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IN-FLIGHT SIMULATION OF THE LATERAL-DIRECTIONAL HANDLING QUALITIES OF ENTRY VEHICLES

ROBERT P. HARPER, JR.

CORNELL AERONAUTICAL LABORATORY, INC.

NOVEMBER 1961

AERONAUTICAL SYSTEMS DIVISION

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FLIGHT CONTROL LABORATORY
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AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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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(616)-5823, Part I, Paragraph B, Item V.

The work reported herein was performed by the Flight Research Department of the Cornell Aeronautical Laboratory under the sponsorship of the Aero-Space Mechanics Branch, Flight Control Laboratory, Wright Air Development Division, Wright-Patterson Air Force Base, Dayton, Ohio, as Project No. 8219, Task No. 82163. WADD project engineers have been S. Hawkins, R. Ringgenberg and R. Wasicko.

Significant contributions to the engineering effort of this project were made by the following members of the Flight Research Department: J. L. Beilman, N. L. Infanti, and P. A. Reynolds.

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ABSTRACT

The initial results of a flight research program to simulate the handling qualities of winged vehicles during atmospheric entry are reported and discussed. The purpose of the program is to evaluate in flight the effects on pilot-vehicle performance of the dynamic flight characteristics of atmospheric entry vehicles, and to determine their suitability for the entry mission.

The evaluations were conducted in a three-axis variable stability T-33 airplane. Different sets of handling characteristics were evaluated in maneuvering flight and rated as to their suitability for the entry mission. Emphasis was placed upon the lateral handling characteristics, and one hundred twenty-nine configurations were examined by one pilot. An effort is made to relate pilot objections and the attendant poor ratings to their causative vehicle characteristics. The piloting difficulties involved in the control of vehicles with either static or dynamic directional instabilities are discussed.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

C.B. Westbrook

C. B. WESTBROOK
Chief, Aero-Space Mechanics
Branch
Flight Control Laboratory

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LIST OF SYMBOLS

b	Wing span, ft
c	Mean aerodynamic chord of the wing
$C_{1/2}$	Cycles to damp to one half amplitude, $= \frac{.11\sqrt{1-\zeta_d^2}}{\zeta_d}$
C_{ℓ_r}	Rolling moment coefficient per non-dimensional yawing velocity, $= \partial C_\ell / \partial\left(\frac{rb}{2V}\right)$
C_{L_α}	Lift force coefficient per angle of attack, positive upwards, $= \partial C_L / \partial\alpha$
C_{m_q}	Pitching moment coefficient per non-dimensional pitching velocity, $= \partial C_m / \partial\left(\frac{qc}{2V}\right)$
C_{n_r}	Yawing moment coefficient per non-dimensional yawing velocity, $= \partial C_n / \partial\left(\frac{rb}{2V}\right)$
C_{y_β}	Side force coefficient per angle of sideslip, $= \partial C_y / \partial\beta$
NOTE;	Other $C_{(i)}$ coefficients are similarly defined
F	Force, lb
g	Gravitational acceleration, ft/sec^2
I_x	Moment of inertia about fuselage reference roll axis, slug-ft^2
I_z	Moment of inertia about fuselage reference yaw axis, slug-ft^2
I_{xz}	Product of inertia with respect to fuselage reference axis, slug-ft^2
$K_{\dot\theta\delta_{ES}}$	Steady state pitch rate per elevator stick motion, rad/sec per in.
$K'_{\dot\theta\delta_{ES}}$	$\omega_{SP}^2 K_{\dot\theta\delta_{ES}}$, 1/sec^3 per in.
$K_{\dot\phi\delta_{AS}}$	Steady state roll rate per aileron stick motion, rad/sec per in.

$$L_i' = \frac{L_i + \frac{I_{xz}}{I_x} N_i}{1 - \frac{I_{xz}^2}{I_x I_z}}$$

$$L_p = (q_0 S b) \frac{b}{2V} \frac{C_{l_p}}{I_x} \quad , \ 1/\text{sec}$$

$$L_r = (q_0 S b) \frac{b}{2V} \frac{C_{l_r}}{I_x} \quad , \ 1/\text{sec}$$

$$L_\alpha = (q_0 S) \frac{C_{L_\alpha}}{mV} \quad , \ 1/\text{sec}$$

$$L_\beta = (q_0 S b) \frac{C_{l_\beta}}{I_x} \quad , \ 1/\text{sec}^2$$

$$L_{\delta_A} = (q_0 S b) \frac{C_{l_{\delta_A}}}{I_x} \quad , \ 1/\text{sec}^2$$

$$L_{\delta_E} = (q_0 S) \frac{C_{L_{\delta_E}}}{mV} \quad , \ 1/\text{sec}$$

$$L_{\delta_R} = (q_0 S b) \frac{C_{l_{\delta_R}}}{I_x} \quad , \ 1/\text{sec}^2$$

$$M_q = (q_0 S c) \frac{c}{2V} \frac{C_{m_q}}{I_y} \quad , \ 1/\text{sec}$$

$$M_\alpha = (q_0 S c) \frac{C_{m_\alpha}}{I_y} \quad , \ 1/\text{sec}^2$$

$$M_{\dot\alpha} = (q_0 S c) \frac{c}{2V} \frac{C_{m_{\dot\alpha}}}{I_y} \quad , \ 1/\text{sec}$$

$$M_{\delta_E} = (q_0 S c) \frac{C_{m_{\delta_E}}}{I_y} \quad , \ 1/\text{sec}^2$$

m	Mass, slugs
n_z	Incremental normal acceleration from 1 g level flight, g's

$$N_i' = \frac{N_i + \frac{I_{xz}}{I_z} L_i}{1 - \frac{I_{xz}^2}{I_x I_z}}$$

$$N_p = (q_o S b) \frac{b}{2V} \frac{C_{n_p}}{I_z} \quad , \ 1/\text{sec}$$

$$N_r = (q_o S b) \frac{b}{2V} \frac{C_{n_r}}{I_z} \quad , \ 1/\text{sec}$$

$$N_\beta = (q_o S b) \frac{C_{n_\beta}}{I_z} \quad , \ 1/\text{sec}^2$$

$$N_{\delta_A} = (q_o S b) \frac{C_{n_{\delta_A}}}{I_z} \quad , \ 1/\text{sec}^2$$

$$N_{\delta_R} = (q_o S b) \frac{C_{n_{\delta_R}}}{I_z} \quad , \ 1/\text{sec}^2$$

p	Rolling velocity, rad/sec
q	Pitching velocity, rad/sec
q_o	Dynamic pressure, lb/ft^2
r	Yawing velocity, rad/sec
s	Laplace operator
S	Wing area, ft^2
$T_{1/2}$	Time to damp to one half amplitude, $= \frac{.693}{\zeta_d \omega_d}$
V	True airspeed, ft/sec

$$Y_\beta = (q_o S)\frac{C_{y_\beta}}{mV}\text{ , 1/sec}$$

$$Y_{\delta_R} = (q_o S)\frac{C_{y_{\delta_R}}}{mV}\text{ , 1/sec}$$

α	Angle of attack, rad
β	Sideslip angle, rad
δ	Control surface deflection, rad; control stick or rudder pedal deflection, in.
ζ_d	Dutch roll damping ratio
ζ_{SP}	Longitudinal short period damping ratio
ζ_ϕ	Damping ratio of numerator quadratic in roll to aileron input transfer function
θ	Pitch attitude, rad
τ_R	Roll mode time constant, sec
τ_S	Spiral mode time constant, sec
τ_θ	Longitudinal short period lead time constant, sec
ϕ	Bank angle, rad
$\left\vert \phi/\beta \right\vert$	Roll to sideslip ratio at Dutch roll frequency
ω_d	Dutch roll undamped natural frequency, rad/sec
ω_{SP}	Longitudinal short period undamped natural frequency, rad/sec
ω_ϕ	Undamped natural frequency of numerator quadratic in roll to aileron input transfer function ,rad/sec
$(\dot{\ })$	Time derivative, $\frac{d(\,)}{dt}$

Subscripts

O	Trim value
A	Aileron
AS	Aileron stick
E	Elevator
ES	Elevator stick
R	Rudder
RP	Rudder pedal
SS	Steady state

Axes and Sign Conventions

The airplane response sensors in the T-33 airplane are oriented with respect to the fuselage reference axes. These are the body axes with their origin at the c.g., and defined by the leveling points in the airplane such that when the airplane is laterally and longitudinally level the X and Y axes lie in the horizontal plane with the X axis in the plane of symmetry pointing forward along the fuselage. The Y axis is normal to the plane of symmetry with its positive direction out the right wing. The Z axis lies in the plane of symmetry with its positive axis downward.

The moments and products of inertia, I_x , I_z , and I_{xz} are specified for this fuselage reference axis system. The equations of motion in Appendix A are written with respect to this axis system, and hence the stability derivatives, (e.g., Y_β , N_β , L_β , C_{y_β} , C_{n_β} , C_{ℓ_β} , etc.) are computed for this axis system.

The "primed" yawing and rolling moment derivatives N'_β , L'_β , etc., are linear combinations of the fuselage reference axis derivatives, N_β , L_β , etc., and are defined in the List of Symbols.

SECTION I
INTRODUCTION

Under the sponsorship of the Flight Control Laboratory, Wright Air Development Division, Air Research and Development Command, U. S. Air Force, a comprehensive research program has been undertaken to determine the suitable range of handling quality parameters for atmospheric entry vehicles. This work is being performed by the Flight Research Department of the Cornell Aeronautical Laboratory, Inc., Buffalo, New York, in a continuing effort to expand the knowledge of handling qualities for advanced piloted vehicles.

The principal objective of the over-all program is to determine the effects of the vehicle dynamic flight characteristics on the pilot-vehicle performance during the entry and descent phases of flight. A particular entry vehicle is not studied; instead, the range of dynamic flight characteristics investigated is made sufficiently wide as to encompass the probable characteristics of future piloted vehicles.

This report contains the results of an investigation of a wide variety of dynamic flight characteristics, concentrating on the effects of large excursions of lateral-directional handling qualities on the pilot control of the vehicle and including a look at the interaction effects of different longitudinal characteristics. This work covers both good and bad characteristics in order to supply information to define the desirable dynamic flight characteristics for the entry task and to provide a measurement of the degradation of pilot-vehicle performance as the flight characteristics are worsened.

The method by which these evaluations are made is a series of experiments in which a pilot is put in control of a vehicle whose dynamic flight characteristics are alterable. The flight characteristics under consideration are set up on the vehicle, one group at a time, and the pilot performs a series of maneuvers representative of those maneuvers which he might be called upon to perform during an actual entry and descent. His comments regarding his control difficulties, his objections to the dynamic flight characteristics of the vehicle, and his subjective evaluation of the suitability of these characteristics for the accomplishment of the task form the bulk of the evaluation data.

The pilot-vehicle combination is a dynamic system, and the evaluation of the suitability of a variety of vehicles should be made with the complete system being used in the accomplishment of the required tasks. It is not yet possible to represent the human pilot analytically with enough accuracy and completeness so as to perform these evaluations theoretically. Since an experiment is thus required, it would be desirable to measure the pilot-vehicle performance and use its degradation as a measure of the lack of suitability of the vehicle's characteristics. Attempts to do this have met with little success, principally because the pilot is so adaptable in his own dynamic performance as the controlling element that he maintains near-constant pilot-vehicle performance over wide excursions of vehicle handling characteristics in the types of tasks (generally tracking maneuvers) which have been examined. At the same time that he is achieving good performance, the pilot says he is so saturated with the poor characteristics that he could not handle other requirements of the mission except under ideal circumstances. Hence the subjective evaluation is relied upon because of our inability to devise a suitable performance measure which will adequately weigh all aspects of the contribution of the particular vehicle characteristics toward the accomplishment of the mission. It should be noted that the subjective evaluation is so-called expert testimony, not just hearsay. It consists of detailed comments made and recorded during the evaluation, as well as summary ratings given at the completion of each evaluation. The comment data is extensively studied, and is heavily weighed in the establishment of the boundaries on the plots of pilot ratings versus configuration characteristics.

The pilot has a variety of sensory inputs which affect his actions both as a dynamic controlling element and as the evaluator of the suitability of the vehicle characteristics. The in-flight simulator does subject the pilot to the motion and acceleration environment of the simulated vehicle, but it does not entirely reproduce the emotional stress on the pilot in an actual entry mission. But since he is actually in flight, the emotional stress level is approached. The evaluation pilot is inherently faced with the realism of the issue, and is constantly aware that this is no game he is playing - the g's he feels pushing him down into the seat are also bending the wings of his warm, happy home.

In this report, the evaluation program is discussed first, with an examination of the airplane parameters which are to be varied, the maneuvers to be performed, the frame of reference within which the evaluations are made, and the rating scale to be used. The method by which the airplane response parameters are specified is discussed.

The program results are presented, first as the roll mode parameters are varied, next as the other lateral-directional characteristics are varied, and finally for an abbreviated examination of the effects on these evaluations of different longitudinal short period response characteristics.

SECTION II
EVALUATION PROGRAM

The principal objective of this research program was to carry out a systematic investigation in flight of a wide range of lateral-directional handling characteristics and determine the probable pilot ratings of the performance of the pilot-airplane combination in the accomplishment of the re-entry task. The simulator vehicle used for the handling qualities research reported herein is the variable stability airplane, an airplane whose transfer functions between pilot control inputs and airplane response outputs can be altered in flight, independent of the flight test condition of airspeed and altitude.

A. EQUIPMENT

The variable stability airplane used for these evaluations is the three-axis T-33 which was designed and built by the Cornell Aeronautical Laboratory for the Flight Control Laboratory, Wright Air Development Division, U.S. Air Force, and is described in References 1, 2, and 3. A paper presented to the IAS in 1955 by Breuhaus (Reference 4) describes the use of variable stability airplanes for flight research. For the purpose of this report, the following brief description should suffice. A standard T-33 was modified in such a manner that its transfer functions, or handling characteristics, about the pitch, roll, and yaw axes, can be changed in flight by simply repositioning a set of gain controls in the rear cockpit. These changes in the handling characteristics are made in such a manner that the evaluation pilot is unaware of the means by which the changes occur. This is important, and it is achieved. He feels as if the airplane itself has been changed – not something in it.

Two pilots are aboard the T-33. The pilot in front is the evaluation pilot, while the rear pilot acts as safety pilot and system manager. The flight tests described herein were conducted at Edwards Air Force Base, California, in November and December of 1959. A base flight condition of 25,000 feet and M = .6 was used for the evaluations, and the duration of each flight was slightly over two hours. As an example of the reliability of the equipment, fifty evaluation flights were made in a calendar period of six weeks, including an airplane and engine periodic inspection in this period.

B. EVALUATION PROCEDURE

Of fundamental importance in any evaluation program is the mission or task which the pilot-vehicle combination is called upon to perform. Often, there is no one simple task which can be easily duplicated. The specific mission of a vehicle re-entering the atmosphere is to descend and land safely without exceeding the limitations of the vehicle or pilot. This mission encompasses many control tasks, and an evaluation of the vehicle handling characteristics regarding their suitability for the mission can be approached by having the evaluation pilot perform selected tasks which are representative of some of the required tasks. Four tasks, or maneuvers, were used for this evaluation program:

a) Straight flight, including small turns (heading change less than 30°) and pitch corrections ($0 < n_z < 3$ g) about level flight.

b) Turning flight. Shallow ($\phi = 30°$) and steeply-banked ($\phi = 60°$) turns involving heading changes of at least 90°, with particular attention to the control of nose position with bank angle while holding constant angle of attack.

c) Rolling flight. Slow (normally used) and rapid (maximum safe) rolling maneuvers, including 180° and 360° rolls when handling characteristics permit.

d) Straight flight and turning flight in the presence of simultaneous pitch, roll, and yaw disturbances.

The first three maneuvers are all pilot-initiated, and each has its role in the evaluation of the requirements for the entry mission.* The last maneuver

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* Maneuver (c) enables the pilot to examine the response to sustained roll control inputs as might be experienced in recoveries from excessively steep bank angles or inadvertently-attained unusual attitude.

was included because it was felt that in an evaluation of short duration, it was possible for the evaluation pilot to miss a relevant characteristic simply because the manner in which he (in particular) performed his control tasks did not cause the characteristic to become evident. Maneuver (d) caused the pilot to respond to external disturbances which were not of his own making. The disturbances were produced by white noise inputs fed through a low-pass filter that cornered at 7 cps, and thereafter, fed as commands to the three control surface servos.

The primary evaluation was conducted as visual flying. However, for each configuration, the pilot performed abbreviated maneuvers (a), (b), and (c) in simulated instrument flight. The evaluation comments and ratings are given principally for visual flying, but assume that much pilot attention is given to his instruments.

The evaluation pilot performed the four maneuvers in order. He wire-recorded his comments after each maneuver. Following his comments on Maneuver (d) he briefly summed up his over-all impression of – and objections to – the configuration. He then assigned a rating to the configuration as to its general suitability for the entry mission. A ten-point rating scale was used, similar to that described in Reference 6, except that no consideration is given in the ratings for a secondary mission.

The rating scale is shown in Table I. It will be noted that the rating consists of both a number and one or more adjectives. The evaluation pilot relied entirely upon the words – it was only by use of the words that he could assign a rating to the configuration. The numbers meant nothing until they were defined by words. In this report, however, it is more convenient to discuss the ratings in terms of the numbers, a convenient shorthand.

In order to arrive at a summary rating, the evaluation pilot first assigned the configuration to one of three categories. It was either satisfactory, unsatisfactory but still acceptable, or unacceptable. Then an adjective which corresponded to this selection was given as the rating. There was one final category corresponding to the Rating 10. This rating was applied to unflyable configurations; i.e., those configurations in which the pilot lost control during the evaluation maneuvers.

C. TEST PROGRAM

During the fifty-flight program, the following parameters were varied:

1. Dutch roll mode undamped natural frequency, ω_d
2. Dutch roll mode damping ratio, ζ_d
3. Magnitude of roll-to-sideslip motion in Dutch roll mode, $|\phi/\beta|$
4. Undamped natural frequency of numerator quadratic in roll-to-aileron transfer function, ω_ϕ
5. Steady state roll rate per inch of aileron stick motion, $K_{\dot{\phi}\delta_{AS}}$
6. Roll mode time constant, τ_R

In addition, during the brief interactions evaluation, longitudinal short period undamped natural frequency, ω_{SP}, and damping ratio, ζ_{SP}, were varied. The spiral mode root was made neutrally stable for these evaluations ($1/\tau_s \rightarrow 0$). Thus, the roll transfer function to aileron stick motion inputs for rudder-fixed is of the form (derivation and equations of motion shown in Appendix A):

$$\frac{\phi}{\delta_{AS}} = \frac{K_{\dot{\phi}\delta_{AS}}\left(\frac{s^2}{\omega_\phi^2} + \frac{2\zeta_\phi}{\omega_\phi}s + 1\right)}{s\left(\frac{s^2}{\omega_d^2} + \frac{2\zeta_d}{\omega_d}s + 1\right)\left(\tau_R s + 1\right)} \qquad (1)$$

where the control system dynamics are neglected.

