A SURVEY OF HANDLING QUALITIES CRITERIA AND THEIR APPLICATIONS TO HIGH PERFORMANCE AIRCRAFT

FINAL REPORT

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ABSTRACT

A SURVEY OF HANDLING QUALITIES CRITERIA AND THEIR APPLICATIONS TO HIGH PERFORMANCE AIRCRAFT

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This report is a survey of various handling qualities criteria and their application to high performance aircraft including state-of-the-art and highly augmented aircraft. Neal-Smith, Bandwidth, Equivalent Systems, and Military Specification 8785 criteria are applied to flight test data from aircraft such as the F-8 Digital Fly-By-Wire, the YF-12, and an Advanced Fighter Aircraft. Backgrounds and example applications of each criteria are given. The results show that the handling qualities criteria investigated can be applied to highly augmented aircraft with fairly good results in most cases; however, since no one method excelled, more than one criterion should be used whenever possible. Equivalent time delays appear to be the most frequent critical factor in determining pilot rating levels of highly augmented aircraft.

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LIST OF SYMBOLS

Symbol	Description
BW_{min}	minimum bandwidth frequency (rad/sec)
g	acceleration of gravity (ft/s^2)
G_{HOS} , G_{LOS}	higher order and lower order system gains (dB)
HOS	higher order system
I_x, I_y, I_z	moments of inertia about the roll, pitch, and yaw axis ($ft\text{-}lb\text{-}s^2$)
I_{xz}	product of inertia ($ft\text{-}lb\text{-}s^2$)
K_p	pilot model gain (deg/deg)
K_q	q/δ_{e_s} gain (deg/deg)
K_r	yaw-rate feedback gain (deg/(deg/sec))
K_β	β/δ_r gain (deg/deg)
K_ϕ	ϕ/δ_{a_s} gain (deg/inch)
K_θ	pitch-attitude model gain ((deg/sec)/deg)
$K_{\dot\theta}$	pitch-rate feedback gain (deg/(deg/sec))
LOS	lower order system
L_p, L_r, L_β	dimensional lift coefficients
M	mismatch function
n/α	change in normal acceleration per change in angle of attack (g's/rad)
N_p, N_r, N_β	dimensional yaw moment coefficients
p	roll rate (deg/sec)
r	yaw rate (deg/sec)
t_q	q/δ_{e_s} equivalent time delay (sec)

LIST OF SYMBOLS (cont.)

Symbol	Description
T_W	washout time constant (sec)
t_β	β/δ_r equivalent time delay (sec)
t_ϕ	ϕ/δ_{a_s} equivalent time delay (sec)
V	true velocity (ft/sec)
Y_β	dimensional roll moment coefficient
α	angle of attack (deg)
β	sideslip angle (deg)
δ_{a_s}	aileron stick position (deg)
δ_e	elevator angle (deg)
δ_{e_s}	elevator stick position (deg)
δ_r	rudder pedal position (inches)
ϕ	roll angle (deg)
ϕ_1	phase angle corresponding to ω_1 (deg)
$\phi_{HOS,LOS}$	higher order and lower order system phases (deg)
θ	aircraft pitch angle (deg)
θ_c	desired aircraft pitch angle (deg)
τ_1, τ_2	lead and lag actuator time constants (sec)
τ_p	pitch-attitude estimated time delay (sec)
τ_{p_1}, τ_{p_2}	lead and lag pilot compensation time constants (sec)
τ_R, τ_s	roll mode and spiral mode time constants (sec)
$\tau_{\beta_1}, \tau_{\beta_2}, \tau_{\beta_3}$	numerator time constants for the β/δ_r transfer function (sec)

LIST OF SYMBOLS (cont.)

Symbol	Description
τ_{θ_2}	pitch-attitude time constant (sec)
ω_{BW}	bandwidth frequency (rad/sec)
ω_1	any frequency greater than the neutral stability frequency (rad/sec)
ω_{180}	neutral stability frequency (rad/sec)
ζ_s, ω_s	flight control system damping ratio and undamped natural frequency (rad/sec)
ζ_{sp}, ω_{sp}	pitch-attitude short period damping ratio and undamped natural frequency (rad/sec)

INTRODUCTION

The handling qualities of an aircraft are described by the pilot skill and work load required to maneuver the aircraft while performing a specific task and thus are subject to qualitative judgments of individual pilots. In an attempt to create a consistent method by which handling qualities could be defined quantitatively, the Cooper-Harper (Reference 1) pilot rating scale was developed. Using the decision making process as illustrated in Figure 1, the pilot can assign to the aircraft a rating from 1 to 10 based on the aircraft's controllability and accuracy in performing a given task. Based on varying pilot skills and backgrounds, different pilot ratings may be issued for the same aircraft in the same flight condition.

Various techniques and criteria have been developed in attempt to predict pilot rating levels. Military aircraft are required to meet the handling qualities requirements established in the Military Specification 8785C (Reference 2). Other handling qualities criteria that are commonly used include Neal-Smith, Bandwidth, and Equivalent Systems criteria. These criteria generally yield good results when they are applied to most conventional aircraft. However there is some question as to the validity of applying these criteria to modern aircraft with highly augmented flight control systems.

This report is a survey of various handling qualities criteria and their application to high performance aircraft including state-of-the-art and highly augmented aircraft. Neal-Smith, Bandwidth, Equivalent Systems, and Mil Spec criteria will be applied to flight test data from aircraft such as the the F-8 Digital Fly-By-Wire, the YF-12, and an Advanced Fighter Aircraft (AFA).

Recently there has been some question as to the proper method of including the effects of feel system dynamics in the control model when applying handling qualities criteria. The control system models created for the aircraft in this report will exclude feel system dynamics due to the non-availability of feel system models for these aircraft. Thus all results in this report will be based on stick position rather than stick force, however the possible effects of typical feel systems will be considered. Generally, feel system dynamics can be modeled with a pure time delay thus could be easily implemented into the results of this report if such information should become available.

The first part of this report is devoted to the familiarization of the handling qualities criteria used herein. Each technique is given a brief description and then utilized in an example case using a simple model of the F-104 fighter aircraft. The F-104 was chosen as an example because it is a high performance aircraft yet is easily modeled.

NEAL-SMITH CRITERIA

Background

The Neal-Smith criteria (Reference 3) is a method by which a pilot model is estimated by predicting the pilot's response required to control an aircraft for a given task. Figure 2 shows the pitch attitude tracking model which includes a pilot model and a simulated flight control system (FCS) plus airframe model. The typical pilot model consists of a variable gain (K_p), a time delay, and a variable first-order lead-lag compensation network.

It is assumed that the pilot will attempt to achieve good low-frequency performance (a reasonable bandwidth, with a minimum of low-frequency droop), and good high-frequency stability where $\left|\frac{\theta}{\delta_{e}}\right|$ (pitch angle / elevator stick position) is as small as possible. Typical values for minimum bandwidth (BW_{min}) range from 3.0 to 3.5 rad/sec. A maximum low-frequency droop of -3 dB was arbitrarily selected as a performance requirement by Neal-Smith.

The minimum bandwidth is a measure of the aggressiveness at which a pilot attacks the given task. Greater bandwidths correspond to more aggressiveness. It is possible to predict a pilot rating based on the pilot's aggressiveness, however it is unclear as to how to determine the BW_{min} at which the pilot is operating. For fighter type aircraft, Neal-Smith found these values to range somewhere between 3.0

and 3.5 rad/sec depending on task and flight configuration. A minimum bandwidth of 3.0 rad/sec was used for tasks where n/α = 18.5 g's/rad (normal acceleration per angle of attack), and 3.5 rad/sec was used when n/α = 50 g's/rad. Reference 4 applies the Neal-Smith criteria to landing tasks and suggests a bandwidth of 3.0 rad/sec for landing tasks where n/α is very low.

Neal-Smith makes use of the Nichols chart to apply the desired performance standards to the frequency response of the airframe plus FCS. Figure 3 shows an example of a Nichols chart with the Neal-Smith performance standards labeled and frequency response curves from some typical pitch attitude models. The minimum bandwidth is the frequency at which the frequency response curve intersects a closed loop phase of -90°. The portion of the curve where the frequencies $(\omega) \leq BW_{min}$, must remain above a closed loop amplitude of -3 dB to meet the maximum low frequency droop requirement. Curve #1 on Figure 3 shows an aircraft configuration that meets bandwidth and droop requirements (3.0 rad/sec and -3 dB) thus requiring no pilot compensation for optimum performance. Curve #2 shows an aircraft configuration with a bandwidth that exceeds the BW_{min} requirement. This configuration will require some lag compensation by the pilot for optimum performance. Curve #3 gives an example of an aircraft configuration that will require pilot lead compensation to meet the maximum droop requirement for optimum performance.

To apply the Neal-Smith criteria, a pilot model is created that meets the requirements for optimum performance. Then a pilot rating level is determined by plotting the amount of pilot lead or lag compensation required and the closed loop resonance onto a Neal-Smith parameter plane (Figure 4). The pilot rating level boundaries on the Neal-Smith parameter plane are based on previous flight test data and are purely empirical. The Neal-Smith criteria is only applicable to the longitudinal (pitch) axis therefore will not be applied to the lateral axis.

Application of the Neal-Smith Criteria to the F-104

The following is an example of the Neal-Smith procedure as it was applied to the F-104. For this example, the F-104 was considered to be in a cruise flight condition where M = 0.84 and h = 30,000 feet, and the following data was gathered from Reference 5;

τ_{θ_2} = 2.315 sec. = pitch-attitude time constant

ζ_{sp} = 0.161 = short period damping ratio

ω_{sp} = 3.48 rad/sec. = short period natural frequency

The hydraulic actuator for the elevator was modeled with a lag network where the time constant (τ_2) equaled 0.1 seconds. To improve the damping characteristics of the F-104, a pitch rate feedback was utilized. After performing a root locus, a feedback gain of $K_{\dot{\theta}}$=0.303 was chosen as a typical value to give desirable damping - the actual value was not available. Figure 5 shows the resulting airframe plus FCS model.

In applying Neal-Smith, first a time delay (τ) is inserted into the pilot model to account for the pilot's reaction time. Neal-Smith (Reference 3) uses a time delay of 0.3 seconds for up and away flight, and Reference 4 uses 0.2 seconds for landing approaches. For this report, a compromise of τ = 0.25 seconds will be used, as it seems unlikely that the pilot's reaction time is a function of task. Then the open loop frequency response of a model containing the airframe, FCS, and pilot delay is plotted on a amplitude-phase diagram (Figure 6). By overlaying a Nichols chart (Figure 3) onto Figure 6 and adjusting it up or down, it can be determined whether the pilot can achieve optimum performance by simply applying a gain.

For this example we will try to achieve a BW_{min} of 3.5, therefore some pilot lead compensation in addition to gain will be necessary. An initial guess of 20° lead compensation at $\omega = BW_{min}$ is substituted into the pilot model. The pilot lead time constant (τ_{P_1}) can be found using

$$\tau_{P_1}\omega = \tan 20°$$

where $\omega = BW_{min}$ = 3.5 resulting in a time constant of τ_{P_1} = 0.104. Figure 7 shows the resulting amplitude-phase diagram for 20° pilot lead compensation. When overlaying a Nichols chart onto Figure 7, the Neal-Smith requirements are much more closely met than prior to pilot compensation. A new guess at pilot compensation is to be made and the procedure is reiterated until all of the requirements are met.

