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FLIGHT INVESTIGATION OF LATERAL-DIRECTIONAL FLYING QUALITIES AND CONTROL POWER REQUIREMENTS FOR STOL LANDING APPROACH USING THE X-22A AIRCRAFT. VOLUME I. TECHNICAL RESULTS

R. E. Smith, et al

Calspan Corporation

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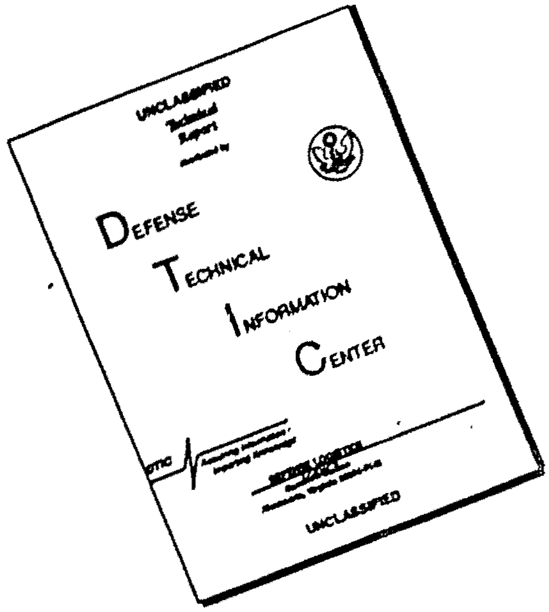

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FLIGHT INVESTIGATION OF LATERAL-DIRECTIONAL FLYING QUALITIES AND CONTROL POWER REQUIREMENTS FOR STOL LANDING APPROACH USING THE X-22A AIRCRAFT

VOLUME I: TECHNICAL RESULTS

FINAL REPORT

By:

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R.C. Radford

Prepared Under Contract N00019-72-C-0417

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FOREWORD

This report was prepared for the United States Naval Air Systems Command, the National Aeronautics and Space Administration Langley Research Center, the Federal Aviation Agency, and the United States Air Force Flight Dynamics Laboratory under Contract Number N00019-72-C-0417 by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.), Buffalo, New York.

The flying qualities experiment reported herein was performed by the Flight Research Department of Calspan. Mr. J.L. Beilman was the Program Manager; Mr. R.E. Smith was the Project Engineer and also served as pilot. Messrs. J.V. Lebacqz and R.C. Radford were the research engineers, and Mr. R.D. Till was the project engineer for the X-22A aircraft electronic systems. Technical monitoring was performed by the X-22A Flight Research Steering Group, chaired by Mr. R. Siewert of the Naval Air Systems Command. The authors are grateful to Mr. Siewert and the members of the Steering Group for their interest and support throughout the program, and wish to acknowledge their appreciation to: Mr. C. Mazza, NADC; Messrs. R.J. Tapscott, J. Garren, and J. Brewer, NASA; Mr. J. Teplitz, FAA; and Mr. T.L. Neighbor, USAF.

Research programs using the X-22A aircraft require extensive efforts and contributions from a large number of individuals at Calspan. For the flight program and subsequent analyses reported upon herein, the authors are particularly grateful to: Mr. J.L. Beilman, X-22A Program Manager, for his careful attention to the daily operation of the flight program; Mr. N.L. Infanti, Calspan Chief Pilot, for his assistance in the conduct of the flights, both as safety pilot and as advisor; Mr. J.L. Lyons, who was responsible for the extensive computer programming and digital data reduction required on this program; and Mrs. J.A. Martino, Technical Editor for this report, who aided the authors immeasurably in its preparation. The counsel and advice of J.M. Schuler is also acknowledged. The outstanding contributions of the following persons are also gratefully acknowledged:

Messrs. G.W. Hall and G. Bull - Evaluation Pilots
Mr. G. Ewers - Aircraft Crew Chief
Messrs. J. Wilson and J. Shattuck - Electronics maintenance
Messrs. H. Chmura, D. Dobmeier, R. Hoen, W. Howell, E. Melbourne, R. Solo - Aircraft maintenance
Messrs. T. Gavin and J. Panzarella - Digital Data Acquisition System
Messrs. F. Erny and W. Wilcox - Aircraft maintenance supervision.

In addition, special thanks are due to Dr. R.T.N. Chen for the development of the example on input design presented in Appendix III of this report.

ABSTRACT

A flight investigation of the influence of lateral-directional dynamics and control power requirements on flying qualities for STOL aircraft in terminal area operations was conducted using the X-22A variable stability aircraft. The primary dynamic variables of the experiment were roll mode time constant, Dutch roll undamped natural frequency, roll-to-sideslip ratio, and yaw due to aileron; in addition, the roll control power available was varied by electrically limiting the lateral stick command of the evaluation pilot. Three pilots performed 102 evaluations of various combinations of these variables at a representative STOL approach condition of $\gamma = -7.5^{\circ}$, V = 65 kts. During the evaluations, a qualitative separation of ambient turbulence level was made through approximate measurements from the aircraft. The configuration dynamics were identified and verified with a digital identification technique developed for the X-22A, and data analyses include statistical measurements of pilot workload and performance, as well as correlation of pilot rating data with these measures, the configuration dynamics, and the roll control power available. The results from the experiment are compared with applicable requirements of MIL-F-83300, MIL-F-8785B, and Calspan's proposed revisions to the Dutch roll frequency for Level 1 flying qualities was found to be lower than required by MIL-F-83300. Roll mode time constant requirements of MIL-F-83300 and MIL-F-8785B (Class II-L) were larger than those determined for Level 1 flying qualities. The roll control powers that were determined in this experiment were less than those required by the specifications.

TABLE OF CONTENTS

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TABLE OF CONTENTS (CONT.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont.)

LIST OF TABLES

Section I

INTRODUCTION

For most aircraft, the landing approach is a critical phase of flight which demands accurate positioning of the aircraft relative to the runway with a limited margin for error. The need for satisfactory flying qualities and adequate control power in this critical flight phase is clear. Unfortunately, in the case of STOL aircraft, the combination of slow approach speeds and relatively high inertias generally leads to a deterioration in flying qualities during landing approach. In particular, the demands on lateral control power may be considerable at the very time when the control effectiveness of the aerodynamic controls is reduced due to the low approach speeds. Most STOL aircraft may therefore need to have their control effectiveness augmented in some manner, which can result in unwanted weight or power penalties. Lateral control power requirements, though exceedingly important as a design parameter, are unfortunately very poorly defined. Therefore a need exists for a systematic investigation of the control power required to perform the STOL landing approach task.

This report describes the results of an in-flight simulation program, using the X-22A variable stability aircraft, whose objectives were directed at providing lateral-directional flying qualities and control power data for STOL aircraft in the landing approach. Specifically, the two main objectives were:

1. To determine control power requirements, particularly those in roll, and to investigate how these requirements change with various lateral-directional parameters for STOL aircraft in the landing approach, and

2. To obtain lateral-directional flying qualities data in support of the appropriate requirements in MIL-F-83300 (References 1 and 2), or MIL-F-8785B(ASG) (References 3 and 4), for STOL aircraft in terminal area operations (Class II Aircraft - Flight Phase Category C).

To achieve these objectives, an experiment was designed to evaluate the suitability of a variety of lateral-directional response characteristics for the approach flight phase using a representative STOL approach velocity (65 knots) and glide path (7.5 deg). Attention was focused upon VFR and IFR approaches in both smooth and moderately turbulent ambient conditions. For each approach the control power used, as opposed to that available, was measured when there was essentially unlimited authority. The roll control power available was then systematically reduced for selected lateral-directional configurations to determine the minimum lateral control power required.

Three evaluation pilots participated in the program and made a total of 102 evaluations of 17 different combinations of lateral-directional characteristics. Each pilot recorded his comments during the evaluations and then assigned two pilot ratings using the Cooper-Harper Scale (Reference 5): one rating for the aircraft considering the VFR approach task alone, and an overall rating for the aircraft in the context of STOL terminal area operations, based upon both approach tasks. In each case, a turbulence effect rating was assigned based upon the degree of deterioration in task performance due to ambient turbulence. Aircraft flight variables were recorded continuously during all flights and processed digitally to obtain identification of evaluation configuration dynamic characteristics and statistical measures of control usage, task performance, and ambient turbulence levels.

The report is divided into two volumes. Volume I is a summary of the experiment and the important results, while Volume II contains the details of the experiment and the analysis of the data and provides specific background information for the contents of Volume I. This volume of the report is organized as follows. Section II discusses the design of the experiment; Section III outlines the conduct of the experiment, including a brief description of the equipment used. The results of the experiment in the form of pilot ratings and comments are presented in Section IV, while Section V presents the results of the sub-experiment to determine minimum lateral control power requirements. A summary of the statistical measures is presented in Section VI, and correlations of the data with existing flying qualities criteria are given in Section VII. Finally, the conclusions are given in Section VIII. Appendix I from Volume II is repeated in this volume as a summary of applicable background data.

Section II

DESIGN OF THE EXPERIMENT

The purpose of the experiment was to generate lateral-directional flying qualities data and to determine the minimum lateral control power for STOL aircraft during terminal area operations (Flight Phase Category C). To best accomplish this objective, the approach subphase was chosen as the area in which to concentrate quantitatively, with the actual landing to receive attention through extrapolation. The approach subphase encompasses the following elements: visual approach "tracking", localizer and glide slope capture, ILS tracking, breakout, visual runway line up, and wave off. As is discussed in the next section, the evaluation task was designed to exercise all of these elements, thereby studying the approach subphase.

This section will describe the design of the experiment, including a brief summary of the rationale behind the selection of the lateral-directional characteristics, and present the details of the evaluation configurations.

2.1 BACKGROUND AND PURPOSE

The landing approach is perhaps the most critical phase of flight for STOL aircraft which fall within the Class II category in the military specifications. This phase of flight presents the pilot with an exacting task, and is often complicated by IFR flight conditions requiring precise instrument flying, a transition to visual flight with a possible lateral offset from the runway, and a landing in a limited period of time. Additional factors such as turbulence and crosswinds can further complicate the pilot's already demanding task. Obviously, in this critical portion of his flight, the pilot should be provided with the best possible flying qualities and adequate control power.

Unfortunately, the flying qualities, as well as the available control power, of STOL designs are adversely affected by the relatively high inertias of the aircraft in combination with the slow approach speeds. In particular, the demands on lateral control power may be high at a time when aerodynamic control effectiveness is reduced due to the low approach speeds. In many cases, depending on the design, the control effectiveness may therefore need to be augmented in some manner, which can be costly in the form of unwanted weight or power penalties. The designer is therefore interested in knowing what <u>minimum</u> control power is required to do the task, in this case the STOL landing approach. In addition, he is concerned about the flying qualities requirements and how the control power requirements are related to these characteristics. This experiment was designed to produce data to help clarify these problem areas. Specifically, the experiment was aimed at the determination of minimum lateral control power requirements for the STOL landing approach task for a variety of lateral-directional response characteristics.

Part of the reason for the paucity of control power data, particularly for STOL aircraft, is the fact that in most investigations, with both real aircraft and simulators, the actual control power used to perform a specific task is not documented -- typically, only the control power available is quoted. Reference 6 is an example of an extensive investigation of lateral-directional flying qualities, applicable to STOL aircraft, which reported no control usage data. The approach used in the current experiment, therefore, was to measure the actual control power used when there was essentially unlimited authority, and then to reduce the control power available to determine the minimum amount required. A recent investigation (Reference 7), using the USAF/Calspan variable stability T-33, concerned itself with the problem of determining the minimum roll control power requirements for executive jet and related military Class II airplanes, and was used as a guideline for the design of this experiment.

There are many aircraft and task variables which influence the control power required to perform a given mission or series of tasks. Since all these factors interact with each other, the result is an extremely complex situation. A more detailed discussion of the many aircraft and task variables involved can be found in the back-up documents for the military specification (References 2 and 4). The primary factor is, of course, the mission; for this experiment, STOL aircraft terminal area operations were of interest, including both IFR and VFR approaches. In general, for this mission, control power is required to:

(1) trim, i.e. maintain some steady flight condition for normal states and failure states,

(2) maneuver, i.e. perform the necessary tasks about trim, and

(3) correct for disturbances, i.e. correct the effects of external disturbances and failure transients.

The lateral-directional parameters which have the most direct effect on lateral control power and the aircraft flying qualities are summarized briefly below:

- roll mode time constant, τ_R
- Dutch roll mode frequency and damping ratio, ω_d, ζ_d
- frequency and damping ratio of the numerator factor in the ϕ/δ_{AS} transfer function, ω_ϕ, ζ_ϕ
- roll to sideslip ratio in the Dutch roll mode, $|\phi/\beta|_d$
- gust response represented by the important input derivatives, L'_p, L'_β, N'_β

- crosswind component on approach
- control sensitivity, $L'_{\delta_{AS}}$
- control linearity, stick travel and force gradients.

A thorough investigation of the influence on lateral control power requirements of all of these parameters is generally beyond the scope of a single experiment. Of the potential aircraft and task characteristics listed above, the test program was designed to focus expressly on the effects on the aircraft's flying qualities and control power requirements of :

1. roll mode time constant, τ_R, Dutch roll frequency, ω_d, roll to sideslip ratio in the Dutch roll mode, $|\phi/\beta|_d$, and the coupling parameter $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ which determines the yaw due to aileron inputs and the values of ω_ϕ, ζ_ϕ

2. approach conditions, VFR or IFR

3. wind (crosswind) and turbulence (gust response)

Sections 2.3.1 and 2.3.2 present the values of the modal parameters chosen as most important for systematic variation in this program, thus defining the resulting evaluation configurations. For these lateral-directional configurations, the control power used during the landing approach task was measured during each evaluation. To determine the minimum control power required for Level 1 and Level 2 flying qualities, the available lateral control power was systematically limited to values below the level used when there was no limitation. This procedure is described in Section 2.3.3.

2.2 FLIGHT CONDITION

The aircraft characteristics for the flight condition chosen for this investigation are summarized in the following table:

V_0 kt/fps	λ deg	$-\gamma$ deg	$\dot{h}$ (zero wind) fpm	n_γ/α g/rad	$d\gamma/dV$ deg/kt	$\left(\frac{\Delta Z}{\Delta X}\right)_{\delta_c}$
65/110	50	7.5	860	1.7	-0.22	-1.65

The duct angle of 50° was chosen to optimize the rate of descent capability of the X-22A at the 65 knot approach speed (see Appendix VII). This duct-angle-approach-speed combination was the primary flight condition in the first research program using the X-22A (Reference 3), in which variations in longitudinal flying qualities were made while the lateral-directional characteristics were held at satisfactory values. For that program, a glide path angle relative to the ground (γ) of -9 deg was used for the primary investigation. During the practice evaluations for this experiment using γ = -9 deg, however, the pilots thought that the level of pilot workload with deteriorated lateral-directional flying qualities was too high to perform the evaluations properly. This interesting observation demonstrates the importance of the interaction between flying qualities, required performance (steep glide path), and aircraft performance limitations such as maximum rate-of-descent caused by stall or buffet boundaries. As a result of the pilot comments, a shallower but still representative STOL glide path of -7.5 deg was selected for this lateral-directional program to insure sufficient margin from the X-22A buffet boundaries and hence obviate performance constraints as a consideration. Although no attempt was made to "optimize" the final glide path chosen, it is thought that the value of γ = -7.5 deg allowed valid evaluations of lateral-directional characteristics to be performed. It is clear that further studies of this interaction are desirable, however.

2.3 EVALUATION CONFIGURATIONS

The evaluation configurations were selected after a careful review of previous experiments (References 6 and 7, for example), and the values of the parameters used in the experiment are representative of the ranges expected in STOL aircraft. Each configuration consisted of three parts: a set of values of τ_R, $|\phi/\beta|_d$ and ω_d; a value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$; and a value of lateral control power available, $L'_{\delta_{AS}}\delta_{AS_{MAX}}$.

A summary of all the pertinent data associated with each evaluation configuration, including the identified stability derivatives and lateral-directional modal parameters, is contained in Appendix I. Various response time histories are presented in Appendix II. Appendix III outlines the calibration procedures and the digital identification technique used during the program, while Appendix VII explains the mechanization of the simulated configurations on the variable stability X-22A aircraft.

2.3.1 Variations in τ_R, $|\phi/\beta|_d$, and ω_d

The specific combinations of these parameters that comprised the seven base evaluation configurations are shown in the following table. The circled numbers in the blocks are the configuration identification numbers which will be used throughout the report to facilitate correlation of the data. Section 2.3.4 will describe the full configuration identifier, which also includes an appropriate code to indicate the variations in yaw due to aileron, $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, and the amount of control power limiting for each configuration.

	$\omega_d \doteq 0.4$ (rad/sec)	$\omega_d \doteq 1.4$		
	$\tau_R \doteq .35$ (sec)	$\doteq .35$	$\doteq .75$	$\doteq 1.45$
$\lvert\phi/\beta\rvert_d \doteq 0.4$		②	④	⑥ ← CONFIGURATION NUMBERS
$\lvert\phi/\beta\rvert_d \doteq 1.4$	①	③	⑤	⑦

Note: 1. $\zeta_d \doteq 0.20$ for all configurations

2. The spiral mode varied for each configuration but had times to double amplitude > 18 seconds or times to half amplitude > 6 seconds.

All the values of the parameters shown represent nominal values with variations in the values among the configurations of approximately ±10%. The exact values for each configuration are summarized in Appendices I and IV.

2.3.2 Variations in $N'_{\delta_{AS}}/L'_{\delta_{AS}}$

Each of the seven base configurations described in the previous section was evaluated with an "optimum" value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$. This "optimum" value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ was calculated prior to the evaluation flights on the basis of minimizing the sideslip response to aileron-only inputs using the $\Delta\beta_{max}/k$ criterion of Reference 3. These values were, therefore, optimum in the "theoretical" sense only. Flight time constraints in the program precluded the determination of a true optimum value through pilot evaluations.

For configurations 1 through 5, at least two variations in the values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ were also evaluated: one to produce large adverse yaw due to aileron inputs and the other in the proverse direction.

2.3.3 Variations in $L'_{\delta_{AS}}\delta_{AS_{MAX}}$ - Lateral Control Power

All of the 17 configurations described above (7 with "optimum" values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, plus 10 with variations in $N'_{\delta_{AS}}/L'_{\delta_{AS}}$), were first evaluated with no limits on the lateral control power available. The available lateral control power for configurations 2, 3, 4 and 5 was then systematically reduced to determine the minimum lateral control power required for Level 1 (PR ≤ 3.5) and Level 2 (PR ≤ 6.5) flying qualities.

Figure 2-1 presents a schematic diagram of the method of electronically limiting the lateral control available and therefore the lateral control power. According to Reference 7, this method of electronically limiting the lateral control authority is preferable to adjusting mechanical stops in the cockpit or changing the lateral control sensitivity. A more detailed discussion of the control limiter mechanization can be found in Appendix VII.

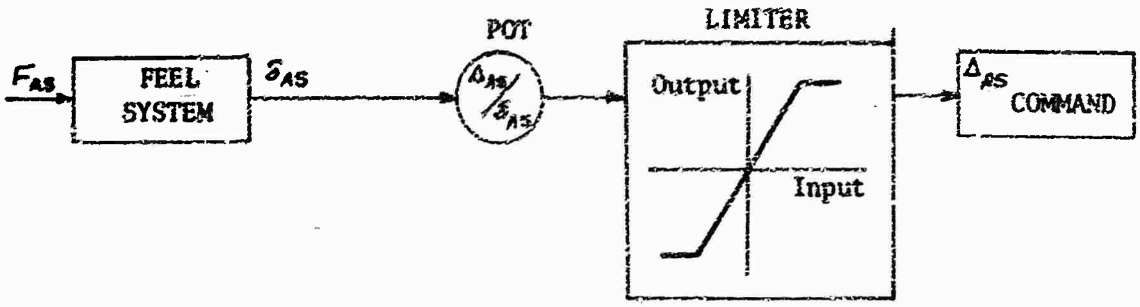


Figure 2-1 Aileron Limiter Schematic

2.3.4 Configuration Identifier

The full identifier for each evaluation configuration consists of:

1. A number to identify the set of τ_R, $|\phi/\beta|_d$ and ω_d values used, 1 through 7.

2. A letter to identify the value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ used, "O" for optimum, "A" for adverse, "P" for proverse

3. Two digits to indicate the degree of lateral control limiting used, "00" for no limiting up to 99 for the maximum control limiting (i.e., minimum lateral control power available).

For example: 3-A-00 is configuration 3 with $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ adverse and no control limiting.

2.4 LATERAL AND DIRECTIONAL GEARING

The gearing ratio between the evaluation pilot's lateral stick and the X-22A lateral control determines the value of $L'_{\delta_{AS}}$, while the ratio between the evaluation pilot's and X-22A's rudder pedals determines $N'_{\delta_{RP}}$. These gearings and therefore the lateral and directional control sensitivities were selected by the pilot at the beginning of each evaluation. This process was used in an attempt to avoid having pilot opinion affected by control sensitivity. Ideally, each dynamic configuration should have been evaluated with several values of the lateral and directional gearing ratios, but this was not possible within the flight time allowed for this program.

2.5 LATERAL-DIRECTIONAL FEEL SYSTEM CHARACTERISTICS

The lateral and the directional feel system dynamics and force gradients were held constant for all the evaluations. The dynamics are second order, and had the following values:

Feel System	Lateral	Directional
ω_{FS} ~ rad/sec	12	9
ζ_{FS}	0.7	0.7
Force Gradient ~ lb/in.	3	30
Breakout Force ~ lb	0.5	7
Travel ~ in.	±4.1	±3.2

These feel system dynamics were considered to be "fast" for the landing approach task with the range of aircraft dynamics simulated and therefore were not considered to be a degrading factor in the flying qualities evaluations.

2.6 LONGITUDINAL AND THRUST CONTROL CHARACTERISTICS

Representative longitudinal STOL characteristics (Configuration 10, Reference 5) were selected and held constant for all the evaluation flights. The pilot comments indicate that these characteristics did not influence the pilot ratings obtained in the evaluations.

The longitudinal characteristics, obtained from in-flight measurements, are summarized in the following table.

ω_{SP}	2.1	rad/sec
ζ_{SP}	0.[illegible]	
ω_p	0.20	rad/sec
ζ_p	0.35	
$M_{\delta_{ES}}$	0.37[illegible]	rad/sec^2/in.
F_{ES}/δ_{ES}	6	lb/in.
$M_{F_{ES}}$	0.056	rad/sec^2/lb
F_{BO}	1	lb
$\delta_{ES_{max}}$	±3.6	in.

The evaluation pilot controlled the thrust directly with a collective type control. No time lag of any significance was present in the thrust control system and the pitching moment due to collective, M_{δ_c}, was essentially zero.

2.7 TURBULENCE AND WIND CONSIDERATIONS

Turbulence level and mean wind speed and direction are important task variables in STOL terminal area operations. The present capabilities of the X-22A VSS are not sufficiently developed to simulate these variables in a controlled manner, however, and they were therefore introduced in the experiment by use of existing ambient conditions within the necessary constraints of program efficiency.

Originally, it was planned to fly the majority of the approaches directly into the wind by suitable alignment of the approach guidance systems, and to fly a selected number of configurations in crosswind conditions, in order to properly investigate the effects of crosswinds. However local airport traffic constraints dictated otherwise and, as a result, the approaches were flown with a representative variety of wind directions relative to the approach path. The variation in turbulence level was introduced by performing the evaluation flights either in light winds with negligible turbulence present or in moderate winds with an associated higher turbulence level. This procedure allows a qualitative distinction to be made concerning the effects of turbulence level on the evaluations. An unfortunate by-product of the operational and atmospheric constraints within which the flight program was performed is that fewer evaluations were performed in turbulent conditions than desired. A discussion of the measurement of the ambient turbulence during the program and the simulation of turbulence response characteristics in a variable stability aircraft is given in Appendix V. A summary of the wind/turbulence environment for the evaluation configurations is contained in Appendix I.

Section III

CONDUCT OF THE EXPERIMENT

3.1 VARIABLE STABILITY X-22A AIRCRAFT

The desired dynamic characteristics of the evaluation configurations discussed in Section II, both longitudinal and lateral-directional, were mechanized on the variable stability X-22A (Figure 3-1). Briefly, the X-22A is a four-ducted-propeller V/STOL aircraft with the capability of full transition between hover and forward flight. The four ducts are interconnected and can be rotated to change the duct angle (λ) and therefore the direction of the thrust vector to achieve the desired operating flight condition defined by a particular speed and duct angle combination. The thrust magnitude is determined by a collective pitch lever, very similar to a helicopter. Normal aircraft-type pitch, roll and yaw controls in the cockpit provide the desired control moments by differentially positioning the appropriate controls in each duct (propeller pitch and/or elevon deflection). A mechanical mixer directs and proportions the pilot's commands to the appropriate propellers and elevons as a function of the duct angle.

In this aircraft, the evaluation pilot occupies the left hand seat in the cockpit, which is shown in Figure 3-2. The system operator, who also serves as the safety pilot, occupies the right hand seat. The evaluation pilot's inputs, in the form of electrical signals, operate the appropriate right hand flight controls through electrohydraulic servos when the VSS is operating. In addition to these signals proportional to the evaluation pilot's inputs, signals proportional to appropriate aircraft motion variables, for example, β_V, p, and r, are fed back to move the right hand controls in the required manner and thus modify the aircraft's response characteristics as desired. The response-feedback and input gain controls are located beside the safety pilot and were used to set up the simulation configurations in flight. Note that the evaluation pilot cannot feel the X-22A control motions produced by the variable stability system. Also, in this experiment, he had no knowledge of the detailed characteristics of the configurations being evaluated.

Control feel to the evaluation pilot's stick and rudder pedals was provided by electrically controlled hydraulic feel servos which provide opposing forces proportional to the stick or rudder deflections: in effect, a simple linear spring feel system. An adjustable friction level was provided for the collective stick.

The evaluation pilot's instrument panel is shown in Figure 3-2. Instrumentation for IFR flight was comprised of the normal X-22A flight instruments plus an attitude indicator with integrated ILS cross-pointers, thereby providing a "baseline" or minimum IFR instrument package for the experiment (e.g., no flight director, etc.). Full scale deflection of the

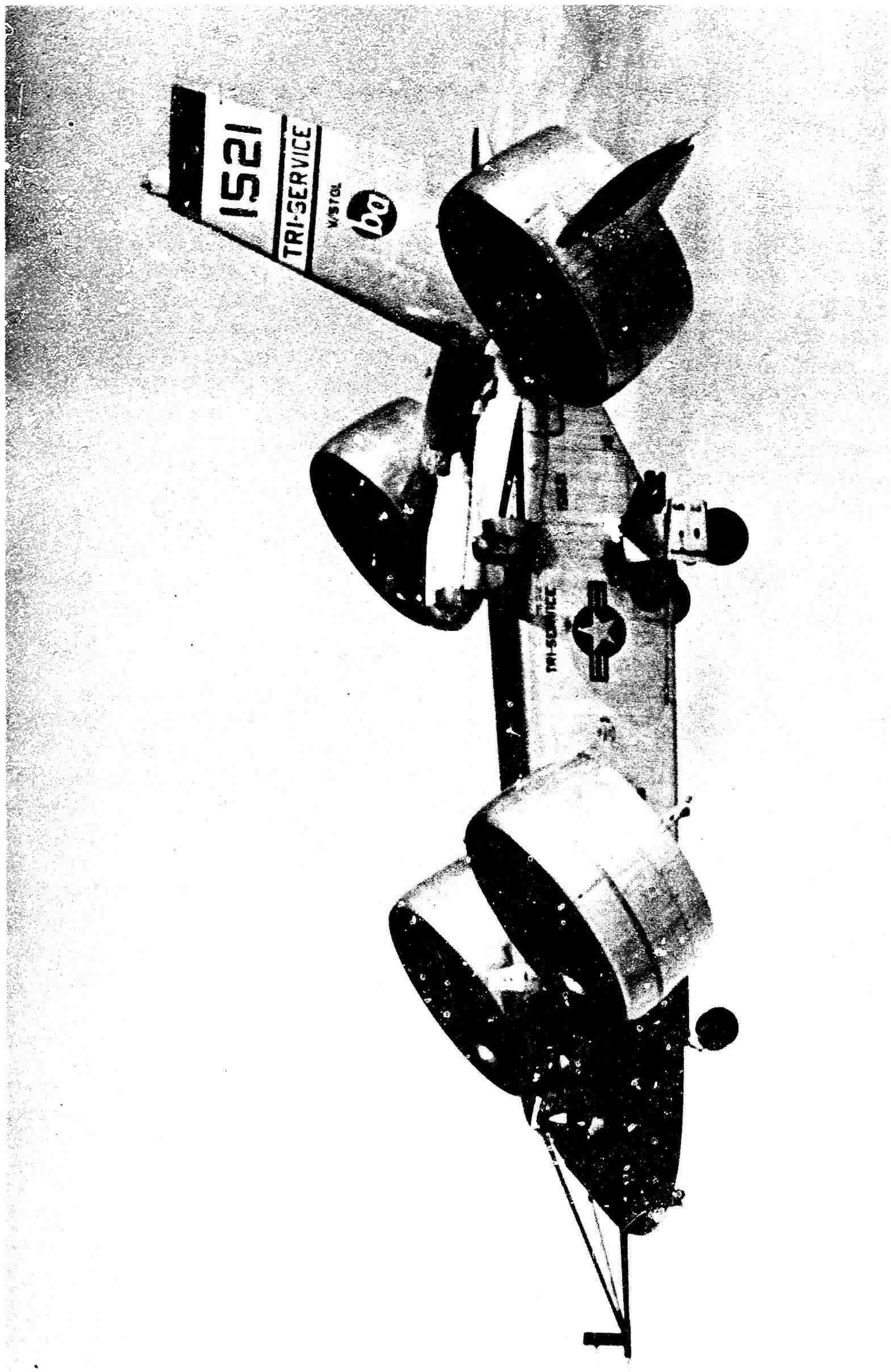
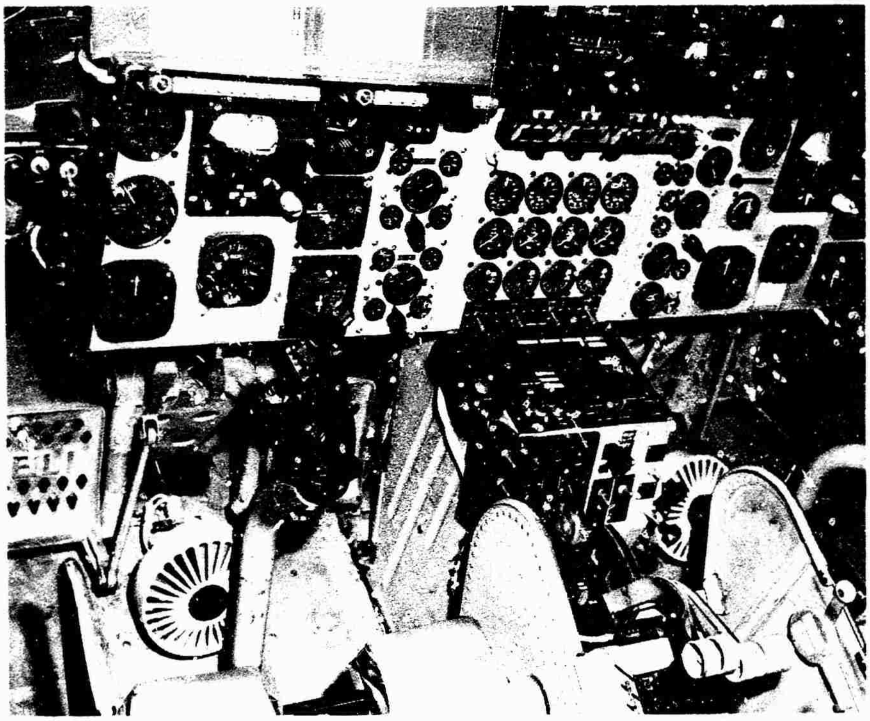


Figure 3-1 VARIABLE STABILITY X-22A AIRCRAFT



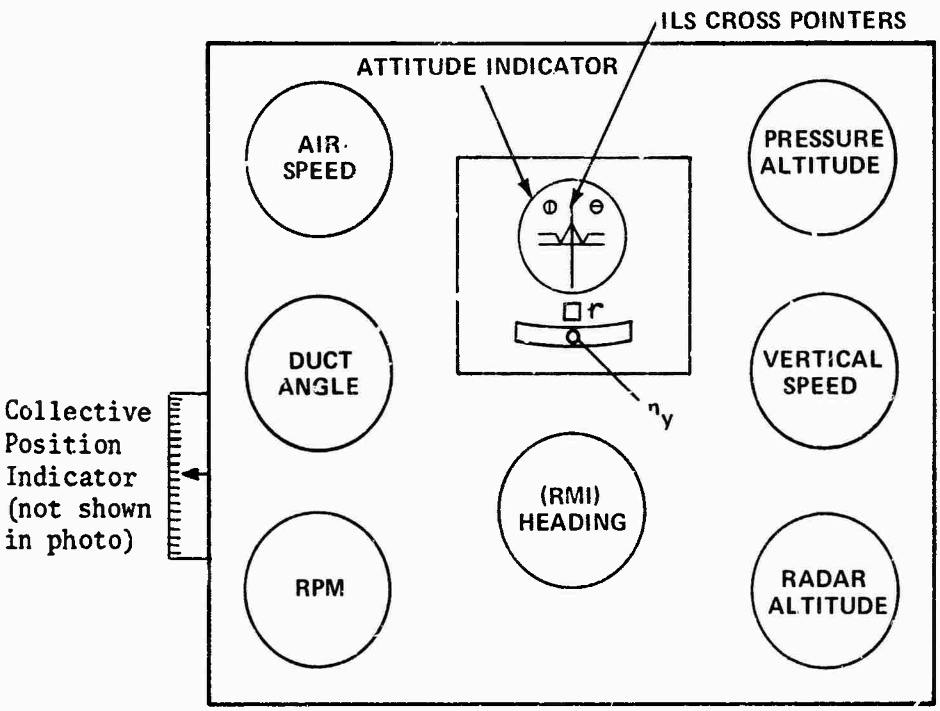


Figure 3-2 EVALUATION PILOT'S INSTRUMENT DISPLAY

ILS cross pointers represented localizer errors of ±4.5 degrees and glide path errors of ±2.8 degrees for the instrument landing system used for the experiment.

More details for the X-22A aircraft and the mechanization of the variable stability system for the experiment are contained in Appendix VII. The next subsection describes the other equipment essential to the conduct of the experiment.

3.2 OTHER EQUIPMENT

Two approach guidance systems were employed during the program. For the IFR approaches, a TALAR high angle microwave landing system (ILS) with a variable glide path capability was used. Sensitivities of this unit were ±4.5 deg on the localizer and ±2.8 deg on the glide path. These sensitivities were found to be satisfactory for the glide path angle of -7.5 deg used in the experiment.

For the VFR approaches, a Navy mirror landing system was used which was intended to constrain, to some extent, the VFR approaches to the glide path angle used for the IFR approaches. Glide path sensitivity of the "meatball" with respect to the datum lights was approximately ±0.8 deg. This approach aid did not really present localizer information since the approaches could be made from ±50 deg to the centerline of the mirror. In effect. this approach aid makes the VFR approach a semi-precision task for glide path control, much like having some form of head-up display, but does not so constrain lateral position. During the evaluations, the pilots noted that the sense of the glide path errors displayed by the mirror was opposite to that of the ILS display. The pilot flew towards the ILS needle to zero the error whereas "meatball" errors on the mirror were zeroed by flying the ball back to the center of the mirror. This was a source of confusion to some of the pilots in the early evaluation flights.

Figure 3-3 shows the mirror landing system, as well as the TALAR unit, in position for an evaluation flight.

