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FOREWORD

This report was prepared for the National Aeronautics and Space Administration by Calspan Corporation, Buffalo, New York, in fulfillment of Task 6 of NASA Contract Number NAS4-2534 and describes the results of a study of landing flying qualities criteria for highly augmented aircraft.

The study reported herein was performed by the Flight Research Branch of Calspan under sponsorship of the NASA Hugh L. Dryden Flight Research Center, Edwards, California. Mr. Donald Berry was the NASA technical monitor for this study; his assistance is gratefully acknowledged.

Completion of this report was dependent on the contributions of Mr. Ed Onstott from the Northrop Corporation and Mr. John Hodgkinson from the McDonnell-Douglas Corporation. Mr. Onstott provided the solutions for the LAHOS cases using his criterion and extensive consultation; Mr. Hodgkinson made available the MCAIR equivalent system solutions for the LAHOS data used in this report. Their assistance deserves special acknowledgement.

This report represents the combined efforts of many members of the Flight Research Branch. Mr. Rogers Smith and Mr. Robert Radford were the project engineers assisted by Mr. Randall Bailey. Mr. Norman Weingarten performed the study reported in Appendix A. Dr. Philip Reynolds was the Program Manager for the overall contract of which this study was a part. Finally, the excellent work of Mses Pat Ford, Chris Turpin and Mrs. Janet Cornell in the preparation of this report warrants special recognition.

ABSTRACT

A study of several existing longitudinal flying qualities evaluation criteria applicable to highly augmented aircraft was performed. The criteria evaluated were: Calspan Neal-Smith; Onstott (Northrop) Time Domain; McDonnell-Douglas Equivalent System Approach; R. H. Smith Criterion. Each criterion was applied to the same set of longitudinal approach and landing flying qualities data. A revised version of the Neal-Smith criterion which is applicable to the landing task was developed and tested against other landing flying qualities data. Results indicated that both the revised Neal-Smith criterion and the Equivalent System Approach are good discriminators of pitch landing flying qualities; Neal-Smith has particular merit as a design guide, while the Equivalent System Approach is well suited for development of appropriate military specification requirements applicable to highly augmented aircraft.

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D	Onstott's Pilot Model Switching Time (sec)
dB	Decibel units for amplitude, where amplitude in decibels $= 20\ \log_{10}$ [amplitude]
F_S, F_{ES}	Pitch control stick force, positive aft (lb)
K_p	Pilot model gain
K_{I_c}	Pilot's integral control element: Onstott's Tracking Pilot Model
$K_{\dot{\theta}}$	Steady state gain of constant speed $\dot{\theta}/F_{ES}$ transfer function or equivalent steady state gain of constant speed $\dot{\theta}/F_{ES}$ transfer function
L_α	$\approx 1/\tau_{\theta_2}$
$M_{(\ )}$	$= \frac{1}{I_y} \frac{\partial M}{\partial (\ )}$ body axis dimensional pitching moment derivative (rad/sec per ( ))
n_z	Incremental normal acceleration at c.g., positive for pullup (g's or ft/sec^2)
n_z/α	Steady state normal acceleration per angle of attack (g's/rad or ft/sec^2/rad)
s	Laplace operator (1/sec)
t_1	Time to first peak of pitch rate response to unit step input (sec)

T_{lag}	Time constant of pilot's lag element (sec)
T_L, T_{lead}	Time constant of pilot's lead element (sec)
V_{ind}	Indicated airspeed (knots)
α	Angle of attack (deg or rad)
$\delta_{E_{I,F}}$	Commanded elevator deflection, Onstott's Pilot Model
δ_{ES}	Pitch stick deflection at grip, positive aft (inch)
ζ_{sp}	Short period damping ratio
ζ_{sp_e}	Equivalent short period damping ratio
ζ_3, ζ_4	Damping ratio of control system filter dynamics
θ	Pitch attitude (deg or rad)
θ_c	Commanded pitch attitude (deg or rad)
θ_ε	Pitch attitude error, $\theta_\varepsilon = \theta_c - \theta$ (deg or rad)
θ/θ_c	Closed-loop pitch attitude transfer function
$\lvert\theta/\theta_c\rvert_{max}$	Magnitude of resonance peak in the θ/θ_c Bode amplitude plot (dB)
θ/F_s	Open loop pitch attitude to pitch control stick force transfer function

LIST OF SYMBOLS (CONT'D)

τ	Pure time delay (sec)
τ_e	Equivalent time delay (sec)
τ_p	Pilot time delay (sec)
τ_{θ_2}	Airframe lead time constant in constant speed θ/F_{ES} transfer function (sec)
$\tau_{\theta_{2e}}$	Equivalent airframe lead time constant in constant speed transfer function (sec)
τ_1	Lead time constant of first order control system prefilter
τ_2	Lag time constant of first order control system prefilter
ω_B	Bandwidth frequency, frequency at which phase angle of the θ/θ_c transfer function = -90° (rad/sec)
ω_c	R. H. Smith Criterion frequency (rad/sec)
ω_{sp}	Undamped natural frequency of short period mode (rad/sec)
ω_{sp_e}	Equivalent natural short period frequency (rad/sec)
ω_3, ω_4	Undamped natural frequency of control system filters (rad/sec)
$\angle_{pc}$	Phase angle of the pilot compensation at ω_B (deg)
$\lvert\ \rvert$	Signifies amplitude of a transfer function

$(\ )_I$	Signifies Onstott's Acquisition Pilot Model
$(\ )_F$	Signifies Onstott's Target Tracking Pilot Model

ABBREVIATIONS

AFWAL	Air Force Wright Aeronautical Laboratory
deg	Degree
ESP	Equivalent Systems Program
ft	Feet
FCS	Flight Control System
LAHOS	Landing Approach Higher Order Systems
lb	Pound
MCAIR	McDonnell Aircraft Company
NASA	National Aeronautics and Space Administration
OCT	Octave
PIO	Pilot-Induced Oscillation
PR	Pilot Rating
rad	Radian
RMS	Root Mean Square
sec	Second
SPR	Safety Pilot Rating
TOT	Time on Target

Section 1
INTRODUCTION AND PURPOSE

Full-authority electronic augmentation systems are an important feature of the latest aircraft designs; witness the F-16, YF-17, F-18A aircraft and the Space Shuttle . Incorporation of the necessary system redundancy coupled with the dramatic increase in reliability of modern electronic systems has made this "breakthrough" in flight control system design possible. Those latest aircraft designs include sophisticated digital flight control concepts and, in two cases, revolutionary pure "fly-by-wire" flight control systems. The flight control designer now literally has the capability to tailor the aircraft's flying qualities as desired.

Unfortunately, the potential of this new design power has not been realized. In every aircraft design incorporating a sophisticated modern flight control system, significant flying qualities problems were evident during the final evaluation process. A major factor in creating this undesirable situation was the lack of suitable flight control design criteria, or flying qualities requirements, applicable to modern highly augmented aircraft. Specifically, there is an urgent need for suitable criteria to cover the critical landing phase (approach, flare and touchdown). The primary purpose of the study presented in this report was, therefore, to explore the available criteria and using a suitable flying qualities data base, attempt to develop appropriate pitch landing flying qualities criteria for augmented aircraft.

A brief review of the background to this study is in order. The demand for increased capability and expanded flight envelopes, in combination with the advent of reliable full-authority electronic augmentation systems, have led to the evolution of increasingly complex flight control systems. It is apparent that in part at least, this additional complexity is related to a natural desire to implement our new technology rather than to any real design requirement. In any event, this additional complexity which is evident in modern designs, although not necessarily a problem in itself, introduces significant additional control system dynamics which can potentially alter the flying qualities of the aircraft dramatically. For modern, highly augmented aircraft such as the F-16, YF-17, F-18A and Space Shuttle

(References 1, 2, 3), the response to pilot inputs is "higher order" and cannot be adequately described, directly, by the classic aircraft response parameters such as those used in MIL-F-8785B (Reference 4). New flying qualities criteria, or requirements, were clearly required.

In partial response to this need, new longitudinal flying qualities criteria were developed, initially directed at up-and-away tracking (Flight Phase Category A). Examples are: Calspan Neal-Smith criterion (Reference 5), McDonnell-Douglas (MCAIR) equivalent system approach (Reference 6), and Onstott (Northrop) time domain criterion (Reference 7). Following these initial efforts, Chalk (Reference 8) attempted to extend the Calspan criterion to include the landing task (Flight Phase Category C). This extrapolation was based on the prevailing assumption that the landing approach pitch task was significantly less demanding than the pitch tracking task. Observations made during the in-flight simulation phase of the YF-17 development process (Reference 1) suggested otherwise. Subsequent in-flight flying qualities research programs at Calspan (Reference 9) and NASA Dryden (Reference 10) clearly demonstrated that the touchdown phase of the landing task (the last 50 ft) is indeed a very demanding pitch task which is comparable to the fighter tracking task. Further, the reports showed that the pitch flying qualities of highly augmented aircraft can degrade in an explosive fashion (a "flying qualities cliff" exists) during the landing task when significant higher order control system effects (lags, or equivalent time delays) are present. The landing task is therefore a very critical task and flying qualities criteria are urgently needed which can be used to expose deficiencies early in the development process. Recent dramatic flight experiences during landing with the Space Shuttle on Flight 5 (Reference 11), where unexpected and potentially dangerous pilot induced oscillations occurred during landing, serve to illustrate this last point.

In summary, this report presents the results of a study program whose purpose was:

- To review existing longitudinal flying qualities criteria applicable to highly augmented aircraft and assess the application of the criteria to the landing task.

- If possible, to develop new landing flying qualities criteria for augmented aircraft,

- To recommend new research programs or criteria development strategies to produce the requisite criteria.

The primary data base for this study is the LAHOS (Landing Approach Higher Order System) program. This program (Reference 9) was an in-flight investigation using the AFWAL/Calspan NT-33 aircraft to evaluate the longitudinal flying qualities of a wide variety of representative higher order systems. More details on this experiment are presented in Section 2.

The remainder of this report is organized as follows:

- Section 2: Neal-Smith Criterion
  - The results of applying the Neal-Smith criterion to the LAHOS data base are presented including the development and application of a modified criterion. Other data, including the Space Shuttle, are also evaluated using the modified criterion.

- Section 3: Onstott (Northrop) Criterion
  - The criterion is reviewed and applied to the LAHOS data base; comparisons are made between the Neal-Smith and Onstott results and modifications suggested.

- Section 4: MCAIR Equivalent System Approach
  - The application of this method of evaluating the landing flying qualities of highly augmented aircraft to the LAHOS data base is summarized using Reference 12 in which a complete analysis is presented. This method is, in fact, the basis for the approach specified in the new military flying qualities specification, MIL-8785C (Reference 13).

- Section 5: Ralph Smith Criterion
  - The results of applying the criterion to the LAHOS data base are presented.

- Section 6: Study Overview
  - The results from the study are presented in summary form for each criterion examined; overall observations are also presented.

- Section 7: Recommendations
  - A brief summary of suggested areas for further work to improve existing criteria or develop required criteria is presented.

Section 2
NEAL-SMITH CRITERION

The purpose of this section is primarily to present the results of applying the Neal-Smith criterion to the LAHOS data base. A secondary purpose is to present a summary of the LAHOS data base to which all the flying qualities criteria investigated in this study program are applied.

2.1 LAHOS DATA BASE (Reference 9)

The Landing Approach Higher Order Systems (LAHOS) program, to which all the criteria in this study program are applied, was an in-flight investigation of longitudinal approach and landing flying qualities using the AFWAL/Calspan NT-33 variable stability aircraft.

Briefly, the piloting tasks included realistic instrument and visual terminal area tasks, during which actual touchdowns were performed as well as intentional approach-only evaluations. Where possible, pilot ratings were given for both the flare and touchdown task and the overall terminal area task. For the purposes of this study program, the average pilot rating is used where multiple evaluations for a configuration occurred. Pilot ratings should not, of course, be reviewed separately from the pilot comments which are documented fully in Reference 9.

As shown in Figure 1 and Table 1, the LAHOS experiment variables were the short period and the flight control system dynamics. Five short period configurations spanning the military specifications were simulated; the phugoid and lateral-directional characteristics remained essentially constant. First-order lag and lead/lag networks, second-order prefilters, and a fourth-order Butterworth filter (approximating a pure time delay) made up the control system parameters. In addition, the modified and original control systems of the simulated YF-17 (Reference 2) were included. A total of 45 LAHOS configurations were used in this study program.

The results from the LAHOS program clearly showed that the flare and touchdown task was the critical piloting area in the overall approach and landing task. Severe degradations in longitudinal flying qualities ("cliffs") typically occurred in the last 50 ft prior to touchdown for configurations with significant additional control system lag.

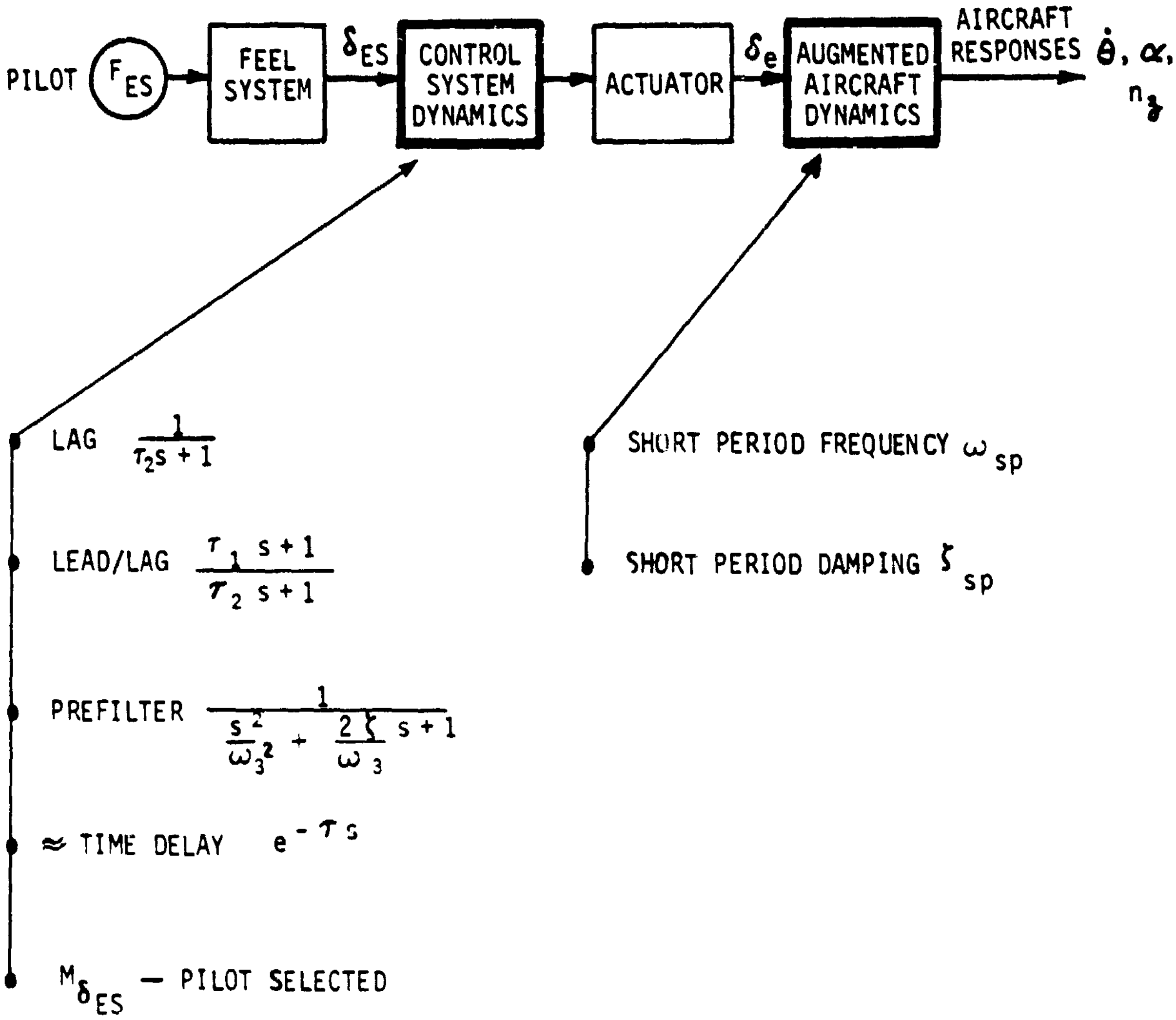


Figure 1 LAHOS EXPERIMENT VARIABLES

TABLE 1
SUMMARY OF LAHOS CONFIGURATIONS

CONTROL SYSTEM DYNAMICS				SHORT PERIOD DYNAMICS (Nominal) V_{ind} = 120 Kt; n_z/α = 4.5 g/rad; τ_{θ_2} = 1.4 sec — ω_{sp}/ζ_{sp}				
τ_1	τ_2	ω_3/ζ_3	ω_4/ζ_4	1.0/.74	2.3/.57	2.2/.25	2.0/1.06	3.9/.54
0.4	0.1	-	-	1-A	2-A			
0.3	0.1	-	-	1-B				
0.2	0.1	-	-	1-C	2-C	3-C	4-C	
0	0	-	-	1-1	2-1	3-1(3-0)*	4-1 (4-0)*	5-1
	0.1	-	-	1-2	2-2	3-2		
	0.25	-	-	1-3	2-3	3-3	4-3	5-3
	0.5	-	-	1-4	2-4		4-4	5-4
	1.0	-	-					5-5
	0	16/.7	-	1-6	2-6	3-6	4-6	5-6
		12/.7	-		2-7	3-7	4-7	5-7
		9/.7	-	1-8				
		6/.7	-		2-9			
		4/.7	-		2-10		4-10	
0	0	16/.93	16/.38	1-11	2-11		4-11	5-11

*ω_{sp}/ζ_{sp} for Configuration 3-0 is 2.1/.14; for configuration 4-0, 2.1/1.23

CONFIGURATION	CONTROL SYSTEM DYNAMICS	ω_{sp}/ζ_{sp}
6-1 (YF-17 Original)	$\dfrac{(.5s+1)(.43s+1)}{(.2s+1)(1.1s+1)\left(\frac{s^2}{4^2}+\frac{2(.7)}{4}s+1\right)}$	1.9/.65
6-2 (YF-17 Modified)	$\dfrac{(.5s+1)(.43s+1)(.06s+1)}{(.25s+1)(.1s+1)(1.1s+1)}$	1.9/.65

NOTES:
- Total configuration dynamic model includes feel system and actuator dynamics. Time delay is approximated using a fourth ordered Butterworth filter - described by ζ_3/ω_3, ζ_4/ω_4. (See Reference 9).
- Configurations 4-0, 7-1, 7-2, and 7-3 not used in analysis (see Section 2.5)

An exception to these observations was evident for the unaugmented, lightly damped short period configurations and the unstable cases (Configuration 7, not used in this analysis). In several instances better pilot ratings were given for the flare and touchdown task than for the approach task. In fact, no PIO tendencies were observed in the flare and touchdown even with a very low short period damping ratio.

2.2 NEAL-SMITH CRITERION REVIEW

The Neal-Smith closed loop flying qualities criterion was originally developed as a longitudinal flying qualities evaluation tool, or "yardstick", for highly augmented fighter aircraft performing precision tracking tasks (Flight Phase Category A). An attempt was later made to extend the application of the criterion to the approach and landing task (Flight Phase Category C) but the results were poor. In this work (Reference 8) the faulty assumption was made that the landing task was a low gain, undemanding task relative to a fighter tracking task. Subsequent evidence from the YF-17 simulation program (Reference 2) and the LAHOS program itself indicated that the flare and touchdown phase of the landing task was indeed a demanding, high gain task.

In the study reported in this section, the Neal-Smith criterion, which is based on the applicability of a simple closed-loop pitch attitude tracking task, is applied to the LAHOS data from a "fresh" viewpoint. It is obvious that the landing task involves more elements than pitch attitude control; speed and flight path control are also clearly important elements. However, on the basis that good inner-loop attitude control is a necessary, but perhaps not sufficient, condition for good approach and landing flying qualities, the application of the criterion to the LAHOS data is credible.

Complete details on the criterion are contained in Reference 5. Briefly, the criterion assumes a simple closed-loop pitch attitude tracking task as shown in Figure 2. The pilot block in the closed loop should be viewed, more properly, as a pitch attitude compensator since even though the form of the "pilot model" used is representative, the model was not experimentally confirmed. The criterion represents a "flying qualities test" and as such is not dependent on the accuracy of the "pilot model" assumed.

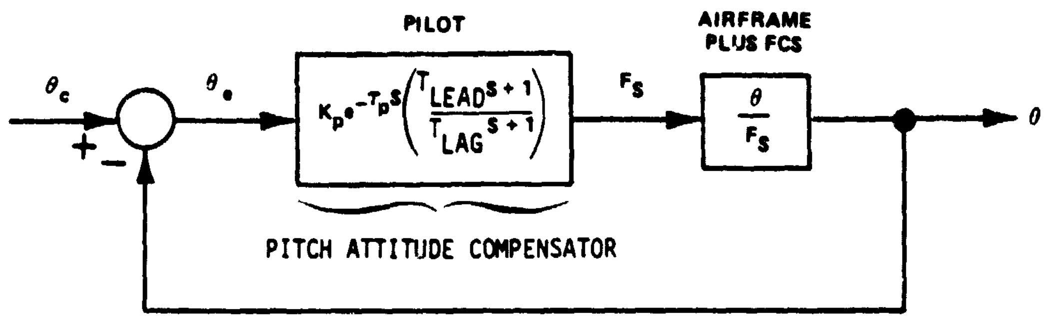


FIGURE 2 CRITERION PITCH TRACKING TASK

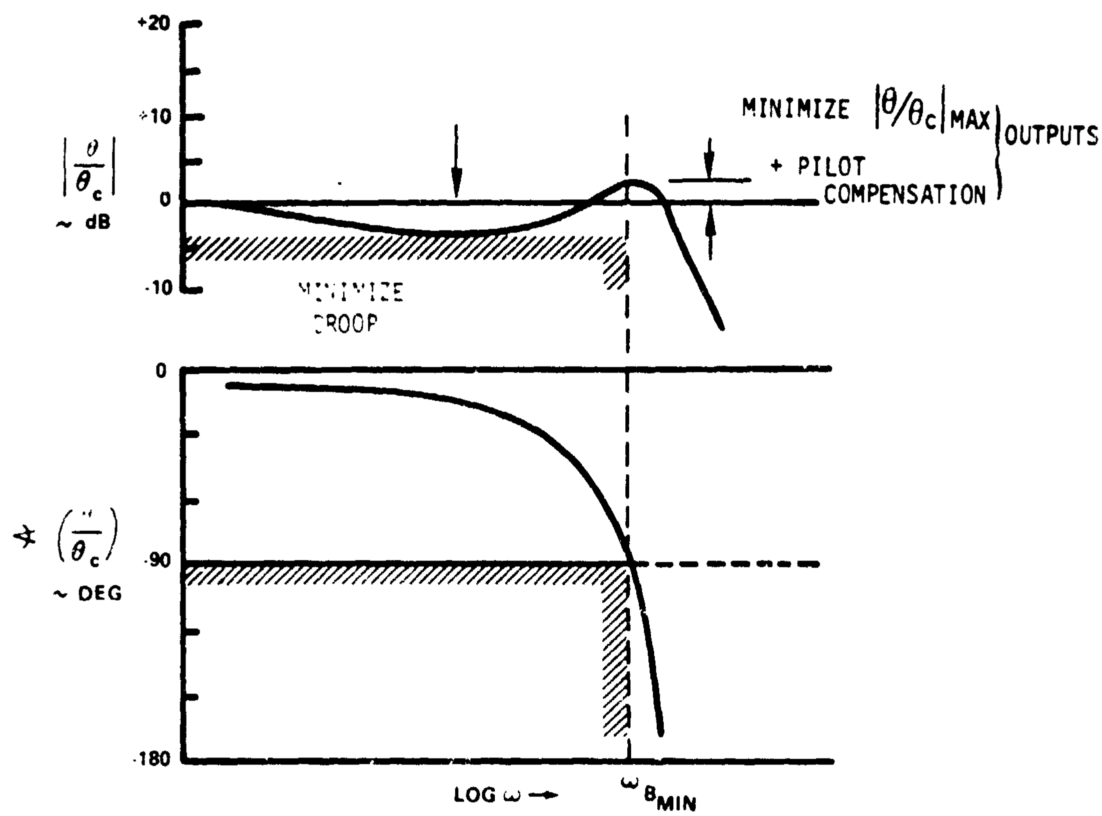


Figure 3 CRITERION PARAMETERS

The criterion assumes a certain "performance standard", or degree of aggressiveness, with which the "pilot" closes the loop. This standard is defined in the frequency domain as a bandwidth frequency (ω_B). This bandwidth is task dependent; the value for a particular task is determined heuristically using pilot rating and comment data to obtain the best overall correlation with the criterion parameters. For a given desired bandwidth, the "loop is closed" and the compensator, or pilot model, parameters are varied to yield the best overall closed-loop performance.

