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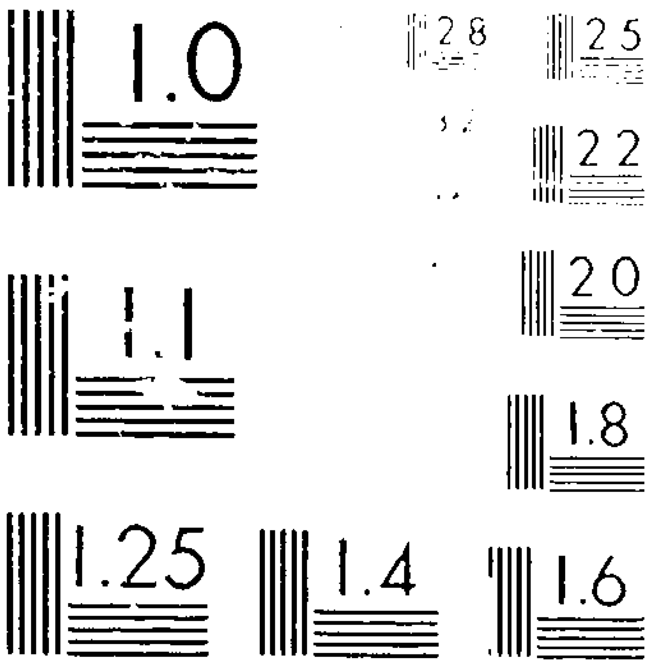

NASA CR-137635

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DEVELOPMENT OF LONGITUDINAL HANDLING QUALITIES CRITERIA FOR LARGE ADVANCED SUPERSONIC AIRCRAFT

FINAL REPORT

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MARCH 1975

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16. Abstract

Longitudinal handling qualities criteria in terms of airplane response characteristics have been developed by The Boeing Company under contract NAS2-7966. The criteria cover high speed cruise maneuvering, landing approach and stall recovery. This report contains data substantiating the study results which are reported in NASA CR-137635, "Development of Longitudinal Handling Qualities Criteria for Large Advanced Supersonic Aircraft.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

1.0 SUMMARY

A piloted simulation study has been made with the objective of advancing the development of longitudinal handling qualities criteria for large supersonic cruise aircraft. This work was conducted on the Flight Simulator for Advanced Aircraft (FSAA) located at NASA Ames Research Center. For this study the simulator was programmed with the math model representation of the Boeing 2707-300PT Supersonic Transport as it existed at termination of the National SST Program.

Areas of study included high speed cruise maneuvering, landing approach for normal and minimum-safe operating conditions, and stall recovery control power. The results of these evaluations were primarily based on pilot ratings. Additional analysis capability was developed which consisted of a pilot model analysis technique and pilot workload measurement techniques. The pilot model results were obtained and utilized successfully for some of the conditions evaluated in the landing approach (normal operation) study area. Pilot workload was measured by two techniques; by a side task technique, and by a computation of the physical work done by the pilot through the control column. The side task technique was not successful. The physical measurement was useful in analyzing landing approach conditions where major pilot rating scatter existed.

The results of this study are a combination of new criteria and modifications of existing criteria. All pre-existing criteria utilized in the final results were those developed during the National SST Program. Other criteria were considered but found to be less satisfactory. For high speed cruise and landing approach (normal operation), modifications to the SST Time Response Criteria, which were based on the Shomber-Gertsen Criteria, . re found to

adequately define the handling qualities results of this study. Results from the landing approach (minimum-safe) study were found to be best defined by the Pitch Divergence Criterion established during the National SST Program. The stall recovery control power study has resulted in a new criterion in terms of nose-down angular acceleration capability. This criterion has not been previously established by quantitative test results.

Continuation of this study is recommended in those areas not covered by this study and in those areas where unanswered questions exist. These areas are as follows:

- o High speed cruise maneuvering with a simulator having substantial greater load factor reproduction capability
- o Stall recovery with varying stability levels at stall
- o Landing flare
- o Effect of structural modes
- o Climb, cruise and transonic speed stability

Future work in the area of handling qualities criteria development should utilize a generalized math model that includes nonlinear characteristics, speed dependent derivatives to represent the effects due to changes in Mach number and airspeed, and structural modes. Also, it would be essential to provide the capability to control all of the above and the aerodynamic characteristics easily. Such a math model would allow a more efficient program to be conducted.

2.0 INTRODUCTION

This document presents the results of the piloted simulation study conducted under NASA contract (NAS2-7966) "Development of Longitudinal Handling Qualities Criteria for Large Advanced Supersonic Aircraft." The purpose of this study was to improve the data base and handling qualities criteria for large supersonic cruise aircraft with highly augmented flight control systems.

Research work conducted during the National SST Program has shown that important benefits in aircraft economics will be gained through advancements in flight control system design. These advanced flight control systems characteristically result in airplane dynamic response which is not adequately specified by existing handling qualities criteria. Existing military (Reference 1) and civil (Reference 2) flying qualities criteria were found inadequate to provide design guidance for the flight control system development of the large, low design load factor, SST aircraft. An extensive set of criteria was developed and documented (Reference 3) during the National SST Program which was based on previous work done by NASA and other investigators as well as extensive contractor fixed base in-house simulation.

Generalized criteria are required for flight control system design guidance for both normal operation and minimum-safe operation. For normal operation, these criteria will establish control system design requirements, augmentation system requirements, and the requirements for control surface rates and authority. Criteria for minimum-safe operation are required to establish minimum stability levels and key elements in the basic airplane design such as fore and aft limits of longitudinal balance and tail sizing derived from control power requirements.

The piloted simulation study covered in this report was conducted using the NASA-Ames moving base simulator designated as the Flight Simulator for

Advanced Aircraft (FSAA). Two simulation test periods were utilized, covering the periods from May 15 through June 6, 1974, and from September 11 through October 25, 1974. During these two periods there were 61.7 hours of piloted evaluation time utilized. In addition to piloted evaluation, these periods were also used to conduct the necessary checkout work and do the required test set up and calibration work.

This study contract covered the time period from January 15, 1974 through March 31, 1975.

3.0 STUDY AREAS

There were four basic study areas investigated during this piloted simulation study:

1. High Speed Cruise Maneuvering
2. Landing Approach (normal operation)
3. Landing Approach (minimum-safe operation)
4. Stall Recovery Control Power

These represent the most important problem areas in terms of longitudinal handling qualities criteria identified during the National SST Program. Also, the selection of the study areas was influenced by the applicability to each study area of the type of evaluations possible, the facility being used, and the availability of evaluation test time. For example, these studies did not include evaluation where large sustained load factor was required due to the limited vertical stroke built into the motion system of the FSAA simulator.

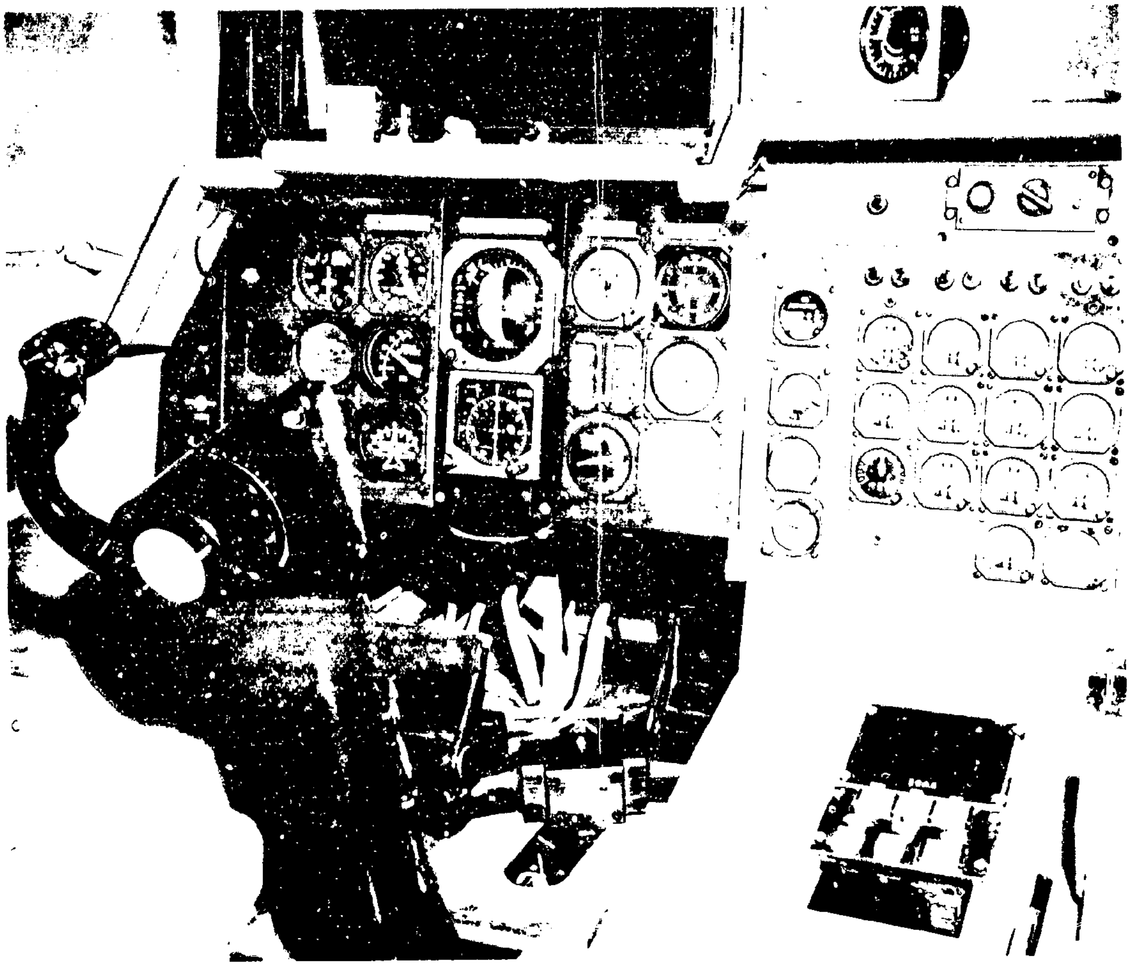
The results of evaluations conducted in each study area will be discussed under separate heading in this report. Criteria arrived at in each study area will be identified in the discussions of the test results and will be summarized in the conclusions.

4.0 TEST FACILITY

The facility used for all evaluation testing was the Flight Simulator for Advanced Aircraft (FSAA) at NASA-Ames Research Center. This simulator consists of a large cab with two crew stations mounted on a six degree of freedom motion system. A visual system is provided at each pilot station by means of a color television system using a terrain model display. The entire facility is controlled by a Sigma 8 computer which, in the case of this simulation evaluation, was programmed with the complete math model representation of the Boeing 2707-300PT Supersonic Transport (Reference 4).

Two cockpit configurations were used for this evaluation. These configurations differed in the attitude display instrument. As shown in Figure 4-1, the mechanical attitude display indicator (HZ-6F) was used during the first simulation study period and had a pitch attitude display sensitivity of .07 inches per degree (.18 centimeters per degree). The other configuration presented in Figure 4-2 utilized the electronic attitude director indicator (EADI) which was developed for the 2707-300PT during the National SST Program. This was the configuration for the second simulation study period, and had a normal pitch attitude sensitivity of .16 inches per degree (.41 centimeters per degree). For high speed cruise evaluations the sensitivity was increased to .30 inch per degree (.76 centimeters per degree). The mechanical ADI was used to accomplish all of the landing approach (normal operation) evaluations except those cases evaluated by Pilot "F". The EADI was utilized for all of the other evaluations and the details of this display are presented in Figure 4-3.

A flight path angle display was available to the pilot in either cockpit configuration. The display consisted of actual and potential flight path angle indicators. With the ADI configuration the angles were presented on two



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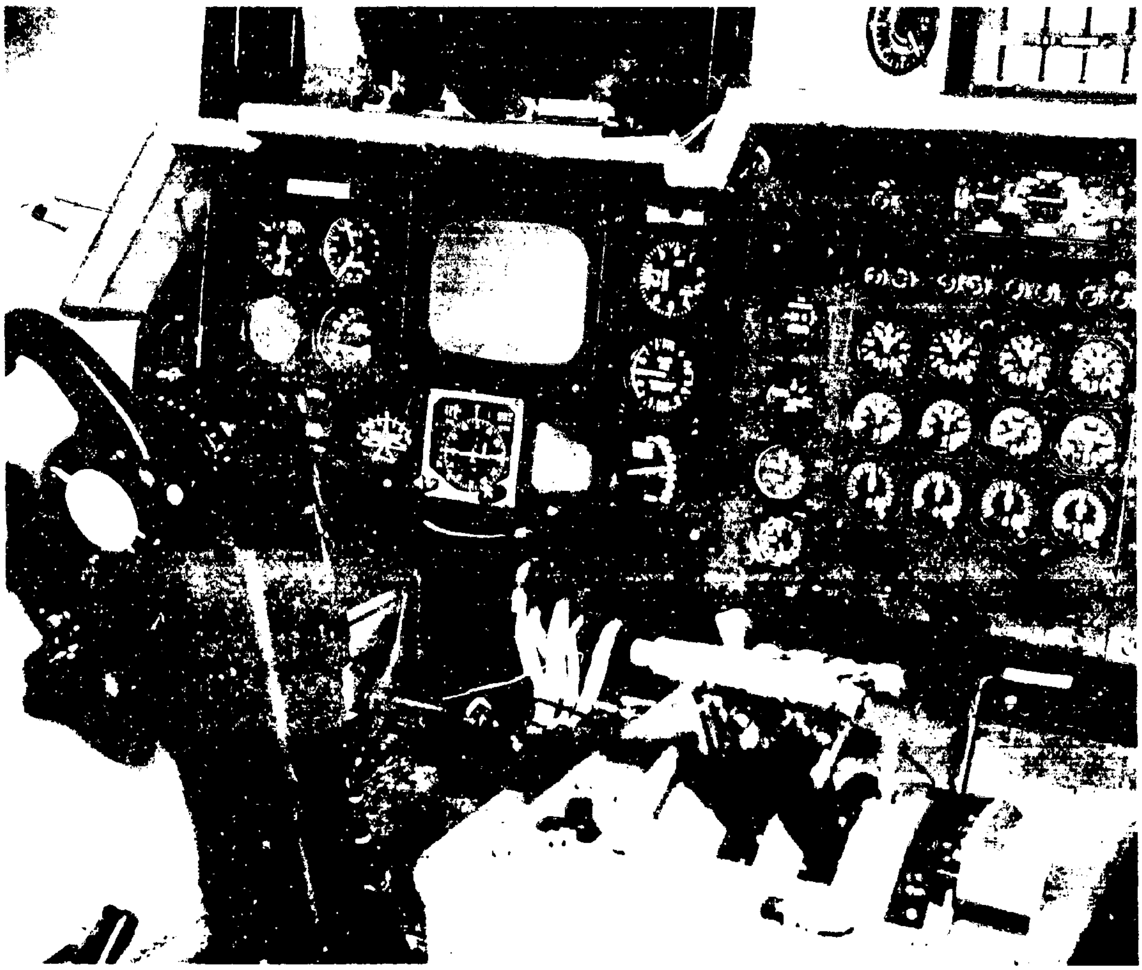
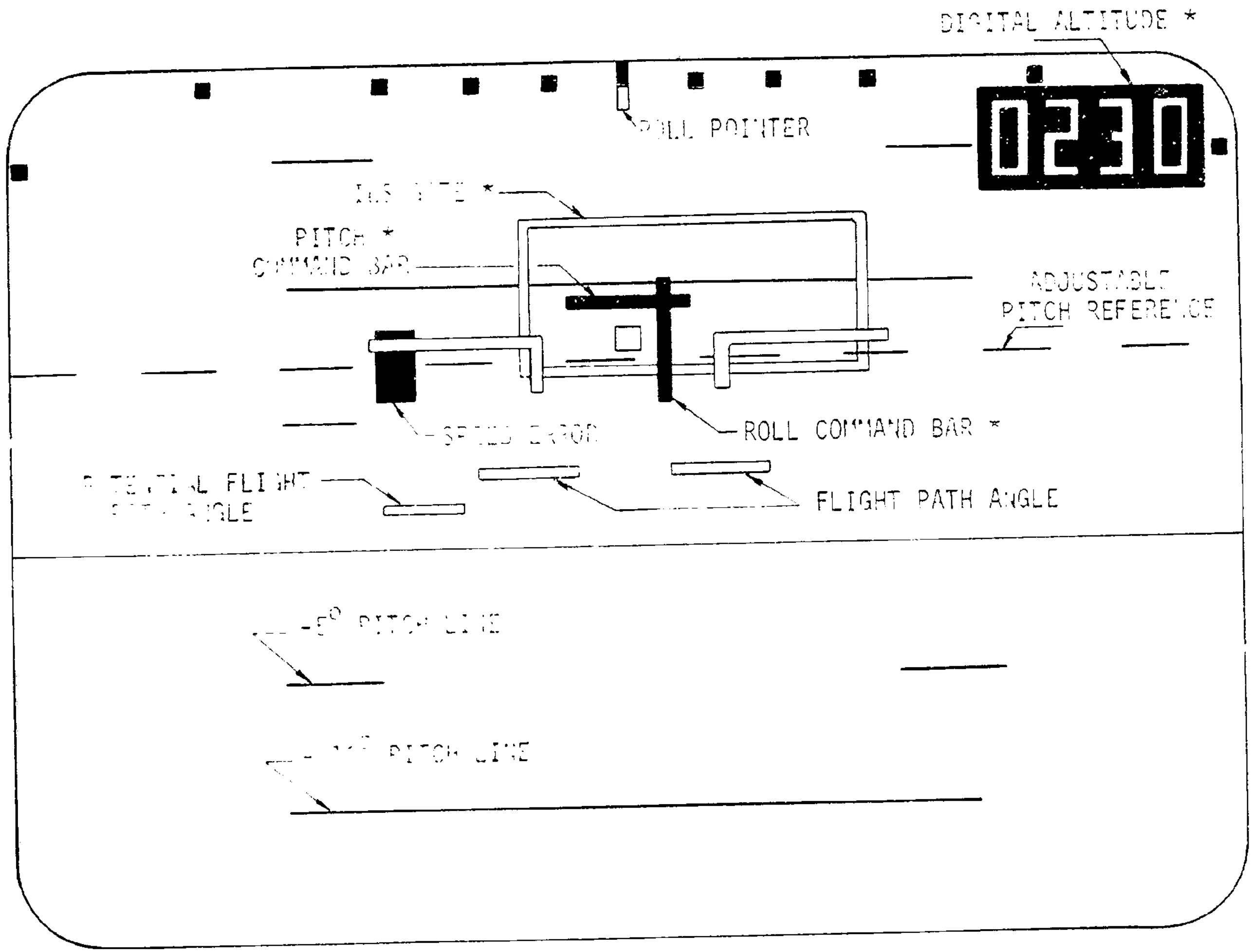




ELECTRONIC ATTITUDE DIRECTOR INDICATOR

Figure 4-

* USED DURING LANDING APPROACH ONLY

adjacent vertical scale instruments located to the immediate right of the ADI (Figure 4-1). With the EADI configuration these angles were displayed directly on the EADI display sclope (Figure 4-3).

The purpose of this flight path angle presentation was to aid the pilot in stabilizing the aircraft. When the potential and actual flight path angle are the same, the aircraft is neither accelerating nor decelerating. When the potential is less than the actual flight path angle the aircraft is decelerating and vise versa. With this additional presentation, thrust management, particularly at high speed, is much improved and does not detract from the primary task of longitudinal handling.

For a more detailed description of the technical aspects of the test facility, refer to the section of the Appendix titled "Simulation Facility Description".

This facility did prove to be a very useful tool in conducting this type of evaluation. Numerous pilot comments were received that favored the moving base feature over a fixed base simulator due to the added realism. The added realism was especially noticeable when attempting to stabilize the aircraft where the small variations in load factor were an aid to the pilot.

5.0 TEST AND ANALYSIS TECHNIQUE

The objective of this study was to develop handling qualities criteria for large advanced supersonic aircraft. The criteria were to be developed in terms of airplane response characteristics with primary emphasis on the longitudinal modes of motion. All experimental results were based on the results of piloted simulation evaluation using both Boeing and NASA test pilots.

The basic approach taken was to identify study areas where criteria development was important to future design concepts, and compatible with a piloted evaluation study using the FSAA. For each study area critical airplane response parameters were identified based on previous experience gained during the National SST Program and follow-on SST studies. Each parameter was then varied in a systematic manner holding all other parameters constant or near constant, and piloted evaluations conducted. For some study areas the effect of control force gradient, atmospheric turbulence, and pitch attitude display sensitivity were also evaluated as contributing parameters to the handling qualities criteria. The pilot evaluations of each test condition were done while flying the simulator through a specific sequence of tasks which were standardized for each study area. The pilots then rated each test condition using the Cooper-Harper rating scale (Reference 5) for the handling qualities rating, and a turbulence rating scale (Reference 6) for the cases involving turbulence. The pilot also provided comments to specific questions which were standardized for each study area. In addition to these evaluation ratings and comments provided by the pilot, data were obtained consisting of pilot describing function measurements, pilot workload measurements, and pilot performance measurements in conducting the tasks.

The parameters that were varied for the purpose of this evaluation will be described in the discussions of the test results covering each study area. Math model configurations required to achieve each specific response characteristic were defined during engineering calibration runs prior to the piloted evaluations. These calibration runs were achieved by measuring the longitudinal airplane response to either a column step or pulse command while making changes to the math model in the following areas:

- o longitudinal SAS gain
- o longitudinal SAS time constants
- o forward loop column prefilter
- o airplane center of gravity
- o airplane longitudinal moment of inertia
- o additional tail lift and pitching moment increments

All evaluations were made using the math model of the Boeing SST configuration, the 2707-300PT. The math model representation of this aircraft is described in Reference 4.

5.1 PILOT RATING SCALES

Pilot ratings were obtained using the Cooper-Harper rating scale (Reference 5) for the basic airplane handling qualities, and a turbulence rating scale (Reference 6) to describe the effect of atmospheric turbulence.

The Cooper-Harper rating scale (Figure 5-1) was used by all pilots to describe the longitudinal handling qualities immediately after conducting the specific pilot tasks which were standardized for each study area. Two lines of division were established on this rating scale to define normal operation and minimum-safe operation limits. These limits are the same as used during the National SST Program and have been universally accepted. The limiting pilot rating (PR) for normal operation tests was established as a rating of 3.5. This rating is the dividing line between a rating that requires no improvement (PR=3.0) and one that does warrant improvement (PR=4.0). Therefore, character-

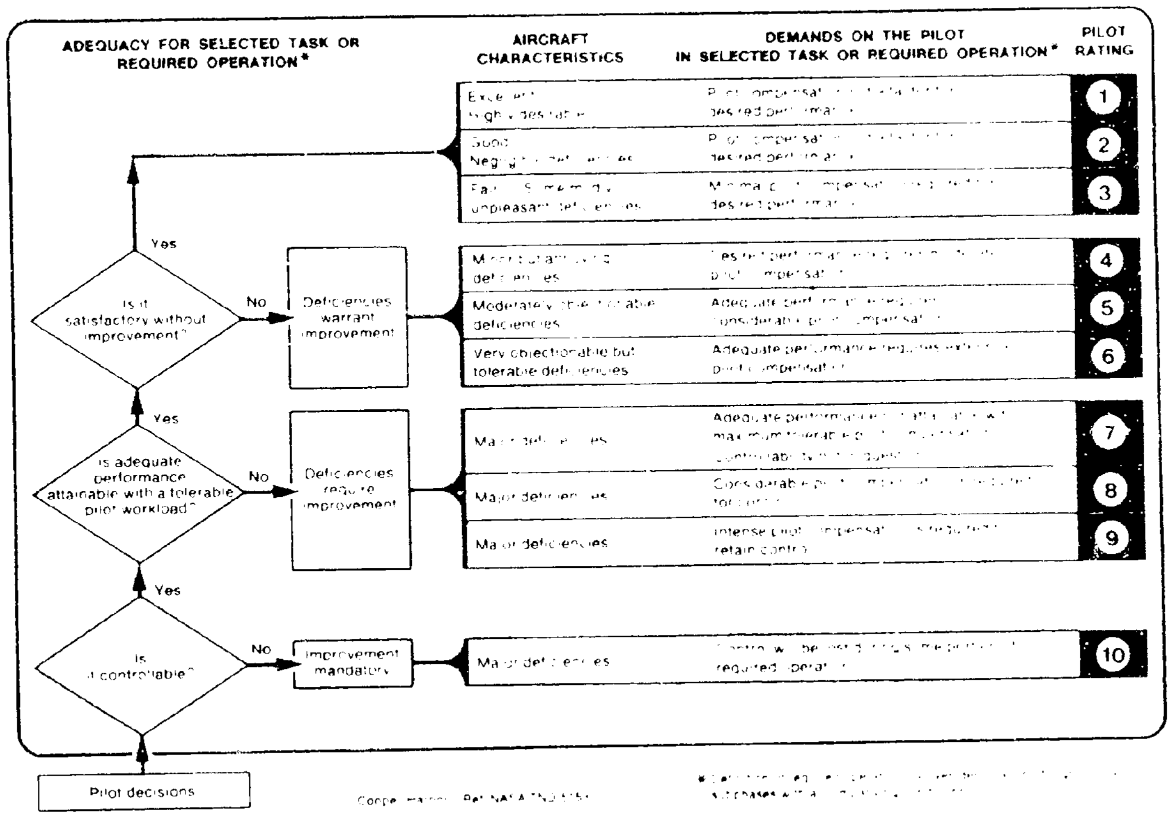


Figure 5-1. Handling Qualities Rating Scale

istics that result in a pilot rating of 3.5 or better are said to have satisfactory handling qualities for normal operation.

The other dividing line was established in a like manner at 6.5 for minimum-safe operation. This is half way between a rating that describes barely adequate performance and tolerable workload (PR=6.0) and one that describes inadequate performance and an untolerable workload (PR=7.0). Therefore, a characteristic that is rated 6.5 or better is considered acceptable for minimum-safe operation.

The turbulence rating schedule (Figure 5-2) describes the effects atmospheric turbulence has on handling qualities and pilot workload. As in the case with the Cooper-Harper scale, a boundary has been selected that represents the dividing line between acceptable versus unacceptable ratings. This represents the dividing line between a rating that describes a configuration where all tasks can be performed and one where some tasks cannot be performed. A rating of "F" or better represents a condition that is acceptable. A rating of "G" or worse represents a condition that is unacceptable.

5.2 PILOT MATH MODEL

The purpose for determining the pilot math model was to support the understanding and interpretation of the pilot rating data as well as advance the state-of-the-art in this area. The approach taken was to develop a method whereby the pilot rating trends could be predicted based on the pilot describing function along with additional performance and workload parameters readily available from the experimental data. In this way configurations resulting in large pilot rating scatter could be re-evaluated based on the pilot describing function technique and an indication of the best data fairing obtained. This approach was successful to a very limited degree in the landing approach (normal operation) study area and was the only study area where this approach was used.

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

FIGURE 5-2 - TURBULENCE EFFECT RATING SCALE

Data analysis by this technique requires extensive additional engineering effort in both data recording and set up requirements, as well as data reduction and analysis effort. Also, special piloted evaluation runs with a different but similar pilot task, were required to obtain the necessary data for analysis. This technique was applied only in the landing approach (normal operation) study area. This was dictated by a reduction in available evaluation test time over that originally planned and the need to conduct higher priority testing.

A description of this analysis technique is included in the appendix of this document, and includes the theory behind the approach, the calculation techniques, data handling, and analysis techniques. The correlation between the results of this analysis technique and the pilot rating data will be discussed in the appropriate section of the discussion covering test results of the landing approach (normal operation) study area.

5.3 WORKLOAD MEASUREMENTS

The measurement of pilot workload was accomplished by two different techniques. One was by the use of a side task for which the performance could easily be measured, and the second was by integrating the work produced by the pilot through column deflection over the test run.

Measuring pilot workload by the use of a side task is accomplished by measuring the performance of the pilot in performing the side task. In theory, an increase in pilot workload in performing the primary task, flying the airplane, will result in a decrease in his performance in accomplishing the side task. This should be true if the side task is considered by the pilot to be only a side task that is to be accomplished on a totally non-interference basis with respect to the primary task.

The side task selected for this particular study was a light cancelling task. Three lights were located in the cockpit, programmed to come on in a random fashion. The pilot was to turn the lights off when they did come on by pressing the light fixture itself. The performance measurement of this task was made by averaging the time the lights stayed lit. The longer the time duration, the poorer the performance of the side task.

This approach to a side task was believed representative of a normal side task that would occur in an aircraft cockpit which the pilot would need to perform during an actual flying situation. Location of the lights was selected to support this idea. One light was located directly in front of the pilot on the glare shield. Another was located at the far left of the instrument panel, on the window sill, and the third was located on the aisle stand immediately aft of the throttle quadrant which was just at the edge of his peripherial vision. These locations covered the full range of visual scan normally maintained by the pilot during the piloted tasks being flown.

This approach to measuring the pilot workload was not successful. Tests where the workload was obviously increasing, such as in the case with increased turbulence, resulted in a decrease, in some cases, in the average time the lights remained lit (Figure 5-3). This was exactly opposite to the expected results. The main reason attributed to the failure of this approach was the color of the lights used. The lights were amber, which usually denotes a significant malfunction in the cockpit. The attention, therefore, given to the side task was higher than desired. With an increase in work load, the pilot worked harder to keep the lights off in order to minimize his distractions.

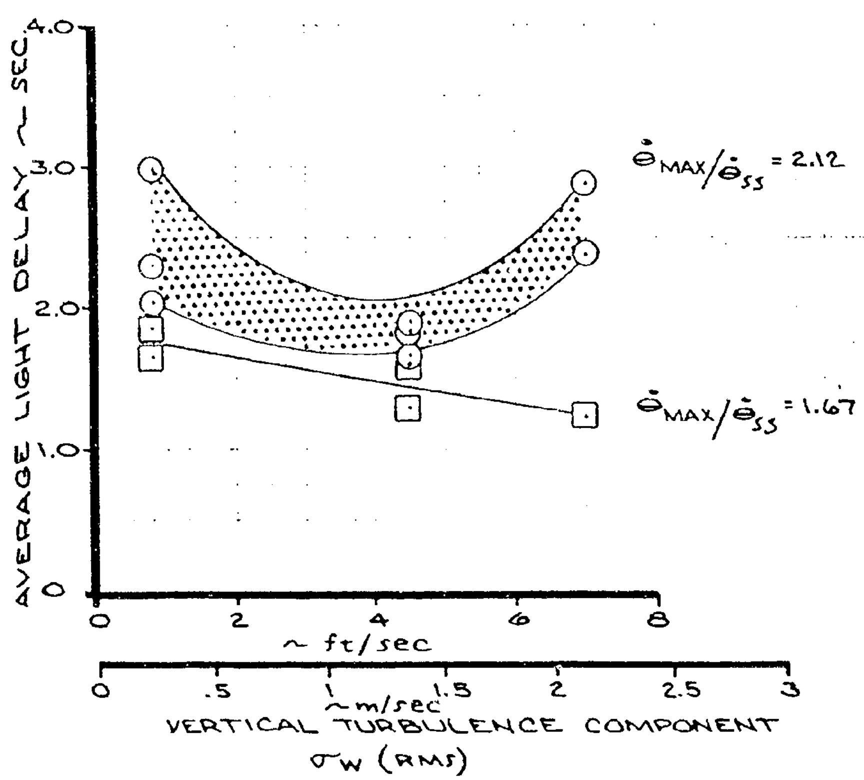
Plans were implemented to repeat this evaluation of the workload measurement technique using the side task with different colored lights, such as blue. Chances of success with blue lights were believed to be much greater since it is a color that the pilot is not trained to look out for and react to. However, this was not done due to a shortage of simulation evaluation time and higher priority work that needed to be accomplished.

RESPONSE CONFIGURATION:

- $\zeta \omega_h \approx .75$
- $T_{\dot{\theta}_{MAX}} \approx 1.5$ SEC.
- $F_{COL}/g = 50$ lb/g (222 N/g)

V_C = 144 kts (74 m/sec)
G.W. = 415,000 lb (188,240 kg)
C.G. = .54 C_R
GEAR DOWN
FLAPS = 20°

PILOT - C



			REVISED	DATE		
CALC					PILOT WORKLOAD SIDE TASK RESULTS WITH TURBULENCE	
CHECK						
APPD						FIG. 5-3
APPD					THE BOEING COMPANY	PAGE 18

The second method for measuring pilot workload was to integrate the work the pilot does through the control column over the test run. This is represented by the following formula:

$$\text{COLUMN WORK LOAD} = \frac{1}{T}\int_0^T (F_{col} \times \delta_{col})\, dt$$

This approach did represent the physical work the pilot was required to perform and was used to judge the validity of some of the pilot ratings, particularly in areas of large data scatter. This will be pointed out in the specific portion of the Study Results section where the workload data was successfully used to help interpret the pilot rating data.

5.4 WIND MODEL

The wind model was based on information contained in Reference 7. A summary of the wind model parameters is also contained in the appendix of this report.

Evaluations with the wind model were conducted for all but the high speed cruise evaluations that included the landing approach for normal and minimum-safe operation and the stall recovery control power tests. In all cases the maximum turbulence level was based on a probability of exceedence of 10^{-3} which defines a crosswind velocity of 25 knots (12.86 meters/second) at the reference height of 20 feet (6.1 meters). For the landing approach (normal operation) study and the stall recovery study, a terrain roughness factor (z_0) of 1.0 was used which defines the roughest terrain expected in the vicinity of any airport. With the combination of the wind velocity and roughness factor, the wind model produces a root mean square vertical turbulence component (σ_w) value of approximately 7.0 fps (2.13 meters per second). For the landing approach (minimum-safe operation) a terrain roughness factor of .15 was used which represents the normal airport terrain. Justification for using the lower roughness factor was based on the reduced probability of the minimum-safe configuration occurring. All probability estimates used in establishing the wind model configurations for each study area were obtained from probability studies conducted during the National SST Program.

6.0 EXISTING CRITERIA COMPARISON

The purpose of this study was to develop a handling qualities data base of aircraft response characteristics that will improve the data base of design criteria for large advanced supersonic aircraft. Emphasis was placed on the longitudinal axes since this is the area of greatest benefit in terms of increased airplane efficiency.

Comparisons against existing criteria were done where possible in order to substantiate, modify or de-emphasize the criteria established by previous studies. Where this approach was not appropriate new criteria were established. By accomplishing the analysis in this manner the strongest data base for longitudinal handling qualities criteria were believed to result for those areas investigated during this study.

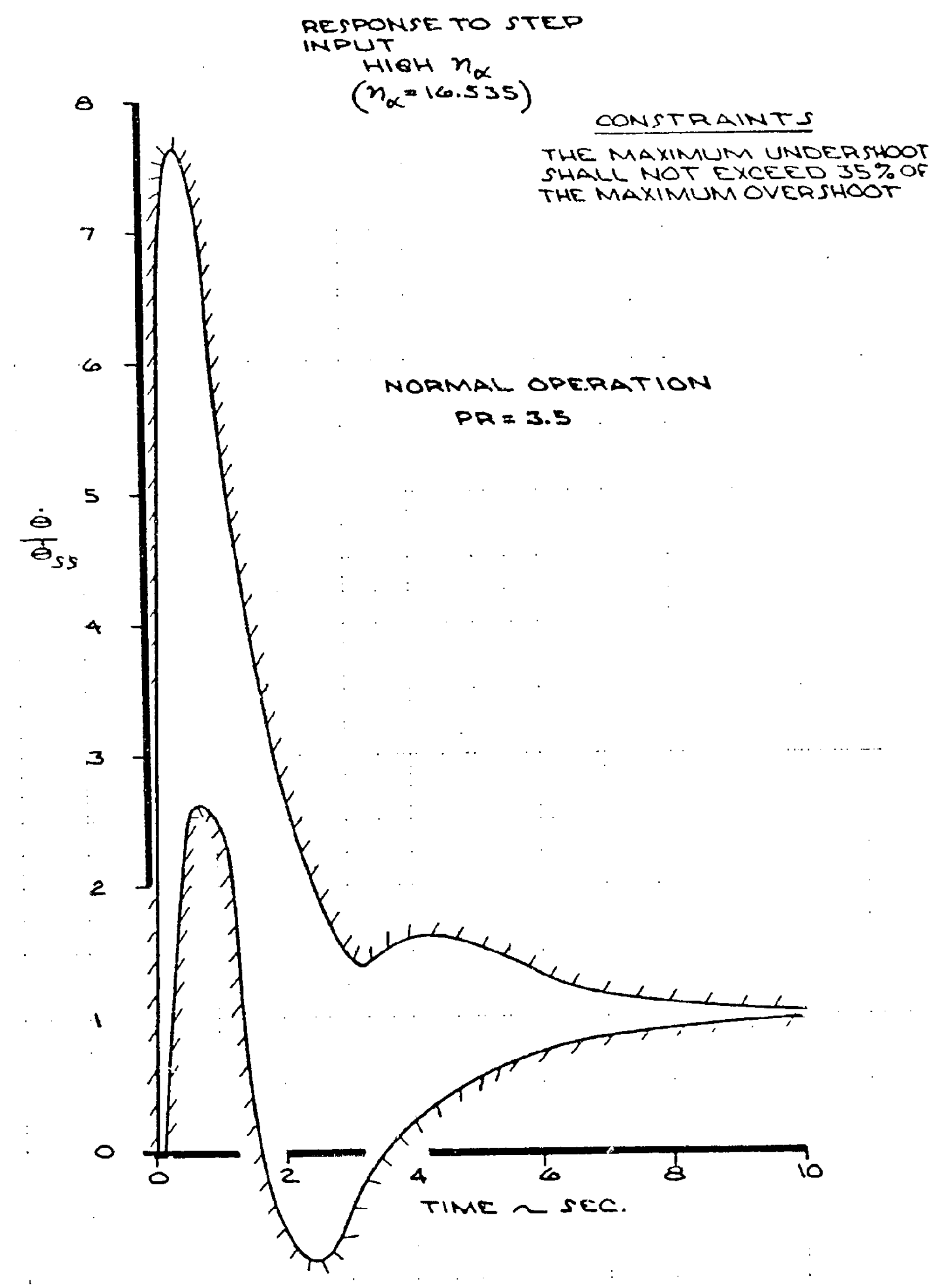
The greatest source of existing longitudinal handling qualities criteria for this type of vehicle has been from the National SST Program. During the National SST Program the sensitivity of airplane design to criteria variation, and hence the need for adequate criteria, was demonstrated. A considerable data base was established during that program since existing criteria at that time were found to be inadequate for maximum design efficiency of a vehicle of this type. The criteria from this data base used for comparison purposes were the SST Time Response Criteria for normal operation and the Pitch Divergence Criterion for minimum-safe operation. Other criteria used for comparison purposes consisted of the C* Longitudinal Handling Qualities Criterion and applicable criteria from the military handling qualities specification, MIL-F-8785B.

The SST Time Response Criteria were obtained from Reference 3. These criteria are in the form of time history envelopes in response to a step column input. Pitch rate and normal load factor are the terms used to define these time history envelopes as seen in Figures 6-1 through 6-3. These envelopes and these criteria are based on the Shomber-Gertsen Criteria. The Shomber-Gertsen Criteria are based on the results of several other studies and is expressed in terms of L_α/ω_n and n_α/ω_n versus damping ratio (ξ). By expressing the results of the other studies in these terms the results were found to converge into common boundaries as detailed in Reference 8 and presented in Figure 6-4.

The problem with using the Shomber-Gertsen Criteria directly is that they are based on a simple second order system and direct comparison with higher order systems would be inappropriate. However, such a comparison is possible by comparing the time history response to a common input command such as a column step of the second order system to the higher order system. This was the approach taken during the National SST Program in developing the longitudinal response time history criteria which will be referred to as the SST Time Response Criteria in this report.

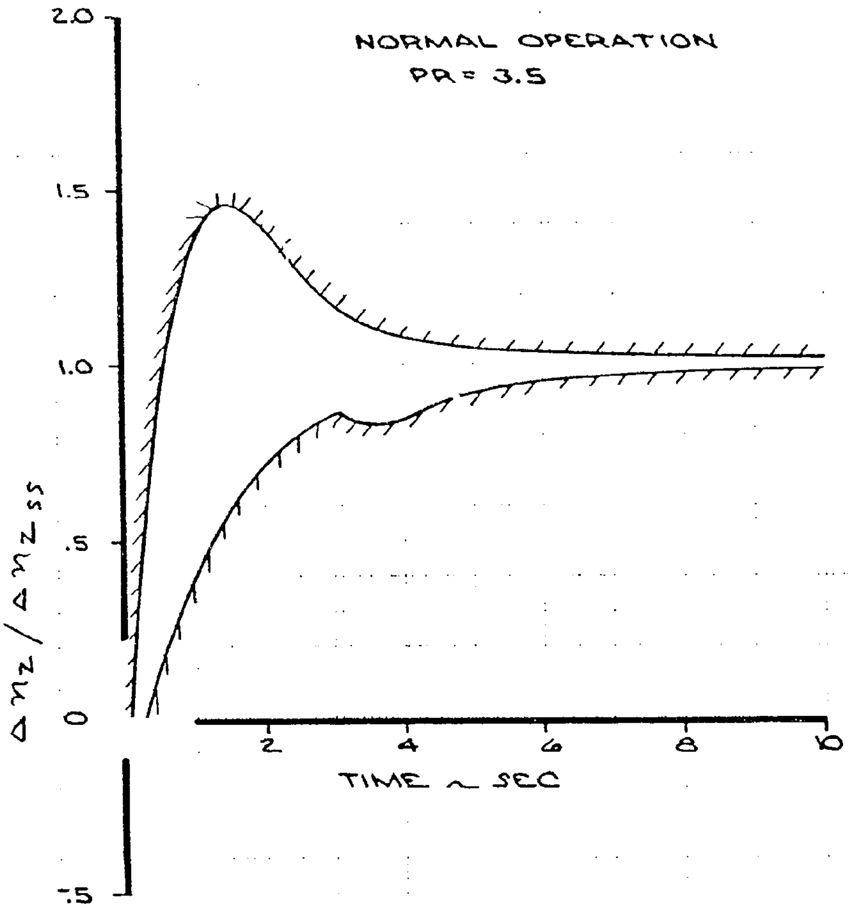
The pilot rating scale used in the Shomber-Gertsen Criteria was the Cooper rating scale (Reference 8) presented in Figure 6-5. This rating scale is a simplified version of the present Cooper-Harper rating scale (Reference 5), presented in Figure 5-1. Results obtained with this earlier scale are believed comparable with results obtained using the later scale. The critical dividing lines are the same. That is, between the ratings 3 and 4 the airplane handling qualities change from satisfactory (indicating no improvement necessary) to unsatisfactory; and between the ratings 6 and 7 the airplane handling qualities change from acceptable to unacceptable. These are the same critical judgments made during this simulation study.

The C* criterion was derived by Boeing using flight test results from the Cornell Aeronautical Laboratories (now known as Calspan) variable stability airplane and the Boeing Model 367-80 variable stability airplane (Reference 9). The criterion consists of a term designated C* which is computed using both



CALC			REVISED	DATE	SST HIGH SPEED PITCH RATE RESPONSE CRITERION	FIG. 6-1
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 23

RESPONSE TO STEP INPUT
HIGH n_α
($n_\alpha = 16.535$)



			REVISED	DATE		
CALC					SST HIGH SPEED LOAD FACTOR RESPONSE CRITERION	
CHECK						
APPD						FIG. 6-2
APPD					THE BOEING COMPANY	PAGE 24

AD 4982 C

6 5000

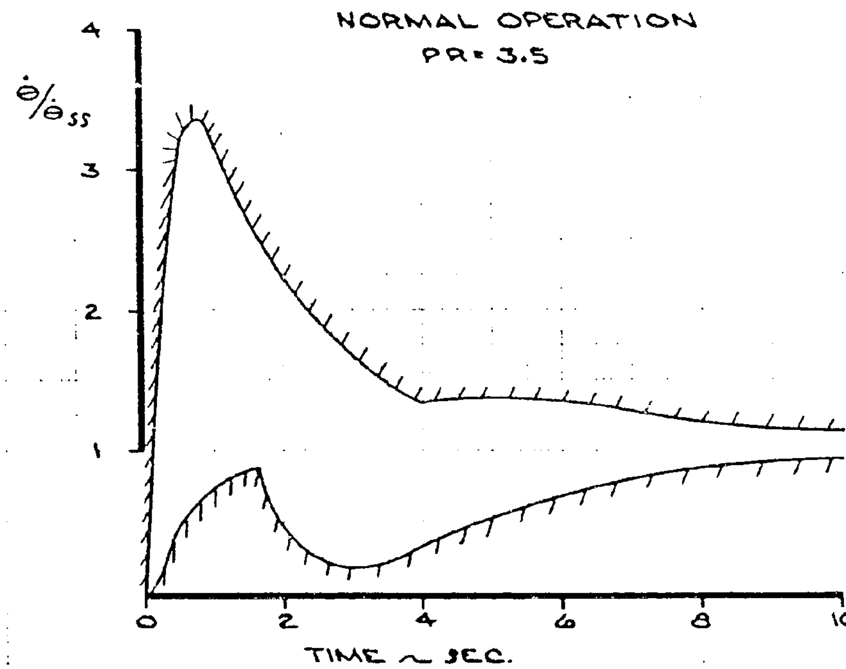
RESPONSE TO STEP INPUT

LOW η_α

$(\eta_\alpha = 3.981)$

CONSTRAINTS

1) THE MAXIMUM UNDERSHOOT SHALL NOT EXCEED 35% OF THE MAXIMUM OVERSHOOT.
2) WHEN THE MAXIMUM OVERSHOOT IS LESS THAN 20% OF $\dot{\theta}_{ss}$, THE RISE TIME FROM 0.10 TO 0.70 $\dot{\theta}_{ss}$, SHALL NOT EXCEED .8 SEC.

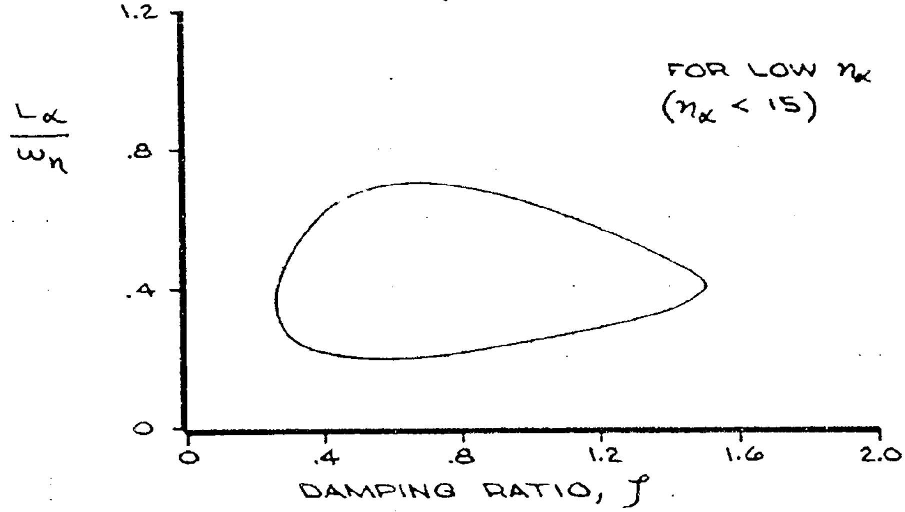


CALC			REVISED	DATE	SST LOW SPEED PITCH RATE RESPONSE CRITERION	FIG. 6-3
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 25

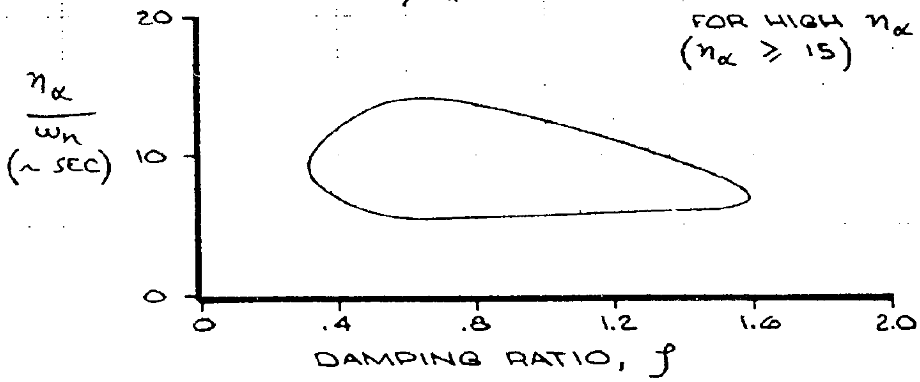
NORMAL OPERATION

PR = 3.5

L_α/ω_n CRITERIA



n_α/ω_n CRITERIA



REFERENCE:
AIAA PAPER
65-780

CALC			REVISED	DATE	SHOMBER - GERTSEN LONGITUDINAL HANDLING QUALITIES CRITERIA	FIG. 6-4
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 26

COOPER RATING SCALE

CATEGORY	ADJECTIVE DESCRIPTION WITHIN CATEGORY	NUMERICAL RATING
ACCEPTABLE AND SATISFACTORY	EXCELLENT	1
	GOOD	2
	FAIR	3
ACCEPTABLE BUT UNSATISFACTORY	FAIR	4
	POOR	5
	BAD	6
UNACCEPTABLE	BAD	7
	VERY BAD	8
	DANGEROUS	9
	UNFLYABLE	10

ADDITIONAL DEFINITIONS OF UNACCEPTABLE CATEGORY:

7 BAD - AIRCRAFT CONTROLLABLE, BUT REQUIRES MAJOR PORTION OF PILOT'S ATTENTION

8 VERY BAD - AIRCRAFT CONTROLLABLE, BUT ONLY WITH A MINIMUM OF COCKPIT DUTIES

9 DANGEROUS - AIRCRAFT JUST CONTROLLABLE WITH COMPLETE ATTENTION

10 UNFLYABLE

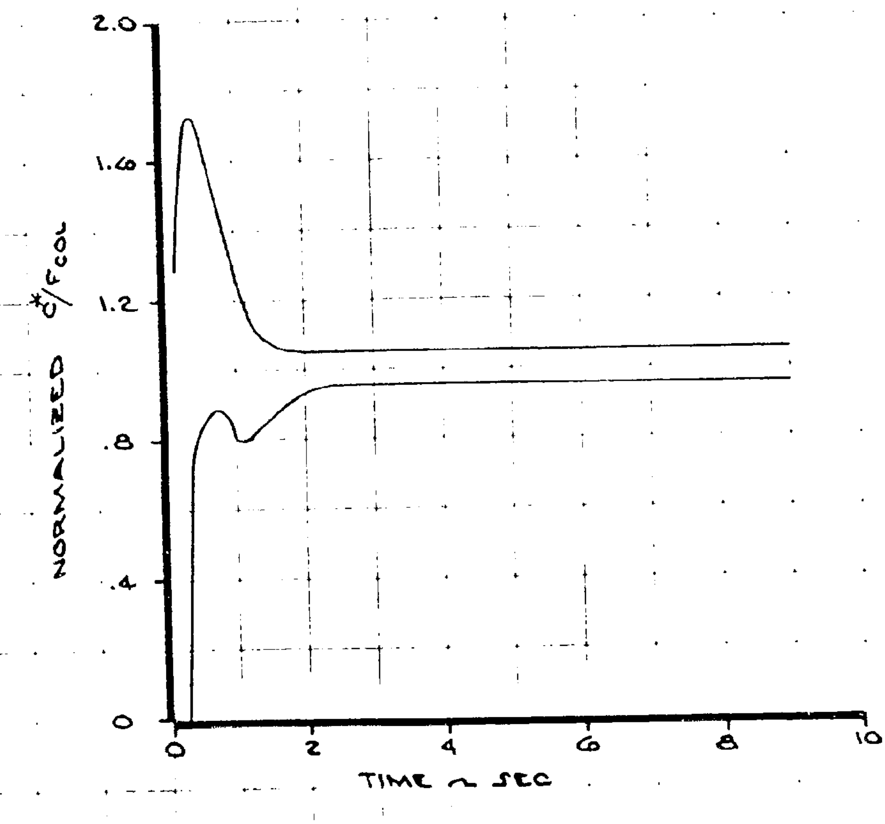
FIGURE 6-5

pitch rate and normal acceleration. The time history of this term in response to a column step input must fit inside a specified time history response envelope for the handling qualities to be acceptable (Figure 6-6).