The final values for the pilot model are;

$$\tau = 0.3 \text{ sec}$$

$$K_p = 0.826$$

$$\tau_{p_1} = 0.085 \text{ for } 16.7° \text{ lead,}$$

resulting in the final closed loop pitch attitude tracking model as shown in Figure 8. Figure 9 shows the amplitude-phase diagram of the pilot compensated model plotted on a Nichols chart. From Figure 9 the closed loop resonance is found to be 3.07 dB. Plotting the closed loop resonance and 16.7° pilot lead compensation onto a Neal-Smith parameter plane results in a Level 2 pilot rating. Figure 10 shows a Neal-Smith parameter plane with points plotted for minimum bandwidths ranging from 2.0 to 4.0 rad/sec and demonstrates the dependence Neal-Smith criteria has on the selection of a minimum bandwidth.

BANDWIDTH CRITERIA

Background

References 6 and 7 present a criteria which proposes the use of bandwidth as a measure of handling qualities of highly augmented aircraft operating in a tight tracking task. The bandwidth (ω_{BW}) for this criteria is the maximum frequency at which closed loop tracking can be performed without losing stability of the aircraft in contrast to the Neal-Smith criteria where bandwidth was required as a priori. In general, aircraft capable of operating at greater bandwidths will perform better.

The bandwidth is found from the frequency response (or Bode plot) of θ / δ_{e_s} and is defined as the frequency at which the phase margin is 45 degrees or the gain margin is 6 dB, whichever frequency is lower (Figure 11). After the bandwidth is determined, it is plotted versus an estimated time delay (τ_p) on Figure 12 or 13 and a pilot rating level is predicted. The bounds on Figures 12 and 13 were established empirically in Reference 6. The estimated time delay is calculated using the linear relationship:

$$\tau_p = - \frac{\phi_1 + 180^\circ}{57.3\ \omega_1}$$

where ω_1 is some frequency greater than the frequency for neutral stability (ω_{180°), and ϕ_1 is the phase corresponding to ω_1. Generally ω_1 is taken as twice the neutral stability frequency (i.e. $\omega_1 = 2\,\omega_{180°}$). Like the Neal-Smith criteria, the Bandwidth criteria is only applicable to the longitudinal (pitch) axis. Difficulties sometimes arise in using the Bandwidth criteria when applying it to shelf-like amplitude plots.

Application of the Bandwidth Criteria to the F-104

The F-104 will be considered to have the same flight conditions and flight control system as in the previous chapter. From the Bode plot of the θ/δ_{e_s} transfer function (Figure 11) the bandwidth can be determined. The 45° phase margin frequency ($\omega_{BW_{phase}}$) is found where the phase is equal to the phase margin minus 180° - for this case, $\omega_{BW_{phase}}$ = 6.85 rad/sec at ϕ = -135°. The 6 dB gain margin frequency ($\omega_{BW_{gain}}$) is found where the gain is 6 dB greater than the gain at $\omega_{180°}$ - for this case, $\omega_{BW_{gain}}$ = 6.13 rad/sec. Since $\omega_{BW_{gain}}$ is the smaller of the two frequencies, it will be used to determine the handling qualities of the F-104. The estimated time delay is found to be τ_p = .05 seconds. Level 2 handling qualities are predicted when plotting the bandwidth frequency and estimated time delay on Figure 12. This is consistent with the previous prediction using Neal-Smith criteria. It can be seen from Figure 12 that the inclusion of a feel system in the form of a pure time delay will degrade rating level; however, if the time delay is small, it will have little effect on the rating level.

EQUIVALENT SYSTEMS

Background

The equivalent systems approach, as described in References 8 through 11, is a method that involves approximating a higher order system (HOS) of a highly augmented aircraft with a lower order system (LOS) transfer function. Handling qualities criteria from the Mil Spec 8785C can then be applied to the LOS.

The lower order transfer functions for the lateral axis are:

$$\frac{\phi}{\delta_{a_s}} = \frac{K_\phi (s^2 + 2\zeta_\phi \omega_\phi s + \omega_\phi^2) e^{-\tau_\phi s}}{(s + 1/\tau_R)(s + 1/\tau_s)(s^2 + 2\zeta_{DR}\omega_{DR} s + \omega_{DR}^2)}$$

$$\frac{\beta}{\delta_r} = \frac{K_\beta (s + 1/\tau_{\beta_1})(s + 1/\tau_{\beta_2})(s + 1/\tau_{\beta_3}) e^{-\tau_\beta s}}{(s + 1/\tau_R)(s + 1/\tau_s)(s^2 + 2\zeta_{DR}\omega_{DR} s + \omega_{DR}^2)}$$

and for the longitudinal axis:

$$\frac{q}{\delta_{e_s}} = \frac{K_q (s + L_\alpha) e^{-\tau_q s}}{s^2 + 2\zeta_{sp}\omega_{sp} s + \omega_{sp}^2}$$

The parameters in these equations are varied iteratively to obtain a best fit with the HOS Bode plots. Typically the HOS and LOS frequency responses are matched over a frequency range of 0.1 to 10 radians per second. The degree of accuracy at which these curves match is represented by a mismatch function:

$$M = \frac{20}{n} \sum_{\omega_1}^{\omega_n} \left[(G_{HOS} - G_{LOS})^2 + 0.01745 (\Phi_{HOS} - \Phi_{LOS})^2 \right]$$

where n is the number of frequencies spaced evenly on the logarithmic scale, G_{HOS} and G_{LOS} are the HOS and LOS amplitudes, and ϕ_{HOS} and ϕ_{LOS} are the HOS and LOS phases. When the mismatch is less than 20, then an adequate fit has been made.

It isn't always possible to obtain an adequate fit using equivalent systems. It has been suggested in Reference 8 that aircraft that exhibit a poor LOS fit (M > 20) generally have no better than Level 2 handling qualities. It is important that the starting values for the LOS parameters are reasonable estimates so that the LOS converges properly. These estimates can usually be obtained from the HOS.

<u>Application of Equivalent Systems to the F-104</u>

For this analysis the F-104 will again be considered in the cruise flight condition, however this time the lateral handling qualities will be investigated.

The lateral-directional equations of motion are:

$$\begin{bmatrix} 1 & -I_{xz}/I_x & 0 & 0 \\ -I_{xz}/I_z & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{r} \\ \dot{\beta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} L_p & L_r & L_\beta & 0 \\ N_p & N_r & N_\beta & 0 \\ \alpha_o & -1 & Y_\beta & g/V \\ 1 & \theta_o & 0 & 0 \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \\ \phi \end{bmatrix} + \begin{bmatrix} L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta_r} \\ Y_{\delta_a} & Y_{\delta_r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{a_s} \\ \delta_r \end{bmatrix}$$

Nondimensional stability derivatives for the F-104 are obtained from Reference 12 and converted to dimensional derivatives resulting in the following equations of motion:

$$\begin{bmatrix} 1 & -0.734 & 0 & 0 \\ -0.0453 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{r} \\ \dot{\beta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -1.66 & 1.12 & -56.4 & 0 \\ -0.0192 & -0.225 & 7.79 & 0 \\ 0.084 & -1 & -0.15 & 0.037 \\ 1 & 0.084 & 0 & 0 \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \\ \phi \end{bmatrix}$$

$$+ \begin{bmatrix} 14.3 & 9.61 \\ 0.297 & -2.46 \\ 0 & 0.019 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{a_s} \\ \delta_r \end{bmatrix}$$

To improve the lateral damping characteristics of the F-104, a yaw rate feedback with a washout network was implemented (Figure 14). For this example, a yaw rate feedback gain of $K_r = 4.0$ and a washout time constant of $T_W = 3.0$ seconds were chosen as typical values - the actual values were not available. Figures 15 and 16 show the resulting frequency response (Bode plot) from this configuration.

Applying the equivalent systems technique to the F-104 required iteratively solving for some parameters while holding others constant. This method was initiated for each transfer function alternately until all parameters were freed and acceptable mismatches were obtained. Starting values for the roll mode time constant (τ_R) and the spiral mode time constant (τ_s) were estimated from the time history response to a aileron step input (Figure 17). The roll mode time constant was estimated by finding the time required to achieve 63% of steady state roll rate. From

Figure 17, the value of τ_R was found to be approximately 0.2 seconds. The spiral mode time constant can be found from this same figure by finding the time required for the roll rate amplitude to halve or double (T_{double}) after the initial response. Subsequently the spiral mode time constant can be found from the relation:

$$\tau_s = \frac{\ln 2}{T_{double}}$$

For this example, the roll rate appears to remain constant after the initial response, therefore $T_{double} = \infty$ and $\tau_s = 0$.

For the first iteration, values for τ_R and τ_s were held constant while all other parameters were varied until a optimum fit was made on the Φ/δ_{as} (roll angle / aileron stick position) transfer function. The procedure for identifying the LOS parameters is not well defined and basically becomes a trial and error process. Table 1 demonstrates the subsequent procedure in which the parameters were identified and their corresponding values. The final step involved a simultaneous fit of both Φ/δ_{as} and β/δ_r (side slip angle / rudder pedal position) transfer functions where all parameters were freed with the exception of τ_s and τ_R . The resulting frequency response of the equivalent LOS's are plotted on Figures 15 and 16, and show good matches to the HOS's.

Handling qualities criteria from the Mil Spec 8785C can now be applied to the results of the equivalent lower order system. This will be accomplished in the following chapter.

MILITARY SPECIFICATION 8785C

Background

The Mil Spec 8785C (Reference 2) specifies handling qualities requirements for military aircraft. Aircraft are categorized into four different classes. Of primary interest in this report are class IV aircraft which includes all fighter type aircraft. Flight phase categories are defined in the Mil Spec as follows:

Category A - "Those nonterminal flight phases that require rapid maneuvering precision tracking or precise flight-path control."

Category B - "Those nonterminal flight phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may required."

Category C - "Terminal flight phases are normally accomplished using gradual maneuvers and usually require accurate flight path controls."

The Mil Spec divides handling qualities into 3 levels. These levels correspond to the Cooper-Harper pilot rating scale (Figure 1) as follows:

Level 1 = P.R. 1 to 3.5

Level 2 = P.R. 3.5 to 6.5

Level 3 = P.R. 6.5 to 9

The predicted handling qualities level of an aircraft in a given category of flight phase should reflect the worse level predicted from the various criteria. When making correlations between predicted handling qualities and actual pilot ratings it is important to take notice of any pilot comments. These comments will often indicate which criteria are critical in determining the pilot rating given.

In this report, handling qualities criteria from the Mil Spec 8785C will be applied to longitudinal and lateral transfer functions derived from the equivalent systems approach. Emphasis will be placed on criteria considered to have the greatest significance on handling qualities for high stress tasks (Categories A and C). These criteria will be described in the following paragraphs.

