

FLYING QUALITIES DESIGN CRITERIA APPLICABLE TO SUPERSONIC CRUISE AIRCRAFT*

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SUMMARY

A comprehensive set of flying qualities design criteria has been prepared for use in the NASA Supersonic Cruise Research Program. The framework for stating the design criteria is established and design criteria are included which address specific failures, approach to dangerous flight conditions, flight at high angle of attack, longitudinal and lateral-directional stability and control, the primary flight control system and secondary flight controls. In this paper, examples are given of lateral-directional design criteria limiting lateral accelerations at the cockpit, time to roll through 30° of bank and time delay in the pilot's command path. Flight test data from the Concorde certification program are used to substantiate a number of the proposed design criteria.

INTRODUCTION

NASA/Langley Research Center and the three system study contractors are beginning to perform analysis and simulation studies to define the flying qualities, ride qualities and flight control characteristics of the large flexible aircraft which are typical of supersonic cruise aircraft concepts. To facilitate comparison of the flying qualities characteristics of the aircraft concepts being studied by the system study contractors and to aid NASA/LRC in directing flying qualities research activities, a comprehensive set of flying qualities design criteria have been prepared by Calspan Corporation (Ref. 1) under NASA/LRC sponsorship. These design criteria are not intended to replace the Federal Aviation Regulations, FAR, in any formal or legal sense. The proposed design criteria are more quantitative than the FAR's and are more similar to the requirements of the military specification for flying qualities, MIL-F-8785B(ASG). The design criteria are intended to aid the system study contractors and to provide NASA with a common basis for comparison of design concepts for supersonic cruise aircraft.

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FORMAT OF DESIGN CRITERIA DOCUMENT

The general format of the design criteria document is similar to MIL-F-8785B(ASG), however, the structure is simplified because only one class of aircraft is being addressed. The concepts of Flight Phases and Levels of flying qualities are employed to permit tailoring the design criteria to the task and to indicate how much degradation in the stability and control characteristics can be tolerated in particular circumstances. The designer is required to define airplane normal states (i.e., combinations of weight, center of gravity, moments and products of inertia, and configuration), failure states, operational flight envelopes and service flight envelopes for the aircraft and its operational role.

The possibility that the airplane may be required to operate under abnormal conditions is recognized and a degraded Level of flying qualities is permitted for flight outside the operational envelope, for failure of airplane components and for combinations of these circumstances. The design procedure for determining theoretical compliance with airplane failure state requirements is adopted from MIL-F-8785B(ASG). This procedure is illustrated in Figure 1. (This figure is taken from Ref. 2 which contains a comprehensive review of the methods used, in various civil and military flying qualities documents, to deal with system failures that degrade flying qualities.) The probabilistic approach to the treatment of failure effects illustrated in Figure 1 is supplemented in Ref. 1 by inclusion of design criteria for specific failure cases which must be considered regardless of the probability of occurrence.

The general content and organization of Ref. 1 is indicated by the outline of major sections illustrated in Figure 2. The number of design criteria paragraphs contained in Ref. 1 prohibits presenting a detail review of the criteria in this paper; however, three design criteria relating lateral-directional responses to pilot roll controller commands are presented and discussed in a following section. In preparing the design criteria, the author has drawn on previous work performed by Calspan during development of MIL-F-8785B(ASG), MIL-F-83300 and the study to revise MIL-F-8785B(ASG) reported in Ref. 3. In addition, flying qualities special conditions developed by the FAA for certification of the Concorde were reviewed as were the TSS standards developed by the French and British certification authorities for application to the Concorde. The results of flying qualities experiments such as those reported in Refs. 4 and 5 have also been used to formulate and to substantiate the design criteria.

With permission from British Aerospace, Inc. and Aerospatiale, the flight test data, Ref. 6, used for certification of the Concorde by the British, French and U.S. authorities was made available to Calspan and has been used where appropriate to substantiate the proposed design criteria. Additional Concorde flight test data taken by FAA test teams is contained in Ref. 7.

Since MIL-F-8785B(ASG) was adopted in 1969, the Air Force has sponsored a number of studies to compare the characteristics of existing aircraft with the flying qualities requirements of that specification. Ref. 8 documents the comparison of the C-5A aircraft with MIL-F-8785B(ASG) requirements. Flight test data in Ref. 8 were also used to substantiate the proposed design criteria.

EXAMPLES OF DESIGN CRITERIA

Lateral Acceleration at the Cockpit During Rolling Maneuvers

In 1977, Calspan performed in-flight simulation tests, Ref. 9, of a supersonic cruise aircraft equipped with a flight control system designed by NASA/LRC engineers. Although this configuration had been given satisfactory pilot ratings, Ref. 10, when evaluated on the NASA/LRC fixed base simulator, it was rated unacceptable when evaluated in the TIFS in-flight simulator. Figure 3. This configuration was rated unacceptable even though it satisfied the lateral-directional flying qualities requirements of MIL-F-8785B(ASG) and the revised versions of these requirements recommended in Ref. 3. The major reason for the unacceptable pilot ratings was the lateral acceleration response at the pilot's station during rolling and turning maneuvers. The configuration being evaluated had the pilot located 44.2 m ahead of the C.G. and 11 m above the x stability axis. Thus, angular accelerations in roll and yaw following an abrupt roll controller input caused lateral acceleration at the pilot's station. This problem was ameliorated by redesign of the flight control system to reduce proverse yaw due to aileron and by filtering the pilot's roll commands with a low-pass first-order filter to reduce the roll acceleration. This solution makes it more difficult to meet roll performance requirements and tends to introduce phase shift and effective time delay in the pilot's roll command channel.