Extensive work was done in the area of minimum-safe handling qualities criteria. The purpose of such criteria is to define the allowable degradation of handling qualities (as could result from stability augmentation system failures) that would still provide safe handling qualities under emergency situations. The primary area of importance for this problem is landing approach, which was one of the study areas selected for this study contract. The minimum-safe criteria established during the National SST Program were based on the rate of pitch divergence as the result of a momentary pitch disturbance such as a longitudinal pulse input. This same approach was taken during this study, and a typical response is presented in Figure 6-7. The divergence rate determined acceptable during the National SST Program was a time-to-double pitch amplitude of 6.0 seconds. The divergence rate criterion from the National SST Program was based on the most unstable root. Basing the criterion on the most unstable root was done for ease of control system design. During this simulation study the method for measuring the divergence rate is believed to result in a measurement of the most unstable root. This allows direct comparison with the National SST Pitch Divergence Criterion.

The military specification, MIL-F-8785B, was examined in terms of the specified limits of short period natural frequency, pitch damping ratio and column force gradient. However, the criteria in this specification have been based on parameter variations of a second order system which are not directly applicable to the results of this study. This study utilizes an actual non-linear airplane math model and augmentation system which results in pitch response characteristics of a much higher order than a second order system. This study, as well as the National SST criteria development study, was direc

LEVEL 1
PILOT RATING 3.5



			REVISED	DATE	
CALC					C* HIGH SPEED CRITERION
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APPD					THE BOEING COMPANY

FIG. 6-6

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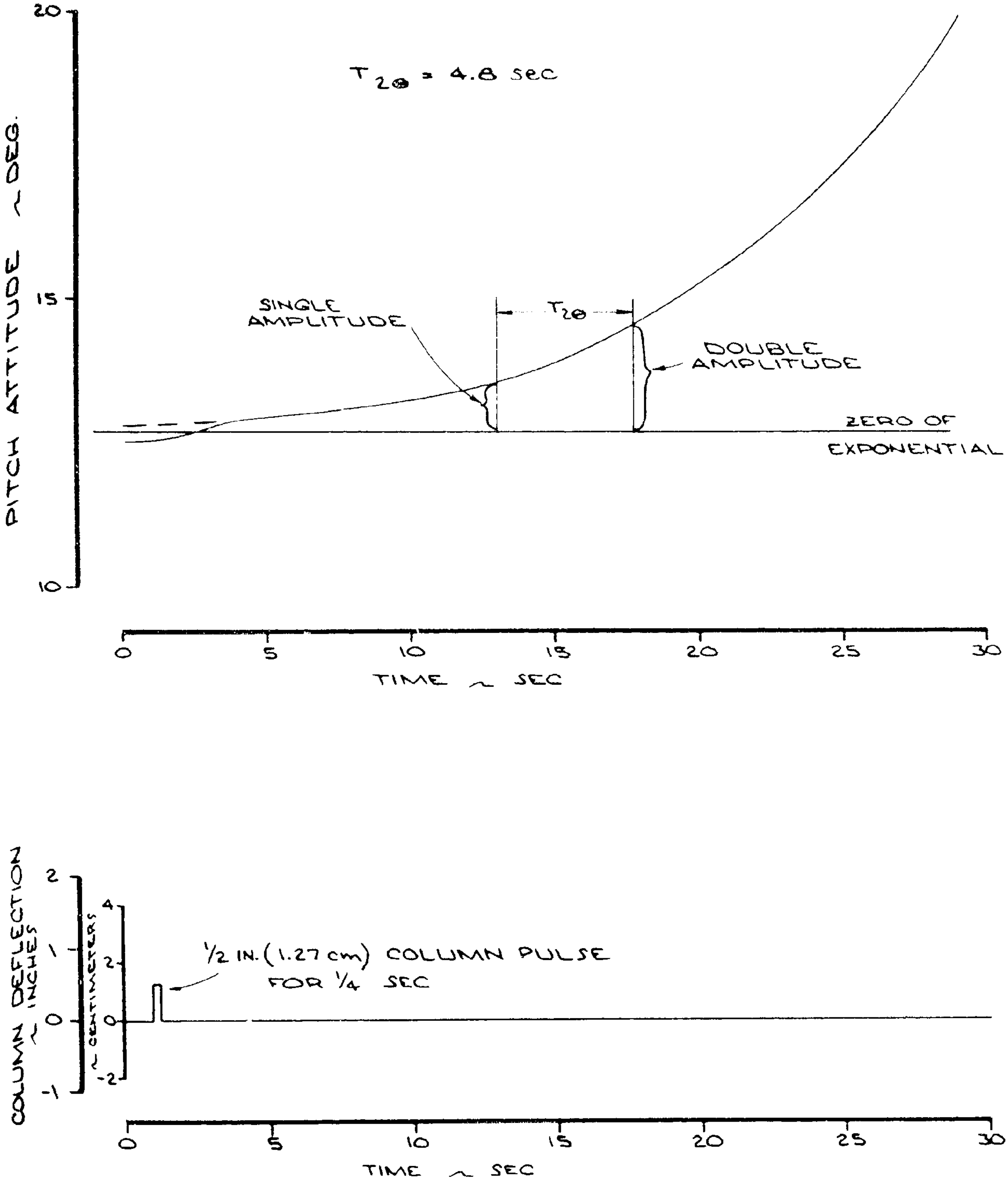

ENGR			REVISED	DATE	MINIMUM - SAFE CALIBRATION TIME HISTORY	FIG. 6-7
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at developing a criteria data base that could be applied to aircraft that had predominantly higher order pitch response characteristics.

7.0 STUDY RESULTS

This piloted simulation study was broken down into separate study areas each covering a particular flight regime or characteristic. The results of the work done in each study area will be presented separately along with a description of the test techniques and a description of the analysis used.

7.1 HIGH SPEED CRUISE MANEUVERING

High speed cruise presents a different set of handling qualities requirements than does low speed. This is mainly attributable to the large true velocity vector and the resulting sensitivity of rate of climb or descent to longitudinal attitude and rate of change of attitude. These requirements are reflected in the pitch attitude display sensitivity requirements, the desired longitudinal response characteristics, and the importance of load factor as a short period parameter.

The flight condition for this evaluation was the condition occurring at the end of supersonic climb for the 2707-300PT airplane, identified as follows:

- o Mach 2.7
- o 60,000 feet altitude (18,288 meters)
- o 567 knots CAS (292 meters per second)
- o 555,000 pounds gross weight (251,744 kilograms)
- o 62% center of gravity (aft limit)

The parameters identified for evaluation of this study area were the short period response parameters measured in terms of pitch rate and expressed in the following terms:

- o pitch rate overshoot ratio, $\dot{\theta}_{max}/\dot{\theta}_{ss}$
- o time-to-peak pitch rate, $T_{\dot{\theta}_{max}}$
- o pitch damping constant, $\zeta\omega_n$

These expressions define the pitch axis short period response characteristics evaluated and are the same parameters evaluated in the landing approach (normal operation) study area. These same short period responses were also analyzed in terms of the normal load factor response characteristics.

The response characteristics just identified were developed according to the technique described in the "Test and Analysis Technique" section of this report. The forcing function for the engineering calibration runs was an unpiloted column step input.

In addition to the short period response parameters, the effect of variations of the column force gradient and pitch attitude display sensitivity were also evaluated. Table 7-I presents the complete matrix of the parameters used in the evaluation of this study area. Time histories for the short period response parameters in terms of normalized pitch rate are presented in Figures 7-1 through 7-3. These same short period response conditions in terms of normalized load factor response, are presented in Figures 7-4 through 7-6. Both sets of time histories have been normalized to a steady state value of unity.

Results of the evaluation of each parameter will be discussed separately in the following sections. Under each section the results will be compared against the existing criteria listed below:

- o SST Time Response Criteria
- o C* Longitudinal Handling Qualities Criteria
- o Military Specifications (MIL-F-8785B)

The pilot task description for evaluation of this study area is presented in Figure 7-7.

7.1.1 Pitch Attitude Display Sensitivity

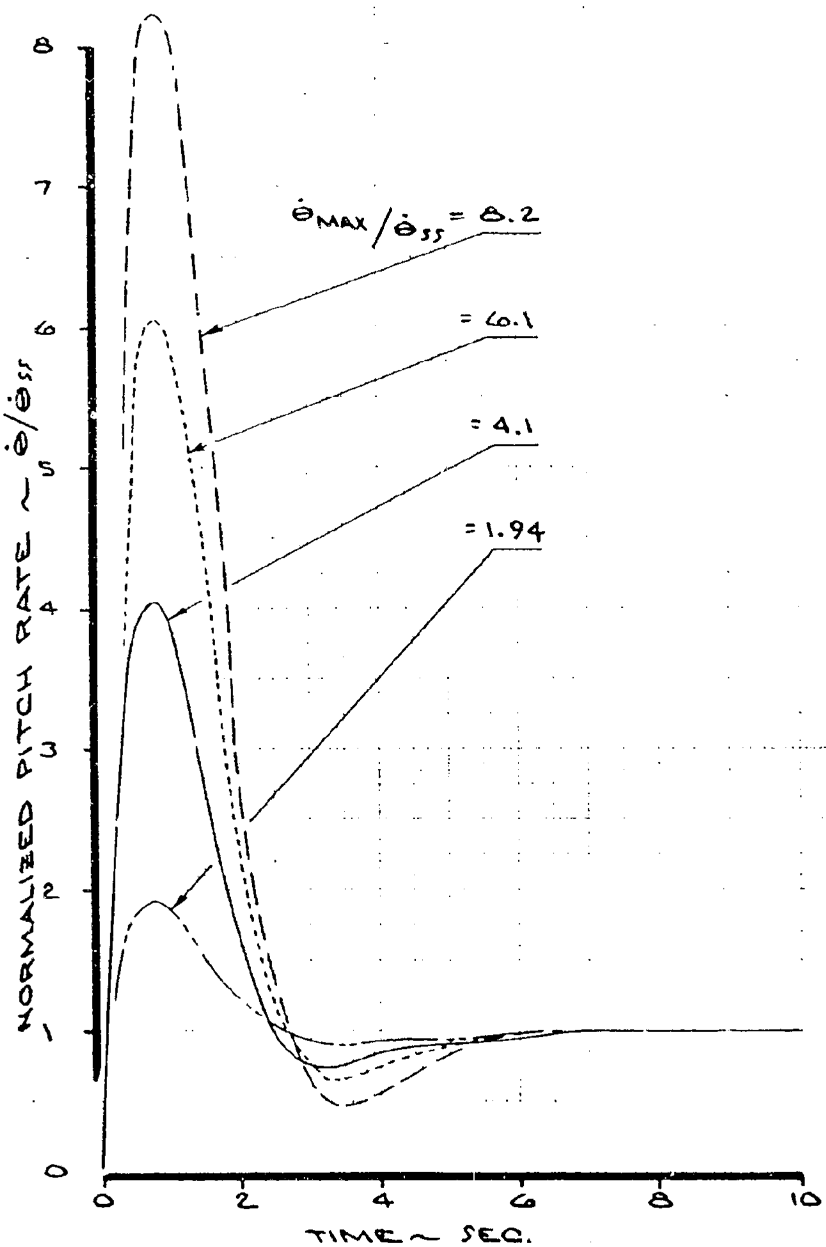
For all testing in this study area the electronic attitude director indicator (EADI) was used (Figure 4-3). Variation of the pitch attitude scale

TABLE 7-I

HIGH SPEED CRUISE MANEUVERING TEST CONDITIONS

PARAMETERS VARIED	NUMBER OF PILOTS EVALUATING (Smooth Air)
EADI PITCH SCALE	
in/deg = .16	2
.23	2
* .30	2
PITCH RATE OVERSHOOT RATIO	
$\dot{\theta}_{max}/\dot{\theta}_{ss}$ = 1.94	2
* 4.10	-
6.10	2
8.2	2
TIME TO PEAK PITCH RATE	
$T_{\dot{\theta}_{max}}$ = .45 sec	2
* .80	-
1.40	2
2.0	2
DAMPING CONSTANT	
$\zeta\omega_n$ = .36	2
* .90	-
2.42	2
COLUMN FORCE GRADIENT	
F_{col}/q = 10 lb/q	1
* 25	-
45	1
64	1

* Baseline configuration



			REVISED	DATE	PITCH RATE OVERSHOOT RATIO RESPONSES HIGH SPEED CRUISE	FIG. 7-1
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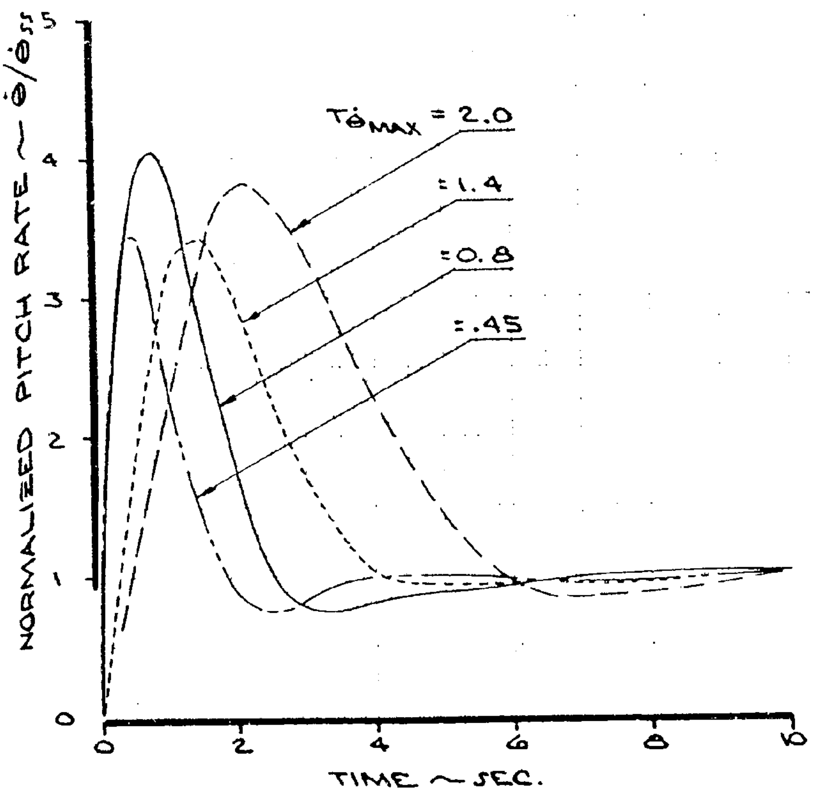
		-			THE BOEING COMPANY	PAGE 35



CALC			REVISED	DATE	TIME-TO-PEAK PITCH RATE RESPONSES HIGH SPEED CRUISE	
CHECK						FIG. 7-2
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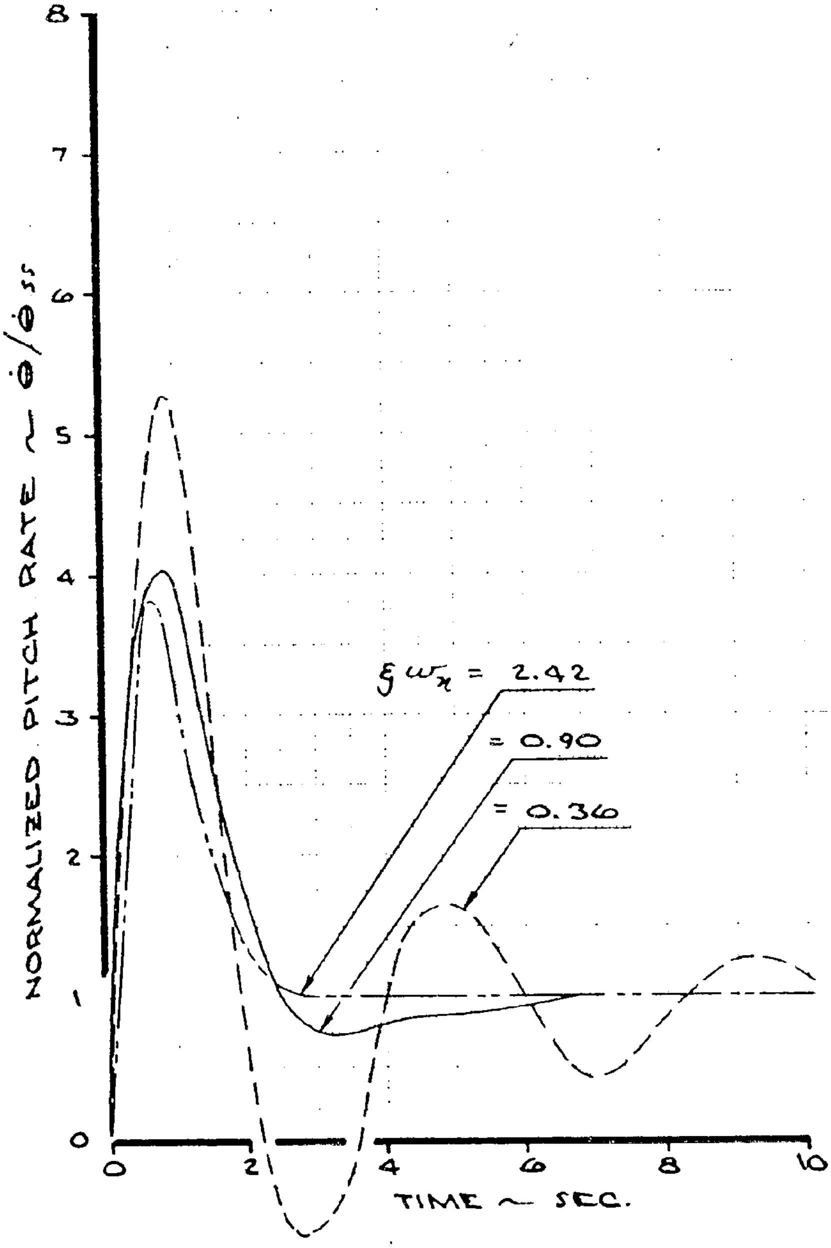
APPD					THE BOEING COMPANY	PAGE 36



CALC			REVISED	DATE	PITCH DAMPING RESPONSES HIGH SPEED CRUISE	FIG. 7-3
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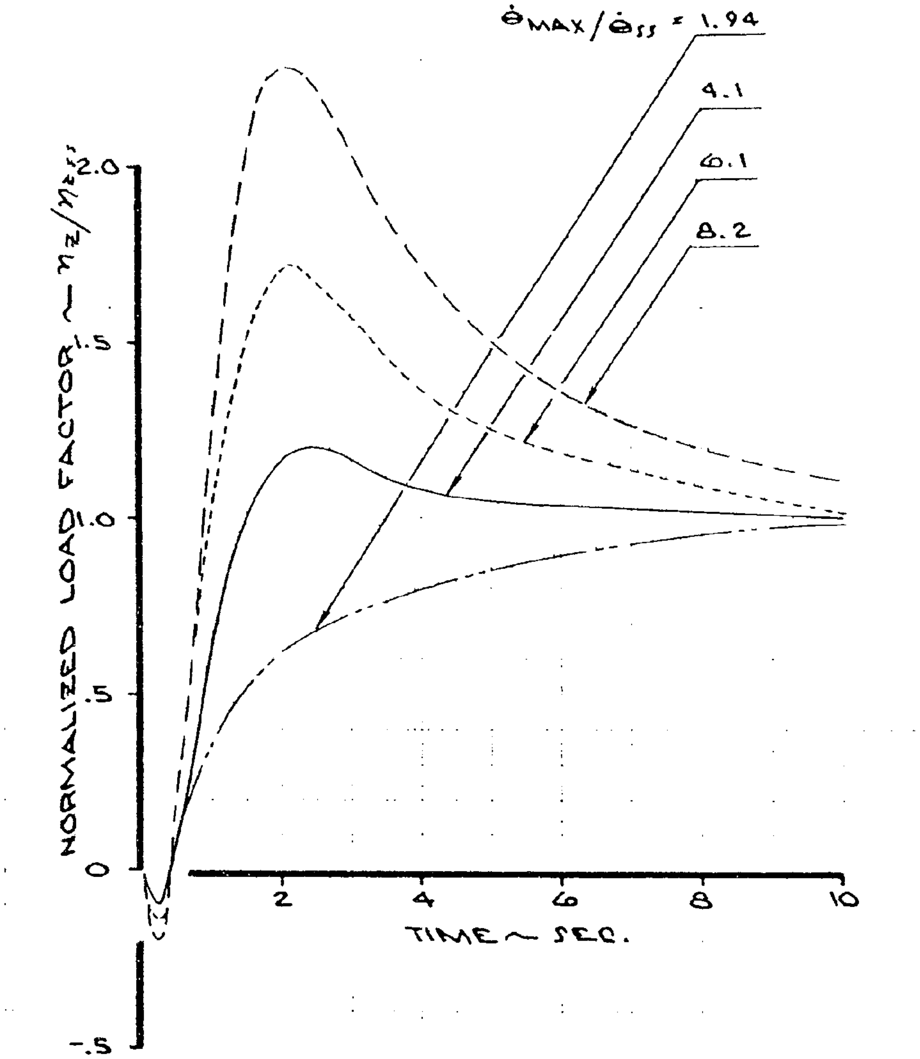
APPD					THE BOEING COMPANY	PAGE 37



CALC			REVISED	DATE	LOAD FACTOR RESPONSES TO PITCH RATE OVERSHOOT RATIO TESTS HIGH SPEED CRUISE	FIG. 7-4
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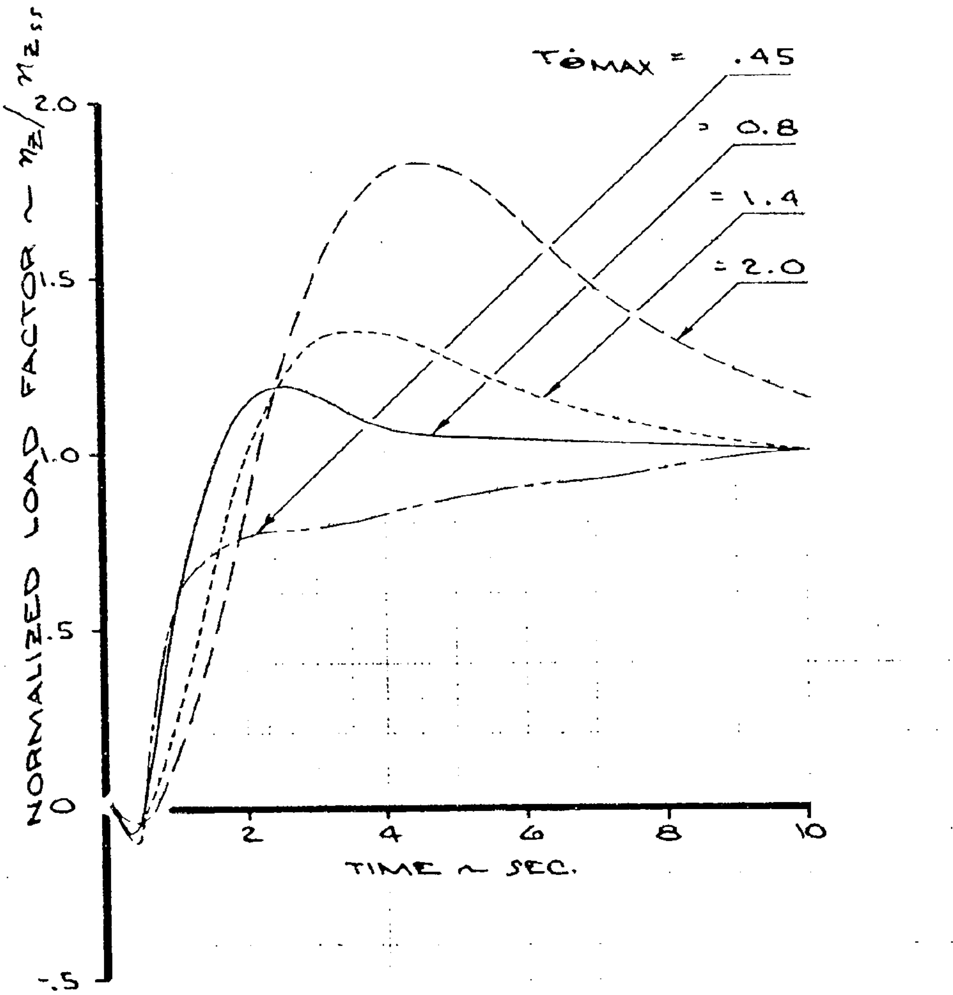
APPD					THE BOEING COMPANY	PAGE 38



CALC			REVISED	DATE	LOAD FACTOR RESPONSES TO TIME-TO-PEAK PITCH RATE TESTS HIGH SPEED CRUISE	FIG. 7-3
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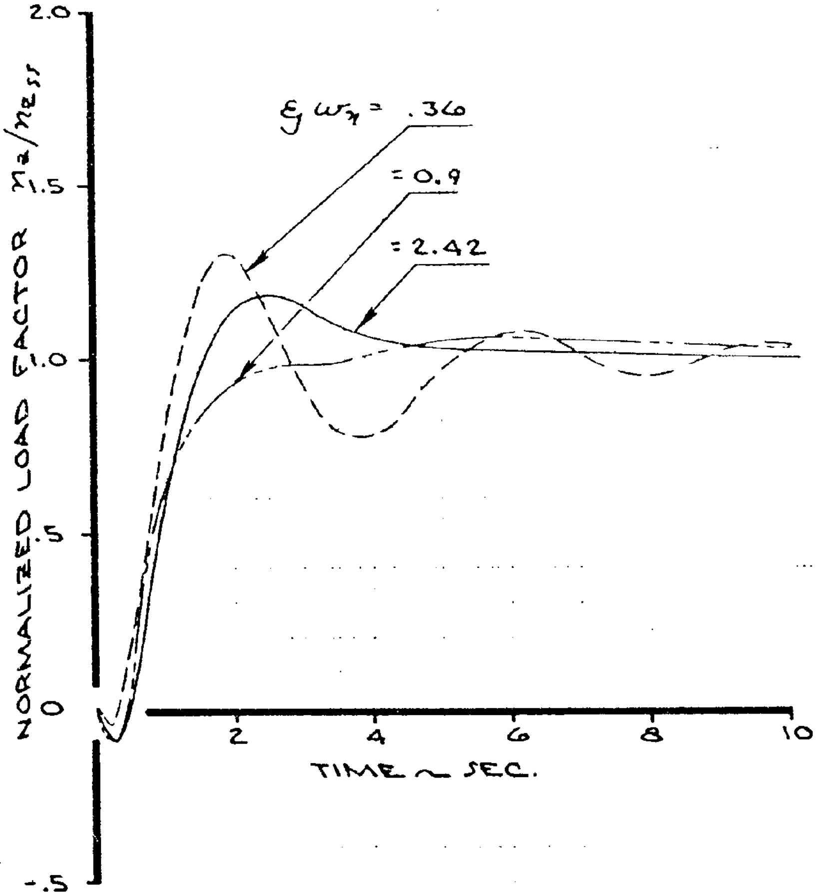
APPD					THE BOEING COMPANY	PAGE 39



CALC			REVISED	DATE	LOAD FACTOR RESPONSES TO PITCH DAMPING TESTS HIGH SPEED CRUISE	FIG. 7-6
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APPD					THE BOEING COMPANY	PAGE 40

HIGH SPEED CRUISE MANEUVERING
PILOT TASK

ALTITUDE CHANGES (HOLDING MACH NO. CONSTANT):

1. CLIMB 250 FT @ 500 FPM (76M @ 152M/MINUTE) AND STABILIZE
2. DESCEND 750 FT @ 1000 FPM (229M @ 305M/MINUTE) AND STABILIZE
3. CLIMB 1000 FT @ 2000 FPM (305M @ 610M/MINUTE) AND STABILIZE
4. DESCEND 500 FT @ 500 FPM (152M @ 152 M/MINUTE) AND STABILIZE

AIRSPEED CHANGES (HOLDING ALTITUDE CONSTANT):

1. INCREASE SPEED 20 KNOTS AND STABILIZE
2. DECREASE SPEED 40 KNOTS AND STABILIZE
3. INCREASE SPEED 20 KNOTS AND STABILIZE

HEADING CHANGES (HOLDING ALTITUDE AND AIRSPEED CONSTANT)

1. TURN 15^{o} LEFT IN 15^{o} BANK AND LEVEL OFF
2. TURN 20^{o} RIGHT IN 30^{o} BANK AND LEVEL OFF

FIGURE 7-7

was desired as part of the evaluation of this study area since a greater sensitivity is required at high supersonic cruise speeds than at subsonic cruise speeds. The pitch attitude scale sensitivity requirement should be roughly proportional to the magnitude of the true velocity vector which defines the relationship between a change in vertical velocity and a change in pitch attitude. For example, one degree of pitch attitude at Mach 2.7 results in 2900 feet per minute vertical velocity. At Mach .8 one degree of pitch change results in approximately 800 feet per minute vertical velocity. With the requirement established for a greater pitch attitude sensitivity, the objective was to first define the optimum pitch attitude sensitivity and then conduct all other evaluations at that scale sensitivity value.

Three pitch scale values were evaluated as seen in Table 7-I. The results of this study are presented in Figure 7-8. Both pilots preferred the .30 inches/deg. (.762 centimeters/deg) sensitivity according to the ratings given and according to their comments. They were both given their choice of any of the three settings for the remainder of the evaluation of this study area, and both selected the most sensitive setting. Also, it should be pointed out that this was the most sensitive setting possible with the EADI system available. This was due to the spacing of the pitch bars approaching the limit of the screen size available. Pilot comments were received during evaluation of other parameters indicating a more sensitive pitch scale would be desirable.

7.1.2 Pitch Rate Overshoot Ratio

The data are plotted and faired in Figure 7-9. The fairing selected shows the optimum value of overshoot ratio to be less than the lowest value tested of 1.94. Therefore, a lower limit could not be established from these tests. The upper limit, however, is shown to be 7.1, which compares favorably with the peak value of 7.6 obtained from the SST High Speed Pitch Rate Response Criterion

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} = 4$

$T\dot{\theta}_{MAX} = 0.9$ SEC

$\zeta\omega_n = 0.9$

$F_{COL}/g = 25$ LB/g (111 N/g)

TEST CONFIGURATION

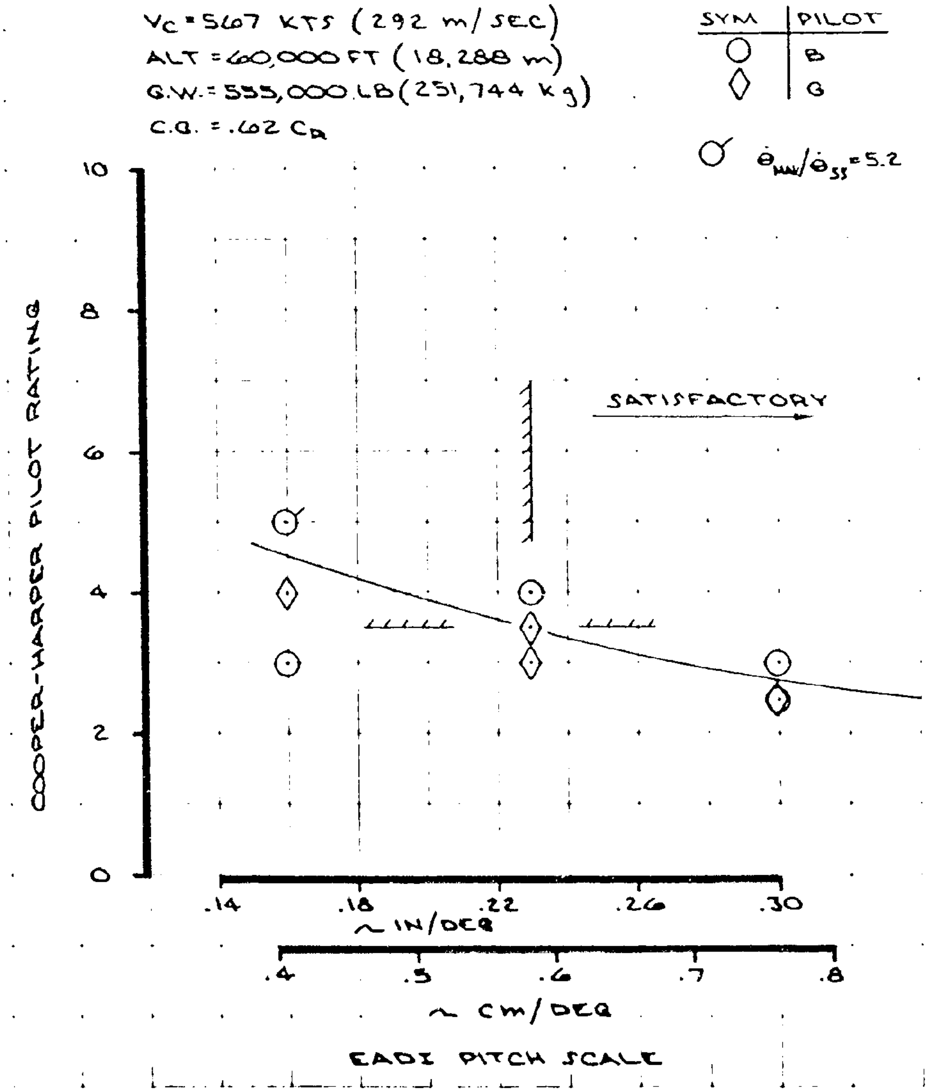
MACH NO. = 2.7

$V_C = 567$ KTS (292 m/SEC)

ALT = 60,000 FT (18,288 m)

G.W. = 555,000 LB (251,744 kg)

C.G. = .62 C_R



CALC			REVISED	DATE	HIGH SPEED CRUISE EVALUATION OF EADI PITCH SCALE SENSITIVITY	FIG. 7-8
CHECK						
APPD					THE BOEING COMPANY	PAGE 43
APPD						

RESPONSE CONFIGURATION

$T_{\dot{\theta}_{MAX}} \approx 0.9$ SEC

$\zeta\omega_n \approx 0.9$

$F_{COL}/g = 25$ LB/g (111 N/g)

EADI SCALE = .30 IN/DEG (43.7 cm/RAD)

TEST CONFIGURATION

MACH NO. = 2.7

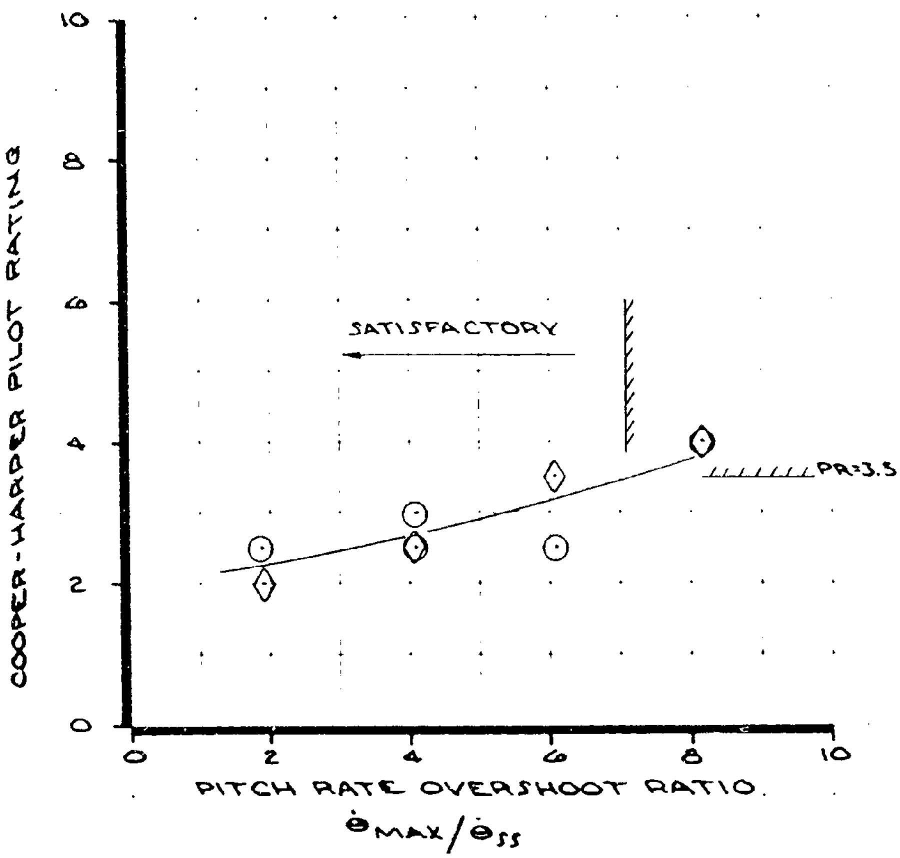
V_C = 567 KTS (292 m/SEC)

ALT = 60,000 FT (18,288 m)

G.W. = 555,000 LB (251,744 kg)

C.G. = .62 C_R

SYM	PILOT
○	B
◇	G



CALC			REVISED	DATE	HIGH SPEED CRUISE EVALUATION OF PITCH RATE OVERSHOOT RATIO	FIG. 7-9
CHECK						
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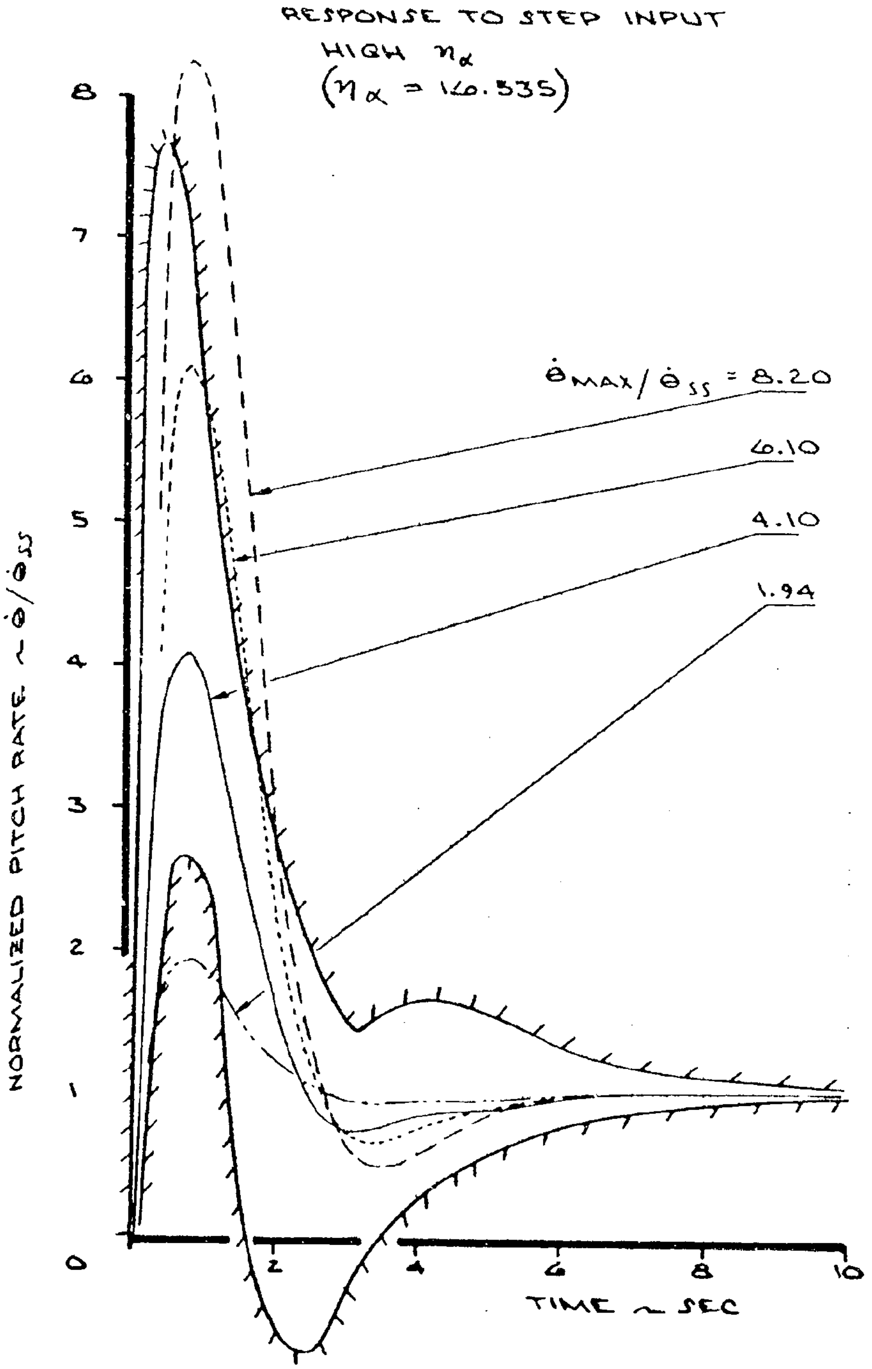
APPD					THE BOEING COMPANY	PAGE 44

(Figure 7-10). However, as seen in this figure, the criterion shows a time to reach this overshoot ratio as .5 seconds, and for these tests the time to reach an overshoot ratio of 7.1 can be interpolated to be .9 seconds, which could account for the slight difference in the satisfactory maximum level. By comparing this value of overshoot ratio and time-to-peak value against the time history envelope of the SST High Speed Pitch Rate Response Criterion, it can be seen that the limiting response condition would fall just slightly outside the boundary. Based on the scatter in the pilot rating data, and the fact the described differences are very slight, no change is recommended in the upper limit of the SST High Speed Pitch Rate Response Criterion time history envelope as a result of this test.

On the low side of the envelope, however, the SST High Speed Pitch Rate Response Criterion is not satisfactory. Considering a time-to-first peak of .9 seconds, as was used for the overshoot ratio tests, the minimum acceptable overshoot ratio should be lowered. How low it can go and still be satisfactory is unknown at this time. However, since steady state pitch rate values for a given load factor are quite low at this Mach number, it is logical to assume that pitch rate overshoot ratio becomes unimportant at low values. Therefore, no justification is apparent for requiring a minimum value greater than 1.0 (i.e. no overshoot). Therefore, a recommended boundary modification is to truncate the lower boundary at an overshoot ratio of 1.0. The initial response rate at low overshoot ratios becomes the important parameter, and will be covered in the next section.

A comparison with the SST High Speed Load Factor Response Criterion for the same set of responses just discussed is presented in Figure 7-11. The load factor responses do not compare favorably with the criterion. This poor comparison could be attributed to the fact that the system evaluated is a much higher order than the second order one represented by the criterion. This



			REVISED	DATE		
CALC					PITCH RATE OVERSHOOT COMPARISON WITH THE SST HIGH SPEED PITCH RATE RESPONSE CRITERION	
CHECK						
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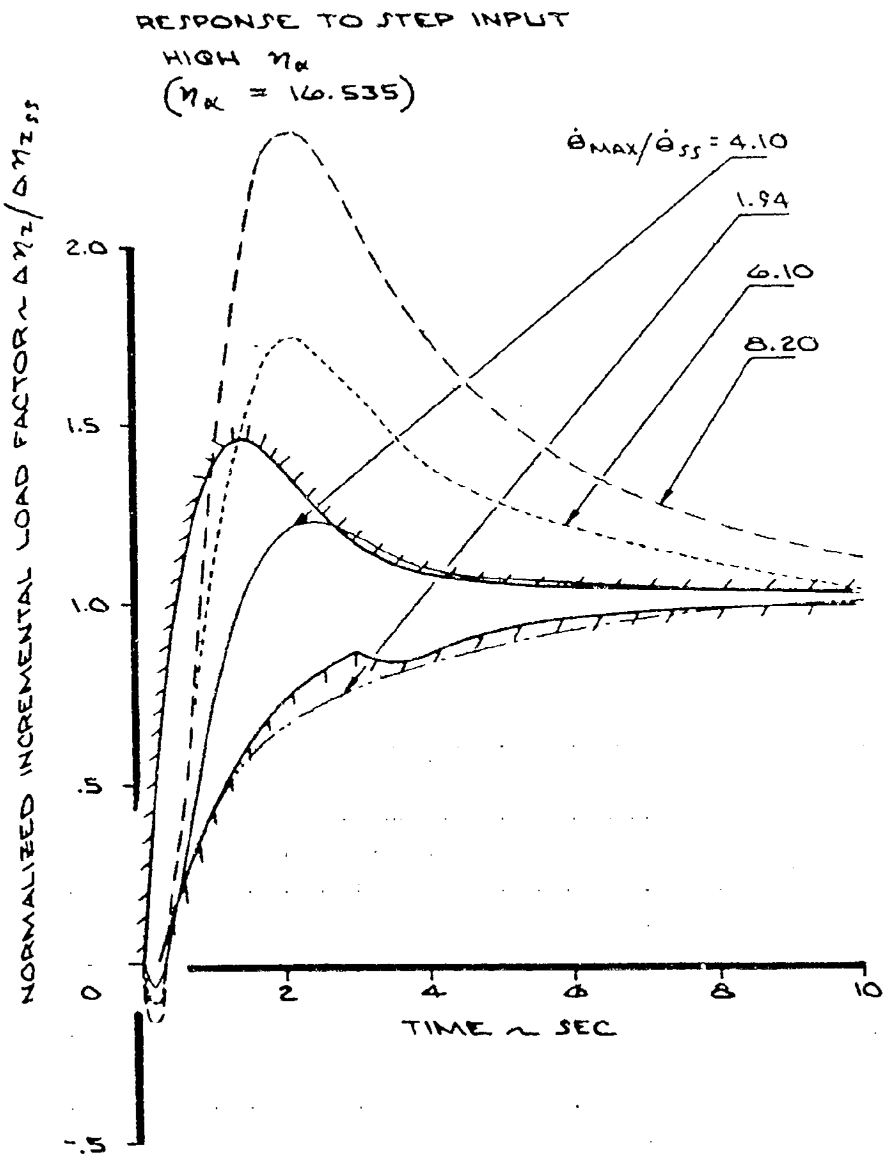
APPD						
					THE BOEING COMPANY	PAGE 46



CALC			REVISED	DATE	PITCH RATE OVERSHOOT COMPARISON WITH THE SST HIGH SPEED LOAD FACTOR RESPONSE CRITERION	FIG. 7-11
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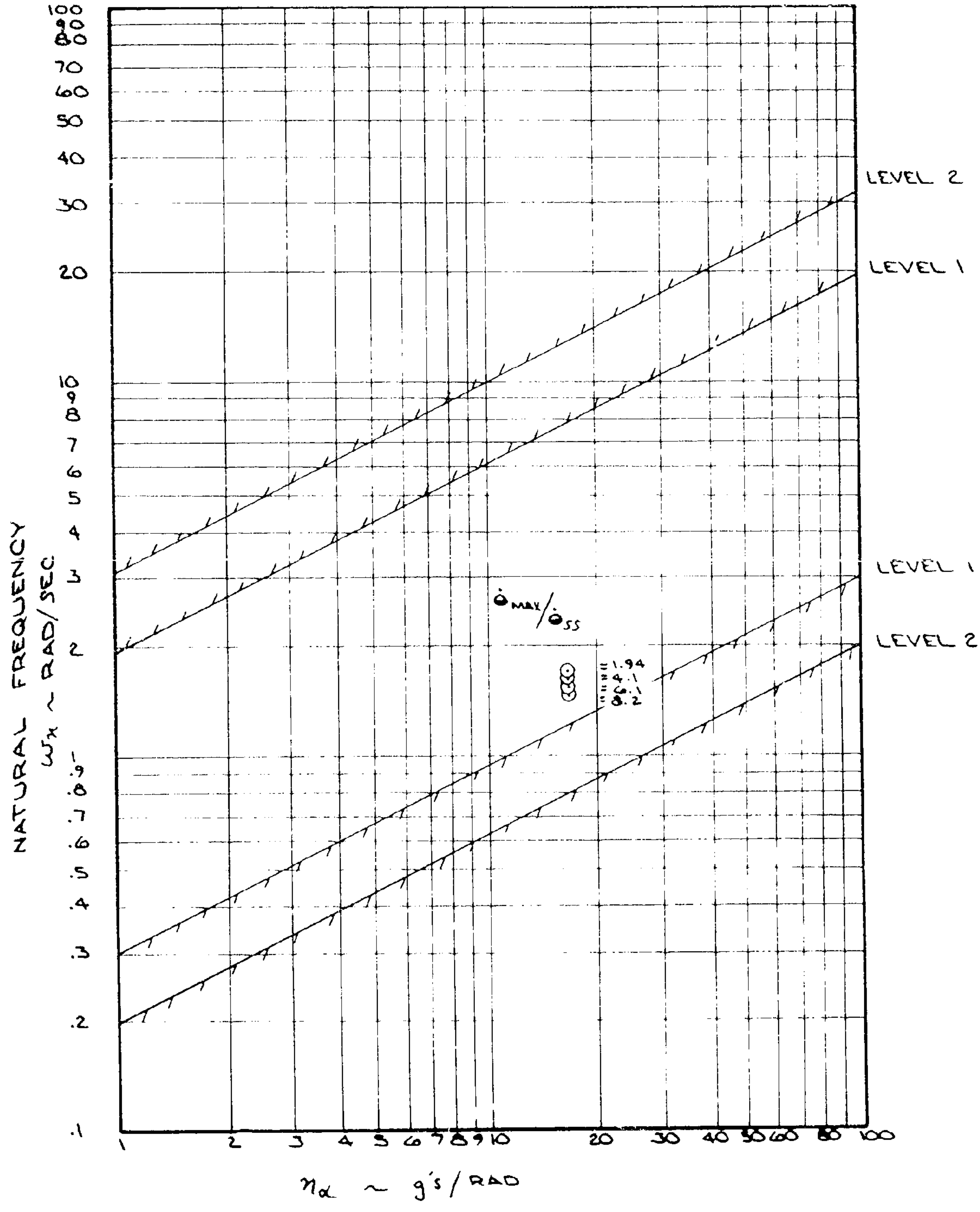
APPD					THE BOEING COMPANY	PAGE 47

particular set of response conditions does not behave like a second order system. The pitch rate time history envelope comparison is much better for this set of conditions.

Another point to be considered when analyzing any load factor response data is that the motion system used for this study had very limited vertical travel (± 4 feet or ± 1.22 meters), and therefore, limited load factors reproduction fidelity. This limited capability could account for the poor comparison with the criterion. Therefore, it is recommended that additional work be conducted in the future in the area of high speed handling qualities using a moving base simulation with greater load factor reproduction capability.

The military specification (Reference 1) criteria, expressed in terms of natural frequency (ω_n) and n_α, is compared against the results of this test in Figure 7-12. As can be seen, all points fall within the satisfactory range, even the point for an overshoot ratio of 8.2 that received a pilot rating of 4.0. Again, this criteria is based on a second order system which is not representative of the system evaluated.

A comparison was also made with the C* criterion and is presented in Figure 7-13. This comparison is for the baseline configuration which was given a pilot rating of 2.5 and 3.0. Since the C* response computed violates the satisfactory boundary, there is disagreement between this criterion and previous conclusions. In this portion of the flight regime the reason is attributed to the differences between the n_α of the math model used in this evaluation and the test aircraft (variable stability F-94) used in the development of the criterion. The 2707-300PT math model has a low n_α compared to the F-94 aircraft. This effect is seen in Figure 7-13 in the increased rise time of C* over that defined by the criterion. This increased rise time is primarily due to the load factor contribution to the C* parameter.



