DEVELOPMENT OF LONGITUDINAL HANDLING QUALITIES CRITERIA FOR LARGE ADVANCED SUPERSONIC AIRCRAFT*

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SUMMARY

A piloted simulation study was conducted with the aim of advancing the development of longitudinal handling qualities criteria for large supersonic cruise aircraft. The areas of study investigated, using the NASA Ames Flight Simulator for Advanced Aircraft, included high-speed cruise maneuvering, stall-recovery control power, and landing approach for normal and minimum-safe operation. Only the first two areas are discussed in this paper. Comparisons were made with existing criteria and, for the cruise condition, a time response criterion was developed which correlated well with pilot ratings and comments. For low-speed stall recovery a new criterion was developed in terms of nose-down angular acceleration capability. The results of the study were reported in reference 1.

INTRODUCTION

Developmental research conducted during the National SST Program showed the important benefits in aircraft economics that could be gained through advancements in flight control system design. For example, a sophisticated stability and control augmentation system can provide satisfactory handling qualities in an airplane after the low-speed static stability of the bare airframe has been sacrificed to minimize supersonic trim drag.

These highly-augmented control systems characteristically generate airplane dynamic responses that are more complex than ordinarily observed, and which are not adequately specified by existing handling qualities criteria (refs. 2 and 3). The simulation study described herein was conducted to improve the data base for establishing generalized handling qualities criteria for large supersonic cruise aircraft with these advanced flight control systems, thus allowing definition of control system design requirements for normal operation, and establishment of factors contributing to minimum stability levels for minimum-safe operation.

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SYMBOLS AND ABBREVIATIONS

CAS	calibrated airspeed (knots)
cg	center of gravity (% C_R)
C_L	lift coefficient
cm	centimeters
C_R	root chord
deg	degree
EADI	electronic attitude director indicator
F_{col}	column force (N, lb)
fpm	feet per minute
fps	feet per second
ft	feet
g	gravity (m/sec^2, ft/sec^2)
in	inches
L_α	normalized lift per angle of attack ($1/_{sec}$)
lb	pounds
max	maximum
NASA	National Aeronautics and Space Administration
n_α	normalized load factor per angle of attack (g's/rad)
N	newton
n_Z	normal load factor (g's)
$n_{Z_{ss}}$	steady state normal load factor (g's)
PR	pilot rating
PT	prototype
$\dot{q}$	pitch angular acceleration (deg/sec^2)

rad	radian
rms	root mean square
sec	seconds (time)
SST	supersonic transport
T	time (seconds)
$T_{2\theta}$	time-to-double pitch attitude (seconds)
$T_{\dot{\theta}_{max}}$	time-to-maximum pitch rate (seconds)
ξ	damping ratio
θ	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)
σ_w	vertical turbulence component, rms (m/sec, fps)
ω_n	natural frequency (rad/sec)

SIMULATION FACILITY

The pilot evaluations were performed using the NASA-Ames Flight Simulator for Advanced Aircraft (Fig. 1). The cockpit is outfitted with two crew stations and is mounted on a large-motion system having six degrees of freedom. In addition to conventional cockpit control and instrument arrangements, the simulator incorporates a visual display generated by a closed-circuit color television system with visual models for high-altitude cruise or landing approach. All control forces were simulated by means of hydraulic control loaders with adjustable force gradients. Real-time computations necessary for the simulation were performed by a large capacity digital computer. A complete mathematical model of the Boeing 2707-300 PT (Fig. 2) served as the baseline aircraft for this study.

The cockpit instrument panel configuration used for the portions of the study discussed herein is shown in Figure 3. Dominating the center of the panel was an electronic attitude director indicator, or EADI, with which it was possible to vary the pitch attitude display sensitivity from 0.41 cm/deg. to 0.76 cm/deg. (0.16 in/deg to 0.30 in/deg) for the high-speed cruise maneuvering case.

HIGH-SPEED CRUISE MANEUVERING

The handling qualities criteria data base for high speed cruise maneuvering was to be based on aircraft response characteristics and parameters related to longitudinal handling qualities. Response parameters were selected that describe the airplane's short period mode characteristics. These parameters were derived from a series of airplane pitch response characteristics resulting from a given input command. Selected as an input command, representative of a typical pilot input, was a column step input. The response parameters were pitch rate overshoot ratio ($\dot{\theta}_{max}/\dot{\theta}_{ss}$), time-to-peak pitch rate ($T_{\dot{\theta}_{max}}$), and damping constant ($\xi\omega_n$). Response parameters were selected as a criteria data base in order to allow evaluation of airplane handling qualities with airplanes that have non-linear longitudinal characteristics, airplanes that cannot be represented by a simple second order system. Such criteria would be more generally applicable to large supersonic aircraft, the subject of this study.

Other parameters that relate to longitudinal handling qualities that were evaluated in this study were the column force gradient and the sensitivity of the pitch attitude display indicator, in this case an EADI. These parameters were considered relevant since they are parameters in the pilot-airplane control loop, and conceivably would impact the handling qualities perceived by the pilot.

A complete list of all parameters evaluated along with parameter values is presented in Table I. Each parameter was varied by the magnitudes indicated, and evaluated independently with the other parameters set at the nominal values as indicated by the arrow in the Table.

To be consistent through the evaluation a set of defined pilot tasks was established for each area studied. The pilot tasks defined for the high speed maneuvering study area discussed here are presented in Table II. All pilot evaluations were rated using the Cooper-Harper pilot rating scale reproduced in Figure 4.

The flight condition selected for the high-speed evaluations was the condition occurring at the end of supersonic climb for the 2707-300PT airplane, identified as follows:

- o Mach 2.7
- o 18,288 meters (60,000 feet)altitude
- o 567 knots CAS
- o Gross weight 251,744 kilograms (555,000 pounds)

- o 62% C_R center of gravity (aft limit)

Results of the high-speed maneuvering evaluations can be summarized as follows:

- o Most sensitive EADI scale available was found most desirable.
- o Short period response parameters could be categorized in terms of a time response envelope criterion.
- o Column force gradient was insensitive within the range evaluated.

The evaluation sequence was to first determine the desired sensitivity of the attitude display indicator which for these tests was an electronic attitude director indicator (EADI) and is described in Figure 5. Then the desired EADI sensitivity was used for all of the remaining high speed evaluations. Detailed results of these evaluations will be presented in the following paragraphs.

Pitch Attitude Display Sensitivity

For all testing at high speed cruise the EADI was used. Variation of the pitch attitude scale was desired as part of the high-speed evaluation 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 853 m/min (2800 feet per minute) vertical velocity, while at Mach .8 one degree of pitch change results in approximately 244 m/min (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 I. The results of this study are presented in Figure 6. Both pilots conducting this evaluation preferred the .762 cm/deg (.30 in/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 high-speed evaluation, and both selected this setting, the most sensitive. 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 the evaluation of other parameters indicating a more sensitive pitch scale would be desirable.

