Report No. FAA-RD-71-26

AN IN-FLIGHT INVESTIGATION OF LATERAL-DIRECTIONAL DYNAMICS AND ROLL-CONTROL POWER REQUIREMENTS FOR THE LANDING APPROACH

G. Warren Hall and Edward M. Boothe

Cornell Aeronautical Laboratory, Inc.

Buffalo, N.Y. 14221

OCTOBER 1971

FINAL REPORT

178

Prepared for

DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

Systems Research & Development Service

Washington D.C., 20590

This report has been prepared by Cornell Aeronautical Laboratory, Inc., for the Systems Research and Development Service, Federal Aviation Administration, under AF Contract No. F33615-69-C-1664. The contents of this report reflect the views of the contractor, who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of the FAA. This report does not constitute a standard, specification, or regulation.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-RD-71-26		

4. Title and Subtitle
An In-Flight Investigation of Lateral-Directional Dynamics and Roll-Control Power Requirements for the Landing Approach

5. Report Date
October 1970

6. Performing Organization Code

7. Author(s)
G. Warren Hall and Edward M. Boothe

8. Performing Organization Report No.
CAL, BM-2821-F-5-A

9. Performing Organization Name and Address
Cornell Aeronautical Laboratory, Inc.
Buffalo, N. Y. 14221

10. Work Unit No.

11. Contract or Grant No.
Agreement FA-69-WA-163

12. Sponsoring Agency Name and Address
Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington, D. C. 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
This report was prepared for the United States Air Force in partial fulfillment of Contract F33615-69-C-1664 and for the Federal Aviation Administration.

16. Abstract
Lateral-directional handling qualities and roll control power requirements for the executive jet class of airplanes in the landing approach flight phase were investigated in the USAF/CAL variable stability T-33 airplane. Particular emphasis was placed on the effects of crosswinds and turbulence. Simulated IFR ILS approaches and VFR offset and crosswind approaches were made. Specifically, two Dutch roll frequencies, three Dutch roll damping ratios, three roll-to-sideslip ratios and three roll mode time constants were investigated. It was found that for the range of parameters investigated, lateral-directional dynamics do not establish a limiting crosswind value; however, they do determine the ease or difficulty with which a crosswind approach can be accomplished. Roll control power requirements were determined from actual control usage data obtained throughout the evaluation program and were found to be a function of the lateral-directional dynamics. Minimum acceptable levels of roll control power were determined by re-evaluating a number of configuartions with limited roll control power. It was found that available roll control power can establish a limiting crosswind component.

17. Key Words

18. Distribution Statement
Availability is unlimited. Document may be released to the National Technical Information Service, Springfield, Virginia 22151, for sale to the public.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	167	

Form DOT F 1700.7 (8-69)

ACKNOWLEDGMENT

This report was prepared for the United States Air Force by Cornell Aeronautical Laboratory, Inc. (CAL), Buffalo, New York in partial fulfillment of Contract F33615-69-C-1664.

The program was performed by the Flight Research Department of CAL under the sponsorship of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, and the Aircraft Development Service,* Federal Aviation Administration, as part of Project No. 8219, Task No. 821905. Mr. David K. Bowser was project engineer for the USAF and Mr. Jerome Teplitz was program manager for the FAA.

This report is being published as CAL Report No. BM-2821-F-5A. The work in this document represents the efforts of a number of individuals whom the authors wish to acknowledge: Lt. Colonel Wayne T. Frye, USAF and Mr. Rogers E. Smith, the evaluation pilots; Mr. Ronald W. Huber, who was responsible for the modifications, calibration, and maintenance of the variable stability system, and Mr. Floreal R. Prieto, the technical editor. The CAL T-33 project manager was Mr. Fred Newell.

* The Aircraft Development Service is now a part of the Systems Research and Development Service.

TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

TABLE OF CONTENTS CONTINUED

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS CONTINUED

LIST OF ILLUSTRATIONS CONTINUED

LIST OF ILLUSTRATIONS CONTINUED

LIST OF TABLES

Section 1
INTRODUCTION

The landing approach phase of flight is perhaps the most critical phase for the executive jet class of airplanes. The routine demands placed on the pilot-airplane combination are greater and the margin for error less in the landing approach than in the up-and-away mission phase. Pilot workload is especially high when performing an instrument approach in turbulence with the possibility of "breaking out" at a low altitude with a lateral offset from the runway and having to make the landing in a crosswind. Good handling qualities are desirable in order not to unnecessarily add to the pilot's workload during this critical flight phase.

The desire for low landing approach speeds means flight at high angles of attack and/or flight with various combinations of high lift devices. The reduction in dynamic pressure alone influences the stability characteristics of the basic airplane and reduces the effectiveness of the controls. The result is usually a deterioration in handling qualities. Reference 1, which addresses the problem of low landing speeds for STOL aircraft, reported, "of the various handling qualities, the lateral-directional characteristics were the most troublesome and, therefore, were considered to require immediate attention particularly for instrument flight operation." At the other e of the spectrum, Reference 2 investigated the low-speed characteristics of a powered-lift jet transport during the landing approach and reported, "although there were no large detrimental effects on flight characteristics resulting from the use of powered lift, there were areas in which the handling qualities did noticeably deteriorate." It was also noted that the deterioration in handling qualities was not a function of the particular test airplane, but rather was related to Dutch roll characteristics and lateral-directional cross coupling inherent at the lower approach speeds.

The objectives of this flight test investigation were two fold: one, to determine the effect of variations in the lateral-directional dynamics on the landing approach handling qualities when landing in crosswinds and atmospheric turbulence and two, the determination of roll control power requirements and the effect of limited roll control power on the handling qualities of executive jet airplanes.

Specifically, the effects of Dutch roll frequency and damping ratio, roll-to-sideslip ratio, roll mode time constant, and aileron yaw characteristics were examined. The flight investigation was accomplished by performing simulated IFR ILS approaches and VFR lateral offset and actual crosswind approaches in the USAF/CAL variable stability T-33 airplane. Throughout the entire investigation, pilot control usage data were recorded which allowed the determination of roll control power requirements necessary to perform the landing approach task in varying crosswind and turbulence environment conditions. Additionally, a number of configurations were re-evaluated with varying degrees of limited roll control power to determine the effect on the handling qualities. The longitudinal characteristics were held constant so that the evaluations of the lateral-directional dynamics would not be influenced by varying longitudinal handling qualities.

Section 2
TECHNICAL DISCUSSION

2.1 THE PROBLEM

As previously discussed, the landing approach is perhaps the most critical phase of flight for the executive jet class of airplanes. This phase of flight is an exacting task requiring accurate positioning of the airplane relative to the runway with a limited margin for error. The landing approach is often complicated by IFR conditions requiring precise instrument flying, a transition to visual flight with a possible lateral offset from the runway, and landing in a limited period of time. Additional complications are turbulence and crosswinds. To perform such a demanding task, the pilot should be provided with the best possible handling qualities.

The requirement for low landing speeds often dictates flight at high angles of attack and/or with various high lift devices. The low speed tends to reduce the aerodynamic damping as well as the effectiveness of the control surfaces. The result is often a deterioration in lateral-directional as well as longitudinal handling qualities at a time when the task and environment are quite demanding. Therefore, the pilot should be provided with very good handling qualities. This experiment was directed toward determining acceptable lateral-directional handling qualities and roll control power requirements for the landing approach.

2.1.1 Crosswind Landings

A very important aspect of lateral-directional handling qualities in the landing approach is the ability to handle the crosswind landing problem. Two fundamentally different techniques are usually used in crosswind landings: the wing-down (crossed-controls) approach, and the drift (crabbed) approach. In the wing-down method, the airplane is headed down the runway and thus experiences a steady-state sideslip which is proportional to the strength of the crosswind and inversely proportional to the approach speed. The resulting aerodynamic side force is countered by banking the airplane into the wind and trimming out the sideslip-induced yawing and rolling moments by appropriate control movements. In the crabbed approach, the airplane is flown with zero sideslip but with a heading correction into the wind to keep the airplane from drifting with respect to the ground. Because of the lack of sideslip, the rudder and ailerons are essentially held neutral and the wings are level. Just before touchdown the airplane heading is aligned with the runway. Crossed controls are required in either type of approach. In the wing-down method, the rudder and ailerons are crossed during the entire approach; for the crabbed approach, during the decrab maneuver only. Reference 3 points out, however, that in practice the two techniques are usually combined.

2.1.2 Roll Control Power

In the landing approach the provision of adequate roll control power is necessary to cope with a combination of normal landing approach maneuvers while the pilot is simultaneously dealing with the problems of crosswinds and turbulence or gust upsets. A lateral offset may further make stringent demands on the roll control power available. The minimum acceptable approach speed can, and has been in some cases, dictated by the provision for adequate lateral control power.

In the landing approach configuration at the slow speed associated with the landing approach, the aerodynamic forces, including aileron effectiveness, are reduced from those acting at high speed cruise conditions. The use of small airports by high-speed executive jets requires low landing approach speeds. But approach speed cannot be reduced if adequate roll control power is not maintained at the low speeds. In a strong crosswind, both the wing-down and "decrab" approach make heavy demands on roll control; i.e., balancing the roll due to the sideslip and rudder with aileron control while maintaining runway alignment, or maintaining wings level with aileron while using the rudder to decrab. As the landing approach speed is reduced, the sideslip required to maintain runway alignment for a similar crosswind component is increased or the crab angle relative to the runway is increased. Hence, with either crosswind approach method, decreasing final approach airspeed increases the demands on lateral control power. Without adequate roll control power it would be impossible to maintain the necessary sideslip or to hold the wings level during the decrab maneuver. This would either restrict, possibly severely, the crosswind capability of the airplane or induce accidents since it would not be possible to precisely position the airplane relative to the runway.

Roll control power requirements are also related to the differences in gust response of various airplanes. If the airplane is susceptible to a large rolling response to side gusts, as with a large dihedral effect, then roll control power requirements may be greater than for airplanes with low dihedral. The gust response is of prime importance during the approach and landing. Lateral gust upsets from which a recovery cannot be made fast enough can lead to aborted landing attempts or to wing tips or wing tip fuel tanks actually striking the ground, possibly with catastrophic results.

2.2 PURPOSE

The primary purpose of this program was to investigate problems associated with the lateral-directional stability and control characteristics of the executive jet class of airplanes during the landing approach in turbulence and crosswinds. This required:

a. Evaluating those lateral-directional parameters which may affect, or possibly limit, the capabilities of the pilot-airplane system in the performance of the landing approach flight phase in a modern high-performance jet airplane with particular emphasis on the crosswind landing problem.

b. Investigating the aileron control power requirements for the class of airplanes mentioned above and the effect on the landing qualities of limited roll control power.

2.3 SCOPE OF INVESTIGATION

To completely study the effects of lateral-directional dynamics on the handling qualities in the landing approach is not feasible in one investigation. Thus, it was necessary to select those dynamics which are considered most important. The parameters discussed below were chosen after analysis of available data on executive jet and medium weight military Class II airplanes in the landing approach. These data and past flight research indicate that these parameters, which cover the range of lateral-directional dynamics for this class of airplanes, are the most significant to low-speed lateral control in turbulence and crosswinds.

2.3.1 Roll Mode

The roll mode is a primary factor in the way the airplane rolls in response to aileron control inputs. It is usually a short term response and strongly influences the pilot's control of bank angle. Past research shows that the roll mode affects not only the precision with which the pilot can control bank angle but also the technique used. Short roll mode time constants, which are usually associated with high aspect-ratio, straight-wing airplanes, result in ailerons that are roll rate ordering. With this characteristic, roll rate is essentially proportional to aileron deflection. Long roll mode time constants are associated with low aspect ratio wings and the resulting low roll damping, or airplanes with high rolling inertias such as those caused by wing-mounted external fuel tanks. This characteristic results essentially in roll acceleration being proportional to aileron deflection, requiring the pilot to use pulse-like inputs to the ailerons to control roll rate. Many executive jet class airplanes have swept wings and/or externally mounted wing or tip fuel tanks and thus have low roll damping and/or high rolling inertias resulting in long roll mode time constants. The roll mode time constant is a fundamental lateral-directional parameter and was considered a primary variable in this investigation. Three values were evaluated: a $\tau_R \approx 0.4$ second, which is representative of high roll damping and/or low rolling inertias, a moderate $\tau_R \approx 1.0$ second and a long $\tau_R \approx 2.0$ second, which is representative of airplanes with low damping and/or high rolling inertias.

2.3.2 Spiral Mode

The spiral mode is usually a long term response with little effect during a continuous closed-loop tracking maneuver. Since the landing approach falls into this category, the spiral mode may be less important than many of the other lateral-directional dynamics. Although the effects of the spiral mode are still not fully known for VFR or IFR landing approaches, the spiral root in this investigation was held essentially at the origin and thus the effects of varying spiral characteristics were not investigated.

2.3.3 Dutch Roll Mode

The Dutch roll characteristics strongly affect the control techniques that the pilot will employ. In the past, the Dutch roll mode has been considered a nuisance parameter, but increasing understanding of its importance to lateral-directional handling qualities calls for systematic consideration of its effects.

Dutch roll damping can significantly affect bank angle controllability in the presence of external disturbances. Reference 2 points out that increasing the Dutch roll damping significantly improved the handling qualities of the low dihedral effect configurations. Since Dutch roll damping is usually augmented when the damping itself becomes a problem, three values of Dutch roll damping ratio were investigated: $\zeta_d \approx 0.03$, $\zeta_d \approx 0.1$, and $\zeta_d \approx 0.3$. These values represent very light damping, normal damping, and augmented Dutch roll damping ratios, respectively.

Dutch roll frequency affects the pilot's ability to control heading. Excursions in sideslip and heading are in part determined by the level of directional stability, N'_β, and hence are related to ω_d. Excursions in sideslip can be a particular problem when sideslip and bank angle are being controlled in a coupled manner to hold a crosswind correction. As indicated in Reference 6, a low roll-to-sideslip ratio with high ω_d causes rapid snaking motions that are difficult to control with precision; with low ω_d, the large persistent yaw excursions require considerable pilot effort to control heading. Low Dutch roll frequency may complicate the pilot's ability to handle a crosswind because of the difficulty in quickly establishing the airplane's steady-state values. Consequently, two values of Dutch roll frequency were investigated: $\omega_d \approx 1.0$ rad/sec and $\omega_d \approx 2.0$ rad/sec. These values are representative of the extremes determined to exist for the executive jet class of airplanes in the landing approach.

2.3.4 Roll-to-Sideslip Ratio and Dihedral Effect

Because of the coupling required between the lateral and directional controls in the crosswind approach, the roll-to-sideslip ratio is also an important Dutch roll characteristic that has a strong effect on the airplane's handling qualities in a crosswind maneuver. It also affects the piloting technique used for bank angle control. With a low roll-to-sideslip ratio, very little rolling motion occurs from a sideslip disturbance. If the sideslip response becomes a problem, the pilot will find an increased need for rudder inputs since the ailerons are quite ineffective in controlling sideslip. In other words, for a low roll-to-sideslip ratio, the Dutch roll mode shows up mostly in sideslip and will be controlled primarily with the rudder. As the roll-to-sideslip ratio is increased, the Dutch roll oscillation will show up more and more predominantly in the roll response, in which case the pilot will primarily use the ailerons to control the Dutch roll.

Studies performed at Princeton, References 5 and 6, indicate that L'_β rather than $|\phi/\beta|_d$ may be a more important handling quality parameter. Roll-to-sideslip ratio and L'_β, as shown in Appendix I, are related as follows:

$$\left.\frac{\phi}{\beta}\right|_{S = \text{DUTCH ROLL ROOT}} = \frac{(L_r')S - (L_\beta' + Y_\beta L_r')}{S^2 - L_p' S - \frac{g}{V} L_r'}$$

which, upon evaluation, can be written

$$\left|\frac{\phi}{\beta}\right|_d \approx \left|\frac{L_\beta'}{N_\beta'}\right| \left(\frac{1 + \frac{N_\beta' L_r'^2}{L_\beta'^2}}{1 + \frac{L_p'^2}{N_\beta'}} \right)^{1/2}$$

In a crosswind approach, especially when sideslip is not zero, dihedral effect is indeed important in both the wing-down approach and in the decrabbing maneuver because of the rolling response to rudder inputs.

Both L_β' and the magnitude of the roll-to-sideslip ratio strongly affect the susceptibility of a particular airplane to turbulence in the lateral-directional modes. As shown in Appendix I, when the term $N_p' - \frac{g}{V}$ is not equal to zero, a direct variation in L_β' can cause significant changes in the Dutch roll damping ratio and roll mode time constant as well as the magnitude of the roll-to-sideslip ratio. Thus, if changes are made only in L_β', it is difficult to assess whether the effect on the handling qualities is due solely to the change in dihedral effect or to the changes in other important lateral-directional parameters. It is also true that holding the roll-to-sideslip ratio constant and constraining the Dutch roll damping ratio and roll mode time constant at preselected values results in attendant changes in L_β'. For the latter case, recognized handling qualities parameters are at least held fixed. Three values of roll-to-sideslip ratio were evaluated: $|\phi/\beta| \approx 0.25$, 1.5 and 3.0. These values cover the spectrum of roll-to-sideslip ratios of the executive jet class of airplanes for which data were available.

2.3.5 Yaw Coupling

The yaw coupling effects of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ and N'_p are important factors in the pilot's control of bank angle. These effects are manifested to the analyst by the locations of the numerator zeros relative to the Dutch roll poles in the bank angle to aileron input transfer function and to the pilot by Dutch roll excitation to aileron control inputs. Since the class of airplanes to be investigated incorporates both ailerons and spoilers or combinations of both, it was important to determine the effects of proverse as well as adverse yaw due to roll control inputs. A minimum of five values of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ was evaluated for each group of configurations representing both adverse and proverse yaw due to aileron and/or spoilers. A representative value of N'_p, based on a literature survey, was determined to be $N'_p \approx -0.08$. This value was held essentially constant throughout the program.

2.3.6 Control Sensitivities

Aileron and rudder sensitivities, $L'_{\delta_{AW}}$ and $N'_{\delta_{RP}}$ respectively, are important parameters because they largely determine the amounts of rudder and aileron control inputs that must be used. Reference 7 shows these control motions to be functions of the lateral-directional dynamics present in the system. To minimize the effect of control motion gradients on the evaluation of the given airplane dynamics, and to provide additional data on the selection of these parameters, the evaluation pilot was required to select both the aileron and rudder sensitivities for each evaluation configuration.

2.3.7 Turbulence

In the landing approach, consideration must be given to the importance of atmospheric turbulence. Characteristics acceptable in smooth air may be quite undesirable in turbulence. A turbulence field can be divided into side gust, vertical gust, and fore and aft gust components. Each of these components produces aerodynamic loads on the airplane resulting in forces and moments that excite the airplane dynamics. The airplane response to the gust component is related to the corresponding stability derivatives. The transfer functions of the airplane's lateral-directional responses to gust inputs are presented in Appendix I.

Two general approaches to the turbulence problem were considered. The first would be to always fly on calm days when the air is smooth and to simulate the turbulence and wind disturbances (see Refs. 5 and 7). This approach severely constrains flight operations. In addition, the lack of independent force-producing surfaces makes it impossible to simulate crosswind effects. The second approach would be to fly routinely from day to day, documenting the environment during each evaluation (see Ref. 8). This approach would have the disadvantage of introducing an uncontrolled variable into the experiment. To account for the important effects of the uncontrolled environment, it would be necessary to document the environment during each evaluation and to increase the number of evaluations or the sample size of the experiment. For this investigation these two approaches were combined. When the natural turbulence level was considered to be less than "moderate," random disturbance inputs to the control surfaces were used. When the natural turbulence level was moderate or greater, these inputs were not used. The random disturbance generator is discussed in Section 3.5.

2.3.8 Roll Control Power Requirements

Roll control power data for the executive jet class of airplanes is somewhat limited. Therefore, it was important to study roll control power requirements and the effect limited roll control power may have on the landing approach handling qualities. To this end, the pilots' roll control usage was measured during each evaluation to determine the roll control power used to perform the landing approach under varying turbulence and crosswind conditions. Further, it was important to determine the minimum acceptable roll control power required. This was accomplished by methodically reducing the roll control power for different values of the roll mode time constant and the roll-to-sideslip ratio at constant values of Dutch roll frequency and damping ratio.

Section 3

DESCRIPTION OF EXPERIMENT

3.1 TEST PROGRAM

Existing relevant background data, References 1 through 66, were comprehensively reviewed to evaluate those parameters which predominantly affect airplane lateral-directional handling qualities during the landing approach flight phase and how these parameters affect the capabilities of the pilot-airplane combination to satisfactorily perform the task. A further purpose was to determine representative values of lateral-directional parameters of modern executive jets, and related medium weight and low to medium maneuverability airplanes in the landing approach. Numerical data were available on 13 airplanes, ranging from detailed stability derivatives to graphical airplane responses to control inputs.

On the basis of the data review and previous related flight research experience, a flight test program was developed. Table I describes the matrix of basic evaluation groups.

Table I EVALUATION GROUPS

ω_d	2.0 rad/sec			1.0 rad/sec				
τ_R	0.4 sec			0.4 sec			1.0 sec	2.0 sec
ζ_d	0.03	0.10	0.30	0.03	0.10	0.30	0.10	0.10
$\left\|\frac{\phi}{\beta}\right\|_d = 0.25$					11_L	12	13	
$\left\|\frac{\phi}{\beta}\right\|_d = 1.5$	1	2	3	5	6_L	7	14_L	16_L
$\left\|\frac{\phi}{\beta}\right\|_d = 3.0$		4		8	9_L	10	15	

L - REEVALUATED WITH LIMITED AILERON CONTROL POWER

The values shown in Table I adequately cover the range of lateral-directional characteristics for the class of airplanes to be investigated and for which numerical data were available.

Numerals shown in the matrix of Table I are the identification numbers of the basic evaluation groups with their respective positions in the matrix identifying their modal parameters. Each basic group represents a minimum of five evaluation configurations consisting of different pole zero combinations in the bank angle-to-aileron input transfer function. The different locations of the zeros were obtained by varying the aileron yaw parameter, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$, in the adverse and proverse senses. The evaluation configurations were identified by the basic group identification numeral followed by A3, A2, A1, N0, P1, P2, or P3, according to the value of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$: N0 corresponding to $N'_{\delta_{AW}}/L'_{\delta_{AW}} = 0$; P3 to $N'_{\delta_{AW}}/L'_{\delta_{AW}} = +0.15$, the most proverse aileron yaw case; A3 to $N'_{\delta_{AW}}/L'_{\delta_{AW}} = -0.15$, the most adverse aileron yaw case; and so on, through the range of zeros evaluated. A number of configurations were re-evaluated with varying degrees of limited aileron control power. The groups from which these configurations were chosen are marked with an L in Table I.

3.2 EQUIPMENT

Evaluations for this program were performed in the USAF/CAL three-axis, variable-stability T-33 airplane, Figure 1, modified and operated by CAL for the AFFDL, Air Force Systems Command. Since most executive jet class airplanes are wheel controlled, a wheel controller was installed in the front cockpit (Figure 2) for the evaluations. The variable stability equipment is described in Reference 67.

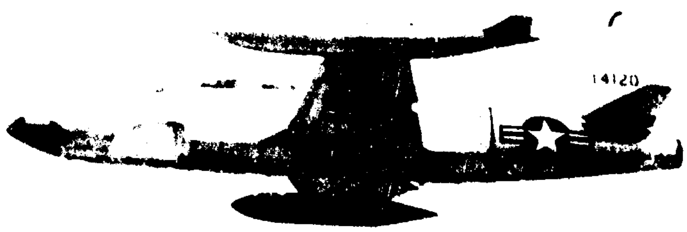
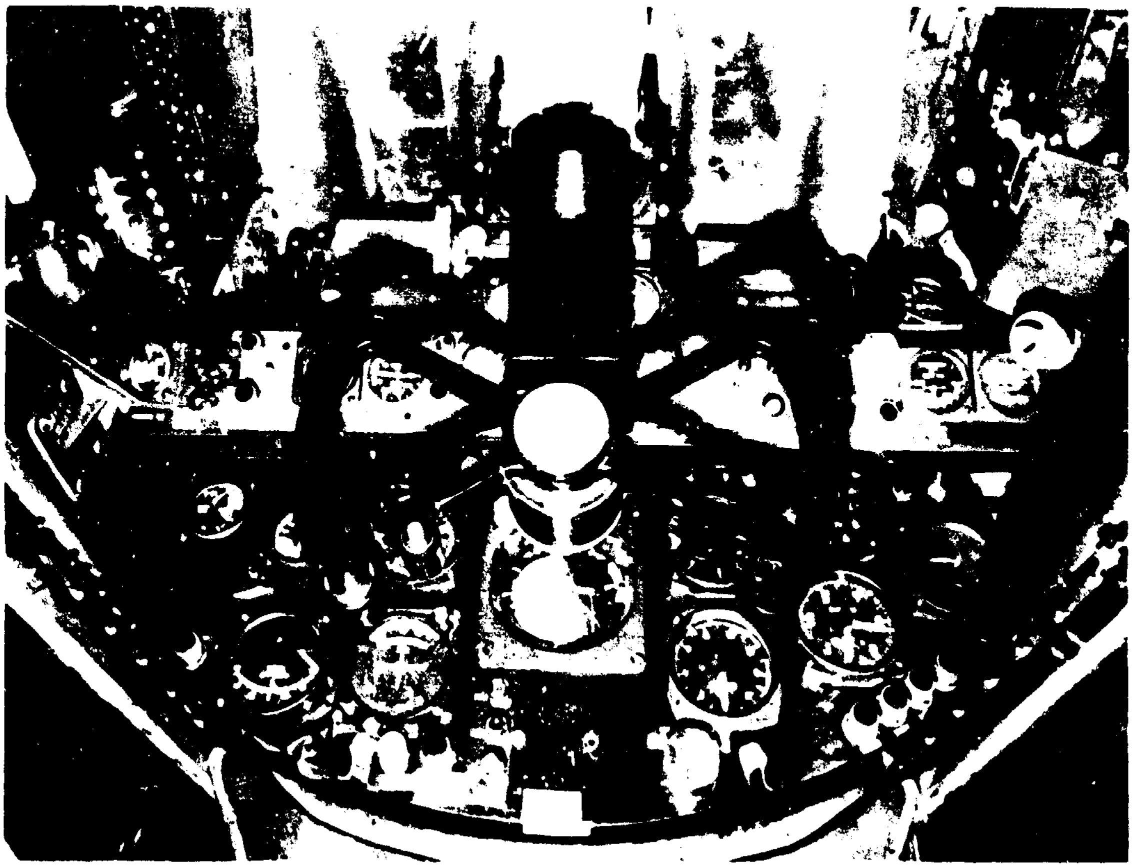


Figure 1 USAF/CAL VARIABLE STABILITY T-33 AIRPLANE



NOT REPRODUCIBLE

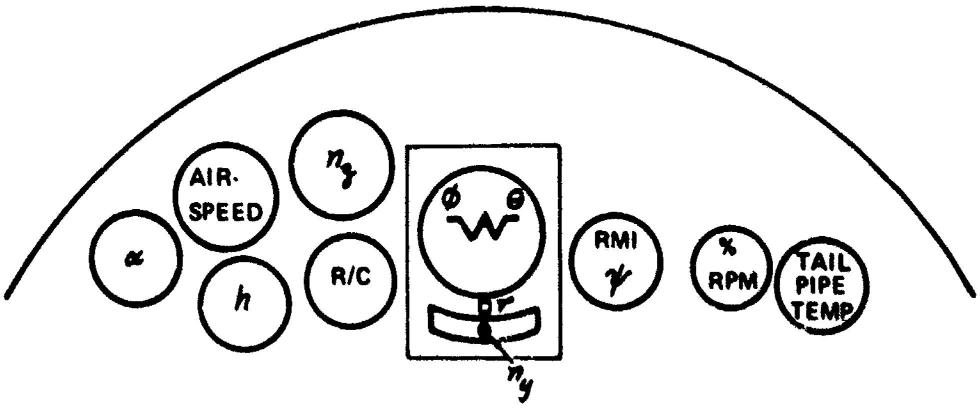


Figure 2 EVALUATION PILOT'S COCKPIT IN VARIABLE STABILITY T-33

In this airplane, the system operator, who is also the safety pilot in the rear cockpit, may modify the handling qualities about all three axes by changing the settings of response feedback gain controls. The evaluation pilot could not feel the control surface motions resulting from the variable stability system signals.

Control feel to the wheel and rudder pedals was provided by electrically controlled hydraulic feel servos which provide opposing forces proportional to the control wheel or rudder pedal deflections; in effect, a simple linear spring feel system. The longitudinal and lateral control system had zero breakout force and no hysteresis. The feel system dynamics and spring rates were held constant at the values shown below:

Feel System

Aileron	Rudder	Elevator
ω_{FS} = 25 rad/sec	ω_{FS} = 25 rad/sec	ω_{FS} = 25 rad/sec
ζ_{FS} = 0.70	ζ_{FS} = 0.70	ζ_{FS} = 0.70
F_{AW}/δ_{AW} = 1.0 lb/deg	F_{RP}/δ_{RP} = 141.0 lb/in	F_{EW}/δ_{EW} = 25 lb/in.

Since the purpose of the experiment was to study the lateral-directional handling qualities in the landing approach, the longitudinal characteristics were held constant throughout the program at sufficiently good values so as not to cause any degradation of pilot ratings. The longitudinal dynamics are listed below.

Longitudinal Characteristics

ω_{sp} = 1.6 rad/sec	n_z/α = 6.94 g/rad
ζ_{sp} = 0.5	$1/\tau_{\theta_2}$ = 0.91

To investigate the effects of limited aileron control power, the maximum rolling moment that the evaluation pilot could command was reduced by limiting the amount of aileron deflection he could command. Maximum wheel displacement was held constant at $\pm$ 45 degrees. Aileron deflection was limited by limiting the maximum electrical signal from the aileron wheel to the aileron surface servo actuator as shown in Figure 3.

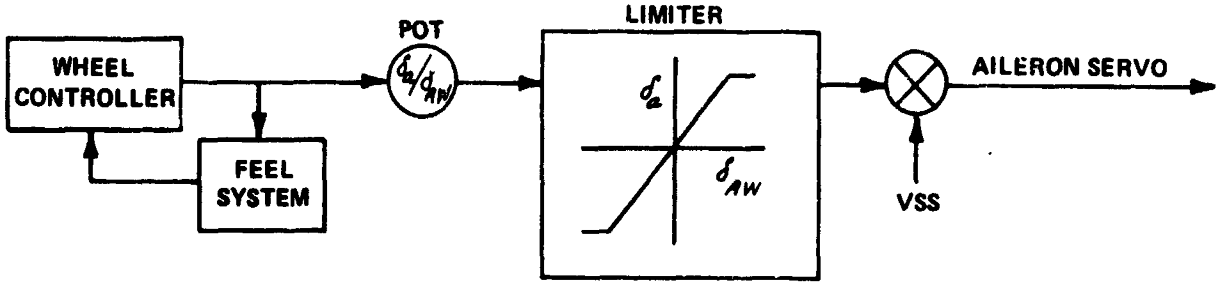


Figure 3 AILERON LIMITER SCHEMATIC

The response to turbulence and the turbulent environment experienced are of special significance. The T-33 does not have the capability to vary the lift response to gust-induced angle of attack changes; thus, the heaving motion normally associated with vertical gusts can not be simulated in still air. In natural turbulence the heaving motion will be that which is normally associated with the basic T-33 airplane. On the other hand, the lateral-directional responses to gusts are more realistically simulated in still air because they are primarily felt as angular accelerations of the airplane. Although it is not a true simulation of turbulence, a random noise source was used to provide an external disturbance to the airplane during the evaluations when the natural turbulence environment was not considered to be of moderate intensity. The random disturbances were obtained by driving the T-33 control surface actuators by a random noise signal. The signal was generated by a diode noise source passed through the bandpass filter shown in Appendix II. The amplitudes of the disturbance signals to the ailerons and rudder were determined to represent turbulence of moderate intensity for configuration 6NO and varied with roll-to-sideslip ratio and Dutch roll frequency, respectively, from the values selected as being representative.

3.3 EVALUATIONS

3.3.1 Mission Definition

The mission evaluated was strictly the terminal task of IFR and VFR landing approaches, including an ILS approach under the hood, a VFR lateral offset maneuver, and a crosswind approach. Special emphasis was placed on crosswind and turbulence considerations. All aspects of the mission were discussed at length with the evaluation pilots to ensure that both pilots were evaluating the simulated airplane for the same mission requirements.

3.3.2 Evaluation Procedure

Three evaluations were performed on each flight. Each evaluation included actual landing approaches under both simulated IFR and VFR conditions. The T-33 airplane was configured for the approach with the landing gear down, flaps at 30 degrees, and speed brakes extended. The final approach speed of 145 knots was dictated by the stall limits, and resulting safety of flight considerations, of the basic T-33 with high quantities of fuel remaining.

A total of 131 evaluations were performed. This included 108 evaluations (84 different configurations and 24 repeats) with no limits on roll control power and 23 configurations with limited roll control power. Pilot A evaluated 63 configurations and Pilot B, 68 configurations.

3.3.3 Evaluation Tasks

The actual sequence of tasks during each evaluation was as follows:

1. Familiarization with the configuration.
   a. Select control sensitivities.
   b. Determine trimmability--ability to stabilize and trim.

c. Perform small maneuvers to determine ability to make precise changes in bank angle and heading.

2.* Radar vectored track to ILS final approach course.

3. Hooded ILS approach from outside the outer marker to published instrument minimums for the facility being used.

4. Visual final approach to flare.

5. Visual waveoff followed by a visual approach to the instrument runway for a 200-foot lateral offset approach to the flare.

6.* Visual waveoff followed by a visual circling approach to the most crosswind runway available. This approach was also carried to flare and included a level post-flare flight path to assess lineup and/or decrab capability.

7. Waveoff and climb for additional turning flight evaluation if required. Pilot comment and rating data were recorded at this time.

3.3.4 Pilots

Two evaluation pilots participated in the program. A summary of their experience is presented below:

Pilot A: USAF pilot and graduate of the USAF Aerospace Research Pilot School with extensive experience in flight test. He served as a staff member and instructor at the USAF Aerospace Research Pilot School and had a total of 3800 hours in jet trainers and fighters.

* If the natural turbulence level was sufficiently low to warrant the use of the random noise disturbance inputs, these inputs were used during the radar vector to the ILS final approach course, but not during the ILS or offset maneuver approaches. They were, however, again used on the crosswind approach.

Pilot B: CAL research pilot with experience as an evaluation pilot in handling qualities investigations employing variable stability aircraft and ground simulators. His flight experience of 2700 hours is mostly in jet trainers and fighters with 100 hours in current executive turbo-prop airplanes.

3.3.5 Pilot Comment and Rating Data

Pilot comments and ratings were the primary data source. The pilot rating can only be properly interpreted and objections properly assessed if good comments are obtained. Pilot comments were encouraged at any time during the evaluation that the pilot felt appropriate. For data consistency, it was required that the pilot comment on the items listed in Table II either during or at the completion of each evaluation.

Table II

PILOT COMMENT CARD

A. MAKE COMMENTS AT ANY TIME DESIRED.

B. COMMENT ON LATERAL-DIRECTIONAL HANDLING QUALITIES IN GENERAL.

C. COMMENT ON THE FOLLOWING SPECIFIC ITEMS:
   1. ABILITY TO TRIM.
      a. LATERAL.
      b. LONGITUDINAL.
   2. FEEL CHARACTERISTICS.
      a. FORCES.
      b. DISPLACEMENTS.
   3. COMMENT ON CONTROL SENSITIVITY.
      a. EXPLAIN.
      b. COMPROMISES.
   4. AIRPLANE RESPONSE TO PILOT INPUTS.
      a. ROLL CONTROL.
      b. YAW DUE TO ROLL RATE.
      c. COORDINATION.
      d. OSCILLATORY CHARACTERISTICS.
   5. HOW SUITABLE ARE THESE CHARACTERISTICS FOR THE LANDING APPROACH?
   6. DIFFERENCE BETWEEN IFR AND VFR FLIGHT.
   7. EFFECTS OF TURBULENCE.
      a. COMMENT ON TURBULENCE PRESENT DURING EVALUATION.
   8. ILS PERFORMANCE.
   9. HOW DOES A CROSSWIND AFFECT THE HANDLING QUALITIES?

D. SUMMARY COMMENTS.
   1. GOOD FEATURES.
   2. OBJECTIONABLE FEATURES.
   3. SPECIAL PILOTING TECHNIQUES.
   4. PILOT RATING BASED ON MISSION.
   5. PRIMARY REASON FOR RATING.
   6. TURBULENCE RATING.

An overall pilot rating was assigned by the pilot to each configuration in accordance with the Cooper-Harper rating scale established and described in Reference 68 and shown in Figure 4. The pilot rating assigned by the evaluation pilot to each configuration included the effects that natural turbulence and/or random noise disturbances may have had on the handling qualities.

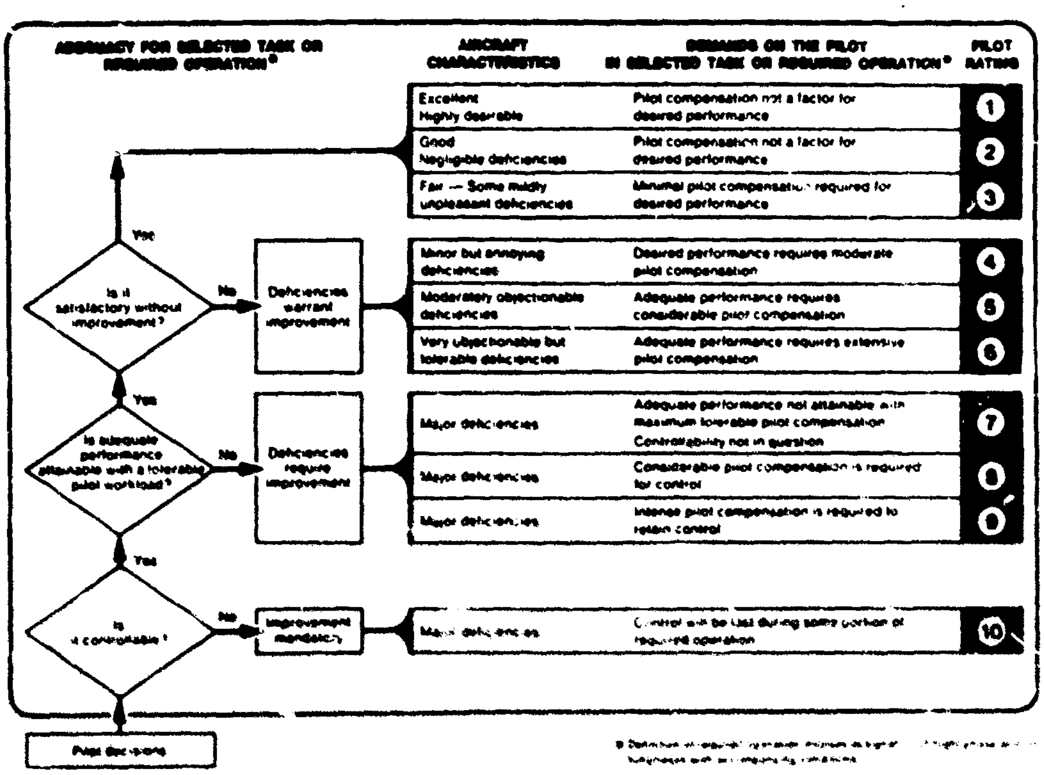


Figure 4 COOPER-HARPER HANDLING QUALITIES RATING SCALE

In addition, an alphabetical turbulence rating was assigned which was solely an assessment of the combined effects on the handling qualities of natural turbulence and/or random noise disturbances. These ratings were established in accordance with the turbulence effect rating scale, Table III.

Table III

TURBULENCE EFFECT RATING SCALE

INCREASE OF PILOT EFFORT WITH TURBULENCE	DETERIORATION OF TASK PERFORMANCE WITH TURBULENCE	RATING
NO SIGNIFICANT INCREASE	NO SIGNIFICANT DETERIORATION	A
MORE EFFORT REQUIRED	NO SIGNIFICANT DETERIORATION	B
	MINOR	C
	MODERATE	D
BEST EFFORTS REQUIRED	MODERATE	E
	MAJOR (BUT EVALUATION TASKS CAN STILL BE ACCOMPLISHED)	F
	LARGE (SOME TASKS CANNOT BE PERFORMED)	G
UNABLE TO PERFORM TASKS		H

3.3.6 Supporting Data Acquisition

The intensity of natural turbulence present during the evaluations was assessed by the safety pilot, and reported using the standard descriptive terminology provided in the Department of Transportation, Federal Aviation Administration, "Airman's Information Manual," and Department of Defense Flight Information Publications. The turbulence reporting criteria table is shown in Appendix III.

The crosswind components were determined from wind velocities provided by air traffic control personnel during each landing approach. Oscillograph recordings and digital tape recordings were made during the ILS, lateral offset, and crosswind approaches. Variables recorded are listed in Appendix III.

Section 4
DISCUSSION OF RESULTS

4.1 EVALUATION GROUPS

The primary objective in defining a configuration matrix was to cover adequately the range of lateral-directional characteristics for the executive jet and related medium weight and low to medium maneuverability airplanes (military Class II), in the landing approach. The evaluation matrix shown in Table I is repeated below for convenience.

EVALUATION GROUP

ω_d	2.0 rad/sec			1.0 rad/sec				
τ_R	0.4 sec			0.4 sec			1.0 sec	2.0 sec
ζ_d	0.03	0.10	0.30	0.03	0.10	0.30	0.10	0.10
$\left\|\frac{\phi}{\beta}\right\|_d = 0.25$					11_L	12	13	
$\left\|\frac{\phi}{\beta}\right\|_d = 1.5$	1	2	3	5	6_L	7	14_L	16_L
$\left\|\frac{\phi}{\beta}\right\|_d = 3.0$		4		8	9_L	10	15	

L - REEVALUATED WITH LIMITED AILERON CONTROL POWER

Sixteen basic groups of configurations were evaluated representing variations in Dutch roll frequency and damping ratio, the magnitude of the roll-to-sideslip ratio in the Dutch roll mode, and the roll mode time constant. Each group consisted of a minimum of five evaluation configurations. The configurations were defined by the location of the numerator zero in the bank angle-to-aileron input transfer function. Variation in the locations of the numerator terms was obtained by varying the aileron yaw parameter, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ in both the adverse and proverse senses, representing lateral control by ailerons and spoilers. N'_p was held essentially constant at a value representative of the executive jet class of airplanes. The spiral root was held essentially at the origin.

The complete equations defining the interactions of the stability derivatives in forming the modal characteristics are presented in Appendix I. Because of the natural turbulence levels encountered during most of the evaluations, it was not possible to obtain useable calibration records on each flight. Therefore, the modal parameters listed for each group of configurations are the average values obtained from calibration records taken on smooth days, before, during, and at the end of the evaluation flight program. The Dutch roll frequency and damping ratio were measured from the airplane response to a rudder doublet input. The roll and spiral mode time constants were obtained by analog matching of the airplane response to an aileron step input using the technique presented in Reference 69. The short period longitudinal characteristics were obtained by analog matching the airplane response to an elevator step input by the technique explained in Reference 70.

The natural turbulence level and crosswind components are listed for each configuration in Appendix IV. The reader is reminded that when the natural turbulence level was less than moderate, random noise disturbances were fed to the aileron, elevator and rudder to simulate external disturbances being applied to the airplane.

4.2 RESULTS OF CROSSWIND LANDINGS

The crosswind landing approach was considered a primary evaluation task. Since flights were performed on a day-to-day basis, the available wind provided the crosswind. The bar chart shown in Figure 5 indicates the number of configurations evaluated for 5-knot intervals of the crosswind component.

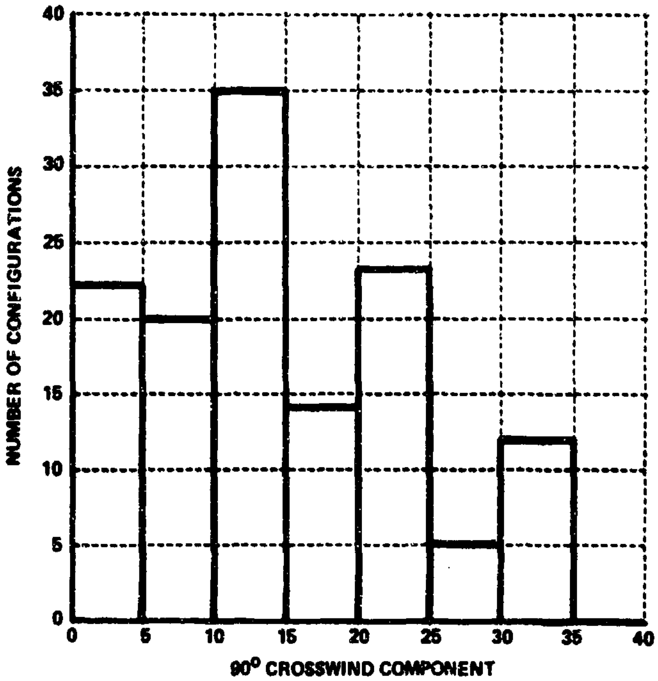


Figure 5 CONFIGURATIONS EVALUATED AT CROSSWIND COMPONENT INTERVALS

At least one configuration out of each group was evaluated with a 90° crosswind component exceeding fifteen knots, and at least one configuration in all but three groups was evaluated for a crosswind exceeding twenty knots. None of the approaches were flown to touchdown; however, all were flown to a level flare to assess the line-up and/or decrab capabilities of the configuration.

The various combinations of lateral-directional dynamics evaluated did not prevent completing the crosswind approach in any of the cases for which sufficient aileron and rudder control power were available. This does not mean, however, that the pilots found all combinations desirable or even acceptable, only that with sufficient control power they were able to perform the crosswind approach in the maximum crosswinds available.

Low Dutch roll damping ratio was not a serious problem in the crosswind approach at the high Dutch roll frequency, but became a major problem at the low frequency. The low static directional stability resulted in a slow directional response, making it difficult to be precise with heading control in either the wing-down or decrab maneuver. The continuous nose oscillations resulting from the low damping ratio required continuous rudder control during the final approach. There was a strong tendency to overcontrol directionally during the wing-down approaches and a tendency to set up a directional oscillation when attempting to execute the decrab maneuver.

One crosswind approach for the low Dutch roll frequency, low damping ratio and high $|\phi/\beta|_d$ configuration, 5A1, was described as "truly staggering." The aileron forces were described as large and uncomfortable even with two hands. Directional control required occasional rudder reversals, resulting in continuous manipulation of the aileron control. Because of the excessive lateral forces required for a wing-down approach, it was concluded that a combination of wing-down and crabbed approach was best. Even then, the workload required to perform a crosswind approach in even a modest crosswind of 10 to 15 knots was considered high.