ENGR			REVISED	DATE	MIL-F-8785B CRITERION COMPARISON OF HIGH SPEED CRUISE PITCH RATE OVERSHOOT RATIO	FIG. 7-12
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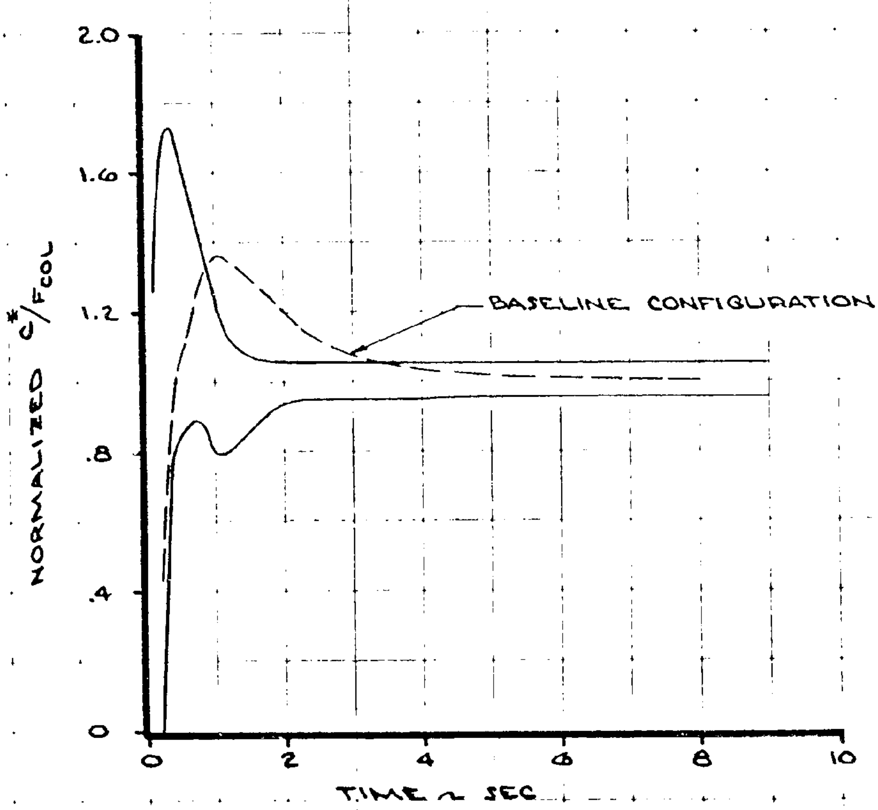
APR					BOEING	49

LEVEL 1
PILOT RATING 3.5



CALC			REVISED	DATE	HIGH SPEED CRUISE COMPARISON WITH C* CRITERION (BASELINE CONFIGURATION)	
CHECK						FIG. 7-13
APPD						
APPD					THE BOEING COMPANY	PAGE 50

In conclusion, the modified SST High Speed Pitch Rate Response Criterion is the best criterion for judging satisfactory pitch rate overshoot ratio characteristics.

7.1.3 Time-to-Peak Pitch Rate

This parameter gave the greatest variation in pilot rating of all the parameters tested for this study area. The results are presented in Figure 7-14, and include the estimate of the satisfactory limit.

As was the case with the overshoot ratio parameter, no lower acceptable limit could be determined from these tests. The lowest limit tested was .45 seconds, which gave the most satisfactory pilot ratings and compares favorably with the SST High Speed Pitch Rate Response Criterion (Figure 7-15). Lower values are not believed to be of practical interest for large aircraft due to other aircraft parameters such as pitch inertia or structure modal characteristics causing the predominant restrictions. Therefore, the upper limit is the only concern for this evaluation, and is estimated to be 1.2 seconds.

Close analysis of these results indicates the pilot is not evaluating the initial response, but is evaluating the duration the overshoot exists. This can be exemplified by comparing the time history curve for the $T_{\dot{\theta}_{max}}$ of 2.0 seconds (Figure 7-2) which was rated 6.0 and 7.0 with the time history curve for the $\dot{\theta}_{max}/\dot{\theta}_{ss}$ of 1.94 (Figure 7-1) which was rated 2.0 and 2.5. Both curves have nearly the same initial response up to the steady state value. The difference is in the overshoot magnitude and duration. In this area the SST High Speed Pitch Rate Response Criterion is very accurate in defining satisfactory limits.

These test results compare very well with the SST High Speed Pitch Rate Response Criterion (Figure 7-15). The time-to-peak of 1.4 seconds is just outside of the pitch rate time history boundary and is rated slightly unsatisfactory. The time-to-peak of 2.0 seconds is considerably outside the boundary

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} \approx 4$

$\xi\omega_n \approx 0.9$

$F_{COL}/g = 25$ LB/g (111 N/g)

TEST CONFIGURATION

MACH NO. = 2.7

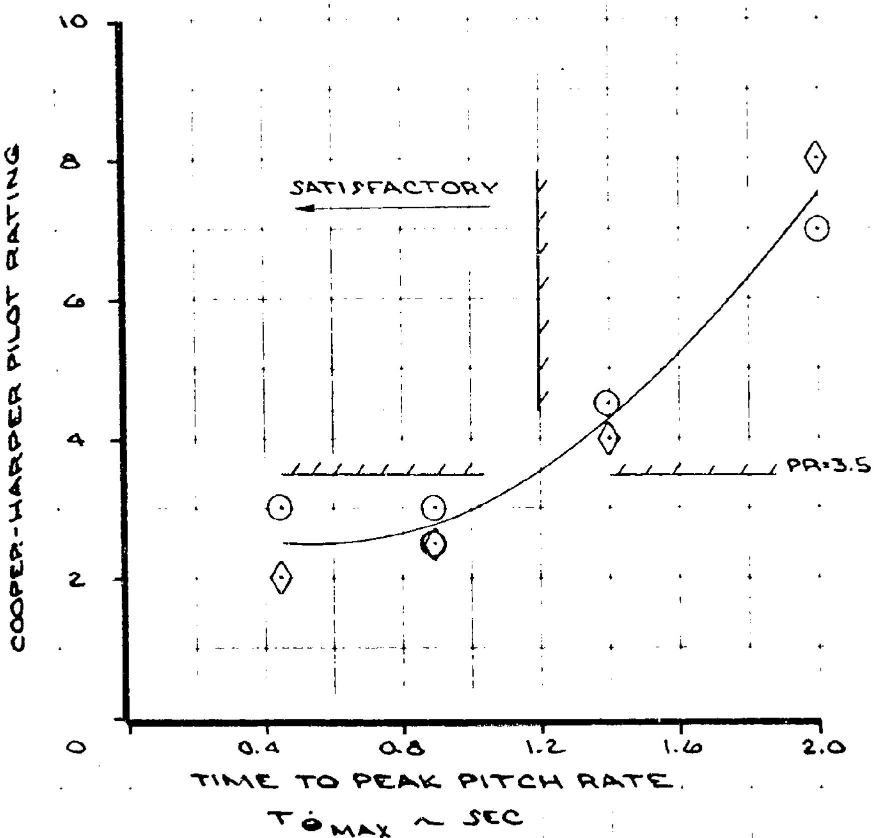
V_C = 567 KTS (292 M/SEC)

ALT = 60,000 FT (18,288 M)

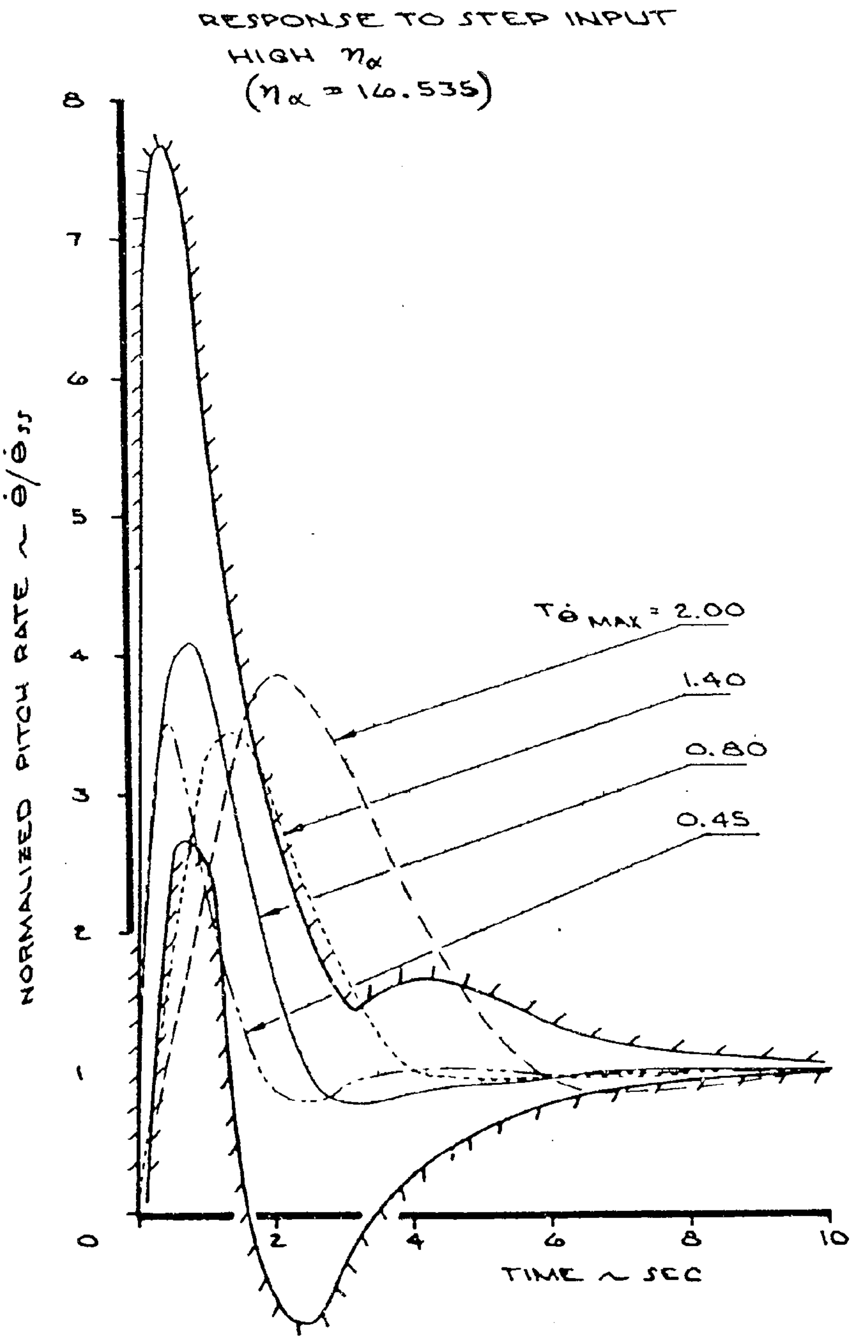
G.W. = 555000 LB (251,744 kg)

C.G. = .62 C_R

SYM	PILOT
○	B
◇	G



			REVISED	DATE		
CALC					HIGH SPEED CRUISE EVALUATION OF TIME TO PEAK PITCH RATE	
CHECK						FIG. 7-14
APPD						
APPD					THE BOEING COMPANY	PAGE 52



CALC			REVISED	DATE	TIME-TO-PEAK PITCH RATE COMPARISON WITH THE SST HIGH SPEED PITCH RATE RESPONSE CRITERION	FIG 7-15
CHECK						
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APPD					THE BOEING COMPANY	PAGE 53

and the pilot ratings definitely reflect this. The only area of any slight disagreement exists with the time-to-peak of .45 seconds. This does slightly violate the boundary on the low side. However, it should be remembered that this portion of the boundary is definitely in disagreement with the overshoot ratio test results, and should be modified as recommended in the discussion of those test results. With this recommended modification to the boundary, the response for the time-to-peak of .45 seconds will then not violate the pitch rate response envelope.

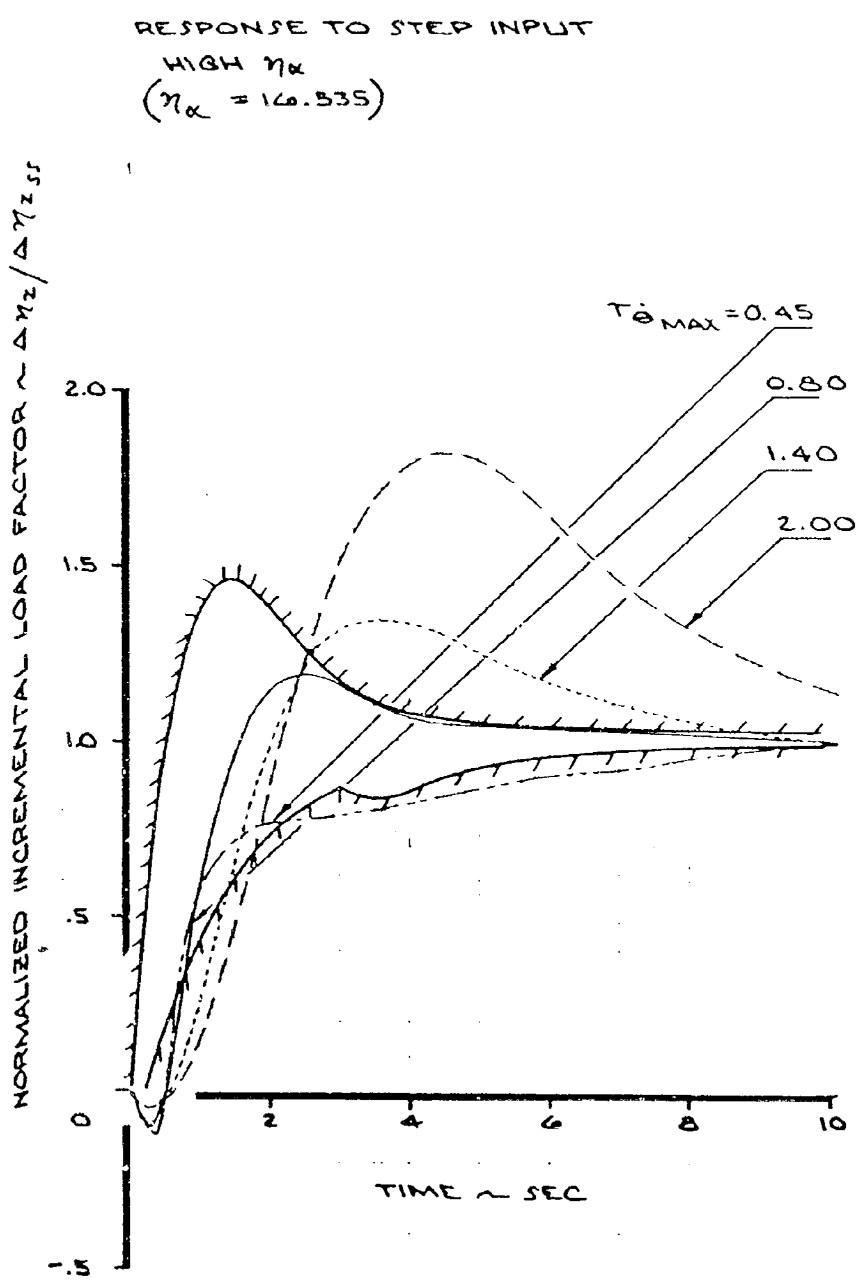
These same responses expressed in terms of normal load factor in comparison with the SST High Speed Load Factor Response Criterion, are presented in Figure 7-16. This comparison is reasonably good in that both time histories for condition rated unsatisfactory are definitely outside of the envelope. The other two conditions which were rated satisfactory are just within or slightly outside the boundary. However, the pitch rate envelope criterion is judged more accurate in defining satisfactory conditions for this type of response variation.

These same test conditions were compared against the MIL-F-8785B natural frequency criterion (Figure 7-17). The results of this comparison compare favorably with the pilot ratings received. Meeting the Level 1 boundary is considered necessary for normal operation. In this respect the $T_{\dot{\theta}_{max}}$ value of 1.4 is just inside the Level 1 boundary, and was rated 4.0 and 4.5, which shows this boundary to be optimistic.

In conclusion, the SST High Speed Pitch Rate Response Criterion with the lower boundary modification was found adequate for judging satisfactory levels of time-to-peak pitch rate with the corresponding overshoot ratios.

7.1.4 Pitch Damping Constant

This parameter has the same basic characteristics as the other parameters



CALC			REVISED	DATE	TIME-TO-PEAK PITCH RATE COMPARISON WITH THE SST HIGH SPEED LOAD FACTOR RESPONSE CRITERION	FIG. 7-16
CHECK						
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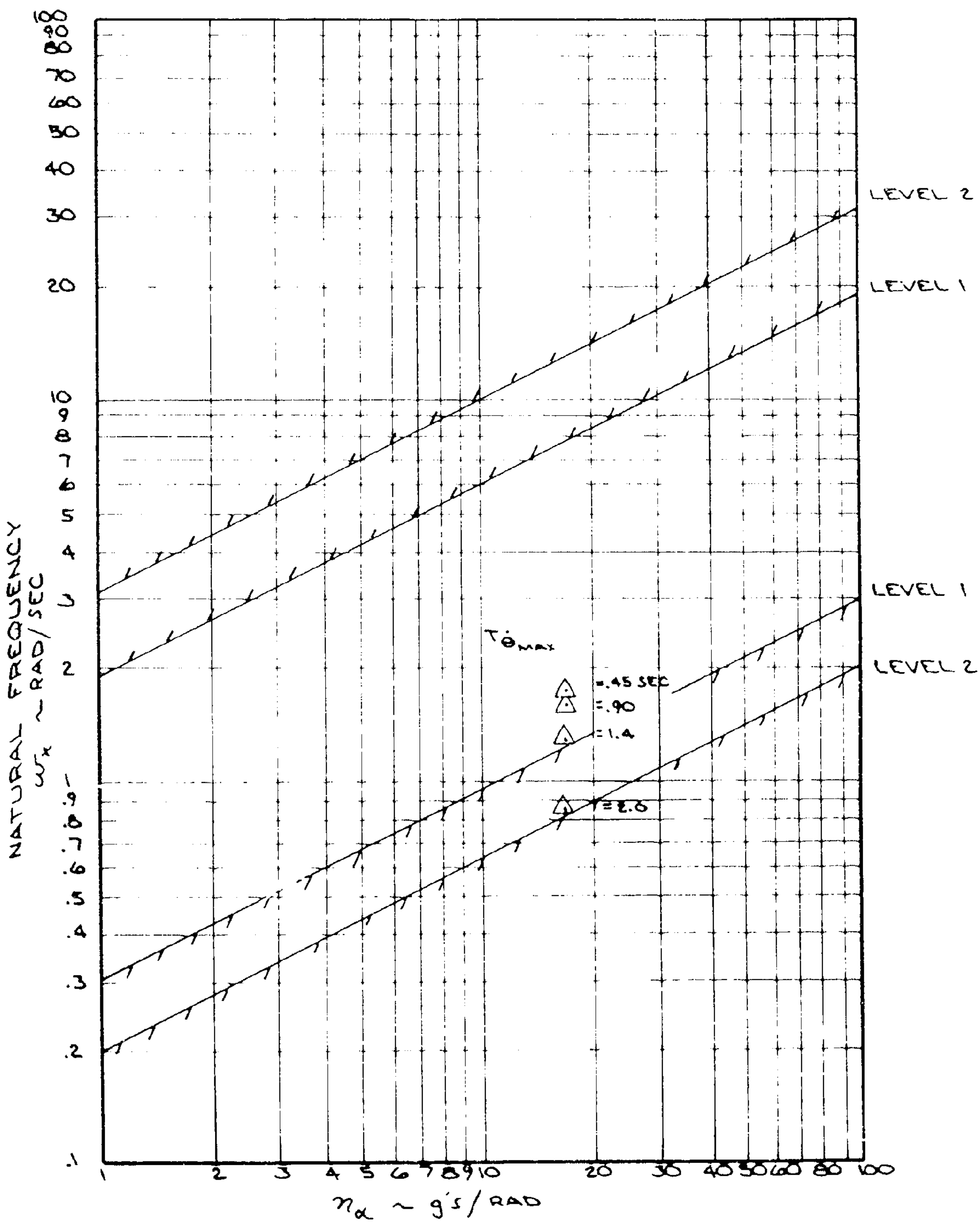
APPD					THE BOEING COMPANY	PAGE 55



ENGR		REVISED	DATE	MIL-F-8785B CRITERION COMPARISON OF HIGH SPEED CRUISE TIME TO PEAK PITCH RATE	FIG. 7-17
CHECK					
APR					
APR				**BOEING**	56

tested in that only one limit, the lower limit in this case, was identified. The results are presented in Figure 7-18, and show a minimum satisfactory limit of $\xi\omega_n$ = .55 for a pitch overshoot ratio of approximately 4, and a time-to-peak of approximately .9 seconds. Analysis of this data is believed to be very straight forward. The pilot rated the low damping case as unacceptable due to the oscillatory nature of the aircraft response. This is verified by the pilot comments, and is also supported by the SST High Speed Pitch Rate Response Criterion. The comparison is presented in Figure 7-19. The response for the $\xi\omega_n$ = .36 condition was found unacceptable and violates the envelope on both the low and high side due to the oscillatory tendency of this response. All other measurements of this particular response, such as the overshoot ratio and time-to-first peak, would have otherwise been satisfactory. The other two responses are well within the envelope and are rated satisfactory.

A comparison of these same conditions expressed in terms of load factor response with the SST High Speed Load Factor Response Criterion is presented in Figure 7-20. This comparison is reasonably good in that the time history curve for the $\xi\omega_n$ = .36 condition definitely violates the envelope and received unsatisfactory pilot ratings. The other two time histories are close to the boundary with one slightly outside. This envelope comparison is sensitive and judged not as good for comparison as the pitch rate envelope.

Comparing these test conditions with the MIL-F-8785B frequency criteria (Figure 7-21) gives the expected unsatisfactory results with all data points in the satisfactory region. However, this specification covers damping separately by defining a satisfactory minimum value of damping ratio (ξ). For this particular aircraft configuration the lowest satisfactory value of ξ, defined by MIL-F-8785B, is 0.30. The minimum satisfactory value determined from the curve in Figure 7-20 was ξ = 0.34, which shows MIL-F-8785B to be slightly optimistic. This value of ξ = 0.34 is obtained by taking the minimum satis-

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS}$ = 5.3 TO 3.8

$T_{\dot{\theta}MAX}$ = .7 TO .95 SEC

F_{COL}/g = 25 LB/g

EADI SCALE = .30 IN/DEG (43.7 cm/RAD)

TEST CONFIGURATION

MACH NO. = 2.7

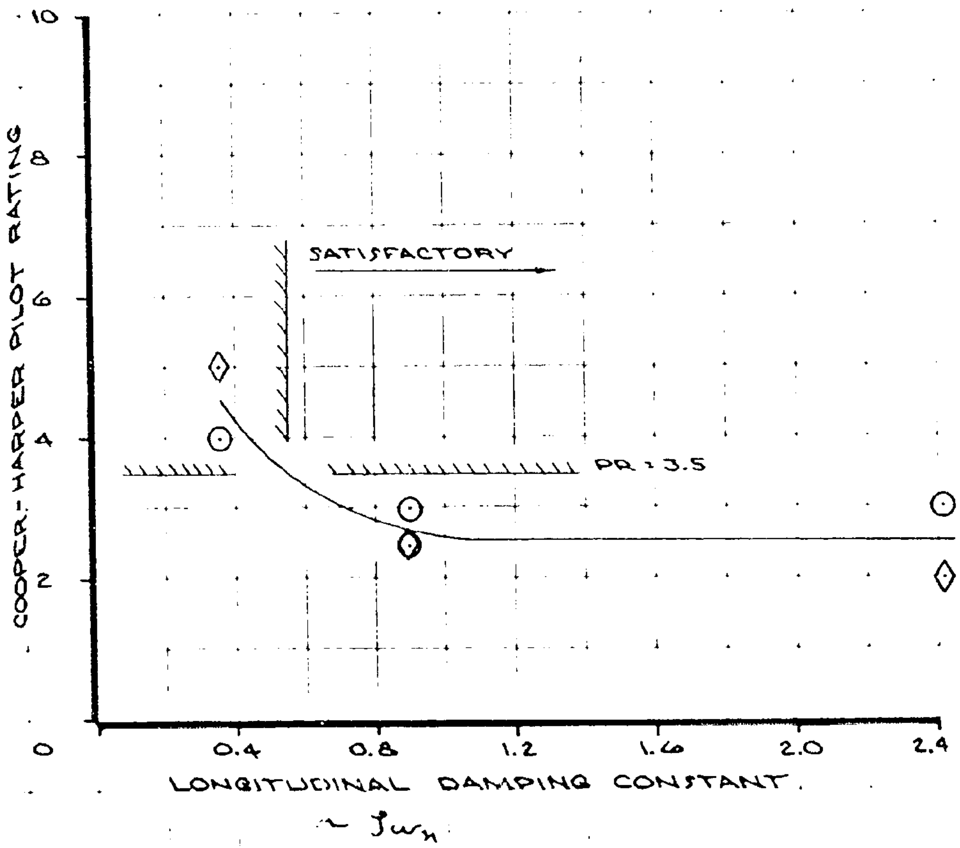
V_C = 567 KT (292 m/SEC)

ALT = 60,000 FT (18,288 m)

G.W. = 555,000 LB (251,744 kg)

C.G. = .62 C_R

SYM	PILOT
○	8
◇	6



CALC			REVISED	DATE	HIGH SPEED CRUISE EVALUATION OF LONGITUDINAL DAMPING	FIG 7-18
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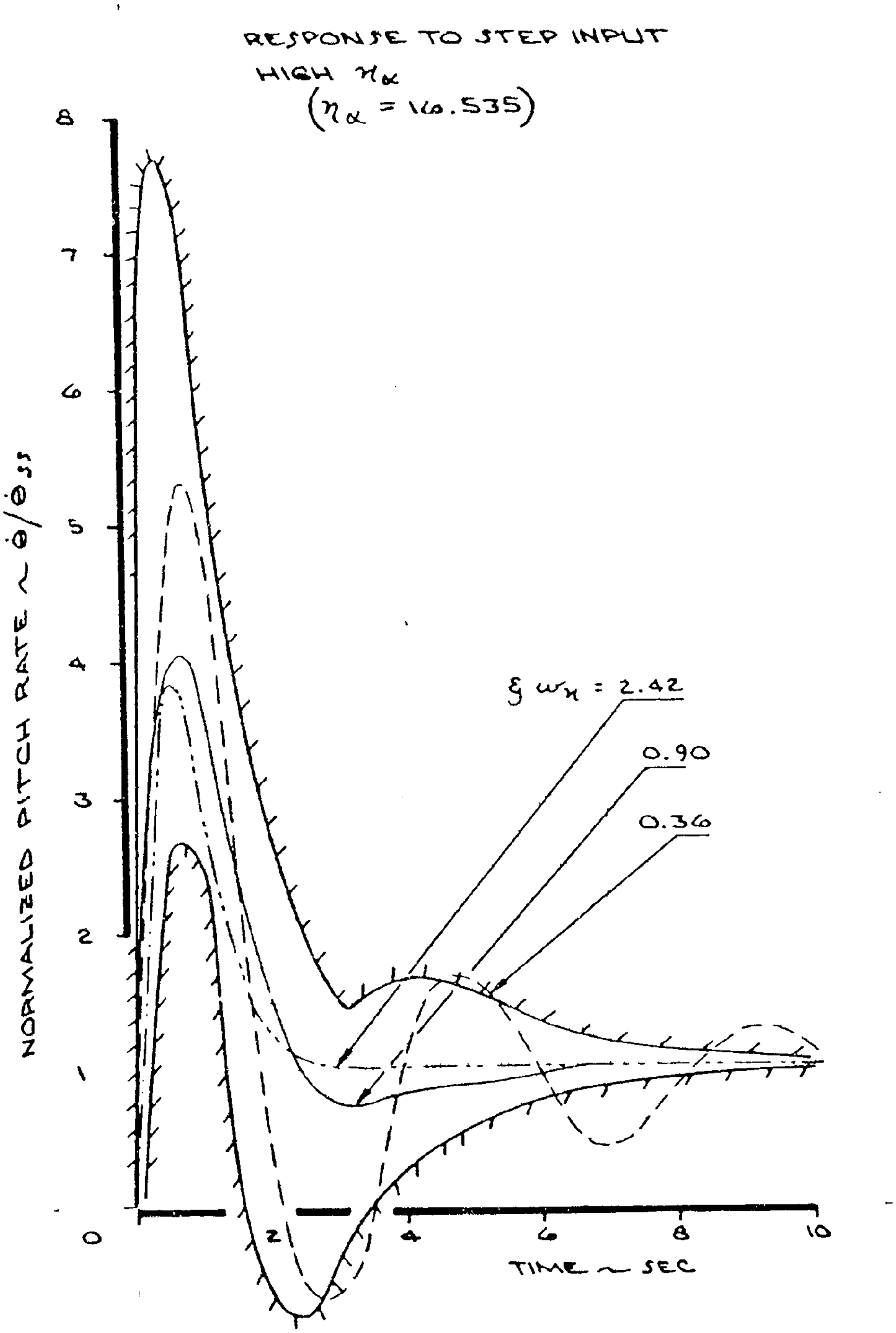
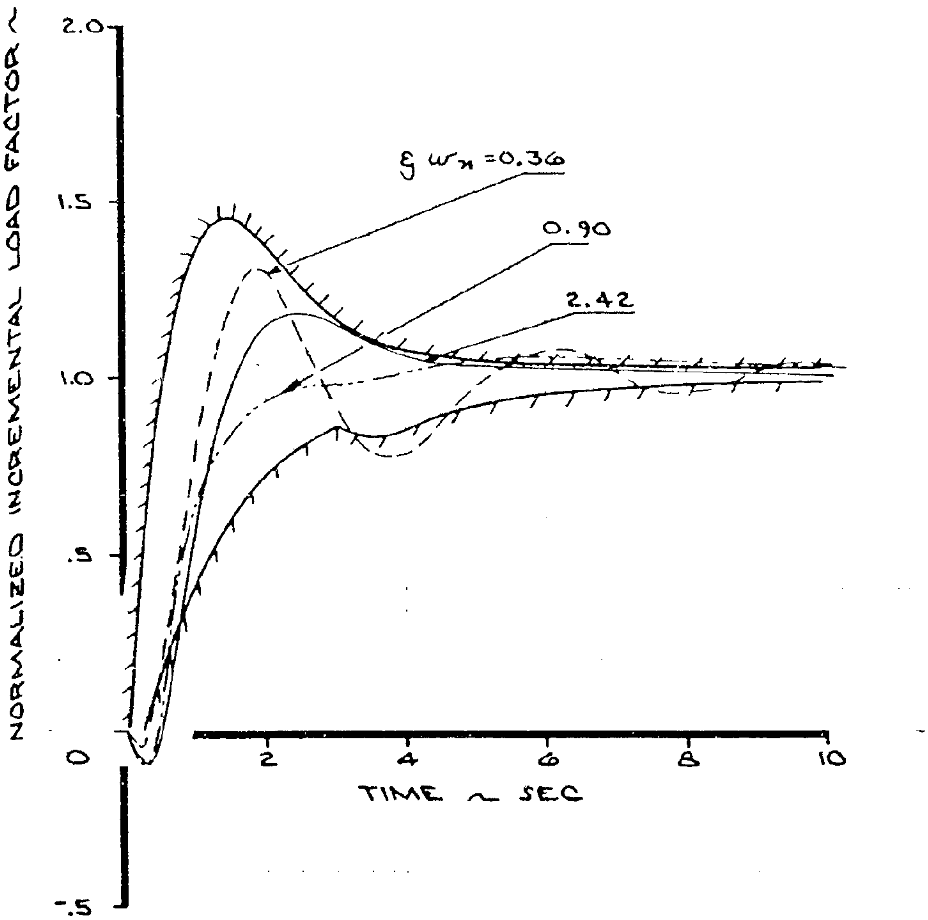
APPD						
APPD					THE BOEING COMPANY	PAGE 58



CALC			REVISED	DATE	PITCH DAMPING COMPARISON WITH WITH THE SST HIGH SPEED RATE RESPONSE CRITERION	FIG. 7-19
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 59

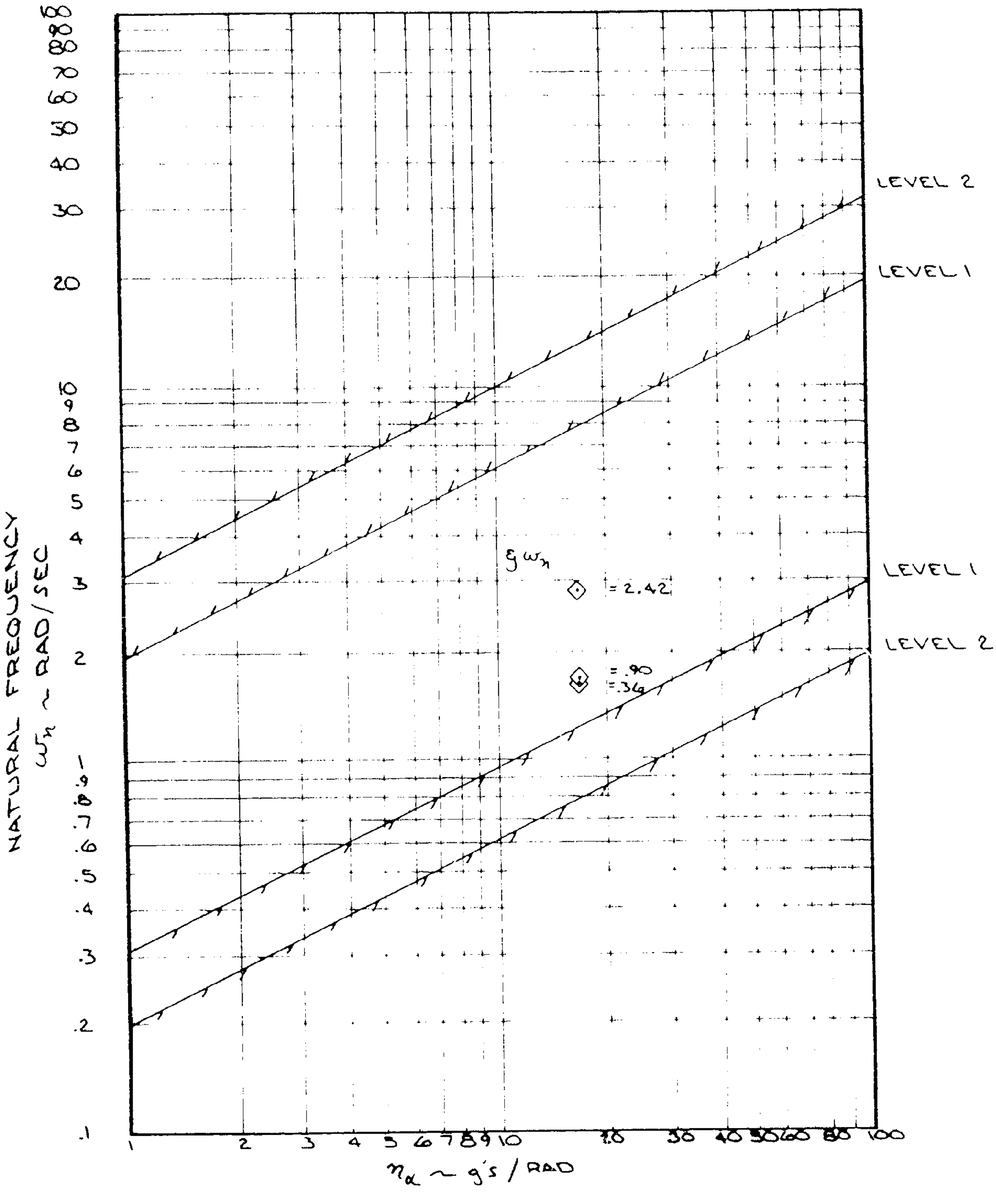
AD 4982 C

RESPONSE TO STEP INPUT
HIGH n_α
(n_α = 16.535)



			REVISED	DATE		
CALC					PITCH DAMPING COMPARISON WITH THE SST HIGH SPEED LOAD FACTOR RESPONSE CRITERION	
CHECK						
APPD						FIG. 7-20
APPD						
					THE BOEING COMPANY	PAGE 60

AD 4983 C



ENGR			REVISED	DATE	MIL-F-8785B CRITERION COMPARISON OF HIGH SPEED CRUISE PITCH DAMPING	FIG 7-21
CHECK						
APR						
APR					BOEING	61

J18 047

factory value of $\xi\omega_n = 0.55$ and dividing by $\omega_n = 1.6$ rad/sec, which is the value of ω_n at the test conditions on either side of the intercept point.

Therefore, the High Speed Pitch Rate Response Criterion with the lower boundary modification is judged as the best method for predicting satisfactory characteristics for the pitch damping response parameter.

7.1.5 Column Force Gradient

The results of the column force gradient evaluation are presented in Figure 7-22. With the small amount of column deflection normally used at the high speed cruise flight condition ($\pm$ 0.8 inches or $\pm$ 2.0 centimeters), the level of the column force gradient is found to be relatively unimportant. The MIL-F-8785B limits are also presented in the above figure for reference.

No specific gradient limits are recommended as a result of this evaluation. The nominal column force gradient is estimated to be approximately 40 lbs/g (178 N/g).

7.2 LANDING APPROACH (NORMAL OPERATION)

The purpose of this section of the study was to develop longitudinal handling qualities criteria based on airplane response characteristics for the landing approach portion of the mission. For this particular landing approach study the criteria was to be applicable to airplanes landing under normal operating conditions as differentiated from airplanes landing under minimum-safe operating conditions, as will be covered in the next section.

As described previously in this report, the criteria is based on airplane response parameters. The parameters used to evaluate this study area were as follows:

- o pitch rate overshoot ratio ($\dot{\theta}_{max}/\dot{\theta}_{ss}$)
- o time-to-peak pitch rate ($T_{\dot{\theta}_{max}}$)
- o pitch damping constant ($\xi\omega_n$)

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} = 4$

$T\dot{\theta}_{MAX} = 0.9$

$\zeta\omega_n = 0.9$

EADI SCALE = .30 IN/DEG (43.7 cm/RAD)

TEST CONFIGURATION

MACH NO. = 2.7

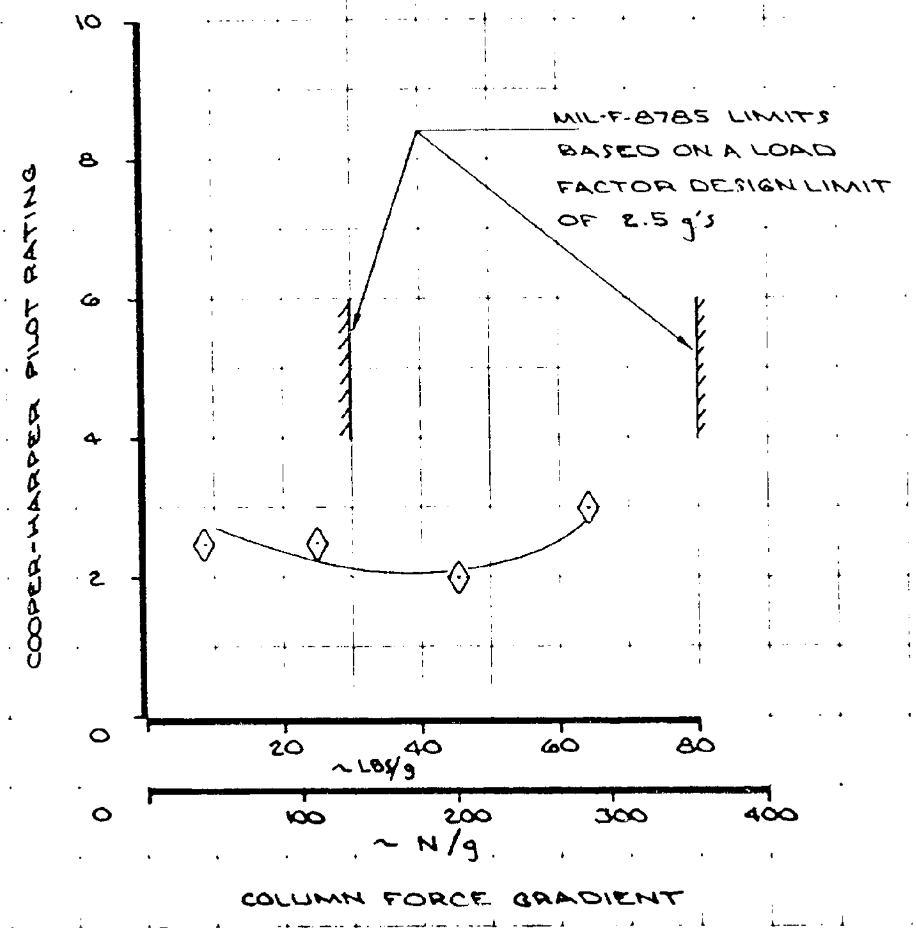
V_C = 567 KT (292 m/SEC)

ALT = 60,000 FT (18,288 m)

G.W. = 555,000 LB (251,744 kg)

C.G. = .62 C_R

SYM	PILOT
◊	B



CALC			REVISED	DATE	HIGH SPEED CRUISE EVALUATION OF COLUMN FORCE GRADIENT	FIG. 7-22
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 63

o column force gradient (F_{col}/g)

The column force gradient is applicable since it is a measure of the feel the pilot has for the longitudinal response characteristics, even though this is not a response parameter as such.

The complete matrix of parameters evaluated is presented in Table 7-II. Included in the table are the conditions under which the evaluations were performed, special tests measurements taken and number of pilots evaluating each case.

The parameter variations were calibrated using the response from an unpiloted column step command. To obtain the desired variations of the above parameters, changes were made in the pitch SAS by adjusting the gain and filter time constants and by changing the column forward loop prefilter terms.

The pilot task is presented in Figure 7-23. This pilot task was performed by all pilots evaluating the landing approach configurations for both the normal and minimum-safe study areas. When conducting the landing approach pilot task the visual scene was fogged over until an altitude of 200 feet (61 meters) was reached. At that altitude the fog was lifted and the pilot continued the landing through flare and touchdown using the visual scene.

The initial flight condition for this evaluation was the normal landing approach conditions for the 2707-300PT airplane as follows:

- o 1800 feet altitude (549 meters)
- o 144 knots CAS (74 meters/sec)
- o 415,000 pounds gross weight (188,240 kilograms)
- o 54 center of gravity (forward limit)
- o 20 degrees flaps
- o gear down

Considerable scatter exists in the pilot rating data obtained. Pilot technique, simulation experience and the large number of pilots used for this

TABLE 7-II

LANDING APPROACH (NORMAL OPERATION) TEST CONDITIONS

PARAMETER VARIED	NUMBER OF PILOTS EVALUATING			
	Smooth Air	Turbulence Evaluation	Pilot Describing Function	Workload Side Task
Pitch Rate Overshoot Ratio $\dot{\theta}_{max}/\dot{\theta}_{ss}$ = 1.12	2			
*1.67	5	2	2	1
2.12	4	1		1
3.24	2			
Time to Peak Pitch Rate $T_{\dot{\theta}_{max}}$ = 1.0 sec	2	1		
*1.5	—	—	—	—
2.0	3	1	1	
3.0	3	2	1	
Damping Constant $\zeta\omega_n$ = .16	4	1	2	1
.56	2	1		
*.75	—	—	—	—
1.10	3			
Column Force Gradient F_{col}/g = 10 lb/g	3	1	1	
28	3	1		
*50	—	—	—	—
71	3	1		
87	2			

* Baseline configuration

LANDING APPROACH PILOT TASK

1. START ON RUNWAY HEADING OFFSET TO ONE SIDE OF LOCALIZER AND BELOW GLIDESLOPE

2. CAPTURE LOCALIZER

3. FLY STRAIGHT AND LEVEL TO CAPTURE GLIDESLOPE

4. AFTER STABILIZING ON GLIDESLOPE DEVIATE ABOVE GLIDESLOPE BY 3/4 TO ONE DOT HIGH AND STABILIZE

5. RECAPTURE GLIDESLOPE USING NORMAL TECHNIQUE

6. CONTINUE APPROACH BREAKING OUT OF OVERCAST AT 200 FEET (61 METERS)

7. CONDUCT NORMAL FLARE AND TOUCHDOWN ATTEMPTING TO TOUCHDOWN AT THE 1000 FOOT (305 METER) MARK

FIGURE 7-23

test series, contributed to the scatter. Using a large number of pilots is normally advantageous, if all can fly all or most of the test conditions. In this case some were used only to obtain a few data points, some evaluating as few as one or two test conditions. Familiarization was, therefore, not extensive for some of the pilots involved and rechecking and repeating of questionable data points with the same pilot usually was not possible.

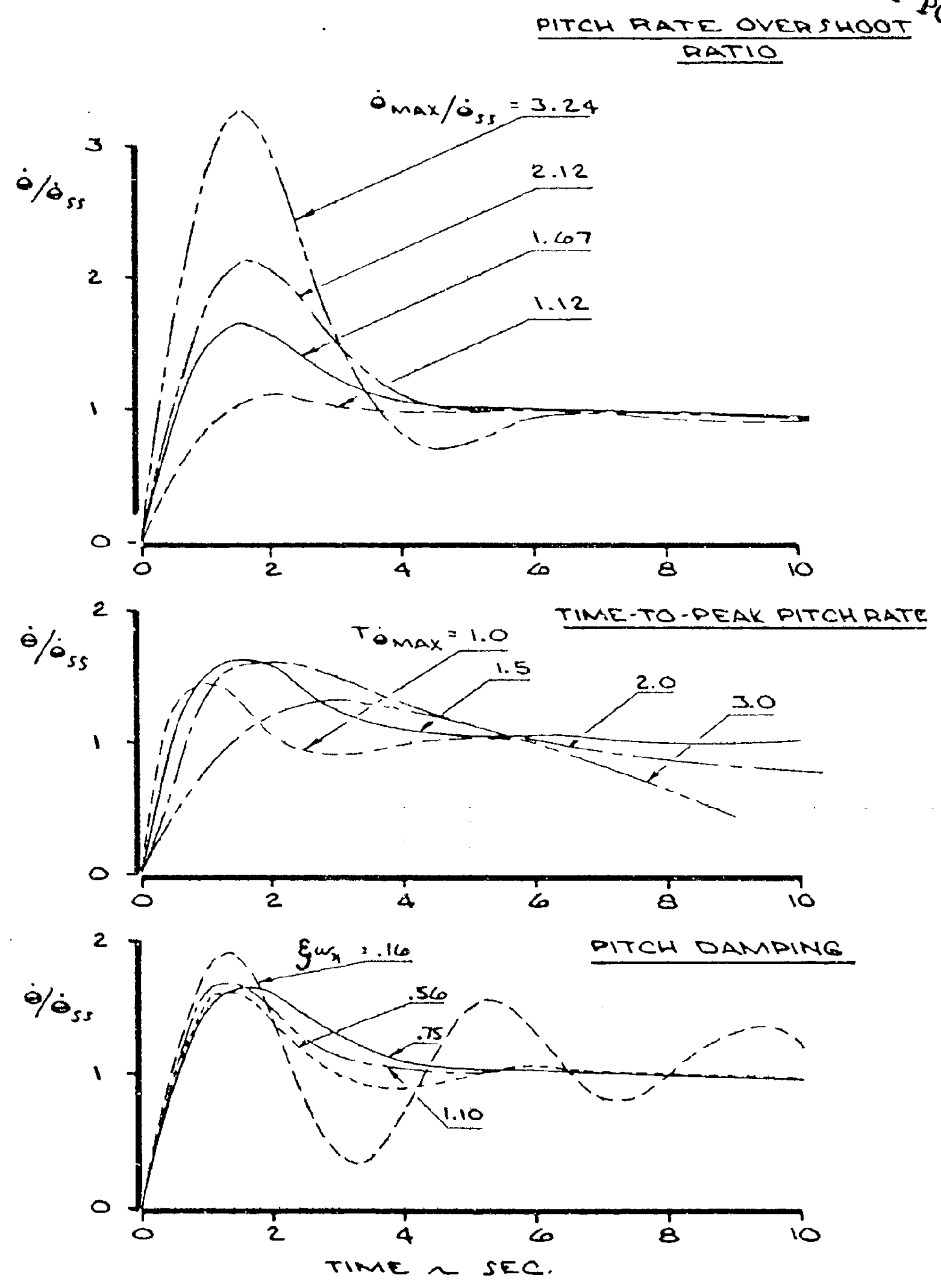
7.2.1 Pitch Rate Overshoot Ratio

The time history responses of the parameter variations tested are presented in Figure 7-24. These time histories have been normalized to a steady state value of unity.

The results of this evaluation are presented in Figure 7-25. As mentioned previously, considerable scatter exist with this particular data. The fairing is based on a complete analysis of the data including a comparison with existing criteria.

The greatest amount of scatter occurs at the overshoot ratio of 3.24. Some insight can be obtained by comparing the results with the SST Low Speed Pitch Rate Response Criterion (Figure 7-26). As can be seen in this comparison, the overshoot value of this test condition does not exceed the maximum value allowed by this criterion; but the time history response does fall outside the envelope due to a greater response lag than allowed by the criterion. Pilot acceptance or lack of acceptance of the greater lag could explain the amount of scatter and the unsatisfactory pilot ratings. The best location for the fairing at this maximum overshoot ratio point was selected as the center of the scatter.