Both experimental and flight safety data were telemetered to and monitored by the Digital Data Acquisition and Monitoring System developed expressly for the X-22A by Calspan and housed in a mobile van. Since the complexity of the X-22A makes it impossible for the pilot to monitor all the important flight safety parameters, it is essential to have ground monitoring of the flight safety variables. The flight safety variables were monitored on chart recorders and by a digital mini-computer in the van. In addition, a continuous recording of all telemetered data was obtained on the "bit-stream" recorder for later analysis and processing. An oscillograph in the X-22A provided a backup source for the pertinent experimental data. During the program, good telemetry coverage was achieved at ranges between the van and the X-22A of up to twenty miles. The details of the Digital Data Acquisition System are covered more fully in Appendix VIII.

Figure 3-3 MIRROR LANDING SYSTEM AND TALAR UNIT

3.3 SIMULATION SITUATION

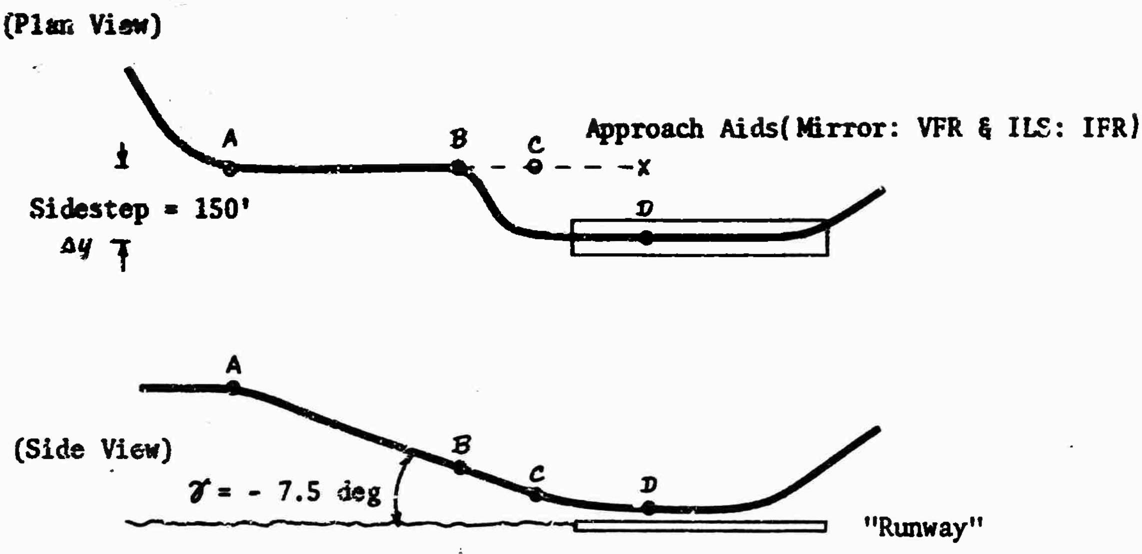
To obtain valid flying qualities data in the form of pilot ratings and comments, careful attention must be given to defining, for the evaluation pilot, the mission which the aircraft/pilot combination will perform and the conditions in which it will be performed. For the current experiment, the simulated aircraft was defined as an all-weather STOL transport (Class II of MIL-F-83300, MIL-F-8785B, References 1 and 3) performing terminal area operations; the aircraft was considered a two-pilot operation to the extent that no allowance was made for typical additional duties, e.g., flap setting, communications. Additional factors such as passenger comfort were not considered by the pilot in making his evaluation.

3.4 EVALUATION TASKS

Although the mission involves many tasks, an evaluation of the vehicle flying qualities can be accomplished by having the evaluation pilot perform a series of maneuvers representative of those tasks anticipated in the mission. With the general conditions defined as above, the specific tasks to be accomplished for each evaluation were defined as a VFR approach followed by an IFR approach. These tasks are summarized in Figure 3-4. The evaluation tasks were designed to exercise all of the elements of the approach subphase of the overall terminal area operation (Flight Phase Category C, References 1 and 3). The actual landing subphase received attention only through pilot extrapolation, since operational constraints prevented the evaluation pilot from actually touching down. It is feasible for the pilot to carry out such an extrapolation with some confidence in this experiment, which is concerned with lateral-directional problems, since the unknown problems of the flare and touchdown are largely related to the longitudinal and thrust characteristics of the aircraft.

3.5 EVALUATION PROCEDURES

The evaluation procedure was as follows. At approximately 1200 feet AGL, the safety pilot engaged the VSS and gave control of the aircraft to the evaluation pilot under VFR conditions. The evaluation pilot trimmed the aircraft carefully and took the necessary calibration records to allow post-flight verification of the configuration characteristics, as is discussed in Appendix III. After sampling the aircraft briefly, the evaluation pilot selected the lateral and the directional control sensitivities and then initiated the VFR approach using the mirror landing system as a guide. At approximately 200 ft AGL he performed a 150 foot lateral offset, or sidestep maneuver, to line up with a 500 ft simulated runway centerline. At 100 ft AGL he lined up with the runway and then at approximately 50 ft AGL he arrested the rate of descent, leveled off, and performed a wave-off maneuver. While flying back to the initial point for the instrument approach, he tape-recorded comments with reference to a short comment card and assigned a VFR-only pilot rating and turbulence rating for the configuration. The Cooper-Harper pilot rating scale shown in Figure 3-5 was used; the turbulence effect rating scale is shown in Figure 3-6.



HEIGHT OF POINTS ABOVE GROUND LEVEL		
	Height (ft)	
Point	VFR	IFR
A (Acquisition)	1200	1500
B (VFR Sidestep or IFR Breakout and Sidestep)	200	200
C (Level Off)	100	100
D (Waveoff)	50	50

Figure 3-4 APPROACH TASKS, IFR AND VFR

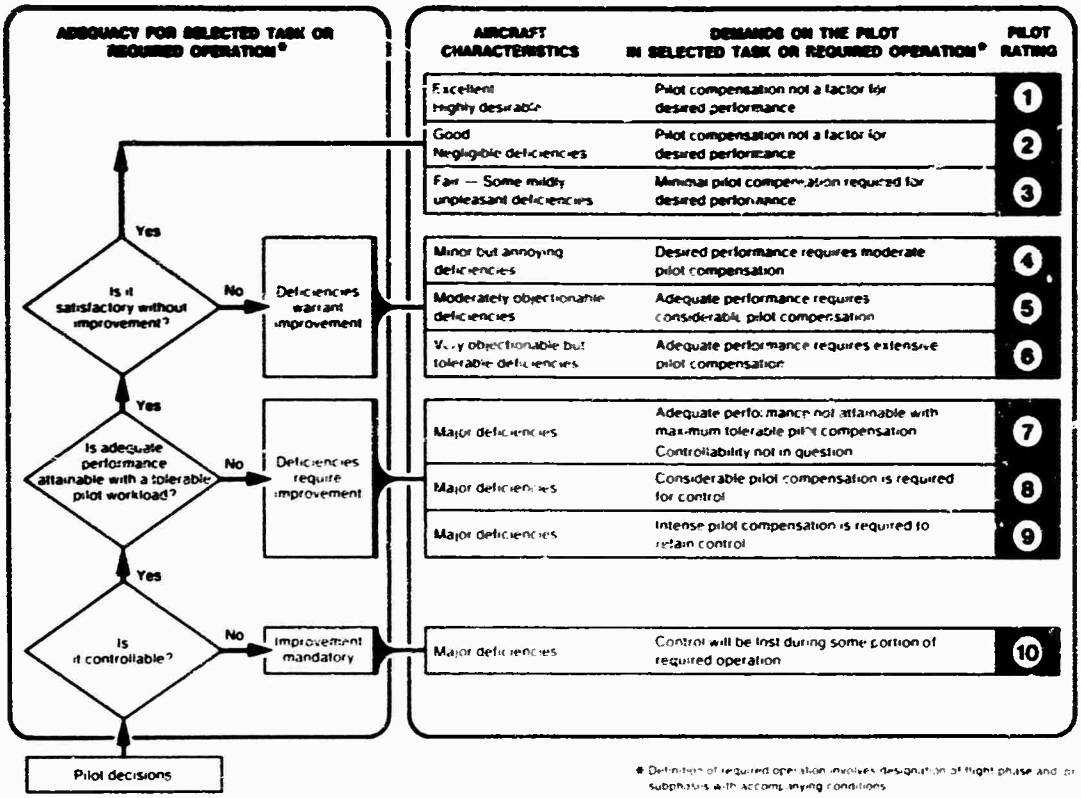


Figure 3-5 COOPER-HARPER PILOT RATING SCALE

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
	MODERATE	E
BEST EFFORTS REQUIRED	MAJOR (BUT EVALUATION TASKS CAN STILL BE ACCOMPLISHED)	F
	LARGE (SOME TASKS CANNOT BE PERFORMED)	G
UNABLE TO PERFORM TASKS		H

Figure 3-6 TURBULENCE EFFECT RATING SCALE

The complete Pilot Comment Card is reproduced below. After the visual approach, the evaluation pilot commented on only the VFR designated items.

PILOT COMMENT CARD

A. SPECIFIC COMMENTS

1. Ability to trim
   a) Lateral/directional
2. Control sensitivity
   - factors influencing choice
   - any compromises? any final complaints?
   - lateral-directional forces, displacements?

[VFR]* 3. Response to inputs required to perform task
   a) Roll attitude control
      - initial response, predictability (precision) of final response
      - describe pilot inputs required
   b) Directional control
      - complaints?
   c) Turn coordination requirements in the context of the task

[VFR] 4. Approach performance
   a) Satisfactory?
   b) Sidestep maneuver
      - any special problems?

5. Could you land from ILS approach?
6. Special control techniques?
7. Differences between VFR and IFR flight
   - if large, explain
   - any second thoughts on VFR rating?
8. Effects of turbulence/wind
   - which axes?
   - major problem with turbulence?
9. Longitudinal and thrust control characteristics
   - satisfactory?
10. Any simulation deficiencies?

B. SUMMARY COMMENTS

[VFR] 1. Good features

[VFR] 2. Objectionable features

[VFR] 3. Pilot rating
   - record decision making process
   - identify deficiency which most influenced rating

[VFR] 4. Turbulence rating

* Note: Comments for VFR approach as well as overall rating

Upon completion of the VFR comments and rating, the evaluation pilot went "under the hood" at approximately 1500 ft AGL and followed simulated radar vectors to intercept the localizer. He then performed an IFR approach with a breakout at 200 ft AGL, after which he visually performed a sidestep maneuver to the pseudo runway centerline. At approximately 50 ft AGL over the "runway" he levelled off and performed the wave-off. After the wave-off, the safety pilot set up the next evaluation configuration while the evaluation pilot made comments with reference to the complete pilot comment card. After finishing his detailed comments, the evaluation pilot assigned an overall pilot rating for the aircraft in the context of STOL terminal area operations, including both the VFR and IFR approaches, and a turbulence rating.

Two salient points in the evaluation procedure as described bear consideration.

1. Note that a VFR only, as well as an overall, rating was assigned to the aircraft. In general, a useful pilot rating should include the pilot's weighting of the performance achieved in all tasks representative of the flight phase or subphase under consideration - hence, the overall rating assigned during the evaluation. However, the possibility existed that the minimal sophistication of the instrument display used in this experiment might downgrade the IFR portion of the evaluation to an unrealistic extent in terms of future instrument displays. Therefore, brief comments and a rating on the VFR only approach, which might be considered the target for future IFR operations with more sophisticated displays, were also obtained to ascertain whether or not this effect was present in the overall rating. In the recent X-22A longitudinal flying qualities experiment (Reference 8), the difference between these ratings was not significant, apparently because the visual approach is a semi-precision longitudinal task when using the visual approach guidance system, but it was not known whether this characteristic would also be evident for lateral-directional evaluations.

2. The turbulence rating was not a quantitative indication of the turbulence level encountered. The overall pilot rating properly includes the pilot's weighting of the aircraft/pilot system in a turbulence environment and the purpose of the turbulence effect rating is primarily to provide a qualitative indication to the analyst of how much turbulence affected the task performance.

3.6 DATA REQUIRED

As was briefly mentioned in Section 3.2, a continuous recording of all the required telemetered data was made on a "bit-stream" recorder in the mobile van for later analysis and processing. More details about the Digital Data Acquisition System are covered in Appendix VIII.

The data acquired from this experiment fell into the following categories:

1. Pilot Ratings and Comments

2. Control Usage and Task Performance

3. Wind and Turbulence

4. Aircraft Response

Data on aircraft response was required to identify the dynamic characteristics of the evaluation configurations (See Appendix III). The first three data categories are closely interrelated since information on control usage (workload), performance and ambient atmospheric conditions is required before the pilot ratings and comment data can be properly interpreted. Section IV discusses the experimental results in the form of pilot comments and ratings, while Section V presents the results of the evaluations designed to determine the minimum lateral control power requirements for STOL landing approach. The details of the statistical analyses of control usage and task performance are presented in Appendix VI while Appendix V summarizes the techniques used to measure the turbulence levels during the evaluation.

3.7 EVALUATION SUMMARY

Three evaluation pilots participated in this flying qualities investigation; their backgrounds are summarized below:

Pilot A - Calspan Research Pilot with extensive experience as an evaluation pilot in flying qualities investigations. His flight experience of 3300 hours includes over 500 hours in helicopters and he is a qualified X-22A pilot.

Pilot B - Calspan Research Pilot with experience as an evaluation pilot in flying qualities investigations using both variable stability aircraft and ground simulators. His flight experience of 9200 hours includes 6000 hours in multi-engine aircraft in addition to trainers and helicopters.

Pilot C - Calspan Research Pilot with extensive experience in V/STOL flying qualities research. He has approximately 3500 hours flying time of which 500 hours are in helicopters and is qualified in the X-22A aircraft.

A total of 63.1 hours was flown in this research program with the X-22A aircraft, of which 33.6 hours were devoted to evaluation flights; the remaining hours were primarily devoted to calibration flights and practice evaluations. Approximately 5 hours was used for development of the X-22A's hover/transition capability on the variable stability system which is reported in Reference 9. The three pilots performed a total of 102 evaluations of 17 different combinations of lateral-directional dynamics. Of this total, 20 evalustions were performed with the lateral control power limited to some degree.

The distribution of evaluations is summarized in the following table.

Pilot A	64	(19)
Pilot B	17	
Pilot C	21	(1)
Totals	102	(20)

The numbers in parentheses represent the number of evaluations performed with some degree of lateral control power limiting. Appendix I summarizes the distribution of evaluations with respect to the ambient turbulence present during the evaluations.

Section IV

EXPERIMENTAL RESULTS - EFFECT OF MODAL PARAMETERS ON FLYING QUALITIES

This section summarizes and discusses the effects of the modal parameters investigated in this experiment on the flying qualities of the simulated aircraft. The effects of limited roll control power are discussed in Section V of this report; the results presented in this section are therefore independent of control power available, as the maximum roll control power available in the basic X-22A was not approached in any of the "unlimited" cases. The configuration identifiers used in this section have therefore been simplified by excluding the final two digits which describe the degree of control limiting (see Section 2.3.4). The pilot ratings for all the evaluations are tabulated in Appendix I, and summaries of the pilot comments are given in Appendix II.

For clarity in ascertaining trends, the results are presented in terms of "averaged" pilot ratings and the nominal modal characteristics discussed in Section II. These "averaged" pilot ratings represent the average of all the evaluations for a given configuration and are therefore simple averages. Average pilot ratings are shown both for all evaluations of a given configuration and for the evaluations separated according to whether negligible or noticeable turbulence was present; the criteria for this separation and the resulting groups of ratings are given in Appendix I. For completeness, the total spread of pilot ratings about the average is shown on the plots presented in support of the discussions in this section; in addition, the number of pilot ratings which are included for each point on these summary plots is given in parentheses.

4.1 EFFECT OF ROLL MODE TIME CONSTANT (τ_R)

The effect of roll mode time constant on pilot rating may be seen by comparing the ratings of Configurations 2-0, 4-0 and 6-0 with each other (for $|\phi/\beta|_d \doteq 0.4$) and 3-0, 5-0 and 7-0 with each other (for $|\phi/\beta|_d$ = 1.4). The ratings for these configurations are summarized in Figures 4-1a and 4-1b, again depending on whether or not turbulence effects are separated out. Since the trends are identical in both cases, consider for the purposes of discussion the negligible turbulence results in Figure 4-1a, and the overall results in Figure 4-1b.

The following trends are evident from the graphs:

- No significant deterioration of average pilot rating with τ_R is evident between $\tau_R \doteq 0.35$ and 0.75 for either $|\phi/\beta|_d$. The average pilot rating for these values of τ_R varies between 2.5 and 3.5 as $|\phi/\beta|_d$ increases in negligible turbulence.

- The spread of pilot ratings is larger at $\tau_R \doteq 0.75$ than at $\tau_R \doteq 0.35$ for both values of $|\phi/\beta|_d$.

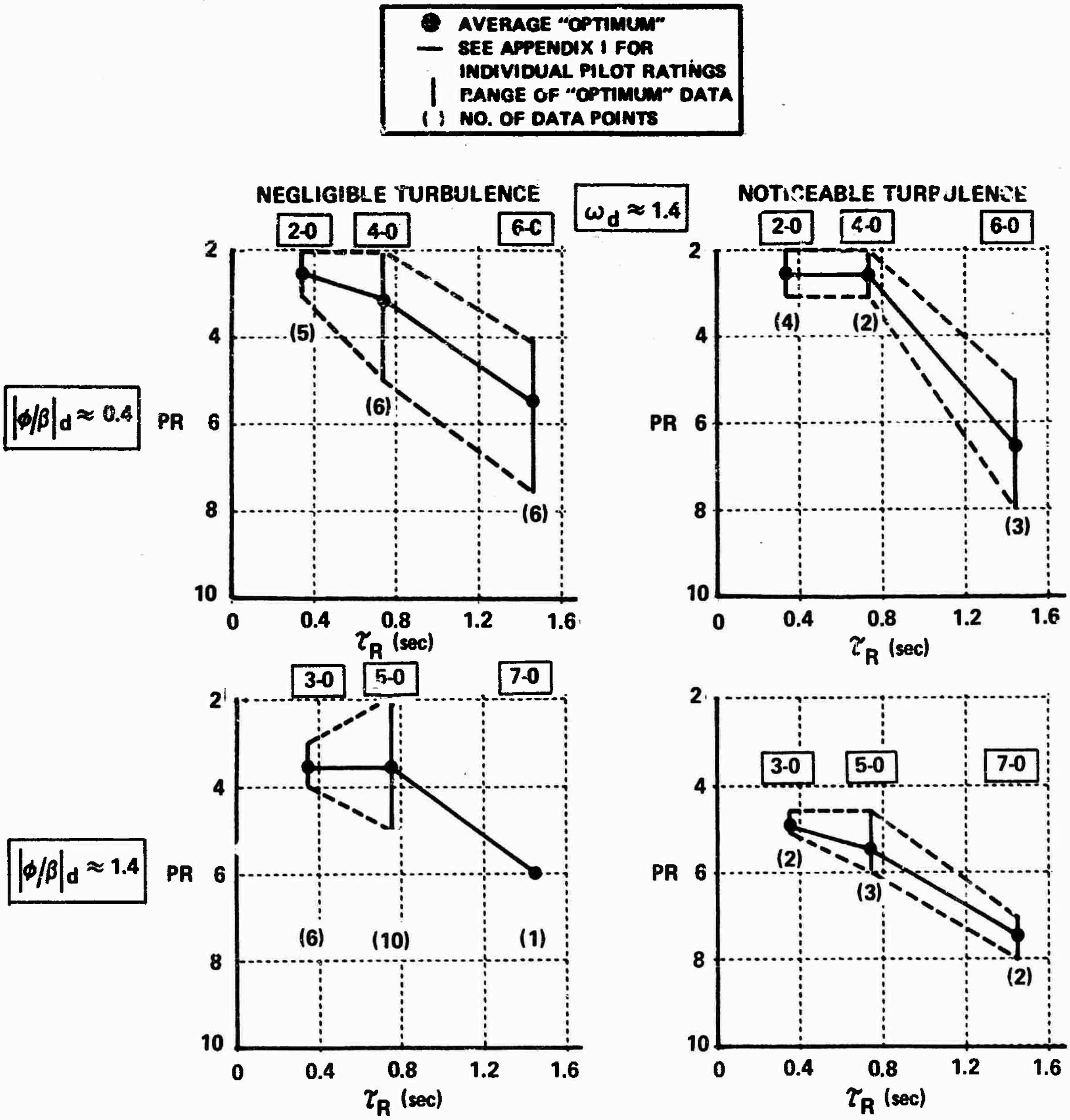


Figure 4-1a EFFECT OF τ_R ON PILOT RATING (TURBULENCE EFFECTS SEPARATED)

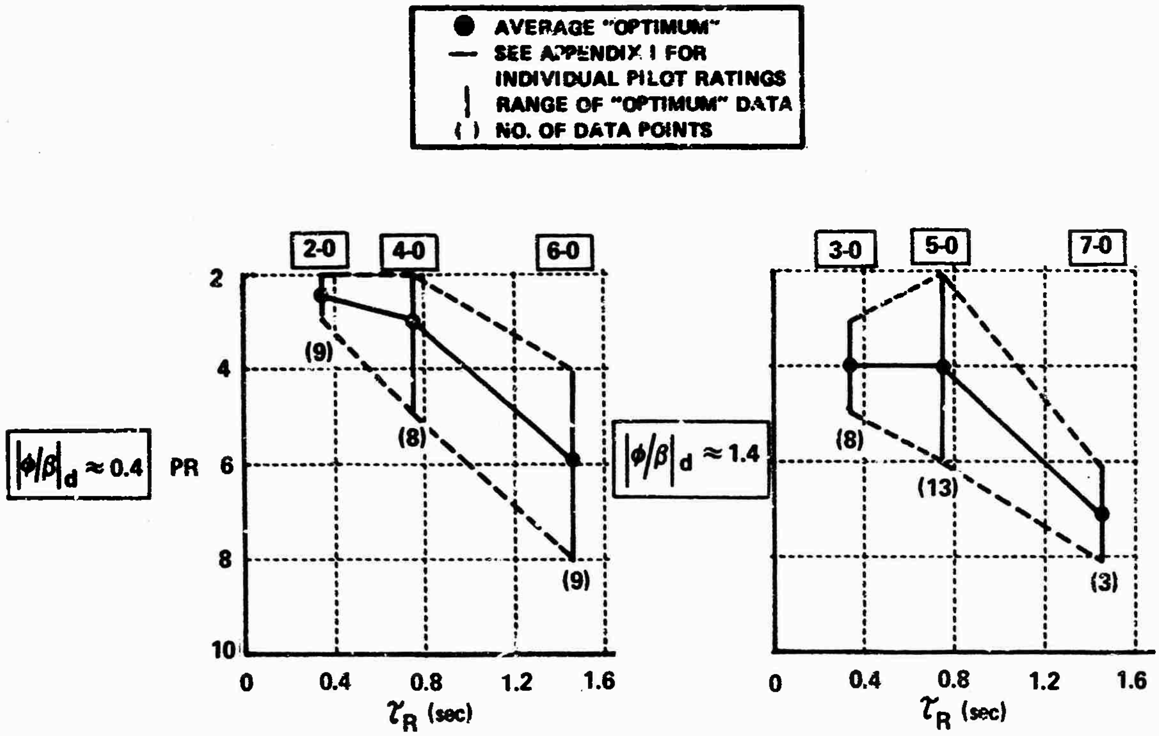


Figure 4-1b EFFECT OF τ_R ON PILOT RATING (ALL EVALUATIONS)

- A significant deterioration of average pilot rating, as well as of both the maximum and minimum values given, occurs for a change of τ_R from 0.75 to 1.45. The change is approximately three pilot rating units for both values of $|\phi/\beta|_d$, and in both cases changes the airplane from satisfactory (PR ≐ 3.5) to adequate (PR ≐ 6.5) in negligible turbulence.

Consider initially the evaluations of the low $|\phi/\beta|_d$(≐ 0.4) cases, i.e., Configurations 2-0 (τ_R ≐ .35), 4-0 (τ_R ≐ .75) and 6-0 (τ_R ≐ 1.45). Pilot comments for Configuration 2-0 uniformly approve of the very predictable final response due to the high roll damping. Several comments for both Pilots A and B object to a "sluggishness" or "heaviness" in the initial response, but these characteristics are generally attributable to their selection of somewhat low roll control sensitivities ($L'_{\delta_{AS}}$). All the comments note good approach tracking performance and a good and easily performed sidestep maneuver for this configuration. The spread in pilot ratings for this configuration is relatively small, and, in fact, it appears to have been somewhat down-rated generally due to the poor choice of sensitivities by Pilots A and B.

Pilot comments for Configuration 4-0 tend to reflect the increased spread of the pilot ratings. Pilot A liked the roll performance very well each time he evaluated the configuration, feeling that the initial response was satisfactorily snappy and the final response sufficiently predictable. Both Pilots B and C, however, noted a tendency to overcontrol and even PIO in bank angle tracking, and degraded the configuration on this basis. This variance in pilot opinion is probably typical of configurations which are marginally satisfactory, as details of pilot technique and preference become of more importance to the rating; hence, even though the average pilot rating remains the same as for Configuration 2-0 which has a roll mode time constant twice as fast, it is likely that the roll mode time constant of 0.75 sec in Configuration 4-0 is less satisfactory.

Configuration 6-0 has a roll mode time constant of $\tau_R \doteq 1.45$ sec, the longest investigated in this experiment. Pilot comments for this configuration reflect the fact that this roll mode time constant generally leads to difficulties in both the initial and the final roll response to aileron stick inputs. In general the comments note that the initial roll response was somewhat sluggish, that the airplane "wallowed" laterally, and that the final response was unpredictable with a tendency to overshoot and oscillate about the desired bank angle. It is interesting to note that the comments are more consistent than the pilot ratings for this configuration and hence the spread of ratings shown in Figure 4-1 is somewhat misleading (cf. the comments of Pilot C on Flights F-89 and F-90). The average pilot rating is significantly deteriorated for this configuration over the previous two, with the change being about three pilot rating units, and hence this roll mode time constant leads to an airplane that is marginally adequate (PR $\doteq$ 6.5).

The trends with roll mode time constant are the same at the higher $|\phi/\beta|_d$ (Configurations 3-0, 5-0, and 7-0) as those discussed for the lower $|\phi/\beta|_d$. Again, very little change in pilot rating is evident between $\tau_R \doteq$ 0.35 sec and $\tau_R \doteq$ 0.75 sec, but the spread of pilot ratings is larger at $\tau_R \doteq$ 0.75 sec (Configuration 5-0). Examination of the pilot comments for this configuration again shows the marginally satisfactory nature of the configuration. Pilot A, in particular, noted tendencies to overcontrol in roll (leading to a requirement to lead the final response) but did not downrate the configuration for this characteristic (cf. comments on Flights F-75 and F-79). As in the cases with low $|\phi/\beta|_d$, a significant deterioration in pilot rating is evident in changing from $\tau_R \doteq$ 0.75 to $\tau_R \doteq$ 1.45 sec. The problems associated with overcontrol in roll are even more evident at the higher $|\phi/\beta|_d$, and the configuration is considered only marginally adequate at best (cf. all comments for Configuration 7-0). It should also be noted that the effect of turbulence is much larger at the higher $|\phi/\beta|_d$, degrading the average pilot ratings for all roll mode time constants.

On the basis of the average pilot rating lines presented in Figures 4-1a and 4-1b in noticeable turbulence, the general conclusions that may be drawn are:

- For low $|\phi/\beta|_d$ ($\doteq$ 0.4), a marginally satisfactory (PR = 3.5) value of roll mode time constant is on the order of τ_R = 0.9 seconds, and a marginally adequate (PR = 6.5) value is τ_R = 1.5 seconds.

- For high $|\phi/\beta|_d$ ($\doteq$ 1.4), the satisfactory and adequate values of τ_R given above for low $|\phi/\beta|_d$ remain approximately valid in negligible turbulence. In noticeable turbulence however, all the configurations were unsatisfactory (PR > 3.5) and the marginally adequate (PR $\doteq$ 6.5) value of roll mode time constant is $\tau_R \doteq$ 1.1 seconds.

4.2 EFFECT OF DUTCH ROLL FREQUENCY (ω_d)

The effect of Dutch roll undamped natural frequency on pilot rating may be seen by comparing the evaluations for Configurations 1-0 and 3-0, both of which were at the higher $|\phi/\beta|_d$ and smallest τ_R investigated in this experiment. These ratings are summarized in Figures 4-2a, separated according to level of turbulence, and 4-2b, which averages all the evaluations for these configurations. It is clear that, regardless of whether or not turbulence is present,

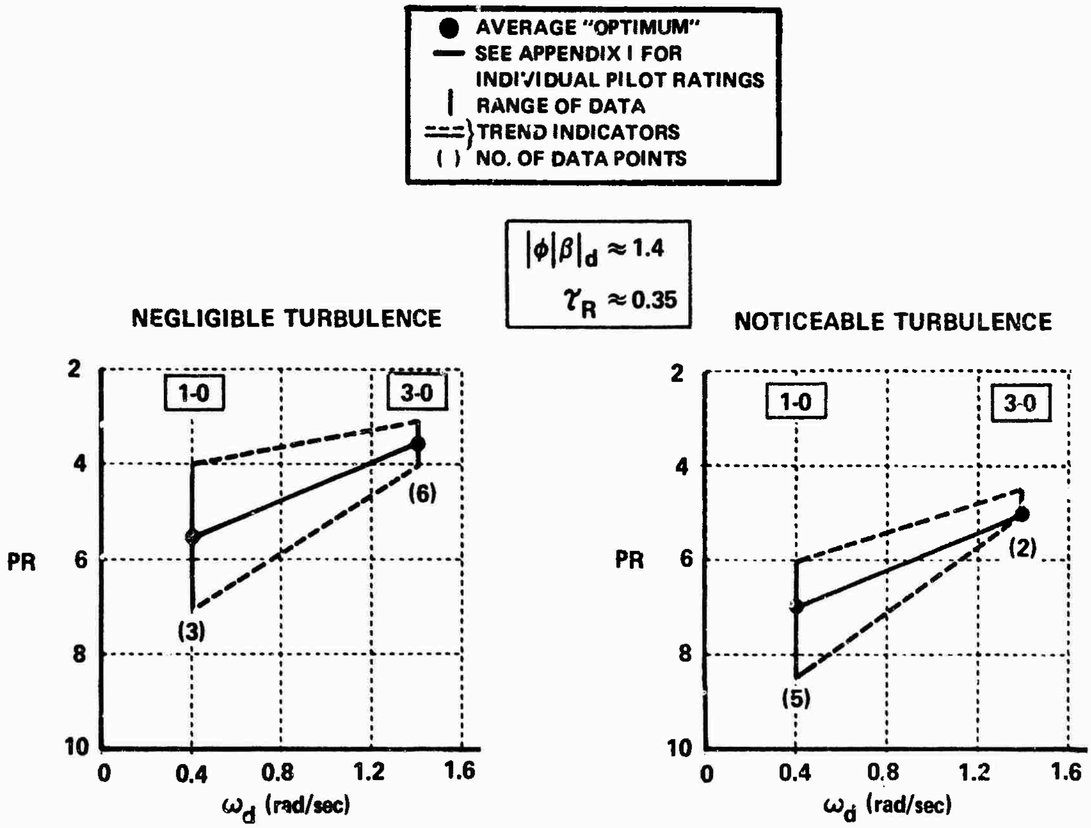


Figure 4-2a EFFECT OF ω_d ON PILOT RATING (TURBULENCE EFFECTS SEPARATED)

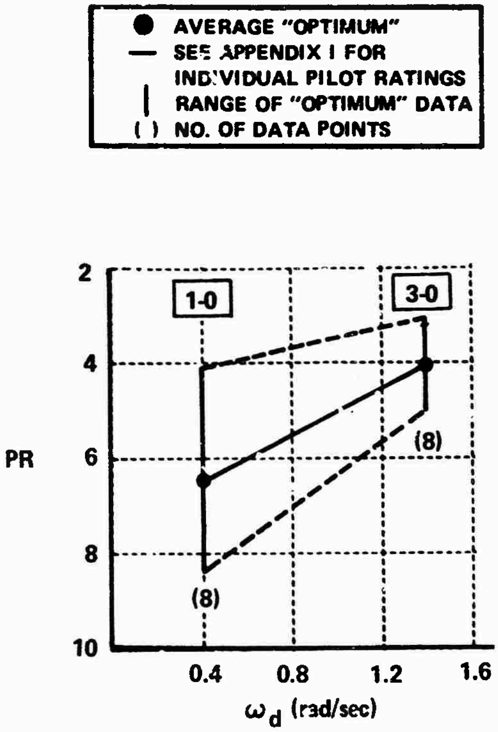


Figure 4-2b EFFECT OF ω_d ON PILOT RATING (ALL EVALUATIONS)

a significant degradation in pilot rating occurs in changing from the higher ω_d ($\doteq$ 1.4) to the lower one ($\doteq$ 0.4) investigated. Pilot comments for the lower ω_d (Configuration 1-0) indicate that the primary deficiencies included difficulty in controlling the sideslip (large ball excursions) and the requirement to attempt to hold a tight directional loop with the rudders, both of which caused the airplane to be considered marginally acceptable, particularly in turbulence (cf. comments for 1-0 on Flights F-77 and F-90, Appendix II). Although the comments for Configuration 3-0 are masked somewhat by the fact that the "optimum" $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ used was in fact somewhat proverse, the directional control was generally considered a good feature for this configuration with $\omega_d \doteq 1.4$.

Although these results do not provide sufficient data to define precise boundaries, the line joining the average pilot ratings in Figure 4-2a (noticeable turbulence) indicates that a generally acceptable value (i.e. PR $\lesssim$ 6.5) for Dutch roll undamped natural frequency would be $\omega_d \gtrsim 0.7$ rad/sec.

4.3 EFFECTS OF ROLL-TO-SIDESLIP RATIO ($|\phi/\beta|_d$)

The effects of $|\phi/\beta|_d$ on pilot rating for the two values investigated in this experiment may be seen by comparing the evaluations of the following configuration pairs: 2-0 and 3-0, 4-0 and 5-0, and 6-0 and 7-0. These comparisons are shown in averaged form on Figure 4-3, from which the following trends may be observed. In negligible turbulence, there is very little effect of $|\phi/\beta|_d$ on pilot rating for any of the roll mode time constants investigated. This trend is to be expected, since, in the absence of turbulence, the pilot will not particularly notice $|\phi/\beta|_d$ if he can control the aircraft well and perform coordinated maneuvers; only when the controllability degrades and sideslip excursions increase will the higher $|\phi/\beta|_d$ ($\doteq$ 1.4) become evident. In noticeable turbulence, however, it is clear that pilot rating degrades with increased $|\phi/\beta|_d$. This degradation follows from the fact that, for the same roll mode, spiral mode, and Dutch roll roots, a higher value of $|\phi/\beta|_d$ corresponds to a higher L'_β and hence more roll excitation from lateral gusts.

The results from this experiment indicate that $|\phi/\beta|_d \doteq 1.4$ precludes a satisfactory aircraft for any of the roll mode time constants investigated if turbulence is present. From the graphs, a maximum value of $|\phi/\beta|_d \doteq$ 0.8 would provide a satisfactory aircraft if the roll mode were satisfactory. This value, which is "low" to some extent for conventional aircraft, may be caused by the lower approach velocity investigated in this experiment.

4.4 EFFECTS OF TURBULENCE

In this experiment, attempts were made to fly the evaluations in either smooth air or representative levels of turbulence, and then to obtain a measure of the ambient level present (Appendix V). Unfortunately, the weather conditions prevalent during the flight phase of the program were such that, if atmospheric conditions were suitable for flying evaluations, the level of turbulence was generally low; hence, only about 20% of the evaluations were performed in noticeable turbulence, and the data base for comparisons is therefore not extensive. The evaluation data were divided into the two turbulence categories using the pilot comments, turbulence effect ratings, and turbulence measures for guidance. This division should not be construed as an indication that the evaluations were performed in two consistent levels of turbulence (see Appendix I for details).