The most significant effect on crosswind performance can be attributed to the $|\phi/\beta|_d$. At the low $|\phi/\beta|_d$ evaluated ($|\phi/\beta|_d \approx 0.25$), the ability to handle the crosswind, even under extreme conditions (26 gusting to 33 knots), was considered good with either technique. The low $|\phi/\beta|_d$ was not, however, evaluated for the low Dutch roll damping or the high Dutch roll frequency. The wing-down method was preferred in the heavy crosswinds because of the reluctance to kick out the resulting large crab angles near the ground, although either method was satisfactory. There were occasional complaints about high rudder forces as the crosswind component became 20 knots or greater, but no complaints about the aileron forces. The story was completely different for the high $|\phi/\beta|_d$ configurations ($|\phi/\beta| \approx 3.0$) evaluated. The large roll response to rudder required large aileron forces in the wing-down approach. The decrab maneuver also required large aileron forces to counteract the large and rapid roll response to rudder. Heavy aileron forces were a common complaint for these configurations even when the pilot stated that he had selected the aileron as sensitive as he thought compatible for small maneuvers. The large roll response due to rudder created an uncomfortable transient for most decrab maneuvers in even modest crosswinds. The effects of the high $|\phi/\beta|_d$ at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) seemed less objectionable than at the low frequency; however, the maximum crosswind component evaluated was only 17 knots for the high frequency configurations. The higher directional stability tended to reduce the total bank angle excursions even though the initial roll response to a turbulence input was quite rapid. Pilot B pointed out that with the high $|\phi/\beta|_d$, it was possible to use up the available aileron control power with increasing rudder input. A discussion of roll control power requirements and how it relates to the crosswind landing problem can be found in Section 4.3.

There was little difference in the pilots' ability to handle the crosswind approaches for roll mode time constants of 0.4 seconds and 1.0 seconds. The effect of roll mode time constant did show up, however, for the configurations with $\tau_R \approx 2.0$ seconds. The tendency to overcontrol in roll was degrading when encountering gusty crosswinds near the ground.

It can be concluded that even though the lateral-directional dynamics per se, when flown with unlimited roll control power, did not establish a limiting crosswind value, they did in fact determine the difficulty or ease with which the pilot could counter crosswind effects. Low Dutch roll damping ratio combined with low Dutch roll frequency resulted in a tendency to overcontrol directionally during a wing-down approach and to set up a directional oscillation during the decrab maneuver. Low $|\phi/\beta|_d$ was desirable for the crosswind approach. High $|\phi/\beta|_d$ led to high aileron forces in the wing-down approach and a reluctance to kick off even modest crab angles near the ground because of the large, rapid roll response to rudder inputs. A long roll mode time constant also created crosswind control problems because of the inability to achieve precise roll control when encountering gusty crosswinds near the ground.

4.3 RESULTS OF ROLL CONTROL POWER INVESTIGATION

In this inflight investigation, the evaluations were performed under varying turbulence and crosswind conditions for a wide spectrum of lateral-directional dynamics. For this reason, the actual roll control usage should realistically determine the roll control power requirements for the executive jet in the landing approach. Table IV shows the maximum, average, and minimum values of roll control power used for each evaluation group. These values were determined from the pilot-selected values of aileron sensitivity, $L'_{\delta_{AW}}$, and cumulative probability density plots of the pilots' aileron wheel inputs.

Table IV

MAXIMUM, AVERAGE AND MINIMUM VALUES OF ROLL CONTROL POWER (DEG/SEC^2) USED BY THE PILOTS IN EVALUATION OF THE SIXTEEN BASIC GROUPS OF MODAL PARAMETERS

ω_d	2.0 rad/sec			1.0 rad/sec				
τ_R	0.4 sec			0.4 sec			1.0 sec	2.0 sec
ζ_d	0.03	0.10	0.30	0.03	0.10	0.30	0.10	0.10
$\|\phi/\beta\|_d$ = 0.25					(57) 43* [25]	(58) 46* [37]	(45) 30* [21]	
$\|\phi/\beta\|_d$ = 1.5	(51) 46* [38]	(50) 42* [31]	(59) 45* [30]	(61) 45* [34]	(42) 36* [30]	(56) 47* [35]	(32) 24* [17]	(24) 20* [14]
$\|\phi/\beta\|_d$ = 3.0		(86) 44* [25]		(79) 61* [45]	(93) 50* [47]	(72) 43* [30]	(38) 31* [22]	

( ) Maximum values * Average values [ ] Minimum values

The range between the minimum and maximum values shown in Table IV reflects the variations in atmospheric conditions, variations in the aileron yaw parameter and individual pilot technique but since they are the values that the pilot actually used, they represent the roll control power necessary for maneuvering to accomplish the landing approach task. The values presented do not include that increment of additional roll control power that may be necessary to cope with asymmetric power or loading conditions or other states of aircraft failure.

Having accumulated aileron wheel sensitivity data and aileron wheel deflection data, a basis was formed from which further investigation of roll control power requirements for selected configurations could progress. Additional evaluations were performed to investigate the effects of limited roll control power and to determine those parameters that are most significant in establishing minimum roll control power requirements.

Several options were available to limit the roll control power available, including:

1. Selection of aileron control sensitivities to limit the maximum roll control power.
2. Mechanical stops to limit the aileron wheel travel.
3. Limits on the electrical signal representing wheel deflection. In this case, the mechanical stops remain fixed at ±45°.

It was decided not to change the aileron wheel sensitivities from those previously selected by the evaluation pilots as optimum. Instead it was decided to maintain the sensitivity for small inputs at the value selected by the pilot when there was no control power limit, and to use option 3 to limit control power. A more complete experiment would have been to repeat each case with the control power limited and to allow the pilot to select the best control sensitivity for use with the limited control power. However, time did not permit these additional tests to be made. Limiting roll control power by mechanical stops was considered undesirable. Since the evaluation pilots would have been aware of hitting the stops, a psychological factor would have entered the experiment which would have been difficult, if not impossible, to evaluate. Therefore, the aileron control system was mechanized, as shown in Figure 6.

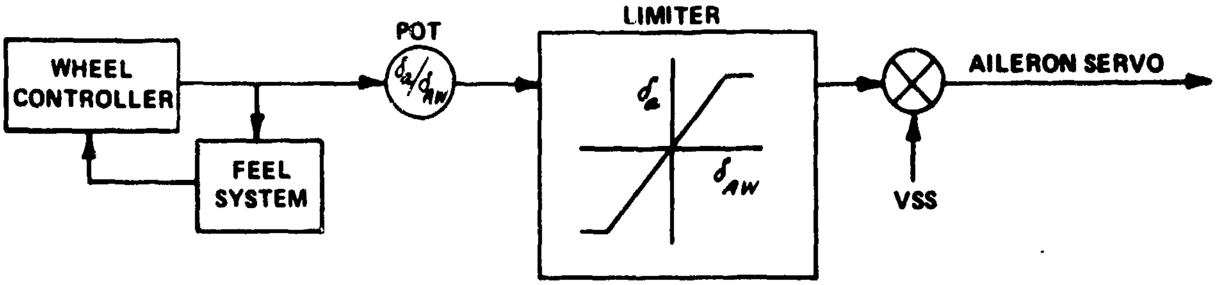


Figure 6 AILERON LIMITER SCHEMATIC

This mechanization allowed the system operator/safety pilot to select the effective aileron wheel deflection, $\delta_{AW_{EFF}}$. That is, the aileron wheel controller would command aileron deflections only through a predetermined range of its travel, $\delta_{AW_{EFF}}$. The evaluation pilot could continue rotating the control wheel to the stops, but after exceeding $\delta_{AW_{EFF}}$, no further aileron deflection could be obtained. Since the sensitivities used were those previously selected by each evaluation pilot, the only variable from previously evaluated configurations was $\delta_{AW_{EFF}}$, which limited $L'_{\delta_{AW}}\delta_{AW}$.

To limit roll control power at various incremental values, $\delta_{AW_{EFF}}$ was limited as shown in Figure 7. The same $\delta_{AW_{EFF}}$ provided each pilot with different values of $L'_{\delta_{AW}}\delta_{AW_{EFF}}$ because, as noted above, each pilot had previously selected the sensitivity he considered optimum. The selection of the values of $\delta_{AW_{EFF}}$ was based on examination of control usage data collected during the evaluations of the groups depicted in Table I, Section 3. These data indicated that $\delta_{AW} \geq 15$ degrees was seldom used in the highest $|\phi/\beta|_d$ case, and $\delta_{AW} \geq 10$ degrees was seldom used in other evaluations. Therefore, in this part of the study, $\delta_{AW_{EFF}}$ was limited to values less than or equal to 15 degrees.

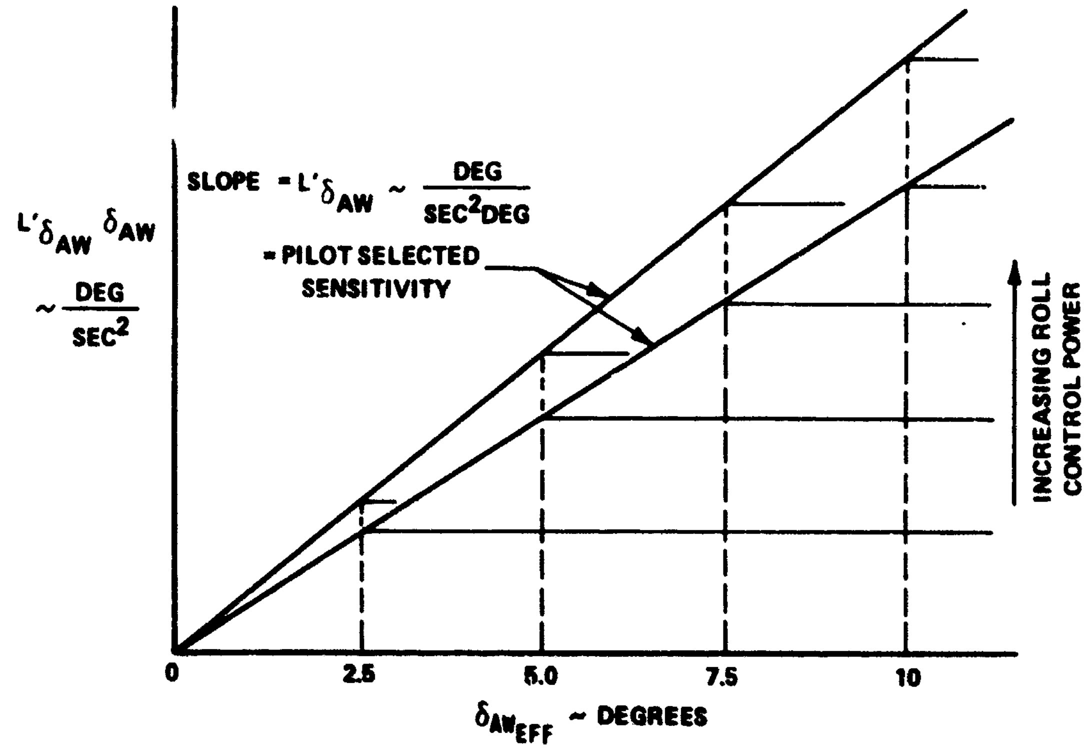


Figure 7 LIMITING OF $\delta_{AW_{EFF}}$

Evaluations were conducted for configurations 6P1, 9P1, 11P1, 14P1, and 16P1; that is, the proverse aileron yaw evaluation configuration, $N'_{\delta_{AW}}/L'_{\delta_{AW}} = +0.05$, at which pilot ratings were near optimum from previous evaluations. This allowed limited roll control power data to be compared to near optimum pilot ratings for the unlimited roll control power cases previously evaluated.

The roll control power was always, of course, limited by the basic T-33 airplane; however, this does not constrain the evaluation so long as the maximum rolling acceleration capability of the T-33 is not exceeded by the combination of the pilot's control input, the variable stability response feedback, and the random disturbance turbulence simulation. For the configurations evaluated in this program, the maximum rolling acceleration capability of the T-33 airplane was not exceeded.

As previously discussed, because control usage data were recorded, it was possible to determine how much of the available roll control power was actually used by the pilot. Although time and funds did not allow power spectral densities of the control motions to be calculated, cumulative probability density functions were determined for a majority of the ILS, offset, and crosswind approaches. Cumulative probability density functions do not show how the controls were used, but they do determine how much control was used. In other words, a pilot may use smooth low-frequency inputs or rapid high-frequency inputs and achieve different airplane responses but still have a similar cumulative probability density function.

Figures 8 through 12 show the degradation of pilot rating with decreasing roll control power for the five groups evaluated. The roll control power numbers shown in these figures were determined from either: (1) the maximum δ_{AW} used if δ_{AW} was not limited, (2) the maximum δ_{AW} used if the maximum used was less than the limiting value of δ_{AW} , or (3) the limiting δ_{AW} if the actual control usage exceeded the limiting δ_{AW} value. The maximum values presented are the maximum values recorded during the particular evaluation. The probability of exceeding these values is only 0.02; they include the ILS, offset, and crosswind approaches. Values of ϕ_1 , $\phi_{1.8}$ and p_{ss} shown on these figures were determined using the same δ_{AW} criteria.

Both evaluation pilots generally tended to complain about decreased sensitivity as the effective aileron wheel throw was progressively limited, only occasionally mentioning the need for more aileron control power. As the wheel moved beyond the effective wheel throw against a constant spring gradient, the pilot would observe a reduced roll rate and consider the control sensitivity reduced. However, as the control power became more severely limited, both evaluation pilots commented on the low steady-state roll rates available. Even with severely limited roll control power, neither pilot encountered much difficulty with small magnitude maneuvers, but performing crosswind and lateral offset approaches, especially in turbulence, often became a formidable task. Neither pilot recognized that a nonlinearity existed in the control system.

CONF	PILOT/PR	$L'_{\delta_{AW}}$ (DEG/SEC² DEG)	ROLL CONTROL POWER USED (DEG/SEC²)	MAXIMUM $\delta_{AW_{EFF}}$ (DEG)	MAXIMUM δ_{AW} USED (DEG)	ϕ_1* (DEG)	$\phi_{1.8}$* (DEG)	P_{SS}* (DEG/SEC)
1	A/3	0.70**	[illegible]	±10	11	12.2	26.1	17.1
2	B/4	0.70	35.0	±7.5	8	6.9	16.9	12.9
3	B/1.5	0.70	31.0	±45	6.5	7.7	16.4	10.8
4	A/3	3.00	30.0	±10	12	7.6	16.3	10.7
5	B/6	0.70	23.0	±5	17	5.9	12.6	8.3
6	A/9	3.00	7.7	±2.5	25	1.9	9.1	2.7

**INCORRECTLY FLOWN WITH SENSITIVITY SELECTED BY PILOT B.

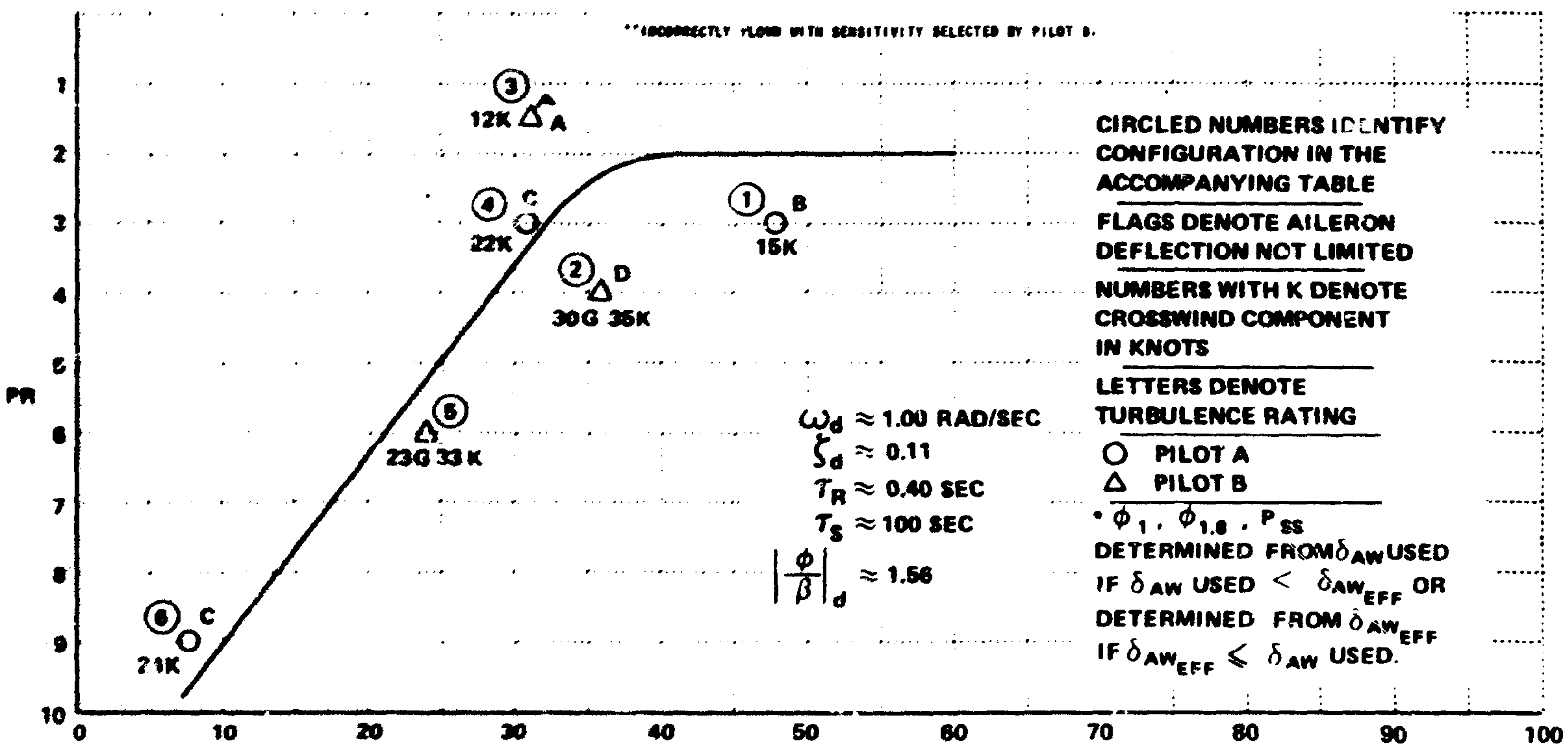


Figure 8 PILOT RATING VERSUS MAXIMUM ROLL CONTROL POWER USED--GROUP 6

CONF	PILOT/PR	$L'\delta_{AW}$ (DEG/SEC^2 DEG)	ROLL CONTROL POWER USED (DEG/SEC^2)	MAXIMUM $\delta_{AW_{EFF}}$ (DEG)	MAXIMUM δ_{AW} USED (DEG)	ϕ_1* (DEG)	$\phi_{1.8}$* (DEG)	P_{SS}* (DEG/SEC)
1	B/5	6.66	93.2	±15	14	22.3	46.3	27.0
2	B/8	6.66	66.6	±10	16	15.9	33.1	19.3
3	B/5.5	6.66	53.3	±45	8	12.7	26.5	15.4
4	B/10	6.66	50.0	±7.5	24	12.0	24.8	14.5
5	A/8	3.01	30.1	±10	26	7.2	15.0	8.7
6	B/8.5	[illegible].66	16.6	±2.5	18	4.0	8.3	4.8
7	[illegible]/9	2.57	12.9	±5.0	30	[illegible]	6.4	3.7

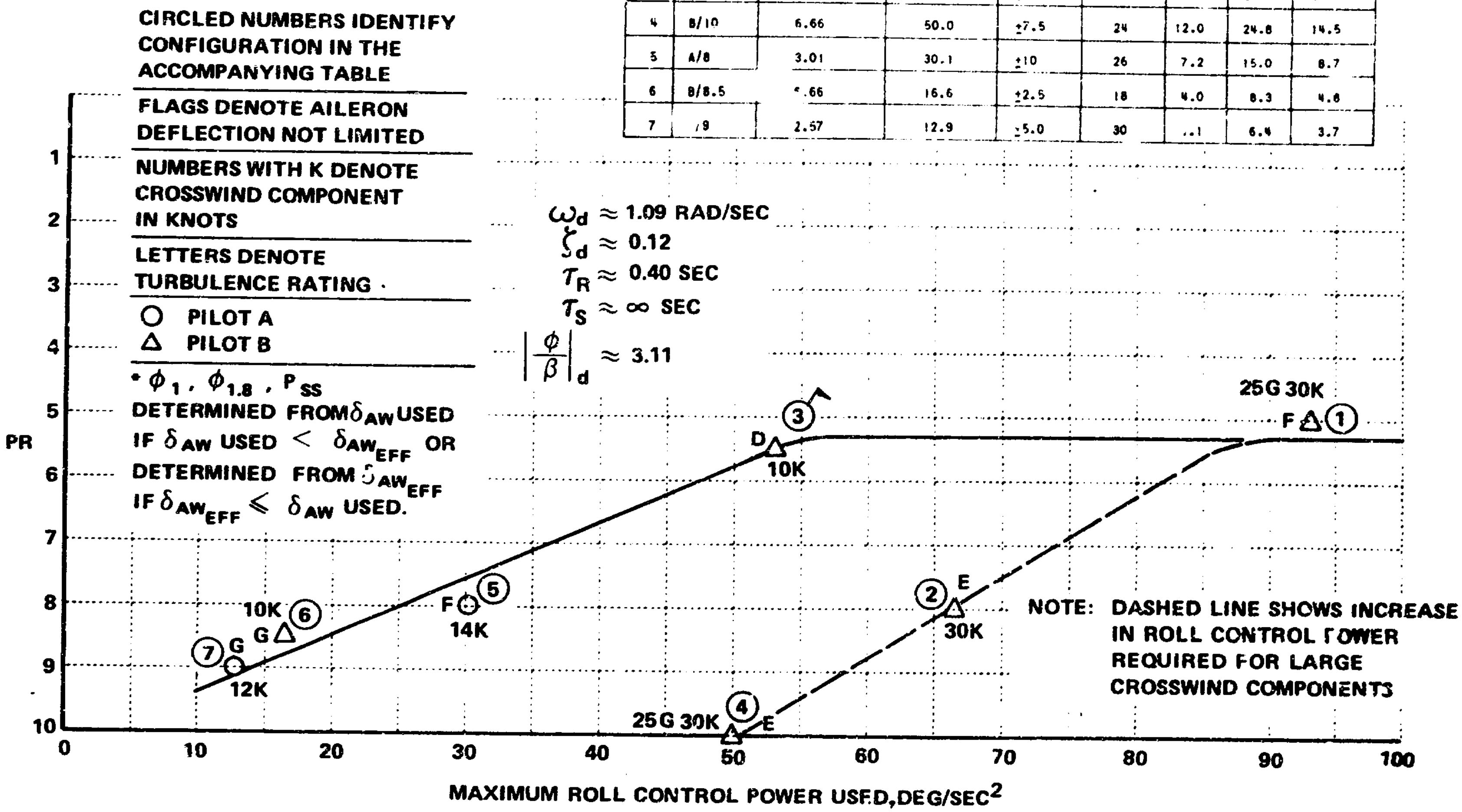


Figure 9 PILOT RATING VERSUS MAXIMUM ROLL CONTROL POWER USED–GROUP 9

CONF	PILOT/PR	$L'_{\delta_{AW}}$ (DEG/SEC^2 DEG)	ROLL CONTROL POWER USED (DEG/SEC^2)	MAXIMUM $\delta_{AW_{EFF}}$ (DEG)	MAXIMUM δ_{AW} USED (DEG)	ϕ_1* (DEG)	$\phi_{1.8}$* (DEG)	P_{SS}* (DEG/SEC)
1	A/3.5	3.08	49.3	±45	16	11.6	24.8	16.9
2	B/2.5	3.83	46.0	±45	12	10.8	23.2	15.8
3	B/2.5	3.83	30.6	±10	8	7.2	15.4	10.5
4	A/5	3.08	23.1	±7.5	29	5.4	11.6	7.8
5	A/7	3.08	15.4	±5	16	3.6	7.8	5.3
6	B/7	3.83	9.6	±2.5	14	2.3	4.8	3.3

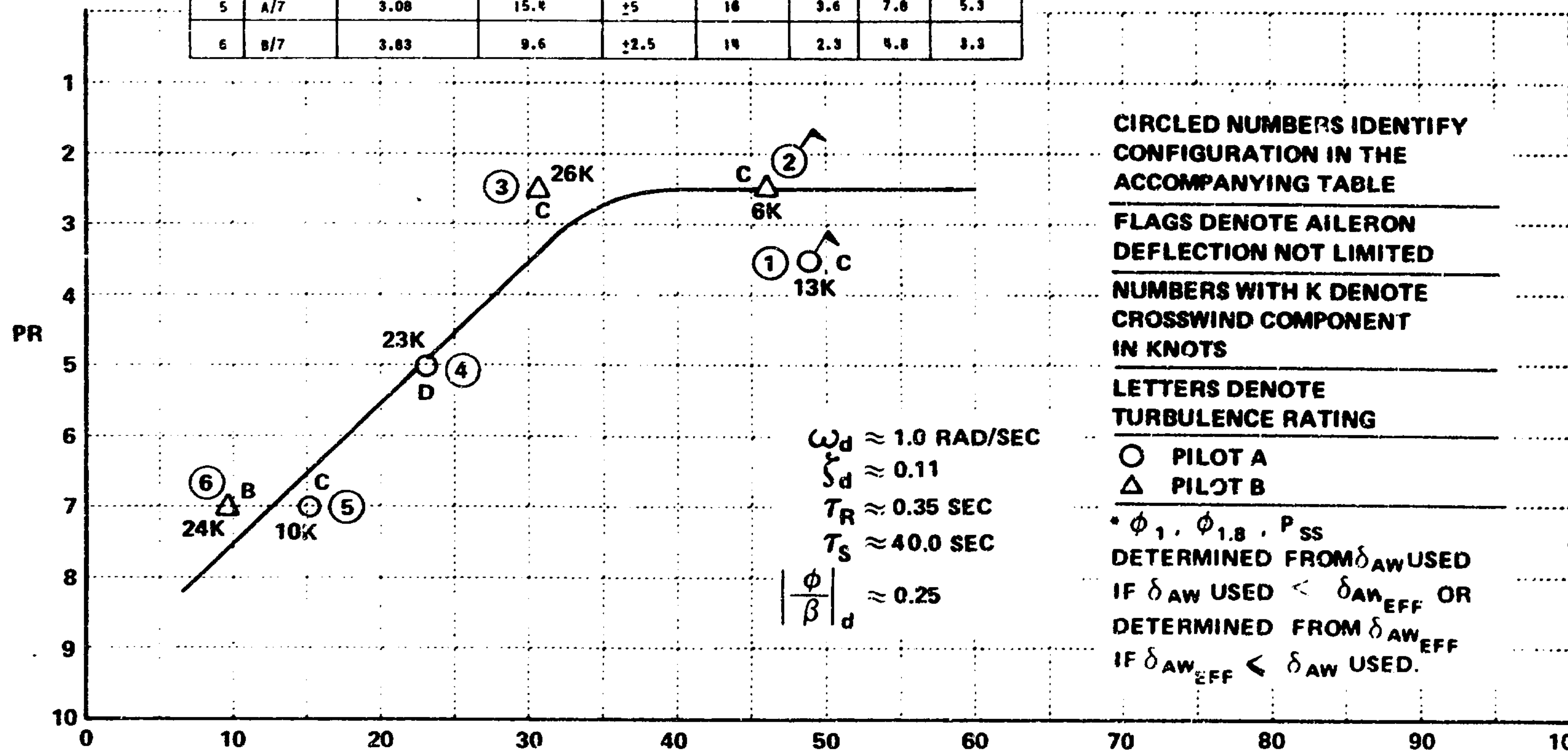


Figure 10 PILOT RATING VERSUS MAXIMUM ROLL CONTROL POWER USED--GROUP 11

CONF	PILOT/PR	$L'\delta_{AW}$ (DEG/SEC^2 DEG)	ROLL CONTROL POWER USED (DEG/SEC^2)	MAXIMUM $\delta_{AW_{EFF}}$ (DEG)	MAXIMUM δ_{AW} USED (DEG)	ϕ_1* (DEG)	$\phi_{1.8}$* (DEG)	P_{SS}* (DEG/SEC)
1	B/3	2.12	17.0	±45	8	6.6	17.4	15.8
2	B/3	2.12	15.9	±7.5	9	6.1	16.3	14.8
3	A/2	1.57	15.7	±10	15	6.1	16.1	14.6
4	A/6	1.57	7.8	±5	24	3.0	8.0	7.3
5	B/10	2.12	5.3	±2.5	26	2.0	5.4	4.9

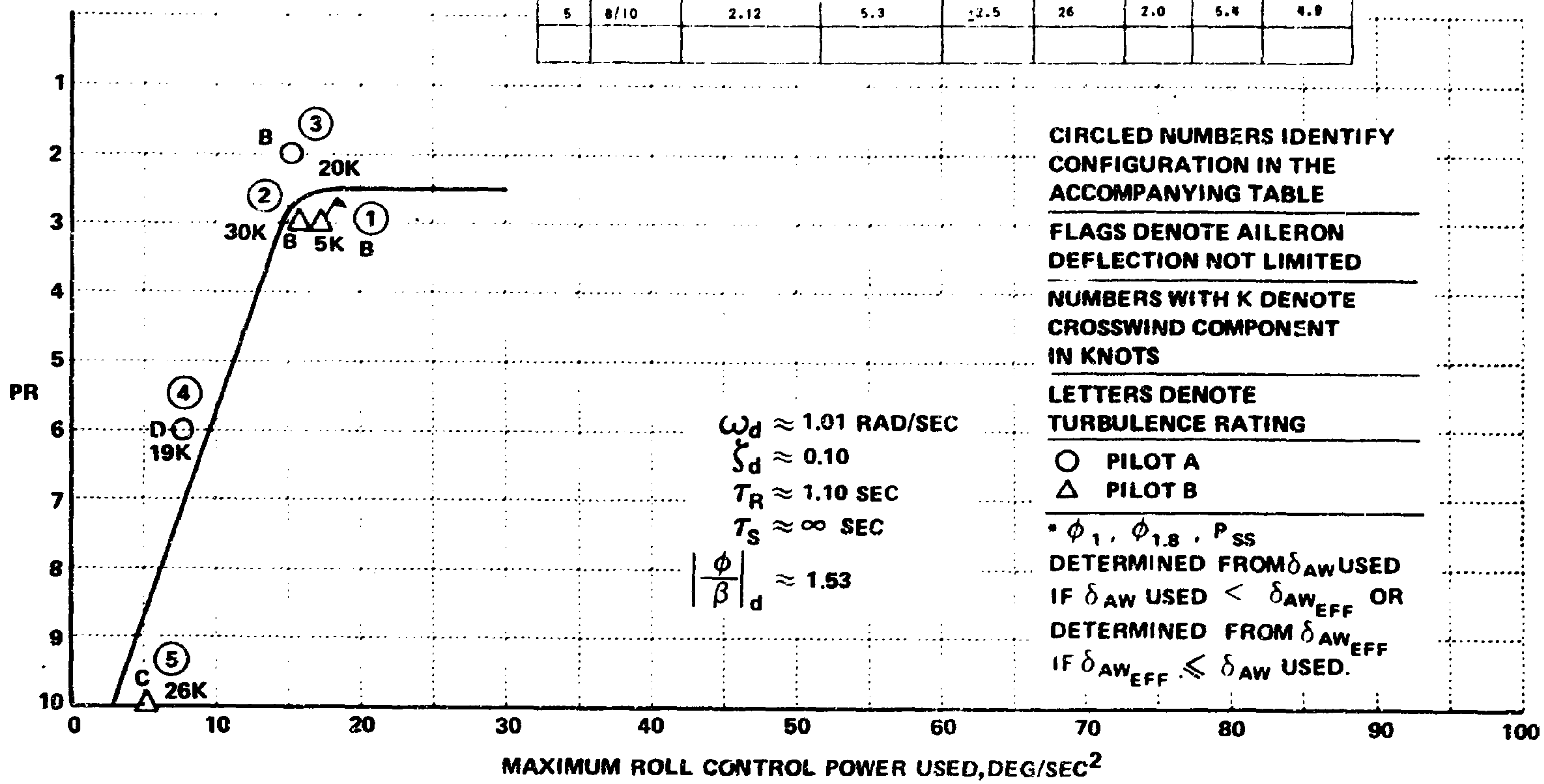
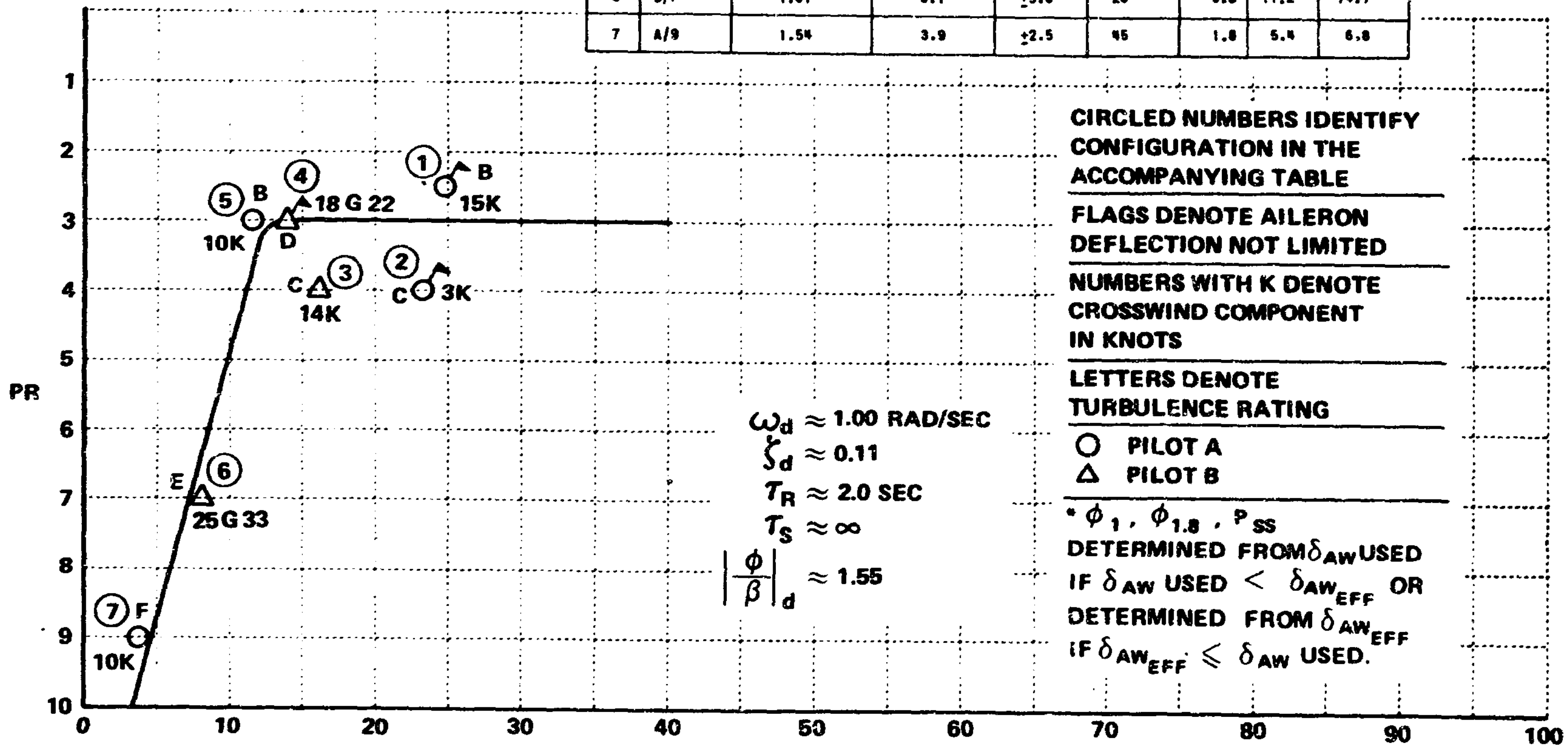


Figure 11 PILOT RATING VERSUS MAXIMUM ROLL CONTROL POWER USED--GROUP 14

CONF	PILOT/PR	$L'\delta_{AW}$ (DEG/SEC^2 DEG)	ROLL CONTROL POWER USED (DEG/SEC^2)	MAXIMUM $\delta_{AW_{EFF}}$ (DEG)	MAXIMUM δ_{AW} USED (DEG)	ϕ_1* (DEG)	$\phi_{1.8}$* (DEG)	P_{SS}* (DEG/SEC)
1	A/2.5	1.54	24.6	±45	16	11.4	34.0	43.0
2	A/4	1.54	23.1	±45	15	10.7	32.0	40.4
3	B/4	1.61	16.1	±10	12	7.5	22.3	28.1
4	B/3	1.61	13.7	±45	6.5	6.4	19.0	23.8
5	A/3	1.54	11.5	±7.5	17	5.3	15.8	20.1
6	B/7	1.61	8.1	±5.0	20	3.8	11.2	14.1
7	A/9	1.54	3.9	±2.5	45	1.8	5.4	6.8



MAXIMUM ROLL CONTROL POWER USED,DEG/SEC^2

Figure 12 PILOT RATING VERSUS MAXIMUM ROLL CONTROL POWER USED--GROUP 16

Configurations 6P1 and 11P1, which have essentially the same roll mode time constant but respective roll-to-sideslip ratios of 1.5 and 0.25, show the same trend in pilot rating with decreasing roll control power. As shown in Figures 8 and 10, both configurations had a maximum roll control power usage of approximately 50 deg/sec^2. Both configurations were flown in crosswinds exceeding 20 knots and were rated satisfactory for roll control power as low as 30 deg/sec^2. In configuration 6P1 (2) (circled numbers identify configurations on appropriate figures), which was limited to a roll control power of 35.7 deg/sec^2, the pilot could perform the crosswind approach in a 30 gusting to 35-knot crosswind, but he did not consider the overall configuration satisfactory (PR=4). A 6.5 pilot rating boundary for these two configurations (6P1 and 11P1) would be defined by roll control power requirements between 15 and 20 deg/sec^2. The similarity between the roll control power requirements for these two configurations is consistent with pilot comments and pilot rating data obtained for these two groups during the unlimited roll control power evaluations. There were essentially no differences between the two evaluation groups.

Group 9, Figure 9, had the same roll mode time constant as groups 6 and 11; however, in comparison it had a high roll-to-sideslip ratio, $|\phi/\beta|_d = 3.10$. The 9P1 configurations are interesting because they clearly show the effect of crosswind component on required roll control power for an airplane with appreciable dihedral. None of these configurations were rated satisfactory, making it impossible to define a PR=3.5 boundary, however, a PR=6.5 boundary for crosswinds of 10 to 15 knots and roll control power of 40 to 45 deg/sec^2 can be defined. Configurations (1), (2) and (4) on Figure 9 which were evaluated in 25 to 30-knot crosswinds show much higher roll control power requirements. Pilot comments for configuration (2) indicate that "control limits did not prevent you from doing the crosswind even though the crosswind component was staggering....the problem is handling large lateral upsets close to the ground....it takes a whole lot of aileron to get the wing up." Configurations (4) and (1) were flown on the same flight. On configuration (4) the pilot commented that "...I don't think I could get it on the ground in the kind of crosswind (25, gusting to 30) we had today. You might be lucky enough to have it stabilize just as you hit the ground but you just might not. You get into severe overcontrolling in the crosswind when trying to land straight ahead in the wing-down method, and in the crabbed approach you've ultimately got to get straight so you have problems with the sideslip....It's mainly the roll due to rudder that hurts you in the crosswind....Because of the crosswind, I'm going to have to rate it a 10 because I don't think I could get it on the ground." The pilot followed his rating of 10 with the following comment, "If you want to know what it would be like out of the crosswind - without the crosswind -it's certainly in the controllable category and I think all things considered, if you didn't have to worry about the crosswind you could optimize the gearing a little better. I think it would be an acceptable airplane but unsatisfactory." Configuration (1) was flown in the same crosswind conditions with increased roll control power available and the pilot commented, "I can handle the crosswind to my satisfaction and the wing-down method was what I would use and I could do it with no problems." A PR=6.5 boundary to handle a 25- to 30-knot crosswind for the Group 9 configuration is between 70 and 80 deg/sec^2.

Configuration 14P1, Figure 11, was characterized by a moderate roll mode time constant (τ_R = 1.1). The maximum roll control power used for this configuration was 17 deg/sec^2. Satisfactory ratings were obtained in crosswinds of 20 to 30 knots. With a roll control power limit of 8 deg/sec^2, the pilot was still able to cope with a 19-knot crosswind, but found his roll control barely adequate for the lateral offset approach and cautioned that rapid rolling maneuvers should be avoided. When the roll control power was reduced to 5 deg/sec^2, the pilot could not perform the crosswind approach. There was insufficient roll control power to perform a wing-down approach in the 26-knot crosswind. When the pilot attempted to decrab on a crabbed approach, there was insufficient roll control to keep the airplane from being blown off the runway. The pilot commented, "I'd lose control dramatically by making a hole in the ground somewhere off to the edge of the runway" and rated the airplane a PR = 10.

Configuration 16P1, Figure 12, had a long roll mode time constant (τ_R = 2.0). The maximum control power used for this configuration was 25 deg/sec^2. Configuration (4) was evaluated in a crosswind of 18 gusting to 22 knots with no limits on the roll control power (within, of course, the constraints of the T-33 variable stability airplane) and was rated satisfactory with a maximum roll control power usage of 14 deg/sec^2. With the roll control power reduced to 8 deg/sec^2, (6) , the pilot had no difficulty with a 25 gusting to 33-knot crosswind. The major problem was the inability to stop a given roll rate with sufficient precision close to the ground. The configuration with a roll control power of 4 deg/sec^2, (7) , was only evaluated in a 10-knot crosswind but the pilot commented that once a roll was started it required full aileron and rudder opposite to the direction of turn to stop the roll, often leading to very uncoordinated situations. There were occasions when the pilot nearly lost control of the airplane because of the roll control.

The values of roll control power found to correspond to a PR = 3.5 in Table V or, in the case of group 9, roll control power values found to correspond to a PR = 6.5 shown in Table VI, agree well with the minimum values shown in Table IV. Thus it was possible to limit the roll control power to minimum values recorded during the basic group evaluations without degrading the pilot ratings.

MIL-F-8785B(ASG) places a requirement on roll control power in the landing approach for Class II airplanes of 30° in 1.8 seconds for Level 1 flying qualities. References 38 and 59 discuss bank angle in 1.0 seconds as a measure of roll performance in the landing approach. The values of ϕ_1 and $\phi_{1.8}$ shown on the tables in Figures 8 through 12 were obtained by ratioing the appropriate bank angle obtained from calculated transient responses of the configurations by the corresponding $L'_{\delta_{AW}} \delta_{AW}$. Thus, the values presented represent the actual airplane response with the rudder fixed and are those that would be experienced for the actual roll control power used. MIL-F-8785B(ASG) allows rudder inputs to minimize sideslip that retards roll

Table V

ROLL PERFORMANCE MEASURES FOUND TO CORRESPOND TO PR = 3.5

$\omega_d \approx 1.0$ RAD/SEC, $\zeta_d \approx 0.10$, $\lvert\phi/\beta\rvert_d \approx 1.5$						
CONF	τ_R SEC	ROLL CONTROL POWER DEG/SEC^2	ϕ_1 DEG	$\phi_{1.8}$ DEG	p_{SS} DEG/SEC	MAXIMUM X-WIND KNOTS
6P1	0.4	30	7.4	15.9	10.4	22
11P1*	0.4	30	7.1	15.1	10.4	26
14P1	1.1	14	5.5	14.4	13.8	30
16P1	2.0	12	6.5	16.6	16.6	20
* $\lvert\phi/\beta\rvert_d$ = 0.25 FOR CONFIGURATION 11P1.						

Table VI

ROLL PERFORMANCE MEASURES FOR CONFIGURATION 9P1*

$\omega_d \approx 1.0$ RAD/SEC, $\zeta_d \approx 0.10$, $\lvert\phi/\beta\rvert_d \approx 3.0$						
CONF	τ_R SEC	ROLL CONTROL POWER DEG/SEC^2	ϕ_1 DEG	$\phi_{1.8}$ DEG	p_{SS} DEG/SEC	MAXIMUM X-WIND KNOTS
9P1*	0.4	77	18.4	38.5	22.3	30
9P1*	0.4	42	10.1	20.8	12.2	10
*Configuration 9P1 was never rated better than PR = 5; thus, these numbers represent roll control power requirements for a PR = 6.5.						

rate in meeting the roll performance requirements. Because the configurations evaluated during the roll control power experiment were close to being the minimum sideslip configurations, obtaining $\phi_{1.8}$ with the rudder fixed is not considered inappropriate. For the moderate and low $|\phi/\beta|_d$ cases, it was found that values of ϕ_1 as low as 6.0 degrees were acceptable. The value of $\phi_{1.8} = 15°$ is only half the required value of $\phi_{1.8}$ for Level 1 flying qualities MIL-F-8785B(ASG). For approaches made in crosswinds of 30 knots with $|\phi/\beta|_d = 3.1$, the results indicate roll control power corresponding to $\phi_{1.8}$ = 38.5 degrees would be required to avoid significant pilot rating degradation because of lack of roll control power. Table V gives the approximate values of roll control power, ϕ_1 , $\phi_{1.8}$, and p_{ss} values found to be satisfactory (PR ≤ 3.5) for the configurations evaluated in this investigation. Table VI shows the values that resulted for configuration 9P1 corresponding to a PR = 6.5 This configuration was never rated better than a PR = 5.0 and therefore, it was not possible to determine values of roll control power necessary for a satisfactory pilot rating.

In summary, adequate roll control power is a function of roll mode time constant as well as roll-to-sideslip ratio. As the roll mode time constant is increased, the requirement on roll control power is reduced. As the roll-to-sideslip ratio is increased, the requirements on roll control power are correspondingly increased. The roll control power available can establish a limiting crosswind value.

Steady-state roll rates of 10 deg/sec to 20 deg/sec were found to provide satisfactory roll performance. The values of p_{ss} were obtained from $p_{ss} = L'_{\delta_{AW}} \delta_{AW} \tau_R (\omega_\phi/\omega_d)^2$. This is in good agreement with Reference 58, which shows that in NASA simulator studies of SST approaches, values of 10-15 deg/sec roll performance were satisfactory. Peak roll rates near 10 deg/sec were reported in Reference 74 during the landing approach work with the XB-70.

4.4 THE EFFECT OF N'_p

In this investigation, the value of N'_p was essentially constrained to be -0.08, a value that was determined to be representative of the class of airplanes to be evaluated. All but four groups of configurations had values within ±0.01 of -0.08. Three of these groups were the moderate roll mode time constant ($\tau_R \approx 1.0$ seconds) groups, 13, 14, and 15, which had N'_p values of -0.094, -0.033 and -0.105 respectively. The fourth group had an N'_p = -0.0515.

As shown in Appendix I, for fixed values of Dutch roll frequency, damping ratio, and $|\phi/\beta|_d$, the value of N'_p strongly influences the position of the ϕ/δ_{AW} numerator zero with respect to the Dutch roll pole along the real axis $(\zeta_d \omega_d - \zeta_\phi \omega_\phi)$. The vertical displacement of the zero is then determined by $N'_{\delta_{AW}}/L'_{\delta_{AW}}$.

It was shown in Reference 7 that the optimum value of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ for a configuration is primarily a function of the yaw due to roll rate parameter, N'_p. For a low $|\phi/\beta|_d$ configuration the optimum value of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ is the value that in combination with N'_p results in minimum sideslip response. For a higher $|\phi/\beta|_d$ configuration, where the pilot is concerned primarily with the roll response, the optimum value of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ is the value that in combination with N'_p produces the best roll rate response.