The very low overshoot ratio value of 1.1 results in marginal pilot ratings. This is predicted by the SST Low Speed Pitch Rate Response Criterion, as seen in Figure 7-26. The initial response of this configuration is just inside the



CALC			REVISED	DATE	PITCH RATE RESPONSES	
CHECK					LANDING APPROACH	FIG. 7-24
APPD						
APPD					THE BOEING COMPANY	PAGE 68

RESPONSE CONFIGURATION

$\zeta\omega_n = .75$

$T\dot{\theta}_{MAX} = 1.5$ SEC

$F_{COL}/g = 50$ LBS/g (222 N/g)

TEST CONFIGURATION

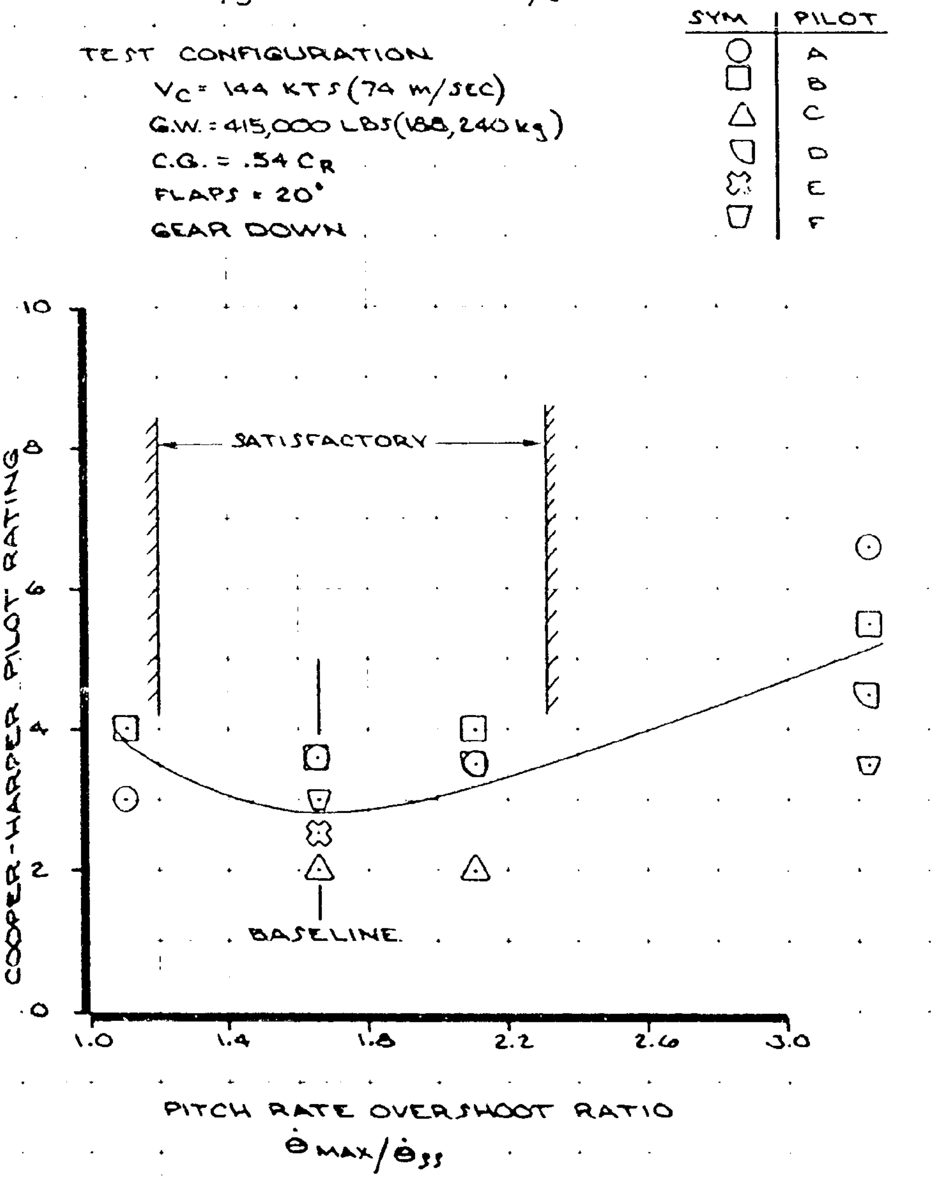
$V_C = 144$ KTS (74 m/SEC)

G.W. = 415,000 LBS (188,240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN

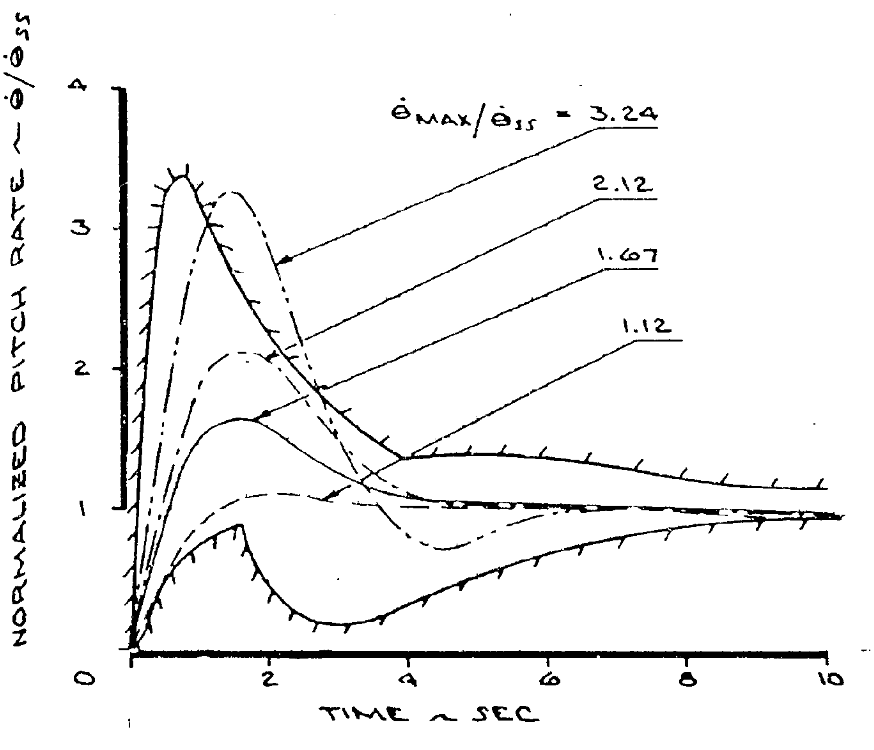


CALC		REVISED	DATE	LANDING APPROACH EVALUATION OF PITCH RATE OVERSHOOT RATIO
CHECK				
APPD				
APPD				

FIG. 7-25

AD 3982 A

RESPONSE TO STEP INPUT
LOW η_α
$(\eta_\alpha = 3.981)$



CALC			REVISED	DATE	PITCH RATE OVERSHOOT COMPARISON WITH THE SST HIGH SPEED PITCH RATE RESPONSE CRITERION	FIG 7.26
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 70

envelope. Results from this test indicate the envelope to be slightly optimistic.

The results of the turbulence evaluation of this parameter is presented in Figure 7-27. As can be seen, the variation of this parameter does not result in different turbulence ratings. Also the highest level of turbulence did not result in an unacceptable turbulence rating. Therefore, no additional restrictions on the criterion are required as a result of the turbulence evaluation.

As a result of these tests, the SST Low Speed Pitch Rate Response Criterion is demonstrated to be a valid criterion for evaluating the pitch rate overshoot parameter, considering the test accuracy.

7.2.2 Time-to-Peak Pitch Rate

The time-to-peak pitch rate time history responses normalized to a steady state value of unity are presented in Figure 7-24. For the response with long time delay the steady state value was difficult to obtain. For a time-to-peak pitch rate of 3.0 seconds, the best estimate of the steady state value was used in deriving the normalized time history.

The results of this study, correlated with pilot ratings, are presented in Figure 7-28. Again, considerable scatter exists, particularly at the two longer times. This scatter, along with the degraded ratings, is due to the high pilot workload. The integrated workload measurements show this to require the highest workload by the pilot in terms of physical column work. Different pilots rate this effect very differently, depending on their background and experience, and personal likes and dislikes.

Comparing the time history responses to the SST Low Speed Pitch Rate Response Criterion shows that criterion to be unsatisfactory for this particular parameter (Figure 7-29). As can be seen, all response time histories lie

RESPONSE CONFIGURATION

$\zeta\omega_{n} \approx .75$

$T\dot{\theta}_{MAX} \approx 1.5$ sec

$F_{COL}/g = 50$ lb/g (222 N/g)

TEST CONFIGURATION

$V_C = 144$ kts (74 m/sec)

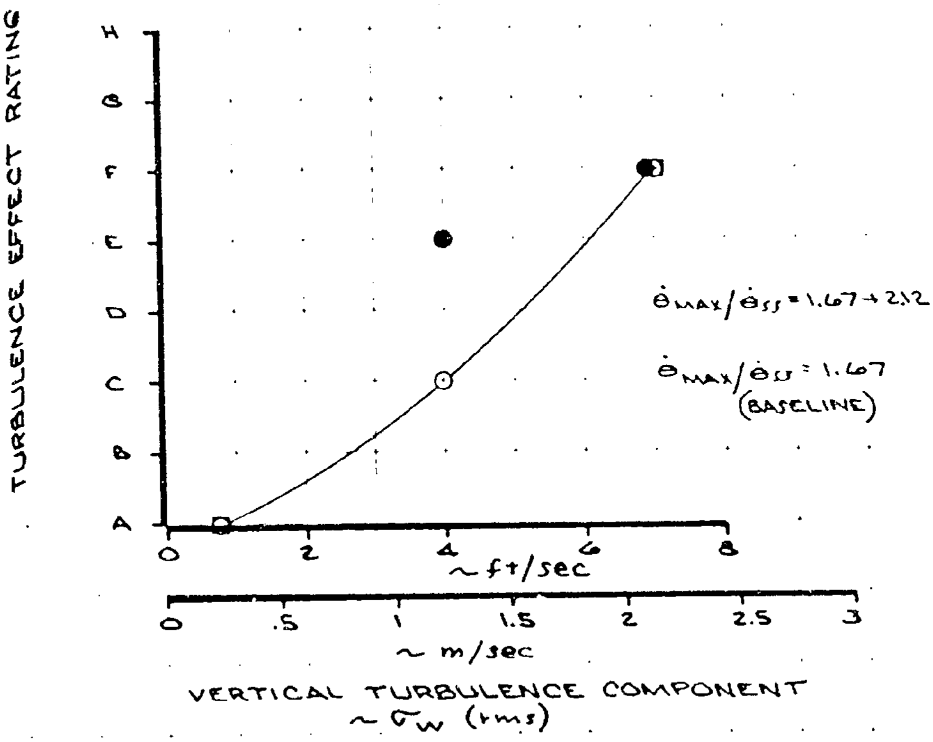
G.W. = 415,000 lb (188,240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN

SYM	PILOT
OPEN	C
SOLID	F



CALC			REVISED	DATE	PITCH RATE OVERSHOOT RATIO TURBULENCE EVALUATION	FIG 7-27
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 72

RESPONSE CONFIGURATION:

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} = 1.4 \rightarrow 1.61$

$\zeta\omega_n \approx .7 \rightarrow .75$

$F_{COL}/g = 50$ LB/g (222 N/g)

TEST CONFIGURATION

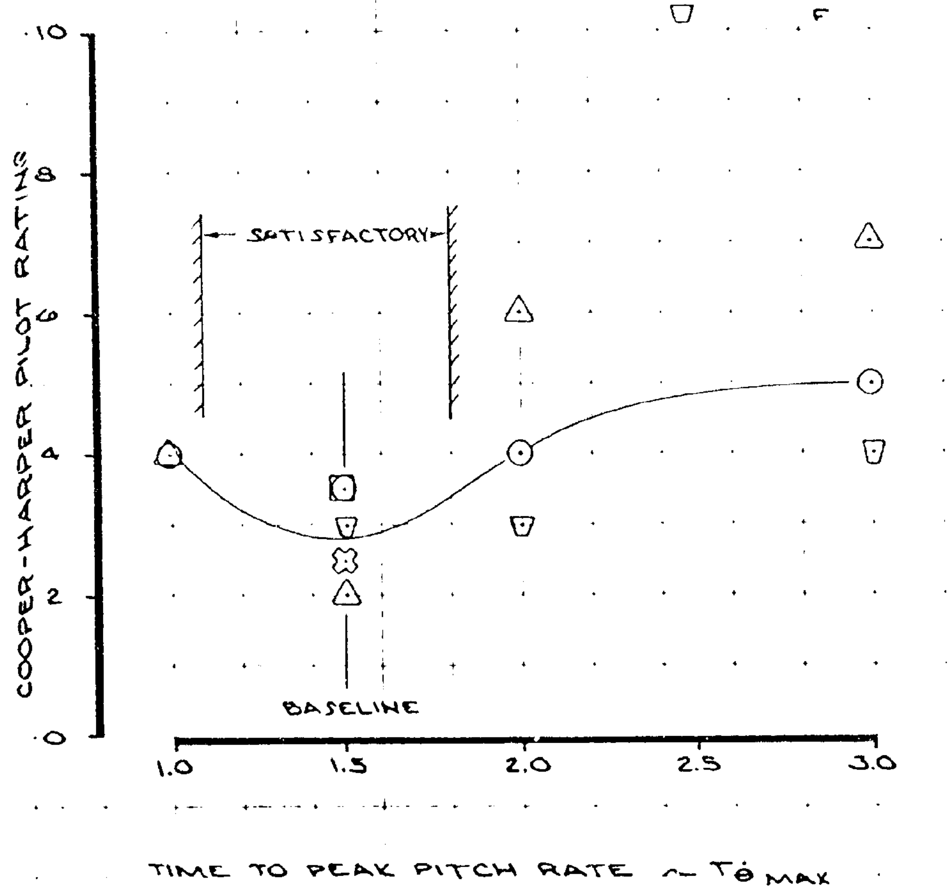
$V_C = 144$ KT (74 m/SEC)

G.W. = 415,000 LB (188,240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN

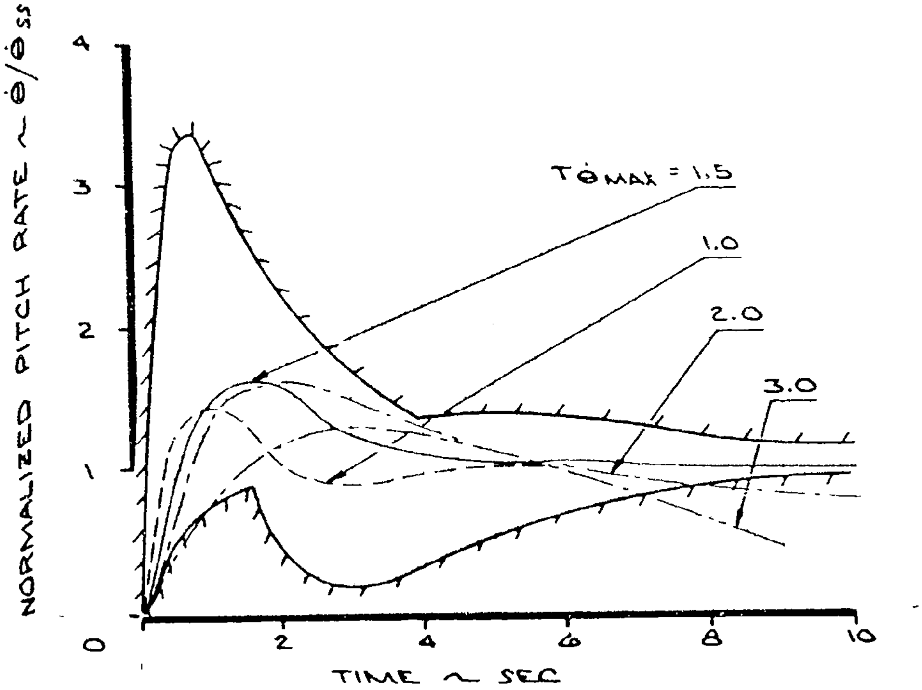


CALC			REVISED	DATE	LANDING APPROACH EVALUATION OF TIME TO PEAK PITCH RATE	FIG. 7-28
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 73

AD 4993 A

4 5000

RESPONSE TO STEP INPUT
LOW n_α
(n_α = 3.981)



CALC			REVISED	DATE	TIME-TO-PEAK PITCH RATE COMPARISON WITH THE SST HIGH SPEED PITCH RATE RESPONSE CRITERION	FIG. 7-29
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 74

substantially in the envelope except after a time period of seven seconds. The additional constraint concerning rise time (constraint 2 in Figure 6-4) is of no benefit either, since the overshoot for all responses is always greater than 20% of the steady state value. The criterion is not judged applicable to the time-to-peak pitch rate response parameters evaluated. An additional constraint in terms of time-to-peak pitch rate is recommended as follows: the time-to-peak pitch rate to a column step input should be between 1.1 and 1.8 seconds if all other criteria are met.

The turbulence evaluation of this parameter is presented in Figure 7-30. By comparing this figure with Figure 7-28, a direct correlation between the pilot ratings and turbulence ratings can be seen. All configurations, except the baseline, result in unsatisfactory pilot ratings and unacceptable turbulence ratings at the turbulence level of 7.0 feet/sec (2.13 meters/sec). No recommended changes to the handling qualities criterion as a result of the turbulence study are necessary.

7.2.3 Pitch Damping Constant

The response time histories of the variations of the pitch damping constant are presented in Figure 7-24. These time histories, as are all others, are normalized to a steady state value of unity.

Correlation of the pilot rating data with the variations of the pitch damping constant are presented in Figure 7-31. These data show good correlation with less scatter than the data for the other parameters with the exception of the rating of 2.0 given by pilot "C" at the minimum damping case. Analysis of the performance achieved by pilot "C" for this case shows unsatisfactory control of pitch rate in comparison to the rating given. Control of pitch rate by pilot "C" was essentially the same as that achieved by both pilot "A" and "B". These two pilots rated this configuration 5.0 and 4.5 respectively. Comments

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} \approx 1.4 \rightarrow 1.67$

$\xi\omega_n \approx .75$

$F_{COL}/g = 50$ lb/g (222 N/g)

TEST CONFIGURATION

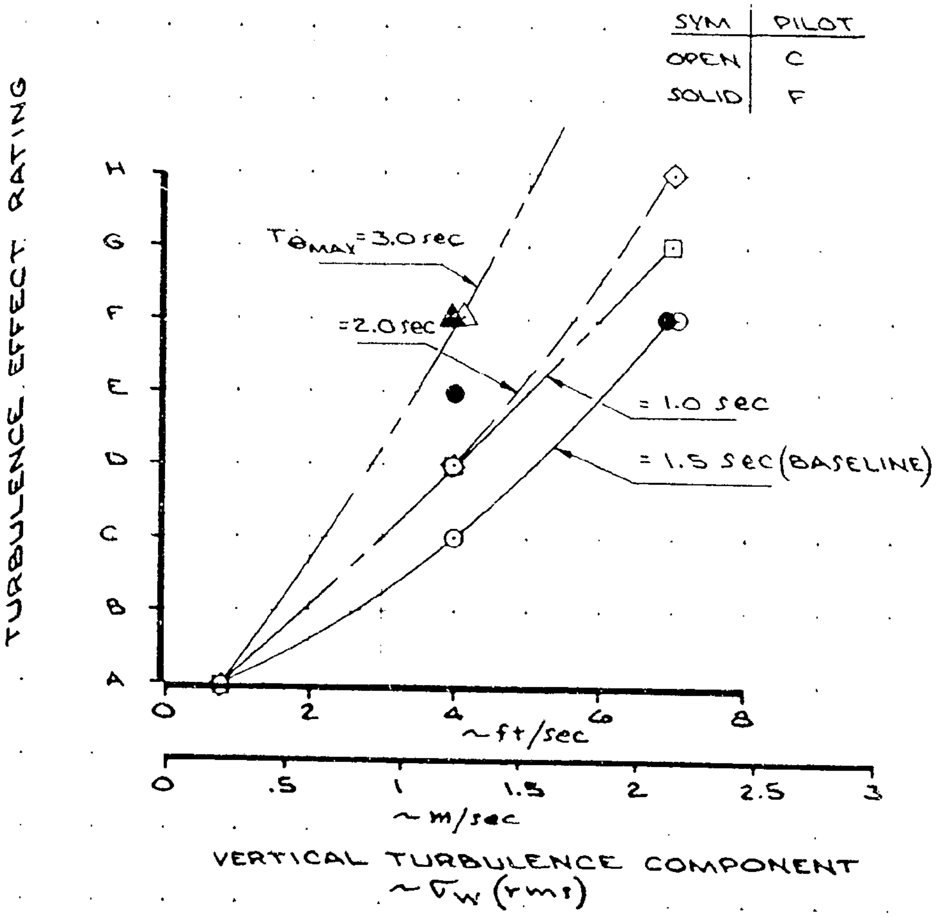
V_C = 144 kts (74 m/sec)

G.W. = 415,000 lb (188,240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN



CALC			REVISED	DATE	TIME TO PEAK PITCH RATE TURBULENCE EVALUATION	FIG. 7-30
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 76

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} \approx 1.6$

$T_{\dot{\theta}_{MAX}} = 1.2 \rightarrow 1.5$ SEC

$F_{COL}/g = 50$ LB/g (222 N/g)

TEST CONFIGURATION

$V_C = 144$ KT (74 m/SEC)

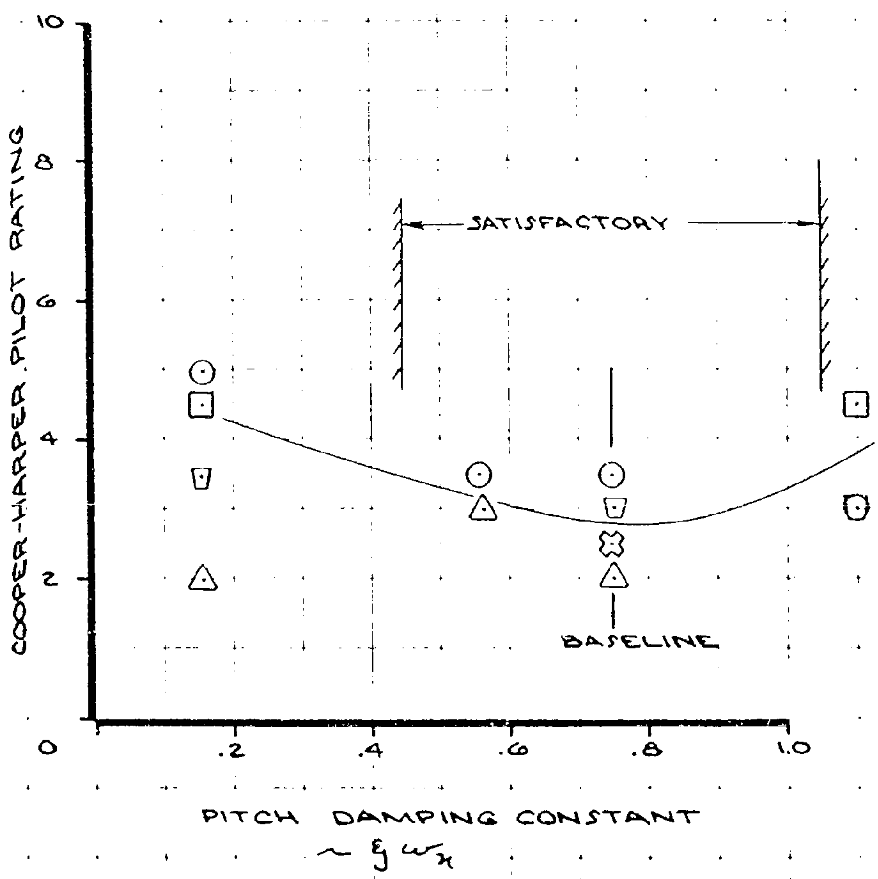
G.W. = 415,000 LBS (188,240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN

SYM	PILOT
○	A
□	B
△	C
✕	E
▽	F



CALC		REVISED	DATE	LANDING APPROACH EVALUATION OF PITCH DAMPING
CHECK				
APPD				FIG. 7-31
APPD				THE BOEING COMPANY

AD 4992 A

8 5000

received from this pilot indicated a strong desire for light column forces (see Appendix E). This reduced pitch damping probably appeared as a reduced column force gradient in transient maneuvers, even though this was not the steady state case. In turbulence this same pilot gave an unacceptable pilot rating for this same condition. (Turbulence rating = "H" at σ_W = 7 fps (2.13 m/sec) rms). For these reasons this particular data point has been disregarded in making the fairing.

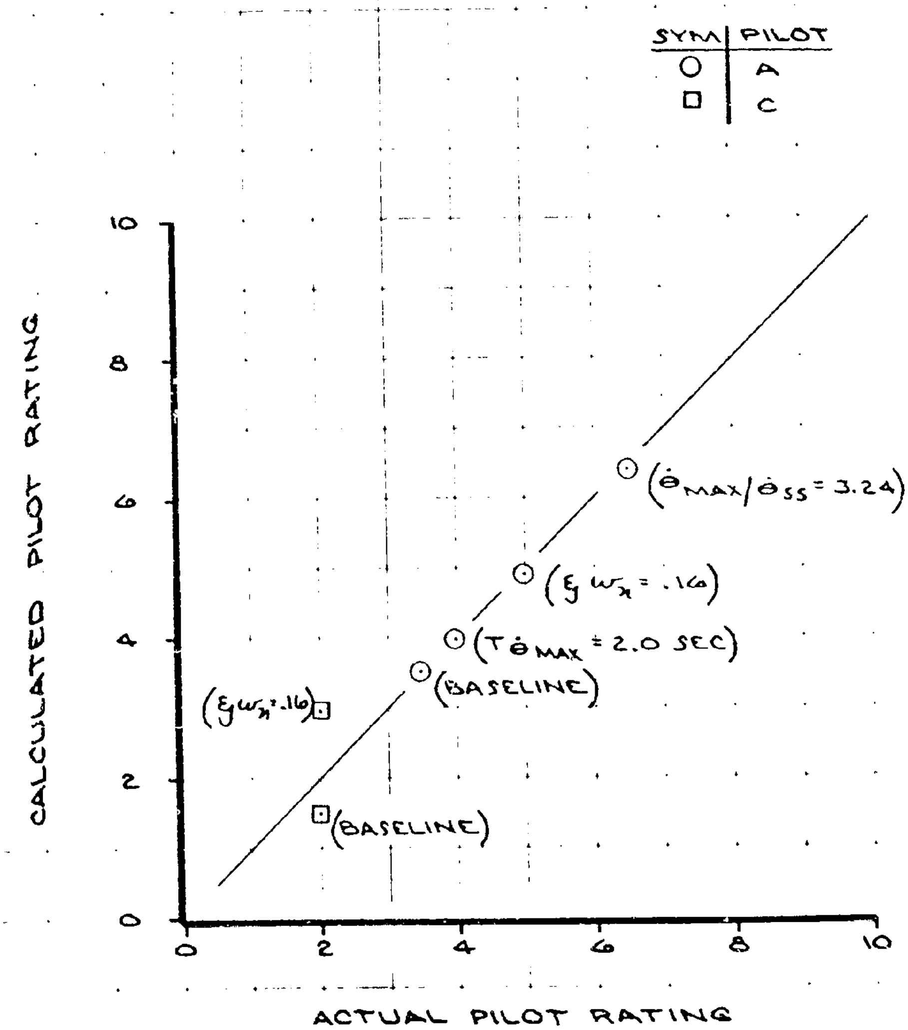
Also, additional information can be obtained by comparing the ratings given by pilot "C" and pilot "A", using the pilot math model analysis technique. This analysis technique consists of a method for correlating pilot ratings based on the pilot describing function developed for each test condition (see Appendix B for a detailed description). The results of this analysis technique are presented in Figure 7-32. These results show that the rating by pilot "C" at the $\xi\omega_n$ value of .16 should be raised by one unit. It also shows the rating given by pilot "C" at the baseline case should be lowered by about one half unit. If these changes were made, the shape of the results from pilot "C" would be more compatible with the other results, but lower. This analysis tends to support the data fairing selected.

Comparing the data against the SST Low Speed Pitch Rate Response Criterion (Figure 7-33) shows that all responses meet the criterion except the minimum damped configuration. The configuration of maximum damping does not violate the criterion or even approach the boundary which does not agree with the results of this evaluation. In general, the SST Low Speed Pitch Rate Response Criterion will allow pitch damping of greater and lesser magnitude than was rated satisfactory by this pilot evaluation.

The results of the turbulence evaluation of this parameter are presented in Figure 7-34. These results show unacceptable turbulence ratings only at the minimum damped configuration ($\xi\omega_n$ .16). The other end of the spectrum

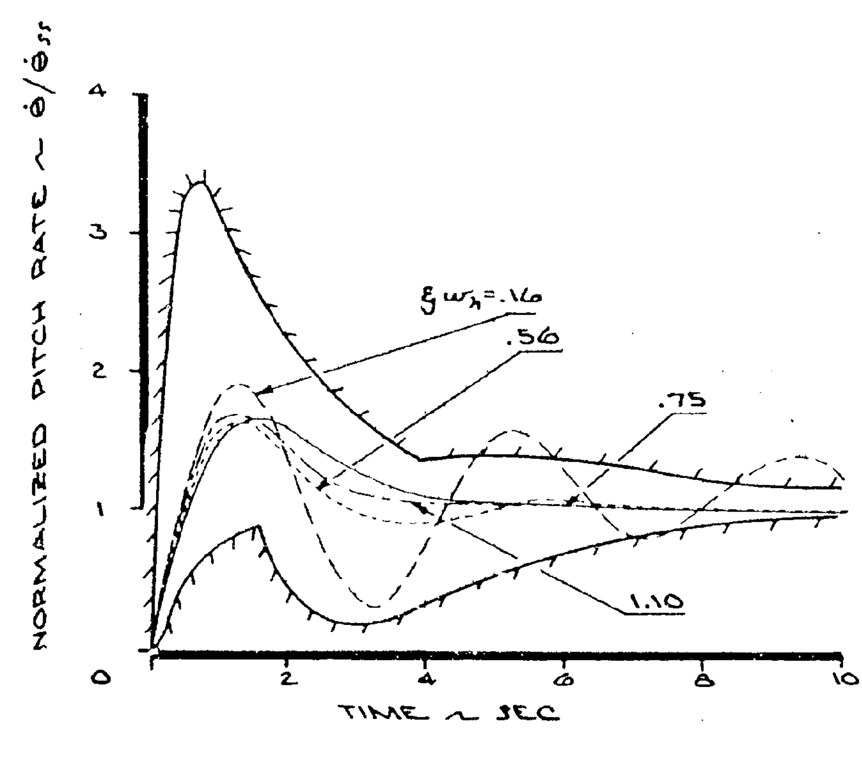
PILOT RATING (CALCULATED) =

$$-13.3 + \frac{1.85}{T_L} + 3.88\,\tilde{\delta} + \frac{30.3}{\bar{\epsilon}}$$



CALC			REVISED	DATE	COMPARISON OF PILOT RATING PREDICTION TECHNIQUE	FIG. 7-32
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 79

RESPONSE TO STEP INPUT
LOW η_α
$(\eta_\alpha \approx 3.981)$



			REVISED	DATE		
CALC					PITCH DAMPING COMPARISON WITH THE SST HIGH SPEED PITCH RATE RESPONSE CRITERION	FIG. 7-33
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 80

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} \approx 1.6$

$T\dot{\theta}_{MAX} \approx 1.2 \rightarrow 1.5$ sec

F_{COL}/g = 50 lb/g (222 N/g)

TEST CONFIGURATION

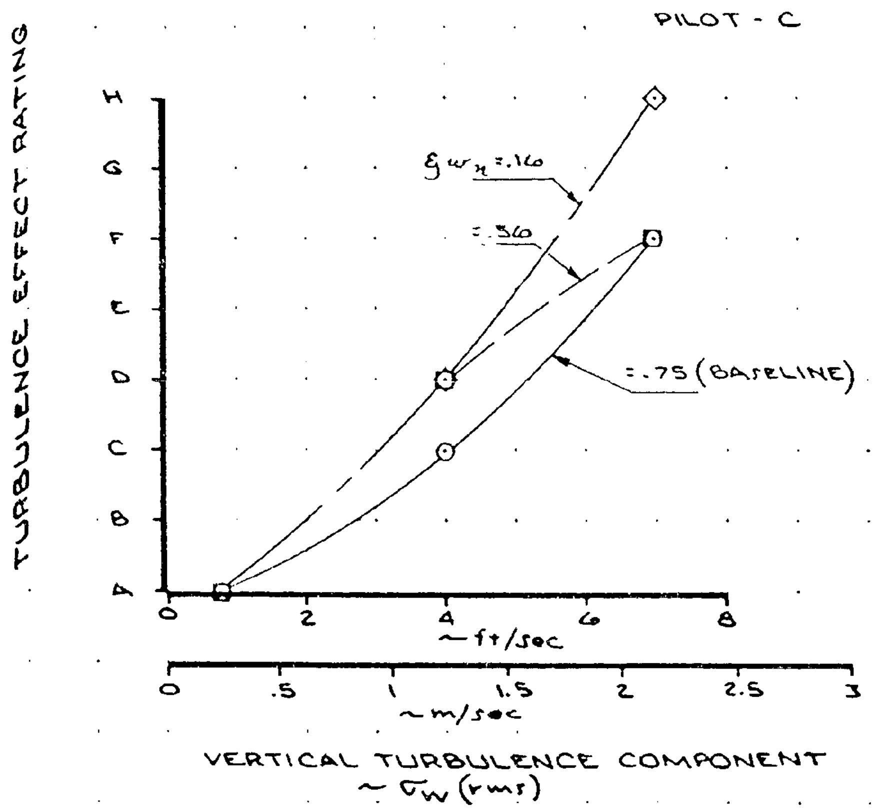
V_C = 144 kts (74 m/sec)

G.W. = 415,000 lb (188,240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN



CALC			REVISED	DATE	PITCH DAMPING TURBULENCE EVALUATION	FIG. 7-34
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 81

($\zeta \omega_n$ = 1.1) was not evaluated in turbulence. No change to the criterion is recommended as a result of this turbulence evaluation.

As a result of the evaluation of pitch damping, it is recommended that an additional pitch damping criterion be established that requires the damping constant to be between a $\zeta \omega_n$ value of 0.5 and 1.05.

7.2.4 Column Force Gradient

The column force gradient was evaluated in combination with the response parameters just discussed. This is not, strictly speaking, a response parameter, but is a measure of the pilot's feel of the longitudinal axis, and was considered applicable to this simulation study.

Results of this evaluation are presented in Figure 7-35. Considerable scatter is indicated, particularly with the low pilot ratings given by pilot "C" at the low column force gradient. As stated previously, this pilot indicated a strong desire for lower column forces. An analysis of the performance achieved on the runs where these low ratings were given, shows that control of pitch rate was severely degraded, in particular at the 10 lb/g (44 N/g) condition. This performance does not match the pilot ratings given. For this reason ratings given by pilot "C" at the low column gradients were not considered in fairing the data.

The results of this column force gradient evaluation indicate that a column gradient between 25 and 85 pounds per "g" (111 and 378 N/g) would be satisfactory for landing approach. The military handling qualities specification MIL-F-8785B indicates the column gradient range should be between 75 and 109 pounds per "g" (333 and 485 N/g) for a wheel controller for a level 1 characteristic. This MIL-F-8785B criterion is influenced by the relatively low limit load factor of the 2707-300PT for landing approach (n_L 1.6 g's) and the relatively small value of (n_α 4.5g). The satisfactory range of the Military Specification criterion

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} = 1.61$

$\zeta\omega_n = .75$

$T\dot{\theta}_{MAX} = 1.5$ SEC

TEST CONFIGURATION

V_C = 144 KT (74 m/SEC)

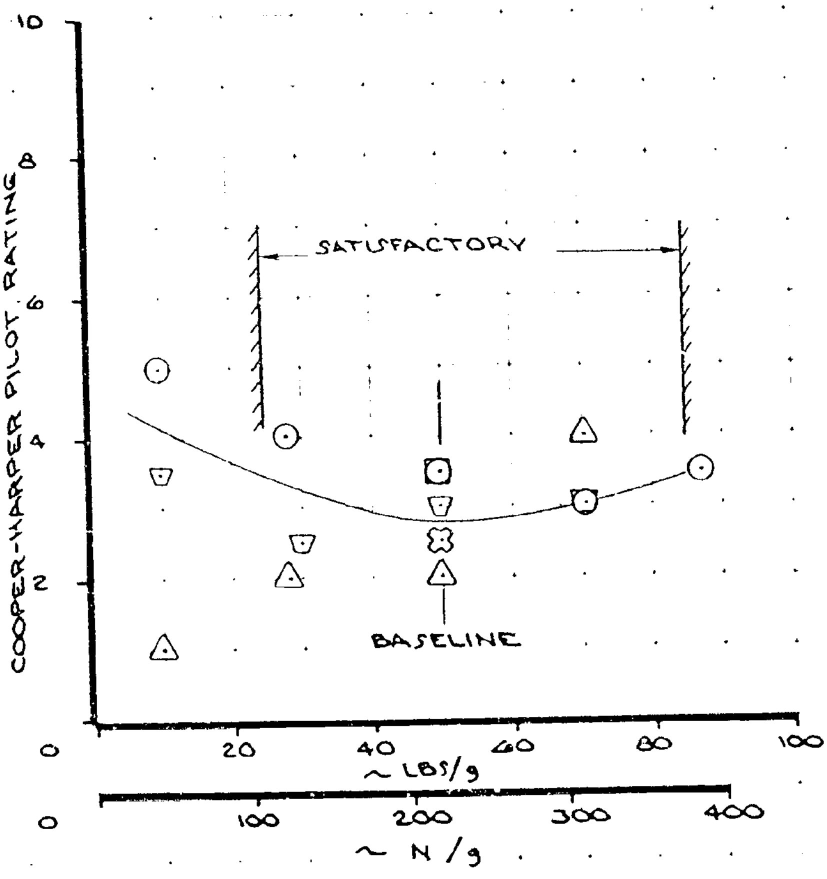
G.W. = 415,000 LB (188,240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN

SYM	PILOT
○	A
□	B
△	C
⊗	E
▽	F



CALC			REVISED	DATE	LANDING APPROACH EVALUATION OF COLUMN FORCE GRADIENT	FIG. 7-35
CHECK						
APPD						PAGE
APPD					THE BOEING COMPANY	83

does not compare with the results obtained in this evaluation. Therefore, the column force gradient recommended criterion is 25 to 85 pounds per "g" (111 to 378 N/g) with the optimum value being 50 pounds per "g" (222 N/g).

The turbulence evaluation of the column force gradient is presented in Figure 7-36. Acceptable turbulence ratings were obtained for all configurations evaluated in turbulence except the 10 lb/g configuration. Since the 10 lb/g configuration was judged unsatisfactory, no change to the column force gradient criterion is recommended as a result of this turbulence evaluation.

7.3 LANDING APPROACH (MINIMUM-SAFE OPERATION)

The purpose of this study area was to determine a criterion that defines the minimum acceptable level of longitudinal stability under which a safe approach and landing can be conducted. This minimum acceptable level is defined as that resulting in a pilot rating of 6.5 on the Cooper-Harper pilot rating scale (Figure 5-1). The task for this evaluation was the same as that used in the normal operation evaluation of landing approach (Figure 7-22).

Previous studies during the National SST Program yielded a criterion in terms of pitch divergence rate resulting from an initial disturbance such as a column pulse input. Also the maneuver point location or maneuver margin has been found to be of significant interest. However, the divergence criterion has in the past been the most important since it does include the effects of speed divergence and thus the effect of speed dependent stability terms as well as the actual measurement of static stability. Both the pitch divergence rate and maneuver margin have been compared against the test results. Table 7-III presents the parameter values and test conditions used for this study area.

7.3.1 Time-to-Double Pitch Attitude

The longitudinal pitch divergence was measured in terms of time-to-double amplitude of pitch attitude. Pitch attitude was selected based on the belief

RESPONSE CONFIGURATION

$\dot{\theta}_{MAX}/\dot{\theta}_{SS} = 1.67$

$\xi \omega_n = .75$

$T\dot{\theta}_{MAX} = 1.5$ sec

TEST CONFIGURATION

$V_C = 144$ kts (74 m/sec)

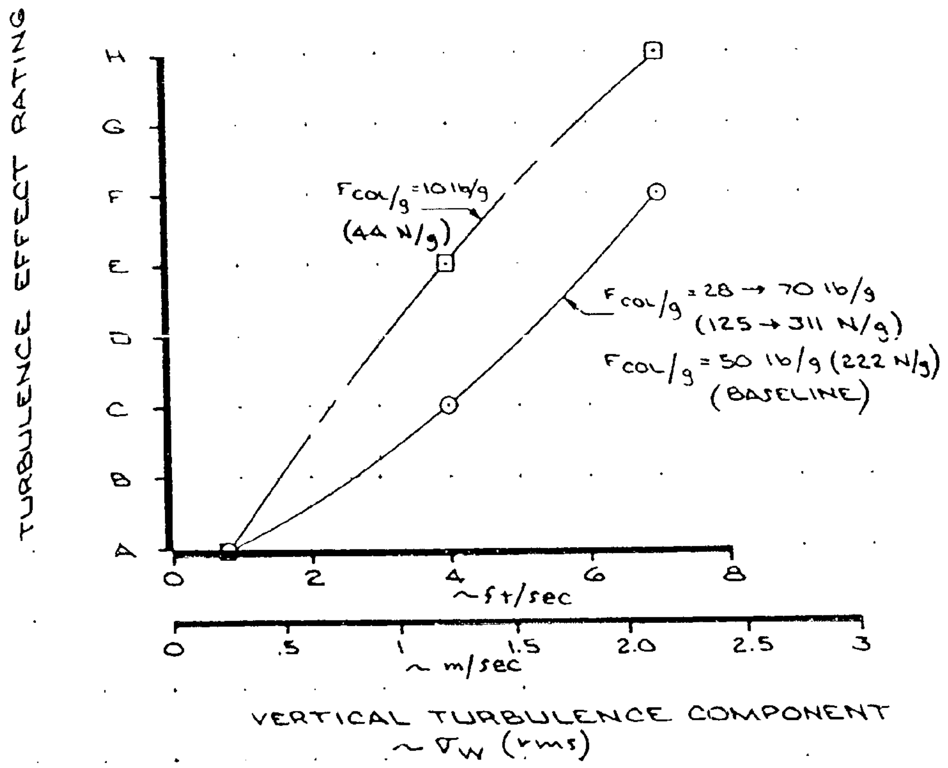
G.W. = 415,000 lb (188, 240 kg)

C.G. = .54 C_R

FLAPS = 20°

GEAR DOWN

PILOT C



CALC			REVISED	DATE	COLUMN FORCE GRADIENT TURBULENCE EVALUATION	FIG.7-36
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 85

TABLE 7-III

LANDING APPROACH (MINIMUM-SAFE OPERATION) TEST CONDITIONS

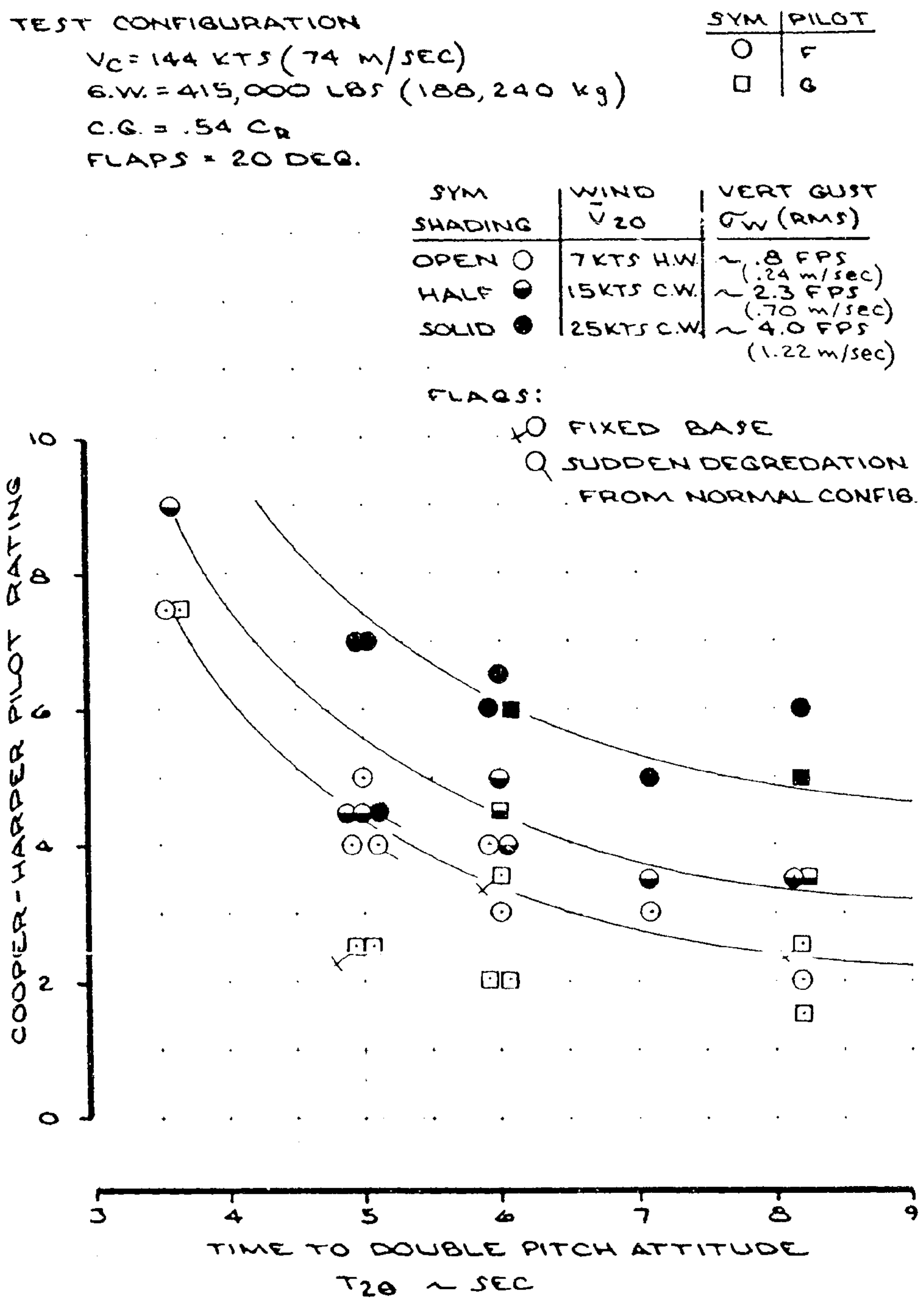
PARAMETERS VARIED		NUMBER OF PILOTS EVALUATING			
		SMOOTH AIR	TURBULENCE	F_{col}/q EFFECTS	FIXED BASE
$T_{2\theta}$	MANEUVER MARGIN				
9.2 sec	18.7 C_R	1	1		
8.2	15.8	2	2		
7.1	12.5	1	1		
6.0	9.2	2	2	1	1
5.0	6.2	2	1		
3.6	2.0	2	1	1	

REV SYM

that pitch attitude is the primary airplane motion "cue" that the pilot is attempting to control during landing approach under the minimum-safe condition. The disturbance input was a small column pulse (½ inch (1.27 centimeters) for ¼ second) in the nose-up direction. The nose-up direction was selected because that is the divergent direction of most concern to the pilot due to his concern about maintaining airspeed and avoiding possible stall.

The configuration selected that would result in a pitch attitude divergence under the condition described in these tests was flown with the handling qualities SAS turned off and with the minimum-safe augmentation (hard SAS) on. Variation of the divergence rate was achieved by varying the gain of the minimum-safe augmentation. Also, the aircraft center of gravity was selected at a value that resulted in as near an exponential divergence as possible with a minimum of initial delay. This also results in the most unstable root predominating and direct measurement of that root as possible. As it turned out, this cg selection was exactly the basic airplane maneuver point (50 C_R).

The divergence rate evaluation results are presented in Figure 7-37. These results show that a divergence rate of 5.6 seconds can be tolerated at the most severe turbulence level evaluated. This turbulence level, having a root mean square vertical turbulence component of approximately 4 fps, (1.22 m/sec), had been previously selected during the National SST Program as the worst probable turbulence considering the probability of encountering the minimum-safe configuration. This was based on a probability study that concluded the combination of this level of turbulence occurring in combination with this airplane configuration to be extremely remote. For any new configuration this probability study would have to be exercised again to establish the required turbulence level and, therefore, the acceptable divergence rate. For this reason the data just shown in Figure 7-37 has been cross-plotted against the turbulence level at the pilot rating of 6.5. This cross-plotted data is shown



CALC		REVISED	DATE	MINIMUM-SAFE LANDING APPROACH TIME-TO-DOUBLE PITCH ATTITUDE EVALUATION	FIG. 7-37
CHECK					
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APPD				THE BOEING COMPANY	PAGE 88

in Figure 7-38 and represents the generalized form of the divergence criterion recommended from this study. During the National SST Program a divergence criterion value of six seconds for the most unstable root was selected, which is the high side of the scatter and, therefore, substantiates the results of this evaluation (see Reference 5).

7.3.2 Maneuver Margin

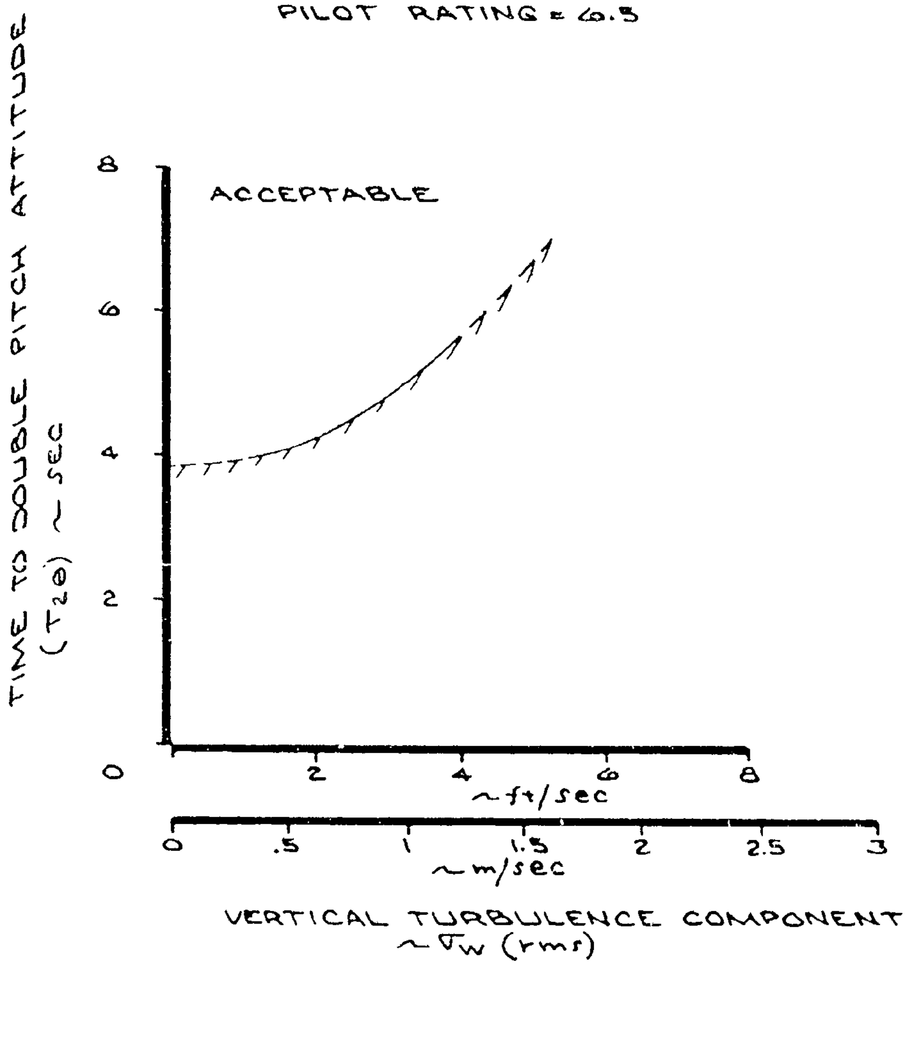
The results described above were also plotted against maneuver margin. The maneuver margin is not believed as general a parameter as the pitch divergence rate since it does not consider airspeed variation. The results are presented in Figure 7-39 and show an 8 percent maneuver margin requirement at the maximum turbulence level evaluated.

7.3.3 Sudden Degradation to Minimum-Safe

Included in the planning for this test series was an evaluation to determine the effect of the pilot learning curve when conducting a long series of minimum-safe piloted evaluations. In other words, does the pilot learn how to fly the minimum-safe airplane configurations, and then give better ratings than he would if he were to suddenly encounter the situation due to a system failure when he had been flying an airplane with good normal handling qualities. This question was approached by a test series designed to identify this problem. These tests were performed at the end of a series of tests investigating normal landing approach handling qualities. The pilot initiated the test run, and during the run the handling qualities SAS was turned off, which reverted the airplane to the minimum-safe augmentation which had been set up for the desired divergence rate level. Also, the center of gravity had been previously established at the position needed for the minimum-safe configuration. The data points depicting these results are identified by flags on Figure 7-37.