In the longitudinal axis, the equivalent short period damping ratio and the short-period undamped natural frequency will be considered. Table 2 shows the required limits for short period damping. The limits for the short period natural frequency versus n/α for Categories A and C (Category B will not be used in this report) are shown on Figures 18 and 19. The parameter n/α can be calculated from the equivalent lift due to angle of attack (L_α) using the formula $n/\alpha = L_\alpha(V/g)$ where V is the true velocity and g is the accelaration of gravity. Table 3 shows the specified limits of the time delay for an aircraft's response to a stick force input.

In the lateral axis, limits for Dutch roll characteristics (damping ratio and undamped natural frequency) are specified in Table 4. Limits for the roll mode time constant and the time for bank angle to double in amplitude (T_{double}) are specified in Tables 5 and 6 respectively. Time delays t_ϕ (roll mode delay) and t_β (side slip delay) will have the same limits as specified for the longitudinal case in Table 3.

Another criteria that will be used in this paper comes from Monagan, Smith, and Baily (Reference 13) which uses the combination of the effective time delay (τ_{EFF}) and roll mode time constant (τ_R) for establishing pilot rating level bounds as shown in Figures 20 and 21. This criteria will be referred to as the LATHOS (Lateral Higher Order System) criteria. When using equivalent systems, it will be assumed that $t_\phi \cong \tau_{EFF}$. The purpose for using this criteria in addition to the Mil Spec is due to a phenomena called roll ratcheting which occurs when τ_R is small.

<u>Application of Mil Spec Handling Qualities Criteria to the Lateral Equivalent Systems Model of the F-104</u>

Using the results from the equivalent systems analysis (Table 1), the Mil Spec handling qualities criteria can now be applied to the F-104. The F-104 is a Class IV type aircraft, and for this example, will be considered to be flying in a Category A flight phase.

Minimum Dutch roll damping and frequency requirements for Level 1 handling qualities are met by the F-104 (refer to Tables 1 and 4). Time delays for both transfer functions (t_ϕ and t_β) also meet Level 1 handling qualities requirements (see Table 3). Level 1 handling qualities requirements for time to double roll amplitude (T_{double}) are met (see Table 6). From Table 5 it appears as if the roll mode time constant (τ_R = .186) is Level 1, however, since τ_R is low, the possibility of roll ratcheting should be investigated. Using the roll mode time delay (t_ϕ = .06) and plotting it versus τ_R on Figure 20 results in Level 2 handling qualities. Therefore the F-104 in this example, in a Category A flight phase, is predicted to exhibit Level 2 handling qualities due to roll ratcheting or over sensitivity.

APPLICATIONS OF CRITERIA

F-8 DFBW

The F-8 Digital Fly-By-Wire is a modified F-8C single engine, single place Navy fighter. It was modified by removing the entire mechanical control system linking the stick and rudder pedals to the actuators and replacing it with a digital fly-by-wire control system whereby various control laws could be implemented. This aircraft was used for the study of flight control augmentation systems, and was used to study the effects that the time delay within the control system had on handling qualities.

Data from several flights, including some time delay studies, was used to apply the various handling qualities criteria and compare the results. The flight configurations that were analyzed, along with their corresponding pilot ratings, are listed in Table 7. Data for the Shuttle simulations was obtained from Reference 14. Figure 22 shows the F-8 DFBW's longitudinal stability augmentation system (SAS), and Figure 23 shows the lateral SAS. All of the lateral system's gains where scheduled according to angle of attack and the pitch rate feedback gain was scheduled according to the dynamic pressure. Feel system dynamics were excluded (a model of the feel system was not available) and all inputs were based on stick position.

Using stability derivatives obtained from unpublished flight test data and the control system models (Figures 22 and 23), frequency responses and time histories were calculated using John Edwards' "Control" program (Reference 15). Then Neal-Smith, Bandwidth, Equivalent Systems, and Mil Spec 8785C criteria were applied. The results of the Neal-Smith criteria are shown in Table 8 which includes results using minimum bandwidths of 2.5, 3.0, and 3.5 rad/sec. The rating levels which are found using the recommended BW_{min} corresponding to n/α are indicated with asterisks. Table 9 shows the Bandwidth criteria results. The results using Equivalent Systems and applying Mil Spec criteria are tabulated in Table 10.

The results from all of the criteria applied to the longitudinal axis are summarized in Table 11. Of the three methods investigated, Equivalent Systems appears to be the most consistent with actual pilot ratings, however all three of the methods gave reasonable results for most flight configurations. By including feel system dynamics in the form of time delay (if delays are significantly large) the correlation of results would be degraded. The Neal-Smith criteria gives poor results for flight configuration E. This is most likely due to the poor damping exhibited by the F-8 DFBW in flight configuration E, as Neal-Smith criteria tends to become unworkable for poorly damped aircraft. Flight configuration G was given a Level 1 pilot rating, however it is predicted Level 2 from all three methods.

This might be explained by the fact that a pilot rating of 3 is given and is marginally Level 1, therefore a predicted Level of 2 is within reason.

Lateral handling qualities were evaluated using Equivalent Systems and applying the Mil Spec criteria. Table 12 shows the results for flight configurations A, B, C, and D. Flight configurations A, B, and D are predicted Level 1 when only the Mil Spec is applied, however, applying the LATHOS criteria (Table 13) results in Level 2 handling qualities which is in good agreement with actual pilot ratings. According to the LATHOS criteria, the F-8 exhibits roll-ratcheting or over sensitivity which agrees with pilot comments, but is not accounted for in the Mil Spec criteria. Table 14 shows the comparison of the predicted rating levels with the actual pilot ratings.

<u>YF-12</u>

The YF-12 airplane is an advanced, twin engine, delta-wing interceptor designed for long-range cruise at Mach numbers greater than 3 and altitudes above 80,000 feet. Its stability augmentation system includes rate feedbacks which are scheduled according to altitude and dynamic pressure.

A longitudinal handling qualities analysis was performed on the YF-12 for one flight condition. Data was obtained from Reference 16 in the form of a frequency response of θ / δ_{e_s}. This frequency response was then converted to q/δ_{e_s} (pitch rate / elevator stick position) and an equivalent LOS was matched to it. The results of applying Neal-Smith, Bandwidth, Equivalent Systems, and Mil Spec criteria to the YF-12 are shown in Tables 8, 9, and 10 respectively and are summarized in Table 11. The YF-12 is rated Level 1 for longitudinal tracking in this flight condition therefore agrees well with the predicted results.

Advanced Fighter Aircraft

This Advanced Fighter Aircraft (AFA) is a highly augmented, high performance fighter type aircraft. The flight control system has three modes of operation: one primary (or normal) mode and two back-up modes.

Longitudinal handling qualities criteria were applied to four different flight conditions of the AFA. The flight control system was in the normal mode for flight conditions 1 and 2 and in the back-up mode for flight conditions 3 and 4. Data was obtained in the form of frequency sweeps where δ_e, was the input variable and q was the output. To obtain frequency response plots, fast Fourier transforms were performed on the frequency sweeps.

Equivalent Systems was applied to the frequency responses. Since the frequency response data was somewhat noisy, slightly higher than normal mismatches were allowed. Figure 24 shows an example of an equivalent lower order system overplotted onto a frequency response obtained from flight test data. Despite a mismatch of 27.2, the LOS shows a fairly good match with the HOS.

The results of applying the Mil Spec to the equivalent systems of the AFA are tabulated in Table 10. Due to the noisy data, Neal-Smith and Bandwidth criteria could not be applied directly to the flight test data, therefore these criteria were applied to the equivalent LOS models. Table 8 shows the results of the Neal-Smith criteria and Table 9 shows the results of the Bandwidth criteria.

The results from all of the criteria are summarized in Table 11. The AFA has been rated at Level 2 for tracking maneuvers throughout the flight envelope. However it should be noted that these rating levels are based on both longitudinal and lateral axis, and, as with the F-8 DFBW, all feel systems dynamics have been excluded. Therefore the predicted rating levels could conceivably be lower than the actual pilot rating levels. Despite this, the predicted rating levels are in relatively good agreement with actual pilot ratings.

CONCLUSIONS

This report has shown that Equivalent Systems, Bandwidth, Neal-Smith, and Mil Spec criteria can be applied to highly augmented or unconventional aircraft with fairly good results. Referring to Tables 11 and 13, all of the criteria investigated gave predicted pilot ratings that were within less than 1 level of the actual pilot rating better than 50% of the time. No one method was significantly better than the rest, therefore it is recommended that more than one criterion be applied whenever possible.

The aircraft investigated in this paper reveal that the equivalent time delay is often the critical factor in determining the handling qualities of a highly augmented aircraft (refer to Table 10). While these augmentation systems do a great deal towards maintaining stability and enhancing the frequency and damping requirements, they often induce significant time delays into the aircraft. There is some question as to the validity of including feel system dynamics when determining equivalent time delays. Feel system dynamics were excluded in all of the evaluations done in this report and good results were obtained; however, it was unknown how much the feel systems would have contributed to the time delays - if the feel systems were fast they would have had little effect on the results. Correlation of the results in this report would have been degraded by the inclusion of feel system time delays.

Of the criteria discussed, Bandwidth criteria is the most easily implemented as it is not an iterative process like Neal-Smith and Equivalent Systems. However difficulties arise in applying Bandwidth criteria to some shelf-like Bode plots where crossover frequencies are not well defined.

Neal-Smith was the only criteria investigated in this report that takes pilot compensation into consideration. This has the advantage of giving the user the capability to change the pilot model, however selecting appropriate pilot time delays and minimum bandwidths for a given task tends to be confusing. Neal-Smith criteria does not apply well to aircraft exhibiting poor damping qualities.

By using the Military Specification 8785 criteria in conjunction with the Equivalent Systems criteria it is possible to be more specific as to the critical factors in determining the pilot rating level. However additional criteria needs to be established in the Mil Spec 8785 to account for oversensitivity in the roll mode (roll ratcheting) as seen with the F-8 DFBW.

Care should be taken in selecting starting values for LOS parameters. For the longitudinal case, L_α should be derived by an independent method to determine if the value determined by Equivalent Systems is reasonable. If not, L_α should be held at a constant value. For the lateral case, initial values for τ_s , τ_R , τ_ϕ , and τ_β can be estimated from time histories.

Due to the large number of parameters to be identified, equivalent systems as applied to the lateral-directional case has enjoyed limited success. A consistent procedure of parameter identification is often difficult to establish and thus becomes a trial and error process. Lower order systems with mismatches greater than 20 (M > 20) are generally considered to have no better than Level 2 handling qualities. This standard can be relaxed slightly when applying Equivalent Systems to noisy flight test data.

Care should be taken when comparing predicted pilot ratings with flight test pilot ratings. Pilot ratings are not definitive values, as they are based on opinions of individual pilots with varying skills and experience. It is important to investigate pilot comments whenever their available to better understand the bases of the pilot's rating.

For handling qualities criteria, flight test data is generally obtained from either frequency sweeps or stability derivatives. Using data from frequency sweeps is the more direct approach however this data is often noisy. It is difficult to apply Bandwidth or Neal-Smith criteria to noisy data, therefore it is recommended that these criteria be applied to the equivalent lower order system if a good Equivalent Systems fit is made.