To the extent that comparisons may be made, Figure 4-3 shows the average change in pilot rating between noticeable and negligible amounts of turbulence for the three roll mode time constants and two values of $|\phi/\beta|_d$ investigated in this experiment. It can be seen that, in general, the presence or absence of turbulence is essentially immaterial to the pilot rating for the low $|\phi/\beta|_d$ ($\doteq$ 0.4) configurations, although some degradation is apparent at the longest roll mode time constant. For the high $|\phi/\beta|_d$ ($\doteq$ 1.4) configurations, however, a significant degradation ($\sim$ 2 PR units) is evident in noticeable

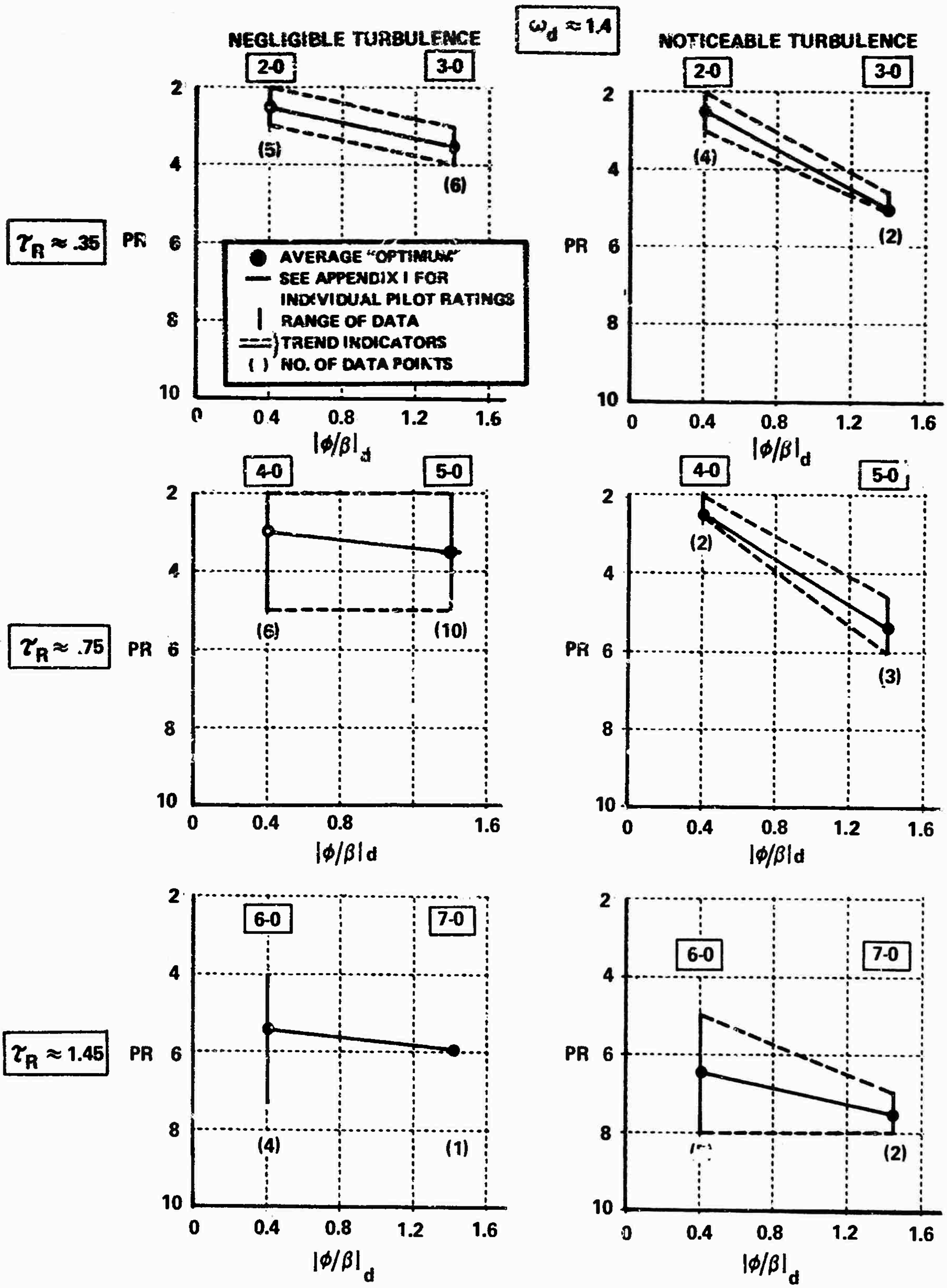


Figure 4-3 EFFECT OF $|\phi/\beta|_d$ ON PILOT RATING (TURBULENCE EFFECTS SEPARATED)

turbulence. As has been discussed previously (see also Appendix V and the time histories in Appendix II), the high $|\phi/\beta|_d$ cases correspond to large values of L'_β and a ratio of $L'_\beta/N'_\beta > 1$, whereas the low $|\phi/\beta|_d$ cases have smaller values of L'_β and $L'_\beta/N'_\beta < 1$. In the high $|\phi/\beta|_d$ cases, then, lateral gust inputs tend to upset the aircraft primarily in roll, which is disturbing to the pilot in that it deteriorates his control of bank angle. It is also to be expected that the effect of turbulence would be increasingly degrading to pilot rating as roll mode damping is reduced, as the control problem is becoming more difficult in this case.

A further point, which may explain the trends discussed above, is worth noting. For a given value of $|\phi/\beta|_d$, it can be seen from the time histories given in Appendix II that the magnitude of the aircraft responses to a lateral gust does not vary greatly as the roll damping is reduced. This characteristic is a consequence of the fact that, to maintain $|\phi/\beta|_d$ constant as roll damping is reduced, the value of L'_β must be reduced as L'_p is reduced. As a result of this characteristic, the increase in workload due to turbulence is a function primarily of $|\phi/\beta|_d$ and is essentially independent of roll mode damping for the configurations investigated in this report.

4.5 EFFECTS OF $N'_{\delta_{AS}}/L'_{\delta_{AS}}$

The effect of yaw due to aileron ($N'_{\delta_{AS}}/L'_{\delta_{AS}}$) may be seen by comparing the pilot ratings for the "adverse" or "proverse" evaluations to those for the "optimum" evaluations for Configurations 1 through 5 (i.e., 1-A and 1-P with 1-0 etc.). These ratings are summarized in Figure 4-4 for the evaluations in negligible turbulence. Note that, in some cases, additional values of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ that were not the "nominal" settings were investigated, and are marked as $(\ )^{\dagger}$. As is discussed in Appendix IV, the ratio $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ affects the position of the zeros in the numerator of the ϕ/δ_{AS} transfer function. The position of these zeros relative to the Dutch roll poles provides a measure of the Dutch roll oscillation that will appear in the roll response to aileron. Specifically, in the proverse case the roll response may appear "quickened" to the pilot, and the final response becomes unpredictable and may lead to a PIO. Conversely for adverse values of $N'_{\delta_{AS}}$, the airplane may appear to hesitate after the control input is applied. The importance of this flying qualities parameter is well recognized in the literature, and the primary reason for the variations included in this experiment was to provide additional data. The usual trends are apparent from the graphs. Some of the large variations in pilot ratings (cf. 3-A and 4-P) were associated with the pilot's extrapolation to the landing during their evaluations. The importance of controlling the heading of the aircraft during the touchdown is crucial and this factor was emphasized to the pilots during the later portions of the program. An aircraft that was satisfactory in all other areas could degrade markedly to a PR > 6.5 in this control task when large values of adverse or proverse $N'_{\delta_{AS}}$ precluded precise heading control. Compare, for example, the evaluations of 4-P by Pilot A (F-67) with the evaluations of the same configuration by Pilot B (F-34).

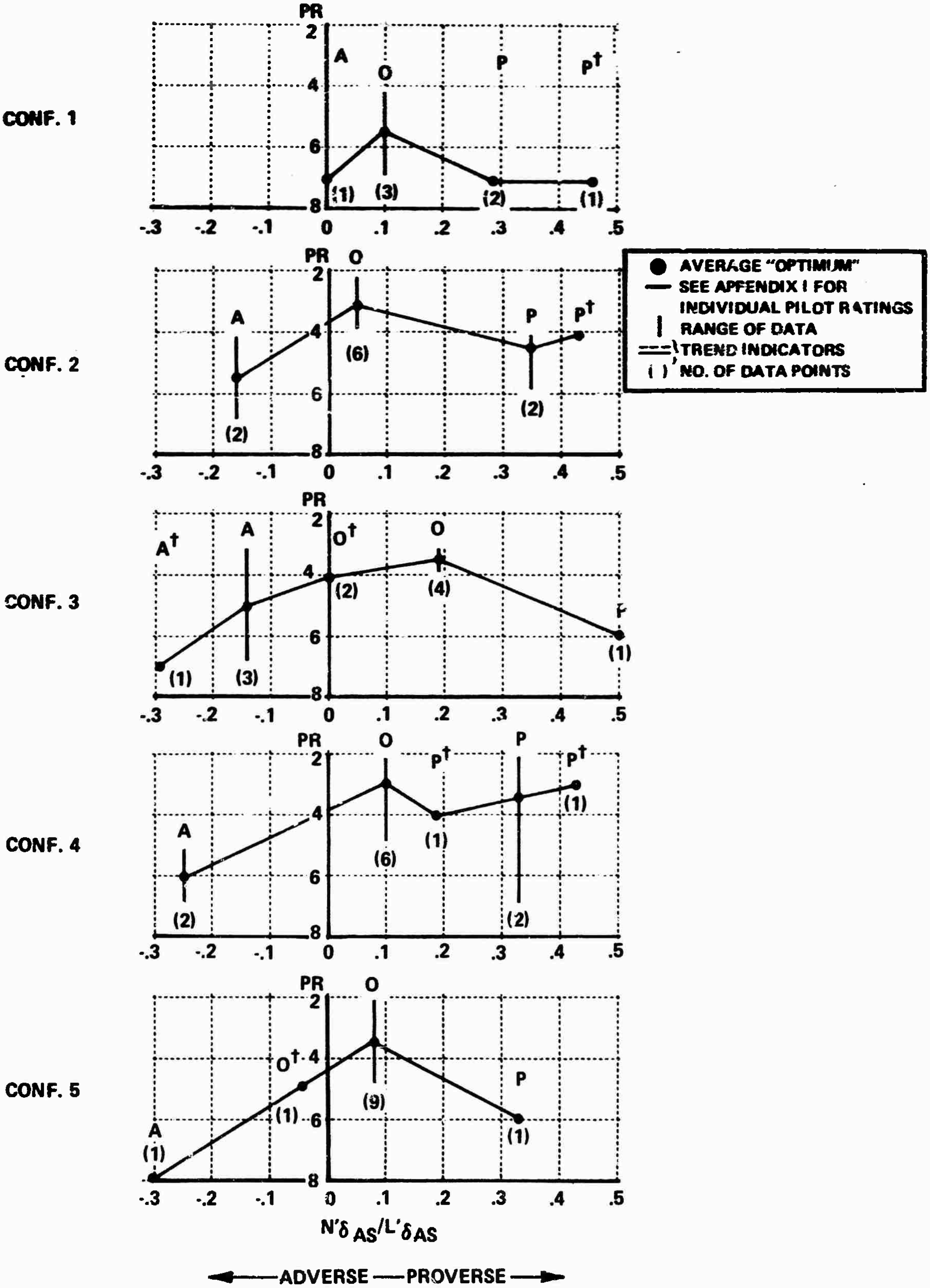


Figure 4-4 EFFECT OF $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ ON PILOT RATINGS (NEGLIGIBLE TURBULENCE)

The specific implications of these data in terms of comparison with existing flying qualities criteria will be presented in Section VII of this report. It should be noted, however, that the value of $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ denoted as "optimum" in this experiment may still not be the best obtainable. In particular, the values chosen for Configurations 3-0 and 6-0 may have been slightly too proverse, as the pilot comments for these indicate slightly "ratchety" and "swinging around" responses.

4.6 LATERAL CONTROL SENSITIVITY ($L'_{\delta_{AS}}$)

In this experiment, the lateral control sensitivity was selected by the evaluation pilot prior to each evaluation. As is shown in Appendix VII, this selection is made by electrically varying the gearing between the evaluation pilot's stick position and that of the basic aircraft. The control sensitivity is related to the stick force sensitivity $L'_{F_{AS}}$ through the spring gradient of the force feel system, which was constant throughout the experiment at 3 lbs/in., with a 1/2 lb breakout force; hence, the control sensitivities discussed here may be easily converted to force sensitivities if desired. It should be noted that the mechanization of the VSS is such that the ratio $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ remains constant as the lateral gearing is changed.

The procedure of having the pilot select the sensitivity was followed because the available evaluation hours precluded the inclusion of $L'_{\delta_{AS}}$ as a controlled variable in the experiment. It is well known that a general relationship between $L'_{\delta_{AS}}$, τ_R, and pilot rating exists and the objective of having the pilot select his sensitivity was to approach the "best" $L'_{\delta_{AS}}-\tau_R$ relationship, thereby eliminating $L_{\delta_{AS}}$ as a factor in the pilot rating.

The averaged values of $L'_{\delta_{AS}}$ and the total spread of selected values for the six "optimum" configurations with $\omega_d \doteq 1.4$ (Configurations 2-0 to 7-0) are shown in Figure 4-5. The values selected for Configuration 1-0 were similar to the 2-0 values shown. In addition, the average value selected in each case for proverse yaw-due-to-aileron is shown as an 0, and for adverse as an X. The following general trends are evident:

- The selected $L'_{\delta_{AS}}$ decreases as roll mode damping is decreased for both $|\phi/\beta|_d$ cases.
- The selected $L'_{\delta_{AS}}$ at a given τ_R is generally smaller for the higher $|\phi/\beta|_d$ than the lower one.
- The selected $L'_{\delta_{AS}}$ for large proverse $N'_{\delta_{AS}}$ is generally smaller than for the optimum; for large adverse $N'_{\delta_{AS}}$, the selected $L'_{\delta_{AS}}$ is generally larger than for the optimum.

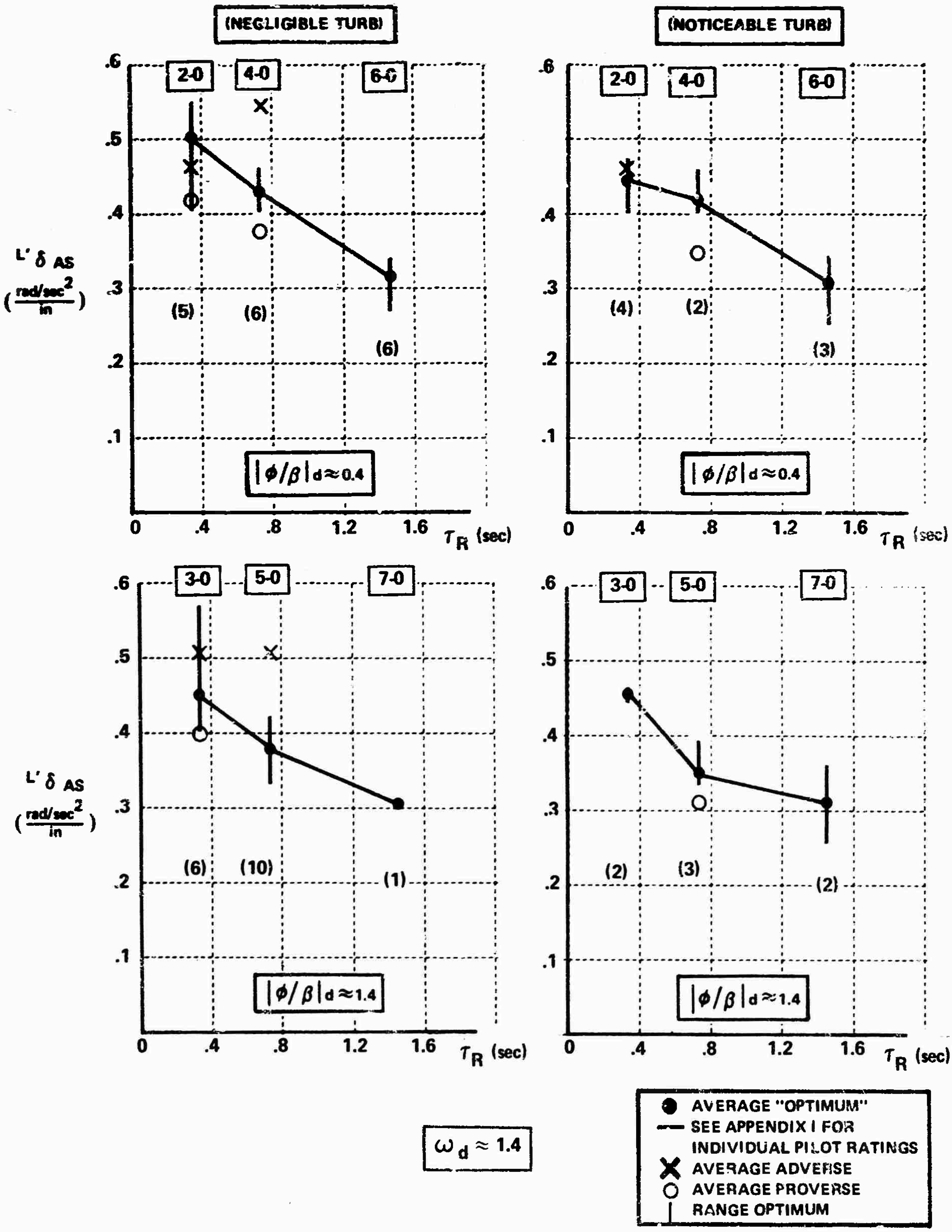


Figure 4-5 EFFECT OF τ_R ON LATERAL CONTROL SENSITIVITY

- The spread of selected values of $L'_{\delta_{AS}}$ at a given roll mode time constant is generally independent of the value of the roll mode time constant.

- The selected $L'_{\delta_{AS}}$ is generally independent of whether or not turbulence is present.

The pilot's selection of $L'_{\delta_{AS}}$ is a complex process and involves a trade-off between the rapidity of the initial response for a given input magnitude and the ability to stop the roll response in a predictable fashion. Unfortunately, the rationale behind the pilot's selection of $L'_{\delta_{AS}}$ is not obvious from the results shown in Figure 4-5.

4.7 DIRECTIONAL CONTROL SENSITIVITY ($N'_{\delta_{RP}}$)

The directional control sensitivity was also selected by the pilot prior to each evaluation. As can be seen from the data summary (Appendix I), the selected values were essentially independent of configuration, and the only differences were between pilots. The average values selected were:

Pilot A: $N'_{\delta_{RP}}$ = 0.49 (rad/sec^2)/in.

Pilot B: $N'_{\delta_{RP}}$ = 0.29 (rad/sec^2)/in.

Pilot C: $N'_{\delta_{RP}}$ = 0.38 (rad/sec^2)/in.

The mechanization of the VSS in the rudder channels, unlike the aileron stick channel, did not keep the ratio $L'_{\delta_{RP}}/N'_{\delta_{RP}}$ constant as directional control sensitivity was changed. As a result, the values of $L'_{\delta_{RP}}$ varied somewhat for each pilot as follows:

Pilot A: $L'_{\delta_{RP}}$ = 0.0 (rad/sec^2)/in.

Pilot B: $L'_{\delta_{RP}}$ = 0.12 (rad/sec^2)/in.

Pilot C: $L'_{\delta_{RP}}$ = 0.06 (rad/sec^2)/in.

Analysis of the pilot ratings and comments (Appendix II) indicates that these $L'_{\delta_{RP}}$ variations were not a significant factor in the evaluations. The effects of variations in $L'_{\delta_{RP}}$ are discussed further in Appendix IV.

4.8 EFFECT OF TASK CONDITION: VFR AND IFR

Any effects of VFR versus IFR flight can be seen by comparing the VFR and overall ratings for all the evaluations. The average change in these ratings is negligible, with a maximum change of one pilot rating unit occurring infrequently. Possibly the reason for this agreement is that the VFR task was to some extent a precision task using the mirror landing system for visual guidance and constrained to the same approach path as the IFR task with a similar sidestep maneuver.

4.9 PILOT VARIABILITY

Figure 4-5 presents each pilot's ratings for all the configurations with "optimum" $N'_{\delta_{AS}}/L'_{\delta_{AS}}$, with the individual averages and spread of ratings. With regard to intrapilot variability, insufficient repeats were performed by Pilot B to evaluate his repeatability. It can be seen that the repeatability of Pilot A is excellent for all configurations - generally within one PR unit. The intrapilot variability for Pilot C is quite a bit larger for the configurations with $\tau_R \geq 0.75$ (Configurations 4-7), and his comments reflect the increasing susceptibility of these configurations to pilot technique and external disturbances on a day to day basis. With regard to interpilot variability, the difference between the averages of Pilot A and Pilot C is occasionally as high as two pilot rating units, with the largest differences occurring for Configurations 4-0 and 5-0; Pilot B generally gives a rating in between these extremes. It is felt that this rather large interpilot variability for these two configurations properly reflects the marginally satisfactory nature of the configurations with $\tau_R \doteq 0.75$; the occasionally long lapses between repeat evaluations that were dictated by operational considerations further emphasized their susceptibility to pilot technique.

4.10 DUTCH ROLL DAMPING RATIO AND SPIRAL MODE TIME CONSTANT

Controlled variations in Dutch roll damping ratio and the spiral mode time constant were not made in this experiment. Instead, these parameters were selected at "good" values, and attempts were made to keep their variation minimal.

The nominal value of Dutch roll damping ratio was $\zeta_d \doteq 0.20$, with variations around this value of ± 0.04. These values are all well within the Level 1 boundary of MIL-F-83300 (Reference 1), and above the value of $\zeta_d = 0.1$ given in Reference 7 as the value at which pilot rating starts degrading. In general, no objections were made by the pilots to the Dutch roll damping, and it therefore probably did not degrade any of the ratings.

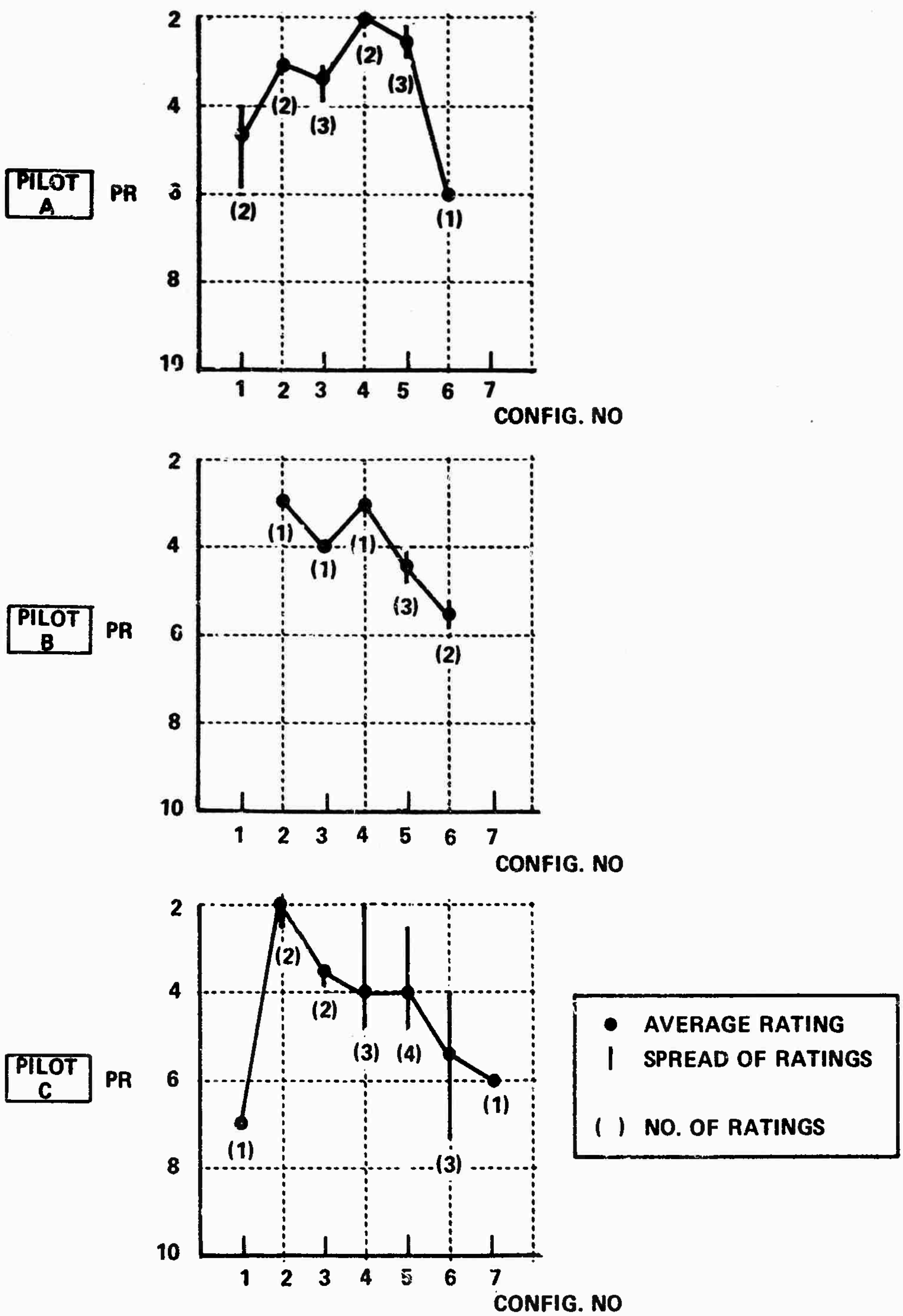


Figure 4-6 SUMMARY OF INDIVIDUAL PILOT RATINGS FOR "OPTIMUM" CONFIGURATIONS, UNLIMITED LATERAL CONTROL POWER

Rather large changes in spiral stability in the configurations are evident, with the most unstable value being $\tau_S = -26$, and the most stable $\tau_S = +9$; the unstable root corresponds to a time to double amplitude of ~ 18 seconds, while the time to half amplitude of the most stable root is ~ 6 seconds. These values both fall essentially within the boundaries for satisfactory operation given in Reference 10, although the unstable limit is given there as 20 seconds. It is felt that the range of spiral mode characteristics obtained during this experiment do not compromise the pilot ratings for a task which required continuous closed-loop control, and the total lack of any pilot comments about the spiral supports this conclusion.

4.11 SUMMARY REMARKS

This section has presented the averaged pilot ratings obtained as functions of the modal parameters investigated in this experiment. In this concluding subsection, these ratings in conjunction with typical pilot comments are used to qualitatively indicate characteristics not explicitly demonstrated by the pilot rating data.

All of the pilot comment data are given in Appendix II. For the purposes of this discussion, the comments for the "optimum" $N'_{\delta_{AS}}$ cases are collected in "averaged" form below.

- Configuration 1-0 ($\omega_d \doteq .4$, $\tau_R \doteq .35$, $|\phi/\beta|_d \doteq 1.4$):

  Roll control okay. Directional control major problem. Tendency to generate large sideslip angles, particularly during sidestep maneuver. Requirement for pilot to hold tight directional loop is unsatisfactory. Tendency to get into a directional oscillation and for ball to get way out.

- Configuration 2-0 ($\omega_d \doteq 1.4$, $\tau_R \doteq .35$, $|\phi/\beta|_d \doteq 0.4$)

  Very good roll control. Airplane feels very stable. Initial response to aileron a bit heavy, but final response very predictable. No directional complaints, no problem with turn coordination. Excellent performance on both the ILS and side step maneuver. Airplane seems insensitive to turbulence.

- Configuration 3-0 ($\omega_d \doteq 1.4$, $\tau_R \doteq .35$, $|\phi/\beta|_d \doteq 1.4$):

  Roll control pretty good. Initial response perhaps a little heavy, and final response a bit unpredictable since Dutch roll oscillation gets into roll response. Aileron inputs cause nose to oscillate - nose leads turn. Turn coordination a bit of a problem, but works okay if you leave rudder alone. Only real complaint is directional oscillation set up by aileron control. Turbulence stirs up both lateral and directional.

- <u>Configuration 4-0</u> ($\omega_d \doteq 1.4$, $\tau_R \doteq .75$, $|\phi/\beta|_d \doteq 0.4$):

  Roll control is very responsive. Initial response okay, quite snappy. Final response quite predictable (Pilot A). Predictability of final response somewhat degraded, tendency to overshoot, can even lead to small PIO IFR (Pilots B, C; Pilot A on one evaluation). Directional control and turn coordination good.

- <u>Configuration 5-0</u> ($\omega_d \doteq 1.4$, $\tau_R \doteq .75$, $|\phi/\beta|_d \doteq 1.4$):

  In negligible turbulence, roll control is pretty good, quite responsive initially. Final response has tendency to overshoot, particularly IFR. In noticeable turbulence, roll control is not very good: airplane is rolly, and response seems to start out slowly and then accelerate so that final response is quite unpredictable and oscillatory, with Dutch roll influencing it a lot. Directional response gets stirred up a little with the aileron, but ball excursions are too fast to do much. Directional control generally a good feature. Turbulence upsets the airplane in roll quite dramatically.

- <u>Configuration 6-0</u> ($\omega_d \doteq 1.4$, $\tau_R \doteq 1.45$, $|\phi/\beta|_d \doteq 0.4$):

  Roll control not good. Initial response sluggish, airplane then takes off in roll and is very unpredictable. Noticeable tendency to oscillate in roll and even PIO, particularly IFR. This tendency to overcontrol in roll is most objectionable feature of airplane. Directional response fair; tendency for nose to hesitate and then swing around rapidly. Sidestep maneuver marginal due to overcontrol in roll.

- <u>Configuration 7-0</u> ($\omega_d \doteq 1.4$, $\tau_R \doteq 1.45$, $|\phi/\beta|_d \doteq 1.4$):

  Roll control is poor. Initial response sluggish, final response very unpredictable. Airplane is extremely rolly, and it tends to get away from you in roll. Tendency to overcontrol is even more noticeable IFR. Directional control and response okay, not a factor. Airplane stirred up in roll quite a bit by turbulence. Roll control is major objection - it's a bit ridiculous

The pilot comments as summarized above may be used to "weight", to some degree, the numerical results in terms of pilot rating. This weighting is desirable to summarize concisely the effect of the modal characteristics on the flying qualities. The <u>"interpreted"</u> effects to be discussed below represent the authors' best estimates based on all the data gathered in this experiment; while they are generally confirmed by the pilot ratings, nuances indicated by the pilot comments have been used to further separate effects.

The following conclusions are drawn:

- For the $|\phi/\beta|_d \doteq 0.4$ cases with $\omega_d \doteq 1.4$ rad/sec, a $\tau_R \doteq 0.4$ sec provides a good airplane (PR $\doteq$ 2), a $\tau_R \doteq 0.9$ sec provides a marginally satisfactory airplane (PR $\doteq$ 3.5), and a τ_R = 1.5 sec provides a marginally adequate airplane (PR $\doteq$ 6.5). These results are essentially independent of turbulence except at the longest time constant investigated at which some degradation is possible (~1 PR).

- In noticeable turbulence, none of the roll mode time constants provides a marginally satisfactory (PR = 3.5) airplane for $|\phi/\beta|_d$ = 1.4. The marginally adequate (PR $\doteq$ 6.5) value of roll mode time constant is $\tau_R \doteq 1.1$ sec. A maximum $|\phi/\beta|_d$ for the approach conditions of this experiment (V = 65 kts, $\gamma = -7.5^{\circ}$) to allow satisfactory airplanes in turbulence appears to be approximately 0.8.

- In negligible turbulence, the effect on pilot rating of $|\phi/\beta|_d$ for the two values investigated is essentially negligible for all three roll mode time constants investigated. The primary effect of $|\phi/\beta|_d$ is in the degradation of the flying qualities with increasing turbulence level.

- A change in the value of ω_d from $\doteq$ 1.4 rad/sec to $\doteq$ 0.4 rad/sec degrades the flying qualities approximately two pilot rating units for $\tau_R \doteq 0.35$, $|\phi/\beta|_d \doteq 1.4$. It is likely that a similar degradation would occur for the lower $|\phi/\beta|_d \doteq 0.4$, although this change was not investigated. The general indication is that the Dutch roll undamped natural frequency should be $\gtrsim$ 1.0 rad/sec to provide satisfactory flying qualities, although the data in this area is limited.

- The "best" control sensitivity $L'_{\delta_{AS}}$ decreases with decreasing roll mode damping (increasing τ_R). For a given τ_R, the best control sensitivity increases with adverse yaw-due-to-aileron and decreases for proverse yaw-due-to-aileron.

Section V

EXPERIMENTAL RESULTS - CONTROL POWER REQUIREMENTS

This section is concerned with the second objective of this research program, namely, to determine the control power requirements, particularly those in roll, and how these requirements change with various lateral-directional parameters for STOL aircraft in the landing approach. For each evaluation flown during the program, the lateral, directional and longitudinal control power used, as opposed to that available, was measured when the control authority was essentially unlimited. The control power in this context is defined as the maximum angular acceleration commanded by the pilot during the evaluation tasks. Configurations 2-0, 3-0, 4-0, and 5-0 were selected for study with systematic reductions in the lateral control power available below the values used with unlimited authority. As was discussed in Section IV, the flying qualities of Configurations 1-0, 6-0, and 7-0 were marginally adequate at best and were therefore not selected for lateral control power variations.

The results of the control power measurements for the evaluations with unlimited authority are presented first. In the following subsections, the effects on the lateral control power used of configuration dynamics, the task (i.e., ILS tracking versus the total approach including the sidestep maneuver), turbulence and wind, and pilot technique are discussed. The results of the sub-experiment with lateral control power limiting are then presented in the form of pilot rating versus maximum lateral control power used, which is determined by the electronic limiter setting. From these plots, the minimum lateral control power required for Level 1 (PR = 3.5) and Level 2 (PR = 6.5) flying qualities are estimated as a function of the lateral-directional characteristics.