MINIMUM-SAFE OPERATION

PILOT RATING = 6.5



CALC			REVISED	DATE	EFFECT OF TURBULENCE ON LANDING APPROACH (MIN-SAFE) TIME TO DOUBLE PITCH ATTITUDE	FIG 7-38
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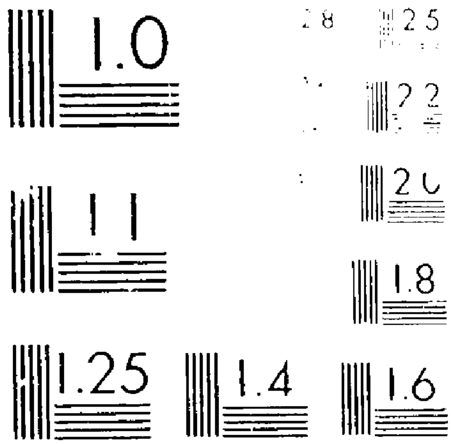

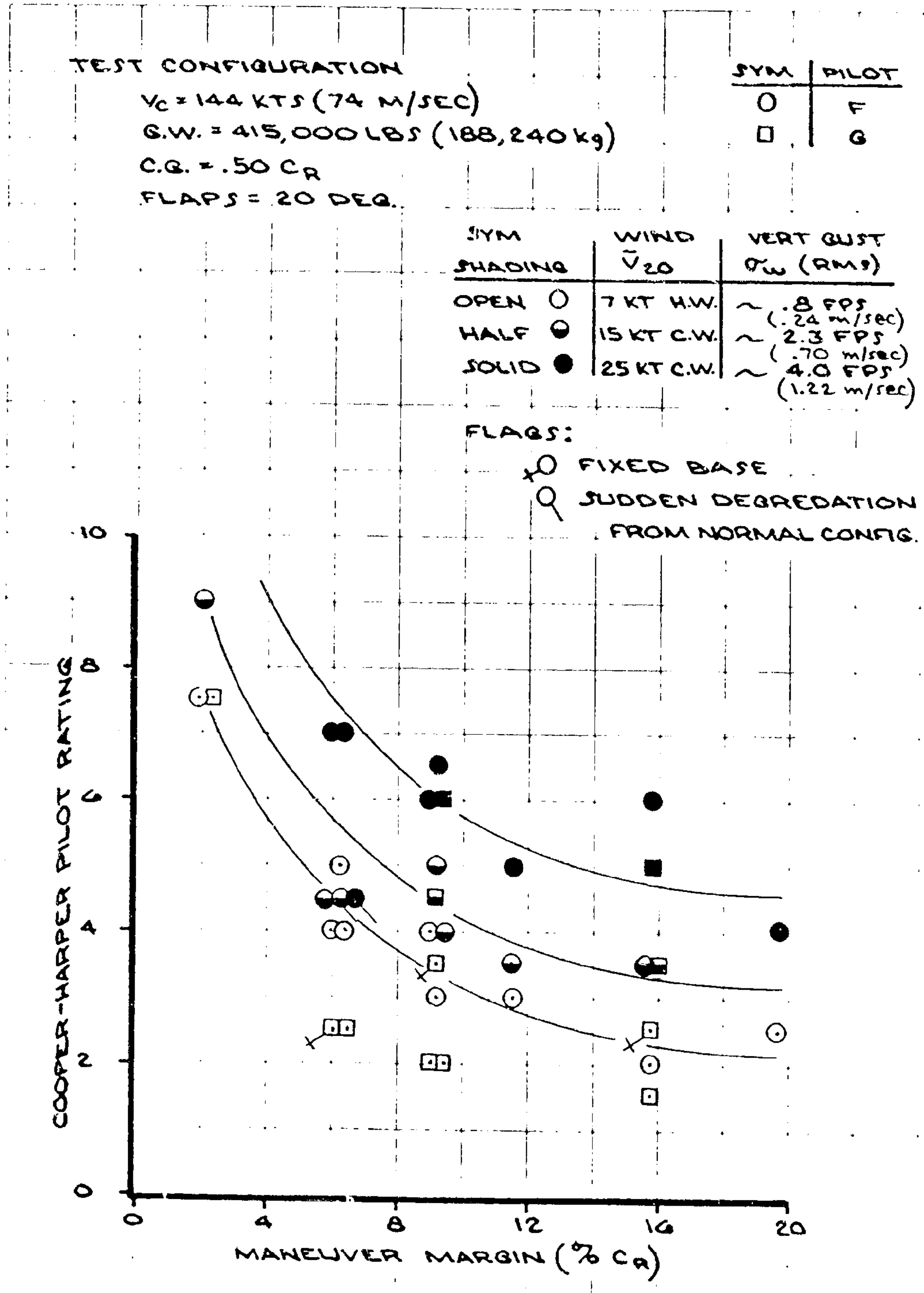

CALC		REVISED	DATE	MINIMUM SAFE LANDING APPROACH MANEUVER MARGIN EVALUATION	FIG. 7-39
CHECK					
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APPD				THE BOEING COMPANY	PAGE 91

The first time this evaluation was attempted it was done for a divergence level of 5 seconds at a turbulence level of 4 feet per second (1.22 meters per second), a configuration previously rated 7.0. The normal configuration which existed at the start of the run had been previously rated 3.5-4. The degradation to minimum-safe was performed as the pilot was deviating above the glideslope as called for in the pilot task description. Immediately following the run the pilot was asked to concentrate on the latter part of the run and was given no other information, and was not aware the configuration changed during the run. The pilot rating given was 4.5 instead of the previous 7.0, which was opposite to the expected trend. This lower rating was probably due to the influence of the first part of the run which the pilot could not ignore. A second run was immediately made, leaving the airplane in a minimum-safe configuration that existed at the termination of the previous run. The pilot rating for this run was 7.0, which was exactly the rating he had given this configuration during the test series where he was evaluating minimum-safe configurations. From these results it was concluded that there was not a significant learning trend established during the minimum-safe evaluation series that affected the pilot ratings in an optimistic direction which would cause concern. Additional runs were made using the sudden degradation technique at the same divergence rate, but at the lower turbulence levels immediately following the series just described. The pilot was aware during these runs of the purpose of the tests, but was not aware as to what run the sudden degradation would occur. He successfully identified each time it did occur, even though the runs were randomly mixed with runs where no degradation occurred. As can be seen in Figure 7-37, the ratings were again the same as had been given previously during the minimum-safe evaluation series. These additional results support the previous conclusion that whatever learning occurs during a long series of flights with degraded configurations does not result in optimistic ratings with this particular pilot.

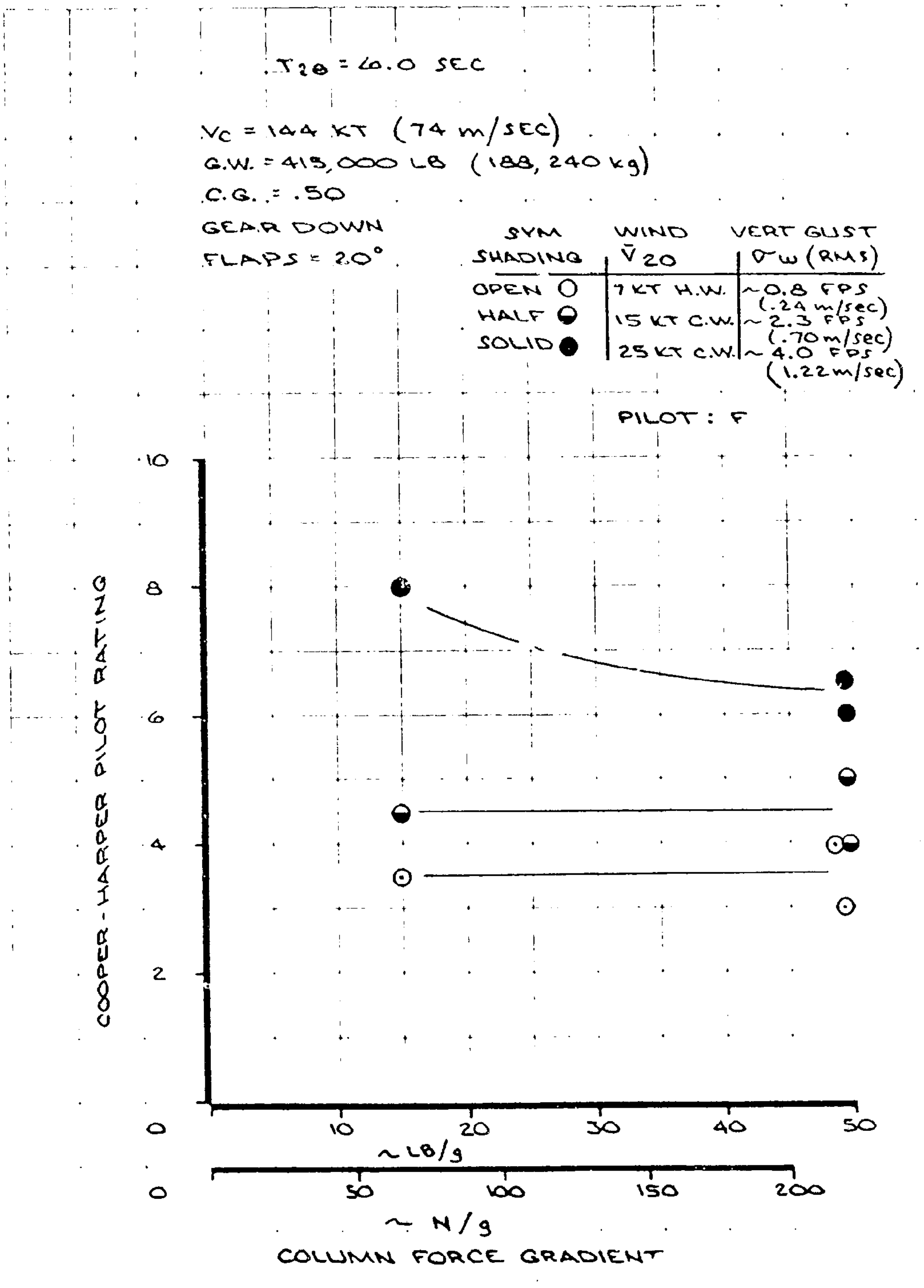
7.3.4 Column Force Gradient

The effect of column force gradient was evaluated and the results are presented in Figures 7-40 and 7-41. Reducing column force gradient to as low as 15 lb/g (66.7 N/g) had no effect at the criterion limit of $T_{2\theta}$ = 6.0 seconds, as seen in Figure 7-40. Reducing the column force gradient did have a significant effect at the shorter divergence time of $T_{2\theta}$ = 3.6 seconds, as seen in Figure 7-41. The better pilot rating at the lower gradient was due to the reduced physical workload. At this divergence rate of 3.6 seconds a very high level of column activity with large deflections is required to control the airplane, and a reduction in the column gradient is beneficial. However, this benefit at $T_{2\theta}$ = 3.6 seconds cannot be realized since the divergence rate limit is 6.0 seconds time-to-double amplitude where no benefit due to reduced column gradient is predicted.

In summary, the recommended criterion for landing approach (minimum-safe operation) is the SST Pitch Divergence Criterion. Considering the data scatter and test accuracy, the recommended minimum time-to-double pitch attitude of the most unstable root is 6.0 seconds. This divergence rate is based on the turbulence level resulting from the 2707-300PT probability study. For other turbulence levels refer to Figure 7-38.

7.4 STALL RECOVERY CONTROL POWER

The purpose of evaluating stall recovery control power was to develop a criterion that defines the magnitude of longitudinal control power needed for safe positive recovery from the high angle of attack, minimum speed condition. This minimum speed condition for conventional aircraft is normally defined by the stall condition ideally associated with a nose down pitch reaction which



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LANDING APPROACH (MIN-SAFE) EVALUATION OF COLUMN GRADIENT ($T_{2\theta}$ = 6.0 SEC)

FIG. 7-40

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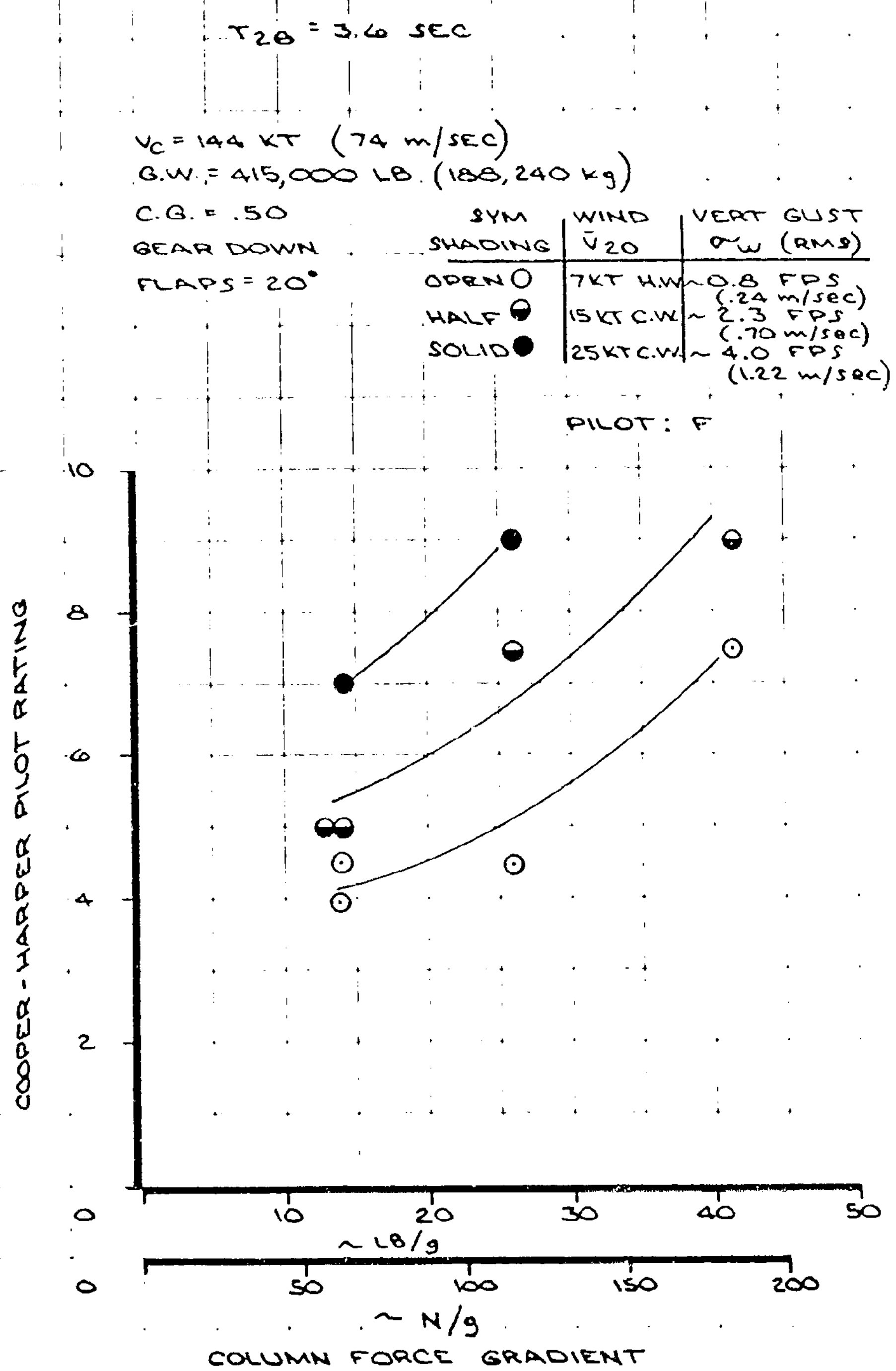
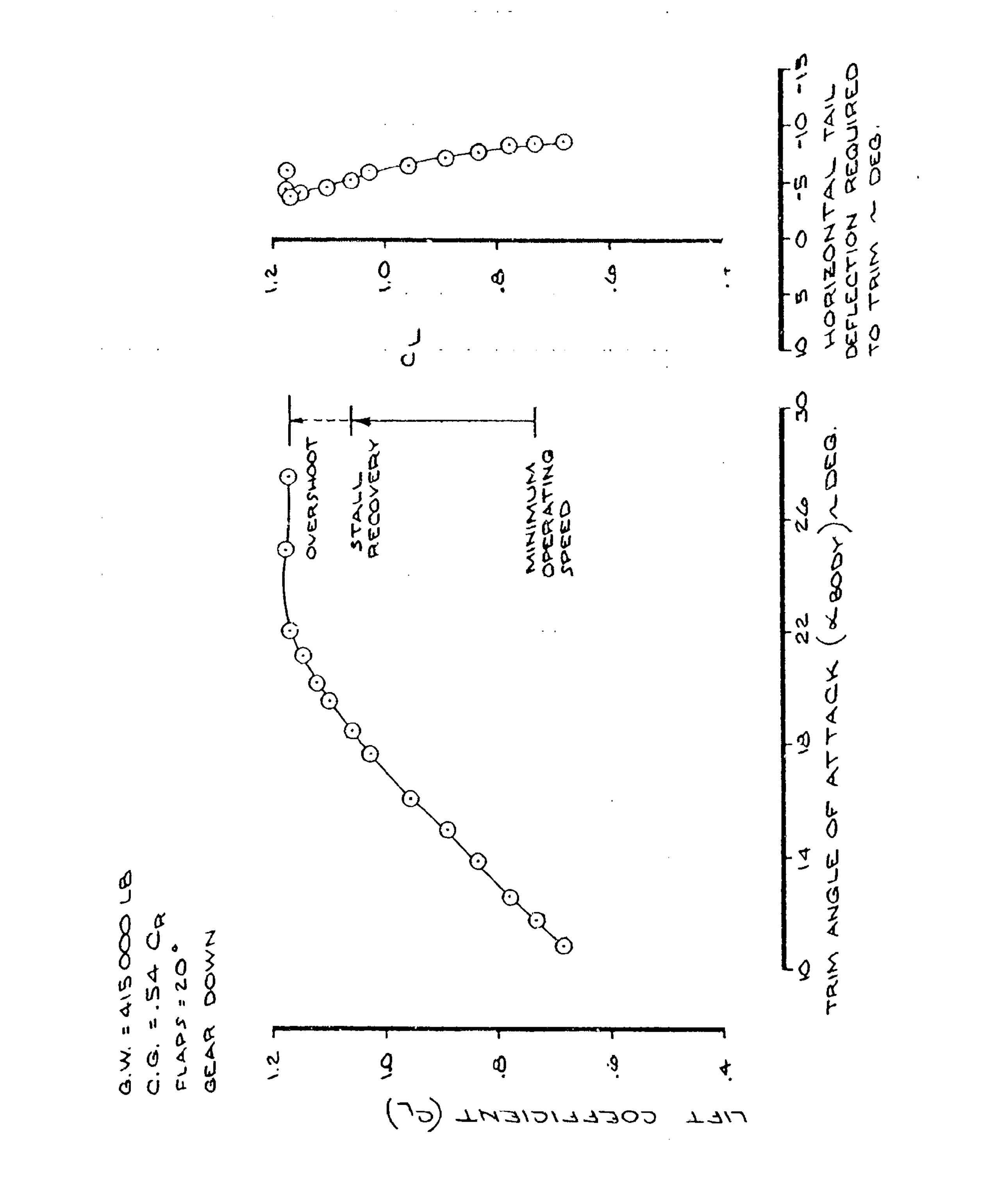


CALC		REVISED	DATE	LANDING APPROACH (MIN-SAFE) APPROACH EVALUATION OF COLUMN GRADIENT ($T_{2\theta}$: 3.6 SEC)
CHECK				FIG. 7-41
APPD				THE BOEING COMPANY
APPD				PAGE

results in a stable stall recovery situation with minimum reaction required from the pilot. For delta wing and arrow wing configurations such a conventional stall reaction is not the situation. These wing configurations do not exhibit the characteristic stall. There is normally not a nose down moment and not a sudden loss of lift at the minimum speed condition. With such configurations the stall speed is a defined speed known as the minimum demonstrated speed, or in more general terms, the speed associated with the maximum demonstrated lift coefficient and angle of attack. One of the items that might be limiting at the defined stall speed is the amount of longitudinal control power available in the nose down direction, since the pilot must recover the aircraft from the defined stall speed manually. Other conditions which may influence the establishment of the defined stall speed are conditions such as a loss of directional stability or sudden degradation in longitudinal stability. These conditions are not addressed in this study. The defined stall speed must be established sufficiently far away from the onset of stability problem areas, if they exist, so the aircraft will not enter this region inadvertently by overshooting the defined stall speed flight condition. This then leaves the requirement for a nose down control power criterion at the defined stall speed for an aircraft that has been given sufficient margin from any undesirable high angle of attack stability characteristics.

The defined stall speed (minimum demonstrated speed) and the speed for stall warning (minimum operating speed) used in this study area were defined during the National SST Program. Definition of these speeds was not part of this study.

Figure 7-42 defines the measured stability in the approach to stall, stall, and region of stall overshoot. The aircraft exhibits near neutral longitudinal stability which is typical of the stability that would exist with airplanes that use a defined stall speed and have sufficient margin from any degraded



CALC			REVISED	DATE	LONGITUDINAL STABILITY - STALL RECOVERY EVALUATION	
CHECK						
APPD						FIG. 7-42
APPD					THE BOEING COMPANY	PAGE 97

stability characteristics. The lateral axis stability was not measured, but was reported to be satisfactory, and was not an influencing factor in any of these tests.

The stall recovery evaluation was conducted by varying the magnitude of the longitudinal control power and having the pilot fly a series of typical stall approaches terminated with manual stall recovery for each level of longitudinal control power. In addition, the atmospheric turbulence level was varied in order to define the effect of turbulence on this evaluation. For each series the pilot would give a pilot rating and a turbulence rating where applicable.

The longitudinal control power was varied by introducing additional increments of tail pitching moment and lift into the math model build-up equations. These increments were programmed as a function of the control column deflection with the increments increasing from zero at zero column deflection to maximum at full forward column deflection. By making these increments a function of control column deflection, the basic airplane stability was retained constant for all levels of longitudinal control power.

The magnitude of the longitudinal control power was calibrated by conducting full nose down control inputs, unpiloted, and measuring the initial peak longitudinal angular acceleration. These unpiloted tests were conducted varying the maximum magnitudes of the tail lift and pitching moment increments over the necessary range to provide the desired variation of longitudinal angular acceleration tested and the test conditions (Table 7-IV).

Due to making the control system modification by the technique just described, the pilot was required to maintain near neutral trim during the approach to the stall recovery condition in order to have available for stall recovery the same nose down control power as existed for the unpiloted calibration runs. This was not a problem from a piloting standpoint since near neutral

TABLE 7-IV

STALL RECOVERY CONTROL POWER TEST CONDITIONS

PARAMETER VARIED	NUMBER OF PILOTS EVALUATING	
	SMOOTH AIR	TURBULENCE
MAXIMUM NOSE DOWN ANGULAR ACCELERATION AVAILABLE		
$\ddot{\theta}$ = 6.4 deg/sec^2	1	1
= 5.2	1	1
= 4.1	1	1
= 3.6	1	1
= 3.0	1	1
= 2.5	1	1
= 1.9	1	

stability existed with the basic math model anyway. On those tests where neutral trim was not maintained to a satisfactory degree, a correction was applied to the angular pitch acceleration parameter. This correction consisted of applying a ratio to the angular acceleration parameter equal to the control column available from the test trim condition divided by the control column available from the trim used during the engineering calibration runs.

The pilot task for these evaluations is presented in Figure 7-43.

Figure 7-44 shows the results of these tests with fairings for the three levels of turbulence. In turn, the intersection of these fairings at pilot rating 3.5 are cross-plotted in Figure 7-45 to show the trend of nose down angular acceleration requirements with turbulence level at the satisfactory pilot rating boundary.

Pilot rating 3.5 was selected as the boundary for satisfactory stall recovery control power since that is the dividing line between a configuration needing improvement and one not needing improvement. The stall is an emergency condition caused by a piloting, operational, or mechanical problem, or combination thereof. The control power for stall recovery must be satisfactory without needed improvement in order to safely recover from stall under the emergency adverse condition encountered. When referring to the pilot rating scale (Figure 5-1) it can be seen that 3.5 is the limit pilot rating for a condition not needing improvement.

The values of nose down angular acceleration in Figure 7-44 have been corrected for any slight out-of-trim condition at initiation of stall recovery as described above. Also, some data points have been omitted due to pilot familiarization problems, significant out-of-trim at stall recovery initiation, or excessive angle of attack overshoot with corresponding excessive airspeed undershoot. The resulting data still have some scatter, but satisfactory fairings have been applied which result in the final cross plot in Figure 7-45.

STALL RECOVERY PILOT TASK

1. INITIATE TEST TRIMMED AT MINIMUM OPERATION SPEED (145 KNOTS CAS)

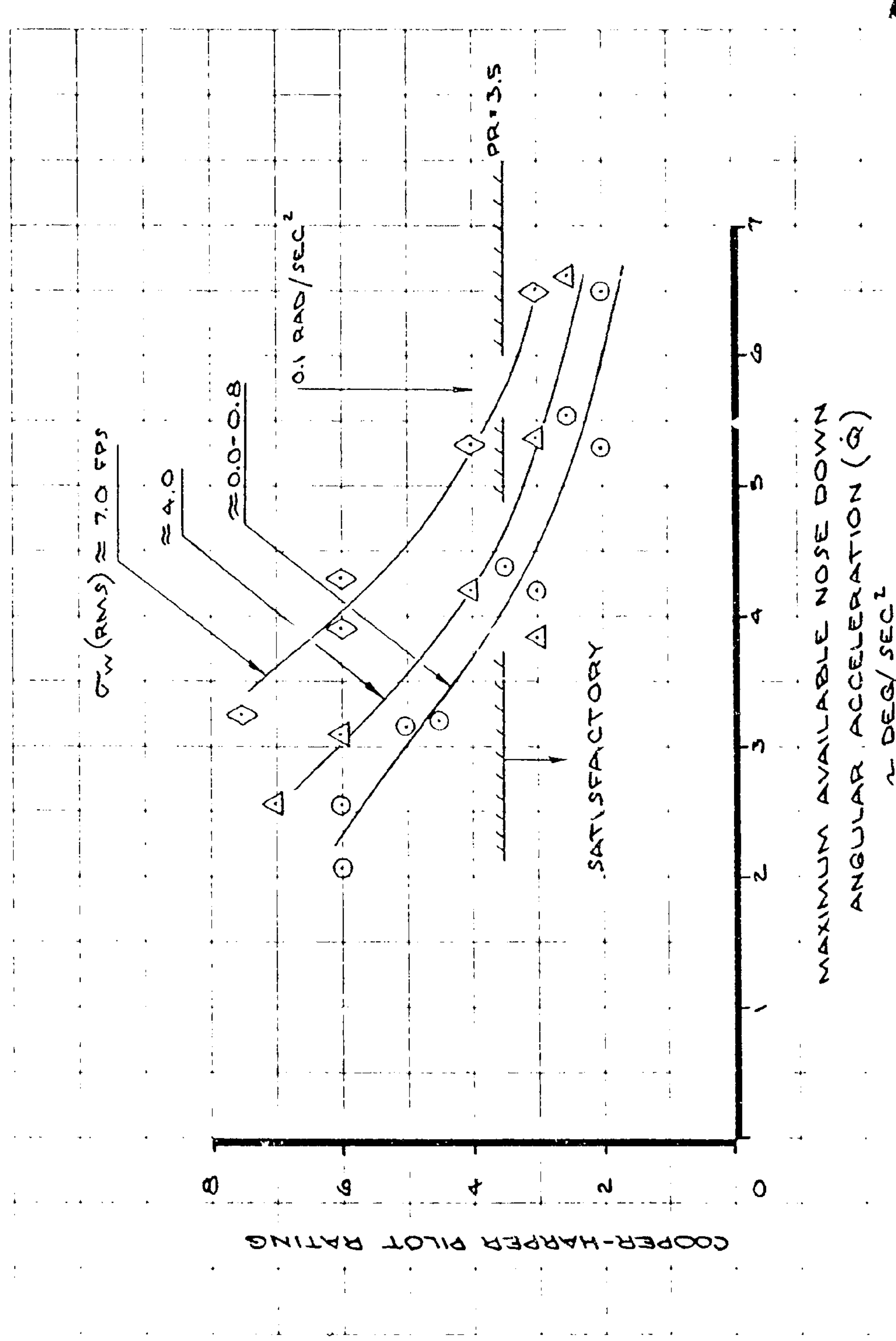
2. REDUCE THRUST TO ESTABLISH AIRCRAFT DECELERATION RATE

3. AT MINIMUM DEMONSTRATED SPEED (118 KNOTS CAS) INITIATE MAXIMUM EFFORT STALL RECOVERY TECHNIQUE (UP TO FULL NOSE DOWN LONGITUDINAL CONTROL)

4. STALL RECOVERY TO BE CONTINUED USING THRUST AS NECESSARY TO MINIMIZE ALTITUDE LOSS UNTIL ALTITUDE STABILIZED AND AIRCRAFT ACCELERATING

5. CONDUCT THIS TEST THREE TIMES VARYING AIRCRAFT DECELERATION RATE WITH 1 KNOT/SEC AS THE NOMINAL

FIGURE 7-43



			REVISED	DATE	
CALC					STALL RECOVER CONTROL POWER EVALUATION
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APPD					FIG. 7-44
APPD					THE BOEING COMPANY

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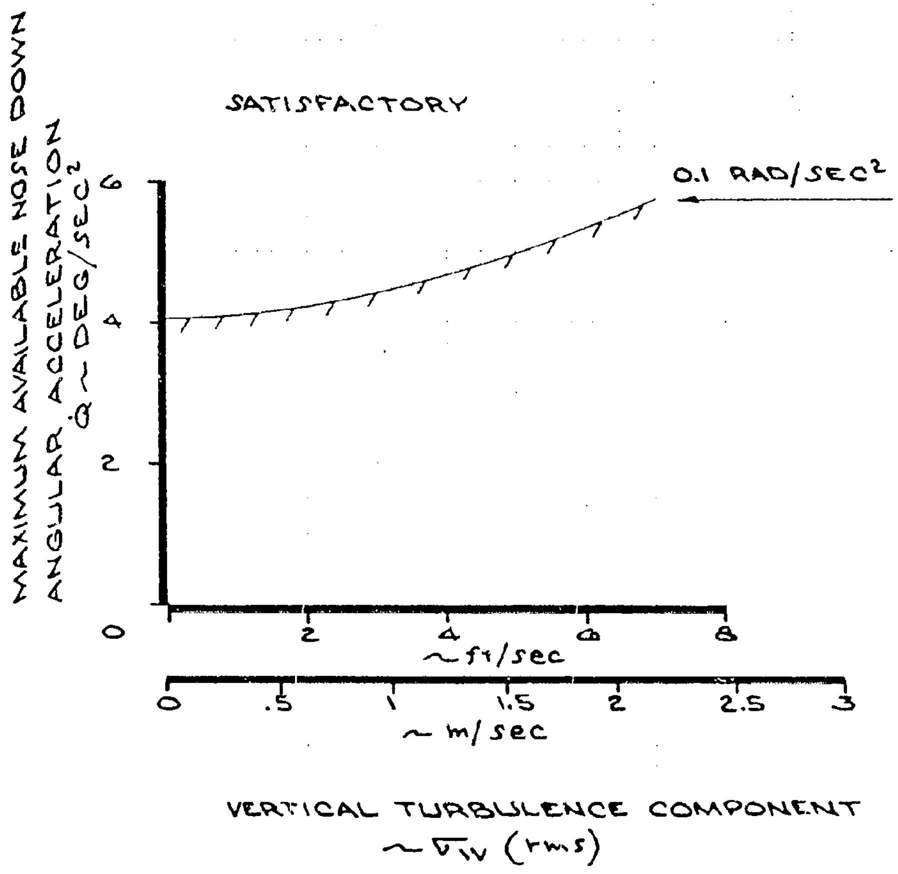
NORMAL OPERATION

PILOT RATING = 3.5



CALC			REVISED	DATE	EFFECT OF TURBULENCE ON STALL RECOVERY CONTROL POWER	
CHECK						
APPD						FIG. 7-45
APPD						
					THE BOEING COMPANY	PAGE 103

The recommended Stall Recovery Control Power Criterion is 0.1 rad/sec^2 at the maximum turbulence level tested during this evaluation. The satisfactory variation of nose down angular acceleration with turbulence level is presented in Figure 7-45.

8.0 FOLLOW-ON STUDIES

As a result of this simulation study, additional areas of investigation are recognized as desirable for future studies to continue development of the handling qualities criteria data base. These are listed as follows:

- o High speed cruise criteria evaluation using a moving base simulator having greater load factor simulation capability
- o Stall recovery control power evaluation considering variation of basic airplane stability at stall
- o Landing flare criteria evaluation
- o Determine the structural modal effect on handling qualities criteria
- o Climb, cruise and transonic speed stability criteria evaluations

For future studies in the above areas it is recommended that a generalized math model be used instead of an actual aircraft math model. This generalized math model should be detailed to the extent of including non linear characteristics, speed dependent derivatives, and structural modes. The advantages of such a generalized math model over the one used for this study would be the amount of independent control over the basic parameters in the math model. This control would necessarily be an important factor in the design of such a generalized math model.

9.0 CONCLUSIONS

Refined handling qualities criteria have been developed in the four areas of study. These criteria are based on previous existing criteria which in some cases are unchanged. However, in all cases a greater understanding and confidence level exist with all criteria recommended in this report.

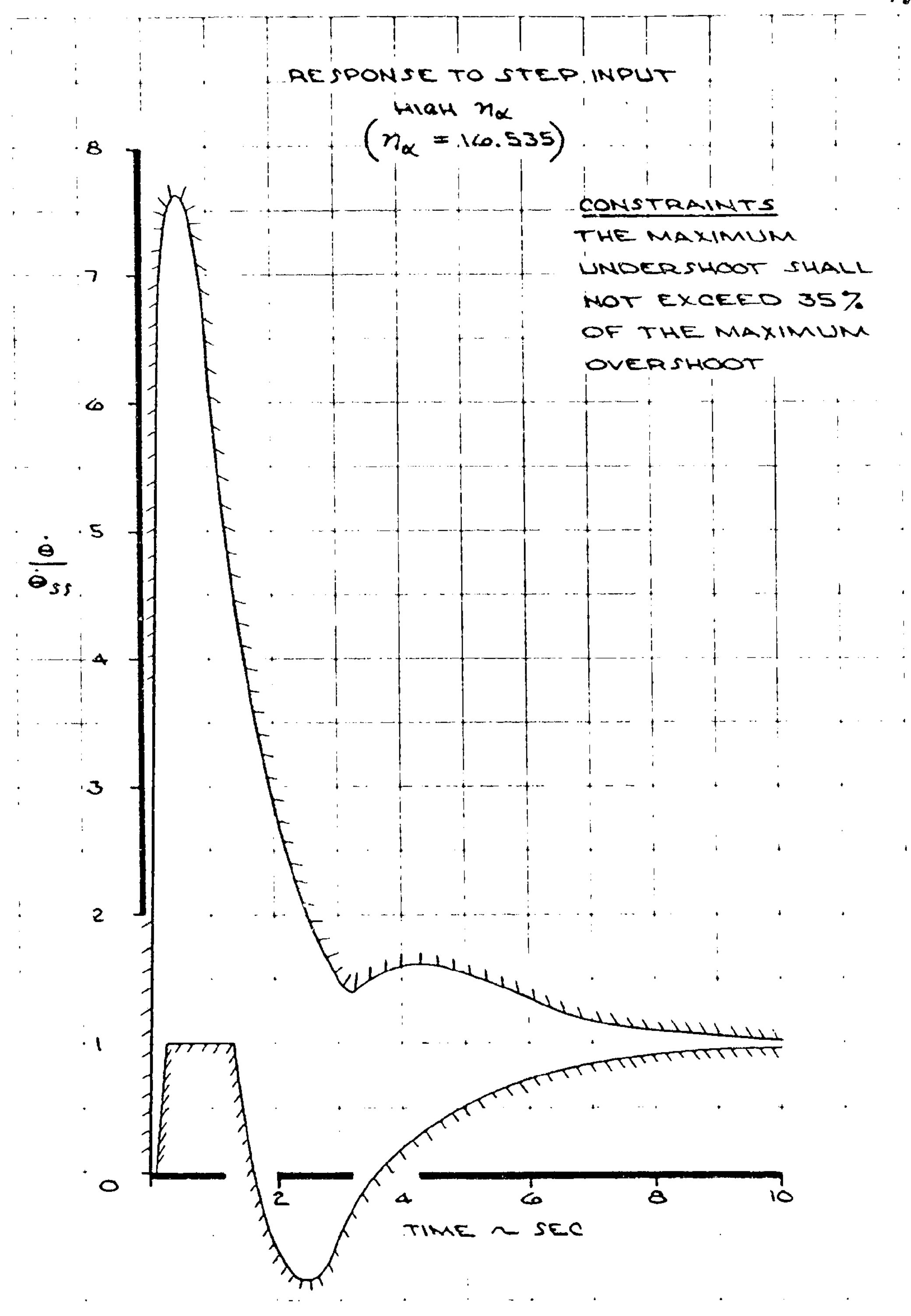
The recommended criteria will be summarized under each study area for which it applies.

9.1 HIGH SPEED CRUISE MANEUVERING

1. Minimum pitch attitude display sensitivity requirement is 0.23 inches per degree (.584 centimeters per degree) for this flight regime.
2. The SST High Speed Pitch Rate Response Criterion is satisfactory for this flight regime with the minimum overshoot requirement removed as presented in Figure 9-1.
3. The optimum column force gradient for this flight regime is 40 pounds per "g" (178 newtons per "g").

9.2 LANDING APPROACH (NORMAL OPERATION)

1. The SST Low Speed Pitch Rate Response Criterion with additional specifications for time-to-peak pitch rate and pitch damping is satisfactory. The time-to-peak pitch rate resulting from a column step input should be between 1.1 and 1.8 seconds. The damping constant ($\xi \omega_n$) should be between .5 and 1.05. These criteria are summarized in Figure 9-2.
2. The column force gradient should be between 25 and 85 pounds per "g" with the optimum being 50 pounds per "g".



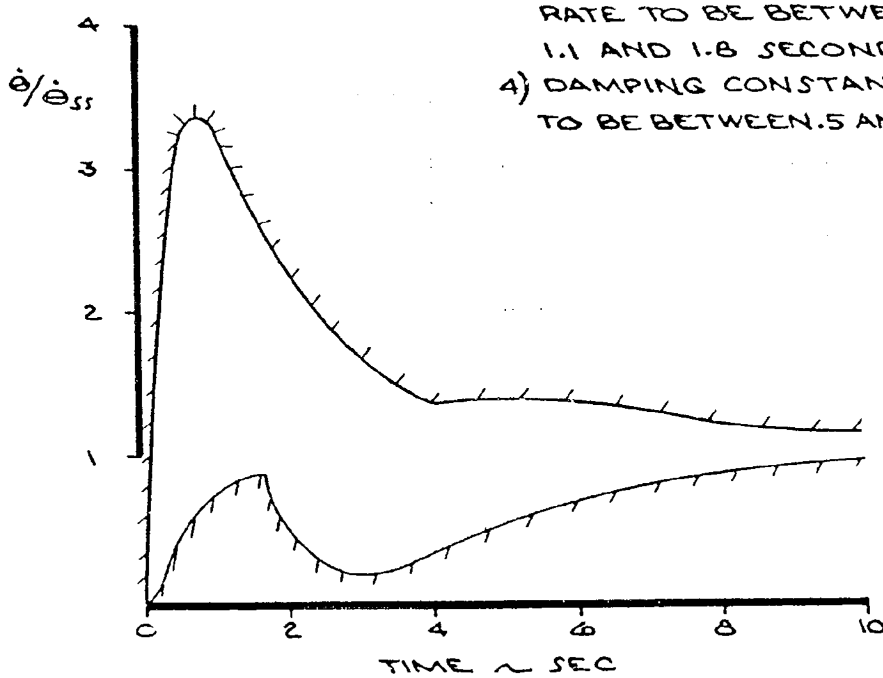
CALC			REVISED	DATE	MODIFIED SST HIGH SPEED PITCH RATE RESPONSE CRITERION	
CHECK						
APPD						FIG. 9-1
APPD					THE BOEING COMPANY	PAGE 107

RESPONSE TO STEP INPUT
LOW η_α
($\eta_\alpha = 3.981$)

CONSTRAINTS

1) THE MAXIMUM UNDERSHOOT SHALL NOT EXCEED 35% OF THE MAXIMUM OVERSHOOT.
2) WHEN THE MAXIMUM OVERSHOOT IS LESS THAN 20% OF $\dot{\theta}_{ss}$, THE RISE TIME FROM 0.10 TO 0.70 $\dot{\theta}_{ss}$, SHALL NOT EXCEED .8 SEC.
3) TIME-TO-PEAK PITCH RATE TO BE BETWEEN 1.1 AND 1.8 SECONDS.
4) DAMPING CONSTANT ($\xi\omega_n$) TO BE BETWEEN .5 AND 1.05.

NORMAL OPERATION
PR = 3.5



CALC		REVISED	DATE	MODIFIED SST LOW SPEED PITCH RATE RESPONSE CRITERION	FIG. 9-2
CHECK					
APPD					
APPD				THE BOEING COMPANY	PAGE 108

9.3 LANDING APPROACH (MINIMUM-SAFE OPERATION)

Acceptable handling qualities are defined by the SST Pitch Divergence Criterion with a time-to-double pitch attitude of 6.0 seconds or greater for the most unstable root. This divergence rate is based on the vertical turbulence component of 4.0 fps (1.22 m/sec) rms which corresponds to a probability level of exceedence of 10^{-3} per flight. This criterion is presented as a function of turbulence in Figure 9-3.

9.4 STALL RECOVERY CONTROL POWER

For aircraft with near neutral stability up to the maximum angle of attack, a minimum nose-down angular acceleration capability of 0.1 radians per sec^2 should exist. This is valid for a vertical turbulence component of up to 7.0 fps (2.13 m/sec) rms. This turbulence level corresponds to a probability level of exceedence of 10^{-3} per flight. This criterion is presented as a function of turbulence in Figure 9-4.

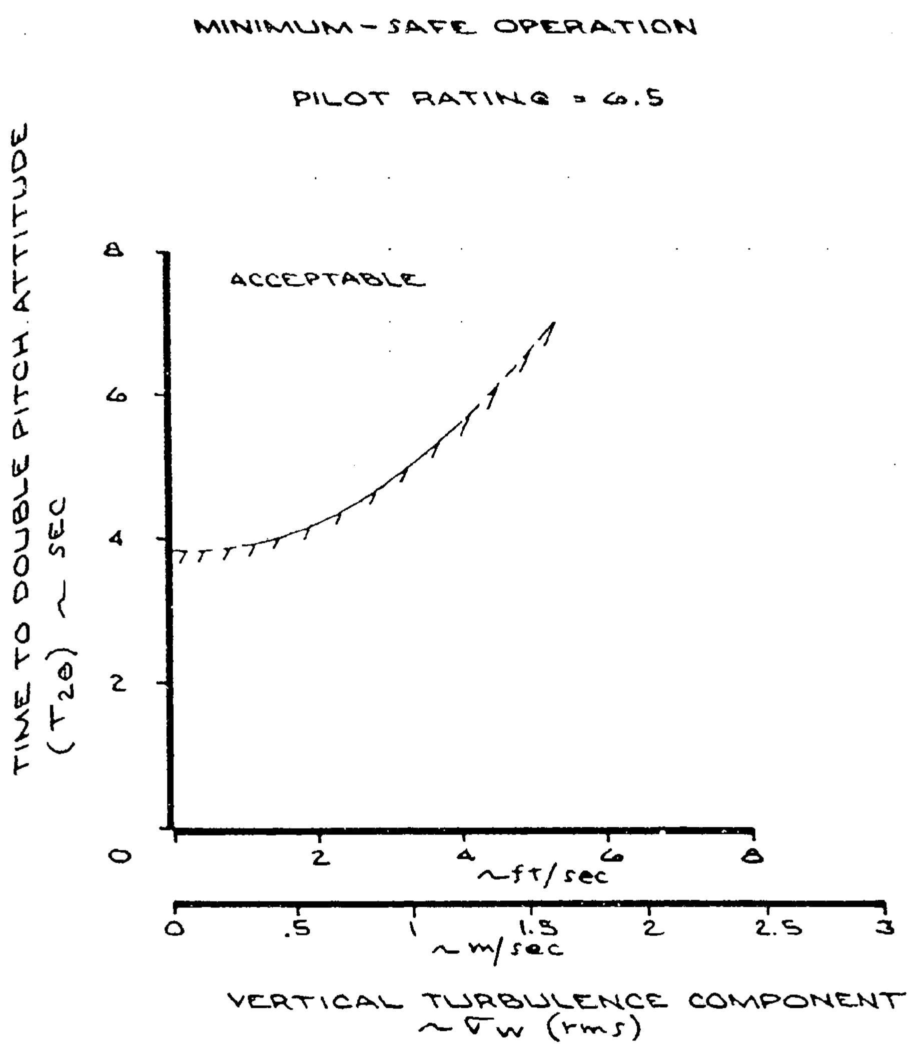
9.5 PILOT DESCRIBING FUNCTION STUDY

1) Pilot frequency response characteristics display pronounced high-order lag (4th order or greater) and lead or lead-lag equalization which is usually second-order and is configuration-dependent.

2) The lag characteristics are essentially constant among the pilots and configurations tested and are assumed to represent human neuromuscular phenomena.

3) Comparison with other published data suggests that the neuromuscular lags are dependent on controller type.

4) Nonlinear, "bang-bang" control activity predominates at and beyond the neuromuscular break frequency.



CALC			REVISED	DATE	LANDING APPROACH (MIN-SAFE) CRITERION	FIG 9-3
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APPD						
APPD					THE BOEING COMPANY	PAGE 110

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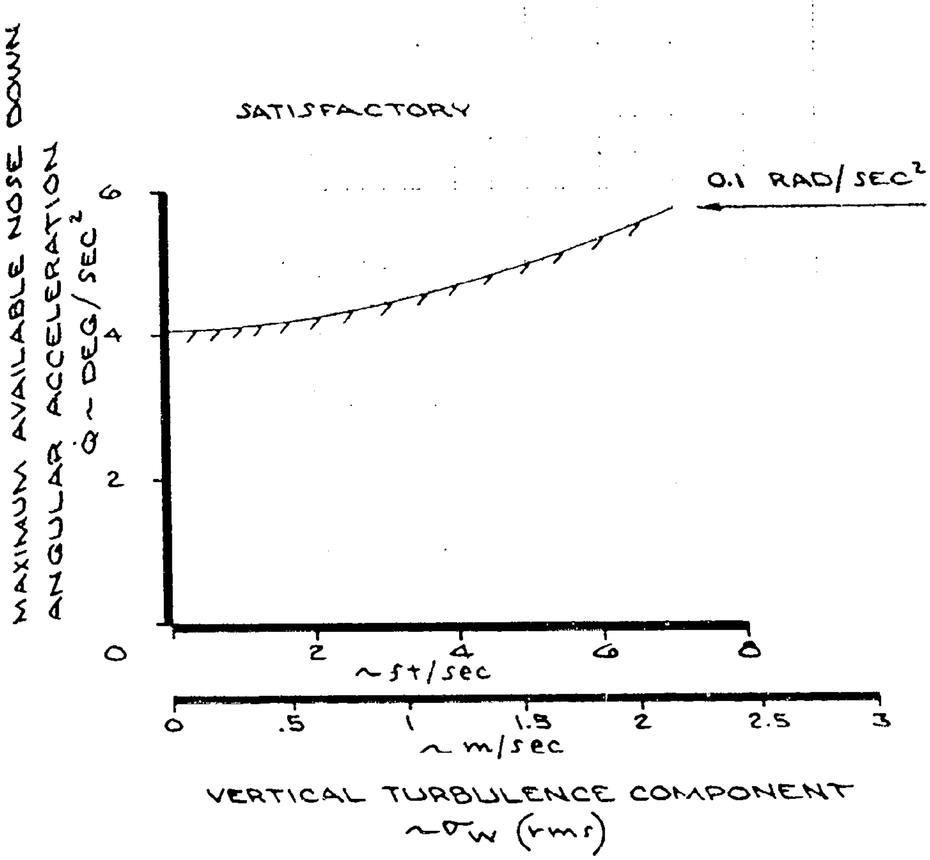
4 6000

NORMAL OPERATION

PILOT RATING = 3.5



CALC			REVISED	DATE	STALL RECOVERY CONTROL POWER CRITERION	FIG. 9-4
CHECK						
APPD						
APPD					THE BOEING COMPANY	PAGE 111

5) Tracking performance, control activity, configuration characteristics, and pilot preferences are the principal variables affecting pilot rating.

6) Good agreement was obtained with observed data using a linear regression model to predict pilot rating, but the present data base is too small to give sufficient statistical confidence levels.

7) Only small differences were observed between pilot frequency response on moving and fixed base simulators.

SYMBOLS AND ABBREVIATIONS

ADI	attitude director indicator
ALT	altitude (feet, meters)
A/P	airplane
c	output of nonlinear element
CAS	calibrated airspeed (knots, m/sec)
cg	center of gravity (% C_R)
C_L	lift coefficient
cm	centimeters
CW	cross wind
C_R	root chord
deg	degree
dB	decibel
EADI	electronic attitude director-indicator
F_{col}	column force (lb, N)
fpm	feet per minute
fps	feet per second
ft	feet
g	gravity (ft/sec^2, m/sec^2)
GW	gross weight (pounds, kilograms)
h	altitude (ft, m)
h_{REF}	reference altitude (ft, m)
HW	head wind (knots)
hz	Hertz (cycles)
i	system input
in	inches
kg	kilogram

kts	knots
L_α	normalized lift per angle of attack (sec^{-1})
lb	pounds
L_u	longitudinal integral scale length (ft, m)
L_v	lateral integral scale length (ft, m)
L_w	vertical integral scale length (ft, m)
m	system output
max	maximum
NASA	National Aeronautics and Space Administration
n_α	normalized load factor per angle of attack (g's/rad)
$N (j\omega)$	linear pilot representation
n_L	limit load factor (g's)
N	newton
n_Z	normal load factor
$n_{Z_{ss}}$	steady state normal load factor
PR	pilot rating
PT	prototype
rad	radian
rms	root mean square
$R(\tau)$	correlation function
$R_{xx}(\tau)$	auto-correlation function
$R_{xy}(\tau)$	cross-correlation function
sec	seconds (time)
SST	supersonic transport
T	time (seconds)
t	time increment (seconds)
T_L	lead time (seconds)

$T_{2\theta}$	time-to-double pitch attitude (seconds)
$T_{\dot{\theta}_{max}}$	time-to-maximum pitch rate (seconds)
$\bar{V}$	wind velocity vector (knots)
V_C	calibrated airspeed (knots)
$\bar{V}_{REF}$	reference wind velocity vector (knots)
$\bar{V}_{20}$	wind velocity vector at 20 feet altitude (knots)
$x\ (t)$	independent variable
$x^*\ (t)$	complex conjugate of x (t)
$y\ (t)$	independent variable
Y_p	pilot describing function
z_o	terrain roughness factor (ft, m)
α	angle of attack (deg)
$\bar{\delta}$	column deflection, rms (in, cm)
δ_{col}	column deflection (in, cm)
ϵ	closed loop error signal (in, cm)
$\bar{\epsilon}$	tracking error (rms) (in, cm)
ξ	damping ratio
θ	pitch attitude (deg)
θ_C	pitch attitude command (deg)
θ_ϵ	pitch attitude error (deg)
$\theta_{A/P}$	airplane pitch attitude (deg)
$\dot{\theta}$	pitch rate (deg/sec)
$\dot{\theta}_{max}$	maximum pitch rate (deg/sec)
$\dot{\theta}_{ss}$	steady state pitch rate (deg/sec)
ρ	coherence function
σ_u	longitudinal turbulence component, rms (fps, m/sec)
σ_v	lateral turbulence component, rms (fps, m/sec)

σ_w	vertical turbulence component, rms (fps, m/sec)
τ	pilot's time delay (seconds)
$\Phi_{xx}(\omega)$	power-spectral density of x (t)
$\Phi_{xy}(j\omega)$	cross-spectral density of x (t) and y (t)
ω	frequency (rad/sec)
ω_n	natural frequency (rad/sec)

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APPENDIX A

Simulation Facility Description

The study was conducted using the Flight Simulator for Advanced Aircraft (FSAA) at NASA Ames Research Center. This simulator has six degrees of motion freedom, and is described in References A-1 and A-2 (only five degrees of motion freedom were operable for the study reported in Reference A-1). Details of the simulator pertinent to this study are summarized below.