In terms of so-called "unprimed" derivatives [primed derivatives are formed when the yawing and pitching moment equations are rewritten to eliminate explicitly the acceleration terms, $\left(I_{xz}/I_z\right)\dot{p}$ and $\left(I_{xz}/I_x\right)\dot{r}$, respectively], the expression for ω_ϕ^2 is as follows:

$$\omega_\phi^2 = \frac{(N_\beta + Y_\beta N_r) - \frac{N_{\delta_A}}{L_{\delta_A}}(L_\beta + Y_\beta L_r)}{1 + \frac{N_{\delta_A}}{L_{\delta_A}}\frac{I_{xz}}{I_x}} \qquad (2)$$

In terms of the "primed" derivatives:

$$\omega_\phi^2 = (N'_\beta + Y_\beta N'_r) - \frac{N'_{\delta_A}}{L'_{\delta_A}}(L'_\beta + Y_\beta L'_r) \qquad (3)$$

An approximation for ω_d^2 is:

$$\omega_d^2 \approx N'_\beta + Y_\beta N'_r \qquad (4)$$

Thus, an approximate expression for $\frac{\omega_\phi}{\omega_d}$ is:

$$\frac{\omega_\phi}{\omega_d} \approx \sqrt{1 - \frac{N'_{\delta_A}}{L'_{\delta_A}}\frac{(L'_\beta + Y_\beta L'_r)}{(N'_\beta + Y_\beta N'_r)}} \qquad (5)$$

A further approximation is evident when the products $Y_\beta L'_r$ and $Y_\beta N'_r$ are small compared to L'_β and N'_β, respectively:

$$\frac{\omega_\phi}{\omega_d} \approx \sqrt{1 - \frac{N'_{\delta_A}}{L'_{\delta_A}}\frac{L'_\beta}{N'_\beta}} \qquad (6)$$

With the six above listed parameters to be evaluated, a thorough examination of all possible combinations of the parameters could not be accomplished within this flight program. Interest was centered, during these evaluations, on the parameters ω_d, ζ_d, $|\phi/\beta|$, and the ratio ω_ϕ/ω_d. The latter variable,

ω_ϕ/ω_d, has been suggested by Ashkenas and McRuer in Reference 5 as a parameter which might tie together the sometimes contradictory results of lateral-directional handling qualities evaluations of ω_d, ζ_d, and $|\phi/\beta|$. The numerator characteristic, ω_ϕ, can be varied independently of the other three variables in the variable stability T-33 airplane through variations in the yawing moment due to aileron deflection, N_{δ_A}, and hence provides the capability to examine the effects on pilot ratings of ω_ϕ/ω_d for widely separated combinations of the other parameters.

A survey was also made of the roll mode characteristics, τ_R and $K_{\dot\phi\delta_{AS}}$, principally at one base condition of Dutch roll characteristics. It should be noted that $K_{\dot\phi\delta_{AS}}$ is defined herein for the rudder-fixed case, and is the steady state roll rate per aileron stick motion, including the roll rate produced by the steady state sideslip.

The pilot's controls were a conventional center stick and rudder pedals. The aileron force versus position gradient was held constant at 2 lb per inch of travel at the stick grip. The rudder pedal gradient was 250 lb per inch of pedal travel, and the elevator gradient was 40 lb per inch of elevator stick travel at the grip. The rudder deflection per rudder pedal deflection was varied so as to maintain constant steady sideslip per rudder pedal displacement.

The longitudinal short period characteristics were held approximately constant at $\zeta_{SP} = 0.5$, $\omega_{SP} = 3$ rad/sec, and $F_{ES}/n_z = 8$ lb/g for the bulk of evaluations reported here. These provided desirable longitudinal characteristics so as to permit a maximum excursion of pilot ratings due to the variations in lateral-directional parameters. A brief survey was made at the end of the program of the effects of different longitudinal characteristics.

The roll mode evaluations of $K_{\dot\phi\delta_{AS}}$ and τ_R were conducted first, followed by the evaluations of combinations of ω_d, ζ_d, $|\phi/\beta|$, and ω_ϕ/ω_d for constant $K_{\dot\phi\delta_{AS}}$ and τ_R. A total of one hundred twenty-nine different configurations were examined during the program. These configurations are listed in Table II with the parameters that define the response characteristics evaluated. Except for the separation of the program into the three categories: roll mode, lateral-directional, and longitudinal interactions, the configurations were given the pilot in a random order. He was never informed of what parameters were being varied nor of their values until after the entire program was completed. He had to view each configuration separately without direct comparison to what had gone before.

Because the evaluations were of an exploratory nature of a large range of several parameters, it was necessary that the evaluations be conducted by one pilot in order to stay within the funded program. Only three actual repeat points were evaluated during the program. These resulted in identical ratings in two cases, and the ratings differed by one number in the third case. In addition, the data results indicate good repeatability of the pilot ratings in the general smoothness of the rating variations with parameter values being evaluated in a random order. The pilot attempted to force each configuration into one of the ten ratings. He was fairly successful at this (though often with mental reservations), but occasionally had to rate halfway between ratings. This indicated that he was unable to assign it to either the higher or lower category without feeling in error.

It is worth emphasizing here the important contribution of the pilot comment data to the data results of this and any similar subjective evaluation program. It is a complex process by which the pilot arrives at a decision regarding the suitability of a given set of characteristics for a task, and he does not understand all of the process himself. Consequently, if he discusses the configuration and his attendant control problems and difficulties, and if these are recorded for the analyst, they form a volume of data as important as the summary rating. For it is here that the analyst may determine the "why" of the objection. This may, in turn, point the way to a better analytical model of the human pilot.

The pilot comment data in this program averaged ten minutes of recorded observations for each configuration. Thus, in one hundred twenty nine configurations, something over twenty hours of pilot comment data was amassed. This data was typed, edited for gross transcription errors, digested by the analyst, and reviewed constantly in comparing configurations with and among each other. The curves presented in the Discussion of Results in this report are a product, not just of the pilot ratings themselves, but of the comment data as well. It is unfortunate that this comment data cannot be reported, but it is obviously too voluminous to be reported verbatim and the editing task to condense it is beyond the scope of this work.

D. AIRPLANE RESPONSE DATA

A necessary part of this and any evaluation program is the specification of the dynamic flight characteristics of each configuration evaluated. A number of the configurations which were to be evaluated were such as to make analysis of the usual flight records of aileron- and rudder-fixed control response maneuvers impossible. This was because the configurations had such poor characteristics that the pilot was unable to let go of the controls long enough to achieve a steady state - if one existed. For this and other reasons, an equations-of-motion program was set up for a digital computer to extract the stability derivatives of the simulated vehicle from flight records made during the pilot's evaluation of each configuration. This technique would make possible the extraction of the vehicle characteristics while the pilot was manipulating the controls with both disturbing and stabilizing inputs as necessary.

Considerable difficulty was encountered in making this program work due both to computer programming difficulties and to some airplane recording instrumentation problems. These difficulties were such as to render useless this computational program for feeding back information to the project as to the accuracy with which the desired configurations were being set up. As a consequence of this, the execution of the evaluation program depended on hand analysis of response transients, in areas where such could be obtained, as the sole information feedback. This was slow and arduous, and the principal reason, for example, that parameters such as ζ_d were not the same for the evaluations at one value of $|\phi/\beta|$ as for another. The variability of ζ_d at one $|\phi/\beta|$ is also due to this. As the program progressed and more measurements were obtained to compare with shot-for values, the computational scheme for computing variable stability system gains in order to achieve the desired lateral-directional characteristics was greatly improved, but not nearly as rapidly as had been planned.

After the evaluation program was completed and the project personnel returned to Buffalo, considerable additional analysis brought about accurate extraction of the larger stability derivatives using the equations-of-motion program, but the smaller, yet important, derivatives were not accurately extracted. Hence, the project had to return to the analysis of the fixed control responses. The computational method and parameter values were refined with the measurements from the flight test data until the computations accurately fitted the measured data points. The values shown in Table II and presented in the figures of this report were then computed for all configurations.

SECTION III

DISCUSSION OF RESULTS

A. ROLL MODE EVALUATIONS

The evaluations began with a brief look at the roll parameters $K_{\dot{\phi}\delta_{AS}}$ and τ_R at a base condition of good lateral-directional characteristics. The results are summarized in Figures 1 and 2. The pre-selected range of values of $K_{\dot{\phi}\delta_{AS}}$ was sufficient to produce the desired variations in pilot ratings, but the range of variation of τ_R was not.

1. Effects of $K_{\dot{\phi}\delta_{AS}}$ for Good Base Configuration

Pilot rating is high for values of $K_{\dot{\phi}\delta_{AS}} = .13$, .37, and 1.23 rad per sec/inch with a peak between .13 and .37. The pilot is tolerant of fairly wide roll control effectiveness because of the nature of the task – control of bank angle is more important than rapid maneuverability; therefore, the rather slow roll rates experienced with the low effectiveness are not harmful. When effectiveness gets very low, the pilot begins to lose the degree of roll precision which he requires for the maneuvering requirements of the task and his ratings drop off rapidly. He also becomes concerned as to his ability to adequately control the bank angle in the presence of external disturbances. When the roll control is too effective ($K_{\dot{\phi}\delta_{AS}}$ large), the ability to produce and control low roll rates is lost, and with it goes the precision of control of bank angle which he requires for the task. There is a tendency with the high effectiveness to experience roll oscillations, particularly when there are external disturbances to control. Any control system friction aggravates the situation with high values of $K_{\dot{\phi}\delta_{AS}}$. A substantial roll rate in one direction or the other can result when the stick is allowed to self-center, and it is difficult to arrive at the stick position for zero roll rate. The bank angle is constantly changing, and thus requires an undue amount of the pilot's attention.

2. Effects of τ_R for a Good Base Configuration

The roll mode time constant, τ_R , was varied from 0.1 seconds to 1.2 seconds with only a small change in pilot ratings. The highest ratings were given for values of τ_R = .37 and .52 seconds. There is a deterioration in rating for higher and lower values of τ_R . Here again, as the task does not put much premium on maneuverability (as contrasted with the requirements for air-to-air combat in fighters), a wide range of variation is acceptable. When τ_R becomes large, the ailerons are essentially acceleration-ordering because the pilot seldom waits long enough between aileron inputs for the roll rate to reach its steady value (approximately three times τ_R when the Dutch roll is undisturbed). The pilot generally prefers to order either roll rate or bank angle, so he tends to fly configurations with large τ_R using a series of aileron pulse inputs. These inputs produce steady roll rates initially, and steady state changes in bank angle if he waits long enough. This type of control is generally adequate (though not desirable) in situations where there are few, if any, external disturbances, where the pilot can devote considerable attention to the task, and where the penalty for imprecise control is not catastrophic.

When τ_R is reduced to very low values (around 0.1 seconds and less) while maintaining a constant value of $K_{\dot{\phi}\delta_{AS}}$, the steady roll rate becomes more and more nearly in phase with the aileron input. Hence, the roll accelerations in achieving a particular roll rate are steadily increased as τ_R is lowered. The roll accelerations become objectionably high around τ_R = 0.1 seconds, and to reduce these accelerations, the pilot begins to use slower applications of aileron control. However, there are times when he reacts instinctively and suddenly, and it is these situations which bring on the poorer ratings. He reduces his roll channel gain as τ_R is reduced, but in an emergency situation, he reverts to a higher gain and his control problem becomes difficult. A pilot-airplane closed-loop oscillation takes place in roll until he can reduce his gain once more.

Reference 6 presents results obtained from a moving-cockpit ground-based simulator for tests during which roll mode time constant and maximum rolling acceleration available to the pilot were varied. It was shown that a criterion for the satisfactoriness of lateral control could be formed from these two quantities. Although the number of values of these quantities used in the flight investigation reported herein was limited, the results obtained agree reasonably well with those of Reference 6. However, a more extensive flight investigation would be required before a complete comparison could be made. It should be noted that good Dutch roll dynamics were present during the flight evaluations of the effects of τ_R and $K_{\dot{\phi}\delta_{AS}}$. The simulator tests of Reference 6 did not include Dutch roll dynamics – only a single degree-of-freedom roll mode was simulated.

B. LATERAL-DIRECTIONAL EVALUATIONS

Values of $K_{\dot{\phi}\delta_{AS}} = .36$ rad/sec per in. and $\tau_R = .37$ sec were selected from the results of the roll mode evaluations, and were held approximately constant at these values for the lateral-directional evaluations. As is evident in Figures 1 and 2, pilot ratings about the optimum values of $K_{\dot{\phi}\delta_{AS}}$ and τ_R were relatively insensitive to variations in these values. Thus, variations during the test program were not critical. Three values of ω_d , nominally 4, 2, and 1 rad/sec, were used to represent three areas of re-entry flight conditions corresponding to high, moderate, and low dynamic pressure conditions. A fourth ω_d corresponding to very low dynamic pressure was set up and evaluated at only one value of $|\phi/\beta|$.

The base conditions of ω_d were evaluated at two values of ζ_d . For each combination of ω_d and ζ_d , the results are presented in graphical form as pilot ratings versus ω_ϕ/ω_d for several values of $|\phi/\beta|$. A discussion of these results follows.

1. High ω_d and Low ζ_d :

The pilot ratings are summarized in Figure 3 for this condition. The data is shown for an average $\omega_d = 4.3$ rad/sec. ζ_d was not held as nearly constant as was desired, so the actual value of ζ_d is shown adjacent to each point. Some analysis difficulty is introduced by the inability to hold ζ_d constant during the evaluations. ζ_d has a powerful effect on pilot opinion, particularly when ζ_d is low, and small changes can produce relatively large effects on pilot opinion. However, if we look at the data plotted in Figure 3, some interesting results can be deduced after allowing for the effects of ζ_d. Evaluations were made for four ranges of roll-to-sideslip ratio, $|\phi/\beta| = 1.07 - 1.20$, 2.42 - 3.19, 3.93 - 4.53, and 7.06 - 7.40. For each range of $|\phi/\beta|$, evaluations were made at four values of ω_ϕ/ω_d corresponding to one value of adverse yaw due to aileron deflection ($\omega_\phi/\omega_d < 1$), one value of zero, and two values of favorable yaw due to aileron deflection ($\omega_\phi/\omega_d > 1$).

Refer first to the data shown for $|\phi/\beta| = 1.07 - 1.20$. A definite preference is shown for $\omega_\phi/\omega_d = 1$ ($N_{\delta_A}{}' = 0$). The rating is enhanced by somewhat higher ζ_d than for the other points at $|\phi/\beta| = 1.07 - 1.20$, but even when allowance is made for this effect, there is a definite preference for $\omega_\phi/\omega_d = 1$. Both favorable and adverse yaw due to aileron deflection seem equally objectionable.

As a contrast with the low $|\phi/\beta|$ situation above, the data in Figure 3 for $|\phi/\beta| = 7.06 - 7.40$ shows a distinctly different trend of pilot opinion with ω_ϕ/ω_d, one in which there is a decided preference for adverse yaw due to aileron deflection over favorable yaw. Furthermore, there appears a significant preference for adverse yaw over zero yaw. At first glance, this result seems contrary to any notion about what a pilot should like. It seems that a pilot should like zero yaw best – and he did for the low $|\phi/\beta|$ evaluations. But when $|\phi/\beta|$ gets large, the pilot-airplane closed-loop situation changes. The Dutch roll oscillation is now predominant in the roll response whereas the roll motion was relatively small for $|\phi/\beta| = 1.07 - 1.20$. Where the control of the Dutch roll mode was a rudder input task with low $|\phi/\beta|$, it is now an aileron input task. Because the frequency is high and large roll rates are involved (low ζ_d and high $|\phi/\beta|$), the pilot's gain is high. It has been shown theoretically by Ashkenas and McRuer in Reference 5 that the closed-loop damping will be higher in the situation with adverse yaw due to aileron deflection than with favorable yaw (or zero) for these airplane root locations. The open-loop Dutch roll damping is already lower than desirable, and the decreased closed-loop damping for $\omega_\phi/\omega_d > 1$ is quite objectionable. In fact, the pilot commented that for $\omega_\phi/\omega_d = 1.2$, there was a definite pilot-induced oscillation whenever the ailerons were used to inhibit the roll oscillation. CONFIG 102

The curves in Figure 3 for $|\phi/\beta| = 2.42 - 3.19$ and $3.93 - 4.53$ exhibit intermediate trends between the results for the low and high $|\phi/\beta|$. When adjustment is made for the low ζ_d at $\omega_\phi/\omega_d = 1$, the curve for $|\phi/\beta| = 3.93 - 4.53$ exhibits a similar trend to that for $|\phi/\beta| = 7.06 - 7.40$. That is, pilot preference is for some adverse yaw due to aileron deflection, and for the same reasons outlined above. Pilot-induced oscillations are reported for the highest value of ω_ϕ/ω_d (favorable yaw). In fact, this point was almost unflyable – it was reported dangerous – because ζ_d was nearly zero open-loop and the oscillation easily became divergent closed-loop. When the pilot tried to maintain a particular bank angle, a pilot-induced oscillation resulted immediately. The random noise gain could not be increased to its reference value for Maneuver (d) because of the pilot's control problems. CONFIG 94

The apparent pilot opinion trend with $|\phi/\beta| = 2.42 - 3.19$ is distorted somewhat at the end points by the variations in ζ_d. At the extreme values of ω_ϕ/ω_d, there appears to be a small preference for adverse yaw over favorable, since the pilot rated the adverse yaw configuration better (a six) than the favorable yaw configuration (a seven) even though the former had lower Dutch roll damping ($\zeta_d = .05$) than the latter ($\zeta_d = .07$). The best ratings are given for $\omega_\phi/\omega_d = .99$ and 1.09. The pilot reported that the yaw due to aileron input was negligibly small for both, that the configurations were both acceptable and satisfactory for entry, but that they were responsive in roll to disturbances.

It is desirable now to discuss the pilot comments regarding the appearance of this base flight condition from the cockpit, including pertinent control techniques. A predominant characteristic is the very high directional stiffness. The airplane has a very strong tendency to stay pointed the way it is going. This stiffness is so strong that there is little need for coordination for slow inputs. The sideslip which results from the lack of coordination is small; and further, when the sideslip disturbance - aileron input with yaw due to aileron - is reduced, the airplane immediately initiates a return toward zero sideslip. With low $\left|\phi/\beta\right|$ and reasonably high ζ_d, the pilot tends to fly two-control, i.e., does not use the rudder to coordinate the aileron inputs. When the roll due to sideslip is high however, there is a need for coordination, not because the side acceleration is objectionable, but because the roll rate performance is so strongly influenced by sideslip. The tendency then is for the pilot to use the rudder in rolling maneuvers in a manner to make the roll rate "right" for his aileron input.

It has already been shown that the closed-loop pilot-airplane dynamics are made worse by favorable yaw due to aileron deflection, and hence, objectionable to the pilot. There is a further objection to the favorable yaw which can be seen by examining the control task in a rolling maneuver with favorable yaw and high $\left|\phi/\beta\right|$. To initiate a left roll calls for left stick and right rudder to coordinate the favorable yaw. To stop the roll requires centering the aileron and releasing the right rudder. This cross-coordination is difficult for normally-trained pilots and yet it is important to the pilot to coordinate properly so that his roll performance is predictable from his aileron inputs. When he reacts suddenly - as he will occasionally - he mis-coordinates and his control performance is poor.

2. High ω_d and Moderate ζ_d:

The pilot opinion ratings are plotted in Figure 4 for the high Dutch roll undamped natural frequency (approximately 4.3 rad/sec) as a function of ω_ϕ/ω_d for several values of $\left|\phi/\beta\right|$.