In 1978 a second in-flight simulation program was performed in the TIFS airplane to obtain data which could be used to draft a design criterion to limit the magnitude of the lateral acceleration at the pilot's station, which occurs when the pilot performs rolling and turning maneuvers. Configurations evaluated in this experiment included a simulation of the lateral-directional dynamics and cockpit location of the Boeing 747, but mostly the configurations were based on a supersonic cruise aircraft defined by NASA/LRC and variations of the lateral-directional stability and control augmentation system. One version of the flight control system produced an airplane that could be maneuvered, in roll and turning maneuvers, with the roll controller without producing any sideslip. This configuration had the spiral root at the origin and quite high roll damping although the Dutch roll mode was low frequency and not very heavily damped. This configuration was used to explore the effects of locating the pilot's station at various positions in the rigid body. The

following coordinate locations in the stability axis system were simulated.

x_s	z_s	
44.2	-11	Nominal pilot location
44.2	0	On x_s stability axis
0	-11	Above C.G.
0	0	At C.G.

Thus, the airplane dynamics and conventional flying qualities parameters were identical for these four configurations, but the linear accelerations experienced by the pilot were different. The simulation concept is illustrated by the profile drawing of Figure 4. This type of simulation is possible in the TIFS airplane because it is equipped with six independent force and moment controls which permit forcing the evaluation cockpit to follow the motions of any designated point in the model axis system.

The lateral acceleration response to a step roll controller command, for each of the simulated cockpit locations, is illustrated in Figure 5. The roll rate response, which is common to all of the configurations, is also shown in Figure 5.

The two sets of roll rate and lateral acceleration time histories shown in Figure 6 illustrate the effect of adding a first-order low-pass filter in the pilot's roll command channel. The filter is effective in reducing the initial lateral acceleration transient, but it also slows the development of maximum roll rate which increases the time required to change bank angle by 30° . Also, the filter causes an effective time delay, which, depending on the magnitude of the total time delay in the roll channel, may cause degraded flying qualities.

The pilot ratings from this TIFS experiment were correlated with a parameter derived from the roll rate and the side acceleration (at the pilot) time histories resulting from a step roll controller input

$$\frac{n_{y_{pilot}}^{max}}{P_{max}} \quad \left| \begin{array}{l} \text{step input} \\ t \leq 2 \text{ sec} \end{array} \right.$$

The intent is to limit the magnitude of the lateral acceleration at the pilot location resulting from pilot roll commands. The lateral acceleration measure is divided by the roll rate measure as a somewhat arbitrary technique for normalizing the parameter for various magnitude control commands. The pilot rating data are plotted in Figure 7 and lines are sketched on the figure to illustrate the interpretation of the data that were employed to establish the following design criteria:

<i>Level</i>	$\frac{n_{y_{pilot\ max}}}{P_{max}}$	step input $t \leq 2.5\ sec$
1	.012 g/deg/sec	
2	.035 g/deg/sec	
3	.058 g/deg/sec	

This design criteria should influence the aircraft and control system design as follows:

- Avoid excitation of Dutch roll by roll controller commands.
- Avoid proverse yaw due to roll controller commands.
- Limit the roll acceleration resulting from pilot commands.
- Locate the pilot near the C.G..
- Locate the pilot near the x stability axis, i.e., keep the fuselage at low angle of attack.

Roll Control Effectiveness

Included in the design criteria of Ref. 1 is one which limits the time required to change bank angle by 30° . This design criteria is analogous to the roll performance requirement of MIL-F-8785B(ASG) except the application to Flight Phases is different, i.e., takeoff is grouped with nonterminal Flight Phases and the values of the time permitted to change bank angle by 30° are larger. The justification for increasing the t_{30} values, i.e., reducing the required roll performance relative to that specified in MIL-F-8785B(ASG) is firstly, that the roll performance required by MIL-F-8785B(ASG) was not well substantiated by data specific to large aircraft; secondly, flight test data for the C-5A and the Concorde aircraft are now available, Figures 8, 9, 10 and 11, which do not substantiate the Class III roll performance requirements of MIL-F-8785B(ASG) and, thirdly, flight experiments have been performed in which the roll control power used by the pilot during landing was measured. The roll control power available to the pilot was then progressively limited to smaller values in subsequent evaluations until the pilot ratings were degraded beyond the 6.5 boundary, see Ref. 11. These tests included the effects of crosswinds in the range 20-30 kts. The data set from Ref. 11 that is most typical of supersonic cruise aircraft in the landing Flight Phase is presented in Figure 12. Translation of this data into t_{30} values gives the following

<i>Pilot Rating</i>	t_{30}
3.5	3.27
6.5	4.80
8.5	6.80

where an increment $\Delta t = 0.3 \text{ sec}$ has been included to account for the time required for the control input to reach 50% of final amplitude. These t_{30} values do not substantiate the roll performance values for Class III airplanes in the Landing Flight Phase required by MIL-F-8785B(ASG) which are: Level 1, $t_{30} = 2.5$; Level 2, $t_{30} = 3.2$; Level 3, $t_{30} = 4.0$.

Because the side acceleration problem described in the previous section may cause designers to limit the roll acceleration that the pilot can command, which may degrade the roll performance, it is considered necessary to define minimum roll performance design criteria. Therefore, the preliminary draft of Ref. 1 includes the following limits on t_{30} .

<i>Level</i>	<i>Landing</i>	<i>Takeoff and nonterminal</i>
1	$t_{30} \leq 3.2 \text{ sec}$	$t_{30} \leq 4.0 \text{ sec}$
2	$t_{30} \leq 4.0$	$t_{30} \leq 5.0$
3	$t_{30} \leq 5.0$	$t_{30} \leq 6.0$

These are preliminary values which may be changed after further review of substantiation data.