5.1 LATERAL CONTROL POWER USED (NO LIMITING)

The maximum lateral control powers used for the total IFR approach task, which encompasses acquisition and tracking of the localizer and glide path plus the visual side step and level off tasks are presented in Figure 5-1 as a function of roll mode time constant for Configurations 2-0 through 7-0. No significant differences were noted for the VFR approaches and hence they are not shown. $L'_{AS_{MAX}}$ is the maximum control power used at any time during the total approach and is equal to $L'_{\delta_{AS}} \cdot \delta_{AS_{MAX}}$, where $\delta_{AS_{MAX}}$ is the maximum lateral control deflection used during the approach. No attempt was made to "cut" the tails of the distribution of control used, since the maximum control power was usually determined by the control used in the sidestep maneuver. Eliminating these larger, and admittedly infrequent control excursions, would exclude the control power data for the most critical task in the total approach (in the absence of crosswinds). The data in Figure 5-1 represent the average values of $L'_{AS_{MAX}}$ for each configuration from all of the evaluations. In addition, the spread of values and the number of evaluations used in the

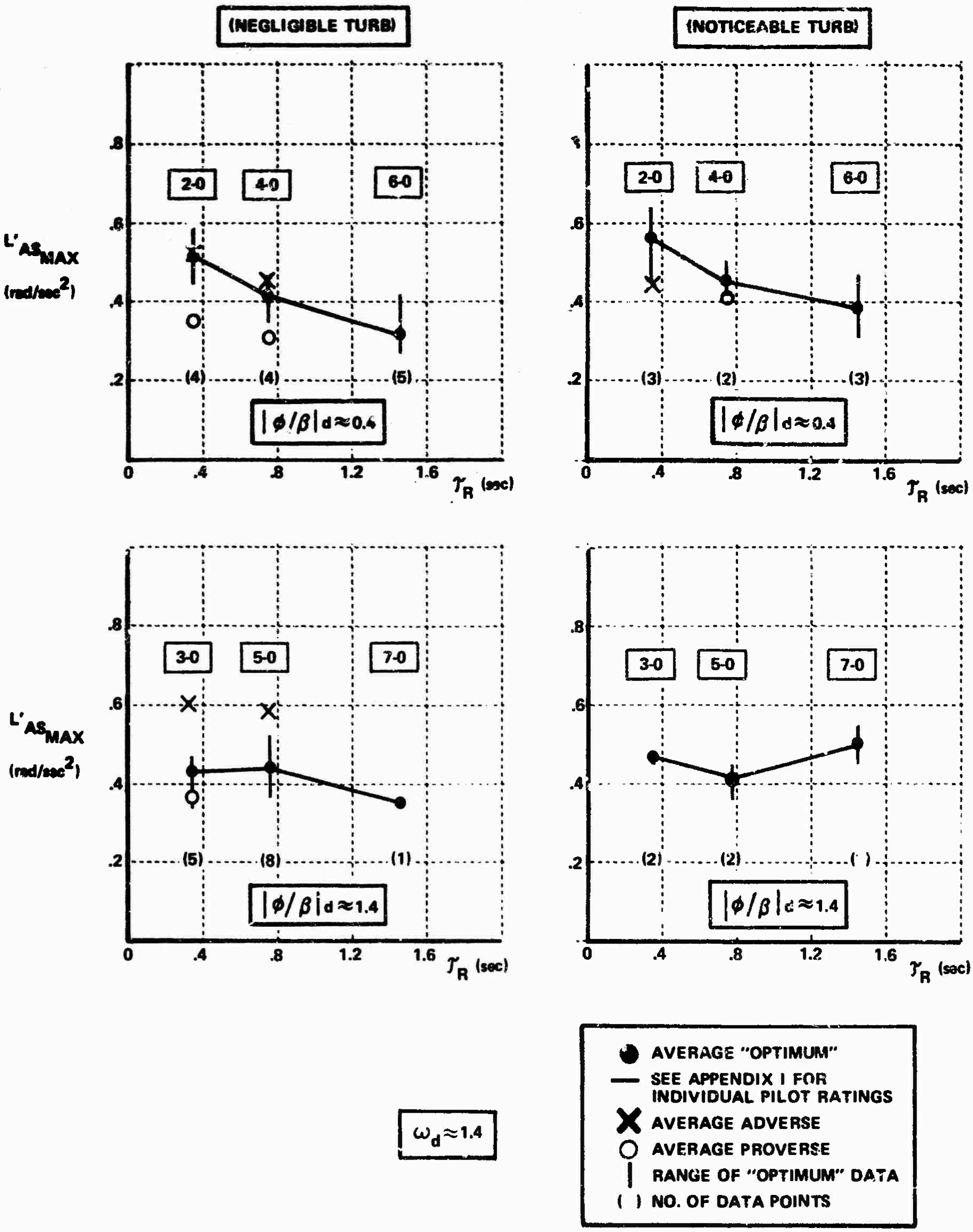


Figure 5-1 EFFECT OF τ_R ON $L'_{AS_{MAX}}$ FOR TOTAL APPROACH (TURBULENCE EFFECTS SEPARATED)

average are shown. A complete summary of all the L'_{AS} statistical data is given in Appendix VI as well as selected examples of the L'_{AS} probability density function (control displacement) and power spectral density (control frequency). Appendix I contains a complete summary of all the pertinent data for each configuration. Note that a majority of the data necessary for the statistical analyses of the evaluations done by Pilot B was lost through telemetry difficulties.

At the lower value of $|\phi/\beta|_d$, in negligible turbulence, there is a trend toward reduced $L'_{AS_{MAX}}$ with decreased roll damping (τ_R increasing). This trend seems reasonable since equal roll rates require smaller control inputs as τ_R increases. The reduction in $L'_{AS_{MAX}}$ from Configuration 2-0 to Configuration 6-0 is not, however, in the same ratio as the increase in τ_R, which is on the order of a factor of 4. This trend of reduced $L'_{AS_{MAX}}$ is not as evident at the higher value of $|\phi/\beta|_d$, which may be related to the increased roll that can be generated by the rudder pedals through sideslipping the aircraft. In fact, the primary effect of $|\phi/\beta|_d$ shown by the results is the reduced $L'_{AS_{MAX}}$ for Configuration 3-0 as compared to 2-0.

In noticeable turbulence, the trends with τ_R for Configurations 2-0, 4-0, and 6-0 ($|\phi/\beta|_d \doteq 0.4$) are similar to the results in no turbulence and there is therefore no significant change in $L'_{AS_{MAX}}$. In contrast, the values of $L'_{AS_{MAX}}$ for Configurations 3-0, 5-0, and 7-0 ($|\phi/\beta|_d = 1.4$) in noticeable turbulence show the opposite trend with variations in τ_R. Although the effects of turbulence in roll are essentially constant for each value of $|\phi/\beta|_d$ for all the τ_R values tested (cf. the time histories in Appendix II), the increased control power required with increasing τ_R at $|\phi/\beta|_d \doteq 1.4$ may reflect the pilot's increased difficulty in controlling the aircraft in turbulence. The $\Delta L'_{AS_{MAX}}$ due to turbulence at $|\phi/\beta|_d \doteq 1.4$ is not consistent but has a maximum value of .15 rad/sec^2 for Configuration 7-0.

Figure 5-2 presents the variations of $L'_{AS_{MAX}}$ as a function of $|\phi/\beta|_d$ for all configurations in negligible turbulence. The variations are minor but do indicate a trend towards reduced values of $L'_{AS_{MAX}}$ with increasing $|\phi/\beta|_d$. In noticeable turbulence, the trends are similar for $\tau_R \doteq 0.35$ seconds but opposite at the $\tau_R \doteq 1.45$ seconds.

The variations of $L'_{AS_{MAX}}$ with Dutch roll frequency are presented in Figure 5-3 for Configurations 1-0 and 3-0. Again the variations are small, indicating a slight reduction in $L'_{AS_{MAX}}$ with increasing values of ω_d.

The following general conclusion may be drawn from these data:

- the only significant correlation of $L'_{AS_{MAX}}$ with configuration dynamics occurs at $|\phi/\beta|_d \doteq 0.4$, where $L'_{AS_{MAX}}$ decreased with increasing values of τ_R in both negligible and noticeable turbulence.

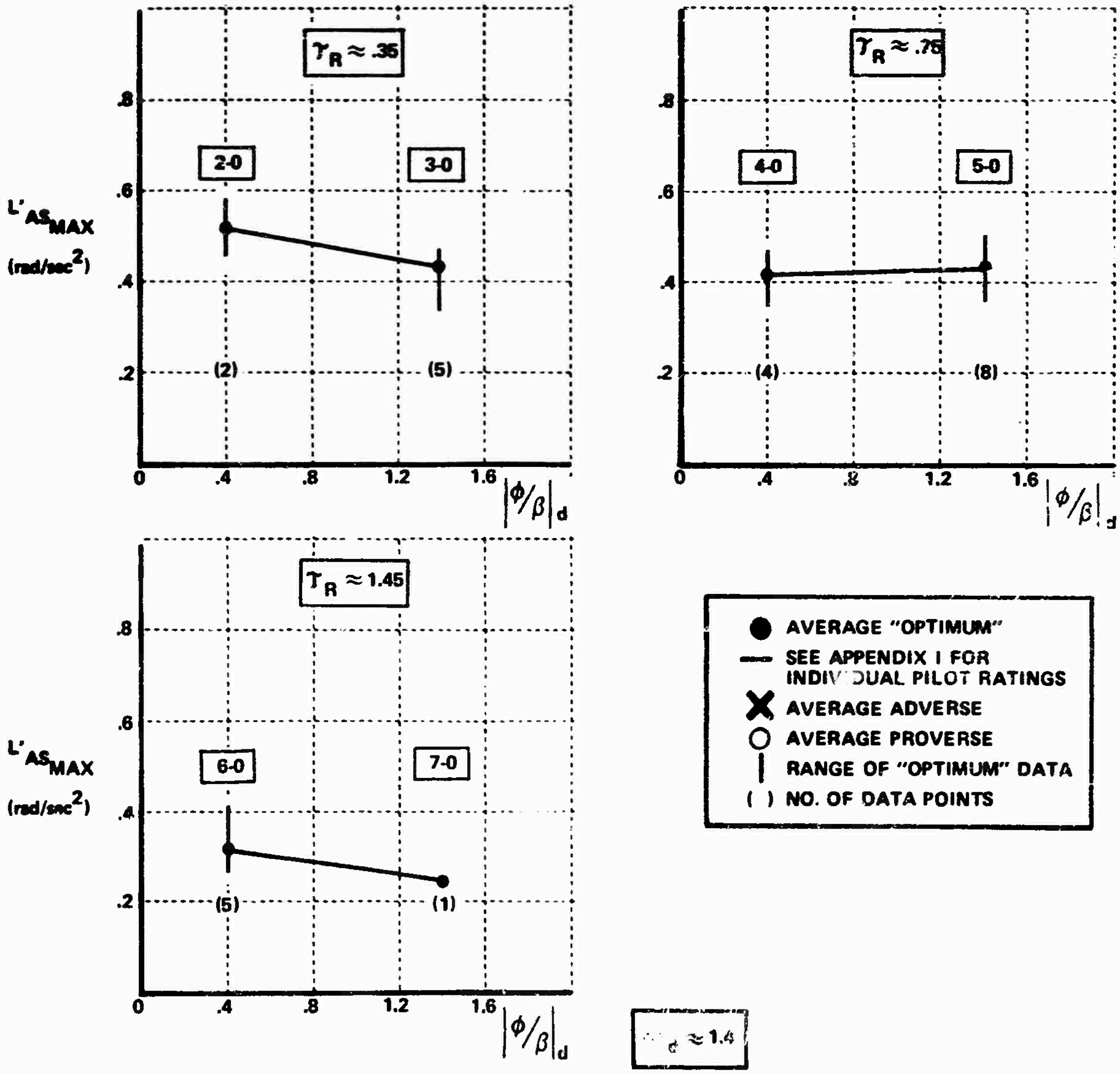


Figure 5-2 EFFECT OF $|\phi/\beta|_d$ ON $L'_{AS_{MAX}}$ FOR TOTAL APPROACH IN NEGLIGIBLE TURBULENCE

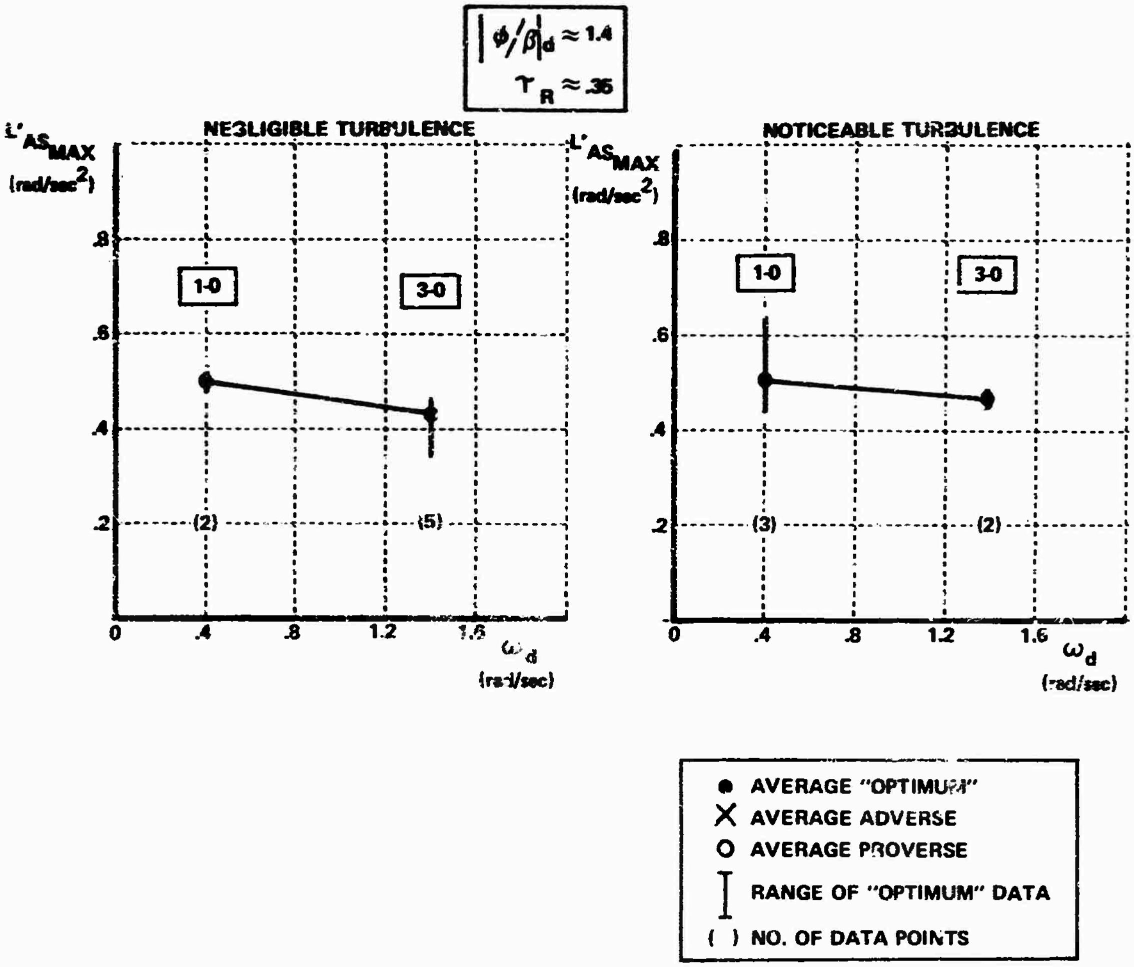


Figure 5-3 EFFECT OF ω_d ON $L'_{AS_{MAX}}$ FOR TOTAL APPROACH

5.1.1 Standard Deviations of L'_{AS}

Figure 5-4 shows the standard deviation of L'_{AS} for each optimum Configuration, 1-0 through 7-0 for Pilots A and C. These data are an example of the detailed statistical information contained in Appendix VI. When the distribution is normal, which is essentially the case for all the evaluations without control limiting, the standard deviation is a measure of probability of the stick deflection, and therefore L'_{AS}, falling within a certain range. Specifically, there is approximately a 63% probability that L'_{AS} will be within the standard deviation value.

The plots show that the standard deviation for Pilot A is nearly a constant for all the optimum configurations whereas the results for Pilot C show a decreasing trend with increasing roll mode time constant.

5.1.2 L'_{AS} Required for the Sidestep Maneuver

In general, the $L'_{AS_{MAX}}$ measured for the total approach was greater than that measured for the ILS tracking portion of the approach tasks. The difference ($\Delta L'_{AS}$) was largely the additional control power required to perform the gross maneuvering task, which was the sidestep or lateral offset maneuver at the end of each approach. The difference could also be a function of the lateral control power required to trim out the effects of a steady crosswind which will be discussed in the next subsection. Figure 5-5 shows the average $\Delta L'_{AS}$ required to perform the sidestep maneuver using all the data available for each optimum configuration in negligible turbulence. Any crosswind effects are then part of the averaged data. The data show a constant average value of approximately 0.1 rad/sec^2 across all the configurations, although the variations about the average are quite large.

5.1.3 Effects of Turbulence and Wind

Control power is required to trim, maneuver and suppress external disturbances. The lateral control power required to maneuver was presented in Figures 5-1, 5-2, 5-3, and 5-5. Estimation of the $\Delta L'_{AS}$ due to turbulence is very difficult since the pilot may not necessarily attempt to suppress the turbulence to the same extent for all configurations. For those configurations with degraded flying qualities, such as Configurations 6-0 and 7-0, the pilot may tend to "go along for the ride" if the disturbances are bad enough and he will tend to use little extra control power since attempts to control the upsets with the poor roll response characteristics make matters worse.

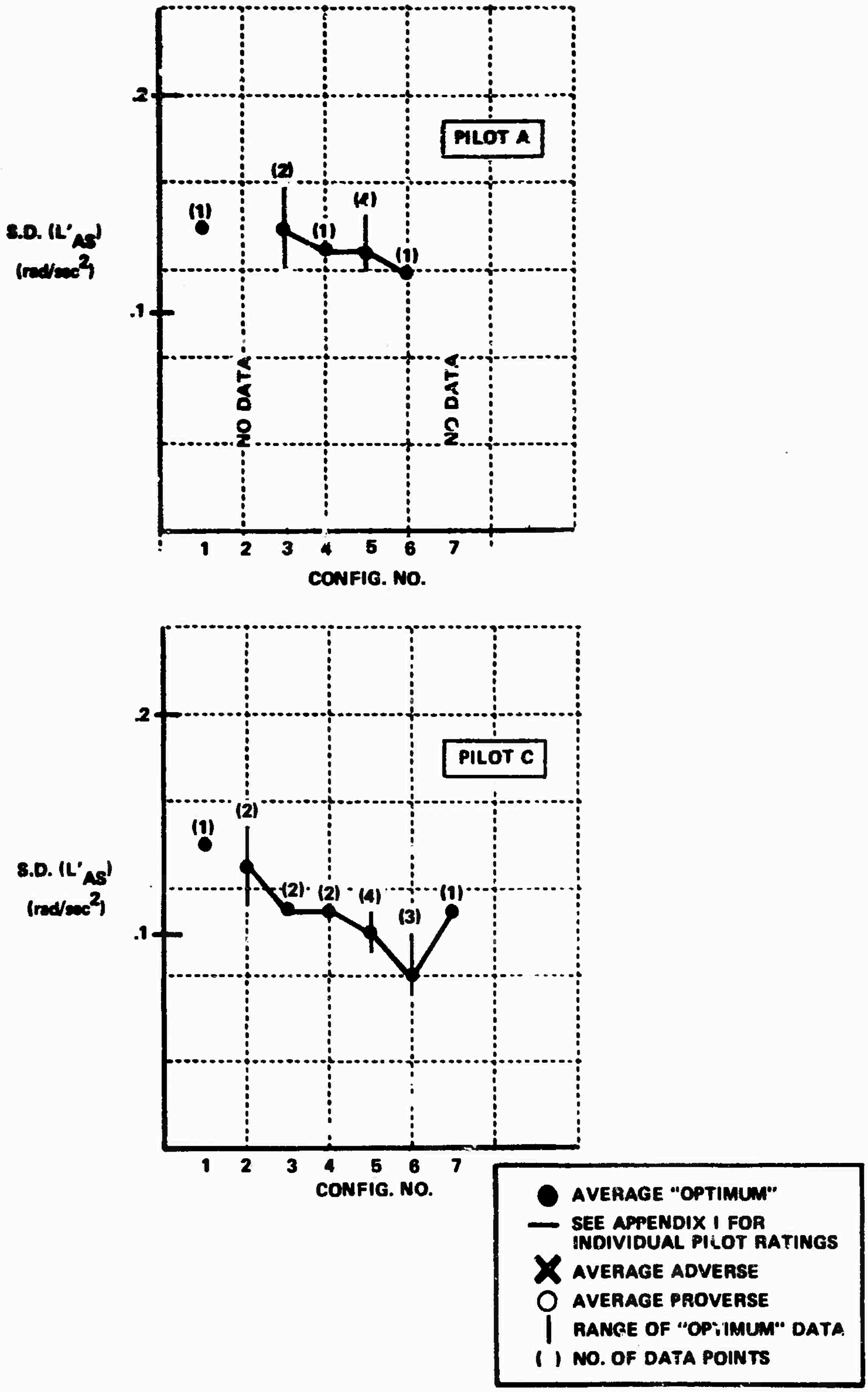


Figure 5-4 VARIATION OF S.D. OF L'_{AS} WITH "OPTIMUM" CONFIGURATIONS FOR TOTAL APPROACH IN NEGLIGIBLE TURBULENCE (PILOTS A AND C)

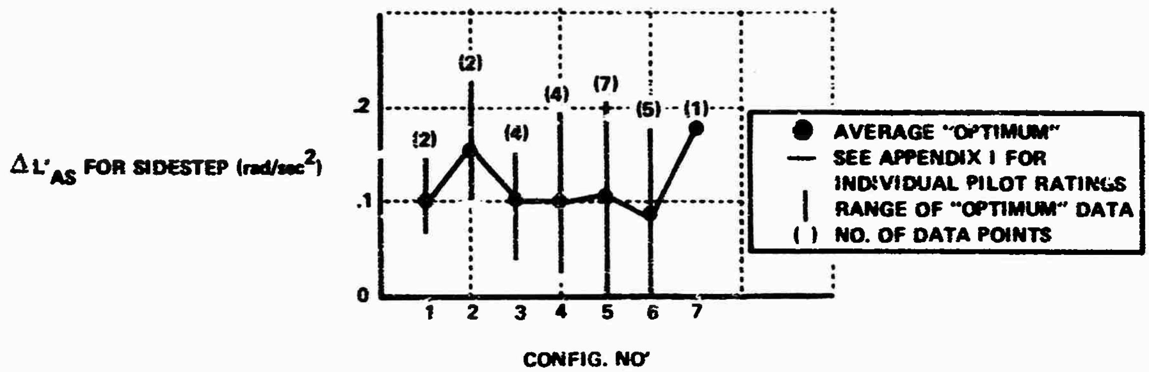


Figure 5-5 $\Delta L'_{AS}$ REQUIRED FOR SIDESTEP MANEUVER IN NEGLIGIBLE TURBULENCE ("OPTIMUM" CONFIGURATIONS)

The lateral control power required to trim out the effects of a 10 knot crosswind during a sideslipping or "wing-down" approach to touchdown is shown in Figure 5-6. Appendix V describes the details of this calculation, for $L'_{\delta_{RP}} = 0$, which is generally the case for the evaluations, showing that the L'_{AS} required is simply $L'_\beta \beta$. The values of L'_β for each configuration are given in Appendix I. For aircraft with high values of L'_β , such as Configurations 3-0 and 5-0, the control power requirements in crosswinds can be the critical factor.

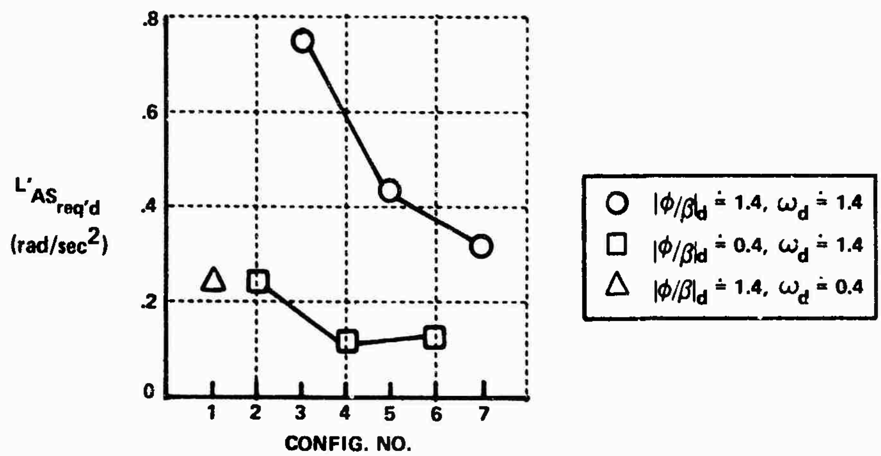


Figure 5-6 ROLL CONTROL POWER REQUIRED FOR "WING-DOWN" RUNWAY TRACKING IN 10 KT CROSSWIND

In this experiment, which used a relatively short pseudo runway centerline, the pilots often did not have enough time to properly evaluate the effects of crosswinds, and thus the $L'_{AS_{MAX}}$ measured was somewhat less than expected. For configurations such as 3-0 with high values of L'_{β}, the pilots never achieved a perfect sideslipping approach but used some crab angle into wind as well. In this case a crab angle of only 3 degrees from the centerline would reduce the L'_{AS} required by about .25 rad/sec^2. In fact, it is doubtful that pilots can judge their touchdown angle much more accurately than ± 3 degrees in which case the runway tracking task performed by the pilots was realistic.

5.1.4 Pilot Technique

Figure 5-7 presents the variation in $L'_{AS_{MAX}}$ between Pilots A and C for the ILS tracking portion of the approach task. The purpose of this figure is to illustrate typical variations in lateral control power usage between pilots. In general, Pilot C used less control power than did Pilot A, whose $L'_{AS_{MAX}}$ was essentially constant for all configurations. The difference between the pilots, $\Delta L'_{AS_{MAX}}$, ranges from .01 to .17 rad/sec^2, with an average value of approximately .09 rad/sec^2.

5.2 DIRECTIONAL CONTROL POWER USED

The average values of maximum rudder control power, $N'_{RP_{MAX}}$, used for the total approach task in negligible and noticeable turbulence are shown in Figure 5-8 for Configurations 2-0 through 7-0. Considering the typical magnitudes of N'_{RP} shown, the variations with τ_R and $|\phi/\beta|_d$ do not appear to be significant. As might be expected, there is an increase in $N'_{RP_{MAX}}$ in turbulence on the order of .05 rad/sec^2. N'_{RP} for Configuration 1-0 was not significantly different than for 3-0.

5.3 LONGITUDINAL CONTROL POWER USED

The average longitudinal control power, $M_{ES_{MAX}}$, used during the total approach task for all the unlimited configurations was essentially constant with an average value for Pilot A of 0.21 rad/sec^2 and 0.17 rad/sec^2 for Pilot C. Some increase in M_{ES} occurred when lateral control limiting degraded the lateral control capabilities. In these cases, which will be discussed in the next subsection, the average M_{ES} was 0.28 rad/sec^2 for Pilot A.

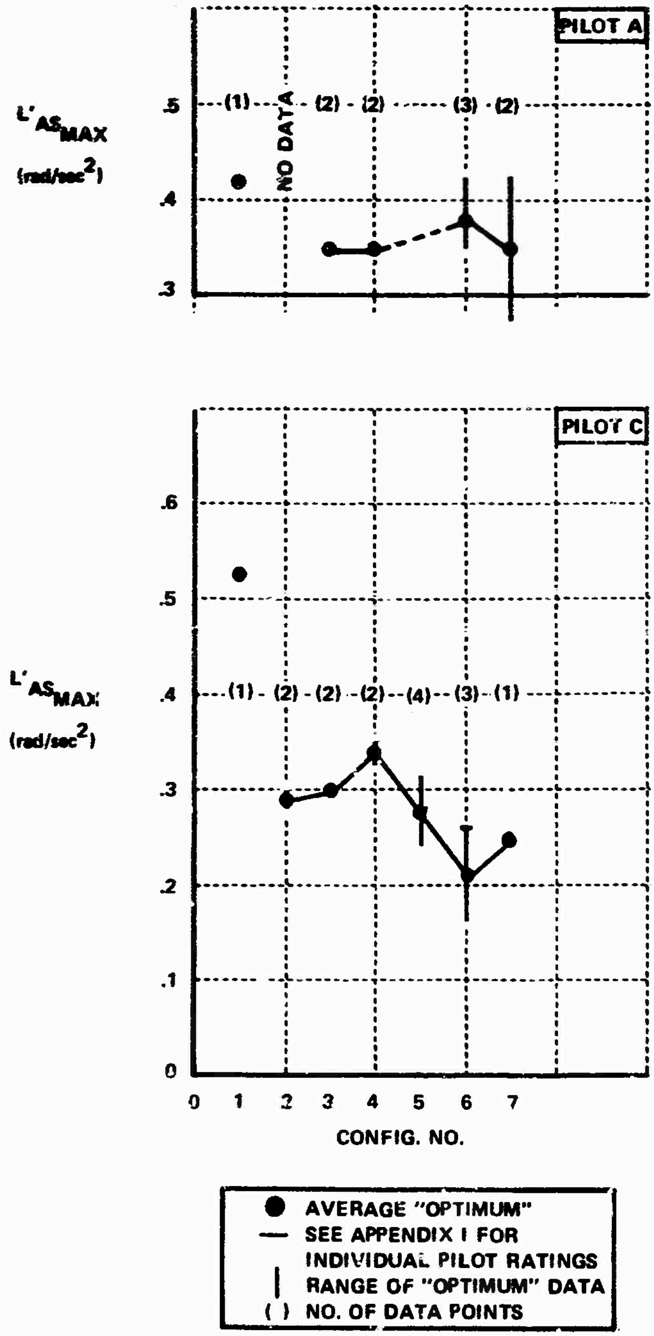


Figure 5-7 VARIATION OF $L'_{AS_{MAX}}$ WITH "OPTIMUM" CONFIGURATIONS FOR ILS TRACKING IN NEGLIGIBLE TURBULENCE (PILOTS A AND C)

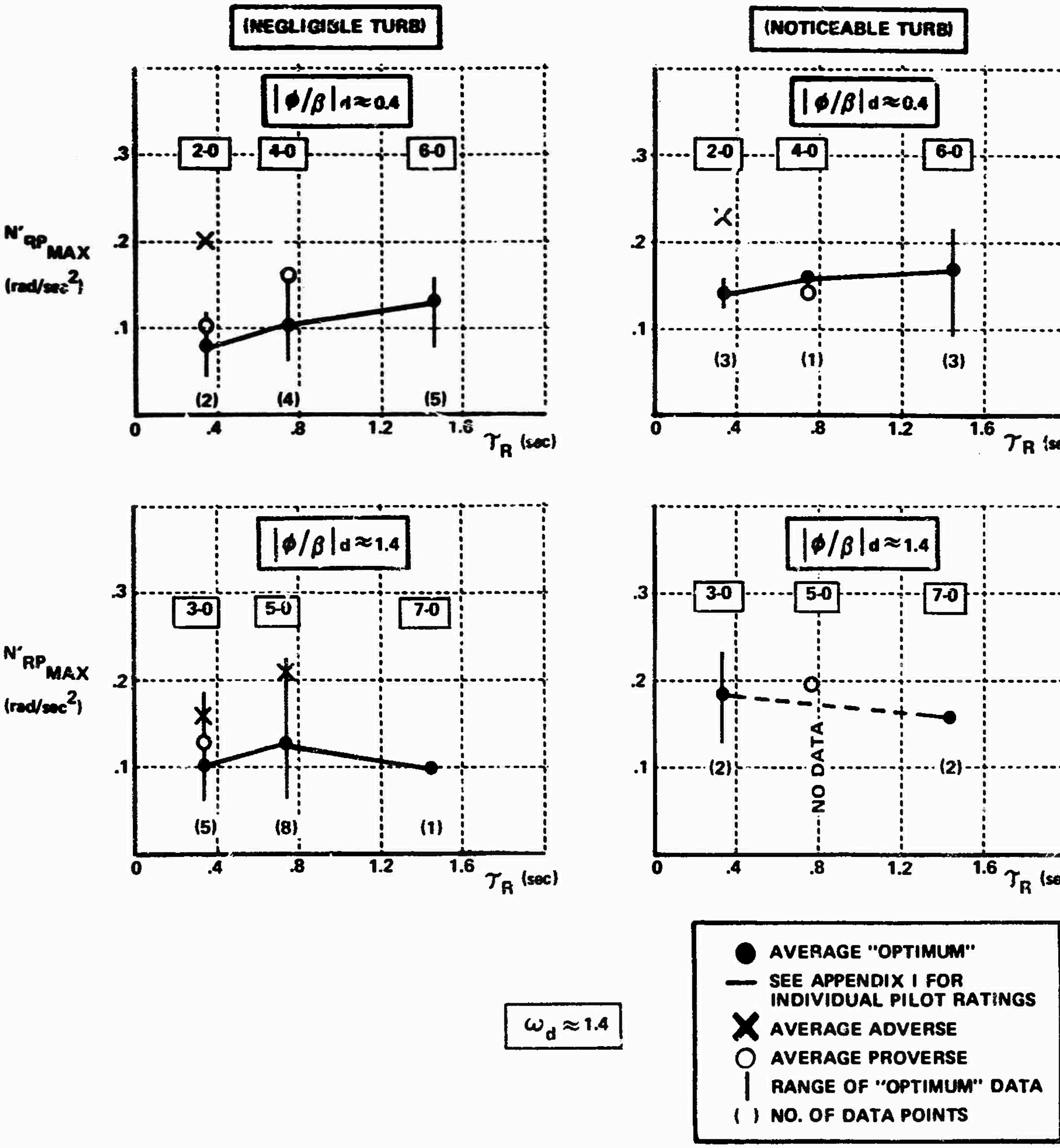


Figure 5-8 EFFECT OF τ_R ON $N'_{RP_{MAX}}$ FOR TOTAL APPROACH (TURBULENCE EFFECTS SEPARATED)

5.4 MINIMUM LATERAL CONTROL POWER REQUIREMENTS

Configurations 2-0, 3-0, 4-0 and 5-0 were evaluated with various levels of lateral control power limiting. As described in more detail in Section 2.3.3 and in Appendix VII, the L'_{AS} was systematically limited electronically to values less than the pilot used in the unlimited evaluations. The objective of this phase of the program was to determine the minimum values of L'_{AS} required for Level 1 (PR = 3.5) and Level 2 (PR = 6.5) flying qualities for the STOL landing approach task. For example, measuring the L'_{AS} used for an aircraft with a pilot rating of 3.5 does not necessarily indicate what minimum L'_{AS} could be used without a degradation in pilot rating. In this case the minimum L'_{AS} would be the value for which the pilot rating starts to degrade, which can be found by plotting the control power used versus pilot ratings, as L'_{AS} is systematically reduced.

The following subsections describe the method of limiting the lateral control power, the criterion used for selecting the values of L'_{AS} used to correlate with pilot rating, the results of this sub-experiment, and a summary of the resulting minimum control power requirements for Level 1 and Level 2 flying qualities.

5.4.1 Control Power Limiting Technique

The electronic limiting was mechanized such that for a given limiter the L'_{AS} available was fixed regardless of the $L'_{\delta_{AS}}$ selected by the evaluation pilot. For each configuration, the initial evaluations were done with near maximum control limiting (the last two digits of the configuration identifier large and therefore minimum L'_{AS} available) and then the subsequent evaluations were performed with progressively less limiting until the value of L'_{AS} was essentially the same as the unlimited evaluations.

The lateral control limiting was not always symmetrical due to an electrical offset problem in the evaluation pilot's lateral feel system (see Appendix VII for details). It should be noted, however, that even if the limiter was perfect and provided symmetrical limiting on VSS engagement, subsequent lateral stick/rudder pedal trimming by the evaluation pilot for any reason would produce the same asymmetry problem. Sideslipping approaches in steady crosswind also have the same asymmetric effect on the control power available.

5.4.2 Selection of Limited L'_{AS} Values

A major problem associated with those evaluations where the control limiting was not symmetric is the selection of the L'_{AS} value with which to correlate the pilot rating. As background to this discussion, it should be noted that the evaluation pilot never complained or even commented on any asymmetry in his lateral control response (Appendix II). Consider the example of Configuration 2-0 limited at -95 (2-0-95). As shown in the data presented in Appendix VI, when the effects of the electrical offset are accounted for, the L'_{AS} available ranges from - .09 to + .35 rad/sec^2. Perfect limiting would provide ± .23 rad/sec^2. Use of the maximum L'_{AS} (.35) seems out of the question since the limiting caused the PR to degrade from 2.5 to 8 and this value of L'_{AS} is on the order of the values used in unlimited evaluations. Correlation of PR with the minimum value (.09) is also questionable since the data and comments do not allow extrapolation to the case where symmetric limiting of ± .09 rad/sec^2 existed. In this case, simple calculations based on the assumption that the pilot's inputs (after the limiter) are a perfect series of pulses show that the pilot would spend 65% of the time on the .09 limit and 35% on the .35 limit. A "weighted" average in this case would give an L'_{AS} of about .18 which is within 20% of the ideal (symmetric) value of ± .23 rad/sec^2. Example probability density functions are given in Appendix VI for the limited cases of Configuration 4, and representative degrees of asymmetry may be seen there.

