FOREWORD

This report was prepared for the United States Air Force by the Cornell Aeronautical Laboratory, Inc., Buffalo, New York in partial fulfillment of Contract AF33(615)-1253.

The work reported herein was performed by the Flight Research Department of the Cornell Aeronautical Laboratory under the sponsorship of the Air Force Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, as Project No. 8219, Stability and Control Investigations; Task No. 821905, Handling Qualities Requirements. The RTD project engineer has been Mr. R. K. Wilson.

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The evaluation pilots for this experiment were Mr. R.P. Harper, Jr. and Mr. G. Bull.

This technical report has been reviewed and is approved.

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ABSTRACT

A systematic investigation of the lateral handling qualities of fighter aircraft on an en route IFR mission was made in a fixed-base ground simulator. The suitability of a wide range of roll and spiral mode root locations was examined with particular emphasis placed upon determining the effects of complex roll-spiral roots. The complex roll-spiral roots were produced with several feasible combinations of stability derivatives. Interaction effects of the Dutch roll mode roots were examined, including the effects of the proximity of these roots to the complex roll-spiral mode roots. Assessment of the flying qualities is reported in terms of the evaluation comments and ratings given by two pilots. In general the complex roll-spiral configurations that were evaluated were too difficult to control in roll to consider their handling quality characteristics as acceptable for fighter aircraft. (U)

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LIST OF SYMBOLS

a_i	general constant
g	gravity constant
I_x	moment of inertia about X axis
I_z	moment of inertia about Z axis
I_{xz}	product of inertia
k	$1 - \dfrac{I_{xz}^2}{I_x I_z}$
K_A	airplane gain
K_p	pilot gain
L	rolling moment, ft-lb

$$L_r = \frac{1}{I_x} \frac{\partial L}{\partial r}$$

$$L_p = \frac{1}{I_x} \frac{\partial L}{\partial p}$$

$$L_\beta = \frac{1}{I_x} \frac{\partial L}{\partial \beta}$$

$$L_{\dot\beta} = \frac{1}{I_x} \frac{\partial L}{\partial \dot\beta}$$

$$L_{\delta_a} = \frac{1}{I_x} \frac{\partial L}{\partial \delta_a}$$

$$L_{\delta_r} = \frac{1}{I_x} \frac{\partial L}{\partial \delta_r}$$

$$L'_i = \frac{1}{k}\left(L_i - \frac{I_{xz}}{I_x} N_i\right) ; \; i = p, r, \beta, \dot\beta, \delta_a, \delta_r$$

M	Mach number
N	yawing moment, ft-lb

$$N_p = \frac{1}{I_z} \frac{\partial N}{\partial p}$$

$$N_r = \frac{1}{I_z} \frac{\partial N}{\partial r}$$

$$N_\beta = \frac{1}{I_z} \frac{\partial N}{\partial \beta}$$

$$N_{\dot{\beta}} = \frac{1}{I_z} \frac{\partial N}{\partial \dot{\beta}}$$

$$N_{\delta_a} = \frac{1}{I_z} \frac{\partial N}{\partial \delta_a}$$

$$N_{\delta_r} = \frac{1}{I_z} \frac{\partial N}{\partial \delta_r}$$

$$N'_i = \frac{1}{k} \left(N_i - \frac{I_{xz}}{I_z} L_i \right) ; \; i = p, r, \beta, \dot{\beta}, \delta_a, \delta_r$$

p	roll rate, rad/sec
$\dot{p}$	roll acceleration, rad/sec^2
r	yaw rate, rad/sec
$\dot{r}$	yaw acceleration, rad/sec^2
s	Laplace operator
V	velocity, ft/sec
Y	side force, lb

$$Y_\beta = \frac{1}{mV}\frac{\partial Y}{\partial \beta}$$

$$Y_{\delta_r} = \frac{1}{mV}\frac{\partial Y}{\partial \delta_r}$$

α_o	X body axis angle of attack
β	sideslip angle
$\dot{\beta}$	sideslip angle rate
δ_a	aileron displacement
δ_{AS}	aileron stick motion
δ_r	rudder displacement
ζ_d	Dutch roll damping ratio
ζ_{SR}	roll-spiral damping ratio
τ_R	roll mode time constant
τ_S	spiral mode time constant
ϕ	bank angle
$\left\lvert \frac{\phi}{\beta} \right\rvert_d$	roll to sideslip ratio at Dutch roll frequency
ω_d	Dutch roll undamped natural frequency
ω_{SR}	roll-spiral undamped natural frequency
$\frac{\omega_\phi}{\omega_d}$	ratio of roll mode numerator frequency to Dutch roll frequency

SECTION I

INTRODUCTION

The adequate control of airplane bank angle is fundamental to almost every mission or task which the human pilot performs with an airplane. This is evident when one remembers that to alter the flight path of the airplane, the pilot must change the magnitude and/or direction of the normal force vector. The magnitude is changed through elevator control of angle of attack, and the direction is altered through aileron/rudder control of bank angle. Bank angle control is of the same order of importance to the pilot as is angle of attack control.

The control of bank angle is influenced by a large number of factors relating to the basic airplane characteristics. Particular importance is assigned to the terms – or stability derivatives – in the equations of motion which determine the airplane response to aileron input. These effects may either be examined in terms of the stability derivatives or the coefficients of the denominator and numerator terms of the bank angle to aileron input transfer function. Both methods of examination are equally valid, but neither one is the whole story to the pilot. Generally, the pilot uses both aileron and rudder to control bank angle, and hence the response of bank angle to the pilot's combined use of aileron and rudder is the situation to be considered.

The characteristic equation which describes the free-oscillation modal characteristics of the airplane alone is the denominator common to the expressions for bank angle response to both aileron and rudder. This characteristic equation is of the form:

$$s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0 \qquad (1)$$

and may be factored into two quadratic roots:

$$(s^2 + 2\zeta_d \omega_d s + \omega_d^2)(s^2 + 2\zeta_{SR} \omega_{SR} s + \omega_{SR}^2) \qquad (2)$$

The first quadratic (subscript d) is called the Dutch roll mode, and for conventional airplanes is usually a lightly-damped, oscillatory mode. The second quadratic (subscript SR, roll-spiral) usually has two real roots and is often written:

$$s^2 + 2\zeta_{SR} \omega_{SR} s + \omega_{SR}^2 = \left(s + \frac{1}{\tau_R}\right)\left(s + \frac{1}{\tau_S}\right) \qquad (3)$$

The first root is normally called the roll mode root since it often has a dominant effect in the rapid bank angle response to aileron inputs. The second root is termed the spiral mode root, since this root has a dominant effect on the long term bank angle response to disturbances. It must be remembered, however, that regardless of the names given to each mode individually, each response (bank angle, sideslip, etc.) includes the contribution of all four roots of the characteristic quartic.

The four roots of the characteristic quartic (Equation 2) determine the control-fixed response of the airplane. To assess the contribution of the roots to the flying qualities of the airplane – the pilot-airplane system – one can systematically alter each root and observe the effect of the change on the pilot's assessment of the flying qualities. A number of such efforts are reported and/or summarized in the literature, and listed herein as References 1 through 14. These data form the basis of our knowledge of goodness and badness for a substantial range of variation in these roots and other pertinent lateral-directional handling qualities parameters.

References 1 through 14 report the assessment results for a wide range of values of the parameters which describe the airplane. However, one area has received little or no systematic attention: that is, flying qualities of the airplane with coupled roll-spiral roots. "Coupled" means either that the two normally real roll and spiral roots are in such proximity to each other that they are not easily identifiable as separate, first-order modes, or that the roots have combined and formed another complex conjugate pair of roots in addition to the Dutch roll complex pair. This additional pair of complex roots is called the complex roll-spiral mode or the lateral phugoid.

Interest in the coupled roll-spiral roots has developed because relatively recent trends in airplane design and operating environment have led to predicted aircraft characteristics of this nature. Airplanes designed to fly at high speed at high altitude tend to have low values of roll damping, $\mathcal{L}'_p$, and may have low directional stiffness, N'_β , at high Mach numbers. In this case, coupled roll-spiral roots can exist, particularly if the effective dihedral derivative, $\mathcal{L}'_\beta$, is large. The coupled roll-spiral roots may give the appearance of a second-order, over-damped response if the two roots are in close proximity, but real. If the roots are complex, then the motion is oscillatory, and in the extreme, the oscillatory case may be negatively damped - a dynamic oscillatory divergence.

The only known in-flight experience with a complex roll-spiral mode was in the USAF-CAL variable stability T-33 program reported in Reference 12. The piloting difficulties which were experienced, together with the expectation that at least two new V/STOL airplanes and one fighter would exhibit coupled roll-spiral roots in a portion of the flight envelope, generated the research interest in the program which is reported herein.

The goal of the present program is to examine the piloting difficulties and mission limitations which may be imposed by coupled roll-spiral roots, and to examine the influence of the other important lateral-directional parameters on these difficulties. Because of the exploratory nature of the study, a fixed-base ground simulator was used for the investigation. Either a V/STOL aircraft in cruise flight or a fighter performing a high altitude mission could have been chosen as the subject of the assessment. The generalized fighter mission was selected for evaluation, and the assessment tasks were oriented toward the enroute IFR considerations of that mission due to the inherent task limitations in a fixed-base simulator with conventional cockpit instrument displays.

For this study the assumed airplane weighs 70,000 pounds and is travelling at Mach 1.2 at an altitude of 30,000 feet. The primary study parameter is $\mathcal{L}'_p$, the roll damping derivative. This parameter was reduced in value until the conventional roll and spiral roots converged to form the desired coupled mode. The parameter was further reduced to obtain several different roots of the coupled mode. Separation between the Dutch roll frequency and the lateral phugoid frequency varied between $2 \leq \omega_d/\omega_{s\ell} \leq 10$. Yaw due to rolling velocity was proverse, which is typical of aircraft in supersonic flight. Aileron yaw was varied from adverse to proverse but was generally adverse. The pilots were allowed to vary the aileron gearing ratio and to choose the value that gave them the best control for each set of characteristics which they evaluated. Two pilots performed the evaluation task. That task was to fly a tactical fighter under en route, IFR conditions.

A general result of this study is the lateral phugoid mode characteristics that were investigated are unacceptable for the mission considered. This results from the pilot having to remain closed loop to keep the airplane under control in bank. Many configurations were barely controllable and some were uncontrollable. In general, both pilots complained of an apparent lack of roll damping.

The detailed discussion of this study is arranged as follows in the remainder of the report:

Section II	Design of the Experiment
Section III	The Experiment
Section IV	Results and Discussion
Section V	Conclusions

SECTION II

DESIGN OF THE EXPERIMENT

Many modal constants must be simultaneously considered whenever the lateral-directional modes of motion are specified in detail. In particular, if specific modal constants are desired, a study of the equations of motion is required to determine the stability derivatives which will give the desired modal constants. A complication of such a study is that a complete set of modal constants is seldom specified because reasonable values for, and the effects of, some of the constants are not known. Therefore incomplete sets are chosen and each of these can be satisfied by more than one set of stability derivatives. As a consequence of this situation, an additional constraint is imposed that requires each set of desired modal constants be obtained from a feasible set of stability derivatives. The required study was based on the following set of linearized equations in body axes which, for α_o equal to zero, have the X axis initially aligned with the flight path.

$$Y_\beta \beta - \dot{\beta} - r + \frac{g}{V}\phi + \alpha_o p = Y_{\delta_r}\delta_r$$

$$N_\beta \beta + N_{\dot{\beta}}\dot{\beta} + N_r r - \dot{r} + N_p p + \frac{I_{xz}}{I_z}\dot{p} = N_{\delta_a}\delta_a + N_{\delta_r}\delta_r$$

$$L_\beta \beta + L_{\dot{\beta}}\dot{\beta} + L_r r + \frac{I_{xz}}{I_x}\dot{r} + L_p p - \dot{p} = L_{\delta_a}\delta_a + L_{\delta_r}\delta_r$$

where

$$Y_i = \frac{1}{mV}\frac{\partial Y}{\partial i}, \quad N_i = \frac{1}{I_z}\frac{\partial N}{\partial i}, \quad L_i = \frac{1}{I_x}\frac{\partial L}{\partial i}, \quad i = p, r, \beta, \dot{\beta}, \delta_a, \delta_r$$

Alternatively and with α_o equal to zero, the equations are written in the form:

$$(Y_\beta - s)\beta - r + \frac{g}{V}\phi = Y_{\delta_r}\delta_r$$

$$(N'_\beta + N'_{\dot{\beta}} s)\beta + (N'_r - s)r + N'_p s\phi = N'_{\delta_a}\delta_a + N'_{\delta_r}\delta_r$$

$$(L'_\beta + L'_{\dot{\beta}} s)\beta + L'_r r + (L'_p s - s^2)\phi = L'_{\delta_a}\delta_a + N'_{\delta_a}\delta_a$$

where

$$N'_i = \frac{1}{k}\left(N_i + \frac{I_{xz}}{I_z}L_i\right), \quad L'_i = \frac{1}{k}\left(L_i + \frac{I_{xz}}{I_x}N_i\right), \quad k = 1 - \frac{I_{xz}^2}{I_x I_z}, \quad i = p, r, \beta, \dot{\beta}, \delta_a, \delta_r$$

In this alternate form of the equations, the primed derivatives include the inertia and product of inertia constants. The transformation from the first set of equations to the primed set is described in Reference 14. These equations are programmed on a digital computer and this program was used in this study.

Solution of the equations can result in either of the two following forms for the characteristic equation:

$$(s^2 + 2\zeta_d \omega_d s + \omega_d^2)\left(s + \frac{1}{\tau_R}\right)\left(s + \frac{1}{\tau_s}\right) = 0$$

or

$$(s^2 + 2\zeta_d \omega_d s + \omega_d^2)(s^2 + 2\zeta_{sR} \omega_{sR} s + \omega_{sR}^2) = 0$$

where the first equation represents the more common case of the Dutch roll mode and real-root roll and spiral modes, and the second equation represents the case of the Dutch roll mode and the lateral phugoid mode. It was found in the parameter variation study that complex roll-spiral roots can be produced by various combinations of the stability derivatives. The derivative L'_p is somewhat unique in its effect because a reduction in the magnitude of L'_p produces complex roll-spiral root locations, as shown in Figure 1, with relatively little alteration in the location of the Dutch roll roots.

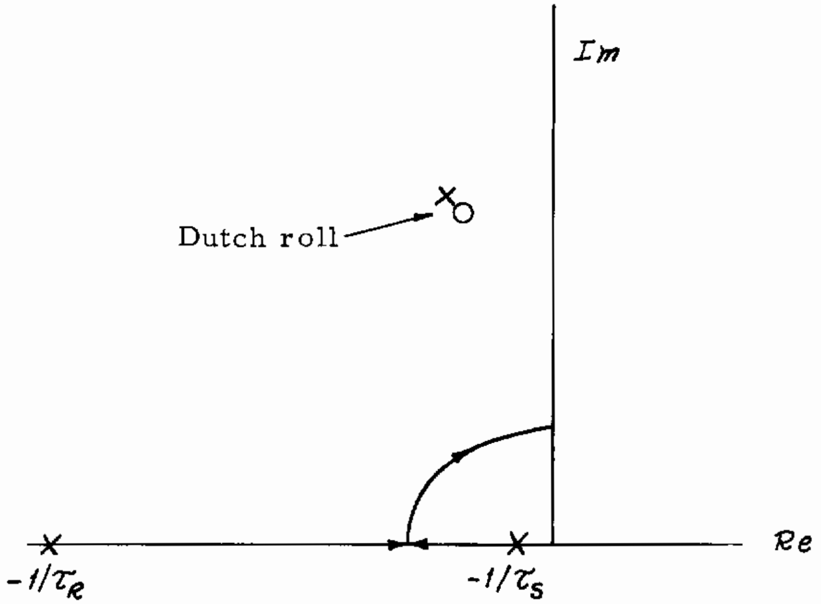


Figure 1. Root Locus for Decreasing Roll Damping

The experiment is designed, primarily, to determine the effect of the roll-spiral mode parameters, ω_{sR} and ζ_{sR}, on aircraft handling qualities. The experiment is also designed to determine the influence and interaction effects of the Dutch roll and aileron yaw parameters ζ_d, $|\phi/\beta|_d$ and ω_ϕ/ω_d.