Pitch Response Parameters

Results of the evaluation of the three pitch response parameters (pitch rate overshoot ratio, time-to-peak pitch rate, and pitch damping constant) are presented in Figures 7, 8, and 9. The overshoot ratio parameter indicates an upper limit at 7.1 but no lower limit. That is, the smaller overshoot ratio the better. Also, the time-to-peak pitch rate results show an upper limit of 1.2 seconds but no lower limit. The quicker responding the better as long as that is combined with good overshoot characteristics and good damping. Results of pitch damping evaluation show a lower limit of $\xi\omega_n = .55$ with no upper limit; the more damping the better as long as good quick response exists.

These results just described say that pilots like an airplane that responds precisely and quickly and has high damping. Such results are logical and to be expected, which tend to lend confidence in these test results.

The problem now becomes one of summarizing these results in an analytical manner to form the basis for longitudinal handling qualities criteria.

Criteria Development

Previously established criteria were investigated to determine if any were adequate and complete for this area of study. These criteria were:

Mil F-8785B

C* Longitudinal Handling Qualities Criterion

National SST Time Response Criteria (Based on the Shomber-Gertsen Criteria)

Both the Mil F-8785 (Reference 1) short period response criteria and the C* Longitudinal Handling Qualities Criterion (Reference 4) were found to be unsatisfactory in a significant number of cases. The SST time response criteria (reference 5) were found to correlate very favorably with the results of this evaluation; and with a slight modification they are believed to be satisfactory criteria by which to judge high-speed longitudinal handling qualities.

As mentioned previously, the SST time response criteria are based on the Shomber-Gertsen Criteria (Reference 6) which are defined in Figure 10. 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 and non-linear 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 paper.

The SST Time Response Criteria were developed from the Shomber-Gertsen Criteria by selecting points around the boundary and determining the response to a step input for each point. All responses for all points selected were then normalized based on the steady state value following the input and overlaid on top of each other. A boundary was then drawn that enclosed the overlaid normalized responses and this boundary then established the time response criteria. Boundaries can be developed using either pitch rate or normal load factor as presented in Figure 11. The boundaries for high-speed cruise must be based on the Shomber-Gertsen boundary for high n_α values ($n_\alpha \geqslant 15$) since the math model being evaluated had $n_\alpha = 16.535$ g/rad.

The SST Time Response Criteria in terms of pitch rate and load factor were both compared with the results of the piloted evaluation discussed previously. However, the load factor envelope was not as consistent with the results as the pitch rate envelope was. Therefore, only comparisons with the pitch rate boundary will be made in this paper.

Comparison of the pitch response characteristics of the three response parameters and the SST Time Response Criterion are presented in Figures 12, 13, and 14. In Figure 12 the pitch rate overshoot ratio comparison is made. As seen in this figure, the comparison is quite good. Those responses that are within or on the envelope boundary are rated satisfactory or better. The only serious exception is at the lower boundary where the criterion calls for at least an overshoot ratio of 2.65. As seen, the response with an overshoot ratio of 1.94, which has the best pilot rating of 2.3, violates the boundary. No justification is apparent for requiring a minimum overshoot ratio value as the criterion presently does. At these low pitch rate values associated with Mach 2.7, for a given load factor, the pitch rate overshoot ratio becomes less important to the pilot at the lower overshoot ratio. Therefore, a boundary modification is recommended to this criterion consisting of truncating the lower boundary at an overshoot ratio of 1.0.

Figure 13 presents the comparison of the time-to-peak pitch rate responses with the time response criterion envelope. These responses and corresponding average pilot ratings compare well with the envelope boundaries. 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 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 criterion envelope.

Comparison of the pitch responses based on damping constant ($\xi\omega_h$) with the criterion envelope is very straightforward as seen in Figure 14. All responses that were rated satisfactory are well within the envelope and the one response that was unsatisfactory (pilot rating = 4.5) violates the boundary.

The conclusion is that the SST Time Response Criterion with the recommended boundary modification presented in Figure 15 does provide an adequate and complete method for verifying satisfactory high-speed longitudinal handling qualities for the parameters investigated.

Column Force Gradient

Results of the evaluation of column force gradient are presented in Figure 16. As seen, these results did not establish any preferred boundary over the range tested. No real conclusions were drawn from these data.

STALL RECOVERY CONTROL POWER

The purpose of evaluating stall recovery control power was to develop a criterion that defines the magnitude of elevator control power needed for safe, positive recovery from this high angle of attack, minimum speed condition.

Normal stall is associated with a sudden loss of lift and a nose-down pitch reaction which results in a stable stall recovery with minimum reaction required from the pilot. Delta wing and arrow wing configurations do not exhibit the normal stall characteristic, that is, there is normally not a sudden loss of lift nor a nose-down moment. 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. Establishment of the defined stall speed is based on restricting the aircraft to avoid encountering undesirable high angle of attack characteristics such as a loss of directional stability, pitch up, etc. Also, one of the items that might be limiting at the defined stall speed is the amount of elevator control power available in the nose-down direction, since the pilot must recover the aircraft from the defined stall speed manually. Defining a criterion covering elevator control power for stall recovery was the purpose of this simulator evaluation.

The stall recovery control power evaluation was conducted by varying the magnitude of the elevator control power and having the pilot fly a series of typical stall approaches terminated with manual stall recovery. A detailed description of the pilot task is presented in Table III.

Longitudinal stability from this evaluation was near neutral as seen in Figure 17, which is typical for an airplane of this type. Variations of the elevator control power were made in such a manner as to not affect the longitudinal stability.

In addition to evaluating the variation in elevator control power the effect of atmospheric turbulence was also determined. Atmospheric turbulence was varied from zero to 2.13 m/sec (7.0 ft/sec) root mean square vertical gusts.

Results of this study are presented in Figure 18 as a function of nose-down angular acceleration rather than elevator control power to make the results generally applicable. Nose-down angular acceleration was based on full nose-down elevator at the defined stall speed from a trimmed flight condition. Corrections to the data were applied for any out of trim condition at initiation of stall recovery.

Some data scatter does result as can be seen in Figure 18, but satisfactory fairings have been generated. Also, a boundary is shown corresponding to a pilot rating of 3.5. The pilot rating of 3.5 was selected as the boundary for required stall recovery control power since that is the dividing line between a configuration needing improvement and one not needing improvement. Stall recovery is an emergency maneuver for commercial airplanes and airplanes must be judged satisfactory with no improvement needed for this maneuver to insure positive recovery.