EFFECTIVE TIME DELAY IN COMMAND PATH

Flight experiments performed by Calspan in variable stability aircraft (NT-33, B-26 and C-131H) have shown that phase shift and transport time delay in the pilot's command channel has a very degrading effect on the closed-loop pilot-airplane dynamic system. See for example Refs. 12 and 13. Similar results have been reported in Ref. 14 from experiments performed in the Princeton University variable stability Navion. Examples of the degradation in pilot rating that resulted from introduction of transport time delay in the pilot's pitch and roll command paths are illustrated in Figures 13 and 14 which are taken from Ref. 13. The effect on pilot rating of a first-order filter in the roll command path was also evaluated in Ref. 13 and the results are shown in Figure 15. Ref. 14 contains data on the effects of varying the sample rate of a zero-order sample and hold device in the pilot's command channel. All of these experiments demonstrate that phase shift and transport time delay can cause degraded flying qualities.

Phase shift and transport time delay can result from cascading dynamic elements in the command path such as a feel system, linkage boost servos, surface actuators, and shaping networks or prefilters. Digital flight control hardware such as A/D and D/A converters, sample and hold, computer iteration cycle, etc. can also introduce phase shift and transport time delay in the command path. As was indicated in the discussion of lateral acceleration

at the pilot's station, limiting the pilot's ability to command roll acceleration by including a filter in his command path is effective in ameliorating the lateral acceleration but it tends to increase phase shift and time delay in the command path. Also, in large flexible aircraft, the designer may include a filter on the pilot's commands to prevent excitation of structural modes.

Thus, there are design pressures which may tend to cause higher than desired amounts of phase shift or transport time delay in the command paths and because the degrading effects of having too much are so severe, it is highly important that the flying qualities design guide include design criteria to address this potential problem.

The flight experiments of Refs. 12, 13, and 14 demonstrate that the amount of phase shift and time delay that can be tolerated is highly task dependent, i.e., tasks requiring tight closed-loop control are most sensitive. Also, the tests indicate that the effects of low sample rate, pure transport delay or cascaded dynamic elements may not be equivalent and, therefore, specific analysis and simulation may be necessary to evaluate a given case.

The design guidance contained in Ref. 1 is stated as follows: In general, the designer should make every effort to provide a linear or smoothly varying response to cockpit controller displacement and to control force for all amplitudes of control input, including values of stick force within the range of allowable breakout forces. In particular, the phase lag and transport time delay in the pilot's pitch, roll and yaw command channels shall be kept to a minimum to avoid pilot-induced oscillations and degradation of the dynamic control capability with the pilot in the loop.

It is desirable to include command channel dynamic effects in an overall design criteria, such as paragraph 3.5.6 "Pitch Dynamics with the Pilot in the Loop"; however, limit values of effective time delay in the **pitch**, roll and yaw command channels are separately stated as follows:

t_1 ~ Effective Time Delay in Command Path		
Level	Pitch	Roll and Yaw
1	.14 sec	.20 sec
2	.19 sec	.28 sec
3	.22 sec	.33 sec

These time delay values are maximums found tolerable in combination with good airplane dynamics. Significantly smaller command path time delays may be required to realize acceptable flying qualities in specific cases.

CONCLUDING REMARKS

This paper has briefly described the work performed by Calspan during the first phase of a contracted effort with NASA/LRC which has dealt primarily with flying qualities of the rigid aircraft. The next phase of the effort will be concerned with mathematical models used for representation of airframe structural modes and the effects of airframe flexibility on flying qualities, ride qualities and flight control system design.

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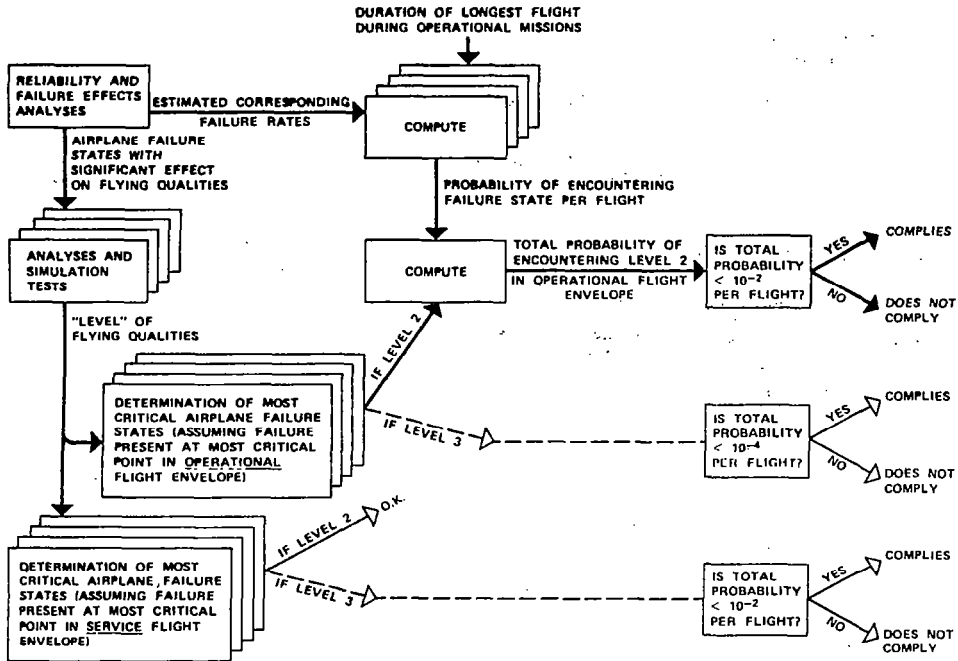


Figure 1.- MIL-F-8785B (ASG) procedure for determining theoretical compliance with airplane failure state requirements.