Cockpit - The interior of the three-man FSAA cab was representative of a transport aircraft flight deck equipped for flight test. The panel instruments and controller mechanical design and location were representative of SST category airplanes. The lateral controller was a conventional control wheel, and was powered by a hydraulic control loader, as were column and rudder controllers. The mechanical characteristics of the flight controls are presented in Table A-I.

The panel instruments provided appropriate sensitivities for an airplane of this category and can be seen in Figure 4-1 and 4-2. The two separate figures are used to show the two types of attitude displays used in this study. Figure 4-1 shows the mechanical attitude director indicator (ADI) which was used during the first simulator study period; and Figure 4-2 shows the electronic attitude director indicator (EADI) used during the second study period. The ADI, model HZ-6F, had a pitch scale sensitivity of approximately 1.8 mm/deg (.07 in/deg) at the nominal pitch attitude being flown. The EADI had a pitch attitude sensitivity normally at 4.1 mm/deg (.16 in/deg), but was increased up to 7.6 mm/deg (.30 in/deg) for this study during the high speed evaluation.

The airspeed indicator had a scale of 300 knots per revolution of the dial face. Annunciator lights below the glare shield indicated individual main and nose gear touchdown. Immediately to the right of the ADI in Figure 4-1 can be

TABLE A-I - CONTROL SYSTEM MECHANICAL CHARACTERISTICS

CONTROLLER	MAXIMUM DISPLACEMENT	SURFACE GEARING	FORCE GRADIENT	BREAKOUT FORCE	HYSTERESIS
WHEEL (RAM's HORN)	$\pm$ 60 deg	$\pm$ 1.0 deg/deg (See simulator document for individual surface gearing)	$\pm .85 \frac{N}{deg}$ $(0.19 \frac{lb}{deg})$	$\pm$ 11.6 N (2.6 lb)	0.3 deg
COLUMN	$\pm$ 15.2 cm (6.0 in)	$\pm .98 \frac{deg}{cm}$ $(2.5 \frac{deg}{in})$	$\pm 26.3 \frac{N}{cm}$ $(15.0 \frac{lb}{in})$	$\pm$ 17.8 N (4.0 lb)	.08 deg
RUDDER PEDALS	$\pm$ 8.9 cm (3.5 in)	$\pm 3.39 \frac{deg}{cm}$ $(8.6 \frac{deg}{in})$	Non linear (see simulator document for individual surface gearing)	$\pm$ 49 N (11 lb)	.3 deg

seen the actual and potential flight path angle display. When using the EADI this information is displayed on the screen (Figure 4-3). Therefore, to provide additional room required by the EADI the separate flight path angle display along with the trim tab position indicator, were eliminated.

The isle stand and throttle configuration is the one seen in Figure 4-2. The configuration in Figure 4-1 was not used during this study. Also, in Figure 4-2, the workload lights can be seen. Three of these lights exist. One is on the left window sill left of the glare shield, another on the glare shield directly over the EADI, and the other is immediately aft of throttle levers three and four.

Motion system - The six-degrees-of-freedom motion system of the FSAA is distinguished by its extensive lateral travel of $\pm$ 40 feet. The motion axis of primary interest for these tests, however, was the vertical, which had $\pm$ 4.0 feet of usable travel. This provided a capability for effectively simulating motion resulting from a turbulent flight environment and the initial onset of maneuvering accelerations, but does not permit large motions which would result from sustained normal accelerations.

The D.C. drive signals to the servo motors were high-pass filtered to constrain motion within the allowable limits for each axis. Discussions of these filters and the effectiveness of FSAA motions on the piloted task are contained in Reference A-1 and in Appendix A of Reference A-2. Specifications for the motion system are summarized in Table A-II.

Briefly summarized, the FSAA motion logic was configured as follows: fourth order high-pass "wash-out" filters were generally applied to the drive signals. The damping ratios, break frequencies and filter format used to drive each degree of freedom are presented as follows:

TABLE A-II - SPECIFICATIONS FOR MOVING BASE SIMULATOR

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California

Flight Simulator for Advanced Aircraft (FSAA)

Motions Generated:	Displacement	Acceleration	Velocity	Frequency @ 30^{0} Phase Lag
Roll	$\pm 45^{0}$	[illegible] Rad/Sec^{2}	1.77 Rad/Sec	3.1 Hz
Pitch	$\pm 22\frac{1}{2}^{0}$	2 Rad/Sec^{2}	0.7 Rad/Sec	1.5 Hz
Yaw	$\pm 30^{0}$	2 Rad/Sec^{2}	0.7 Rad/Sec	1.7 Hz
Vertical	$\pm$ 5 Ft	12 Ft/Sec^{2}	8.65 Ft/Sec	2.2 Hz
Longitudinal	$\pm$ 4 Ft	10 Ft/Sec^{2}	6.32 Ft/Sec	1.8 Hz
Lateral	$\pm$ 50 Ft	12 Ft/Sec^{2}	17.00 Ft/Sec	1.0 Hz

Drives: Ward-Leonard Electric Servos

Program: Closed Loop Operation with Digital and Analog Computation

General Comments: Stability, landing, and related transport aircraft handling are within the capabilities of this simulator. Both digital and analog computation allow more complete simulation of aircraft dynamics. Studies of crew tasks may be investigated. Hydraulic-powered controls permit variation of control-force parameters. A visual scene from the Visual Flight Attachment VII is used.

$$\frac{KS^3}{(S^2+2\xi\omega S+\omega^2)\ (S^2+2\xi\omega S+\omega^2)}$$

(Fourth order high-pass "wash-out" filters applied to pilot station accelerations)

where:

		x	y	z	P	Q	R (degree of freedom)
ξ	=	1.4	1.4	1.4	1.4	1.4	1.4
ω	=	.4	.15	.4	.2	.15	.15
K	=	.5	1.0	.75	.5	1.0	1.0

Note: The S in the numerator is only third order because of the necessity to integrate acceleration to a rate signal to drive the simulator.

The roll-lateral and the pitch-longitudinal modes used the residual-tilt technique of washing-in cab angular attitude to provide a steady-state component of linear acceleration. These sustained linear accelerations were provided at full scale for lateral, and one-half scale for longitudinal. The residual tilt time constants are as follows:

lateral acceleration - $\frac{\Phi - Y}{.25}$

longitudinal acceleration - $\frac{\theta - X}{1.0}$

Visual system - The pilot and copilot were each provided a 21 inch (diagonal measure) color television monitor mounted in the windshield with a viewing field of 38^0 vertically and 46^0 horizontally, with unity magnification. The pilot's monitor had a collimating lens to place the image at an infinite distance.

The landing scene was the closed-circuit TV image of a model airport with surrounding terrain, as viewed by the computer-commanded servo-driven TV camera. Model scale was 1:600 and provided a runway 8000 ft. long and 150 ft. wide.

Specifications for the visual display are presented in Table A-III.

TABLE A-III - SPECIFICATIONS FOR VISUAL DISPLAY

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California

Name of Apparatus: Visual Flight Attachment VII

Uses: Visual Scene Presentation

Mechanical Characteristics:	Displacement	Acceleration	Velocity	Resolution	Frequency at 30° Phase Lag
Roll	$\pm 180^\circ$	90 Rad/Sec^2	5.5 Rad/Sec	0.014 Rad	2.8 Hz ($\pm$.1 Rad)
Pitch	$\pm 25^\circ$	22 Rad/Sec^2	2.5 Rad/Sec	0.0003 Rad	2.9 Hz ($\pm$.1 Rad)
Yaw	Continuous	30 Rad/Sec^2	3.3 Rad/Sec	0.0003 Rad	2.9 Hz ($\pm$.1 Rad)
Longitudinal	64 Ft	1.00 Ft/Sec^2	0.68 Ft/Sec	$\pm$ 0.218 cm	0.28 Hz ($\pm$.1 Ft)
Lateral	15 Ft	1.00 Ft/Sec^2	0.9 Ft/Sec	$\pm$ 0.051 cm	0.29 Hz ($\pm$.1 Ft)
Vertical	4 Ft (Max) 0.072 In (Min)	1.8 Ft/Sec^2	1.4 Ft/Sec	$\pm$ 0.013 cm	0.32 Hz ($\pm$.1 Ft)

Model Scale: 1:600

Drives: Electrical Servo-Position

Television Characteristics: Scan Lines - 525; Field/Frame Rate - 60/30; Color (Plumbicon) - Red/Green/Blue; EIA Resolution (Vertical) - Approximately 390 Lines; EIA Resolution (Horizontal) - 490 Lines; Model Resolution - 12 Lines per Degree From 0.04 Feet to 4 Feet

Sound system - A sound generator simulated jet engine noise which was proportional to thrust, and aerodynamic noise which was proportional to aircraft speed. These sounds were introduced by speakers on each side of the cabin. In addition to adding realism, a primary benefit of this sound environment was to mask the noise of the simulator motion drive systems.

APPENDIX A REFERENCES

A-1 Bray, Richard S.: Initial Operating Experience with an Aircraft Simulator Having Extensive Lateral Motion. NASA TM X-62,155, May 1972.

A-2 Snyder, C. T., Forrest, R. D., Drinkwater, F. J. III, and Fry, E. B.: A Study of Takeoff Certification Considerations for Large Subsonic and Supersonic Transport Airplanes Using the Ames Flight Simulator for Advanced Aircraft, NASA TN D-7106, 1972.

APPENDIX B

PILOT MATH MODEL

Introduction

The purpose of this appendix is to present details of the pilot modeling technique used to aid in landing approach (normal operation) handling qualities evaluation. Pilot dynamic characteristics were evaluated using the describing function technique in an attempt to gain quantative substantiation for the pilot ratings given. Results of this analysis provided a means by which pilot ratings could be correlated and applicable average ratings estimated where considerable pilot rating scatter existed.

Discussion

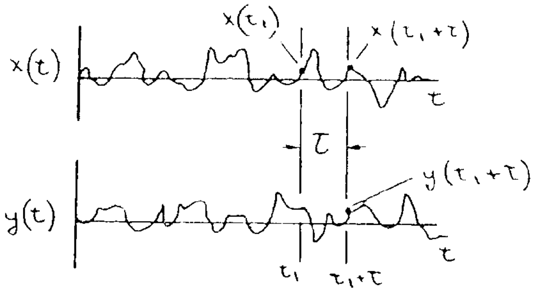
A quasi-linearization technique was used to model the pilot in the frequency domain by the combination of a describing function, which represented the linear elements, and a remnant, which represents the pilot response not linearily correlated with the input. The describing function used was the random input describing function with white noise providing the input signal. Calculation of the random input describing function is based on the cross- and power-spectral density functions, or by computational techniques using the cross-correlation and auto-correlation functions. The theoretical background, experimental procedure, and the analysis and synthesis techniques will be presented in this discussion.

Theoretical background: The starting point for describing function analysis (based on spectral analysis) is the correlation function $R(\tau)$ of which there are two kinds: the auto-correlation function $R_{xx}(\tau)$ and the cross-correlation function $R_{xy}(\tau)$ which are defined, respectively as

$$R_{xx}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x^*(t)\, x(t+\tau)\, dt$$

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x^*(t)\, y(t+\tau)\, dt$$

where x (t) and y (t) are independent variables, x* (t) is the complex conjugate of x (t), and τ is a time increment. The purpose of these functions is to establish the linear correlation between two time histories: in the case of auto-correlation, between the signal x (t) and itself, shifted in time, and in the case of auto-correlation, between the signal x (t) and the signal y (t), shifted in time. This is illustrated in the following sketch:



Note that when $\tau = 0$, $R_{xx}(\tau)$ is simply the mean square average value of x (t). If x (t) is random, $R_{xx}(\tau) = 0$ because past and future values of x (t) have no relationship to each other. Similarly, if $R_{xy}(\tau)$ is zero, the two signals x (t) and y (t) have no linear dependence on each other. This is a means of determining the linearity of a control system element.

The concept of linear correlation is carried from the τ domain to the more useful domain (frequency) by the Fourier transform. If Φ represents the Fourier transform of R,

$$\Phi_{xx}(j\omega) = 2 \int_{-\infty}^{\infty} R_{xx}(\tau)\, e^{-j\omega\tau}\, d\tau$$

$$\Phi_{xy}(j\omega) = 2 \int_{-\infty}^{\infty} R_{xy}(\tau)\, e^{-j\omega\tau}\, d\tau$$

Now, $\Phi_{xx}(j\omega)$ is defined to be the power spectral density of x (t) and $\Phi_{xy}(j\omega)$ is defined to be the cross-spectral density of x (t) and y (t). $R_{xx}(\tau)$ is an even function of τ, so

$$\Phi_{xx}(j\omega) = 4\int_0^{\infty} R_{xx}(\tau)\cos\omega\tau\, d\tau = \Phi_{xx}(\omega)$$

and has zero phase angle.

The power- and cross-spectral densities may also be expressed in terms of the Fourier transforms of the functions x (t) and y (t). If X (jω) and Y (jω) are these transforms, then

$$\Phi_{xx}(\omega) = \left\{\lim_{T\to\infty}\frac{1}{T^2}\left[X(j\omega)\,X(-j\omega)\right]\right\}\pi\delta(\omega-\omega_n)$$

$$\Phi_{xy}(j\omega) = \left\{\lim_{T\to\infty}\frac{1}{T^2}\left[X(-j\omega)\,Y(j\omega)\right]\right\}\pi\delta(\omega-\omega_n)$$

The functions of time of the control loop, Figure B-1, may be Fourier-transformed and the control laws derived in terms of these transforms. We have, referring to Figure B-1:

$$E(j\omega) = \frac{I(j\omega) - G(j\omega)R(j\omega)}{1+G(j\omega)N(j\omega)}$$

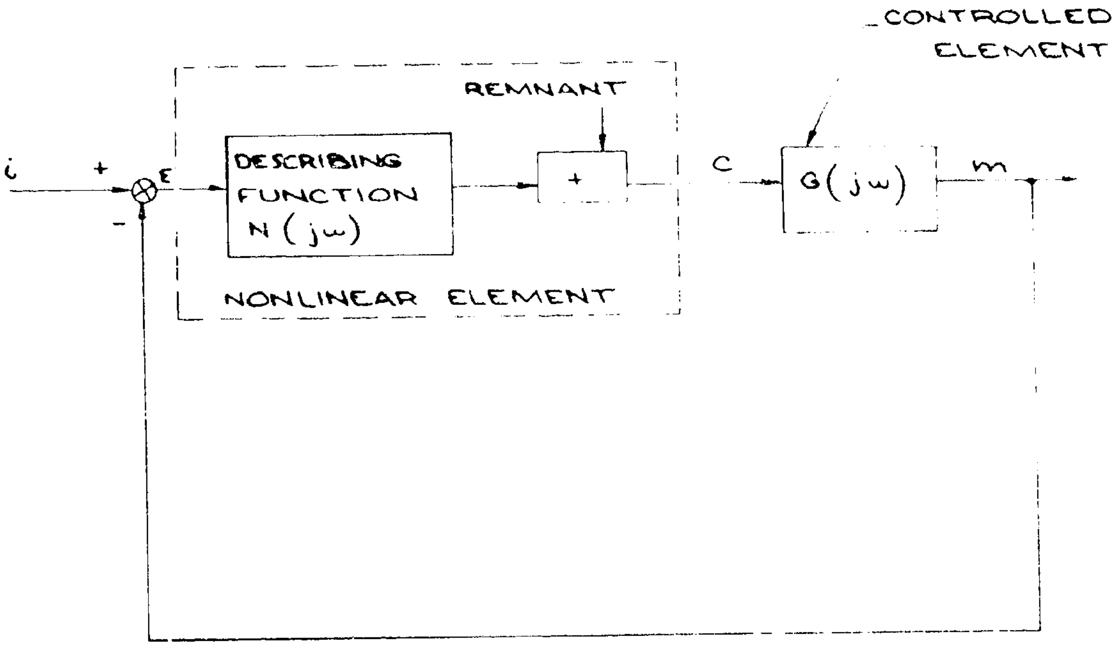
$$C(j\omega) = \frac{N(j\omega)I(j\omega) + R(j\omega)}{1+G(j\omega)N(j\omega)}$$

$$M(j\omega) = \frac{G(j\omega)N(j\omega)I(j\omega) + G(j\omega)R(j\omega)}{1+G(j\omega)N(j\omega)}$$

Forming the products I (jω) *L (jω) and I (jω) *C (jω) and noting that I (jω) *R (jω) = 0, we can, by equation (3) write

$$\Phi_{i\epsilon}(j\omega) = \frac{\Phi_{ii}}{1+GN}$$

$$\Phi_{ic}(j\omega) = \frac{N\Phi_{ii}}{1+GN},$$



ENGR		REV	REPRESENTATIVE SINGLE LOOP CONTROL SYSTEM	FIG. B-1
CHECK				
APR				
APR			BOEING	120

from which it directly follows that the item of interest, N, is

$$N(j\omega) = \frac{\Phi_{ic}(j\omega)}{\Phi_{i\epsilon}(j\omega)}$$

Since, in this experiment, $i_c = \theta_C$, $c = \delta$ [illegible], $\epsilon = \theta_\epsilon$, and N represents the pilot, Yp, we have

$$Y_P(j\omega) = \frac{\Phi_{\theta_C \delta_{COL}}}{\Phi_{\theta_C \theta_\epsilon}}$$

as the needed pilot describing function.

The linear correlation, the fraction of the output of an element that is linearly correlated to the input, is the designated coherence function, (ρ), where

$$\rho^2 = \left|\frac{N}{1+GN}\right|^2 \frac{\Phi_{ii}}{\Phi_{cc}}$$

Noting that

$$\Phi_{ic} = \frac{N\,\Phi_{ii}}{1+GN}$$

we obtain

$$\rho = \frac{|\Phi_{ic}|}{\sqrt{\Phi_{ii}\,\Phi_{cc}}}$$

which is related to the remnant as

$$\Phi_{rr} = \left|\frac{\Phi_{ii}}{\Phi_{i\epsilon}}\right|^2 \Phi_{cc}\left(1-\rho^2\right)$$

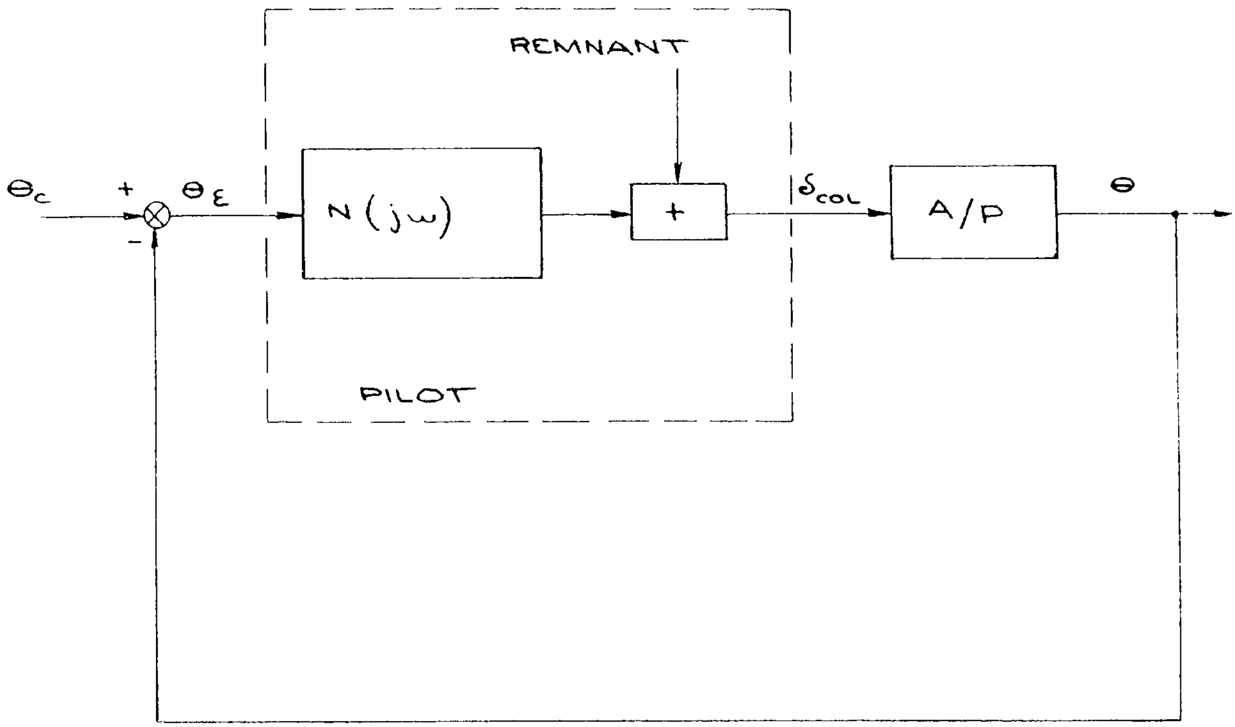
The value of ρ itself is usually [illegible] adequate indication of linearity. Actual construction [illegible] with the above equation.

This brief discussion has been to show the [illegible] history to power spectrum and [illegible] the describing [illegible] that represent a nonlinear control system element. [illegible] the method followed in analysis of experimentally-measured signal time histories. For a more detailed discussion of describing function analysis the reader is referred to Reference B-1.

A description of the present system, from the point of view of control system theory, is as shown in Figure B-2. In this study the variable θ_ϵ is the system forcing function, and it is comprised of two signals: filtered white noise from an external source, which provided the random input signal, and a signal proportional to the airplane's deviation from a reference pitch attitude, which provided the pilot task. These signals, combined, controlled the displacement of the pitch command bar from neutral in a standard flight director indicator, Figure B-3. This was the total visual cue to the pilot. The second signal enters through the flight director command bar equations, which are so designed that the command bar is centered if the pilot is either on the glideslope or flying toward it, and was retained for purposes of realism. The pilot's task was to move the column so as to eliminate the bar displacement, as in an actual approach: if the bar is high, he pulls the column back. Physically, this represents a case in which, flying below the glideslope beacon, he pulls back to climb and regain the glideslope. The key point from the standpoint of control system theory is that the pilot moves one controller (the column) in response to one visual cue (the command bar offset) and thus creates a single loop, compensatory tracking system. The objective is to determine the pilot's column deflection frequency spectrum as he attempts to keep the bar centered.

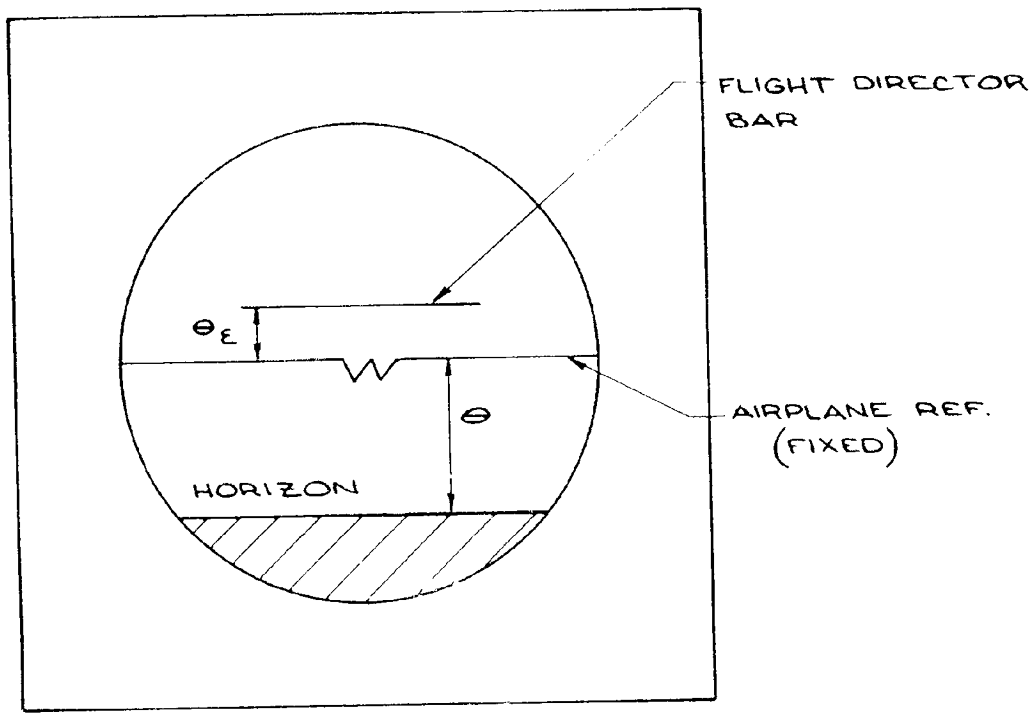
During a pilot model measurement run the aircraft is held at a fixed altitude in order to maintain fixed flight director gains and to allow the run times to be as long as desired.

Experimental Procedure: The pilot was instructed to pursue the horizontal flight director bar, the position of which was controlled by signals proportional to the airplane's pitch attitude and glideslope error. In this study,



DESCRIBING FUNCTION $N(j\omega) = \dfrac{\Phi_{\theta_c \delta_{COL}}}{\Phi_{\theta_c \theta_\varepsilon}}$

ENGR			REVISED	DATE	SINGLE LOOP AIRPLANE TRACKING SYSTEM	
CHECK						FIG B-2
APR						
APR					BOEING	132



			REVISED	DATE		
ENGR					TRACKING INSTRUMENT GEOMETRY	
CHECK						FIG 8-3
APR						133
APR					BOEING	

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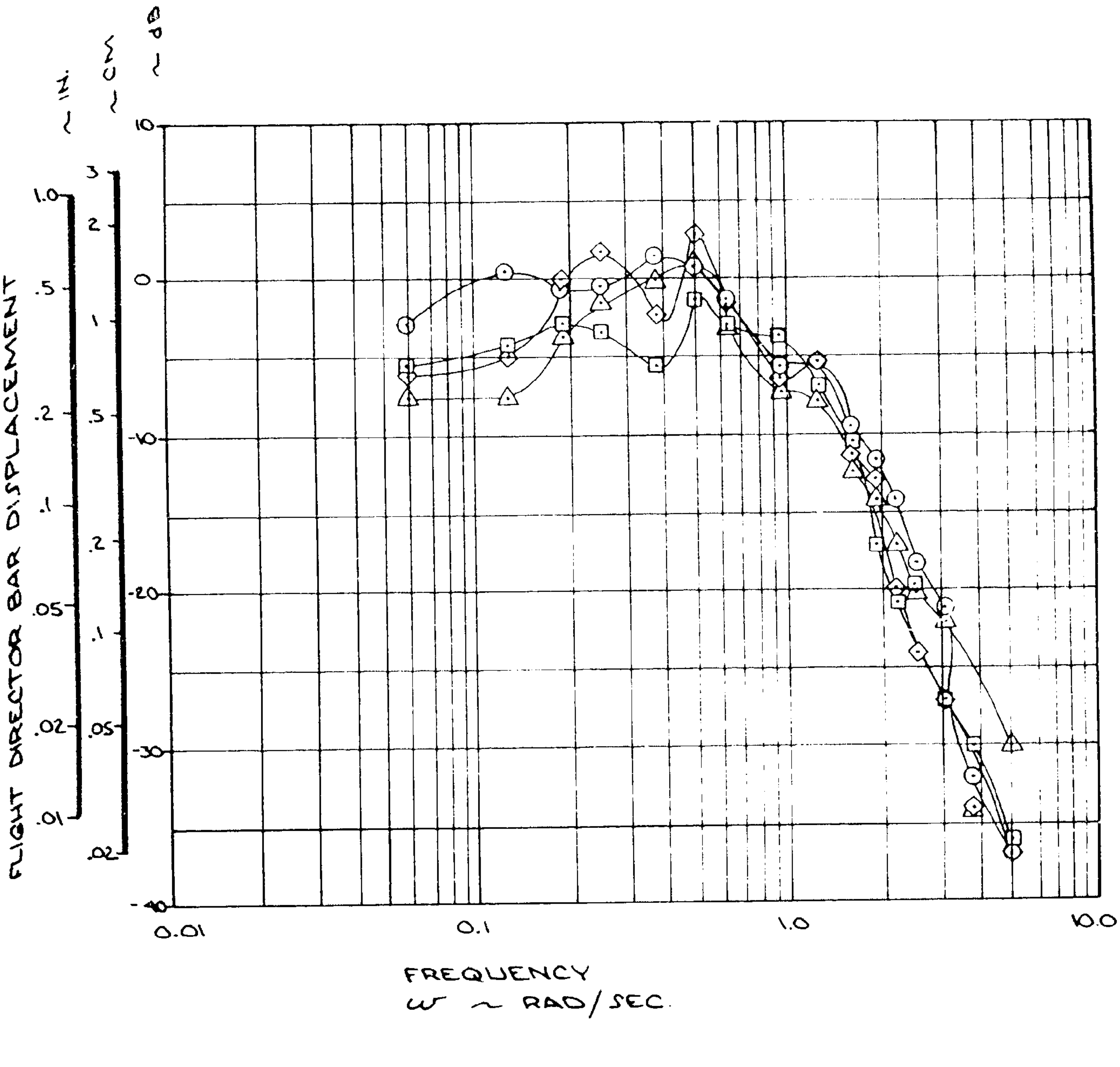
a random signal with a second-order filter at 1 rad/sec was used instead of a true glideslope error, to drive the system. Glideslope error is converted to a pitch command error signal by the flight director, which is to be removed by the pilot by "flying to" the bar. The pilot thus essentially closes a pitch attitude control loop. Figure B-4 shows the measured spectral content of the glideslope error and flight director command signal. To ensure maximum pilot attention and activity a large command bar deflection of about ± 1 inch (2.54 cm) was employed. This is larger than would be seen in flight, but was used because of the extremely small column deflections observed in the usual approach flying.

The pilots were offered practice runs each time the aircraft's characteristics were changed, but after initial familiarization with the system usually declined and performed for data.

Digital signals generated by the Xerox Sigma - 8 computer of the FSAA facility are customarily changed to analog voltages by digital-to-analog converters (DAC's), for display on multiplexed strip chart recorders. The variables needed for the pilot describing function analysis were recorded directly from the DAC's; the 100 volt DAC output was reduced to 1.414 volts (peak to peak) by an amplifier, and input to an FM tape recorder. The recorder hookup is indicated by the schematic in Figure B-5. Scaling for adequate signal strength was accomplished within the computer, before output to the DAC. The limiting of the input voltage to 1.414 volts maximum peak-peak (1 volt rms) was recommended for minimum tape recorder distortion.

Tape input signals were monitored with an oscilloscope during recording to verify the presence of data on the tape, and to ascertain proper scale limits. Signals could also be sent to strip chart recorders for simultaneous visual monitoring of all channels. Figure B-6 shows typical time history traces of the principal control system variables as they appear on the strip chart record.



ENGR			REVISED	DATE	MEASURED FORCING FUNCTION AMPLITUDE SPECTRUM	FIG 8-4
CHECK						
APR						
APR					BOEING	135

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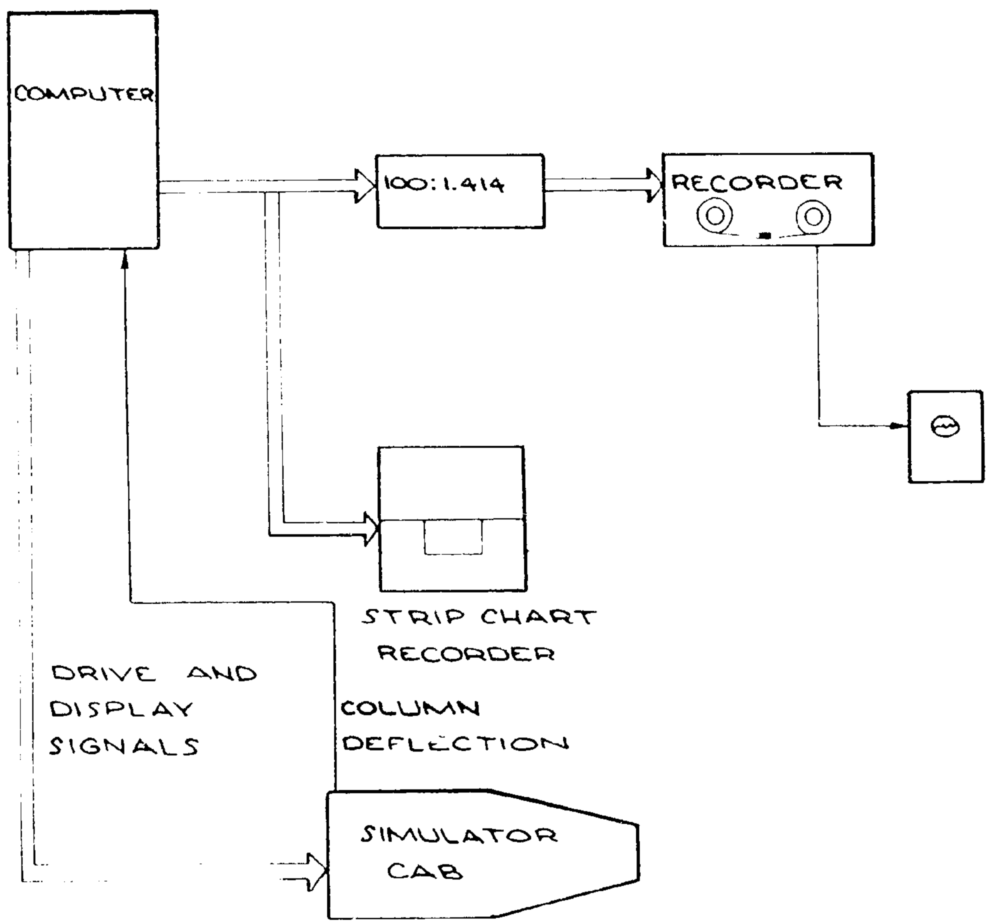
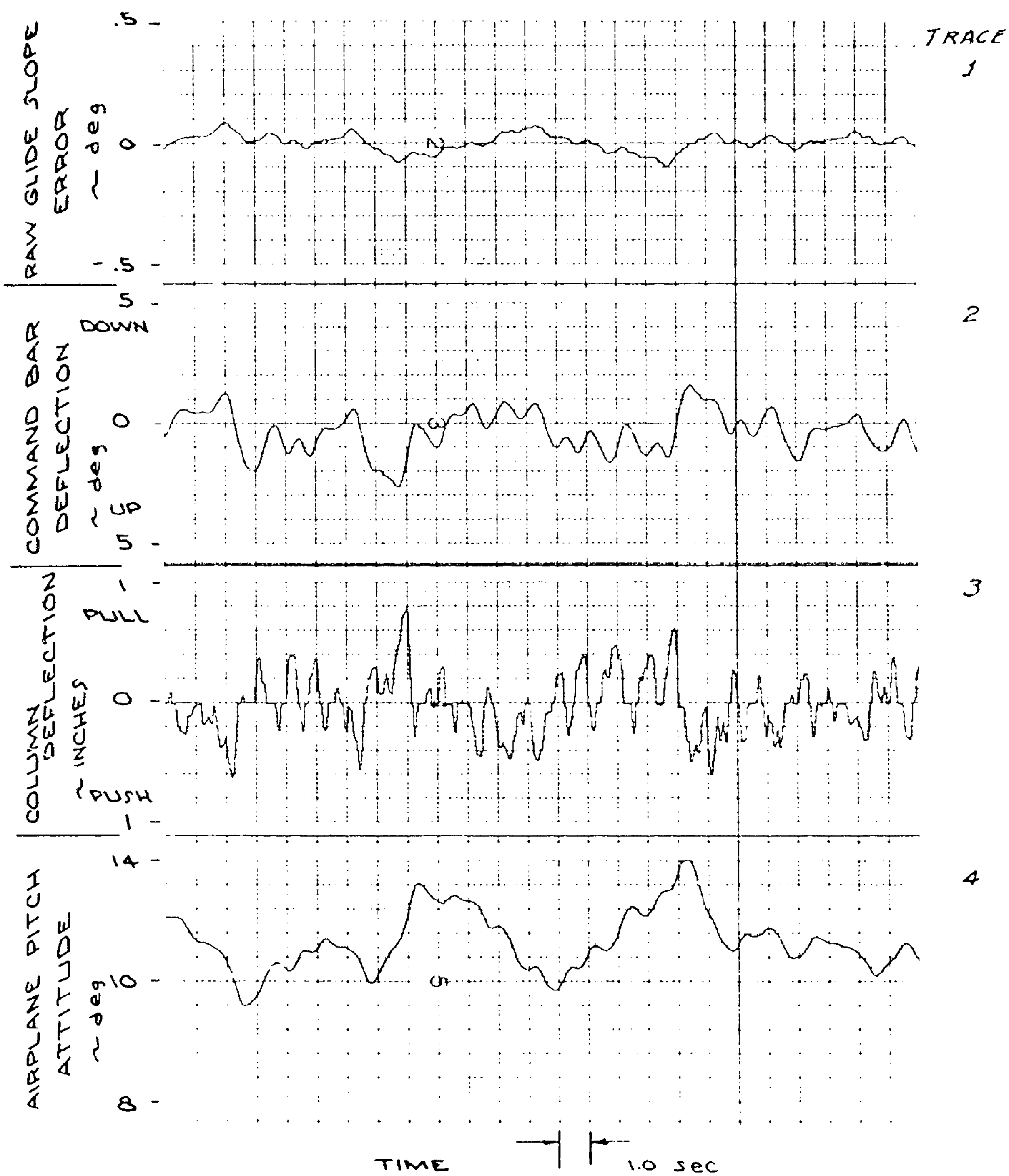


ENGR		REVISED	DATE	DATA RECORDING SCHEMATIC	FIG B-5
CHECK					
APR					
APR				BOEING	136



NOTE:
DATA USED TO CHECK PEAK VALUE ONLY

ENGR			REVISED	DATE		
CHECK					EXAMPLE TIME HISTORY OF CONTROL SYSTEM VARIABLES	FIG B6
APR						
APR					BOEING	137

The FM magnetic tape data were analyzed using a digital computer program existing within the Boeing Aerospace Company. Cross spectral densities $\Phi_{\theta_C \delta_{COL}}$ and $\Phi_{\theta_C \theta_\epsilon}$ were computed by power spectral analysis from time history traces of bar displacement θ_ϵ, column deflection δ_{COL}, and effective pitch angle command θ_C formed from θ_ϵ and the airplane pitch attitude (since θ_ϵ [illegible] $\theta_{A/P}$). The pilot describing function is the ratio of the two cross spectral densities:

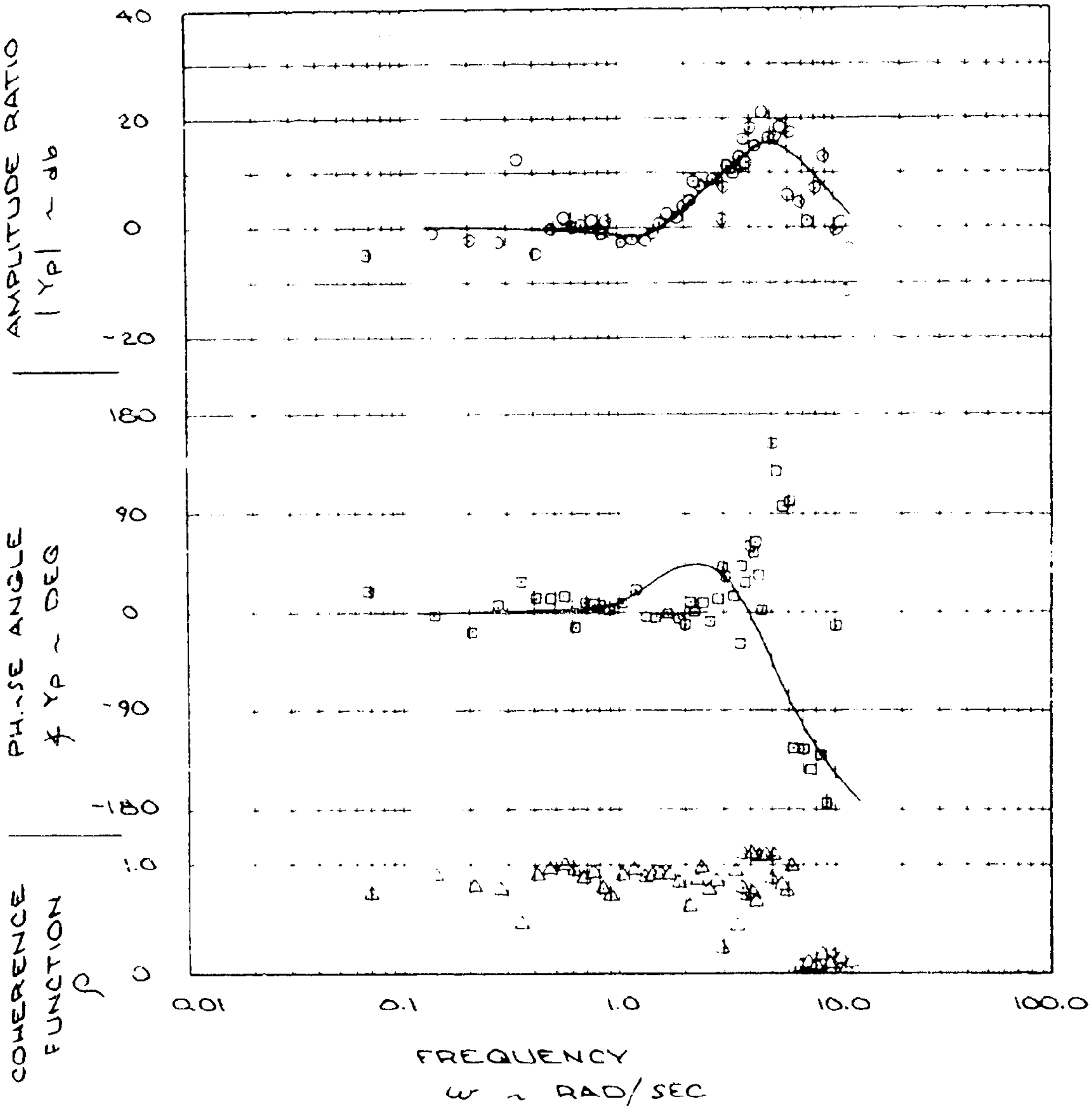
$$Y_P(j\omega) = \frac{\Phi_{\theta_C \delta_{COL}}(j\omega)}{\Phi_{\theta_C \theta_\epsilon}(j\omega)}$$

In these data the coherence function to which the remnant is directly related is shown as an equivalent measure of response linearity. The program produced magnitude and phase plots and listings for spectral density and coherence functions between the desired variables. Describing functions were hand computed by ratioing the appropriate cross spectral densities.

Analysis and Synthesis Technique: From the form of the describing function, consisting of a Bode plot showing magnitude and phase versus frequency, an analytical model was derived by inspection. The general features of the curves were modelled, then smaller configuration related differences were taken into account. This was in lieu of a curve matching computer program that was found to be too sensitive to data scatter and low- and high-frequency boundary conditions.

The principal data obtained during this study are the [illegible] Figures B-7 through B-14, which present the magnitude, phase, and coherence [illegible] pilot describing functions for various airplane dynamics (the [illegible] [illegible] and will be discussed later). Figures B-7 through B-11 are for Pilot [illegible] flying the basic configuration, then configurations with [illegible] pitch rate overshoot, low short period damping, and low [illegible] rate response, individually. Pilot [illegible], in Figures B-12 through B-14, flew the basic

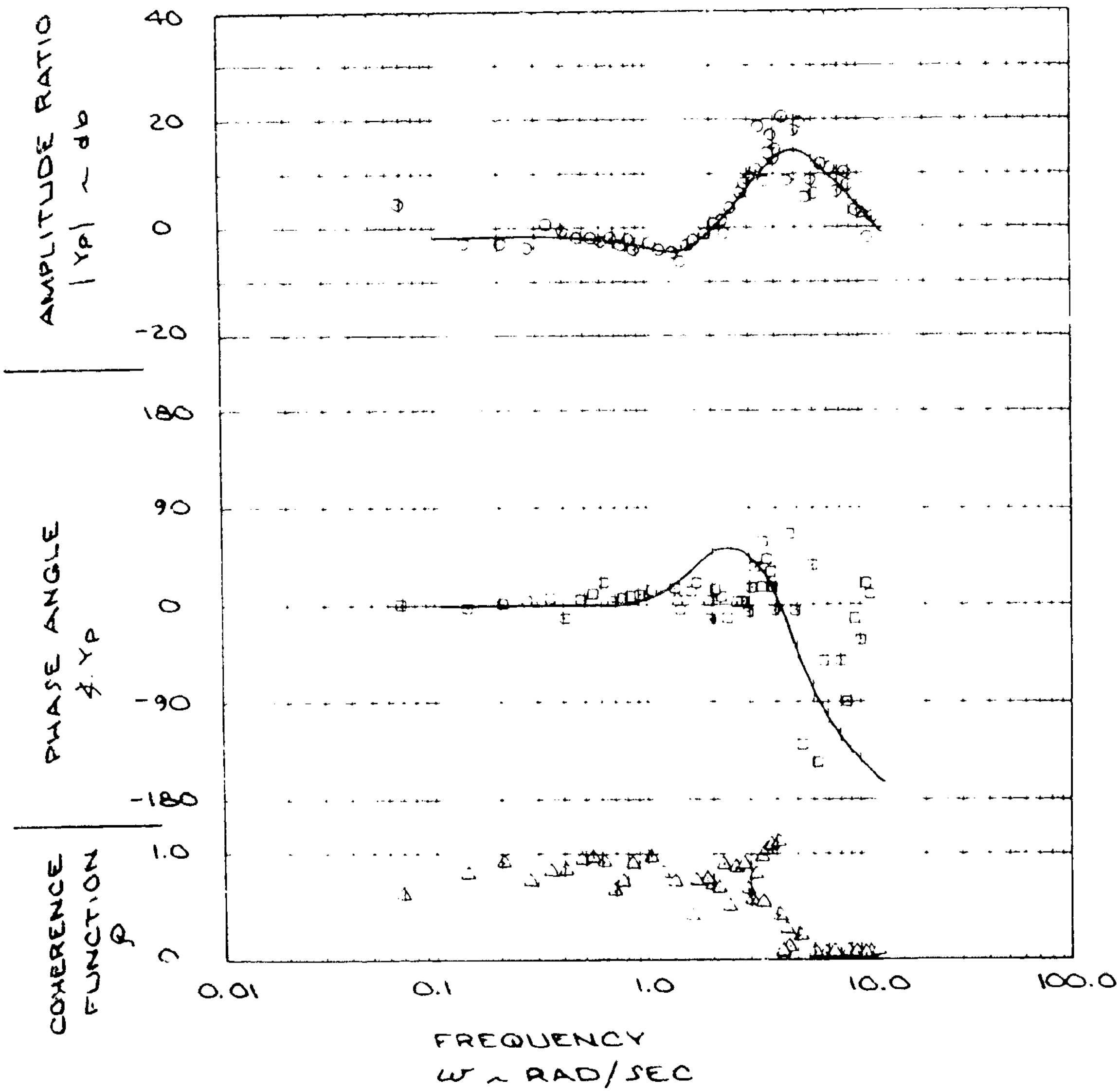
LANDING APPROACH CONFIGURATION
RUN DF-17



ENGR		REVISED	DATE	PILOT DESCRIBING FUNCTION
CHECK				PILOT A MOVING BASE
APR				BASELINE CONFIGURATION FIG. 87
APR				BOEING