The criterion output parameters are the pilot compensation (workload) required and the resulting closed-loop performance as measured by the maximum value of closed-loop resonance ($|\theta/\theta_c|_{max}$). Low frequency performance is constrained by limiting the "droop" up to the bandwidth frequency. These criterion parameters are illustrated in Figure 3.

Evaluation of a specific LAHOS configuration using the Neal-Smith criterion consists of the following steps:

- Specify the bandwidth appropriate for the task; must be determined for each task by data correlation (the purpose of this study).

- Adjust pilot model parameters, the compensation, (using a fixed value of time delay) to meet the "performance standard" set by the bandwidth requirement.

- Measure the closed-loop compensation required (pilot workload) and the closed-loop maximum resonance($|\theta/\theta_c|_{max}$).

- Typically, pilot workload is measured by the phase angle of the compensation required at the bandwidth frequency ($\measuredangle_{pc}$).

- Plot measured values against Neal-Smith flying qualities boundaries to evaluate the flying qualities. Boundaries for the original tracking data are shown in Figure 4; typical pilot comments around the Neal-Smith parameter plane are illustrated in Figure 5.

All of this analysis is performed using a digital computer program.

In the original analysis (Reference 5), a pilot time delay of $\tau_p = 0.3$ sec was assumed and a maximum droop of -3 dB was imposed. For the flight condition most representative of a fighter tracking and maneuvering environment (350 knot case), a bandwidth of 3.5 rad/sec was selected.

2.3 CORRELATION WITH LAHOS DATA

As a first step in the process of developing a form of the Neal-Smith criterion which is applicable to the landing task, the LAHOS data was reviewed using a low bandwidth (1.2 rad/sec) as suggested in Reference 8. Not surprisingly, the correlation was poor since, as shown in the YF-17 example, the landing task is clearly a higher bandwidth task.

The next step in the correlation process was to use the tracking values of bandwidth and pilot delay (3.0 and 3.5 rad/sec and 0.3 sec respectively) employed in Reference 5. In this case correlation was better since higher bandwidth is more appropriate for the landing task but significant anomalies were still present.

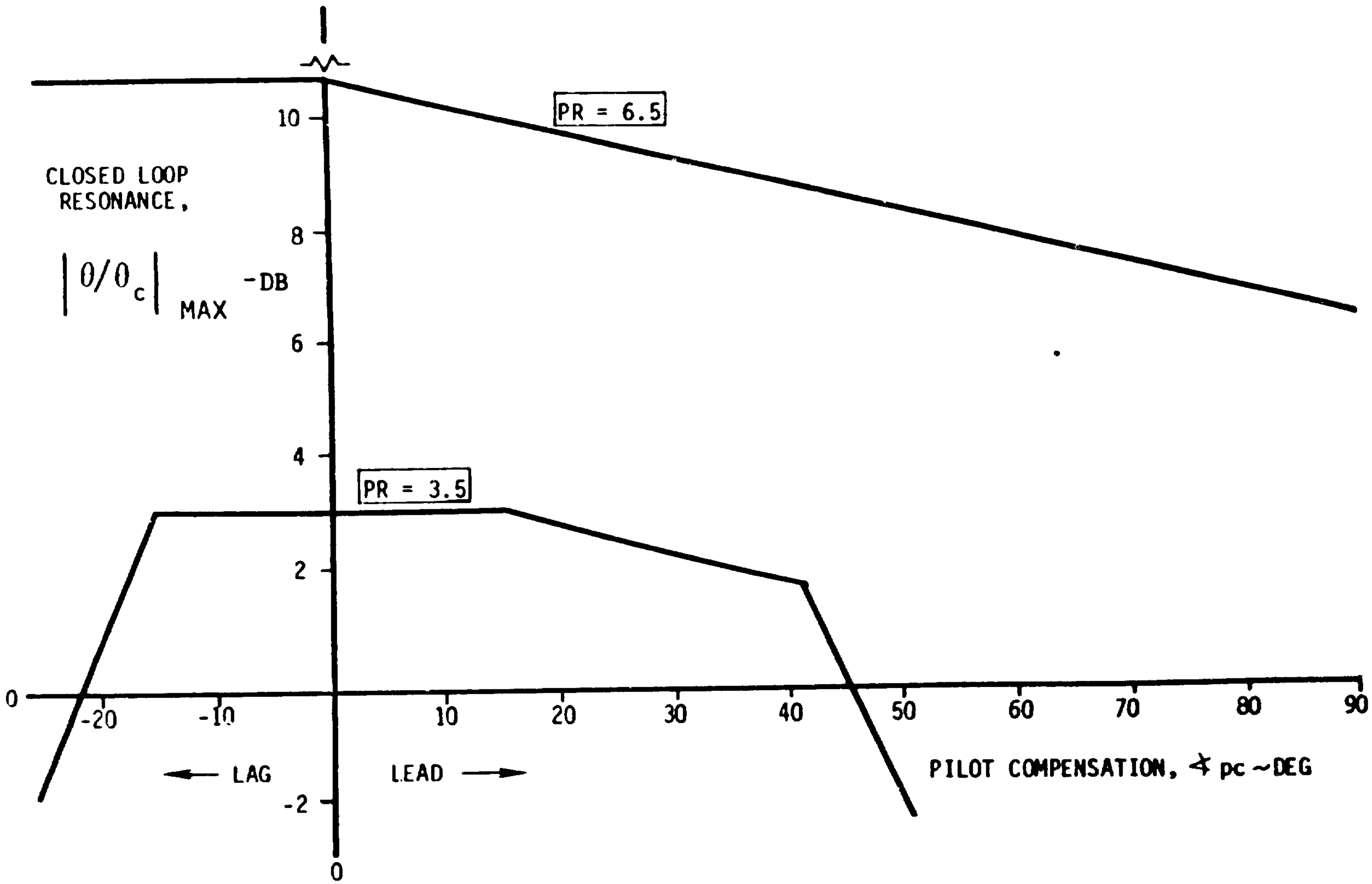


Figure 4 NEAL-SMITH PARAMETER PLANE

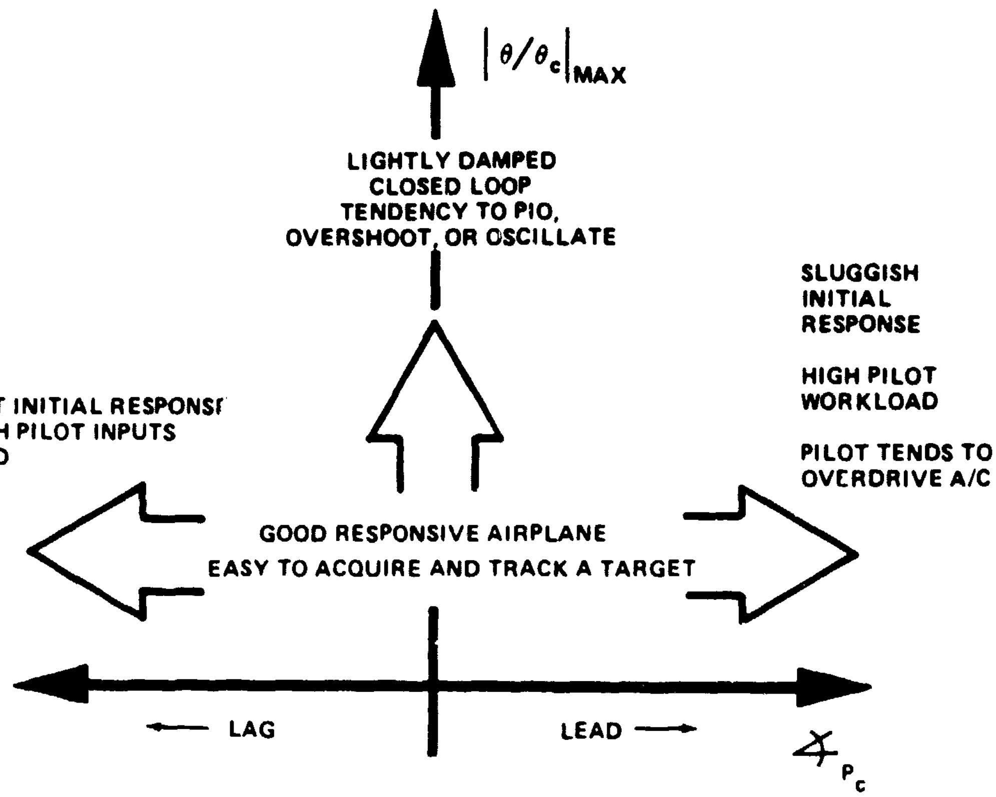


Figure 5 TYPICAL PILOT COMMENTS

Finally, it was decided to take a "fresh" look at the criterion parameters (bandwidth and pilot delay) for the analysis of the LAHOS data. As a starting point, attention was centered on two "benchmark" configurations whose flying qualities were good and were well substantiated. Configurations 2-1 and 6-2 (modified YF-17) were selected for this purpose.

The objective was to select values of bandwidth and time delay which placed the benchmark configurations in sensible locations on the criterion plane and further, to provide discrimination of the remaining LAHOS data. Pilot ratings, comments and discrete error tracking records were used for guidance in this correlation process. For reference, the effects of increasing bandwidth on the location of a particular configuration on the Neal-Smith plane are presented in Figure 6.

As shown in the plot presented in Figure 7, the closed-loop resonance at a particular bandwidth is significantly affected by the value of pilot time delay selected above 0.2 sec. Since the "benchmark" configurations were observed by the pilots to have well damped closed-loop performance, it was necessary to select a value of time delay of 0.2 secs to achieve a reasonable correlation between the comments and the criterion closed-loop performance.

The criterion parameters for best correlation of the LAHOS data which evolved from the correlation process were:

- Bandwidth of 3.0 rad/sec
- Pilot time delay of 0.2 sec

All the LAHOS data are presented in Figure 8A on the Neal-Smith parameter plane using these criterion parameters and the original flying qualities boundaries of Reference 5. The LAHOS configuration identifier for each data point is presented on Figure 8B. The grouping of the data is comparable to the original Neal-Smith analysis. Configurations with negative resonance are a consequence of forcing the criterion low frequency "droop" constant. Relaxation of this constraint for configurations with no closed-loop resonance concerns is discussed in the next subsection.

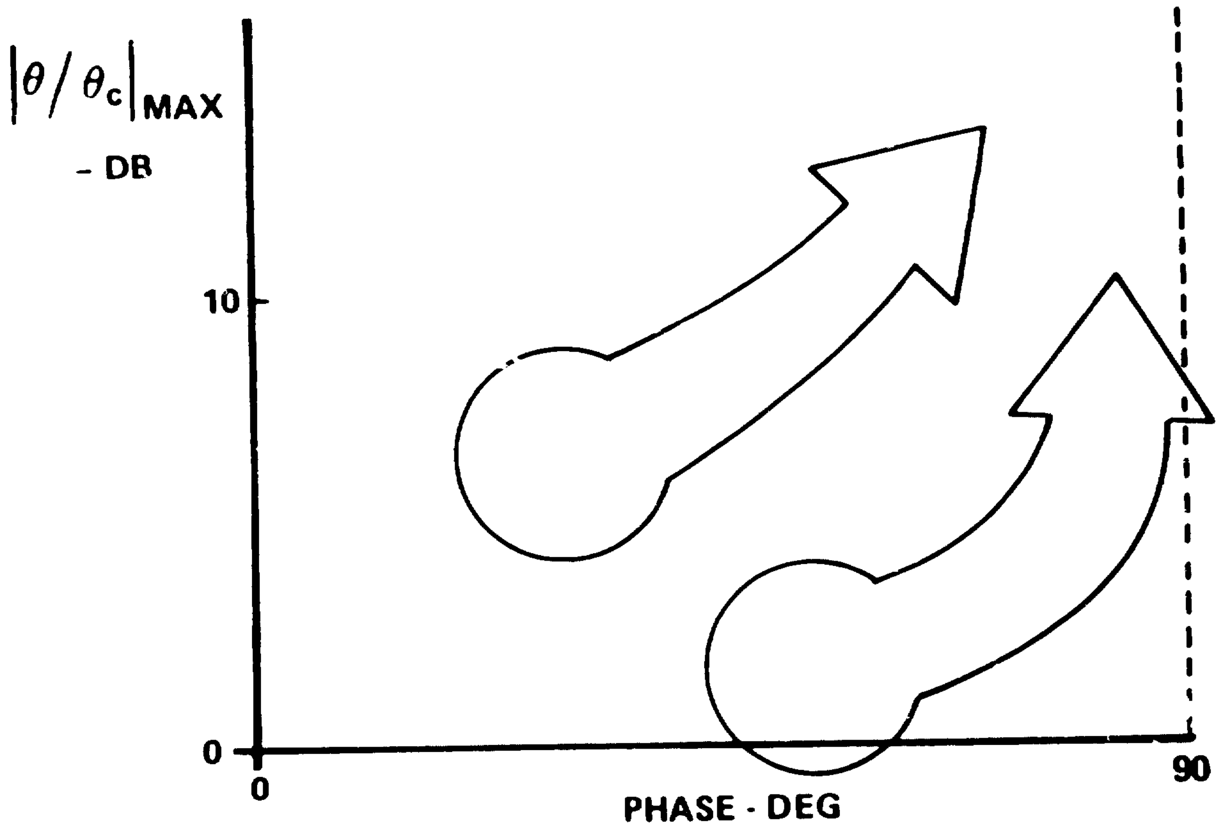


Figure 6 EFFECTS OF INCREASED BANDWIDTH ON CONFIGURATION MAPPING IN NEAL-SMITH PARAMETER PLANE

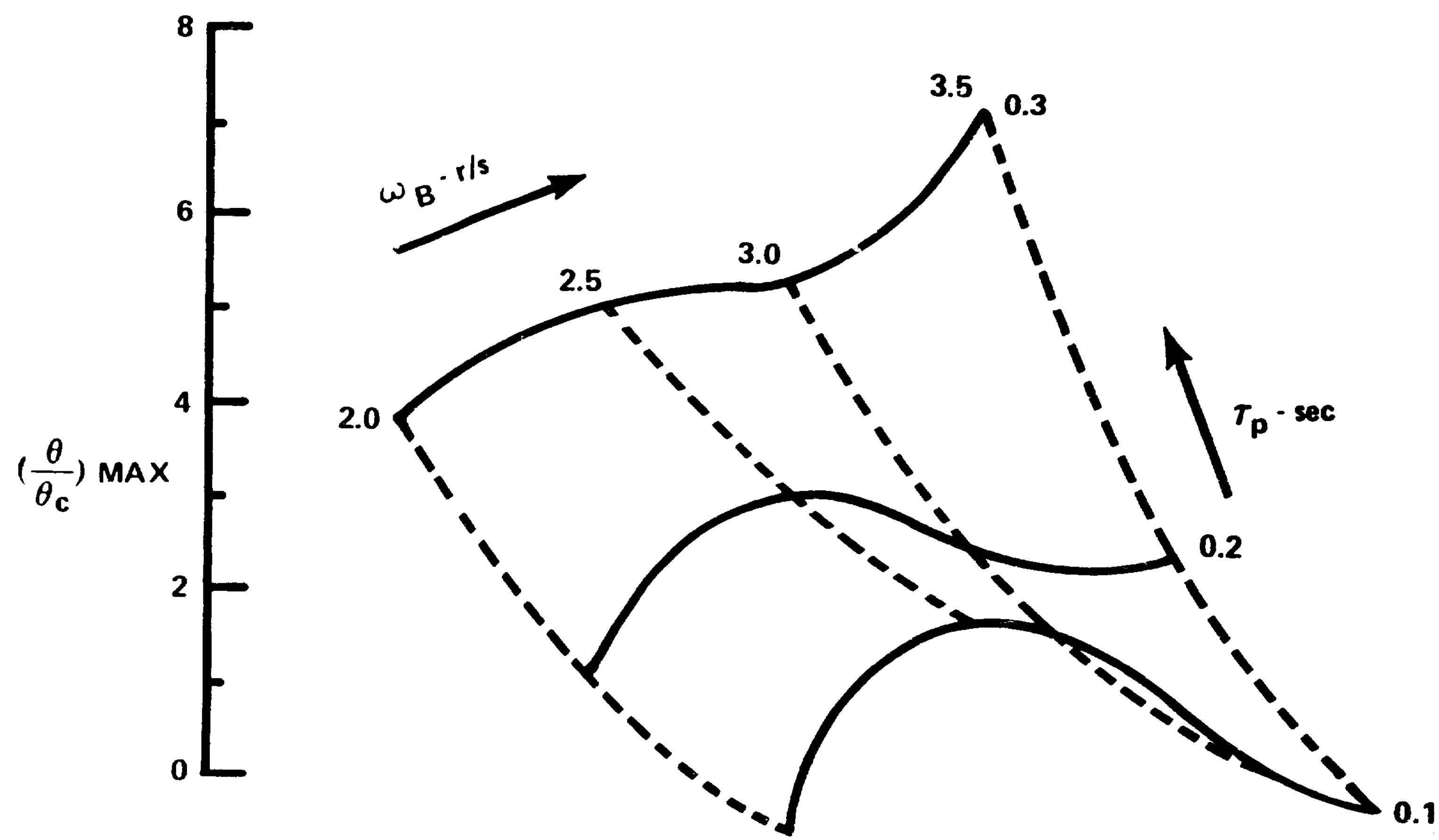


Figure 7 VARIATION OF $|\theta/\theta_c|_{MAX}$ WITH BANDWIDTH (ω_B) AND PILOT TIME DELAY (τ_p) FOR LAHOS CONFIGURATION 2-1

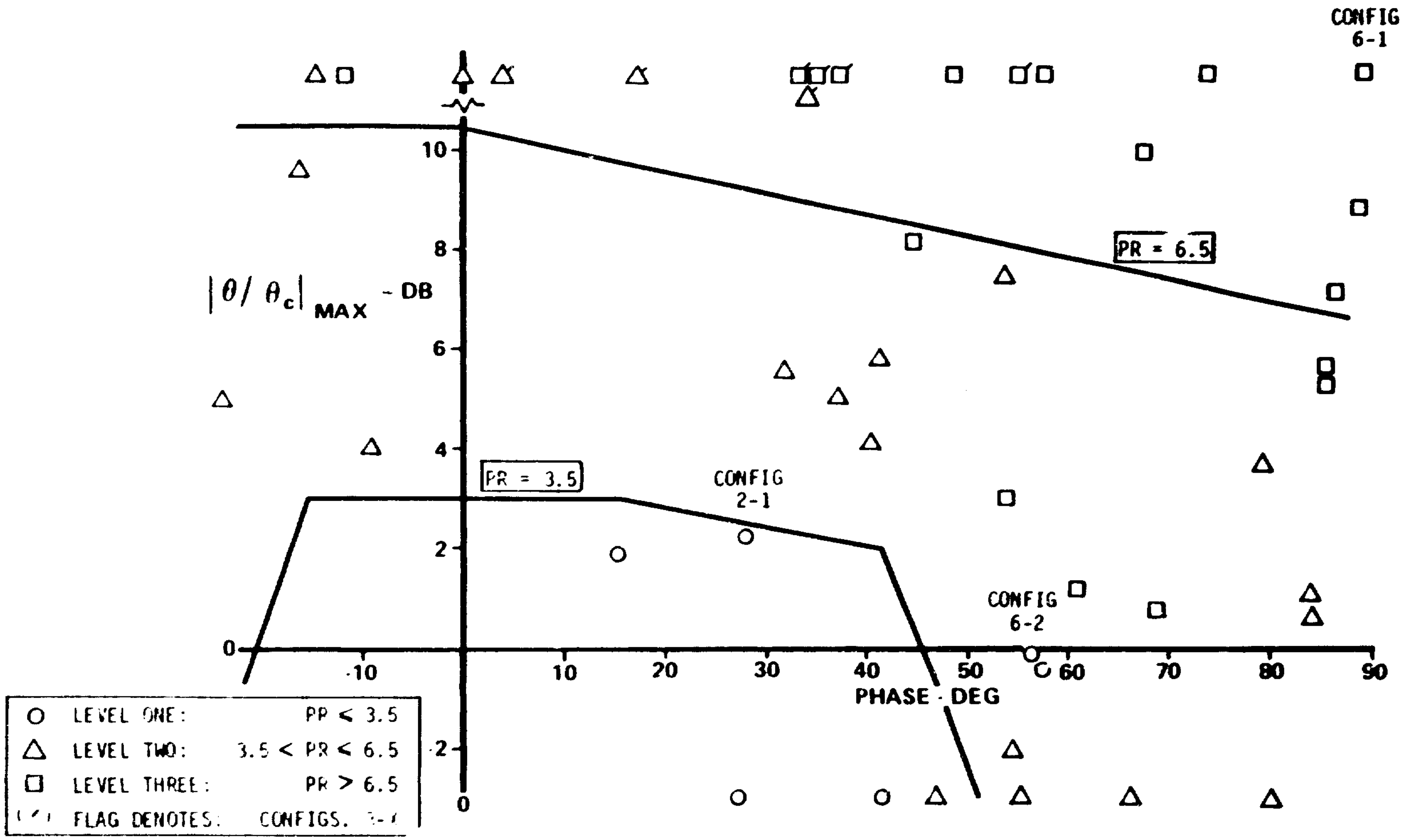


Figure 8A LAHOS DATA: $\omega_B = 3.0$ r/s, $\tau_p = 0.2$

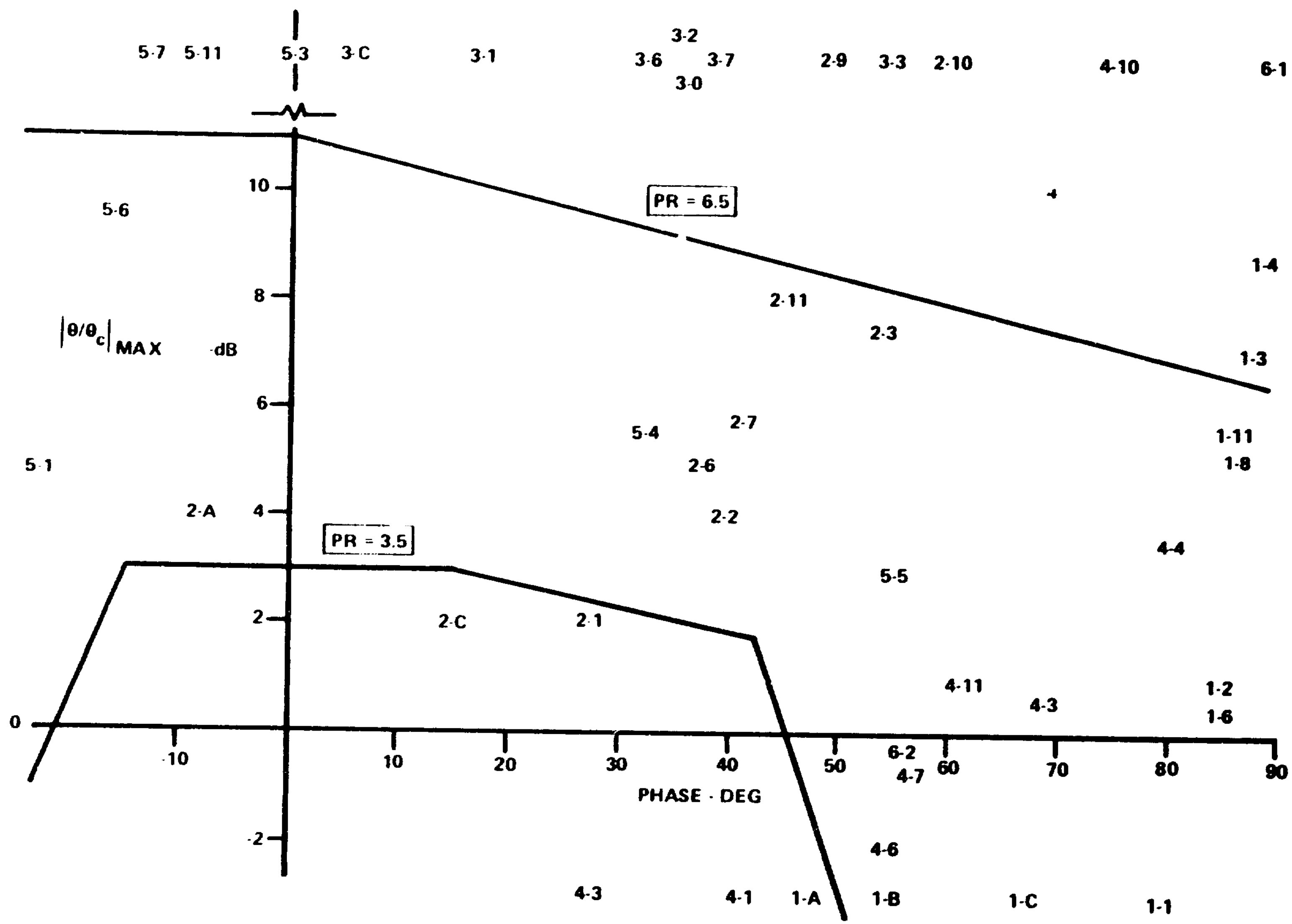


Figure 8B LAHOS DATA: $\omega_B = 3.0$ r/s, $\tau_p = 0.2$

Also presented in the next subsection is the final "best" criterion for the landing task (Flight Phase Category C) including refined flying qualities boundaries. A discussion of the anomalies in the final application of the revised criterion to the LAHOS data base is presented in Subsection 2.5.