OUTLINE

1. SCOPE AND CLASSIFICATIONS
 - APPLICABILITY
 - FLIGHT PHASES
 - LEVELS OF FLYING QUALITIES
2. DEFINITIONS AND ASSOCIATIONS
 - AIRPLANE STATES
 - FLIGHT ENVELOPES
 - ASSOCIATION OF LEVELS - AIRPLANE STATE - FLIGHT ENVELOPES
3. FLYING QUALITIES DESIGN CRITERIA
 - SPECIFIC FAILURE STATES
 - APPROACH TO DANGEROUS FLIGHT CONDITIONS
 - FLIGHT AT HIGH ANGLE OF ATTACK
 - LONGITUDINAL DESIGN CRITERIA
 - LATERAL-DIRECTIONAL DESIGN CRITERIA
 - CHARACTERISTICS OF THE PRIMARY FLIGHT CONTROL SYSTEM
 - CHARACTERISTICS OF SECONDARY CONTROL SYSTEMS
4. SYMBOLS AND DEFINITIONS

Figure 2.- Outline of major sections of reference 1.

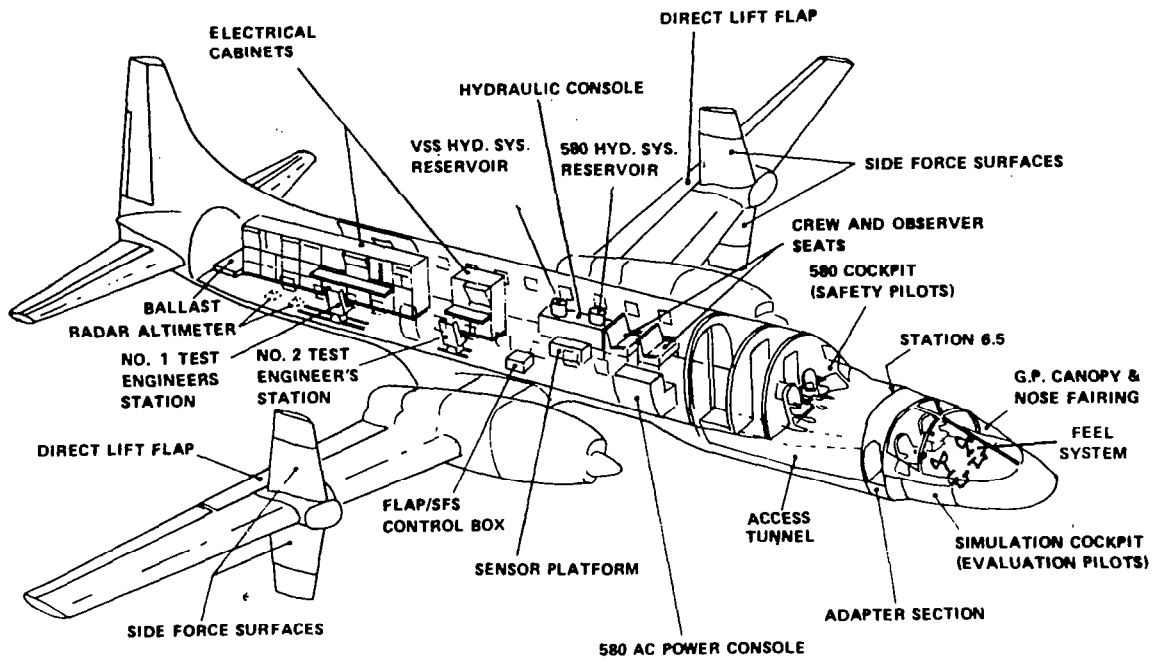


Figure 3.- USAF/Calspan TIFS airplane.

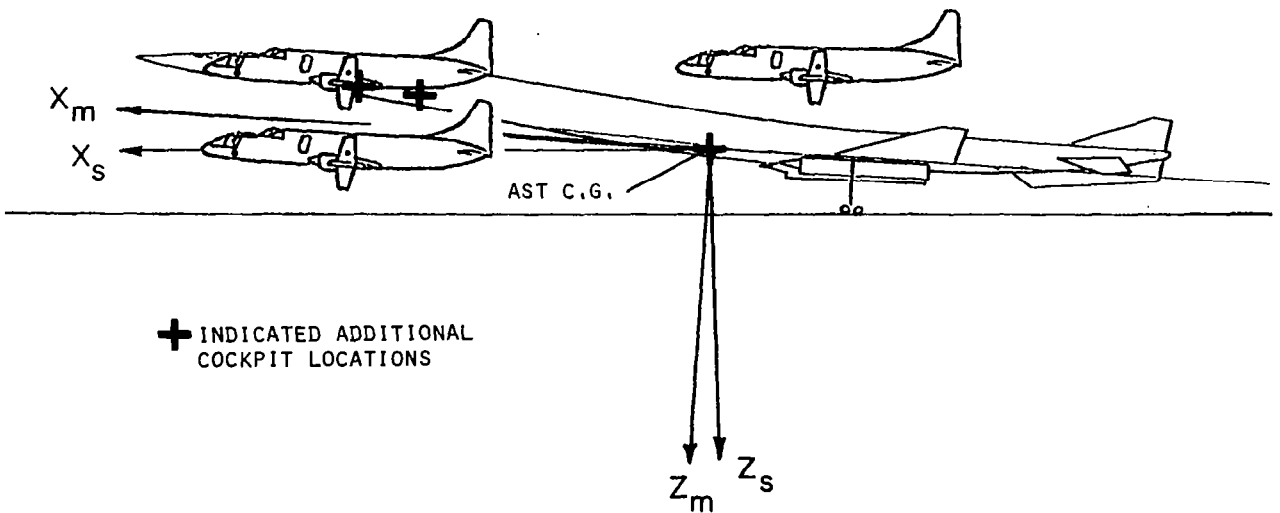


Figure 4.- Cockpit locations simulated in TIFS experiment.