Investigation of the β/δ_{AW} transfer function shown in Appendix I indicates that when the spiral root is at the origin and

$$Y_{\delta_{AW}} = \alpha_3 = \frac{g}{V}\left(L'_{\delta_{AW}} N'_r - N'_{\delta_{AW}} L'_r\right) \approx 0$$

the β/δ_{AW} transfer function can be written as follows:

$$\frac{\beta}{\delta_{AW}} \approx \frac{-N'_{\delta_{AW}}\left\{s - L'_p + \frac{L'_{\delta_{AW}}}{N'_{\delta_{AW}}}\left(N'_p - \frac{g}{V}\right)\right\}}{\left(s + \frac{1}{T_R}\right)\left(s^2 + 2\zeta_d \omega_d s + \omega_d^2\right)}$$

From this expression, using the final value theorem, the steady-state sideslip for an aileron input is a minimum when:

$$\frac{N'_{\delta_{AW}}}{L'_{\delta_{AW}}} \approx \frac{N'_p - \frac{g}{V}}{L'_p}$$

Since L'_p is negative, it can be seen that for negative values of N'_p, minimum steady state sideslip will occur for positive values of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ (i.e., proverse yaw due to aileron wheel inputs). The converse is true when N'_p is positive and greater than g/V, minimum steady-state sideslip will occur for negative values of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ (i.e., adverse yaw due to aileron wheel inputs).

In this investigation, all but four groups reached an optimum pilot rating for a positive or proverse value of yaw due to aileron wheel deflection. Two groups reached an optimum rating at $N'_{\delta_{AW}}/L'_{\delta_{AW}}=0$ and two groups for adverse yaw due to aileron wheel deflection. The latter two groups and one of those at which the optimum pilot rating occurred at $N'_{\delta_{AW}}/L'_{\delta_{AW}}=0$ were groups with very light Dutch roll damping ratios (ζ_d = 0.03). For these three groups, the adverse yaw due to aileron wheel inputs tended to increase the closed loop Dutch roll damping ratio and consequently were rated better.

The results of this experiment agree with those of References 7, 46 and 50 in that proverse yaw due to roll control is desirable when the airplane has adverse yaw due to roll rate.

4.5 HIGH DUTCH ROLL FREQUENCY, LOW ROLL MODE TIME CONSTANT

The results obtained for the evaluations performed at a Dutch roll frequency of 2.0 rad/sec and a roll mode time constant of 0.4 seconds are discussed in the following four subsections.

4.5.1 Group 1 -- Low Dutch Roll Damping Ratio, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 2.02 rad/sec $|\phi/\beta|_d$ = 1.62

ζ_d = 0.026 τ_R = 0.40 sec τ_S = 40 sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 13 and the experimental results in Figure 14.

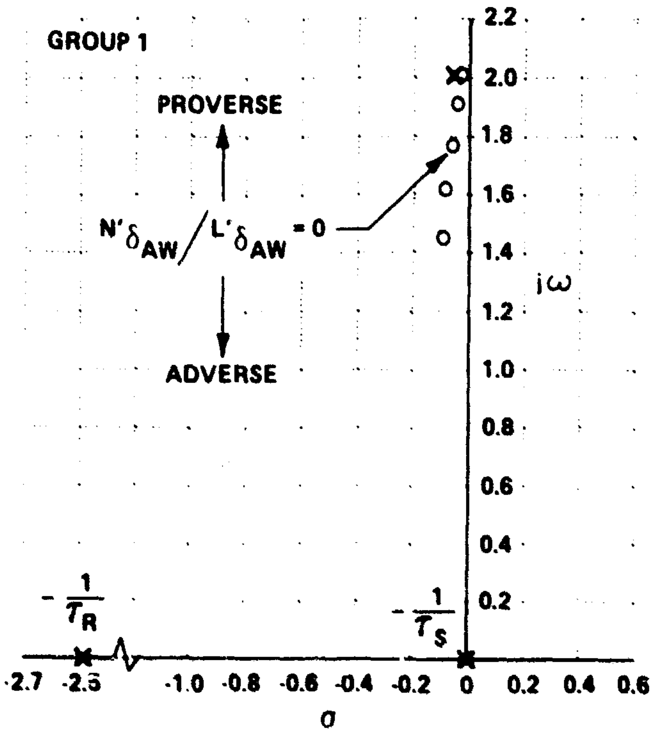


Figure 13 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 1

All configurations within this group except the most adverse aileron yaw case were reported to have good precise roll control and minor or no coordination requirements. Maneuverability was listed as a favorable feature. Pilot comments for the most adverse aileron yaw case were lost because of recorder malfunction.

The overwhelming objection to this group of configurations was the airplane's response to turbulence. In turbulence there were oscillations, particularly in roll, but also in yaw. The objectionable turbulence response was a result of the low Dutch roll damping. One pilot comment indicated that it was only the turbulence response that made the configuration unsatisfactory for the landing approach. For all but the $N'_{\delta_{AW}}/L'_{\delta_{AW}} = 0$ case, the effects

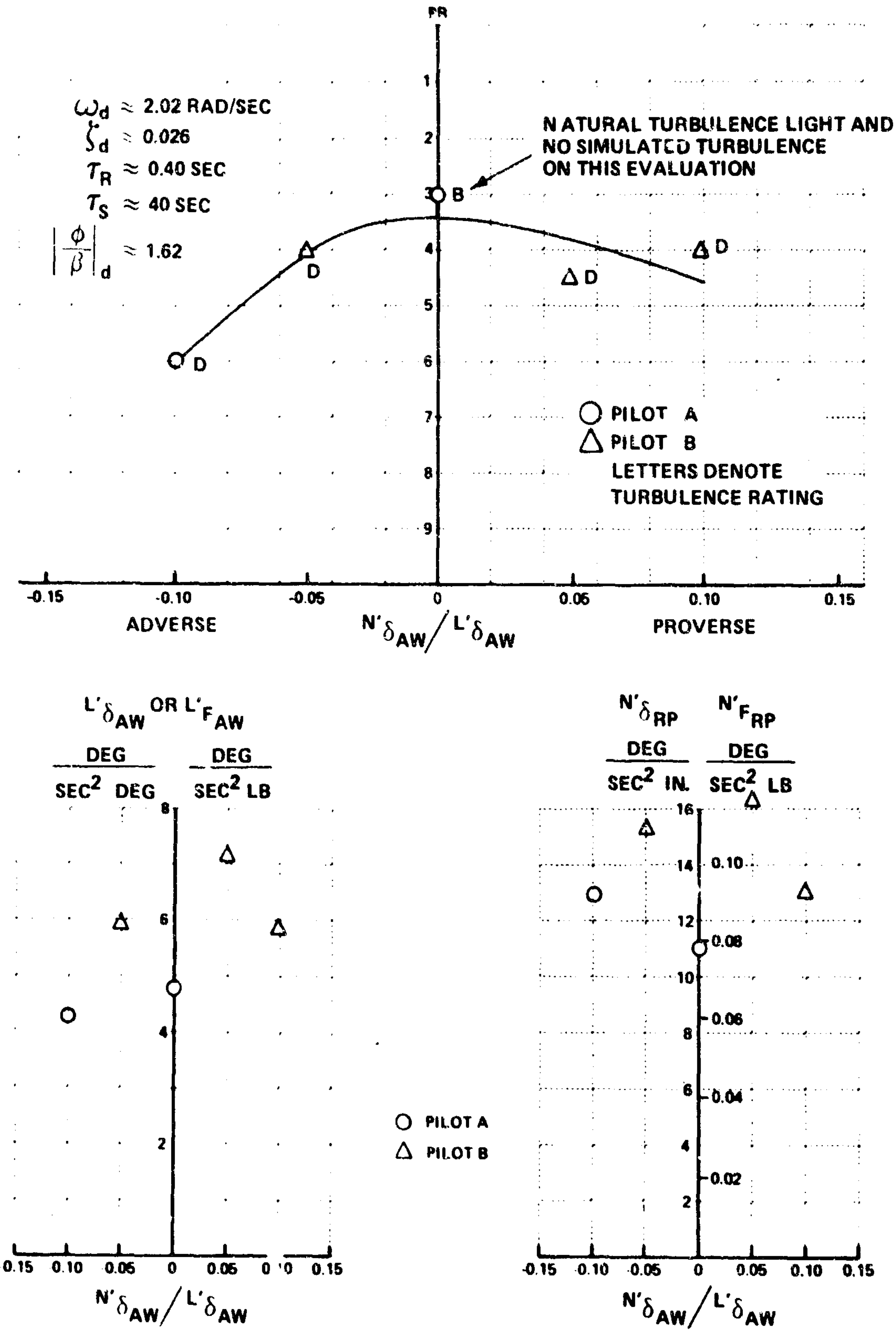


Figure 14 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 1 WHEEL CONTROLLER

of turbulence produced a moderate deterioration in task performance. The $N'_{\delta_{AW}}/L'_{\delta_{AW}} = 0$ case was evaluated during the very early part of the flight program without the benefit of the random noise disturbances to the controls. It is felt that this accounts for the apparent discrepancy in turbulence rating.

Pilot-selected values of control sensitivities show considerable scatter. In general, Pilot B selected higher sensitivities than Pilot A. Out of turbulence, the airplane was quite good. The roll control was excellent and very little rudder coordination was required. There was no difficulty in performing either the crabbed or wing low technique in the crosswind approaches.

4.5.2 Group 2 -- Medium Dutch Roll Damping Ratio, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

$\omega_d = 1.98$ rad/sec $\quad |\phi/\beta|_d = 1.71$

$\zeta_d = 0.10 \quad \tau_R = 0.40$ sec $\quad \tau_S = \infty$ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 15, and the experimental results in Figure 16.

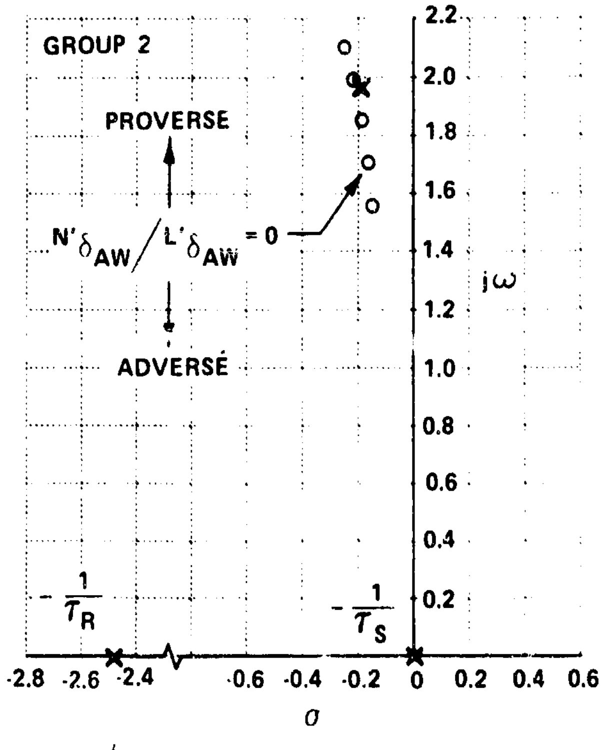


Figure 15 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 2

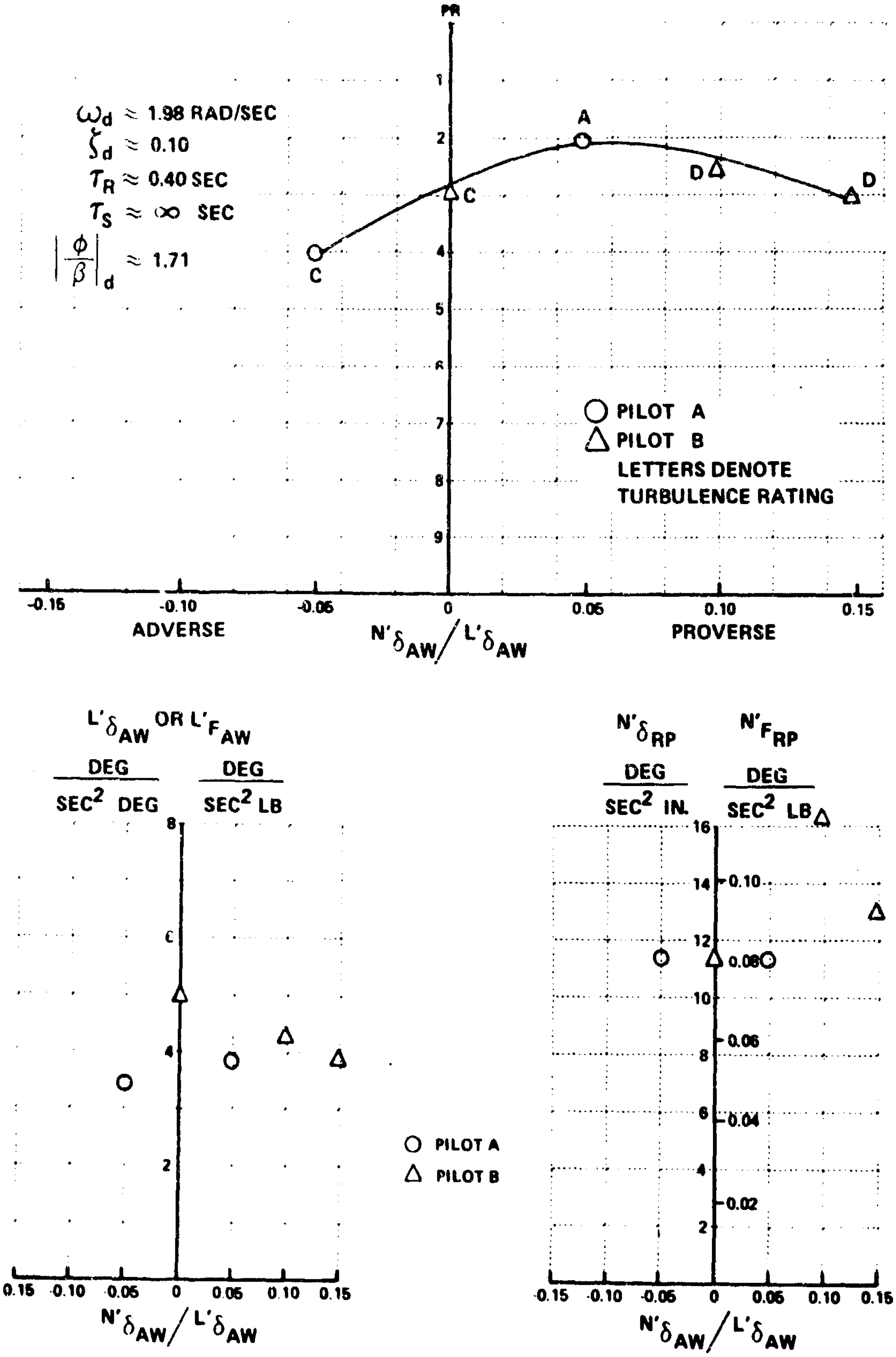


Figure 16 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 2 WHEEL CONTROLLER

The overall lateral-directional handling qualities for this group of configurations were considered to be quite good. The moderate frequency Dutch roll mode and reasonable damping ratio were liked by both evaluation pilots.

There was very little change in pilot rating over the range of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ evaluated. Only the most adverse yaw due to aileron configuration was rated as unsatisfactory. This was due primarily to roll rate oscillations that occurred following aileron inputs. This particular configuration was also the only one that required rudder coordination in a turn. The crosswind approaches presented no particular problem with these configurations for either technique.

The control sensitivities selected by both pilots were quite consistent. The high rudder control sensitivity for the moderate proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ case was selected to provide light rudder pedal forces to combat the 20-knot crosswind which existed for that particular evaluation. The pilot commented that since rudder coordination was not required, the high rudder sensitivity was acceptable.

4.5.3 Group 3 -- High Dutch Roll Damping Ratio, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 2.01 rad/sec $|\phi/\beta|_d$ = 1.50

ζ_d = 0.24 τ_R = 0.40 sec τ_s = ∞ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 17, and the experimental results in Figure 18.

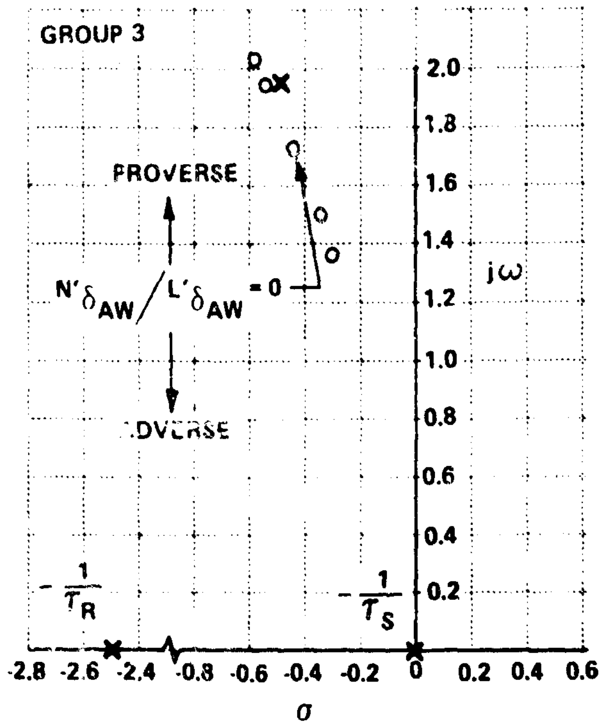


Figure 17 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 3

This group of configurations was the best evaluated. The combination of moderate Dutch roll frequency and relatively high damping ratio resulted in a smooth flying airplane with a minimal turbulence response. The directional stiffness of the airplane tended to minimize the coordination requirements. The roll control was good for all cases. Crosswind approaches presented no particular problems.

There was good agreement between pilots in their selection of control sensitivities. The pilot commented that the aileron sensitivity for the most proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ configuration evaluated was a little too sensitive. The lack of a significant turbulence response was listed as a good feature for all the configurations in this group.

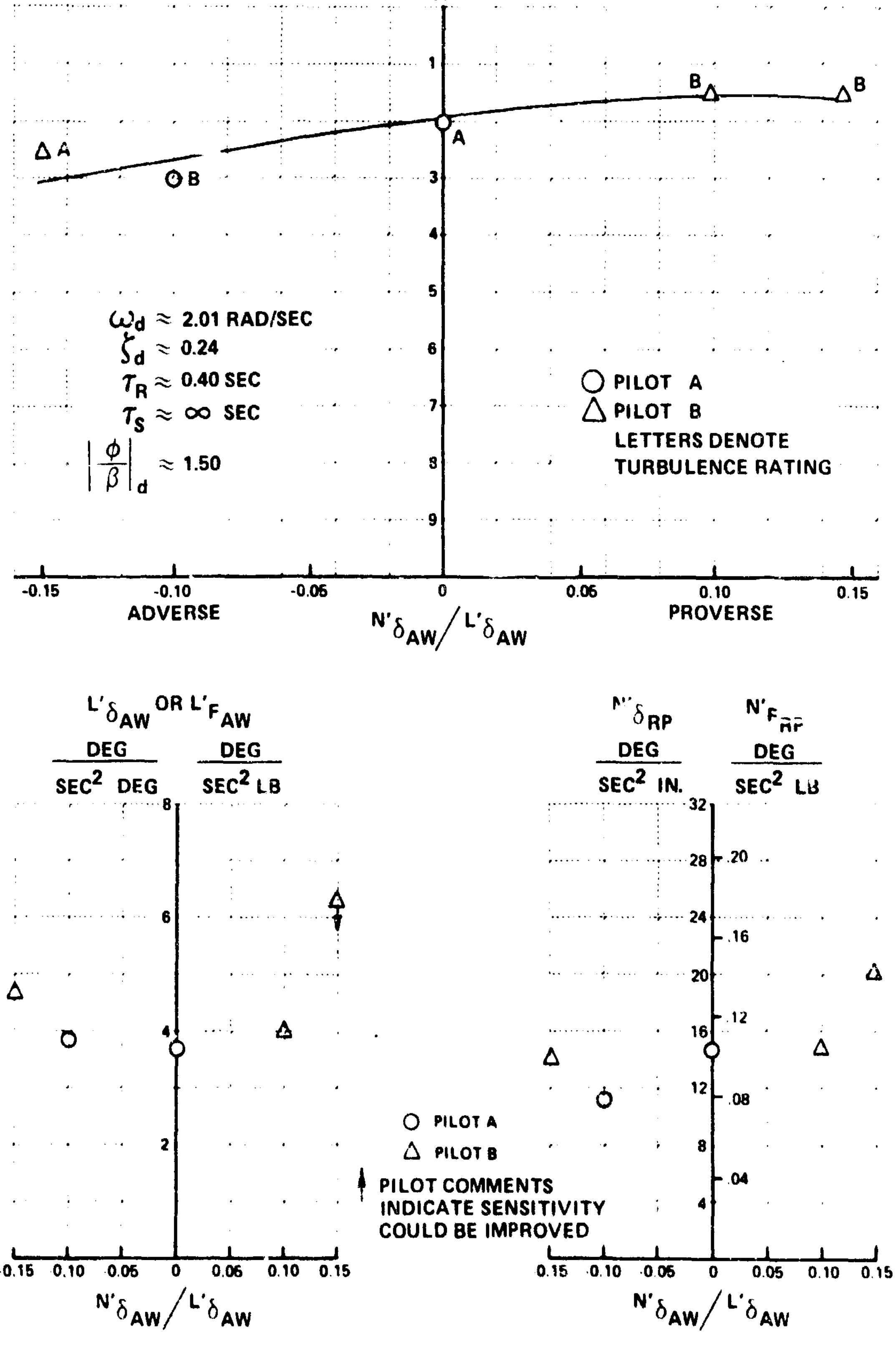


Figure 18 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 3 WHEEL CONTROLLER

4.5.4 Group 4 -- Moderate Dutch Roll Damping Ratio, High $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 2.02 rad/sec $|\phi/\beta|_d$ = 3.14

ζ_d = 0.10 τ_R = 0.40 sec τ_S = 100 sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 19, and the experimental results in Figure 20.

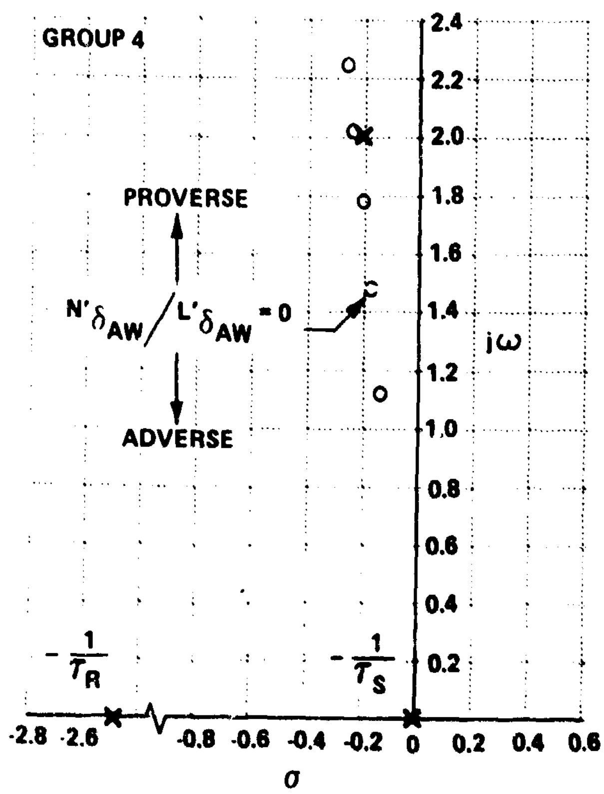


Figure 19 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 4

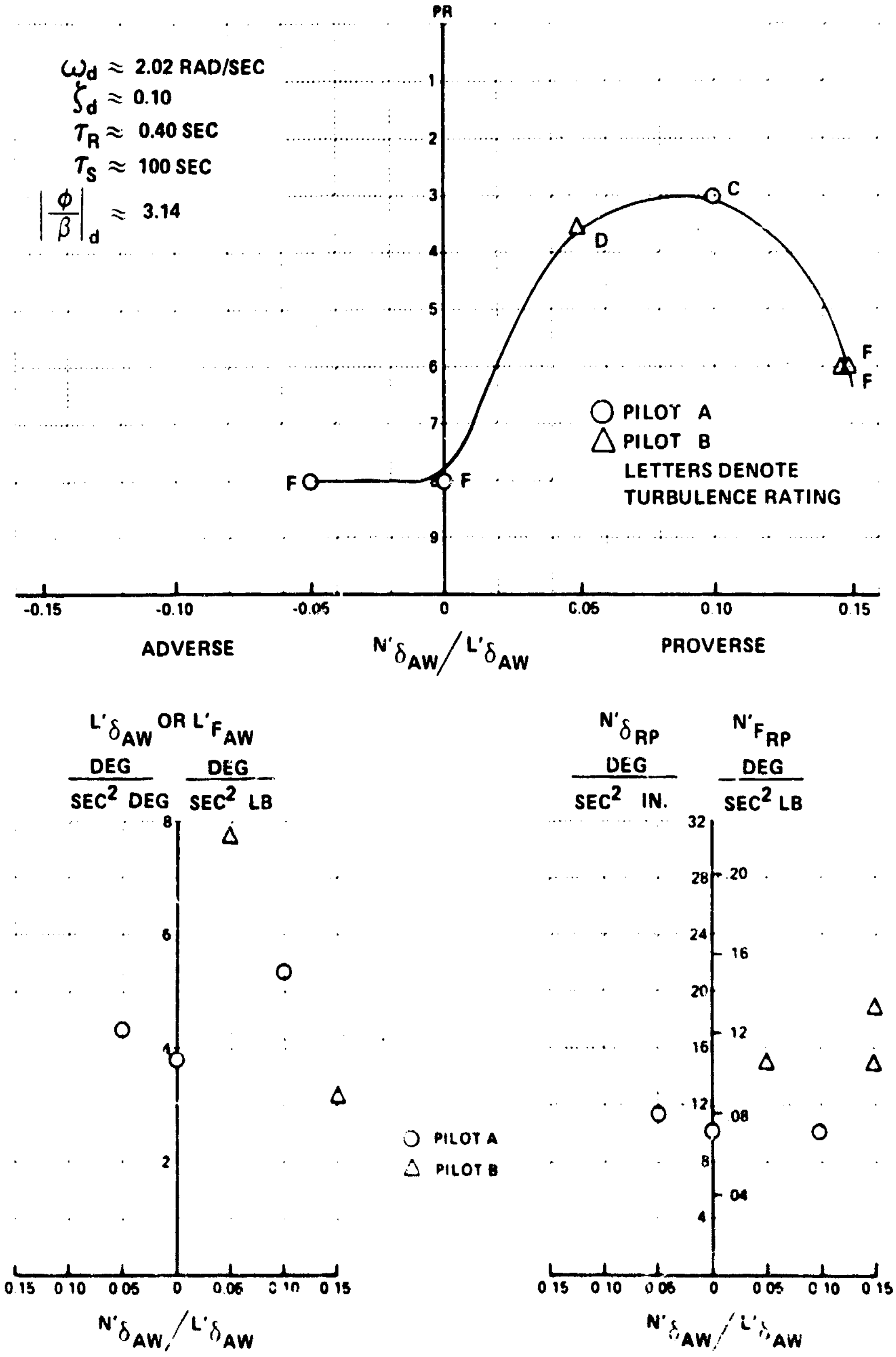


Figure 20 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 4 WHEEL CONTROLLER

The high roll-to-sideslip ratio of these configurations accentuated the roll response to turbulence. It also increased the effect of varying $N'_{\delta_{AW}}/L'_{\delta_{AW}}$, and caused a much larger movement of the numerator zeros in the ϕ/δ_{AW} transfer function. The result was a much larger variation in pilot rating as a function of the control variable, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ due to greater excitation of the Dutch roll resulting from aileron inputs.

The major objection for all the configurations was the crisp, rapid roll response to turbulence. The Dutch roll mode primarily showed up as a roll oscillation. For the adverse and zero $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ values evaluated, the Dutch roll pole and numerator zero in the ϕ/δ_{AW} transfer function are widely separated. This means the ailerons are quite effective in exciting the Dutch roll mode. The pilot can actually compound the roll response to an external disturbance if he miscoordinates with the rudder or continues to excite the Dutch roll with the ailerons. In either case, the primary reason for the unacceptable ratings for these cases was the exaggerated aileron control motions required to counter the large rolling response generated by turbulence.

The turbulence response was equally as objectionable for the most proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ case evaluated. In addition, there were increased complaints about the unpredictability of the basic roll control resulting from the phasing of the Dutch roll mode which had effectively increased the apparent roll mode time constant. A root locus closure likewise indicates a lightening of the Dutch roll damping ratio as the pilot closes on bank angle with the ailerons, assuming the pilot to be a pure gain controller.

There was considerable scatter in the control sensitivities selected for these configurations, especially for the ailerons. No explanation was given by the evaluation pilot for the quite high aileron sensitivity selected for the slightly proverse aileron yaw configuration.

4.6 LOW DUTCH ROLL FREQUENCY, LOW ROLL MODE TIME CONSTANT

The results for evaluations performed at a Dutch roll frequency of 1.0 rad/sec and a roll mode time constant of 0.4 seconds are discussed in the following eight subsections.

4.6.1 Group 5 -- Low Dutch Roll Damping Ratio, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 0.99 rad/sec $|\phi/\beta|_d$ = 1.54

ζ_d = 0.03 τ_R = 0.35 sec τ_S = 100 sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 21, and the experimental results in Figure 22.

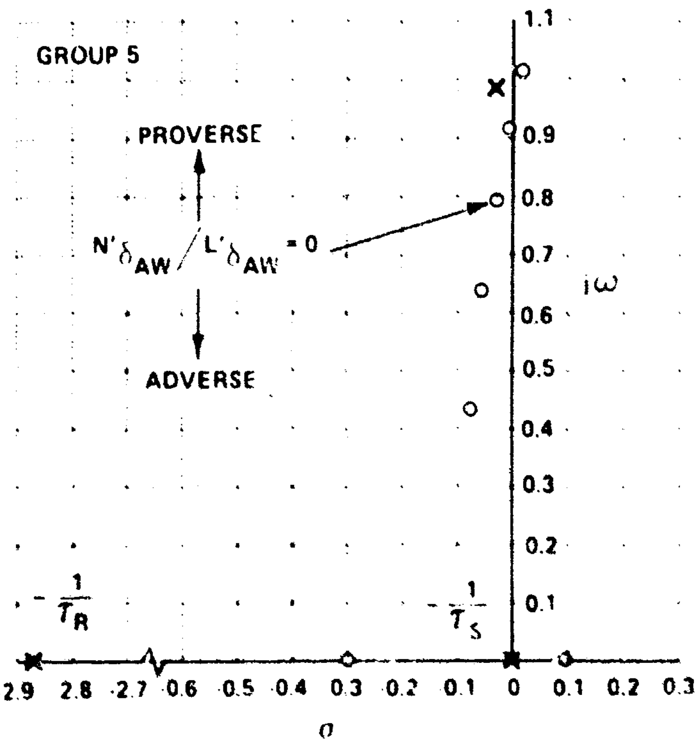


Figure 21 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 5

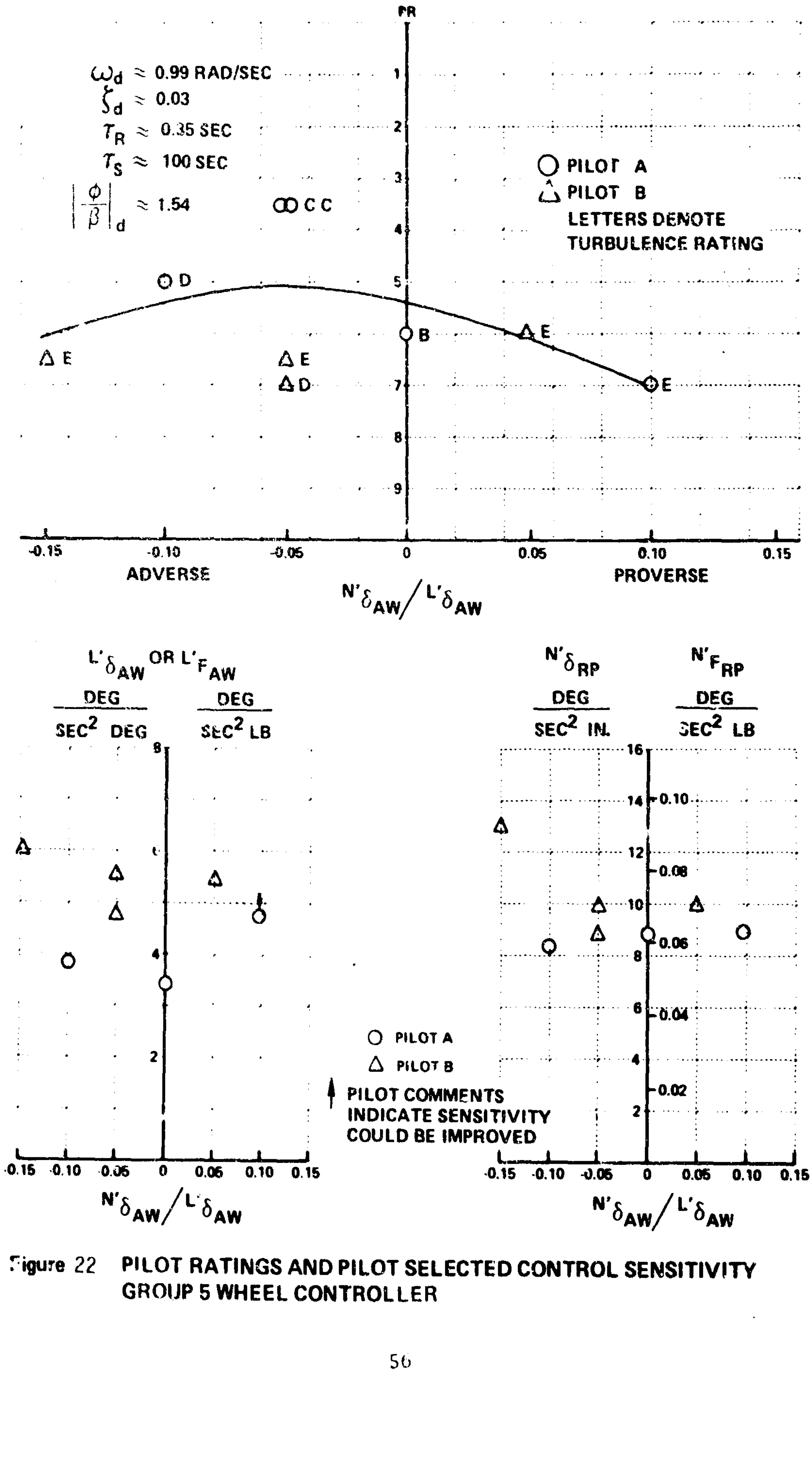


Figure 22 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 5 WHEEL CONTROLLER

These configurations were unsatisfactory for the landing approach at all tested values of the aileron yaw parameter, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$. The optimum average pilot rating was five. From Figure 22, it is noted that the configuration with $N'_{\delta_{AW}}/L'_{\delta_{AW}} = -0.05$ was twice rated as good as 3.5 and also at 6.5 and 7. This apparent discrepancy is believed to result from the pilots' assessment of the configuration's response to turbulence as indicated by the turbulence ratings accompanying the plotted pilot ratings.

There were three dominating pilot comments for all values of aileron yaw tested: (1) Coordination requirements were severe and difficult to achieve, often leading to overcontrolling with the rudder. (2) There were persistent directional oscillations which also compounded the coordination problem. (3) Response to turbulence was predominantly directional and easily excited; though slow, the nose excursions were large and difficult to control.

The coordination difficulties in the most adverse aileron yaw case were caused by the large sideslip response and small bank angle response to an aileron input. The pilot commented that he would typically overcontrol with the rudder. When he tried to coordinate the large nose "hang-up" during turn initiation, the nose would swing in the opposite direction, i.e., into the turn, leading to further rudder use in attempting to zero the sideslip. As aileron yaw became more proverse, the coordination should have become easier; however, as already mentioned, coordination and directional oscillations were problems at all values of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$.

If the pilot is assumed to be a simple proportional controller, a root locus closure indicates that for the proverse aileron yaw cases the pilot could actually drive the Dutch roll mode unstable by tightening his control through attempts to track bank angle more accurately and may induce bank angle oscillations. For the adverse aileron yaw cases, the pilot may actually increase the closed loop damping, hence, a reason for the optimum pilot rating occurring at a small value of adverse aileron yaw.

There was considerable variation between pilots in the selected values of $L_{\delta_{AW}}$. The selected values of $N'_{\delta_{RP}}$ show less variation which can be attributed to the almost overwhelming coordination and directional control problems which made both pilots sensitive to rudder forces.

4.6.2 Group 6 -- Moderate Dutch Roll Damping Ratio, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.00 rad/sec $\quad |\phi/\beta|_d$ = 1.56

ζ_d = 0.11 $\quad \tau_R$ = 0.40 sec $\quad \tau_S$ = 100 sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 23, and the experimental results in Figure 24.

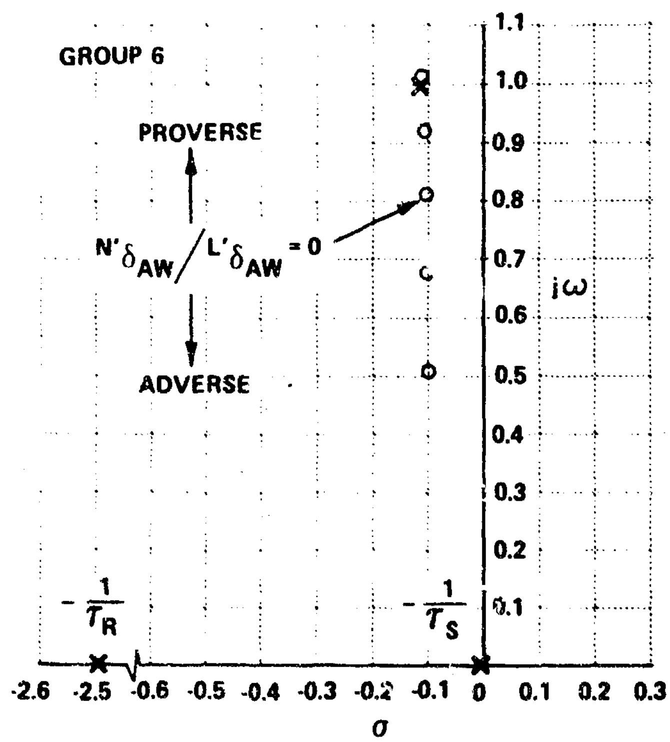


Figure 23 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 6

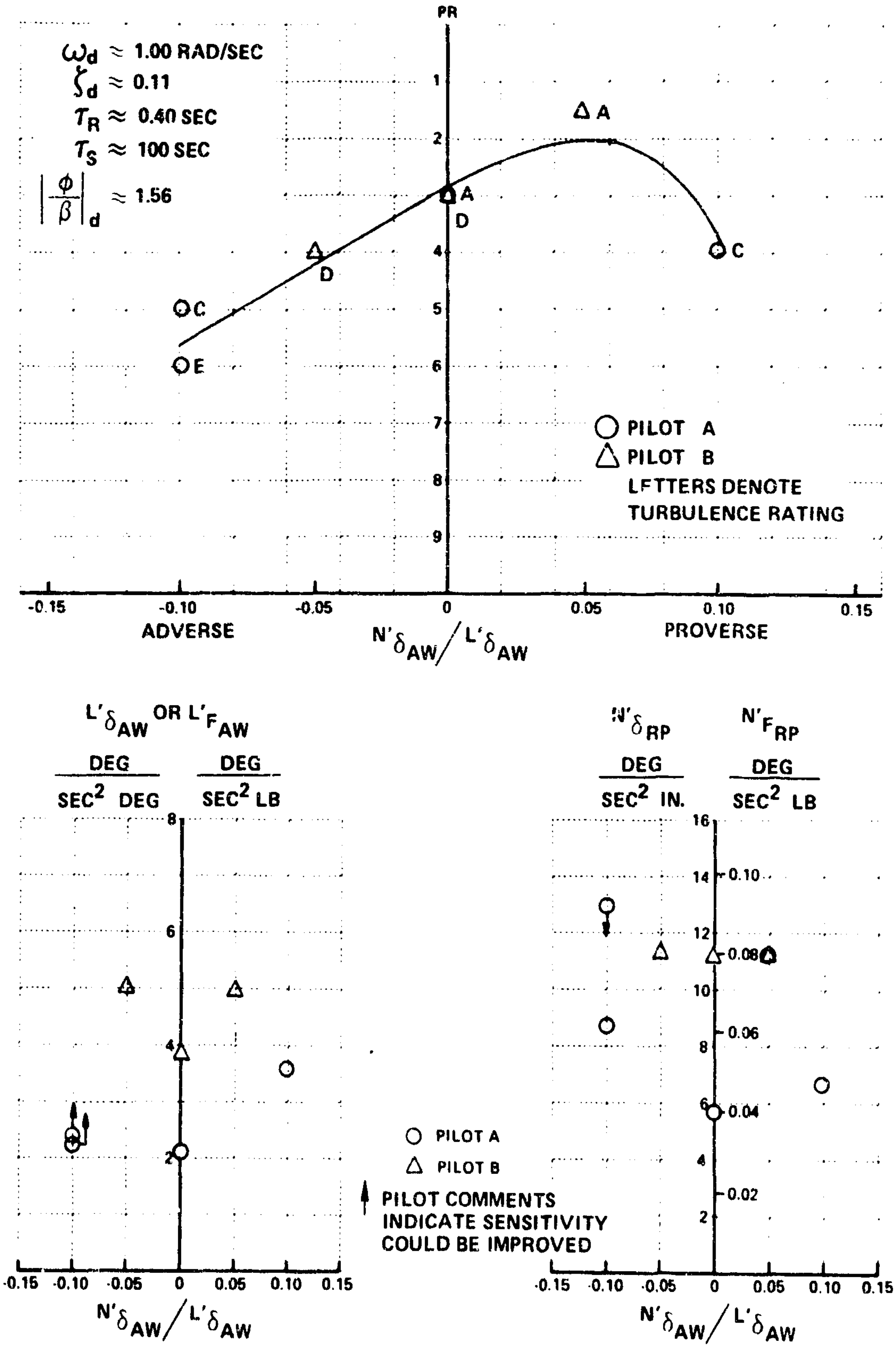


Figure 24 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 6 WHEEL CONTROLLER

The optimum pilot rating occurred at the small proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ tested, where both pilots commented that the roll control was precise and predictable. Little or no turn coordination was required, but when required, it was in the normal sense, requiring rudder into the turn. Turbulence response was fast and small in magnitude causing no difficulty. Neither pilot expressed any difficulty with crosswinds.

For the most proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ evaluated, the sideslip for an aileron input was very small, but the pilot comments indicate that there was difficulty with coordination, requiring frequent rudder use in the direction opposite the turn and a nose oscillation that continued for a considerable period of time. There was also difficulty in maintaining heading, especially in turbulence. The pilots realized that coordination was necessary and that it had to be applied in an unnatural manner. Upon turn entry, a slight amount of rudder was required in the direction opposite the turn because of the proverse aileron yaw, but as the roll rate developed, rudder into the turn was required to counteract the negative, or adverse, yaw due to roll rate, N'_p. Actual inflight records show that when the pilot was occupied with a tracking task, such as the ILS, he used the rudder in the normal manner; that is, right aileron inputs were accompanied by right rudder inputs and vice versa. In so doing he may have made the configuration appear to have even more proverse aileron yaw, thus driving the zero of the ϕ/δ_{AW} transfer function farther above the Dutch roll pole. A root locus closure indicates that if the pilot acts as a proportional controller in closing the bank angle loop, he could make the Dutch roll mode less stable. If he does, in fact, use the rudder in the normal coordination sense, he could further decrease the closed loop damping. Another objection in the most proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ case was the response to turbulence and the difficulties it caused with directional control. It should be pointed out that although the turbulence response of the open loop airplane is independent of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$, the pilot rates the turbulence response of the closed loop pilot-airplane combination which is affected by changes in $N'_{\delta_{AW}}/L'_{\delta_{AW}}$.

In the adverse aileron yaw cases, the pilots' primary objections were the coordination difficulties and momentary heading excursions in the direction opposite to the intended turn, making small heading corrections very difficult.

The selection of $L'_{\delta_{AW}}$ values shows considerable scatter. In the most adverse aileron yaw case, the pilot stated that after he selected $L'_{\delta_{AW}}$, the forces and displacements were too large, indicating that his selection of sensitivity was too low. All other values selected were considered satisfactory by the pilots. It should be noted that there is a difference in the level of sensitivities selected at all values of aileron yaw by the two evaluation pilots, in that Pilot B had a definite tendency to select higher sensitivities than Pilot A.

4.6.3 Group 7 -- High Dutch Roll Damping Ratio, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.01 rad/sec $\quad |\phi/\beta|_d$ = 1.48

ζ_d = 0.29 $\quad \tau_R$ = 0.40 sec $\quad \tau_s$ = ∞ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 25, and the experimental results in Figure 26.

Except for the extreme adverse and proverse aileron yaw cases, the evaluation pilots were pleased with the roll response and the precision with which they could maneuver. Coordination requirements were minimal, and there was no significant increase in pilot effort associated with the turbulence response. The pilot's primary objection in the most adverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ case

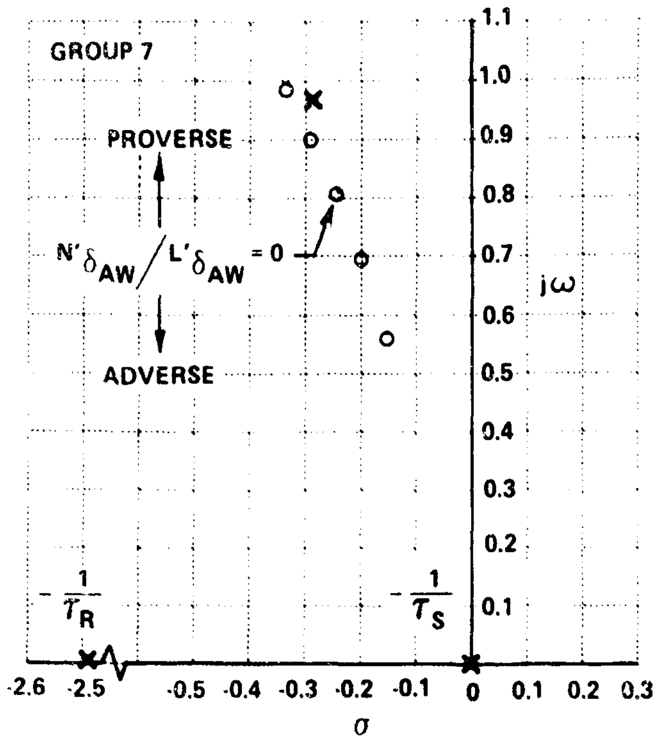


Figure 25 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 7

was the difficulty in maintaining directional control and coordinated flight. In the most proverse aileron yaw case, there was lit*le need for coordination, but the pilot noticed that a slight amount of cross control was often necessary with the rudder. In both cases, the pilots objected to the slowness with which the airplane would return to coordinated flight after a heading disturbance.

There was considerable scatter in the selection of control sensitivities for both the aileron and rudder. Pilot B selected values at a more sensitive value than Pilot A, basing his selection on crosswind considerations and one-handed operation on the final approach. Pilot A had minor complaints about heavy aileron forces after making his selections based on normal maneuvering.