It is interesting to note the decided preference for ω_ϕ/ω_d = 1 and the considerable objection to both adverse and favorable yawing moment due to aileron deflection for the lowest $\left|\phi/\beta\right|$. Examination of the pilot comment data shows two primary reasons. First, the Dutch roll damping was higher ($\zeta_d = .38$) for the ω_ϕ/ω_d = 1 point than for the other three configurations ($\zeta_d \cong .27$). Although this isn't a major difference in damping, it is important at this high value of ω_d. The pilot had complained strongly about the "looseness" or susceptibility to disturbance of this value of ω_d for the configurations where ζ_d was low (0.1). This objection is offered here (though not as strongly) for the three configurations where $\zeta_d \cong 0.27$, causing, according to the pilot comments, a decrease in rating of at least one point, but not more than two points, due to the responsiveness to the random disturbances of Maneuver (d). These comments are absent for the ω_ϕ/ω_d = 1 point where ζ_d was equal to .38. For this reason, the pilot opinion curve has been drawn one-half rating below the ω_ϕ/ω_d = 1 point and corresponds to the probable opinion variation for $\zeta_d \cong .27$.

The other reason for the preference for ω_ϕ/ω_d = 1 at the lowest value of $\left|\phi/\beta\right|$ is the lack of rolling in the Dutch roll motion in this configuration and the attendant discomfort of side acceleration without rolling. When $\omega_\phi/\omega_d = 1$, there is a minimum of sideslip disturbance. When there are yawing moments due to aileron inputs (ω_ϕ/ω_d greater or less than unity), the resulting side accelerations with so little roll cause pilot discomfort and insecure feelings about his complete mastery of the configuration.

Observe the pilot rating trends for $\left|\phi/\beta\right| = 2.34 - 2.49$. First of all, these configurations were rated as high or higher than any of those at the other values of $\left|\phi/\beta\right|$ so this seems to be a desirable level of $\left|\phi/\beta\right|$ for this base condition. The opinion curve is fairly flat, with all ratings but the highest ω_ϕ/ω_d being rated acceptable and satisfactory (Rating 3 or better). There is a slight preference for $\omega_\phi/\omega_d = 1$. It is interesting to note the pilot's comments regarding the two configurations for $\omega_\phi/\omega_d > 1$, particularly that for $\omega_\phi/\omega_d = 1.22$. The pilot notices and comments that there is favorable

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Interesting.

yawing moment due to aileron deflection, but says that it is fairly small. Wha he does say repeatedly, however, is that he experiences roll oscillations in simulated IFR flight (flight by reference to his cockpit display instruments only), but they disappear when he returns to visual contact flight. He notes that his difficulty begins when he tries to concentrate on, and fly precisely, his bank angle presentation on the artificial horizon instrument. He can stop the oscillation by returning to contact flight, and also by forcing down his responsiveness - or gain - to bank angle errors. These characteristics are noticeable and somewhat annoying, but they are not a strong objection because the pilot can learn to live with them and adjust his own characteristics to accomplish this.

Next observe the curve in Figure 4 for $\left|\phi/\beta\right| = 3.42 - 3.61$. The adverse and zero yaw points are rated the same as for the $\left|\phi/\beta\right| = 2.34 - 2.49$, but the ratings drop off quite sharply for the favorable yaw configurations. The pilot objections to $\omega_\phi/\omega_d > 1$ are strong and directed toward the roll oscillations. The comments are that the roll oscillations are present whenever he tries to track bank angle. The oscillations are still controllable in most maneuvers where the pilot initiates the disturbance. However, the external disturbances of Maneuver (d) cause him a great deal of difficulty in just flying straight and level because of the roll oscillations which take place whenever he is in the loop. He is able to fly it in the presence of the standard amount of noise input, but remarks that he wouldn't be able to take a whole lot more.

The pilot rating curve of Figure 4 for $\left|\phi/\beta\right| = 5.12 - 5.31$ shows a similar trend except that the drop-off of rating with the extreme value of favorable yaw is the most severe of all. The pilot's comments are similar but stronger regarding the roll oscillation problem for the largest ω_ϕ/ω_d. The most notable comments occur during Maneuver (d), on the basis of which he downrates the configuration from a possible Rating 4 to a Rating 8. Since the maneuvers were done in order (a) through (d), the pilot has flown the configuration long enough at the end of Maneuver (c) to form a reasonable impression of it and give a tentative rating. For most configurations which the pilot evaluated, Maneuver (d) did very little to affect the impression the pilot had of the configuration. But for the high ω_d , high $\left|\phi/\beta\right|$, high ω_ϕ/ω_d configurations, the pilot changed his impression and rating grossly after flying Maneuver (d). The reasons for this are believed to be twofold: the frequency content of the random input and the closed-loop nature of the task. The most important one is the latter in that difficulties with these configurations arise when the pilot-airplane combination is closed-loop, principally in bank angle. With no external disturbances, the pilot can handle the configuration moderately well by keeping his gain down, flying his bank angle loosely enough to stay out of difficulty, and never using the controls so suddenly as to introduce high (relative to the Dutch roll natural frequency) frequency inputs.

The random noise input does have relatively high frequency content (flat spectrum to 7 cps), and the airplane has the dynamics with which it can pass on to the pilot fairly fast airplane responses which he is then supposed to control. It is difficult for him to keep his gain down and still do an acceptable job of keeping the airplane under control. Generally, then, his gain is higher in this maneuver than in the others. If his troubles are closed-loop stability of the pilot-airplane combination as they are here, it is Maneuver (d) which will demonstrate his control problems.

An excellent theoretical groundwork was laid out by Ashkenas and McRuer of Systems Technology, Inc., which predicted these control problems with favorable yawing moment due to aileron deflection ($\omega_\phi/\omega_d > 1$). In Reference 7, the controller was considered as a bank angle autopilot in a tracking task, and the locus of the roots of the characteristic equation of the pilot-airplane combination was plotted as a function of the pilot gain. It was shown that, for aileron-only control inputs, the locus of the closed-loop "Dutch roll" oscillatory roots would progress toward regions of lesser damping for $\omega_\phi/\omega_d > 1$ (favorable yaw due to ailerons), and toward regions of greater damping for $\omega_\phi/\omega_d < 1$ as the controller's gain (aileron input per bank angle error) was increased. This situation is analyzed in greater detail in Reference 5 with realistic pilot models.

This trend is quite evident in certain of the pilot evaluations reported herein. The degradation of pilot rating with $\omega_\phi/\omega_d > 1$ is strongest with the high frequency, high roll-to-sideslip configurations which had low to moderate Dutch roll damping. The effect of damping is self-evident. If the closed-loop damping is reduced from the open-loop damping with $\omega_\phi/\omega_d > 1$, then the more (within limits) damping the configuration has to start with, the better the closed-loop situation is damping-wise.

The role of $\left|\phi/\beta\right|$ in this control problem is to transfer the task of minimizing the Dutch roll oscillations from the rudder with low $\left|\phi/\beta\right|$ to the aileron with large $\left|\phi/\beta\right|$. If $\left|\phi/\beta\right|$ is very low, the ailerons will not be much used at the Dutch roll frequency, and the assumption of roll-only control is relatively poor. One would expect less opinion loss with increasing ω_ϕ/ω_d (> 1), and this is the case. But with large $\left|\phi/\beta\right|$, control of the Dutch roll oscillation becomes an aileron control task, and the yaw-producing characteristics of the ailerons become all-important, particularly regarding the phase of these moments. The phase is such that the yawing moment produced by aileron control applied in opposition to bank angle changes is such as to enforce the Dutch roll oscillation when $\omega_\phi/\omega_d > 1$, and to reduce it when $\omega_\phi/\omega_d < 1$.

3. Moderate ω_d and Low ζ_d :

At an average Dutch roll mode of $\omega_d = 2.3$ rad/sec and $\zeta_d = .12$, a series of evaluations was made for $\left|\phi/\beta\right| = .65 - .66$, 1.00, $2.92 - 3.54$, $5.46 - 6.97$, and $8.05 - 9.34$. The pilot rating results are shown in Figure 5 versus ω_ϕ/ω_d.

The trend of the ratings with ω_ϕ/ω_d is quite interesting. The shape of the curves vary from an almost straight line for $\left|\phi/\beta\right| = 8.05 - 9.34$ to a very sharply peaking curve for $\left|\phi/\beta\right| = .65 - .66$.

Examine first the ratings for $\left|\phi/\beta\right| = .65 - .66$. Here, a strong preference is shown for $\omega_\phi/\omega_d \cong 1$ with extremely little tolerance of variations of ω_ϕ/ω_d in either direction. Only a small range of ω_ϕ/ω_d about 1.0 is satisfactory for the task. When the pilot comments are examined, it is found that the principal objection is the large yawing moment due to aileron deflection. An approximate expression for ω_ϕ/ω_d is:

$$\frac{\omega_\phi}{\omega_d} \approx \sqrt{1 - \frac{N'_{\delta_A} L'_\beta}{L'_{\delta_A} N'_\beta}} \qquad (6)$$

Since L'_β/N'_β is a major contributor to $\left|\phi/\beta\right|$, it can be readily seen that as $\left|\phi/\beta\right|$ is reduced, larger and larger values of N'_{δ_A} are required for given values of ω_ϕ/ω_d. At the low values of $\left|\phi/\beta\right|$, the pilot is troubled primarily by the large sideslip angles produced due to these large values of N'_{δ_A} by use of his ailerons and hence he is more intolerant of the variations of ω_ϕ/ω_d.

As $\left|\phi/\beta\right|$ is increased, the disturbance inputs to the Dutch roll are decreased for a given ω_ϕ/ω_d, and the pilot ratings decrease less rapidly for variations of ω_ϕ/ω_d about 1.0. The curve for $\left|\phi/\beta\right| = 2.92 - 3.54$ is thus broader. It also has a higher peak rating, indicating a preference for some roll due to sideslip. Note that for $\omega_\phi/\omega_d \cong 1$, a rating of 1.5 is given for the somewhat low $\zeta_d = .12$. The pilot commented that the Dutch roll was oscillatory if disturbed, but that for maneuvering requirements of the task in smooth air, the Dutch roll was seldom disturbed. In Maneuver (d), the Dutch roll mode was disturbed but easily handled. There was sufficient roll motion that the ailerons provided adequate control of the roll and sideslip oscillations, and with N'_{δ_A} near zero, the aileron inputs did not further disturb the airplane. The pilot remarked that this set of Dutch roll characteristics, particularly the value of directional stiffness, was very good and well matched to the longitudinal response.

When $\left|\phi/\beta\right|$ was further increased to 5.46 - 6.97, the rate of decrease of pilot rating with adverse yaw became even smaller, partly because of the reduced value of N'_{δ_A} (since L'_β/N'_β was larger). In addition, the increased closed-loop damping of the Dutch roll mode with $\omega_\phi/\omega_d < 1$ partly offset the sideslip-disturbing effect of N'_{δ_A}. The pilot rating curve has not completely lost its symmetry, and the ratings decrease sharply for $\omega_\phi/\omega_d > 1$. The pilot comments on oscillatory tendencies when trying to maneuver in roll, and in trying to minimize the sideslip oscillations with ailerons. He also comments that the roll due to sideslip has become objectionable, although he can still perform all of the required maneuvers.

For $\left|\phi/\beta\right| = 8.05 - 9.34$, the variation of pilot rating with ω_ϕ/ω_d becomes almost a straight line for the range of $.83 < (\omega_\phi/\omega_d) < 1.11$ with the highest rating given to the value of .83. For ω_ϕ/ω_d about 1.0, the pilot objected to the extreme roll rates produced by a small amount of sideslip, caused either by inadvertent rudder inputs, by side gust, or by the random noise input. When favorable yaw due to aileron deflection was added to the configuration, he had difficulties with roll oscillations which caused his opinion to decrease. The introduction of adverse yaw due to ailerons did not eliminate the objection to the high $\left|\phi/\beta\right|$, but it did aid his control of the roll oscillations and hence, his rating was higher. It is indicated in his comments that a further decrease in ω_ϕ/ω_d by additional N'_{δ_A} would not continue to increase his ratings because the size of the sideslip disturbance would become objectionable, and hence it is expected that his rating would soon begin to decrease as ω_ϕ/ω_d was further reduced.

4. Moderate ω_d and Moderate ζ_d:

For $\omega_d = 2.3$ rad/sec, a series of evaluations was conducted at a nominal value of $\zeta_d = 0.4$, for $\left|\phi/\beta\right| = .57 - .67, 1.37 - 1.80, 2.49 - 2.99, 3.93 - 5.53$ and $6.76 - 7.46$, summarized in Figure 6. Perhaps the most significant thing about this figure is that all configurations except two were rated Satisfactory (Rating 3 or better). This would indicate what has been established many times before - that a little Dutch roll damping goes a long way toward minimizing many lateral-directional ills.

The rating curves are flat for the two highest $\left|\phi/\beta\right|$; in fact, there is so little difference between the two that one rating curve is drawn for both. One evaluation fell significantly below the curve, that for $\omega_\phi/\omega_d = 1.04$ and $|\phi/\beta| = 6.76 - 7.46$. A review of the pilot comments indicated that some system difficulty was probably responsible for the lower rating, causing Dutch roll damping to be initially lower than intended, but changing during the evaluation to the recorded value.

The rating curves of $|\phi/\beta| = 2.49 - 2.99$ show some curvature, bending downward with both favorable and adverse yaw. The ratings remain 2 or above for $.85 < (\omega_\phi/\omega_d) < 1.15$ with a peak rating of 1 at about $\omega_\phi/\omega_d = 1$.

The ratings for $|\phi/\beta| = .57 - .67$ exhibit the same sharp break discussed earlier with increasing and decreasing ω_ϕ/ω_d from a value of unity. This is due to the large values of N'_{δ_A} which are required to vary ω_ϕ/ω_d when $|\phi/\beta|$ is very small, with the attendant large sideslip disturbance whenever the ailerons are used. The favorable yaw is very difficult to coordinate with rudder, and hence, the very sharp decrease of rating with $\omega_\phi/\omega_d < 1$.

Two additional evaluations for $|\phi/\beta| = 1.37 - 1.80$ are spotted on Figure 6. For one, $\omega_\phi/\omega_d = .98$; for the other, $\omega_\phi/\omega_d = 1.09$. These indicate a rating curve intermediate between that for $|\phi/\beta| = .57 - .67$ and 2.49 - 2.99 as one would expect.

It appears that for this base condition of moderate frequency and damping and for $\omega_\phi/\omega_d = 1$, the pilot is tolerant of a wide range of $|\phi/\beta|$, preferring the low values to the higher ones. If some variation of ω_ϕ/ω_d is expected to occur in the region of these base characteristics, a value of $|\phi/\beta| = 2.49 - 2.99$ is preferable.

The highest-rated configurations of this base condition repeatedly brought forth a pilot comment that he felt he was almost "wearing the airplane". By this he meant that the handling characteristics were very well matched both to himself and the task; that control was very precise during all maneuvers, particularly in holding a given "g" or angle of attack and varying nose position or flight path by varying bank angle. He remarked that these were near-optimum lateral-directional characteristics for the task, and that he felt these were the desirable characteristics to aim toward for the re-entry mission where possible.

5. Low ω_d and Moderately Low ζ_d :

The evaluation results shown in Figure 7 are for ω_d = 1.1 rad/sec and ζ_d = .2, and show the pilot ratings for $|\phi/\beta|$ = 0.71, 1.17 - 1.40, 1.75 - 2.55, and 2.90 - 4.56. Many of these evaluations were done early in the program, and so there is some variability in the parameters, particularly $|\phi/\beta|$, but the trends can still be seen.

Generally, the trends appear similar to those with ω_d = 2.3 rad/sec, except somewhat lower in ratings. The $|\phi/\beta|$ = 1.17 - 1.40 configuration was rated "Good" or Rating 2, for $.95 < (\omega_\phi/\omega_d) < 1$ and the pilot commented they were satisfactory for the task although he preferred more directional stiffness. The decrease in rating was sharp for both adverse and favorable aileron yaw beyond these limits of ω_ϕ/ω_d.

For $|\phi/\beta|$ = 1.75 - 2.55, the highest ratings were 3, dropping off slightly less rapidly with adverse yaw than with favorable.

Due to an error in setting the variable stability gains, no evaluations were made with $\omega_\phi/\omega_d > 1$ for $|\phi/\beta|$ = 2.90 - 4.56. One evaluation was made with ω_ϕ/ω_d = .61, the lowest value evaluated during the entire program. Although the pilot objected to the very strong adverse yaw and considered it unsatisfactory, it was still acceptable for the mission.

The Dutch roll damping was higher than intended for these evaluations, and this undoubtedly contributed to the acceptability of the configurations.

6. Low ω_d and High ζ_d :

The low frequency, high damping results are shown in Figure 8. Again, it is interesting to note the effect of ζ_d in that all configurations examined were rated Satisfactory (Rating 3 or better). The pilot noted that these were not the kind of characteristics he would want, for example, in an air-to-air interceptor, but that they are satisfactory characteristics for the mission as defined. He remarked often that the airplane was lacking in directional stiffness, but that he had adequate control to keep it pointed the way it was going.

A significant thing to note is the tolerance to both adverse and favorable yaw which is shown. This, at first, seems contradictory to the results of the moderate and high frequency configurations discussed earlier where the rating fell off sharply at low $|\phi/\beta|$ with $\omega_\phi/\omega_d > 1$. The explanation lies in the fact that the roll characteristics, τ_R and $K_{\dot{\phi}_{\delta_{AS}}}$, have been kept constant while the Dutch roll frequency has been lowered drastically. When the pilot uses his ailerons for a roll task, he can still roll as rapidly as ever, and hence, his aileron inputs are of short duration. The yawing moment due to aileron deflection is applied, however, to a relatively inert system (due to the low directional stiffness and high damping). The pilot achieves his desired roll angle and the aileron input is removed before there has been any objectionable amplitude of sideslip response. With the large damping, the growth of sideslip is slow and when the control is released, the rate of increase of sideslip stops and there is little overshoot. The pilot comments that when he maneuvers, the sideslip does change, but very slowly and it is easily controlled if necessary. He remarks that when the controls are released, the sideslip seems to "squeeze back to zero".

There is a definite preference in the pilot comments for the configurations with ω_ϕ/ω_d near unity, but the pilot states that the larger values of adverse and favorable yaw do not limit his ability to perform the required maneuvers. He has one reservation, however, regarding recovery from unusual attitudes which may require prolonged aileron control application. This would be a difficult task with the larger values of adverse and favorable yaw. If this is an important consideration of the mission, then those configurations should be downrated from the values shown in Figure 8.

This has an important bearing on the likely circumstance that when the Dutch roll characteristics are this ponderous, it is probable that the roll mode would be similarly affected. This would require longer periods of aileron control application for maneuvering, causing larger sideslip disturbances, and generally making the large adverse and favorable yaw configurations considerably less acceptable.

7. Near-Zero ω_d :

Eight configurations were set up and evaluated in which it was attempted to achieve small, but positive, directional stiffness and low and moderate directional damping, all with small $\left|\phi/\beta\right|$. The calculated characteristics for these (Configurations 11 through 18 in Table II) show all to have little or no tendency toward weathercock stability. Configurations No. 12, 14, and 16 are slightly unstable and the rest are stable.