LANDING APPROACH CONFIGURATION

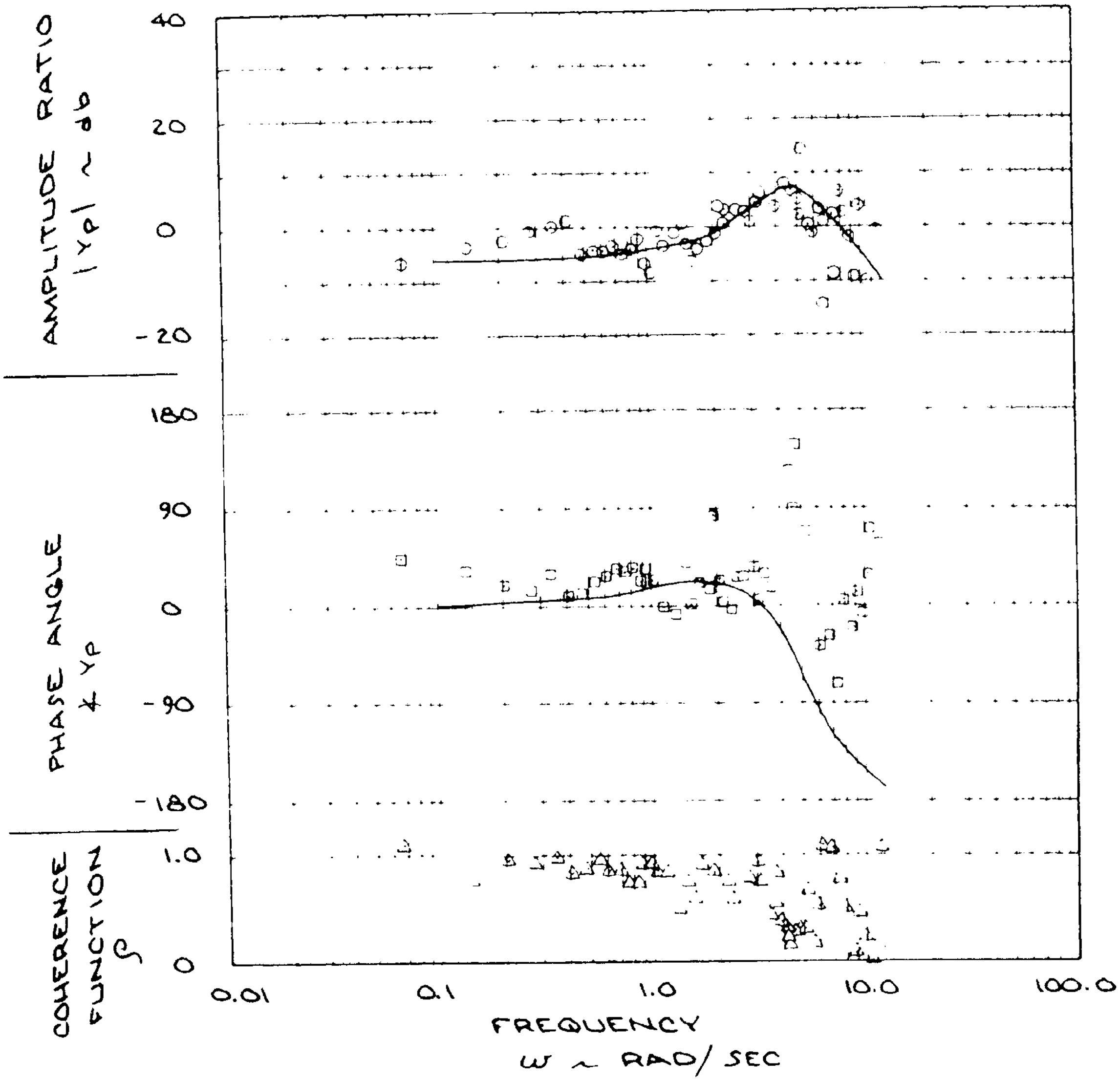
RUN DF-18



ENGR	PILOT DESCRIBING FUNCTION
CHECK	PILOT A MOVING BASE
APR	$\dot{\theta}_{MAX}/\dot{\theta}_{SS}$: 3.24
APR	BOEING

FIG B-8

LANDING APPROACH CONFIGURATION
RUN DF-19

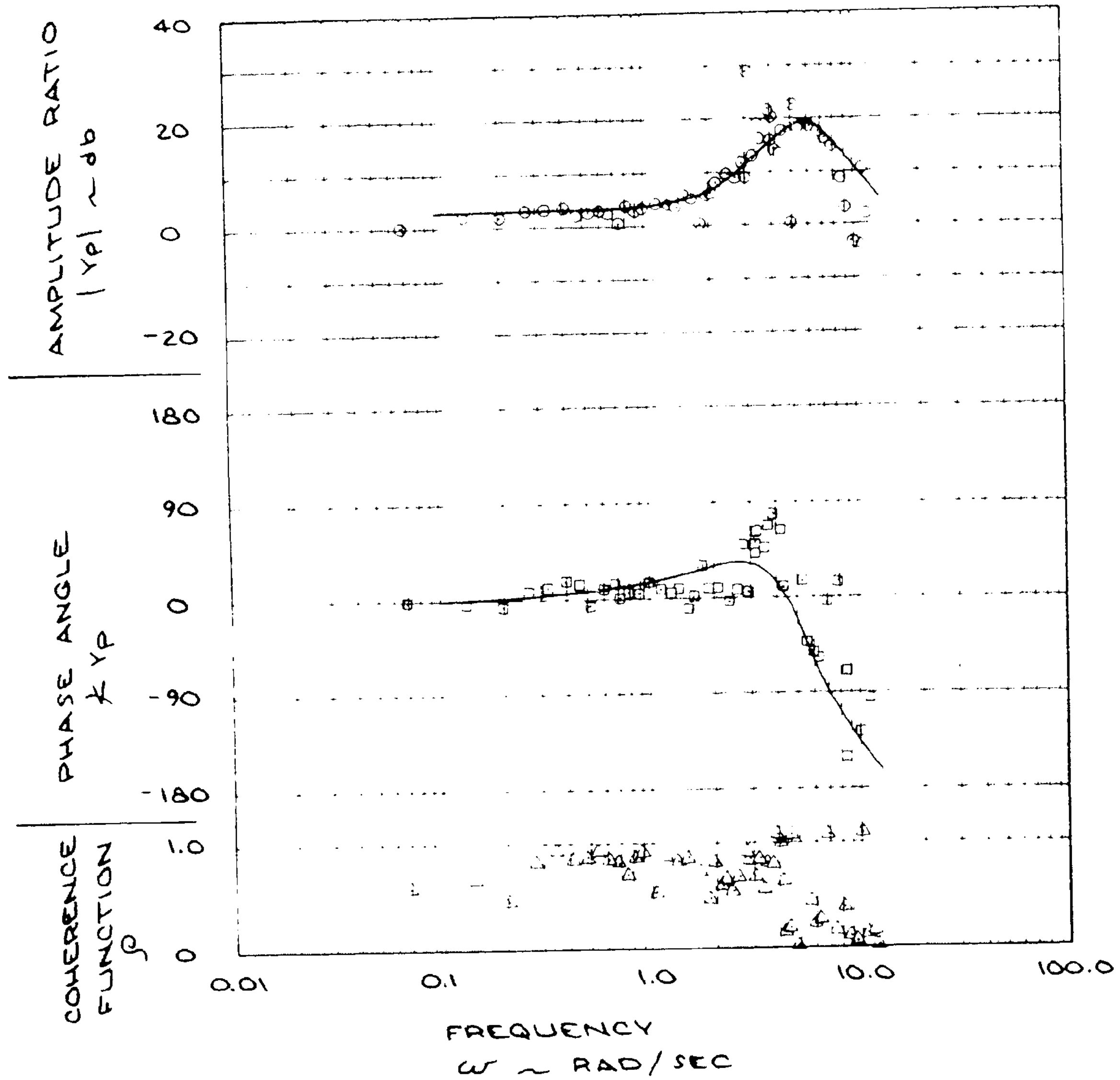


ENGR		REVISED	PILOT DESCRIBING FUNCTION
CHECK			PILOT 'A' MOVING BASE
APR			$\xi\ \omega_n = 0.16$
APR			BOEING

FIG. B-9

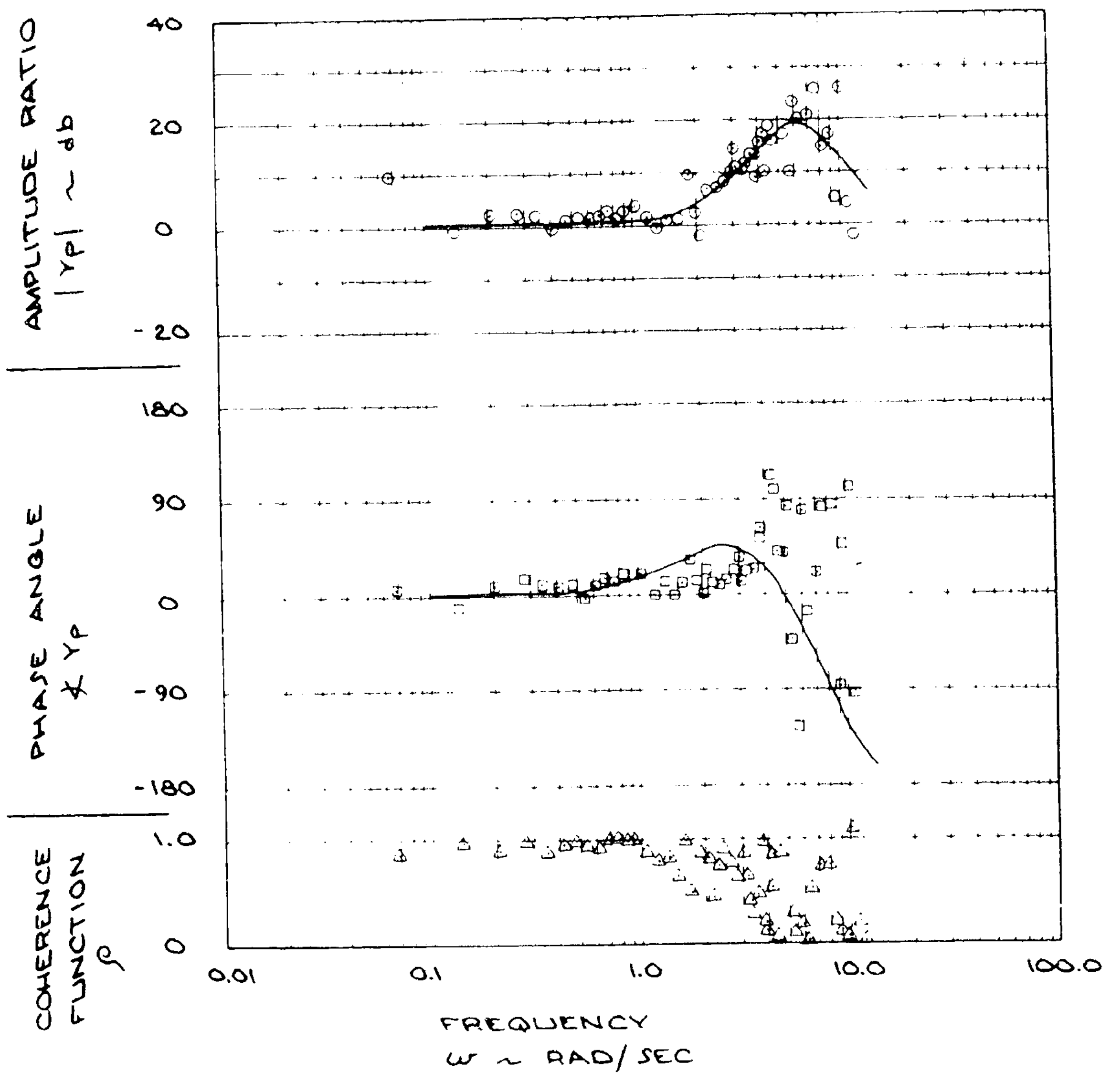
14'

LANDING APPROACH CONFIGURATION
RUN DF-20



ENGR		PILOT DESCRIBING FUNCTION	FIG B-10
CHECK		PILOT A MOVING BASE	
APR		$T_{\dot{\theta}_{MAX}}$ = 2.0 SEC	
APR		BOEING	142

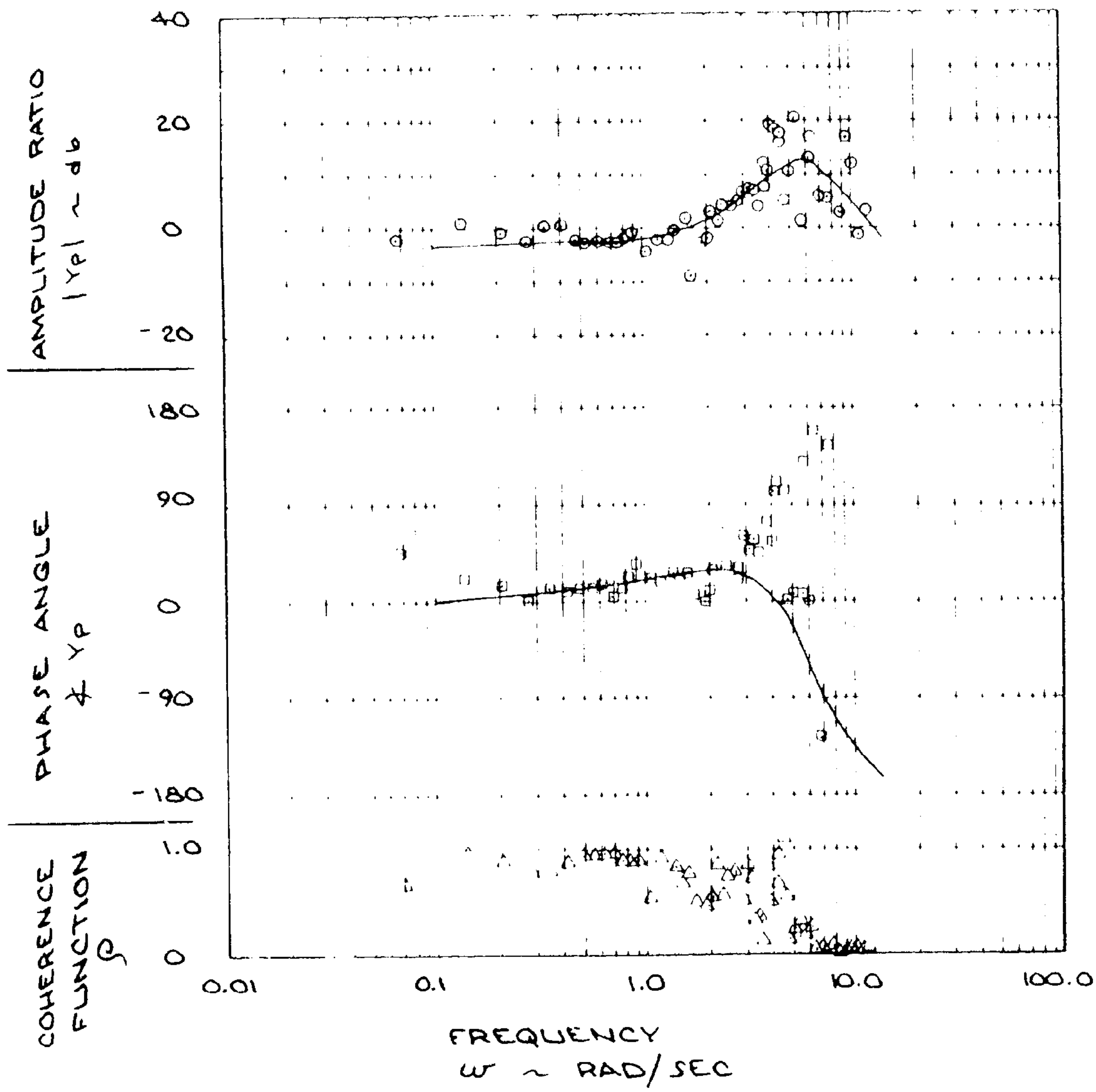
LANDING APPROACH CONFIGURATION
RUN DF-21



ENGR		REV SED	DATE	PILOT DESCRIBING FUNCTION PILOT 'A' FIXED BASE BASELINE CONFIGURATION	FIG B-11
CHECK					
APR					
APR				BOEING	143

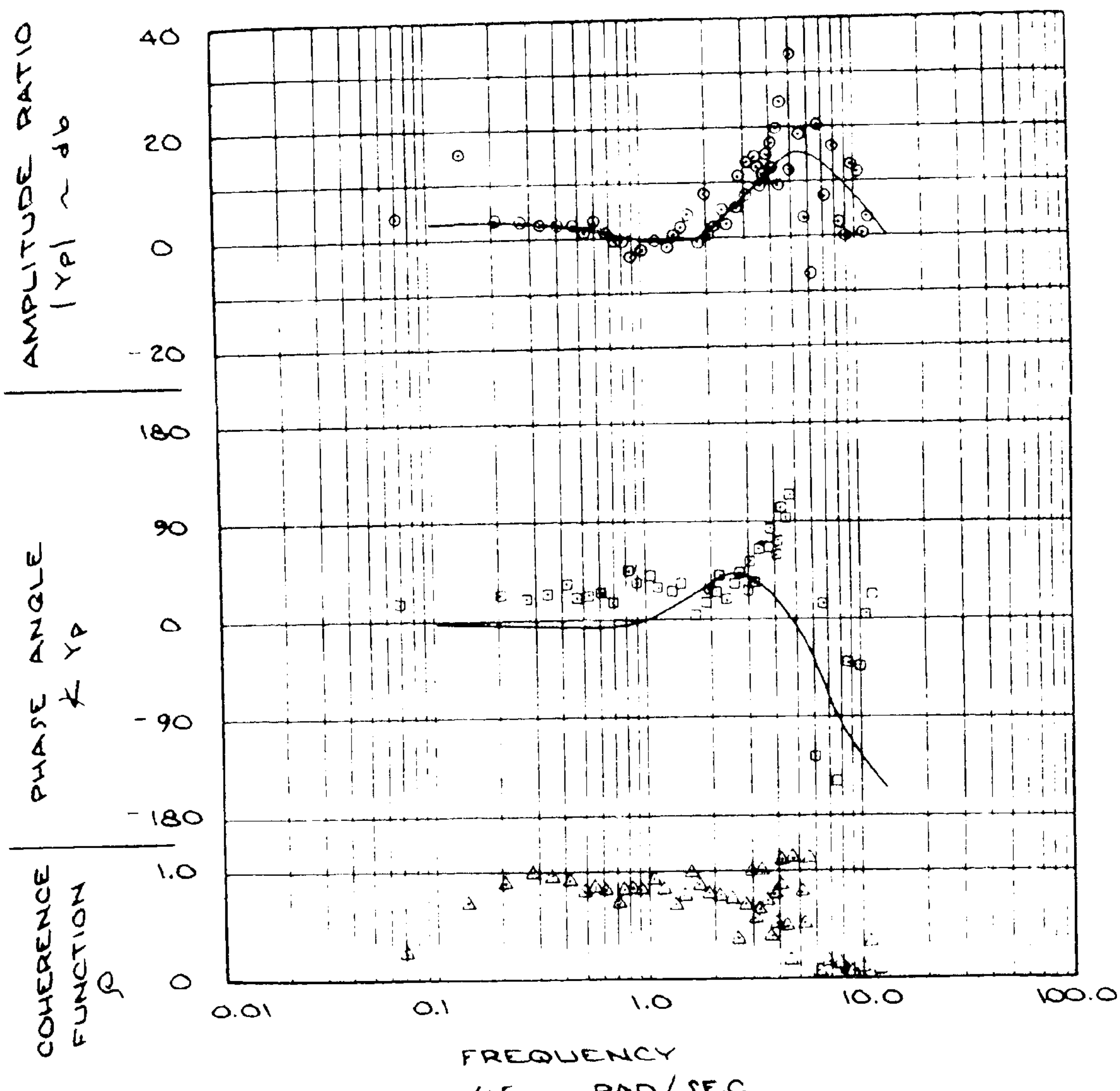
D1 4100 5320 REV. 8/71

LANDING APPROACH CONFIGURATION
RUN DF-23



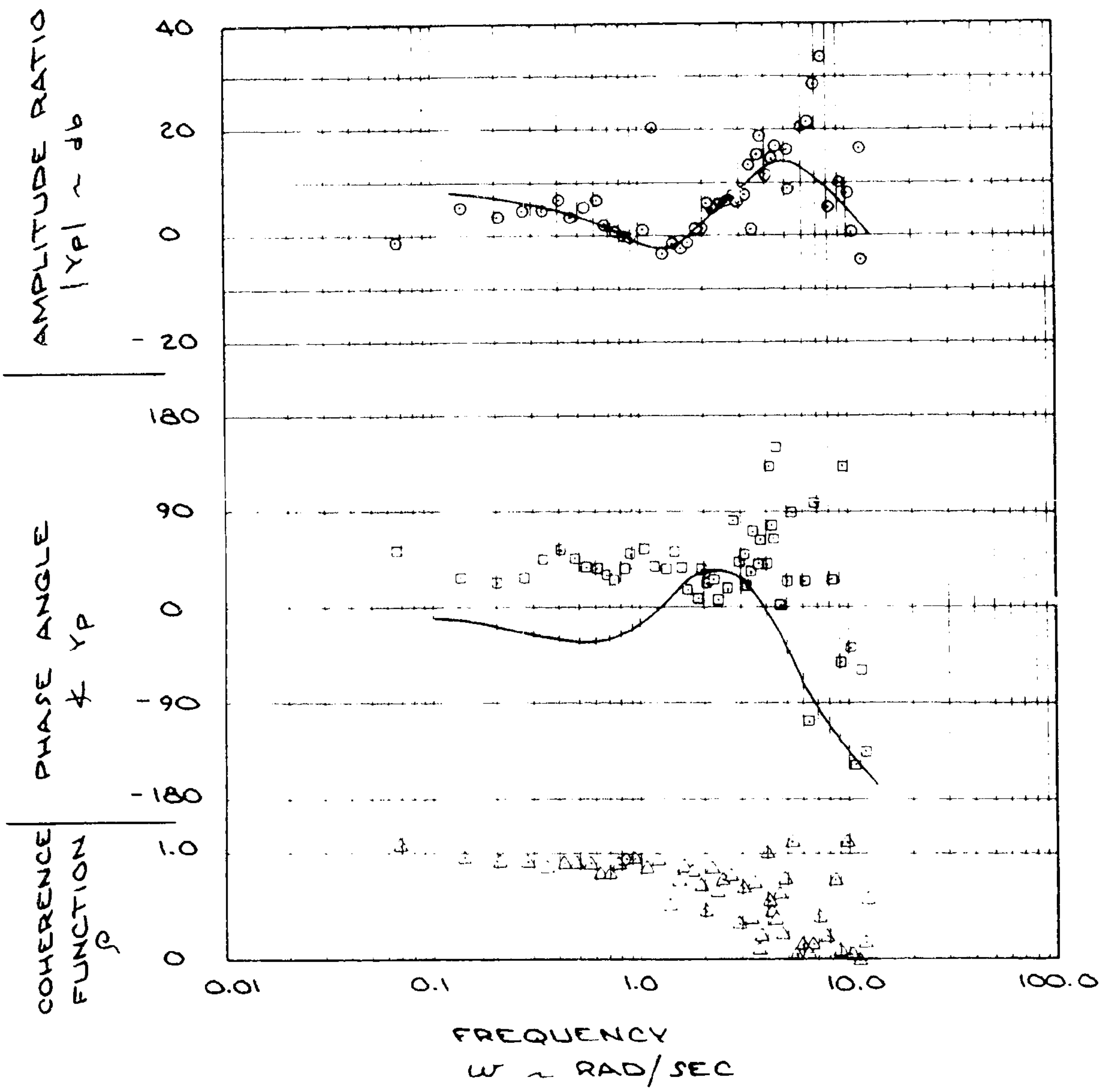
ENGR		REVISED	DATE	PILOT DESCRIBING FUNCTION PILOT "C" FIXED BASE BASELINE CONFIGURATION	FIG B-12
CHECK					
APR					
APR				BOEING	144

LANDING APPROACH CONFIGURATION
RUN DF-24



ENGR		REVISED	DATE	PILOT DESCRIBING FUNCTION PILOT C MOVING BASE BASELINE CONFIGURATION	FIG B 13
CHECK					
APR				**BOEING**	145
APR					

LANDING APPROACH CONFIGURATION
RUN DF-25



ENGR			REVISED	DATE	PILOT DESCRIBING FUNCTION PILOT "C" MOVING BASE $\xi\ \omega_n = .16$	FIG B-14
CHECK						
APR					**BOEING**	
APR						146

and low-damped configurations. Both pilots in this study are Boeing instructor pilots experienced with large aircraft; pilot A, however, has considerably more experience with simulator flying. Figures B-11 and B-12 are fixed-based simulations.

In general, the data all show essentially flat magnitude curves to about 1 rad/sec, then an upward break followed by a sharp downward break at about 5 rad/sec, accompanied by increased data scatter. Phase angle curves are flat at small angles, out to about 5 rad/sec, where a large amount of scatter begins. Some curves, such as in Figures B-8 and B-14 show evidence of additional equalization prior to the 1 rad/sec break.

Some indication of the significance of the scatter is obtained from the trend of the coherence function, ρ, plotted on each figure. As discussed previously, a value of ρ = 1.0 indicates the system is completely linear; a value ρ = 0 means the system output has no linear correlation with the input. In the data of Figs. B-7 through B-14 the value of ρ is generally in the area of 0.85-1.00 at low frequencies, which indicates almost perfect linearity, but decreases to nearly zero at higher frequencies. This indicates that above approximately 5 rad/sec, pilot response assumes a nonlinear form, and the linear representation of the data in magnitude and phase curves loses significance.

This nonlinearity is in agreement with observed pilot behavior. Pilot column movement tended to be of small amplitude, rarely exceeding $\pm$ 1 inch even under vigorous pursuit tasks, and impulse-like, or "bang-bang" as a relatively fixed-amplitude deflection was imposed at varying intervals of time. The contrast between command bar deflection and column motion is shown in traces 2 and 3 of Figure B-6, taken from the present data.

It is convenient for purposes of discussion, and essential for purposes of pilot model synthesis, to describe the pilot frequency response curves in terms of lead and lag dynamics of various orders. Basic boundary conditions on the pilot model are self-evident, and the work of previous investigators provides guidance on details. For boundary conditions we have: (a) pilot response must be finite at very low frequencies, and (b) the response must approach zero at very high frequencies. A single lead term, commonly used as a pilot model, is therefore an incomplete model because it fails to show how pilot response decreases with increasing frequency. Lag, therefore, must be present.

In a very detailed pilot model developed in Ref. B-3, the limiting human neuro-muscular lag characteristics are assumed to be third order, of the form,

$$\frac{1}{(T_N\, j\omega + 1)\left[\left(\frac{j\omega}{\omega_N}\right)^2 + \frac{2\,\xi_N}{\omega_N}\, j\omega + 1\right]}$$

Since all the data show evidence of a high-order lag at about 5 rad/sec, the pilot model for this study was assumed to be of the form

$$Y_P(j\omega) = (T_L\, j\omega + 1)\frac{1}{(T_N\, j\omega + 1)\left[\left(\frac{j\omega}{\omega_N}\right)^2 + \frac{2\,\xi_N}{\omega_N}\, j\omega + 1\right]}\cdot K_P \quad -(4)$$

Use of this model requires acceptance of the fact that it does indeed describe the data, while leaving unanswered the question of the physical significance of the so-called "neuromuscular damping ratio", ξ_N or what, in fact, sets the neuromuscular break frequency, ω_n. It is not known if pilot physiology alone is the controlling factor, or whether it is situation (i.e., task) dependent or influenced by such variables as pilot body attitude and restraint. Some data will be presented later to show indications of the effect of these variables.

The form of the above model for $Y_P(j\omega)$ was adjusted as required to give a magnitude curve that agreed with the magnitude data of each of Figs. B-7 through B-14. In some cases a large amount of additional lead and lag was introduced, instead of the simple lead T_1 shown in the expression. The pilot's time delay, τ, usually appearing in models as $e^{-\tau j\omega}$, was not included here because it could not be determined with any accuracy from the phase data. Additional lead and lag is viewed as equalization generated by the pilot to obtain adequate performance from the airplane, and it is this that we hope to eventually relate to pilot rating.

The pilot models deduced in this way from the data of Figs. B-7 through B-14 are presented in Table B-1, and are plotted on top of the data to show the matches achieved. Also shown in Table B-1 are the pilot ratings given to the configuration of each case on a representative landing approach task proceeding to touchdown. The simplest model that gave a reasonable fit was selected in each case. The following five points may be made regarding the models:

1) The neuromuscular lag is relatively constant among all configurations and both pilots.

2) The model lag was increased from third to fourth order to better match the perceived roll-off at the neuromuscular break frequency.

3) Pilot lead equalization generally occurred near the airplane short period natural frequency.

4) Equalization varied in its dynamic characteristics from case to case, but remained essentially constant in form.

5) In some cases two forms for the equalization appeared equivalent; choosing the simpler led to the less damped, second order lead model. In other cases only this model can match the form of the data.

The lack of agreement between predicted and observed phase angles for some runs may be due to insufficient higher-frequency system excitation, to additional low frequency pilot dynamics not readily visible in the magnitude data, or to systematic experimental error. Further work is required to resolve

TABLE B-1 PILOT DESCRIBING FUNCTION MODELS

RUN NO.	MODEL	PILOT	PILOT RATING	CONFIGURATION
DF-17	$\frac{\left[\left(\frac{j\omega}{1.5}\right)^2 + \frac{2(.5)}{1.5} j\omega + 1\right]}{(.33 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{5.0}\right)^2 + \frac{2(.35)}{5.0} j\omega + 1\right]}$	A	3.5	Baseline
DF-18	$\frac{\left[\left(\frac{j\omega}{1.6}\right)^2 + \frac{2(.4)}{1.6} j\omega + 1\right]}{(.30 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{5.0}\right)^2 + \frac{2(.3)}{5.0} j\omega + 1\right]}$	A	6.5	$\dot{\theta}_{max}/\dot{\theta}_{ss} = 3.24$
DF-19	$\frac{(.4 j\omega + 1)^2}{(.2 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{5.0}\right)^2 + \frac{2(.3)}{5.0} j\omega + 1\right]}$	A	5.0	$\xi\omega_n = .16$
DF-20	$\frac{\left[\left(\frac{j\omega}{1.9}\right)^2 + \frac{2(.8)}{1.9} j\omega + 1\right]}{(.2 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{6.0}\right)^2 + \frac{2(.35)}{6.0} j\omega + 1\right]}$	A	4.0	$T_{\dot{\theta}_{max}} = 2.0$ sec
* DF-21	$\frac{\left[\left(\frac{j\omega}{1.7}\right)^2 + \frac{2(.6)}{1.7} j\omega + 1\right]}{(.2 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{6.0}\right)^2 + \frac{2(.35)}{6.0} j\omega + 1\right]}$	A	3.5	Baseline

TABLE B-1 - Continued

RUN NO.	MODEL	PILOT	PILOT RATING	CONFIGURATION
* DF-23	$\frac{\left[\left(\frac{j\omega}{2.0}\right)^2 + \frac{2(.9)}{2.0} j\omega + 1\right]}{(.2 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{5.5}\right)^2 + \frac{2(.35)}{5.5} j\omega + 1\right]}$	C	2	Baseline
DF-24	$\frac{(1.25 j\omega + 1)\left[\left(\frac{j\omega}{1.8}\right)^2 + \frac{2(.5)}{1.8} j\omega + 1\right]}{(2.0 j\omega + 1)(.2 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{5.5}\right)^2 + \frac{2(.35)}{5.5} j\omega + 1\right]}$	C	2	Baseline
DF-25	$\frac{(.33 j\omega + 1)\left[\left(\frac{j\omega}{1.3}\right)^2 + \frac{2(.4)}{1.3} j\omega + 1\right]}{(2.0 j\omega + 1)(.2 j\omega + 1)} \cdot \frac{1.0}{(.1 j\omega + 1)^2\left[\left(\frac{j\omega}{5.0}\right)^2 + \frac{2(.35)}{5.0} j\omega + 1\right]}$	C	2	$\xi\omega_x = .16$

* Fixed-base

this difficulty. The general form of the pilot model is thus:

$$Y_P(j\omega) = K_P \cdot \frac{\left[\left(\frac{j\omega}{\omega_L}\right)^2 + \frac{2\zeta_L}{\omega_L} j\omega + 1\right]}{(T_I\, j\omega + 1)} \cdot \frac{(T_L'\, j\omega + 1)}{(T_I'\, j\omega + 1)} \cdot \frac{1}{(T_N\, j\omega + 1)^2 \left[\left(\frac{j\omega}{\omega_N}\right)^2 + \frac{2\zeta_N}{\omega_N} j\omega + 1\right]}$$

as derived by comparison to the data, with frequencies and time constants adjusted to match each data set.

One of the principal uses of a pilot model is the prediction of pilot ratings by using model parameters, such as equalization time constants. In this investigation an attempt was made to relate the characteristics of the pilot models discussed above to the pilot ratings that were given the various airplane configurations by pilots flying a landing approach task simulation that included glideslope capture, maneuvering about the glideslope, and touchdown at a desired point on the runway.

It has been pointed out in several references (e.g., Refs. B-7 through B-9) that pilot equalization parameters alone are insufficient to predict pilot ratings, and must be combined with measures of performance or workload. This fact was borne out by the data of the present experiment.

In Figure B-15 is shown a plot of pilot rating vs. the time constant of the principal, second-order lead equalization* of the models in Table B-I, for

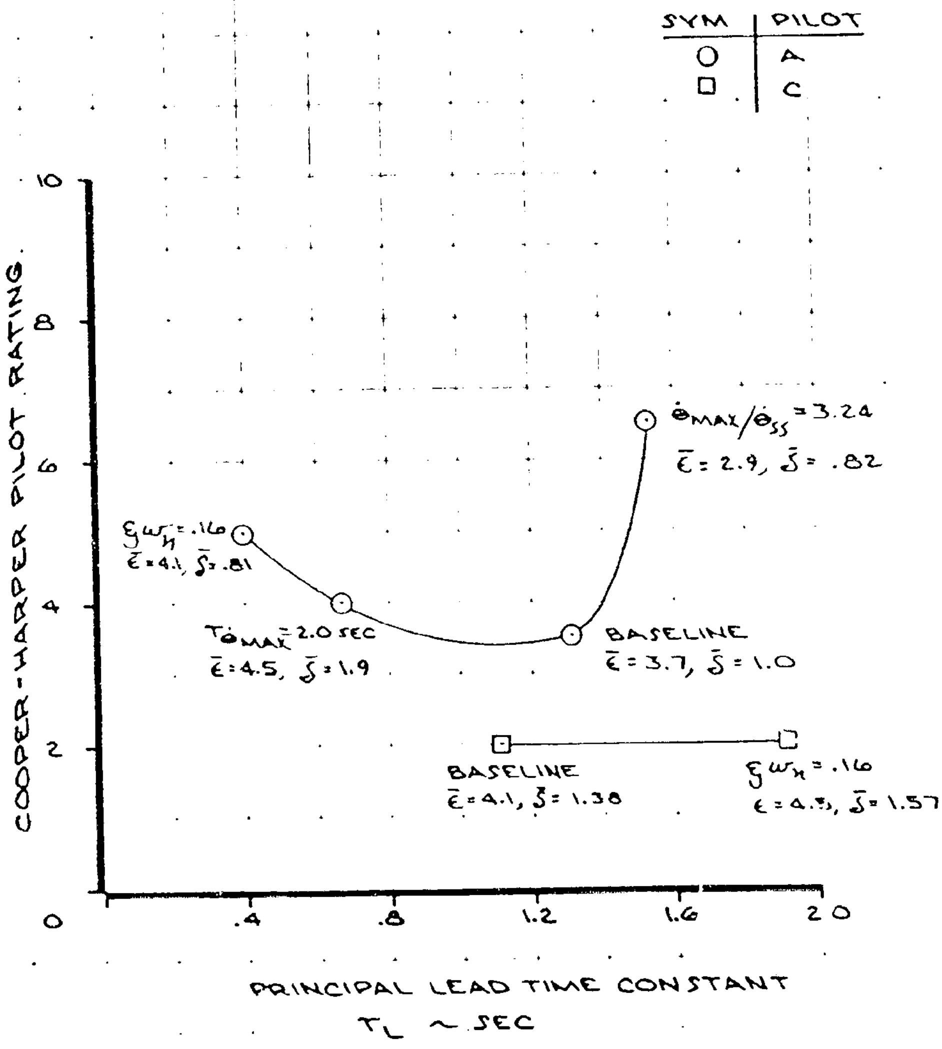
* The time constant for a second-order system with the characteristic equation

$$\lambda^2 + 2\zeta\omega_n \lambda + \omega_n^2 = 0 \quad \text{is} \quad T = \frac{1}{|\zeta\omega_n|} \ \text{sec}$$

NOTE:

$\bar{\epsilon}$ = RELATIVE MEASURE OF RMS TRACKING ERROR

$\bar{\delta}$ = RELATIVE MEASURE OF RMS COLUMN ACTIVITY



CALC		REVISED	DATE	VARIATION OF PILOT RATING WITH LEAD EQUALIZATION	FIG B-15
CHECK					
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APPD				THE BOEING COMPANY	PAGE 153

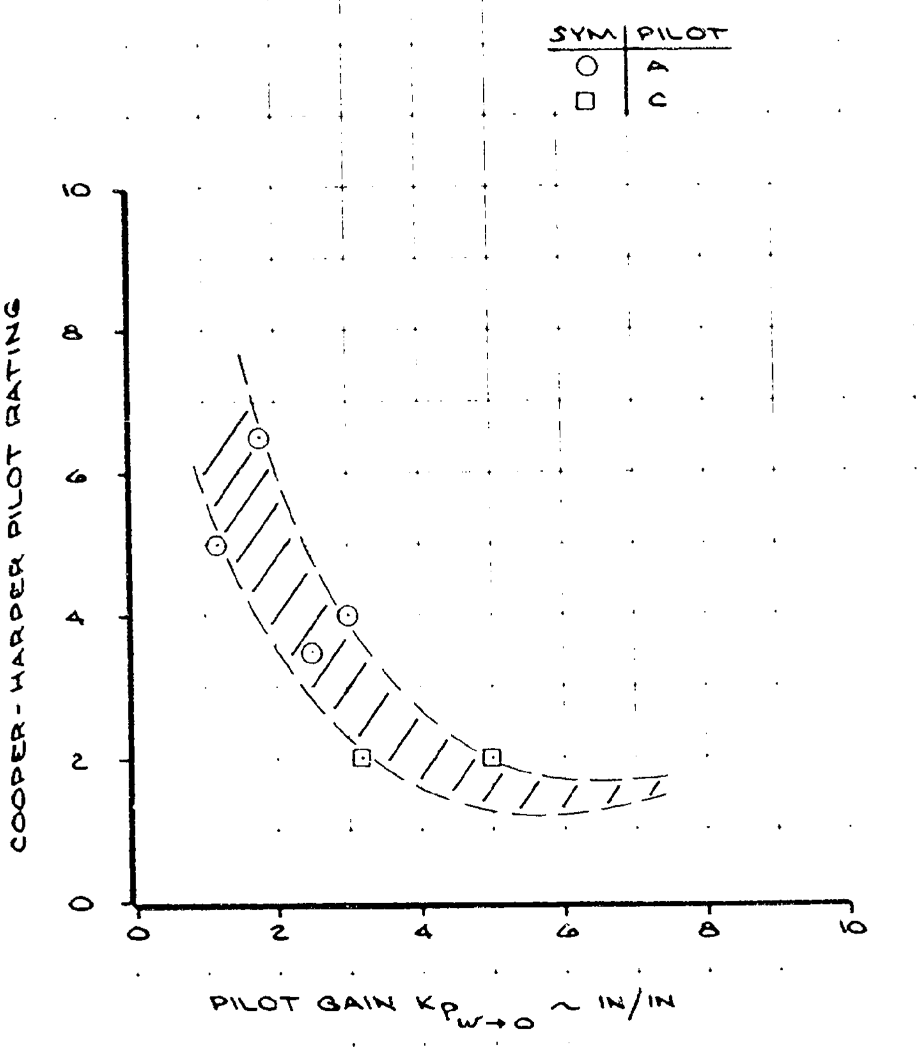
each configuration tested. Noted as parameters on Fig. B-15 are a relative measure of tracking accuracy, $\bar{\epsilon}$, defined as root mean square pitch command bar displacement, $\theta_{\epsilon_{rms}}$, divided by rms glideslope command (recall, filtered white noise) $\gamma_{c_{rms}}$, and a relative measure of workload, $\bar{\zeta}$, defined as the rms column deflection. Both averages are taken over the length of the data sample, and were taken during the fixed altitude describing function runs, not the approach runs. The relationships among the parameters of Fig. B-16 and the configurations tested are clarified by Table B-II.

Figure B-15 clearly shows that there is no direct linear relation between pilot rating and equalization time constant. It also shows that two different pilots rated one configuration entirely differently.

Pilot [illegible] rated the baseline configuration 3.5. The configuration with high pitch rate overshoot ratio was rated a 6.5, a poor rating, but the performance, as measured by the ratio $\bar{\epsilon}$ improved. Apparently, tighter control was sought due to a concern about controllability. The configurations with low damping and slow pitch rate response were rated 5.0 and 4.0, respectively, but now performance degraded. It appears in these two cases that the ratings were made on the basis of performance rather than perceived stability, or perhaps on a combination of both.

Pilot C rated both the baseline and the low-damped configuration a [illegible]. Performance and workload between these two configurations were relatively constant, but both revealed more equalization - in addition to second-order lead - than used by Pilot [illegible], as seen from Table B-I. Pilot C apparently added equalization until the performance of the low-damped configuration equalled that of the baseline, then rated on performance.

A plot of pilot rating versus low frequency pilot gain, Figure B-16, suggests an optimum pilot gain, but the factors that may explain this trend cannot be determined from the present data.



			REVISED	DATE		
CALC					LOW FREQUENCY PILOT GAIN CHARACTERISTIC	
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APPD					THE BOEING COMPANY	PAGE 155

TABLE B-II - PILOT PARAMETERS AND RATINGS

Run	Configuration	Pilot	Lead Equalization Time Constant, sec	col_{rms}	$\frac{\theta_{rms}}{c_{rms}}$	Pilot Rating
DF-17	Baseline	A	1.33	.43	3.66	3.5
-18	$\dot{\theta}_{MAX}/\dot{\theta}_{SS} = 3.24$		1.56	.35	2.94	6.5
-19	$\xi\omega_n = .16$		.40	.34	4.12	5.0
-20	$T_{\dot{\theta}_{MAX}} = 2.0$ sec		.66	.82	4.48	4.0
-24	Baseline	C	1.11	.59	4.10	2.0
-25	$\xi\omega_n = .16$		1.91	.67	4.50	2.0

An attempt was made to correlate pilot rating to the variables T_L, $\bar{\epsilon}$, and $\bar{\zeta}$. Figure B-17 presents the results of a multiple linear regression analysis on the six data points of Figure B-15; the best functional relationship obtained among the variables or their reciprocals is:

$$PR = -13.3 + \frac{1.85}{T_L} + 3.88\,\bar{\zeta} + \frac{50.3}{\bar{\epsilon}} \qquad -(5)$$

As seen in Fig. B-17, this expression fits the data of Pilot A very well, while the data of Pilot C are not well predicted. It appears that Pilot C's data are suspect, but at the same time it should be noted that with only 6 data points the functional is only statistically valid to approximately the 90% level, or below. More data are needed, but in view of Fig. B-15, the correlation obtained is promising.

Given a means of selecting T_L, one way being the establishing of first order dynamic characteristics near the pilot-airplane open-loop crossover frequency, as discussed in Ref. B-3, prediction of the pilot rating from an airplane model would follow from excitation of the closed-loop compensatory system by a random input, and measurement of the variables $\bar{\zeta}$ and $\bar{\epsilon}$ that resulted, followed by the use of a pilot rating functional, such as Eq. (5).

Once this technique is explored and verified to a sufficient statistical confidence level, it may prove useful in choosing between candidate aircraft control system designs and allow a large number of systems and failure modes to be screened before piloted simulator analysis is undertaken.

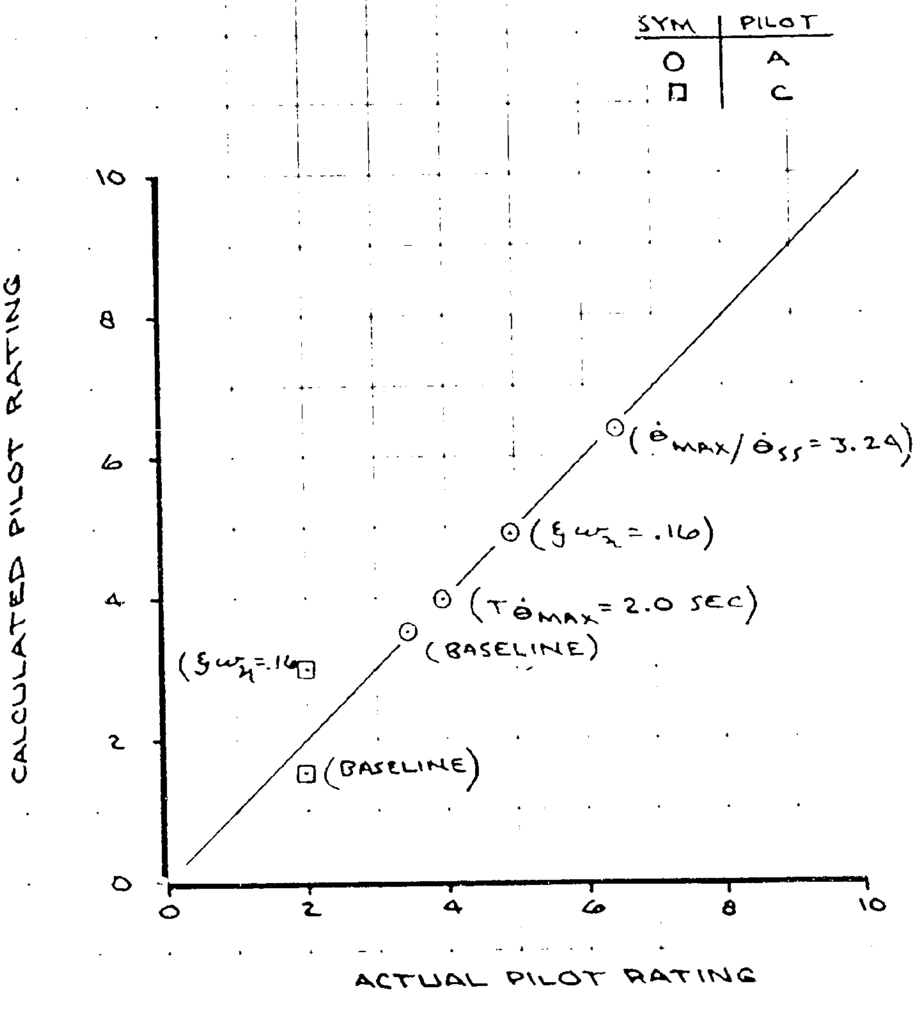
Conclusions

Based on this study, the following points can be made:

1) Pilot frequency response characteristics display pronounced high-order lag (4th order or greater) and lead or lead-lag equalization which is usually second-order and is configuration-dependent.

PILOT RATING (CALCULATED) =

$$-13.3 + \frac{1.85}{T_L} + 3.88\,\zeta + \frac{50.3}{\bar{\varepsilon}}$$



CALC		REVISED	DATE	COMPARISON OF PILOT RATING PREDICTION TECHNIQUE
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FIG. B-17

2) The lag characteristics are essentially constant among the pilots and configurations tested and are assumed to represent human neuromuscular phenomena.

3) Comparison with other published data suggests that the neuromuscular lags are dependent on controller type

4) Nonlinear, "bang-bang" control activity predominates at and beyond the neuromuscular break frequency.

5) Tracking performance, control activity, configuration characteristics, and pilot preferences are the principal variables affecting [illegible] rating.

6) Good agreement was obtained with observed data using a linear regression model to predict pilot rating, but the present data base is too small to give sufficient statistical confidence levels.

7) Only small differences were observed between pilot frequency response on moving and fixed base simulators.

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APPENDIX B REFERENCES

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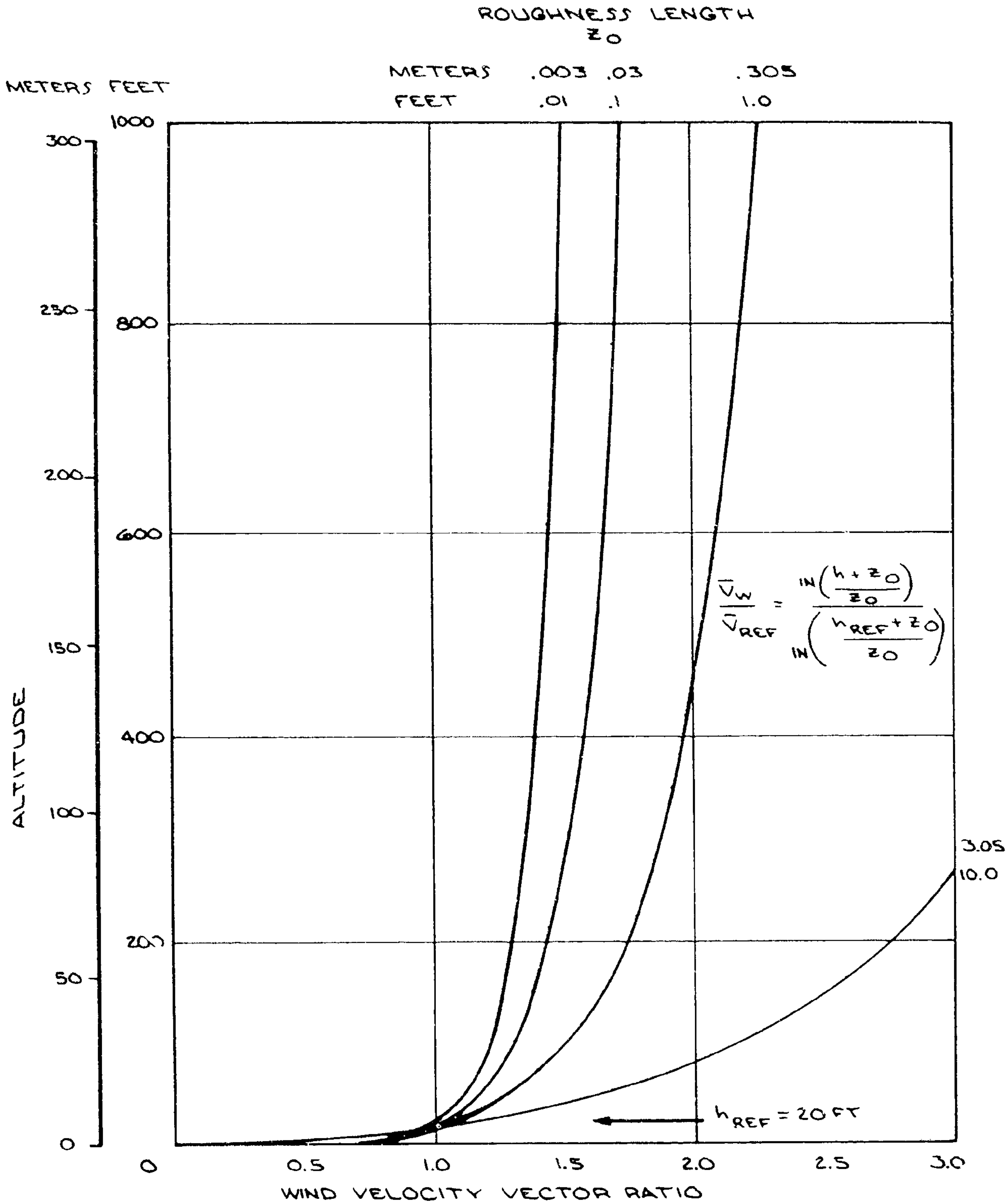
APPENDIX C

WIND AND TURBULENCE MODEL

The wind and turbulence model was the same as that used for all evaluations of the YC-14 at the same simulation facility as used for this study. The model is based on work done under contract for the Federal Aviation Administration by The Boeing Company (Reference 7). This work was specifically aimed at developing wind models for simulation studies.

Basic parameters that define the wind model used for this simulation study are presented in Figures C-1 through C-4.