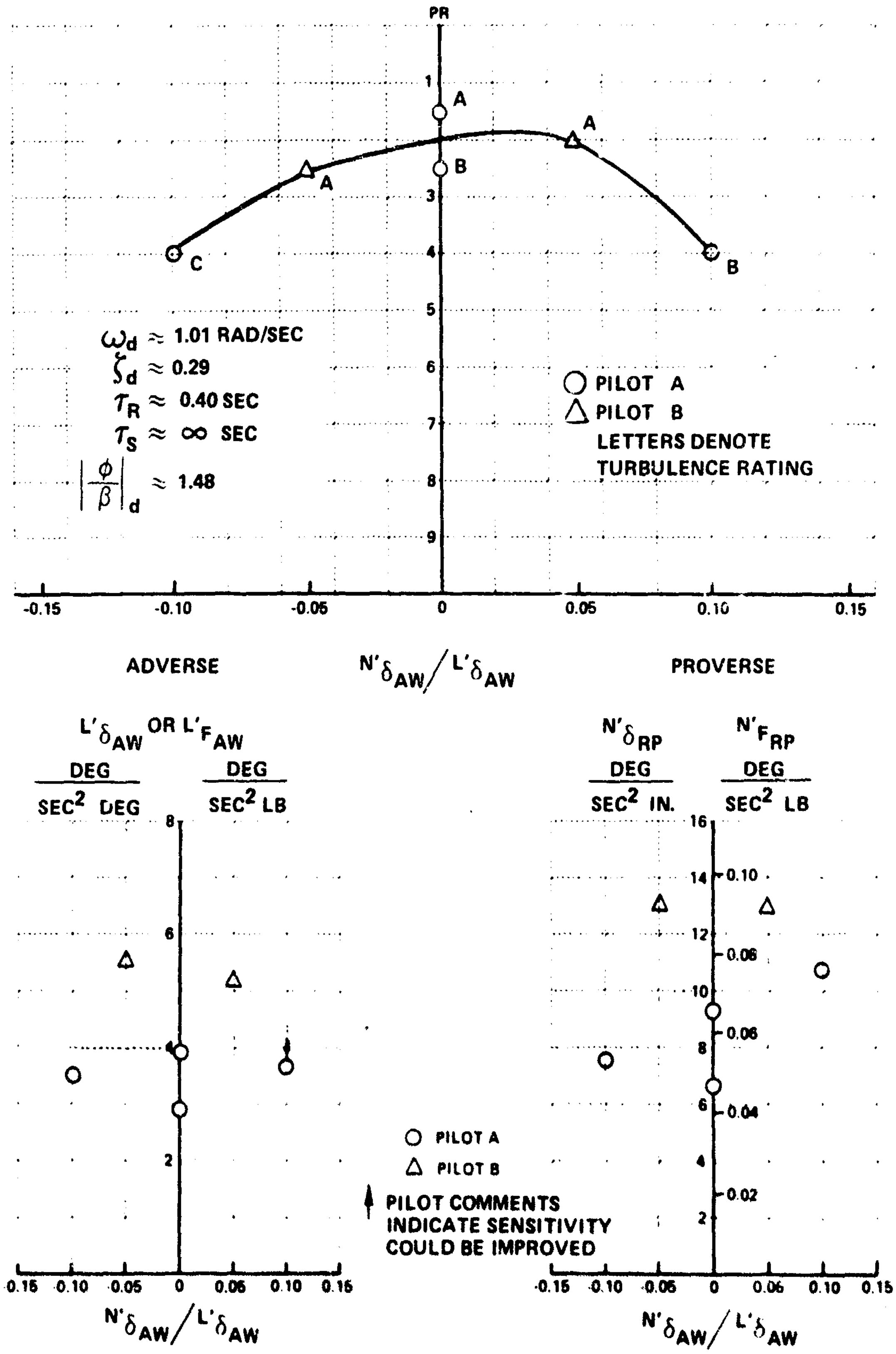


Figure 26 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 7 WHEEL CONTROLLER

1.6.4 Group 8 -- Low Dutch Roll Damping Ratio, High $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.04 rad/sec $|\phi/\beta|_d$ = 2.97

ζ_d = 0.051 τ_R = 0.35 sec τ_s = ∞ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 27, and the experimental results in Figure 28.

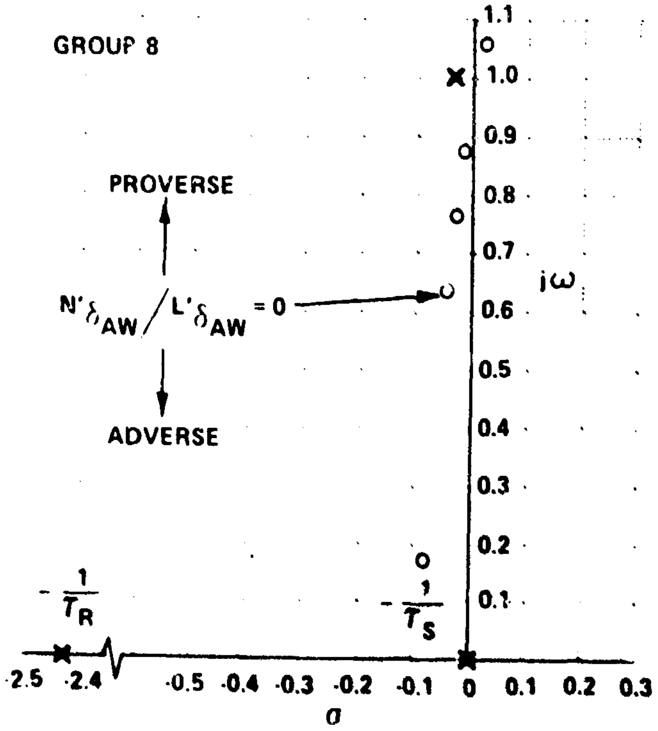


Figure 27 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 8

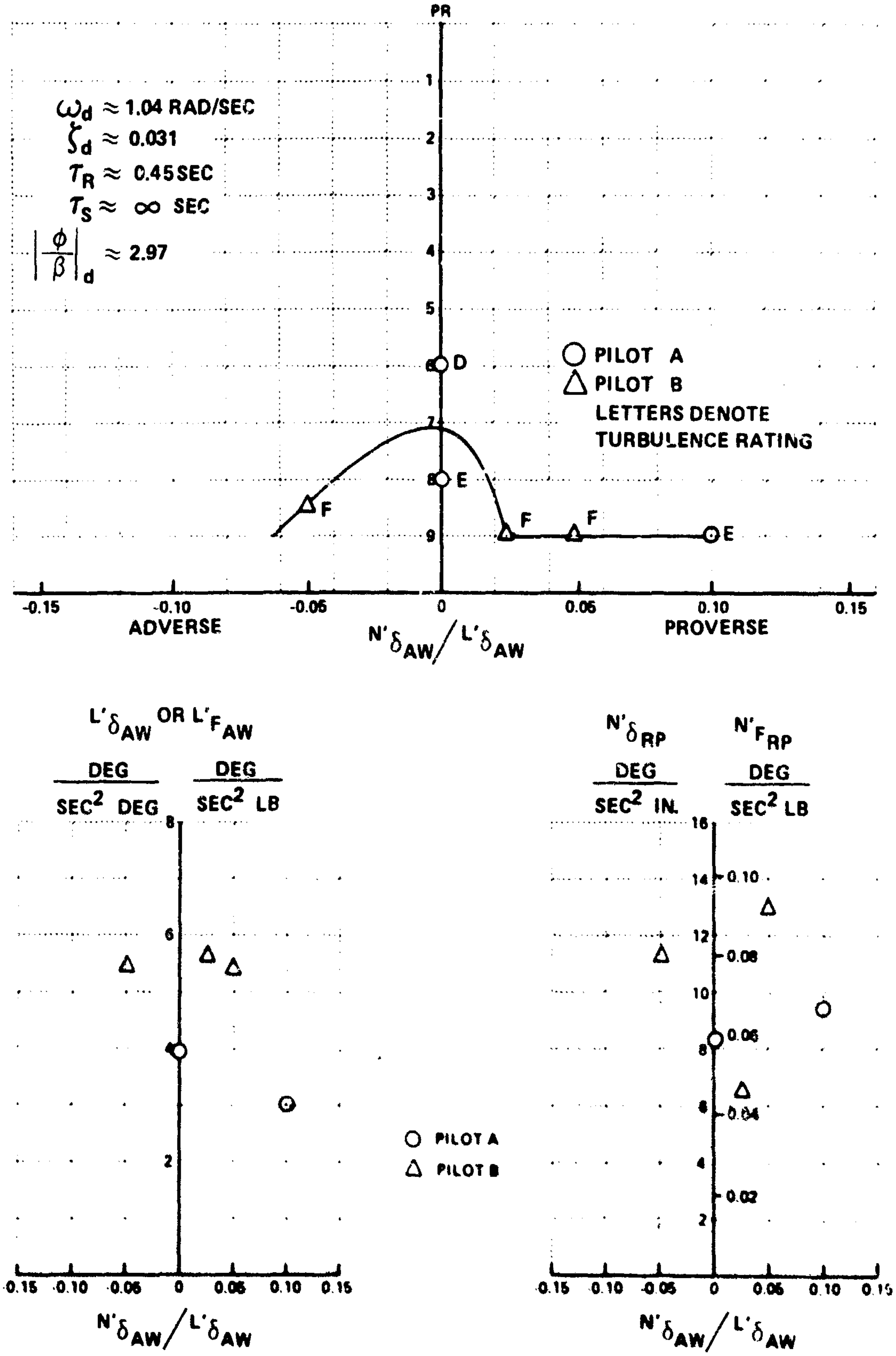


Figure 28 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 8 WHEEL CONTROLLER

The configurations in this group were unacceptable for all evaluation points. The main objections were severe coordination problems, large interaction between roll and sideslip, and difficulties with the response to turbulence. Both pilots commented that continuous rudder manipulation was required to even approach a coordinated flight maneuver and that just to control the airplane was laborious. During crosswind approaches, directional control was poor and led to difficulties in controlling bank angle because of the large roll response to small rudder inputs. The turbulence response was predominantly a sustained roll oscillation.

The control sensitivities shown reflect considerable spread between the two pilots. Pilot B based his selection on aileron forces during crosswind approaches so that he could fly with one hand. The pilot comments offered no explanation for the scatter in rudder sensitivity selections.

4.6.5 Group 9 -- Moderate Dutch Roll Damping Ratio, High $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.09 rad/sec $|\phi/\beta|_d$ = 3.11

ζ_d = 0.12 τ_R = 0.40 sec τ_s = ∞ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 29, and the experimental results in Figure 30.

The optimum pilot ratings occurred at a quite large value of proverse aileron yaw and degraded sharply with changes in the aileron yaw parameter in either direction. None of these configurations were found to be satisfactory at any test condition.

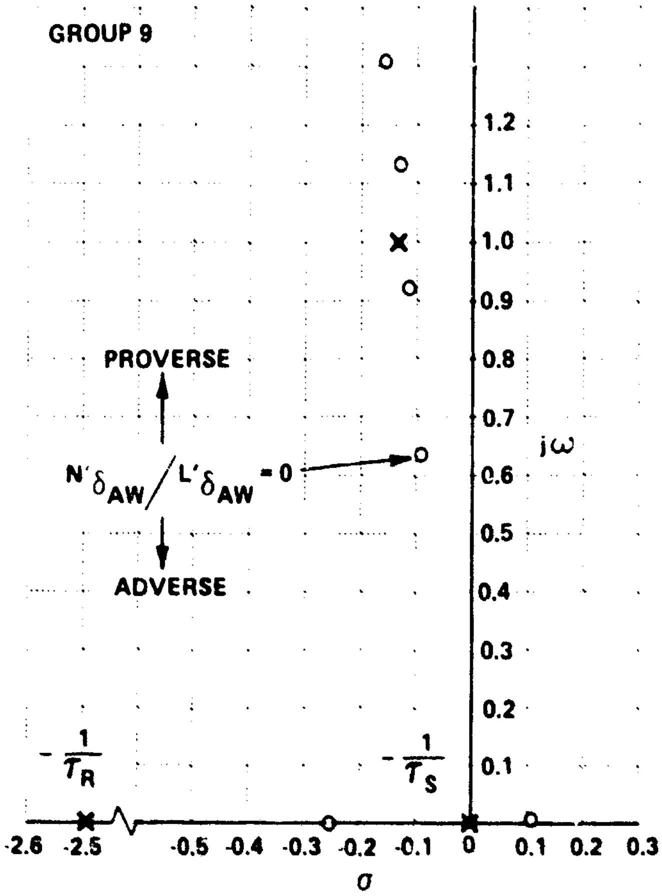


Figure 29 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 9

Near the optimum pilot rating there were moderate objections to the turbulence response, coordination requirements and trimmability. Turbulence disturbances resulted predominantly in rolling oscillations. The large roll response due to small rudder inputs complicated the coordination requirements. The pilots found it best to tolerate small sideslip angles rather than attempt precise coordination. Sideslip excursions caused variations in the aileron forces, but the roll control itself was acceptable.

Because the roll response to rudder inputs was so large, the pilots had difficulty with the crosswind approach. With the wing-down method, there was

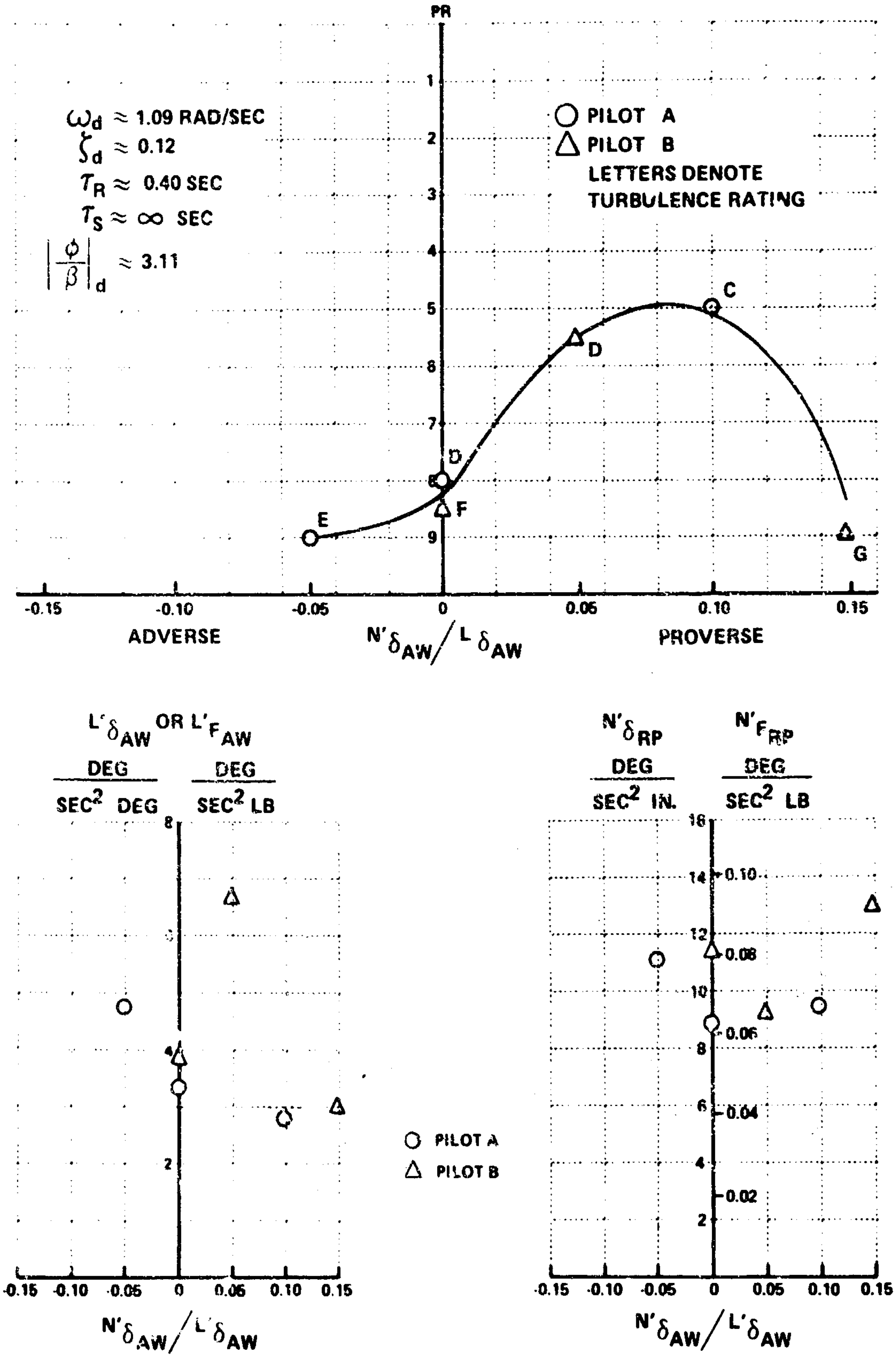


Figure 30 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 9 WHEEL CONTROLLER

difficulty holding the nose straight and holding the high aileron forces. With the crabbed approach method, abrupt rudder inputs required to de-crab, near the ground, produced large bank angle changes.

In the most proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ case, there was a tendency to overbank and for the roll rate to accelerate following an aileron input. Any rudder use resulted in such large roll rates that it had to be counteracted with large aileron inputs. The roll response to a step aileron input indicated that the apparent roll mode time constant, τ_R, was about two seconds although the actual value of τ_R was only 0.4 seconds. This is a result of the phasing of the Dutch roll mode with roll mode, causing the bank angle to continue to accelerate and, from the pilot's point of view, producing an unpredictable roll control.

For the more adverse aileron yaw cases, the major complaints were also the result of the large roll-to-sideslip ratio. Pilot comments indicate that it was imperative to keep the sideslip near zero by rudder use, and it required constant attention. As a result, the required coordination was very difficult to achieve. Turbulence compounded the coordination problem.

With the exception of one point, the selection of control sensitivities followed a very definite trend. Generally there was a compromise in that aileron sensitivities were selected to provide high enough forces to prevent inadvertent inputs and overcontrol in normal maneuvering but this resulted in heavy forces in turbulence and during crosswind approaches.

4.6.6 Group 10 -- High Dutch Roll Damping Ratio, High $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.03 rad/sec $\quad |\phi/\beta|_d$ = 2.90

ζ_d = 0.25 $\quad \tau_R$ = 0.40 sec $\quad \tau_s$ = ∞ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 31 and the experimental results in Figure 32.

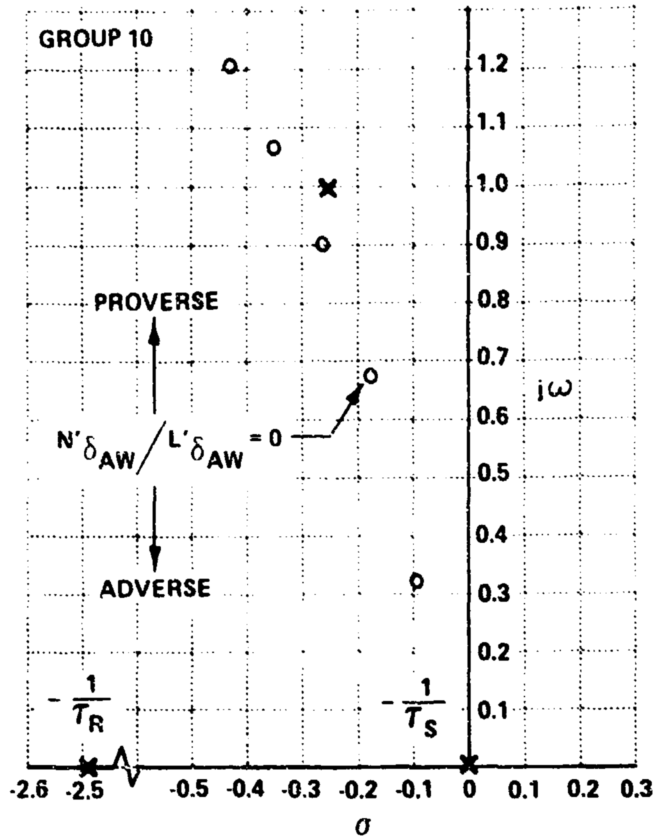


Figure 31 $\frac{\phi}{\delta_{AW}}$ **POLE-ZERO LOCATIONS FOR GROUP 10**

This group was marginally satisfactory for most test points. From the optimum pilot rating, the pilot ratings degraded very rapidly for increases in aileron yaw in the adverse direction. For increases in the proverse direction, the configuration remained marginally satisfactory at best. Near the optimum rating, the pilots liked the roll control. It was predictable and there was no tendency to overcontrol. They had no difficulties with the cross-wind approach and found the overall maneuverability good. There was some objection to the turbulence response where small excursions in sideslip were accompanied by large rolling motions. Coordination required constant rudder into the turn. This too was found somewhat objectionable since small rudder inputs produced large roll rates in the direction of the turn.

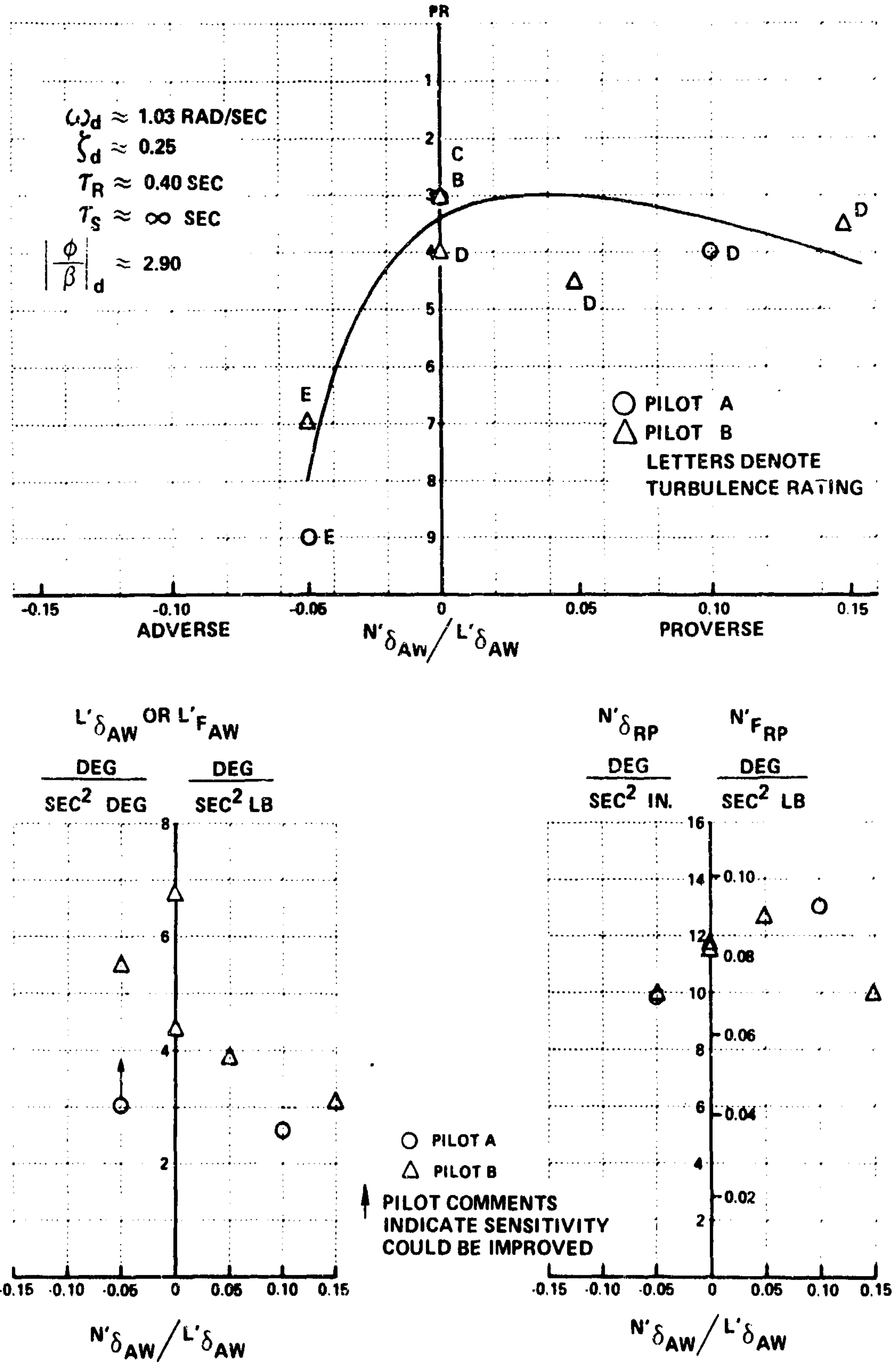


Figure 32 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 10 WHEEL CONTROLLER

In the most adverse aileron yaw case, coordination was very difficult. There was little tendency toward any oscillations; however, the nose appeared to diverge slowly to one side and would have to be returned with rudder, then it would begin going in the other direction. With the high $|\phi/\beta|_d$, rudder inputs had to be accompanied by large aileron inputs in the opposite direction.

Control sensitivity selections show considerable scatter for both the ailerons and rudder.

4.6.7 Group 11 -- Moderate Dutch Roll Damping Ratio, Low $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 0.98 rad/sec $\quad |\phi/\beta|_d$ = 0.24

ζ_d = 0.11 $\quad \tau_R$ = 0.40 sec $\quad \tau_S = \infty$ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 33, and the experimental results in Figure 34.

For these configurations, the pilots found that the roll control was good. The response was smooth and predictable, and there was no tendency to overcontrol. Except for the most adverse aileron yaw cases, coordination requirements were minimal. A little rudder helped to be more precise, but the airplane could be maneuvered very well without the use of rudder. The major objection to the most adverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ configurations was the large sideslip excitation following an aileron input which caused coordination difficulties and yawing oscillations. Neither pilot expressed any difficulty with any of the configurations in coping with crosswinds and either method could be used with equal success. A minor objection was that the response to turbulence was largely a snaking oscillation of the nose, a result of the low dihedral effect, but it did not affect the pilot's ability to maintain heading.

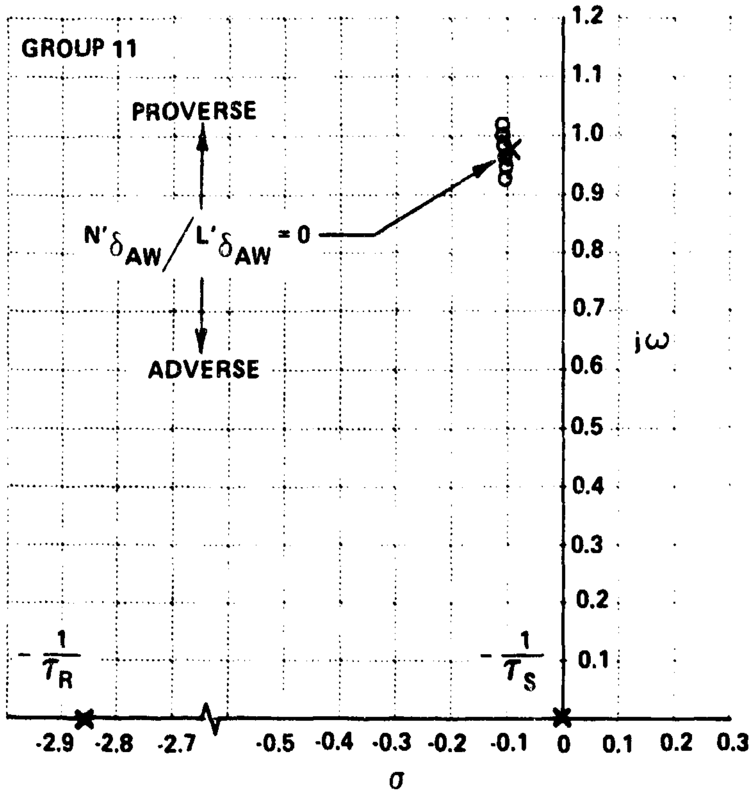


Figure 33 $\frac{\phi}{\delta_{AW}}$ **POLE-ZERO LOCATIONS FOR GROUP 11**

Control sensitivity selections show fairly consistent trends. For the aileron wheel control sensitivities, the two selections which are obviously low resulted in pilot complaints about high wheel forces.

4.6.8 Group 12 -- High Dutch Roll Damping Ratio, Low $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 0.98 rad/sec $\quad |\phi/\beta|_d$ = 0.24

ζ_d = 0.34 $\quad \tau_R$ = 0.40 sec $\quad \tau_s$ = ∞ sec

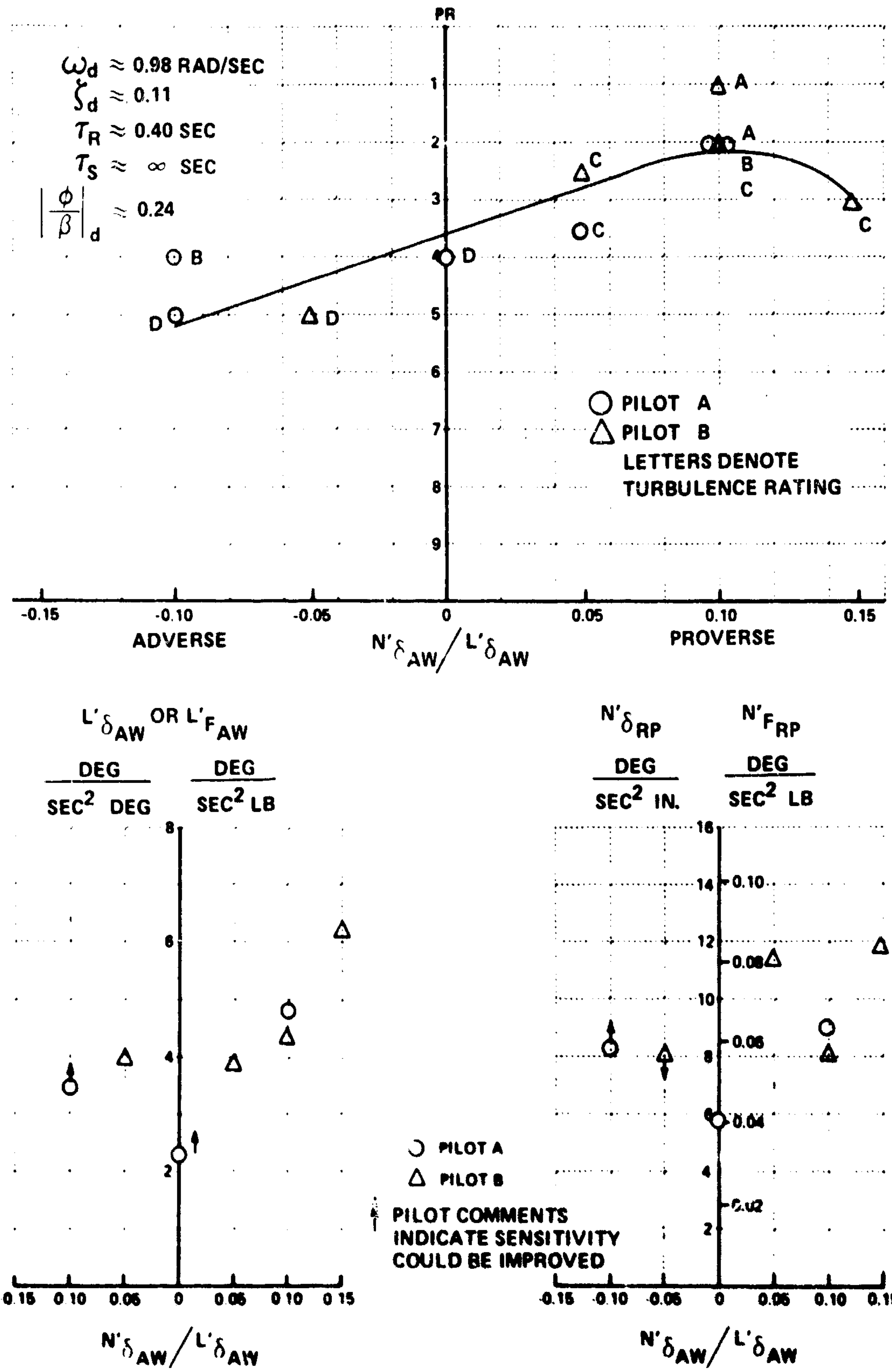


Figure 34 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 1 WHEEL CONTROLLER

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 35, and the experimental results in Figure 36.

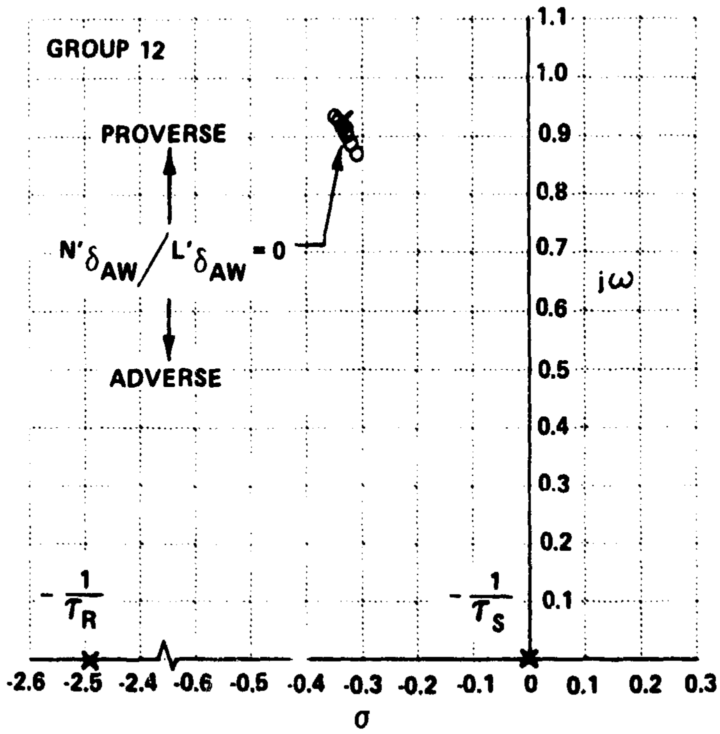


Figure 35 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 12

The pilots liked the smooth responsive roll control. Small heading corrections were easily accomplished. Directional and roll responses seemed to be separated, so there was little effect in roll from rudder use. Neither pilot expressed any difficulties with the crosswind approach. There was a small increase in pilot workload in turbulence, but it did not degrade pilot performance. For the case with the largest value of adverse aileron yaw, coordination was required, but it didn't have to be precise and was easily accomplished. In the most proverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ case, the pilot found the airplane highly desirable and reported no objections.

There was considerable difference in the selection of aileron control sensitivities between the two pilots; however, the pilot comments do not indicate that any compromises were involved; all selections were satisfactory.

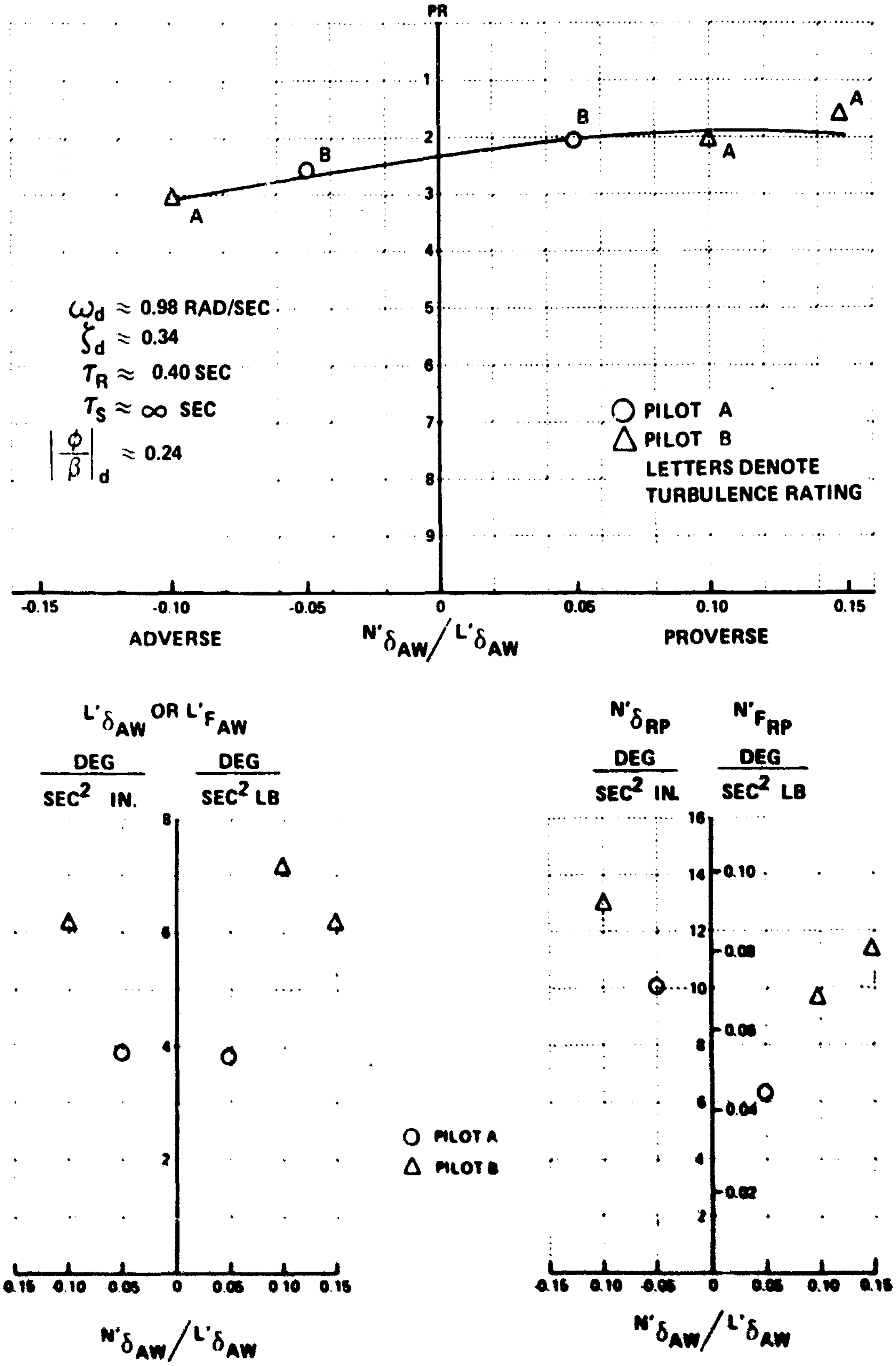


Figure 36 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 12 WHEEL CONTROLLER

4.7 LOW DUTCH ROLL FREQUENCY, MODERATE DUTCH ROLL DAMPING RATIO, MODERATE ROLL MODE TIME CONSTANT

The results for evaluations performed at a Dutch roll frequency of 1.0 rad/sec, a Dutch roll damping ratio of 0.1, and a roll mode time constant of 1.0 second are discussed in the following three subsections.

4.7.1 Group 13 - Moderate Roll Mode Time Constant, Low $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.00 rad/sec $|\phi/\beta|_d = 0.31$

ζ_d = 0.099 $\tau_R = 0.95$ sec $\tau_S = \infty$ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 37, and the experimental results in Figure 38.

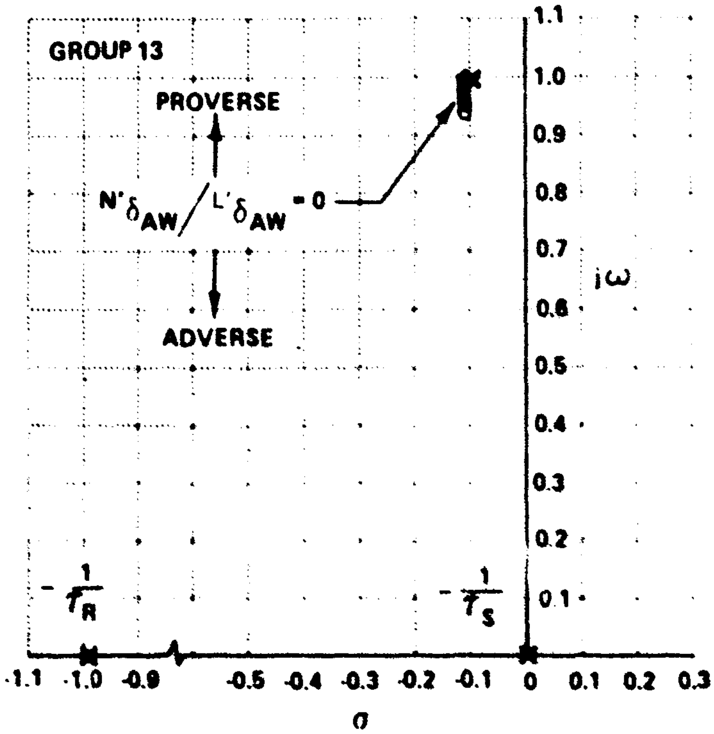


Figure 37 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 13

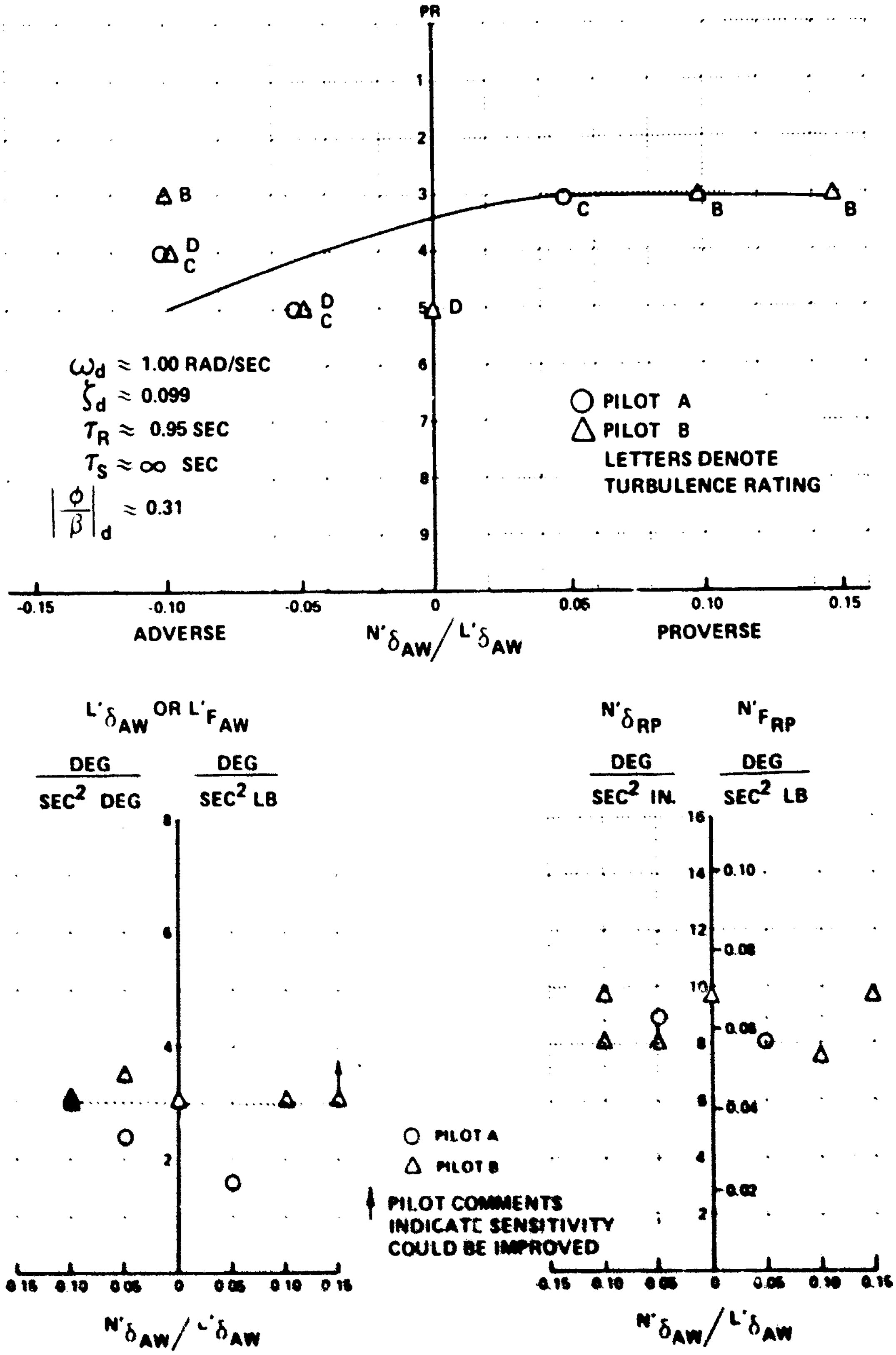


Figure 38 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 13 WHEEL CONTROLLER

In general, the pilots liked the smoothness and responsiveness of the roll control. Pilot B reported, however, a mild tendency to overcontrol in bank angle and that, on occasion, the airplane felt as if it were "taking off just a bit" in roll.

The low roll-to-sideslip ratio of the Dutch roll mode presented an interesting but possibly explainable variation in pilot rating as a function of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$. The zero and slightly adverse yaw due to aileron configurations are rated worse (one to two pilot ratings) than the most adverse aileron yaw case that was evaluated. For the most adverse $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ case, the initial nose displacement was quite opposite to the turn, but coordination was relatively easy and natural. For the zero and slightly adverse aileron yaw cases, coordination was required, but difficult to achieve, occasionally leading to overcontrolling tendencies. The conclusion was that it was best not to coordinate these configurations and just accept the resulting sideslip oscillations. Since the pilots were given the opportunity to select the rudder sensitivity, it would seem a simple matter to decrease the rudder sensitivity for these cases and to eliminate the overcontrolling tendencies. This was not possible, however, because the crosswind requirements dictated the desired rudder sensitivities. Although the rudder sensitivity selections, Figure 38, were quite consistent, Pilot A selected lower aileron sensitivities than Pilot B.

The turbulence response for these configurations was primarily in sideslip, requiring a conscientious effort by the pilot to suppress the resulting oscillations with the rudder. For the crosswind approaches, the crabbed technique was preferred by Pilot A and the wing-down method by Pilot B. Pilot B commented that he felt uncomfortable kicking out large crab angles near the ground with this configuration.

4.7.2 Group 14 - Moderate Roll Mode Time Constant, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

$$\omega_d = 1.01 \text{ rad/sec} \quad |\phi/\beta|_d = 1.53$$

$$\zeta_d = 0.10 \quad \tau_R = 1.10 \text{ sec} \quad \tau_S = \infty \text{ sec}$$

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 39, and the experimental results in Figure 40.

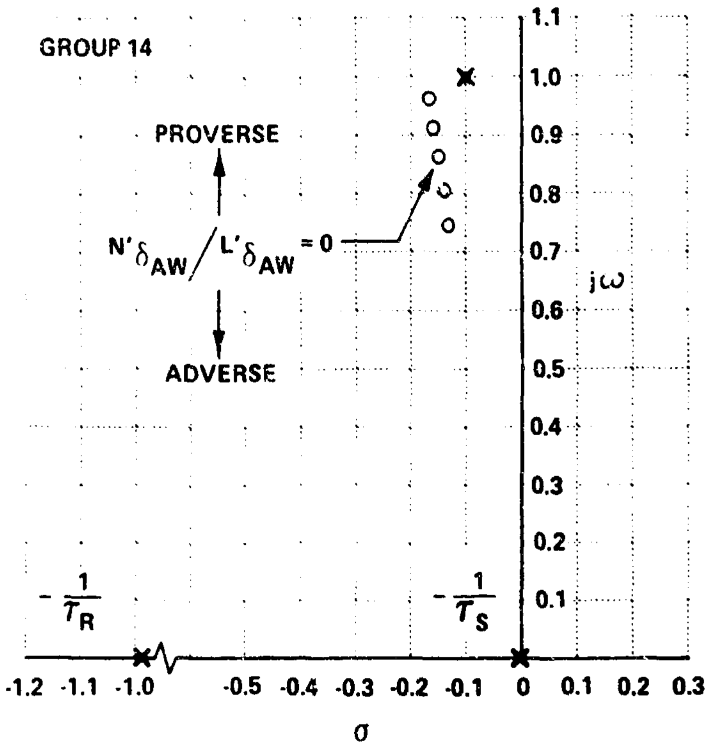


Figure 39 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 14

The overall lateral-directional handling qualities of this group of configurations were considered to be quite good. Both pilots noted a small tendency to overshoot in bank angle but considered the roll control satisfactory. Pilot A commented that the airplane was slow to respond initially to an aileron input. The roll control, for the most adverse aileron yaw case evaluated, was considered unpredictable.