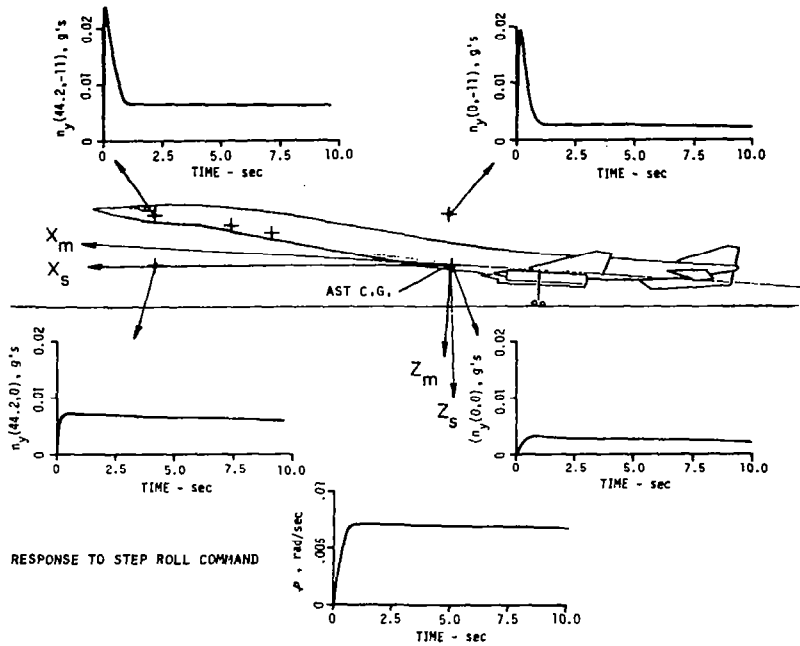


Figure 5.- Response to step roll command.

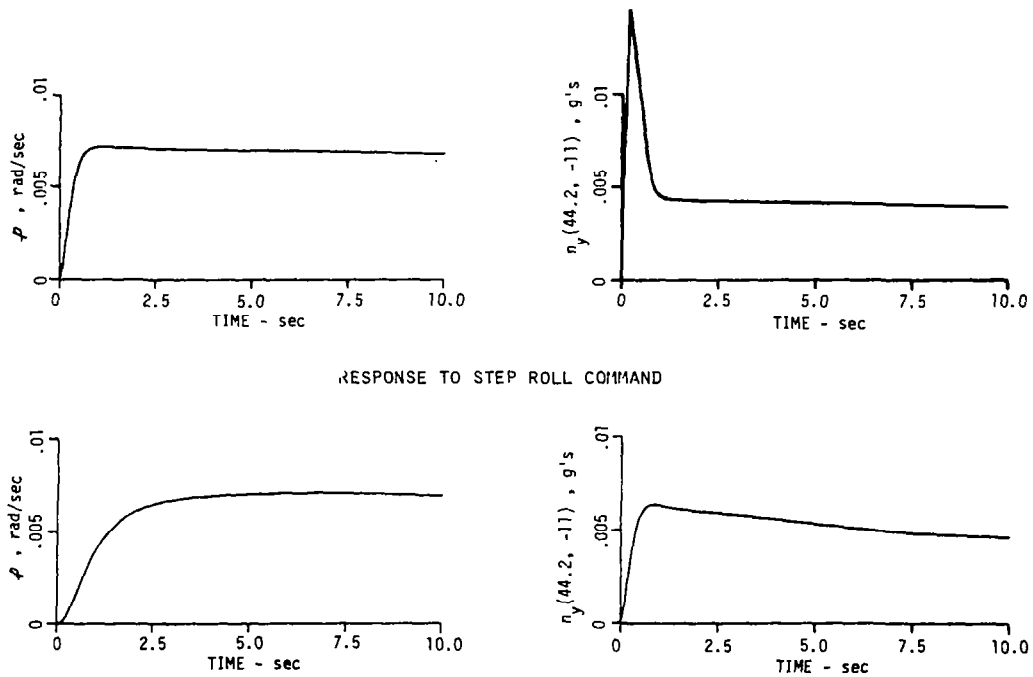
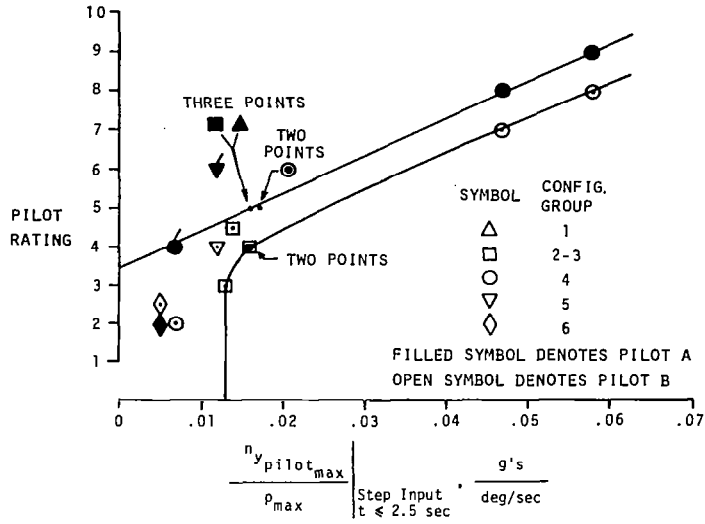


Figure 6.- Response to step roll command through first order filter with time constant, $T = 0.91$.