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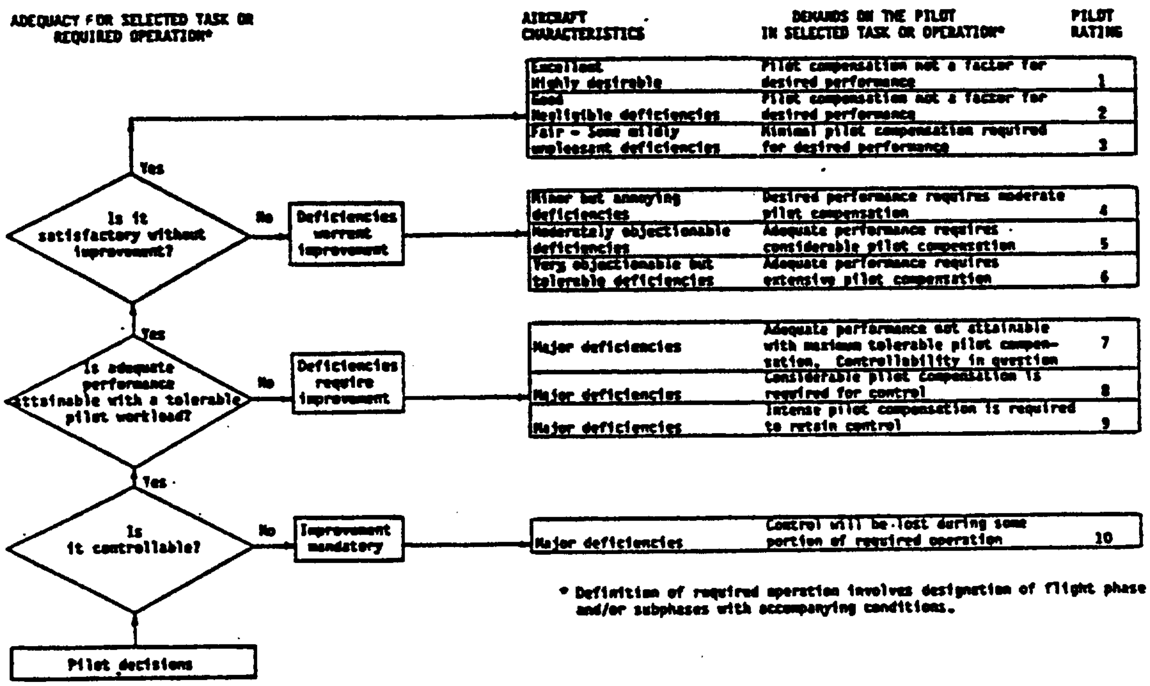