The independent examination of these factors requires an iterative determination of the stability derivatives that produce the variations in the factors for constant Dutch roll root locations. Therefore the experiment was designed by stipulating the desired Dutch roll roots, either τ_R and τ_s, or the lateral phugoid roots, and $|\phi/\beta|_d$. From these stipulated values, estimates of the required stability derivatives were made by using the approximate factors of Reference 16 in which factors exist for both the conventional case and the lateral phugoid case. The estimated derivatives were entered into the computer program and the equations of motion were solved for the exact roots and modal constants. It was found that in some instances the approximate factors were reasonable predictors, while in others, they were inaccurate.

However, the approximate factors afforded good starting points and the final, desired results could be approached closely by iteration. The value of the real part of the Dutch roll root was closely controlled by iterating with $N'_{\dot{\beta}}$. The greatest difficulty occurred in obtaining the desired combinations of ω_d , ω_{SR} and $|\phi/\beta|_d$ because these parameters have common stability derivatives, e.g., a stability derivative which alters the value of ω_d also affects the values of ω_{SR} and $|\phi/\beta|_d$.

Aileron yaw was predominantly adverse throughout the experiment. Some consideration was given to the effects of different values of ω_ϕ/ω_d as obtained by changing the value of N'_{δ_a} . This was to obtain comparisons of adverse and proverse aileron yaw for a few configurations.

A list of the configurations that were "shot for" is given in Table I. The exact values are given in Table II of the appendix. A presentation of these configurations is made in root locus form in Figures 2a through 2g. It can be noticed from the table and the figures that the organization of the experiment is based upon the roll-spiral characteristics, the Dutch roll characteristics, $|\phi/\beta|_d$ and ω_ϕ/ω_d . The configuration numbers listed in the table are not particularly consecutive or sequential because they are the bookkeeping numbers for the iteration runs on the digital computer. The pilots were not given and never used the configuration numbers. They evaluated each configuration as a run and identified each run by using the letters of the alphabet sequentially.

TABLE I
PLANNED VALUES OF CONFIGURATION PARAMETERS

Config.	ω_{SR}	ζ_{SR}	ω_d	ζ_d	$\lvert\phi/\beta\rvert_d$	ω_ϕ/ω_d
9	0.23	0.7	2.05	0.2	6.6	≈ 0.95
10	↓	0.2	↓	↓	↓	↓
11	↓	0.05	↓	↓	↓	↓
15	↓	0.7	↓	0.05	↓	↓
16	↓	0.2	↓	↓	↓	↓
3	↓	0.7	↓	0.2	11	↓
37	↓	↓	↓	0.05	↓	↓
38	↓	0.2	↓	↓	↓	↓
21	↓	0.7	1.2	0.2	20	↓
22	↓	0.2	↓	↓	↓	↓
29	0.07	↓	2.05	↓	9.2	↓
33	0.65	0.7	1.2	↓	20	↓
47	0.23	0.2	2.05	↓	6.6	< 0.9
48	↓	↓	↓	↓	↓	> 1
49	↓	↓	↓	↓	11	< 0.9
50	↓	↓	↓	↓	↓	> 1
	$1/\tau_s$	$1/\tau_R$	ω_d	ζ_d	$\lvert\phi/\beta\rvert_d$	ω_ϕ/ω_d
43	0.01	3.4	2.05	0.2	3.85	≈ 0.95
8	0.15	0.272	↓	↓	6.6	↓
14	↓	0.269	↓	0.05	↓	↓
1	0.05	0.966	↓	0.2	11	↓
2	0.15	0.311	↓	↓	↓	↓
26	0	1.53	↓	↓	↓	↓
25	0.05	0.112	↓	↓	↓	↓

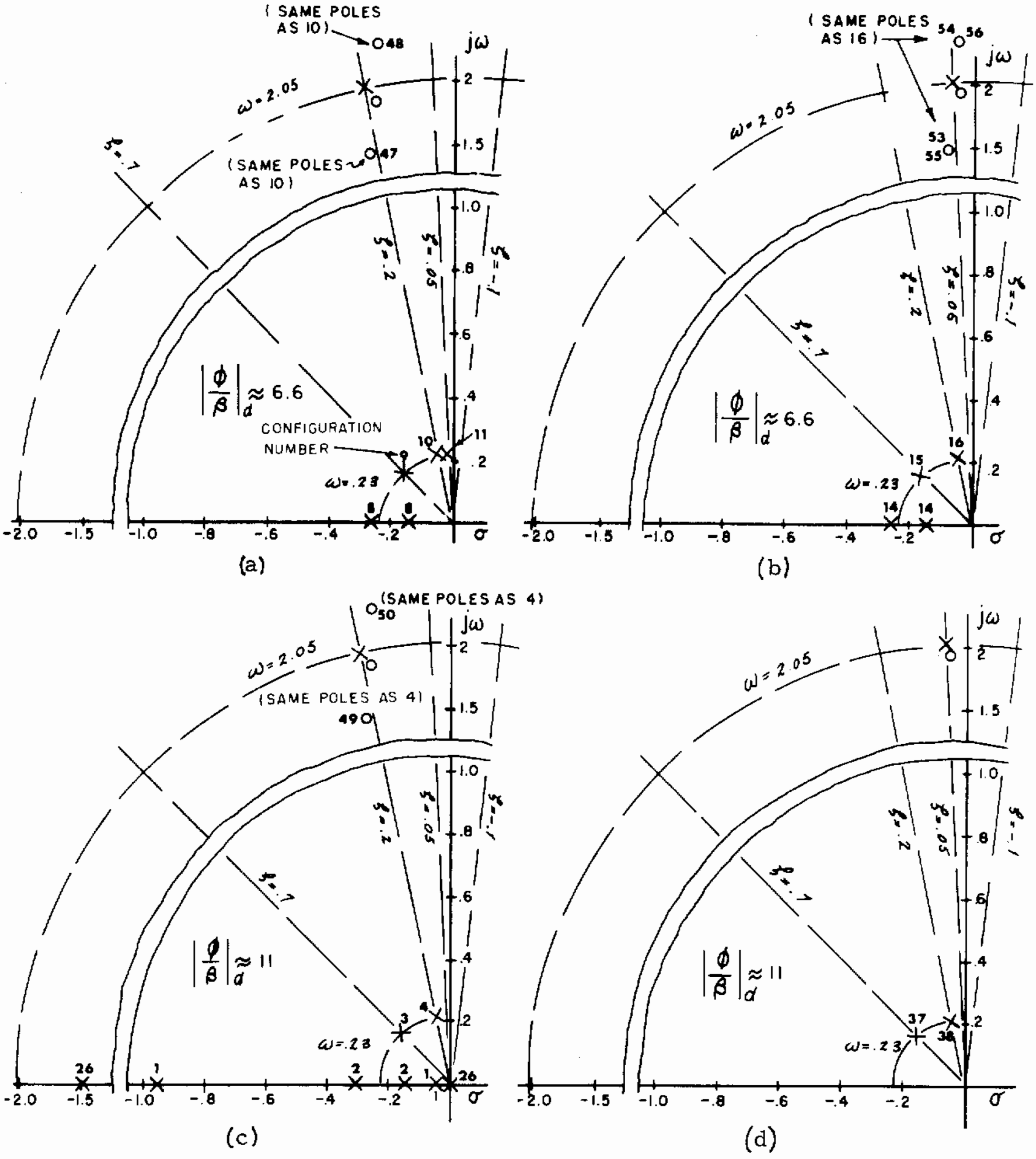
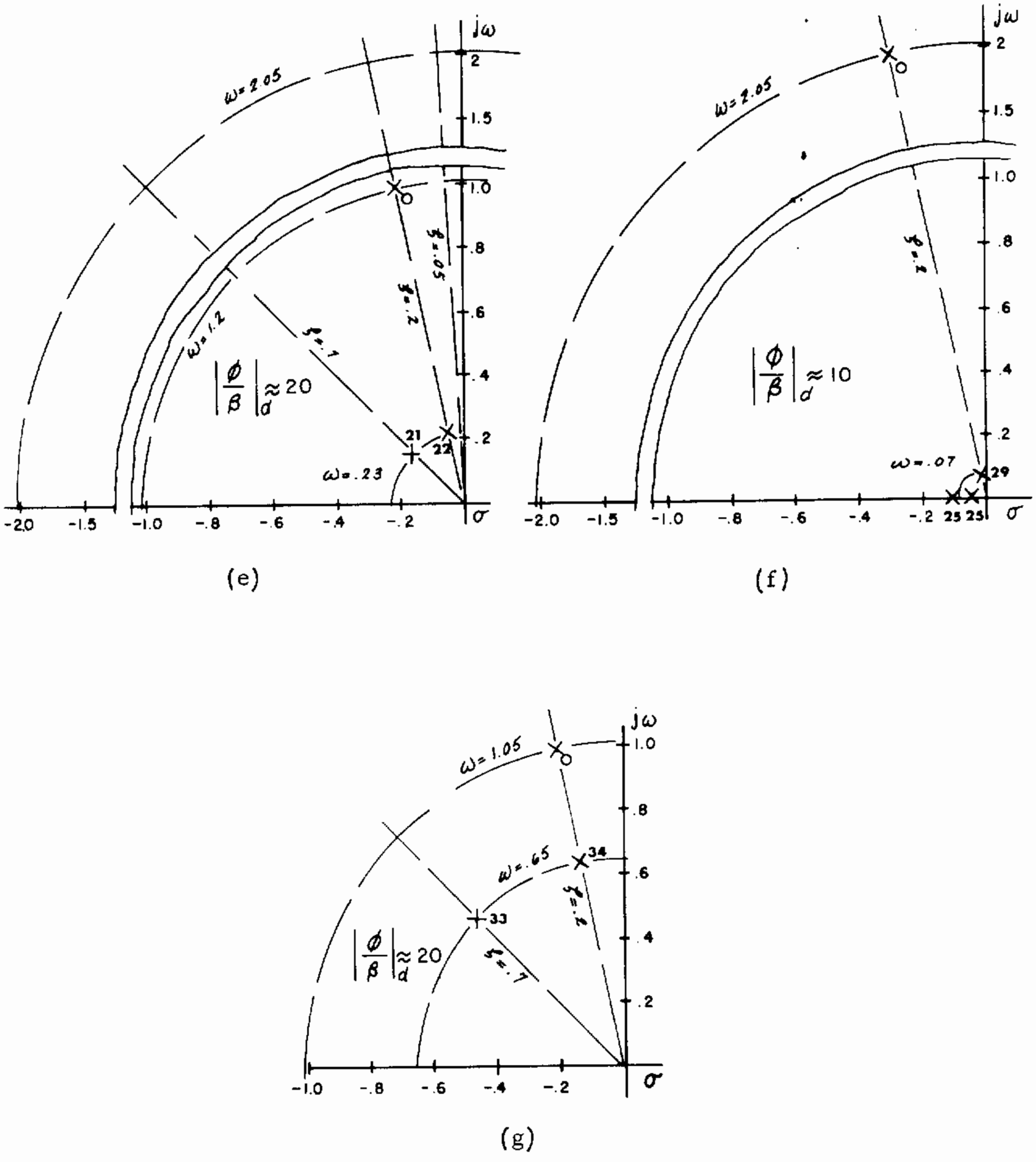


Figure 2. Configuration Root Locations



(e)

(f)

(g)

Figure 2. Configuration Root Locations (concluded)

SECTION III
THE EXPERIMENT AND EQUIPMENT

The experiment was performed in the T-33 variable stability airplane ground simulator shown in Figure 3. The computers used in conjunction with the T-33 are three PACE TR-10 transistorized analog computers. Reference 15 contains the equations used in the computers. However, the drag equation for the present study is a simple linear equation and the hypothetical airplane was well on the front side of the drag polar.

Both pilots coordinated in optimizing a longitudinal configuration which became the only set of longitudinal dynamics used throughout the experiment. These dynamics resulted in an evaluation rating of 3 which could not be improved because of the elevator stick feel and the problem of controlling rate of descent or climb through pitch attitude. For high speeds, the attitude angle displayed on present-day standard attitude instruments does not afford sufficient resolution to permit fine control of rate of descent. As can be seen from the equation $\dot{h} = V \sin(\theta - \alpha)$, an increase in V requires a finer resolution in θ to obtain the same $\dot{h}$.

Rough air tasks were presented to the pilots on each evaluation run by introducing noise through the angle of attack and sideslip channels in the analog computer. The noise generator used for this purpose is a set of motor-driven cams with three noise output channels. Each channel is made up of two cams which revolve slowly with respect to each other. The arm of a cam-following potentiometer rides whichever of the two cams that protrudes the furthest. Because the two cams revolve slowly with respect to each other, the cam that is seen by the cam-follower continually changes shape. This device is built by the Link Division of General Precision, Inc. and was obtained from a C-11 simulator. The procedure of introducing the rough air noise through the angle of attack and sideslip permits the computer to automatically scale the gust response of each configuration.

The purpose of the noise is to give the pilots a tracking task with reasonable but unpredictable disturbances. This procedure allows the pilot to evaluate each configuration on a basis that is separate from tracking self-induced noise.

To add to the realism of the en route IFR task, the pilots were requested to copy a hypothetical but standard form IFR clearance. Thus they were presented with a realistic task under which they could accurately evaluate the effects of open-loop control and whether or not they could expect to fly open loop for necessary periods of time. Only a few clearances were used and the pilots became reasonably familiar with them. This does not detract from the realism of the task, because in practice, pilots prepare their own IFR flight plans and the clearances received are based upon these plans. Therefore, in receiving a clearance, the pilot is usually aware of what it will be.

Evaluations were made of climbing, diving and level turns and of both slow and rapid entries into 30° and 60° banks. In addition, the pilots flew the airplane in any fashion they desired. Flight in both simulated smooth air and simulated rough air was accomplished. Pilot evaluation comments were wire recorded.

T-33 Fixed-Base Simulator and Analog Computer Setup

Evaluation Pilot's Cockpit Display

Figure 3. Arrangement of Airplane and Analog Computer

The comment card that was used by the pilots lends consistency to the points considered and commented on by the pilot. However, prior to commenting specifically on the basis of the comment card, the pilots commented freely to clear their minds of immediate observations before forgetting them. Since the comment card served to remind the pilots of their observations, they preferred to use it after giving their free style comments. A reproduction of the comment card used in this program follows.

COMMENT CARD

1. Briefly describe your over-all reactions if possible in the order of:
    - roll control (trim, maneuvering, response, feel)
    - heading control (trim, maneuvering, response, feel)
    - pitch control (trim, maneuvering, response, feel)
    - interactions (trim, maneuvering, response, feel)

Define the following

2. Bank angle control precision (good, fair, poor, bad) for:
    a. trim
    b. maneuvering
    amount of closed-loop necessary for:
    30° bank slow entry
    60° bank rapid entry (describe input and responses)
    60° bank slow entry
    60° bank rapid entry
    c. Demonstrate on oscillograph if reasonable.