The effect of turbulence was to require an increased nose-down angular acceleration with increased turbulence levels. In order to generalize the criterion the data were cross plotted to provide angular acceleration required as a function of turbulence level for a pilot rating of 3.5. This criterion is presented in Figure 19.

This generalized criterion then gives the designer the option of establishing the required nose-down angular acceleration based on his particular probable maximum turbulence level associated with stall. As long as stall recovery is not coupled with some other stability or control problem, this criterion is satisfactory.

CONCLUDING REMARKS

Results of this study have shown a requirement for increased sensitivity of the pitch attitude display at high-speed cruise. The desired sensitivity established for this evaluation was .762 cm/deg (.3 in/deg).

Short period longitudinal response parameters have been shown to correlate with the previously defined SST Time Response Criterion. This criterion with a recommended modification will define satisfactory handling qualities considering the type of response characteristics evaluated in this study.

A minimum level of longitudinal control power was defined for stall recovery for aircraft that exhibit the delta wing or arrow wing stall characteristics. The control power was found to be affected by atmospheric turbulence. Correlation of longitudinal control power with atmospheric turbulence as a general criterion was accomplished.

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2. Anon: Military Specification, Flying Qualities of Piloted Aircraft, MIL-F-8785 (ASG), United States Air Force, August 7, 1969.
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4. Malcom, L. G. and Tobie, H. N., "New Short Period Handling Quality Criteria for Fighter Aircraft," Boeing Document No. D6-17841-T/N, September, 1965.
5. SST Engineering Staff, "Stability and Control, Flight Control, and Hydraulic Systems Design Criteria," Boeing Document No. D6-6800-5, 1970.
6. Shomber, H. A. and Gertsen, W. M., "Longitudinal Handling Qualities Criteria," AIAA Paper No. 65-780, November, 1965.

TABLE I.- HIGH-SPEED CRUISE MANEUVERING TEST CONDITIONS

VARIED PARAMETERS		RANGE	
EADI PITCH SCALE SENSITIVITY		.41 cm/deg	(.16 in/deg)
		.58	(.23)
		.76 ◁	(.30) ◁
PITCH RESPONSE TO A COLUMN STEP INPUT	PITCH RATE OVERSHOOT RATIO, $\dot{\theta}_{max}/\dot{\theta}_{ss}$	1.94	
		4.10 ◁	
		6.10	
		8.20	
	TIME-TO-PEAK PITCH RATE, $T\dot{\theta}_{max}$	.45 sec	
		.90 ◁	
		1.40	
		2.00	
	DAMPING CONSTANT, $\xi\omega_n$	.36 1/sec	
		.90 ◁	
		2.42	
COLUMN FORCE GRADIENT, F_{col}/g		45 N/g	(10 lb/g)
		111	(25)
		200 ◁	(45) ◁
		285	(64)

◁ NOMINAL VALUES

TABLE II.- HIGH-SPEED CRUISE MANEUVERING PILOT TASK

ALTITUDE CHANGES (HOLDING MACH NO. CONSTANT):

1. CLIMB 76M @ 152M/MINUTE (250 FT @ 500 FPM) AND STABILIZE
2. DESCEND 229M @ 305M/MINUTE (750 FT @ 1000 FPM) AND STABILIZE
3. CLIMB 305M @ 610M/MINUTE (1000 FT @ 2000 FPM) AND STABILIZE
4. DESCEND 152M @ 152M/MINUTE (500 FT @ 500 FPM) 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 15^0 LEFT IN 15^0 BANK AND LEVEL OFF
2. TURN 20^0 RIGHT IN 30^0 BANK AND LEVEL OFF

TABLE III.- STALL RECOVERY PILOT TASK

1. TRIMMED AT MINIMUM OPERATION SPEED (145 KNOTS CAS)
2. REDUCE THRUST TO ESTABLISH DECELERATION RATE
3. AT MINIMUM DEMONSTRATED SPEED (118 KNOTS CAS) INITIATE MAXIMUM EFFORT STALL RECOVERY
4. USE THRUST AS NECESSARY TO MINIMIZE ALTITUDE LOSS
5. CONDUCT TEST THREE TIMES VARYING AIRCRAFT DECELERATION RATE WITH 1 KNOT/SEC AS NOMINAL

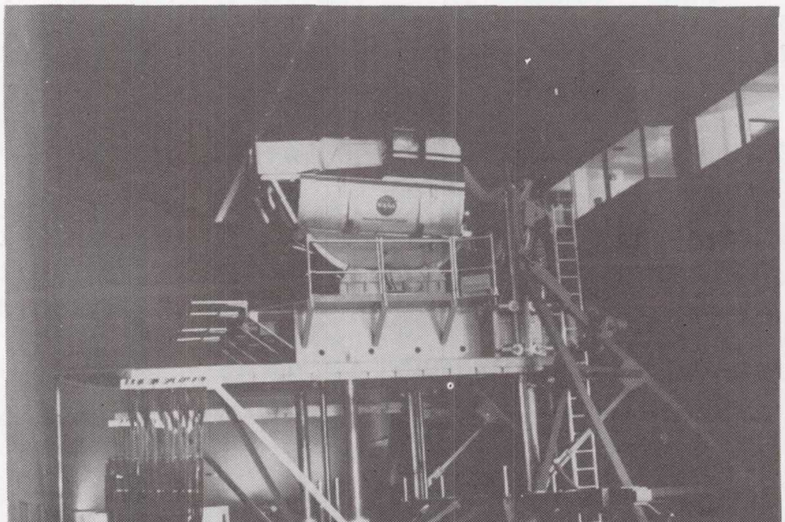


Figure 1.- Flight simulator for advanced aircraft.