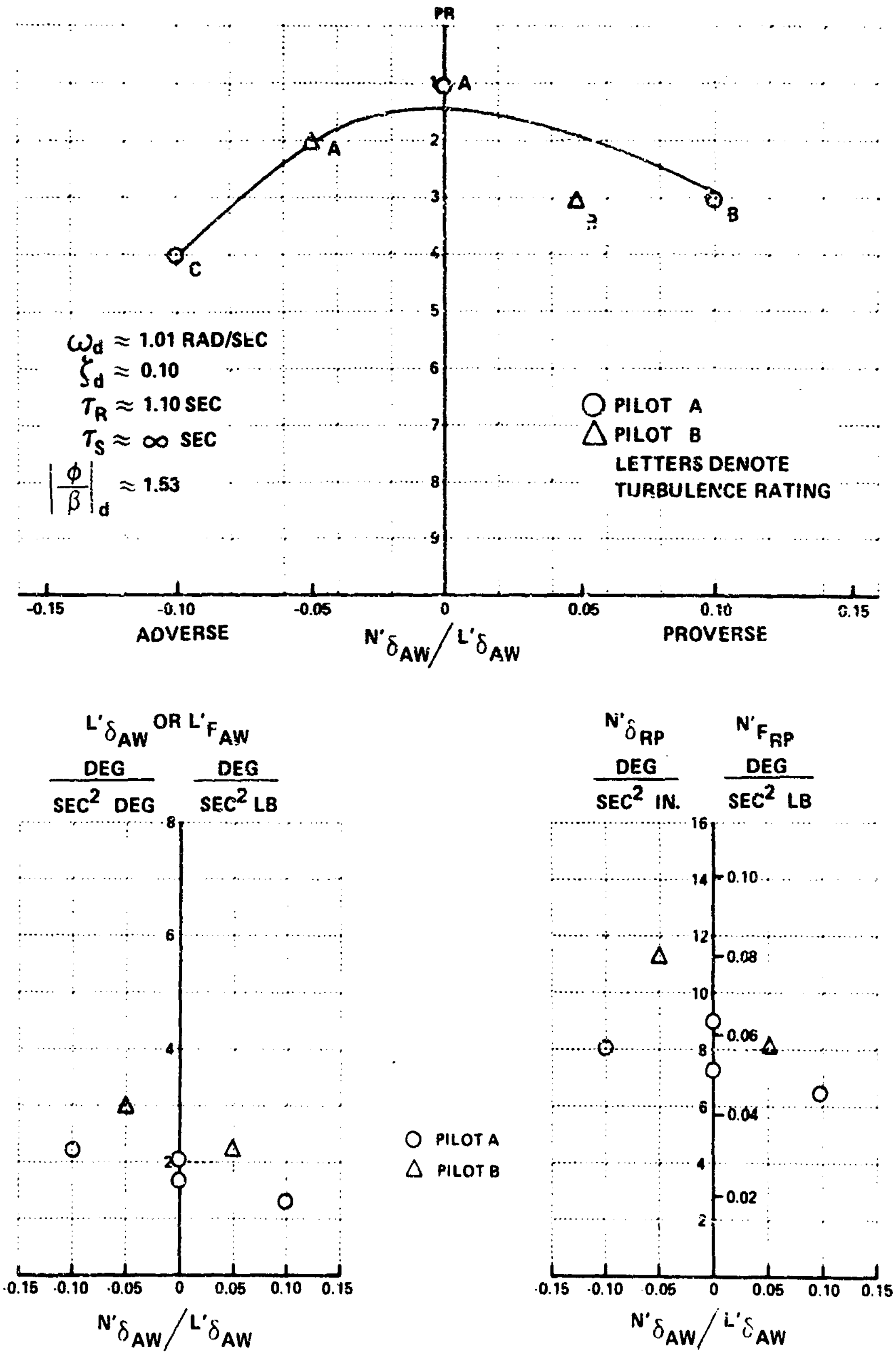


Figure 40 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 14 WHEEL CONTROLLER

The effects of turbulence were noticeable, but did not significantly deteriorate the handling qualities. Likewise, the crosswind approaches were easily accomplished and presented no particular problems. Both pilots were consistent in their selection of aileron control sensitivities.

4.7.3 Group 15 - Moderate Roll Mode Time Constant, High $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.13 rad/sec $|\phi/\beta|_d$ = 3.50

ζ_d = 0.09 τ_R = 0.95 sec τ_s = ∞ sec

The ϕ/δ_{AW} transfer function zer locations with respect to the nominal Dutch roll pole are shown in Figure 41, and the experimental results in Figure 42.

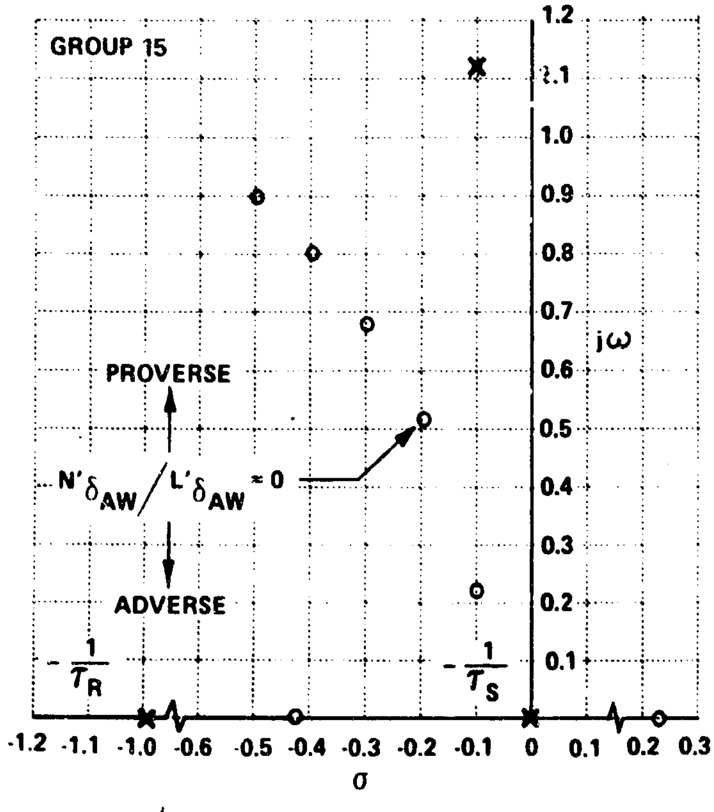


Figure 41 $\frac{\phi}{\delta_{AW}}$ POLE-ZERO LOCATIONS FOR GROUP 15

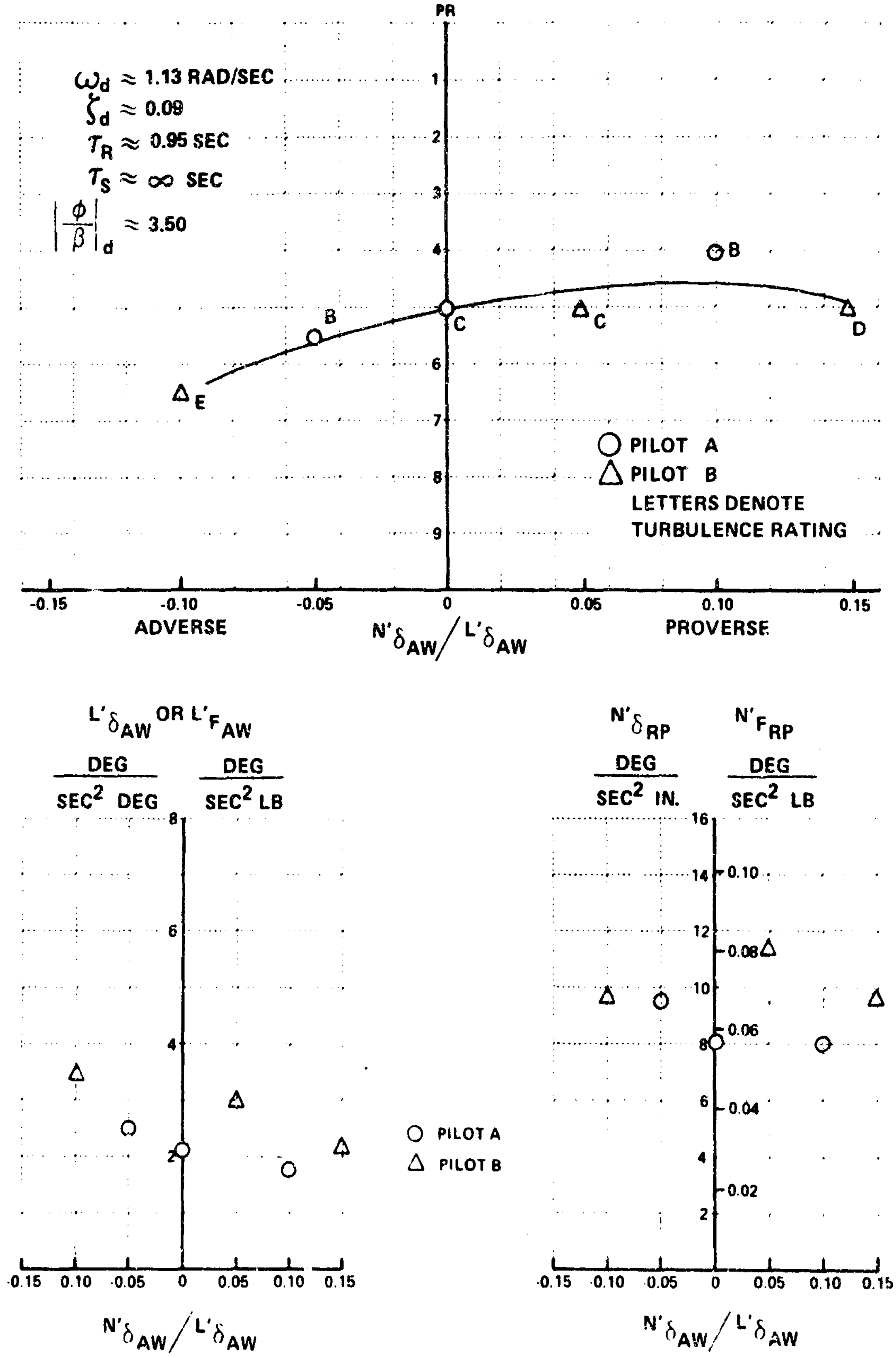


Figure 42 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 15 WHEEL CONTROLLER

None of the configurations in this group were considered to have satisfactory lateral-directional handling qualities. The roll control was the primary objection, with the rudder coordination requirements being almost equally objectionable. The combination of high roll-to-sideslip ratio and long roll mode time constant compounds the pilot's control of bank angle. Because of the high dihedral effect, the rudder was quite effective in producing a roll rate. Consequently, attempts to coordinate, which was a requirement for each of these configurations, tended to cause overbanking. The airplane was described as having a slow initial response and an unpredictable final response, with a tendency to accelerate in roll rate, resulting in overbanking.

The most adverse aileron yaw case evaluated had a non-minimum phase roll rate and bank angle response. Consequently, the pilot had to use the rudder for coordination to obtain a desired bank angle. The pilot commented that coordination was a definite requirement, and that he quickly learned to lead each turning maneuver with a rudder input. The requirement for constantly having to use the rudder was a major objection.

The large roll response associated with turbulence was considered objectionable. In turbulence it was considered a moderate control task just to maintain a given bank angle or to keep the wings level. The only complaint for the crosswind approaches was the large aileron forces encountered during a wing-down approach and in a decrab maneuver. Both pilots were quite consistent in their selection of control sensitivity for both the rudder and aileron.

4.8 LOW DUTCH ROLL FREQUENCY, MODERATE DUTCH ROLL DAMPING RATIO, LONG ROLL MODE TIME CONSTANT

The following section discusses the results for an evaluation group performed at a Dutch roll frequency of 1.0 rad/sec, a Dutch roll damping ratio of 0.1, and a roll mode time constant of 2.0 seconds.

4.8.1 Group 16 - Long Roll Mode Time Constant, Moderate $|\phi/\beta|_d$

These configurations had the following lateral-directional mode characteristics:

ω_d = 1.00 rad/sec $|\phi/\beta|_d$ = 1.55

ζ_d = 0.11 τ_R = 2.0 sec τ_s = ∞ sec

The ϕ/δ_{AW} transfer function zero locations with respect to the nominal Dutch roll pole are shown in Figure 43, and the experimental results in Figure 44.

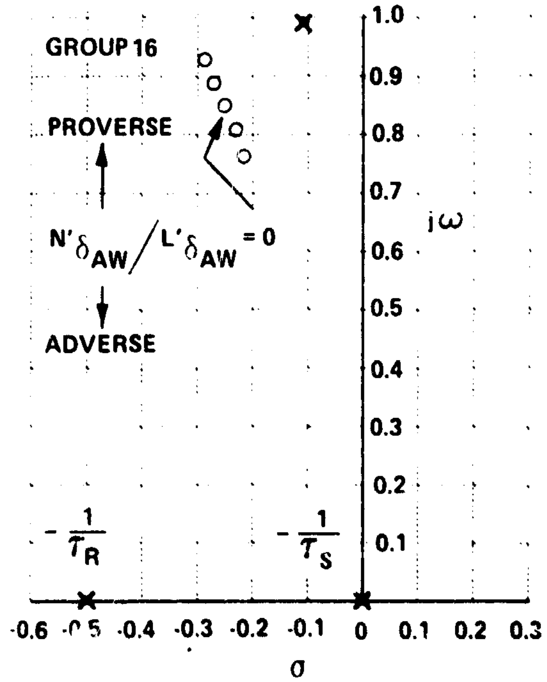


Figure 43 $\frac{\phi}{\delta_{AW}}$ **POLE-ZERO LOCATIONS FOR GROUP 16**

These configurations, at best, must be considered borderline cases. That is, they are between satisfactory (no improvement necessary) and unsatisfactory (deficiencies warrant improvement). There was little variation in pilot rating over the range of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ evaluated. This follows from the relatively small displacements of the numerator zeros in the ϕ/δ_{AW} transfer function, as shown in Figure 43.

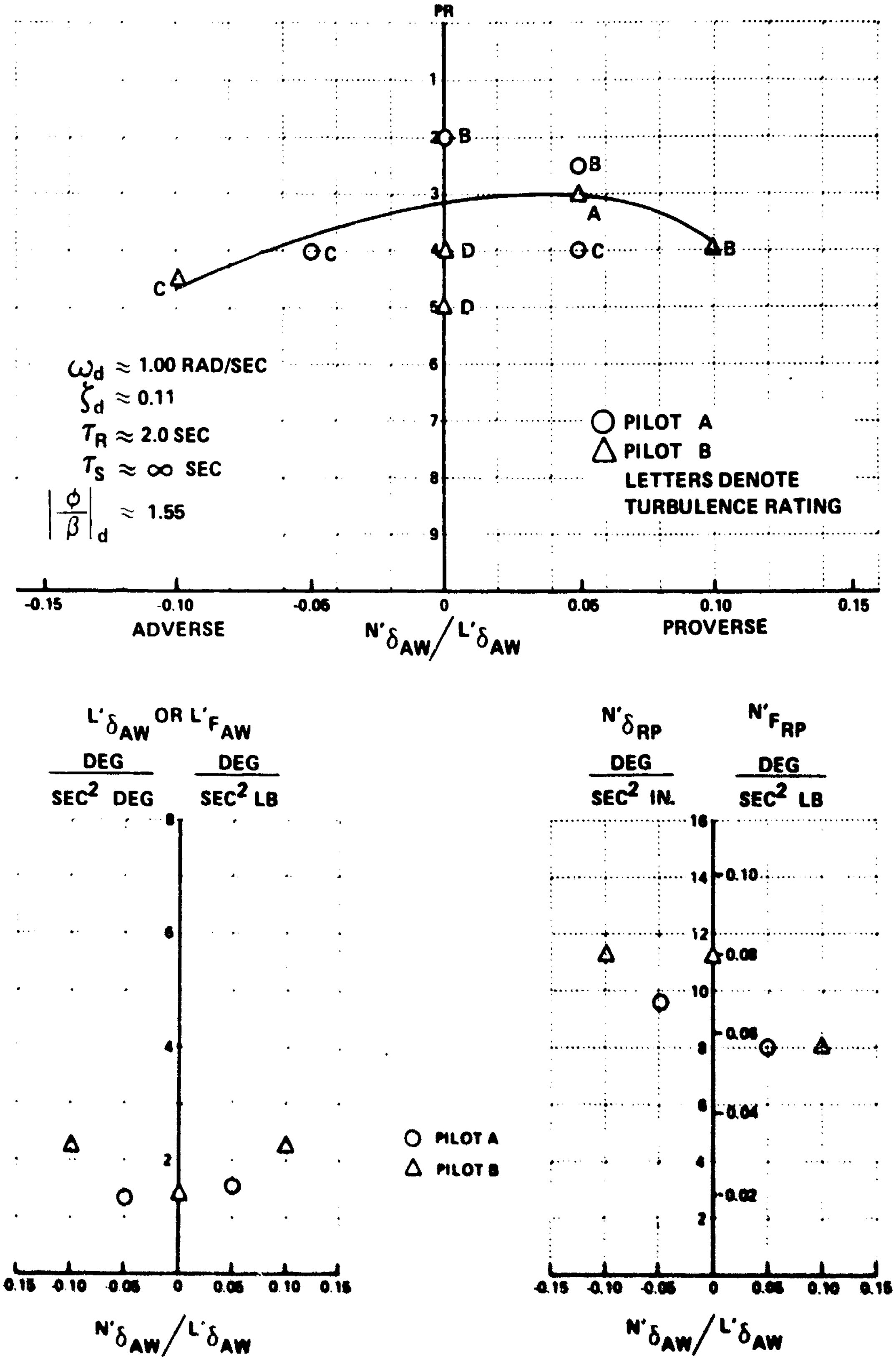


Figure 44 PILOT RATINGS AND PILOT SELECTED CONTROL SENSITIVITY GROUP 16 WHEEL CONTROLLER

The major problem with these configurations was the effect of the long roll mode time constant and not the effects of adverse or proverse yaw due to aileron. The roll control was described as unpredictable. There was a tendency for the initial roll response to be slow followed by an acceleration in roll rate, making the final response hard to predict, resulting in overbanking. This complicated the selection of aileron wheel sensitivity. If the sensitivity was sufficiently high to allow good control for small aileron inputs, then the overbanking tendency for large maneuvers was exaggerated; the converse was true if low sensitivities were selected. The resulting compromise made the aileron forces feel as if they were heavy for starting and stopping roll rates. The pilots were quite consistent in their selection of both the aileron and rudder sensitivities.

The effects of the long roll mode time constant were especially noticeable during the offset approach maneuver and the crosswind landings. The overbanking tendency, the feeling that the roll rate was going to "get away" from the pilot, and the requirement for large abrupt aileron inputs to start and stop roll rates were objectionable features. Rudder coordination in turns was listed as a requirement but did not present a major problem.

Turbulence primarily created problems with the roll control. The requirement for numerous aileron inputs tended to increase the pilot workload but the effect on the overall handling qualities was never worse than a minor deterioration in task performance. Neither evaluation pilot was satisfied with the slow initial roll response during the crosswind approaches. The wing-down method for correcting for crosswinds was preferred in order to avoid abrupt maneuvering near the ground.

4.9 COMPARISON OF PILOT RATINGS WITH VARIATIONS IN LATERAL-DIRECTIONAL DYNAMICS

The matrix of configurations evaluated allows a number of comparisons to be made. Comparisons of Dutch roll frequency, damping ratio, roll-to-sideslip ratio and roll mode time constant are presented.

4.9.1 Comparison of Pilot Rating Data Obtained at Two Dutch Roll Frequencies

Pilot rating data for Dutch roll frequencies of 1.0 and 2.0 radians per second are compared at three values of Dutch roll damping ratio in Figures 45a, b and c, and for two values of roll-to-sideslip ratio in Figure 46.

The most significant difference in pilot ratings for the two frequencies evaluated occurred at the low value of Dutch roll damping ratio (Figure 45a) where better pilot ratings were obtained at the high frequency than at the low. Although both groups were quite susceptible to turbulence, the low frequency configurations were further degraded because of the difficult coordination requirements associated with the slow directional response. This is consistent with References 4 and 29 which indicate that an increase in damping ratio is desirable as the Dutch roll frequency is reduced in order to keep the total damping of the system, $\zeta_d \omega_d$, above an acceptable level. Reference 71 requires a minimum $\zeta_d \omega_d = 0.15$ for Level 1 flying qualities.

As shown in Figure 45b, there is essentially no difference in the pilot ratings between those configurations evaluated at the two different Dutch roll frequencies for the moderate damping ratio. The pilot ratings do, however, show a more rapid deterioration at the highest proverse yaw due to aileron case for the low frequency than for the high. Since the closed loop Dutch roll damping ratio is reduced for these higher proverse configurations,

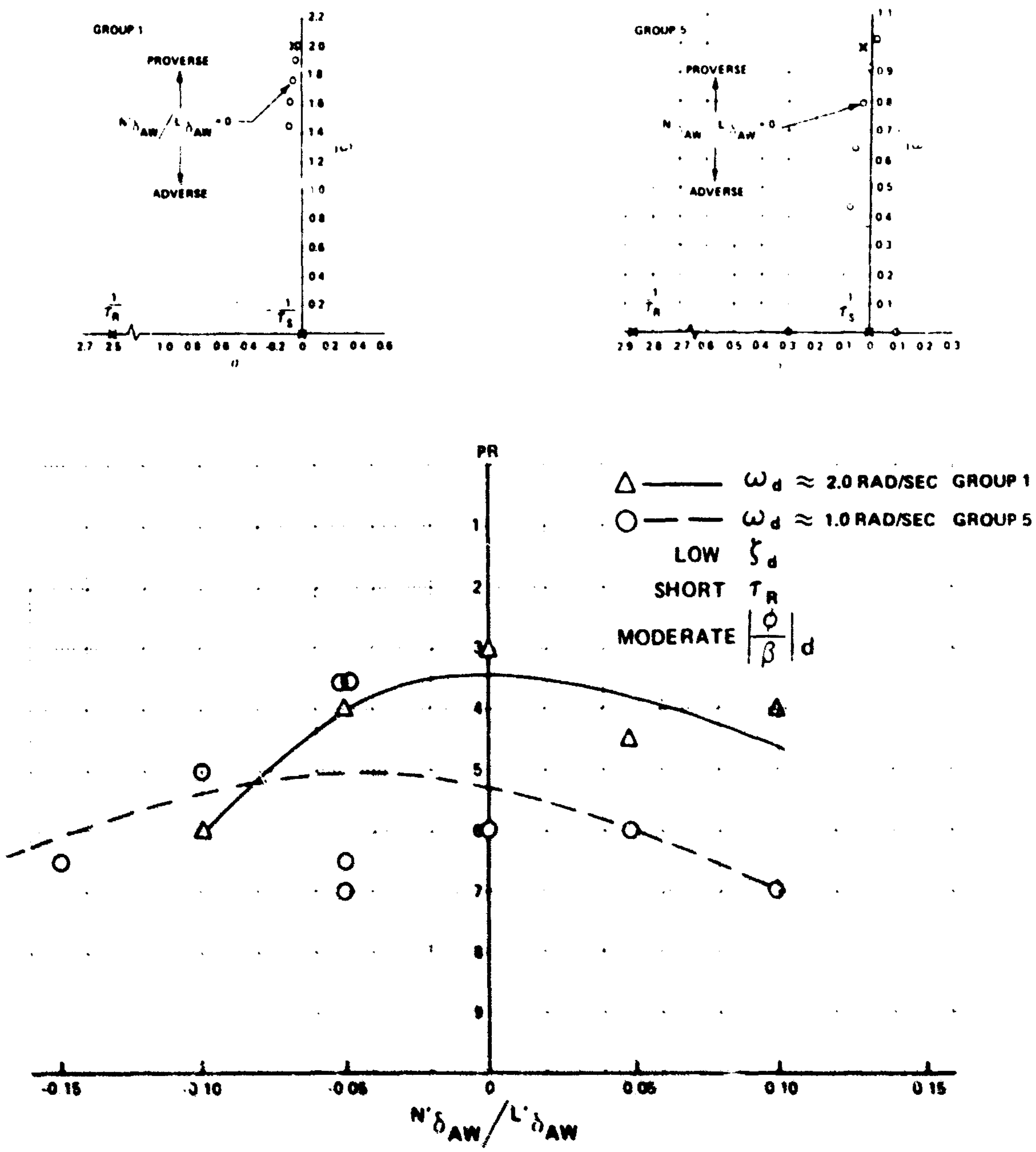


Figure 45a COMPARISON OF PILOT RATINGS AT TWO DIFFERENT FREQUENCIES WITH LOW ζ_d

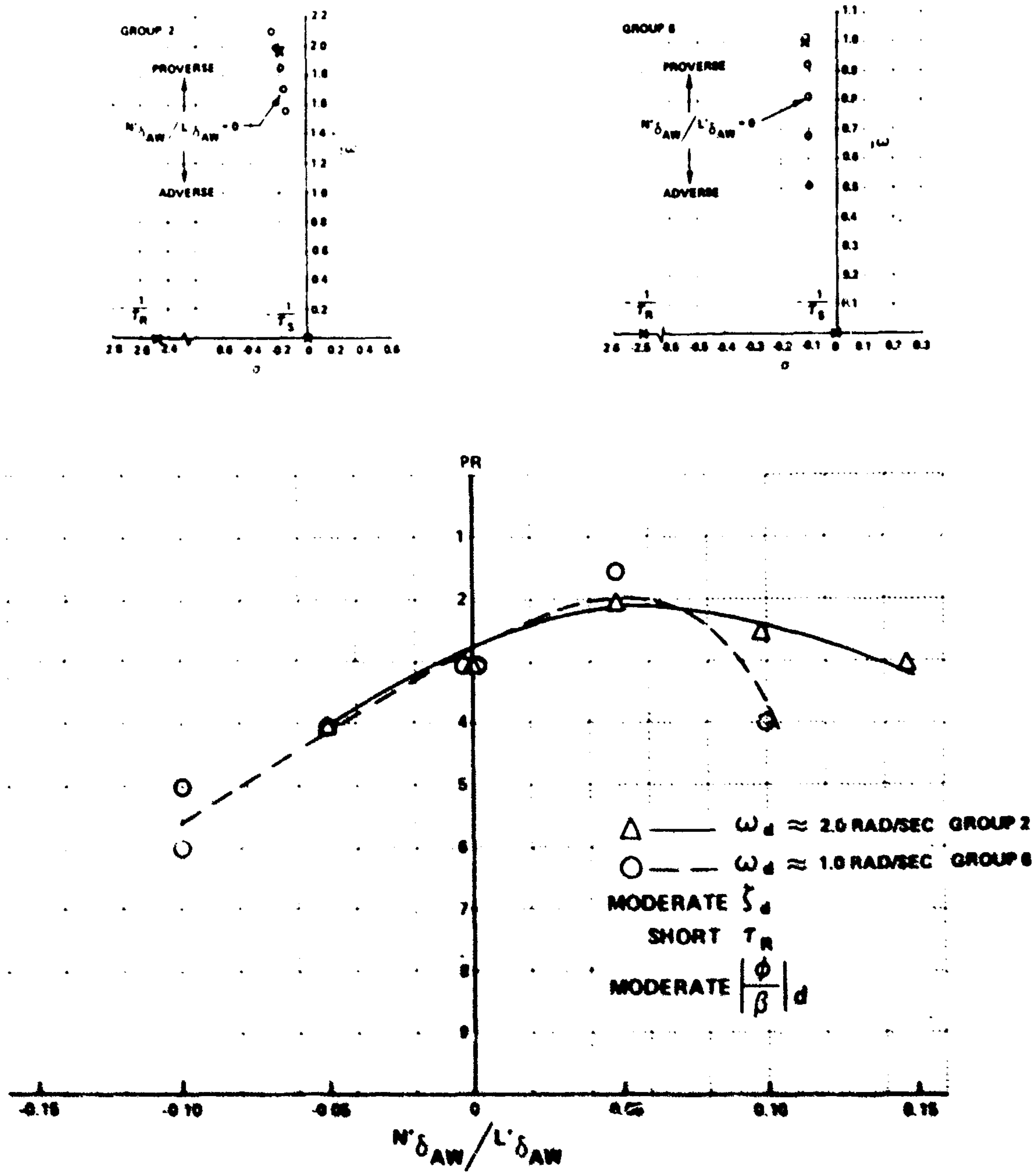


Figure 45b COMPARISON OF PILOT RATINGS AT TWO DIFFERENT FREQUENCIES WITH MODERATE ζ_d

the more rapid deterioration in pilot rating for the low-frequency case is consistent with the results for the low damping configurations described above, indicating that the pilot may be sensitive to small $\zeta_d \omega_d$.

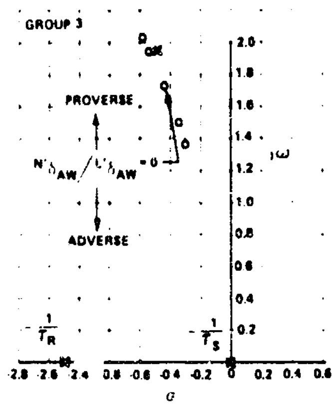
At the higher Dutch roll damping ratio, $\zeta_d \approx 0.25$, (Figure 45c) the low Dutch roll frequency cases were rated equal with the high-frequency case at the "optimum" $N'_{\delta_{AW}}/L'_{\delta_{AW}}$, but show a more rapid deterioration for $N_{\delta_{AW}}/L'_{\delta_{AW}}$ values to either side. When the numerator zero is separated from the Dutch roll pole and coordination becomes a factor, the low-frequency configurations are downrated because of the slowness of the directional response.

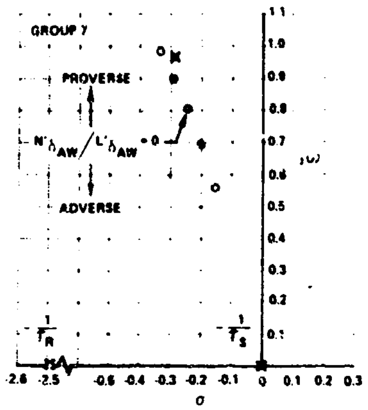
Figure 46 compares the pilot rating data obtained for the high $|\phi/\beta|_d$, moderate ζ_d configurations at the two Dutch roll frequencies. The trend in pilot rating as a function of the control parameter $N'_{\delta_{AW}}/L_{\delta_{AW}}$ is essentially the same at both frequencies; however, the high-frequency cases are consistently rated one to two ratings better than the low. The lower directional stability associated with the low Dutch roll frequency leads to large sideslip excursions and, consequently, larger roll angles with a corresponding degradation in roll control. Since the turbulence response for the low-frequency configurations is also a major complaint, the combination of turbulence response and roll control difficulties makes these configurations less desirable than the higher frequency configurations.

4.9.2 Comparison of Pilot Rating Data Obtained at Different Dutch Roll Damping Ratios

Pilot rating data are compared for the three values of Dutch roll damping ratio at the moderate value of $|\phi/\beta|_d$ for both Dutch roll frequencies, and at the high $|\phi/\beta|_d$ for the low frequency. Data are also compared for the two higher values of ζ_d , for the lowest $|\phi/\beta|_d$ and low Dutch roll frequency.

As shown in Figures 47a and 47b, the handling qualities improved two or more pilot ratings at the optimum pilot rating, for a change in damping





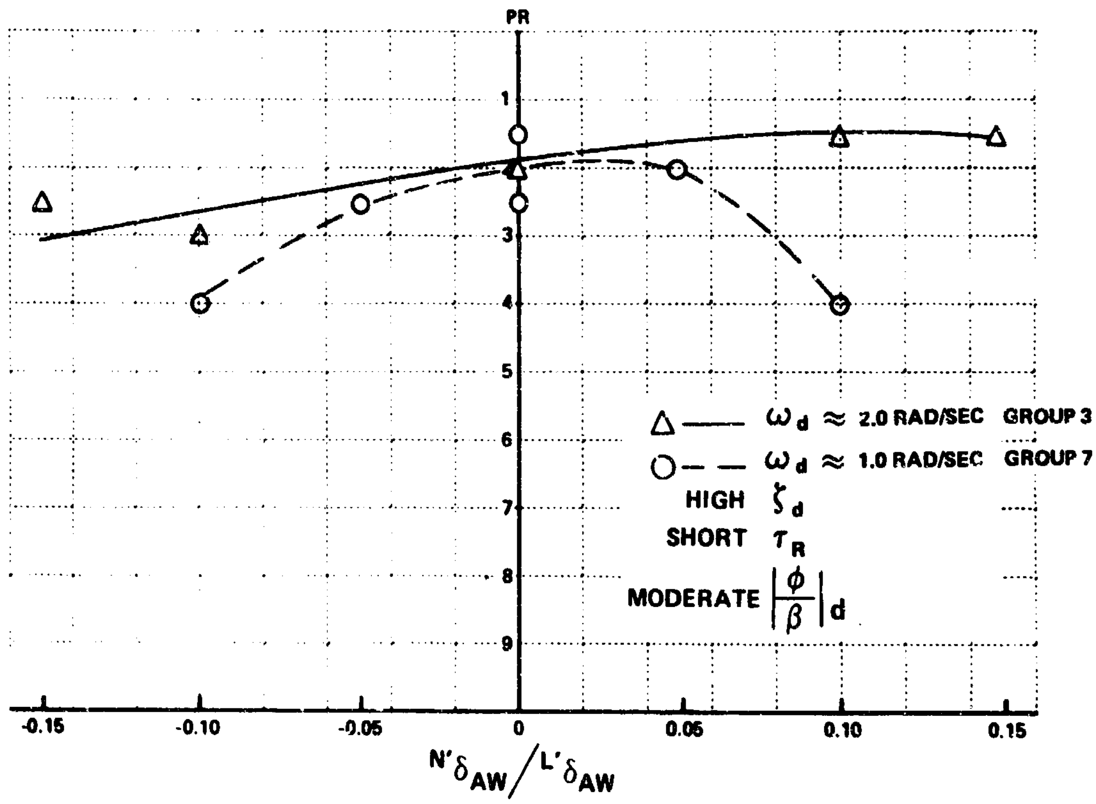


Figure 45c COMPARISON OF PILOT RATINGS AT TWO DIFFERENT FREQUENCIES WITH HIGH ζ_d

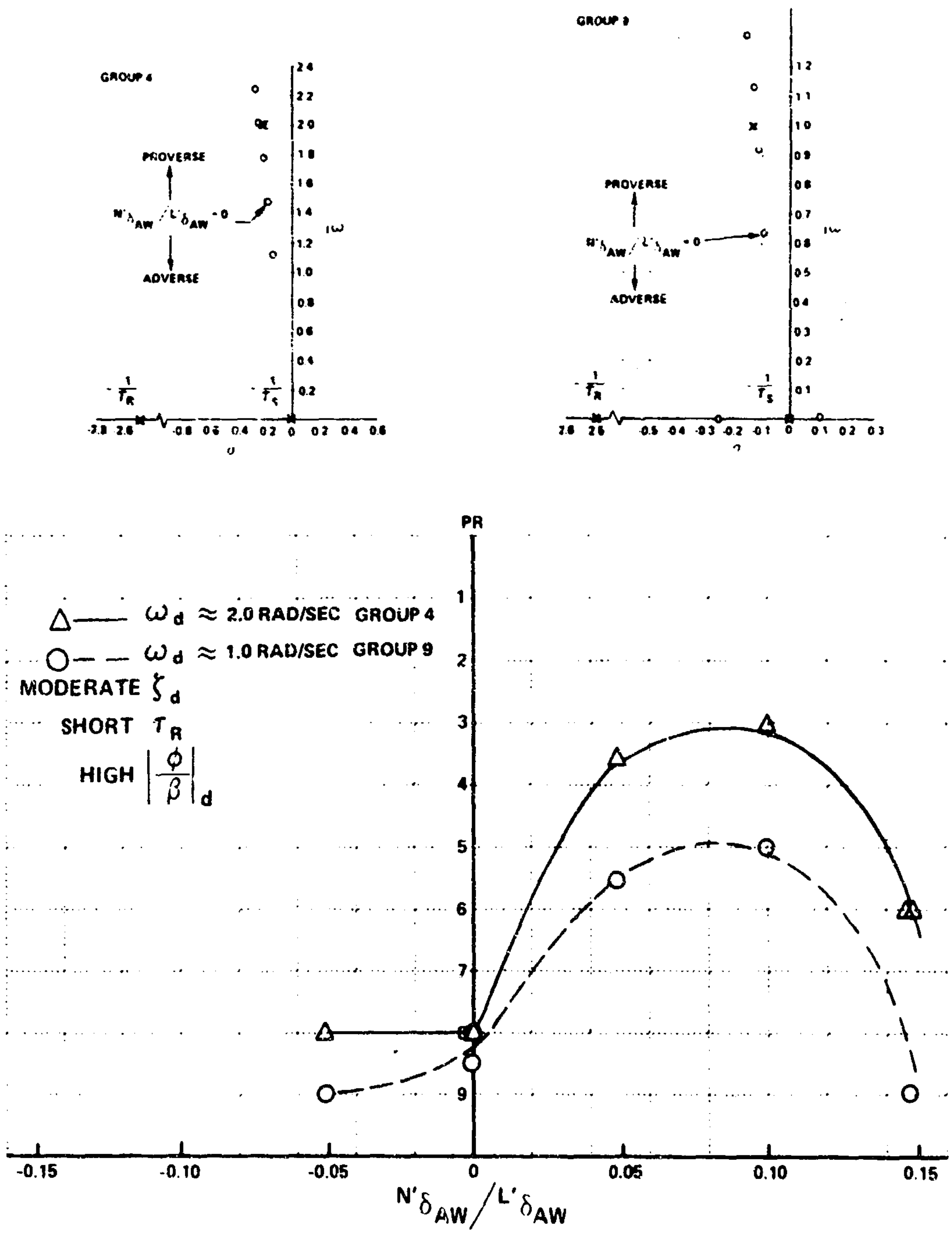


Figure 46 COMPARISON OF PILOT RATINGS AT TWO DIFFERENT FREQUENCIES WITH HIGH $\left|\frac{\phi}{\beta}\right|_d$

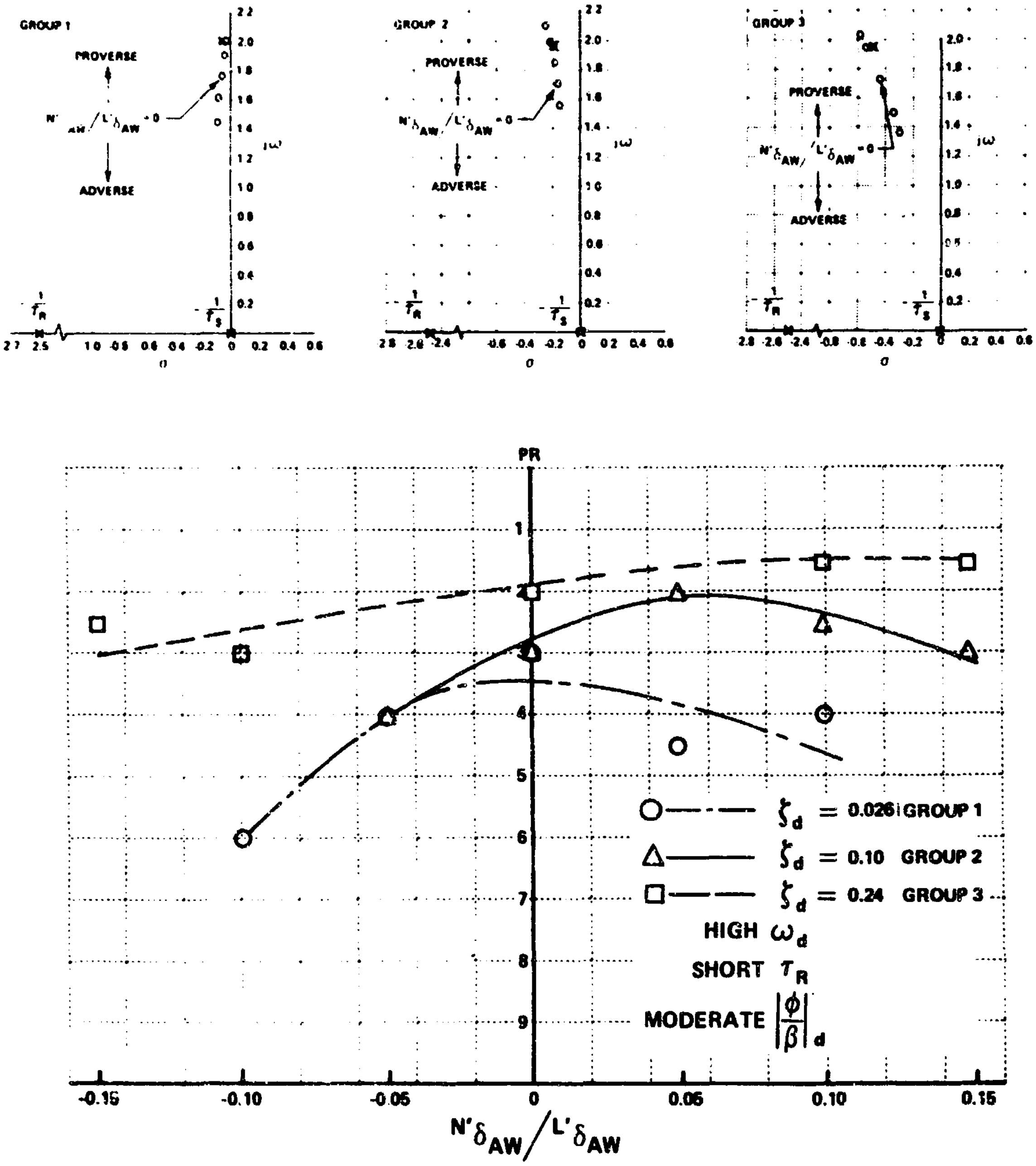


Figure 47a COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF ζ_d WITH HIGH ω_d

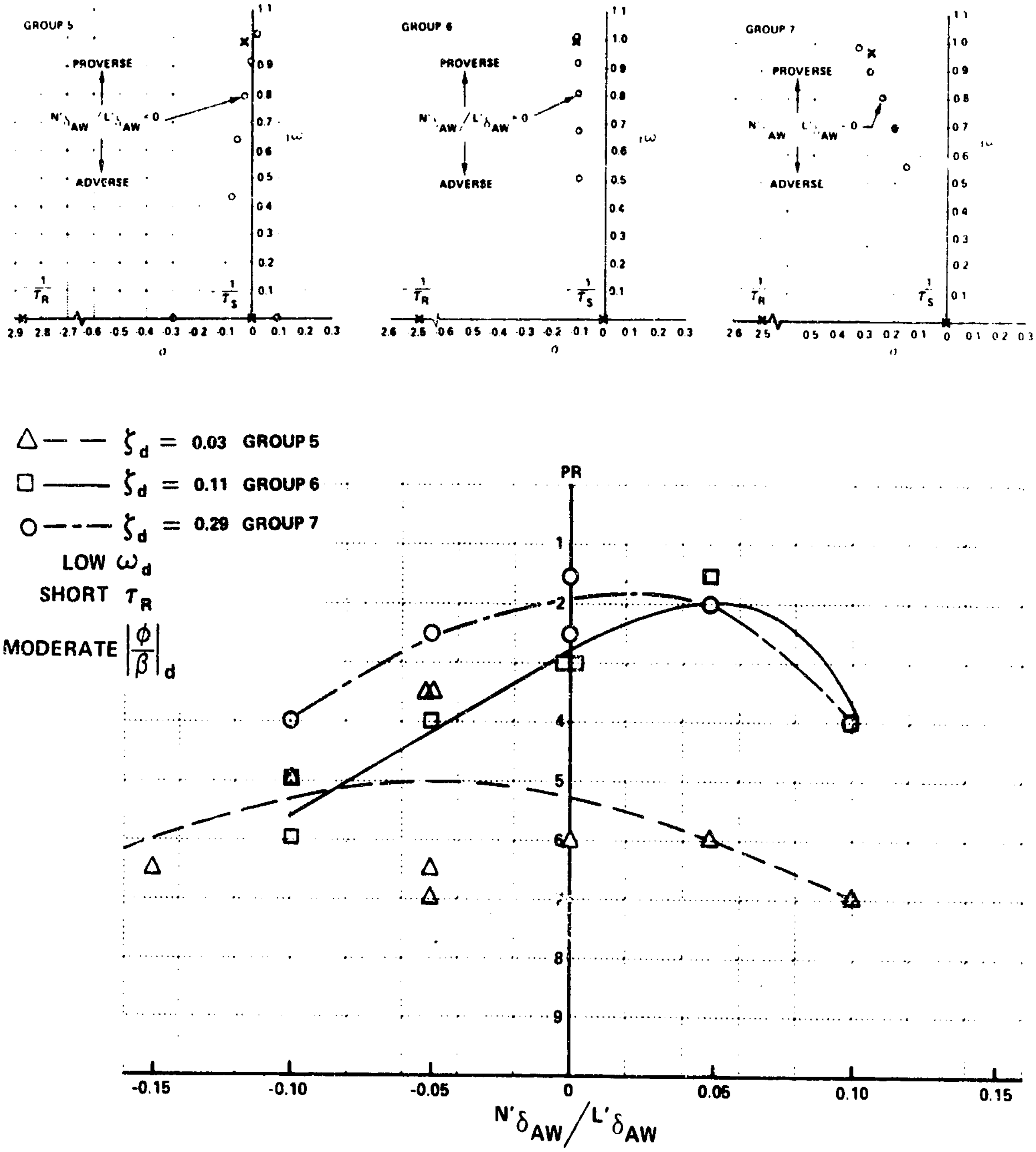


Figure 47b COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF ζ_d WITH LOW ω_d

ratio from $\zeta_d = 0.03$ to $\zeta_d = 0.1$ for the moderate $|\phi/\beta|_d$ configurations at both Dutch roll frequencies evaluated. A further increase in damping ratio to the high value of ζ_d shows no significant improvement in the optimum pilot rating; however, there was an improvement in the more adverse yaw configurations.

For both frequencies evaluated, the pilots accepted greater variations in $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ at the highest damping ratio than at the moderate or low. In this experiment, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ primarily determined the amount of Dutch roll excitation to an aileron input. With the higher damping ratio, the Dutch roll oscillations decayed rapidly and, consequently, were less of a problem. The primary difference between the low and high damping ratios evaluated was the airplane's response to turbulence. In smooth air, even the lightly damped configurations were considered "not too bad"; however, in turbulence, both the riding qualities and the handling qualities deteriorated significantly. The reduction in turbulence response for an increase in damping ratio from $\zeta_d = 0.1$ to $\zeta_d = 0.3$ is quite significant. In many cases at the higher damping ratio, the lack of excitation due to turbulence was listed as a good feature. Thus, an increase in Dutch roll damping ratio above $\zeta_d = 0.1$ may not significantly improve the airplane handling qualities, but it does enhance the turbulence response and riding qualities of the airplane.