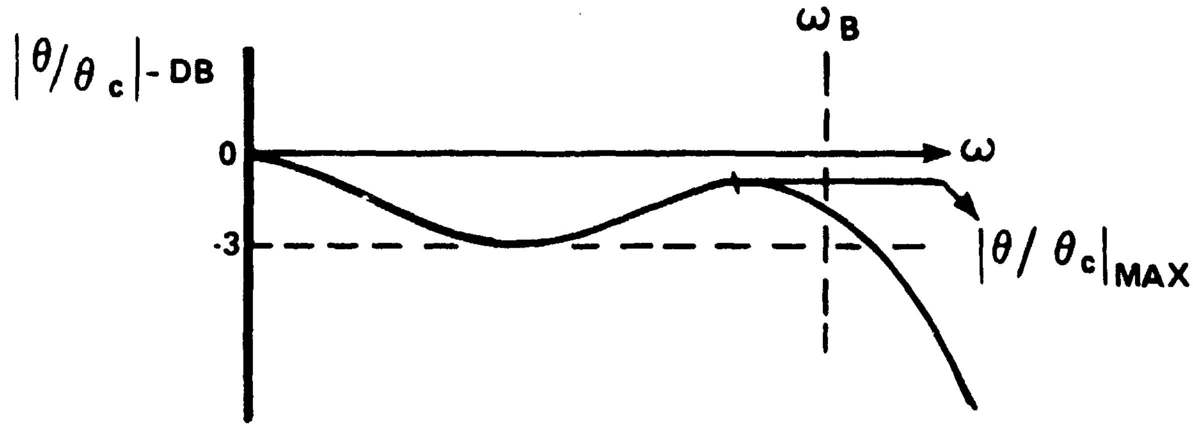
2.4 REVISED NEAL-SMITH LANDING FLYING QUALITIES CRITERION

For aircraft configurations with no tendency toward closed-loop oscillations (low resonance), insistance on meeting the original -3 dB droop requirement as well as the desired bandwidth can lead to unnecessary additional "pilot" compensation. To make the compensation more realistic, this droop constraint was relaxed for configurations with resonance less than 2 dB as shown in Figure 9.

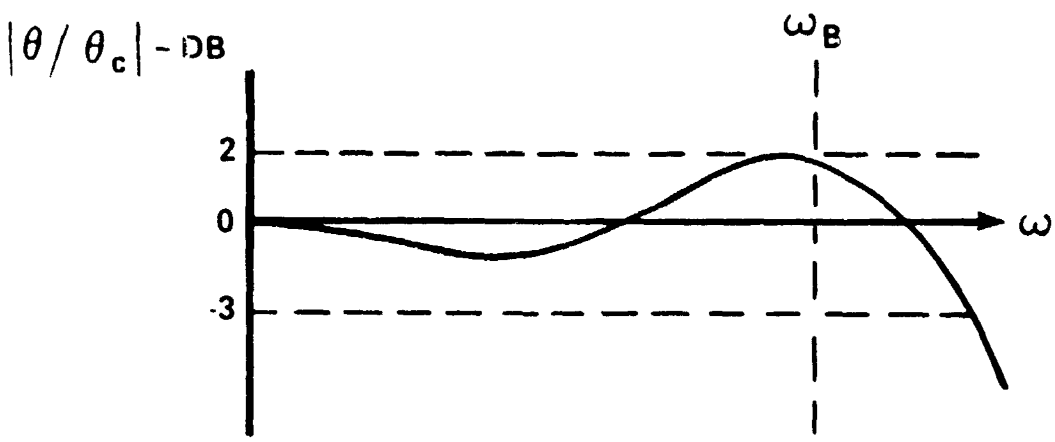
The final results of the correlation of the LAHOS data on the Neal-Smith parameter plane are presented in Figure 10. New slightly modified criterion flying qualities boundaires applicable to the approach and landing task were required as shown on the figure.

The correlation is good; there are, however, anomalies. One such group is enclosed in the dashed box. Note that on Figure 10 the configuration locations are identical to those on Figures 8A and B above a resonance of 2 dB. All the criterion correlation anomalies are discussed in the next subsection.

Since a critical function of a flying qualities evaluation criterion is to expose or eliminate systems which have significant problems, it is reasonable to consider a correlation "failure" as follows. If the predicted flying qualities level is better than the actual pilot rating level, then the criterion has failed. Since the criterion is directed at a set of requirements simultaneously, it is a reasonable assumption that should this rating comparison occur it is because the criterion is wrong and not due to other factors not included in the criterion. For the purposes of this report, the converse (predicted worse than actual) is not considered to be a failure; conservative designs can result in this instance but, unless this situation occurs often, it is not a major criterion concern.



(a) DROOP REQUIREMENT FORCED



(b) DROOP REQUIREMENT RELAXED

Figure 9 EFFECT OF DROOP REQUIREMENT ON LOW RESONANCE CONFIGURATIONS

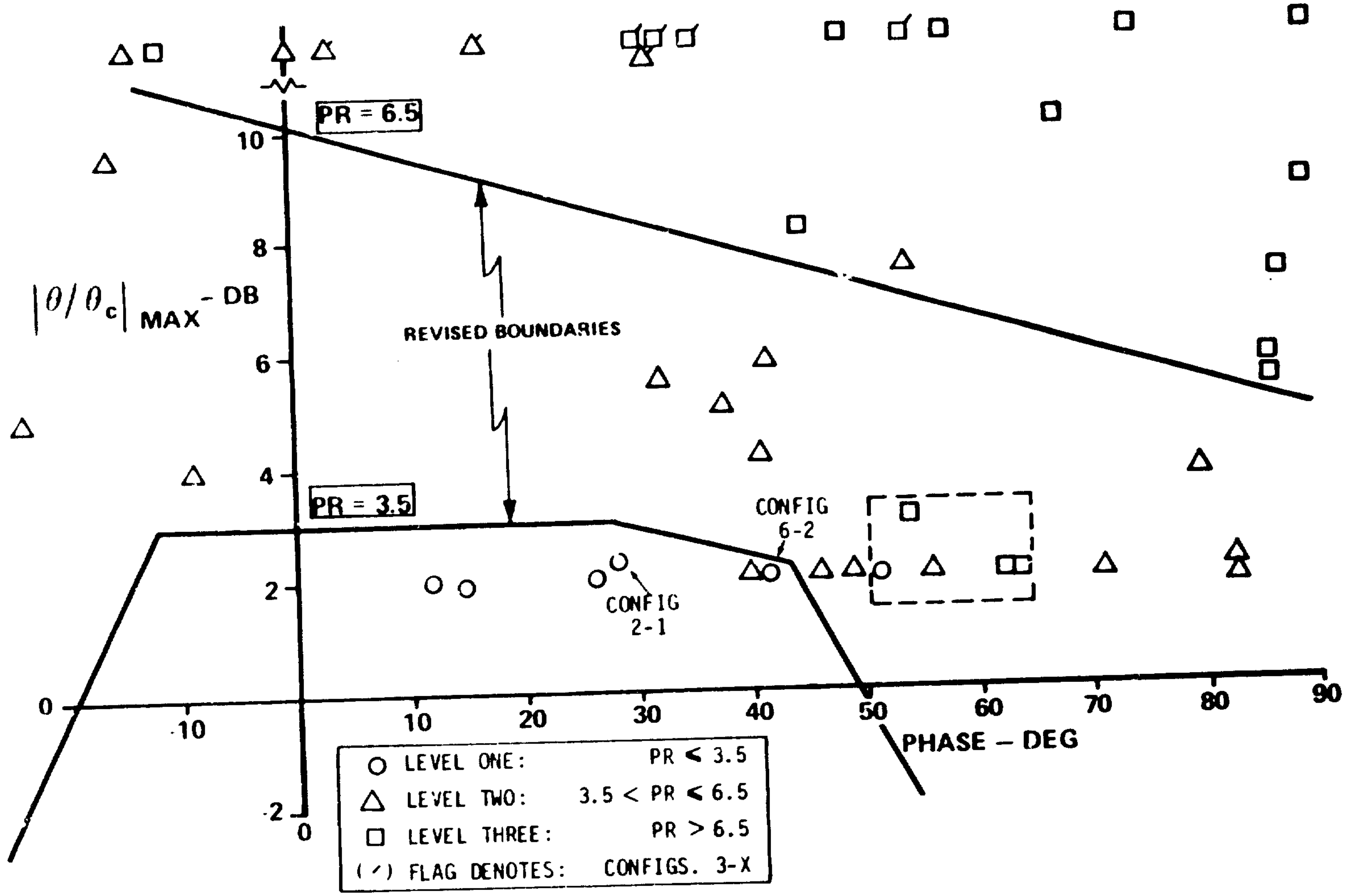


Figure 10 LAHOS DATA - 3 dB DROOP CRITERION RELAXED ω_B = 3.0 r/s τ_p = 0.2

With these correlation rules, the revised Neal-Smith criterion correlation is very good, approximately 90%. If all significant incorrect predictions are counted, the correlation is approximately 80%. If the essentially unaugmented, low damping ratio cases are removed from consideration the correlation is again approximately 90%.

The test of the revised criterion, which has been "tuned-up" using the LAHOS data base, is by application to other landing data. Subsection 2.7 contains the results of such an application of the criterion to the Space Shuttle data and the data from the recent NT-33 Equivalent Systems Verification Program (Reference 14).

2.5 CRITERION CORRELATION ANOMALIES

There are several anomalies in the criterion correlation presented in Figure 10. Most bothersome are those cases where the criterion predicts better ratings than were given by the pilots, since the prime function of a criterion is to provide design guidance which will avoid flying qualities problems. The various anomalies are discussed under the following headings:

- Low Damping Configurations (3-Series)

The 3-series configurations without lags (3-C, 3-0, 3-1) were predicted by the revised criterion to be worse than observed by the pilots. For the configurations with additional lag (3-2 to 3-7), the predicted and actual pilot ratings were both Level 3. Although in these cases the resonance predicted by the criterion was typically somewhat higher than indicated by the pilot comments, the correct flying qualities level was at least predicted.

The lightly damped cased without lags (3-C, 3-0, 3-1) were rated Level 2 but predicted by the criterion to be solid Level 3 aircraft. Pilot comments suggest that the aircraft were not flown in a closed-loop fashion, particularly in the flare and touchdown phase. It is in this phase that the pilot flies in a tight closed-loop fashion for the majority of the other configurations which have significant initial delay to a pilot input.

It would appear that for these unaugmented configurations with reasonable initial response but oscillatory final response that the pilot in the evaluation environment is able to fly in an essentially open-loop fashion. For example, Pilot A commented that there was "No PIO, just an airplane bounce." Poor initial response brought about by an initial delay or lag appears to force the pilot to fly in a closed-loop fashion, witness the reasonable correlation of the majority of the data. It is entirely possible that evaluation of these configurations in moderate to heavy turbulence would force the pilot to fly in a closed-loop fashion and result in pilot ratings more consistent with the criterion.

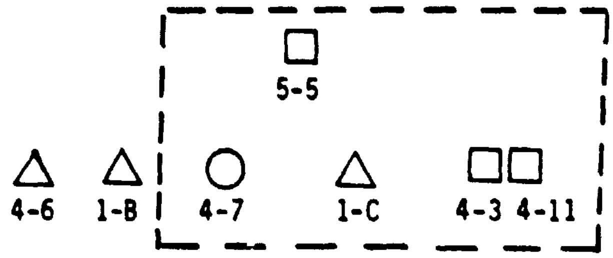
Unaugmented, lightly damped aircraft are not typical of today's highly augmented vehicles and are, therefore, not a primary factor in evaluating the usefulness of the criterion. However, the fact remains that the landing closed-loop criterion does not handle such aircraft. The pilot ratings for the low damping configurations without lags are also not consistent with the existing requirements (-8785B); again evaluation in low turbulence levels may be responsible for these discrepancies.

- Configurations in the Dashed Box (Figure 10)

To assist in this discussion, the configurations in question are presented in Figure 11.

Configurations 4-6, 1-B, 4-7 and 1-C all are rated marginal Level 1 aircraft; when the safety pilot ratings are used for guidance, the placement of these configurations on the Neal-Smith plane appears reasonable. For each evaluation, the safety pilot gave an independent rating for the configuration based on his observation of the performance. This rating does not, obviously, account for any deficiencies related to pilot workload but can be used by the analyst to uncover inconsistent performance related ratings.

Configuration 5-5 is rated Level 3 (PR = 7) but the safety pilot rating was significantly different (PR = 4). Since both ratings were based on observed performance which was degraded by a tendency to overcontrol, this rating is not considered to be a significant anomaly.



RATINGS

CONFIG.	TOTAL APPROACH	APPROACH
4-6	4	1 ½
1-B	5	-
4-7	3	3
1-C	4	-
4-3	5 → 8	2 → 5
4-11	8	3
5-5	7	2

Figure 11 LAHOS CORRELATION ANOMALIES

The ratings for Configuration 4-3 which was evaluated three times show considerable variability. The average rating is around the Level 2 boundary. This configuration appears to be sensitive to pilot technique and turbulence conditions.

Configuration 4-11 was only evaluated once and was given a clear Level 3 rating by the pilot; it is, therefore, an anomaly which stands out.

Configurations 5-5, 4-3 and 4-11 have one feature in common: in each case, there is a sharp degradation in flying qualities as the task requirement and corresponding pilot "gain", or standard of performance, increases near the ground. Note the rating change between approach and touchdown shown on Figure 11. The sensitivity of these configurations to changes in criterion parameters is reviewed in the next subsection. It appears that, for reasons which are not immediately obvious from the comments, the pilot is unable to achieve a consistent performance standard for these configurations.

- Other Configurations of Interest

Configuration 4-0 from the original LAHOS data set was not used in this study. The pilot rating (PR = 6) appears inconsistent when compared with 4-1 (PR = 2) which was used as the base configuration for the highly damped series. Configuration 4-0 would plot in the Level 1 region but was rated Level 2. This inconsistency is mentioned since the trend in modern control system designs is toward overdamped systems. A more thorough evaluation of very highly damped configurations is required.

Configuration 1-A appears (see Figure 10) with a Level 2 symbol in the revised criterion Level 1 region. The configuration was rated Level 1 by the Safety Pilot and Level 2 (PR = 6) by the pilot; it does not represent, therefore, a serious violation.

2.6 CONFIGURATION SENSITIVITIES TO CRITERION PARAMETERS

It is clear that some aircraft dynamic combinations are particularly sensitive to changes in task environment or piloting technique. In this context, sensitive means that large changes in flying qualities can occur with different pilots or with small changes in the task standard of performance. For these aircraft, large variations in pilot ratings for the same task are common. Indeed, the measure of a good aircraft is its insensitivity to pilot techniques or small task variations. From a flying qualities requirement viewpoint, application of the criterion at a specific bandwidth is likely required; however, from a design criterion viewpoint, evaluation of the changes in performance over a realistic range of bandwidths provides the more important information. This point is illustrated in the examples which follow.

In the context of the Neal-Smith criterion, the "sensitivity" of a configuration can be evaluated by observing the changes in closed-loop performance (resonance) and pilot workload (compensation) for changes in the criterion parameters, such as bandwidth frequency. As noted in the last subsection, the key anomalous configurations (5-5, 4-3 and 4-11) all have large changes in ratings between the approach and touchdown tasks. It is these configurations which are of particular interest in this subsection. The sensitivity of a configuration to changes in criterion parameters can be nicely illustrated using carpet plots which show the variation in resonance, $|\theta/\theta_c|_{max}$, for various combinations of bandwidth (ω_B), "droop" and pilot lead compensation (T_L). For these plots, pilot time delay is fixed at 0.2 Secs. Lead time constant is used for these plots not phase angle of the compensation at the bandwidth frequency (ϕ_{pc}) to clarify the trends. Indeed, it is not entirely clear which parameter is the appropriate way to reflect workload.

- <u>"Good" Configuration (2-1)</u>:

The carpet plot for Configuration 2-1 is presented in Figure 12. It is clear from the figure why this aircraft was chosen as a "benchmark" configuration (PR = 2): at a given value of the droop constraint (say -3 dB, the original criterion value), large increases in bandwidth (2.5 to 3.5 rad/sec) can be achieved by modest increases in pilot lead with very little increase in

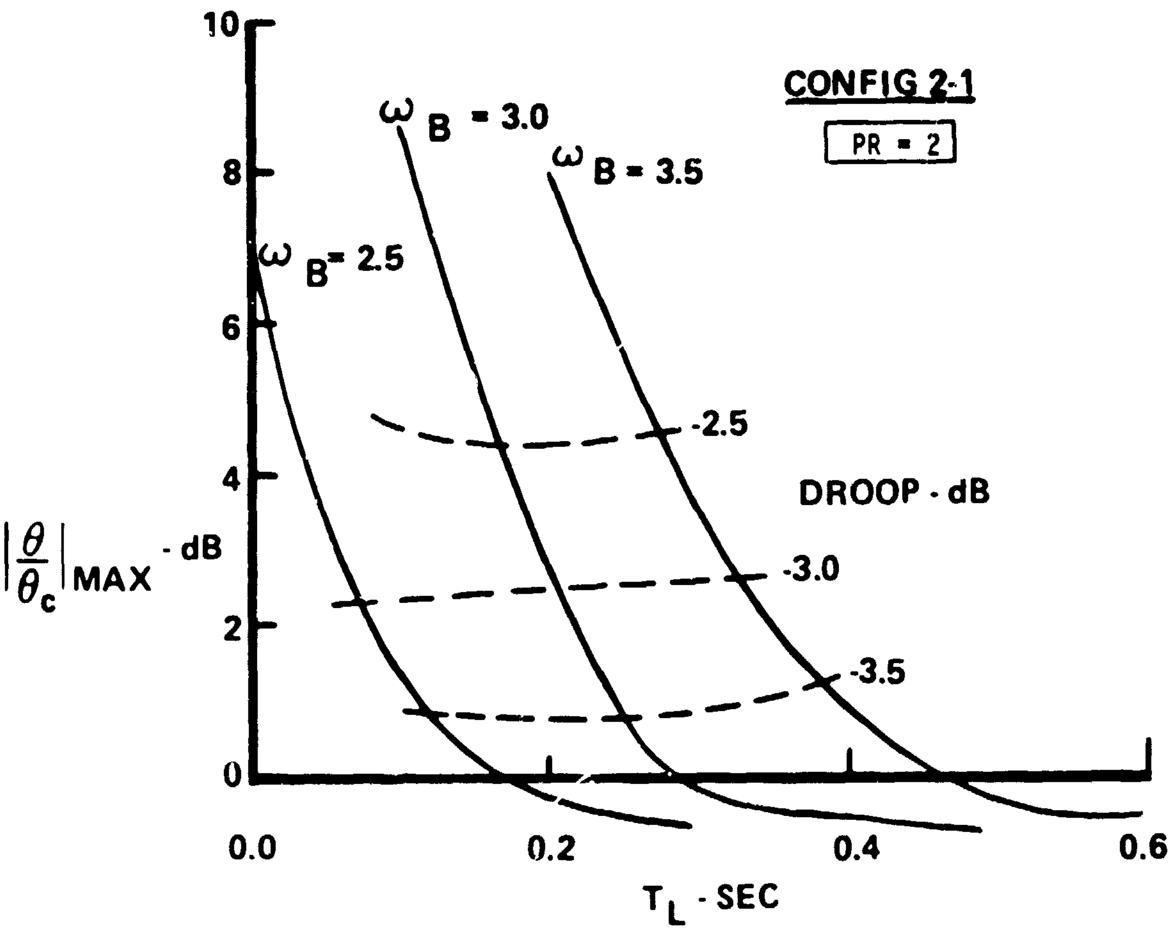


Figure 12: VARIATION OF RESONANCE AND DROOP WITH BANDWIDTH AND LEAD COMPENSATION (CONFIG. 2-1)

resonance. The pilot can fly a variety of tasks (bandwidths) with this aircraft and not see any dramatic changes in task performance. He can respond to that unexpected gust or correct an inadvertent error quickly without an explosive change in the aircraft flying qualities.

- <u>"Bad" Configuration (2-9):</u>

The contrast is evident in Figure 13 which shows the carpet plot for this very poor, PIO prone, aircraft (PR = 10). For this case, dramatic increases in resonance occur with changes in bandwidth. Clearly, this is a very sensitive aircraft with a lurking "flying qualities cliff." For the approach task, it's not great (PR = 5) but the job can be done; in the flare with the higher gain task, explosive changes in flying qualities can occur.

If a flying qualities criterion serves no other purpose, it must expose these configurations.

- <u>"Marginal" Configurations (5-5, 4-3 and 4-11):</u>

The carpet plots for these configurations are presented in Figures 14, 15, and 16. In each case, there is a steep slope of resonance versus pilot lead for a given droop constraint. The large changes in pilot ratings between the approach and touchdown tasks are further evidence of this sensitivity. These are configurations, therefore, which are impossible to evaluate properly by application of the criterion at only one bandwidth.

From a design point of view, each configuration should be tested using a means of observing the configuration "sensitivity",such as by using a carpet plot, before a final flying qualities prediction can be made.