The pilot rating data are shown in Figure 9 for both values of damping. As would be expected, the higher damping configurations are rated measurably better. It should be noted that the abscissa of Figure 9 is $N_{\delta_{AS}}$, not ω_ϕ/ω_d as on the preceding plots, because of the zero and negative values of ω_d^2 . The pilot comment data indicates that zero directional stability configurations can be flown, even with zero damping, if the yawing moments due to aileron inputs are not excessive; but they are generally not suitable for the entry task. The pilot must direct too much attention to merely keeping the vehicle pointed the way it is going to the exclusion of other necessary piloting tasks. The addition of directional damping is definitely helpful, making the vehicle less susceptible to disturbances and slowing the yaw rate caused by a given disturbance.

Another reason these configurations rate poorly is that in attempting to achieve a small $|\Phi/\beta|$, the simulation actually ended up with a positive L_{β}, or negative effective dihedral. No attempt is made to connect the points in Figure 9 because of the variation of the parameters between configurations.

A completely unflyable configuration (No. 11) was evaluated and rated a 10. Because of a miscalculation in variable stability system gain setting, it had a tremendous value of adverse $N_{\delta_{AS}}$ which in combination with the low directional stiffness made an unflyable combination - the evaluation pilot would lose control in sideslip whenever the ailerons were used.

C. LONGITUDINAL INTERACTIONS

Considerable discussion took place during the formative stages of this evaluation program regarding the level of longitudinal handling characteristics which should be maintained during the lateral-directional evaluations. There were generally two schools of thought: (1) that the longitudinal characteristics should be representative of the class of vehicle in order that the evaluation results would be more directly applicable to a particular vehicle, and (2) that the longitudinal characteristics should be near-optimum to isolate the lateral-directional problems from any longitudinal factors which might be an influence, and also to permit a maximum excursion of pilot rating as the lateral-directional characteristics are varied.

The latter sentiment prevailed, and hence a small program was undertaken to assess the possible effects on the lateral-directional evaluations of differing longitudinal handling qualities. It was intended that a set of lateral-directional configurations (No. 19, 20, 22, 10, 44, 52, and 64) be repeated with a slow- and a fast-responding longitudinal mode. However, during this phase of the program, the servo which supplies dynamic pressure information to the angle of attack computer failed, causing a fourfold increase in the system angle-of-attack gain. This caused several supposedly low frequency longitudinal short period configurations to be violently divergent. The servo failure was not discovered until after the program was completed, and all of the "low frequency" points were in the unstable region, as can be seen in Figure 10.

In Figure 10, the longitudinal short period characteristics are shown graphically. The symbols identify each set of lateral-directional characteristics for which evaluations were made at five different longitudinal characteristics. (The three divergent configurations would have been a single configuration except for the malfunction noted above.) The number adjacent to each symbol is the evaluation pilot's rating of that combination of lateral and longitudinal characteristics. For example, Configuration No. 44, which was rated a 2 at the nominal short period characteristics, was rated a 4 at the high short period frequency (as Configuration No. 127) and a 10 at the divergent, negatively damped point (as Configuration No. 124).

It should be pointed out that the values shown for the longitudinal short period characteristics are computed from measurements made of the gain change caused by the servo failure. They are approximately correct based on flight record measurements made at the high short period frequency. It is interesting to note that even the most unstable longitudinal configuration could be flown with the better lateral-directional characteristics. (The 9.5 rating indicates that it could be flown for short intervals.)

SECTION IV
CONCLUSIONS

The flight evaluation results reported here are a beginning in the extension of current knowledge of pilot-airplane handling characteristics to include the mission of hyper-velocity, high altitude vehicles which must re-enter the atmosphere under pilot control. These evaluations have surveyed the area of lateral handling qualities in the light of the new task, and provide the designer of these vehicles with results from which at least preliminary estimations can be made of the acceptability of his vehicle in its various flight regimes.

The pilot comments and ratings have confirmed the importance of the numerator of the roll to aileron input transfer function. Two separate effects of the numerator term (designated ω_ϕ) have been obtained in the investigation. When the Dutch roll damping is low, and particularly when the ratio $|\phi/\beta|$ is large (and hence the pilot tends to stabilize the airplane by use of the ailerons), values of the ratio ω_ϕ/ω_d greater than unity are accompanied by a tendency toward closed-loop instability by the pilot-airplane combination. This provides experimental verification of the theoretical analysis contained in Reference 5.* When the Dutch roll damping is reasonably high, and particularly when the ratio $|\phi/\beta|$ is small, values of the ratio ω_ϕ/ω_d which differ appreciably from unity result in the excitation of excessive amounts of sideslip angle when the ailerons are used. It is this excitation of sideslip (rather than closed-loop dynamic instability) which becomes objectionable in this case.

With roll control parameters (sensitivity of steady state rolling velocity corresponding to pilot input, and roll mode time constant) fixed at values which were found to be desirable, pilot ratings were affected independently by variations of Dutch roll damping (ζ_d), yawing moments due to aileron (ω_ϕ/ω_d), roll-to-sideslip ratio ($|\phi/\beta|$), and, to a lesser degree, Dutch roll frequency (ω_d). The effects of the first three quantities were clearly significant. The effect of Dutch roll frequency was rather small and not consistent, except that degradation of the pilot's rating always occurred at the highest frequency when

My mistake. Wrong ref.

~~*RATHER AMAZING COMMENT SINCE IT WAS ASSUMED IN REF 5 THAT DUTCH ROLL EFFECTS WERE OF NO IMPORTANCE~~

the roll-to-sideslip ratio was relatively high.

It is believed that the data obtained during the program is sufficient to demonstrate that at least five, and possibly six, parameters are important in specifying a sufficiently broad criterion for satisfactory lateral-directional handling qualities. However, it is recognized that the amount of data available at this time is insufficient to permit quantitative formulation of a reliable statement of this criterion. Additional data will be required to permit prediction of the satisfactoriness of future hyper-velocity vehicles which may possess different combinations of values of the lateral-directional parameters that have been investigated to date.

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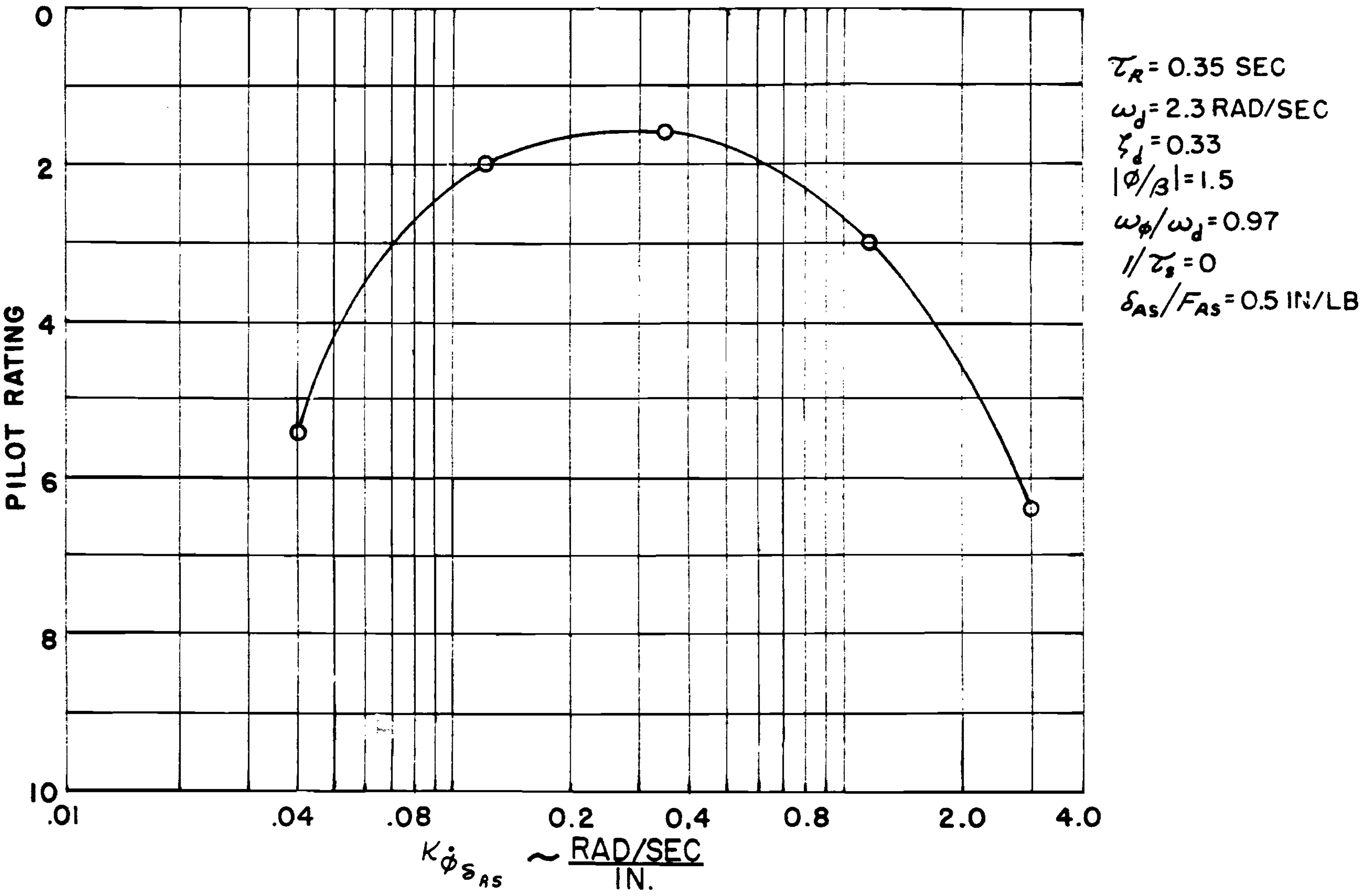
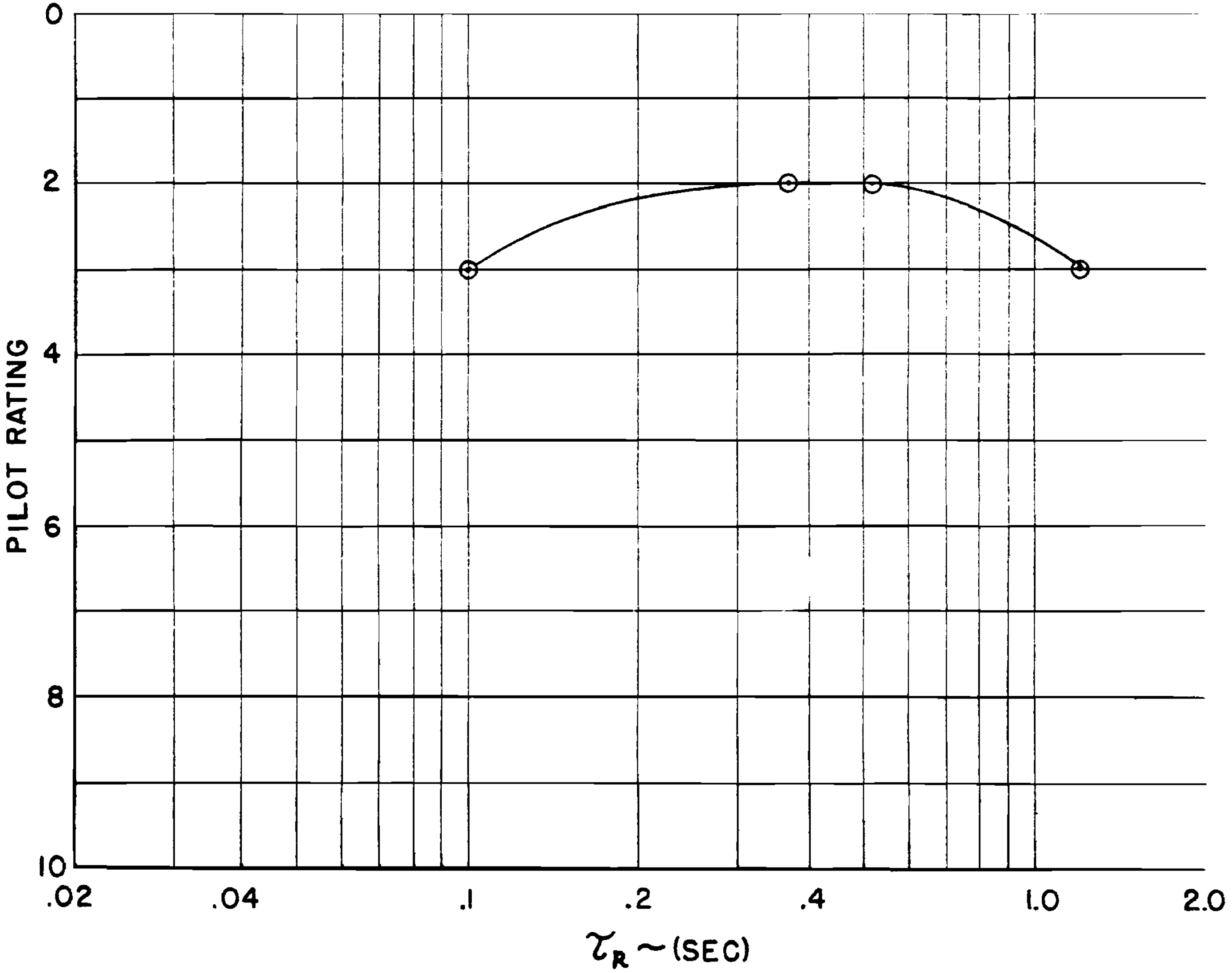


FIGURE 1 PILOT RATING VERSUS STEADY STATE ROLL RATE PER INCH OF AILERON STICK DISPLACEMENT



$K_{\dot{\phi}_{\delta_{AS}}}$ = 0.36 RAD/SEC/IN
ω_d = 2.4 RAD/SEC
ζ_d = 0.33
$|\phi/\beta|$ = 1.5
ω_ϕ/ω_d = 0.97
$1/\tau_s$ = 0

FIGURE 2 PILOT RATING VERSUS ROLL MODE TIME CONSTANT

NOMINAL BASE CONDITION	
DUTCH ROLL MODE	ω_d = 4.3 RAD/SEC ζ_d = 0.1
ROLL MODE	τ_R = 0.37 SEC $K_{\dot{\phi}_{\delta_{AS}}}$ = 0.36 RAD/SEC/IN
SPIRAL MODE	$\frac{1}{\tau_s}$ = 0 SEC^{-1}

SYMBOL	$\lvert\phi/\beta\rvert$
—○—	1.07-1.20
- - △ - -	2.42-3.19
—◇—	3.93-4.53
·······▷·······	7.06-7.40

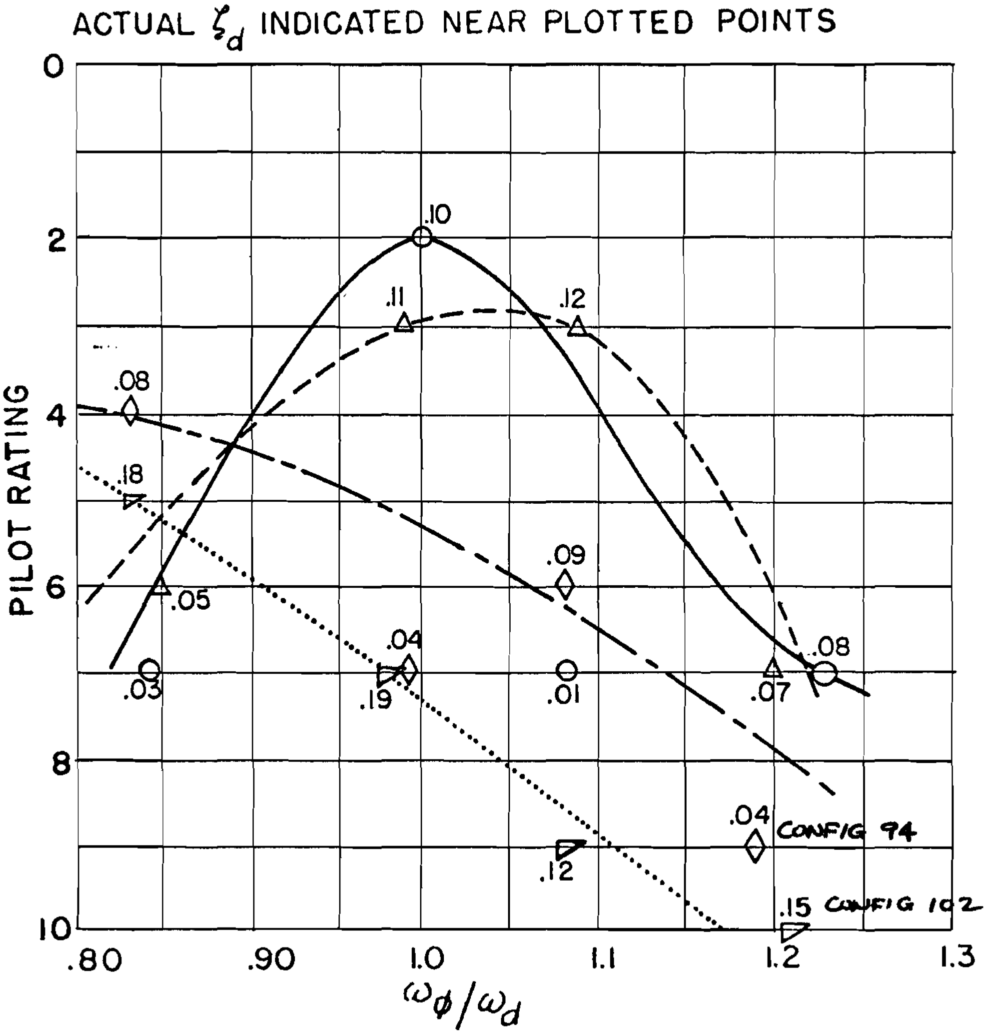


FIGURE 3 PILOT RATING VERSUS ω_ϕ/ω_d FOR HIGH FREQUENCY, LOW DAMPING DUTCH ROLL

NOMINAL BASE CONDITION	
DUTCH ROLL MODE	ω_d = 4.3 RAD/SEC ζ_d = .4
ROLL MODE	τ_R = 0.37 SEC $K_{\dot{\phi}_{\delta_{AS}}}$ = 0.36 RAD/SEC/IN
SPIRAL MODE	$1/\tau_s$ = 0 SEC^{-1}

SYMBOL	$\lvert \phi/\beta \rvert$
—○—	1.05 – 1.08
····□······	2.34 – 2.49
– –◇– –	3.42 – 3.61
–·–◇–·–	5.12 – 5.31