Figure 48a shows the pilot rating comparison for the high $|\phi/\beta|_d$ case as the damping ratio is varied from $\zeta_d = 0.03$ to $\zeta_d = 0.25$. In this comparison there is a much greater improvement in pilot rating with an increase in damping ratio than for the moderate $|\phi/\beta|_d$ configurations. Because of the low Dutch roll frequency, $\omega_d \approx 1.0$ rad/sec, the static directional stability is low and the airplane is quite susceptible to sideslip excursions. With the higher roll-to-sideslip coupling, these sideslip excursions manifest themselves as roll control problems. The turbulence response was not really liked by either evaluation pilot for any of these configurations. It is in the area of turbulence response that the increased damping ratio had its most beneficial

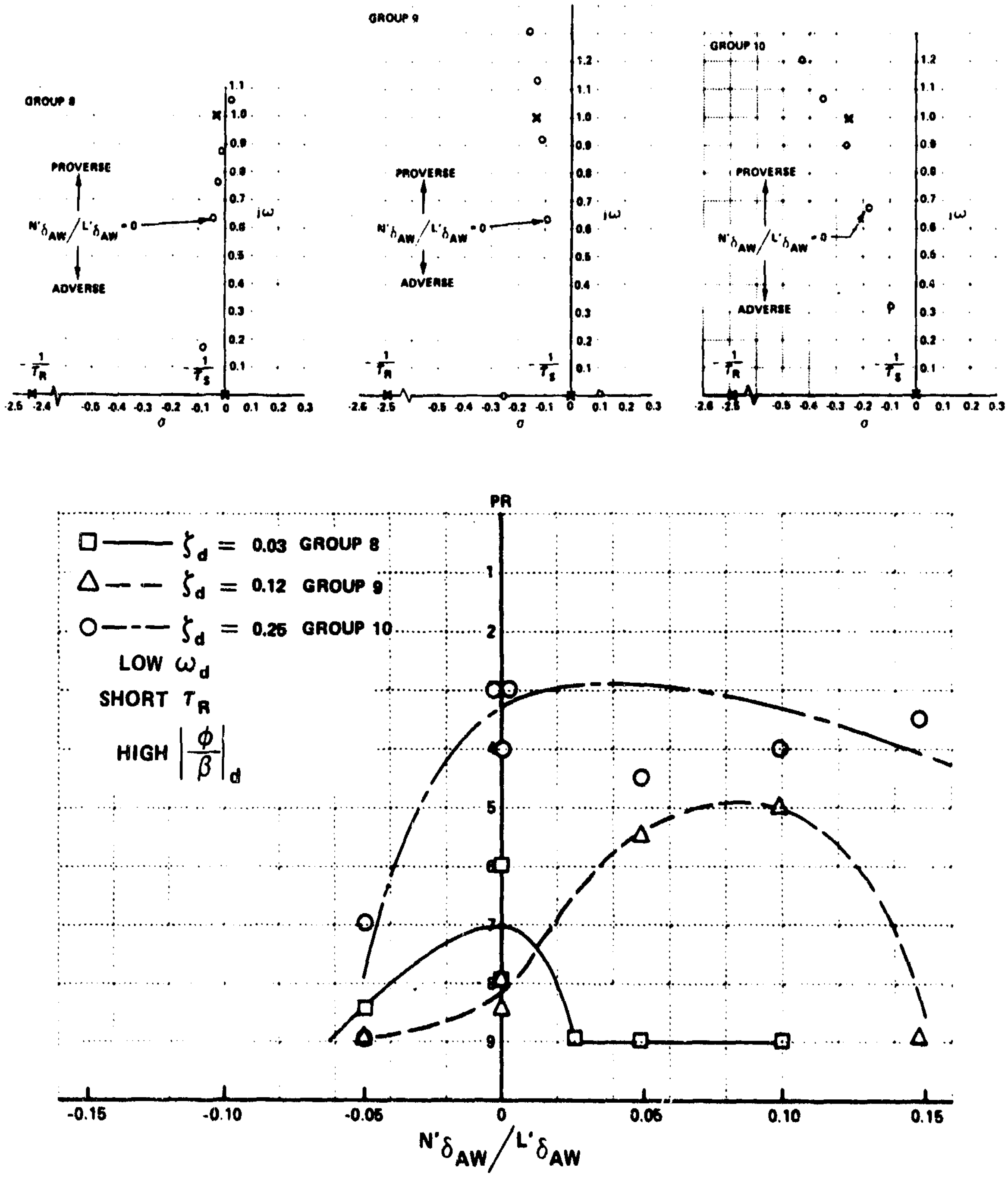


Figure 48a COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF ζ_d WITH HIGH $\left|\frac{\phi}{\beta}\right|_d$

effect. The only two pilot ratings that were satisfactory ($\zeta_d \approx 0.25$, $N'_{\delta_{AW}}/L'_{\delta_{AW}} = 0$) had turbulence ratings of B and C, with all others rated D or lower. It can be concluded that the desired level of Dutch roll damping ratio is strongly influenced by the amount of roll-to-sideslip coupling. An increase in damping ratio has a more significant and beneficial effect on the handling qualities as the roll-to-sideslip ratio increases.

Figure 48b compares moderate and high damping ratios for the low roll-to-sideslip ratio. The major improvement in handling qualities with an increase in damping ratio at this low dihedral effect is again in the turbulence response and riding qualities of the airplane. At the lower damping ratio, the turbulence response was considered a minor objection. At the higher damping ratio, the turbulence response was considered negligible and listed as a favorable feature. The higher damping ratio significantly reduced the snaking motion normally associated with low roll-to-sideslip airplanes and noticeably improved the riding qualities.

4.9.3 Comparison of Pilot Rating Data Obtained at Different Ratios of Roll-to-Sideslip in the Dutch Roll Mode

Pilot rating data are compared at two values of $|\phi/\beta|_d$ at the high Dutch roll frequency with the moderate damping ratio and also at the low Dutch roll frequency with the low damping ratio. Three values of $|\phi/\beta|_d$ are compared at the low Dutch roll frequency and short roll mode time constant, for the low and moderate damping ratios, and also at the low Dutch roll frequency with the moderate damping ratio and moderate roll mode time constant. These comparisons are shown in Figures 49 through 51.

Comparison of the moderate and high roll-to-sideslip ratios, at the high Dutch roll frequency and moderate damping ratio, Figure 49, shows only one pilot rating difference (with the lower roll-to-sideslip ratio rated better) at the optimum $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ value evaluated. The L'_β for the high roll-to-sideslip ratio was -19.4 and was -10.3 for the low. This combination of L'_β and Dutch roll frequency compares quite well with the results of the Princeton

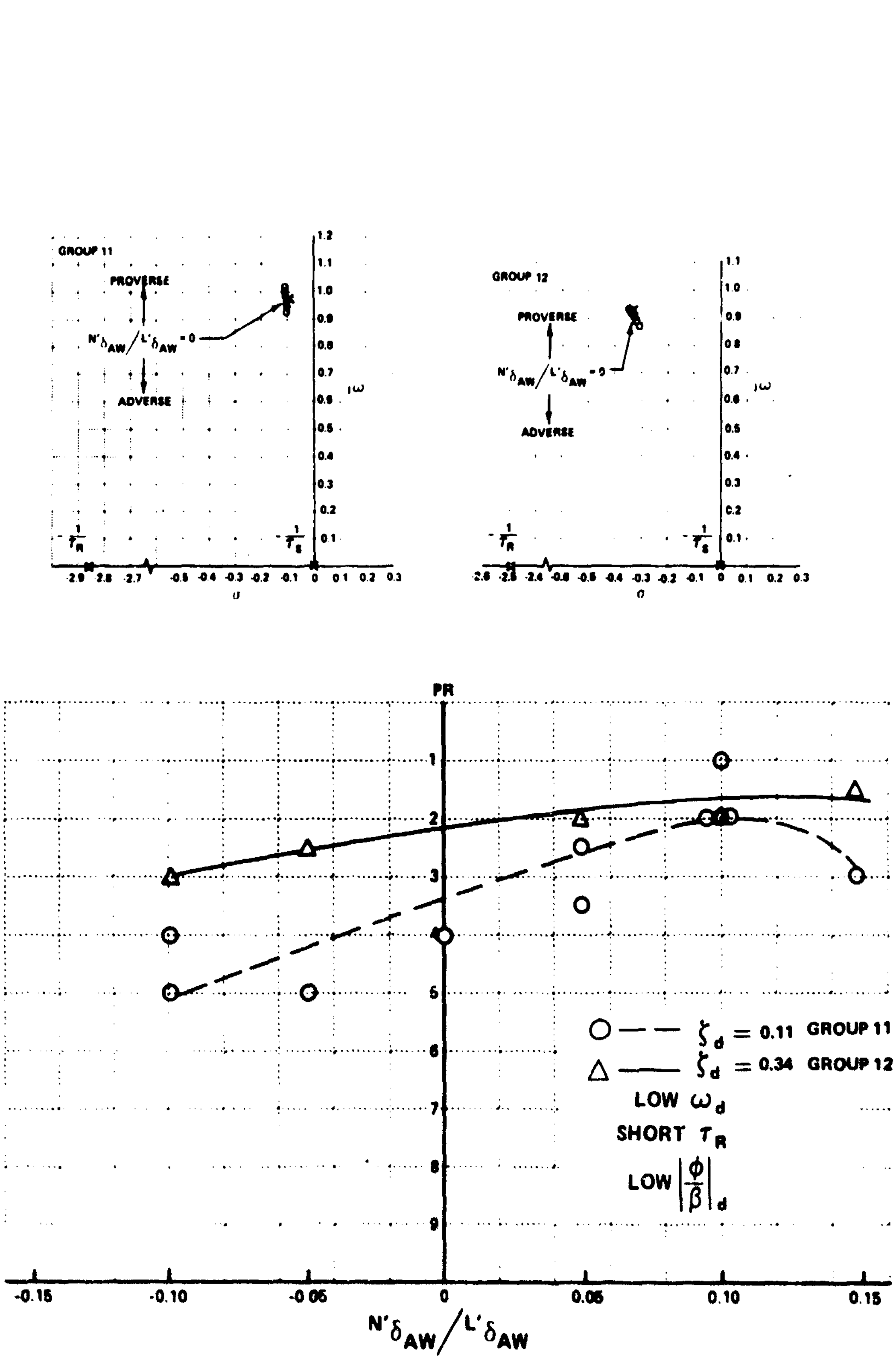


Figure 48b COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF ζ_d WITH LOW $\left|\frac{\phi}{\beta}\right|_d$

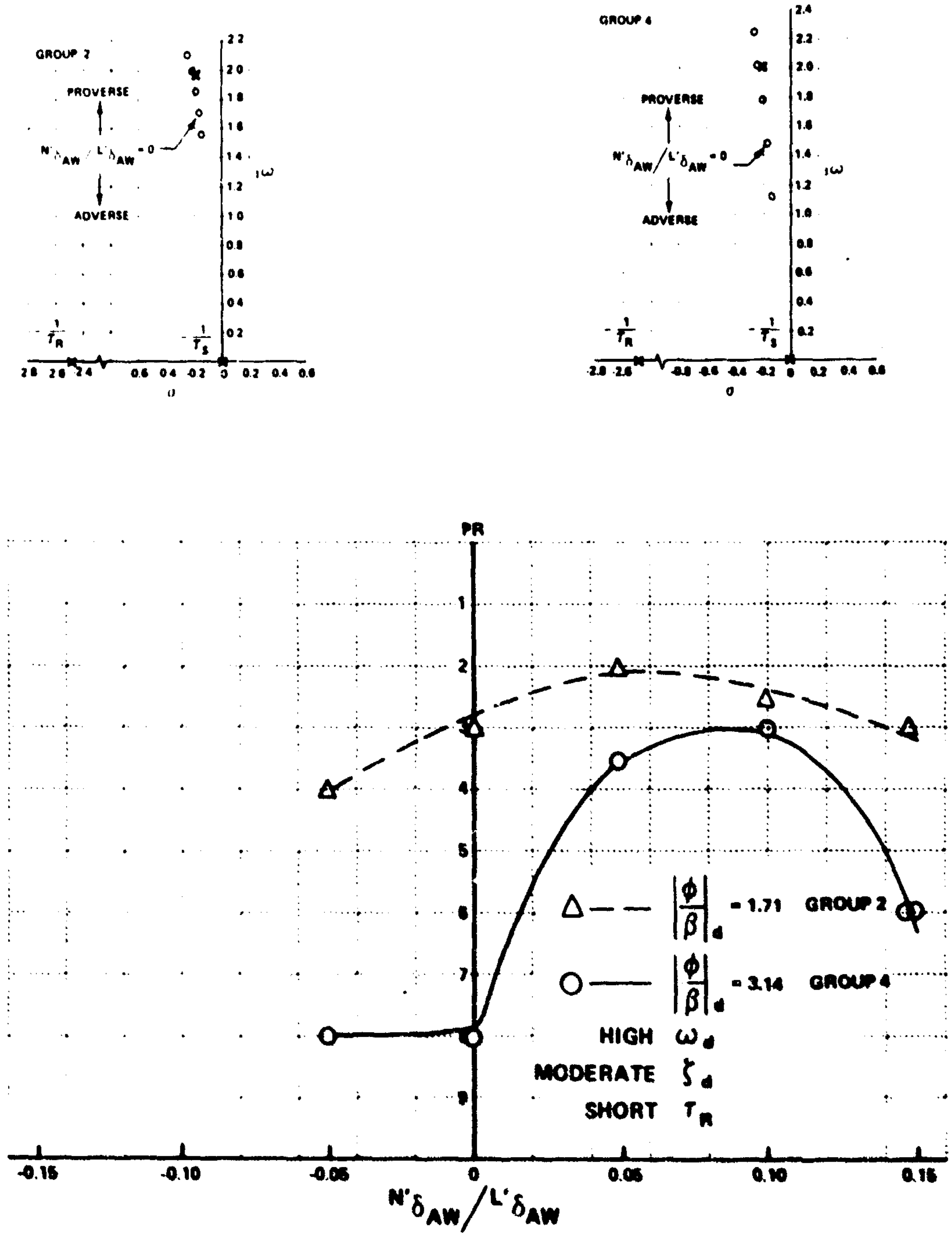


Figure 49 COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF $|\phi/\beta|_d$ WITH HIGH ω_d

data, Reference 72, which were obtained for an ILS task for small general aviation airplanes. The primary difference between these two groups was the roll response to turbulence which was considerably worse for the high roll-to-sideslip configurations. e greater amount of Dutch roll excitation with the high $|\phi/\beta|_d$ resulted in a rapid degradation in pilot ratings for values of aileron yaw more adverse or proverse than that for which the best pilot ratings occurred.

At the low frequency and low damping ratio, Figure 50a indicates that the moderate $|\phi/\beta|_d$ ratio is still preferred over the high value. Neither group of configurations was very good because of the low static directional stability and low damping ratio. This combination of characteristics precipitated continuous excursions in sideslip which, when coupled with the high roll-to-sideslip ratio, created roll as well as directional control problems. The turbulence response was considered excessive for both groups primarily because of the light Dutch roll damping.

Figure 50b compares the pilot ratings obtained for the three roll-to-sideslip ratios at the low Dutch roll frequency and moderate damping ratio. Although the best pilot rating occurs at a slightly different value of $N'_{\delta_{AW}}/L'_{\delta_{AW}}$, there is essentially no difference in the pilot's assessment of the handling qualities at the optimum configuration for the low and moderate roll-to-sideslip ratios. Although the turbulence response for the low $|\phi/\beta|_d$ configurations showed up primarily as a snaking motion and for the moderate $|\phi/\beta|_d$ cases as a coupled lateral-directional motion, the overall effect on the handling qualities was essentially the same. The pilot ratings for the high $|\phi/\beta|_d$ configurations were considerably degraded from either of the lower $|\phi/\beta|_d$ values. Again, the major objection was centered on the roll response to turbulence.

Figure 50c compares three roll-to-sideslip ratios at the low Dutch roll frequency but with the high damping ratio. There is essentially no difference in the optimum pilot rating obtained for the two lower roll-to-sideslip ratios. Both groups were rated slightly better than the high roll-to-sideslip ratio configurations. The improvement in turbulence response for

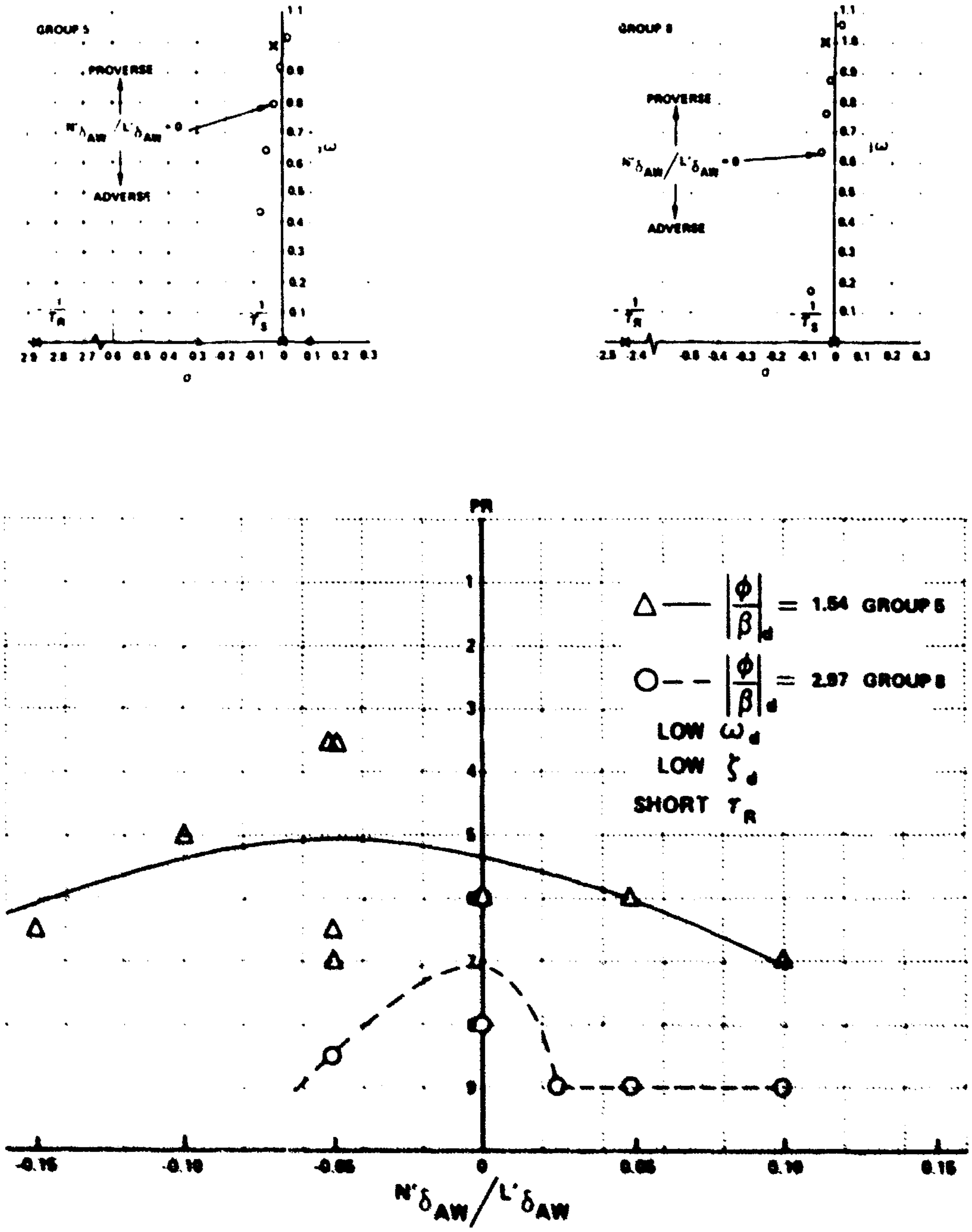


Figure 50a COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF $|\phi/\beta|_d$ WITH LOW ζ_d

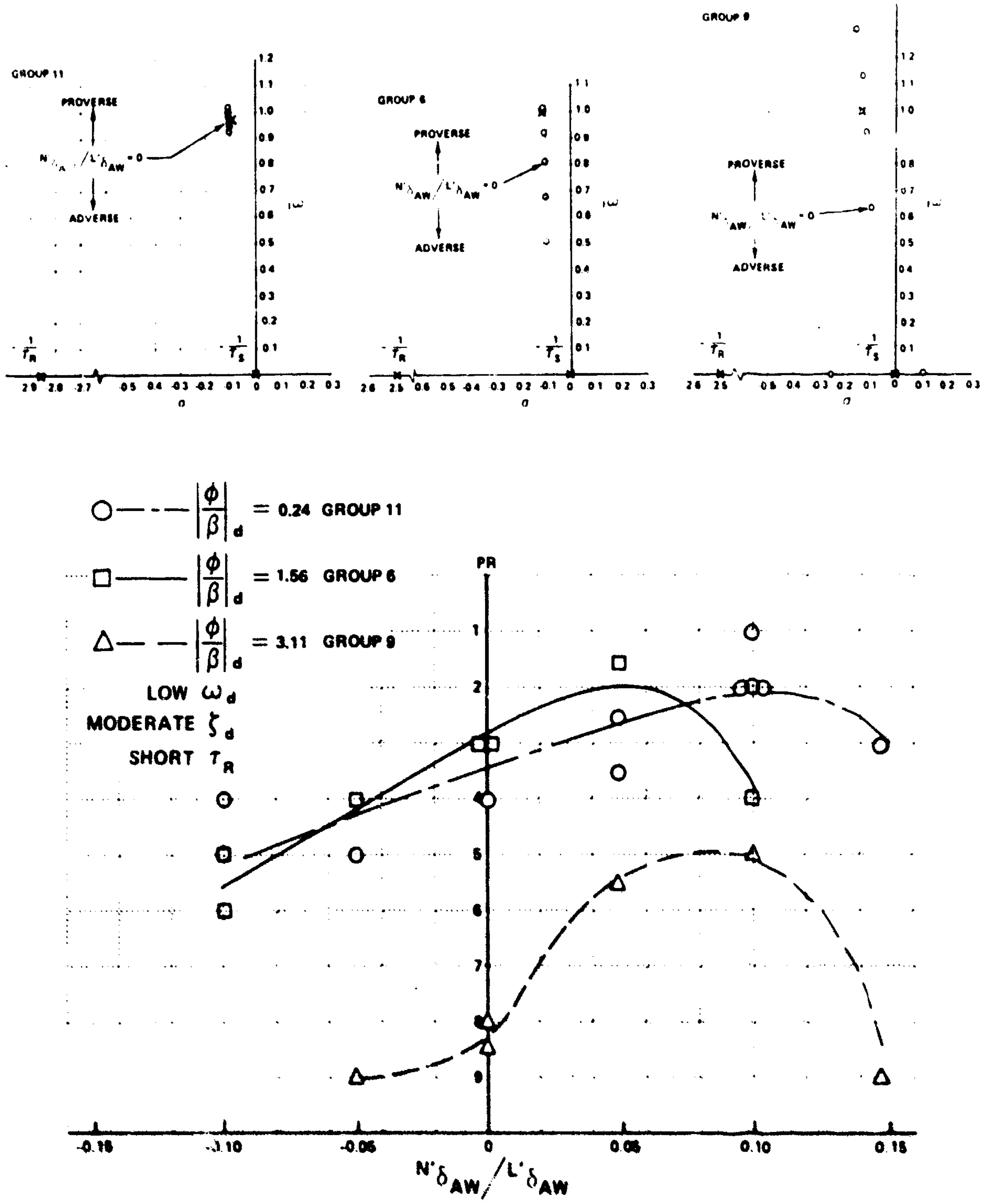


Figure 50b COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF $\left|\frac{\phi}{\beta}\right|_d$ WITH MODERATE ζ_d

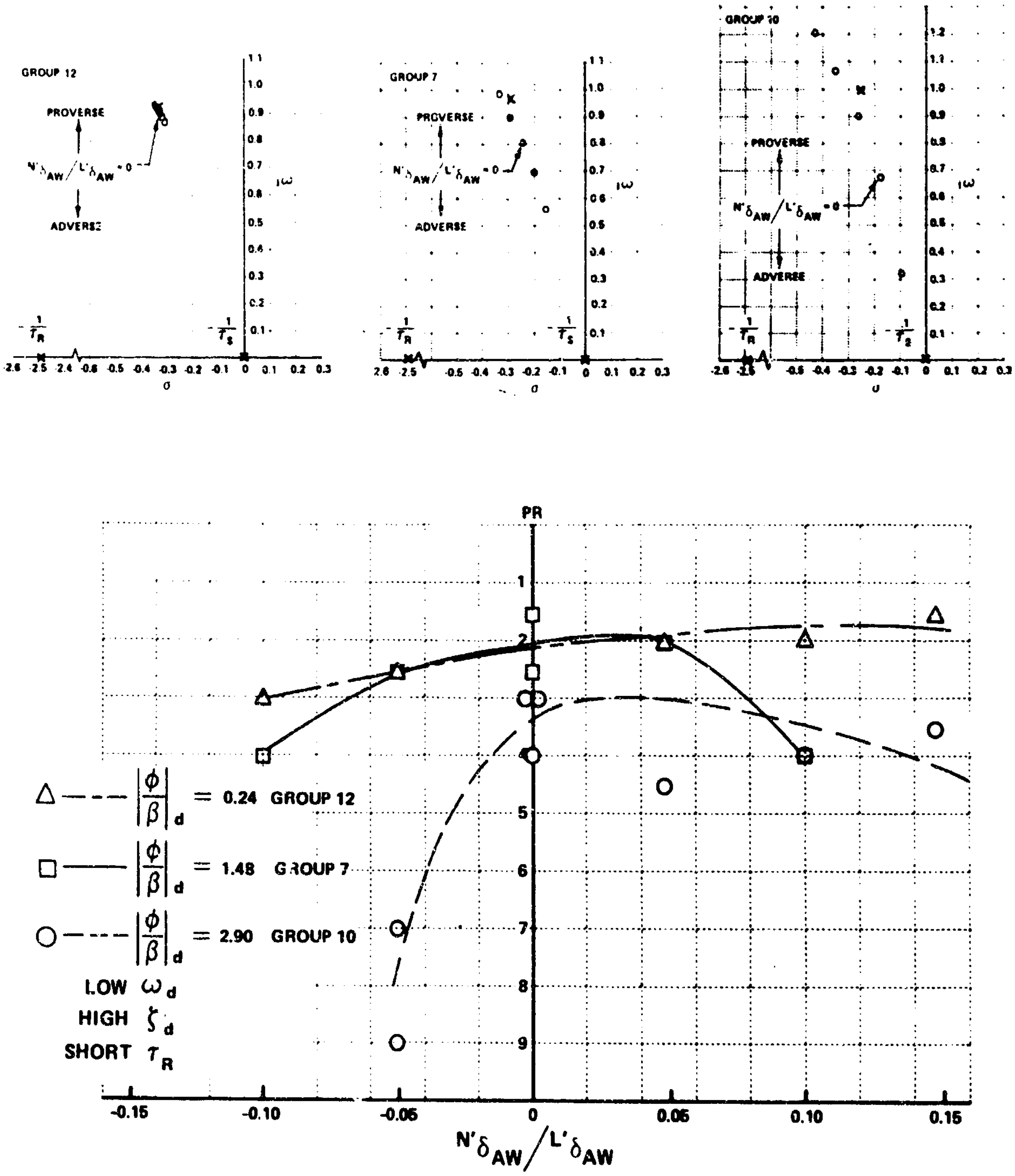


Figure 30c COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF $\left|\frac{\phi}{\beta}\right|_d$ WITH HIGH ζ_d

the high $|\phi/\beta|_d$ configurations accounts for the smaller differences in pilot ratings with the high damping ratio compared to those obtained at the moderate damping ratio.

All the previous comparisons were made for a short roll mode time constant of $\tau_R \approx 0.4$ seconds. Figure 51 compares dissimilar roll-to-sideslip ratios at the low Dutch roll frequency and moderate damping ratio for the moderate roll mode time constant of approximately 1.0 second. Comparing Figure 50b with Figure 51, it is immediately apparent that for the moderate roll mode time constant configurations there is less pilot rating variation for a corresponding change in $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ than there is for the short roll mode groups. This results from the respectively lower values of L'_β for the moderate roll mode time constant configurations. Since L'_p appears in the denominator of $|\phi/\beta|_d$ (see Appendix I) and L'_p is significantly less for the moderate roll mode time constant than for the short roll mode time constant configurations, there is a corresponding decrease in L'_β required to achieve the same $|\phi/\beta|_d$ relationships. The moderate $|\phi/\beta|_d$ configurations were rated better than the low $|\phi/\beta|_d$ configurations primarily because the adverse yaw due to aileron created a Dutch roll phase relationship in roll rate that tended to reduce the effect of the longer roll mode time constant. The zeroes in the ϕ/δ_{AW} transfer function are quite widely separated from the Dutch roll pole for the high roll-to-sideslip ratio configurations, making a direct comparison with the two lower $|\phi/\beta|_d$ configurations less meaningful at the moderate roll mode time constant. The pole-zero separations are indicativ of the Dutch roll excitation due to aileron inputs, and hence, any aileron input for the high $|\phi/\beta|_d$ case produced considerably more Dutch roll excitation than a corresponding input for the two lower $|\phi/\beta|_d$ groups. Consequently, in this comparison, the difference in pilot rating between the high $|\phi/\beta|_d$ and the two lower $|\phi/\beta|_d$ values cannot be attributed solely to the effects of a change in $|\phi/\beta|_d$.

The following conclusions can be reached from the above comparisons. Roll-to-sideslip ratio is indeed a good measure of the lateral turbulence

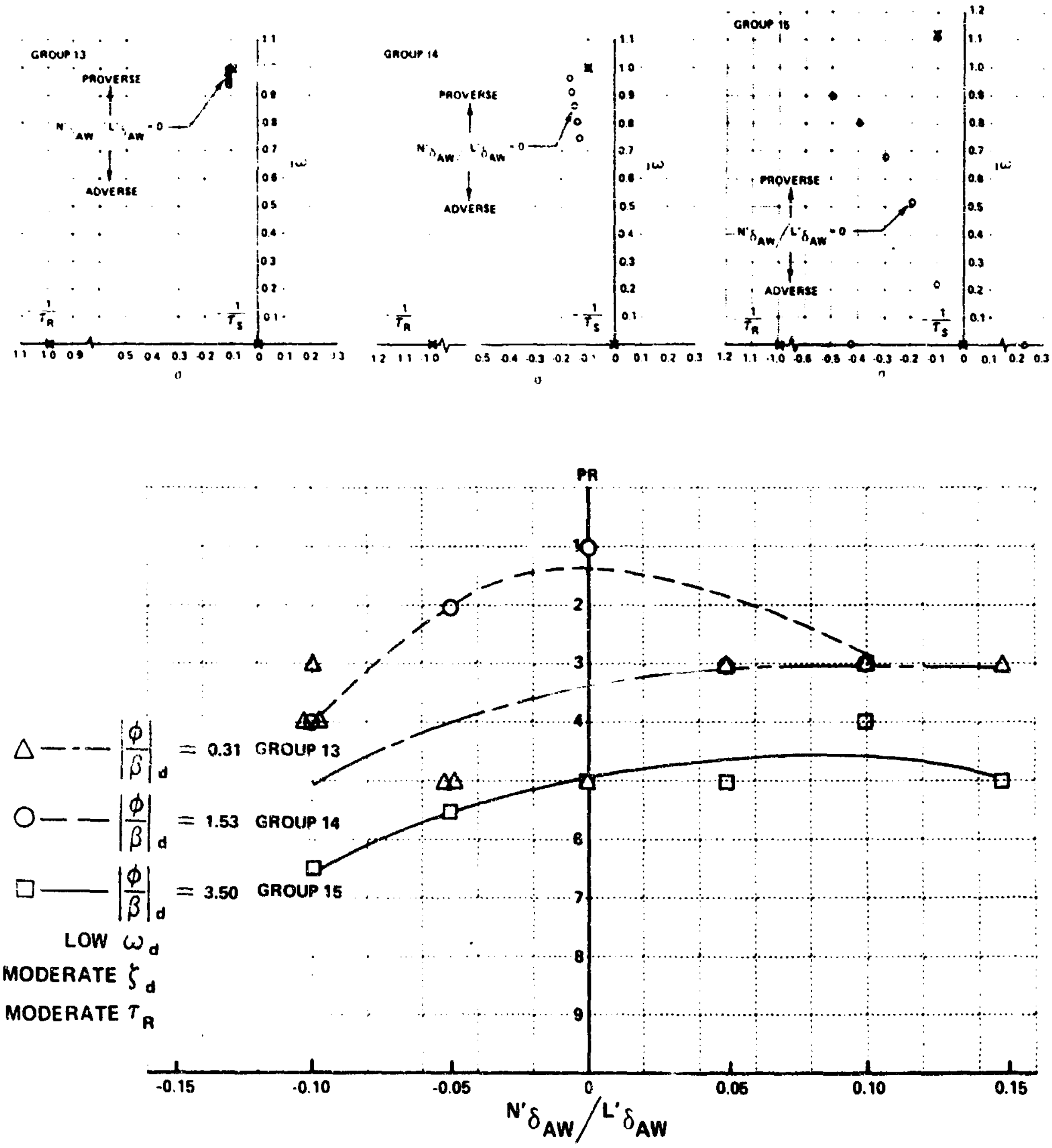


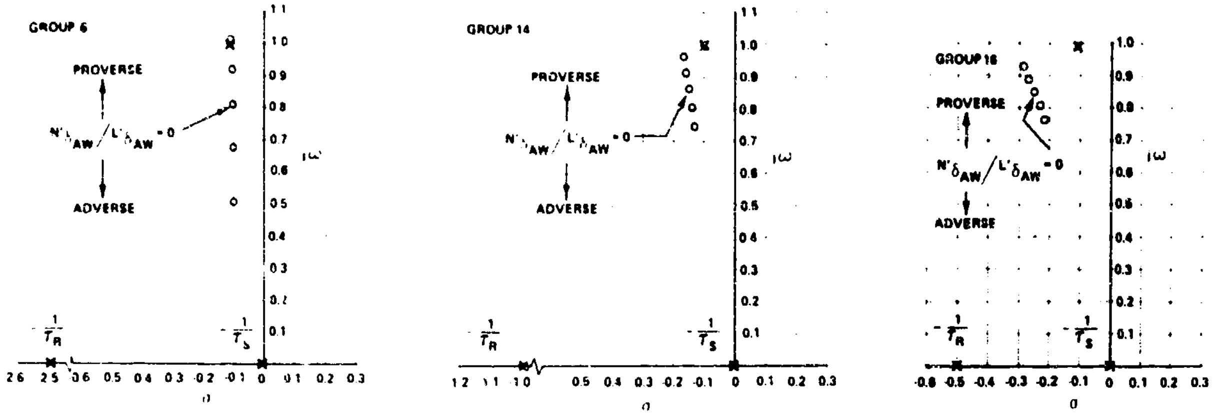
Figure 51 COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF $\left|\frac{\phi}{\beta}\right|_d$ WITH MODERATE τ_R

response that can be anticipated for a given airplane. The high roll-to-sideslip ratio was less degrading at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) evaluated than at the low frequency. The combination of low Dutch roll frequency ($\omega_d \approx 1.0$ rad/sec), low Dutch roll damping ratio ($\zeta_d \approx 0.03$), and high roll-to-sideslip ratio ($|\phi/\beta|_d \approx 3.0$), was completely unacceptable. The same Dutch roll frequency and damping ratio with the moderate roll-to-sideslip ratio ($|\phi/\beta|_d \approx 1.5$) was rated barely acceptable, but unsatisfactory. Increasing the Dutch roll damping ratio can significantly improve the acceptability of the handling qualities of a high roll-to-sideslip configuration. There is essentially no difference in the desirability of the handling qualities between configurations with the same Dutch roll frequency and damping ratios and roll-to-sideslip ratios of about 0.25 to 1.50.

4.9.4 Comparison of Pilot Rating Data Obtained at Different Values of Roll Mode Time Constant

Pilot rating data are compared for three roll mode time constants, $\tau_R \approx 0.4$, 1.0, and 2.0 seconds at the low Dutch roll frequency, moderate damping ratio and moderate $|\phi/\beta|_d$. Two roll mode values, $\tau_R \approx 0.4$ and 1.0 seconds, are compared at the same Dutch roll frequency and damping ratio for the lowest and highest values of $|\phi/\beta|_d$.

Figure 52a compares three values of roll mode time constant at the moderate $|\phi/\beta|_d$. The pilots described the roll control for the short τ_R configurations as precise and predictable. For the moderate τ_R, the roll control was considered satisfactory and good with one minor complaint: the airplane was slow to respond initially and there was an occasional tendency to over control in bank angle. In general, there was very little, if any, difference in the roll control per se between these two groups of configurations. Analysis of the pilot comment data indicated that the major difference was in the turbulence response. For the short τ_R configurations, $L'_\beta \approx -4.07$, for the moderate τ_R, $L'_\beta \approx -1.88$, the approximate factor of two difference in L'_β primarily accounts for the more objectionable turbulence



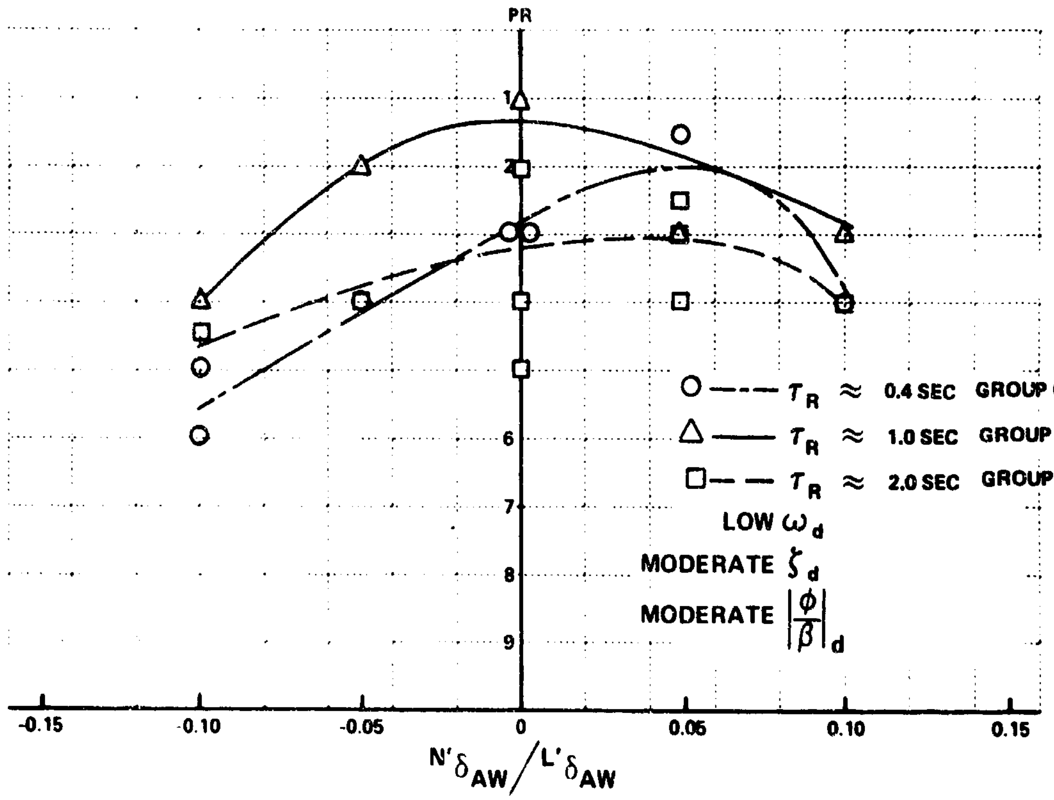


Figure 52a COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF τ_R WITH MODERATE $\left|\frac{\phi}{\beta}\right|_d$

ratings given to the low roll mode time constant configurations. The higher L'_β ($L'_\beta \approx -4.07$) also accounts for the greater pole zero separation in the ϕ/δ_{AW} transfer function, resulting in greater Dutch roll excitation with the ailerons at the short roll mode time constant. This excitation is responsible for the more rapid deterioration in pilot rating with change in the aileron yaw parameter, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$. The pilot comments for the long or two-second roll mode time constant were primarily directed at the roll control itself. The roll control was described as unpredictable with a slow initial response followed by an acceleration in roll rate with a resulting overbanking tendency. The turbulence response also created roll control difficulties requiring numerous aileron inputs, but caused very little degradation in the overall handling qualities. L'_β for these configurations was -1.50. Although there are differences in pilot ratings, Figure 52a, for the three roll mode time constants evaluated, differences are relatively minor, with all three optimum configurations rated as satisfactory, i.e., PR $\leq$ 3.5.

Figure 52b compares the short and moderate roll mode time constants at the low Dutch roll frequency, moderate damping ratio, and high $|\phi/\beta|_d$. Here again, little difference in pilot rating can be directly attributed to the change in roll mode time constant. The L'_β for the moderate roll mode time constant configurations was -4.39, and for the 0.4-second configurations, -8.91. This accounts for the greater separation between the zeroes of the ϕ/δ_{AW} transfer function for the short roll mode time constant configuration as the aileron yaw parameter was varied. Consequently, there is a more rapid degradation in pilot rating as $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ was varied from its "optimum" value. The turbulence response in roll was less for the moderate roll mode time constant configurations; however, the pole-zero separation was considerably greater in all cases, with a corresponding requirement for rudder coordination for each configuration.

The roll mode time constant comparison (τ_R = 0.4 and 1.0 seconds) for the low $|\phi/\beta|_d$ configurations is shown in Figure 52c. The L'_β for the short roll mode time constant is approximately three times (-2.86 compared to -1.03)

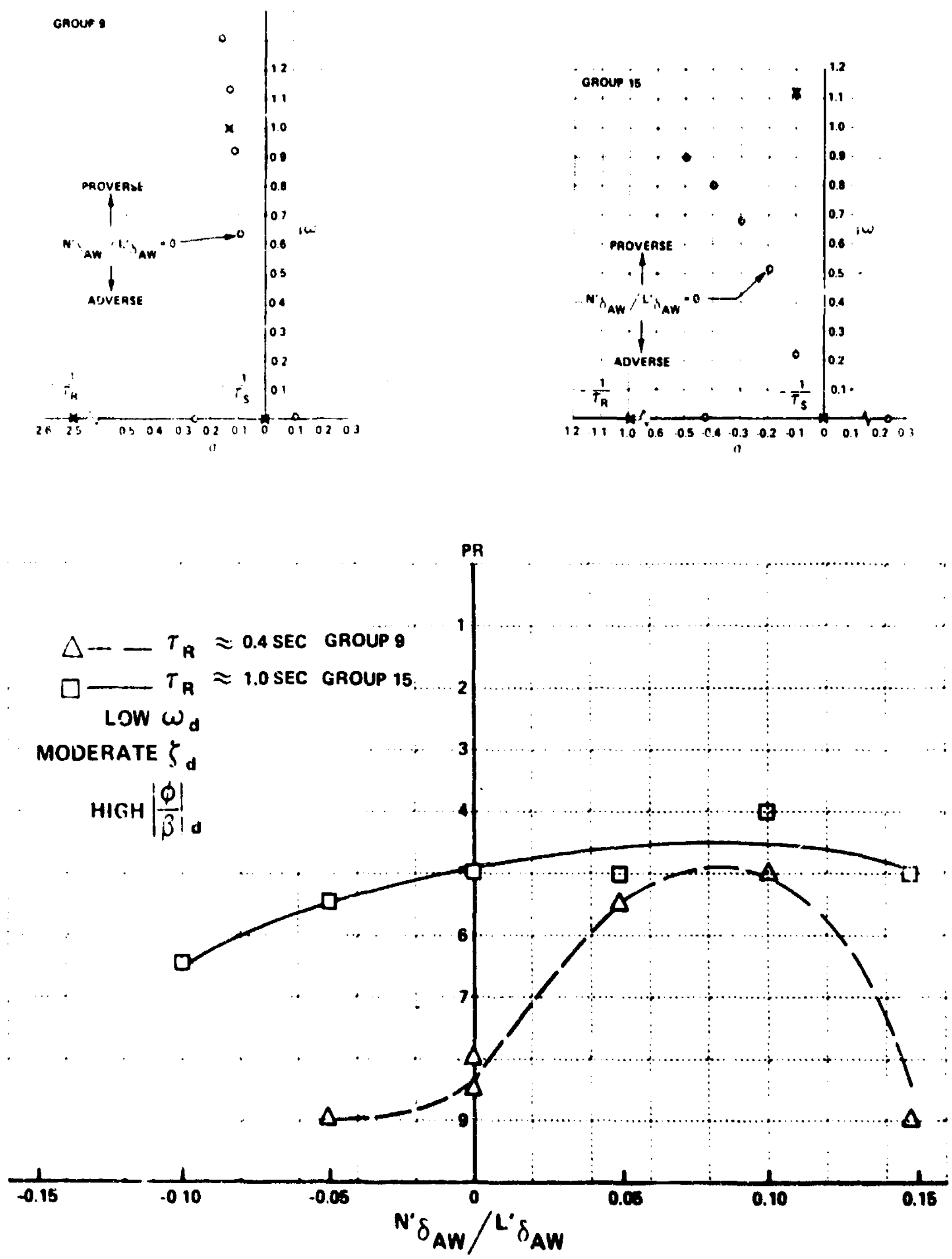


Figure 52b COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF τ_R WITH HIGH $\left|\frac{\phi}{\beta}\right|_d$

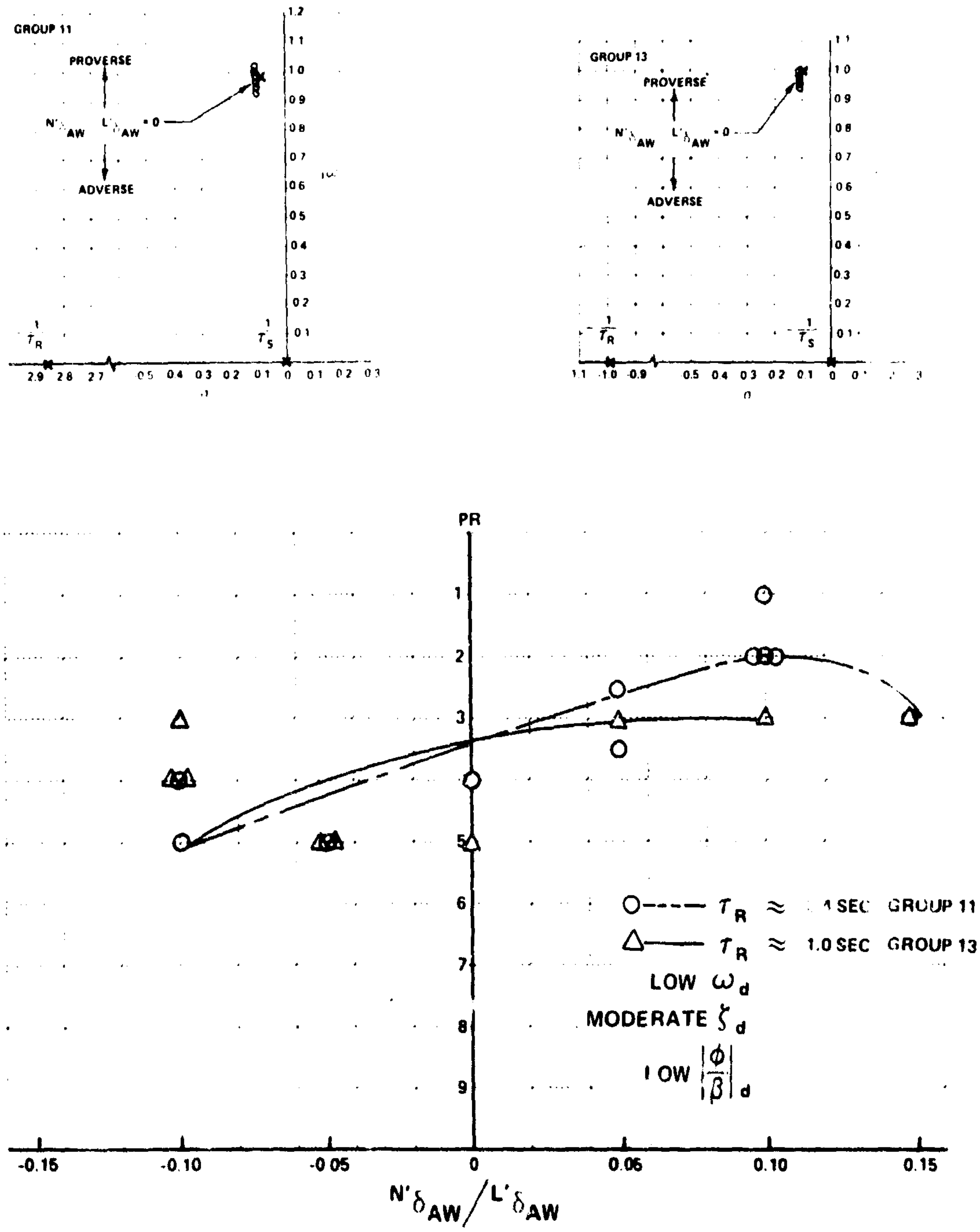


Figure 52c COMPARISON OF PILOT RATINGS WITH DIFFERENT VALUES OF τ_R WITH LOW $\left|\frac{\phi}{\beta}\right|_d$

that of the moderate roll mode time constant but the overall effect on the numerator terms in the ϕ/δ_{AW} transfer function is relatively small. Because of the closeness of the numerator zeroes to the Dutch roll pole, the roll rate trace closely approximates a pure first-order response. The roll control was considered good for both values of roll mode time constant. The pilots liked the smoothness and predictability of the roll control. The airplane was considered to be responsive in roll at the longer roll mode time constant, and this was occasionally listed as a favorable feature.