Figure 1: Cooper-Harper pilot rating scale

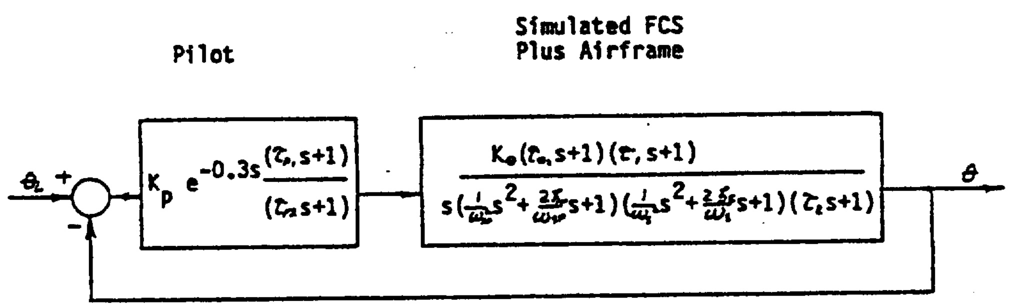


Figure 2: Pitch attitude tracking model

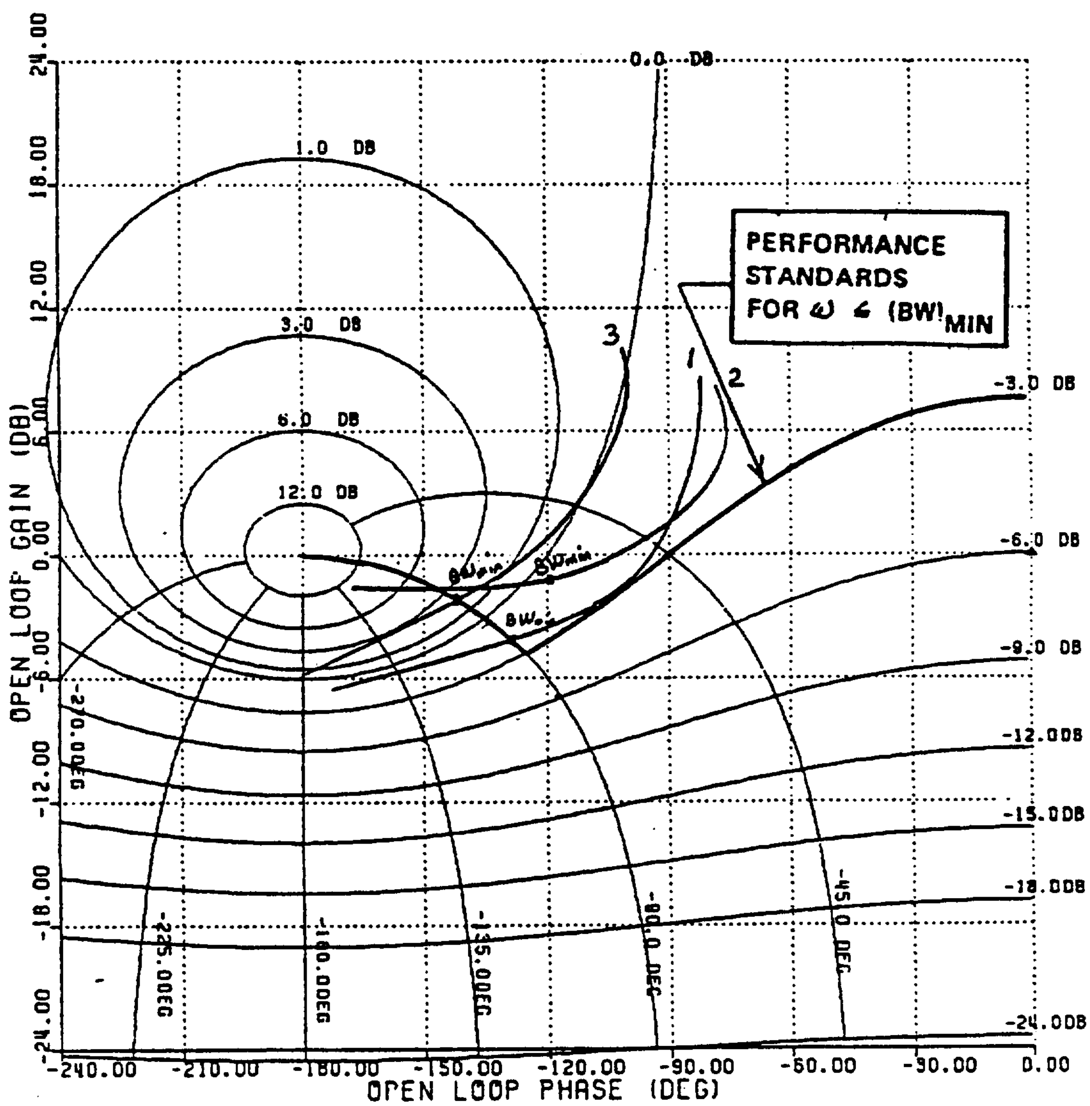


Figure 3: Nichols chart with Neal-Smith performance standards

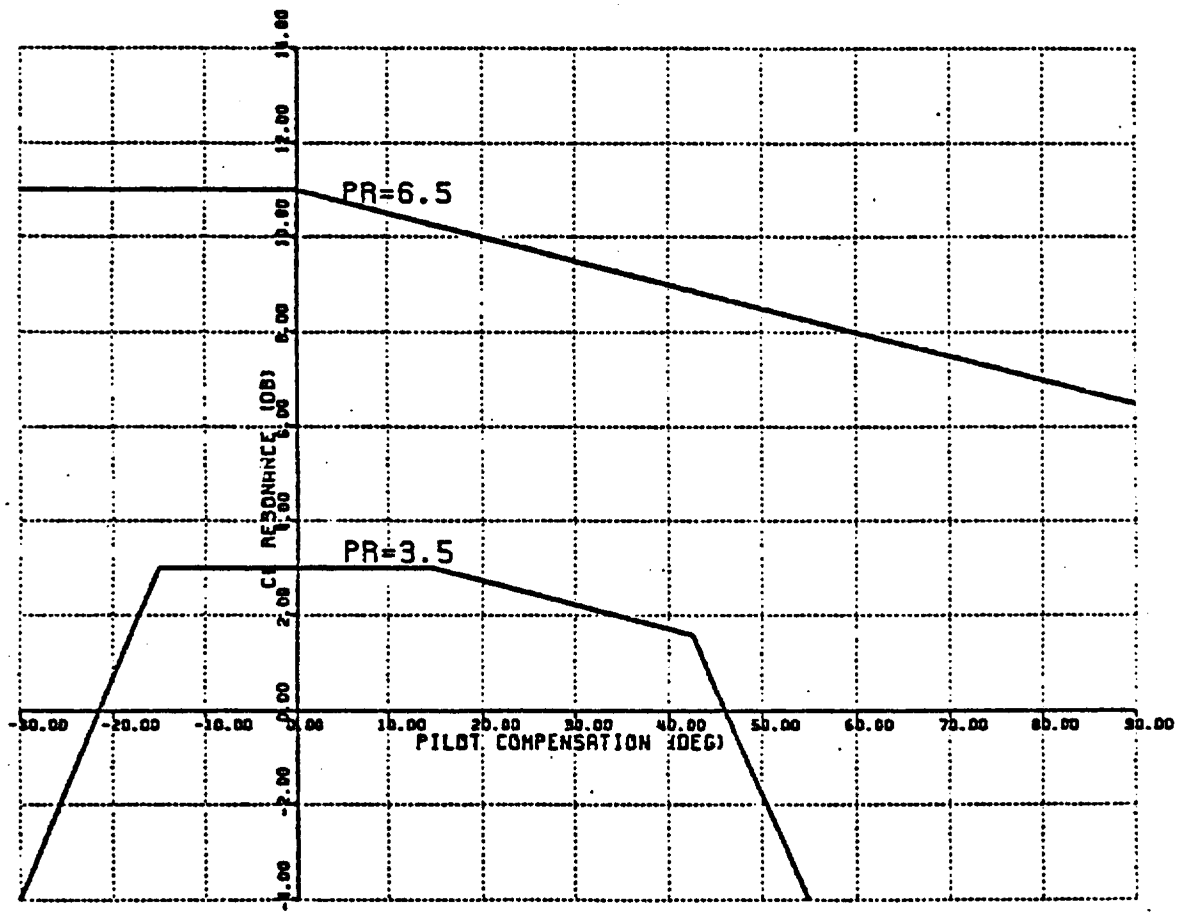


Figure 4: Neal-Smith parameter plane

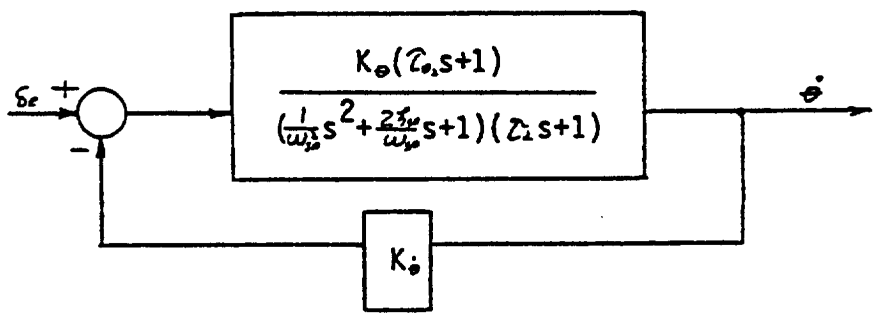


Figure 5: F-104 plus flight control system model

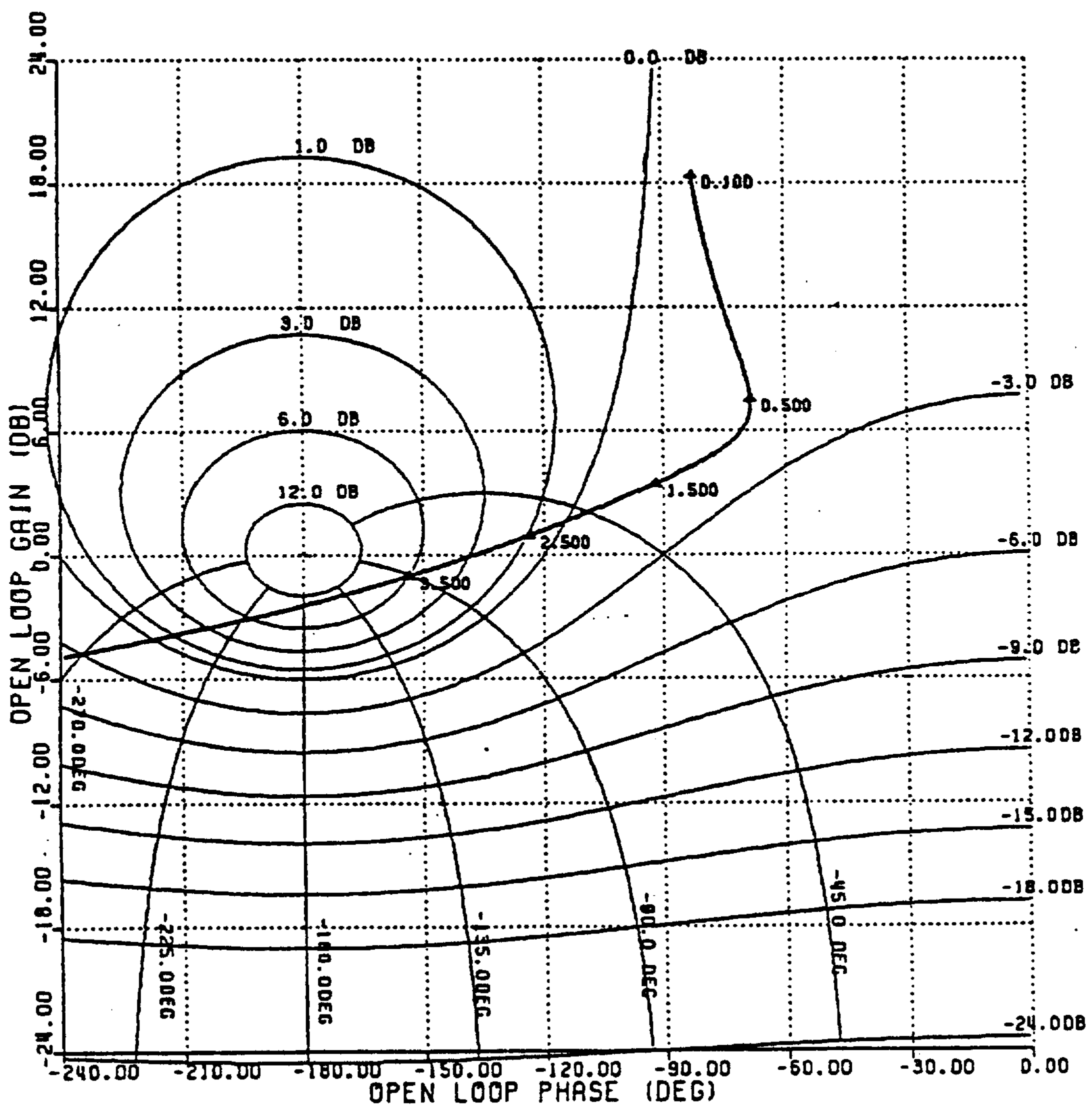


Figure 6: Amplitude-phase diagram (F-104 plus 0.3 second
pilot delay, no lead or lag compensation)

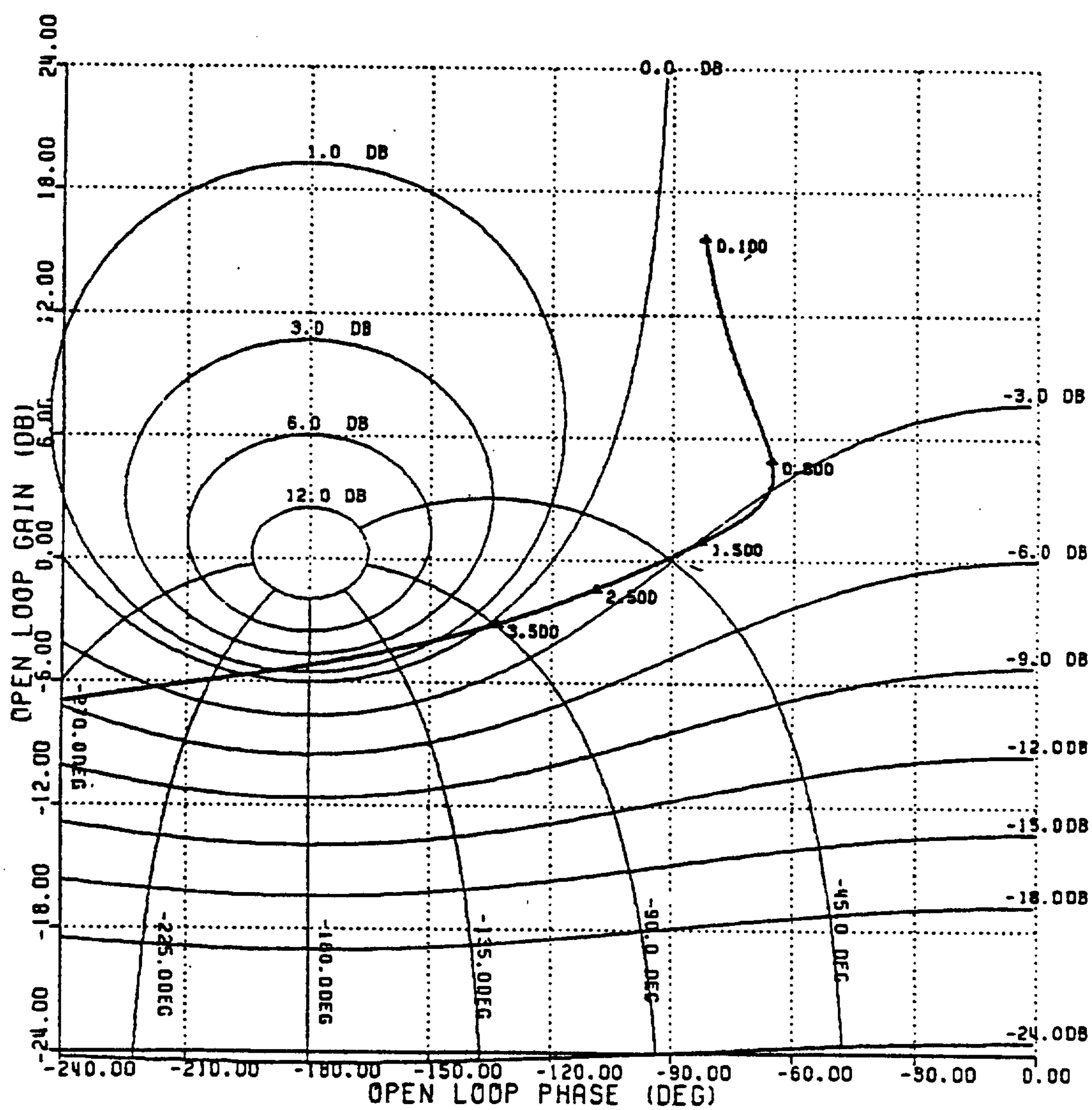


Figure 7: Amplitued-phase diagram (20° lead compensation, K_p = .78)

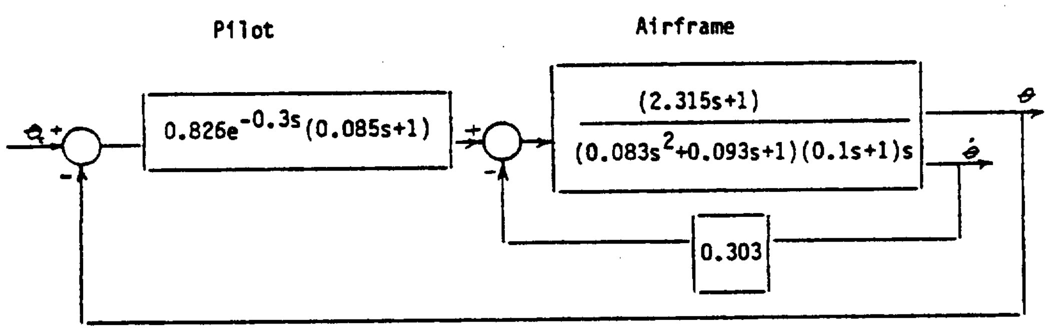


Figure 8: Pilot compensated closed loop model (F-104)