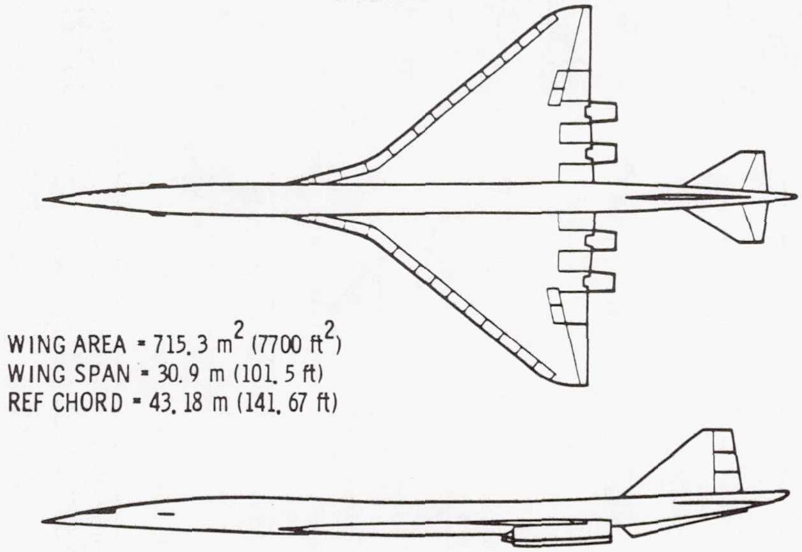
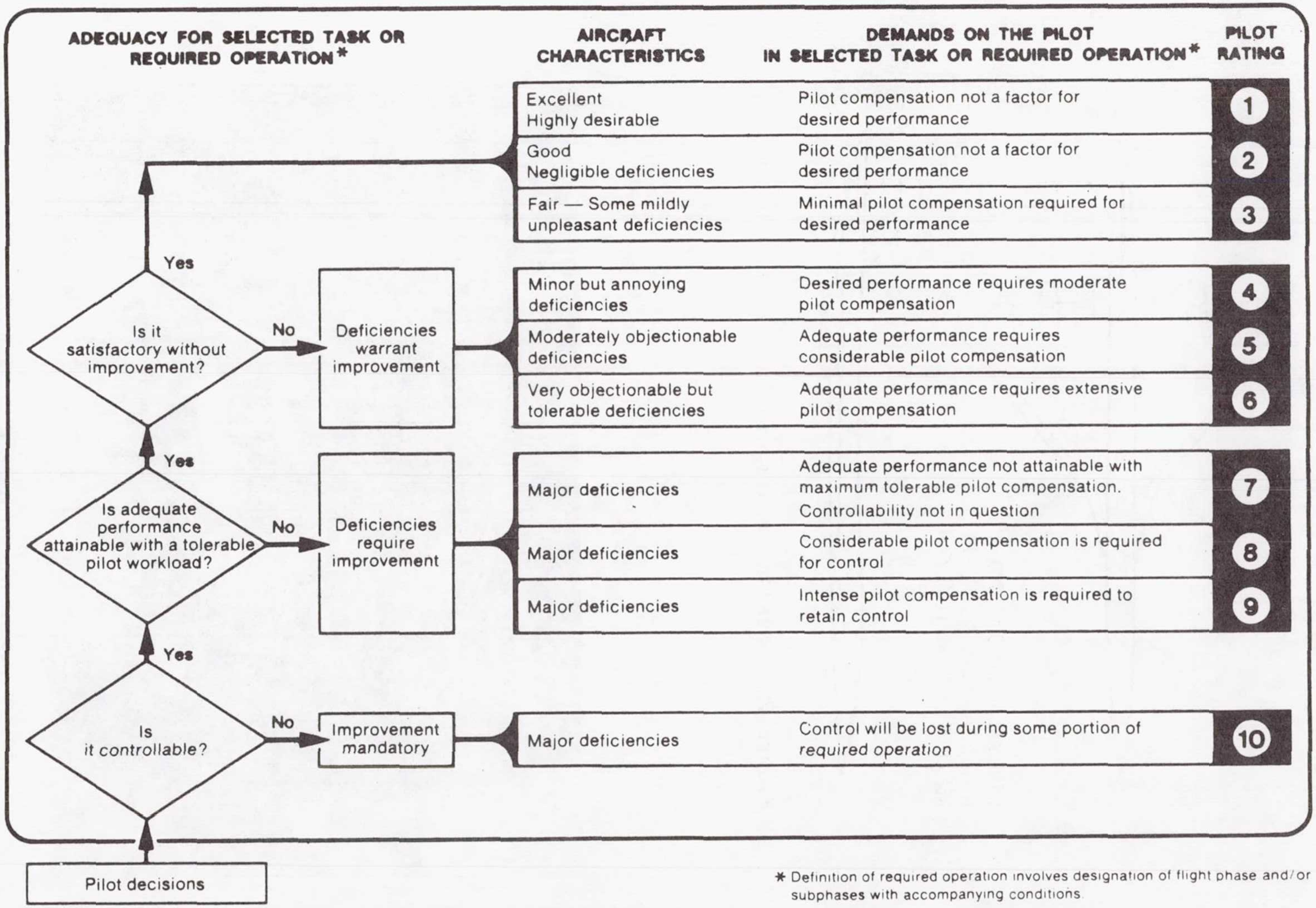


Figure 2.- Baseline configuration (2707-300 PT).

Figure 3.- Simulator cockpit.



AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair — Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of *required operation*	10

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 4.- Handling qualities rating scale.

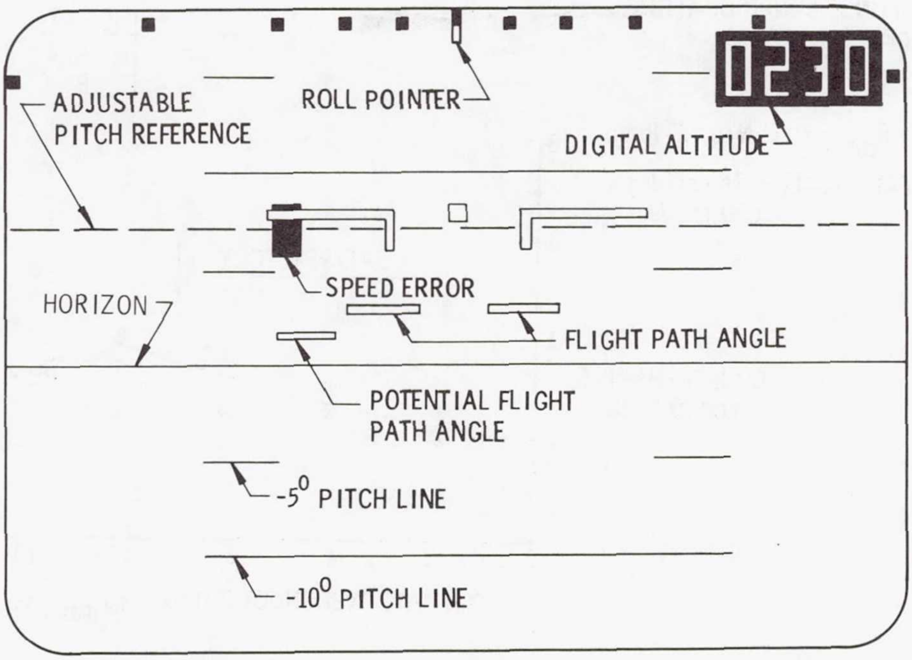


Figure 5.- Electronic attitude director indicator.