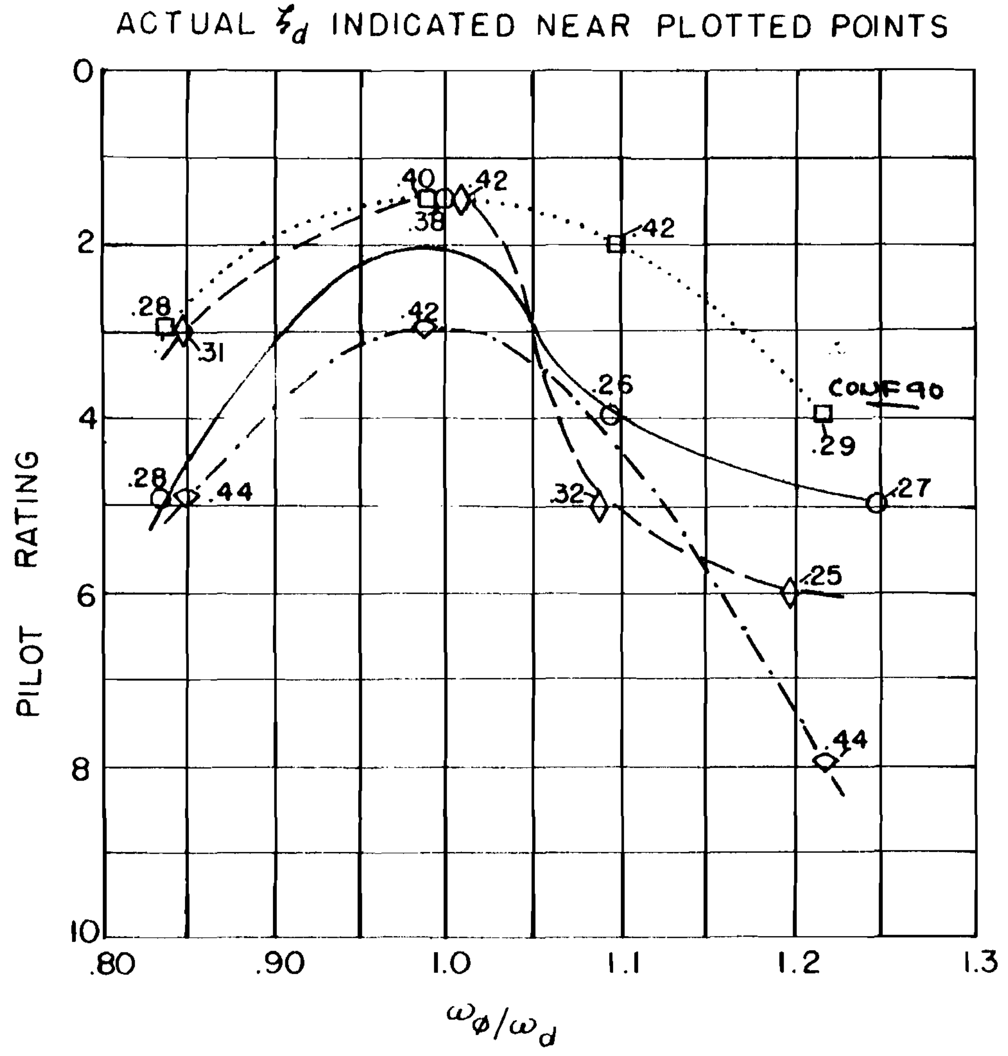


FIGURE 4 PILOT RATING VERSUS ω_ϕ/ω_d FOR HIGH FREQUENCY, MODERATE DAMPING DUTCH ROLL

NOMINAL BASE CONDITION	
DUTCH ROLL MODE	$\omega_d = 2.3$ RAD/SEC $\zeta_d = .12$
ROLL MODE	$\tau_R = 0.37$ SEC $K_{\dot{\phi}\delta_{AS}} = 0.36$ RAD/SEC/IN.
SPIRAL MODE	$1/\tau_s = 0$ SEC^{-1}

SYMBOL	$\lvert \phi/\beta \rvert$
—○—	.65 – .66
⌓	1.00
– –△– –	2.92 – 3.54
······⬭······	5.46 – 6.97
—·—×—·—	8.05 – 9.34

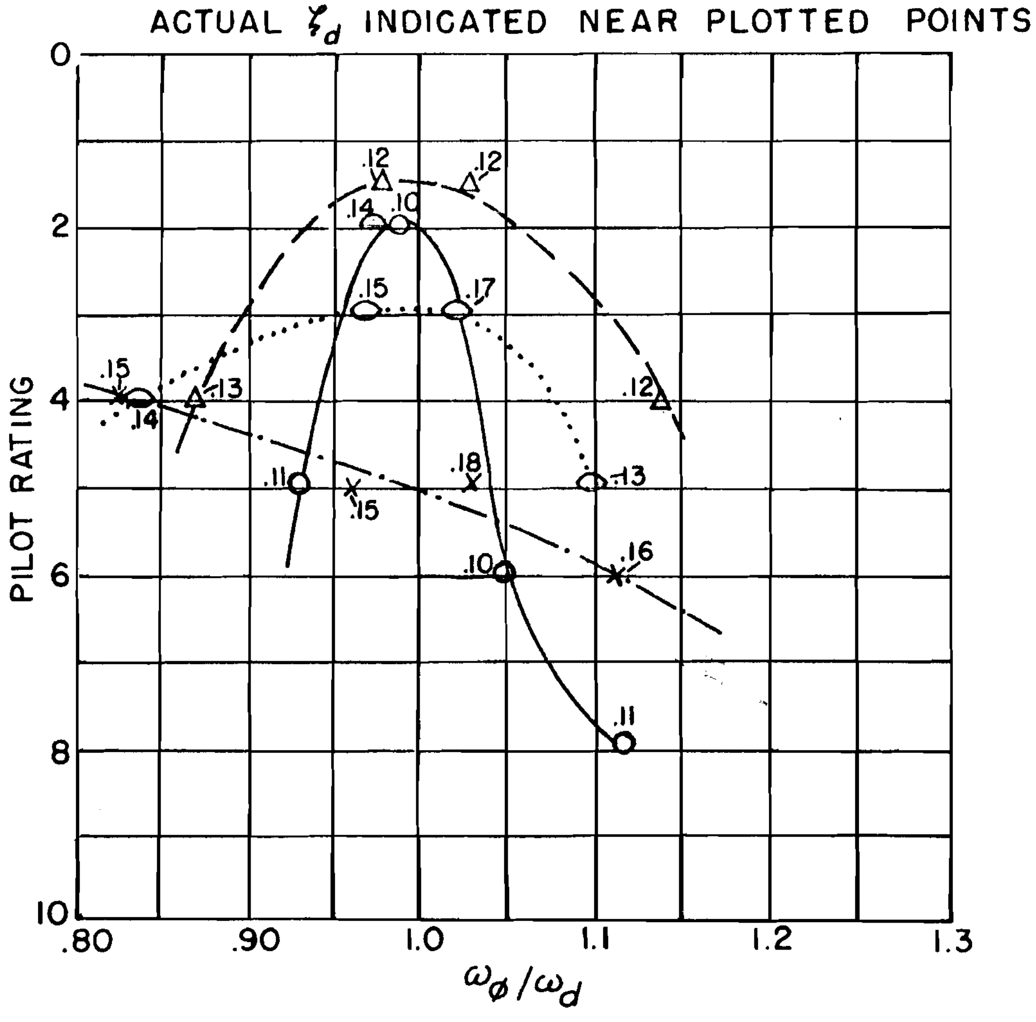


FIGURE 5 PILOT RATING VERSUS ω_ϕ/ω_d FOR MODERATE FREQUENCY, LOW DAMPING DUTCH ROLL

NOMINAL BASE CONDITION	
DUTCH ROLL MODE	ω_d = 2.3 RAD/SEC ζ_d = 0.4
ROLL MODE	τ_R = 0.37 SEC $K_{\dot{\phi}_{\delta_{AS}}}$ = 0.36 RAD/SEC/IN.
SPIRAL MODE	$\frac{1}{\tau_s}$ = 0 SEC^{-1}

SYMBOL	$\lvert\phi/\beta\rvert$
—○—	.57- .67
– –⌂– –	1.37-1.80
—△—	2.49-2.99
·····◇·····	3.93-5.53
X	6.76-7.46

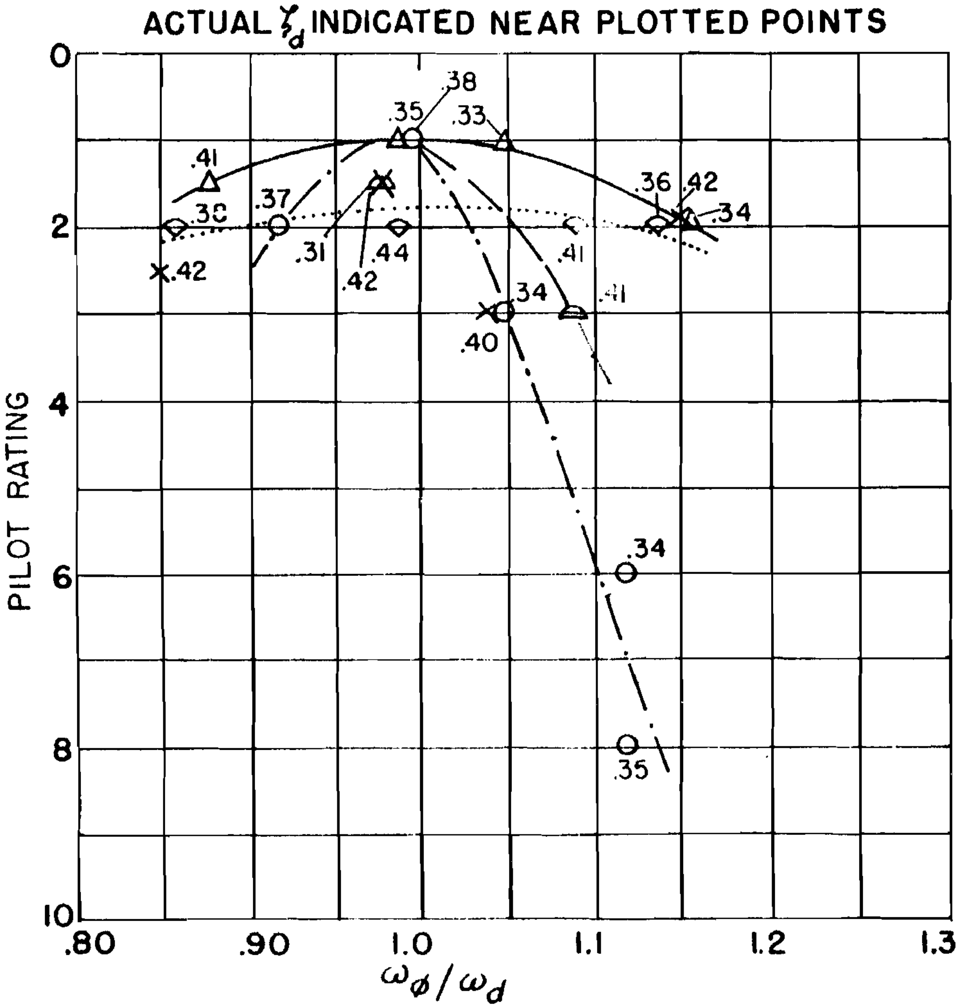


FIGURE 6 PILOT RATING VERSUS ω_ϕ/ω_d FOR MODERATE FREQUENCY, MODERATE DAMPING DUTCH ROLL

NOMINAL BASE CONDITION	
DUTCH ROLL MODE	ω_d = 1.1 RAD/SEC ζ_d = 0.2
ROLL MODE	τ_R = 0.37 SEC $K_{\dot{\phi}_{\delta_{AS}}}$ = 0.36 RAD/SEC/IN
SPIRAL MODE	$\frac{1}{\tau_s}$ = 0 SEC^{-1}

SYMBOL	$\lvert\phi/\beta\rvert$
○	.71
—⌓—	1.17-1.40
---□---	1.75-2.55
·····◇·····	2.90-4.56

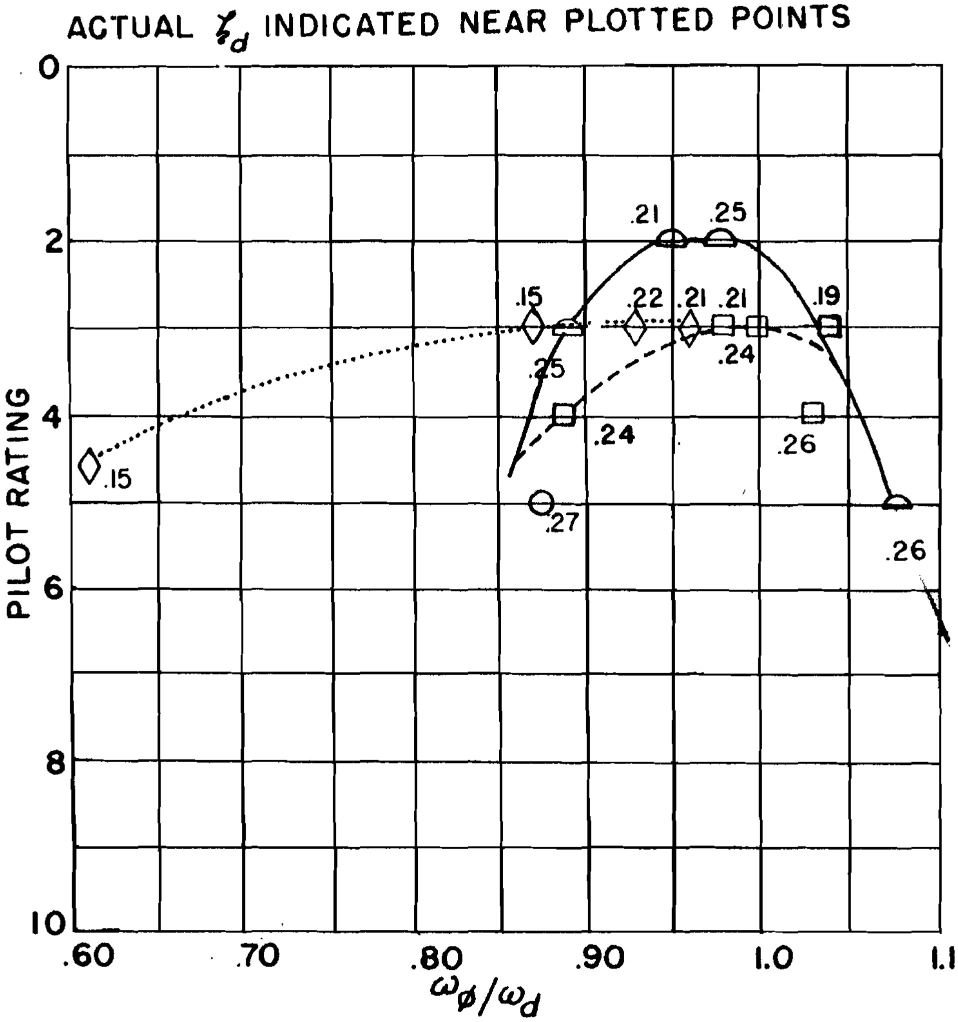


FIGURE 7 PILOT RATING VERSUS ω_ϕ/ω_d FOR LOW FREQUENCY, MODERATELY LOW DAMPING DUTCH ROLL

NOMINAL BASE CONDITION	
DUTCH ROLL MODE	ω_d = 1.1 RAD/SEC ζ_d = .55
ROLL MODE	τ_R = 0.37 SEC $K_{\dot{\phi}_{\delta_{AS}}}$ = 0.36 RAD/SEC/IN
SPIRAL MODE	$\frac{1}{\tau_s}$ = 0 SEC^{-1}

SYMBOL	$\lvert\phi/\beta\rvert$
—○—	.64 - .80
⌓	1.04 - 1.20
△	1.91 - 2.38
◇	4.07

ACTUAL ζ_d INDICATED NEAR PLOTTED POINTS

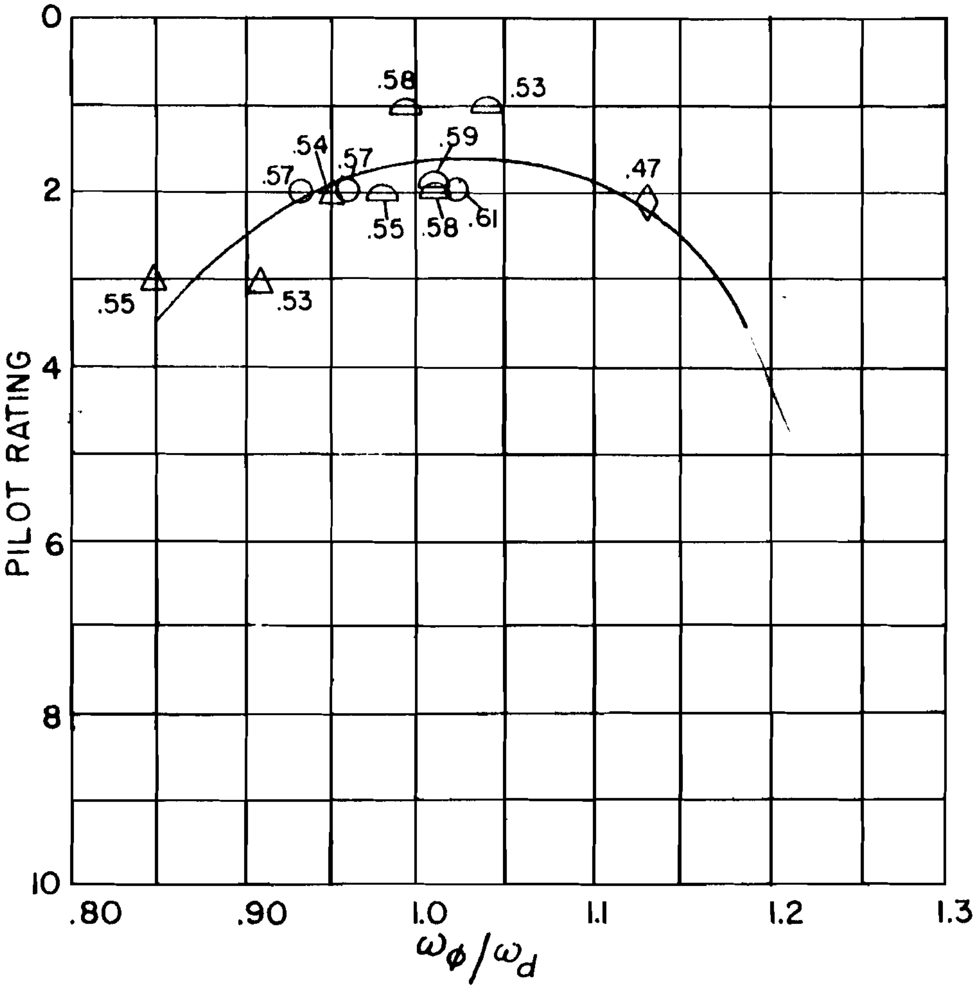


FIGURE 8 PILOT RATING VERSUS ω_ϕ/ω_d FOR LOW FREQUENCY, HIGH DAMPING DUTCH ROLL

NOMINAL BASE CONDITION	
DUTCH ROLL MODE	$\omega_d = 0$
ROLL MODE	$\tau_R = .37$ SEC. $K_{\dot{\phi}_{\delta_{AS}}} = 0.36$ RAD/SEC/IN
SPIRAL MODE	$\frac{1}{\tau_s} = 0$ SEC^{-1}