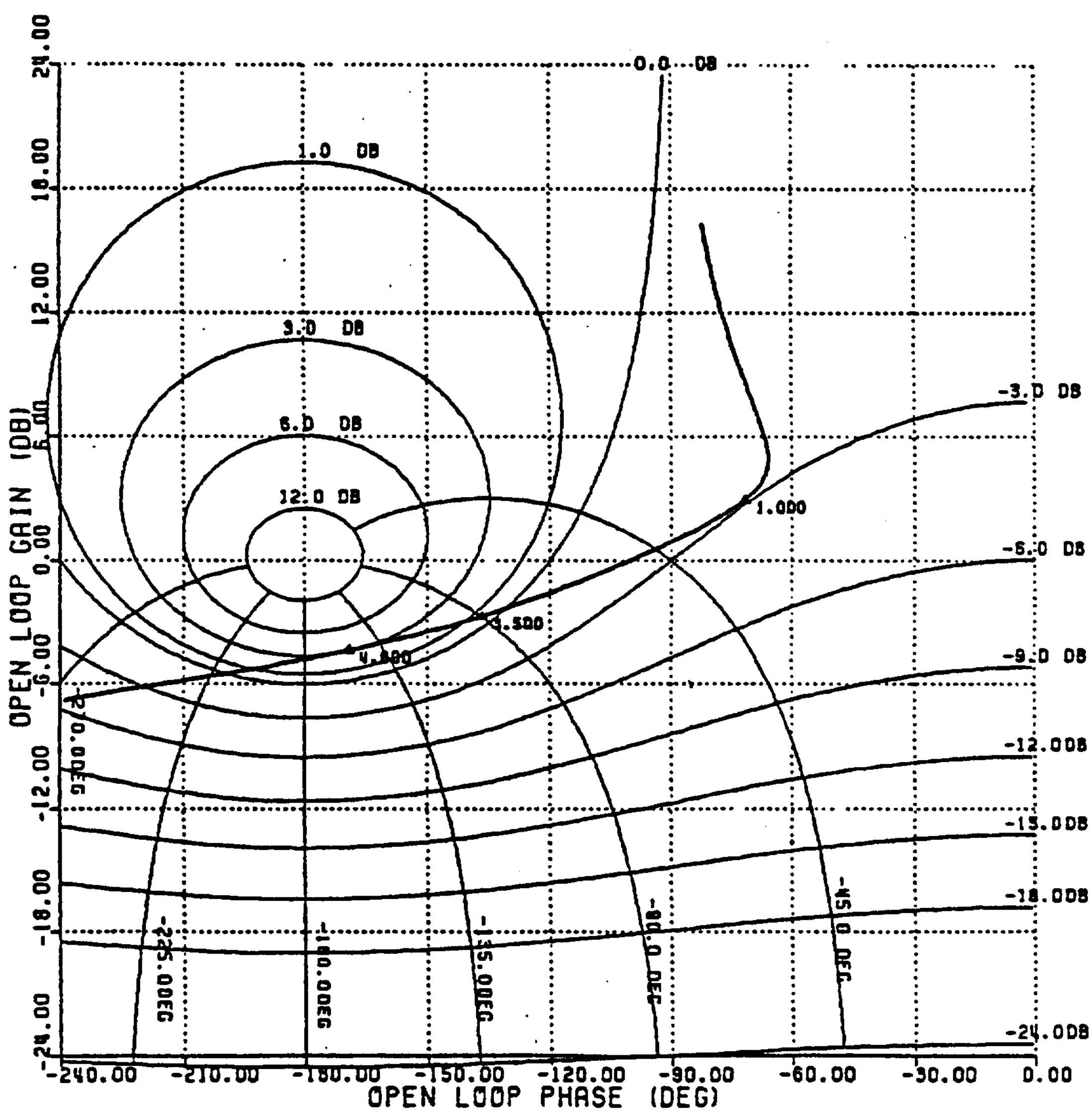


Figure 9: Nichols chart (F-104, 16.7° lead compensation)

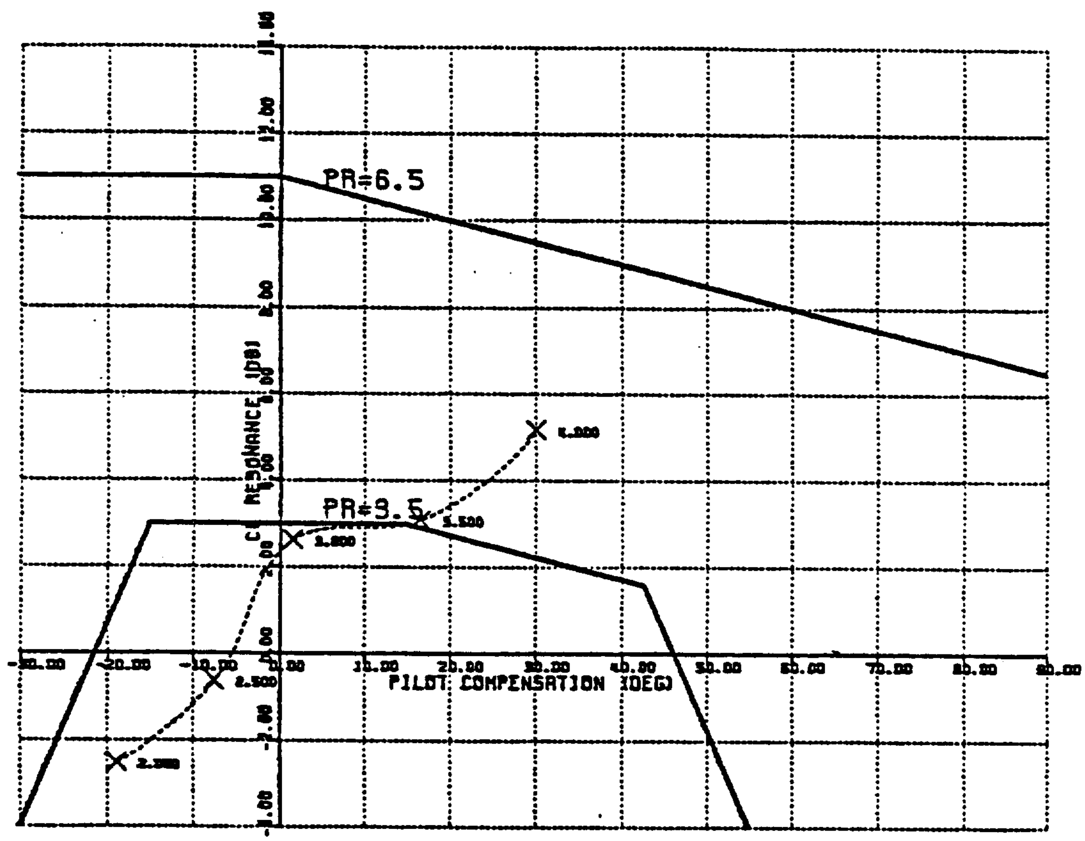


Figure 10: Neal-Smith parameter plane, F-104

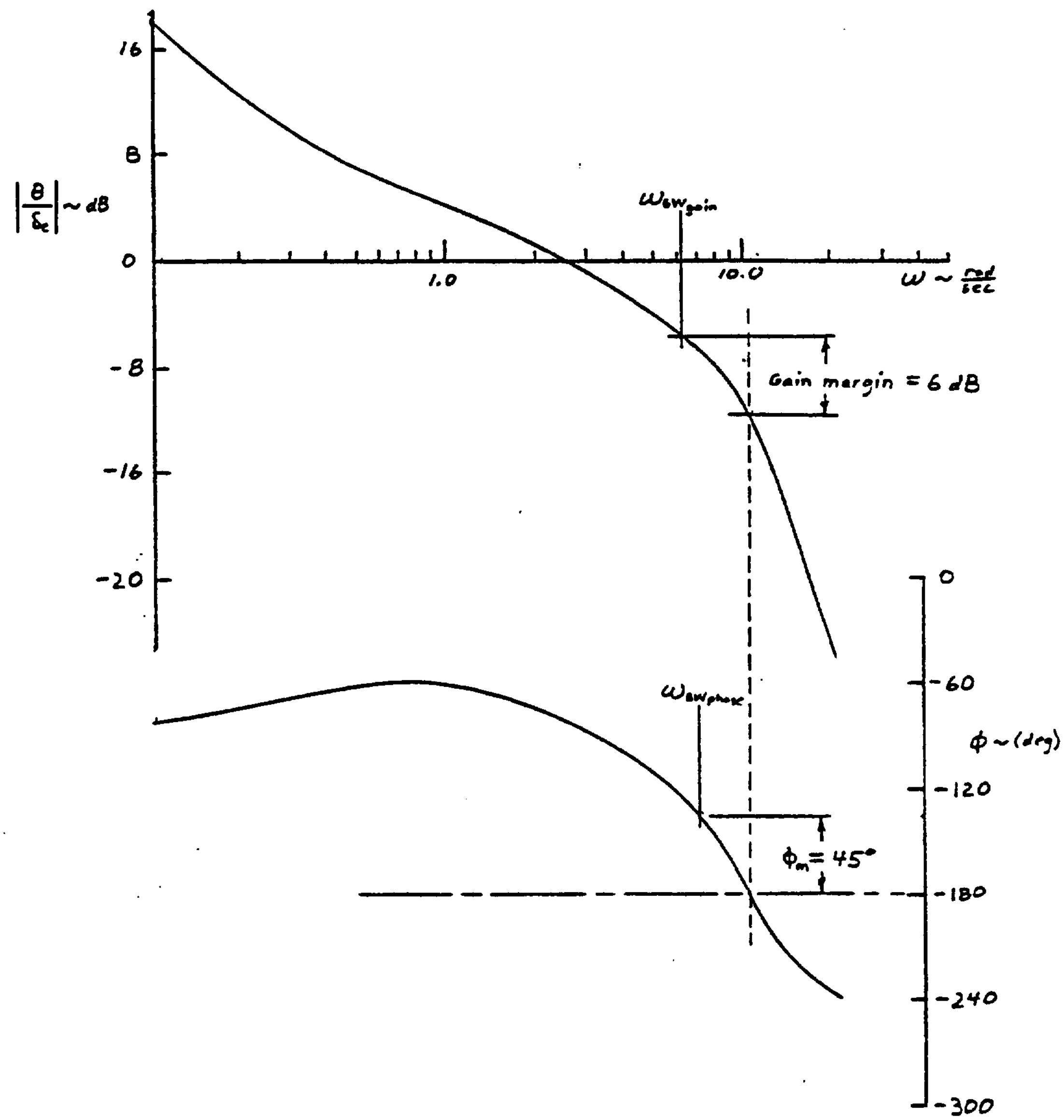


Figure 11: Definition of bandwidth frequency (applied to the F-104)