5.0 Control Sensitivity Selections

During each evaluation, the pilot selected aileron and rudder control sensitivities that he considered optimum for the configuration. The selected values are presented in Section 4.5 through 4.8. The selection of sensitivities was the first step in the evaluation procedure during the pilot's familiarization with the configuration. Arrows shown on the control sensitivity plots designate points that the evaluation pilots reported could be improved. For example, if the pilot comments indicated that the aileron control was a little heavy, an arrow was drawn to indicate that sensitivity should be increased. The plots of aileron control sensitivity reveal a tendency by pilot B to select higher sensitivities than pilot A. Most obvious differences occurred for those groups with the shortest roll mode time constant, $\tau_R \approx 0.4$. Similar differences in the pilots were also noted in the case of rudder sensitivities, although they were not as pronounced.

The differences in sensitivity selections are believed attributable to two factors. First, the physical difference in the two pilots. Pilot A, who is quite large but proportionately trim and muscular, seemed quite willing to accept higher forces than pilot B who, by comparison, is smaller and not as physically powerful as pilot A. Second, as a close examination of the pilot comments will reveal, pilot B was much more sensitive to compromises necessary between tolerable forces in one mission segment and overly sensitive control in another mission segment. This oversensitivity also may be due to pilot B's intolerance to high control forces. It is further evident from the pilot comments that pilot B, on several occasions, re-selected sensitivities after flying a crosswind or lateral offset landing approach and finding that lateral control forces were too heavy for one-handed operation. He considered one-handed operation an essential requirement for the landing approach phase for the class of airplanes being investigated. In one case with a low roll-to-sideslip ratio (Group 11 with $N'_{\delta_{AW}}/L'_{\delta_{AW}} = +0.05$), pilot B commented that since the directional and lateral responses seemed to be separated, he could choose lateral control to suit his desires, and he liked it sensitive. In this case, he selected a very high sensitivity. Thus, it seems that what a pilot considers optimum sensitivity may be significantly influenced by personal preference if the configuration is amenable to a range. The flight experience and background of the two evaluation pilots is quite similar and hence offers no resolution as to their differences in acceptable sensitivities.

Selection of rudder control sensitivities was usually based on turn coordination requirements and often tailored, especially by pilot B, to offer reasonable forces on crosswind landing approaches and yet not be too sensitive for turn coordination during normal maneuvering. Rudder pedal sensitivity increased as Dutch roll frequency became higher. This increase is expected because directional static stability is greater with higher Dutch roll frequency. However, pilots do not wish to accept higher pedal forces with the greater static stability; thus prefer higher sensitivities.

Pilot-selected values of aileron control sensitivity showed variations with the roll mode time constant, τ_R , and variations between the two evaluation pilots. There was no discernible trend of variation with other dynamic modal characteristics. Although pilot comments indicate that crosswinds were occasionally a factor in the selection of control sensitivities, attempts to establish a meaningful correlation proved futile. In Reference 7, pilot-selected values of aileron and rudder sensitivity were shown to correlate with the aileron yaw parameter, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$. Attempts to establish a consistent relationship between sensitivities and $N'_{\delta_{AW}}/L'_{\delta_{AW}}$ for the data obtained in this experiment were unsuccessful.

The control sensitivity plots in Sections 4.5 through 4.8 show that at the smallest value of roll mode time constant evaluated, $\tau_R = 0.4$, there is considerable scatter in the range of pilot-selected control sensitivity. For the moderate and long values of τ_R tested, $\tau_R = 1.0$ and $\tau_R = 2.0$, the range of selected sensitivities was smaller. At $\tau_R = 2.0$, the acceptable range of sensitivities was quite small. Reference 51 reported a similar trend in variations of pilot-selected control sensitivity with roll mode time constant.

At the moderate and long roll mode time constants, the pilots' comments indicate that control sensitivity selection was a compromise between sensitive enough ailerons to preclude heavy forces during the initiation and stopping of roll rates, and low enough sensitivity to prevent overcontrolling tendencies. Thus, if no compromise was required, the control sensitivity selections were strongly influenced by pilot preference; however, when a compromise was required both pilots tended to make uniform selections.

Figure 53 compares plots of pilot-selected values of aileron control sensitivity, $L_{\delta_{AW}}$, versus the roll mode time constant τ_R. Points shown are only for configurations that received a PR of 3.5 or better. The figure shows the tendency of pilot A to select lower sensitivity values than pilot B, and that both pilots selected lower aileron control sensitivity for increasing values of τ_R. This trend is well established in past handling qualities research and is documented in Reference 10.

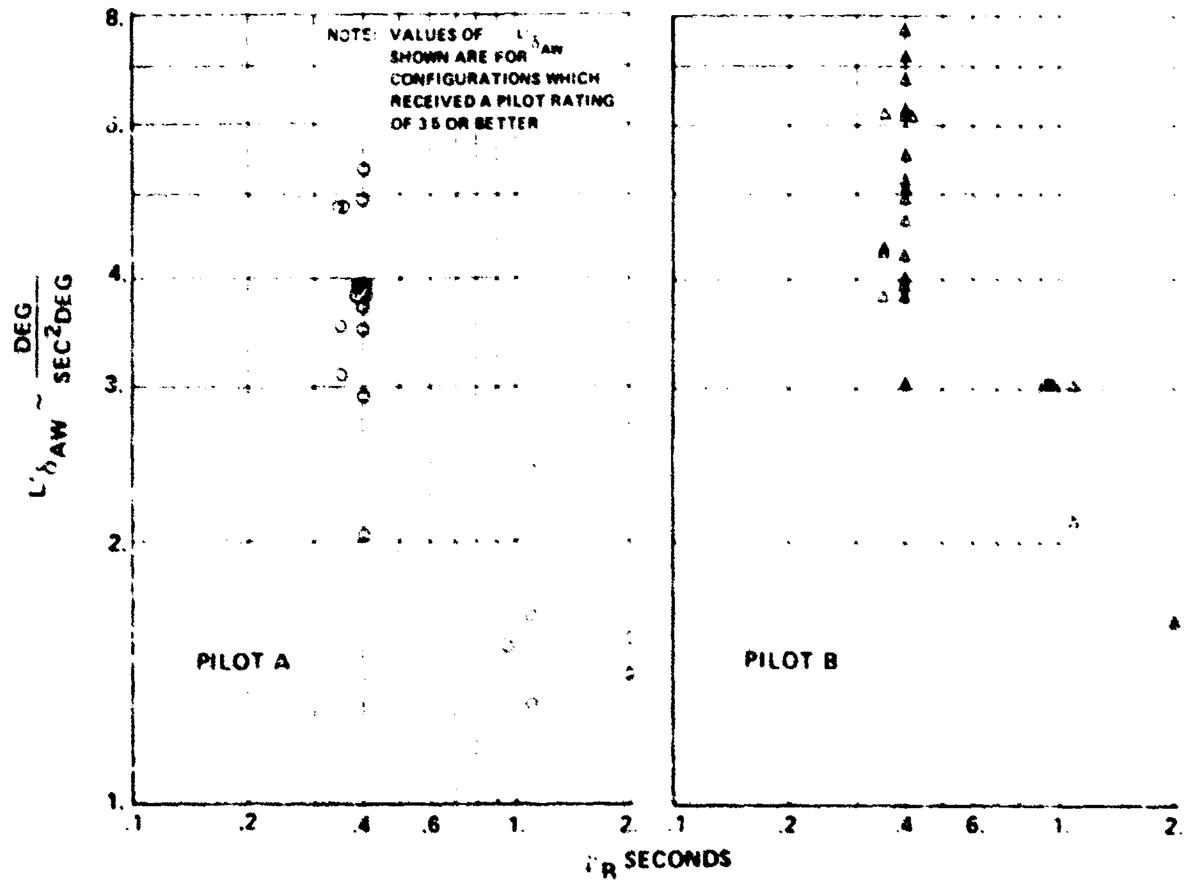


Figure 53 AILERON CONTROL SENSITIVITY VS ROLL MODE TIME CONSTANT

Section 5
SUMMARY AND CONCLUSIONS

An investigation to determine roll control power requirements and the effects of variations in lateral directional dynamics on landing approach handling qualities and cross-wind landing capabilities of the executive jet class of airplanes was conducted in the USAF/CAL variable stability T-33 airplane. A summary of the results and the conclusions drawn are included in the following:

1. The following conclusions were reached concerning the effects of lateral-directional dynamics on the pilot's ability to handle a crosswind approach:

   - Low Dutch roll damping ratio ($\zeta_d \approx 0.03$) did not present a serious problem at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) but became a major problem at the low frequency ($\omega_d \approx 1.0$ rad/sec). The continuous nose oscillations resulting from the low damping ratio, coupled with the slow directional response, caused a tendency to overcontrol directionally in a wing-down approach and a tendency to set up directional oscillations during a decrab maneuver.

   - The magnitude of the roll-to-sideslip ratio significantly influences the pilot's ability to handle a crosswind approach. Low roll-to-sideslip ($|\phi/\beta|_d \approx 0.25$) was desirable, but high roll-to-sideslip ($|\phi/\beta|_d \approx 3.0$) led to high aileron forces in the wing-down approach and a reluctance to kick off even modest sideslip angles near the ground because of rapid and large roll response to rudder inputs.

- Roll mode time constants as long as one second do not adversely affect the pilot's control in a crosswind; however, time constants of two seconds do create control problems. The tendency to overcontrol in bank angle associated with the long roll mode time constant ($\tau_R \approx 2.0$ seconds) was especially degrading when encountering gusty wind conditions near the ground.

2. The amount of roll control power available can directly establish the limiting crosswind component.

3. Roll control power requirements are a function of roll mode time constant and roll-to-sideslip ratio. As the roll mode time constant is increased, roll control power requirements are reduced. As roll-to-sideslip ratio is increased, the requirements on roll control power are correspondingly increased.

4. For the low and moderate roll-to-sideslip cases evaluated, $|\phi/\beta|_d \approx 0.25$ and $|\phi/\beta|_d \approx 1.5$, steady-state roll rates as low as 10 deg/sec provided satisfactory roll performance. For the high roll-to-sideslip configuration, $|\phi/\beta|_d \approx 3.0$, a steady-state roll rate of 20 deg/sec was required.

5. For the low and moderate roll-to-sideslip configurations evaluated, $|\phi/\beta|_d \approx 0.25$ and $|\phi/\beta|_d \approx 1.5$, bank angles in 1.0 seconds as low as 6.0 degrees and bank angles in 1.8 seconds of 15 degrees were acceptable. The MIL-F-8785B(ASG) requirement on bank angle in 1.8 seconds in 30° for Class II airplanes which includes the executive jet class. The results also indicate that for approaches made in 30-knot crosswinds, with $|\phi/\beta|_d \approx 3.0$, roll control power corresponding to a bank angle in one second of 18.4 degrees and a bank angle in 1.8 seconds of 38.5 degrees would be required to avoid significant pilot rating degradation because of lack of roll control power.

6. Low Dutch roll damping ratio ($\zeta_d \approx 0.03$) was more acceptable at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) than at the low ($\omega_d \approx 1.0$ rad/sec). With $\zeta_d \approx 0.03$, both high and low-frequency configurations were quite susceptible to turbulence. The low-frequency configurations were degraded because of coordination requirements associated with the slow directional response that resulted from the reduced static directional stability. The low directional stability leads to over-control with the rudder, and the low damping ratio results in persistent directional oscillations.

7. The best configurations evaluated were those with the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec), high damping ratio ($\zeta_d \approx 0.3$), short roll mode time constant ($\tau_R \approx 0.4$ sec), and moderate roll-to-sideslip ratio ($|\phi/\beta|_d \approx 1.50$).

8. There was essentially no difference in the pilot ratings obtained for the configurations evaluated at the low and high Dutch roll frequencies ($\omega_d \approx 1.0$ and $\omega_d \approx 2.0$ rad/sec) for a Dutch roll damping ratio of $\zeta_d \approx 0.1$ and a moderate roll-to-sideslip ratio ($|\phi/\beta|_d \approx 1.5$).

9. The effect of a high roll-to-sideslip ratio ($|\phi/\beta|_d \approx 3.0$) was less degrading at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) than at the low frequency ($\omega_d \approx 1.0$ rad/sec). The low directional stability associated with the low Dutch roll frequency leads to larger sideslip excursions and consequently larger roll angles with a corresponding degradation in roll control. The large roll disturbance in turbulence was objectionable at both frequencies evaluated.

10. The combination of low Dutch roll frequency ($\omega_d \approx 1.0$ rad/sec) low damping ratio ($\zeta_d \approx 0.03$) and high roll-to-sideslip ratio

was unacceptable for all evaluation points. The combination of low ζ_d and high $|\phi/\beta|_d$ created severe coordination problems and resulted in sustained lateral oscillations in turbulence.

11. For the medium roll-to-sideslip configurations, the majority of the improvement in pilot rating occurred when Dutch roll damping ratio was increased from $\zeta_d \approx 0.03$ to $\zeta_d \approx 0.1$. A further increase in damping ratio to $\zeta_d \approx 0.26$ did not improve the pilot rating proportionately.

12. Although an increase in Dutch roll damping ratio above $\zeta_d \approx 0.1$ does not significantly improve the handling qualities, it does produce a dramatic improvement in the turbulence response (i.e., turbulence rating) and riding qualities.

13. The desired level of Dutch roll damping ratio was strongly influenced by the amount of roll sideslip coupling. When the roll-to-sideslip ratio is high, the Dutch roll damping ratio should also be high.

14. There was essentially no difference in the pilot opinions of handling qualities between the configurations evaluated with the same Dutch roll frequency and damping ratio and roll mode time constant for roll-to-sideslip ratios in the order 0.25 to 1.5.

15. There was little difference in the pilot ratings and pilot comments for similar configurations evaluated at roll mode time constants of 0.4 and 1.0 seconds.

16. A roll mode time constant of 2.0 seconds is marginally satisfactory (i.e., PR $\approx$ 3.5) for the landing approach phase of flight.

17. The combination of high roll-to-sideslip ratio ($|\phi/\beta|_d \approx 3.0$) and moderate roll mode time constant ($\tau_R \approx 1.0$ seconds) is not satisfactory for the landing approach. The large roll rates that result from sideslip excursions or rudder inputs are difficult to counter with the longer roll mode time constant.

18. Lateral-directional dynamics do not impose a limit on the maximum crosswind component, provided sufficient aileron and rudder control power are available to perform the approach. This does not mean, however, that all combinations of lateral-directional dynamics are desirable or even acceptable.

Section 6

REFERENCES

1. S.B. Anderson, H.C. Quigley, R.C. Innis, "Some Performance and Handling-Qualities Considerations for Operation of STOL Aircraft," Conference on Aircraft Operating Problems, NASA SP-83, May 1, 1965, p. 309.

2. R.O. Schade and H.L. Cr ne, "Low-Speed Flight Characteristics of a Powered-Lift Jet Transport During the Landing Approach," Conference on Aircraft Operating Problems, NASA SP-83, May 1, 1965, p. 319.

3. J.F. O'Gara, "Aircraft Crosswind Performance," AGARD Report 492, October 1964.

4. C.J. Mazza, W. Becker, et al., Proposal for Revised Military Specification, "Flying Qualities of Piloted Airplanes," (MIL-F-8785ASG) with substantiating text, NADC-ED-6268, Navy, 22 July 1963.

5. E. Seckel, G.E. Miller, and W.B. Nixon, "Lateral-Directional Flying Qualities for the Power Approach," Princeton University, Report No. 727, September 1966.

6. E. Seckel, J.A. Franklin, and G. . Miller, "Lateral-Directional Flying Qualities for Power Approach Influence of Dutch Roll Frequency," Princeton University, Report No. 797, September 1967.

7. J.I. Meeker and G.W. Hall, "In-Flight Evaluation of Lateral-Directional Handling Qualities for the Fighter Mission," AFFDL-TR-67-98, July 1967.

8. C.R. Chalk, "Flight Evaluation of Various Phugoid Dynamics and $1/T_{h_1}$ Values for the Landing Approach Task," AFFDL-TR-66-2, February 1966.

9. G.W. Hall, "In-Flight Investigation of Longitudinal Short-Period Handling Characteristics of Wheel-Controlled Airplanes," AFFDL-TR-68-91, August 1968.

10. C.R. Chalk, T.P. Neal, T.M. Harris, F.E. Pritchard, (CAL) and R.J. Woodcock (AFFDL), "A Background Information and User Guide for MIL-F-8785B(ASG),' Military Specification--Flying Qualities of Piloted Airplanes,"' AFFDL-TR-69-72, August 1969.

11. M.R. Barber, C.L. Jones, T.R. Sisk, and F.W. Haise, "An Evaluation of the Handling Qualities of Seven General-Aviation Aircraft," NASA TND-3726, November 1966.

12. B. Etkin, Dynamics of Flight Stability and Control (John Wiley & Sons, March 1963).

13. R. Donely, J.W. Jewel, Jr., and P.A. Hunter, "An Assessment of Repeated Loads on General Aviation and Transport Aircraft," Paper presented at 5th I.C.A.F. Symposium, Melbourne, Australia, May 1967.

14. G.W. Hall, "An In-Flight Investigation of Lateral-Directional Dynamics for Cruising Flight," FAA ADS 69-13, December 1969.

15. D.R. Ellis, and E. Seckel, "Flying Qualities of Small General Aviation Airplanes, Part 1 - The Influence of Dutch-Roll Frequency, Dutch-Roll Damping, and Dihedral Effect," Princeton University, Report No. 870, June 1969.

16. G.L. Teper, "Aircraft Stability and Control Data," STI Technical Report 176-1, April 1969.

17. E. Seckel, Stability and Control of Airplanes and Helicopters (New York Academic Press, 1964).

18. D.W. Rhoads, "Flight Evaluation of the Effect of Variable Spiral Damping in a JTB-26B Airplane," CAL Report No. TB-1094-F-1, October 1957.

19. I.L. Ashkenas and D.T. McRuer, "The Determination of Lateral Handling Quality Requirements from Airframe-Human Pilot System Studies," WADC TR 59-135, June 1959.

20. F.F. Eckhart, G.W. Hall and P.A. Martino, "Flight Evaluation of a Stability Augmentation System for Light Airplanes," FAA ADS-83, November 1966.

21. D.O. Dommasch, S.S. Sherby, and T.F. Connelly, Airplane Aerodynamics, (Pitman Publishing Corporation, 1958).

22. D.T. McRuer, C.L. Bates, and Ashkenas, I.L., "Dynamics of the Airframe," BuAer Report AE-61-4II, September 1962.

23. F.D. Newell and M. Parrag, "Lecture Notes on Lateral-Directional Stability," CAL Report No. TB-1961-F-1, July 1965.

24. G. Bull, "A Flight Investigation of Acceptable Roll to Yaw Ratio of the Dutch Roll and Acceptable Spiral Divergence," CAL Report No. TB-574-F-6, February 1952.

25. J.E. Borches, III, "Demonstration Data Report for the T-39D Airplane," North American Aviation Report No. AN-63-456, 10 June 1963.

26. K.L. Martin, C.J. Henshaw and C.S. Cross, "Air Force Evaluation of the Jet Commander Model 1121 Aircraft," AFFTC TR 65-28, September 1965.

27. R.H. Myers, Jr. and C.S. Cross, "C-140 Jet Star Flight Evaluation," AFFTC TR-62-24, February 1963.

28. R.P Harper, Jr., "In-Flight Simulation of the Lateral-Directional Handling Qualities of Entry Vehicles," WADD-TR-61-147, November 1961.

29. I.L. Ashkenas, "A Study of Conventional Airplane Handling Qualities Requirements, Part II. Lateral-Directional Oscillatory Handling Qualities," AFFDL-TR-65-138, November 1965.

30. R.W. Broom, C.J. Henshaw, and C.S. Cross, "Air Force Evaluation of the Lear Jet Model 23 Aircraft," FTC-TR-65-21, August 1963.

31. T.I. Ligum, "Aerodynamics and Flight Dynamics of Turbojet Aircraft," NASA TT F-542, September 1969.

32. W. Taylor,Jr. and K.W. Iliff, "Recent Research Directed Toward the Prediction of Lateral-Directional Handling Qualities," AGARD Report 531, 1966.

33. I.L. Ashkenas, "Some Open- and Closed-Loop Aspects of Airplane Lateral-Directional Handling Qualities," AGARD Report, May 1966.

34. J.I. Meeker, "Evaluation of Lateral-Directional Handling Qualities of Piloted Re-Entry Vehicles Utilizing Fixed-Base and In-Flight Evaluations," CAL Report No. TC-1921-F-5, January 1966.

35. Marion O. McKinney, Jr., "Experimental Determination of the Effect of Negative Dihedral on Lateral Stability and Control Characteristics at High Lift Coefficients," NACA ARR 477, January 1946.

36. Robert C. Innis, "Factors Limiting the Landing Approach Speed of Airplanes from the Viewpoint of a Pilot," AGARD Report 358, 1961.

37. K.J. Staples, "Some Flight Measurements of Crosswind Landings on a Small ta Aircraft (AVRO707A)," R&M No. 3476, Aeronautical Research Council, Britain, April 1965.

38. G. Patterson and W. Spangenberg, "The Provision of Adequate Lateral Control Power for Landing Approach Conditions," AGARD Report 419, January 1963.

39. D.H. Perry, W.G.A. Port, and J.C. Morrall, "A Flight Study of the Sidestep Manoeuvre During Landing," R&M No. 3347, Aeronautical Research Council, Britain, July 1964.

40. W.E. McNeill and R.F. Vomaske, "A Flight Investigation to Determine the Lateral Oscillatory Damping Acceptable for an Airplane in the Landing Approach," NASA Memo 12-10-58A, February 1959.

41. S. Faber, "Comparison of Effectiveness of Coordinated Turns and Level Sideslips for Correcting Lateral Displacement During Landing Approaches," NACA RM L9I29, December 1949.

42. S.M. Harmon, "Aerodynamic Factors Affecting the Ability of a Pilot to Return an Airplane to Level From a Banked Attitude by Use of the Rudder Alone and Without Change of Heading," NACA ARR 88, October 1941.

43. J. Fischel, P. Butchart, G.H. Robinson, and R.A. Tremant, "Flight Studies of Problems Pertinent to Low-Speed Operation of Jet Transports," NASA Memo 3-1-59H, April 1959.

44. J.C. Lane and R.W. Cumming, "Pilot Opinions and Practices on the Approach to Landing: A Questionary Survey Among Australian Civil and Military Pilots," Aeronautical Research Laboratory. Human Engineering Report No. 1, April 1959.

45. T. Hacker, "Some Recent Aspects of the Theory of Stability and Control of Aircraft - Part 2. Problems of Stability and Control Connected with Certain Present-Day Flight and Operating Characteristics," Library Translation No. 1107. Royal Aircraft Establishment, April 1965.

46. W.E. McNeill and R.C. Innis, "The Effect of Yaw Coupling in Turning Maneuvers of Large Transport Aircraft," Conference on Aircraft Operating Problems, NASA SP-83, May 1965.

47. J.P. Campbell, "Operating Problems Peculiar to V/STOL and STOL Aircraft," Conference on Aircraft Operating Problems, NASA SP-83, May 1965.

48. J.P. Reeder, "V/STOL Aircraft Operation in the Terminal Area," Conference on Aircraft Operating Problems, NASA SP-83, May 1965.

49. T.R. Sisk, K.S. Irwin, and J.M. McKay, "Review of the XB-70 Flight Program," Conference on Aircraft Operating Problems, NASA SP-83, May 1965.

50. K.H. Doetsch, D.G. Gould, and D.M. McGregor, "A Flight Investigation of Lateral-Directional Handling Qualities for V/STOL Aircraft in Low Speed Manoeuvering Flight," National Aeronautical Establishment, National Research Council of Canada, August 1969.

51. D. Adamson, "Note on the Effect of Size of Aircraft Upon the Difficulties Involved in Landing an Aircraft," A.R.C. Technical Report, R&M No. 25[illegible], 1951.

52. D. Graham and C. James, "A Flight Investigation of Minimum Acceptable Lateral Dynamic Stability," CAL Report No. TB-574-F-3, April 1950.

53. A. Spence and D. Lean, "Some Low-Speed Problems of High Speed Aircraft." AGARD Report 357, April 1961.

54. A.N. Clifton, "The Problems of Designing for the Take-off and Landing of High Speed Aircraft." AGARD Report 413, January 1963.

55. D.B. Seager, "The Landing of Advanced Flight Vehicles." AGARD Report 428, January 1963.

56. W.J. Oldmixon, "The Acquisition, Reduction, and Analysis of Turbulence Data Associated with PA Configuration Approaches to Carrier Landings." Department of Aeronautical Engineering, Princeton University, Report No. 653, July 1963.

57. A.G. Barnes, "A Simulator Investigation of Rolling Requirements for Landing Approach." R&M No. 3605, Aeronautical Research Council, Britain, August 1967.

58. R.L. Stapleford, D.E. Johnston, G.L. Teper, and D.H. Weir, "Development of Satisfactory Lateral Directional Handling Qualities in the Landing Approach." NASA CR-239, July 1965.

59. P.M. Condit, L.G. Kimbrul, and R.G. Roat, "In Flight and Ground-Based Simulation of Handling Qualities of Very Large Airplanes in Landing Approach." NASA Contract No. NAS2-3224, The Boeing Co., June 1966.

60. W.J.G. Pinsker, "Features of Large Transport Aircraft Affecting Control During Approach and Landing." AGARD Report 421, January 1963.

61. W.H. Phillips and D.C. Cheatham, "Ability of Pilots to Control Simulated Short Period Yawing Oscillations." NACA RM L50D06, November 1950.

62. W.E. Palmer, "A Flight Simulator Study of the Lateral-Directional Stability Requirements of Piloted Air Vehicles." North American Aviation, Inc., NA61H-241, March 1961.

63. J.P. Campbell and J.A. Toll, "Factors Affecting Lateral Stability and Controllability." NACA RM No. L8A28a, May 1948.

64. W.M. Kauffman and R.J. Drinkwater, III, "Variable-Stability Airplanes in Lateral Stability Research." Aeronautical Engineering Review, August 1955.

65. M.O. McKinney Jr., "Experimental Determination of the Effects of Dihedral, Vertical Tail Area, and Lift Coefficient on Lateral Stability and Control Characteristics." NACA TN1094, July 1946.

66. P.L. Bisgood, "A Review of Recent Research on Handling Qualities and its Application to the Handling Problems of Large Aircraft." R&M No. 3458, Aeronautical Research Council, Britain, June 1964.

67. G.W. Hall and R.W. Huber, "System Description and Performance Data for the USAF/CAL Variable Stability T-33 Airplane." AFFDL TR-70-71, CAL Report No. BM-2321-F-2. Air Force Flight Dynamics Laboratory, July 1970.

68. G.E. Cooper and R.P. Harper, "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities." NASA TND-5153, April 1969.

69. G.W. Hall, "A Method of Matching Flight Test Records with the Output of an Analog Computer." CAL FDM No. 400, September 1966.

70. Dennis D. Behm, "Analog Matching Technique for Longitudinal Responses." CAL FDM No. 409, October 1967.

71. Anon., Military Specification, "Flying Qualities of Piloted Airplanes." MIL-F-8785B ASG, 7 August 1969.

72. D.R. Ellis and E. Seckel, "Flying Qualities of Small General Aviation Airplanes Part 1. The Influence of Dutch-roll Frequency, Dutch-roll Damping and Dihedral Effect." Princeton University Report No. 870, June 1969.

73. C.R. Chalk and D.L. Key, "Experiment Design and Data Acquisition for V/STOL Flying Qualities Simulation." Presented at: Society of Automotive Engineers National Aeronautical and Space Engineering and Manufacturing Meeting, October 1969.

74. Donald T. Berry and Bruce G. Powers, "Handling Qualities of the XB-70 In the Landing Approach." NASA TND-5676, February 1970.

Appendix I

LATERAL-DIRECTIONAL EQUATIONS OF MOTION

The lateral-directional equations are written in Laplace notation for a set of body axes using the following basic assumptions:

- The airplane is a rigid body.
- The mass of the airplane does not change during the period of dynamic analysis.
- The airplane is initially in unaccelerated flight and maintains constant altitude.
- The earth is considered to be a flat, inertial, nonrotating, space fixed body.
- The air mass is nonaccelerating.
- The x-z plane is considered to be a plane of symmetry.
- The perturbations from the equilibrium or steady state condition are small enough that the products and squares of the variations are small in comparison with the variations themselves and can be neglected. Also, the perturbation angles are small enough that the sines of these angles may be set equal to the angles and the cosines equal to one. Products of these angles are also negligibly small.
- In the steady flight condition, the airplane is in wings level, symmetric flight with no angular velocity.
- The elevators and ailerons are symmetrically located with respect to the x-z plane and the rudder is located parallel to the x-z plane.
- The control surfaces are movable rigid components attached to a rigid body.
- The airflow around the airplane is quasi-steady.
- The initial pitch angle is zero.

The lateral-directional equations using primed derivatives are as follows:

$$(Y_\beta - s)\beta + (Y_r - 1)r + \left[\frac{g}{V} + (Y_p + \alpha_o)s\right]\phi = -Y_{\delta_{AW}}\delta_{AW} - Y_{\delta_{RP}}\delta_{RP}$$

$$L'_\beta\beta + L'_r r + (L'_p s - s^2)\phi = -L'_{\delta_{AW}}\delta_{AW} - L'_{\delta_{RP}}\delta_{RP} \qquad \text{(I-1)}$$

$$N'_\beta\beta + (N'_r - s)r + N'_p s\phi = -N'_{\delta_{AW}}\delta_{AW} - N'_{\delta_{RP}}\delta_{RP}$$

In matrix form:

$$\begin{bmatrix} Y_\beta - s & Y_r - 1 & \frac{g}{V} + (Y_p + \alpha_o)s \\ L'_\beta & L'_r & L'_p s - s^2 \\ N'_\beta & N'_r - s & N'_p s \end{bmatrix} \begin{bmatrix} \beta \\ r \\ \phi \end{bmatrix} = \begin{bmatrix} -Y_{\delta_{AW}} & -Y_{\delta_{RP}} \\ -L'_{\delta_{AW}} & -L'_{\delta_{RP}} \\ -N'_{\delta_{AW}} & -N'_{\delta_{RP}} \end{bmatrix} \begin{bmatrix} \delta_{AW} \\ \delta_{RP} \end{bmatrix} \qquad \text{(I-2)}$$

The characteristic equation can then be written as:

$$\begin{aligned} |\Delta| = {} & s^4 - \left[Y_\beta + N'_r + L'_p\right]s^3 + \Big[L'_p N'_r - L'_r N'_p + Y_\beta(N'_r + L'_p) \\ & - (Y_r - 1)N'_\beta - (Y_p + \alpha_o)L'_\beta\Big]s^2 + \Big[Y_\beta(L'_r N'_p - L'_p N'_r) \\ & + (Y_r - 1)(L'_p N'_\beta - L'_\beta N'_p) + (Y_p + \alpha_o)(L'_\beta N'_r - L'_r N'_\beta) - \frac{g}{V}L'_\beta\Big]s \\ & + \frac{g}{V}(L'_\beta N'_r - L'_r N'_\beta) \end{aligned} \qquad \text{(I-3)}$$

Using Cramer's rule, the ϕ, r and β transfer functions can be written as follows:

For an aileron wheel input:

$$\begin{aligned} \frac{\phi}{\delta_{AW}} = \frac{1}{|\Delta|}\Big\{ & L'_{\delta_{AW}}s^2 + \left[Y_{\delta_{AW}}L'_\beta - L'_{\delta_{AW}}(N'_r + Y_\beta) + N'_{\delta_{AW}}L'_r\right]s \\ & + Y_{\delta_{AW}}(L'_r N'_\beta - N'_r L'_\beta) + L'_{\delta_{AW}}\left[(Y_\beta N'_r - (Y_r - 1)N'_\beta)\right] \\ & + N_{\delta_{AW}}\left[((Y_r - 1)L'_\beta - L'_r Y_\beta)\right]\Big\} \end{aligned} \qquad \text{(I-4)}$$

which can be written as

$$\frac{\phi}{\delta_{AW}} = \frac{A_{\phi_{\delta_{AW}}}\left(s^2+2\zeta_\phi\omega_\phi s+\omega_\phi^2\right)}{\left(s+\frac{1}{\tau_s}\right)\left(s+\frac{1}{\tau_R}\right)\left(s^2+2\zeta_d\omega_d s+\omega_d^2\right)} \tag{I-5}$$

where $A_{\phi_{\delta_{AW}}} = L'_{\delta_{AW}}$

$$\frac{r}{\delta_{AW}} = \frac{1}{|\Delta|}\Big\{N'_{\delta_{AW}} s^3 + \left[Y_{\delta_{AW}} N'_\beta + L'_{\delta_{AW}} N'_p - N'_{\delta_{AW}}\left(L'_p + Y_\beta\right)\right] s^2$$

$$+\Big[L'_{\delta_{AW}}\left(N'_\beta\left(Y_p+\alpha_0\right) - Y_\beta N'_p\right) + N'_{\delta_{AW}}\left(L'_p N'_\beta - \left(Y_p+\alpha_0\right)L'_\beta\right) \tag{I-6}$$

$$+ Y_{\delta_{AW}}\left(L'_\beta N'_p - N'_\beta L'_p\right)\Big] s + \left[L'_{\delta_{AW}} N'_\beta \frac{g}{V} - N'_{\delta_{AW}} L'_\beta \frac{g}{V}\right]\Big\}$$

which can be written as:

$$\frac{r}{\delta_{AW}} = \frac{A_{r_{\delta_{AW}}}\left(s+\frac{1}{\tau_{r_1}}\right)\left(s^2+2\zeta_r\omega_r s+\omega_r^2\right)}{\left(s+\frac{1}{\tau_s}\right)\left(s+\frac{1}{\tau_R}\right)\left(s^2+2\zeta_d\omega_d s+\omega_d^2\right)} \tag{I-7}$$

where

$$A_{r_{\delta_{AW}}} = N'_{\delta_{AW}}$$

For $N'_{\delta_{AW}} = 0$, the following equation applied:

$$\frac{r}{\delta_{AW}} = \frac{A_{r_{\delta_{AW}}}\left(s^2+2\zeta_r\omega_r s+\omega_r^2\right)}{\left(s+\frac{1}{\tau_s}\right)\left(s+\frac{1}{\tau_R}\right)\left(s^2+2\zeta_d\omega_d s+\omega_d^2\right)} \tag{I-8}$$

where

$$A_{r_{\delta_{AW}}} = Y_{\delta_{AW}} N'_\beta + L'_{\delta_{AW}} N'_p$$

$$\frac{\beta}{\delta_{AW}} = \frac{1}{|\Delta|}\Big\{ Y_{\delta_{AW}} s^3 + \Big[L'_{\delta_{AW}} (Y_p + \alpha_o) + N'_{\delta_{AW}} (Y_r - 1) - Y_{\delta_{AW}} (N'_r + L'_p) \Big] s^2$$

$$+ \Big[L'_{\delta_{AW}} \Big(\frac{g}{V} - N'_r (Y_p + \alpha_o) + (Y_r - 1) N'_p \Big) + N'_{\delta_{AW}} \Big((Y_p + \alpha_o) L'_r$$

$$- (Y_r - 1) L'_p \Big) + Y_{\delta_{AW}} (L'_p N'_r - L'_r N'_p) \Big] s$$

$$+ \Big(N'_{\delta_{AW}} L'_r \frac{g}{V} - L'_{\delta_{AW}} N'_r \frac{g}{V} \Big) \Big\} \qquad \text{(I-9)}$$

which can be written as:

$$\frac{\beta}{\delta_{AW}} = \frac{A_{\beta_{\delta_{AW}}} \left(s + \frac{1}{\tau_{\beta_1}} \right) (s^2 + 2\zeta_\beta \omega_\beta s + \omega_\beta^2)}{\left(s + \frac{1}{\tau_s} \right) \left(s + \frac{1}{\tau_R} \right) (s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \qquad \text{(I-10)}$$

where $A_{\beta_{\delta_{AW}}} = Y_{\delta_{AW}}$

For $Y_{\delta_{AW}} = 0$, the following equation applied

$$\frac{\beta}{\delta_{AW}} = \frac{A_{\beta\delta_{AW}} (s^2 + 2\zeta_\beta \omega_\beta s + \omega_\beta^2)}{(s + 1/\tau_S)(s + 1/\tau_R)(s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \qquad \text{(I-11)}$$

where:

$$A_{\beta_{\delta_{AW}}} = L'_{\delta_{AW}} (Y_p + \alpha_o) + N'_{\delta_{AW}} (Y_r - 1)$$

If it is further assumed that the spiral root is at the origin and that $Y_p \approx Y_r \approx \alpha_o \approx \left(N'_{\delta_{AW}} L'_r \frac{g}{V} - L'_{\delta_{AW}} N'_r \frac{g}{V} \right) \approx 0$, the sideslip per aileron input transfer function can be written as:

$$\frac{\beta}{\delta_{AW}} = \frac{-N'_{\delta_{AW}} \left[s - L'_p + \frac{L'_{\delta_{AW}}}{N'_{\delta_{AW}}} \left(N'_p - \frac{g}{V} \right) \right]}{\left(s + \frac{1}{\tau_R} \right) (s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \qquad \text{(I-12)}$$

when $N'_{\delta_{AW}} = 0$

$$\frac{\beta}{\delta_{AW}} = \frac{L'_{\delta_{AW}} \left(N'_p - \frac{g}{V} \right)}{\left(s + \frac{1}{\tau_R} \right) (s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \qquad \text{(I-13)}$$

The ratio of ϕ/β can be obtained by dividing the Equation I-4 by Equation I-9. For $L'_{\delta_{AW}} = Y_{\delta_{AW}} = 0$ and $N'_{\delta_{AW}} > 0$.

$$\frac{\phi}{\beta} = \frac{L'_r s + (Y_r - 1)L'_\beta - L'_r Y_\beta}{(Y_p - 1)s^2 + \left[(Y_p + \alpha_0)L'_r - (Y_r - 1)L'_p\right] s + L'_r\left(\frac{g}{V}\right)} \qquad \text{(I-14)}$$

For $Y_r \approx Y_p \approx 0$ and for equations referenced to body axes with $\alpha_0 = 0$

$$\frac{\phi}{\beta} = -\frac{L'_r s - (L'_\beta + L_r Y_\beta)}{s^2 - L_p s - L'_r \frac{g}{V}} \qquad \text{(I-15)}$$

From equation I-4

$$\frac{p}{\delta_{AW}} = \frac{\dot{\phi}}{\delta_{AW}} = \frac{A_{\phi\delta_{AW}}\, s\left(s^2 + 2\zeta_\phi \omega_\phi s + \omega_\phi^2\right)}{\left(s + \frac{1}{\tau_S}\right)\left(s + \frac{1}{\tau_R}\right)\left(s^2 + 2\zeta_d \omega_d s + \omega_d^2\right)} \qquad \text{(I-16)}$$

where: $A_{\phi\delta_{AW}} = L'_{\delta_{AW}}$

For the spiral root at the origin, the above equation becomes:

$$\frac{p}{\delta_{AW}} = \frac{A_\phi \delta_{AW}\left(s^2 + 2\zeta_\phi \omega_\phi s + \omega_\phi^2\right)}{\left(s + \frac{1}{\tau_R}\right)\left(s^2 + 2\zeta_d \omega_d s + \omega_d^2\right)} = \left(\frac{L'_{\delta_{AW}} \tau_R \omega_\phi^2}{(\tau_R s + 1)\omega_d^2}\right)\left(\frac{\frac{s^2}{\omega_\phi^2} + \frac{2\zeta_\phi s}{\omega_\phi} + 1}{\frac{s^2}{\omega_d^2} + \frac{2\zeta_d s}{\omega_d} + 1}\right) \qquad \text{(I-17)}$$

Thus the steady-state roll rate per aileron stick input becomes:

$$\frac{p_{ss}}{\delta_{AW}} = \tau_R \left[L'_{\delta_{AW}}\right]\left(\frac{\omega_\phi}{\omega_d}\right)^2 \qquad \text{(I-18)}$$

The following relationships can be written from the ϕ/δ_{AW} transfer function:

$$\omega_\phi^2 = \frac{Y_{\delta_{AW}}}{L'_{\delta_{AW}}}\left(L'_r N'_\beta - N'_r L'_\beta\right) + \left[\left(Y_\beta N'_r - (Y_r - 1) N'_\beta\right)\right] + \frac{N'_{\delta_{AW}}}{L'_{\delta_{AW}}}\left[\left((Y_r - 1) L'_\beta - L'_r Y_\beta\right)\right] \qquad \text{(I-19)}$$

$$2\zeta_\phi \omega_\phi = \left(\frac{Y_{\delta_{AW}}}{L'_{\delta_{AW}}}\right)L'_\beta - N'_r - Y_\beta + \left(\frac{N'_{\delta_{AW}}}{L'_{\delta_{AW}}}\right)L'_r \qquad \text{(I-20)}$$

In this experiment all configurations within a group had the same stability derivatives, however, the control derivatives $N'_{\delta_{AW}}$ and $L'_{\delta_{AW}}$ were varied to change the numerator zeros in the ϕ/δ_{AW} transfer function thus:

$$\omega_\phi^2 = C_1 + C_2 \frac{N'_{\delta_{AW}}}{L'_{\delta_{AW}}} \quad and \quad 2\zeta_\phi \omega_\phi = C_3 + C_4 \frac{N'_{\delta_{AW}}}{L'_{\delta_{AW}}} \tag{I-21}$$

where the constants are determined by the stability derivatives with the major contributions shown below for $Y_{\delta_{AW}} \approx Y_r \approx 0$:

$$C_1 \approx N'_r Y_\beta + N'_\beta \qquad C_2 \approx -L_\beta - L'_r Y_\beta$$

$$C_3 \approx -N'_r - Y_\beta \qquad C_4 \approx L'_r \tag{I-22}$$

from Equation I-3 for $Y_p \approx Y_r \approx \alpha_o \approx 0$

$$|\Delta| = s^4 - \left[Y_\beta + N'_r + L'_p\right] s^3 + \left[L'_p N'_r - L'_r N'_p + Y_\beta (N'_r + L'_p) + N'_\beta\right] s^2 + \left[Y_\beta (L'_r N'_p - L'_p N'_r) - (L'_p N'_\beta - L'_\beta N'_p) - \frac{g}{V} L'_\beta\right] s + \frac{g}{V}(L'_\beta N'_r - L'_r N'_\beta) \tag{I-23}$$

Carrying out the multiplication in the denominator of Equation I-5.

$$|\Delta| = s^4 + \left[\frac{1}{\tau_S} + \frac{1}{\tau_R} + 2\zeta_d \omega_d\right] s^3 + \left[\frac{1}{\tau_S}\frac{1}{\tau_R} + 2\zeta_d \omega_d \left(\frac{1}{\tau_S} + \frac{1}{\tau_R}\right) + \omega_d^2\right] s^2 + \left[2\left(\frac{1}{\tau_S}\frac{1}{\tau_R}\right)\zeta_d \omega_d + \omega_d^2 \left(\frac{1}{\tau_S} + \frac{1}{\tau_R}\right)\right] s + \left(\frac{1}{\tau_S}\frac{1}{\tau_R}\right)\omega_d^2 \tag{I-24}$$

Since $\frac{1}{\tau_s}$ and ζ_d are generally much smaller in magnitude than $\frac{1}{\tau_R}$ and ω_d, the following assumptions can be made:

$$\omega_d^2 >> \frac{1}{\tau_s}\ \frac{1}{\tau_R} + 2\zeta_d\, \omega_d \left(\frac{1}{\tau_s} + \frac{1}{\tau_R}\right)$$

and

$$\frac{\omega_d^2}{\tau_R} >> \frac{\omega_d^2}{\tau_s} + 2\left(\frac{1}{\tau_s}\ \frac{1}{\tau_R}\right)\zeta_d\, \omega_d$$

Thus

$$\Delta \approx s^4 + \left[\frac{1}{\tau_s} + \frac{1}{\tau_R} + 2\zeta_d\, \omega_d\right] s^3 + \left[\omega_d^2\right] s^2 + \left[\frac{\omega_d^2}{\tau_R}\right] s + \left(\frac{1}{\tau_s}\ \frac{1}{\tau_R}\right)\omega_d^2 \qquad \text{(I-25)}$$

Equating the coefficients of the terms of Equations I-23 and I-25

$$\omega_d^2 \approx L'_p N'_r - L'_r N'_p + Y_\beta\left(N'_r + L'_p\right) + N'_\beta \qquad \text{(I-26)}$$

$$\frac{1}{\tau_R} \approx \frac{Y_\beta\left(L'_r N'_p - L'_p N'_r\right) - L'_p N'_\beta + L'_\beta\left(N'_p - \frac{g}{V}\right)}{L'_p N'_r - L'_r N'_p + Y_\beta\left(N'_r + L'_p\right) + N'_\beta} \qquad \text{(I-27)}$$

$$\frac{1}{\tau_s} \approx \frac{\frac{g}{V}\left(L'_\beta N'_r - L'_r N'_\beta\right)}{Y_\beta\left(L'_r N'_p - L'_p N'_r\right) - L'_p N'_\beta + L'_\beta\left(N'_p - \frac{g}{V}\right)} \qquad \text{(I-28)}$$

$$2\zeta_d \omega_d = -Y_\beta - N'_r - L'_p - \frac{1}{\tau_s} - \frac{1}{\tau_R} \qquad \text{(I-29)}$$

Substituting the Equations I-27 and I-28 into I-29, carrying the appropriate crossmultiplication and neglecting multiples of small derivatives, Equation I-29 reduces to:

$$2\zeta_d \omega_d = -Y_\beta - N_r' - \frac{L_\beta'}{N_\beta'}\left(N_p' - \frac{g}{V}\right) \qquad \text{(I-30)}$$

Subtracting Equation I-30 from I-20

$$2\zeta_\phi \omega_\phi - 2\zeta_d \omega_d = \frac{L_\beta'}{N_\beta'}\left(N_p' - \frac{g}{V}\right) + \frac{Y_{\delta_{AW}}}{L_{\delta_{AW}}'} L_\beta' + \frac{N_{\delta_{AW}}'}{L_{\delta_{AW}}'} L_r' \qquad \text{(I-31)}$$

In view of the many pilot comments about the large roll response to external disturbances for the high roll-to-sideslip configurations, it was of interest to consider the bank angle-to-side gust transfer function.