- NOTES: 1. Flagged points are configurations specifically downgraded by Pilot A due to poor Dutch roll damping - not lateral acceleration.
2. The lines indicate degradation in pilot rating to be expected because of ride qualities for an airplane with otherwise satisfactory flying qualities parameters.

Figure 7.- Lateral acceleration criterion versus pilot rating.

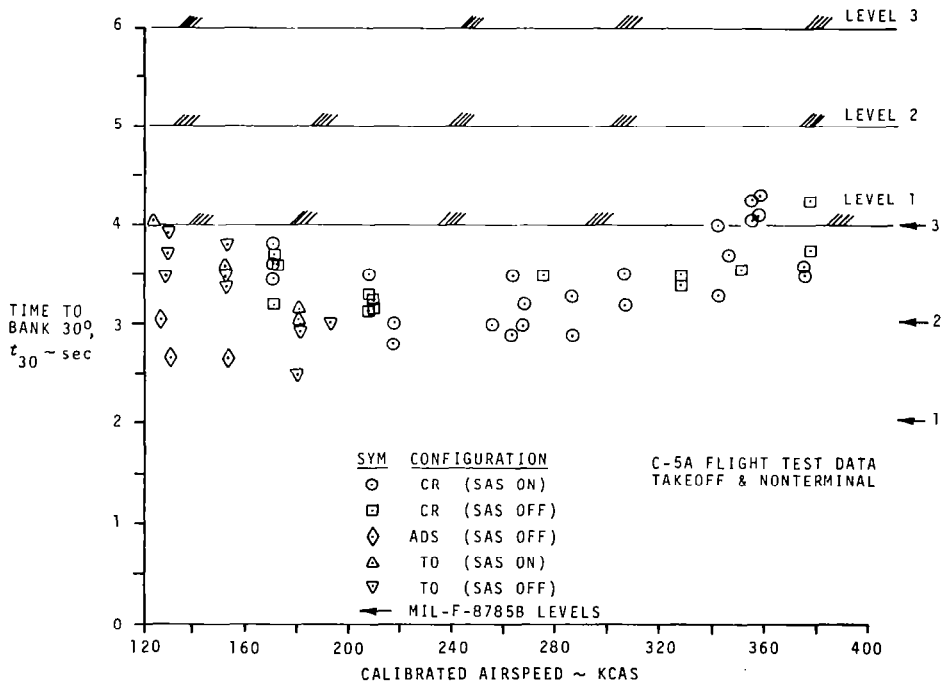


Figure 8.- C 5A flight test data - takeoff and nonterminal.

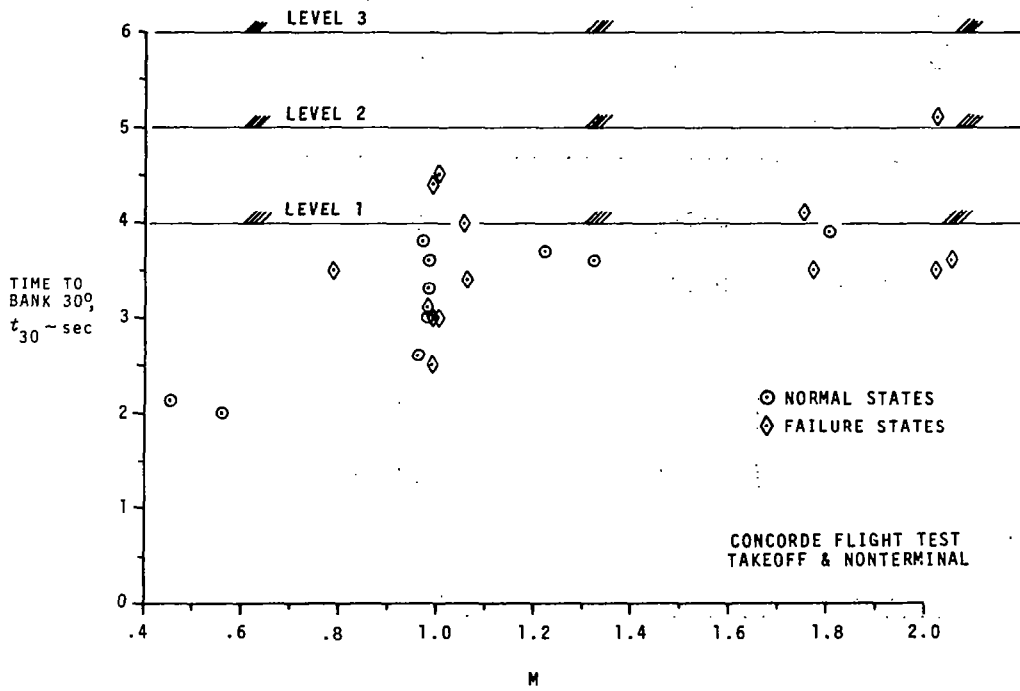


Figure 9.- Concorde flight test data - takeoff and nonterminal.