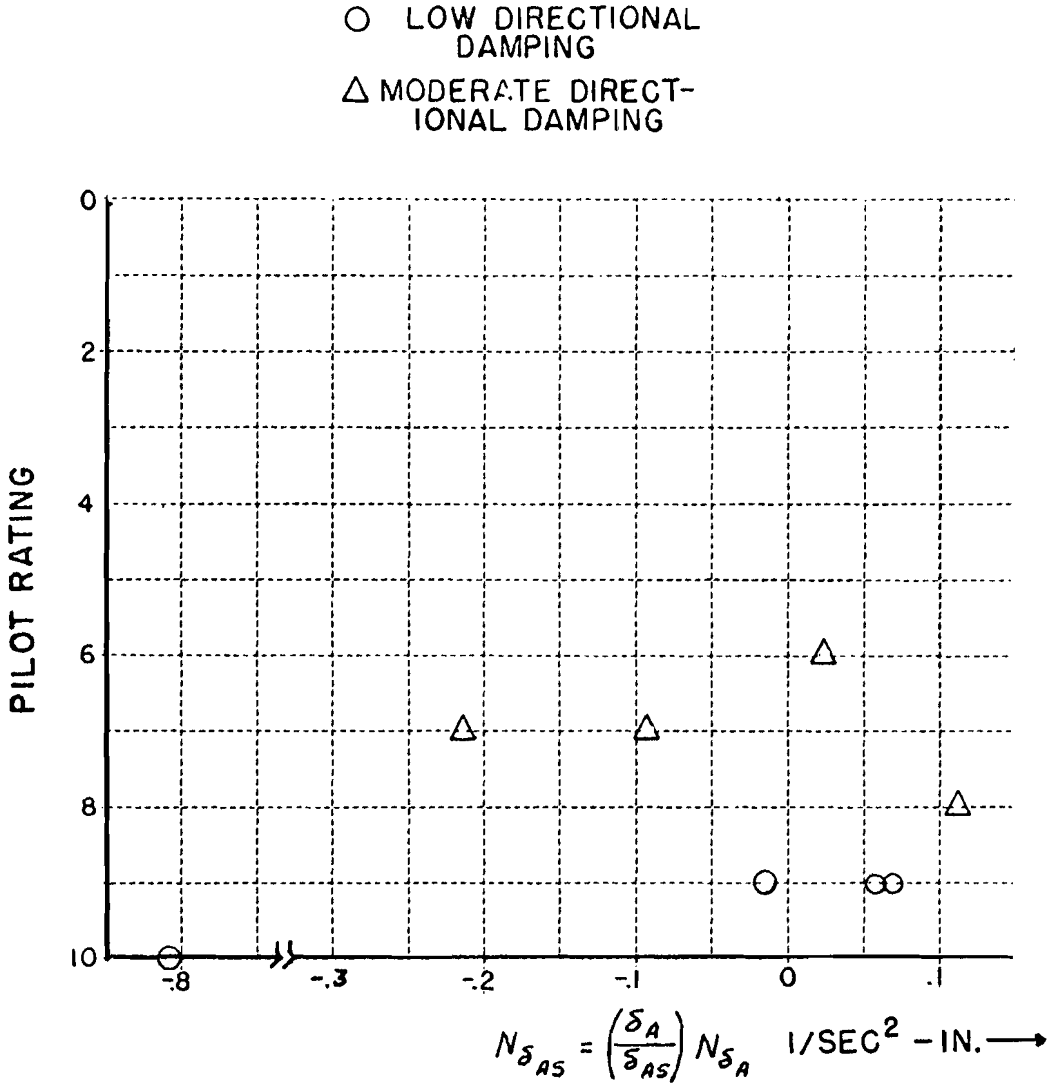


FIGURE 9 PILOT RATING VERSUS $N_{\delta_{AS}}$ FOR NEAR NEUTRAL DIRECTIONAL STABILITY

SYM	CONF. NO.	ω_d	ζ_d	ϕ/β	N_{δ_A}	τ_R
□	19,116,119	LO	MOD.	MOD.	ADV	SM
○	20,117,120	LO	MOD.	MOD.	SM	SM
△	22,118,121	LO	MOD.	MOD.	FAV	SM
⌓	10,122,123	MOD.	MOD.	MOD.	SM	LG
●	44,124,127	MOD.	LO	LO	SM	SM
■	52,125,128	MOD.	LO	MOD.	SM	SM
▲	64,126,129	MOD.	LO	HI	SM	SM

LO ~ LOW
MOD. ~ MODERATE
HI ~ HIGH
ADV ~ ADVERSE
FAV ~ FAVORABLE
SM ~ SMALL
LG ~ LARGE

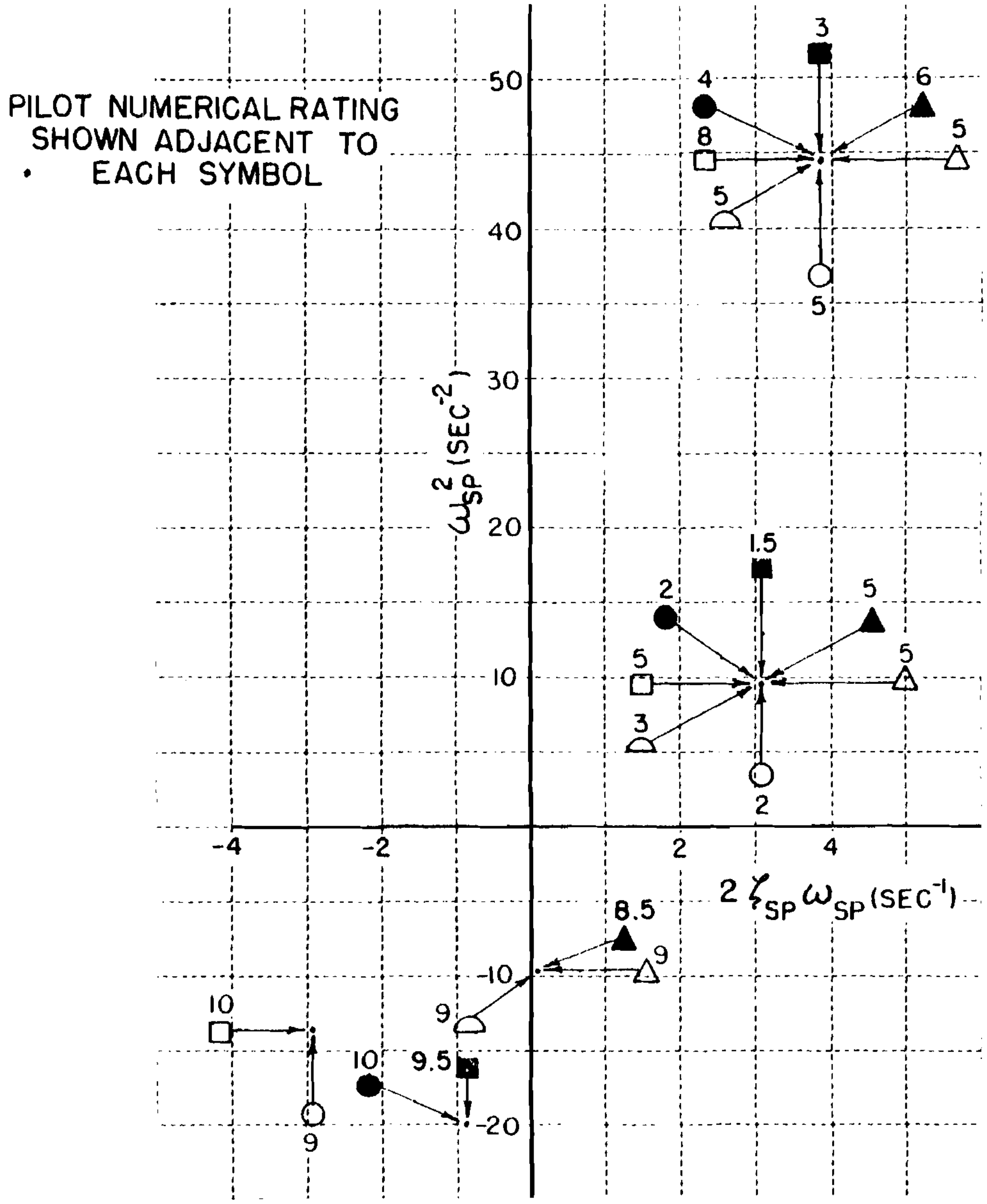


FIGURE 10 LONGITUDINAL INTERACTION EVALUATION

TABLE I

RATING SCALE

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

BODY AXES ; NOT STABILITY AXES.
$\alpha_0 \neq 0$.

TABLE II

a. COMPUTED LATERAL-DIRECTIONAL CHARACTERISTICS

CONFIG.	PILOT RATING	ω_d sec^{-1}	ζ_d	ω_d^2 sec^{-2}	$2\zeta_d\omega_d$ sec^{-1}	$\frac{1}{C_{1/2}}$ $cycle^{-1}$	$\frac{1}{T_{1/2}}$ sec^{-1}	$\left\lvert\frac{\phi}{\beta}\right\rvert$	τ_R sec	τ_S sec	$K_{\dot\phi\delta_{AS}}$ $(sec\text{-}in)^{-1}$	ω_ϕ sec^{-1}	ζ_ϕ	ω_ϕ^2 sec^{-2}	$2\zeta_\phi\omega_\phi$ sec^{-1}	$\frac{\omega_\phi}{\omega_d}$	Y_β sec^{-1}	$Y_{\delta_{RP}}$ $\times 10^2$ $(sec\text{-}in.)^{-1}$	N_β sec^{-2}	$N_{\dot\beta}$ sec^{-1}	N_r sec^{-1}	N_p $\times 10^2$ sec^{-1}	$N_{\delta_{AS}}$ $\times 10^2$ sec^{-2}	$N_{\delta_{RP}}$ $(sec^2\text{-}in.)^{-1}$	L_β sec^{-2}	L_r sec^{-1}	L_p sec^{-1}	$L_{\delta_{AS}}$ sec^{-2}	$L_{\delta_{RP}}$ $(sec^2\text{-}in.)^{-1}$	$\frac{I_{xz}}{I_x}$	$\frac{I_{xz}}{I_z}$
1	5 TO 6	2.15	.281	4.61	1.21	2.65	.874	1.84	.462	28.4	.044	2.09	.306	4.38	1.28	.972	-.162	-.824	4.39	.400	-.723	.580	-.101	.685	-11.6	.394	-2.12	.099	-.449	.0180	.0102
2	2	2.20	.326	4.84	1.43	3.17	1.03	1.22	.344	92.7	.127	2.11	.351	4.44	1.48	.959	-.171	-.680	4.61	.679	-.648	-.997	-1.16	.706	-9.66	.734	-2.86	.401	-.657	.0374	.015
3	1 TO 2	2.38	.309	5.67	1.47	2.95	1.06	1.80	.320	28.3	.372	2.32	.333	5.39	1.54	.975	-.171	-.869	5.38	.490	-.887	.711	-1.06	.841	-16.9	.573	-3.09	1.22	-.653	.0263	.013
4	3	2.50	.323	6.23	1.61	3.06	1.16	1.77	.264	28.2	1.23	2.43	.346	5.92	1.68	.972	-.175	-.888	5.91	.538	-.974	.781	-3.82	.923	-20.5	.697	-3.76	4.91	-.795	.0325	.014
5	7 TO 6	2.19	.325	4.81	1.42	3.06	1.03	1.22	.349	92.7	2.72	2.10	.349	4.42	1.48	.959	-.167	-.667	4.59	.675	-.645	-.991	-24.8	.702	-9.52	.724	-2.82	8.50	-.647	.0366	.0148
7	3	2.50	.399	6.23	1.99	3.96	1.44	0.92	.097	48.0	0.355	2.38	.419	5.64	1.99	.952	-.184	-.650	6.01	.695	-1.12	4.97	-8.70	.671	-26.8	.805	-10.3	4.03	-.626	.0377	.0150
8	2	2.33	.139	5.43	.648	1.27	.494	1.00	.377	49.1	.373	2.29	.148	5.24	.678	.983	-.172	-.782	5.14	-.571	-1.08	1.40	-1.03	.660	-8.60	.729	-2.65	1.03	-.439	.0187	.0105
9	2	2.74	.347	7.50	1.90	3.38	1.37	1.33	.522	33.8	.343	2.72	.366	7.38	1.99	.993	-.189	-.818	7.21	.421	-1.39	.151	-.534	.836	-12.2	1.23	-1.87	.668	-.701	.0307	.0137
10	3	2.29	.321	5.25	1.47	3.06	1.06	2.19	1.21	14.0	.233	2.24	.344	5.00	1.54	.978	-.170	-.720	4.97	.366	-1.05	-.649	-.288	.604	-9.72	3.23	-.677	.203	-.400	.0190	.0106
11	10	.606	.369	.367	.447	3.61	.323	.456	.311	-44.1	1.12	.792	.472	.627	.747	1.31	-.119	-.096	.329	-.046	-.343	-1.38	-87.4	.090	.708	.805	-3.23	2.13	-.067	.0242	.0124
12	9	--	--	-.014	-.002	--	-.001	.094	.223	2.17	.051	.161	1.34	.026	.431	--	-.120	-.066	-.043	-.084	-.413	-1.84	-2.90	.070	1.37	1.14	-4.51	1.86	-.063	.0344	.0143
13	9	.587	.434	.345	.510	4.32	.368	.483	.369	-38.6	.214	.535	.522	.286	.558	.911	-.116	-.094	.292	-.068	-.429	-1.11	7.90	.081	.571	.733	-2.73	.698	-.055	.0196	.0108
14	9	--	--	-.0285	-.146	--	-.105	.596	.396	1.44	.130	--	--	-.285	.427	--	-.119	-.072	-.119	-.103	-.491	-3.30	6.16	.076	2.12	.720	-2.58	.553	-.067	.0341	.0143
15	7	.925	.607	.855	1.12	7.00	.809	.285	.315	-62.8	.409	.941	.512	.886	.964	1.02	-.124	-.096	.791	.519	-.457	-.965	-20.5	.088	.325	.850	-3.19	1.26	-.064	.0273	.0132
16	7	--	--	-.0184	-.118	--	-.085	.364	.358	1.46	.022	--	--	-.0358	.520	--	-.128	-.077	-.118	-.107	-.512	-3.43	-.969	.079	1.57	1.05	-2.84	.812	-.074	.0381	.0151
17	6	.785	.684	.616	1.07	8.40	.773	.576	.364	-32.0	.233	.751	.709	.564	1.02	.957	-.131	-.075	.543	.388	-.493	-3.06	3.79	.078	.923	1.01	-2.79	.698	-.073	.0370	.0149
18	8	.874	.581	.764	1.02	6.43	.736	.298	.384	-62.7	.205	.846	.673	.715	1.14	.968	-.120	-.093	.708	.465	-.409	-.864	12.1	.079	.266	.697	-2.62	.567	-.052	.0188	.0105
19	5	1.10	.273	1.21	.601	2.55	.434	.708	.391	-83.4	.335	1.02	.257	1.05	.525	.927	-.135	-.148	1.07	-.027	-.484	-2.95	-4.57	.155	-1.82	1.48	-2.57	.994	-.143	.0369	.0148
20	2	1.12	.209	1.25	.466	1.94	.336	1.28	.349	168.0	.283	1.06	.226	1.13	.482	.946	-.125	-.189	1.12	.003	-.361	-.714	-.585	.165	-4.38	1.05	-2.86	.895	-.114	.0204	.0112
21	2	1.13	.255	1.28	.577	2.34	.417	1.17	.376	302.4	.258	1.11	.282	1.23	.624	.982	-.141	-.154	1.10	-.027	-.489	-2.98	1.16	.157	-3.76	1.48	-2.66	.717	-.148	.0386	.0152
22	5	1.05	.260	1.10	.545	2.43	.393	1.21	.413	280.1	.260	1.13	.280	1.27	.631	1.08	-.130	-.142	1.04	-.026	-.464	5.37	2.64	.149	-3.32	1.30	-2.42	.542	-.130	.0373	.0149
23	2	1.09	.571	1.18	1.24	6.27	.895	.800	.369	-144.3	.322	1.01	.589	1.02	1.19	.927	-.124	-.187	1.07	.701	-.417	-.701	-3.52	.160	-2.86	1.50	-2.72	1.01	-.108	.0195	.0108
24	2	1.08	.570	1.18	1.24	6.27	.895	.802	.371	-144.3	.288	1.04	.586	1.08	1.22	.963	-.124	-.187	1.07	.698	-.415	-.699	-1.27	.160	-2.84	1.49	-2.70	.847	-.108	.0194	.0107
25	1	1.11	.584	1.23	1.29	6.43	.931	1.04	.395	295.9	.265	1.10	.613	1.21	1.35	.991	-.131	-.144	1.08	.712	-.479	-2.92	1.30	.154	-3.57	1.40	-2.53	.681	-.140	.0358	.0146
26	2	1.10	.611	1.22	1.35	7.00	.975	.641	.386	-126.8	.243	1.13	.628	1.27	1.41	1.03	-.137	-.150	1.08	.722	-.486	-2.97	2.94	.156	-2.33	1.48	-2.61	.603	-.145	.0375	.0150
27a	3	1.14	.249	1.29	.565	2.34	.408	1.40	.393	-2738.0	.304	1.01	.265	1.02	.535	.886	-.132	-.145	1.08	-.026	-.484	-2.93	-2.81	.154	-4.25	1.92	-2.55	.978	-.141	.0360	.0146
✓ 27b	4	1.15	.235	1.33	.543	2.24	.392	1.75	.388	102.1	.288	1.00	.270	1.00	.541	.870	-.133	-.146	1.10	-.026	-.485	-2.93	-2.63	.154	-5.61	1.90	-2.57	.983	-.142	.0363	.0147
28	3	1.08	.216	1.16	.466	2.04	.336	2.55	.358	47.1	.297	1.06	.224	1.12	.475	.981	-.124	-.187	1.13	.003	-.357	5.62	-.572	.161	-8.37	1.49	-2.81	.859	-.109	.0151	.0091
29	4	1.08	.263	1.16	.567	2.44	.409	1.81	.366	90.00	.276	1.11	.280	1.23	.620	1.03	-.140	-.153	1.11	-.027	-.491	5.65	.573	.156	-5.81	1.97	-2.74	.713	-.147	.0396	.0155
✓ 30a	3	1.14	.193	1.31	.442	1.78	.319	2.10	.361	79.4	.228	1.18	.225	1.40	.532	1.04	-.124	-.187	1.12	.003	-.357	-.682	1.90	.161	-7.16	1.51	-2.76	.589	-.109	.0195	.0108
30b	3	1.17	.240	1.36	.560	2.24	.404	1.75	.372	102.2	.229	1.16	.284	1.35	.661	.992	-.141	-.154	1.11	-.027	-.493	-2.98	1.71	.157	-5.85	1.98	-2.68	.615	-.148	.0387	.0152
31	1	1.12	.532	1.25	1.19	5.66	.859	1.91	.374	121.9	.396	1.16	.555	1.35	1.29	1.04	-.124	-.186	1.10	.690	-.417	-.671	2.89	.158	-6.68	2.06	-2.67	.985	-.106	.0190	.0105
32	2	1.19	.547	1.40	1.30	5.95	.939	1.14	.396	-184.8	.299	1.17	.577	1.36	1.34	.983	-.133	-.144	1.23	.702	-.479	-2.85	1.30	.154	-4.12	1.91	-2.53	.778	-.140	.0358	.0146
33	2	1.13	.589	1.27	1.33	6.61	.960	1.12	.386	-429.8	.277	1.14	.617	1.30	1.41	1.01	-.136	-.149	1.09	.720	-.489	-2.95	2.30	.155	-4.10	1.97	-2.60	.699	-.144	.0372	.0149
34	2	1.12	.580	1.25	1.30	6.44	.939	1.20	.397	-2675.0	.235	1.13	.611	1.27	1.38	1.01	-.131	-.143	1.08	.712	-.482	-2.92	1.74	.153	-4.21	1.90	-2.52	.582	-.140	.0352	.0145
35	5 TO 4	1.28	.151	1.65	.388	1.37	.280	4.56	.337	22.69	.134	.786	.265	.618	.417	.614	-.125	-.188	1.26	.003	-.373	-.641	-3.78	.165	-18.88	2.34	-2.93	1.06	-.113	.0154	.0093
36	3 TO 2	1.28	.151	1.65	.389	1.37	.281	4.56	.336	22.68	.220	1.10	.223	1.21	.490	.860	-.125	-.189	1.26	.003	-.373	-.642	-.443	.165	-18.94	2.35	-2.94	.895	-.114	.0162	.0096
37	3	1.23	.216	1.51	.530	2.04	.383	2.90	.376	66.79	.229	1.14	.281	1.40	.642	.927	-.137	-.150	1.14	-.027	-.500	-2.94	.653	.156	-10.13	3.45	-2.65	.704	-.145	.0398	.0155
38	3	1.22	.211	1.48	.514	1.94	.371	2.91	.390	66.75	.210	1.17	.281	1.38	.660	.959	-.130	-.143	1.12	-.026	-.492	-2.89	1.11	.153	-9.75	3.32	-2.55	.580	-.139	.0363	.0147
39	3	1.19	.546	1.41	1.30	5.89	.938	2.25	.375	103.7	.273	1.01	.644	1.01	1.30	.849	-.139	-.152	1.13	.724	-.499	-2.95	-2.06	.156	-8.71	3.24	-2.66	1.01	-.146	.0380	.0150
40	3	1.17	.530	1.37	1.24	5.66	.895	2.38	.400	87.93	.252	1.07	.614	1.14	1.31	.915	-.130	-.142	1.10	.703	-.485	-2.86	-.195	.151	-8.33	3.01	-2.47	.753	-.136	.0345	.0145
41	2	1.19	.541	1.41	1.28	5.79	.924	2.33	.378	87.88	.242	1.13	.612	1.28	1.38	.950	-.137	-.150	1.13	.721	-.497	-2.94	.652	.155	-8.87	3.20	-2.63	.701	-.144	.0374	.0150
42	2	1.23	.474	1.51	1.17	4.84	.845	4.07	.345	25.47	.264	1.39	.505	1.93	1.40	1.13	-.125	-.188	1.22	.712	-.440	-.644	2.31	.163	-16.51	3.27	-2.86	.602	-.111	.020	.011
43	5	2.31	.111	5.34	.513	1.00	.370	.648	.353	-352.3	.315	2.14	.109	4.56	.465	.926	-.173	-.737	5.23	.092	-.254	1.39	-13.86	.642	-5.43	.420	-2.83	1.05	-.440	.0202	.0110
44	2	2.30	.103	5.30	.476	.91	.344	.656	.389	270.5	.297	2.28	.110	5.18	.503	.991	-.171	-.587	5.16	-.041	-.374	-.846	-.668	.624	-5.36	.203	-2.55	.782	-.572	.0360	.0147
45	6	2.26	.102	5.09	.459	.91	.331	.650	.427	270.6	.296	2.37	.107	5.64	.510	1.05	-.167	-.574	4.96	-.039	-.359	-.812	8.17	.599	-4.87	.185	-2.32	.623	-.521	.0328	.0141
46	8	2.32	.105	5.39	.487	1.00	.352	.658	.376	270.5	.290	2.60	.110	6.76	.570	1.12	-.179	-.615	5.23	-.042	-.379	.857	16.64	.633	-5.54	.210	-2.64	.607	-.592	.0378	.0150
47	2	2.34	.369	5.48	1.72	3.61	1.24	.621	.344	-80.78	.314	2.15	.346	4.62	1.49	.919	-.172	-.740	5.20	.520	-1.04	1.36	-15.30	.652	-5.12	1.74	-2.91	1.08	-.453	.0207	.0113
48	1	2.32	.376	5.39	1.75	3.67	1.26	.670	.375	-127.50	.297	2.30	.384	5.27	1.76	.991	-.179	-.609	5.17	.782	-.811	-.895	-.678	.624	-5.50	1.28	-2.65	.813	-.586	.0382	.0151
49	3	2.25	.339	5.06	1.53	3.28	1.10	.573	.374	-64.87	.345	2.36	.360	5.55	1.70	1.05	-.170	-.737	4.94	.377	-.980	7.44	9.13	.623	-3.97	1.59	-2.68	.842	-.415	.0188	.0105
50	8	2.28	.342	5.36	1.60	3.28	1.16	.571	.358	-64.85	.309	2.56	.403	6.55	2.06	1.12	-.171	-.742	5.06	.386	-1.00	7.62	20.90	.639	-4.13	1.66	-2.79	.680	-.433	.0196	.0109
51	4	2.30	.132	5.28	.608	1.18	.439	2.93	.349	46.89	.283	2.00	.131	3.99	.524	.870	-.170	-.585	5.30	.011	-.377	7.87	-5.90	.624	-25.11	.634	-2.94	1.07	-.571	.0359	.0147
52	1.5	2.28	.116	5.19	.531	1.09	.383	3.54	.373	64.19	.364	2.24	.096	5.00	.428	.983	-.170	-.737	5.18	.075	-.184	7.57	-.770	.623	-28.33	.212	-2.80	1.01	-.415	.0188	.0105
53	1.5	2.30	.117	5.29	.539	1.09	.389	3.54	.360	64.16	.335	2.38	.092	5.65	.438	1.04	-.171	-.893	5.29	.077	-.188	7.73	.974	.766	-29.4	.219	2.90	.872	-.518	.0195	.0108
54	4	2.26	.116	5.12	.524	1.09	.378	3.53	.384	64.29	.318	2.58	.084	6.68	.435	1.14	-.169	-.734	5.10	.074	-.181	7.44	3.58	.613	-27.53	.206	-2.72	.634	-.404	.0183	.0103