For fixed controls, Equation I-2 becomes

$$\begin{bmatrix} Y_\beta - s & Y_r - 1 & \frac{g}{V} + (Y_p + \alpha_o)s \\ L_\beta' & L_r' & L_p' s - s^2 \\ N_\beta' & N_r' - s & N_p' s \end{bmatrix} \begin{bmatrix} \beta \\ r \\ \phi \end{bmatrix} = 0 \qquad \text{(I-32)}$$

Implicit in this equation is that the air is a satisfactory inertial reference since it is considered to be fixed to the earth. If we now allow the air mass to have motion along the y axis of the airplane, this must be accounted for in the basic set of equations. We now define:

β_V - the aerodynamic sideslip angle, or the velocity component of the airplane with respect to the air mass along the Y axis divided by V_0. (This will be the sideslip angle displayed to the pilot.)

β_G - the sideslip gust or the velocity of the air mass relative to the inertial axis or in this case the earth along the <u>negative</u> Y axis divided by V_0. Thus a positive β_G disturbance will give a positive β_V indication to the pilot.

On the basis of the above two definitions, the sideslip of the airplane relative to the earth, β_I is:

$$\beta_I = \beta_V - \beta_G$$

and

$$\dot{\beta}_I = \dot{\beta}_V - \dot{\beta}_G$$

but β_V is the total aerodynamic sideslip angle and from above $\beta_V = \beta_I + \beta_G$

We can now rewrite the above equations as follows:

$$\begin{aligned} &Y_\beta \beta_V - s(\beta_V - \beta_G) + (Y_r - 1)r + \left[\frac{g}{V} + (Y_p + \alpha_o)s\right]\phi = 0 \\ &L'_\beta \beta_V + L'_r r + (L'_p s - s^2)\phi = 0 \\ &N'_\beta \beta_V + (N'_r - s)r + N'_p s\,\phi = 0 \end{aligned} \qquad \text{(I-33)}$$

This set can then be written as follows where β_G appears as an input

$$\begin{bmatrix} Y_\beta - s & Y_r - 1 & \frac{g}{V_0} + (Y_p + \alpha_o)s \\ L'_\beta & L'_r & L'_p s - s^2 \\ N_\beta & N'_r - s & N'_p s \end{bmatrix} \begin{bmatrix} \beta_V \\ r \\ \phi \end{bmatrix} = \begin{bmatrix} -s \\ 0 \\ 0 \end{bmatrix} \beta_G \qquad \text{(I-34)}$$

and the characteristic equation is the same as Equation I-3.

The transfer function for the bank angle response to a β_G input from Equation I-34 becomes

$$\frac{\phi}{\beta_G} = \left|\frac{1}{\Delta}\right| \quad (s) \left[L'_\beta s + \left(L'_r N'_\beta - L'_\beta N'_r\right)\right] \tag{I-35}$$

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

In this investigation the spiral root was near the origin, thus from Equation I-28 $\left(L'_r N'_\beta - L'_\beta N'_r\right) \approx 0$

The transfer function then becomes simply:

$$\frac{\phi}{\beta_G} = \frac{-L'_\beta s}{\left(s + \frac{1}{\tau_R}\right)\left(s^2 + 2\zeta_d \omega_d s + \omega_d^2\right)} \tag{I-36}$$

which can be written as

$$\frac{\phi}{\beta_G} \approx -\tau_R \left(\frac{L'_\beta}{\omega_d^2}\right) \frac{s}{(\tau_R s + 1)\left(\frac{s^2}{\omega_d^2} + \frac{2\zeta_d}{\omega_d} s + 1\right)} \tag{I-37}$$

From this expression it can be seen that the bank angle response to a β gust at high frequency is $\frac{-L'_\beta}{s^2}$. The response at all frequencies is proportional to the value of L'_β. At the low frequency the response is proportional to the roll mode time constant and inversely related to the Dutch roll frequency, ω_d. The Dutch roll damping ratio determines the amplification at the Dutch roll frequency.

The bank angle response to a random sideslip disturbance would of course be dependent on the power spectral density of the random disturbance together with the airplane transfer function. The pilot, however, rates the closed loop response to turbulence which is indeed more complicated than the open loop transfer functions developed above.

Appendix II

TURBULENCE SIMULATION

A. AIRPLANE RESPONSE TO A BETA GUST

In abbreviated form the equations for roll acceleration, $\dot{p}$, and yaw acceleration, $\dot{r}$, can be written as follows:

$$\dot{p} = L'_\beta \beta + L'_p p + L'_r r + L'_{\delta_a} \delta_a$$

and

$$\dot{r} = N'_\beta \beta + N'_p p + N'_r r + N'_{\delta_r} \delta_r \qquad \text{(II-1)}$$

In the variable stability airplane with random noise inputs to the aileron and rudder simulating an artificial side gust, the aileron and rudder inputs can be described as follows:

$$\delta_a = \frac{\delta_a}{\beta} \beta_v + \frac{\delta_a}{\delta_{AW}} \delta_{AW} + \frac{\delta_a}{\beta_{ag}} \beta_{ag}$$

and

$$\delta_r = \frac{\delta_r}{\beta} \beta_v + \frac{\delta_r}{\delta_{RP}} \delta_{RP} + \frac{\delta_r}{\beta_{ag}} \beta_{ag} \qquad \text{(II-2)}$$

where β_{ag} is the sideslip generated from an artificial gust and β_v is the angle of sideslip measured by the sideslip probe. Substituting these aileron and rudder inputs into equations II-1, there results:

$$\dot{p} = L'_\beta \beta + L'_{\delta_a} \left(\frac{\delta_a}{\beta}\right) \beta_v + L'_p p + L'_r r + L'_{\delta_a} \left(\frac{\delta_a}{\delta_{AW}}\right) \delta_{AW} + L'_{\delta_a} \left(\frac{\delta_a}{\beta_{ag}}\right) \beta_{ag} \qquad \text{(II-3)}$$

and

$$\dot{r} = N'_\beta \beta + N'_{\delta_r}\left(\frac{\delta_r}{\beta}\right)\beta_V + N'_p p + N'_r r + N'_{\delta_r}\left(\frac{\delta_r}{\delta_{RP}}\right)\delta_{RP} + N'_{\delta_r}\left(\frac{\delta_r}{\beta_{ag}}\right)\beta_{ag} \qquad \text{(II-4)}$$

where

$$\left(\frac{\delta_a}{\beta}\right),\ \left(\frac{\delta_a}{\delta_{AW}}\right),\ \left(\frac{\delta_a}{\beta_{ag}}\right),\ \left(\frac{\delta_r}{\beta}\right),\ \left(\frac{\delta_r}{\delta_{RP}}\right) \text{ and } \left(\frac{\delta_r}{\beta_{ag}}\right)$$

are variable stability gain settings. In smooth air $\beta = \beta_V$, in a real gust $\beta = \beta_V = \beta_I + \beta_G$ and in an artificial gust $\beta = \beta_V = \beta_I$ where β_I is the inertial sideslip. Consequently, in real gusts,

$$\dot{p} = \left(L'_\beta + L'_{\delta_a}\left(\frac{\delta_a}{\beta}\right)\right)\beta_I + L'_p p + L'_r r + \left(L'_\beta + L'_{\delta_a}\left(\frac{\delta_a}{\beta}\right)\right)\beta_G + L'_{\delta_a}\left(\frac{\delta_a}{\delta_{AW}}\right)\delta_{AW} \qquad \text{(II-5)}$$

and

$$\dot{r} = \left(N'_\beta + N'_{\delta_r}\frac{\delta_r}{\beta}\right)\beta_I + N'_p p + N'_r r + \left(N'_\beta + N'_{\delta_r}\left(\frac{\delta_r}{\beta}\right)\right)\beta_G + N'_{\delta_r}\left(\frac{\delta_r}{\delta_{RP}}\right)\delta_{RP}$$

where β_G is the sideslip due to the real gust.

In smooth air with artificial gusts

$$\dot{p} = \left(L'_\beta + L'_{\delta_a}\frac{\delta_a}{\beta}\right)\beta_I + L'_p p + L'_r r + \left(0 + L'_{\delta_a}\left(\frac{\delta_a}{\beta_{ag}}\right)\right)\beta_{ag} + L'_{\delta_a}\left(\frac{\delta_a}{\delta_{AW}}\right)\delta_{AW}$$

and

$$\dot{r} = \left(N'_\beta + N'_{\delta_r}\left(\frac{\delta_r}{\beta}\right)\right)\beta_I + N'_p p + N'_r r + \left(0 + N'_{\delta_r}\left(\frac{\delta_r}{\beta_{ag}}\right)\right)\beta_{ag} + N'_{\delta_r}\left(\frac{\delta_r}{\delta_{RP}}\right)\delta_{RP} \qquad \text{(II-6)}$$

Thus, the rolling acceleration due to a real side gust experienced by the augmented airplane is expressed by

$\left[L'_{\beta_{T-33}} + L'_{\delta_a}\left(\frac{\delta_a}{\beta}\right)\right]\beta_G$ and that due to an artificial gust

by $\left[L'_{\delta_a}\left(\frac{\delta_a}{\beta_{ag}}\right)\right]\beta_{ag}$.

The yawing acceleration due to a real side gust is expressed by

$\left[N'_{\beta_{T-33}} + N'_{\delta_r}\left(\frac{\delta_r}{\beta}\right)\right]\beta_G$ and that due to an artificial gust

by $\left[N'_{\delta_r}\left(\frac{\delta_r}{\beta_{ag}}\right)\right]\beta_{ag}$.

In this experiment an artificial gust level was chosen for the $\left|\frac{\phi}{\beta}\right|_d =$ 1.5 and $\omega_d = 1.0$ case to be representative of moderate turbulence. Since the rolling response to a side gust for any airplane is dependent upon L'_β and the yawing response is dependent upon N'_β, it was necessary to vary $\frac{\delta_a}{\beta_{ag}}$ and $\frac{\delta_r}{\beta_{ag}}$ to arrive at the proper level of artificial turbulence response for the simulated values of $\left|\frac{\phi}{\beta}\right|_d$ (which varies with L'_β) and the simulated values of ω_d (which varies with N'_β).

Hence, for the three values of $\left|\frac{\phi}{\beta}\right|_d$ tested in this experiment, it was necessary to satisfy the following relationship for each value of $|\phi/\beta|_d$

$$\left[L'_{\beta_{T-33}} + L'_{\delta_a}\left(\frac{\delta_a}{\beta}\right)\right]\beta_G = \left[L'_{\delta_a}\left(\frac{\delta_a}{\beta_{ag}}\right)\right]\beta_{ag} \qquad \text{(II-7)}$$

$\left(L'_{\beta_{T-33}} + L'_{\delta_a}\frac{\delta_a}{\beta}\right)$ is the simulated L'_β for the respective groups tested.

Since L'_β (simulated) is approximately doubled when going from $\left|\frac{\phi}{\beta}\right|_d$ = 1.5 to $\left|\frac{\phi}{\beta}\right|_d$ = 3.0, the value of $\frac{\delta_a}{\beta_{ag}}$ was doubled for the $\left|\frac{\phi}{\beta}\right|_d$ = 3.0 Groups over that used for the $\left|\frac{\phi}{\beta}\right|_d$ = 1.5 Groups. For the $\left|\frac{\phi}{\beta}\right|_d$ = 0.25 Groups, the value of $\frac{\delta_a}{\beta_{ag}}$ was reduced to one sixth of that used for the $\left|\frac{\phi}{\beta}\right|_d$ = 1.5 Groups.

Likewise for the two values of ω_d tested it was necessary that

$$\left[N'_{\beta_{T-33}} + N'_{\delta_r}\left(\frac{\delta_r}{\beta}\right)\right]\beta_G = \left[N'_{\delta_r}\left(\frac{\delta_r}{\beta_{ag}}\right)\right]\beta_{ag} \qquad \text{(II-8)}$$

for both values of ω_d tested,

where $\left[N'_{\beta_{T-33}} + N'_{\delta_r}\left(\frac{\delta_r}{\beta}\right)\right]\beta_G$ is the simulated N'_β for the respective groups tested. Since N'_β (simulated) is approximately doubled when going from ω_d = 1.0 to ω_d = 2.0, the $\frac{\delta_r}{\beta_{ag}}$ selected for the low frequency was doubled for the high frequency.

B. RANDOM NOISE TURBULENCE SIMULATION

A random noise source was used to provide an external disturbance to the airplane for turbulence simulation during those evaluations for which the natural turbulence level was less than moderate. Moderate turbulence is defined in Appendix III. Hence, an effort was made to augment natural turbulence so that all evaluations were conducted with nearly the same combined turbulence level.

The random disturbances were obtained by driving the T-33 control surface actuators by a random noise signal. The signal was generated by a diode noise source passed through a bandpass filter. The filter had the frequency response shown in Figure II-1. The amplitudes of the disturbance signals going to the elevator, ailerons and rudder were varied independently.

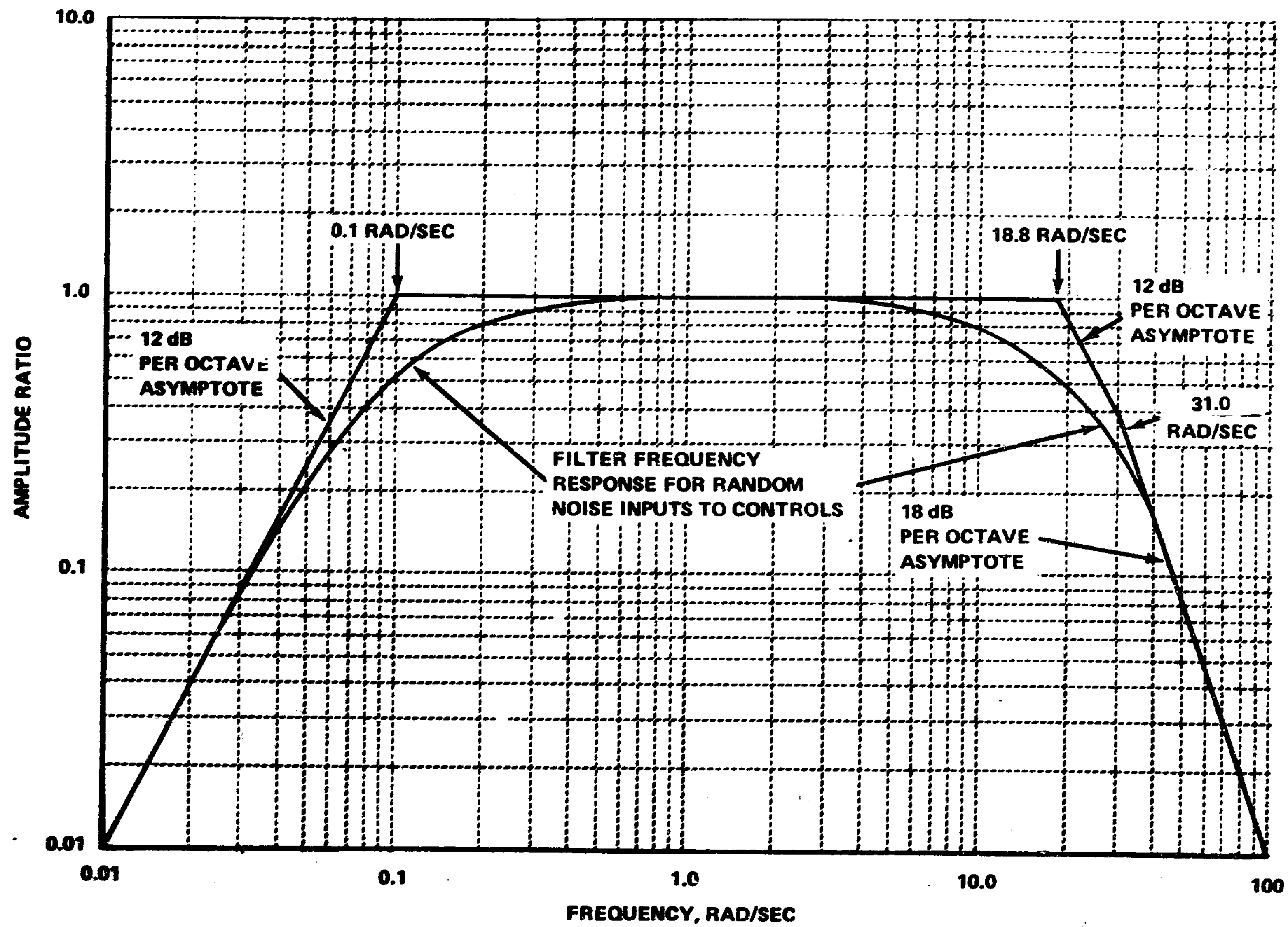


Figure II - 1 RANDOM NOISE FILTER FREQUENCY RESPONSE

Appendix III
DATA RECORDING

A digital recording system and oscillograph recording equipment mounted in the variable stability airplane were used for the acquisition of quantitative data. The following listed variables were recorded on both systems:

$\Delta\alpha_V$	δ_{AS} or δ_{AW}	$\bar{q}_c$ (airspeed)
β_V	δ_{RP}	n_z
p	δ_{ES}	n_y
q	δ_r	Altitude
r	δ_a	ILS localizer
$\dot{p}$	δ_e	ILS glide slope
$\dot{r}$	F_{AS} or F_{AW}	ILS outer marker
ϕ	F_{RP}	
θ	F_{ES}	

In addition to the variables listed above, $\dot{q}$ and $\dot{\alpha}_V$ were recorded on the oscillograph only. Other variables or quantities peculiar to the variable stability system were also recorded on the oscillograph.

The intensity of natural turbulence present during each evaluation was assessed by the system operator/safety pilot in accordance with the descriptive terminology of the Federal Aviation Administration and Department of Defense "Turbulence Reporting Criteria Table" shown on the next page.

Table III-1 TURBULENCE REPORTING CRITERIA

INTENSITY	AIRCRAFT REACTION	REACTION INSIDE AIRCRAFT	REPORTING TERM DEFINITION
LIGHT	TURBULENCE THAT MOMENTARILY CAUSES SLIGHT, ERRATIC CHANGES IN ALTITUDE AND/OR ATTITUDE (PITCH, ROLL, YAW). REPORT AS LIGHT TURBULENCE; OR TURBULENCE THAT CAUSES SLIGHT, RAPID AND SOMEWHAT RHYTHMIC BUMPINESS WITHOUT APPRECIABLE CHANGES IN ALTITUDE OR ATTITUDE. REPORT AS LIGHT CHOP.	OCCUPANTS MAY FEEL A SLIGHT STRAIN AGAINST SEAT BELTS OR SHOULDER STRAPS. UNSECURED OBJECTS MAY BE DISPLACED SLIGHTLY. FOOD SERVICE MAY BE CONDUCTED AND LITTLE OR NO DIFFICULTY IS ENCOUNTERED IN WALKING.	OCCASSIONAL LESS THAN 1/3 OF THE TIME. INTERMITTENT 1/3 TO 2/3. CONTINUOUS MORE THAN 2/3.
MODERATE	TURBULENCE THAT IS SIMILAR TO LIGHT TURBULENCE BUT OF GREATER INTENSITY. CHANGES IN ALTITUDE AND/OR ATTITUDE OCCUR BUT THE AIRCRAFT REMAINS IN POSITIVE CONTROL AT ALL TIMES. IT USUALLY CAUSES VARIATIONS IN INDICATED AIRSPEED. REPORT AS MODERATE TURBULENCE; OR TURBULENCE THAT IS SIMILAR TO LIGHT CHOP BUT OF GREATER INTENSITY. IT CAUSES RAPID BUMPS OR JOLTS WITHOUT APPRECIABLE CHANGES IN AIRCRAFT ALTITUDE OR ATTITUDE. REPORT AS MODERATE CHOP.	OCCUPANTS FEEL DEFINITE STRAINS AGAINST SEAT BELTS OR SHOULDER STRAPS. UNSECURED OBJECTS ARE DISLODGED. FOOD SERVICE AND WALKING ARE DIFFICULT.	
SEVERE	TURBULENCE THAT CAUSES LARGE, ABRUPT CHANGES IN ALTITUDE AND/OR ATTITUDE. IT USUALLY CAUSES LARGE VARIATIONS IN INDICATED AIRSPEED. AIRCRAFT MAY BE MOMENTARILY OUT OF CONTROL. REPORT AS SEVERE TURBULENCE.	OCCUPANTS ARE FORCED VIOLENTLY AGAINST SEAT BELTS OR SHOULDER STRAPS. UNSECURED OBJECTS ARE TOSSED ABOUT. FOOD SERVICE AND WALKING ARE IMPOSSIBLE	
EXTREME	TURBULENCE IN WHICH THE AIRCRAFT VIOLENTLY TOSSED ABOUT AND IS PRACTICALLY IMPOSSIBLE TO CONTROL. IT MAY CAUSE STRUCTURAL DAMAGE. REPORT AS EXTREME TURBULENCE.		

Surface winds during each evaluation performed were obtained from control tower or approach control personnel as read from standard wind speed and direction measuring equipment. Wind information was later converted to the actual ninety degree crosswind component encountered in flight.

Pilot comments and ratings were recorded in flight by use of wire recording equipment installed in the variable stability airplane. The system operator/safety pilot kept handwritten records, during flight, of his turbulence level assessment and the reported surface wind velocity. He also recorded the evaluation pilot's selected value of aileron and rudder control sensitivities. The assigned pilot rating and turbulence rating given by the evaluation pilot were hand recorded for back-up of the wire recording equipment.

Natural turbulence levels and crosswind components are listed in Appendix V. Pilot ratings are listed in Appendix VI.

Appendix IV

CONFIGURATION IDENTIFICATION

GROUP 1 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
1A2	-0.10	6.0	D	A	MODERATE	9	0.07	1.46	1120/2
1A1	-0.05	4.0	D	B	MODERATE	14	0.05	1.62	1139/2
1N0	0.0	3.0	B	A	LT. TO MOD.	14	0.04	1.77	1110/2
1P1	+0.05	4.5	D	B	MODERATE	18	0.03	1.91	1144/3
1P2	+0.10	4.0	D	B	MODERATE	4	0.014	2.04	1135/3

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 1 CONFIGURATIONS

ω_d ~ RAD/SEC	2.02	L'_r ~ SEC^{-1}	-0.685
ζ_d	0.026	N'_β ~ SEC^{-2}	3.20
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	-0.090
τ_S ~ SEC	40	N'_r ~ SEC^{-1}	0.021
$\lvert\phi/\beta\rvert_d$	1.62	Y_β ~ SEC^{-1}	-0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	42.7	$Y_{\dot\beta} - 1$	-1.01
g/V ~ SEC^{-1}	0.131	$Y_p + \alpha_o$	0.098
L'_β ~ SEC^{-2}	-10.4	$Y_r - 1$	-0.997
L'_p ~ SEC^{-1}	-2.50		

GROUP 2 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	[illegible]	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_D	ω_D RAD/SEC	FLIGHT NO.
[illegible]	-0.25	4.0	[illegible]	A	MODERATE(-)	14	0.10	1.57	1114/1
2NO	0.0	3.0	C	B	MODERATE	7	0.10	1.72	1135/1
2P	+0.05	2.0	A	A	LT. TO MOD.	14	0.10	1.87	1110/1
2P2	+0.10	2.5	[illegible]	B	MODERATE	206 26	0.10	2.00	1144/1
2P3	+0.15	3.0	D	B	MODERATE(-)	0	0.11	2.12	1146/3

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 2 CONFIGURATIONS

ω_d - RAD/SEC	1.98	L'_r - SEC^{-1}	0.678
ζ_d	0.10	N'_β ~ SEC^{-2}	2.99
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	-0.088
τ_S - SEC	∞	N'_r - SEC^{-1}	-0.198
$\vert\phi/\beta\vert_d$	1.71	Y_β ~ SEC^{-1}	-0.151
$\angle(\phi/\beta)_d$ - DEG	50.5	$Y_{\dot\beta}$ - 1	-1.01
g/V ~ SEC^{-1}	0.131	$Y_p + \alpha_o$	0.098
L'_β - SEC^{-2}	-10.3	Y_r - 1	-0.997
L'_p - SEC^{-1}	- 2.55		

GROUP 3 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
3A3	-0.15	2.5	A	B	LT. TO MOD.	0	0.21	1.39	1146/1
3A2	-0.10	3.0	B	A	MODERATE(-)	18	0.22	1.53	1114/2
3N0	0.0	2.0	A	A	MODERATE	12	0.25	1.79	1120/1
3P2	+0.10	1.5	B	B	MODERATE	6	0.27	2.01	1139/1
3P3	+0.15	1.5	B	B	MODERATE	20 & 24	0.28	2.11	1144/2

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 3 CONFIGURATIONS

ω_d RAD/SEC	2.01	L'_r - SEC^{-1}	1.93
ζ_d	0.24	N'_β ~ SEC^{-2}	3.14
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	- 0.090
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.073
$\lvert\phi/\beta\rvert_d$	1.50	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ - DEG	55.8	$Y_{\dot\beta}$ - 1	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p + \alpha_o$	0.098
L'_β ~ SEC^{-2}	- 8.32	Y_r - 1	- 0.997
L'_p ~ SEC^{-1}	- 2.58		

GROUP 4 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
4A	-0.05	8.0	F	A	MODERATE	9	0.12	1.13	1120/3
4NO	0.0	8.0	F	A	MODERATE(-)	17	0.11	1.50	1114/3
4P1	+0.05	3.5	D	B	MODERATE	5	0.11	1.79	1135/2
4P2	-0.10	3.0	C	A	LIGHT(+)	14	0.11	2.04	1110/3
4P3	-0.15	6.0	F	B	MODERATE	12	0.13	2.26	1139/3
4P3	-0.15	6.0	F	B	MODERATE(-)	0	0.13	2.26	1146/2

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 4 CONFIGURATIONS

ω_d - RAD/SEC	2.02	L'_r ~ SEC^{-1}	1.29
ζ_d	0.10	N'_β ~ SEC^{-2}	2.25
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	- 0.090
τ_S ~ SEC	100	N'_r ~ SEC^{-1}	- 0.190
$\lvert\phi/\beta\rvert_d$	3.14	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	49.2	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_0$	0.098
L'_β ~ SEC^{-2}	- 19.40	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 2.57		

GROUP 5 CONFIGURATION IDENTIFICATION WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
5A3	-0.15	6.5	E	B	LIGHT	0	λ_{ϕ_1} = 0.097	λ_{ϕ_2} = -0.30	1145/2
5A2	-0.10	5.0	D	A	LIGHT(+)	8	0.18	0.44	1109/2
5A1	-0.05	3.5	C	A	MODERATE(-)	20	0.06	0.64	1156/2
5A1	-0.05	3.5	C	A	LIGHT(-)	14	0.06	0.54	1160/2
5A1	-0.05	6.5	E	B	LT. TO MOD.	20	0.08	0.64	1136/3
5A1	-0.05	7.0	D	B	MODERATE(-)	20	0.08	0.64	1141/3
5N0	0.0	6.0	B	A	LIGHT(+)	18	0.04	0.80	1107/3
5P1	+0.05	6.0	E	B	LIGHT(-)	9	0.005	0.93	1138/3
5P2	+0.10	7.0	E	A	MODERATE	18	-0.02	1.04	1115/3

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 5 CONFIGURATIONS

ω_d ~ RAD/SEC	0.990	L'_r ~ SEC^{-1}	- 0.964
ζ_d	0.03	N'_β ~ SEC^{-2}	0.662
τ_R ~ SEC	0.35	N'_p ~ SEC^{-1}	- 0.080
τ_S ~ SEC	100	N'_r ~ SEC^{-1}	0.090
$\lvert\phi/\beta\rvert_d$	1.54	Y_β ~ SEC^{-1}	- 0.151
$\angle(\phi/\beta)_d$ ~ DEG	59.9	$Y_{\dot\beta}$ - 1	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p + \alpha_0$	0.098
L'_β ~ SEC^{-2}	- 4.67	Y_r - 1	- 0.997
L'_p ~ SEC^{-1}	- 2.87		

GROUP 6 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
6A2	-0.10	6.0	E	A	NIL	0	0.19	0.52	1105/3
6A2	-0.10	5.0	C	A	LIGHT	13	0.19	0.52	1107/1
6A1	-0.05	4.0	D	B	LT. TO MOD.	10	0.15	0.68	1131/2
6N0	0.0	3.0	A	A	NIL	0	0.12	0.82	1105/1
6N0	0.0	3.0	D	B	LT. TO MOD.	5	0.12	0.82	1130/1
6P1	-0.05	1.5	A	B	LT. TO MOD.	12	0.11	0.93	1132/2
6P2	-0.10	4.0	C	A	MODERATE	20	0.10	1.03	1116/3

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 6 CONFIGURATIONS

ω_d ~ RAD/SEC	1.00	L'_r ~ SEC^{-1}	0.040
ζ_d	0.11	N'_β ~ SEC^{-2}	0.671
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	- 0.070
τ_S ~ SEC	100	N'_r ~ SEC^{-1}	- 0.054
$\lvert\phi/\beta\rvert_d$	1.56	Y_β ~ SEC^{-1}	- 0.151
$\angle(\phi/\beta)_d$ ~ DEG	61.8	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_o$	0.098
L'_β ~ SEC^{-2}	- 4.07	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 2.53		

GROUP 6 ROLL CONTROL POWER EXPERIMENT
CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	δ_{AW} AUTHORITY	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
6P1	±45.°	+0.05	1.5	A	B	LT. TO MOD.	12	0.11	0.93	1132/2
6P1	±10.°	+0.05	3.0	C	A	LIGHT(+)	22	0.11	0.93	1158/3
6P1	±10.°	+0.05	3.0	B	A	MODERATE(-)	15	0.11	0.93	1155/3
6P1	±7.5°	+0.05	4.0	D	B	LIGHT(+)	30 G 35	0.11	0.93	1152/3
6P1	±5.0°	+0.05	6.0	C	B	MODERATE(-)	23 G 33	0.11	0.93	1150/1
6P1	±2.5°	+0.05	9.0	C	A	LIGHT(+)	24	0.11	0.93	1158/2

GROUP 7 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
7A2	-0.10	4.0	C	A	LIGHT(-)	0	0.27	0.58	1112/2
7A1	-0.05	2.5	A	B	LIGHT	0	0.28	0.72	1134/2
7N0	0.0	1.5	A	A	LT. TO MOD.	4	0.30	0.84	1118/2
7N0	0.0	2.5	B	A	LIGHT	0	0.30	0.84	1106/2
7P1	+0.05	2.0	A	B	LIGHT(+)	10	0.32	0.95	1131/3
7P2	+0.10	4.0	B	A	LIGHT(-)	18	0.33	1.04	1115/2

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 7 CONFIGURATIONS

ω_d ~ RAD/SEC	1.01	L'_r ~ SEC^{-1}	1.86
ζ_d	0.29	N'_β ~ SEC^{-2}	0.668
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	- 0.072
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.356
$\lvert\phi/\beta\rvert_d$	1.48	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	73.9	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_o$	0.098
L'_β ~ SEC^{-2}	- 3.50	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 2.58		

GROUP 8 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
8A1	-0.05	8.5	F	B	LT. TO MOD.	10	0.42	0.20	1140/2
8NO	0.0	6.0	D	A	MODERATE	20	0.07	0.64	1116/2
8NO	0.0	8.0	E	A	MODERATE	10	0.07	0.64	1161/3
8P1/2	+0.025	9.0	F	B	LIGHT(+)	20	0.04	0.77	1142/3
8P1	+0.05	9.0	F	B	LIGHT(+)	04	0.01	0.88	1134/3
8P2	+0.10	9.0	E	A	LIGHT(+)	03	-0.02	1.06	1111/3

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 8 CONFIGURATIONS

ω_d ~ RAD/SEC	1.04	L'_r ~ SEC^{-1}	- 1.42
ζ_d	0.031	N'_β ~ SEC^{-2}	0.419
τ_R ~ SEC	0.45	N'_p ~ SEC^{-1}	- 0.072
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	0.054
$\lvert\phi/\beta\rvert_d$	2.97	Y_β ~ SEC^{-1}	- 0.151
$\angle(\phi/\beta)_d$ ~ DEG	56.4	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_o$	0.098
L'_β ~ SEC^{-2}	- 7.61	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 2.20		

GROUP 9 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
9A1	-0.05	9.0	E	A	LIGHT	0	λ_{ϕ_1} = 0.11	λ_{ϕ_2} = -0.26	1112/3
9NO	0.0	8.0	D	A	LIGHT	13	0.15	0.64	1108/3
9NO	0.0	8.5	F	B	MODERATE	12	0.15	0.64	1133/2
9P1	-0.05	5.5	D	B	MODERATE	10	0.13	0.93	1140/3
9P2	-0.10	5.0	C	A	LIGHT	8	0.12	1.14	1117/3
9P3	-0.15	9.0	G	B	MODERATE(-)	22	0.12	1.32	1141/2

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 9 CONFIGURATIONS

ω_d ~ RAD/SEC	1.09	L'_r ~ SEC^{-1}	0.881
ζ_d	0.12	N'_β ~ SEC^{-2}	0.417
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	- 0.084
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.042
$\lvert\phi/\beta\rvert_d$	3.11	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	62.7	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_o$	0.098
L'_β ~ SEC^{-2}	- 8.91	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 2.57		

GROUP 9 ROLL CONTROL POWER EXPERIMENT
CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	δ_{AW} AUTHORITY	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
9P1	±45.°	+0.05	5.5	D	B	MODERATE	10	0.13	0.93	1140/3
9P1	±15.°	+0.05	5.0	F	B	MODERATE	25 G 30	0.13	0.93	1164/3
9P1	±10.°	+0.05	8.0	F	A	NIL	14	0.13	0.93	1157/2
9P1	±10.°	+0.05	8.0	F	B	MODERATE	30	0.13	0.93	1150/3
9P1	±7.5°	+0.05	10.0	E	B	MODERATE	25 G 30	0.13	0.93	1164/2
9P1	±5.0°	+0.05	9.0	G	A	MODERATE	12	0.13	0.93	1155/2
9P1	[illegible] 5°	+0.05	8.5	G	B	LIGHT	10	0.13	0.93	1162/3

GROUP 10 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
10A1	-0.05	7.0	E	B	MODERATE	24 G 28	0.30	0.33	1154/3
10A1	-0.05	9.0	E	A	LIGHT(+)	16	0.30	0.33	1113/3
10N0	0.0	3.0	B	A	MODERATE(-)	15	0.26	0.70	1160/1
10N0	0.0	3.0	C	B	LIGHT(+)	20 G 24	0.26	0.70	1137/2
10N0	0.0	4.0	D	B	MODERATE(+)	26 G 32	0.26	0.70	1143/2
10P1	+0.05	4.5	D	B	MODERATE	10	0.29	0.94	1133/3
10P2	+0.10	4.0	D	A	LIGHT	01	0.31	1.12	1111/1
10P3	+0.15	3.5	D	B	LIGHT(+)	01	0.34	1.28	1145/3

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 10 CONFIGURATIONS

ω_d ~ RAD/SEC	1.03	L'_r ~ SEC^{-1}	3.38
ζ_d	0.25	N'_β ~ SEC^{-2}	0.471
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	- 0.052
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.218
$\lvert\phi/\beta\rvert_d$	2.90	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	68.7	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_o$	0.098
L'_β ~ SEC^{-2}	- 7.30	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 2.65		

GROUP 11 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
11A2	-0.10	4.0	B	A	LT. TO MOD.	2	0.11	0.93	1118/2
11A2	-0.10	5.0	D	A	LIGHT(+)	9	0.11	0.93	1161/2
11A1	-0.05	5.0	D	B	LT. TO MOD.	6	0.11	0.95	1130/3
11N0	0.0	4.0	D	A	NIL	0	0.11	0.97	1105/2
11P1	+0.05	2.5	C	B	LT. TO MOD.	6	0.11	0.99	1130/2
11P1	+0.05	3.5	C	A	LIGHT	13	0.11	0.99	1157/3
11P2	+0.10	1.0	A	B	MODERATE	12	0.11	1.01	1132/3
11P2	+0.10	2.0	A	A	LIGHT(+)	8	0.11	1.01	1109/3
11P2	+0.10	2.0	B	A	LIGHT(+)	15	0. 1	1.01	1160/2
11P2	+0.10	2.0	B	B	LIGHT(+)	24 G 28	0.11	1.01	1153/3
11P3	+0.15	3.0	C	B	LIGHT(+)	20	0.11	1.03	1142/2

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 11 CONFIGURATIONS

ω_d ~ RAD/SEC	0.98	L'_r ~ SEC^{-1}	-0.047
ζ_d	0.11	N'_β ~ SEC^{-2}	0.951
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	-0.080
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	-0.065
$\lvert\phi/\beta\rvert_d$	0.2[illegible]	Y_β ~ SEC^{-1}	-0.15[illegible]
$\measuredangle(\phi/\beta)_d$ ~ DEG	67.4	[illegible]	-1.01
g/V ~ SEC^{-1}	0.131	$Y_p + \alpha_o$	0.098
L'_β ~ SEC^{-2}	-0.728	$Y_r - 1$	-0.997
L'_p ~ SEC^{-1}	-2.86		

GROUP II ROLL CONTROL POWER EXPERIMENT
CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	δ_{AW} AUTHORITY	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
IIP1	±45.°	+0.05	2.6	C	B	LT. TO MOD	6	0.11	0.99	1130/2
IIP1	±45.°	+0.05	3.5	C	A	LIGHT	13	0.11	0.99	1157/3
IIP1	±10.°	+0.05	2.5	C	B	LIGHT(+)	26	0.11	0.99	1151/3
IIP1	±7.5°	+0.05	5.0	D	A	MODERATE	19	0.11	0.[illegible]	1156/3
IIP1	±5.0°	+0.05	7.0	C	A	LIGHT(+)	10	0.11	0.99	1150/2
IIP1	±2.5°	+0.05	7.0	B	B	LIGHT	24	0.11	0.99	1153/2

GROUP 12 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
12A2	-0.10	3.0	A	B	LIGHT	6	0.34	0.92	1138/2
12A1	-0.05	2.5	B	A	LIGHT	10	0.34	0.94	1117/2
12P1	+0.05	2.0	B	A	LIGHT	0	0.34	0.97	1106/3
12P2	+0.10	2.0	A	B	LIGHT(+)	22	0.34	0.98	1137/3
12P3	+0.15	1.5	A	B	MODERATE(+)	26 G 34	0.35	1.00	1143/3

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 12 CONFIGURATIONS

ω_d ~ RAD/SEC	0.98	L'_r ~ SEC^{-1}	0.314
ζ_d	0.34	N'_β ~ SEC^{-2}	0.847
τ_R ~ SEC	0.40	N'_p ~ SEC^{-1}	- 0.090
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.504
$\lvert\phi/\beta\rvert_d$	0.24	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	78.1	$Y_{\dot{\beta}} - 1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p + \alpha_0$	0.099
L'_β ~ SEC^{-2}	- 0.532	$Y_r - 1$	- 0.997
L'_p ~ SEC^{-1}	- 2.51		

GROUP 13 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
13A2	-0.10	3.0	B	B	LIGHT(+)	26 G 32	0.12	0.94	1143/1
13A2	-0.10	4.0	D	A	LIGHT(+)	12	0.12	0.94	1159/3
13A2	-0.10	4.0	C	B	LIGHT	0	0.12	0.94	1134/1
13A1	-0.05	5.0	D	A	LIGHT(+)	14	0.12	0.96	1113/2
13A1	-0.05	5.0	C	B	LIGHT(+)	20	0.12	0.96	1136/2
13N0	0.0	5.0	D	B	LIGHT(+)	33	0.12	0.97	1152/2
13P1	+0.05	3.0	C	A	LIGHT(+)	8	0.12	0.98	1109/1
13P2	+0.10	3.0	B	B	LIGHT(+)	20	0.12	0.98	1137/1
13P3	+0.15	3.0	B	B	LIGHT	10	0.12	1.00	1140/1

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 13 CONFIGURATIONS

ω_d ~ RAD/SEC	1.00	L'_r ~ SEC^{-1}	0.034
ζ_d	0.099	N'_β ~ SEC^{-2}	0.939
τ_R ~ SEC	0.95	N'_p ~ SEC^{-1}	- 0.094
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.078
$\lvert\phi/\beta\rvert_d$	0.31	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\dot{\phi}/\beta)_d$ ~ DEG	41.7	$Y_{\dot{\beta}}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_o$	0.098
L'_β ~ SEC^{-2}	- 0.419	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 1.03		

GROUP 14 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
14A2	-0.10	4.0	C	A	LIGHT	0	0.17	0.76	1112/1
14A1	-0.05	2.0	A	B	LT. TO MOD.	12	0.17	0.76	1132/1
14N0	0.0	1.0	A	A	LIGHT	20	0.17	0.88	1107/2
14P1	+0.05	3.0	B	B	LIGHT	5	0.17	0.93	1131/1
14P2	+0.10	3.0	B	A	LIGHT	24 G 30	0.17	0.98	1108/1

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 14 CONFIGURATIONS

ω_d ~ RAD/SEC	1.01	L'_r ~ SEC^{-1}	0.037
ζ_d	0.10	N'_β ~ SEC^{-2}	0.757
τ_R ~ SEC	1.10	N'_p ~ SEC^{-1}	- 0.033
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.151
$\lvert\phi/\beta\rvert_d$	1.53	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	38.4	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_0$	0.098
L'_β ~ SEC^{-2}	- 1.88	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 0.812		

GROUP 14 ROLL CONTROL POWER EXPERIMENT
CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	δ_{AW} AUTHORITY	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
14P1	±45.°	+0.05	3.0	B	B	LIGHT	5	0.17	0.93	1131/1
14P1	±10.°	+0.05	2.0	B	A	LIGHT(+)	20	0.17	0.93	1158/1
14P1	±7.5°	+0.05	3.0	B	B	LIGHT(+)	30	0.17	0.93	1152/1
14P1	±5.0°	+0.05	6.0	D	A	MODERATE(-)	19	0.17	0.93	1156/1
14P1	±2.5°	+0.05	10.0	C	B	LIGHT(+)	26	0.17	0.93	1159/1

GROUP 15 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'\delta_{AW}/L'\delta_{AW}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
15A2	-0.10	6.5	E	B	LIGHT(+)	20	λ_{ϕ_1} = 0.44	λ_{ϕ_2} = -0.43	1142/1
15A1	-0.05	5.5	B	A	LIGHT(+)	9	0.41	0.24	1117/1
15N0	0.0	5.0	C	A	MODERATE	20	0.36	0.55	1116/1
15P1	+0.05	5.0	C	B	LIGHT	6	0.40	0.74	1138/1
15P2	+0.10	4.0	B	A	LIGHT	6	0.45	0.89	1118/1
15P3	+0.15	5.0	D	B	LIGHT	0	0.49	1.02	1145/1

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 15 CONFIGURATIONS

ω_d ~ RAD/SEC	1.13	L'_r ~ SEC^{-1}	4.02
ζ_d	0.09	N'_β ~ SEC^{-2}	0.271
τ_R ~ SEC	0.95	N'_p ~ SEC^{-1}	- 0.105
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.248
$\lvert\phi/\beta\rvert_d$	3.50	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	54.2	$Y_{\dot\beta}-1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p+\alpha_0$	0.098
L'_β ~ SEC^{-2}	- 4.39	Y_r-1	- 0.997
L'_p ~ SEC^{-1}	- 0.860		

GROUP 16 CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	$N'_{\delta_{AW}}/L'_{\delta_{AW}}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
16A2	-0.10	4.5	C	B	LIGHT(+)	20	0.27	0.80	1141/1
16A1	-0.05	4.0	C	A	LIGHT(+)	18	0.28	0.85	1115/1
16N0	0.0	2.0	B	A	LIGHT	9	0.29	0.89	1161/1
16N0	0.0	4.0	D	B	LIGHT	12	0.29	0.89	1162/2
16N0	0.0	5.0	D	B	LT. TO MOD.	10	0.29	0.89	1133/1
16P1	+0.05	2.5	B	A	LIGHT(+)	15	0.29	0.94	1155/1
16P1	+0.05	3.0	D	B	LIGHT(+)	18 G 22	0.29	0.94	1153/1
16P1	+0.05	4.0	C	A	LIGHT(+)	3	0.29	0.94	1113/1
16P2	+0.10	4.0	B	B	LIGHT(+)	20	0.30	0.98	1136/1

NOMINAL LATERAL-DIRECTIONAL MODAL PARAMETERS AND STABILITY DERIVATIVES FOR GROUP 16 CONFIGURATIONS

ω_d ~ RAD/SEC	1.00	L'_r ~ SEC^{-1}	0.715
ζ_d	0.11	N'_β ~ SEC^{-2}	0.754
τ_R ~ SEC	2.00	N'_p ~ SEC^{-1}	- 0.088
τ_S ~ SEC	∞	N'_r ~ SEC^{-1}	- 0.361
$\lvert\phi/\beta\rvert_d$	1.55	Y_β ~ SEC^{-1}	- 0.151
$\measuredangle(\phi/\beta)_d$ ~ DEG	21.2	$Y_{\dot\beta} - 1$	- 1.01
g/V ~ SEC^{-1}	0.131	$Y_p + \alpha_o$	0.098
L'_β ~ SEC^{-2}	- 1.50	$Y_r - 1$	- 0.997
L'_p ~ SEC^{-1}	- 0.211		

GROUP 16 ROLL CONTROL POWER EXPERIMENT
CONFIGURATION IDENTIFICATION
WHEEL CONTROLLER

CONFIG.	δ_{AW} AUTHORITY	$K'\delta_{AW}/L'\delta_{AW}$	P.R.	T.R.	PILOT	NATURAL TURBULENCE	CROSSWIND KNOTS	ζ_ϕ	ω_ϕ RAD/SEC	FLIGHT NO.
16P1	±45.°	+0.05	4.0	C	A	LIGHT(+)	3	0.292	0.94	1113/1
16P1	±45.°	+0.05	2.5	B	A	LIGHT(+)	15	0.292	0.94	1155/1
16P1	±45.°	+0.05	3.0	D	B	LIGHT(+)	18 & 22	0.292	0.94	1153/1
16P1	±10.°	+0.05	4.0	C	B	LIGHT	14	0.292	0.94	1162/1
16P1	±7.5°	+0.05	3.0	B	A	LIGHT	10	0.292	0.94	1159/1
16P1	±5.0°	+0.05	7.0	E	B	LIGHT(+)	25 & 33	0.292	0.94	1151/1
16P1	±2.5°	+0.05	9.0	F	A	NIL	10	0.292	0.94	1157/1

GPO 912-015