3. Define major objection to roll control

4. Are aileron force feel characteristics at all bothersome? Why?

5. How is rudder used?

6. What is pitch control interaction problem?
    a. How could it be improved?

7. How did you select control gains (gearing)?
    a. Aileron
    b. Rudder
    c. Elevator

9. How do these flight characteristics affect your use of instruments? (directly read, checked in peripheral vision, not checked or read) for:
    a. Straight and level
    b. Level turning
    c. Climbing/descending straight flight
    d. Climbing/descending turning flight

10. Assuming you can change altitude or airspeed to obtain more favorable flight conditions, would you accept this configuration for the alternate mission of general recovery from failure of the augmentation system?

11. Summarize major objections/advantages.

The pilots gave evaluation ratings for each configuration. These ratings are based on the rating scale given below which is applied within the context of the task; a tactical fighter, en route IFR.

CAL RATING SCALE

Category	Adjective Description Within Category	Numerical Rating
Acceptable and Satisfactory	Excellent	1
	Good	2
	Fair	3
Acceptable but Unsatisfactory	Fair	4
	Poor	5
	Bad	6
Unacceptable	Bad*	7
	Very Bad**	8
	Dangerous†	9
Unflyable	Unflyable	10

* requires major portion of pilots' attention
** controllable only with a minimum of cockpit duties
† aircraft just controllable with complete attention

Neither pilot who participated in this program ever knew what set of characteristics he was evaluating nor were they given the configurations in the same order. Thus they could not discuss and compare specific configurations with each other. Whenever they discussed the program between themselves they could discuss only generalities and the philosophy of rating. Both pilots are currently rated and experienced instrument pilots and both are experienced evaluation pilots.

Each set of lateral characteristics was evaluated by each pilot for one-half to one hour of "flying". The better configurations were evaluated for longer periods of time because the pilot could perform more maneuvers and consequently could see more response characteristics that needed greater concentration and evaluation time to obtain a valid evaluation and rating. The unflyable configurations needed the least evaluation time because their treacherous characteristics became evident very early in the evaluation period. This simplification between good and unflyable should not be taken as rigid generality because there are some configurations that are bad because of a treacherous characteristic that is subtle and that requires time to discover and evaluate. These types of characteristics usually manifest themselves while the pilot is flying open loop. In this report, what is frequently referred to as open-loop flying means that the pilot monitors the flight instruments periodically but is flying hands-off or with minimum attention to the flight control task while attending to other cockpit duties.

Configuration number 43 was repeated several times throughout the experiment because it was the best and most "airplane-like" of all of the configurations. The pilots needed recurrent looks at configurations like this because it helps them to remain secure in knowing what a "good" airplane is and what can be done with a good airplane. However, they did not realize that the truly good configuration was always the same one and they were not informed of this.

SECTION IV
RESULTS

The most obvious conclusion which is indicated by the results of this experiment is that the coupled roll-spiral configurations investigated represent poor to very bad tactical airplanes. These configurations all are "rolly" in that it is difficult to establish a given, desired roll rate and no matter what roll rate is established it can be difficult to stop at a desired bank angle. This situation leads to pilot-induced oscillation (PIO) in roll rate or bank angle. The pilot cannot extricate himself from the loop and let the airplane settle down by itself because in so doing, the error in roll rate or bank angle becomes too large. This consequence is a manifestation of the very long time required for the airplane to reach the steady state condition of the coupled roll-spiral mode. It is also a reflection of the fact that the roll damping is so low that ailerons appear to be more acceleration-ordering than rate-ordering for step inputs for the amount of time the pilot can afford to watch the free response. Therefore, the pilots attempt to control roll rate by using aileron pulse inputs and thereby reduce the control system to a rate-ordering rather than acceleration-ordering system. In actual fact, in configurations possessing a coupled roll-spiral mode, aileron orders bank angle, but the settling time is so long the pilot seldom realizes it.

The remainder of this section is a review and discussion of the data. Support for the above statements is found in this discussion.

No discernible learning curve is seen in the data, because some evaluations had been done prior to the discovery of a scaling error in the computer. When these evaluations were repeated, the pilots were sufficiently familiar with the configurations that no measurable change in their proficiency was noted.

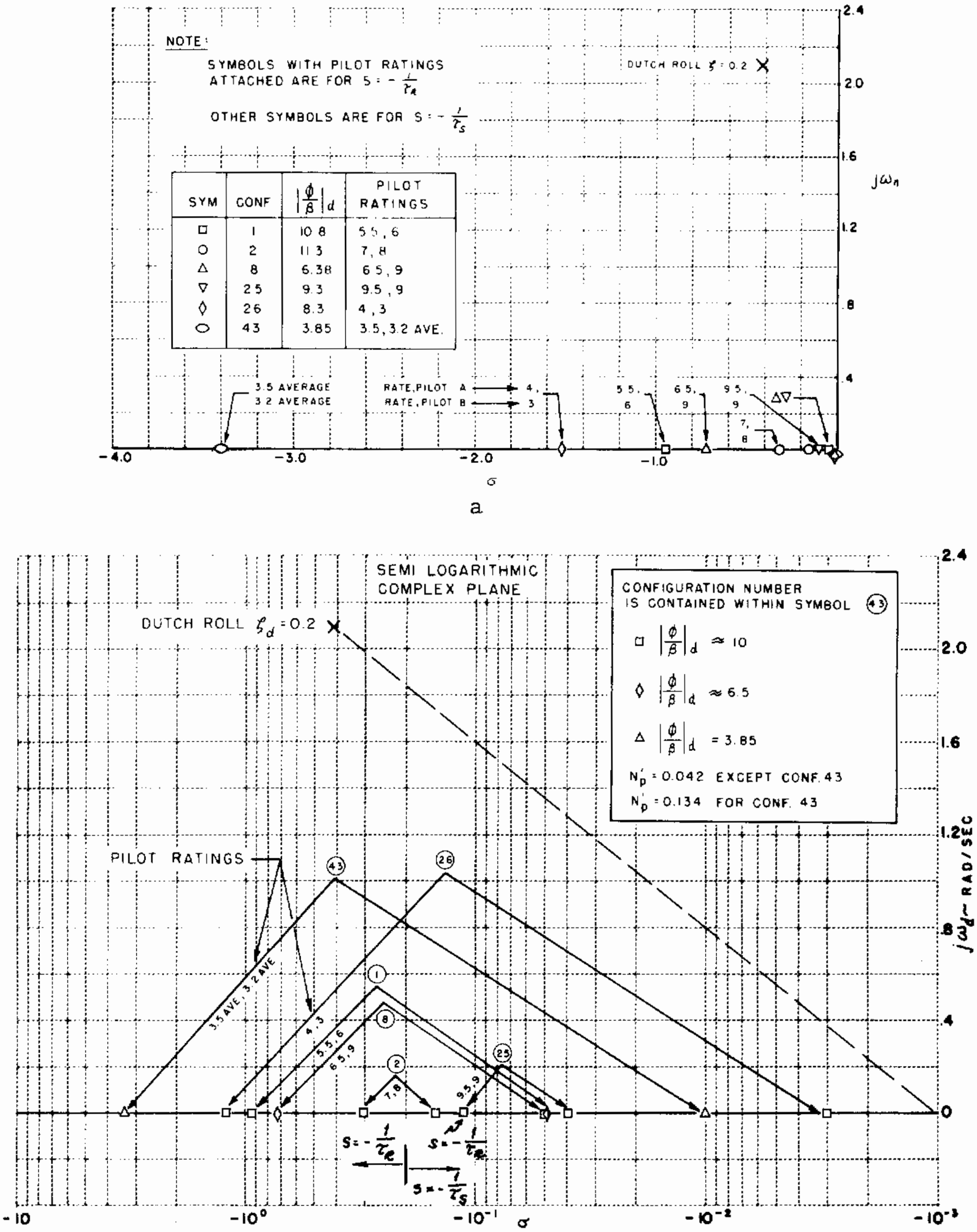
REAL ROOT ROLL AND SPIRAL MODES

Several configurations (from the ensemble shown in Figures 2a through 2g) which have real roll mode and spiral mode roots were evaluated. The value of $|\phi/\beta|_d$ was generally large for these configurations and the spiral root was convergent and variable and never exactly at the origin. The Dutch roll frequency was maintained at 2.1 rad/sec, and half of the configurations were evaluated at a Dutch roll damping ratio of 0.2. The remainder of the configurations were evaluated at various values of the damping ratio of 0.10 or less, including three that were divergent. For the majority of the evaluations, the yaw due to roll rate was proverse with the coefficient N'_p a constant. However, some configurations were evaluated at other values of N'_p including a few that caused adverse yaw due to roll rate. The aileron yaw was always adverse. These evaluations were performed at a Mach number of 1.2 with a standard instrument display which does not present sufficient pitch angle resolution to enable the pilot to closely control flight path angle. That is, the pilot could not see the small changes in pitch attitude that he must see if he is to control flight path angle by controlling pitch attitude.

The variations of the root locations were accomplished by (primarily) varying the value of roll damping, $L'_p \approx -1/\tau_R$. The spiral root was allowed to come out as it would and no control over it was exercised. Usually, as the roll damping decreases, the spiral mode time constant becomes smaller. These root locations are shown on root locus plots in Figures 4a, b, and c. Figures 4a and 4b are for the same configurations with Figure 4b plotted on semi-logarithmic scales to enable a better view of the positions of the spiral roots. In these two figures, the Dutch roll natural frequency is approximately 2.1 rad/sec and the Dutch roll damping ratio is 0.2. In Figure 4c, the roots are plotted for the remainder of the real root configurations which have other Dutch roll roots. It is noted from these figures that the spiral root is non-zero and therefore the effects of the spiral are included in the evaluations.

From Figure 4d, it is seen that as the roll damping decreases, the rating increases (becomes worse). As τ_R becomes longer, and even at $\tau_R \approx 0.6$ sec, the pilots complain that the airplane is sluggish in roll and that pilot lead is required in controlling bank angle and roll rate. This lead is used to overdrive the response in p to obtain the desired p, and then to stop the roll rate at the desired bank angle. As the roll damping is further decreased, then the requirements of lead in the control of bank angle dominate the pilots' technique. When the lead requirements become too great the pilot induces an oscillation in roll because he overcontrols in roll. This results in "rolly" or "too rolly" configurations. Whenever the airplane is "rolly" it is sufficiently difficult to control that the pilot remains closed loop on roll attitude and he does not comment, explicitly, about the effects of the spiral mode. It is interesting that the airplane goes from sluggish to "rolly". This effect arises because the pilot can afford to watch only a small, initial portion of the response before he makes another input. Whenever τ_R is large, but the final response can be predicted from the initial response, then the pilot complains of sluggishness. However, when the final response cannot be predicted from the initial response, then a closed-loop oscillation results which dominates the response and the pilot complains of rolliness.

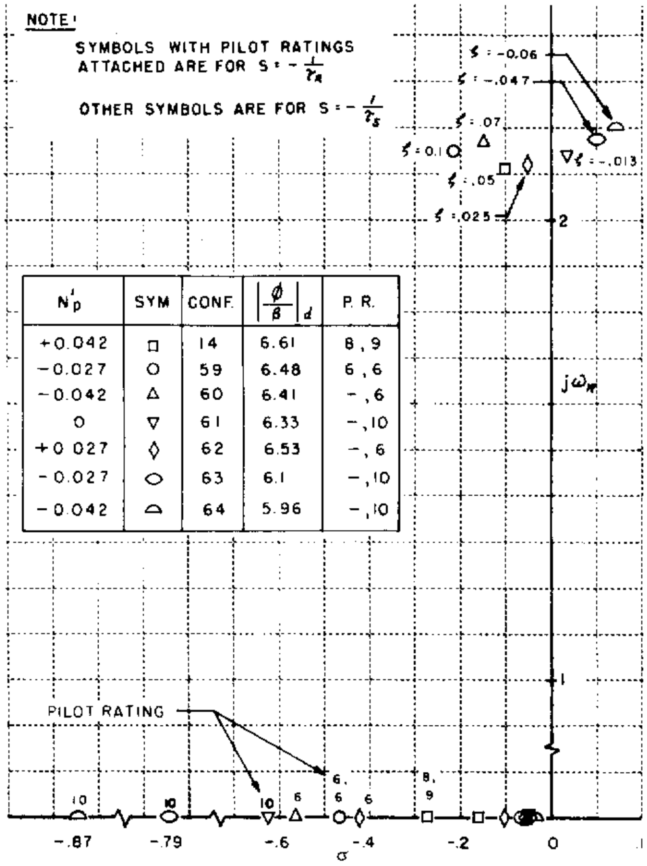
The stability derivative N'_p is listed on Figures 4a, b, and c. For the the great majority of the configurations, the yaw due to roll rate was proverse and compounds the control problems. The pilots were most explicit about the effect of proverse N'_p for the better-rated configurations, but as τ_R becomes longer ($s = -1/\tau_R$ becomes smaller than -1.6) they became less explicit about it, or didn't mention it, because it is apparently sufficiently masked by other difficulties that they don't sort it out. The proverse N'_p effect is that cross-coordination of the aileron and rudder controls is required after a roll rate is built up sufficiently that the proverse yaw due to roll rate overpowers the adverse yaw due to aileron. Both pilots find that it is very difficult to coordinate this effect and so they accept the sideslip that results and they do not use rudder to coordinate. Therefore, another effect is that if a roll rate exists and a step aileron input is made to reduce it, stop it or reverse it, then the sideslip error becomes large. It becomes large because at the initiation of the change in roll rate, the sideslip that occurs from the use of ailerons adds to the sideslip that exists because of a lack of coordinating the N'_p induced sideslip. These effects are noticed by both pilots, one of whom accurately diagnosed the cause. The other pilot may have realized the cause but referred to the result as a "queer phasing in sideslip that occurs with these configurations". The pilots both comment that the use of the rudder with low roll damping aggravates their control difficulties.



a

b

Figure 4. Real Root Roll and Spiral Mode Configurations - Dutch Roll Constant



N'_p	SYM	CONF.	$\left\lvert\frac{\phi}{\beta}\right\rvert_d$	P. R.
+0.042	□	14	6.61	8, 9
−0.027	○	59	6.48	6, 6
−0.042	△	60	6.41	−, 6
0	▽	61	6.33	−, 10
+0.027	◇	62	6.53	−, 6
−0.027	⬭	63	6.1	−, 10
−0.042	⌓	64	5.96	−, 10

Figure 4c. Additional Real Root Configurations – Dutch Roll Variable

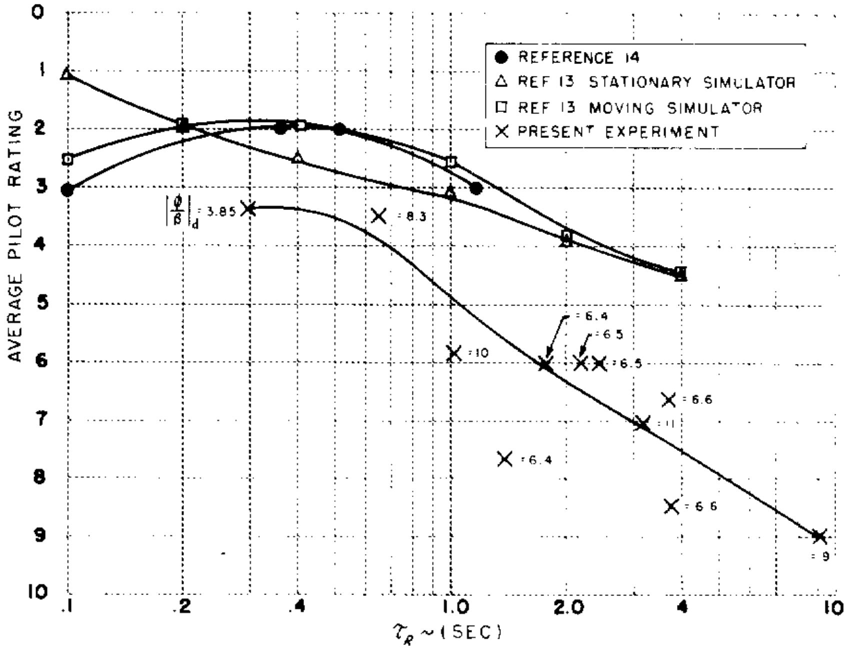


Figure 4d. Average Pilot Rating of Roll Mode Time Constant

A comparison is made between the present results and some results of past experiments on the roll mode time constant. The past experiments are discussed in References 13 and 14. Reference 13 is a NASA report that describes a simulator experiment with and without acceleration applied to the pilot and for the pure roll mode only; that is, no longitudinal, Dutch roll or spiral dynamics were represented. Reference 14 describes an in-flight reentry simulation in a variable stability T-33 airplane. For the experiment of Reference 13 there were longitudinal, Dutch roll, roll mode and spiral mode dynamics but the spiral mode root was at the origin. The results of the experiments of References 13 and 14 are comparable and they are plotted with the results of the present experiment in Figure 4d on a plot of pilot rating versus roll mode time constant.