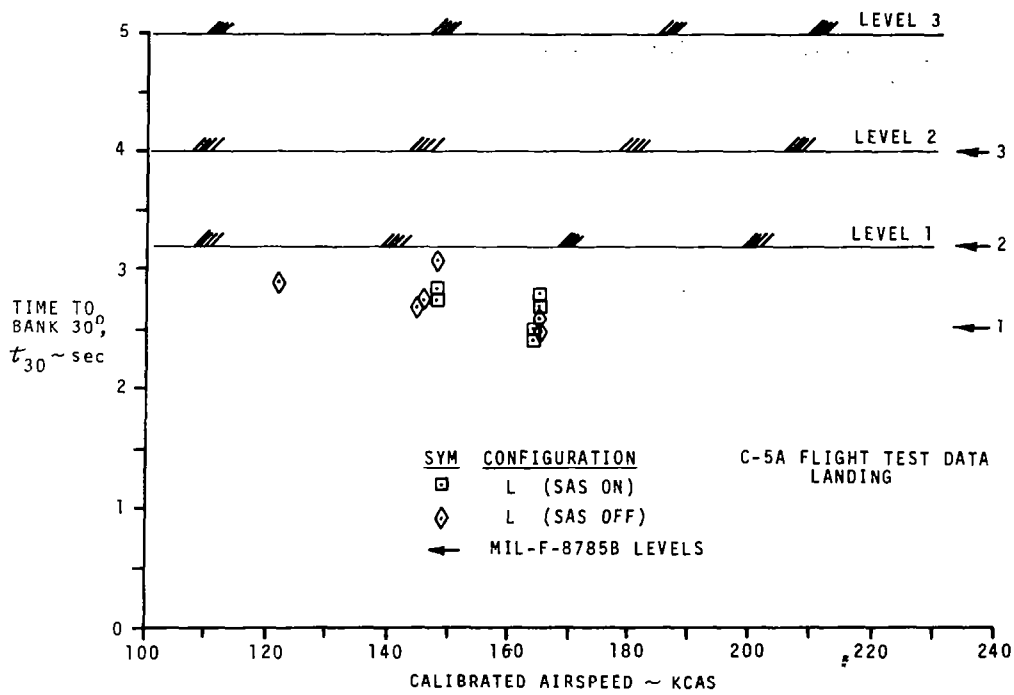


Figure 10.- C-5A flight test data - landing.

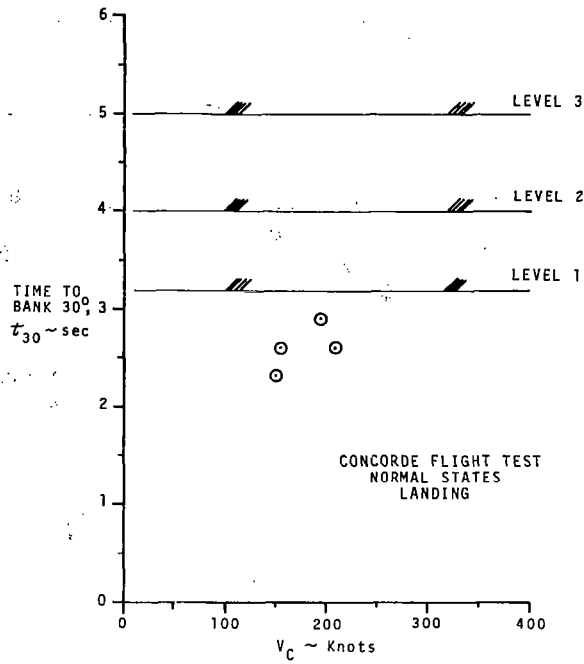


Figure 11.- Concorde flight test normal states landing.

CONF	PILOT/PH	$L^2 \delta_{AW}$ (DEG/SEC ² DEG)	ROLL CONTROL POWER USED (DEG/SEC ²)	MAXIMUM δ_{AW} USED (DEG)	MAXIMUM δ_{AW} USED (DEG)	ϕ_1 [*] (DEG)	$\phi_{1.0}$ [*] (DEG)	P_{AW} [*] (DEG/SEC)
1	A/B	4.70**	47.0	21.0	11	12.3	20.1	17.1
2	B/C	4.70	35.0	27.5	0	8.0	10.0	12.0
3	B/1.5	4.70	31.0	25.0	0.5	7.7	10.4	10.0
4	A/B	5.00	26.0	21.0	12	7.6	10.5	10.7
5	B/C	4.70	22.0	25	17	6.0	12.0	8.0
6	A/B	5.00	7.7	23.5	20	1.0	9.1	2.7

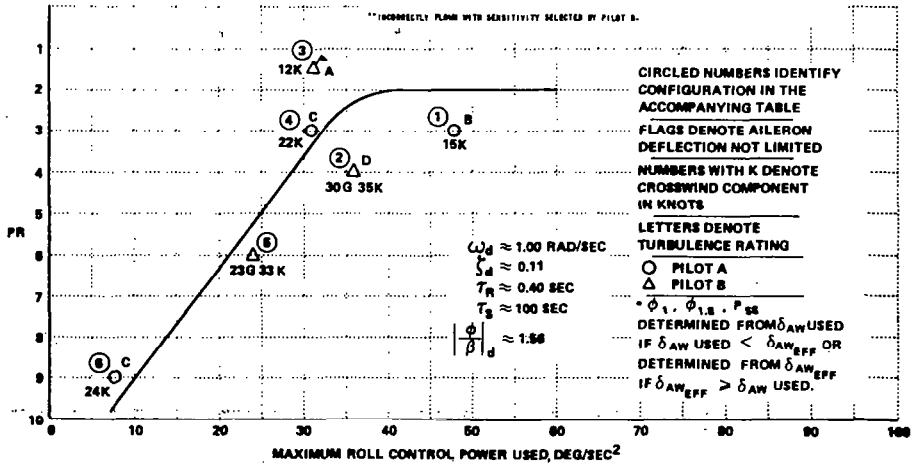


Figure 12.- Pilot rating versus maximum roll control power used - Group 6.