CONFIG.	PILOT RATING	ω_d sec^{-1}	ζ_d	ω_d^2 sec^{-2}	$2\zeta_d\omega_d$ sec^{-1}	$\frac{1}{C_{1/2}}$ cycle^{-1}	$\frac{1}{T_{1/2}}$ sec^{-1}	$\left\lvert\frac{\phi}{\beta}\right\rvert$	τ_R sec	τ_S sec	$K_{\dot\phi\delta_{AS}}$ (sec-in.)$^{-1}$	ω_ϕ sec^{-1}	ζ_ϕ	ω_ϕ^2 sec^{-2}	$2\zeta_\phi\omega_\phi$ sec^{-1}	$\frac{\omega_\phi}{\omega_d}$	Y_β sec^{-1}	$Y_{\delta_{RP}}$ x 10^2 (sec-in.)$^{-1}$	N_β sec^{-2}	$N_{\dot\beta}$ sec^{-1}	N_r sec^{-1}	N_p x 10^2 sec^{-1}	$N_{\delta_{AS}}$ x 10^2 sec^{-2}	$N_{\delta_{RP}}$ (sec^2-in.)$^{-1}$	L_β sec^{-2}	L_r sec^{-1}	L_p sec^{-1}	$L_{\delta_{AS}}$ sec^{-2}	$L_{\delta_{RP}}$ (sec^2-in.)$^{-1}$	$\frac{I_{xz}}{I_x}$	$\frac{I_{xz}}{I_z}$
55	1.5	2.28	.409	5.19	1.87	4.08	1.35	2.49	.351	-199.6	.288	2.00	.405	4.01	1.62	.877	-.168	-.580	5.19	.793	-.899	7.80	-6.41	.622	-21.64	4.02	-2.91	1.07	-.567	.0356	.0145
56	1	2.24	.355	5.03	1.59	3.39	1.15	2.99	.392	-170.3	.368	2.22	.344	4.94	1.53	.991	-.168	-.879	4.97	.473	-.921	7.29	-.743	.725	-23.48	4.64	-2.63	.955	-.471	.0177	.0101
57	1	2.27	.334	5.16	1.52	3.20	1.10	2.98	.373	-170.2	.340	2.38	.329	5.65	1.56	1.05	-.169	-.738	5.11	.375	-.947	7.50	1.22	.621	-24.6	4.86	-2.75	.832	-.412	.0186	.0104
58	2	2.31	.339	5.32	1.56	3.28	1.13	2.97	.351	-169.7	.321	2.67	.348	7.10	1.85	1.16	-.171	-.743	5.29	.388	-.980	7.76	4.19	.641	-26.12	5.16	-2.92	.684	-.435	.0197	.0109
59	4	2.39	.137	5.71	.656	1.27	.474	5.96	.311	35.06	.284	2.02	.113	4.07	.457	.845	-.173	-.763	5.84	.089	-.205	8.39	-3.99	.692	-57.72	.326	-3.44	1.28	-.496	.0221	.0117
60	3	2.22	.154	4.91	.683	1.37	.493	5.46	.343	20.83	.329	2.16	.137	4.66	.592	.973	-.167	-.570	5.01	.043	-.391	7.73	-.925	.605	-45.43	.943	-3.06	1.01	-.555	.0362	.0147
61	3	2.05	.173	4.22	.709	1.56	.512	6.97	.350	23.05	.321	2.09	.131	4.36	.574	1.02	-.156	-.895	4.25	.169	-.222	7.25	.127	.774	-50.70	.311	-3.06	.888	-.528	.0198	.0109
62	5	2.32	.131	5.40	.607	1.18	.438	5.87	.368	36.50	.294	2.56	.085	6.56	.437	1.10	-.170	-.738	5.41	.076	-.185	7.70	1.50	.626	-49.18	.276	-2.92	.656	-.418	.0190	.0106
63	2	2.28	.377	5.20	1.72	3.72	1.24	4.93	.359	218.5	.292	1.96	.354	3.85	1.39	.860	-.169	-.731	5.26	.504	-.997	7.66	-3.86	.623	-43.86	8.08	-2.93	1.10	-.418	.0192	.0106
64	2	1.98	.437	3.91	1.73	4.45	1.25	5.53	.376	19.02	.363	1.96	.425	3.83	1.66	.990	-.154	-.884	4.00	.570	-.998	6.89	-.758	.740	-40.98	7.63	-2.80	.988	-.487	.0183	.0104
65	1.5	2.30	.428	5.28	1.97	4.32	1.42	4.67	.347	23.85	.336	2.40	.413	5.76	1.98	1.04	-.170	-.709	5.37	.515	-1.27	7.82	.341	.613	-45.17	8.41	-3.04	.888	-.418	.0199	.0109
66	2	2.25	.360	5.06	1.62	3.50	1.17	4.95	.366	168.4	.308	2.57	.363	6.61	1.87	1.14	-.168	-.885	5.16	.495	-.978	7.52	1.91	.745	-42.20	7.69	-2.84	.643	-.493	.0185	.0105
67	4	2.38	.153	5.65	.726	1.37	.524	8.33	.321	15.16	.248	1.97	.135	3.88	.530	.828	-.183	-.623	5.93	.001	-.387	8.28	-2.94	.635	-80.82	1.56	-3.36	1.12	-.598	.0385	.0152
68	5	2.37	.146	5.60	.691	1.37	.499	8.05	.361	16.0	.315	2.27	.114	5.15	.519	.958	-.170	-.578	5.77	-.006	-.368	7.97	-.900	.610	-72.12	1.41	-3.02	.948	-.539	.0337	.0143
69	5	2.17	.177	4.69	.766	1.66	.553	9.19	.331	11.4	.304	2.24	.143	5.01	.641	1.03	-.167	-.580	4.91	.068	-.406	7.70	.039	.608	-77.1	1.55	-3.26	.861	-.562	.0368	.0148
70	6	2.41	.160	5.79	.771	1.46	.557	9.35	.322	22.47	.292	2.67	.088	7.13	.471	1.11	-.171	-.904	5.98	.090	-.203	8.32	.907	.804	-90.79	.551	-3.46	.736	-.564	.0212	.0114
71	2.5	2.34	.420	5.45	1.96	4.20	1.42	6.87	.325	36.86	.261	1.98	.417	3.91	1.65	.846	-.181	-.619	5.77	.798	-.954	8.19	-3.20	.634	-69.07	9.93	-3.29	1.12	-.595	.0382	.0151
72	1.5	2.32	.416	5.39	1.93	4.20	1.39	6.76	.338	42.49	.331	2.29	.396	5.22	1.81	.987	-.172	-.690	5.67	.786	-.940	8.06	-.925	.734	-65.35	9.57	-3.16	1.01	-.672	.0360	.0147
73	3	2.30	.398	5.27	1.82	3.92	1.31	7.46	.341	45.15	.318	2.36	.368	5.55	1.73	1.03	-.168	-.895	5.50	.523	-1.06	7.88	-.159	.773	-72.88	12.92	-3.17	.885	-.526	.0198	.0109
74	2	2.34	.421	5.48	1.97	4.20	1.42	6.77	.318	42.39	.289	2.68	.396	7.91	2.12	1.15	-.185	-.746	5.80	.804	-.960	8.24	1.19	.750	-69.18	10.13	-3.34	.690	-.712	.0392	.0153
75	7	4.55	.029	20.7	.268	.27	.193	1.16	.337	109.2	.349	3.85	.023	14.8	.180	.846	-.332	-1.76	20.84	-.442	-.264	15.88	-30.25	1.80	-30.06	-.132	-3.09	1.46	-1.69	.0383	.0151
76	2	4.26	.098	18.2	.838	.91	.605	1.20	.331	73.15	.353	4.25	.087	18.1	7.41	.998	-.312	-2.51	18.13	-.245	-.676	14.53	-.946	2.52	-27.92	.255	-3.14	1.07	-2.39	.0393	.0153
77	7	4.32	.010	18.7	.090	.08	.065	1.07	.432	131.0	.353	4.69	-.004	22.0	-.040	1.09	-.304	-1.61	18.74	-.397	-.084	14.27	9.81	1.62	-23.56	-.229	-2.42	.691	-1.33	.0293	.0135
78	7	4.37	.079	19.1	.691	.72	.499	1.08	.418	82.41	.353	5.39	.061	29.0	.656	1.23	-.305	-1.62	19.02	-.259	-.551	14.49	23.0	1.64	-24.33	.151	-2.50	.549	-1.37	.0301	.0137
79	5	4.33	.282	18.7	2.44	2.65	1.76	1.08	.335	-67.18	.340	3.62	.210	13.1	1.52	.836	-.308	-1.76	18.34	-.109	-2.21	14.60	-34.44	1.80	-24.37	3.79	-3.07	1.46	-1.69	.0383	.0151
80	1.5	4.37	.377	16.81	3.59	3.72	2.59	1.05	.330	-110.6	.353	4.37	.369	19.1	3.22	1.00	-.314	-2.51	18.43	-.110	-3.07	14.68	-1.26	2.52	-24.71	4.66	-3.11	1.07	-2.39	.0391	.0153
81	4	4.32	.262	18.6	2.26	2.44	1.63	1.08	.340	-67.18	.361	4.76	.293	22.6	2.79	1.10	-.302	-1.73	18.23	-.266	-2.19	14.52	13.31	1.79	-24.01	3.74	-3.02	.870	-1.67	.0374	.0150
82	5	4.27	.277	18.3	2.37	2.55	1.71	1.06	.357	-67.08	.362	5.34	.359	28.5	3.84	1.25	-.287	-1.64	17.89	-.107	-2.15	14.24	28.0	1.76	-22.88	3.56	-2.88	.638	-1.59	.0355	.0145
83	6	4.26	.046	18.2	.390	.41	.281	2.89	.369	51.2	.353	3.63	.024	13.2	1.75	.852	-.291	-1.64	18.4	-.293	-.133	14.4	-11.0	1.73	-63.9	-.532	-2.99	1.32	-1.53	.0342	.0143
84	3	4.09	.106	16.7	.867	1.00	.626	3.15	.352	31.3	.346	4.05	.076	16.4	.615	.990	-.274	-2.28	16.9	-.009	-.347	13.8	-.859	2.45	-65.3	-.365	-3.13	1.00	-2.23	.0355	.0145
85	3	4.13	.119	17.0	.978	1.09	.706	3.19	.335	27.3	.349	4.49	.079	20.1	.708	1.09	-.292	-2.43	17.2	-.010	-.439	14.0	3.64	2.49	-68.4	-.303	-3.28	.878	-2.34	.0380	.0150
86	7	4.34	.068	18.9	.587	.63	.424	3.02	.332	51.1	.327	5.21	.023	27.2	.239	1.20	-.314	-2.97	19.2	-.147	-.138	15.1	7.77	3.03	-70.8	-.589	-3.31	.681	-2.85	.0384	.0151
87	3	4.09	.285	16.7	2.33	2.65	1.68	2.42	.423	238.6	.340	3.43	.236	11.7	1.62	.839	-.279	-2.71	16.4	-.076	-2.02	13.1	-12.2	2.73	-48.2	5.73	-2.56	1.15	-2.24	.0295	.0136
88	1.5	3.90	.396	15.2	3.09	3.96	2.23	2.34	.451	19.3	.349	3.88	.382	15.0	2.96	.995	-.264	-2.22	14.8	.013	-2.74	12.2	-.825	2.20	-44.7	6.05	-2.42	.786	-1.75	.0276	.0132
89	2	4.14	.420	17.1	3.48	4.20	2.51	2.45	.335	19.3	.355	4.55	.418	20.7	3.80	1.10	-.288	-2.42	16.8	.015	-3.11	13.8	4.30	2.49	-59.5	8.04	-3.22	.876	-2.33	.0378	.0150
90	4	4.29	.286	18.4	2.45	2.76	1.77	2.49	.354	974.7	.336	5.23	.315	27.3	3.30	1.22	-.289	-2.72	18.3	-.118	-2.17	14.4	9.10	2.90	-57.7	6.79	-3.04	.635	-2.62	.0355	.0145
91	4	3.88	.083	15.1	6.43	.72	.462	3.93	.509	28.9	.340	3.24	.062	10.5	.404	.835	-.270	-2.65	15.0	-.049	-.135	12.0	-6.60	2.50	-66.9	-.694	-2.28	.962	-1.87	.0243	.0125
92	7	4.58	.042	20.9	.383	.37	.277	4.03	.326	36.4	.342	4.55	-.003	20.7	-.024	.993	-.338	-1.78	21.6	-.456	-.084	16.3	-.942	1.81	-105.6	-1.14	-3.50	1.06	-1.71	.0383	.0153
93	6	4.19	.095	17.6	.793	.81	.572	4.53	.337	28.4	.340	4.53	.041	20.5	.371	1.08	-.293	-2.88	18.0	-.059	-.163	14.4	2.14	3.00	-99.5	-1.03	-3.39	.865	-2.78	.0397	.0154
✓ 94	9	4.55	.040	20.7	.362	.37	.261	3.96	.342	36.5	.316	5.40	-.012	29.1	-.131	1.19	-.318	-1.68	21.3	-.448	-.083	16.0	5.15	1.78	-101.0	-1.09	-3.35	.655	-1.63	.0362	.0147
95	3	4.28	.308	18.3	2.63	2.97	1.90	3.61	.328	63.0	.345	3.64	.253	12.2	1.84	.850	-.303	-2.94	18.4	-.084	2.26	14.6	-9.37	3.02	-88.0	9.87	-3.38	1.45	-2.83	.0380	.0151
96	1.5	4.18	.420	17.5	3.51	4.18	2.53	3.42	.331	11.5	.347	4.18	.397	17.5	3.32	1.00	-.293	-2.43	17.4	-.010	3.13	14.1	-.938	2.50	-87.1	10.7	-3.37	1.05	-2.34	.0381	.0151
97	5	4.05	.317	16.4	2.56	3.07	1.85	3.57	.383	37.2	.344	4.40	.304	19.3	2.67	1.09	-.272	-2.73	16.3	-.009	2.14	13.3	2.41	2.84	-75.2	8.55	-2.91	.760	-2.45	.0324	.0140
98	6	4.59	.251	21.0	2.30	2.34	1.66	3.45	.317	-145.3	.317	5.49	.271	30.1	2.97	1.20	-.341	-1.82	21.3	-.433	2.21	16.2	5.91	1.82	-93.0	10.1	-3.48	.695	-1.73	.0395	.0154
99	5	4.14	.183	17.2	1.52	1.66	1.10	7.06	.345	7.79	.331	3.44	.142	11.9	.975	.831	-.275	-2.29	17.6	-.009	-.674	14.1	-5.29	2.45	-155.6	-.911	-3.59	1.39	-2.23	.0356	.0145
100	7	4.17	.188	17.4	1.57	1.75	1.13	7.22	.323	7.79	.329	4.09	.121	16.7	.986	.981	-.297	-2.47	18.0	-.010	-.690	14.4	-.942	2.51	-164.8	-.965	-3.80	1.06	-2.37	.0387	.0152
101	9	4.19	.125	17.5	1.05	1.09	.758	7.23	.329	19.2	.330	4.50	.044	20.2	.393	1.07	-.292	-2.89	18.3	-.047	-.164	14.6	1.01	3.00	-161.2	-1.42	-3.71	.867	-2.79	.0373	.0149
✓ 102	10	4.15	.152	17.2	1.26	1.37	.910	7.40	.318	12.6	.324	5.04	.058	25.4	.582	1.24	-.300	-2.54	18.0	-.010	-.350	14.5	3.06	2.56	-166.0	-1.30	-3.83	.689	-2.42	.0391	.0153
103	5	4.14	.443	17.1	3.67	4.45	2.65	5.31	.319	6.00	.343	3.53	.403	12.4	2.84	.853	-.296	-2.49	17.5	.015	-3.20	14.2	-6.03	2.51	-143.2	16.5	-3.71	1.48	-2.38	.0391	.0153
104	3	3.99	.423	15.9	3.38	4.20	2.44	5.13	.411	5.97	.342	3.94	.388	15.5	3.06	.988	-.267	-2.25	15.9	.014	-2.91	12.9	-.859	2.29	-114.7	13.2	-2.97	.855	-1.91	.0302	.0137
105	3	4.13	.442	17.0	3.65	4.45	2.64	5.30	.325	5.99	.704	6.44	.471	41.5	6.06	1.56	-.290	-2.44	17.4	.015	-3.18	14.1	14.2	2.50	-140.9	16.2	-3.65	.881	-2.34	.0382	.0151
106a	8	4.10	.438	16.8	3.59	4.45	2.59	5.26	.342	5.98	.334	5.02	.421	25.2	4.23	1.22	-.274	-2.26	17.1	.015	-3.13	13.9	3.42	2.41	-135.0	15.6	-3.50	.649	-2.21	.0359	.0146
✓106b	8	4.10	.439	16.8	3.60	4.45	2.60	5.26	.340	5.98	.330	5.00	.420	25.0	4.20	1.22	-.276	-2.27	17.1	.015	-3.13	13.9	3.27	2.41	-135.8	15.7	-3.52	.653	-2.21	.0362	.0147
107	10	2.29	.411	5.26	1.89	4.08	1.36	.943	.874	-11.6	.063	2.16	.540	4.67	2.33	.943	-.182	-.610	5.11	.815	-.902	6.54	2.36	.616	2.13	1.56	-1.07	.080	-.583	.0390	.0152