The results of the present experiment exhibit the same trends but fall below those of the previous experiments. There are several differences that may cause the disparity and they are: (a) that the present experiment includes typical spiral root locations, (b) the N'_p effect discussed earlier, (c) the pilots' extrapolation of a lack of acceleration cues to "real" flight, (d) the fact that $|\phi/\beta|_d$ of the present experiment is much greater than the $|\phi/\beta|_d$ (non-existent and 1.5) of the previous experiments, and (e) the flight path holding problems at M = 1.2 in this experiment versus the lesser degree of this problem in the other experiments. Also, the Dutch roll characteristics are varied in the present experiment.

THE COMPLEX ROLL-SPIRAL ROOTS

The complex roll-spiral roots exist if the lateral characteristic equation can be factored into two sets of complex pairs of roots. One set of roots is the Dutch roll mode and the other set of roots is the complex roll-spiral or lateral phugoid mode. Of course, if the damping ratio of the lateral phugoid is greater than one, then it can be factored into a real roll mode root and a real spiral mode root. For this experiment the complex roll-spiral roots, the Dutch roll roots and the values of $|\phi/\beta|_d$ are all systematically varied. Comparison of the results for the different values of the parameters gives a determination of the effects of ω_{SR}, ζ_{SR}, ζ_d and $|\phi/\beta|_d$. In the following paragraphs, the comparisons that can be made are discussed in detail. The primary interest is in determining the effects of the parameter values on the ability of the pilot to control the airplane.

The rating results of this portion of the experiment are presented in Figures 5 and 6. An over-all summary of the results indicates that the best average rating for configurations with a complex roll-spiral ($\zeta_{SR} < 1$) is 7 and that ratings improve when roll-spiral damping ratio or frequency increase (Figure 5). Figures 6a, 6b, 6c show some of the interaction effects that are included but not shown explicitly in Figure 5.

A discussion of the effects of the individual parameter variations follows.

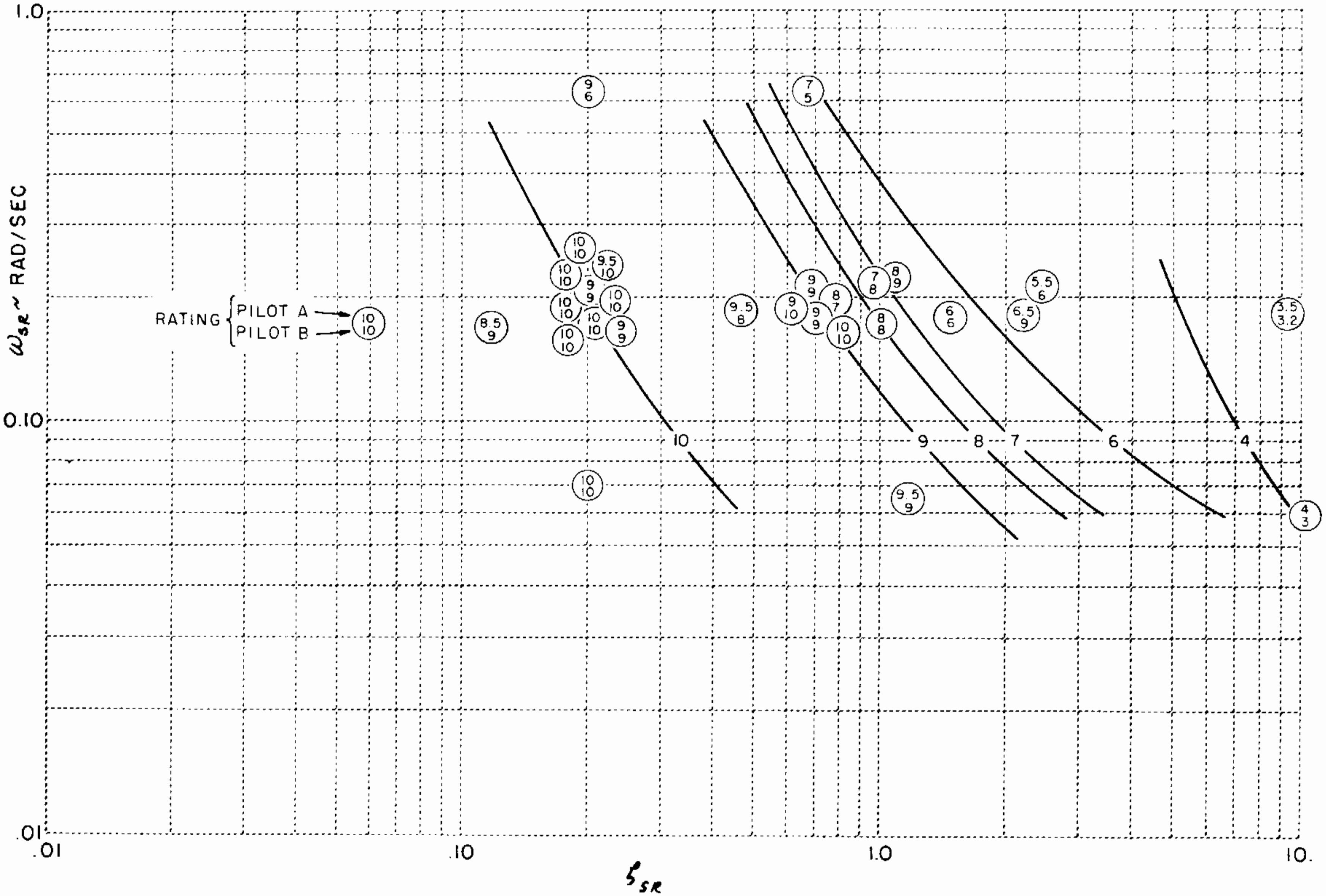


Figure 5. ω_{SR} vs. ζ_{SR} For Convergent Dutch Roll

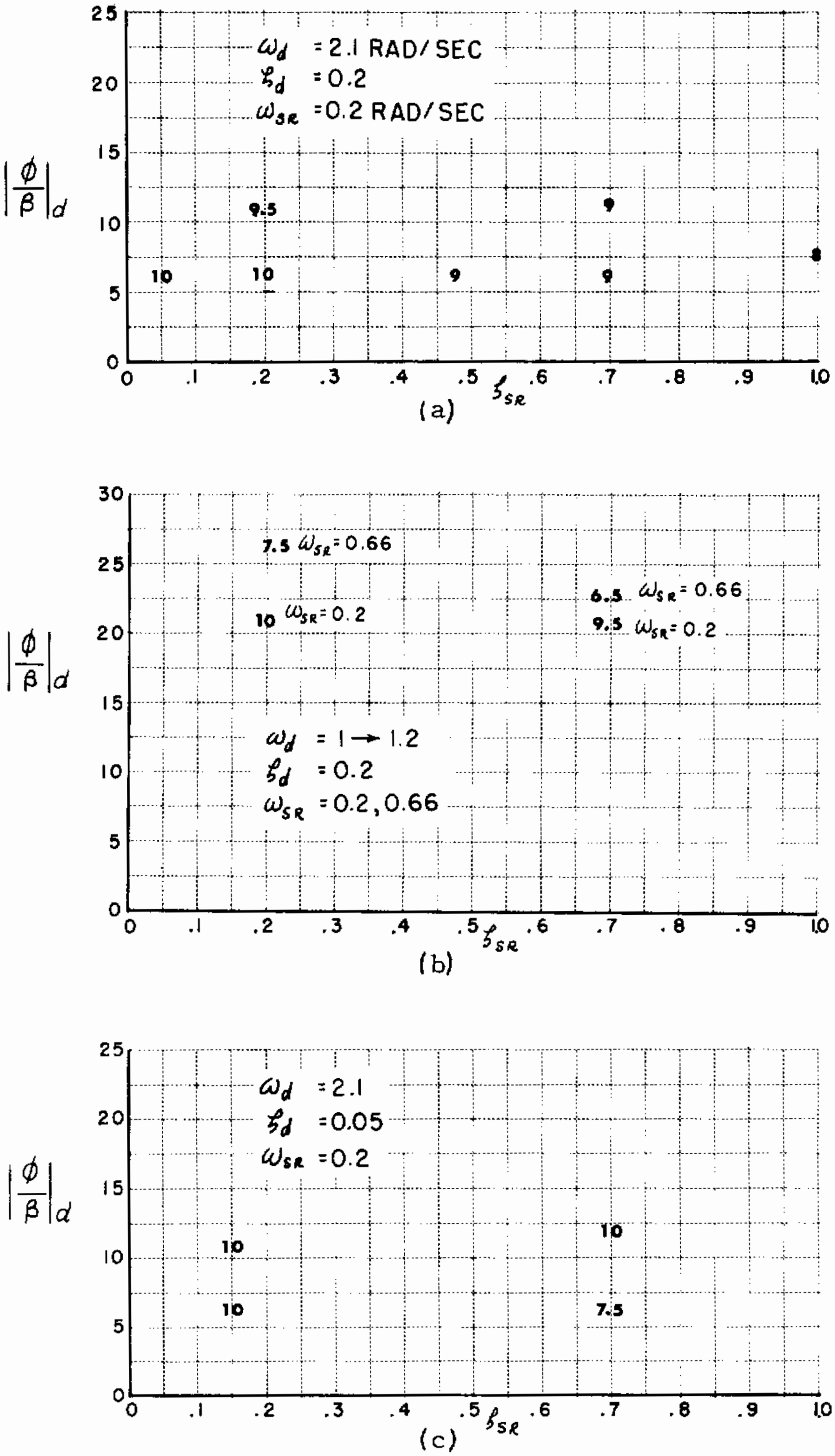


Figure 6. Average Pilot Ratings vs. $\left|\frac{\phi}{\beta}\right|_d$, ζ_{SR}

Effect of ζ_{SR}

		Ratings and Comments		
		Pilot A	Pilot B	
Config.	ζ_{SR}	Rating & Primary Comment	Rating & Primary Comment	Fig.
9	0.7	9, Lacks roll damping	9, Lacks roll damping	2a
10	0.21	10, Lacks roll damping, requires tunnel vision on attitude	10, Lacks roll damping, requires tunnel vision on attitude	2a
11	0.06	10, Sneaky, divergent devil	10, Practical divergence	2a

Modal Similarities: ω_d = 2.14 rad/sec, ζ_d = 0.20

ω_{SR} = 0.18 rad/sec, $|\phi/\beta|_d$ = 6.45, ω_ϕ/ω_d = 0.95

Configuration 9 is "rolly", lacks roll damping, and must be flown continuously closed-loop. The bank angle precision is poor to bad and neither pilot accepted it for the alternate mission. Neither pilot uses the rudder because whenever they try it, they find its use degrades control precision. Use of aileron pulses is helpful.

The lower roll-spiral damping ratio of Configuration 10 results in comments that step aileron inputs order roll acceleration, that there is a lack of roll damping, that closed-loop control requires "tunnel vision" on the attitude indicator, that the bank angle precision is poor to bad, that rudder is not used, and that the configuration is unacceptable for the alternate mission. Apparently this configuration is worse than Configuration 9 primarily because of the worse aileron control, in that the airplane becomes more "rolly", caused by the lower roll-spiral damping ratio.

The still lower roll-spiral damping ratio of Configuration 11 elicits the same objections but in addition it is called sneaky. One pilot calls it a "sneaky divergent devil" and the other says it has a "practical divergence". This one needs only a small kick from any source (such as turbulence, slight out-of-trim condition, or inadvertent inputs) for it to take off with a roll rate. Control of the configuration can be lost easily. The pilots had to concentrate on roll control. Both of them would think they had established zero roll rate only to find several seconds later that the bank angle had changed. This result leads to the comments that it is sneaky and has a practical divergence.

The characteristic of apparent divergence somehow indicates the amount of time a pilot can spend on making a decision and shows that he is aggravated when he finds his decision was wrong. For instance, the settling time ($3/\zeta\omega_n$) for the roll-spiral is 261 seconds and the time to the first bank angle peak is 6.8 seconds. In the region of the peak bank angle, the roll rate will be small for a few seconds. The pilot could easily decide during these few seconds that he had settled the airplane down at an equilibrium bank angle only to find that he had not. Situations like this have always appeared to pilots as a divergence and they are correct in the practical sense because they cannot afford to wait to find out otherwise. Such a practical divergence will lead to a low frequency closed-loop PIO because the pilot believes he is chasing a divergent characteristic. The response is too slow for him to see what his lead characteristic should be and so he uses a "try and see" input system that generally leads to a hunting type PIO.

From these comparisons it is seen that the roll-spiral damping ratio has an effect and if it is to be of benefit in roll control, it must have a large value.

Effect of ζ_d

Config.	ζ_d	Ratings and Comments				Fig.
		Pilot A		Pilot B		
		Rating &	Primary Comment	Rating &	Primary Comment	
16	0.05	10,	no roll damping, increases rapidly	10,	p speeds up, oscillates, stay closed-loop	2b
10	0.2	10,	lacks roll damping,	10,	lacks roll damping	2a

Modal Similarities: ω_d = 2.1 rad/sec, ω_{SR} = 0.21 rad/sec, ζ_{SR} = 0.2

ω_ϕ/ω_d = 0.95, $|\phi/\beta|_d \approx$ 6.5

Config.	ζ_d	Ratings and Comments				Fig.
		Pilot A		Pilot B		
		Rating &	Primary Comment	Rating &	Primary Comment	
15	0.05	8,	very little roll	7,	never stops rolling	2b
9	0.2	9,	lacks roll damping	9,	lacks roll damping	2a

Modal Similarities: ω_d = 2.1 rad/sec, ω_{SR} = 0.2 rad/sec, ζ_{SR} = 0.7,

ω_ϕ/ω_d = 0.95, $|\phi/\beta|_d \approx$ 6.5

Configuration 16 was rated 10 by both pilots and it differs from Configuration 10 by having a value of the Dutch roll damping ratio of 0.05 instead of 0.20. The evaluation comments for Configuration 16 are very similar to those for Configuration 10 and there does not appear to be an explicit difference caused by the lower Dutch roll damping ratio.

Both pilots rate Configuration 15 slightly better than Configuration 9. However, one might expect the reverse rating order to occur because of the lower Dutch roll damping ratio for Configuration 15. A review of the evaluation comments does not help because they seem the same for both configurations and there is no particular difference to focus upon that explains the different ratings. As noted in Table II of the appendix, the $|\phi/\beta|_{SR}$ are different; that is, 248 for Configuration 9 and 136 for Configuration 15. No systematic study of this parameter has been made and the effects of it are unknown. Perhaps the rating difference shown here is an indication that it should be studied.