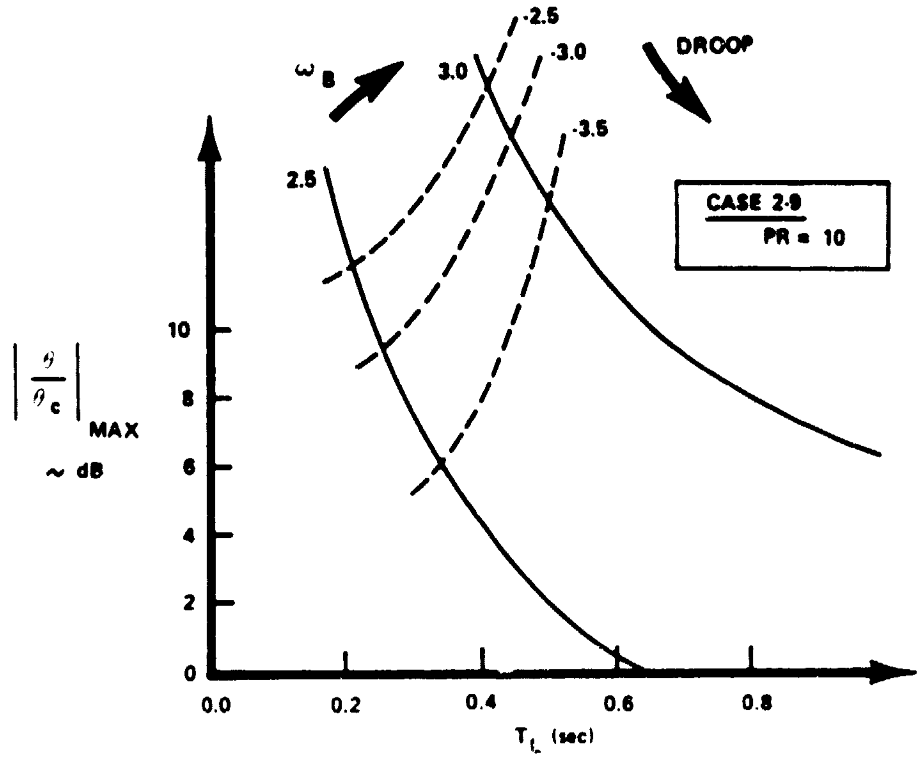


Figure 13 VARIATION OF RESONANCE AND DROOP WITH BANDWIDTH AND LEAD COMPENSATION (CONFIG. 2-9)

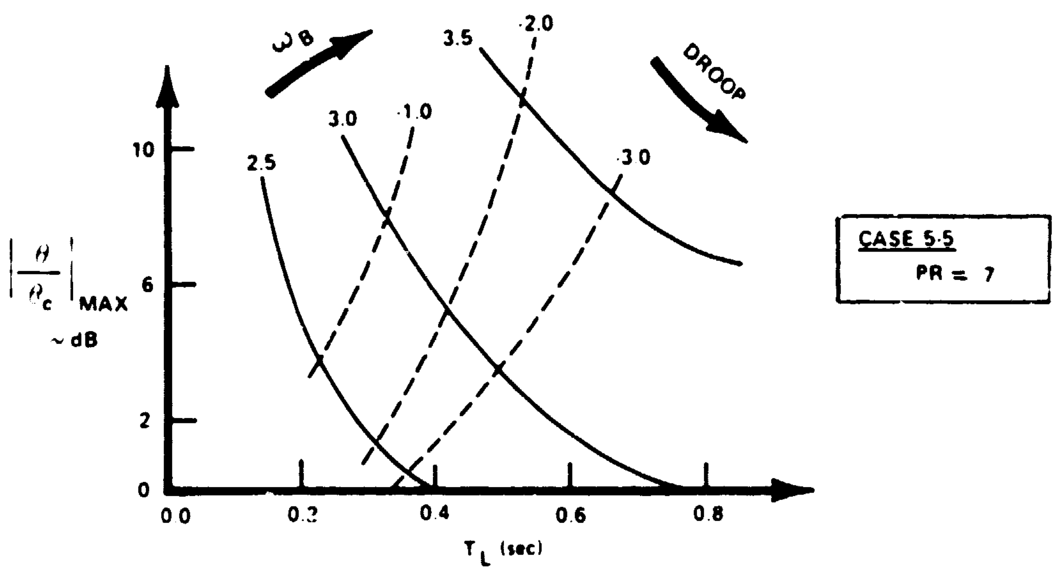


Figure 14 VARIATION OF RESONANCE AND DROOP WITH BANDWIDTH AND LEAD COMPENSATION (CONFIG. 5-5)

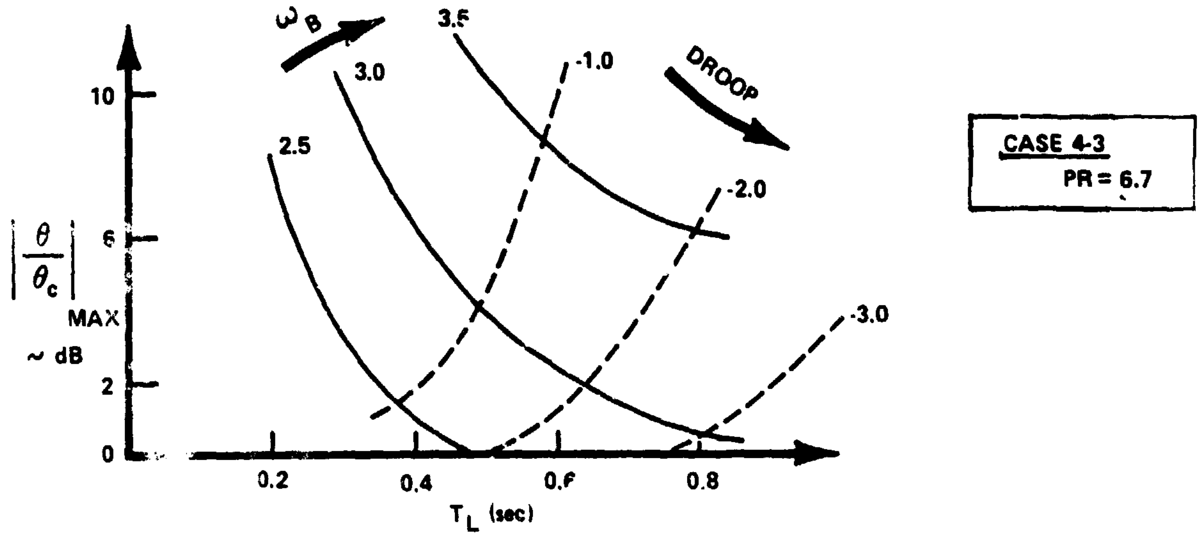


Figure 15 VARIATION OF RESONANCE AND DROOP WITH BANDWIDTH AND LEAD COMPENSATION (CONFIG. 4-3)

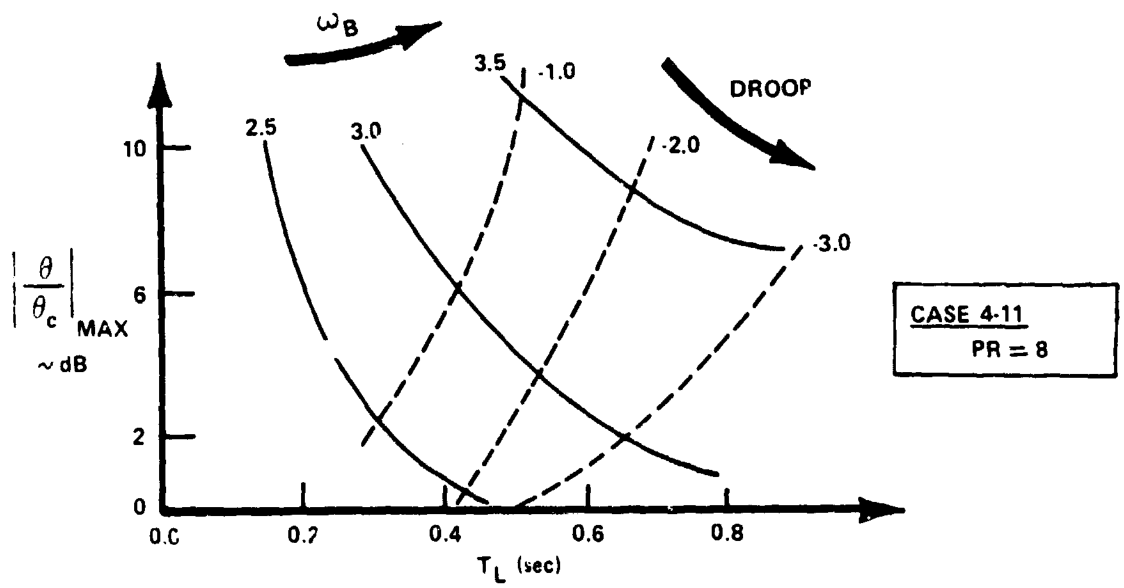


Figure 16 VARIATION OF RESONANCE AND DROOP WITH BANDWIDTH AND LEAD COMPENSATION (CONFIG. 4-11)

There is, therefore, another dimension to the criterion plane; suitable sensitivity parameters are required. From the pilot point of view, this sensitivity reflects the degree of difficulty he has in "adapting" (compensating) as the task requirements change rapidly.

- Potential "Adaptability" Criteria:

Possible "adaptability" metrics are presented in Figure 17. Further study is required to determine the exact nature of a suitable adaptability criterion. It is entirely possible that the complete criterion can be expressed in terms of an adaptability criterion without using a specific bandwidth but requiring certain gradients of, say, resonance with pilot lead, over a range of bandwidths.

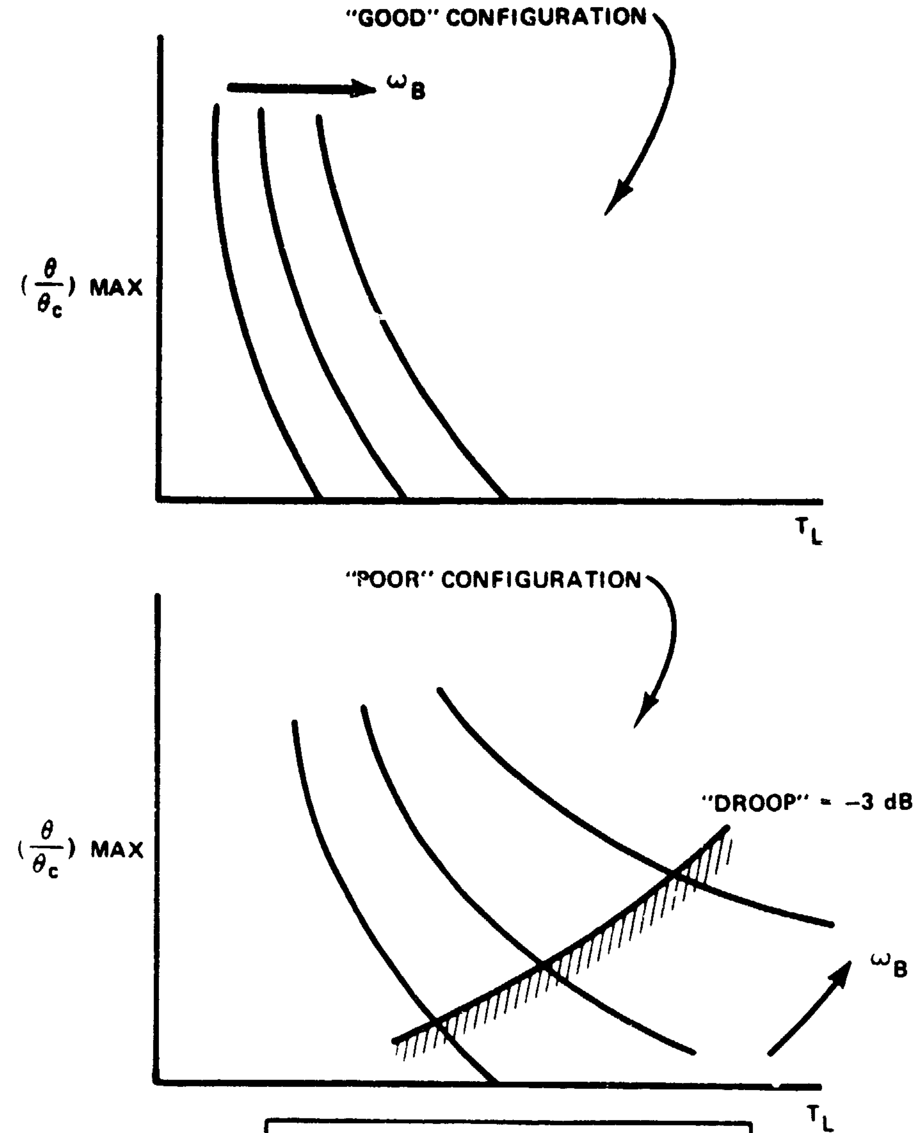
2.7 APPLICATIONS OF THE REVISED CRITERION

The first question that arises when a revision is introduced to a criterion is what the effects of this revision are on the original work. It is appropriate, therefore, to first apply the revised criterion to the original Neal-Smith data base (Reference 5).

- Original Neal-Smith Data:

For this comparison, the 350 knot data from the original Neal-Smith data was selected since this flight condition was observed to be the most realistic fighter tracking environment.

The data are presented in Figure 18 on the Neal-Smith plane using the original criterion parameters of $\omega_B = 3.5$ rad/sec and $\tau_p = 0.3$ sec and the original flying qualities boundaries.



POSSIBLE "ADAPTABILITY" CRITERIA

1. $\frac{dT_L}{d\omega_B}$, $(\theta/\theta_c)_{MAX}$ = CONST
2. $\frac{d(\theta/\theta_c)_{MAX}}{dT_L}$, ω_B = CONST
3. $\frac{d(\theta/\theta_c)_{MAX}}{d\omega_B}$

Figure 17 ADAPTABILITY CRITERIA

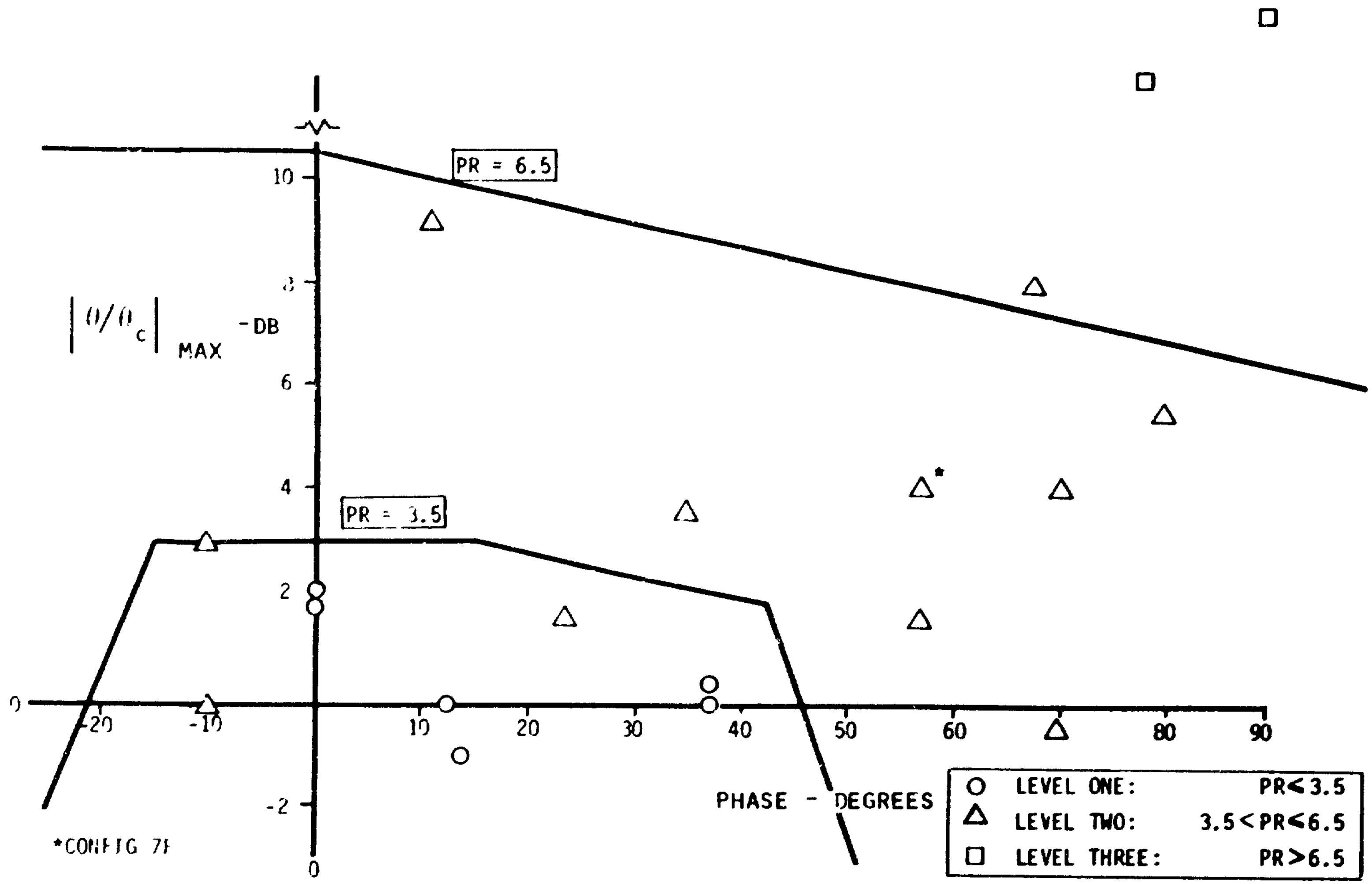


Figure 18 NEAL-SMITH DATA: 350 Knot Cases, ω_B = 3.5 r/s, τ_p = 0.3 sec.

Since the bandwidth required is a function of the task, which in this case is a fighter pitch tracking task, the original data was evaluated at a variety of bandwidths with the pilot delay, τ_p, of 0.2 sec as used in the revised Neal-Smith criterion based on the LAHOS data. The best correlation of the data is presented in Figure 19; criterion parameters were $\omega_B = 4.5$ rad/sec and $\tau_p = 0.2$ sec. Correlation of the data is as good as in the original study. Both the revised (see Figure 10) and original boundaries (see Figure 8A) are shown; these changes do not appear to be significant. The revised boundaries are, therefore, generally applicable.

It is not surprising that the standard of performance (bandwidth) is higher for the fighter tracking task (4.5 rad/sec compared to 3.0 rad/sec). The surprising result in the recent studies of flying qualities in the approach and landing task is that the landing phase of the task is significantly more demanding than previously recognized. In this context, it is worth noting that the majority of the data used to develop the Flight Phase Category C data in MIL-8785B, and -8785C for that matter, is applicable to the approach phase only and not the landing task. For the specifications, Flight Phase Category A requirements are more applicable to the real Category C tasks than are the present landing approach requirements.

A review of the Category C requirements for all aircraft classes is in order therefore, without regard to the degree of augmentation present.

- Space Shuttle Data (Reference 15)

The Space Shuttle is obviously a unique vehicle; of particular interest in the context of this study are the landing flying qualities. During numerous studies, simulations, and indeed during the last flight itself, the aircraft has exhibited less than satisfactory pitch landing flying qualities (see References 11 and 15, for example). In fact, during the last flight (Number 5) a pitch PIO was encountered near touchdown. While there are clearly other factors about the design of this unusual craft that influence the pitch flying qualities, the equivalent time delay associated with the complex digital flight control system is potentially a major source of the problem.

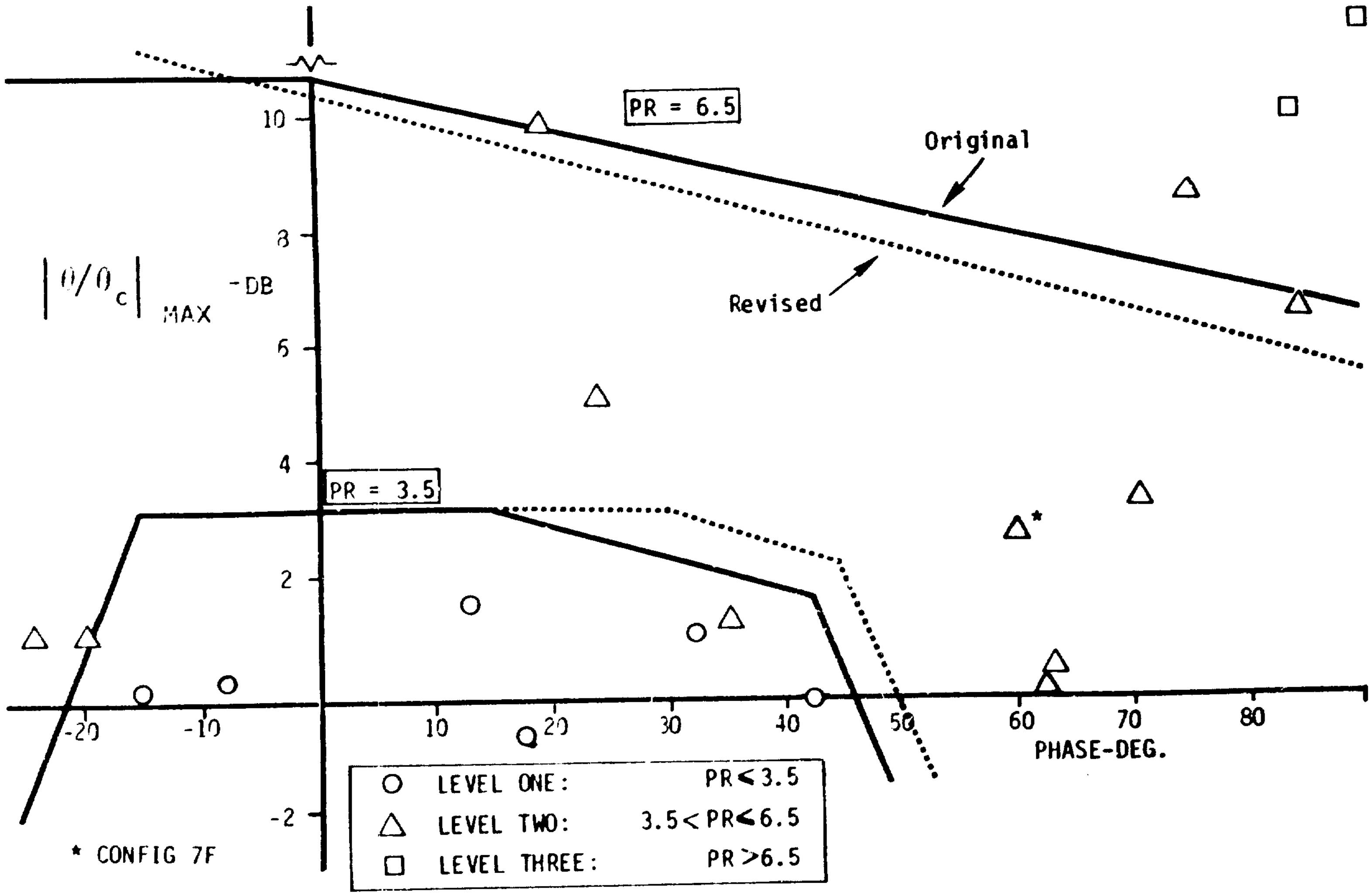


Figure 19 NEAL-SMITH DATA: 350 KNOT CASES/ $\omega_B = 4.5$ r/s, $\tau_p = 0.2$ sec. (ORIGINAL DROOP CONSTRAINT)

Using the Shuttle model developed for the analysis in Reference 15, the Shuttle configuration was evaluated using the revised Neal-Smith Criterion for pitch landing flying qualities. The results are shown in Figure 20 along with the Equivalent System Program results discussed in the next subsection. Also shown on Figure 20 is the large increase in resonance which occurs for a modest bandwidth and lead compensation change.

The criterion confirms what was observed in flight: the Shuttle, as represented by the model used in Reference 15, is PIO prone and a marginally acceptable vehicle in the landing task. Further, the "sensitivity" reflected by the relatively large change in resonance with changes in bandwidth indicates that the flying qualities are subject to rapid deterioration (a "cliff") with changes in task performance standard or pilot technique. In summary, the criterion "predicts" the Shuttle characteristics satisfactorily and is therefore a useful design evaluation tool.

Also shown on Figure 20, is the effect of including a "PIO suppressor", which is, in effect, a command gain changer which operates as a function of pilot input size and frequency. Background to this analysis, which was part of this study, is fully documented in Appendix A. The analysis is approximate since a linear description of the non-linear suppressor was necessary for use with the frequency-domain Neal-Smith criterion. A suitable time-domain closed-loop criterion would not require this approximation. The results of the admittedly approximate analysis show that the suppressor does reduce the PIO tendency but does not cure the explosive nature of the configuration.

Although the specific Shuttle "PIO suppressors" were studied in Reference 3, more general studies are clearly in order. These studies must include simulations with very realistic, stressed, tasks since small changes in task or pilot technique are known to have a dramatic effect on the flying qualities of PIO prone aircraft.