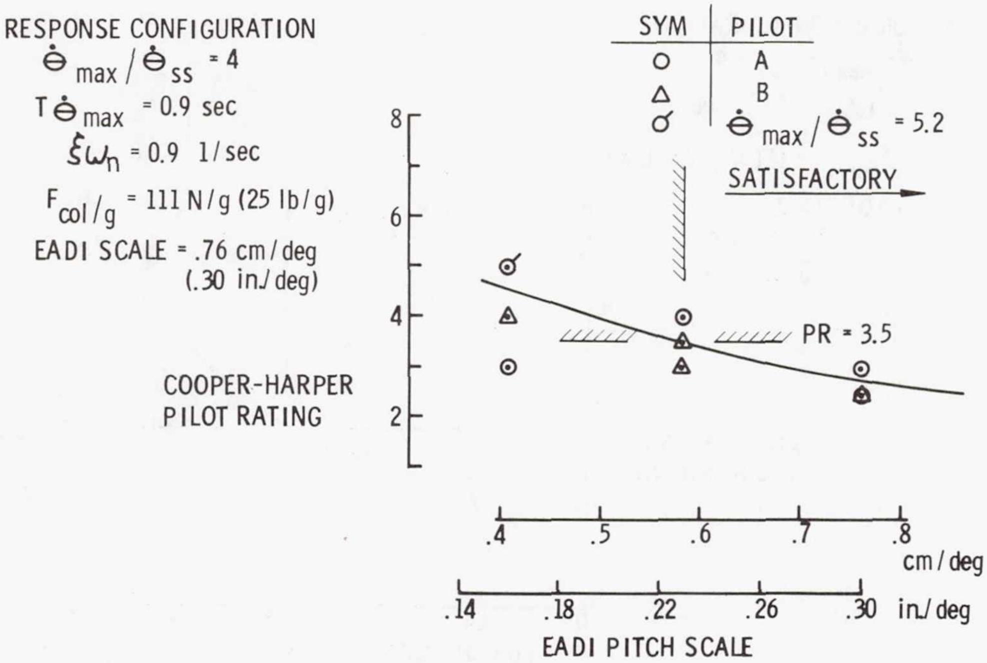


Figure 6.- High-speed cruise evaluation of EADI pitch scale sensitivity.

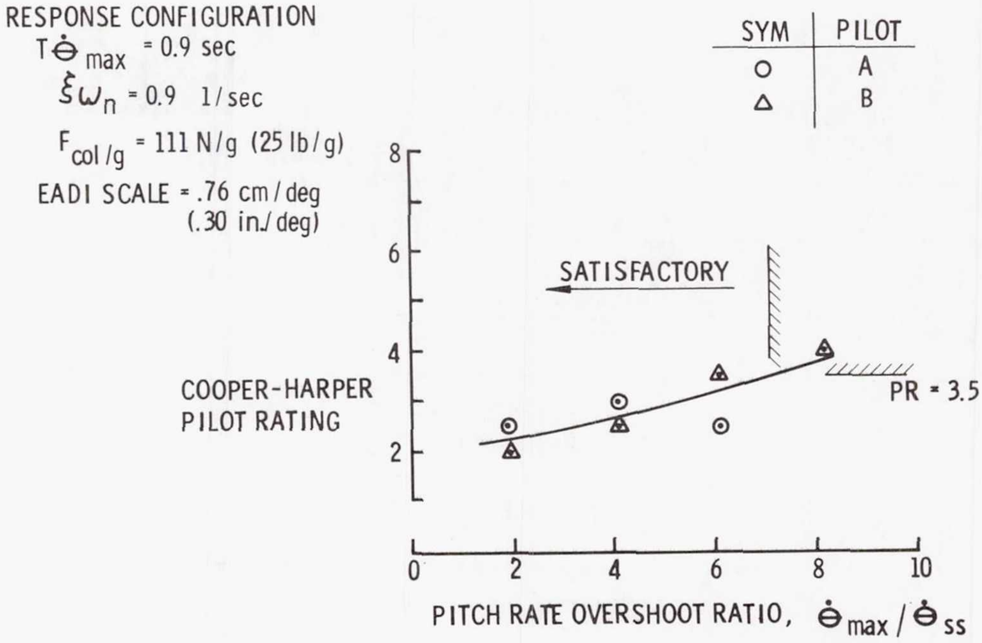


Figure 7.- High-speed cruise evaluation of pitch rate overshoot ratio.

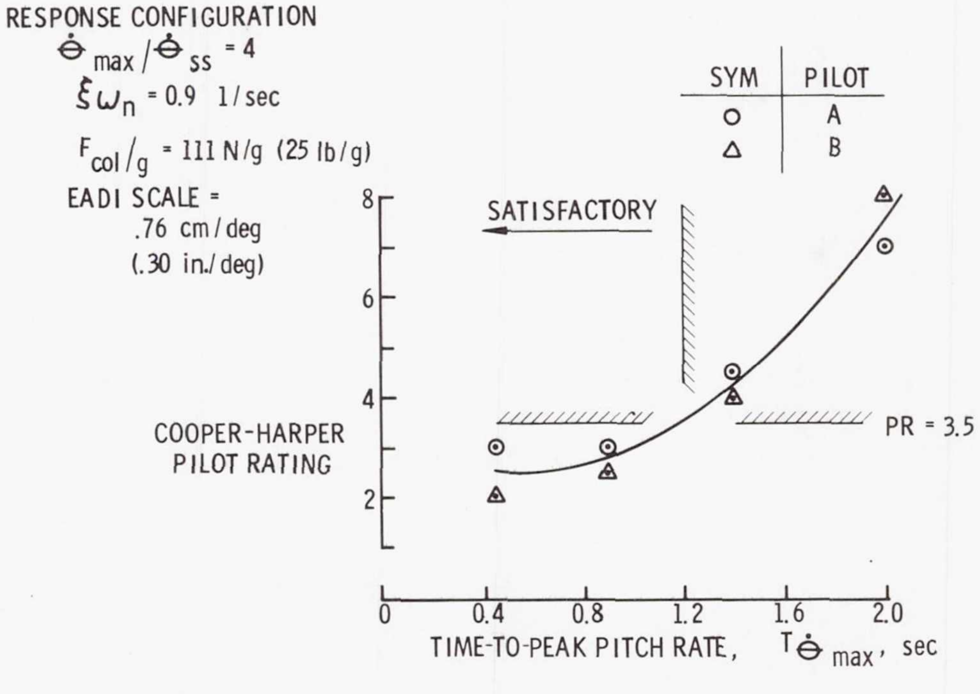


Figure 8.- High-speed cruise evaluation of time-to-peak pitch rate.