Based on these considerations, the following criterion was used to select the L'_{AS} for those evaluations with significant asymmetry in the L'_{AS} available. (These cases are marked with an asterisk in the data table in Subsection 5.4.4.) The L'_{AS} selected is the average control power used, which is the ideal limiter value for the cases where control limiting occurred in both directions. In the previous example the value selected was ± 0.23 rad/sec^2. In effect, this approach is the average L'_{AS} and represents a more conservative, and generally more accurate, determination of the minimum control power required.

5.4.3 Results of Control Power Limiting

Figures 5-9, 5-10 and 5-11 present the results of the control power limiting experiment for Configurations 2-0, 3-0, 4-0, and 5-0. The magnitude of the crosswind is shown with each data point along with the value of the limiter setting which completes the identifier for each configuration. Ideally, evaluations should have been performed in both negligible and noticeable turbulence but the constraints of the flight schedule dictated otherwise. The average pilot rating and associated L'_{AS} for the data gathered with no control limiting from Section 5.1 is shown on each figure. The average pilot rating for unlimited control power shown on the plots is that obtained for all evaluations, including those for which no statistical data was available, and correspond to the average ratings discussed in Section IV. Attention is also drawn to Configuration 4-0-80 (Figure 5-10) in which the control power used was less than that dictated by the limiter in both directions, and hence it is classified as an "unlimited" point.

From these plots the values of L'_{AS} corresponding to the Level 1 (PR = 3.5) and Level 2 (PR = 6.5) boundaries were determined for each configuration. The results for Configurations 2-0, 3-0, and 4-0 are reasonably well documented, but the small amount of data available for Configuration 5-0 make it difficult to properly define the minimum L'_{AS} values, particularly the Level 2 value.

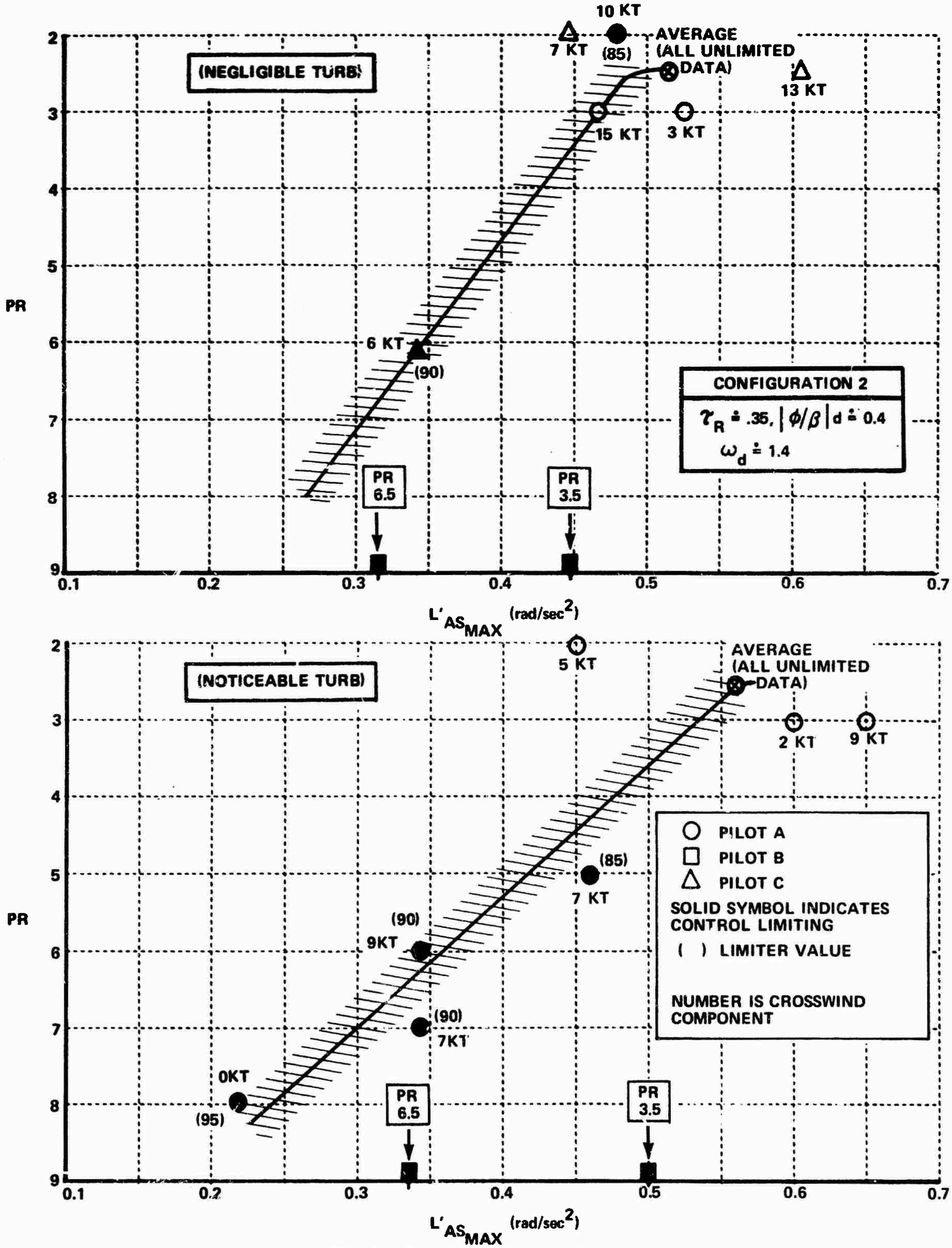


Figure 5-9 PILOT RATING VS MAXIMUM ROLL CONTROL POWER USED (CONFIGURATION 2)

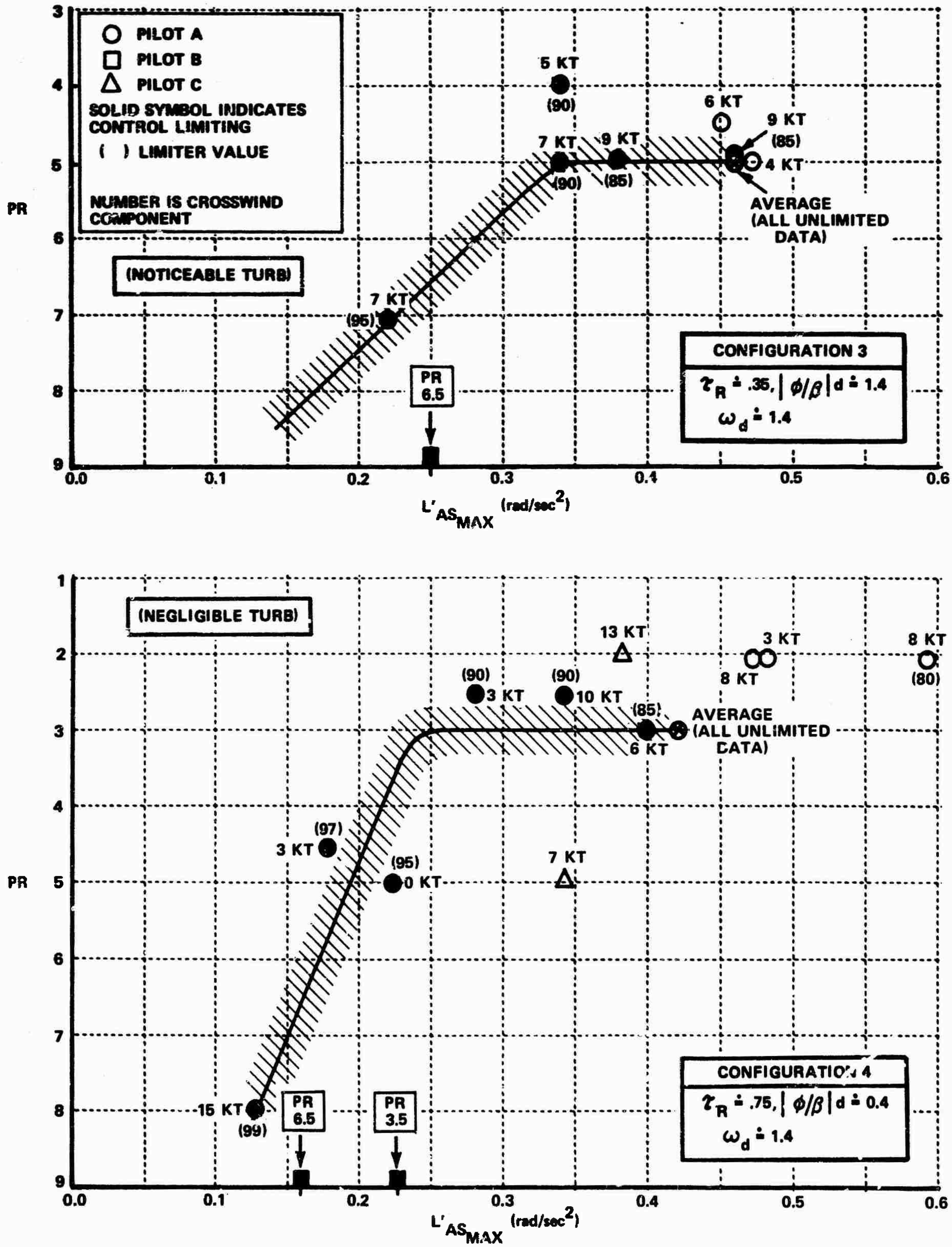


Figure 5-10 PILOT RATING VS MAXIMUM ROLL CONTROL POWER USED (CONFIGURATIONS 3 AND 4)

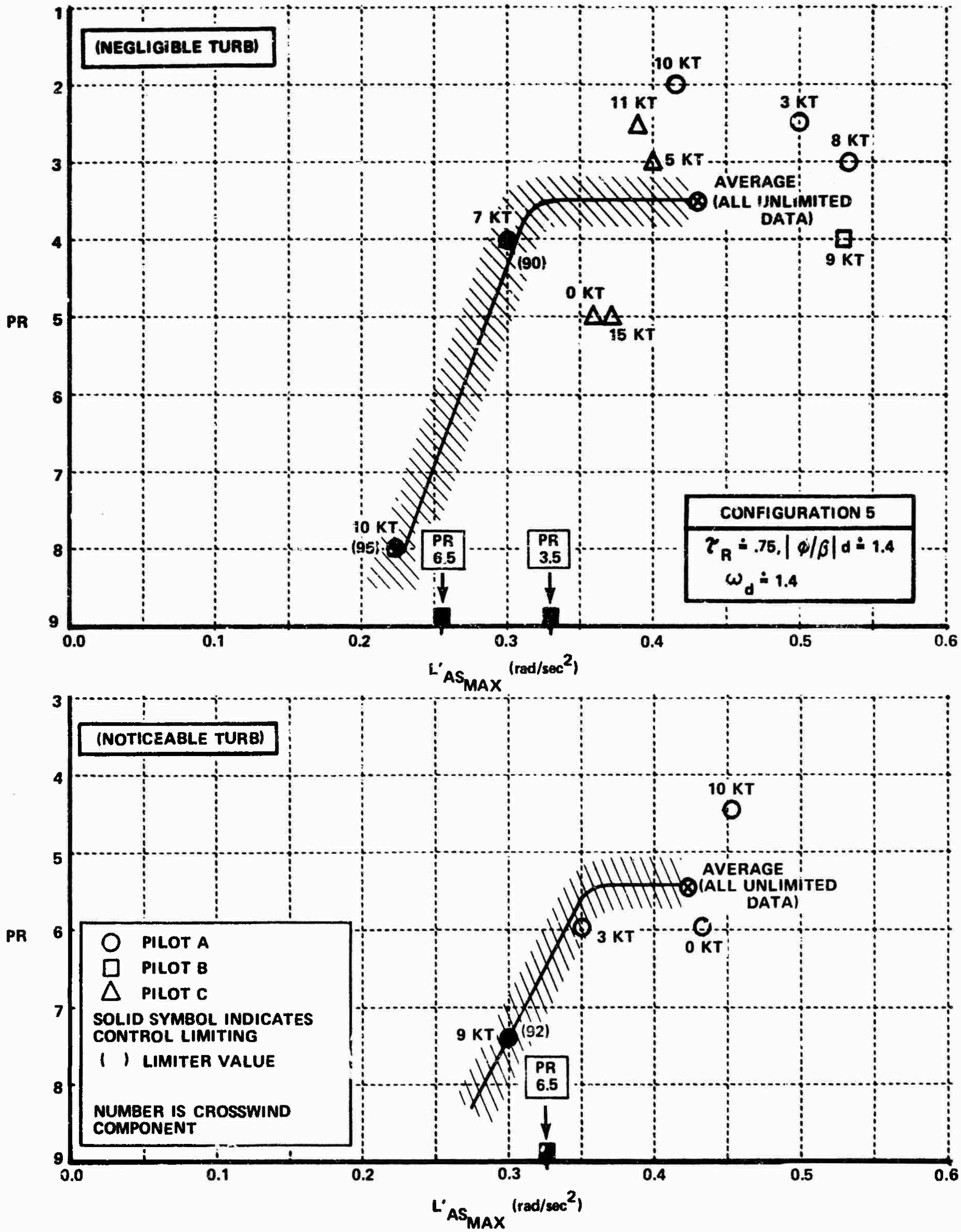


Figure 5-11 PILOT RATING VS MAXIMUM ROLL CONTROL USED (CONFIGURATION 5)

As might be expected, the directional control usage tended to increase as control power available decreased for the $|\phi/\beta|_d \doteq 1.4$ cases, as the pilot tended to use the high roll due to sideslip to perform desired maneuvers. This trend was not as noticeable for the $|\phi/\beta|_d \doteq 0.4$ cases. It is also worth noting that the supporting statistical performance data for those evaluations performed with lateral control limiting show no significant degradation with increased limiting (see Appendix VI). For example, the bank angle excursions and standard deviations are essentially the same as for the evaluations with no limiting. As discussed in Section VI, these performance measures generally do not correlate well with pilot rating.

5.4.4 Summary

Table V-1 summarizes the L'_{AS} values for PR = 3.5 and 6.5 for each configuration. A complete summary of the roll control power, L'_{AS}, used for the configurations with control limiting is presented in Table V-2. Also shown in the table are the times required to reach 30 degrees of bank angle, $t_{\phi=30}$, and the bank angle achieved after 1.8 seconds, $\phi_{1.8}$, with the L'_{AS} values used for each evaluation.

This section has presented the experimental results for the lateral control power experiment and the derived minimum values of L'_{AS} required for PR = 3.5 and 6.5 roll performance. In Section VII, these results are compared with existing roll performance criteria such as in MIL-F-8785B and MIL-F-83300, and modifications to the criteria are discussed where applicable.

TABLE V-1

MINIMUM CONTROL POWER CRITERIA FOR PR = 3.5 AND 6.5

	CONFIGURATION NUMBER	L'_{AS} (rad/sec^2)	
		PR = 3.5	PR = 6.5
	2-0	.44	.31
(T)	2-0	.50	.33
(T)	3-0	--	.25
	4-0	.23	.16
	5-0	.33	.25
(T)	5-0	--	.33

(T) Noticeable Turbulence

	CONFIGURATION NUMBER	PILOT	PILOT RATING	L'_{AS} ~rad/sec^2	$t_{\phi=30°}$ ~ sec	$\phi_{1.8}$ ~ deg
	2-0-00	Avg.	2.5	.51	-	17
	2-0-85	A	2	.47	3.1	16
	2-0-90	C	6	.34	4.2	12
(T)	2-0-00	Avg.	2.5	.56	-	19
(T)	2-0-85	A	5	.46	3.1	16
(T)	2-0-90	A	7	.34	4.2	12
(T)	2-0-90	A	6	.34	4.2	12
*(T)	2-0-95	A	8	.23	6.2	8
(T)	3-0-00	Avg.	5	.46	-	18
(T)	3-0-85	A	5	.46	2.6	18
(T)	3-0-90	A	4	.34	3.5	13
(T)	3-0-90	A	5	.34	3.5	13
(T)	3-0-95	A	7	.23	6.5	9
	4-0-00	Avg.	3	.42	-	22
‡	4-0-80	A	2	.59	1.8	31
	4-0-85	A	3	.40	2.3	21
	4-0-90	A	2.5	.28	3.0	15
	4-0-90	A	2.5	.34	2.6	18
*	4-0-95	A	5	.23	3.6	11
	4-0-97	A	4.5	.18	4.2	9
*	4-0-99	A	8	.13	5.5	7
	5-0-00	Avg.	3.5	.43	-	28
	5-0-90	A	4	.30	2.4	20
*	5-0-95	A	8	.23	2.9	14
(T)	5-0-00	Avg.	5.5	.42	-	27
*(T)	5-0-92	A	7.5	.30	2.4	20

* Limiting Asymmetric (Average value used - see Appendix VI, Volume II)
(T) Evaluated in Noticeable Turbulence
‡ L'_{AS} not Limited

Section VI

EXPERIMENTAL RESULTS - SUMMARY OF STATISTICAL MEASURES OF TASK PERFORMANCE

This section presents a summary of the averaged statistical performance data for the configurations evaluated in simulated IFR conditions. These data were gathered to supplement the pilot rating data discussed in Section IV and the control usage data discussed in Section V of this report. The statistical data for each evaluation and a more complete description of the data gathering process are given in Appendix VI, and only averaged and selected typical results will be discussed here. The primary emphasis of the discussion will be on averaged standard deviations of the selected performance measures, as the standard deviations provide an easily obtained indicator that has been used in other experiments.

6.1 ILS TRACKING PERFORMANCE

Figure 6-1 presents the averaged rms localizer and glide slope ILS tracking errors for all the evaluations for which statistical data are available (Appendix VI). In general, no trends with configuration are evident for either of these performance measures, regardless of turbulence level. By inference, then, these performance measures do not correlate with the pilot rating data presented in Section IV - that is, no trends of ILS tracking performance are evident as pilot rating degrades or improves. In other words, ILS tracking performance is not a major factor in the complex determination of the pilot rating. It is also worth noting that the tracking performance for a given configuration tends to improve in noticeable turbulence over that in negligible turbulence. This trend results primarily because the pilot likely flies tighter loop closures in the presence of external disturbances than in their absence.

This general lack of correlation of ILS tracking performance with either configuration dynamics or pilot rating, and the generally improved tracking performance for most configurations in the presence of turbulence, is an important factor to consider when performing pilot modelling studies or defining flying qualities criteria as a function of these performance indices. The results of this experiment indicate that it is generally fallacious to assume that closed loop pilot-vehicle ILS tracking performance will degrade with degraded flying qualities, and, further, that these performance indices should not be heavily weighted in attempting to explain or predict pilot ratings.

6.2 BANK ANGLE AND LATERAL ACCELERATION TRACKING PERFORMANCE

Other performance indices which may be important as indicators of pilot rating are bank angle tracking and lateral acceleration errors. It is clear that the capability to attain a desired bank angle precisely and quickly is very important to pilot rating, as was discussed in Section IV. In addition, lateral accelerations as evidenced by ball excursions provide an indication of

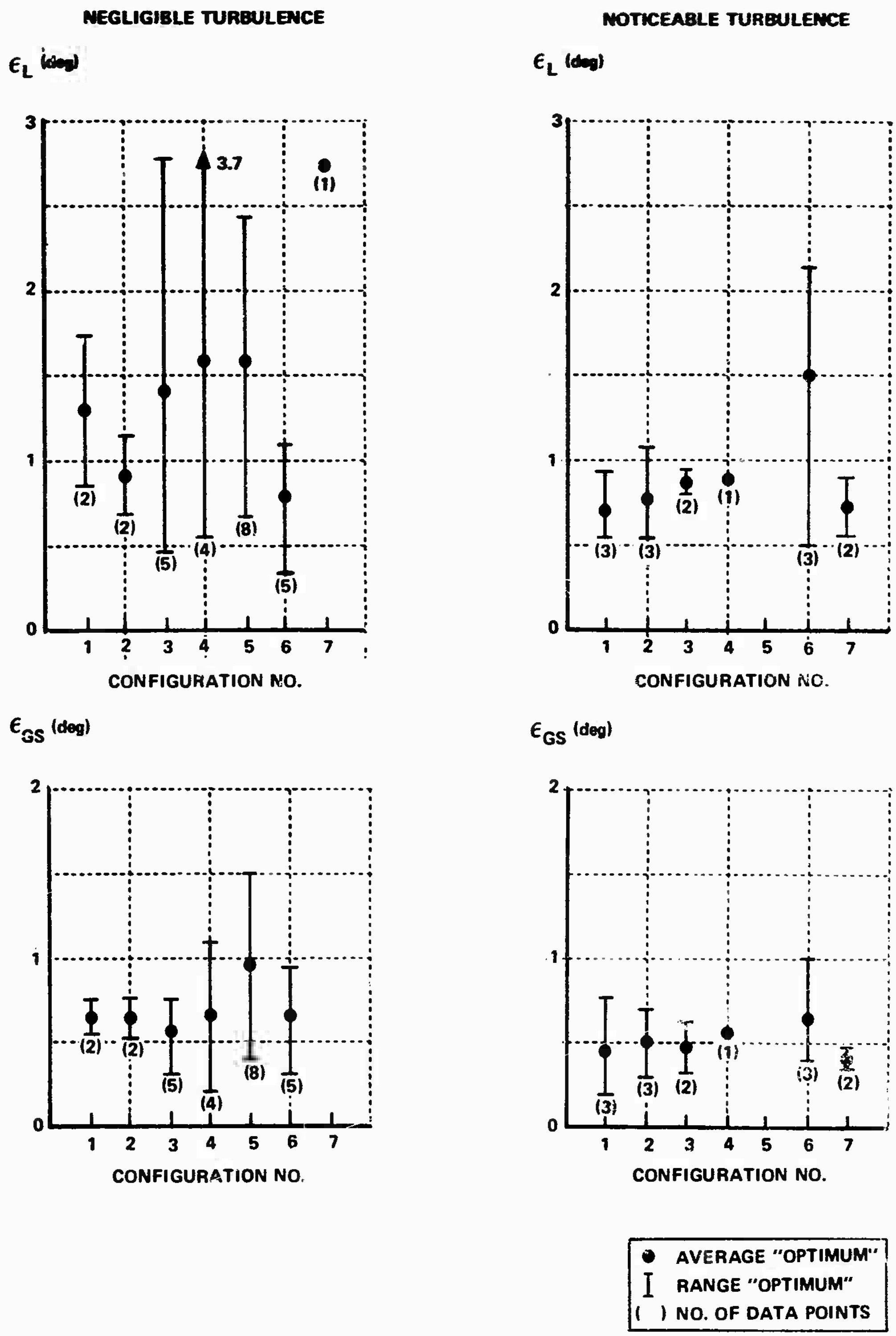


Figure 6-1 RMS DEVIATIONS OF LOCALIZER AND GLIDE SLOPE ILS TRACKING FOR ALL "OPTIMUM" UNLIMITED CONFIGURATIONS

coordination problems, which also influence pilot rating A degree of correlation between the tracking errors of bank angle and/or lateral acceleration and pilot rating or configuration dynamics might therefore be expected.

Figure 6-2 presents the averaged standard deviations of bank angle and lateral acceleration for the configurations evaluated in this experiment. In negligible turbulence, bank angle tracking appears to be uncorrelated with configuration and hence dynamics, with the possible exception of Configuration 2 (lower $|\phi/\beta|_d$, fastest roll mode, higher ω_d). This characteristic implies that the pilot varies his characteristics (e.g., gain, lead) in the bank angle loops as a function of the airplane dynamics to maintain essentially the same tracking performance if no external disturbances are present. In the presence of turbulence, there is some evidence of a degradation in bank angle tracking as roll mode damping is reduced for both values of $|\phi/\beta|_d$ investigated in this experiment. As is discussed in Section IV and can be seen from the time histories presented in Appendix II, for a given value of $|\phi/\beta|_d$ the bank angle and roll rate response magnitudes are essentially independent of roll mode time constant, so that the increment in bank angle error due to turbulence should be essentially the same for Configurations 3, 5, and 7 at one value, and for 2, 4, and 6 at a different value. The trend of decreasing performance with decreasing roll damping in turbulence is therefore probably attributable to the pilot's difficulties in counteracting these disturbances precisely. In any case, relatively few data exist to support this trend, and it must therefore be regarded as only qualitative.

The most evident characteristic in the plots of lateral acceleration standard deviations is the noticeably larger values for Configuration 1 in both negligible and noticeable turbulence. This configuration had a Dutch roll frequency approximately one third that of the other six configurations, and the higher n_y deviations are evidence of the correspondingly higher sideslips that are generated due to the poor directional stability. No particularly significant trends are demonstrated for the remaining configurations. A slight increase in the averages is noticeable in negligible turbulence as the roll mode damping is reduced (Configurations 2→4→6, 3→5→7), which might be attributable to increasing sideslip excursions caused by the degrading lateral control preciseness. This trend, however, is quite qualitative. It can also be seen that the average n_y excursions are larger in noticeable turbulence than in the negligible case, which is to be expected since $n_y \doteq Y_\beta (\beta + \beta_g)$. In fact, the average difference between the n_y standard deviations for Configurations 2 - 7 in and out of turbulence is approximately 0.26 ft/sec^2, which corresponds to a $\Delta\sigma_{v_g}$ = 0.8 ft/sec and is roughly the criterion used to separate the flights according to turbulence level (Appendix I).

An additional interesting point concerns the average maximum bank angle achieved on the total approach (including the sidestep). Although the maximum bank angle is primarily determined by the sidestep maneuver, which is essentially the same for all evaluations, it might be expected that the imprecise roll control for the configurations with low roll damping (particularly 6 and 7) would lead to larger bank angle excursions. Figure 6-3 shows the averaged maximum bank angle excursions for all the configurations. No significant trend is evident in either negligible or noticeable turbulence; the

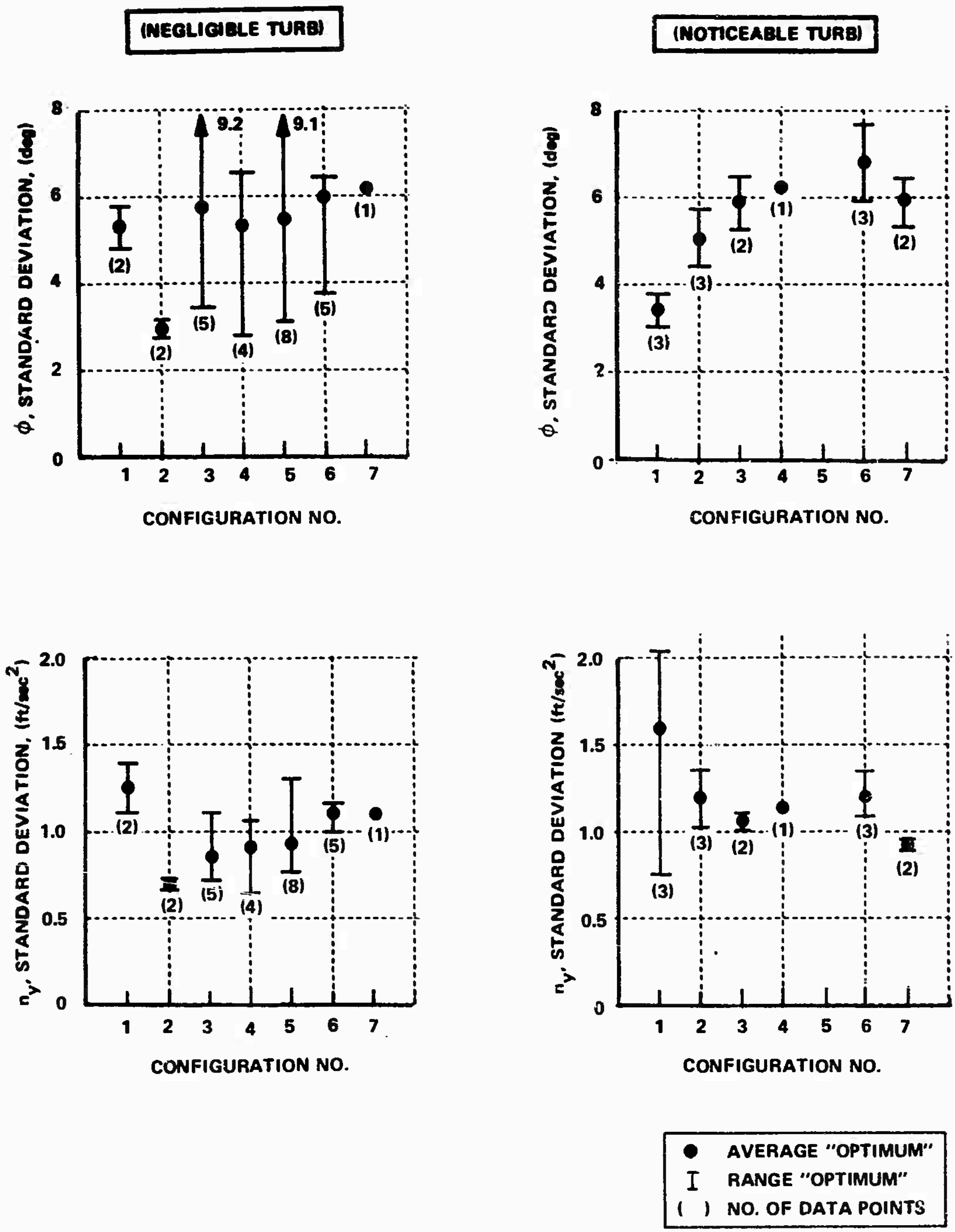


Figure 6-2 STANDARD DEVIATIONS OF ϕ AND n_y IN ILS TRACKING FOR ALL "OPTIMUM" UNLIMITED CONFIGURATIONS

maximum bank angle used is approximately 20 degrees for all configurations.

In general, the standard deviations of bank angle and lateral acceleration provide only tentative, qualitative correlation with the configuration dynamics. As in the case of localizer and glide slope tracking errors, the pilot generally provides compensation to achieve if possible a "standard" level of performance, and it is difficult to relate measures of this performance to his rating of the aircraft.

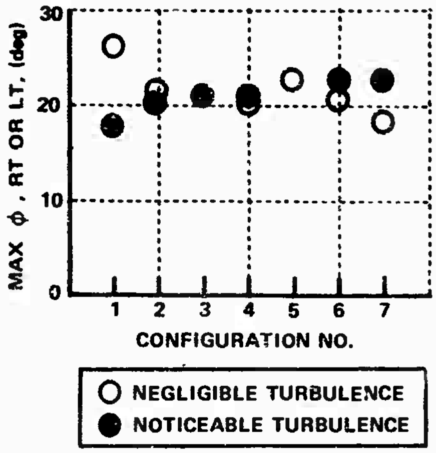


Figure 6-3 MAXIMUM BANK ANGLE FOR TOTAL APPROACH, AVERAGE OF ALL PILOTS

6.3 ROLL AND YAW ACCELERATIONS - STANDARD DEVIATIONS

The roll and yaw accelerations $\dot{p}$ and $\dot{r}$ are proportional to the total aerodynamic moments about the roll and yaw axes, respectively. As such, they represent the sum of the control power being used, the turbulence inputs to the aircraft, and the restoring moments due to the aircraft motions; in a general sense, then, trends in their variations might reflect the pilot rating to some degree. In the first X-22A experiment (Reference 8), some small trend between pilot rating, pitch acceleration standard deviation, and turbulence level appeared to exist for the very limited amount of data that was analyzed. It was therefore considered useful to examine the standard deviations of $\dot{p}$ and $\dot{r}$ in this experiment to ascertain if evidence of a similar trend existed.

Figure 6-4 presents the averaged standard deviations of $\dot{p}$ and $\dot{r}$ for the configurations investigated in this report; the number of data points included in the averages are the same as for Figures 6-1 through 6-3. In

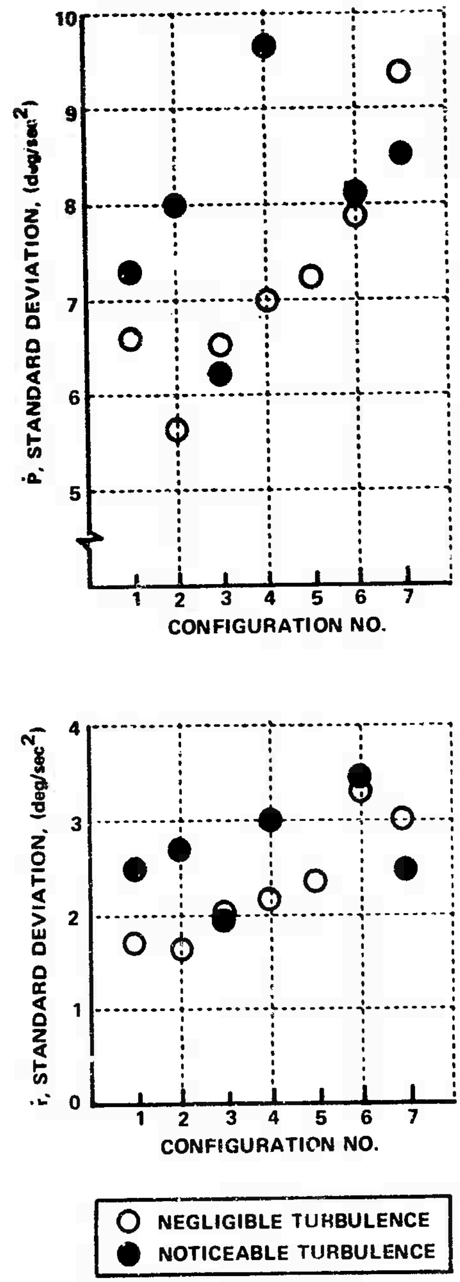


Figure 6-4 SUMMARY OF ANGULAR ACCELERATION RESPONSE BY CONFIGURATION, AVERAGE OF ALL PILOTS IN ILS TRACKING

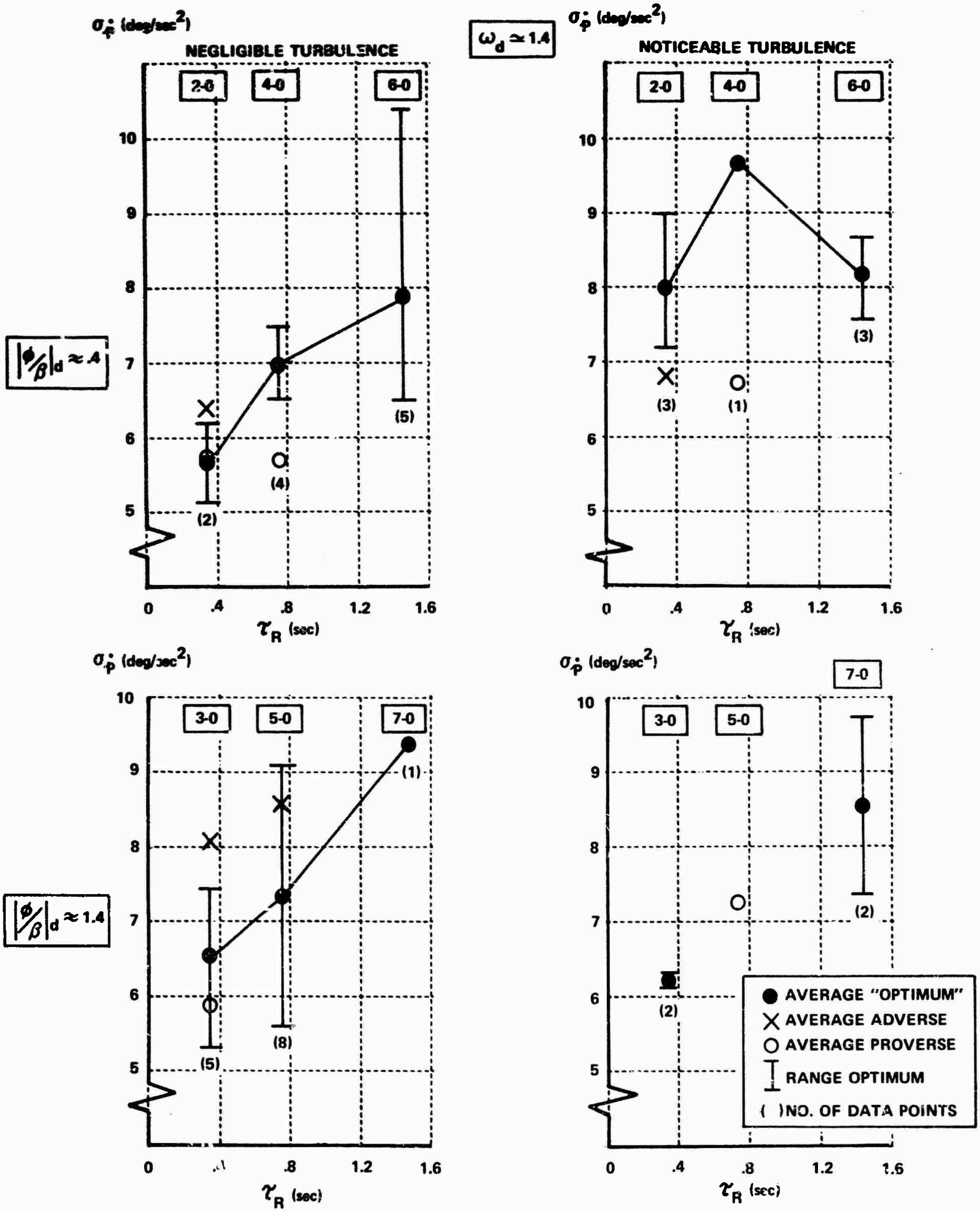


Figure 6-5 EFFECT OF MODAL CHARACTERISTICS AND TURBULENCE ON THE STANDARD DEVIATION OF $\dot{p}$ IN ILS TRACKING TASK

negligible turbulence, a definite trend of increasing $\sigma_{\dot{p}}$ with configuration is evident; no obvious trend in noticeable turbulence is discernible, perhaps because of the relatively few data points available. A similar situation occurs with $\sigma_{\dot{r}}$: a trend toward increasing values with configuration is evident in negligible turbulence, but any trends in noticeable turbulence are compromised by a lack of data.

