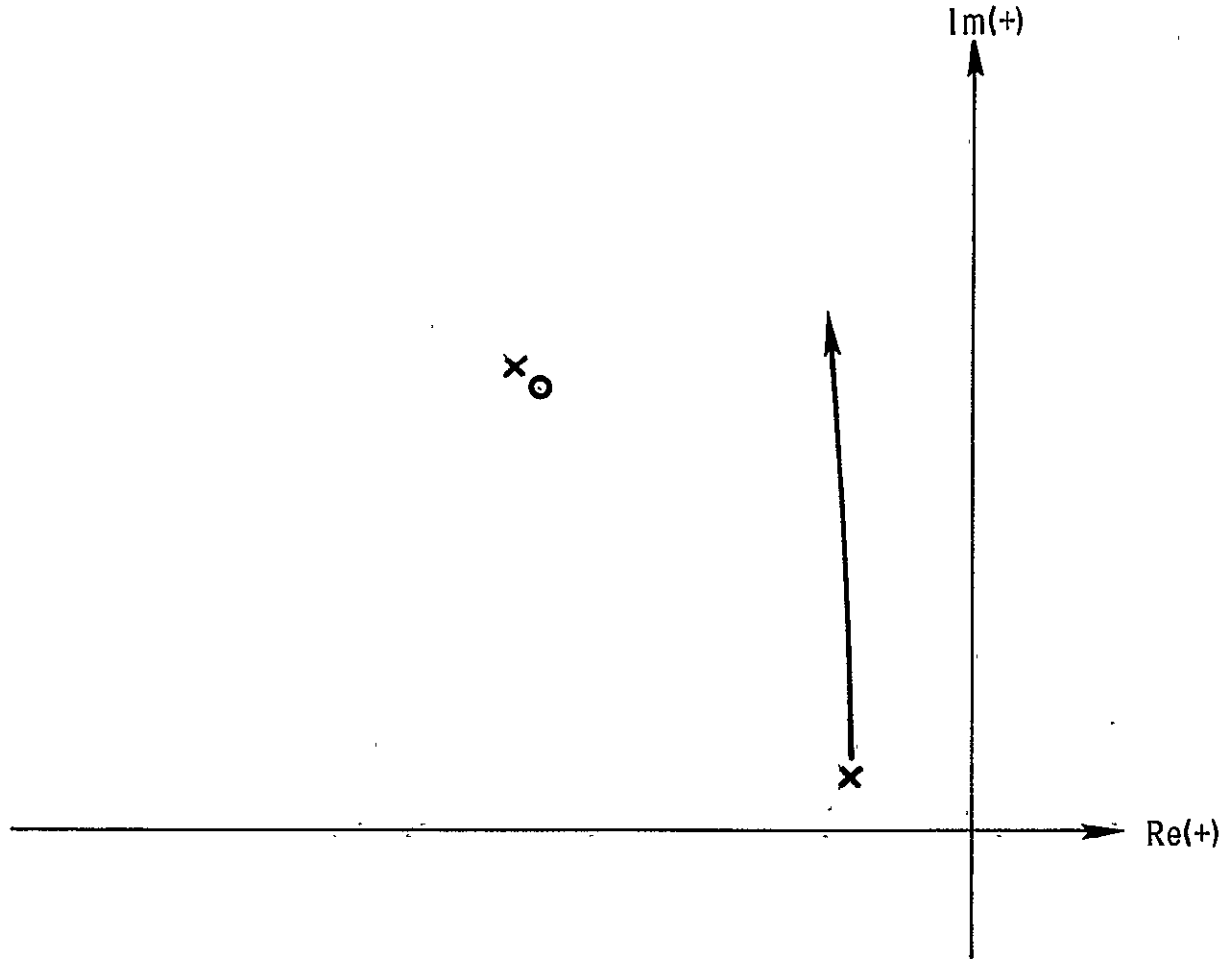
(a) Configuration 1

Figure 11.- Root locus sketches of the closed-loop bank angle transfer function for variation in pilot gain, Kp.



(b) Configuration 22

Figure 11.- Continued.



(c) Configuration 17

Figure 11.- Concluded.