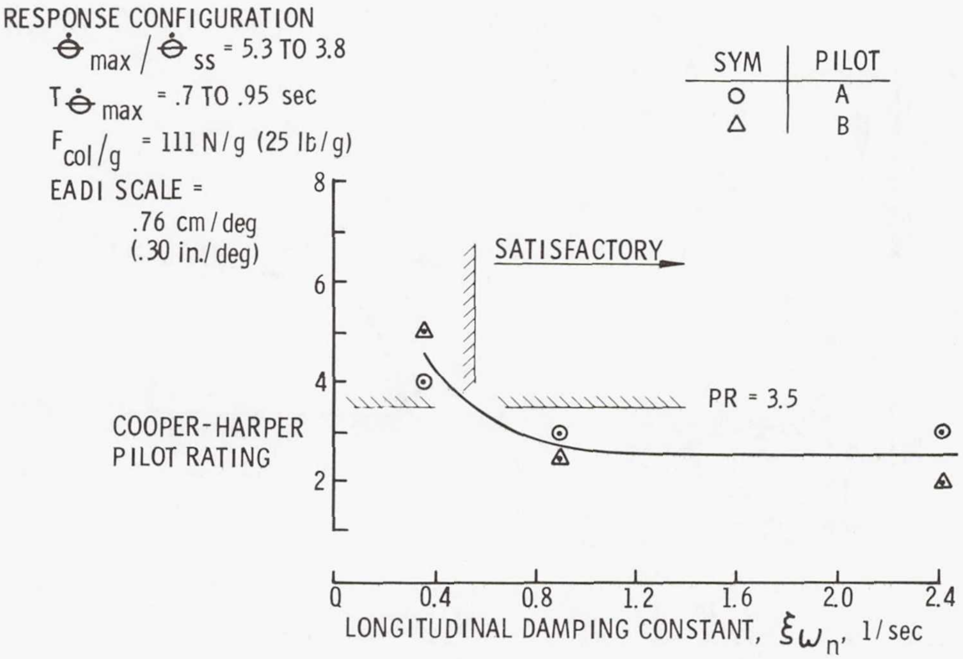
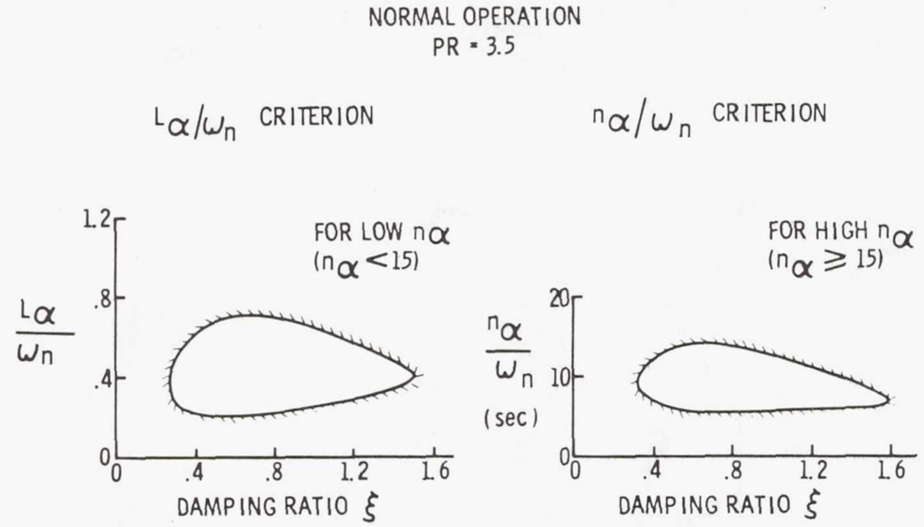


Figure 9.- High-speed cruise evaluation of longitudinal damping.



REFERENCE: AIAA PAPER 65-780

Figure 10.- Shomber-Gertsen longitudinal handling qualities criteria.

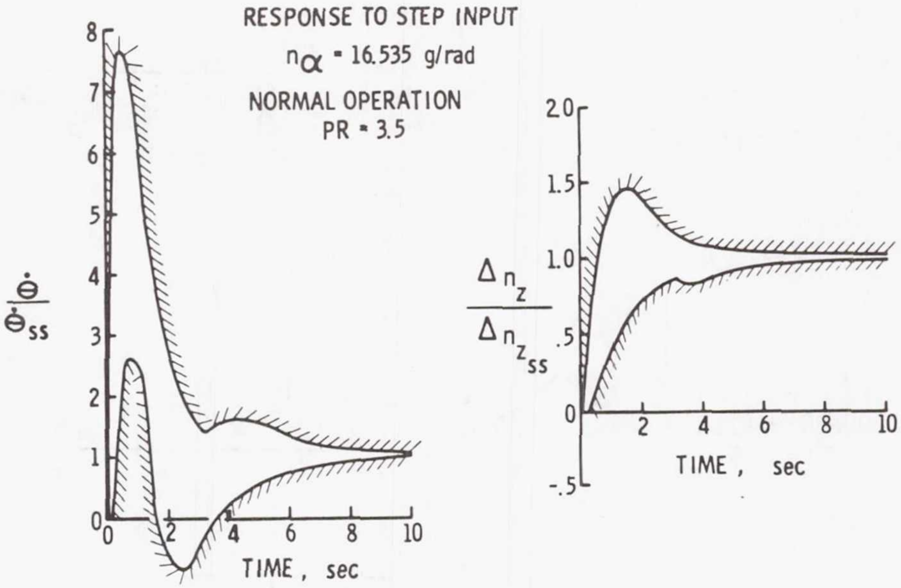


Figure 11.- SST time response criteria (derived from Shomber-Gertsen criteria).

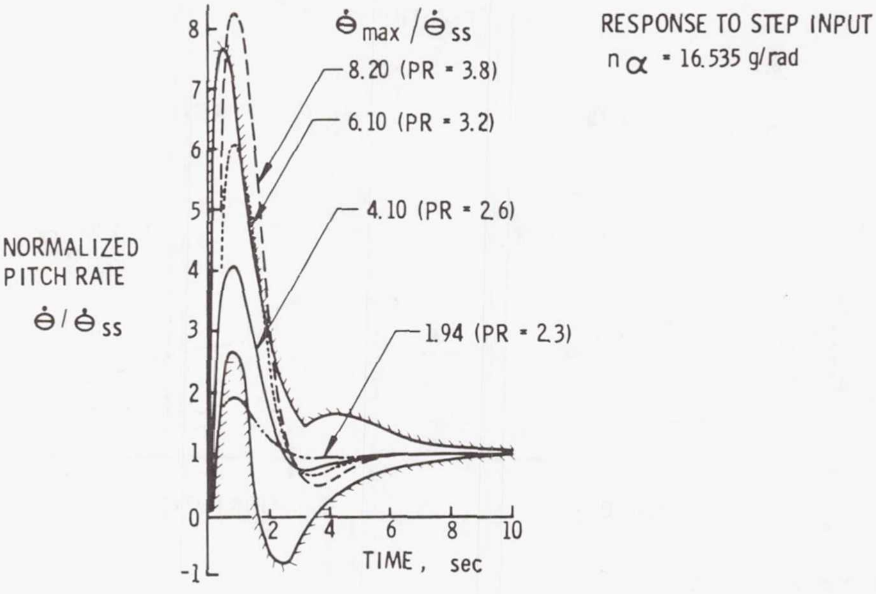


Figure 12.- Pitch rate overshoot comparison with criterion.