To better indicate if trends exist with configuration dynamics, Figure 6-5 presents the averaged $\sigma_{\dot{p}}$ as a function of τ_R and $|\phi/\beta|_d$ for the "optimum" cases, and includes the total spread of standard deviations. It is clear that, in negligible turbulence, the standard deviation of roll acceleration increases as the roll damping decreases for a given $|\phi/\beta|_d$, and further that a small trend toward increasing $\sigma_{\dot{p}}$ with increasing $|\phi/\beta|_d$ is evident. The results in noticeable turbulence should be regarded as inconclusive due to the small number of data points available. The trends of $\sigma_{\dot{p}}$ in negligible turbulence may be compared with the pilot rating data (Section IV, Figure 4-2) and the control usage data (Section V, Figure 5-1). As was shown in Figure 4-2, in negligible turbulence pilot rating remains essentially constant out to $\tau_R \doteq$ 0.75 seconds for both values of $|\phi/\beta|_d$, and then degrades about 3 PR units as τ_R goes to 1.45 seconds; as was shown in Figure 5-1, maximum roll control power used tends to decrease as τ_R is increased, particularly for low $|\phi/\beta|_d$. Since the roll control power being used is tending to decrease, it is likely that some of the increase in $\sigma_{\dot{p}}$ as roll damping is reduced is attributable to the degrading precision of the bank angle control, which is reflected in the degrading pilot rating. This hypothesis, however, must be regarded as purely qualitative, and, in fact, does not imply that the $\dot{p}$ standard deviation can be correlated with pilot rating as has been suggested. This lack of correlation is graphically illustrated in Figure 6-6, which plots pilot rating against $\sigma_{\dot{p}}$ for all the evaluations of the "optimum" configurations. No trends of any sort are evident from this plot, other than a general trend toward higher $\sigma_{\dot{p}}$ in turbulence.

In summary, then, there does appear to be a trend toward increasing $\sigma_{\dot{p}}$ as roll mode damping is reduced and as $|\phi/\beta|_d$ increases. The values of $\sigma_{\dot{p}}$ for a given evaluation, however, do not provide a good indicator of the pilot rating even if the effects of turbulence are separated out.

6.4 POWER SPECTRAL DENSITY OF LATERAL CONTROL USAGE

Although not a measure of task performance, the power spectral densities of lateral control usage can be useful indicators of pilot control technique and, in fact, often add quantitative verification of pilot comments. Several representative plots are given and discussed in Appendix VI; characteristics pertinent to some of the variables investigated in this experiment are summarized below.

- Pilot control activity shifts to lower frequencies as roll mode damping is reduced.

- Pilot control activity also shifts to lower frequencies as the roll control authority is reduced. This characteristic is clearly a result of the pilot applying full control and waiting for the airplane to respond to the desired bank angle.

- Configurations which exhibit some proverse yaw due to aileron (specifically, Configuration 3-0) tend to show increased stick activity at the Dutch roll frequency, particularly in turbulence. This characteristic is probably due to the pilot attempting to damp out the oscillations in roll at the Dutch roll frequency which are stirred up in his attempts to counteract the turbulence disturbances.

A more detailed discussion of these characteristics is presented in Appendix VI.

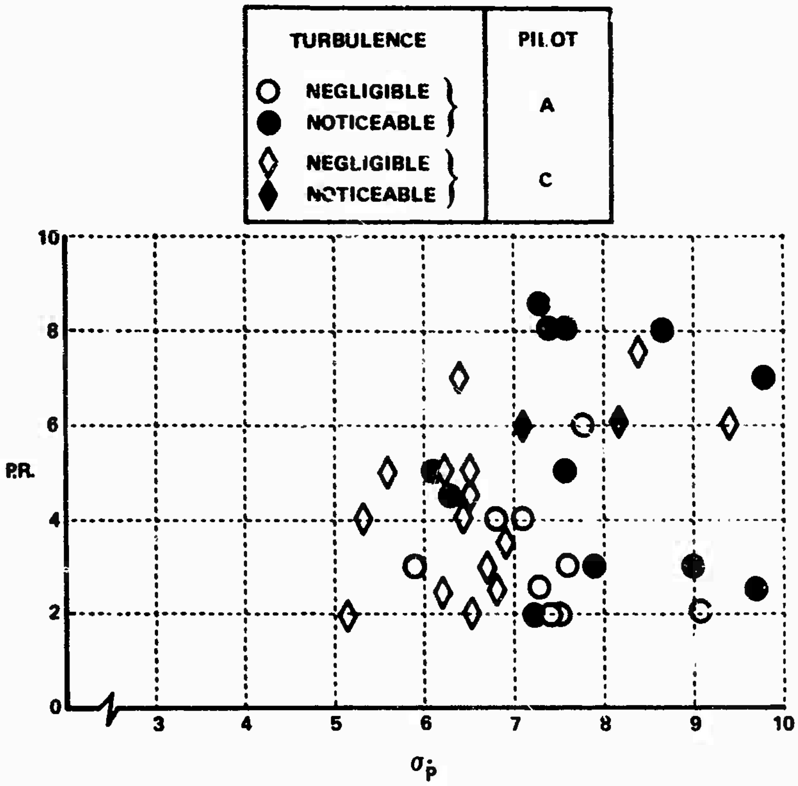


Figure 6-6 STANDARD DEVIATION OF $\dot{p}$, PILOTS A AND C, ALL OPTIMUM CONFIGURATIONS

6.5 SUMMARY REMARKS

This section has compared selected statistical performance measures with configuration dynamics and pilot rating. The general observations which can be made are summarized below:

- RMS ILS tracking errors do not correlate with either pilot rating or configuration dynamics, and do not provide a good indicator of flying qualities.

- In negligible turbulence, bank angle standard deviations do not correlate with pilot rating or configuration dynamics. In noticeable turbulence, a qualitative trend of decreasing bank angle tracking performance with decreasing roll damping is noticeable.

- No significant trend of lateral acceleration standard deviation with configuration dynamics is evident for a given Dutch roll frequency. The lateral acceleration standard deviations increase for $\omega_d \doteq 0.4$ as compared to $\omega_d \doteq 1.4$, which is a result of the degraded control of sideslip. As would be expected, the standard deviations of lateral acceleration increase in noticeable turbulence.

- The standard deviation of roll acceleration increases as roll damping decreases. No strong correlation of any acceleration (translational or rotational) with pilot rating was observed, however.

Section VII

COMPARISON OF RESULTS WITH FLYING QUALITIES REQUIREMENTS

This section compares the flying qualities results obtained in the experiment with applicable flying qualities requirements, principally from MIL-F-83300 (Reference 1), MIL-F-8785B(ASG) (Reference 3), and Calspan's most recently recommended revisions to MIL-F-8785B (Reference 11). The comparison is not intended to be all inclusive, but rather to compare selected characteristics specifically investigated in this experiment with the existing requirements. Appendix I provides a sufficiently detailed data summary to enable further comparisons to be calculated if required.

7.1 ROLL MODE TIME CONSTANT

The requirements on roll mode time constant of the specifications are summarized below:

- MIL-F-83300 (Reference 1)

  $\tau_R \leq$ 1.4 seconds for Level 1

  $\tau_R \leq$ 3.0 seconds for Level 2

- MIL-F-8785B and Recommended Revision (References 3 and 11)

  Carrier-based:

  $\tau_R \leq$ 1.0 seconds for Level 1

  $\tau_R \leq$ 1.4 seconds for Level 2

  Land-based:

  $\tau_R \leq$ 1.4 seconds for Level 1

  $\tau_R \leq$ 3.0 seconds for Level 2

To compare the results of this experiment with these requirements, the average ratings of Configurations 2-0, 4-0, and 6-0 for all evaluations will be used. Using these ratings eliminates the degradation caused by a higher $|\phi/\beta|_d$ in turbulence (Configurations 3-0, 5-0, 7-0), and the degradation that is caused by $\omega_d < 1.4$ rad/sec (Configuration 1). These ratings are summarized below:

2-0: $\tau_R \doteq .35$: PR $\doteq$ 2.5

4-0: $\tau_R \doteq .75$: PR $\doteq$ 3

6-0: $\tau_R \doteq 1.45$: PR $\doteq$ 6.0

It can be seen that neither the MIL-F-83300 requirements nor the land-based requirements of MIL-F-8785B and the proposed revision are substantiated by the results of this experiment. As was discussed in Section IV, the results of this experiment indicate that the roll mode time constant should be less than on the order of .75 - 1.0 seconds to provide satisfactory (PR $\leq$ 3.5) flying qualities, and less than on the order of 1.4 - 1.5 seconds to provide adequate (PR ≤ 6.5) flying qualities. Of the specification requirements listed above, only the carrier-based criteria of 8785B (and the recommended revision) appear to be approximately substantiated by the results of this experiment.

The more stringent requirements on roll mode time constant indicated by this experiment may be a result of the approach speed chosen as typical of STOL aircraft -- that is, 65 kts. For a perfectly coordinated turn at constant bank angle, the yaw rate is related to the bank angle approximately by:

$$r \doteq \frac{g}{V_0}\phi$$

For a given bank angle, then, the turning rate increases as the velocity decreases, and it is worth observing that the pilots on this program noted that the aircraft turned quite rapidly for a given bank angle. For the ILS tracking and subsequent sidestep maneuver used as the task in this experiment, it therefore seems reasonable that increased precision of bank angle control was required to properly track heading. It is interesting to note that the terminal operation for carrier-based Class II aircraft more closely approaches the required tracking precision investigated in this experiment than perhaps that for land-based aircraft, and that the specification requirement for carrier-based aircraft is better substantiated by this experiment than that given in 83300 or in 8785B for land-based aircraft.

The recommended revision to 8785B includes a further requirement on roll mode time constant as well, aimed at improving the response to external disturbances (i.e., turbulence). This requirement is shown in Figure 7-1, with all the configurations investigated in this experiment and the average ratings in noticeable turbulence plotted against it. As was discussed in Section IV, if $|\phi/\beta|_d$ is maintained constant as τ_R is changed for essentially constant Dutch roll frequency, the magnitude of the aircraft responses to a lateral gust is essentially dependent only on $|\phi/\beta|_d$ and not on τ_R. This characteristic can be seen directly from the time responses given in Appendix II, and it can also be shown by computing the amplitude disturbance in roll and yaw at the Dutch roll frequency (Reference 12). Figure 7-2 shows these amplitudes for Configurations 1-0 through 7-0, from which the nearly constant roll response at a given $|\phi/\beta|_d$ and ω_d can be seen. Although the magnitude of the response is therefore nearly the same at a given $|\phi/\beta|_d$ for the values of τ_R investigated in this experiment, pilot rating does degrade as τ_R increases due to increasing difficulty in counteracting the disturbances precisely; in addition, since the magnitude of the responses increases as $|\phi/\beta|_d$ increases, the requirements for more precise control (more roll damping, τ_R decreasing) increase. The criteria shown in Figure 7-1 are an attempt to quantify these requirements. As can be seen from the figure, the results of this experiment substantiate the trends shown by the criteria but indicate that they may be somewhat too lenient.

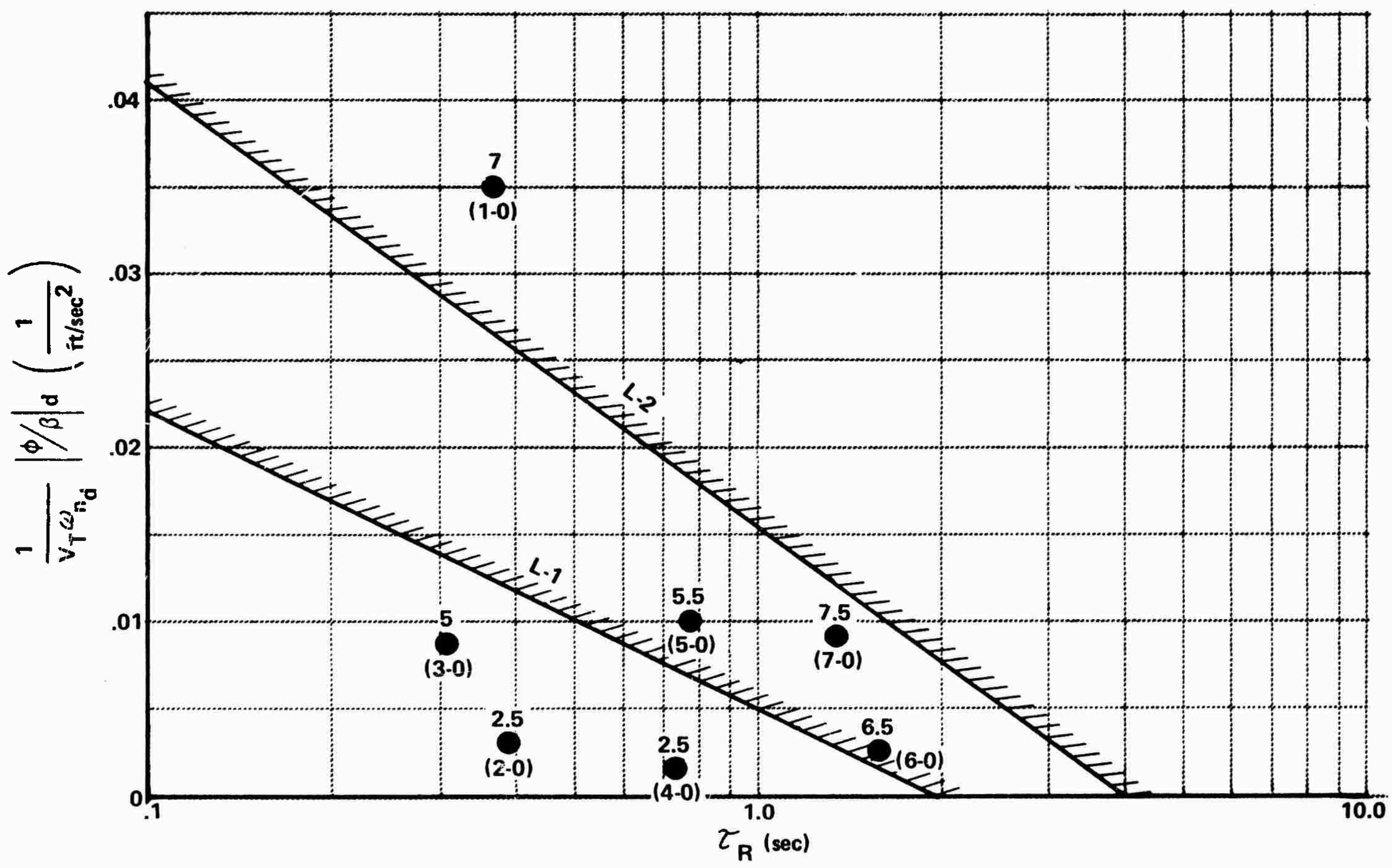


Figure 7-1 COMPARISON OF EVALUATION CONFIGURATIONS WITH ROLL MODE TIME CONSTANT FOR EXTERNAL DISTURBANCES REQUIREMENT OF RECOMMENDED REVISIONS TO MIL-F-8785B (REF. 11), NOTICEABLE TURBULENCE

7.2 ROLL CONTROL EFFECTIVENESS

The roll control effectiveness requirements are given in terms of time to bank to a given angle, and are summarized below, again for Class II, Flight Phase Category C:

- MIL-F-83300 (Reference 1)

  Level 1: time to bank to $30^{\circ} \leq 1.8$ seconds

  Level 2: time to bank to $30^{\circ} \leq 2.5$ seconds

- MIL-F-8785B and Recommended Revisions (References 3 and 11)

  Land-based: same as MIL-F-83300

  Carrier-based:

  Level 1: time to bank to $25^{\circ} \leq 1.0$ seconds

  Level 2: time to bank to $25^{\circ} \leq 1.5$ seconds

To compare the control usage and limiting data gathered in this experiment with these requirements, two alternatives are available. First, the control effectiveness required to meet these requirements can be computed for each configuration and then compared against the directly measured control usage. Secondly, the times to bank to the appropriate angle may be calculated for each control usage measured and compared directly to the requirements. In the interests of consistency with Section V and the data summarized in Appendix I, the first comparisons to be made will be between the actual control powers required and those used. Table VII-1 below lists the control powers necessary to meet the time-to-bank criteria for the seven configurations with the "optimum" values of $N'_{\delta_{AS}} / L'_{\delta_{AS}}$ investigated in this experiment. Note that an ideal step input was used to generate the data in Table VII-1. The roll effectiveness requirements in MIL-F-83300 and MIL-F-9785B are somewhat vague on the type of input that should be used to demonstrate compliance. In the backup document for MIL-F-83300 a suggested rapid roll input consists of a 0.1 sec time delay and a 0.3 sec ramp. While such an input could have been used to generate the data in Table VII-1 the perfect step was felt to be the best choice for this discussion since the data generated is then the most conservative (i.e. smallest control power required) and seems to satisfy the intent of both specifications.

TABLE VII-1

MINIMUM ROLL CONTROL POWER REQUIRED TO MEET SPECIFICATION REQUIREMENTS, RAD/SEC^2

	$t_{\phi=30°}$ = 1.8 (L1)	$t_{\phi=30°}$ = 2.5 (L2)	$t_{\phi=25°}$ = 1.0 (L1)	$t_{\phi=25°}$ = 1.5 (L2)
1-0	.95	.61	1.71	.97
2-0	.88	.59	1.65	.93
3-0	.76	.50	1.65	.84
4-0	.58	.36	1.06	.62
5-0	.46	.27	1.01	.55
6-0	.39	.22	.97	.46
7-0	.35	.20	.86	.39

Figure 7-3 shows the minimum Level 1 control powers resulting from these requirements as tabulated above plotted against the maximum roll control power actually used on all of the evaluations (see Section V, Figures 5-1 and 5-3). The data for configurations 1, 2, and 3, indicate lower control powers required for satisfactory flying qualities (PR 3.5) than the 83300 and 8785B requirements, while the data for configurations 4-7 approximately substantiate them.

As was described in Section V, the effects on pilot rating of reducing the available roll control power were investigated in this experiment by electrically limiting the roll command signal from the evaluation pilot's lateral control stick. The resulting approximate PR = 3.5 and PR = 6.5 minimum control powers were shown on Figures 5-9 through 5-11; these control powers are repeated on Figure 7-4 and plotted against the computed values to reach $\phi = 30^{\circ}$ in 1.8 seconds and 2.5 seconds, which are the 83300 and 8785B requirements for land-based aircraft. The minimum control powers for PR = 3.5 and PR = 6.5 determined in this experiment are, in general, significantly lower than those required in the specifications, but the discrepancy decreases as roll mode time constant increases (compare Configurations 2 to 4 and 3 to 5). The implications of these control powers on times to reach a given bank angle will be discussed shortly.

Before discussing control power in terms of time to bank, however, it is worth noting the implications on control power required of a "requirement" to be able to perform a "conventional" wing-down (zero crab angle) landing in a crosswind. Shown on Figure 7-4 are the control powers required for zero-crab runway tracking in a 10 kt crosswind for each of the configurations (from Figure 5-6, development of approximation given in Appendix V). For the $|\phi/\beta|_d \doteq 0.4$ cases (Configurations 2 and 4), the crosswind requirement is less than the minimum control powers shown by the results of this experiment, but for $|\phi/\beta|_d \doteq 1.4$ (Configurations 3 and 5) the 10 kt crosswind requirement is higher and, in fact, is approximately equal to the requirements of

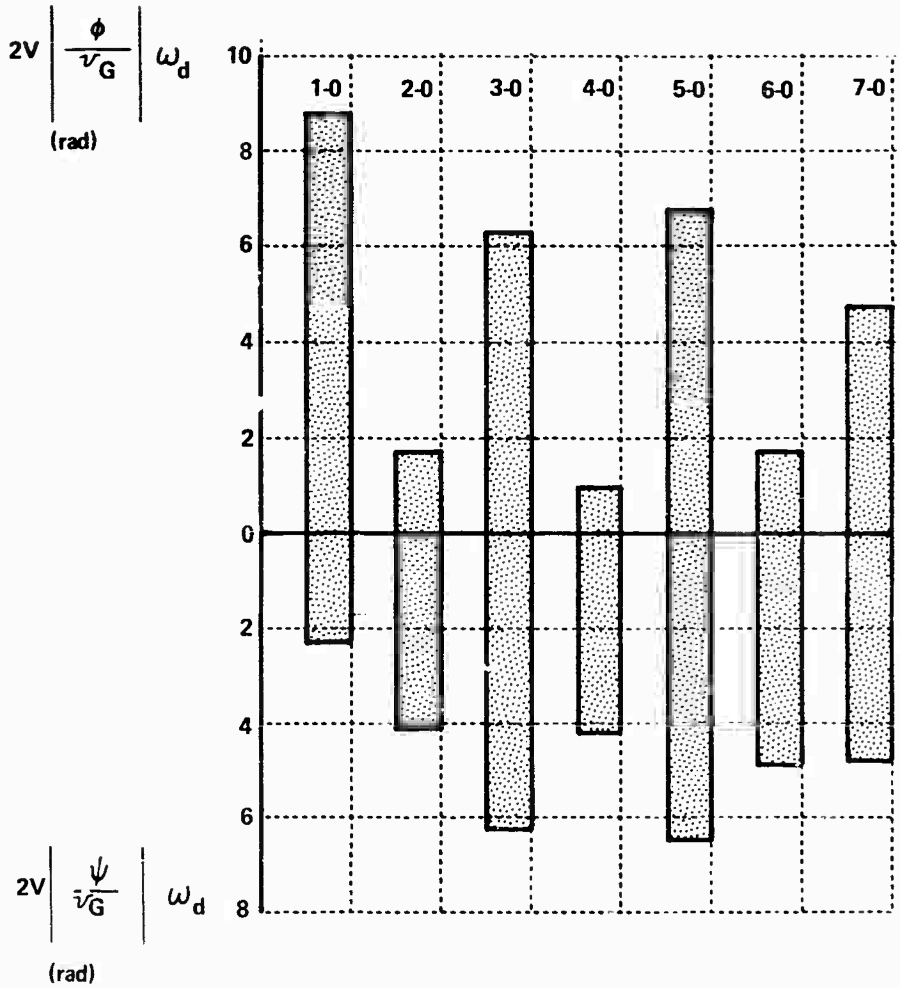


Figure 7-2 RELATIVE ROLL AND YAW ATTITUDE RESPONSE TO LATERAL GUSTS FOR THE BASE CONFIGURATIONS

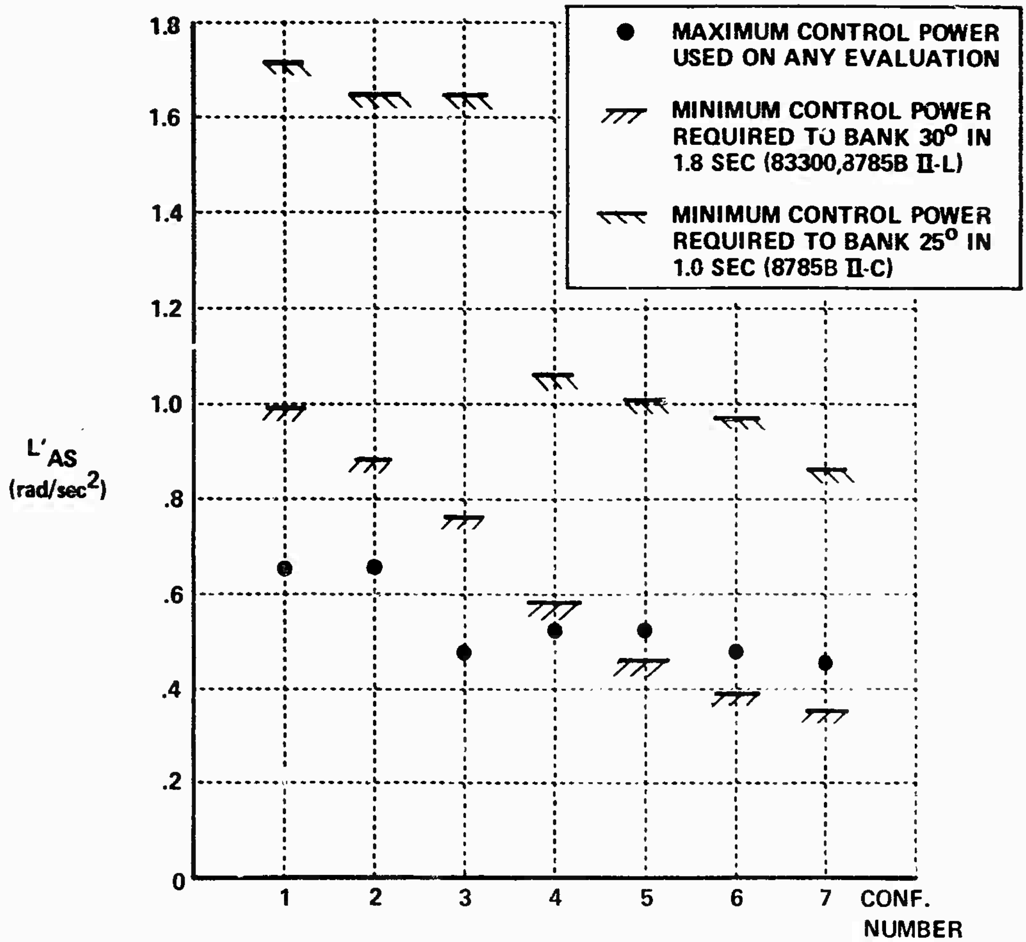


Figure 7-3 MINIMUM LEVEL 1 ROLL CONTROL POWER REQUIREMENTS OF MIL-F-8785B, MIL-F-83300 AGAINST MAXIMUM CONTROL POWER USED

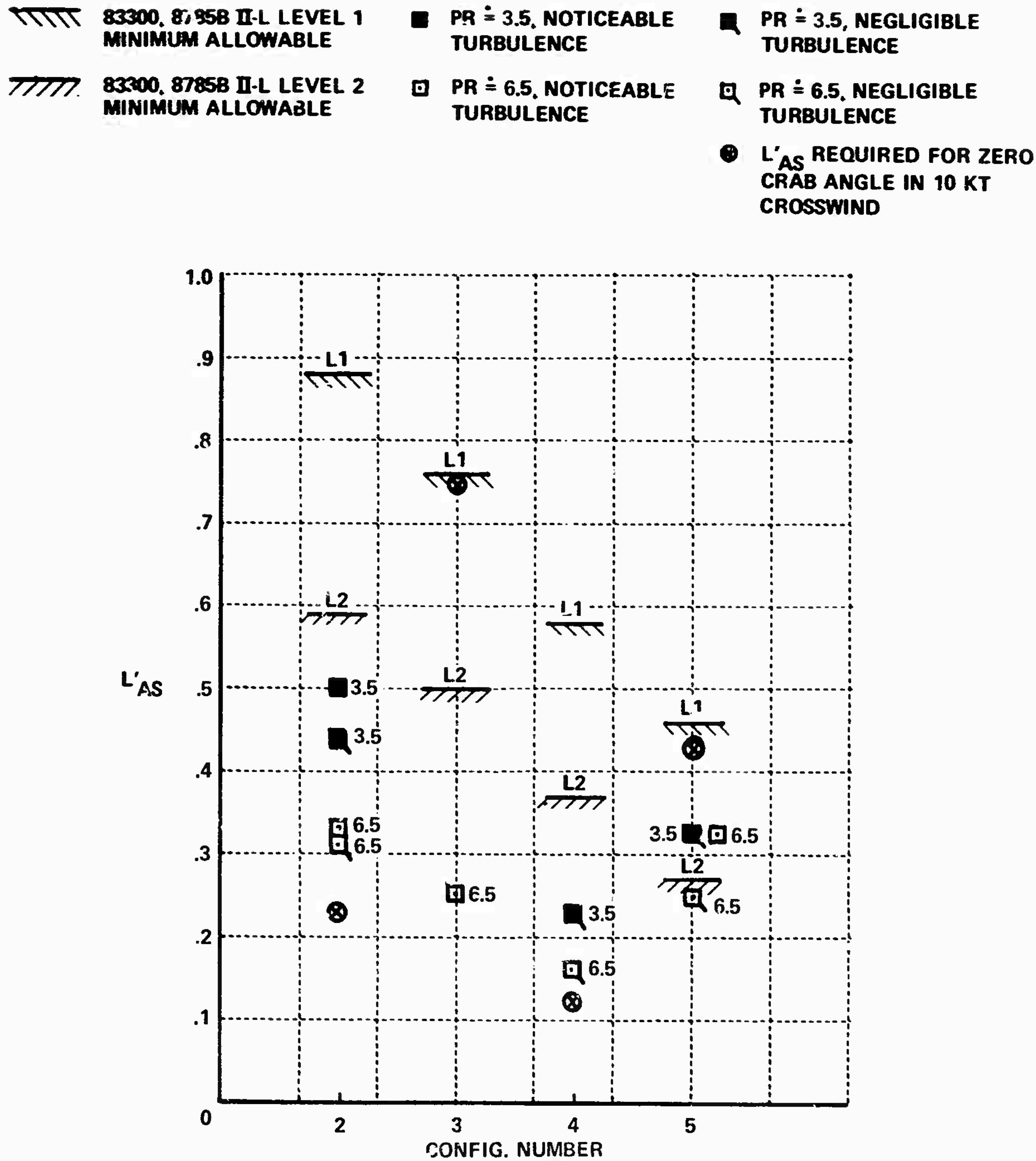


Figure 7-4 MIL-F-83300 MINIMUM LEVEL 1 AND LEVEL 2 ROLL CONTROL POWER REQUIREMENTS AGAINST PR ≐ 3.5 and PR ≐ 6.5 CONTROL POWERS OF EXPERIMENT

83300 and 8785B*. The results of this experiment do not specifically include this additional requirement on roll control power.

The experimentally determined minimum roll control powers shown on Figure 7-4 can be converted to a requirement to achieve a lower bank angle in the same time as given in 83300 and 8785B, or different times to reach the same bank angles. Both of these calculations are presented in Table VII-2 below using a step input. As noted in MIL-F-83300, requirements stated in terms of the time required to achieve a given bank angle (t_ϕ) are less sensitive to input characteristics than are the ϕ_t requirements.

TABLE VII-2

EXPERIMENTALLY DETERMINED MINIMUM CONTROL POWERS

	$t_{\phi=30^\circ}$ (sec) (PR=3.5)	$t_{\phi=30^\circ}$ (sec) (PR=6.5)	$\phi_{t=1.8}$ (deg) (PR=3.5)	$\phi_{t=2.5}$ (deg) (PR=6.5)
2 (Notic.)	2.9	4.3	17	16
2 (Neg.)	3.3	4.5	15	16
3 (Notic.)	--	5.5	--	15
4 (Neg.)	3.6	4.7	12	13
5 (Neg.)	2.3	2.6	21	28
5 (Notic.)	--	2.3	--	36

As can be seen from the table, the results of this experiment, disregarding Configuration 5 due to the small amount of data and weighting the other results in noticeable turbulence more heavily, suggest either: (1) that the minimum times to reach $\phi = 30^\circ$ be increased to approximately 3.1 seconds for Level 1 and 4.8 seconds for Level 2, or (2) that the minimum bank angle achievable in 1.8 seconds (Level 1) or 2.5 seconds (Level 2) should be approximately 17°. It is worth noting that this latter statement of the criteria agrees well with the results obtained in Reference 7, as is discussed in Reference 11. Again, it must be emphasized that these results do not adequately include the requirement on zero-crab tracking in crosswinds.

* It is worth noting that 83300 and 8785B imply an additional requirement to perform essentially zero-crab landings in 30 kt crosswinds (8785B) or approximately 27 kt crosswinds for an approach velocity of 65 kts (83300). This crosswind value is three times the required values shown in Figures 5-6 and 7-3: in the $|\phi/\beta|_d \doteq 1.4$ cases, it is obvious that the time-to-bank-30° requirements will be insufficient to guarantee this capability, and, in fact, the crosswind capability determines the roll control power required. Control power requirements as determined by this experiment or that of Reference 7 do not apply to such an additional specification.

7.3 ROLL RATE OSCILLATIONS

Figures 7-5 through 7-7 present the computed roll rate oscillation characteristics for all of the evaluation configurations plotted against the appropriate criteria from MIL-F-83300, MIL-F-8785B, and the recommended revision to 8785B. There are two primary reasons for including these figures: (1) to provide additional data for the requirements, particularly with regard to the proverse and adverse configurations investigated in this experiment, and (2) to verify if possible that the "optimum" configurations met the Level 1 requirements to avoid a "combination of bads" in the investigation of roll mode time constant and control power limiting. With regard to the first reason, it is apparent that three of the five adverse configurations, in spite of Level 2 (PR 3.5) ratings, fall within the Level 1 boundaries (Configurations 2-A, 4-A, 5-A). It appears that the specifications are not substantiated in the "adverse" direction for the configurations investigated in this experiment. The values of the ϕ/δ_{AS} numerator zeros (in body axes) investigated are shown in Appendix I for further correlation work.