The evaluation comments for Configuration 9 are reviewed on page 22 and they are very much like the comments for Configuration 15.

Configuration 15 is "rolly", has very little roll damping, will roll onto its back if you don't watch it, has a lag in starting and stopping roll rate, has poor to bad bank angle precision, precludes pilot use of rudder, requires continuous closed-loop control for maneuvering, and is not acceptable for the alternate mission.

Effect of $|\phi/\beta|_d$

Config.	$\left\|\frac{\phi}{\beta}\right\|_d$	Pilot Ratings and Comments		Fig.
		Pilot A	Pilot B	
		Rating & Primary Comment	Rating & Primary Comment	
9	6.45	9, Lacks roll damping	9, Lacks roll damping	2a
3	11.0	9, Very large roll rate for small aileron input	9, Incessant rolling, dangerous	2c

Modal Similarities: ω_d = 2.1 rad/sec, ζ_d = 0.2, ω_{SR} = 0.2 rad/sec,

ζ_{SR} = 0.7, ω_ϕ/ω_d = 0.95

Config.	$\left\|\frac{\phi}{\beta}\right\|_d$	Pilot Ratings and Comments		Fig.
		Pilot A	Pilot B	
		Rating & Primary Comment	Rating & Primary Comment	
10	6.45	10, Lacks roll damping, requires tunnel vision on attitude	10, Lacks roll damping	2a
4	11.0	9, Ailerons order $\dot{p}$, continuous closed-loop	9, Can't stop roll, generate lots of β in Dutch roll	2c

Modal Similarities: ω_d = 2.1 rad/sec, ζ_d = 0.2, ω_{SR} = 0.2 rad/sec,

ζ_{SR} = 0.2, ω_ϕ/ω_d = 0.95

		Pilot Ratings and Comments				
		Pilot A		Pilot B		
Config.	$\lvert\phi/\beta\rvert_d$	Rating & Primary Comment		Rating & Primary Comment		Fig.
15	6.6	8,	Very little roll damping	7,	Never stops rolling	2b
37	11.2	10,	Lacks roll damping, ζ_d is very small, $\lvert\phi/\beta\rvert_d$ is large	10,	p is too large, always oscillating, always closed-loop	2d

Modal Similarities: $\omega_d = 2.1$ rad/sec, $\zeta_d = 0.05$, $\omega_{SR} = 0.2$ rad/sec,

$\zeta_{SR} = 0.7$, $\omega_\phi/\omega_d = 0.95$

		Pilot Ratings and Comments				
		Pilot A		Pilot B		
Config.	$\lvert\phi/\beta\rvert_d$	Rating & Primary Comment		Rating & Primary Comment		Fig.
16	6.7	10,	No roll damping, ϕ increases rapidly	10,	p speeds up, oscillates, stays closed-loop	2b
38	11.3	10,	ζ_d is light, $\lvert\phi/\beta\rvert_d$ is high, continuous closed-loop	10,	Rolls onto back, unmanageable, always closed-loop	2c

Modal Similarities: $\omega_d = 2.1$ rad/sec, $\zeta_d = 0.05$, $\omega_{SR} = 0.2$ rad/sec,

$\zeta_{SR} = 0.2$, $\omega_\phi/\omega_d = 0.95$

Comparisons of Configurations 9 with 3, 10 with 4, 15 with 37, and 16 with 38 should show if there is an effect of changing $\lvert\phi/\beta\rvert_d$ from approximately 6.6 to approximately 11. The comparison of the ratings indicate no strong influence of $\lvert\phi/\beta\rvert_d$.

The evaluation comments are much the same for both Configurations 9 and 3, that is, the bank angle precision was bad and neither pilot used rudder very much, partly because they didn't need it and partly because they couldn't sort out what to do with it unless the aileron was accurately trimmed.

On Configuration 3 one pilot did notice that a very small aileron input caused the airplane to roll over and achieve a steady state bank angle, but it would get there in an oscillatory fashion. This pilot believes the configuration has a lightly damped complex roll-spiral. The aileron input that would produce a usable bank angle was so tiny that he had trouble obtaining the small input whenever he was looking for it. The actual roll-spiral damping ratio is 0.71 and apparently it takes a large frequency to make the roll-spiral self-evident to the pilot. The comparison of $|\phi/\beta|_d$ for these two configurations nets no specific information except that the sizable rolling moment produced by sideslip was noticed but it doesn't seem to be excessive. Another noticeable characteristic was that the sideslip that was produced by use of the ailerons was very nearly cancelled by the proverse yaw due to roll rate except when the pilot reversed his roll rate. While he was reversing his roll rate the sideslip due to aileron would add to that due to the initial roll rate. Both pilots agree that the configuration must be flown closed loop.

Comparison of Configuration 10 with Configuration 4 reveals that Configuration 10 was rated 10 by both pilots and Configuration 4 was rated 9 by both pilots. Because both pilots rate each configuration the same, it seems that there may be an explicit difference between the configurations. A careful reading of the comments implies that if there is a difference it may be that Configuration 4 is a wee bit more controllable. In the comparison between Configurations 15 and 37 where the preference is definitely for the smaller value of $|\phi/\beta|_d$, one pilot makes a specific note of the large $|\phi/\beta|_d$ in his comments on Configuration 37. Again the predominant characteristics are those of the roll-spiral and the resultant lack of roll control.

From Figure 5 of Reference 14, given here as Figure 7, we expect a rating of 5 for a configuration with a $|\phi/\beta|_d$ of 8 to 9, a zero spiral root and a Dutch roll frequency and damping ratio of 2.3 rad/sec and 0.15 respectively. Configuration 29 is very close to this point except that it has a roll-spiral with a frequency of 0.07 rad/sec and it is rated 10 by both pilots. The problem with Configuration 29 is that roll rate, for a step aileron input, increases with time and very tight closed-loop control is required. The difference here is directly ascribable to the very long settling time of the roll-spiral mode and the pilot sees only the portion of the response where roll rate appears to increase linearly with time for a step aileron input.

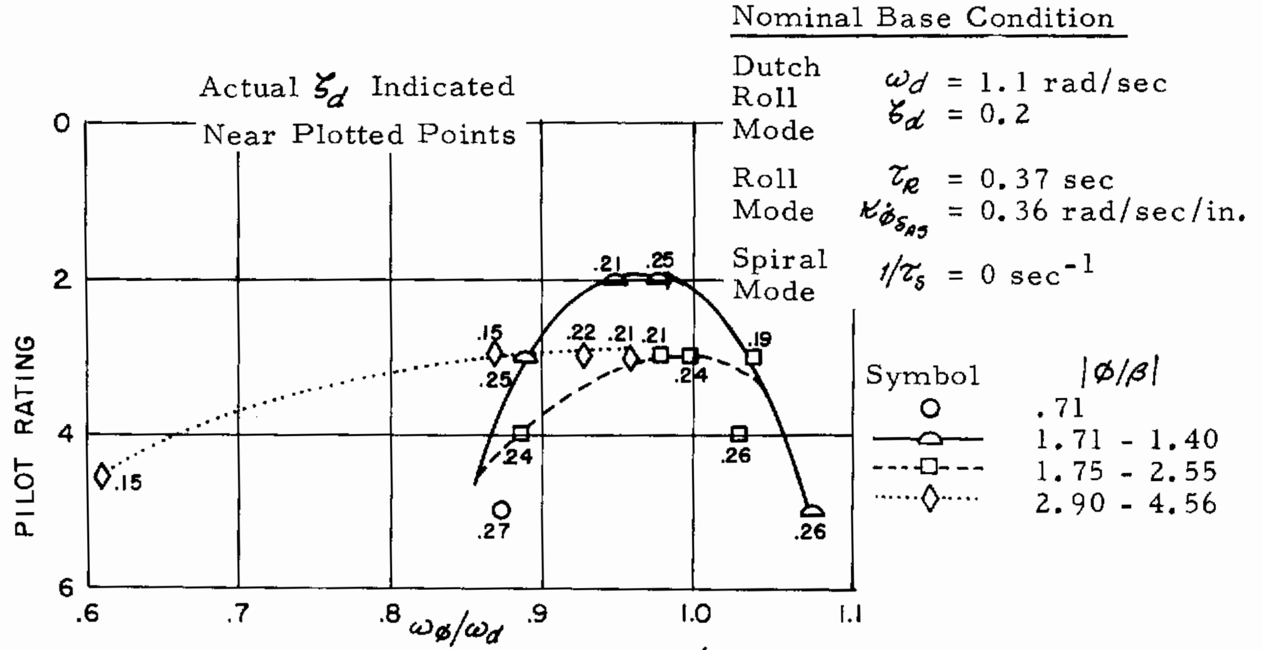


Figure 7. Pilot Rating Versus ω_ϕ/ω_d for Low Frequency, Moderately Low Damping Dutch Roll

Effect of ω_{SR}

Config.	ω_{SR}	Pilot Ratings and Comments		Fig.
		Pilot A	Pilot B	
		Rating & Primary Comment	Rating & Primary Comment	
29	0.07	10, Very, very tight closed-loop on attitude, roll rate increases linearly	10, About to roll on bank, p starts slowly then gets large	2f
4	0.2	9, Ailerons order $\dot{p}$, continuous closed-loop	9, Can't stop roll, lots of β in Dutch roll	2c

Modal Similarities: $\omega_d = 2.11$ rad/sec, $\zeta_d = 0.2$, $\zeta_{SR} = 0.2$,

$|\phi/\beta|_d \approx 10$

The difference in the comments for these two configurations strongly reflects the difference in the roll-spiral mode rise time because both pilots speak of Configuration 4 as having a rapidly increasing roll rate whereas Configuration 29 starts out slowly and then roll rate increases linearly to a large value. The rise time for Configuration 4 is 16 seconds and for Configuration 29 it is 71 seconds. In both cases the response is too slow for the pilot to see what will eventually happen and so he will try to force the response he wants. This comparison is representative of the improvement in handling qualities realized by increasing ω_{SR}.

Combined Effect of ω_{SR}, ζ_{SR}

Config.	ω_{SR}	ω_d	Pilot Ratings and Comments		Fig.
			Pilot A	Pilot B	
			Rating, Primary Comment	Rating, Primary Comment	
21	0.21	1.2	9, Very little roll damping, continuous closed-loop	10, Lose it, rolls impossibly, p builds up, large β	2e
33	0.66	1.0	7, Large $\|\phi/\beta\|_d$, long oscillation in ϕ	5, Bobble in roll, large β, oscillation in roll	2g

Modal Similarities: $\omega_d = 1.2 \rightarrow 1$ rad/sec, $\zeta_d = 0.2$, $\zeta_{SR} = 0.7$,

$|\phi/\beta|_d \approx 21$, $\omega_\phi/\omega_d = 0.95$

Con-fig.	ω_{SR}	ω_d	Pilot Ratings and Comments		Fig.
			Pilot A	Pilot B	
			Rating, Primary Comment	Rating, Primary Comment	
22	0.21	1.2	10, Low roll damping, wants to roll off	10, Hard to control ϕ, continuous closed-loop, p builds up rapidly	2e
34	0.66	1.0	9, Lacks directional stiffness	6, p lags δ_a, tend to PIO	

Modal Similarities: $\omega_d = 1.2 \rightarrow 1$ rad/sec, $\zeta_d = 0.2$, $\zeta_{SR} = 0.2$,

$|\phi/\beta|_d = 20.3$ and 26.5, $\omega_\phi/\omega_d = 0.95$

The comparison of Configurations 21 with 33 and 22 with 34 compare the effects of two different roll-spiral frequencies at essentially the same Dutch roll characteristics. The difference in Dutch roll frequencies between 1.0 rad/sec and 1.2 rad/sec is minor. The pilots appear to differ in their evaluations of Configurations 33 and 34. Part of the discrepancy between the ratings is due to the rating philosophy of the two pilots, one of whom included the fact that the airplane was supposed to be a maneuverable tactical fighter and the other pilot considered primarily the instrument flight requirements and did not strongly include the tactical fighter requirements. However, the evaluation comments of both pilots indicate a preference for Configurations 33 and 34 over Configurations 21 and 22 respectively. Their preference is based upon their recognizable ability to obtain a steady state bank angle for the smaller responses ordered during IFR flight. However, for large disturbance maneuvers neither Configuration 33 nor 34 were at all good because of the large sideslip that could be induced and because neither pilot could determine how to use the rudder to consistently minimize the sideslip. Therefore, the pilots find the better technique is to fly aileron only and let sideslip come out at will. The aileron is bank angle-ordering for Configuration 33 and 34 and the pilots comment that a steady aileron force is required to maintain a steady bank angle. If the force is released, then the bank angle returns to zero. These comments show that the roll-spiral mode is of sufficiently high frequency that the pilots can see and realize the response characteristics of the airplane. They can use the response characteristics to their advantage acceptably well for the slower and smaller responses that are used in IFR flight but find them unacceptable for a general fighter type mission.

In summary, Configurations 33 and 34 are more aceceptable than are Configurations 21 and 22 because of the greater predictability resulting from the shorter rise time. An additional fact concerning Configurations 33 and 34 is that the $|\phi/\beta|_{SR}$ is very low compared to the other configurations. Whatever contribution this may have is unknown but interesting to contemplate in terms of further research.

A direct comparison of Configurations 33 and 34 indicates that the pilots had more difficulty with Configuration 34 in making roll angle settle down and rated it the poorest. Configuration 34 has a lower roll-spiral damping ratio than Configuration 33 and thus has a longer roll-spiral mode settling time. This pilot reaction results from the difference in settling times, which for Configuration 33 is 6.6 seconds and for Configuration 34 is 23 seconds. We reiterate that the pilots found the use of the rudder too confusing to be of practical value. However, the indication of Configurations 33 and 34 is that a roll-spiral may be found which is flyable as a fighter. This, again is interesting and reasonable to contemplate for further research.

The contrast between Configuration 33 and most of the rest of the configurations is shown in Figures 8 and 9 which show responses to aileron step inputs for Configuration 10 and Configuration 33 respectively. A striking difference is noted in the manner and the time required for bank angle to reach a steady state value. It is precisely this persistent difference that has caused so many configurations to be rated unacceptable. The settling time and predictable bank angle response for Configuration 33 is on the borderline of acceptability. The long settling time and oscillatory bank angle response for Configuration 10 causes the pilot to react to only the very initial portion (perhaps as much as 2 to 4 seconds) of the bank angle and roll rate responses from which he feels the ailerons are acceleration-ordering. He therefore feels he must modify his input and that closed-loop attitude control is required for him to settle the airplane down. In general, for configurations like Configuration 10, the pilot will use pulse aileron inputs.

At this point we may contrast the pilots' technique for obtaining bank angle for the standard airplane and airplanes like Configurations 33 and 10. If we assume the standard airplane to have a real root roll mode with a good (small) roll mode time constant and a large τ_s, then the pilot will order roll rate with his ailerons and he will center the ailerons and stop the roll rate whenever the desired bank angle is reached. If the time constant is of a truly desirable value, then the demand on the pilot to generate lead in order to stop on the desired bank angle is negligible or else very simple to learn. Thus, for a good standard airplane, the pilot commands roll rate directly and positively.

For Configuration 33, the pilot orders bank angle directly with aileron position and although the response is slow it is fast enough that the pilot realizes what is happening and he realizes he has control of the airplane. He also realizes that to maintain a given bank angle he must hold a specific aileron position.

The majority of the configurations are similar to Configuration 10 wherein the pilot must decide within a second or two what the result of his input will be. For Configuration 10, he feels that his aileron inputs order roll acceleration and he does not like this indication. Therefore, he operates closed-loop with aileron pulses to generate lead in order to keep the airplane under control as best he can and he characterizes the airplane as being "rolly" and having too little or no roll damping.