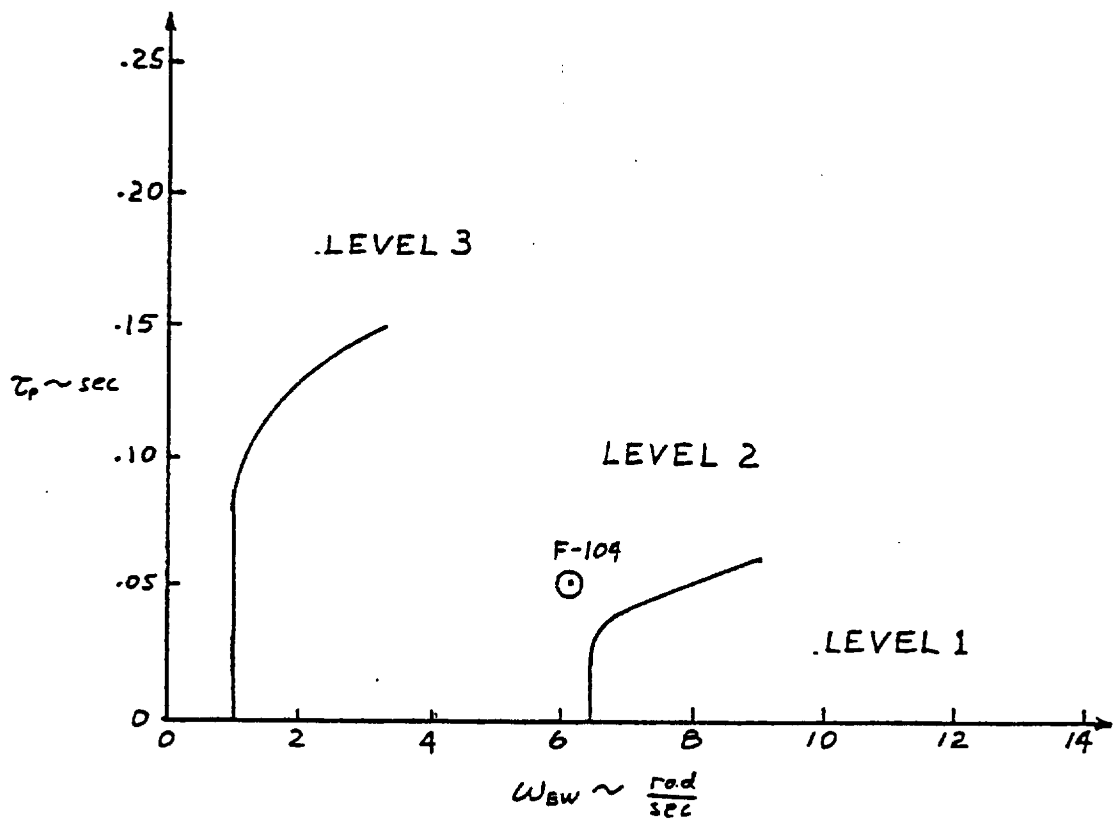


Figure 12: Correlation of pilot ratings with ω_{BW} and τ_p for up and away flight

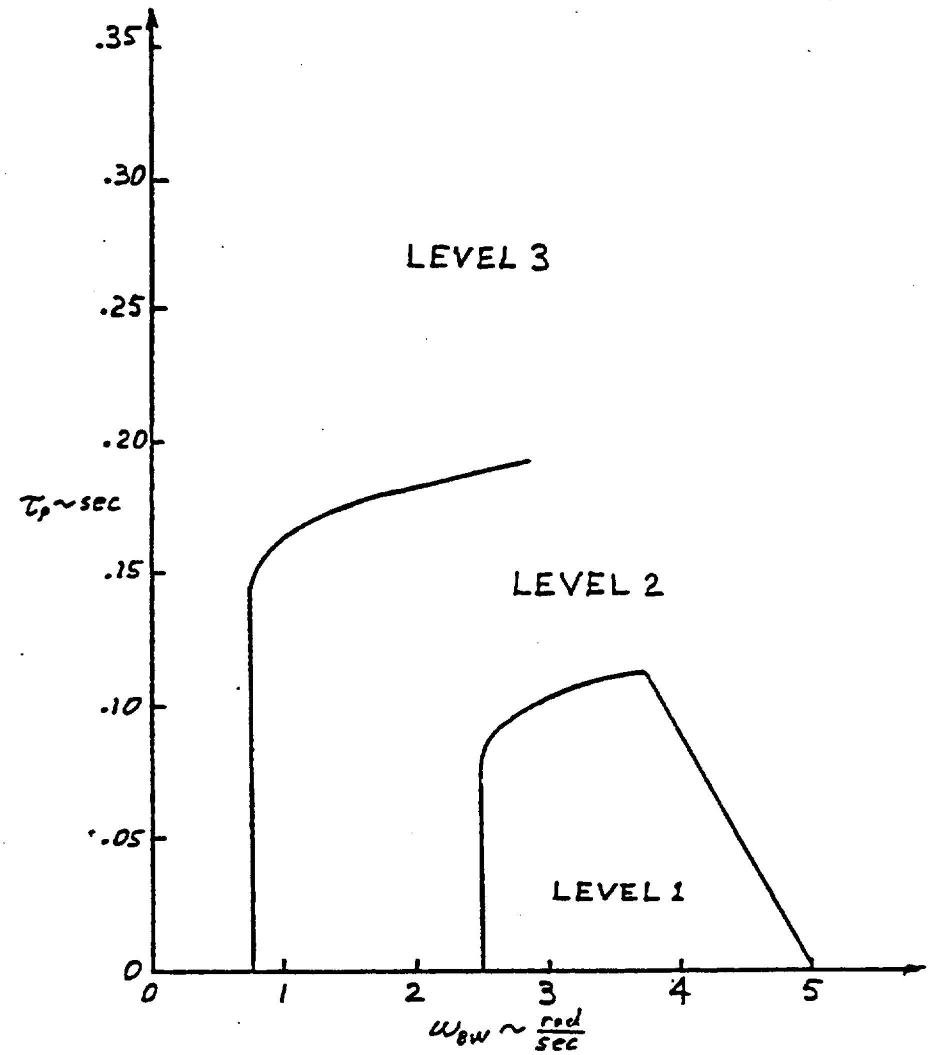


Figure 13: Correlation of pilot ratings with ω_{BW} and τ_p for approach and landing