7.4 DUTCH ROLL UNDAMPED NATURAL FREQUENCY AND DAMPING RATIO

The Dutch roll frequency requirements are summarized below for Class II aircraft in Flight Phase Category C (terminal area operations):

- MIL-F-83300 (Reference 1)

  $\omega_d > 0.25$ rad/sec for Level 1

  $0.25 < \omega_d < 0.5$ rad/sec: $\zeta_d \geq 0$ for Level 1

  $\omega_d > 0.5$ rad/sec: $\zeta_d \geq 0.08$ for Level 1

- MIL-F-8785B (Reference 3)

  Carrier-based: $\omega_d \geq 1.0$ rad/sec, $\zeta_d \geq 0.08$ or $\zeta_d\omega_d \geq 0.15$ for Level 1

  Land-based: $\omega_d \geq 0.4$ rad/sec, $\zeta_d \geq 0.08$ or $\zeta_d\omega_d \geq 0.15$ for Level 1

- MIL-F-8785B Recommended Revision (Reference 11)

  Carrier-based: $\omega_d \geq 1.0$ rad/sec, $\zeta_d \geq 0.08$ or $\zeta_d\omega_d \geq 0.15$ for Level 1

  Land-based: $\omega_d \geq 0.5$ rad/sec, $\zeta_d \geq 0.08$ or $\zeta_d\omega_d \geq 0.10$ for Level 1

To compare the results of this experiment with these requirements, the average ratings of Configurations 1-0 and 3-0 in negligible turbulence may be used; they are:

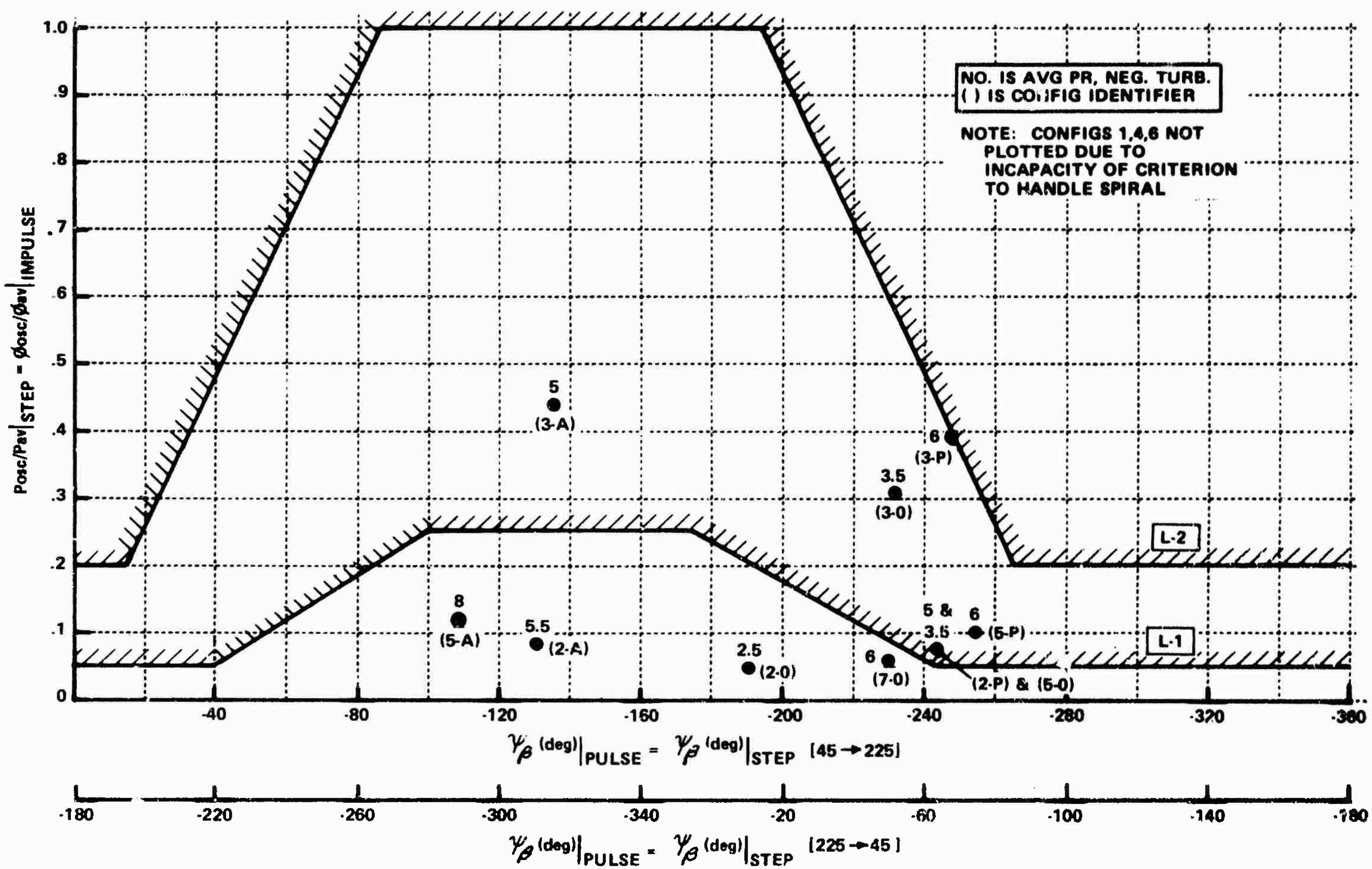


Figure 7-5 COMPARISON OF EVALUATION CONFIGURATIONS WITH ϕ_{osc}/ϕ_{av} REQUIREMENT OF MIL-F-83300 (REFERENCE 1), NEG. TURBULENCE

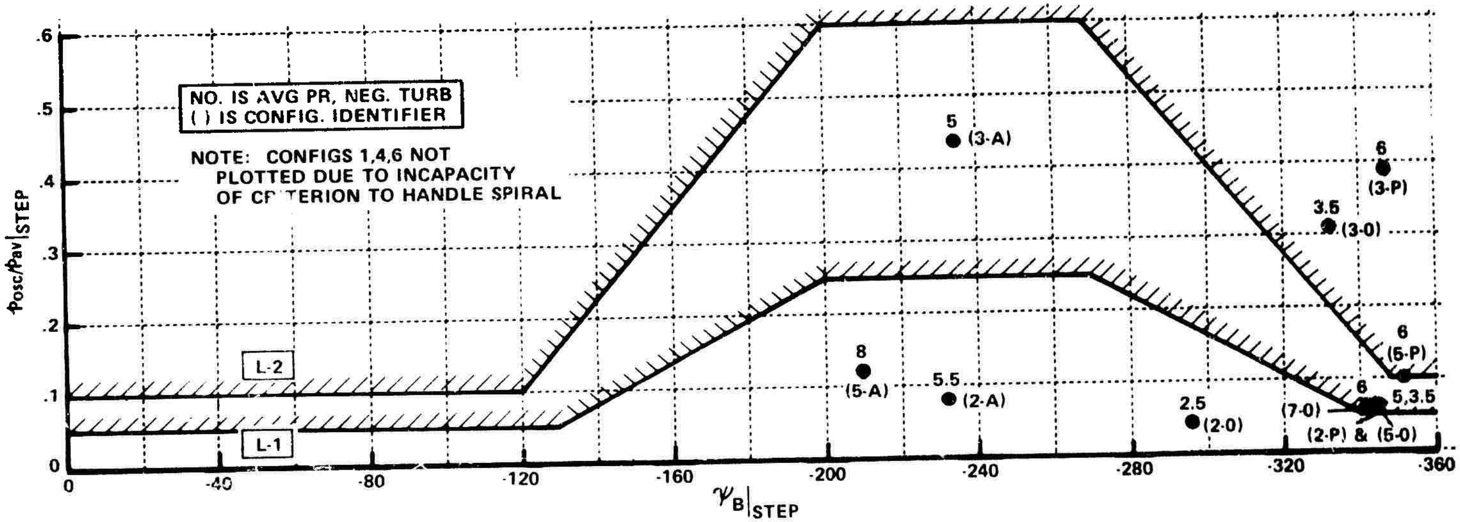


Figure 7-6 COMPARISON OF EVALUATION CONFIGURATIONS WITH ϕ_{osc}/ϕ_{av} REQUIREMENT OF MIL-F-8785B (REF. 3), NEG. TURBULENCE

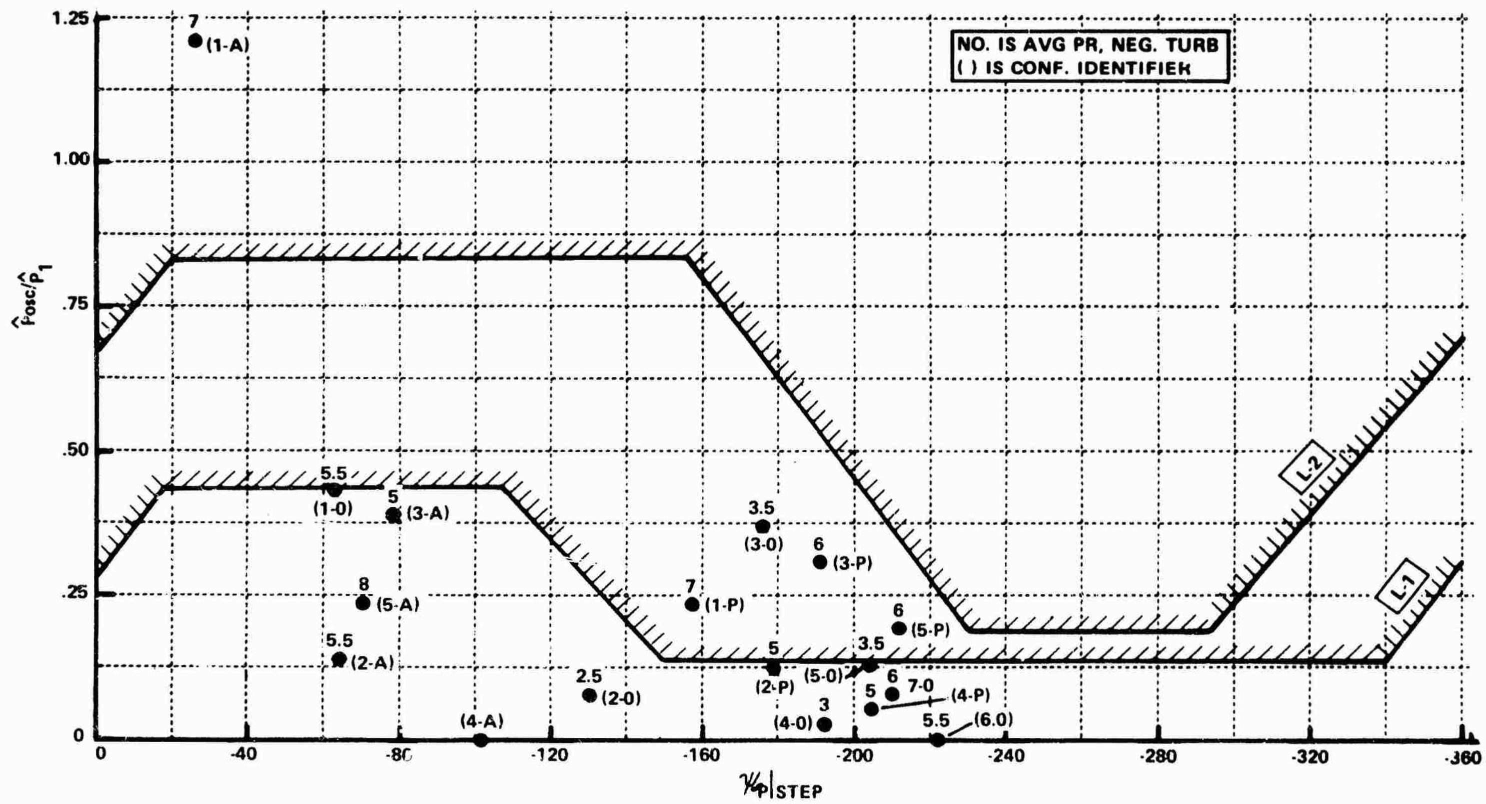


Figure 7-7 COMPARISON OF EVALUATION CONFIGURATIONS WITH PROPOSED REVISION OF MIL-F-8785B $\hat{P}_{os}/\hat{P}_{av}$ REQUIREMENT (REF.11), NEG. TURBULENCE

$1\text{-}0$: $\omega_d \doteq 0.4$ rad/sec, $\zeta_d \doteq 0.20$: PR $\doteq 5.5$ (Level 2)

$3\text{-}0$: $\omega_d \doteq 1.4$ rad/sec, $\zeta_d \doteq 0.20$: PR $\doteq 3.5$ (Level 1)

The results of this experiment demonstrate Level 2 characteristics (PR 3.5) for a natural frequency of 0.4 rad/sec^2, which is well above the minimum 0.25 rad/sec^2 of the 83300 requirement. Comparison of the data with the land-based requirement of MIL-F-8785B is difficult, as $\zeta_d \omega_d$ of 1-0 does not meet the total damping requirement $\zeta_d \omega_d \geq .15$ and the degradation in pilot rating may be caused by this fact. In general, this experiment tends to indicate that the carrier-based (II-C) criteria of both 8785B and the recommended revision are the most appropriate requirements for STOL terminal area operations. As was discussed in Section IV of this report, it appears that at least $\omega_d \gtrsim 1.0$ rad/sec is required to achieve satisfactory flying qualities, given the scatter of the data.

7.5 SIDESLIP EXCURSIONS

Figures 7-8 through 7-10 present the computed sideslip excursion characteristics of the evaluation configurations plotted against the appropriate specification criteria. Again, all the data are plotted both to add substantiating data for the requirements and to verify if possible that the optimum cases meet the Level 1 requirements. Referring to the pilot comments (Section IV, Appendix II), it is clear that the only configurations which specifically presented problems in controlling sideslips were the variations in Configuration 1 (i.e., 1-A, 1-O, 1-P), and this fact should be reflected in the placement of these configurations on the requirement grids. It can be seen that the 83300 and 8785B requirements do not separate out Configurations 1-A, 1-P and 1-O as they probably should. The data seem to substantiate best the proposed revision to 8785B (Figure 7-10). In general, the sideslip excursion characteristics of the remaining "optimum" configurations can be seen to be within the Level 1 boundary of all of the specifications.

7.6 SUMMARY REMARKS

This section has presented comparisons of the results obtained in this experiment with the military specifications for conventional and STOL piloted airplanes. At this point, it is worth summarizing and qualifying if necessary the most pertinent conclusions.

- The results of this experiment indicate that shorter roll mode time constants are necessary for satisfactory (PR$\leq$3.5) and adequate (PR$\leq$6.5) flying qualities than are given by the requirements of MIL-F-83300 and MIL-F-8785B (Class II-L) for the approach conditions investigated (V_o = 65 k , γ = -6.5 deg). The values of roll mode time constant required as determined by this experiment may be slightly influenced by generally proverse yaw-due-to-aileron, but any such influence appears to be minor and does not compromise the results. The values for satisfactory and adequate roll mode time constant found in this experiment tend to corroborate the Class II-C requirements may be more appropriate for STOL aircraft.

- The trend of the proposed requirement on roll mode time constant for external disturbances in the recommended revision to 8785B (Reference 11) appears substantiated by the results of this experiment, although the values of roll mode time constant appear to be too lenient to apply to STOL aircraft as presently formulated.

- The roll control power requirements of MIL-F-83300 and MIL-F-8785B were not substantiated by the results of this experiment. This experiment (assuming a perfect step input) suggests that the bank angle achievable in 1.8 seconds could be ≐ 20 degrees for Level 1 instead of ≐ 30 degrees or the time required to achieve a bank angle of 30 degrees increased to 3.1 secs. This conclusion, however, must be qualified for two reasons:

  (1) For the high $|\phi/\beta|_d$ cases, particularly with high roll damping and correspondingly high values of L'_β, the limiting factor on roll control power is likely to be a requirement to achieve zero-crab tracking in a sizeable crosswind. This capability was not adequately investigated in this experiment nor specifically demonstrated in Reference 7.

  (2) The values used for the amount of roll control power available in the evaluations with electrical roll control limiting are based on symmetric limiting around a zero mean. For cases with large asymmetries, either through mechanization difficulties or through non-zero sideslip trim by the pilot, one could choose to correlate pilot rating with the smaller amount available. Such a correlation would provide even smaller control power requirements than those presented in this section and Section V; however, the average values used in this report are felt to be more accurate, and certainly provide more conservative estimates.

- The results of this experiment indicate a higher value of minimum Dutch roll frequency for satisfactory (PR ≤ 3.5) flying qualities than that given by the MIL-F-83300 minimum requirement.

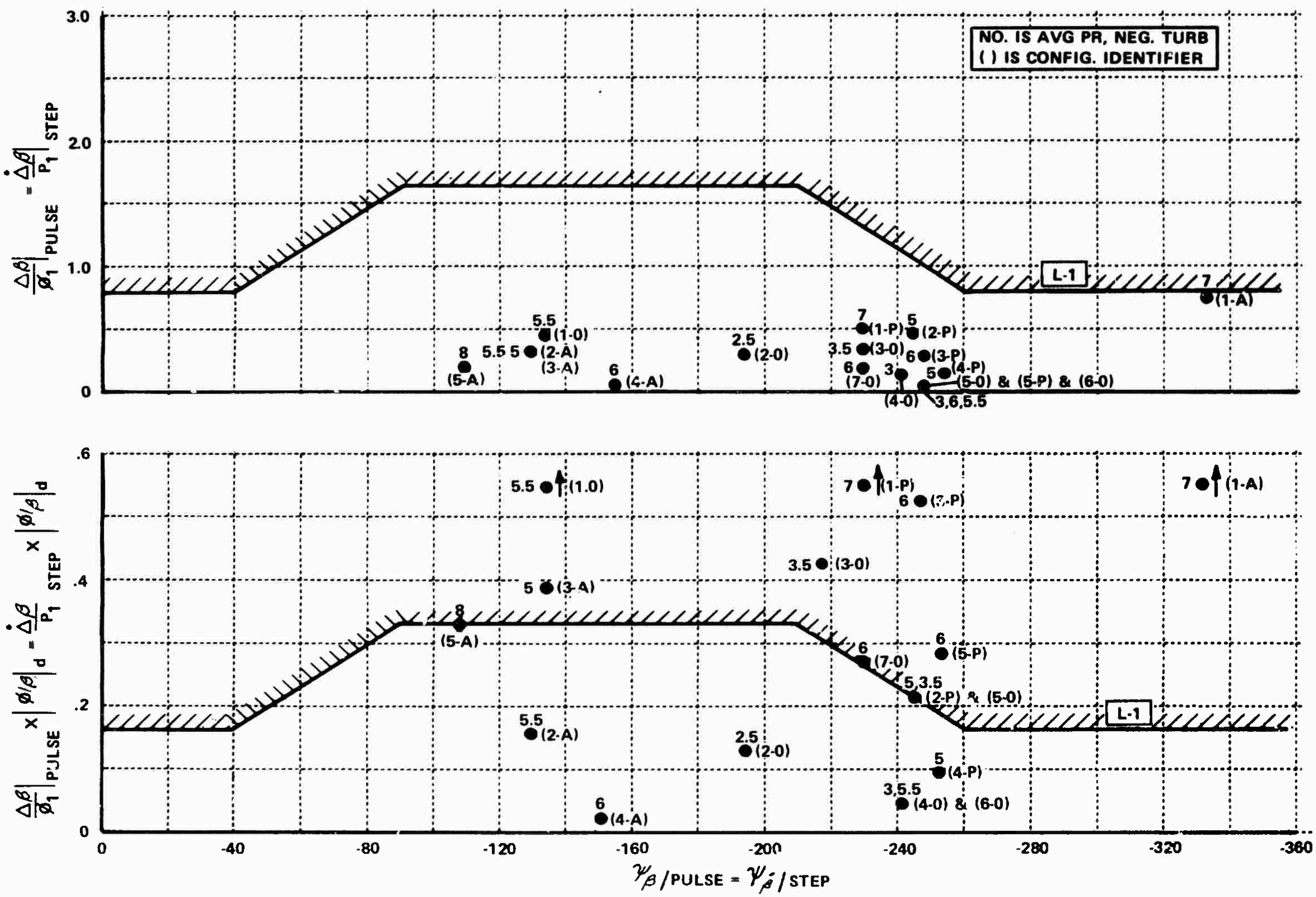


Figure 7-8 COMPARISON OF EVALUATION CONFIGURATIONS WITH SIDESLIP EXCURSION REQUIREMENTS OF MIL-F-83300 (REFERENCE 1), NEG. TURBULENCE

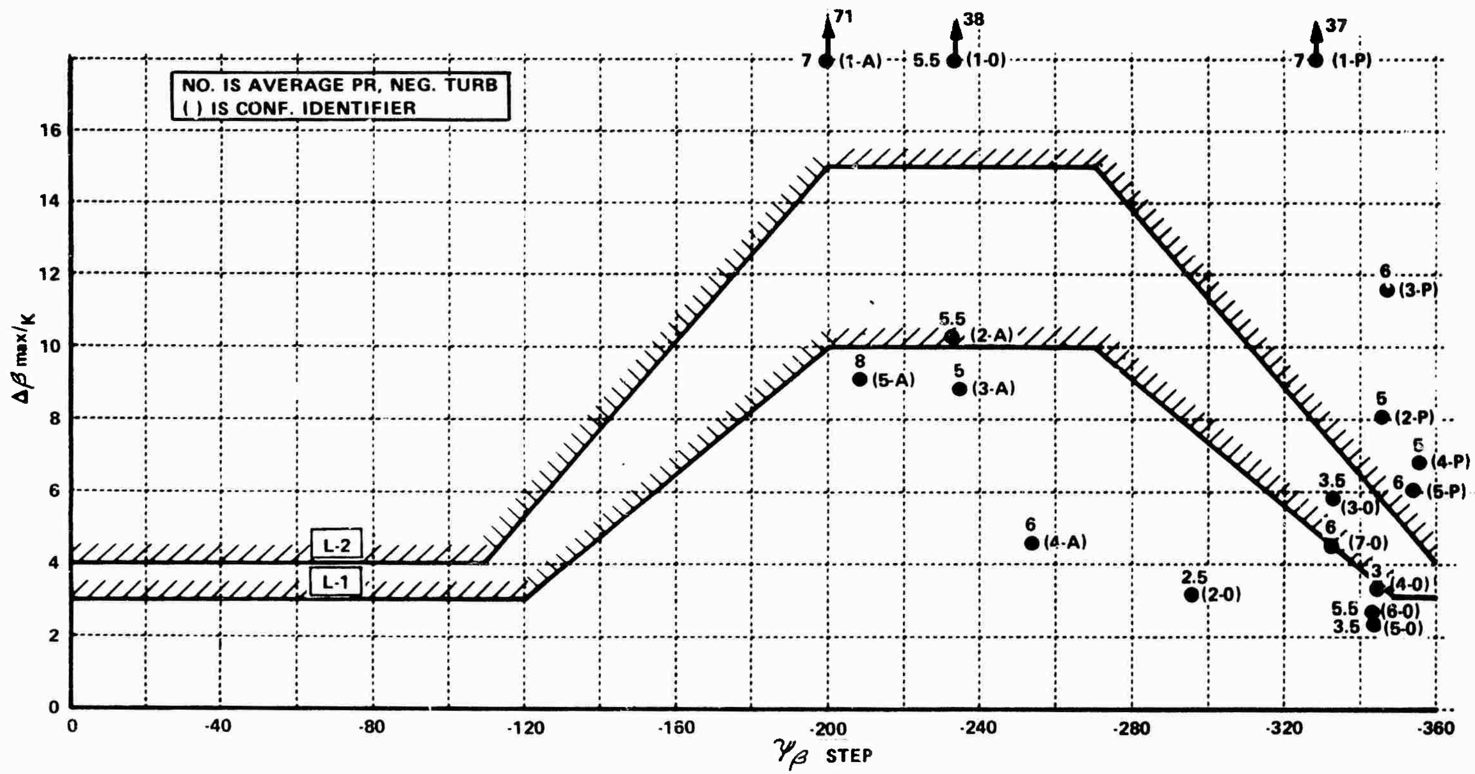


Figure 7-9 COMPARISON OF EVALUATION CONFIGURATIONS WITH SIDESLIP REQUIREMENT OF MIL-F-8785B (REF. 3), NEG. TURBULENCE

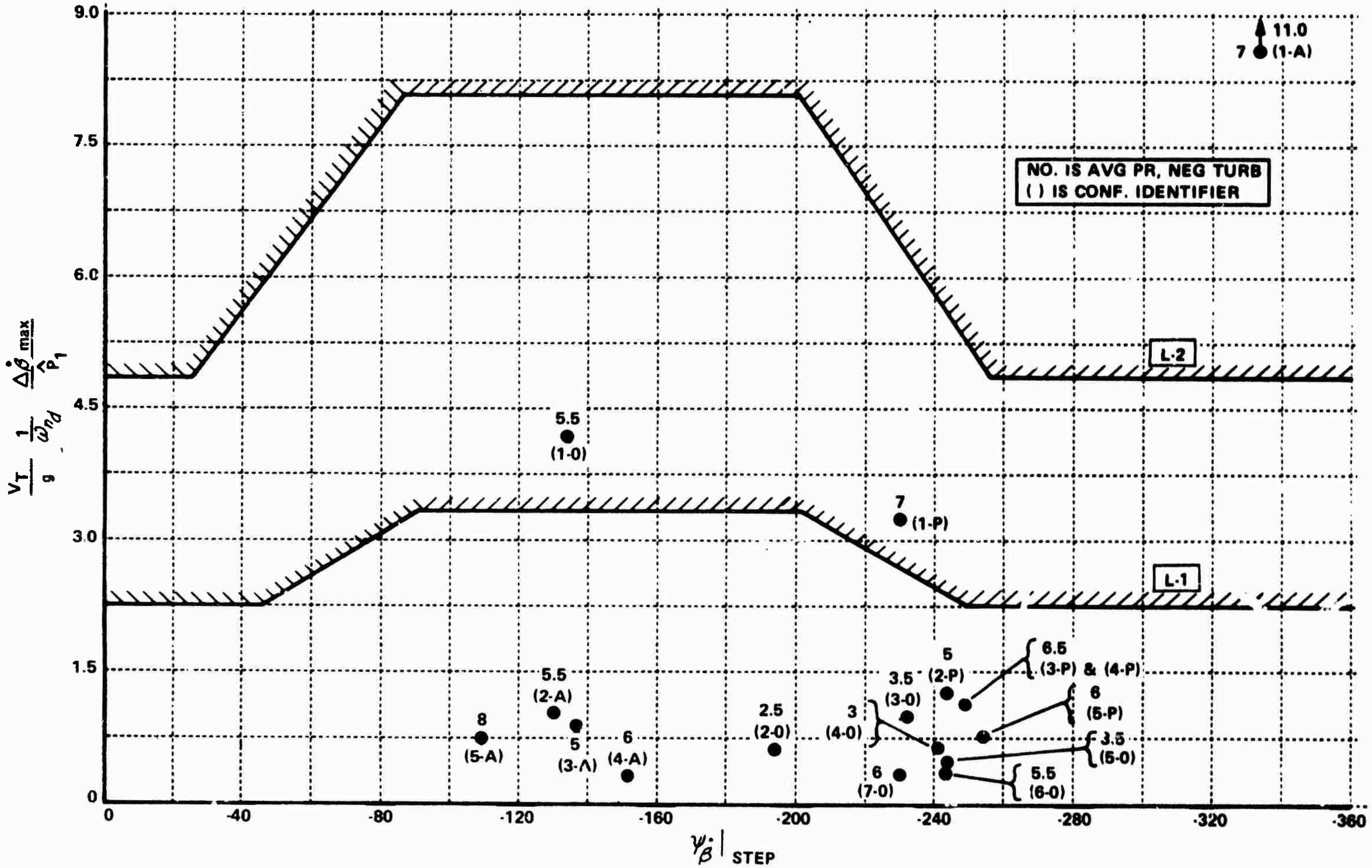


Figure 7-10 COMPARISON OF EVALUATION CONFIGURATION WITH PROPOSED REVISION OF MIL-F-8785B SIDESLIP REQUIREMENT (REF.11), NEG. TURBULENCE

Section VIII

CONCLUSIONS

The experiment described in this report was performed using the X-22A variable stability V/STOL aircraft, which is capable of reproducing a wide range of aircraft dynamic characteristics. The results are therefore largely independent of the actual aircraft employed, and are restricted only by the task and flight conditions considered and the range of dynamics and aircraft parameters realized in the experiment.

Based on the results of this experiment, the effects of the aircraft and performance variables investigated on the lateral-directional flying qualities for STOL approach may be summarized as follows:

- Modal Characteristics

1. For the approach velocity considered in this experiment ($V_0 \doteq 65$ kts), roll mode time constants greater than $\tau_R \doteq 0.9$ sec result in unsatisfactory flying qualities (PR > 3.5), and greater than $\tau_R \doteq 1.5$ sec result in inadequate (unacceptable) flying qualities (PR > 6.5). These characteristics may be partially attributable to: (1) the low approach velocity and correspondingly increased bank angle control precision required to aid the heading tracking, and (2) the task considered, which included a lateral sidestep and line up maneuver at the end of the glide slope tracking.

2. A Dutch roll undamped natural frequency of $\omega_d \doteq 0.4$ rad/sec with $\zeta_d \doteq 0.2$ results in unsatisfactory flying qualities (PR > 3.5) for STOL landing approach. The degradation in pilot rating at this frequency compared to $\omega_d \doteq 1.4$ rad/sec is primarily attributable to poor control of sideslip.

3. For the characteristics investigated, when ω_d is approximately constant ($N'_\beta \doteq$ constant for the mechanization used) the magnitude of the response of the aircraft to lateral turbulence is roughly a function of $|\phi/\beta|_d$ only.

4. In negligible turbulence, no significant effect of $|\phi/\beta|_d$ on flying qualities is evident for the two values investigated.

5. At the lower $|\phi/\beta|_d$ investigated ($|\phi/\beta|_d \doteq 0.4$), the effect of turbulence on pilot rating was not significant, although some degradation at $\tau_R \doteq 1.45$ was evident.

6. Noticeable turbulence degrades pilot rating (Δ PR $\doteq$ 2) for configurations with $|\phi/\beta|_d \doteq 1.4$. This value of $|\phi/\beta|_d$ precludes a satisfactory configuration in turbulence for even the shortest roll mode time constant investigated.

7. The results indicate that the maximum allowable $|\phi/\beta|_d$ to obtain satisfactory flying qualities (PR $\leq$ 3.5) in turbulence is approximately $|\phi/\beta|_d \doteq 0.8$.

8. Pilot rating degraded less with proverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ for $|\phi/\beta|_d \doteq 0.4$ than for $|\phi/\beta|_d \doteq 1.4$. The degradation due to adverse $N'_{\delta_{AS}}/L'_{\delta_{AS}}$ was approximately the same for both values of $|\phi/\beta|_d$.

- Control Power Used

1. The effects of roll mode time constant on maximum lateral control power used (L'_{AS}) were most apparent at the lower $|\phi/\beta|_d$ investigated ($|\phi/\beta|_d \doteq 0.4$) where L'_{AS} used decreased as τ_R increased in both negligible and noticeable turbulence.

2. No significant effect of $|\phi/\beta|_d$ on maximum lateral control power used was evident.

3. No significant effect of roll mode time constant or $|\phi/\beta|_d$ on maximum directional control power used (N'_{RP}) was observed.

4. By limiting electrically the maximum lateral control power used, it was found that a satisfactory level of control power (PR = 3.5) provided ~ 17 degrees of bank angle in 1.8 seconds and an adequate level of control power (PR = 6.5) provided ~ 17 degrees of bank angle in 2.5 seconds. These values are based on perfect step inputs and would be somewhat relaxed for less abrupt inputs. Roll control effectiveness requirements are dependent on the input used and any specifications should clearly define the applicable input shape. For aircraft with high roll due to sideslip (L'_β), additional roll control power may be required to perform a zero-crab runway alignment in a crosswind.

- **Statistical Performance Measures**

1. ILS tracking errors (rms) were independent of both configuration dynamics and pilot rating, and were essentially constant for all evaluations.

2. The standard deviation of bank angle tracking showed a qualitative trend toward increasing deviations with increasing roll mode time constant in noticeable turbulence. No trends in negligible turbulence with either τ_R or $|\phi/\beta|_d$ were evident.

3. For a given value of ω_d, no significant trends of lateral acceleration standard deviation with either τ_R or $|\phi/\beta|_d$ were evident. An increase in these statistics was apparent for $\omega_d \doteq 0.4$ rad/sec as compared to $\omega_d \doteq 1.4$ rad/sec, which is attributable to the decreased precision of sideslip control for this configuration.

4. The standard deviation of roll acceleration tends to increase as roll damping decreases (roll mode time constant increases).

- **Comparison with Military Specifications**

1. For the flight conditions investigated, shorter roll mode time constants are required for satisfactory and adequate flying qualities than are given by the MIL-F-8785B (Class II-L) and MIL-F-83300 Level 1 and Level 2 requirements. The MIL-F-8785B requirements for carrier-based Class II-C aircraft are more appropriate for STOL aircraft.

2. A higher Dutch roll undamped natural frequency is necessary for satisfactory flying qualities than is given by the applicable MIL-F-83300 requirement.

3. The roll control power requirements of MIL-F-8785B and MIL-F-83300 are higher than the values determined by electrically limiting the roll control power in this experiment. For cases with high L'_β, however, the sizing factor on roll control power will be the allowable maximum crosswind.

4. MIL-F-8785B and MIL-F-83300 requirements on roll control effectiveness should define the applicable type of roll control input for compliance calculations.

Section IX

RECOMMENDATIONS

On the basis of the results obtained in this experiment and of the areas of difficulty that were uncovered, the following recommendations are pertinent to future investigations of STOL lateral-directional flying qualities and control power requirements in the landing approach:

1. Further work is necessary to investigate in more detail the apparent requirement for shorter roll mode time constants as approach speed is reduced. A study of this interplay for approach speeds from approximately 40 to 100 kt would be useful.

2. A limited quantity of data were gathered in turbulence during this experiment, and therefore conclusions regarding its effect were only qualitative. Further studies of the effects of turbulence related to roll mode time constant, dihedral effect, and roll-due-to-sideslip are desirable.

3. An interesting ancillary observation that can be made from the results of this experiment is that a somewhat lower glide slope angle (-7.5 deg) was necessary to perform the task with degraded lateral-directional flying qualities than was used in an earlier study on longitudinal flying qualities (Reference 8). There is clearly an interaction between the maximum practical STOL glide slope and the combination of all the aircraft flying qualities in conjunction with performance limitations such as buffet boundaries. Further investigations of these interactions to define maximum practical glide slopes for STOL landing approaches are therefore desirable.

Appendix I

COMPLETE DATA SUMMARY

The appendices to this report present a summary of all the data relevant to the technical discussion contained in Volume I Appendices II-VIII present in detail the following information:

Appendix II:	A complete documentation of the pilot ratings and comments, and representative time histories for all configurations evaluated.
Appendix III:	A documentation of the digital identification procedure used to obtain the stability and control parameters of the simulated airplanes.
Appendix IV:	A development and documentation of the appropriate lateral-directional transfer function characteristics.
Appendix V:	A development and documentation of the theoretical and practical procedures followed in attempting to measure the wind/turbulence environment during the evaluations.
Appendix VI:	A documentation of all of the statistical analyses performed on the data and a complete summary of the resulting statistical indices.
Appendix VII:	A discussion of the X-22A aircraft, its variable stability system, and the mechanization of the evaluation configurations.
Appendix VIII:	A description of the digital data acquisition system used on X-22A experiments.

This appendix summarizes the most pertinent data from the other appendices for ready reference.

Table I-1 is the master summary, by configuration, for all the evaluations conducted. The criterion used to distinguish evaluations performed in negligible turbulence from those flown in noticeable turbulence was a combination of the pilot comment and turbulence effect rating data and the estimated longitudinal gust intensity listed under σ_u (see Appendix V). In general, evaluations with $\sigma_u \leq 2.0$ ft/sec were considered to be performed in negligible turbulence while those with $\sigma_u > 2.0$ were classified as noticeable. For smooth air conditions, σ_u was approximately 1.4 ft/sec which represents the "noise" level of the u-LORAS. Where the pilot turbulence effect rating and comments conflicted with the σ_u estimate, the classification was weighted in favor of the pilot comments.