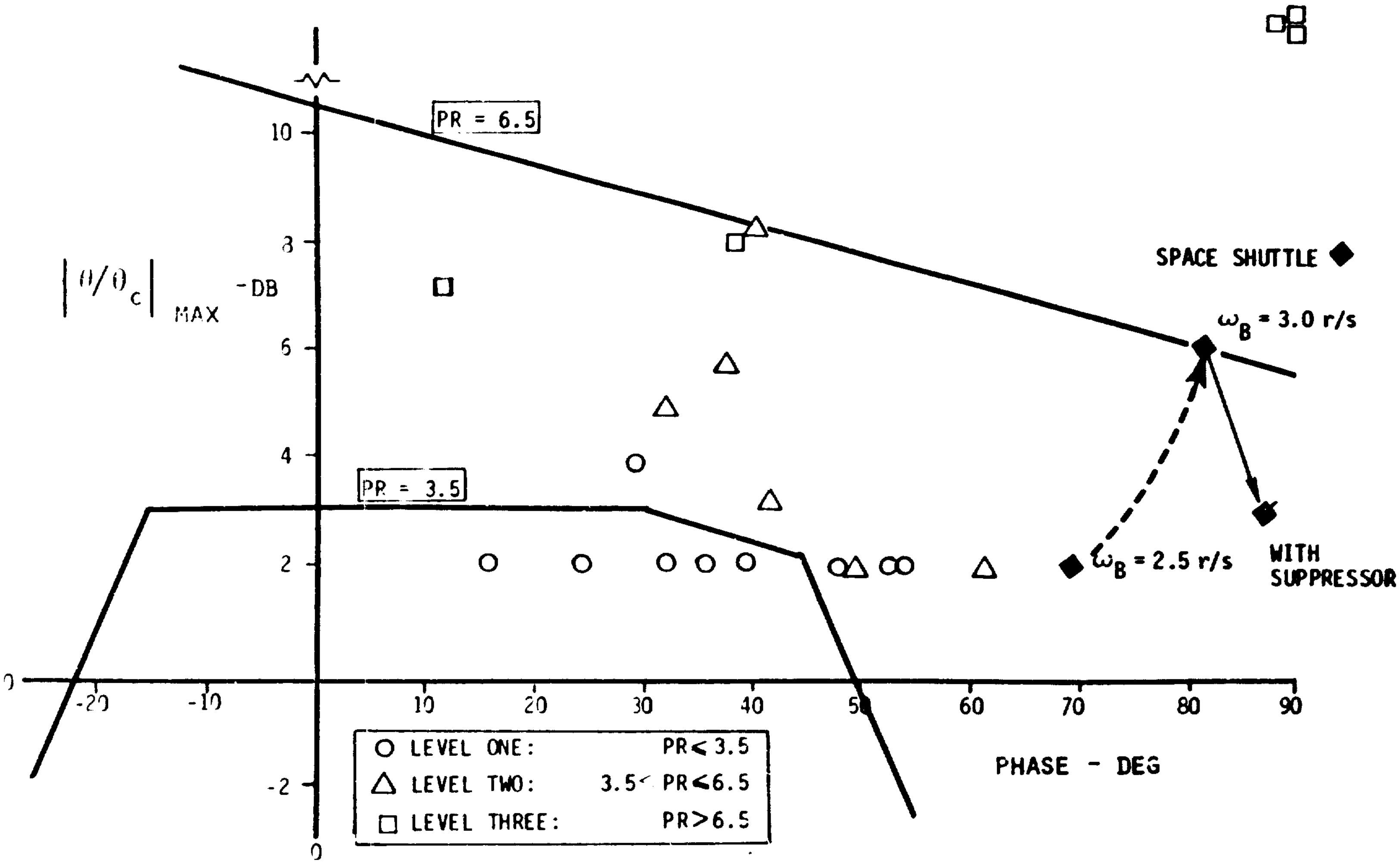


Figure 20 EQUIVALENT SYSTEMS PROGRAM AND SPACE SHUTTLE DATA:
ω_B = 3.0 r/s, τ_p = 0.2 (Revised Boundaries)

- <u>Equivalent Systems Verification Data (Reference 14)</u>

An in-flight simulation program was recently conducted using the AFWAL/Calspan NT-33 aircraft to verify the equivalent system approach and to evaluate pitch landing flying qualities of highly augmented aircraft. The results from the longitudinal portion of this program represents an ideal data package since a wide range of high order systems were evaluated in a realistic landing task. Accordingly, the major configurations from Reference 14 were evaluated using the revised Neal-Smith criterion; the results are presented in Figure 20.

The discrimination of the data is quite reasonable, particularly when the preliminary nature of the equivalent system program is considered. It was a small program conducted on a compressed schedule and therefore the variability of the pilot rating data might be higher than normal.

As discussed in Section 2.4, for comparison purposes, it is reasonable to consider that a correlation "failure" occurs when the predicted flying qualities level is better than the actual pilot rating level. In this context, the converse (predicted worse than actual) is not a failure, but could possibly result in a somewhat conservative flight control system.

With these correlation rules the criterion correlation is very good, approximately 95%. If all incorrect predictions are counted, the correlation is 75%, although few of the violations are really significant.

It should be noted that the same area which produced correlation anomalies with the LAHOS data: 2 dB resonance and 50 to 65 deg of phase, also has some anomalies in this data set. The anomalies in this case are, however, not serious, but would suggest an extension of the Level 1 boundary; however, considering all the data reviewed the revised boundaries shown seem reasonable.

2.8 SUMMARY

From this study of the application of the Neal-Smith closed-loop flying qualities criterion to the landing flying qualities of highly augmented aircraft, the following observations can be made:

- Control of pitch attitude in the landing task is a critical, relatively high bandwidth task.

- A revised version of the Neal-Smith criterion proved to be a good discriminator of pitch landing flying qualities. For the revised criterion:
  - Bandwidth of 3.0 rad/sec and time delay of 0.2 sec were selected,
  - Level 1 and Level 2 boundaries were slightly altered,
  - Droop requirements were relaxed for non-oscillatory aircraft.

- Bare airframe, lightly damped configurations were not adequately evaluated during the LAHOS program and do not correlate with the revised criterion. More study is required in this area, although such configurations are largely of academic interest in the context of today's control system designs.

- More data is required for very heavily damped aircraft to address the applicability of the criterion in this area.

- The required a priori knowledge of the performance (bandwidth) requirements for a particular task, may be eliminated by development of a suitable general adaptability requirement for augmented aircraft.

Section 3

ONSTOTT CRITERION

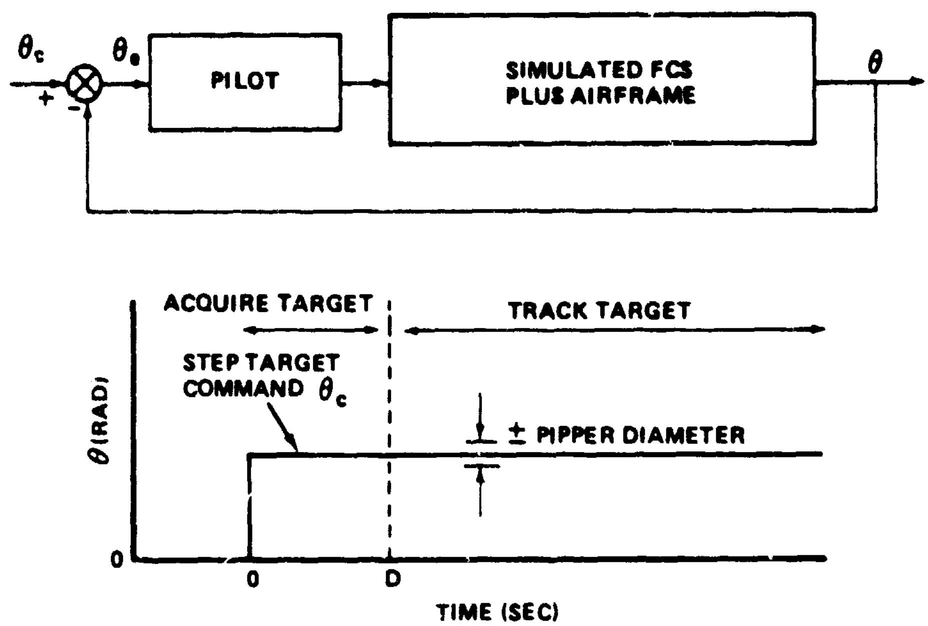
A longitudinal flying qualities criterion developed by Onstott of the Northrop Corporation was included in the current study because of the criterion's ability to correlate the original Neal-Smith data evidenced in Reference 7. Furthermore, because of its time domain formulation, the potential to address non-linear flight control systems is inherent in the method.

3.1 MECHANICS OF CRITERION

The basis of the criterion is a compensatory pilot model of a step target tracking task over a specified time period (Figure 21). The pilot model adopts two control modes during the tracking. In the initial acquisition phase the pilot model employs proportional and rate attitude compensation. At some time, D, switching to a tracking mode takes place and integral attitude compensation is added. This mode switching is intended to provide both rapid initial target acquisition and precise final tracking.

Application of the criterion requires: first, maximizing the time on target (TOT), defined as the total time for which the pitch attitude is within one pipper diameter of the commanded attitude; and, second, the calculation of the RMS tracking error. Since TOT is a function of the five pilot model parameters (K_{p_T}, T_{L_T}, K_{p_F}, T_{L_F}, K_{I_C}) and the switching time D, maximizing TOT is a formidable optimization problem.

In Reference 7, pilot ratings for the Neal-Smith data are shown to correlate with the two tracking performance parameters, TOT and RMS error. The data support the intuitive notion that high TOT and low RMS tracking error are indicators of satisfactory flying qualities. It is worthwhile to note that this criterion is to some extent, equivalent to the Neal-Smith criterion both from the standpoint of the "pilot" model form and the fact that a performance standard is employed to determine the model parameters. When correctly derived the time domain characteristics, TOT and RMS tracking error, are, in some sense, equivalent to bandwidth and resonance in the frequency domain. The most noteworthy difference in the two criteria is the lack of a workload metric in the Onstott criterion.



ACQUISITION

TIME $< D$, $\delta_{e_I} = (\text{DELAY } \tau) \left\{ K_{p_I} \left(\theta_e(t) + T_{L_I} \dot{\theta}_e(t) \right) \right\}$

TRACKING

TIME $\geq D$, $\delta_{e_F} = (\text{DELAY } \tau) \left\{ K_{p_F} \left(\theta_e(t) + T_{L_F} \dot{\theta}_e(t) + K_{1C} \int_0^t \theta_e(s) ds \right) \right\}$

Figure 21 DEFINITION OF STEP TARGET TRACKING TASK

In the Neal-Smith Criterion, the level of flying qualities is a function of both closed loop performance (bandwidth and resonance) and pilot workload (phase lead compensation). In Onstott's criterion, flying qualities are not related to the magnitudes of the computed pilot compensation. At the current level of experience with the Onstott criterion, it is not known whether this absence of a workload metric is a fundamental limitation of the method.

The results of applying the Onstott criterion to selected LAHOS data and the original Neal-Smith data are presented in the next section. This data was generated by Onstott using a recently developed digital computer version of his method. During this process a discrepancy was discovered in the implementation of the closed-loop method; the impact of this discrepancy is discussed in Section 3.3.

3.2 APPLICATION TO LAHOS AND NEAL-SMITH DATA

The calculation of the Onstott pilot model parameters is a complex optimization problem. In Reference 7 the maximization of TOT was performed by manually perturbing each of the parameters and searching for a global maximum TOT. It is noted that the rating data from Reference 5 presented in Reference 7 are in error in that, for repeated evaluations, the best rating was selected as representative of the group. For certain configurations, pilot ratings, which the authors of Reference 5 considered anomalous because of "learning curve" effects, were employed. With these errors corrected, the correlation of pilot rating with TOT and RMS error required slight shifting of the flying qualities boundaries to accommodate the rating changes. Subsequent to the initiation of the current study, Onstott developed an automated program for the optimization of the pilot model parameters and the computation of TOT and RMS error statistics. This program was applied first to an abbreviated LAHOS data base (Reference 9 with second ordered dynamics excluded) and then to recomputing the original Neal Smith data. These new data are plotted in Figures 22A and 23A. The configuration identifiers for each data set are presented in Figures 22B and 23B. At this point, the reader should be

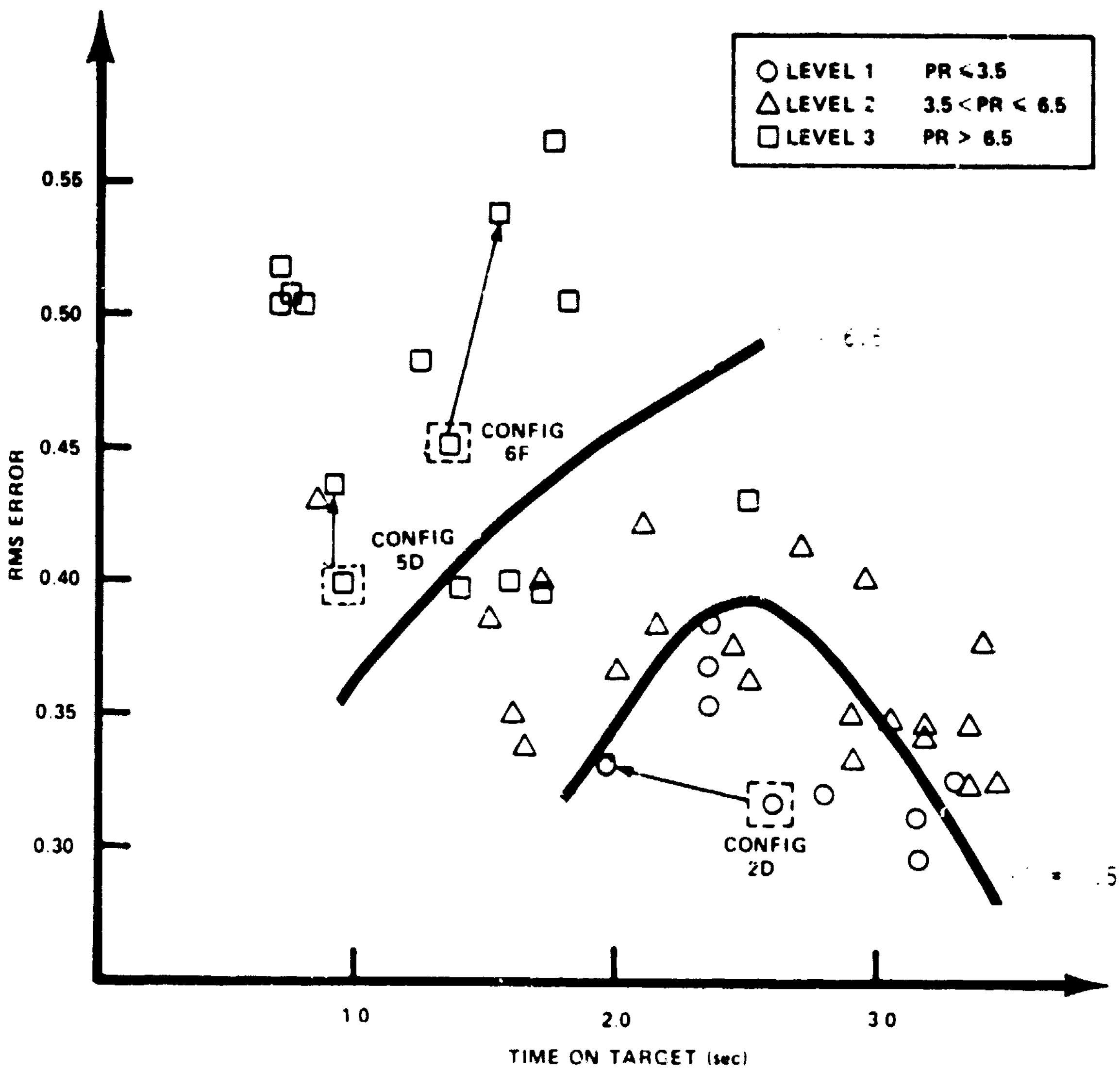


Figure 22A NEAL-SMITH DATA VS TIME HISTORY CRITERION

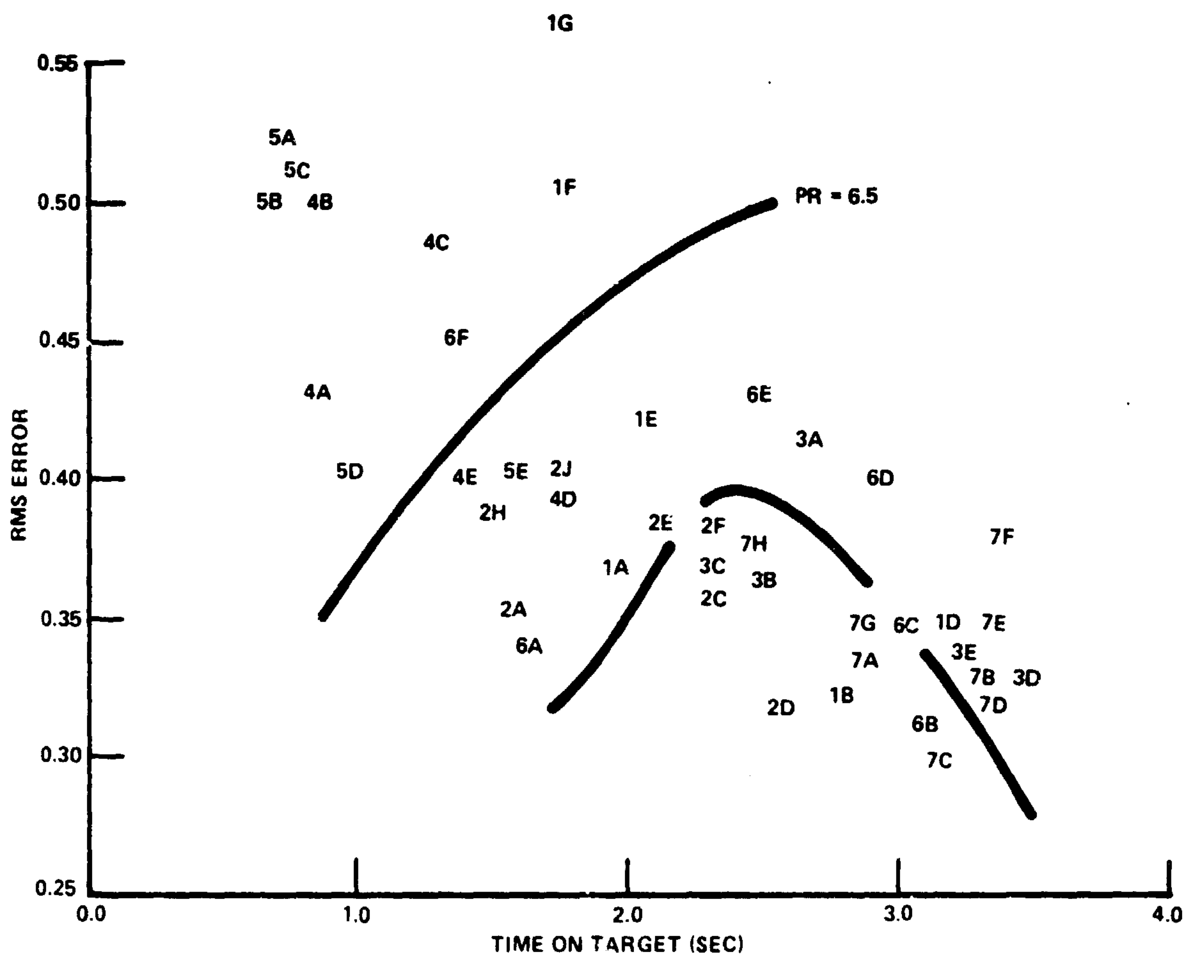


Figure 22B NEAL-SMITH DATA vs TIME HISTORY CRITERION

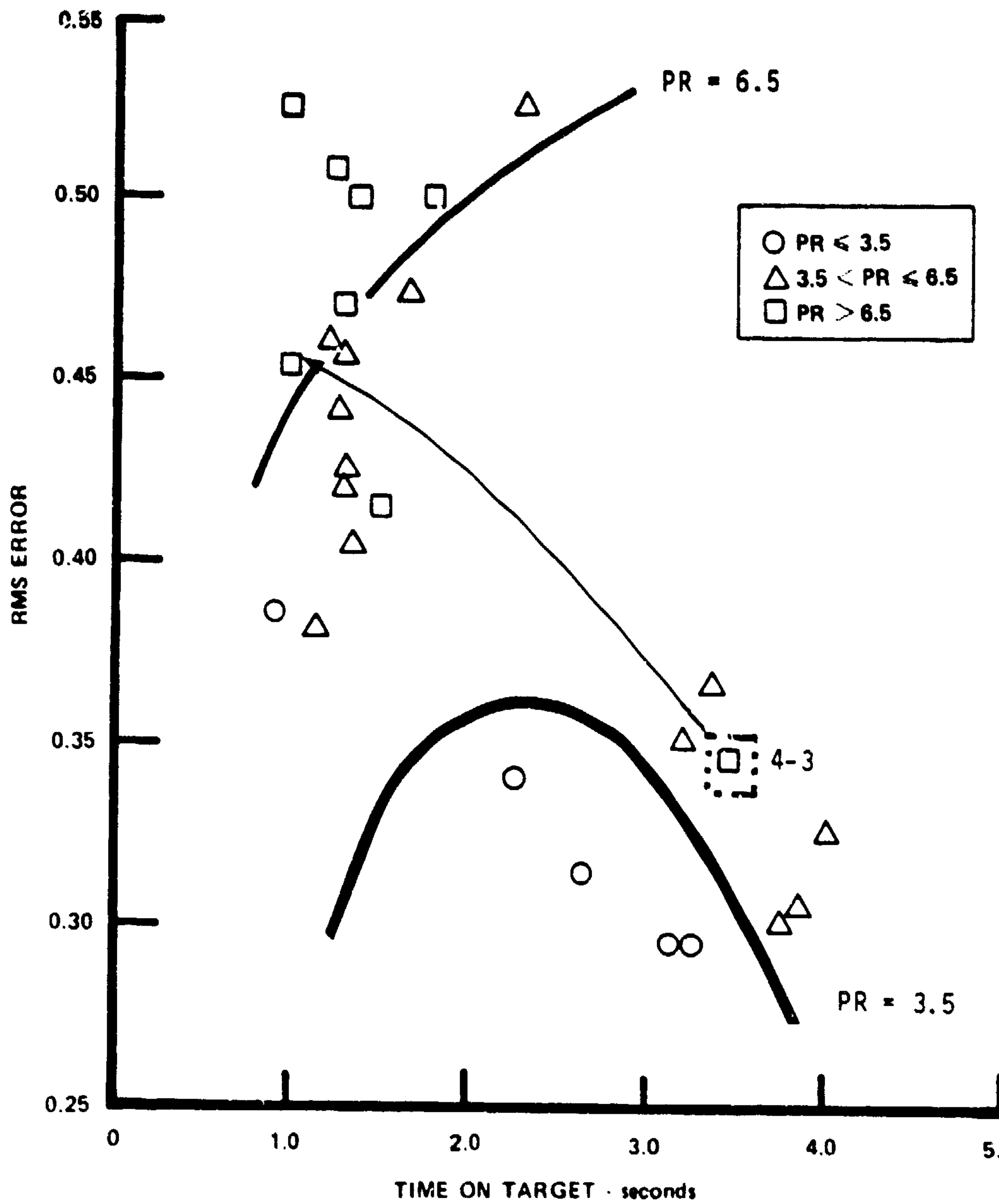


Figure 23A LAHOS DATA VS TIME HISTORY CRITERION

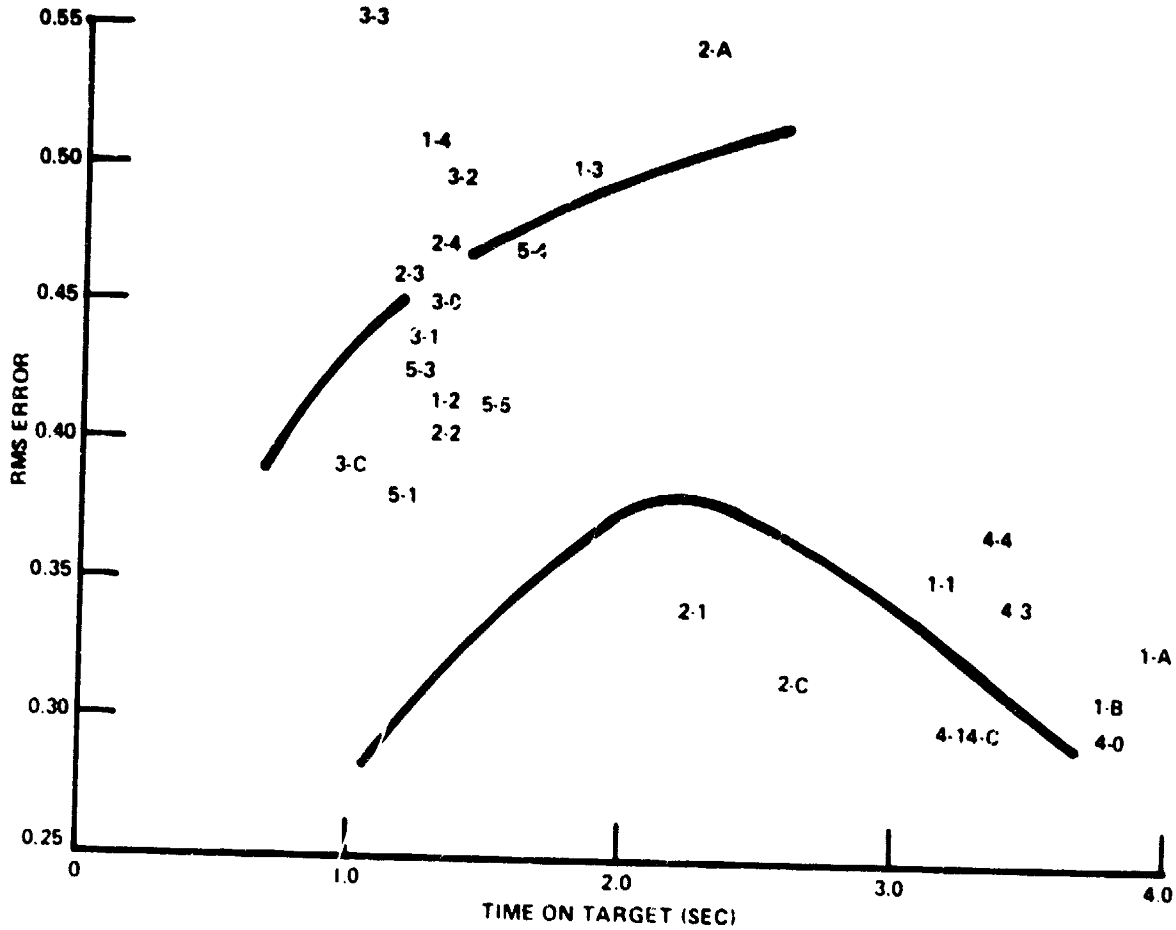


Figure 23B LAHOS DATA vs TIME HISTORY CRITERION forewarned that an implemention error was found in the criterion which biased the data and consequently, its correlation to TOT and RMS error. Details and ramifications of this error are presented in Section 3.3.