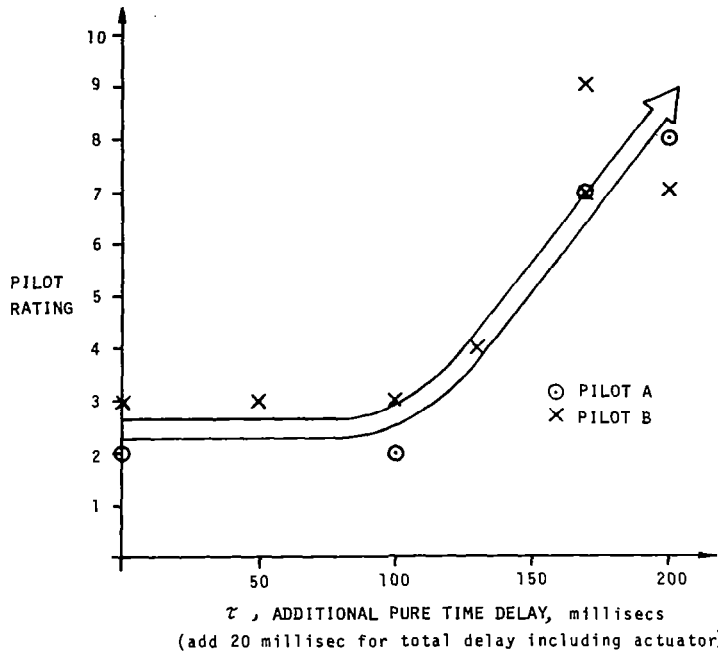


Figure 13.- Effect of pure time delay (pitch).

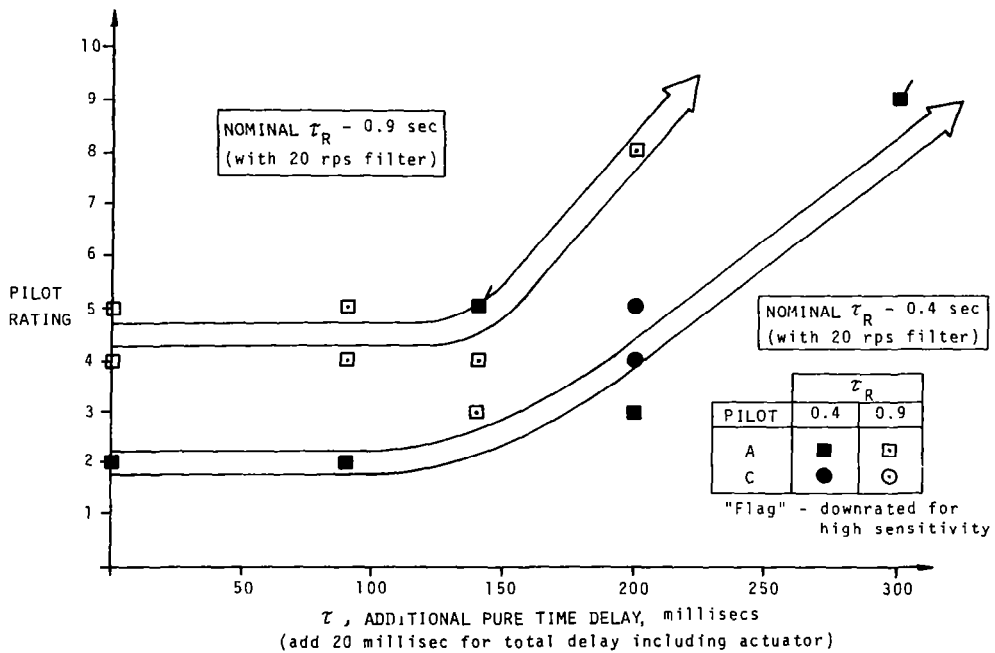


Figure 14.- Effect of pure time delay (roll).

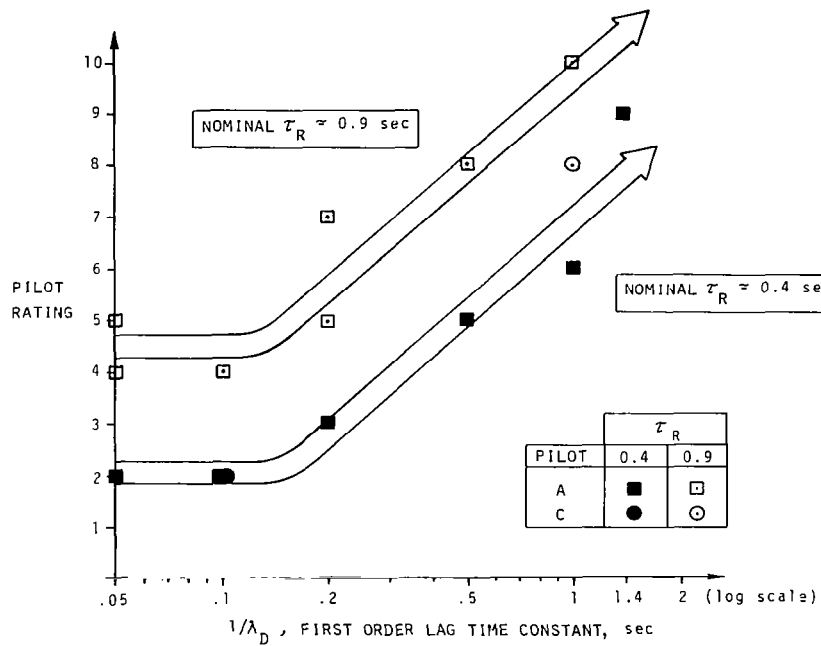


Figure 15.- Effect of lag (roll).