✓ PIO OBTAINED

CONFIG.	PILOT RATING	ω_d sec^{-1}	ζ_d	ω_d^2 sec^{-2}	$2\zeta_d\omega_d$ sec^{-1}	$\frac{1}{C_{1/2}}$ $cycle^{-1}$	$\frac{1}{T_{1/2}}$ sec^{-1}	$\left\lvert\frac{\phi}{\beta}\right\rvert$	τ_R sec	τ_S sec	$K_{\phi_{\delta_{AS}}}$ $(sec\text{-}in.)^{-1}$	ω_ϕ sec^{-1}	ζ_ϕ	ω_ϕ^2 sec^{-2}	$2\zeta_\phi\omega_\phi$ sec^{-1}	$\frac{\omega_\phi}{\omega_d}$	Y_β sec^{-1}	$Y_{\delta_{RP}}$ $\times 10^2$ $(sec\text{-}in.)^{-1}$	N_β sec^{-2}	$N_{\dot\beta}$ sec^{-1}	N_r sec^{-1}	N_p $\times 10^2$ sec^{-1}	$N_{\delta_{AS}}$ $\times 10^2$ sec^{-2}	$N_{\delta_{RP}}$ $(sec^2\text{-}in.)^{-1}$	L_β sec^{-2}	L_r sec^{-1}	L_p sec^{-1}	$L_{\delta_{AS}}$ sec^{-2}	$L_{\delta_{RP}}$ $(sec^2\text{-}in.)^{-1}$	$\frac{I_{xz}}{I_x}$	$\frac{I_{xz}}{I_z}$
108	6	2.29	.366	5.23	1.67	3.62	1.21	1.05	1.61	-21.1	.074	2.40	.382	5.75	1.83	1.05	-.171	-.745	5.06	.502	-1.00	5.44	.445	.641	-4.68	1.50	-.588	.042	-.434	.0196	.0109
109	9	2.30	.414	5.28	1.90	4.08	1.37	4.98	.920	-169.7	.086	2.53	.407	6.41	2.06	1.10	-.171	-.573	5.23	.800	-.912	6.53	.273	.605	-27.9	4.99	-1.18	.076	-.557	.0364	.0147
110	6	2.29	.343	5.24	1.57	3.28	1.13	.662	.354	-90.8	.339	2.56	.381	6.55	1.95	1.12	-.171	-.746	5.10	.389	-1.01	7.68	17.9	.645	-5.29	1.65	-2.83	.761	-.440	.0198	.0109
111	3	2.29	.412	5.23	1.88	4.08	1.36	1.37	.339	-56.7	.288	2.50	.424	6.27	2.12	1.09	-.177	-.592	5.16	.808	-.906	7.86	5.46	.611	-11.9	3.08	-2.97	.705	-.570	.0376	.0150
112	2	2.31	.407	5.35	1.88	4.08	1.36	3.94	.347	-191.4	.282	2.53	.396	6.39	2.00	1.10	-.170	-.563	5.44	.784	-.913	7.93	1.46	.602	-35.8	6.29	-2.99	.679	-.550	.0357	.0145
113	9	2.24	.401	5.00	1.79	3.95	1.29	.587	.380	-121.5	2.06	2.48	.419	6.17	2.08	1.11	-.166	-.557	4.90	.774	-.856	7.50	07.7	.585	-4.58	1.22	-2.64	4.36	-.514	.0335	.0142
114	9	2.30	.373	5.29	1.72	3.62	1.24	1.88	.351	-112.0	2.18	2.58	.384	6.63	1.98	1.12	-.171	-.746	5.21	.506	-1.03	7.74	36.5	.645	-16.3	3.72	-2.89	4.95	-.440	.0199	.0110
115	6	2.29	.420	5.25	1.93	4.20	1.39	4.32	.333	103.0	1.97	2.53	.405	6.40	2.05	1.11	-.177	-.593	5.37	.808	-.931	7.97	10.2	.612	-40.4	6.46	-3.12	4.84	-.571	.0377	.0150
116	10	1.12	.214	1.25	.479	1.94	.346	.953	.346	-101.3	.266	.948	.209	.899	.397	.846	-.126	-.188	1.14	.001	-.363	-.711	-9.20	.165	-3.25	1.09	-2.89	1.08	-.115	.0206	.0112
117	8	1.13	.248	1.28	.563	2.33	.406	1.08	.393	-1.509×10^5	.274	1.07	.266	1.14	.569	.947	-.133	-.162	1.11	-.029	-.479	-2.91	-.764	.173	-3.29	1.42	-2.54	.783	-.158	.0360	.0147
118	9	1.09	.261	1.18	.568	2.44	.410	1.09	.376	-1.42×10^5	.257	1.16	.282	1.35	.654	1.06	-.136	-.166	1.12	-.029	-.483	5.61	2.75	.174	-3.35	1.44	-2.66	.597	-.161	.0370	.0149
119	8	1.14	.268	1.30	.610	2.65	.440	.816	.369	-122.7	.325	1.04	.259	1.09	.541	.912	-.146	-.179	1.14	-.030	-.493	-3.00	-4.66	.177	-2.47	1.55	-2.72	1.05	-.170	.0400	.0155
120	5	1.13	.203	1.28	.459	1.84	.331	1.35	.352	141.0	.282	1.08	.222	1.16	.478	.956	-.125	-.187	1.14	.001	-.358	-.695	-.582	.163	-4.66	1.03	-2.84	.886	-.112	.0202	.0110
121	5	1.08	.260	1.17	.561	2.44	.405	1.09	.382	-142.0×10^5	.257	1.16	.280	1.37	.648	1.07	-.133	-.162	1.11	-.029	-.479	5.57	2.73	.173	-3.29	1.42	-2.62	.587	-.158	.0360	.0147
122	9	2.57	.407	6.58	2.08	4.08	1.50	2.74	.909	-22.7	.124	2.63	.408	6.91	2.14	1.02	-.181	-.788	6.43	.630	-1.28	7.00	.168	.803	-18.1	4.52	-1.13	.129	-.672	.0303	.0137
123	5	2.32	.369	5.38	1.71	3.61	1.23	2.41	1.32	-23.8	.118	2.36	.373	5.59	1.76	1.02	-.172	-.748	5.21	.510	-1.03	5.67	.136	.651	-12.0	3.00	-.747	.086	-.447	.0201	.0110
124	10	2.20	.073	4.85	.322	.63	.232	.635	.421	421.3	.364	2.15	.076	4.60	.327	.977	-.168	-.726	4.75	-.061	-.225	1.28	-3.51	.586	-4.57	.107	-2.37	.908	-.373	.0168	.0098
125	9.5	2.20	.052	4.84	.229	.45	.165	2.70	.447	50.6	.319	2.09	.043	4.38	.179	.950	-.165	-.547	4.80	-.309	-.336	7.07	-1.99	.540	-19.3	.505	-2.30	.789	-.432	.0280	.0133
126	8.5	2.40	.151	5.78	.724	1.37	.523	8.20	.316	15.9	.258	2.10	.127	4.41	.534	.875	-.187	-.615	6.06	-.006	-.387	8.38	-2.27	.618	-81.5	1.59	-3.41	1.07	-.587	.0382	.0151
127	4	2.34	.061	5.47	.286	.54	.206	.611	.372	326.5	.385	2.31	.067	5.35	.309	.987	-.183	-.605	5.32	-.251	-.380	-.826	-.878	.615	-5.33	.219	-2.67	1.06	-.580	.0385	.0152
128	3	2.32	.053	5.37	.247	.44	.178	2.78	.344	50.2	.343	2.29	.043	5.23	.198	.987	-.174	-.576	5.39	-.348	-.378	7.94	-.928	.607	-25.0	.653	-2.98	1.02	-.559	.0366	.0148
129	6	2.40	.160	5.77	.769	1.47	.555	9.34	.326	22.5	.340	2.31	.099	5.33	4.59	.963	-.171	-.752	5.94	-.090	-.202	8.28	-.820	.666	-89.9	.545	-3.43	1.13	-.465	.0209	.0113

b. COMPUTED LONGITUDINAL SHORT PERIOD CHARACTERISTICS

CONFIG.	ω_{SP} sec^{-1}	ζ_{SP}	ω_{SP}^2 sec^{-2}	$2\zeta_{SP}\omega_{SP}$ sec^{-1}	τ_θ sec	$K'_{\theta_{\delta_{ES}}}$ $(sec\text{-}in.)^{-1}$	M_α sec^{-2}	$M_{\dot\alpha}$ sec^{-1}	M_q sec^{-1}	$M_{\delta_{ES}}$ sec^{-2}	L_α sec^{-1}
1-115	3.14	0.50	9.86	3.14	0.83	-1.08	-6.79	-0.708	-0.714	-21.8	1.24
116,117	--	--	-13.3	-2.91	0.87	-.199	+13.7	+4.73	-0.624	-4.03	1.10
118	--	--	-9.70	0.45	0.84	-.199	+6.91	-1.39	+2.14	-4.03	1.14
119-121	6.68	0.29	44.6	3.89	0.85	-.212	-44.3	-2.07	-0.624	-43.7	1.43
122	--	--	-9.70	0.45	0.84	-.199	+6.91	-1.39	+2.14	-4.03	1.14
123	6.68	0.29	44.6	3.89	0.85	-.212	-44.3	-2.07	-0.624	-43.7	1.43
124,125	--	--	-20.5	-0.94	0.83	-.177	+16.4	-1.39	+3.53	-3.54	1.09
126	--	--	-9.70	0.45	0.84	-.199	+6.91	-1.39	+2.14	-4.03	1.14
127-129	6.68	0.29	44.6	3.39	0.85	-.212	-44.3	-2.07	-0.624	-43.7	1.43

APPENDIX A

EQUATIONS OF MOTION AND ROLL TRANSFER FUNCTION

EQUATIONS OF MOTION

The assumed lateral equations of motion in the fuselage reference axes are:

$$Y_\beta \beta - \dot{\beta} - r + \frac{g}{V}\phi + \alpha_o^{*} p = -Y_{\delta_{RP}}\delta_{RP} \tag{A-1}$$

$$N_\beta \beta + N_{\dot{\beta}}\dot{\beta} + N_r r - \dot{r} + N_p p + \frac{I_{xz}}{I_z}\dot{p} = -N_{\delta_{AS}}\delta_{AS} - N_{\delta_{RP}}\delta_{RP} \tag{A-2}$$

$$L_\beta \beta + L_{\dot{\beta}}\dot{\beta} + L_r r + \frac{I_{xz}}{I_x}\dot{r} + L_p p - \dot{p} = -L_{\delta_{AS}}\delta_{AS} - L_{\delta_{RP}}\delta_{RP} \tag{A-3}$$

where $Y_\beta = \frac{1}{mV}\frac{\partial Y}{\partial \beta}$, etc.

$N_\beta = \frac{1}{I_z}\frac{\partial N}{\partial \beta}$, $N_r = \frac{1}{I_z}\frac{\partial N}{\partial r}$, etc.

$L_\beta = \frac{1}{I_x}\frac{\partial L}{\partial \beta}$, $L_r = \frac{1}{I_x}\frac{\partial L}{\partial r}$, etc.

If Equation (A-3) is multiplied by I_{xz}/I_z and the resulting equation added to Equation (A-2), a new yawing moment equation is obtained:

$$k\left(N_\beta + \frac{I_{xz}}{I_z}L_\beta\right)\beta + k\left(N_{\dot{\beta}} + \frac{I_{xz}}{I_z}L_{\dot{\beta}}\right)\dot{\beta} + k\left(N_r + \frac{I_{xz}}{I_z}L_r\right)r - \dot{r}$$

$$+ k\left(N_p + \frac{I_{xz}}{I_z}L_p\right)p = -k\left(N_{\delta_{AS}} + \frac{I_{xz}}{I_z}L_{\delta_{AS}}\right)\delta_{AS} - k\left(N_{\delta_{RP}} + \frac{I_{xz}}{I_z}L_{\delta_{RP}}\right)\delta_{RP} \tag{A-4}$$

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* α_o varied from .0104 to .0034 rad at the flight test condition.

where $$k = \frac{1}{\left(1 - \frac{I_{xz}^{2}}{I_x I_z}\right)}$$

This can be rewritten as:

$$N'_\beta \beta + N'_{\dot\beta} \dot\beta + N'_r r - \dot r + N'_p p = -N'_{\delta_{AS}} \delta_{AS} - N'_{\delta_{RP}} \delta_{RP} \qquad \text{(A-5)}$$

where $$N'_\beta = k\left(N_\beta + \frac{I_{xz}}{I_z} L_\beta\right) \text{, etc.}$$

Similarly, Equation (A-2) is multiplied by I_{xz}/I_x and the resulting equation added to Equation (A-3). This produces a new rolling moment equation:

$$L'_\beta \beta + L'_{\dot\beta} \dot\beta + L'_r r + L'_p p - \dot p = -L'_{\delta_{AS}} \delta_{AS} - L'_{\delta_{RP}} \delta_{RP} \qquad \text{(A-6)}$$

ROLL TRANSFER FUNCTION

For $\delta_{RP} = 0$ (fixed rudder pedal), the roll to aileron stick input transfer function can be written (neglecting servo dynamics):

$$\frac{\phi}{\delta_{AS}} = \frac{A_\phi\left(s^2 + 2\zeta_\phi \omega_\phi s + \omega_\phi^2\right)}{\left(s^2 + 2\zeta_d \omega_d s + \omega_d^2\right)\left(s + \frac{1}{\tau_R}\right)\left(s + \frac{1}{\tau_S}\right)} \qquad \text{(A-7)}$$

$$= \frac{K_{\phi_{\delta_{AS}}}\left(\frac{s^2}{\omega_\phi^2} + \frac{2\zeta_\phi}{\omega_\phi} s + 1\right)}{\left(\frac{s^2}{\omega_d^2} + \frac{2\zeta_d}{\omega_d} s + 1\right)\left(\tau_R s + 1\right)\left(\tau_S s + 1\right)} \qquad \text{(A-8)}$$

where

$$K_{\phi_{\delta_{AS}}} = A_{\phi} \frac{\omega_{\phi}^{2}}{\omega_{d}^{2}} \tau_{R} \tau_{S} \tag{A-9}$$

If the spiral mode root, $1/\tau_S$, approaches zero, then the roll transfer function becomes:

$$\frac{\phi}{\delta_{AS}} = \frac{K_{\dot{\phi}_{\delta_{AS}}} \left(\frac{s^{2}}{\omega_{\phi}^{2}} + \frac{2\zeta_{\phi}}{\omega_{\phi}} s + 1 \right)}{s \left(\frac{s^{2}}{\omega_{d}^{2}} + \frac{2\zeta_{d}}{\omega_{d}} s + 1 \right) \left(\tau_{R} s + 1 \right)} \tag{A-10}$$

where

$$K_{\dot{\phi}_{\delta_{AS}}} = \lim_{1/\tau_{s} \to 0} \left[\frac{K_{\phi_{\delta_{AS}}}}{\tau_{S}} \right] \tag{A-11}$$

$$= A_{\phi} \frac{\omega_{\phi}^{2}}{\omega_{d}^{2}} \tau_{R} \tag{A-12}$$