As can be seen from these plots, the criterion tends to group the data by level of flying qualities with low RMS tracking error and high time on target corresponding to satisfactory flying qualities. The converse is also true. However, one anomalous trend immediately apparent is the tendency for a group of configurations from each experiment which received acceptable but not satisfactory ratings ($3.5 < PR \leq 6.5$) to fall in the region of low RMS tracking error and high TOT. Intuitively this trend appears contradictory to the philosophical basis of a performance only flying qualities criterion.

As a consequence of this anomoly, a more detailed time domain examination of the closed loop characteristics predicted by the Onstott criterion was conducted to determine whether the step response time histories exhibited the properties cited in pilot commentary and ratings. It was found that for some configurations the analytical responses were substantiated by pilot comments while in others the responses were decidedly incorrect. For example, Configuration 5D from the Neal-Smith data (Reference 5) was described by the pilots as PIO prone and received a pilot rating of 8.5 with a PIO rating of 4. Figure 24 illustrates the closed loop attitude responses predicted both by the Onstott and Neal-Smith criteria. It can be seen that both criteria predict responses that are lightly damped and oscillatory with about the same frequency. Furthermore, the Onstott criterion predicts poor performance (low TOT and high RMS tracking error) for this configuration (See Figure 22). For this case, both criteria predict equivalent closed loop characteristics.

In another case, 6F from Reference 5, with similar closed loop flying qualities deficiencies, different characteristics are predicted by the two criteria (Figure 25). The Onstott criterion yields a heavily damped first-order like response with slow rise time. Neal-Smith on the other hand produces an almost zero damped highly oscillatory response which is consistent with the pilot rating of 9 and the PIO rating of 4. In terms of the Onstott

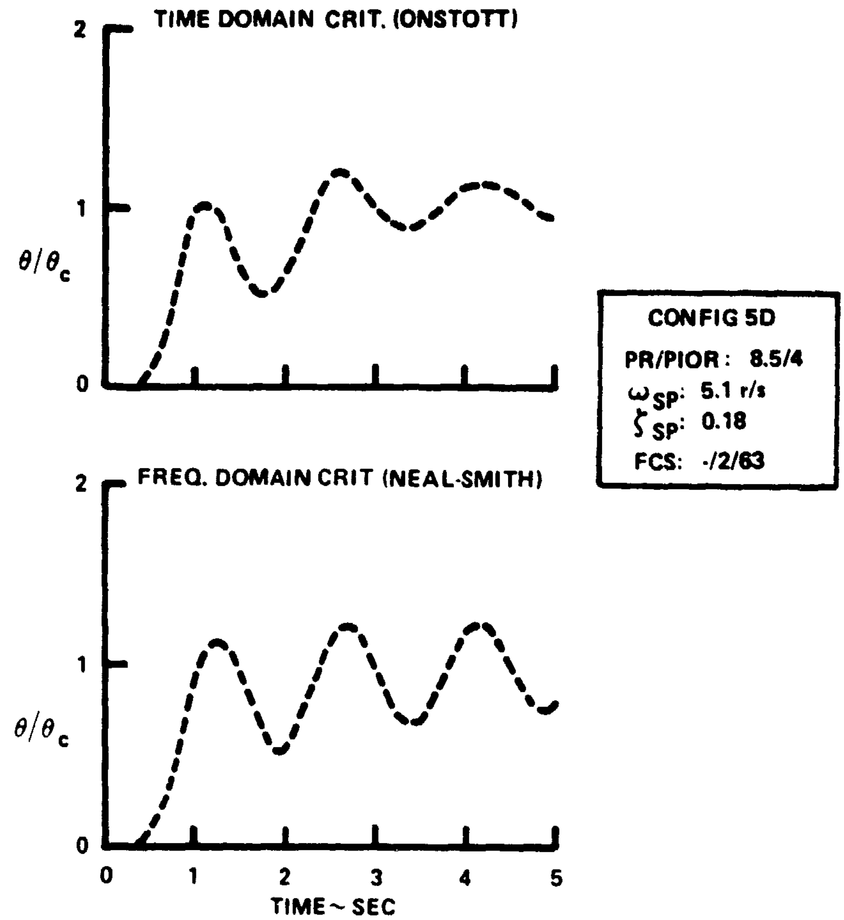


Figure 24 CLOSED-LOOP PITCH ATTITUDE RESPONSE TO A STEP ATTITUDE COMMAND

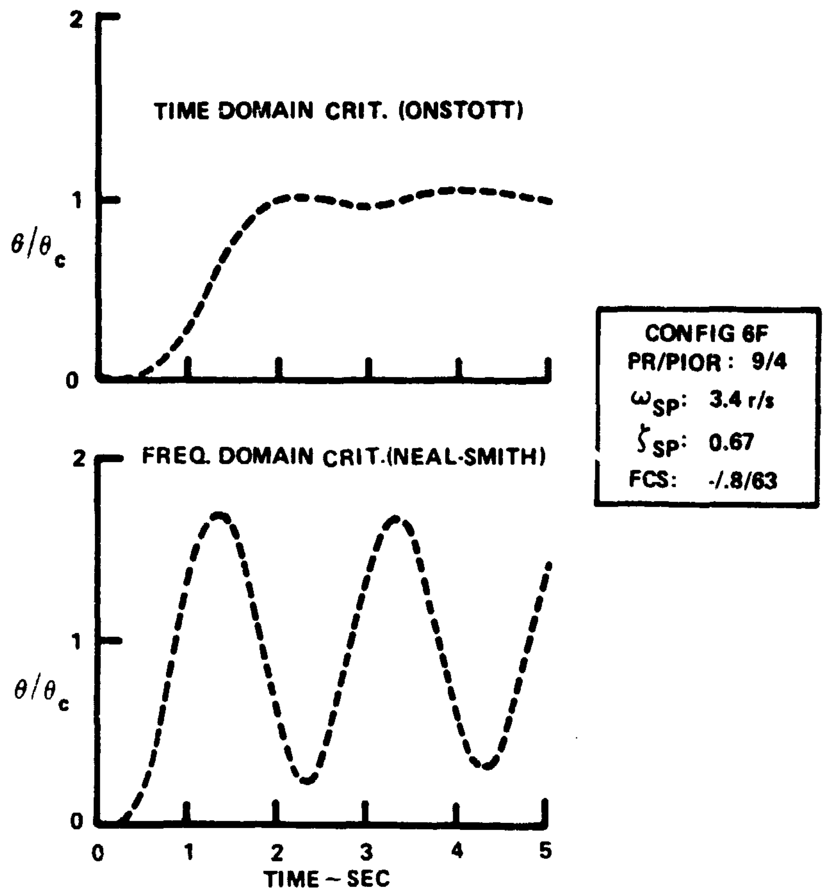


Figure 25 CLOSED-LOOP PITCH ATTITUDE RESPONSE TO A STEP ATTITUDE COMMAND

performance parameters, this configuration yields a high RMS tracking error and low TOT (Figure 22). However, these poor performance characteristics are attributable to the sluggish and nearly dead beat response rather than oscillations as would be expected. Clearly, for this configuration, the Neal-Smith criterion produces time domain results which duplicate the characteristics cited by the pilots while the Onstott criterion predicts response at variance with these observations.

3.3 CRITERION MODIFICATION

As a result of these observations, the program listing for the automatic computation of the Onstott performance criteria was examined to determine possible modifications which might resolve these anomalies with certain configurations. A discrepancy was found with respect to the functional block diagram in Reference 7 and the actual computer implementation. The pilot model is illustrated as a forward loop compensator which operates on the attitude error signal. For example, in the tracking mode, the command to the aircraft is given by:

$$\delta_{e_F} = (delay\ \tau)\left\{ K_{P_F}\left(\theta\varepsilon\,(t) + T_{L_F}\,\dot{\theta}\varepsilon\,(t) + K_{1_c}\int_0^t \theta\varepsilon\,(s)\,ds \right)\right\}$$

However, the error rate term $\dot{\theta}_\varepsilon$ is implemented as $\dot{\theta}_\varepsilon = -\dot{\theta}$ rather than $\dot{\theta}_c - \dot{\theta}_\varepsilon$, which implies that only the proportional and integral terms are series compensation while the rate term is feedback compensation only.

The effect of this implementation on the tracking mode is illustrated in the block diagram of Figure 26.

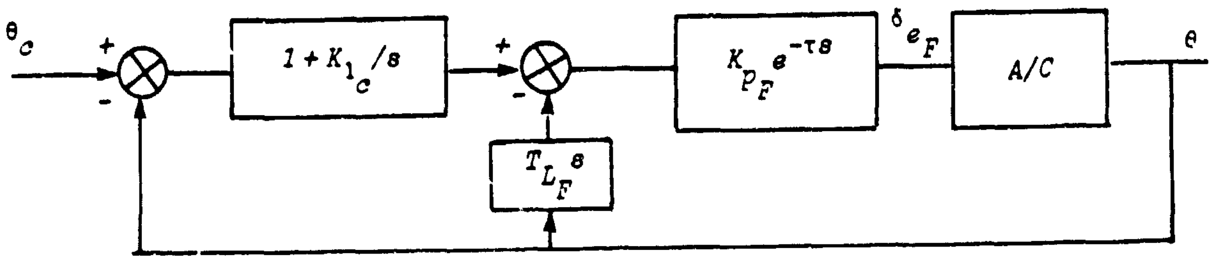


Figure 26 CLOSED-LOOP BLOCK DIAGRAM AS IMPLEMENTED

The acquisition mode is similarly affected. The block diagram for this mode can be realized by setting $K_{I_c} = 0$ and redefining the nomenclature of the command and feedback gains.

As a check, the calculation of $\dot{\theta}_\varepsilon$ in the time history subroutine of the Onstott criterion program was corrected and selected cases were rerun. In each of these cases, the correction had the desired effect, in that, configurations with erroneous damped responses now tended to take on oscillatory characteristics while configurations which were substantially in agreement both with pilot comments and ratings and the Neal-Smith responses were little changed. For example, Figure 27 indicates that Configuration 6F from Reference 5 now exhibits a large initial overshoot and bobble. The final portion of the response, however, indicates a rapid convergence to the commanded attitude which is attributable to the integral of attitude compensation.

Figure 28 is a comparison of time histories for Configuration 2D from Reference 5 using the original and modified Onstott criterion programs and the original Neal-Smith program. Note that each response is similar and in agreement with the pilot rating and PIO rating. For this case, the program modification had little effect on the result.

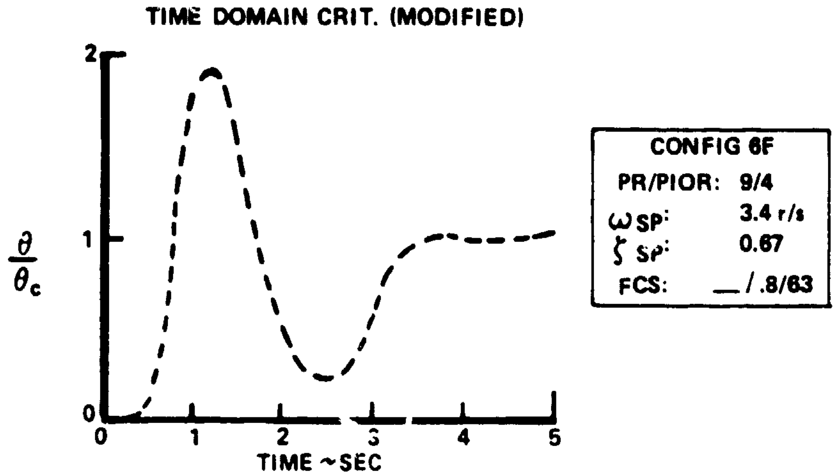


Figure 27 CLOSED-LOOP PITCH ATTITUDE RESPONSE TO A STEP ATTITUDE COMMAND

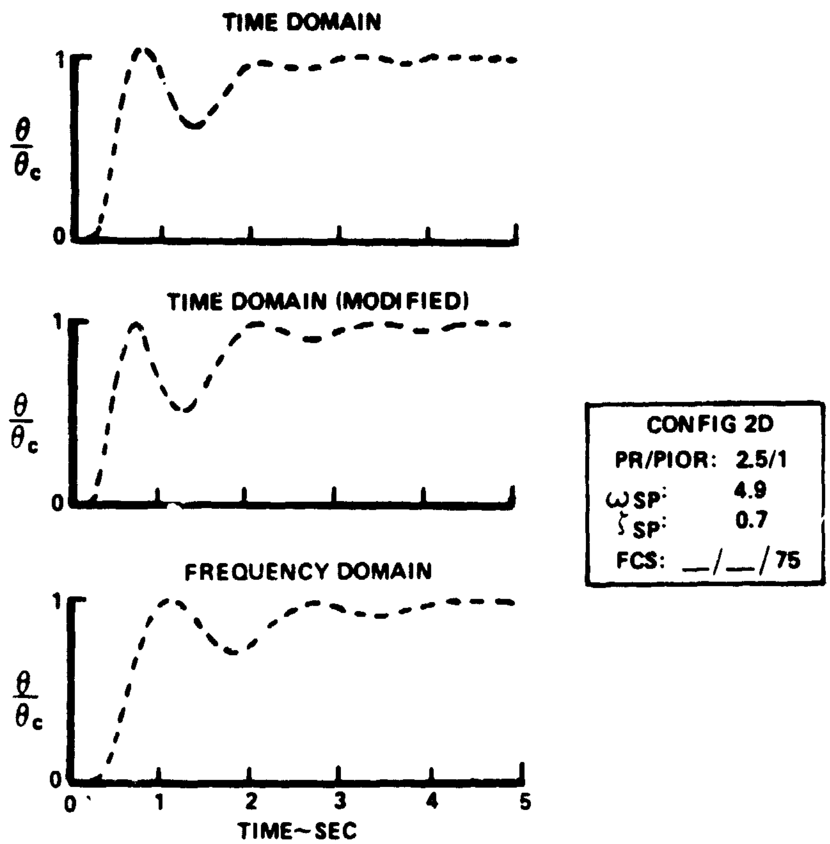


Figure 28 CLOSED-LOOP PITCH ATTITUDE RESPONSE TO A STEP ATTITUDE COMMAND

In the Onstott criterion parameter plane the effect of the program modification is illustrated in Figures 22 and 23. For the Neal-Smith cases illustrated in Figure 22, the program modification resulted in only small changes in TOT and RMS error for the cases which were initially in good agreement with pilot ratings and comments (2D, 5D) while Configuration 6F exhibits a large increase in RMS error. For these data, the program modification appears to increase the discrimination of the criterion.

From the LAHOS data, an anomalous configuration with low RMS error and high TOT was examined (Configuration 4-3). As can be seen from Figure 23, the effect of the program modification is to increase the RMS error considerably and reduce the TOT. The resulting position in the parameter plane is more appropriate to the unacceptable pilot rating which this configuration received.

3.4 SUMMARY

The foregoing analyses indicate that the Onstott criterion has merit but exhibits anomalous results for certain configurations. Specifically, the tendency to place some configurations with Level 2 and 3 pilot ratings in the high TOT, low RMS error region of the parameter plane, and occasionally predict damped responses for configurations which are in fact oscillatory and PIO prone, is not reasonable, particularly for a performance based criterion. The tendency to predict erroneous closed loop time response characteristics for certain configurations appears to be related, however, to an error in the calculation of pilot lead compensation. Examination of selected cases with this error corrected produces both time histories and tracking statistics that are more in agreement with pilot comments and ratings. The single case from the LAHOS experiment (Configuration 4-3) suggests that the anomalous group of Level 2 high TOT, low RMS error configurations may move to more appropriate regions of the parameter plane with the $\dot{\theta}_{\varepsilon}$ computation corrected.

A major improvement in the application of this criterion would be to reduce its computational complexity. One change recommended for consideration is to eliminate the dual mode feature and operate with a proportional plus rate compensation only. This simplification would eliminate the switching time D and the integral gain $K_{1_{\sigma}}$ from the TOT state vector (i.e. 6 parameters reduced to 4) and should produce a considerable reduction in computing time.

Another factor for consideration is the current lack of a workload measure in the criterion as presently formulated. It seems intuitive that configurations with identical performance statistics may receive significantly different pilot ratings depending on the pilot compensation (i.e. workload) required.

It is recommended that further development of a time domain criterion, such as the Onstott technique described here, be pursued. The current trend in FCS design, toward non-linear and even time varying command and feedback networks has created a need for flying qualities design and analysis techniques capable of addressing these systems without resorting to cumbersome and possibly inappropriate approximations such as linearization and describing functions (see for example Appendix A).

Section 4

MCAIR EQUIVALENT SYSTEM APPROACH

The equivalent system approach to the evaluation of the longitudinal flying qualities of highly augmented aircraft involves the representation of a high order aircraft dynamic system with a system of lower order. If a classical aircraft response is chosen then the potential arises that the results are compatible with the present requirements in the military specification. In this case, the equivalent parameters would be used and the only additional complexity would involve the method used for deriving the desired equivalent system.

The McDonnell-Douglas Company (MCAIR) has been a leader in the evolution of this concept; for example, see Reference 6 which fully describes their approach. The purpose of this section is to discuss the application of the equivalent system approach to the LAHOS data base.

4.1 MCAIR EQUIVALENT SYSTEM

To clarify the discussions, a very brief review of the MCAIR equivalent system approach is in order. The form of the low order transfer function used by MCAIR to match the high order, complex system is:

$$\frac{\dot{\theta}}{F_{ES}} = \frac{K_{\dot{\theta}_e}\left(\tau_{\theta_{2e}} s + 1\right) e^{-\tau_e s}}{\left(\dfrac{s^2}{\omega_{sp_e}^2} + \dfrac{2\zeta_{sp_e}}{\omega_{sp_e}} s + 1\right)}$$

This transfer function is the equivalent, constant speed, short-period transfer function with a transport time delay added to provide the ability to match the high order system. A digital computer program is used to produce the best Bode plot match over a frequency range of typically 0.1 to 10 rad/sec using a suitable "cost function" to weight the amplitude and phase errors properly.

The method produces equivalent values of frequency, damping ratio and n_z/α (when variation of $1/\tau_{\theta_2}$ is necessary for a "match") and time delay. These values can then potentially be used to evaluate the flying qualities of the aircraft by comparison with the appropriate requirements in the specification.

MIL-F-8785C (Reference 13), the proposed revision to the existing military specification, incorporates the equivalent system approach but, unfortunately, does not specify how the equivalent system should be derived.

4.2 CORRELATION WITH THE LAHOS DATA

Fortuitously, the LAHOS data have been thoroughly analyzed by MCAIR in Reference 14 using their equivalent system method. The results of this analysis are, therefore, used for the following discussion.

Since the equivalent system transfer function has at least 3 variables and sometimes a fourth (when $1/\tau_{\theta_2}$ is varied), several mil-spec requirements are involved in the evaluation of a configuration's flying qualities:

For the purposes of this correlation study, the new requirements from the proposed new mil-spec, MIL-F-8785C were used:

- ω_{sp_e}, ζ_{sp_e} Category A and Category C
- Allowable Phase Angle at ω_{sp_e} Boundaries

  Level 1 : 15 deg

  Level 2 : 30 deg

  Level 3 : 60 deg

- Time Delay Boundaries

  Level 1 : .10 sec

  Level 2 : .20 sec

  Level 3 : .25 sec

The correlation of the equivalent system data for the LAHOS configurations is presented in Table 2. The predicted flying qualities levels based on each requirement are presented along with the actual pilot rating level assigned in the LAHOS experiment.

For the evaluation of the correlation results, the following rules were used:

- When the assigned pilot rating Level was worse than the <u>worst</u> predicted Level using all the requirements, the prediction was judged to be incorrect. Unlike the previous criterion evaluations, multiple requirements are necessary in conjunction with the equivalent system approach. In fact, five separate requirements must be evaluated to test compliance.

- Level 1 : $PR \leq 3.5$
  Level 2 : $3.5 < PR \leq 6.5$
  Level 3 : $6.5 < PR \leq 9.0$
  Level 4 : $PR > 9.0$

  No distinction was made between Levels 3 and 4 for this correlation evaluation.

- As for the previous criterion evaluations, when the assigned rating was better than the worst predicted Level for the requirements, the prediction was not judged to be a failure.

On this basis, the correlation results are:

- Using -8785C with only the new phase angle requirement, 84% of the cases were correctly predicted.
- Using -8785C with only the new time delay requirement, 89% of the cases were correctly predicted.
- Using -8785C with both the new phase angle and time delay requirements, the correlation was 91%.