ENGR			REVISED	DATE	MEAN WIND PROFILE	
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APR						FIG. C-1
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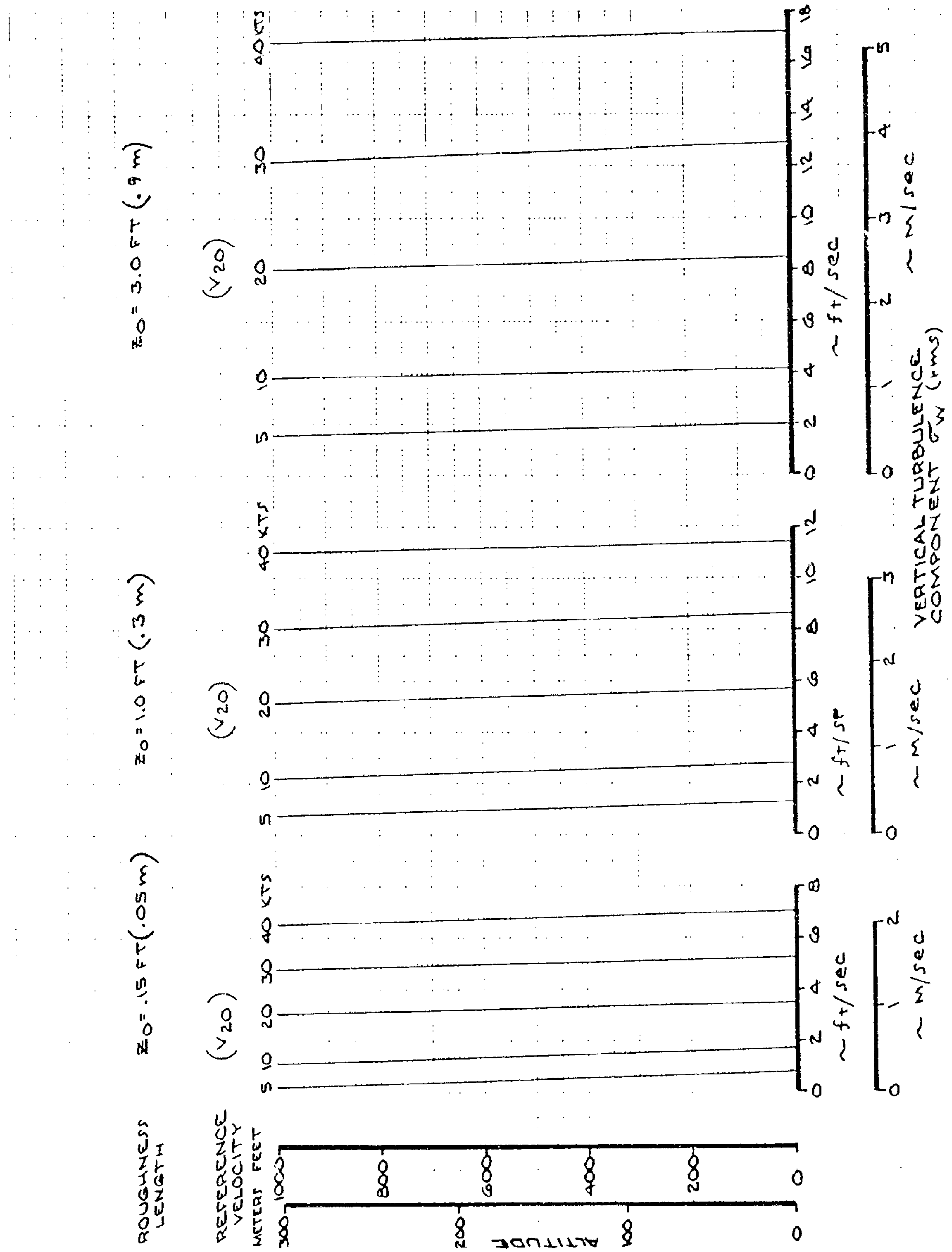

CALC			REVISED	DATE	LOW ALTITUDE VERTICAL TURBULENCE COMPONENT	
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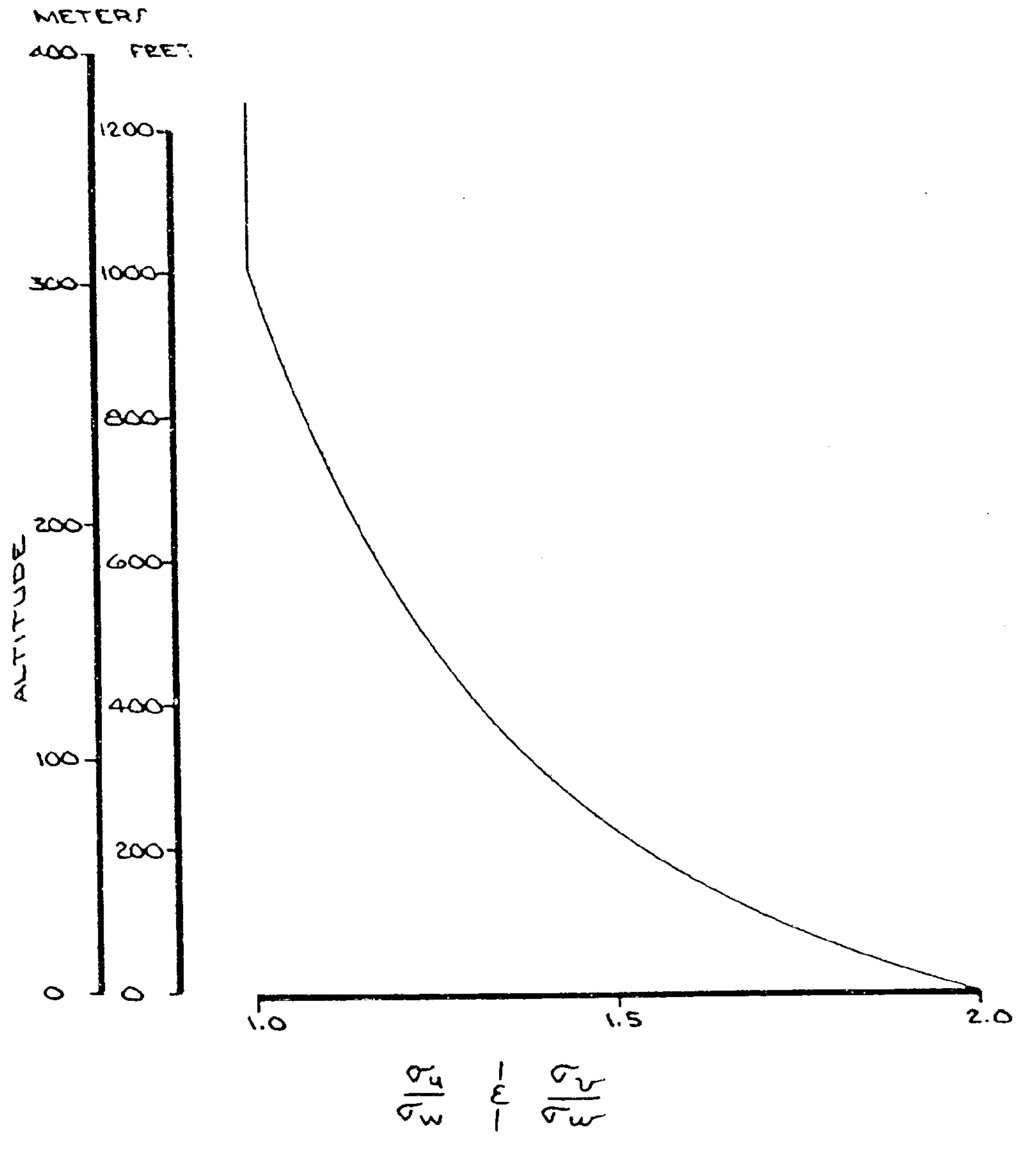

CALC			REVISED	DATE	RELATIONSHIP OF TURBULENCE COMPONENTS	FIG C-3
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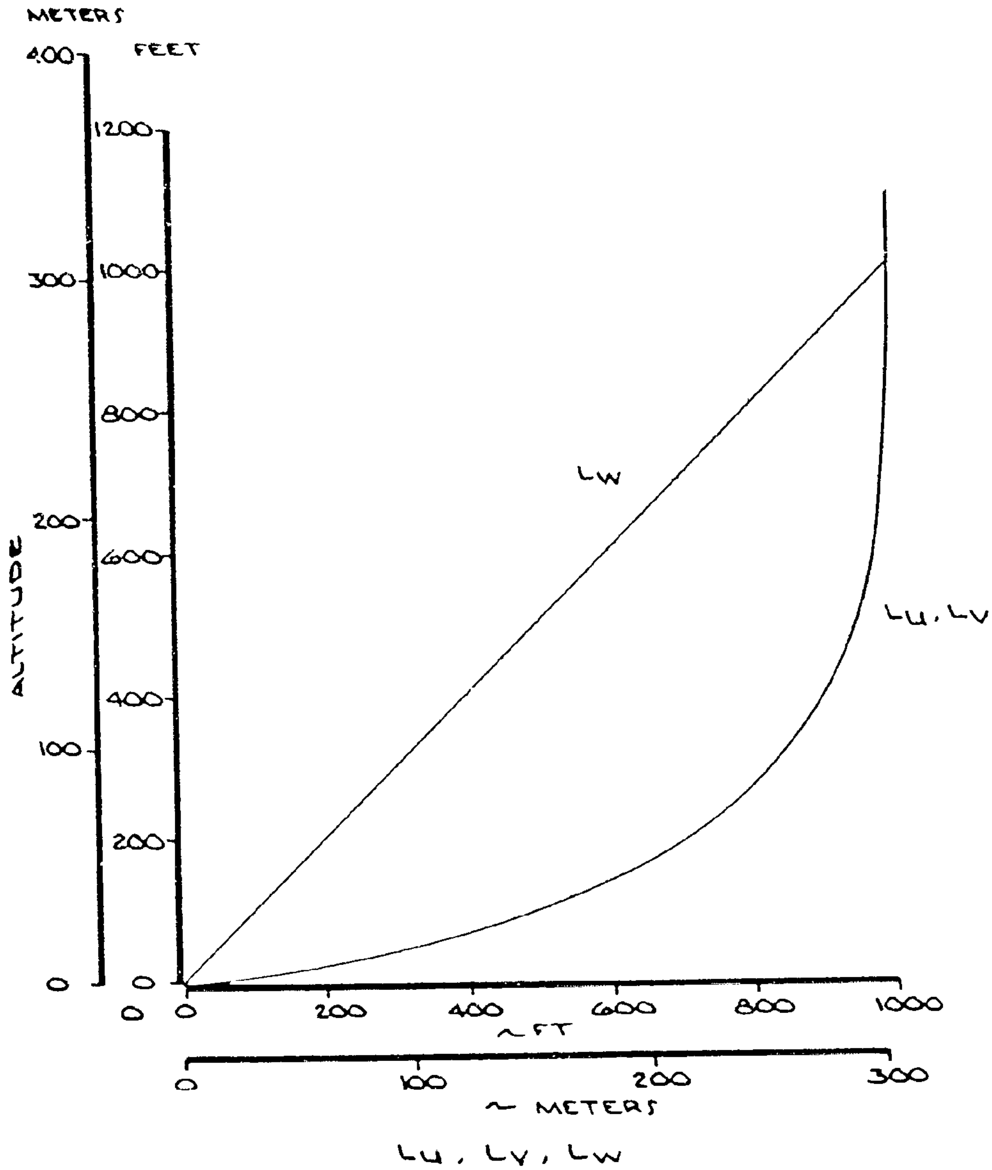

CALC			REVISED	DATE	TURBULENCE SCALE LENGTHS	FIG C-4
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APPENDIX D

PILOT EXPERIENCE

Pilot "A" is a pilot for The Boeing Company. He received his flight training while in the U. S. Navy and was in the Navy for three years. He has been with The Boeing Company for 25 years, working as a flight test engineer for the first five years and as a pilot for the remainder. He was the B-52 Project Pilot for all phases of the flight test program and has been a test pilot for various types of testing on various Boeing airplanes (707, 727, 737, and 747). His 8500 hours flight time have been almost entirely in large subsonic aircraft. Also, several thousand hours of simulator experience, including both moving and fixed base simulators, have been obtained. Presently he is Senior Engineering Test Pilot and Senior Instruction Pilot for The Boeing Company, as well as a NASA consultant on the Shuttle-Orbiter Program.

Pilot "B" is a NASA research pilot and a graduate of the USAF Test Pilot School, with 16 years experience as an Air Force test pilot and 8 years with NASA as an aerospace research pilot. His flight experience of 12,200 hours includes over 2500 hours in heavy, multi-engine jet aircraft (B-52, B-47, B-58, XB-70, C990), 640 hours in medium multi-engine jet aircraft (B-57, YF-12), and 750 hours in single-engine jet fighters (primarily the F-104). He has flown several flights in the Concorde. He has about 300 hours of simulator experience (including VTOL, STOL, Concorde, B-2707, AMST programs). He is presently project pilot for the YF-12 and heavily involved in planning and simulation studies of the B-747 Shuttle Program, flying approximately 30-35 hours per month.

Pilot "C" is a Boeing pilot with his training received in the U. S. Navy. Flight experience consists of 6000 hours, most of which has been in large jet transport aircraft. As a Boeing test pilot he has conducted power plant performance, stability and control, flight load survey, automatic pilot, structural dynamics, and system testing on all Boeing jet aircraft including the B-52 and KC-135. Presently he is a senior engineering test pilot, and is project pilot for the 737 model aircraft. He has also worked on NASA contracts such as the Supersonic Transport Simulator, low-speed handling qualities evaluations of large transports, steep approach studies, noise abatement studies, and boundary layer control development work, all conducted on the Boeing model 367-80. He was project pilot for the Augmentor-Wing Buffalo and has participated in preparation of the design proposal for the Quiet Short-Haul Research Aircraft (QSRA).

Pilot "D" is a Boeing pilot with his flight training received in the Air Force and from the Navy Test Pilot School. His flight experience of 6600 hours includes approximately 4000 hours in large jet transports and approximately 20 hours of supersonic flight. He has about 400 hours of moving base simulator experience distributed over various research programs. Presently, he is the project pilot for the Carrier Aircraft Modification program and the assistant chief pilot for the experimental 747 programs.

Pilot "E" is a NASA research pilot with his training received in the Marine Corps. His flight experience of 8200 hours includes 2500 hours in fighter/attack jet aircraft and 3200 hours in large jet transport type aircraft. His simulator experience is in excess of 750 hours in all classes of aircraft (mostly large transports). Presently he flies approximately 30 hours per month in his capacity of a NASA research pilot.

Pilot "F" is a Boeing pilot with 7 years experience in the Air Force and 8 years with The Boeing Company. His flight experience of 4600 hours includes some supersonic time (T-38 and F-105) and considerable time in the Boeing production aircraft (707, 727, 737, and 747). His simulator experience includes involvement in the initial SST handling qualities studies and the YC-14 program. He has approximately 200 hours of moving base simulator experience. He is presently a production pilot with The Boeing Company, flying approximately 40-50 hours per month.

Pilot "G" is a NASA research pilot and a graduate of the Air Force Test Pilot School. His flight experience of approximately 4000 hours includes 1000 hours in single-engine jet fighters and trainers (F-100, F-104, T-33) and 2500 hours in multi-engine jet transports (C-135, C-141). His simulator experience includes 100 hours in the FSAA and ARC facilities. Presently he flies approximately 40 hours per month in his capacity as a NASA research pilot.

APPENDIX E

RUN SUMMARY

HIGH SPEED CRUISE MANEUVERING: PILOT COMMENTS

EADI SCALE VARIATION

EADI SCALE IN DEG.	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
.16	9 Oct	2	[illegible]	5.0	o Needed to work harder to change altitude o Strong static stability caused problem in maintaining altitude while changing airspeed o Had trouble performing maneuvers for bank angle of 30° o Rate airplane at 3.0 in level flight and shallow banks - at 7.0 in steep banks
	[illegible] Oct	23	[illegible]	[illegible]	o Seemed to be a lack of longitudinal damping o Used longitudinal control more than desired o Devoted some time to holding zero bank o Had some trouble setting rates for initial altitude changes
	[illegible]	23	[illegible]	4.[illegible]	o Fairly high pilot workload in changing altitude - not too precise o Moderately high pilot workload in changing airspeed o Altitude and load factor control tough during banks o Rough ride for passengers o Display makes pitch control hard o Breakout - OK; high stick forces
.23	23 Oct	22	[illegible]	4.[illegible]	o Had some difficulty in setting rates for altitude changes o Appeared to be less pitch damping than for .30 IN/DEG case o Easy to over-pitch o Seemed to have slight negative speed stability o Excessive amount of longitudinal control required to maintain altitude while changing speed
	[illegible] Oct	24	[illegible]	[illegible]	o Much improved over .16 IN DEG case - almost like a different airplane
	7 Oct	15	[illegible]	3.5	o Undesirable trim changes required for power changes o Significant load factor variation for bank angles 20° o Tendency to overshoot pitch attitude on altitude changes - pitch display still not adequate - heavy reliance on other instruments o A little sensitive

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EADI SCALE IN DEG.	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
.30 (baseline)	9 Oct 23 Oct	12 20	B B	2.5 3.0	o "Pleased with altitude control o Some hunting in pitch attitude during banks o Slight overshoot tendency o Good load factor control o No problem with speed changes
	17 Oct	17	[illegible]	2.5	o Accuracy increased in altitude changes and speed changes o Slight tendency to overshoot o Minor improvement in load factor control o Better feeling of stability o Improved airplane o Would like aircraft (in display) on horizon

HIGH SPEED CRUISE MANEUVERING PILOT COMMENTS

PITCH RATE OVERSHOOT RATIO VARIATION

$\dot{\theta}_{max}/\dot{\theta}_{ss}$	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
[illegible]	[illegible] Oct	[illegible]	B	2.5	o Ability to [illegible] altitude and airspeed good o Hunting for bank angle (causing some pitch and load factor oscillation due to distraction) o No tendency to overshoot o Damping good o Pretty good overall aircraft
	[illegible]	[illegible]	G	2.0	o Best configuration of this set o High precision available on both altitude and airspeed changes o Ideal damping o Banking maneuvers would get a lower rating o Less tendency to overshoot than other [illegible] in this set
4.[illegible]	[illegible] Oct	[illegible]	B	2.5	o Pleased with altitude control o Some hunting in pitch attitude during banks
	23 Oct	2[illegible]	B	3.0	o Slight overshoot tendency o Good load factor control o No problem with speed changes
	[illegible] Oct	[illegible]7	G	2.5	o Accuracy increased in altitude changes and speed changes o Slight tendency to overshoot o Minor improvement in load factor control
6.[illegible]	[illegible] Oct	[illegible]	B	2.5	o Good control of altitude and of setting the desired rates o Expanded scale good o Good load factor control o No problem with pitch attitude control

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$\dot{\theta}_{max}/\dot{\theta}_{SS}$	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
6.1	17 Oct	18	G	3.5	o Slight tendency to oscillate in pitch o Problem with large trim changes required for power changes o Load factor excursions at top limit for passenger comfort o Moderate workload required for altitude and airspeed changes o Workload could be relieved with a further expanded EADI scale
	21 Oct	17	G	4.0	
5.2	9 Oct	11	B	4.0	o Some difficulty in setting up rates for altitude changes o A lot of pitch control required to keep desired attitude o High pilot workload required to avoid pitch oscillation during maneuvers o Slight overshoot tendency (perhaps some sort of PIO)
	24 Oct	22	G	4.0	o No problem maintaining rates and attitudes needed for altitude changes o Pitch control "touchy" - too touchy for passenger aircraft o Load factor excursions easy o Slight overshoot tendency (due to responsiveness)

HIGH SPEED CRUISE MANEUVERING PILOT COMMENTS

TIME-TO-PEAK PITCH RATE VARIATION

$T_{\dot{\theta}_{MAX}}$	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
0.45	9 Oct	[illegible]	B	3.0	o Little or no difficulty in changing altitude and airspeed o Small pitch oscillation for bank angle of 30° o Load factor control good o High stick forces
	[illegible] Oct	[illegible]	G	2.0	o Relatively light workload o No problem with altitude and airspeed changes o Very slight overshoot tendency o Responsive
[illegible]	17 Oct	13	B	2.5	o "Pleased" with altitude control o Some hunting in pitch attitude during banks o Slight overshoot tendency o Good load factor control o No problem with airspeed changes
	21 Oct	17	B	3.0	
	17 Oct	17	G	2.5	o Accuracy increased in altitude changes and speed changes o Slight tendency to overshoot o Minor improvement of load factor control
[illegible].4	9 Oct	13	B	4.5	o Some difficulty in maintaining desired rates during altitude changes o High trim changes due to thrust changes o Pitch oscillations during banking maneuvers - especially at 30° o Not as much pitch control as is desired o High stick forces

$T_{\dot{\theta}_{MAX}}$	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
1.4	13 Oct	16	G	4.0	o Constant pilot attention required during altitude and airspeed changes (though workload moderate) o Tends towards oscillations in load factor o Some overshoot tendency o Relatively low damping o Minor distractions could cause gross errors in altutide during banking
2.0	9 Oct	[illegible]	B	7.0	o "A Hell of a time" keeping constant altitude while changing airspeed - airplane flew like it had a low static margin o Easy to overcontrol in pitch - PIO's o Load Factor control completely unacceptable - appeared to be a lack of longitudinal stability o Great tendency to overshoot o Lack of damping
	21 Oct	16	G	8.0	o Practically impossible to perform pilot tasks o Constant attention and very high workload required to maintain control of airplane o Bank angles seemed to improve handling characteristics o High overshoot tendency o Almost no damping evident o There is a lag somewhere in control system o Lousy airplane

HIGH SPEED CRUISE MANEUVERING PILOT COMMENTS

DAMPING PITCH VARIATION

$\xi \omega_n$	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
0.36	9 Oct	15	B	4.0	o Had trouble maintaining desired rates during altitude changes o Excessive trim changes required for power changes - a lot of column force o A little problem seeking out and stabilizing on desired pitch angle during bank o Load factor oscillations (± .1g) in bank
	[illegible] Oct	15	G	5.0	o Fairly high workload maintaining altitude o Hard to obtain rates in altitude changes due to low damping o Fair amount of compensation required in banking maneuvers o Small oscillations in load factor o High overshoot tendency o Quite responsive o Stiffer stick would help oscillations
1.05	9 Oct 23 Oct	12 20	B B	2.5 3.0	o Pleased with altitude control o Some hunting in pitch attitude during banks o Slight overshoot tendency o Good load factor control o No problem with speed changes
	17 Oct	17	G	2.5	o Accuracy increased in altitude and speed changes o Slight overshoot tendency o Minor improvement in load factor control
2.42	23 Oct	18	B	3.0	o No problem with altitude control o A lot of trim changes for power changes - easier to use column control than trimming o Felt pilot performance was sloppy o Some pitch excursions in banks

$\zeta \omega_n$	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
2.42	18 Oct	19	G	1.75	o Light workload - distractions tolerable o Good load factor control o Damping optimized o Trim changes due to power changes barely noticeable o Felt a difference in EADI scaling
5.7	24 Oct	18	G	2.5	o Relatively light workload o No problem in altitude or airspeed changes o Little or no overshoot tendency o Lack of reference on EADI makes pitch control in bank more difficult o Stick forces could be heavier, but it's not a problem
25	17 Oct	7	G	2.5	o No problem in altitude or airspeed changes o Slight tendency to overshoot o Stick forces O.K.
45.4	24 Oct	19	G	2.0	o Low workload o No problem in altitude or airspeed changes o Tendency for aircraft to bobble with thrust changes o "Heavier feel" makes more gradual "G" change o Very precise control o Stick forces seem optimized o There seems to be a pronounced lag in trim system
64.1	24 Oct	20	G	3.0	o No problem in altitude or airspeed changes o Good load factor control - "You'd be hard pressed to cause excessive 'G' load' o Pitch control a little sluggish o Stick force a little high - especially at higher bank angles o Solid airplane - no oscillations

REV SYM

HIGH SPEED CRUISE MANEUVERING: PILOT COMMENTS

COLUMN FORCE GRADIENT VARIATION

F_{col} (lb/g)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
8.7 (39 N/g)	24 Oct	12	G	2.5	o Relatively light workload o No problem in altitude or airspeed changes o Little or no overshoot tendency o Lack of reference or EADI makes pitch control in bank more difficult o Stick forces could be heavier, but it's not a problem
45.4 (202 N/g)	24 Oct	13	G	2.0	o Low workload o No problem in altitude or airspeed changes o Tendency for aircraft to bobble with thrust changes o "Heavier Feel" makes more gradual "G" change Very precise control o Stick forces seem optimized o There seems to be a pronounced lag in trim system
64.2 (286 N/g)	24 Oct	20	G	3.0	o No problem in altitude or airspeed changes o Good load factor control - "You'd be hard pressed to cause excessive "G" load" o Pitch control a little sluggish o Stick force a little high-especially at higher bank angles o Solid airplane - no oscillations

REV SYM

LANDING APPROACH (NORMAL OPERATION): PILOT COMMENTS

PITCH RATE OVERSHOOT RATIO VARIATION

$\dot{\theta}_{max}/\dot{\theta}_{ss}$	WIND & TURBULENCE V_{20} ~kts	σ_w (m/s)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
1.12	0	0	29 May	19	A	3.0	o Easy glideslope acquisition but nose down pitch rate may be faster than would be desirable with passengers o No difficulty in capturing localizer o No overshoot problems o Flight path response appears slow
	7 HW	.8 ~fps (.24 m/sec)	3 June	21	B	4.0	o High elevator workload o Column forces too high o Requires considerable push force to reacquire glideslope from above o Has tendency to flatten approach when nearing runway
	0	0	31 May	43	D	4.0	o Hard to capture glideslope o Tracking OK once on glideslope o Sluggish pitch and altitude response
1.67 Baseline	0	0	29 May	23	A	3.5	o Small short period oscillation with initial column input o Slightly heavy column forces o Satisfactory control effectiveness and workload
	0	.5 ~fps (.15 m/sec)	3 June	33	B	3.5	o Pitch bar easily captured and workload slightly less than cases where overshoot ratio = 1.12 or 2.12 o Good altitude and flight path response o Glideslope tracking easy
	0	0	4 June	31	C	2.0	o Easy capture and tracking of localizer and glideslope with low workload o No overshoot o Excellent column force gradient o Good flight path and altitude response

REV SYM

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$\dot{\theta}_{max}/\dot{\theta}_{ss}$	WIND & TURBULENCE V_{20} ~kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
1.67 (BASELINE)	[illegible]	7 ft/s 2.1[illegible] sec	[illegible] June	47	[illegible]	2.0-[illegible]	o Moderately hard glideslope capture due to turbulence o Tracking localizer annoying due to constant roll oscillation o Good pitch control o Turbulence is ridiculous
	[illegible]	[illegible] ft/s [illegible].24 sec	[illegible] June	[illegible]	[illegible]	2.5	o No problems with localizer or glideslope acqu's. o Good column force gradient o Altitude response OK
			25 Sept	[illegible]	[illegible]	[illegible]	o Glideslope acquisition comparable to 707 727 747 o Auto throttle accuracy not as good as 727 or 747 o Flare normal
	[illegible]	[illegible] ft/s [illegible].22 sec	[illegible] Sept	[illegible]	[illegible]	4.0-D	o Normal G/S acquisition and tracking o Not enough rudder for decrab
	[illegible]	[illegible] ft/s 2.1[illegible] sec	[illegible] Sept	12	F	6.0-F	o Lateral directional effort extreme o Outer limit for landing and then only if absolutely necessary
2.[illegible]	[illegible]	[illegible]	23 May	[illegible]	[illegible]	[illegible].5	o Tends to overshoot slightly o Workload on glideslope distracts from holding localizer o Flight path response appears slow o Normal altitude response

$\dot{\theta}_{max}/\dot{\theta}_{ss}$	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
2.12	7 HW	[illegible] fps (2.24 m/sec)	3 June	17	B	4.0	o Moderately high workload o Easy glideslope capture although tracking requires frequent pitch inputs o No problems on overshoot o Longitudinal control never seems to be in trim - always slight push or pull o Column force gradient slightly high o Breakout forces may be a problem, but not severe o Large nose-down pitch attitude changes (4 to 5 degrees) required to reacquire glideslope
	7 HW	[illegible] fps (2.24 m/sec)	4 June	37	C	2.0	o Easy capture, good tracking o Very low workload o No overshoot o Good column forces o Good altitude and flight path responses
	25 CW	7 fps (2.13 m/sec)	5 June	43	C	2.0-F	o Moderate difficulty in glideslope acquisition - turbulence higher than desired o Moderate workload during flare o Could be more responsive in pitch o Flight path response sluggish o Force gradient too high
	0	0	24 May	40	C	3.5	o Little overshoot on glideslope capture o Slightly sluggish, good otherwise
3.34	0	0	29 May	21	A	6.5	o Glideslope capture was not difficult o Overshoot and pitch oscillation annoying and extremely uncomfortable for any passengers o Longitudinal oscillation while tracking the glideslope controllable but very undesirable: could tolerate only as emergency condition o Poor damping

REV SYM

$\dot{\theta}_{max}$ $\dot{\theta}_{SS}$	WIND & TURBULENCE V knots	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
[illegible]4	[illegible]	[illegible] .24 [illegible]	June	[illegible]	B	5.5	o Workload high following any modest control input o Damping Low o PIO easy to get started when trying to make modest correction o Sluggish flight path and altitude response
	0	0	24 May	31	[illegible]	4.5	o Glideslope acquisition sluggish o Tracking fair - airplane corrections sluggish o Pitch and altitude response very sluggish
	[illegible]	[illegible] .24 [illegible]	[illegible] Sept	15	F	[illegible].5	o Longitudinal control response slow causing tendency to overshoot glideslope after capture o Column force gradient too heavy o Flight path response and altitude response sluggish
	[illegible]	[illegible] .22 [illegible]	[illegible] Sept	5	F	3.0-[illegible]	o Localizer capture and tracking - normal to high workload level o Glideslope capture and tracking more difficult than normal due to heavy damping o High forces after breakout

REV SYM

LANDING APPROACH (NORMAL OPERATION): PILOT COMMENTS

TIME-TO-PEAK PITCH RATE VARIATION

$T_{\dot{\theta}_{max}}$	WIND & TURBULENCE V_{20} ~kts	σ_w (rms	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
1.0	0	0	30 May	43	A	4.0	o Glideslope capture satisfactory o Overshoot no problem o Workload normal o Rough response in elevator action o Satisfactory column forces o Some short period flight path oscillation
	7 HW	.8 fps (.24 m/sec)	6 June	45	C	4.0	o Easy capture and tracking of localizer and glideslope o Low level workload o Easy flare and sink rate control o High column forces o Flight path response good, but slower than desired o Very heavy damping
	25 CW	4 fps (1.22 m/sec)	6 June	46	C	4.0-D	o Same as for no turbulence case
	25 CW	7 fps (2.13 m/sec)	6 June	47	C	4.0-D	o Same as for no turbulence case
2.0	0	0	30 May	35	A	4.0	o Slow to capture glideslope o Required too large pitch changes o Medium workload o Satisfactory column forces o Sluggish flight path response o Satisfactory damping and altitude response

θ_{max}	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
2.0	7 HW	.8 fps (.24 m/sec)	6 June	20	C	6.0	o Moderate to difficult glideslope capture o Some overshoot o Moderate to difficult tracking of glideslope and localizer o Column force gradient too high Flight path response sluggish, but OK
	25 CW	4 fps (1.22 m/sec)	6 June	21	C	6.0-D	o High pitch forces and low pitch response make for workload increase
	25 CW	7 fps (2.13 m/sec)	6 June	22	C	6.0-H	o Extreme turbulence o Never seen in a real aircraft
	7 HW	.8 fps (.24 m/sec)	25 [illegible]	[illegible]	F	[illegible]	o Acquisition easy - low workload o Stick force gradient a little stiff o Flight path response pretty good
3.0	0	0	30 May	39	A	5.0	o Had difficulty holding glideslope o Small overshoot o Workload above average o Higher workload made it harder to maintain glideslope o Airplane response was smooth, but sluggish in flight path response o Satisfactory column forces
	7 HW	.8 fps (.24 m/sec)	5 June	39	C	7.0	o Difficult to capture and track glideslope o Moderate to excessive workload o Control was sluggish with low sensitivity and response; however, damping looked good o Column forces were too high for a given pitch rate

REV SYM

$T_{\dot{\theta}_{max}}$	WIND & TURBULENCE $\bar{V}_{20}$ kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
3.3	25 CW	4 fps (1.22 m/sec)	5 June	46	C	7.0-F	o Same as for no turbulence
	7 HW	.3 fps (.24 m/sec)	25 Oct	45	F	4.0	o Workload higher during glideslope acquisition o Tracking glideslope more difficult o Feels like an aft c.g. - not enough elevator power for precision o Low damping

LANDING APPROACH (NORMAL OPERATION) PILOT COMMENTS

DAMPING RATIO VARIATION

$\zeta\omega_n$	WIND & TURBULENCE (25 KTS)	σ_w rms	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
.16		0	29 May	26	A	5.0	o Satisfactory glideslope acquisition with pitch oscillations while tracking o Increased workload made it difficult to stop oscillation o Landing flare control was abrupt - felt like too light pull force o Pull force was too light, while push force felt too heavy o Damping was poor, but did not result in too large flight path changes o This configuration would be satisfactory for a failure mode
	7 Hw	.3 fps (.24 m/sec)	3 June	26	B	4.5	o Control seemed to lag in response causing an increased workload o I found myself overcontrolling and hunting the pitch bar while tracking the glideslope o Did more pumping of elevator in flare o Flight path response was sluggish
	7 Hw	.3 fps (.24 m/sec)	5 June	27	C	2.0	o Easy capture and tracking of localizer and glideslope with low workload o Good control forces, flight path response, & altitude response
	25 Cw	4 fps (1.23 m/sec)	6 June	28	C	3.0-D	o Same as for no turbulence case
	25 Cw	7 fps (2.13 m/sec)	6 June	33	C	4.0-H	o Could not stay on glideslope

REV SYM

$\xi\omega_n$	WIND & TURBULENCE $\bar{V}_{20}$ kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
.16	7 HW	.8 fps (.24 m/sec)	25 Oct	48	F	3.5	o No overshoot problems o Workload satisfactory during G/S acquisition o Stick force too light o Airplane oversensitive in pitch control
.56	0	0	29 May	29	A	3.5	o Satisfactory glideslope acquisition, but it seemed to take larger than normal pitch changes to hold flight path o Push force felt high for body angle change o Satisfactory flight path and altitude response o This configuration would be satisfactory if pitch changes were not so large
	7 HW	.8 fps (.24 m/sec)	6 June	41	C	3.0	o Easy capture, and good tracking and reacquisition ability o Column force gradient was a little high o Good flight path and altitude response o Good control in flare
	25 CW	4 fps (1.23 m/sec)	6 June	42	C	3.0-D	o Same as for no turbulence case
	25 CW	7 fps (2.13 m/sec)	6 June	43	C	3.0-F	o Same as for no turbulence case
1.10	0	0	30 May	41	A	3.0	o Satisfactory localizer and glideslope acquisition o Moderate workload o Pitch changes to track glideslope about 1° more than desired o Flight path response slightly sluggish but satisfactory o Column forces and altitude response were satisfactory

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1.0

2.5

2.2

2.0

1.1

1.8

1.25 1.4 1.6

$\xi\omega_n$	WIND & TURBULENCE $\tilde{V}_{20}$ ~kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
1.10	7 HW	.8~fps (.24 m/sec)	3 June	31	B	4.5	o Tracking glideslope had some slight PIO in response to modest control inputs
	7 HW	.8~fps (.24 m/sec)	25 Oct	49	F	3.0	o Very similar to low damping case (with 20% reduction in pitch control sensitivity) o Slight tendency to over-control

LANDING APPROACH (NORMAL OPERATION): PILOT COMMENTS

COLUMN FORCE GRADIENT VARIATION

F_{col}/g (~lb/g)	WIND & TURBULENCE V_{20} ~kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
9.7 (43 N/g)	0	0	31 May	34	A	5.0	o Glideslope acquisition easy with very smooth control inputs o Normal workload o Rated 5.0 because of high g's resulting from high pitch rate o Stick force/g too low o Flight path response good, but could cause PIO o May be difficult to handle in rough air o Damping satisfactory
	7 HW	.8 ~fps (.24 m/sec)	6 June	33	C	1.0	o Easy capturing and tracking o No overshoot o Low workload o Excellent control in all respects o Excellent column force o Excellent flight path and altitude responses
	25 CW	4 ~fps (1.22 m/sec)	6 June	34	C	1.0-E	o Same as above o Observing ± .1 to ± .2 g's due to turbulence which I consider extreme in real life
	25 CW	7 ~fps (2.13 m/sec)	6 June	35	C	1.0-H	o Same as above o Unrealistic turbulence level
			27 Sept	8	F	3.5	o Light forces o Over responsive o Tendency for pilot to over control longitudinal axis

F_{col}/g (~lb/g)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
28.1 (125 N/g)	0	0	31 May	33	A	4.0	o Tended to overshoot glideslope o Workload medium o Glideslope tracking satisfactory for small inputs, but if a large input is required, the pitch rate is quite high o Over-rotated and bounced on landing o Stick force/g high; breakout force satisfactory o There is a pitch response lag but high pitch rates o Satisfactory damping
	7 HW	.8~fps (.24 m/sec)	6 June	16	C	2.0	o Easy capture and tracking o Very low workload o Good control, column forces, and altitude and flight path responses
	25 CW	4~fps (1.22 m/sec)	6 June	17	C	2.0-C	o Glideslope acquisition moderately difficult - slight overshoot o Tracking glideslope moderate workload o Pitch gradient a little high
	25 CW	7~fps (2.13 m/sec)	6 June	18	C	3.0-F	o Large pitch changes required to track glideslope o Force gradient too high
			27 Sept	6	F	2.5	o Normal localizer and glideslope capture o Normal workload o High column gradient o Tracking precision good
70.6 (314 N/g)	0	0	31 May	31	A	3.0	o No difficulty in glideslope capture; no overshoot o Normal workload and tracking o Satisfactory column forces and responses o Good damping
	7 HW	.8~fps (.24 m/sec)	6 June	29	C	4.0	o Some overshoot when capturing glideslope o Pitch response a little sluggish o High column force required for given pitch rate

REV SYM

F_{col}/g (~lb/g)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	RUN DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
70.6 (314 N/g)	25 CW	4~fps (1.22 m/sec)	6 June	30	C	4.0-C	o Same as for no turbulence case
	25 CW	7~fps (2.13 m/sec)	6 June	31	C	4.0-F	o Same as for no turbulence case
	7 HW	.8~fps (.24 m/sec)	27 Sept	7	F	3.0	o Normal capture of glideslope o Pitch response rate faster o Forces felt lighter
87.0 (387 N/g)	0	0	31 May	36	A	3.5	o Slow glideslope acquisition due to slower pitch rates o Normal workload o Tended to undershoot glideslope because of slower rotation rates o High stick force/g; would possibly like it better if forces were lighter with no change in ELEV/ COL o Flight path response felt sluggish because of slower pitch rates o Damping good
	7 HW	.8~fps (.24 m/sec)	25 Oct	47	F	3.0	o Workload slightly above average during glideslope acquisition o Stick force gradient a little stiff

LANDING APPROACH (MINIMUM SAFE [illegible]) PILOT COMMENTS

[illegible] VARIATION AT [illegible]

[illegible] ~ SEC	V_{20} kts	WIND & TURBULENCE σ_w (rms)	[illegible]	[illegible]	PILOT [illegible]	PILOT [illegible]	COMMENTS
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	F	[illegible]	o [illegible] capture not possible - can only bracket it o Unable to trim pitch axis or glideslope o Response lag too great in flare [illegible] gradient too high o Unstable pitch axis makes this configuration a poor option for line or emergency operation
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible] o Capture and tracking of glideslope and localizer requires considerable pilot compensation o [illegible] was marginal o Force gradient too high o Flight path response very sluggish o Large lag in pitch commands requires high compensation
	[illegible]	[illegible] fps ([illegible].7 m/sec)	[illegible]	[illegible]	F	9.0 -G	o Capture and tracking of glideslope difficult would be impossible without flight director o Flare requires intense effort - both hands on column o Force gradient too high for response o Flight path response & altitude response are very sluggish with [illegible] or (to neg?) damping o Control could be lost at higher turbulence levels

$T_{2\theta}$ (~SEC)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
5.0	7 HW	0.8-fps (.24 m/sec)	27 Sept	18	F	4.0	o Tendency to overshoot on glideslope acquisition
			3 Oct	81	F	5.0	o Workload increased during tracking due to damping characteristics o Control power low during flare o Aircraft response sluggish - low to negative damping o Not a suitable configuration for line operations
			25 Oct	38	G	2.5	o Glideslope and localizer acquisition task easy with low workload o More difficulty tracking glideslope due to interaction of auto-throttle and trim changes o No problem in flare o Aircraft response good o Flight director and auto-throttle seem to to be interferring with each other o Pleased with aircraft
	15 CW	2.3-fps (.7 m/sec)	3 Oct	82	F	4.5 -C	o Little different than no turb case - some increase in workload - not much
	25 CW	4.0-fps (1.22 m/sec)	3 Oct	83	F	7.0 -E	o Glideslope acquisition and tracking difficult due to gusts - workload high, requires constant attention o Landing becomes victim of turbulence o Insufficient control power to attain desired tracking accuracy - would like more control power o Aircraft response very sluggish

$T_{2\theta}$ (~SEC)	WIND & TURBULENCE $\tilde{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
6.0	7 HW	0.8 fps (.24 m/sec)	4 Oct	7	F	3.0	o Some overshoot tendency on glideslope acquisition
			22 Oct	16	F	4.0	o Excessive column activity to retain tracking accuracy o Above normal workload on flare o Column forces a little high o Aircraft response a little sluggish, damping-low
			25 Oct	26	G	2.0	o Glideslope acquisition and tracking precise - low workload o Good performance on flare o Lag in throttle - but O.K. o Damping O.K. o Good airplane
	15 CW	[illegible] fps (.7 m/sec)	4 Oct	8	F	5-D	o Much the same as no turb case
			22 Oct	17	F	4-C	o Slightly more overshoot on G/S acquisition o Imprecise control authority for small corrections o Workload higher o Pitch change required to effect flight path much greater
			25 Oct	27	G	4.5 -D	o Higher workload for glideslope acquisition and capture o Flare and landing marginal o Altitude response sluggish

$T_{2\theta}$ (~SEC)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
6.0	25 CW	4 fps (1.22 m/sec)	4 Oct	9	F	6.0 -F	o Workload worse due to turbulence on acquisition and tracking of glideslope.
			22 Oct	18	F	6.5 -F	Very difficult to be precise o Sink rate hard to control o Higher turbulence levels would affect success rate
			25 Oct	30	G	6.0 -E	o Glideslope acquisition and tracking very difficult, high workload, low precision, overshoot tendency o Flare very marginal
7.1	7 HW	0.8 fps (.24 m/sec)	3 Oct	34	F	3.0	o Slight overshoot problem on glideslope acquisition o Otherwise aircraft performance was fairly normal o Flight path response a little slow
	15 CW	2.3 fps (.7 m/sec)	3 Oct	35	F	3.5 -C	o Flare easier o Little change in aircraft due to turbulence, except for slightly higher workload
	25 CW	4 fps (1.22 m/sec)	3 Oct	36	F	5.0 -D	o Overshoots easily during G/S capture o Fair precision possible during G/S tracking o Turbulence effects require greater response (less sluggish, less damping)

$T_{2\theta}$ (~SEC)	WIND & TURBULENCE $\bar{V}_{20}$ ~ kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
8.2	7 HW	0.8 fps (.24 m/sec)	18 Oct	37	F	2.0	o Some overshoot noted during G/S capture o One dot low task difficult due to response characteristics o Good control during flare o Flight path response a little sluggish - causes overshoots o Performance O.K.
			25 Oct	31	G	1.5	o Easy capture, low workload on ILS capture o Tracking performance good o Aircraft response good
	15 CW	2.3 fps (.7 m/sec)	18 Oct	3[illegible]	F	3.5 -C	o Same as no turb case with slightly higher workload during tracking due to turbulence. slight float in flare due to de-crab
			25 Oct	28	G	3.5 -C	o No problem with G/S capture o Some difficulty prior to flare due to auto-throttle lag relative to G/S position o Adequate control in flare
	25 CW	4 fps (1.22 m/sec)	18 Oct	39	F	6.0 -E	o Turbulence increases workload considerably o More overshoot on G/S capture o Workload high during tracking o Flight path response sluggish
			25 Oct	29	G	5.0 -D	o No significant problem during G/S acquisition, but increased workload o Tracking adequate, some deviations o Control during crosswind landing - marginal

J15-047

$T_{2\theta}$ (~SEC)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
9.2	7 HW	0.8 fps (.24 m/sec)	3 Oct	76	F	2.5	o Normal capture of localizer and G/S o Auto-throttle response lag increases workload during tracking o Normal flare o Comparable to 707-320B in longitudinal characteristics
	25 CW	2.3 fps (.7 m/sec)	3 Oct	78	F	4.0 -E	o Tendency to overshoot coupled with low control response increases workload during G/S capture o "Low Heave" during tracking tended to create ±1 dot G/S errors o Aircraft response sluggish and low-damped

APPROACH AND LANDING - MINIMUM SAFE CONFIGURATION: PILOT COMMENTS

COLUMN FORCE GRADIENT VARIATION (AT $T_{2\theta}$ = 6.0 SEC)

$F_{co}\gamma^{g}$ (lb/g)	$\bar{V}_{20}$ ~kts	WIND & TURBULENCE σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
15.1 (67 N/g)	7 HW	.8fps (.24 m/sec)	22 Oct	22	F	3.5 -C	o Glideslope capture fairly easy - minor PIO causes overshoot 1 to 4 deg o Tracking glideslope affected by over responsiveness of controls in pitch axis o Moderate workload o Force gradient light - breakout low - response lends itself to over control due to harmony of damping vs stick force (PIO) tendency - feed through of light turbulence is pronounced
	15 CW	2.3fps (.7 m/sec)	22 Oct	23	F	4.5 -D	o PIO tendencies and workload both increased by turbulence o Damping characteristics more visible at this turbulence level
	25 CW	4fps (1.22 m/sec)	22 Oct	24	F	8.0 -F	o Overall workload excessive due to damping o Control response helps but not enough o Noticeably worse damping

APPROACH AND LANDING (MINIMUM SAFE CONFIGURATION): PILOT COMMENTS

COLUMN FORCE GRADIENT VARIATION (AT $T_{2\theta}$ = 3.6 SEC)

F_{col}/g (~lb/g)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
13.1 (58 N/g)	7 HW	0.8 ~fps (.24 m/sec)	4 Oct	10	F	4.5	o G/S capture difficult - overshoots are of greater magnitude o Tendency to drift away from G/S while tracking - workload high o Aircraft response sluggish, poor damping
	15 CW	2.3 ~fps (.7 m/sec)	4 Oct	11	F	5.0 -D	o High workload during flare o Turbulence affects workload o Otherwise, same as no turb case
14.1 (63 N/g)	7 HW	0.8 ~fps (.24 m/sec)	13 Oct	41	F	4.0	o Overshoot tendency during G/S capture due to damping o Workload high during tracking o Appears to handle like aircraft with extreme aft cg - low response, low damping
	15 CW	2.3 ~fps (.7 m/sec)	18 Oct	42	F	5.0 -D	o Same as no turbulence case, except higher workload o Float due to decrab in flare
	25 CW	4 ~fps (1.22 m/sec)	18 Oct	43	F	7.0 -F	o High workload due to turbulence o Poor flight path response o Poor altitude response o Limits reached on column and rudder pedals during attempt to control flight path and sideslip

F_{cs}/g (~lb/g)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
26.1 (116 N/g)	7 HW	0.8 ~fps (.24 m/sec)	22 Oct	19	F	4.5	o High workload during G/S capture o Excessive column activity required for tracking o Lack of response cuts down precision of landing o Stick force gradient is too high for pitch response o Aircraft response very sluggish o Feels like extreme aft cg.
	15 CW	2.3 ~fps (.7 m/sec)	22 Oct	20	F	7.5 -F	o Workload due to turbulence severely worse o Deficiencies not tolerable for normal or emergency service by air carriers o Excessive workload to hold attitude
	25 CW	4 ~fps (1.23 m/sec)	22 Oct	21	F	9.0 -G	o Workload due to turbulence severely worse o Intense control attention required o Not tolerable for use by air carriers

STALL RECOVERY CONTROL POWER: PILOT COMMENTS

$\dot{Q}_{MAX}$ (deg/sec^2)	WIND & TURBULENCE $\bar{V}_{20}$~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
1.3	0	0	30 Sept	76	F	6.0	o Altitude loses are low o Definite pitch-up tendency during recovery o α recovery does not correspond with θ recovery o At high deceleration rate into stall entry (>1 KT/SEC), controllability is in question o Lag between control movement and airplane response is bordorline acceptable o Disconcerting to see α increase while θ decreases
2.5	0	0	30 Sept	33	F	6.0	o Tendency for an increase in deceleration as A/C slows (at ~130, marked at 125) o Tendency to pitch-up in stall situation and when thrust is applied o More lag than desirable between control movement and aircraft response o Marginally enough control power to establish aircraft acceleration o Tendency to return to stall condition o Needs more longitudinal control power
	25	4 fps (1.22 m/sec)	30 Sept	35	F	7.0 -F	o More difficult than smooth air to enter stall o Greater tendency to pitch up in turbulence o There is not sufficient control to readily establish aircraft acceleration o Definite tendency to return to stall o Unsatisfactory longitudinal control power

$\dot{Q}_{MAX}$ (deg/sec^2)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
3.0	7	0.8 fps (.24 m/sec)	3 Oct 24 Oct	30 41	F F	5.0 4.5	o Deceleration rate dependent on most recent pitch adjustment o There is both a response lag and a rate lag between control movement and aircraft response o Not enough longitudinal control power - may need a pusher o Not enough nose-up control power - recovery from the stall recovery was not possible with full stick o Tendency for deceleration to increase in buffett
	25	4 -fps (1.23 m/sec)	3 Oct	44	F	6.0 -C	o Objectionable lag between control input and aircraft response o Insufficient control to readily establish A/C acceleration o Tendency to return to stall - even after achieving initial α, speed is stabilized low, and power must be used to recover o Unsatisfactory longitudinal control - there might be a critical Q or α where recovery would not be possible
	25	7 fps (2.13 m/sec)	3 Oct	47	F	7.5 -F	o Deceleration rate not really established by pilot - just arrives at V_{MIN} o Marked tendency to pitch up during recovery o Insufficient control to readily establish A/C acceleration o Definite tendency to return to stall o Turbulence made a bad control system terrible

$\dot{Q}_{MAX}$ (deg/sec^2)	WIND & TURBULENCE $\bar{V}_{20}$~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
3.6	7	0.8 fps (.24 m/sec)	24 Oct	44	F	3.0	o Deceleration level established fairly easily o No pitch-up tendency o Some control lag - minimal effect o There was satisfactory longitudinal control power - would like to see more
	25	4 fps (1.23 m/sec)	24 Oct 30 Sept	46 78	F F	3.0 -C 2.5 -D	o Turbulence aggravates precision of deceleration o Pretty much the same as case with no turbulence - though precise judgments masked by turbulence
	25	7 fps (2.13 m/sec)	24 Oct 30 Sept	49 80	F F	6.5 -E 6.0 -E	o Oscillating instruments aggravate entry o Marked pitch-up tendency due to gusts o Insufficient control to establish A/C acceleration at this turb level o Longitudinal control power is marginal - considerable tendency to have excessive minimum speed decay with full down column o Turbulence is a major factor - overall configuration marginal
4.1	0	0	3 Oct	59	F	3.0	o Fairly normal stall entry o Some tendency to pitch up at buffett o Small lag between control and aircraft response - not bad o Slight tendency to return to stall o Satisfactory longitudinal control power

$\dot{q}_{MAX}$ (deg/sec^2)	WIND & TURBULENCE $\bar{V}_{20}$ ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
4.1	25	4 fps (1.22 m/sec)	3 Oct	62	F	4.0 -D	o More difficult to establish deceleration due to turbulence o Slight pitch up tendency (losing an additional 7-10 knots) o Response lag creeps up during pitch-up and during recovery o Slight tendency to return to stall o Longitudinal control power is satisfactory if situation is given prompt attention o Turbulence increases workload
	25	7 fps (2.13 m/sec)	3 Oct	65	F	6.0 -F	o Extreme difficulty in establishing initial deceleration o Deceleration level almost uncontrollable o Tendency for pitch-up - both in A/C and due to gusts o V_{MIN} is lower than other cases due to lag between column and response o Tendency to return to stall due to turbulence and control system o Long. control power probably not acceptable because V_{MIN} was too low o With this turb level, more control power needed
5.2	[illegible]	[illegible] fps ([illegible] m/sec)	[illegible]	21	F	2.0	o No problem with stall entry o During stall initiation aircraft remains flat without column inputs - neutral pitch-up tendency o Long. control power satisfactory o Comparable to other aircraft
			24 Oct	38	F	2.5	o No adverse tendency during decel o No pitch-up tendency o Satisfactory longitudinal control

REV SYM

$\dot{Q}_{MAX}$ (deg/sec^2)	WIND & TURBULENCE V_{20} ~kts	σ_w (rms)	DATE	RUN NO.	PILOT	PILOT RATING	COMMENTS
5.2	25	4 fps (1.22 m/sec)	3 Oct	24	F	3.0 C	o Slight tendency for deceleration to increase or decrease (due to turb) o Tendency towards neutral pitch-up o Lag on control column due to high deceleration rate o Satisfactory longitudinal control power
	25	7 fps (2.13 m/sec)	3 Oct	27	F	4.0 E	o Very difficult to establish deceleration EADI big help o Any pitch-up tendency masked by turb. o Minor objectionable lag between column and A/C response o Tendency to return to stall - must exert positive control to prevent secondary stall o Long control power is marginal - only if pilot is quick to respond o Turbulence brings out control deficiencies that go unnoticed in smooth air
[illegible]	0	0	3 Oct	50	F	2.0	o No problem with stall entry o Deceleration level can be set with precision o No pitch up tendency o Slight cycling in α - No effect on control o Control response good o No tendency to return to stall o Good configuration
	25	4 fps (1.22 m/sec)	3 Oct	53	F	2.5 -C	o Same as for no turbulence case o Slightly higher workload
	25	7 fps (2.13 m/sec)	3 Oct	56	F	3.0 -D	o Task becomes more difficult at this turbulence level o Some pitch-up tendency (due to gusts) o Still has sufficient control power to safely recov [illegible]