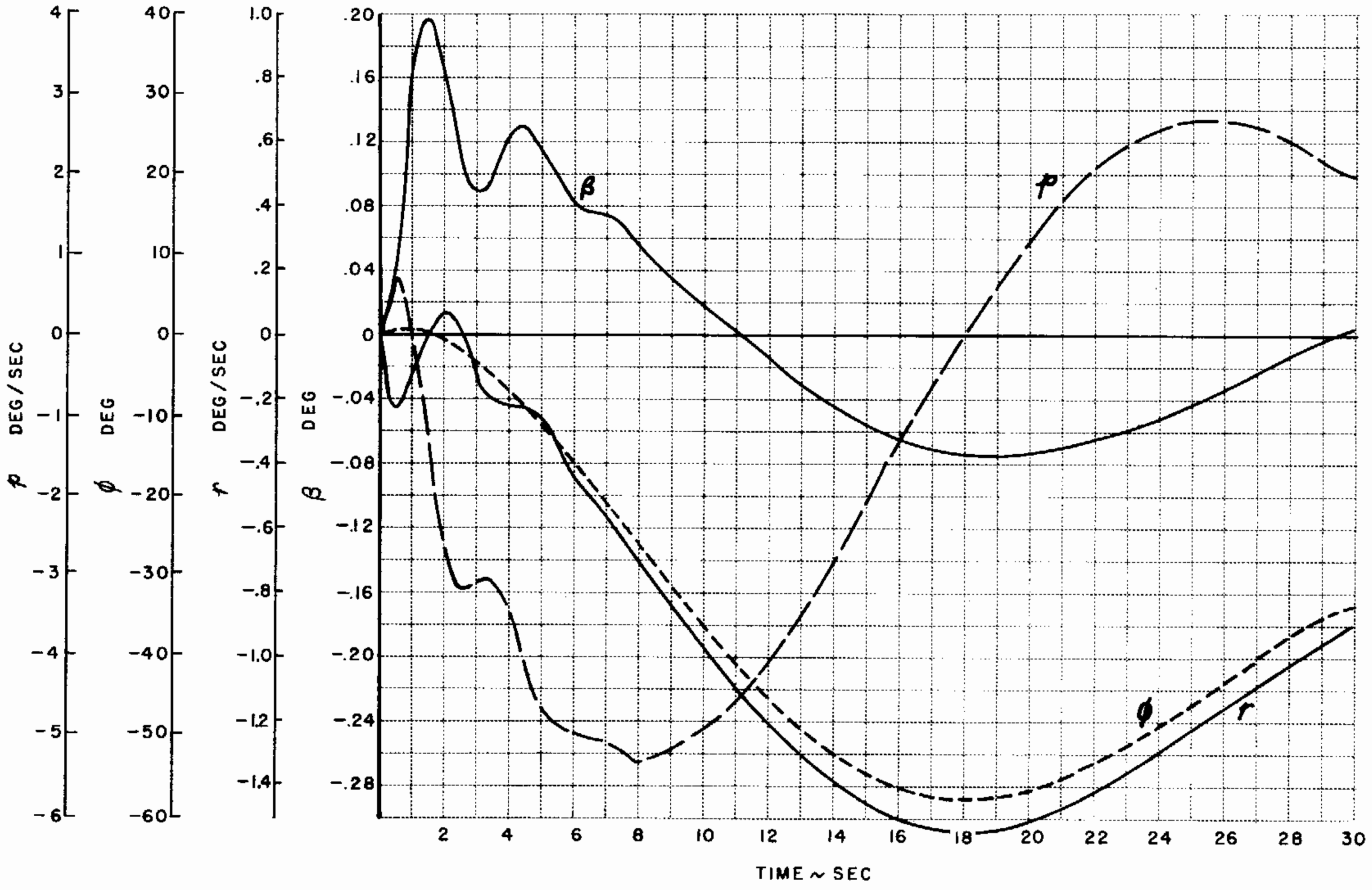


Figure 8. Transient Response of Configuration 10 to Aileron Step Input

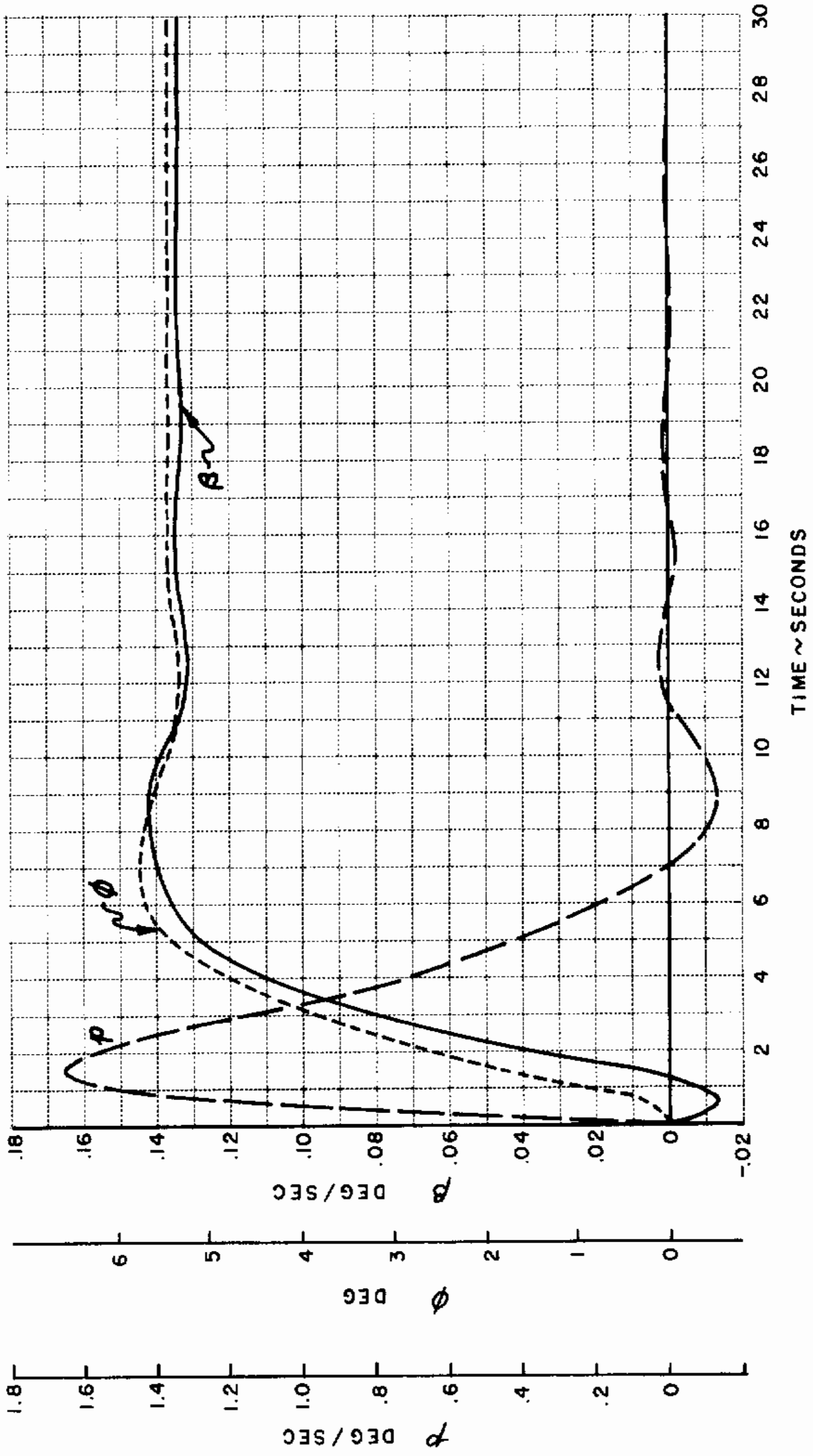


Figure 9. Transient Response of Configuration 33 to Aileron Step Input

Effect of Yaw due to Ailerons

Configurations were evaluated to determine the effects of the yaw due to roll control as expressed by the ratio ω_ϕ/ω_d.

The term ω_ϕ is the numerator "frequency" of the aileron to bank angle angle transfer function:

$$\frac{\phi}{\delta_a} = \frac{A_\phi \left(s^2 + 2\zeta_\phi \omega_\phi s + \omega_\phi^2\right)}{\left(s^2 + 2\zeta_d \omega_d s + \omega_d^2\right)\left(s^2 + 2\zeta_{se}\omega_{se} s + \omega_{se}^2\right)}$$

or

$$\frac{\phi}{\delta_a} = - \frac{L'_{\delta_a} s^2 + \left[N'_{\delta_a}\left(L'_r - L'_{\dot{\beta}}\right) - L'_{\delta_a}\left(N'_r - N'_{\dot{\beta}} + Y_\beta\right)\right] s + \left[L'_{\delta_a}\left(N'_\beta + Y_\beta N'_r\right) - N_{\delta_a}\left(L'_\beta + Y_\beta L'_r\right)\right]}{\left(s^2 + 2\zeta_d \omega_d s + \omega_d^2\right)\left(s^2 + 2\zeta_{se}\omega_{se} s + \omega_{se}^2\right)}$$

The test configurations were 10, 47, 48 and 4, 49, 50 where Configurations 47 and 48 are variations of Configuration 10, and Configurations 49 and 50 are variations of Configuration 4. The ratings for these configurations are given in the following table.

Config.	$\frac{\omega_\phi}{\omega_d}$	Pilot Ratings and Comments			
		Pilot A		Pilot B	
		Rating	Comment on N'_{δ_a}	Rating	Comment on N'_{δ_a}
48	1.05	10, 10	Proverse	10	Lot of proverse
10	0.95	9, 10	None	10	No mention
47	0.80	9, 9	Adverse	9	Strong adverse
50	1.05	10	Can't tell	10	Proverse
4	0.95	9	Tiny bit adverse	9	Zero or small adverse
49	0.80	9.5	Adverse	10	No mention

Unfortunately, both base Configurations 4 and 10 are very bad ones and the variations in ω_ϕ/ω_d are only perturbations on bad situations. Between both pilots they correctly identify the degree and direction of the aileron yaw, but the basic configuration is always so "rolly" that the effect of aileron yaw is just another condition to the pilot and not a primary factor. The only significant effect appears to be the degradation in roll control for the proverse yaw configurations 48 and 50, where the airplane will inadvertently pick up extreme roll rates. This result is probably a consequence of the additive nature of the individually generated components of sideslip which will roll the airplane. Both pilots find this situation obnoxious and the resultant configurations unflyable.

It is interesting to note that each pilot flew both sets of configurations 48, 10, 47 and 50, 4, 49 in sequence and so had the opportunity to compare any configuration with the directly preceding one. Of course, neither pilot was informed that these configurations were in the sequence shown and they were not requested to make explicit comparisons among them. However, pilots do compare sequential configurations and since the configurations were flown in the sequence shown, then credence can be placed in the reality of the small rating differences which occur between the configurations. There is no apparent, strong rating trend caused by the value of ω_ϕ/ω_d.

ADDITIONAL EVALUATIONS

In addition to the configurations discussed so far, several more were evaluated by one or both pilots. They were chosen after a considerable portion of the experiment was completed, and were not part of the original experiment plan. The root locations of these configurations are shown in Figure 10.

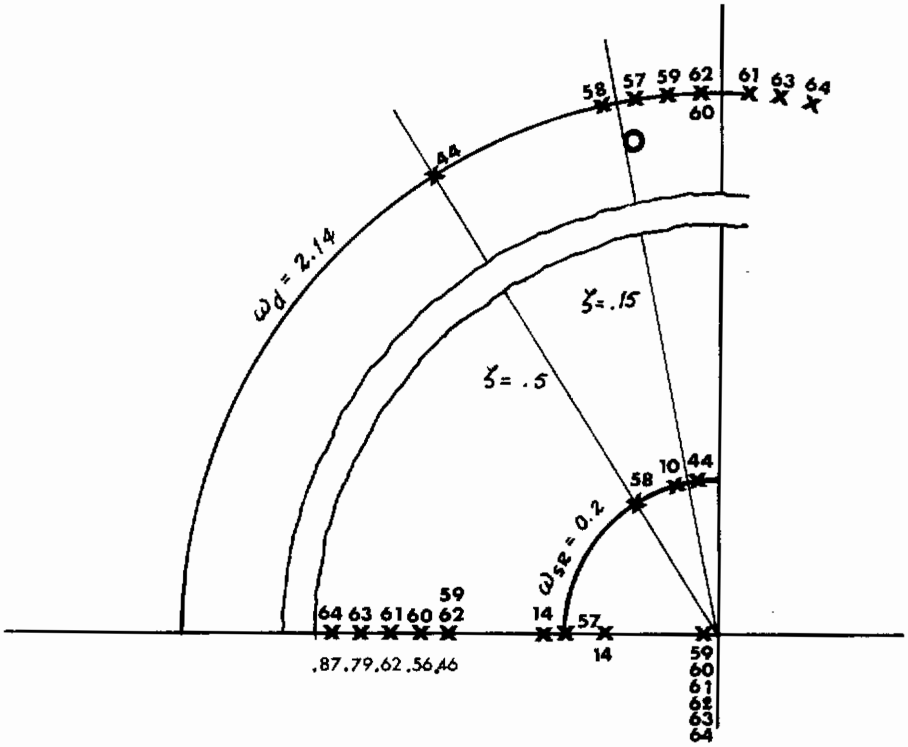


Figure 10. Root Locations of Additional Configurations

Configuration 44 was evaluated by both pilots and differs from Configuration 10 only by the value of the Dutch roll damping ratio which is increased from 0.2 (for 10) to 0.5 (for 44). It is rated 8.5 by one pilot and 9 by the other. In contrast, both pilots rated Configuration 10 as 10. Configuration

44 is easier to fly than many configurations because it is easier to control bank angle and roll rate. Although the configuration is flyable when the pilot remains closed loop, bank angle and roll rate require sufficient attention that the pilot cannot open the bank angle loop long enough to copy a complete clearance.

Configuration 10, however, was always rolling and would roll on its back while a clearance was being copied. The ailerons appeared to be acceleration-ordering and the pilots were constantly trying to control the roll of the airplane. The configuration was considered unflyable. Thus the comparison between Configurations 10 and 44 shows that the higher Dutch roll damping ratio is beneficial because it reduces the effects and resultant complications of a disturbed Dutch roll mode.

Not all of Configurations 57 through 64 were flown by both pilots because of a time limitation and individual pilot availability. These configurations were flown as a preliminary investigation of the effects of yaw due to roll rate. They were undertaken, in preference to some of the planned configurations, because of the consistent pilot complaints about the proverse yaw due to rolling (N'_p positive). Configurations 10 and 14 were used as the base configurations and of all the stability derivatives, only the value of N'_p was varied both positively and negatively, made zero and made equal to $\pm g/V$. N'_p is a powerful derivative and changing it altered the modal constants considerably. For all of these configurations, the aileron yaw was always slightly adverse ($\omega_\phi/\omega_d \approx 0.95$.

Configuration 57 had a value of $N'_p = 0$. It is a variation of Configuration 10 and from the pilot comments, Configuration 57 is found to be more controllable in roll than is Configuration 10. Both pilots rated Configuration 57 as 8 whereas they both rated Configuration 10 as 10. For both configurations, neither pilot can figure how to use the rudder during a Dutch roll oscillation and they both find it better to not use the rudder.

Configuration 58 is the same as Configuration 10, except that $N'_p = g/V = 0.027$ and one pilot rated it 8 and the other rated it 9.5. They both feel the configuration requires constant attention because of roll angle and roll rate control and neither finds the rudder of much use because it is hard to tell what to do with it.