TABLE 2

CORRELATION OF PREDICTED EQUIVALENT SYSTEM RESULTS WITH PILOT RATING LEVELS

LAHOS Config.	Predicted Flying Qualities Levels For Spec Requirements (-8785C)					Actual Pilot Rating Level	
	ζ_e	ω_{e_A}	ω_{e_C}	Phase Angle	Time Delay		
1-A	2	2	3	1	1	2	
1-B	2	2	2	1	1	2	
1-C	1	2	2	1	1	2	
1-1	1	2	1	1	1	2	
1-2	1	2	1	1	2	2	
1-3	1	4	4	1	2	4	
1-4	1	4	4	1	2	4	
1-6	1	2	1	1	2	2	
1-8	1	2	1	1	3	3	
1-11	1	2	1	1	3	3	
2-A	1	1	1	1	1	2	x
2-C	1	1	1	1	1	1	
2-1	1	1	1	1	1	1	
2-2	1	1	1	2	2	2	
2-3	1	1	1	2	2	2	
2-4	2	2	1	2	2	3	x
2-6	1	1	1	[illegible]	2	2	
2-7	1	1	1	2	2	2	
2-9	[illegible]	1	1	3	4	4	
2-10	3	2	1	3	4	4	
2-11	1	1	1	3	3	3	
3-C	2	1	1	1	1	2	
3-0	4	1	1	1	1	2	
3-1	2	1	1	1	1	2	
3-2	3	1	1	2	2	3	
3-3	3	1	1	2	2	4	
3-6	2	1	1	2	2	2	
3-7	3	1	1	2	2	3	
4-C	1	1	1	1	1	1	
4-1	1	1	1	1	1	1	
4-3	1	1	1	2	2	2	
4-4	1	4	2	2	2	2	
4-6	1	1	1	2	2	2	
4-7	1	1	1	2	2	1	
4-10	1	4	2	3	3	3	
4-11	1	1	1	2	3	3	
5-1	1	1	1	1	1	2	x
5-3	1	1	1	2	2	2	
5-4	1	1	1	2	2	2	
5-5	1	2	1	2	2	3	x
5-6	[illegible]	1	1	3	2	2	
5-7	1	1	1	3	2	2	
5-11	1	1	1	3	2	3	
6-1	1	4	2	3	2	4	
6-2	1	1	1	1	1	1	

x: Cases for which actual PR Level > predicted Level.

- Use of Category A vice C frequency boundaries gave slightly better correlation; however, with the new -8785C control system dynamic response requirements incorporated, the difference was not significant.

- The equivalent system method correctly predicted the flying qualities level without using the previous correlation restriction for approximately 85% of the cases.

- Use of time delay boundaries appears to be more appropriate than the phase lag form of the control system dynamics requirement.

4.3 SUMMARY

This review of the applicability of the MCAIR Equivalent System Approach as an evaluation criterion for pitch landing flying qualities has shown that:

- The approach is an excellent discriminator of pitch landing flying qualities for highly augmented aircraft when the new time delay and phase lag requirements of the proposed MIL-F-8785C are used.

- Incorporation of the equivalent system approach into the new military specification (MIL-F-8785C), therefore, has merit. However, much of the progress represented by this step may have been lost since the method of deriving the equivalent parameters is left an open issue. A well established method such as that used by MCAIR should be specified.

- The equivalent system approach is ideally suited to express specification requirements since to a large extent existing requirements can be used. Use of equivalent systems does not allow evaluation of the effects of combinations of marginal characteristics ("combination of bads"); of course, the present and proposed specifications have the same deficiency.

Section 5
R. H. SMITH CRITERION

An open loop longitudinal flying qualities criterion, developed by R. H. Smith, was included in the current study because of the success exhibited in correlating the results of the Neal-Smith experiment (Reference 16) and in analyzing the Shuttle landing PIO incident (summarized in the handout document supplementing R. H. Smith's presentation at the NASA Houston Shuttle Landing PIO briefing by industry representatives including Calspan). It is recognized that this criterion has been evolving over a period of several years and this material may not represent the current state of development. For background information describing the rationale for the criterion and its evolution, Reference 17 and 18 should also be consulted. In this section, only the mechanics of applying the criterion to the LAHOS data will be described.

5.1 MECHANICS OF CRITERION

The R. H. Smith criterion is comprised of two parts directed to first, the short term attitude response dynamics and second, the PIO tendency through the mechanism of pilot normal acceleration tracking. In the LAHOS experiment, n_z/α at the approach speeds employed, is so low that it is doubtful that a pilot n_z loop closure is a viable cause of PIO. Accordingly, the PIO aspect of the criterion was not included in the current study. The pitch attitude criterion is comprised of the following metrics:

(1) $0.2 \le t_q \le 0.9$ ALL LEVELS

(2) $\frac{d}{d\omega}\left|\frac{\theta}{F_s}(j\omega_c)\right| < -2$ DB/OCT LEVELS 1 & 2

(3) $\angle \frac{1}{M_{\delta_e}}\frac{\theta}{F_s}(j\omega_c) \ge -130^\circ$ LEVEL 1

$-130^\circ > \angle \frac{1}{M_{\delta_e}}\frac{\theta}{F_s}(j\omega_c) \ge -170^\circ$ LEVEL 2

$-170^\circ > \angle \frac{1}{M_{\delta_e}}\frac{\theta}{F_s}(j\omega_c)$ LEVEL 3

The first requirement dictates that the peak pitch rate following a step command must be within the designated limits for Level 1 pilot rating. It is intended to exclude configurations with either sluggish or abrupt initial response. Applied to the Neal-Smith data base, no configuration which failed this criterion received a satisfactory pilot rating.

Application of requirements (2) and (3) requires the calculation of a criterion frequency, ω_c, as illustrated in Figure 29. As can be seen from this figure, satisfaction of requirement (2) is equivalent to an upper limit on ω_c i.e. $\omega_c < 5.76$ rad/sec.

Requirement (3) was developed primarily from the Neal-Smith data base. When the pilot ratings from that experiment were plotted against $\angle \frac{1}{M_{\delta_e}} \frac{\theta}{F_{ES}} (j\omega_c)$ it was found that all the data were bounded by two close parallel lines which, in effect, defined a pilot rating functional. (See Figure 30).

Taking the mean of the functional as representative of the average pilot ratings, limits for Levels 1, 2 and 3 flying qualities were established as defined in requirement (3) and illustrated by the hatched boundaries in Figure 30.

5.2 APPLICATION TO LAHOS DATA

The LAHOS data base was evaluated with respect to these requirements. All of the LAHOS configurations passed requirement (2), that is $\omega_c < 5.76$ rad/sec. Averaged pilot ratings for each configuration are plotted versus $\angle \frac{1}{M_{\delta_e}} \frac{\Theta}{F_{ES}} (j\omega_c)$ in Figure 30. Configurations which failed the rate response requirement (1) are designated by flags. No configurations receiving Level 1 pilot ratings failed requirement (1). Unlike the Neal-Smith data base, these pilot ratings are not bounded by the pilot rating functional. Table 3 summarizes the criterion's overall capability in terms of predicted versus achieved ratings. It can be seen that the criterion is conservative in that in only 4 cases are worse ratings achieved than were predicted. In the sense that the achieved ratings were better than or equal to predicted ratings the criterion was 91% successful with the LAHOS data. However, because of this conservatism, the criterion may tend to lead to overdesign, since 36% of the configurations were rated better than predicted. In terms of achieving the

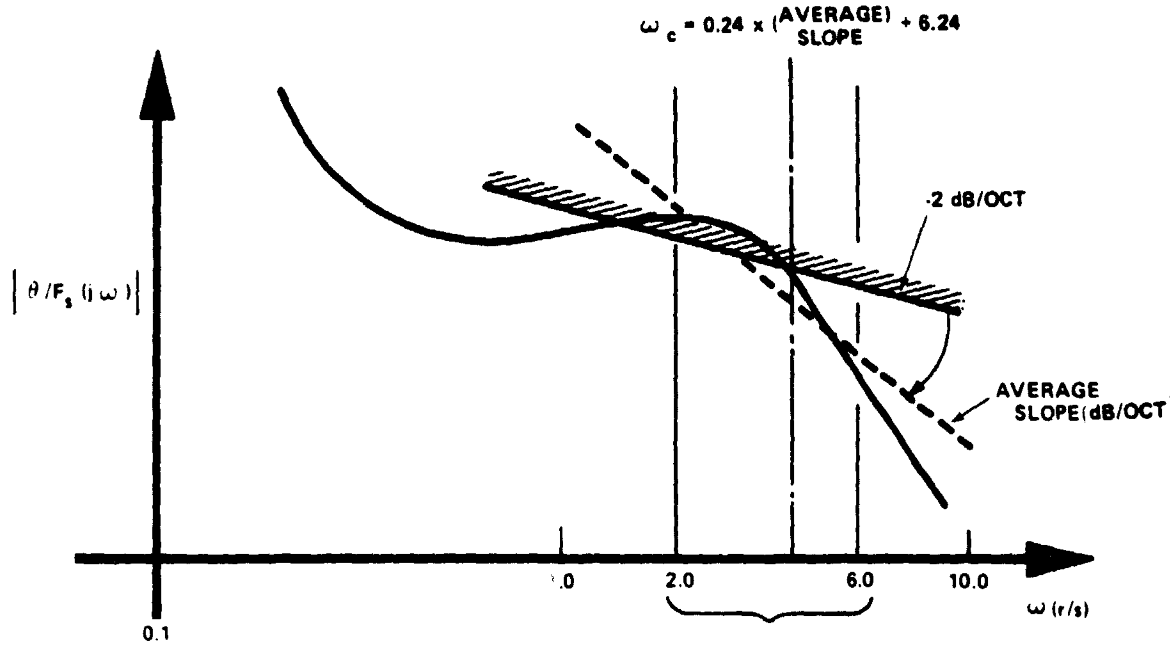


Figure 29 CALCULATION OF CRITERION FREQUENCY

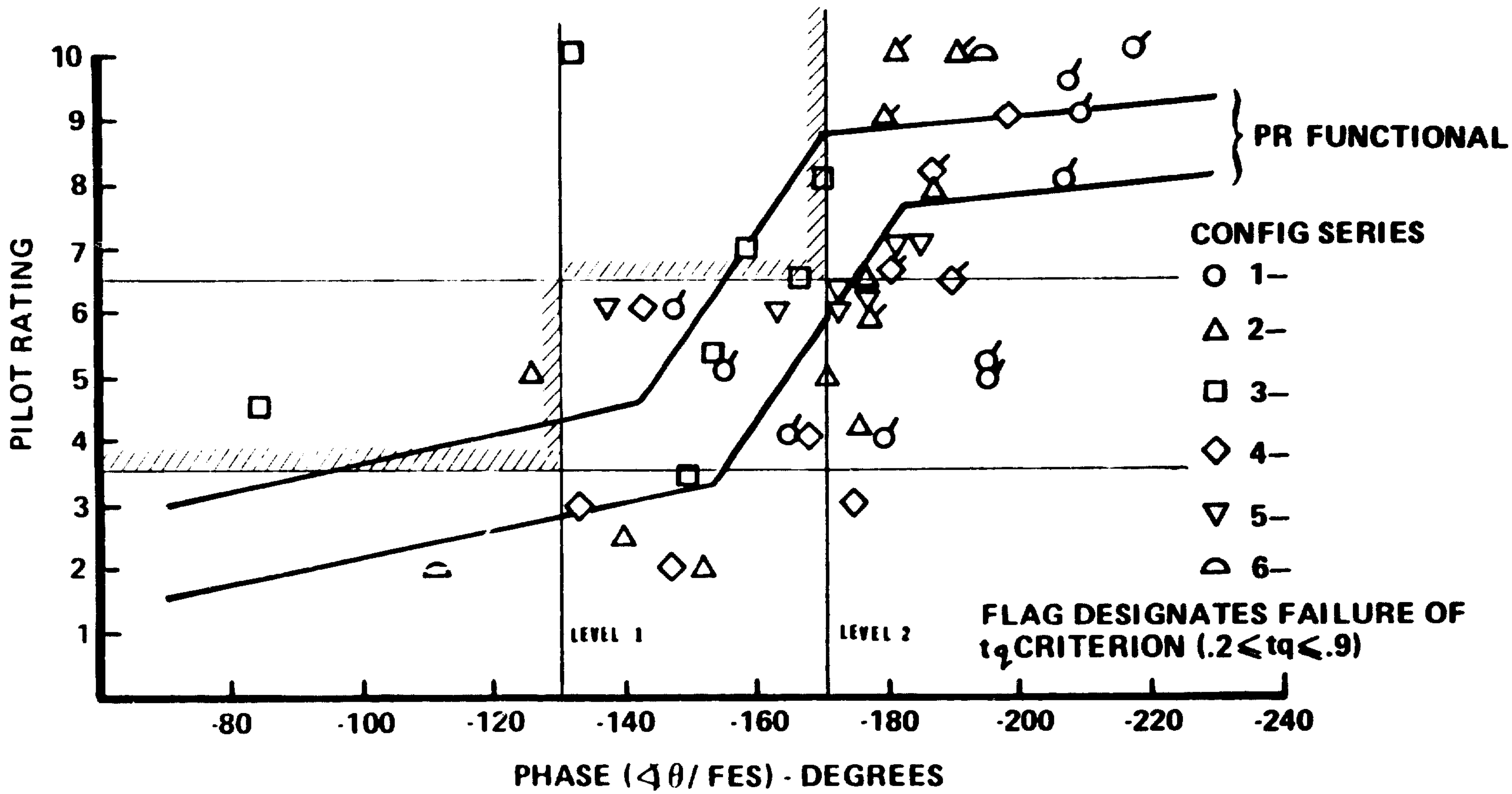


Figure 30 ATTITUDE PHASE CRITERION APPLIED TO LAHOS DATA

TABLE 3

PREDICTED VERSUS ACHIEVED RATINGS FOR LAHOS DATA
USING R. H. SMITH CRITERION, FAILURES of t_q
REQUIREMENT INCLUDED

Achieved Level	Predicted Level 1	Predicted Level 2	Predicted Level 3
3	0	2	15
2	2	9	11
1	1	4	1

predicted Level of flying qualities, the ratio is only 56% as would be expected from the scatter evidenced in Figure 30.

Although overall the data exhibits scatter, tracking the variation in pilot rating for a given short period configuration as the prefilter dynamics are changed reveals a functional independence of pilot rating on $\measuredangle \frac{1}{Y_{\delta_c}} \frac{\theta}{F_{es}} (j\omega_c)$ (Figure 31). It appears that for a given short period, the rating data approximates the shape of the pilot rating functional but the locus for each short period configuration is displaced by some phase increment. Further examination of this characteristic was not within the scope of the current program. However, it is likely that a modification to the equation for the criterion frequency ω_c could be devised to eliminate this phase increment and is justifiable on the basis that the LAHOS data was gathered in the context of a different task than the Neal-Smith data.

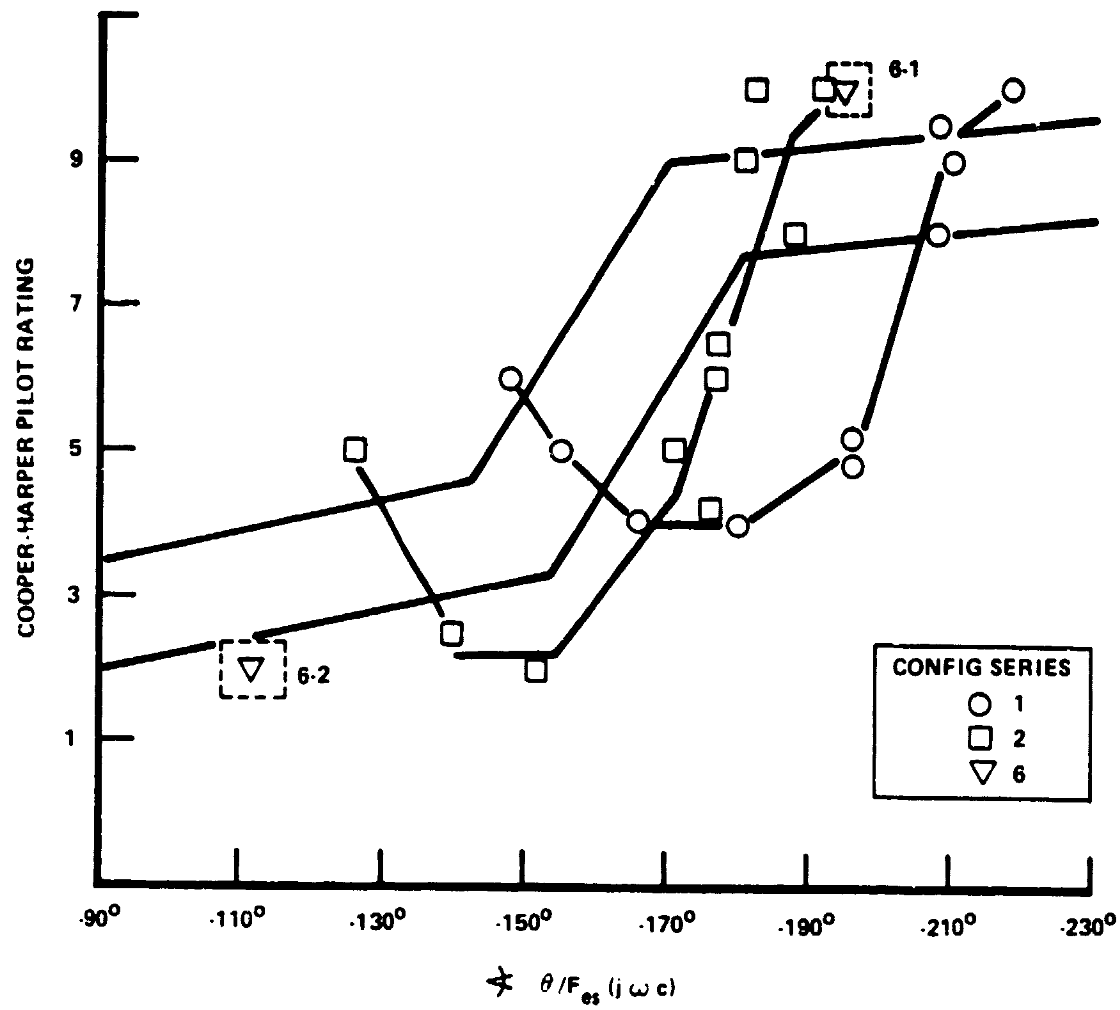


Figure 31 ILLUSTRATION OF EFFECT OF SHORT PERIOD DYNAMICS

5.3 SUMMARY

In summary, it is concluded that although this criterion is reasonably effective in screening out configurations with poor flying qualities, it may lead to overdesign because it is a relatively poor discriminator of pilot rating. It appears that modifications to certain aspects of the criterion such as the definition of ω_c may considerably improve the correlation with the LAHOS data.

Section 6
STUDY OVERVIEW

The purpose of this section is to provide a summary of the results of this study which was directed at the evaluation of several existing pitch flying qualities evaluation criteria for highly augmented aircraft in the landing flight phase. Recommendations for further work in support of the continued development towards suitable flying criteria for today's aircraft with complex flight control systems are presented in Section 7.

6.1 REVISED NEAL-SMITH CRITERION

- Desirable Features:
  - Good pitch landing flying qualities discriminator; exposes bad aircraft consistently.
  - Parameter plane dimensions are directly related to typical pilot comments.
  - Provides a design target area which guarantees good flying qualities if met regardless of system complexity.
  - Evaluation of aircraft's longitudinal maneuvering response characteristics can be done in one step; eliminates "combination of bads" question present in other criteria and military specification.
  - Ideal as a design criterion since "sensitivity" of the aircraft dynamic system to changes in task performance standard or pilot technique can be explored effectively.
- Undesirable Features:
  - Application of the criterion is relatively complex although it can be done efficiently and consistently using the digital computer program.

- Did not predict pitch landing flying qualities accurately for lightly damped unaugmented aircraft; more data in high turbulence is required for a proper evaluation of criterion.
- Requires an additional "adaptability" metric to evaluate properly aircraft which are sensitive to task variations or changes in pilot technique. The criterion does, however, lend itself to such a development.
- Cannot accurately evaluate systems with non-linear elements.

6.2 ONSTOTT (NORTHROP) CRITERION

- Desirable Features:
  - Concept of a time-domain closed-loop criterion has merit; parameters can be related to a real-world piloting task.
  - Complex flight control systems with non-linear elements can potentially be evaluated directly through exact modeling in contrast to frequency domain analyses.
  - Good potential for modification into a viable criterion.
- Undesirable Features:
  - Does not discriminate either pitch landing or tracking flying qualities data in a realistic fashion in its present form.
  - Not correctly formulated; modifications required to introduce consistent "performance standard" to concept.
  - Required computer time to perform necessary optimization required excessive computer time (or a very fast computer).

6.3 MCAIR EQUIVALENT SYSTEM APPROACH

- **Desirable Features:**

  - Good pitch landing flying qualities discriminator when new -8785C control system requirements are used; exposes bad aircraft consistently.

  - Approach is couched in terms of the same parameters as the current and proposed specifications.

- Undesirable Features:

  - The method of deriving the equivalent system parameters is the subject of much debate; proposed new military specification (-8785C) has left the subject open which may negate the usefulness of the inclusion of the approach as a method to evaluate highly augmented aircraft.

  - 3 or 4 separate requirements must be used to evaluate the pitch maneuvering response characteristics; "combination of bad" qualities case is not, therefore, covered.

  - Sensitivity of an aircraft's flying qualities to changes in task performance standard or pilot technique cannot be evaluated using this approach.

  - The relationship of equivalent modal parameters to physically meaningful aircraft parameters or flight control characteristics is neither obvious nor readily determined. See, for example, LAHCS Configuration 2-10 in Reference 14.

6.4 R. H. SMITH CRITERION

- <u>Desirable Features</u>:
  - Appears to expose bad aircraft but is generally not a sufficiently sensitive discriminator of pitch landing flying qualities.
  - Relatively simple to apply.
- <u>Undesirable Features</u>:
  - Not sufficiently sensitive; for example, Level 3 phase angle region contains pilot ratings which range from 3 to 10.
  - Parameters are somewhat abstract and do not relate directly to piloting task.

6.5 SUMMARY COMMENTS

The question of compliance demonstration is an important factor in the assessment of the suitability of a particular criterion as a flying qualities requirement. All criteria assessed in this study require a complete description of the augmented aircraft. Modern flight test techniques can be used to obtain the required information; however, the process is somewhat laborious and potentially open to a variety of interpretations. Other approaches, which rely on metrics measured directly from the augmented aircraft time history response, such as in Reference 19, could potentially eliminate this problem.

Of the criteria reviewed in this study, the revised Neal-Smith criterion and the MCAIR Equivalent System Approach are both adequate criteria for evaluation of the pitch landing flying qualities of highly augmented aircraft. The Onstott method shows promise but needs extensive modifications. Ralph Smith's criterion just is not sensitive enough, in its present form at least, to be considered an adequate general criterion.

In summary, the revised Neal-Smith criterion appears to be the best design guide, while the Equivalent System Approach is the best method to use as a basis for modification of the requirements in the present military specification to cover highly augmented aircraft.

Section 7
RECOMMENDATIONS

This study program assessed the applicability of several existing pitch flying qualities criteria as pitch landing flying qualities criteria and was directed at the development, if feasible, of suitable revised or new criteria. As a result of this exposure, the following recommendations are presented:

(1) The revised Neal-Smith criterion should be tested further using other sources of pitch landing flying qualities data.

(2) More pitch landing flying qualities data are required. Of particular interest are:

- Configurations which are "sensitive" to small changes in task standard of performance or pilot technique.
- The effects on flying qualities of realistic digital mechanizations and their associated equivalent delays. An experiment is required in which a variable digital flight control system can be evaluated using realistic critical tasks.
- The effects of additional representative control system dynamics on the flying qualities of highly augmented aircraft with heavily damped responses.
- The flying qualities of lightly damped unaugmented configurations, although such a study would not be pertinent to modern augmented aircraft designs.
- The effects of command gain on the flying qualities of highly augmented aircraft with significant initial delay in the response to pilot inputs.

(3) Specific attention is required to understand the influence of Class on landing flying qualities; a large aircraft landing flying qualities experiment sponsored by the USAF and NASA is currently in progress using the AFWAL/Calspan TIFS in-flight simulator which should provide data relative to this area.

(4) Further study is required to understand the nature of "sensitive" aircraft - aircraft whose flying qualities degrade rapidly, and typically unexpectedly, with changes in pilot techniques or task standard of performance. Sensitivity (adaptability) metrics should be developed with which such aircraft can be properly evaluated.