Table I-1

SUMMARY OF EVALUATIONS

CONFIG. NO.	FLT NO.	STAT DATA	PILOT	PILOT & TURB RATING VFR	PILOT & TURB RATING OVERALL	σ_u ft/sec	WIND/HEAD WIND kt	CROSS WIND kt	SIDESTEP	$L'\delta_{AS}$	$N'\delta_{RP}$	$L'\delta_{RP}$	$N'\delta_{AS}$	$\bar{U}$	$L'_{AS_{MAX}}$	$N'_{RP_{MAX}}$
1-0-00	F-67	–	A	6D	6D	–	6[2]/04	05L	L	0.40	0.49	0.0	0.04	–	–	–
	F-68	–	A	6C	6D	–	6[2]/06	0	L	0.44	0.49	0.0	0.04	–	–	
	F-70	✓	A	4A	4A	1.5	10/03	09L	L	0.50	0.33	0.10	0.05	122	0.46	0.10
	F-77	✓	A	8E	8D	1.8	20[2]/17	10R	L	0.40	0.49	0.0	0.04	111	0.65	0.18
	F-80	✓	A	8E	8.5E	–	10[2]/-04	09R	R	0.47	0.49	0.0	0.04	122	0.43	0.17
	F-82	–	B	6A	6A	–	8/01	08R	R	0.40	0.29	0.12	0.04	–	–	–
	F-88	✓	C	5B	7A	–	7/01	07R	L	0.47	0.38	0.06	0.04	115	0.53	0.12
	F-90	✓	C	5.5D	6C	1.7	13[2]/0	13R	R	0.50	0.21	0.17	0.05	116	0.46	0.09
1-A-00	F-61	✓	A	6B	7B	1.8	9/0	09L	L	0.59	0.49	0.0	0.0	118	0.59	0.?4
	F-64	✓	B	6C	6C	1.7	10[2]/09	05R	R	0.4?	0.38	0.06	0.0	108	0.40	0.10
1-P-00	F-60	✓	A	6A	7A	1.3	4/03	03L	L	0.40	0.47	0.0	0.11	115	0.50	0.12
	F-62	–	B	6A	7A	–	7/-04	05L	L	0.36	0.49	0.0	0.10	123	–	–
1-P[1]-00	F-66	✓	A	7A	7A	–	4/03	03R	R	0.35	0.49	0.0	0.16	102	0.42	0.12
2-0-00	F-62	–	B	2A	2C	–	9[2]/-04	08L	L	0.40	0.38	0.06	0.02	–	–	–
	F-69	–	A	3B	3B	–	3/0	03R	R	0.55	0.49	0.0	0.03	–	–	0.52
	F-70	–	A	2.5A	3A	–	15/02	15L	L	0.51	0.49	0.0	0.03	–	–	0.46
	F-72	✓	A	4B	3B	2.5	15[2]/15	02L	L	0.51	0.49	0.0	0.03	117	0.60	0.12
	F-73	✓	A	2C	2C	2.5	18[2]/17	05R	L	0.41	0.49	0.0	0.02	120	0.45	0.15
	F-78	✓	A	3B	3B	2.6	18[2]/16	09R	L	0.48	0.49	0.0	0.03	119	0.65	0.15
	F-82	–	B	3A	3A	–	8/-03	08R	L	0.41	0.33	0.09	0.02	–	–	–
	F-88	✓	C	2A	2A	1.9	7/02	07R	L	0.51	0.38	0.06	0.03	120	0.44	0.04
	F-90	✓	C	2.5A	2.5A	–	13/0	13R	R	0.56	0.49	0.0	0.03	112	0.60	0.11
2-0-95	F-73	✓	A	8C	8C	–	15[2]/15	0	L	0.56	0.49	0.0	0.03	118	0.23	0.20
-85	F-77	✓	A	5C	5C	2.0	15[2]/13	07R	L	0.56	0.49	0.0	0.03	114	0.46	0.17
-90	F-77	✓	A	7C	7C	–	15[2]/13	07R	L	0.41	0.49	0.0	0.02	112	0.34	0.20
-85	F-80	✓	A	2.5B	2B	2.0	12/-06	10R	R	0.51	0.49	0.0	0.03	114	0.46	0.12
-90	F-80	–	A	5C	6C	–	10[2]/-05	9R	R	0.56	0.49	0.0	0.03	–	0.34	-
-90	F-88	–	C	6A	6A	2.0	7/02	06R	L	0.56	0.49	0.0	0.03	115	0.34	–
2-A-00	F-64	✓	B	7C	7C	–	10[2]/10	0	R	0.47	0.49	0.0	-0.08	103	0.44[3]	0.20
	F-76	✓	A	4A	4B	1.8	10/-08	05R	L	0.47	0.49	0.0	-0.08	121	0.53	0.18
	F-91	✓	C	7A	7A	1.7	15/15	0	R	0.47	0.35	0.08	-0.08	100	0.50	0.28
2-P-00	F-61	–	A	3A	4B	1.8	9/0	04L	L	0.48	0.49	0.0	0.17	117	–	–
	F-63	✓	B	6B	6B	1.7	8/-08	0	L	0.34	0.38	0.06	0.12	113	0.33	0.07

✓ STATISTICAL DATA OBTAINED

(1) NOTE $N'\delta_{AS}$ DIFFERENT

(2) NOTICEABLE TURBULENCE

Table I-1 (CONT.)
SUMMARY OF EVALUATIONS

CONFIG. NO.	FLT. NO.	STAT. DATA	PILOT	PILOT & TURB RATING		σ_u ft/sec	WIND/HEAD WIND kt	CROSS WIND kt	SIDESTEP	$L'_{\delta_{AS}}$	$N'_{\delta_{RP}}$	$L'_{\delta_{RP}}$	$N'_{\delta_{AS}}$	$\bar{U}$	$L'_{AS_{MAX}}$	$N'_{RP_{MAX}}$
				VFR	OVERALL											
2-P[1]-00	F-86	✓	A	4A	4A	1.6	4/0	04R	R	0.43	0.49	0.0	0.19	107	0.37	0.14
3-0[1]-00	F-61	✓	A	3B	4B	1.8	9/0	09L	L	0.58	0.49	0.0	0.0	117	0.46	0.16
3-0[1]-00	F-64	✓	B	4C	4C	1.8	16/16	05R	R	0.42	0.49	0.0	0.0	107	0.45	0.11
3-0-00	F-68	–	A	3B	3C	–	6/02	06R	L	0.40	0.49	0.0	0.0	–	–	–
	F-71	✓	A	4D	4.5D	–	6[2]/-01	06L	L	0.47	0.35	+0.06	0.09	130	0.45	0.24
	F-73	✓	A	5D	5E	2.2	21[2]/21	04R	L	0.44	0.49	0.0	0.08	117	0.47	0.13
	F-75	✓	A	3A	3A	1.4	8/-01	08L	L	0.42	0.49	0.0	0.08	120	0.47	0.15
	F-86	✓	C	3A	4A	1.7	4/04	02R	L	0.43	0.49	0.0	0.08	116	0.46	0.06
	F-89	✓	C	4B	3.5B	1.9	20/17	10R	L	0.47	0.49	0.0	0.09	112	0.33	0.08
-90	F-78	✓	A	4B	4B	1.8	15[2]/13	05R	L	0.44	0.49	0.0	0.08	114	0.34	0.20
-85	F-78	–	A	4B	5C	2.3	15[2]/16	09R	L	0.47	0.49	0.0	0.09	117	0.46	–
-95	F-76	✓	A	7C	7C	2.1	15[2]/13	07R	L	0.52	0.49	0.0	0.10	116	0.23	0.23
-90	F-78	–	A	5C	–	–	15[2]/13	07R	L	0.44	0.49	0.0	0.08	–	0.34	–
3-A-00	F-76	–	A	4B	4B	–	10/-09	03L	L	0.54	0.49	0.0	-0.08	–	–	–
	F-80	✓	A	3B	3B	–	10/-05	09R	R	0.46	0.49	0.0	-0.07	119	0.66	0.19
3-A[1]-00	F-84	–	B	7A	7A	–	9/03	06L	L	0.51	0.29	0.12	-0.15	–	–	–
	F-91	✓	C	6A	7A	1.6	16/0	15R	R	0.51	0.29	0.12	-0.07	109	0.54	0.13
2-P-00	F-66	✓	A	5A	6B	1.8	4/01	04R	R	0.40	0.49	0.0	0.20	106	0.36	0.13
4-0-00	F-69	–	A	3C	2C	–	3[2]/03	0	R	0.47	0.49	0.0	0.04	–	0.42	–
	F-71	✓	A	2B	2B	1.4	10/05	08L	L	0.47	0.49	0.0	0.04	124	0.47	0.10
	F-72	✓	A	2A	2A	2.1	17/16	03L	L	0.40	0.49	0.0	0.04	119	0.46	0.14
	F-73	✓	A	3C	2.5C	3.4	20[2]/20	03R	L	0.40	0.49	0.0	0.04	117	0.51	0.16
	F-82	–	B	3A	3A	–	8/01	08R	L	0.40	0.29	0.12	0.04	–	–	–
	F-88	✓	C	4A	5B	1.7	7/02	07R	L	0.40	0.38	0.08	0.04	122	0.34	0.06
	F-90	✓	C	2B	2B	1.6	14/05	13R	R	0.47	0.38	0.06	0.04	113	0.38	0.08
	F-91	✓	C	4.5A	4.5A	1.6	15/0	15R	R	0.47	0.38	0.06	0.04	107	–	–
4-0-95	F-72	✓	A	5B	5B	2.3	14/14	0	L	0.55	0.49	0.0	0.05	121	0.23	0.19
-80	F-75	✓	A	3A	2A	1.7	8/-01	08L	L	0.44	0.49	0.0	0.04	123	0.59	0.16
-85	F-75	✓	A	3A	3A	1.7	6/-01	06L	L	0.40	0.49	0.0	0.04	120	0.40	0.14
-90	F-76	✓	A	2.5B	2.5B	1.6	10/-09	03L	L	0.40	0.49	0.0	0.04	121	0.28	0.19
-97	F-76	–	A	5B	4.5C	–	10/-09	03L	L	0.50	0.49	0.0	0.05	–	0.16	–
-90	F-79	✓	A	2.5B	2.5B	2.1	10/-01	10R	R	0.50	0.49	0.0	0.05	121	0.34	0.26
-99	F-79	✓	A	8B	6D	–	16/-05	15R	R	0.55	0.49	0.0	0.05	122	0.13	0.15

✓ STATISTICAL DATA OBTAINED

(1) NOTE $N'_{\delta_{AS}}$ DIFFERENT

(2) NOTICEABLE TURBULENCE

Table I-1 (CONT.)

SUMMARY OF EVALUATIONS

CONFIG. NO.	FLT. NO.	STAT. DATA	PILOT	PILOT & TURB RATING		σ_u ft/sec	GIND/HEAD WIND kt	CROSS WIND kt	SIDESTEP	$L'\delta_{AS}$	$N'\delta_{RP}$	$L'\delta_{RP}$	$N'\delta_{AS}$	$\bar{U}$	$L'_{AS_{MAX}}$	$N'_{RP_{MAX}}$
				VFR	OVERALL											
4-A-00	F-61	–	A	7B	7B	1.9	8/-05	06L	L	0.61	0.49	0.0	-0.15	–	0.46	–
	F-63	–	B	5B	5B	–	8/-08	0	L	0.50	0.38	0.06	-0.13	–	–	–
4-P-00	F-60	✓	A	3A	4A	1.3	4/03	03L	L	0.37	0.38	0.06	0.07	120	0.29	0.14
4-P[1]-00	F-66	✓	A	3A	3A	1.5	4/01	04R	R	0.39	0.35	0.08	0.17	113	0.33	0.18
	F-67	✓	A	2B	2B	1.7	7[2]/05	04L	L	0.35	0.49	0.0	0.11	117	0.41	0.14
	F-84	–	B	7A	7A	–	10/03	09L	L	0.35	0.21	0.17	0.11	–	–	–
5-0-00	F-67	–	A	6E	6E	–	5[2]/05	0	L	0.40	0.48	0.0	0.03	–	0.43	–
	F-71	–	A	4D	4.5D	1.4	10[2]/0	10L	L	0.33	0.49	0.0	0.03	119	0.45	–
	F-73	–	A	6E	6E	2.4	21[2]/21	03R	L	0.33	0.49	0.0	0.03	126	0.35	–
	F-75	✓	A	2A	3A	1.4	8/-01	08L	L	0.40	0.49	0.0	0.03	120	0.53	0.12
	F-78	✓	A	2A	2.5B	1.8	10/-09	03L	L	0.40	0.49	0.0	0.03	125	0.50	0.17
	F-79	✓	A	3B	3B	–	10/-01	10R	R	0.34	0.49	0.0	0.03	113	0.43	0.22
	F-85	✓	B	4A	4A	–	18/16	09R	L	0.40	0.17	0.19	0.03	121	0.53	0.09
	F-85	–	B	5A	5A	–	18/16	09R	L	0.40	0.49	0.0	0.03	–	–	–
	F-85	–	B	5A	5A	2.2	15/15	02R	L	0.43	0.17	0.19	-0.02	120	–	–
	F-86	✓	C	4A	5A	1.5	6/04	0	L	0.33	0.49	0.0	0.03	113	0.36	0.06
	F-89	✓	C	4B	3B	–	16/15	05R	L	0.33	0.38	0.06	0.03	116	0.40	0.15
	F-90	✓	B	2.5C	2.5B	–	11/02	11R	R	0.42	0.38	0.06	0.03	116	0.39	0.14
	F-91	✓	C	4B	5B	1.7	15/0	15R	R	0.33	0.38	0.06	0.03	113	0.39	0.17
5-0-90	F-79	✓	A	3B	4B	–	6/-03	07R	R	0.40	0.49	0.0	0.03	118	0.30	0.13
-95	F-79	✓	A	6C	8E	–	10/-02	10R	R	0.50	0.49	0.0	0.04	116	0.23	0.17
-92	F-80	✓	A	7D	7.5E	2.2	10[2]/-05	09R	R	0.44	0.49	0.0	0.04	116	0.30	0.21
5-A-00	F-89	✓	A	7C	8C	–	2/0	03R	R	0.51	0.49	0.0	-0.16	119	0.58	0.21
5-P-00	F-89	✓	A	5D	6D	1.7	2[2]/02	0	R	0.31	0.49	0.0	0.10	121	0.40	0.20
6-0-00	F-67	✓	A	4D	5D	–	8[2]/08	0	L	0.35	0.49	0.0	0.11	118	0.31	0.22
	F-70	✓	A	5A	6A	2.1	15/03	16L	L	0.30	0.49	0.0	0.06	123	0.32	0.16
	F-77	✓	A	6F	8E	1.7	15[2]/13	07L	L	0.25	0.49	0.0	0.07	112	0.48	0.21
	F-84	–	B	6A	6A	1.6	6/-03	06L	L	0.35	0.29	0.12	0.11	119	–	–
	F-85	✓	B	4A	5A	2.1	14/14	0	L	0.35	0.21	0.17	0.11	117	0.43	0.16
	F-88	✓	C	4.5A	4.5A	–	7/02	06R	L	0.35	0.49	0.0	0.11	127	0.30	0.07
	F-89	✓	C	4B	4B	1.9	18/16	06R	L	0.29	0.35	0.06	0.06	116	0.38	0.14
	F-90	✓	C	5B	8C	–	12[2]/0	12R	R	0.35	0.49	0.0	0.11	115	0.41	0.09
	F-91	✓	C	7A	7.5A	1.7	15/0	15R	R	0.27	0.35	0.08	0.08	117	0.27	0.12
7-0-00	F-71	✓	A	8C	8D	1.6	10[2]/-05	09L	L	0.25	0.49	0.0	0.05	118	0.35	0.16
	F-77	✓	A	7D	7E	1.7	15[2]/13	08L	L	0.37	0.49	0.0	0.06	110	0.55	0.16
	F-89	✓	C	5C	6C	2.2	16/15	05R	L	0.31	0.38	0.06	0.06	113	0.44	0.10

✓ STATISTICAL DATA OBTAINED

(1) NOTE $N'\delta_{AS}$ DIFFERENT

(2) NOTICEABLE TURBULENCE

Table I-2 presents the stability derivatives in aircraft body axes for the seven base configurations of the experiment. Details of the identification technique can be found in Appendix III. This identification was carried out in level flight at 65 kts for which the trim attitude and angle of attack conditions were

$$\alpha_o = \theta_o = -5 \text{ deg}$$

In the descent (γ = - 7.5 deg) the nominal attitude and angle of attack conditions were

$$\alpha_o = -6 \text{ deg}$$

$$\theta_o = -13.5 \text{ deg}$$

The effect of a one degree difference in trim angle of attack was shown to cause no appreciable difference in the modal characteristics from level flight to the descent condition. In addition, power setting differences from level flight to descent make negligible differences in stability and control derivatives. The effects on the calculated stability derivatives of the slightly higher approach velocities ($\bar{u}_{AVG} \doteq 68$ kts) is also not significant.

Table I-3 summarizes the pole-zero characteristics in the ϕ/δ_a transfer function for the seven base configurations together with the zero locations for the proverse and adverse yaw-due-to-aileron variations. These characteristics are also presented in the s-plane plot of Figure I-1.

TABLE I-2

PRIMED DIMENSIONAL STABILITY DERIVATIVES
REFERENCED TO BODY AXES OF EVALUATION CONFIGURATIONS

$$g/V = .291$$
$$Y_\beta/V_o = -.33 \text{ (1/sec)}$$
$$Y_p/V_o + \alpha_o = -.150 \text{ (1)}$$
$$Y_r/V_o - 1 = -.985 \text{ (1)}$$
$$\theta_o = \alpha_o = -5^o$$

Config.	L'_β (1/sec^2)	L'_r (1/sec)	L'_p (1/sec)	N'_β (1/sec^2)	N'_r (1/sec)	N'_p (1/sec)
1	-1.55	0.158	-2.57	-0.0605	-0.080	-0.0808
2	-1.59	0.442	-2.40	1.86	-0.425	0.0061
3	-4.87	0.249	-2.81	1.81	-0.578	0.133
4	-0.72	0.277	-1.24	2.38	-0.414	0.205
5	-2.80	0.692	-0.989	1.89	-0.400	0.276
6	-0.796	0.232	-0.474	2.09	-0.393	0.044
7	-2.05	0.70	-0.35	1.80	-0.70	-0.0124

TABLE I-3

NUMERATOR ROOTS REFERENCED TO BODY AXES
COMPARED TO DUTCH ROLL ROOTS

Config.	ω_d	ζ_d	ω_ϕ	ζ_ϕ	τ_R	τ_S	$\lvert\phi/\beta\rvert_d$
1-0			.33	.58			
1-A	.40	.16	-.095*	.47*	.37	11	1.54
1-P			.64	.33			
2-0			1.44	.28			
2-A	1.43	.22	1.30	.28	.39	-128	.46
2-P			1.61	.29			
3-0			1.71	.29			
3-A	1.30	.17	1.14	.40	.31	9	1.28
3-P			2.10	.25			
4-0			1.61	.26			
4-A	1.55	.23	1.52	.25	.72	-34	.30
4-P			1.66	.27			
5-0			1.49	.26			
5-A	1.27	.18	1.06	.25	.78	-37	1.42
5-P			1.73	.28			
6-0	1.45	.20	1.56	.25	1.57	-26	.40
7-0	1.27	.23	1.56	.38	1.31	23	1.27

* Real roots, values are $1/T_{\phi_1}$, $1/T_{\phi_2}$

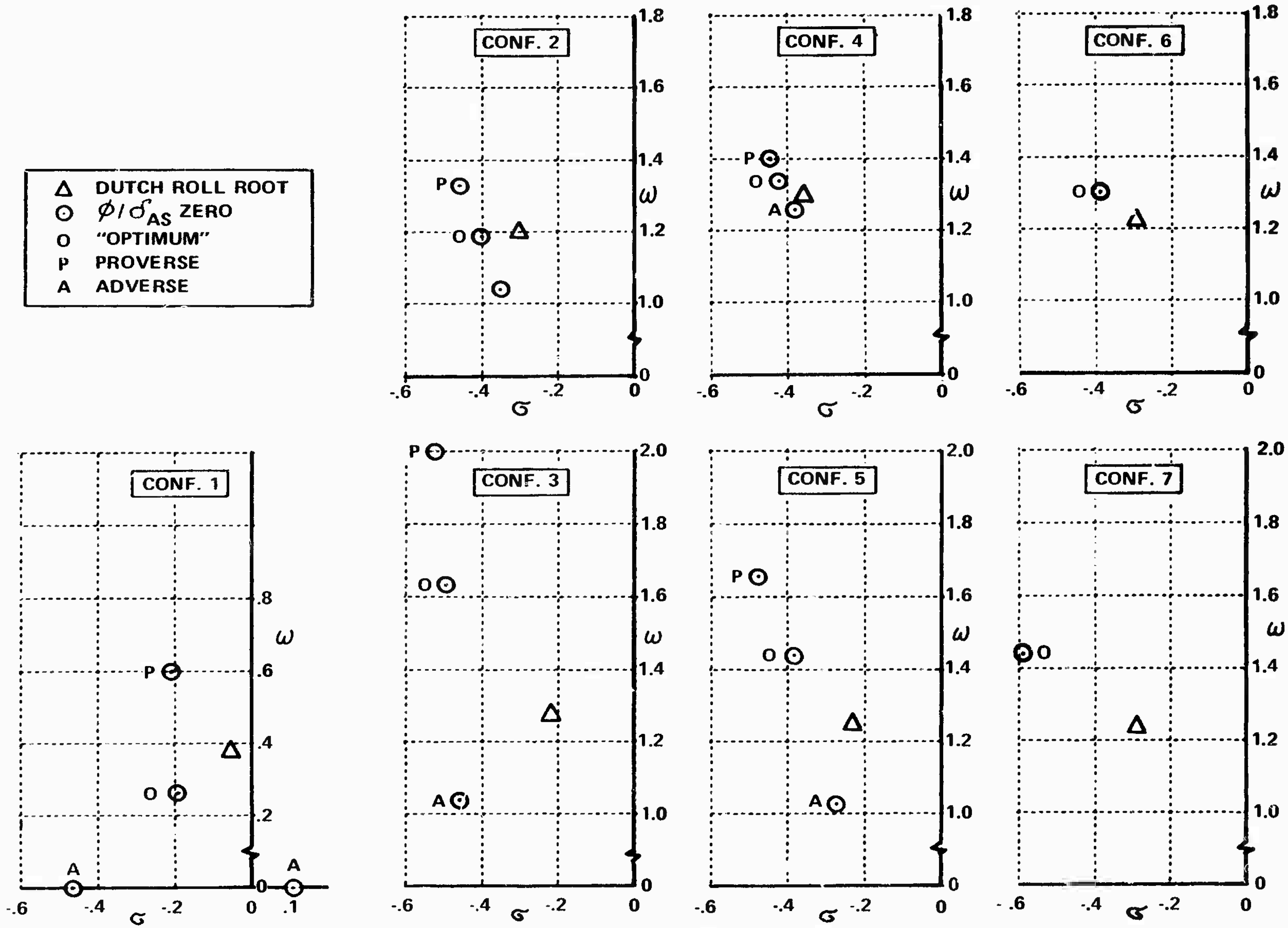


Figure I-1 ϕ/δ_{AS} TRANSFER FUNCTION CHARACTERISTICS

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GLOSSARY OF SYMBOLS

AND ABBREVIATIONS

Symbol

F_{AS}	roll control stick force, positive right, lb
$F_{B.O.}$	breakout force, lb
F_{ES}	pitch control stick force, positive aft, lb
F_{RP}	rudder pedal control force, positive right, lb
g	acceleration due to gravity (32.2 ft/sec^2)
$\bar{g}_E$	gravity force vector
$\dot{h}$	rate of climb (or descent), ft/sec or ft/min
I_x	moment of inertia about x-axis, ft-lb sec^2
I_y	moment of inertia about body y-axis, ft-lb sec^2
I_z	moment of inertia about body z-axis, ft-lb sec^2
I_{xz}	product of inertia in body axes, ft-lb sec^2
K_L	$= (I_y - I_z)/I_x$ nondimensional inertia coupling in roll
K_N	$= (I_x - I_y)/I_z$ nondimensional inertia coupling in yaw
$K_{(i)_{(j)}}$	gain of (i) to (j) transfer function
L	total aerodynamic rolling moment in body axes, ft-lb
L'	total aerodynamic rolling moment in primed axes, ft-lb $= (1 - I_{xz}^2/I_x I_z)^{-1}(L + \frac{I_{xz}}{I_x} N)$
$L'_{( )}$	$= (1 - I_{xz}^2/I_x I_z)^{-1}(L_{( )} + \frac{I_{xz}}{I_x} N_{( )})$, rad/sec^2)/ ( )
L'_{AS}	rolling acceleration commanded by roll control stick, rad/sec^2
L'_{RP}	rolling acceleration commanded by rudder pedals, rad/sec^2
M	total aerodynamic pitching moment in body axes, ft-lb
$M_{( )}$	$= \frac{1}{I_y}\frac{\partial M}{\partial ( )}$, dimensional pitching moment derivative, (rad/sec^2)/( )
N	total aerodynamic yawing moment in body axes, ft-lb
N'	$= (1 - I_{xz}^2/I_x I_z)^{-1}(N + \frac{I_{xz}}{I_z} L)$, total aerodynamic yawing moment in primed axes, ft-lb

GLOSSARY OF SYMBOLS

AND ABBREVIATIONS (cont.)

Symbol	
$N'_{( )}$	$= (1 - I_{xz}^2/I_x I_z)^{-1}(N_{( )} + \frac{I_{xz}}{I_z} L_{( )})$, $(rad/sec^2)/( )$
N'_{AS}	yawing acceleration commanded by roll control stick, rad/sec^2
N'_{RP}	yawing acceleration commanded by rudder pedals, rad/sec^2
$\vec{n}$	total aerodynamic force vector, "g's"
$n_{( )}$	body axes (x, y or z) acceleration, ft/sec^2
n_z/α	steady-state normal acceleration per angle of attack, g's/rad
$P( )$	probability density of ( )
p	body axes roll rate, deg/sec, rad/sec
p_{osc}/p_{AV}	roll rate oscillation parameter of MIL-F-8785B
$\hat{p}_{osc}/\hat{p}_{AV}$	roll rate oscillation parameter of MIL-F-8785B proposed revision
q	body axes pitching rate, deg/sec, rad/sec
r	body axes yaw rate, deg/sec or rad/sec
s	Laplace transform variable, rad/sec
t	time, seconds
$t_{\phi=i}$	time to bank to i degrees, seconds
T	Euler transformation matrix
$T_{(i)(j)}$	real root numerator zero of (i) to (j) transfer function, sec
T_{ϕ_1}, T_{ϕ_2}	real root numerator zeros of ϕ/δ_{AS} transfer function, sec
U_0	trim velocity in body X-axis, ft/sec
u	velocity (also perturbation from trim) along body x-axis, ft/sec
u_L	velocity along body x-axis measured by u-LORAS, ft/sec
v	velocity (also perturbation from trim) along body y-axis, ft/sec
v_g	gust velocity along body y-axis, ft/sec
V_0	trim velocity, ft/sec or kt

GLOSSARY OF SYMBOLS

AND ABBREVIATIONS (cont.)

Symbol	
$\bar{V}_g$	vector velocity of air relative to arbitrary inertial axes, ft/sec
$\bar{V}_I$	vector velocity of aircraft relative to arbitrary inertial axes, ft/sec
$\bar{V}_R$	vector relative velocity, ft/sec
$\bar{V}_m$	vector measured velocity, ft/sec
w_o	trim velocity along body z-axis, ft/sec
w'	velocity (also perturbation from trim) along body z-axis, ft/sec
w_L	velocity along body z-axis measured by w-LORAS, ft/sec
X	total aerodynamic force along body x-axis, lb
$X_{( )}$	$= \frac{1}{m}\frac{\partial X}{\partial ( )}$, dimensional X-force derivative, ft/sec^2/( )
Y	total aerodynamic force along body y-axis, lb
$Y_{( )}$	$= \frac{1}{m}\frac{\partial Y}{\partial ( )}$, dimensional Y-force derivative, ft/sec^2/( )
Δy	lateral offset displacement, ft
Z	total aerodynamic force along body z-axis, lb
$Z_{( )}$	$= \frac{1}{m}\frac{\partial Z}{\partial ( )}$, dimensional Z-force derivative, ft/sec^2/( )
$\Delta Z/\Delta X$	ratio of Z to X forces commanded by collective stick
α	angle of attack, degrees or radians
α_V	angle of attack measured by vane, degrees
β	angle of sideslip, degrees or radians
β_g	angle of sideslip caused by gust, degrees or radians
β_V	angle of sideslip measured by vane, degrees
$\Delta\beta_{MAX}/K$	sideslip response parameter of MIL-F-8785B
$\Delta\beta/\phi_1$	sideslip response parameter of MIL-F-83300
$\Delta\dot{\beta}_{MAX}/\hat{p}$	sideslip response parameter of MIL-F-8785B proposed revision
γ	glide slope angle, degrees

GLOSSARY OF SYMBOLS

AND ABBREVIATIONS (cont.)

Symbol	
$d\gamma/dV$	backsidedness parameter, ^{1}/ft/sec
Δ_{ES}	displacement of safety pilot's pitch control at the center of hand grip, positive aft, inches
Δ_{AS}	displacement of safety pilot's roll control at the center of hand grip, positive right, inches
Δ_{RP}	displacement of safety pilot's yaw control, positive right, inches
$\Delta'_{(\ )}$	summation of VSS electrical command in ( ) channel, inches
δ_C	collective control stick position, degrees
δ_{AS}	rolling moment control stick position at the center of hand grip, positive right, inches
δ_{ES}	pitching moment control stick position at the center of hand grip, positive aft, inches
δ_{RP}	yawing moment control pedal position, positive right, inches
ϵ_{GS}	glide slope error, positive up, degrees
ϵ_L	localizer error, positive right, degrees
ζ_d	damping ratio of Dutch roll characteristic roots
ζ_{FS}	damping ratio of feel system
ζ_P	damping ratio of phugoid characteristic roots
ζ_{ST}	damping ratio of short period characteristic roots
ζ_ϕ	damping ratio of numerator roots in ϕ/δ_{AS} transfer function
$\zeta_{(i)(j)}$	damping ratio of numerator roots in (i) to (j) transfer function
θ	pitch attitude, degrees or radians
λ	X-22A duct angle, measured from horizontal, degrees
λ_R	roll mode characteristic root, 1/sec
λ_S	spiral mode characteristic root, 1/sec

GLOSSARY OF SYMBOLS

AND ABBREVIATIONS (cont.)

Symbol	
$\sigma_{( )}$	standard deviation of ( ) in units of ( )
$\Delta\sigma_{v_g}$	change in standard deviation due to gust, ft/sec
τ_R	roll mode time constant, sec
τ_S	spiral mode time constant, sec
ϕ	roll angle, degrees or radians
ϕ/δ_{AS}	roll to aileron transfer function
$\|\phi/\beta\|_d$	magnitude of roll to sideslip ratio in Dutch roll component
$\phi_{( )}$ or $\phi_{t=( )}$	roll angle achieved in ( ) seconds, degrees
ϕ_{osc}/ϕ_{AV}	roll rate oscillation parameter of MIL-F-83300
$\Phi_{( )}$	power spectral density of ( )
ψ_β, $\psi_{\dot\beta}$, ψ_p	correlation angles for MIL-F-8785B, MIL-F-83300 roll oscillation and sideslip response parameters, deg
ω_d	undamped natural frequency of Dutch roll mode, rad/sec
ω_{FS}	undamped natural frequency of feel system, rad/sec
ω_p	undamped natural frequency of phugoid mode, rad/sec
ω_{ST}	undamped natural frequency of short period mode, rad/sec
ω_ϕ	undamped natural frequency of numerator roots in ϕ/δ_{AS} transfer function, rad/sec
$\omega_{( )_{( )}}$	undamped natural frequency of numerator roots in (i) to (j) transfer function, rad/sec
$\bar\omega$	Euler rate sensor, 1/sec
$\dot{( )}$	time of rate of change of ( ), ( )/sec
$( )_0$	initial or trim value of ( ), ( )
$\bar{( )}$	mean or average value of ( ), ( )
$( )_{AVG}$	average value of ( ), ( )
$( )_L$	value measured by LORAS of ( ), ( )

GLOSSARY OF SYMBOLS

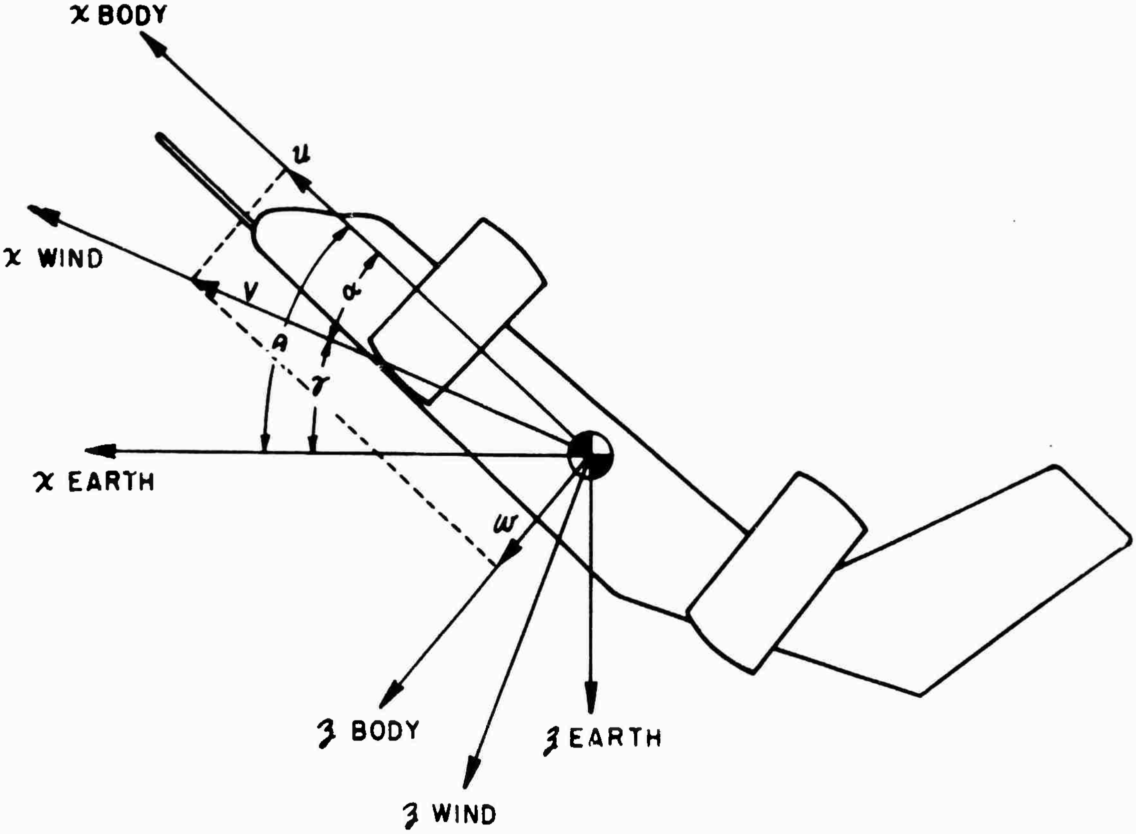
AND ABBREVIATIONS (cont.)

<u>Symbol</u>

$(\ )_m$	measured value of ( ), ( )
$(\ )_{MAX}$	maximum value of ( ), ( )

<u>Abbreviations</u>

AGL	above ground level
CTOL	conventional takeoff and landing
IFR	instrument flight rules
ILS	instrument landing system
LORAS	low range airspeed system
PIO	pilot-induced oscillation
PR	pilot rating (Cooper-Harper)
VAA	visual approach aid
VFR	visual flight rules
VSS	variable stability system
deg	degrees (angle)
fpm	feet per minute
kt	knots (airspeed)
rms	root-mean-square
Hz	frequency (1 Hertz = 1 cycle per second)



BODY AXIS SYSTEM