Configuration 59 has $N'_p = -0.027 = -g/V$ and both pilots rated it 6. This value of N'_p drastically changed the basic configuration from one with a complex roll-spiral to one with a real roll mode root at -0.46 and a real spiral root at -0.071 as can be seen in Figure 10. Thus, this configuration has some roll damping and a roll mode time constant of approximately 2.18 seconds which explains the much improved rating.

Configuration 60 has a value of -0.042 for N'_p and again possesses real roots for the roll mode and the spiral mode. It was rated by only one pilot and it was rated 6. The roll mode root is -0.56 and the spiral mode root is -0.057. The roll mode time constant is approximately 1.78 seconds. The pilot says that it appears the same as the preceding configuration which was number 59.

The next group of four configurations (61 - 64) are variations on Configuration 14 and they were evaluated by only one pilot. Configuration 14 has real spiral and roll mode roots and was rated 9 by both pilots because of the lack of roll damping. Its roll mode time constant was 3.7 seconds.

Configuration 61 has real roots for the spiral and roll modes and the roll mode time constant is approximately 1.52 and a Dutch roll damping ratio of -0.013. The value of N'_p is zero. The pilot rated the configuration 9 because of the divergent Dutch roll.

Configuration 62 has $N'_p = g/V = +0.027$, a spiral root of -0.1 and a roll mode root of -0.426. The roll mode time constant was approximately 2.35 seconds. The Dutch roll damping ratio was 0.026 and the pilot rated the configuration a 6.

Configuration 63 has $N'_p = -0.027$ but also a divergent Dutch roll with a damping ratio of -0.05. The pilot rated it 10.

Configuration 64 had $N'_p = -0.042$ and a divergent Dutch roll with a damping ratio of -0.065. It was therefore rated 10.

The power of N'_p to change the root of the characteristic equation is the most noticeable effect in the comparisons of Configurations 57 through 64.

RÉSUMÉ OF PARAMETER EFFECTS

ζ_{SR} This parameter is best when it has a large value (= 0.70) and its effect is enhanced if ζ_d is also large. For small values of ζ_{SR}(0.06) the airplane shows a practical divergence.

ω_{SR} This parameter is best when it is large (= 0.66) and when it occurs with large ζ_{SR} . It is best under this circumstance because it results in a response which the pilot has time to see sufficiently well that he can predict the outcome. He feels more in control of the airplane. Very low ω_{SR} leads to much too slow a change in roll rate.

$|\phi/\beta|_d$ This parameter is large compared to the value of it for most present-day airplanes. For the values of it in this experiment it does not appear to have a strong influence.

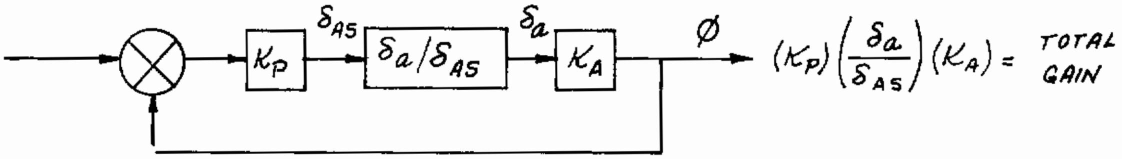
ζ_d This parameter can be helpful if it is large (0.5 or greater) because it can help to reduce the rolliness. A large value is most beneficial if the ζ_{SR} and ω_{SR} are also large because all three effects will tend to reduce rolliness and make the response more predictable.

ω_d, N'_p Although both these parameters were varied, neither was varied independently. Because of the masking effects of the other parameters, no specific comment on the effects of ω_d and N'_p is possible.

ω_ϕ/ω_d This parameter showed no significant effects in this experiment.

FURTHER, GENERAL ANALYSIS

Analytical studies of typical closed-loop root loci, assuming that the pilot is a pure gain, were made to determine the general closed-loop aileron control characteristics that might be expected. The assumption that the pilot operates as a pure gain bank angle controller is of questionable validity for the wide range of characteristics that were examined here. The work of Reference 7 indicates considerably more complete and accurate descriptions of probable pilot behavior as a controller. The purpose of the simple examination reported here (assuming a pure gain pilot) was to undertake a study of the possible piloting difficulties which could be expected with this wide range of lateral handling characteristics if the pilot did not adapt by altering his transfer function. The pure gain assumed here is a reasonable approximation for the pilot of airplanes with "good" (small τ_R) lateral dynamics. Sketches of typical locus patterns are shown in Figure 11 for varying gains. In that figure, sketches 'a' through 'd' represent cases of the coupled roll-spiral mode and sketches 'e' through 'g' represent cases with conventional roll and spiral modes. Sketches 'a' through 'd' show that for low gains, the roll-spiral stability always decreases with increasing pilot gain and in sketches 'b' and 'd' it goes unstable at the higher gains. The roll-spiral shown in sketch 'a' can also go unstable if the damping ratios of the Dutch roll (ζ_d) and the aileron bank angle numerator (ζ_ϕ) are reduced. In cases 'a', 'b', and 'c', the closed-loop Dutch roll always undergoes a reduction in damping, and in case 'c' it becomes divergent. Case 'a' is for $\omega_\phi/\omega_d \lesssim 1$ whereas cases 'b' and 'd' are for $\omega_\phi/\omega_d \gtrsim 1$. Case 'c' shows the loci for ω_ϕ/ω_d both somewhat less than and somewhat greater than 1. Thus, for these cases, it is seen that if the pilot uses a low enough gain he does not seriously alter the stability of either the Dutch roll mode or the roll-spiral mode. We may compare this information with the airplane gear ratios (δ_a/δ_{AS}) chosen by the pilots. This ratio is a gain of the open-loop airplane and contributes to the over-all pilot-airplane gain.



where K_P = pilot gain and K_A = airframe gain.

Each pilot was free to choose the ratio between aileron displacement and aileron stick motions. Plots of the two pilot's choices versus roll damping (and noting pilot rating) are shown in Figures 12a and 12b. It is noticed that most of the poorest-rated configurations for both pilots are for the lowest gains, or lowest values of δ_a/δ_{AS} , and that for one of the pilots this is predominantly the case. In discussing their choices of aileron gear ratio of the poorer rated configurations, both pilots remark that they would prefer very low gains for maneuvering but that they would need a higher gain in order to stop or control the higher roll rates that would develop in rapid rolls to 30° and 60° bank angles or the high roll rates that would develop inadvertently while the pilot was flying in turbulence or copying a clearance. Thus the pilot's choice of gearing, or gain, was not always in terms of control of small maneuvers, but most often was a compromise between good IFR control precision and