(5) Further work is required to develop a closed-loop time-domain criterion using the work presented in this study as a starting point. Such a criterion is necessary to evaluate non-linear flight control system mechanizations. In addition, the Onstott criterion should be evaluated using the corrected version of the criterion and all the available data.

(6) The NASA non-linear suppressor shows potential as a method for reducing the PIO tendencies of an aircraft. The capabilities of the suppressor cannot be fully assessed without very careful in-flight evaluations which include realistic, critical tasks such as touchdowns and actual refueling "plug-ins." As demonstrated in numerous evaluations, the explosive nature of the flying qualities of a poor aircraft can be missed with small changes in task standard of performance or pilot technique.

(7) Finally, very little is known about the effects of control system dynamics on the world of lateral-directional flying qualities for all tasks. Clearly, a substantial data base is required and suitable experiments must, therefore, be conducted. One such experiment which will contribute to the required data base is presently being conducted using the AFWAL/Calspan NT-33 in-flight simulator.

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APPENDIX A

SHUTTLE PIO SUPPRESSOR ANALYSIS

By

Norman C. Weingarten

This appendix documents a brief analysis of the closed loop behavior of the NASA PIO Suppressor. The suppressor is highly nonlinear (frequency and amplitude dependent) and is not easily analyzed in any of our frequency domain closed loop programs. Therefore, an approximation of its mechanization was developed. This approximation was essentially a gain schedule as a function of frequency without phase lag. The gain is actually a function of the amplitude of input, but this functional relation was eliminated by assuming that the pilot flew with basically one amplitude versus frequency function.

The analysis requires an assumed Shuttle PIO Suppressor gain shape: estimated amplitude ratio versus frequency at various amplitude inputs through the PIO suppressor. For the PIO suppressor model, the following assumptions are made.

Model: $\delta_{out} = \delta_{in}(.36 + K_q(.0484)|\delta_{in}|)$

Assume:

1. No dead zone of 1.15°
2. Reference gain of .593 (@ low frequency → $\omega = 0.1$ r/sec)
   (low amplitude → $\delta_{in} = 5$)
3. K_q is a function of frequency of input measured by amplitude ratio of following filter: $.75 \dfrac{s(s+13.3)}{(s+10)^2}$

   $K_q = 1 - 3.846(AR)$ direct ratio (not db)

   $K_{q_{min}}$ limit $= -.15$ @ $AR = .299$

so that

ω(rad/sec)	*AR* db	*AR* Ratio	K_q
.01	-40	.01	.962
.05	-26	.05	.808
1.	-20	.1	.650
2.	-14.5	.188	.277
2.8	-11.7	.260	0
3.	-11.2	.275	-.058
3.3	-10.5	.299	-.150
>3.3	-10.5	.299	-.150
	Limited		

$$\begin{array}{l}\text{pilot stick} \\ \text{gain into} \\ \text{control} \\ \text{system}\end{array} \equiv [.36 + K_q(.0484)|\delta_{in}|]$$

depends on frequency (K_q)
depends on amplitude (δ_{in})

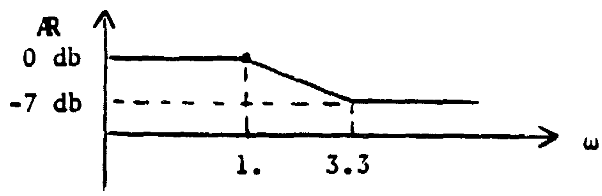
		$\delta_{in} = 5$		$\delta_{in} = 10$		$\delta_{in} = 15$	
ω(rad/sec)	K_q	Gain with PIO_{Sup}	Without	With PIO_{Sup}	Without	With PIO_{Sup}	Without
.1	.962	.593	.602	.626	.844	1.058	1.086
.5	.808	.556		.751		.947	
1.	.65	.517		.675		.832	
2.	.277	.427		.494		.561	
2.8	0	.36		.36		.36	
3.	-.058	.346		.332		.318	
3.3	-.15	.324		.287		.251	
>3.3	-.15	.324	.602	.287	.844	.251	1.086

Obtain *AR* in dB of above gains with respect to reference gain at 0.593 (low frequency, low amplitude)

ω(rad/sec)	AR (db) δ_{in} = 5 deg		δ_{in} = 10 deg		δ_{in} = 15 deg	
	With PIO_{Sup}	Without PIO_{Sup}	With PIO_{Sup}	Without PIO_{Sup}	With PIO_{Sup}	Without PIO_{Sup}
.1	0	+.13	+2.88	+3.07	+5.03	+5.26
.5	- .56		+2.05		+4.07	
1.	-1.19		+1.12		+2.94	
2.	-2.85		-1.59		- .48	
2.8	-4.34		-4.34		-4.34	
3.	-4.68		-5.04		-5.42	
3.3	-5.25		-6.30		-7.47	

These data are plotted in Figure A-1.

To obtain one Amplitude Ratio reduction curve for the Shuttle PIO Suppressor, the pilot was assumed to fly with low amplitudes (5 deg or less at frequencies less than 1. rad/sec) and gradually increase amplitude at higher frequencies in a PIO situation (to about 10 to 15 degrees at 3.3 rad/sec where the gain reduction stops). This approximate gain change with frequency would be for the above shuttle configuration:



(Also see Figure A-1 for chosen gain schedule).

To see how this gain change with frequency works, it was demonstrated on a PIO prone LAHOS configuration (6-1), with various levels of attenuation, and using 1. and 3.3 rad/sec as the break points and attenuations of -2, -4, -6, -8 dB as the final attenuation values, the ω_B was 3.0 rad/sec and pilot delay was .2 seconds - the criterion parameters for the revised Neal-Smith landing criterion.

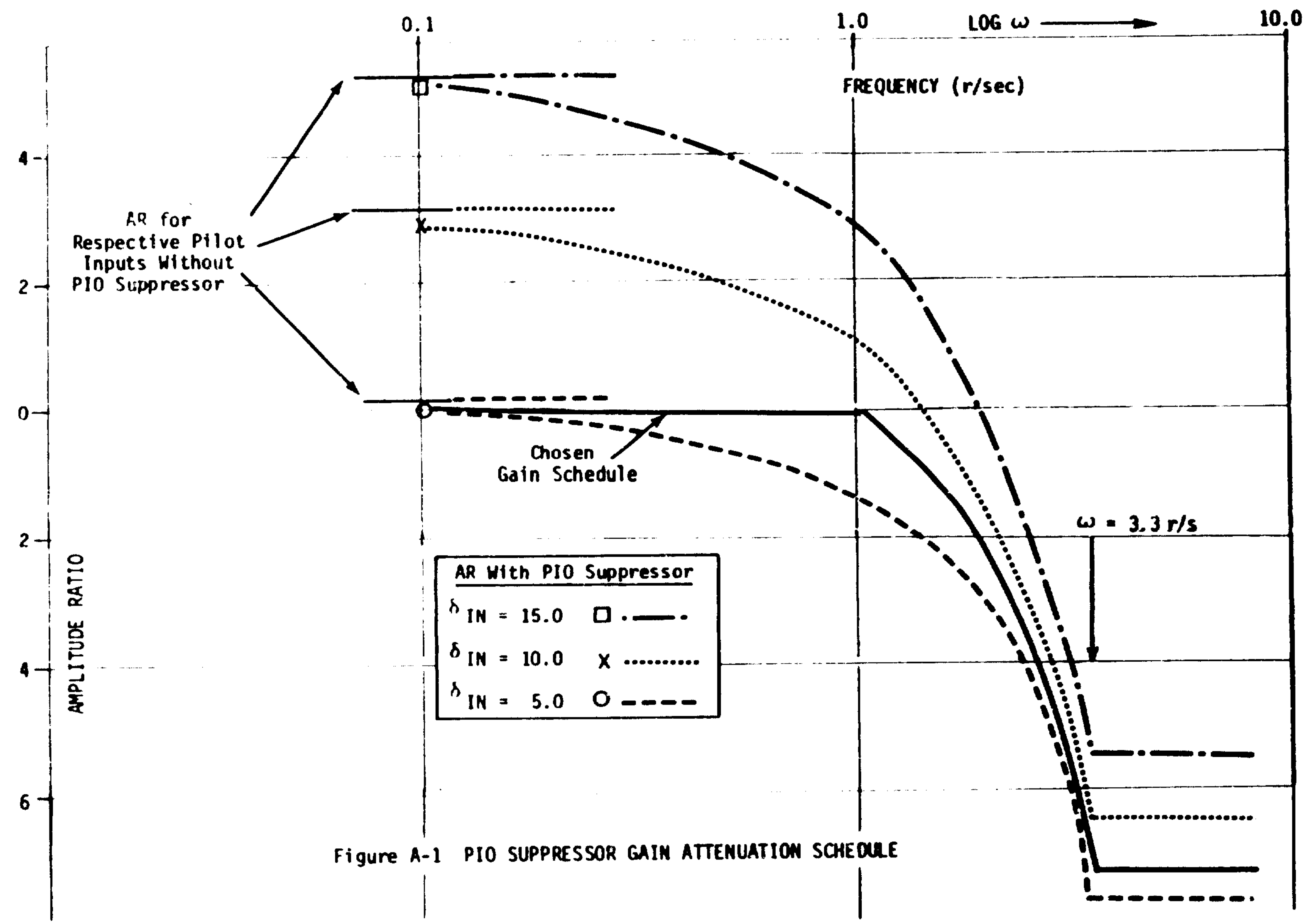


Figure A-1 PIO SUPPRESSOR GAIN ATTENUATION SCHEDULE

Results from Configuration 6-1

Pilot gain as a function of frequency was run on a digital computer general closed loop program. (See results plotted in Figure A-2.) This figure illustrates the change in closed loop resonance and droop for given pilot lead compensation necessary to satisfy the bandwidth requirement as the "suppressor" gain attenuation increases through -9 dB.

The graph indicates that with the suppressor active:

1. Pilot gain K increases
2. Droop decreases
3. Resonance decreases

(items 1–3: holding τ_{lead} constant)

4. τ_{lead} for -3 dB droop increases
5. Resonance at τ_{lead} for -3 dB droop decreases
6. Pilot Gain K at τ_{lead} for -3 dB droop decreases a little

It appears that the PIO Suppressor working on Configuration 6-1 does reduce the resonance and droop at a constant τ_{lead} but the resonance values remain very high. To achieve the -3 dB droop would require more pilot compensation (increased τ_{lead}) which would reduce the resonance further. However, this may not be what the pilot would try to do, since it would be in the direction of increasing droop.

Results Using Shuttle Configuration

Running the PIO Suppressor with the 0 to -7 dB schedule on the Shuttle transfer function showed similar results. The Shuttle model used for this analysis is documented fully in Reference 15. It was run at ω_B = 2, 2.5, and 3.0 rad/sec with a delay for the pilot and control input as .30 and .06 seconds. (See Figure A-3 and A-4 for ω_B = 2.5, 3 and total delay = .36 sec results).

This part of the analysis was run with the original Neal-Smith pilot time delay of 0.3 sec not the revised landing criterion value of 0.2 sec. However, the additional control delay should have been .12 sec rather than .06 sec as used in the model in Reference 15 and in Section 2.7. These results

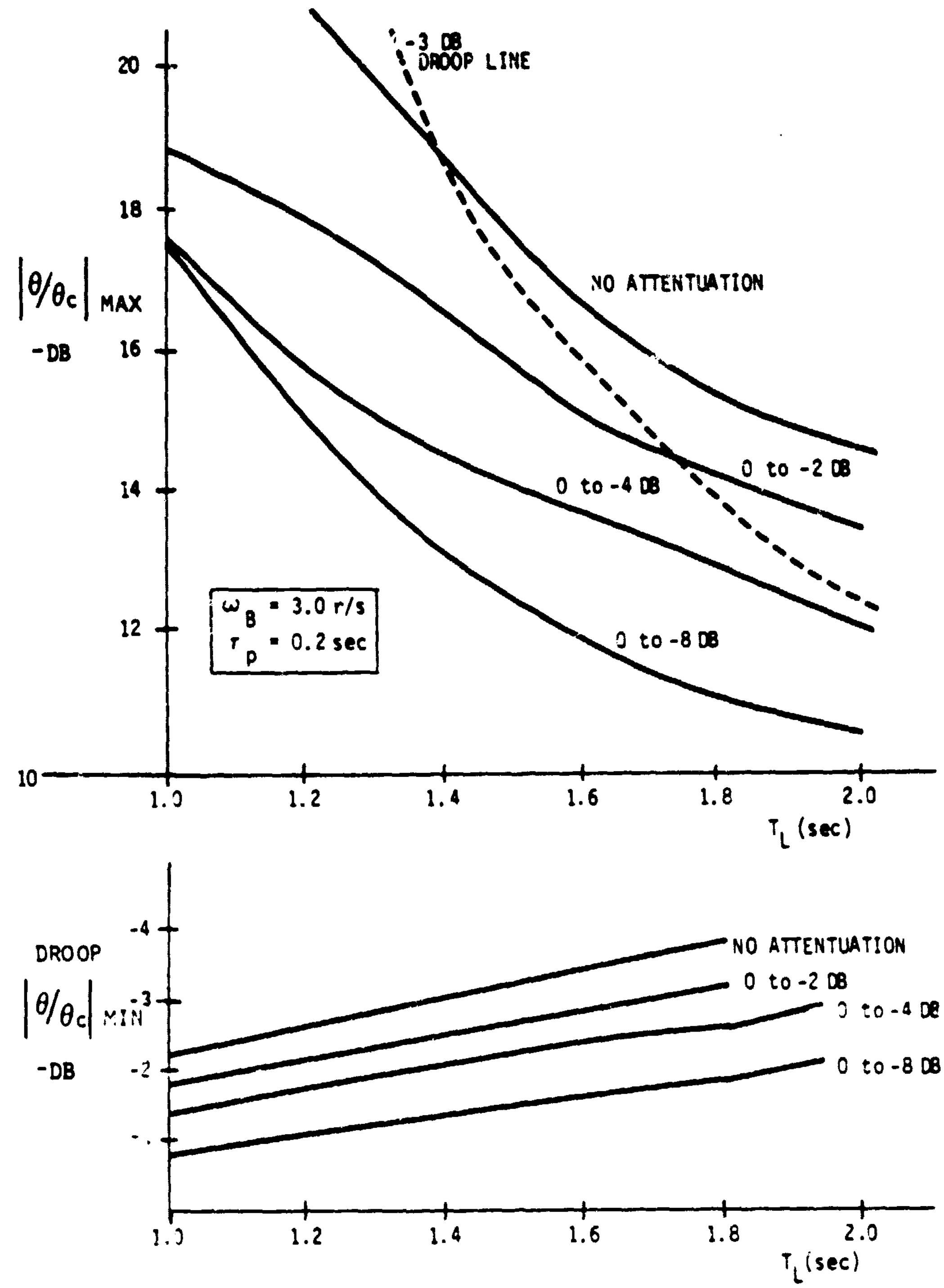


Figure A-2 VARIATION OF RESONANCE, DROOP, AND PILOT COMPENSATION FOR INCREASED SUPPRESSOR GAIN ATTENUATION (CONFIG. 6-1)

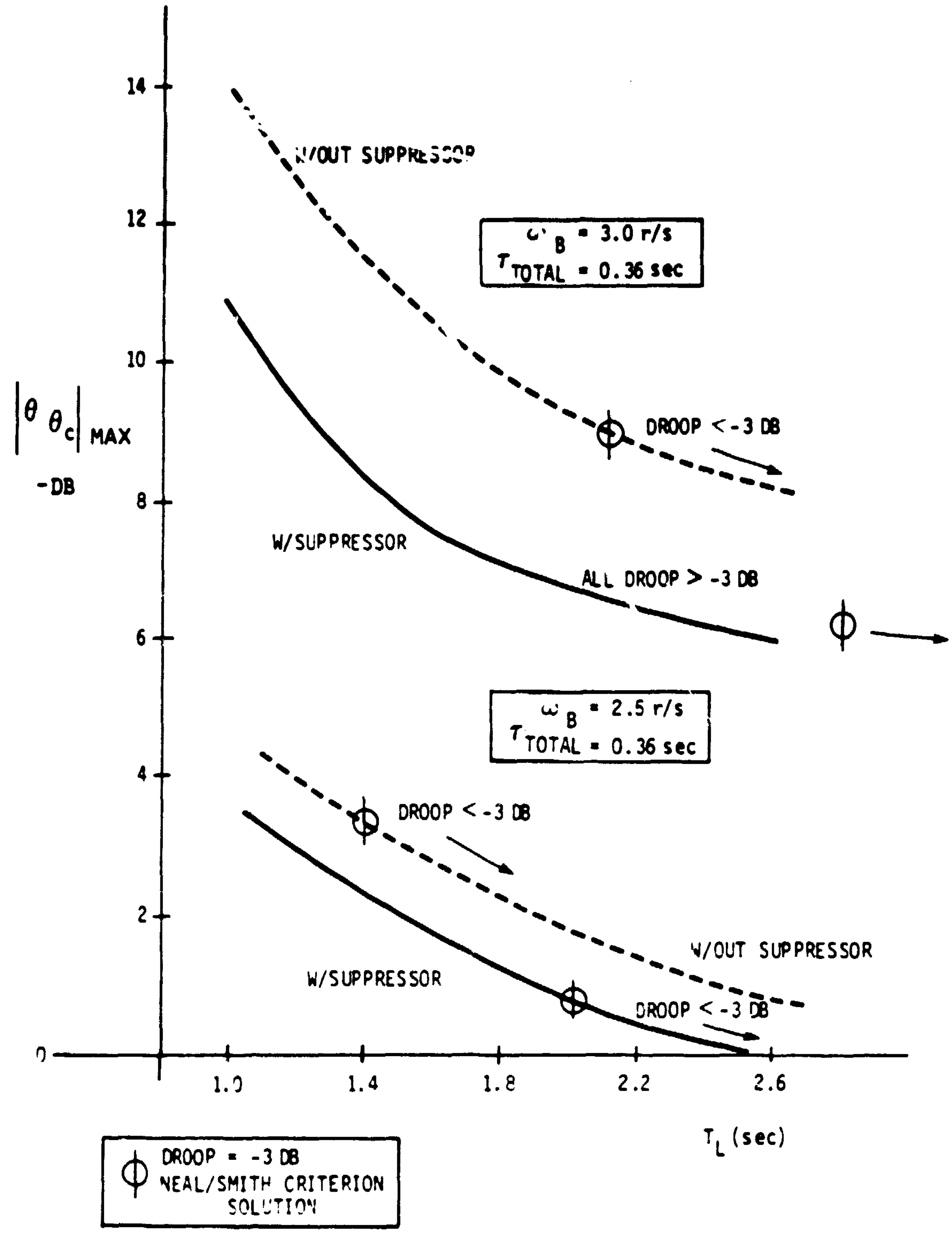


Figure A-3 SPACE SHUTTLE: CLOSED-LOOP RESONANCE FOR ω_B = 2.5 r/s AND 3.5 r/s WITH AND WITHOUT PIO SUPPRESSOR

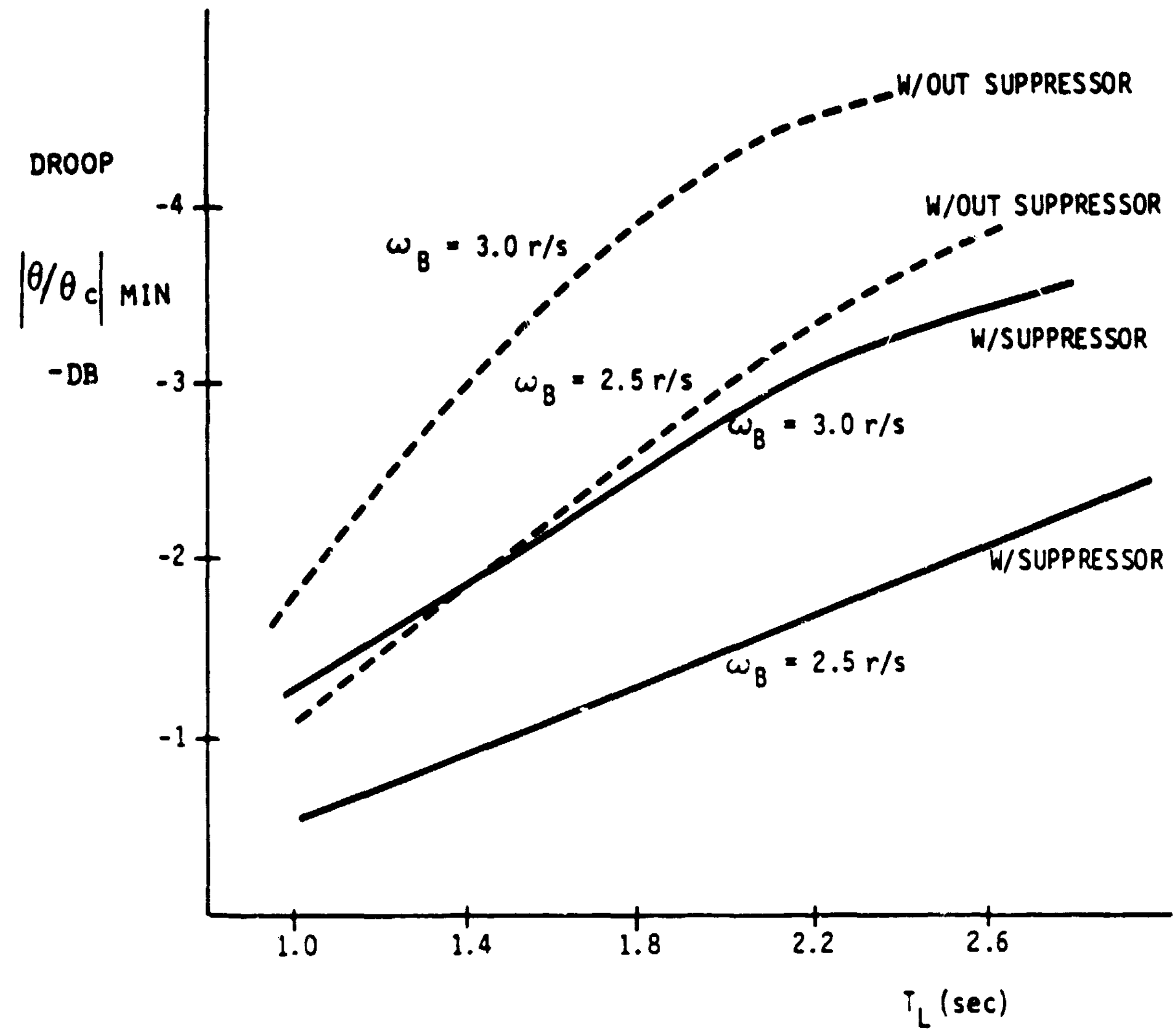


Figure A-4 SPACE SHUTTLE: CHANGE IN DROOP FOR VARIATIONS IN BANDWIDTH WITH AND WITHOUT PIO SUPPRESSOR with a total delay of .36 secs instead of .32 secs are therefore not exact but are sufficient for the purpose of this approximate analysis.

Reduced resonance and droop is evident at constant τ_{lead} with the suppressor. However, at lower bandwidths less reduction in resonance is shown. It should be noted that as bandwidth increases, droop decreases while resonance increases at constant τ_{lead}.

The Neal-Smith solution points indicate that for a given bandwidth, the suppressor reduces the resonance (more at higher bandwidths) but requires more pilot lead to achieve the criterion standards. The relatively large variation in resonance with increases in bandwidth (sensitive configuration) is still present with the suppressor working.

SUMMARY

It appears from this brief and somewhat crude analysis that the PIO suppressor does reduce PIO tendencies (reduced closed loop resonance). The "sensitivity" of a poor configuration - change in resonance with changes in bandwidth - were not, however, significantly altered. Another point, not addressed in this analysis, is the shape of the transient response to pilot inputs with the suppressor. For step-like inputs the response resembles a first-order response with a large lag. For rapid inputs before the suppressor can change the gain, this effect might just make an already poor aircraft worse.

It is clear that very careful simulation is required before the capabilities of the PIO suppressor can be confirmed. Such a simulation must include very realistic, highly stressed tasks. An in-flight simulation which includes touchdowns and an actual in-flight refueling task would present an appropriate test.