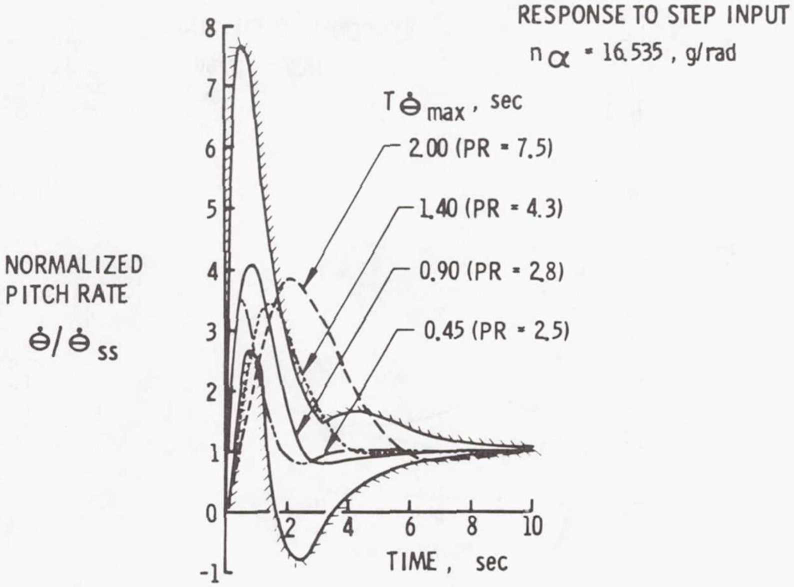


Figure 13.- Time-to-peak pitch rate comparison with criterion.

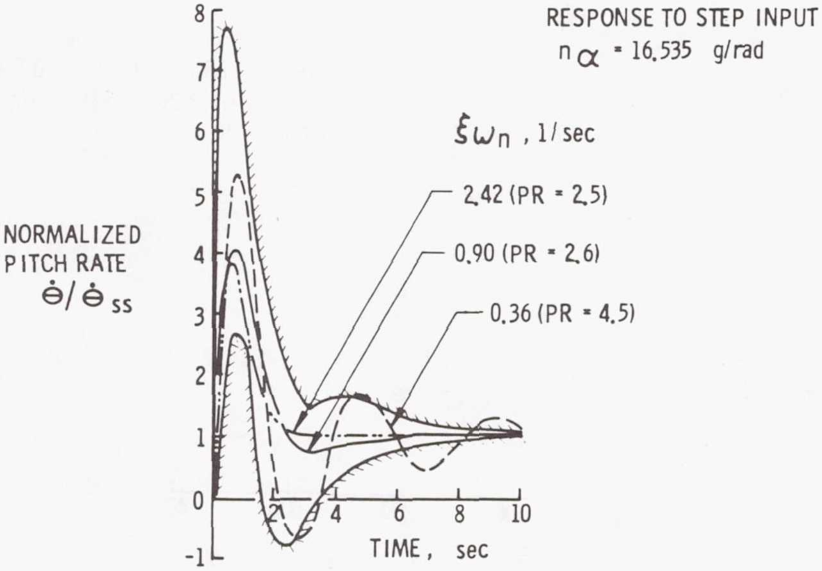


Figure 14.- Pitch damping comparison with criterion.

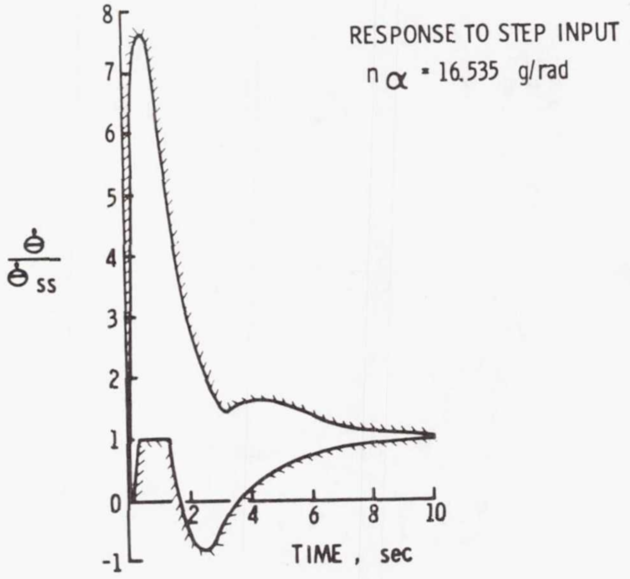


Figure 15.- Modified SST high-speed pitch rate response criterion.