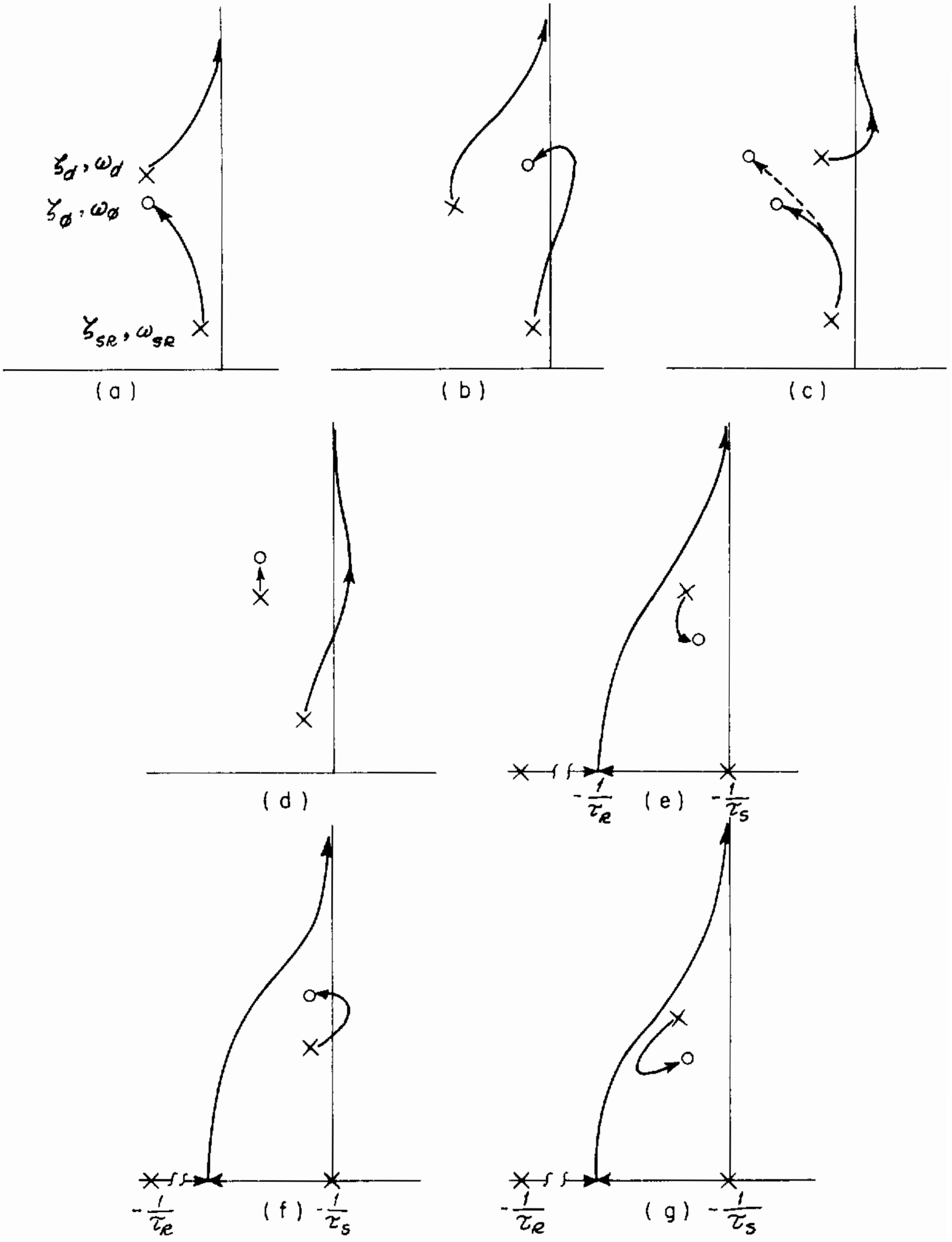


Figure 11. Typical Root Locus Patterns for Pure Gain Pilot

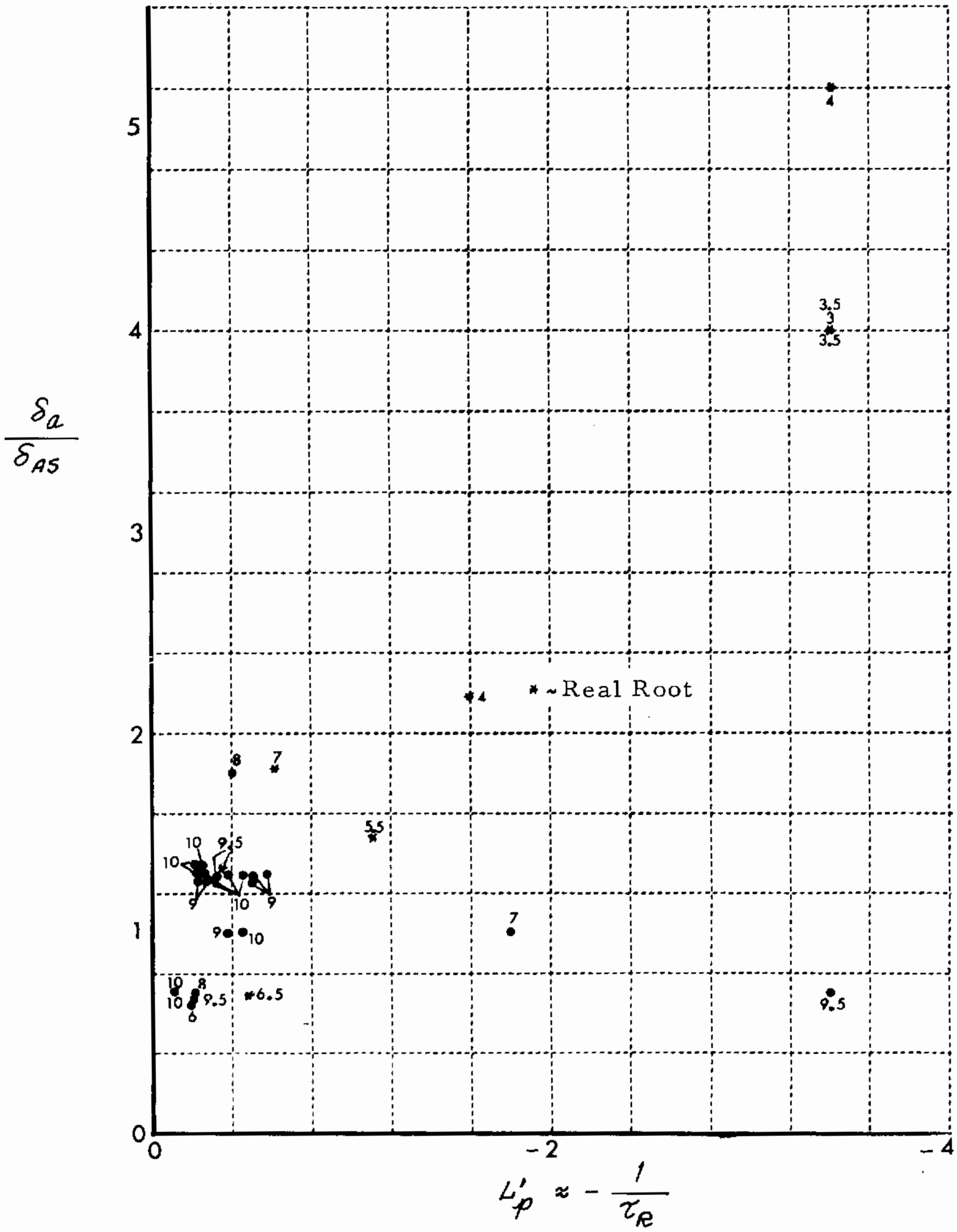


Figure 12a. Pilot A Rating Vs. Aileron Gearing and Roll Damping

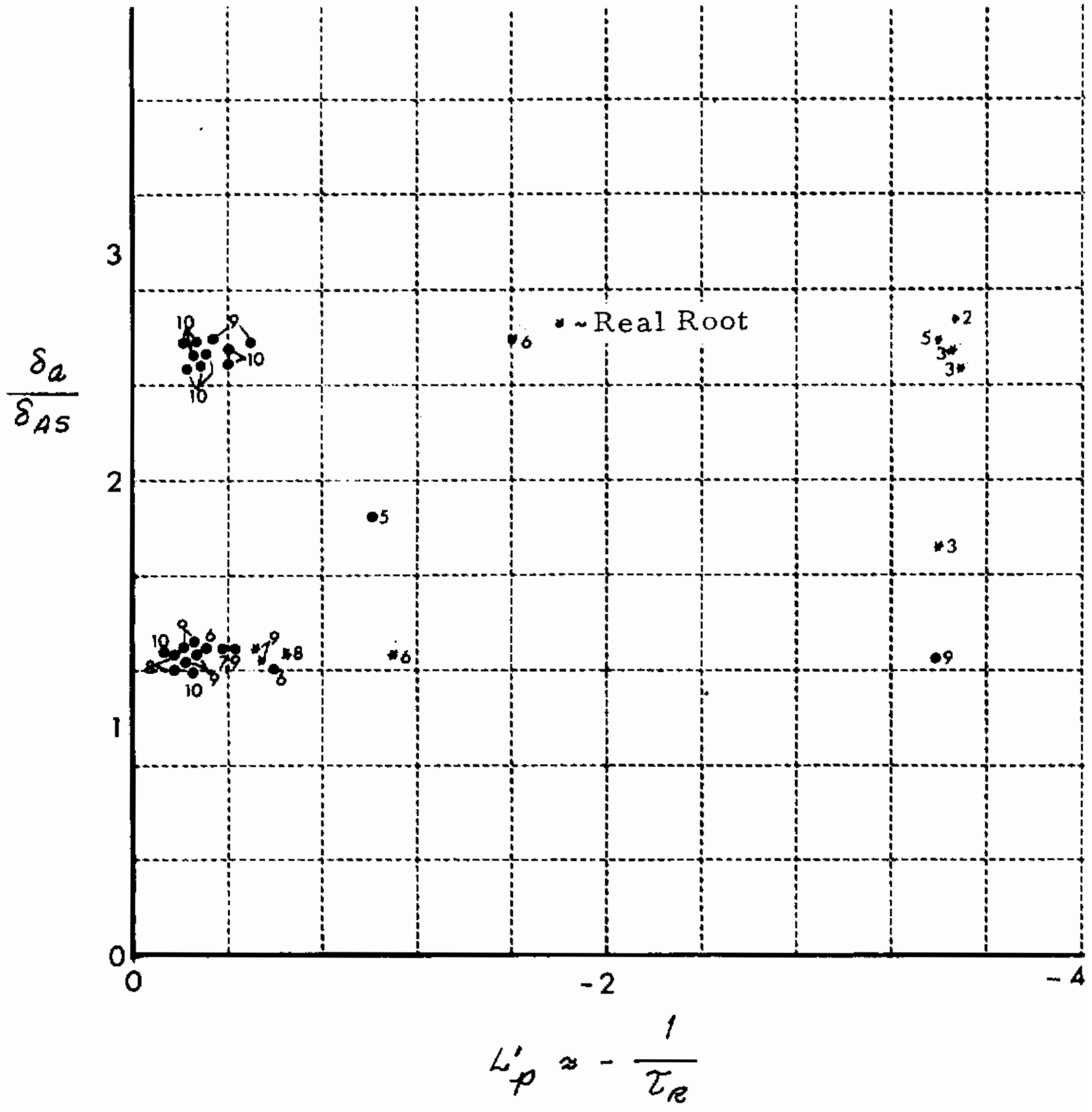


Figure 12b. Pilot B Rating Vs. Aileron Gearing and Roll Damping

maintaining the authority to control high roll rates. The indications of the root loci are that use of the higher gain will cause diminishing stability of either or both the Dutch roll or the roll-spiral. The pilots' comments confirm this because very often they would say they would have to remain tightly closed-loop on roll attitude in order to settle the configuration down and that this could take minutes. They also noted that they could fly with very small inputs by waiting long periods of time but that this was a very impractical way to fly. It was impractical because the wait (to see the result of an input) was too long, the result was not easily predictable, and the small inputs were too hard to resolve. At best, this technique could be used only in very smooth air. Hence, both pilots used gains that were higher than they recognized might be best for careful, precise flying in smooth air. They chose higher gains because they wanted to keep the airplane under control in all circumstances, and because the very small gains would be impractical for continual use, especially in rough air.

The main display of sketches 'e', 'f', and 'g' in Figure 11 is the well-known result that whenever $\omega_\phi/\omega_d > 1$ for $\zeta_\phi \approx \zeta_d$, then the Dutch roll mode stability is less for the closed loop than it is for the open loop and whenever $\omega_\phi/\omega_d < 1$ for $\zeta_\phi \approx \zeta_d$ then the Dutch roll mode stability increases for the closed loop. These results are true (as can be seen here) for "normal airplane" root locations.

Another comparison of the configurations is based on the premise that the configurations are the result of a stability augmentation system failure. Here the pilots were asked if they would accept the configuration for the alternate mission of general recovery from failure of the augmentation system. The agreement between the pilots is quite striking.

Use on Alternate Mission			Use on Alternate Mission		
Config.	Pilot A	Pilot B	Config.	Pilot A	Pilot B
1	Y*	Y	34	N	Y
2	Y	N	37	N	N, N
3	N	N	38	N	N, N
4	N	N	43	Y	Y
8	Y	N	44	Y	N
9	N	N	47	N	N
10	N	N, N	48	N	N
11	N	N	49	N	N
14	N	N	50	N	N
15	N	N	57	Y	Y
16	N	N	58	N	N
21	N	N	59	Y	Y
22	N	N	60		Y
25	N	N	61		N
26	Y	Y	62		Y
29	N	N	63		N
33	Y	Y	64		N

* Y = yes, N = no

For all of the coupled roll-spiral configurations the pilots found the use of the rudder to be very confusing. In general they allowed the sideslip angle to generate into whatever value it would take and they felt that the resultant side acceleration would be tolerable although they always maintained the reservation that it might not be. They estimated side acceleration from the sideslip needle; the side acceleration ball was not operative in the simulation.

We may indicate the problem of using the rudder to coordinate a rolling maneuver by looking at the expression for the rudder required to keep $\beta = 0$ in a rolling maneuver. This expression can be developed by equating $\dot{\beta} = 0$ in the equations of motion and solving for δ_r assuming $Y_{\delta_r}\dot{\delta}_r = 0$. This procedure is indicated in Reference 17 and results in:

$$\delta_r = \frac{-\frac{N'_{\delta_a}}{L'_{\delta_a}}\ddot{\phi} + \left(\frac{N'_{\delta_a}}{L'_{\delta_a}}L'_p - N'_p + \frac{g}{V}\right)\dot{\phi} + \frac{g}{V}\left(\frac{N'_{\delta_a}}{L'_{\delta_a}}L'_r - N'_r\right)\phi}{\left(-N'_r Y_{\delta_r} - N'_{\delta_r} + \frac{N'_{\delta_a}}{L'_{\delta_a}}L'_r Y_{\delta_r} + \frac{N'_{\delta_a}}{L'_{\delta_a}}L'_{\delta_r}\right)}$$

Obviously, unless special conditions exist, the pilot must operate the rudder according to $\ddot{\phi}$, $\dot{\phi}$ and ϕ. This can be a difficult process that depends upon relative magnitudes of the coefficients of $\ddot{\phi}$, $\dot{\phi}$ and ϕ and the pilot's ability to see what should be done. But the pilots find that they cannot successfully determine what to do and therefore they leave the rudder alone. Therefore, sideslip develops and makes the coordination problem more difficult for the pilot to solve. The usual case for these configurations is that the sideslip keeps changing and the pilot cannot determine how to phase his rudder inputs and thereby reduce sideslip. In the "normal" airplane the pilot phases rudder input directly with the sideslip ball or needle.

SECTION V

CONCLUSIONS

1. The most obvious conclusion is that the complex roll-spiral mode configurations that were investigated represent poor to very bad tactical airplanes, primarily because of the lack of roll damping and the resultant "rolly" characteristics.

2. For the real root configurations, the pilot ratings of the roll mode time constant are conspicuously below those in the reference data, however, the trends of all the data are the same. The primary sources of differences between the referenced and the present data are the larger values of $|\phi/\beta|_d$ and the proverse yaw due to roll rate that existed in the present experiment, and the problem of controlling rate of descent with standard instrumentation at $M = 1.2$.

3. Although the aileron orders bank angle (according to linear theory) for any coupled roll-spiral mode, the pilot may well be unaware of this fact because the mode may be so slow to reach a steady state that the pilot cannot recognize its true behavior. The pilot will see the ailerons as acceleration-ordering, rate-ordering or position-ordering according to the amount of the response which he can observe before he feels he must do something about the motion of the airplane. For moderate frequency (0.2 rad/sec) and low damping (roll-spiral modes) the ailerons appeared to order acceleration. With very low frequency (0.07 rad/sec) the ailerons order a linearly increasing roll rate preceded by a sluggish initial response. With a higher frequency (0.65 rad/sec) and higher damping ratio (0.7), the aileron appears to be position-ordering, although with a slow response.

4. The higher the Dutch roll damping ratio, then the less "rolly" the configuration will be. However, the damping ratio must be very high (0.5) to be beneficial.

5. The higher the roll-spiral damping ratio, the less "rolly" the configuration appears.

6. The pilots' choice of roll control gain depends not only on the ability to achieve the best closed-loop stability and control precision for small inputs, but also upon having sufficient gain to control large motions. These choices of gain are anatagonistic and a compromise usually results.

7. The pilots find the use of the rudder to be confusing and so they generally do not use it. In preference they accept the sideslip angles that are generated.

SECTION VI

RECOMMENDATIONS

1. Because Configuration 33 represented an almost acceptable roll-spiral configuration, it would be worthwhile to study more thoroughly the combination of high roll-spiral frequency and damping ratio in conjunction with more highly damped Dutch roll modes.

2. The reasons for the confusion in the use of the rudder pedal should be investigated to determine if there can be a useful purpose for the rudder.

3. A resultant recommendation on the allowable characteristics of the roll-spiral mode should be determined and validated in flight experiments.

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APPENDIX

TABLE II EXACT VALUES OF CONFIGURATION PARAMETERS

Config.	ω_d	ζ_d	ω_{se}	ζ_{se}	$\frac{1}{\tau_s}$	$\frac{1}{\tau_R}$	$\frac{\phi}{\beta}\ d$	$\frac{\omega_\phi}{\omega_d}$	$\frac{\phi}{\beta}\ se$	N'_r	L'_β	N'_β	L'_r	$N'_{\dot\beta}$	L'_p	N'_{δ_a}	N'_p	Pilot Rating	
																		A	B
1	2.08	0.2			0.05	0.966	10.8	0.95		-0.4	-50	4.5	2.7	0.17	-1.1	0.385	0.042	5.5	6
2	2.10	0.2			0.154	0.311	11.3	↓		↓	↓	↓	↓	↓	-0.63	0.340	↓	7	8
3	2.11	0.2	0.218	0.7			11.2	↓	334	↓	↓	↓	↓	↓	-0.48	0.317	↓	9	9
4	2.12	0.2	0.217	0.2			11.0	↓	377	↓	↓	↓	↓	↓	-0.26	0.294	↓	9	9
8	2.14	0.2			0.05	0.72	6.38	↓		-0.6	-30	4.6	↓	0.04	-0.49	0.535	↓	6.5	9
9	2.14	0.2	0.18	0.7			6.37	↓	248	↓	↓	↓	↓	↓	-0.37	0.535	↓	9	9
10	2.14	0.2	0.18	0.2			6.45	↓	272	↓	↓	↓	↓	↓	-0.18	0.535	↓	10	10
11	2.15	0.2	0.18	0.06			6.53	↓	123	↓	↓	↓	↓	↓	-0.13	0.497	↓	10	10
14	2.11	0.05			0.159	0.269	6.61	↓		-0.31	↓	4.5	0.5	-0.32	-0.52	0.52	↓	8	9
15	2.11	0.05	0.21	0.7			6.63	↓	136	↓	↓	↓	↓	↓	-0.39	0.52	↓	8	7
16	2.12	0.05	0.21	0.2			6.71	↓	502	↓	↓	↓	↓	↓	-0.18	0.48	↓	10	10
21	1.2	0.21	0.21	0.7			20.5	↓	277	-0.10	↓	1.5	↓	-0.024	-0.59	0.234	↓	9	10, 10
22	1.2	0.21	0.20	0.2			20.3	↓	331	-0.10	↓	1.5	↓	-0.024	-0.39	0.169	↓	10	10
25	2.11	0.2			0.04	0.112	9.3	↓		-0.05	-42	4.5	4.5	0.084	-0.29	0.384	↓	9.5	9
26	2.08	0.2			0.03	1.53	8.3	↓		↓	↓	↓	↓	↓	-1.6	0.463	↓	4	3
29	2.11	0.2	0.07	0.2			9.2	↓	331	↓	↓	↓	↓	↓	-0.17	0.384	↓	10	10
33	1.03	0.2	0.663	0.7			22.2	↓	60.1	-0.60	-30	1.5	0.5	-0.42	-1.0	0.616	↓	7	5
34	1.04	0.2	0.66	0.2			26.5	↓	56.5	-0.6	-30	1.5	0.5	-0.60	-0.58	0.597	↓	9	6
37	2.09	0.05	0.22	0.7			11.2	↓	340	-0.4	-50	4.5	2.7	-0.466	-0.463	0.362	↓	10	10
38	2.09	0.05	0.22	0.2			11.3	↓	378	-0.4	-50	↓	↓	-0.47	-0.246	0.362	↓	10	10
43	2.1	0.2			0.01	3.4	3.85	↓		-0.6	-30	↓	↓	0.042	-3.40	1.51	0.134	3.5, 3, 4, 3.5	5, 3, 3 3, 2
44	2.17	0.5	0.18	0.11			6.1	↓	270	↓	↓	↓	↓	1.32	-0.18	0.535	0.042	8.5	9
47	2.14	0.2	0.18	0.2			6.45	0.80	272	↓	↓	↓	↓	0.042	-0.18	1.724	↓	9, 9	9
48	2.14	0.2	0.18	0.2			6.45	1.05	272	↓	↓	↓	↓	0.042	-0.18	-0.371	↓	10, 10	10
49	2.12	0.2	0.22	0.2			11.0	0.80	378	-0.4	-50	↓	↓	0.17	-0.26	0.997	↓	9.5	10
50	2.12	0.2	0.2	0.2			11.0	1.05	378	-0.4	-50	↓	↓	0.17	-0.26	-0.2417	↓	10	10
57	2.14	0.14	0.18	1.00			6.54	0.95	400	-0.6	-30	↓	↓	0.042	-0.18	0.535	0	8	8
58	2.14	0.18	0.18	0.484			6.50		283	↓	↓	↓	↓	↓	↓	0.535	0.027	9.5	8
59	2.15	0.10			0.07	0.46	6.48			↓	↓	↓	↓	↓	↓	0.535	-0.027	6	6
60	2.17	0.07			0.06	0.564	6.41			↓	↓	↓	↓	↓	↓	0.535	-0.042		6
61	2.14	-0.013			0.06	0.62	6.33			-0.31	↓	↓	0.5	-0.32	-0.52	0.519	0		10
62	2.12	0.025			0.1	0.42	6.53			↓	↓	↓	↓	↓	↓	0.519	0.027		6
63	2.18	-0.047			0.05	0.79	6.1			↓	↓	↓	↓	↓	↓	0.519	-0.027		10
64	2.20	-0.06			0.04	0.87	5.96			↓	↓	↓	↓	↓	↓	0.519	-0.042		10

Constants

$Y_\beta = -0.124$, $Y_{\delta_a} = 0.02$, $Y_{\delta_r} = 0.049$, $N'_{\delta_r} = -5.7$, $L'_{\dot\beta} = 0$, $L'_{\delta_a} = -30$, $L'_{\delta_r} = 20.25$

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13. ABSTRACT

A systematic investigation of the lateral handling qualities of fighter aircraft on an en route IFR mission was made in a fixed-base ground simulator. The suitability of a wide range of roll and spiral mode root locations was examined with particular emphasis placed upon determining the effects of complex roll-spiral roots. The complex roll-spiral roots were produced with several feasible combinations of stability derivatives. Interaction effects of the Dutch roll mode roots were examined, including the effects of the proximity of these roots to the complex roll-spiral mode roots. Assessment of the flying qualities is reported in terms of the evaluation comments and ratings given by two pilots. In general the complex roll-spiral configurations that were evaluated were too difficult to control in roll to consider their handling quality characteristics as acceptable for fighter aircraft.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Lateral handling qualities						
Fighter aircraft						
Coupled roll-spiral mode						
Lateral phugoid						
Complex roll-spiral roots						
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