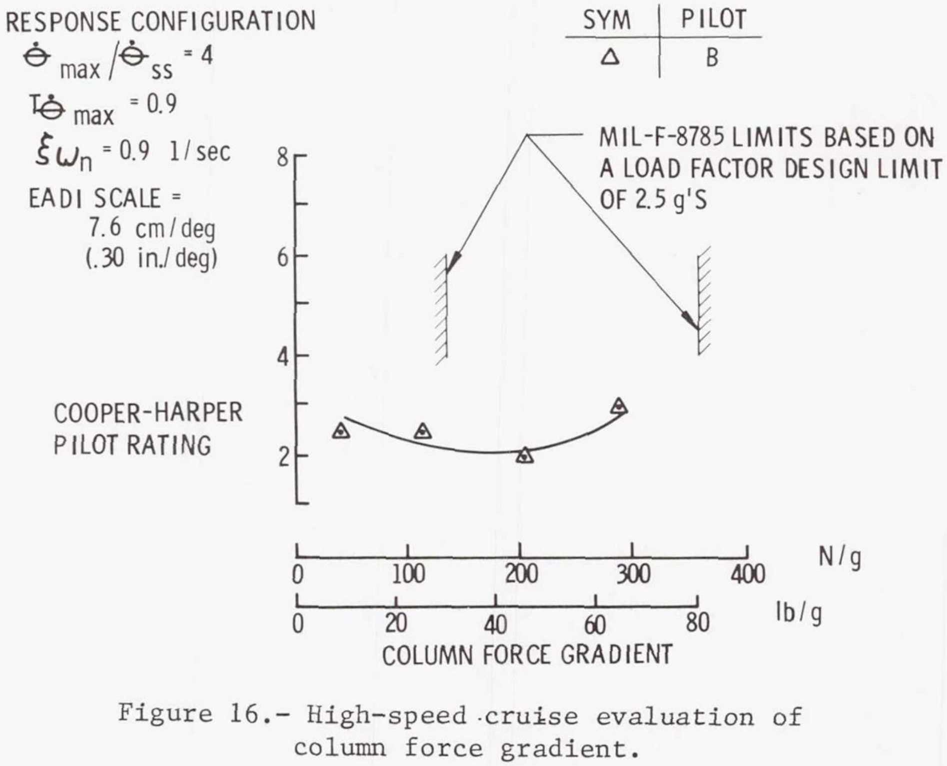


Figure 16.- High-speed cruise evaluation of column force gradient.

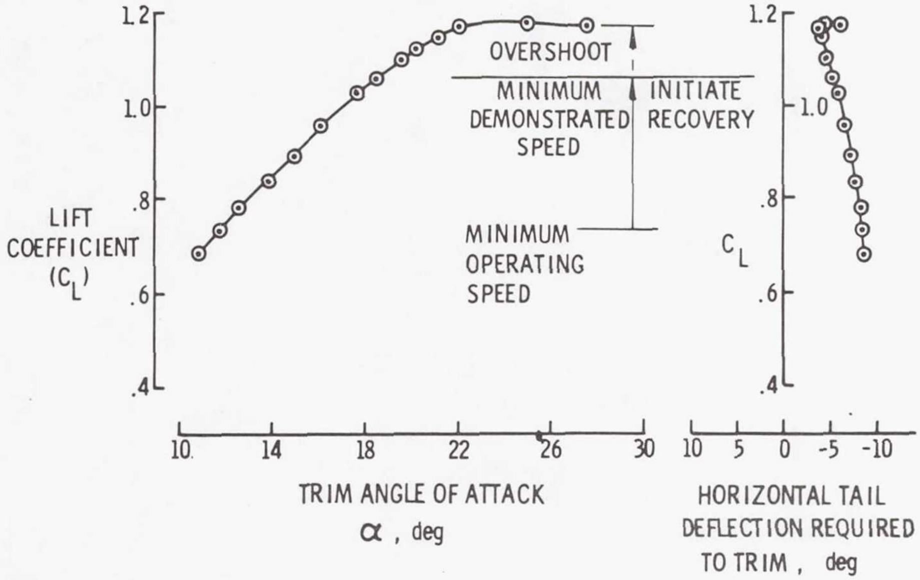


Figure 17.- Longitudinal stability — stall recovery evaluation.

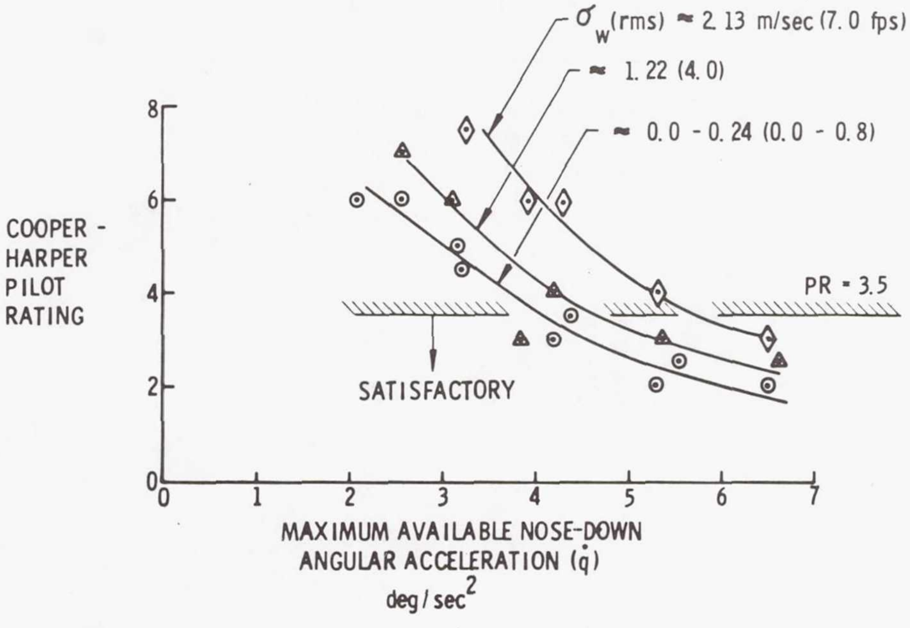


Figure 18.- Stall recovery control power evaluation.

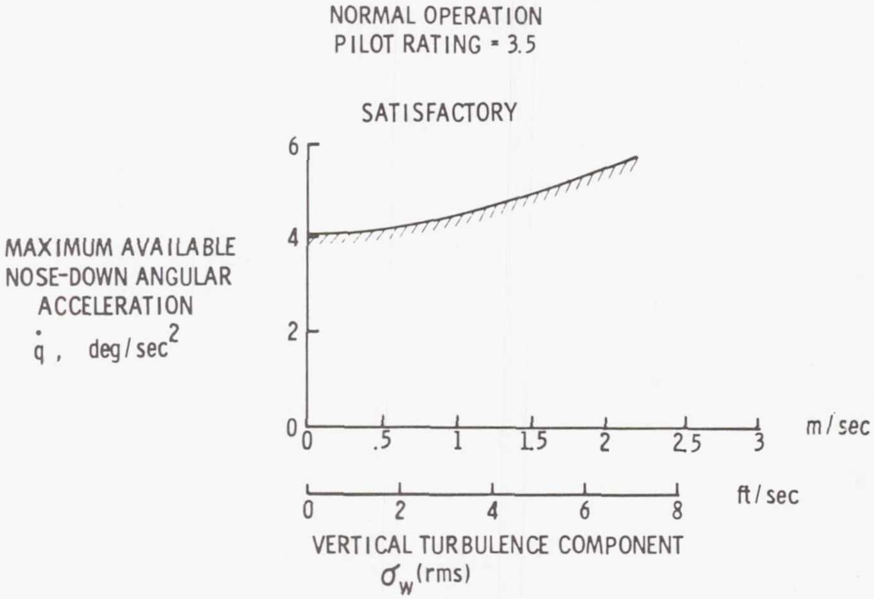


Figure 19.- Effect of turbulence on stall recovery control power.