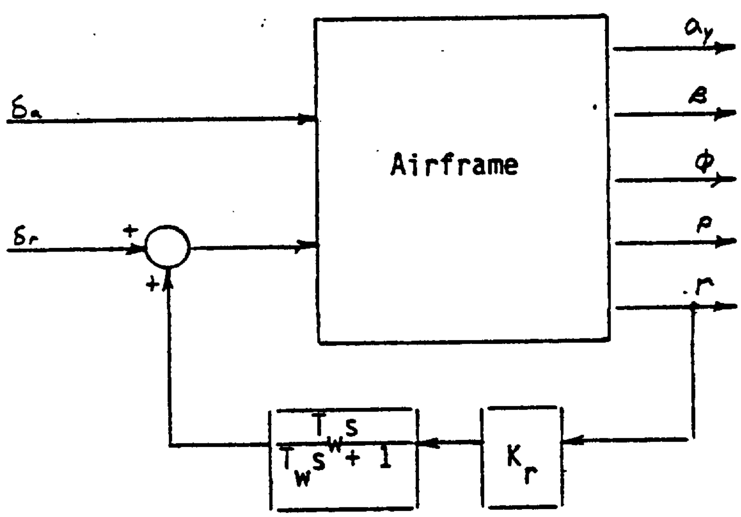


Figure 14: Yaw rate feedback model of the F-104

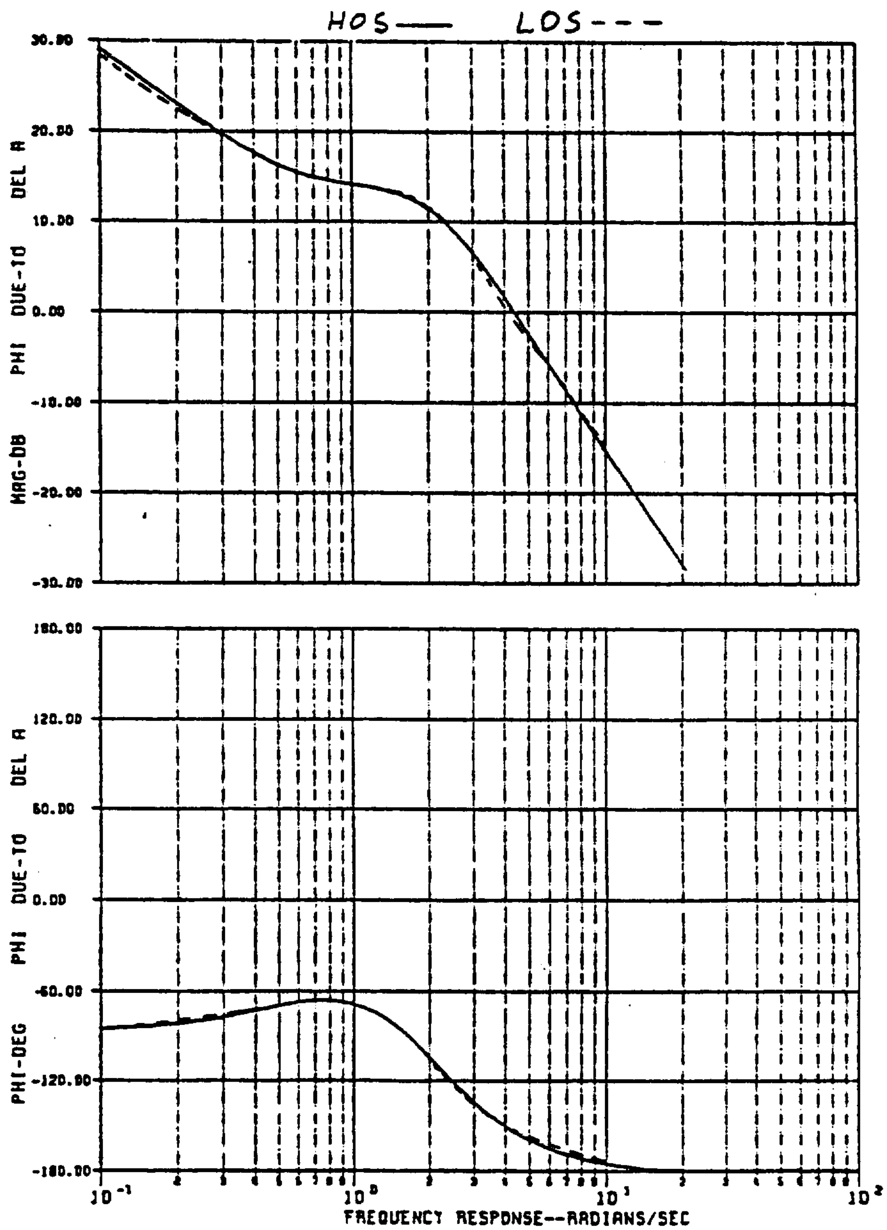


Figure 15: ϕ / δ_a Bode plot

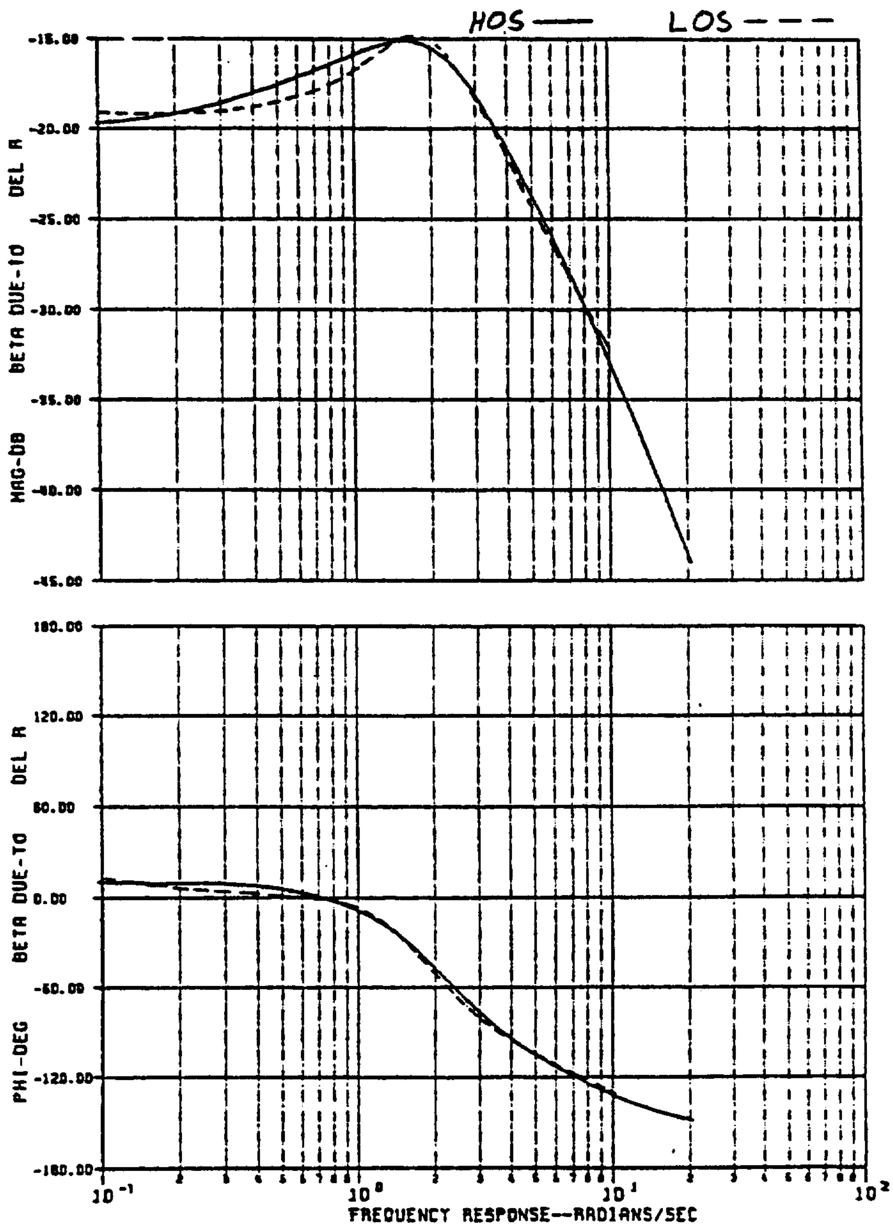


Figure 16: β / ε_A Bode plot

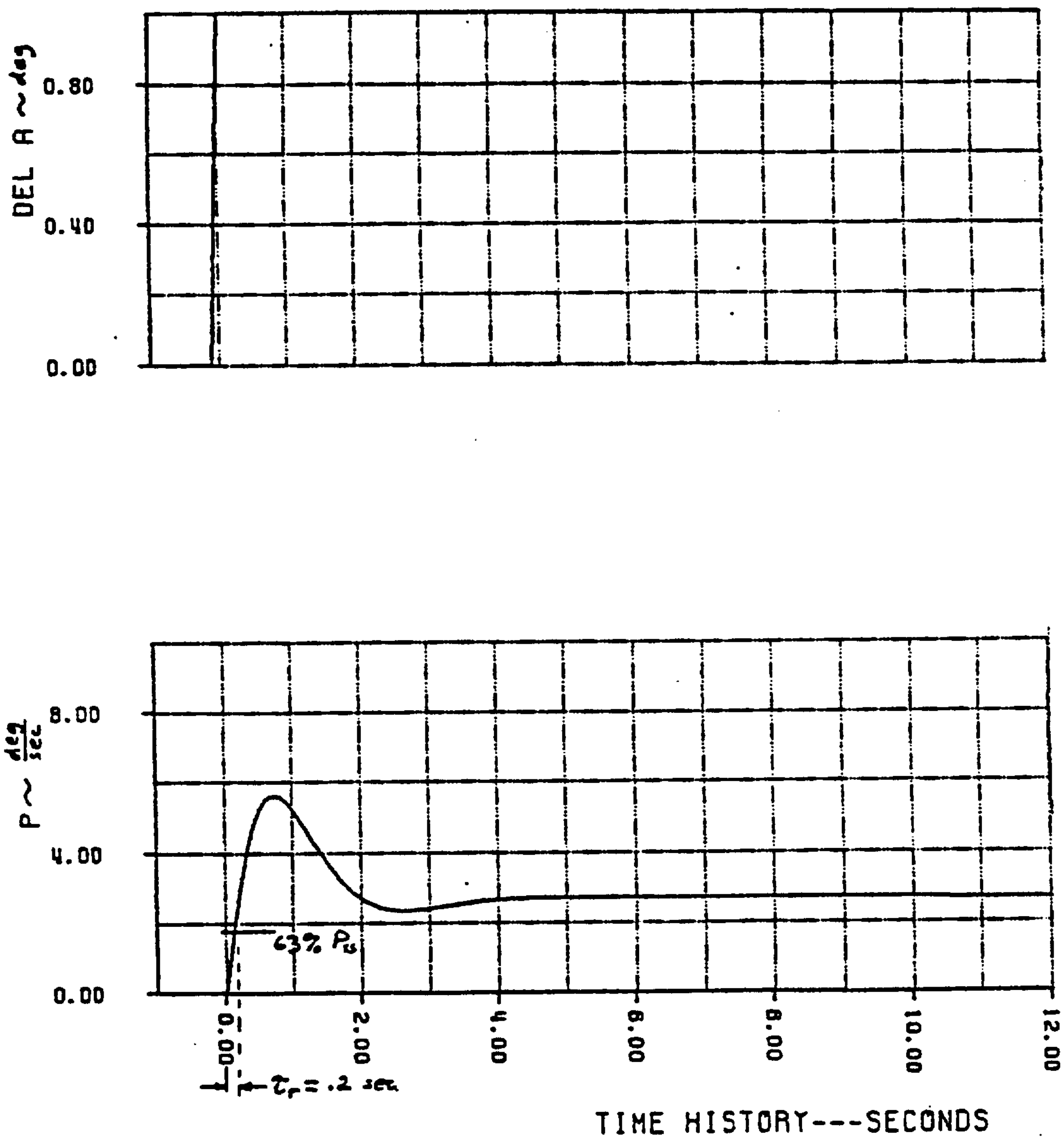


Figure 17: Time history to an aileron step (F-104)

Table 1: Equivalent systems results of the F-104

	$\frac{\phi}{\delta_a}$	$\frac{\beta}{\delta_r}$	$\frac{\beta}{\delta_r}$	Simultaneous Fit
ζ_{DR}	0.586	0.586*	0.611	0.522
ω_{DR}	2.18	2.18*	1.67	1.99
$1/\tau_r$	5.00*	5.00*	5.38	5.38*
$1/\tau_s$	0.0*	0.0*	0.0*	0.0*
K_ϕ	16.89	------	------	19.05
ζ_ϕ	1.58	------	------	1.43
ω_ϕ	1.97	------	------	1.75
t_ϕ	0.0059	------	------	0.0164
K_β	------	0.237	0.220	0.216
$1/\tau_{\beta_1}$	------	-0.018	-0.016	-0.021
$1/\tau_{\beta_2}$	------	1.15	.904	1.34
$1/\tau_{\beta_3}$	------	8.84	8.16	8.30
t_β	------	.067	0.062	0.060
M	1.27	34.7	9.7	6.2

* number held constant throughout iterations

Table 2: Short period damping ratio limits

	Category A and C flight phases		Category B flight phases	
Level	Minimum	Maximum	Minimum	Maximum
1	0.35	1.30	0.30	2.00
2	0.25	2.00	0.20	2.00
3	0.15	-	0.15	-

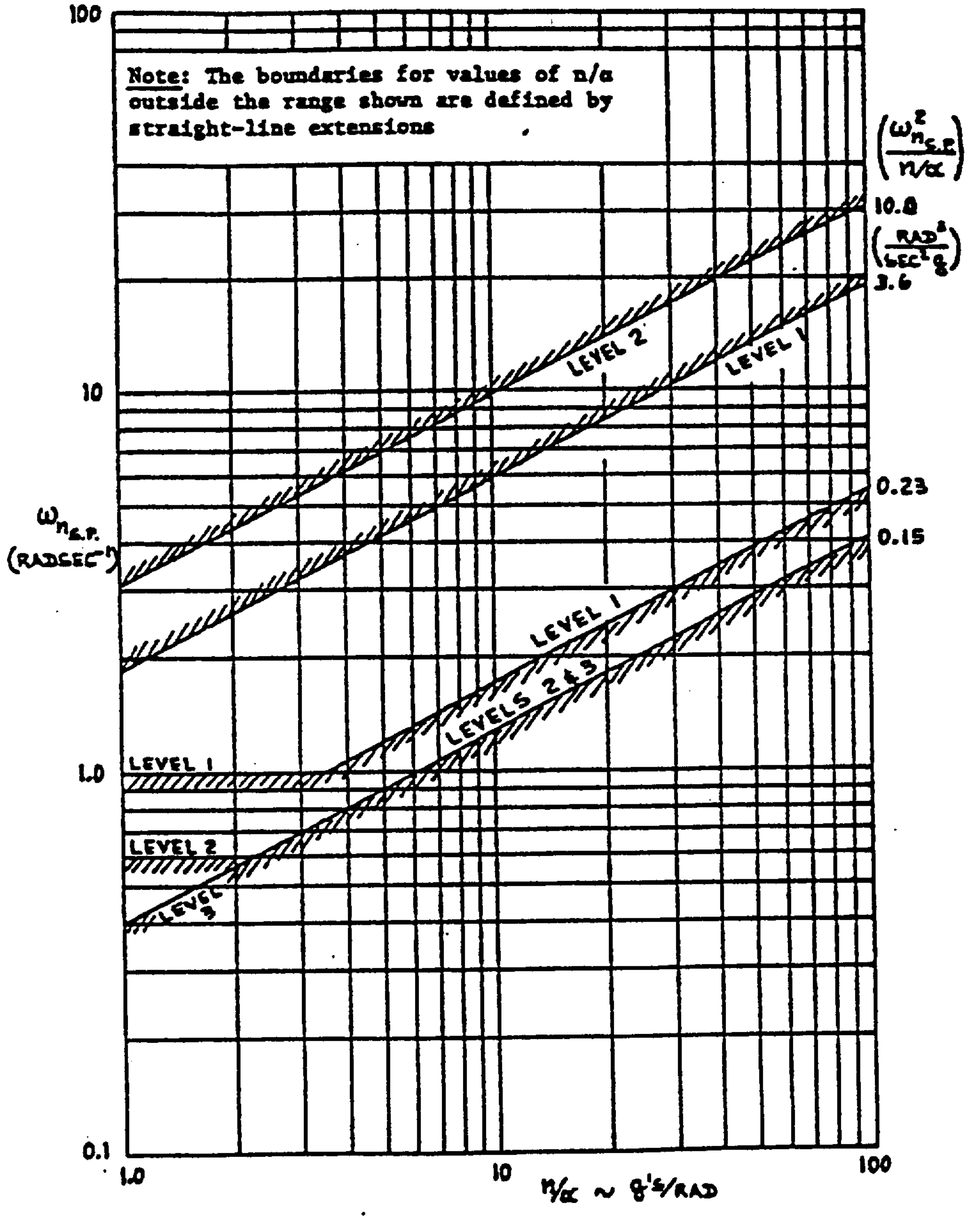


Figure 18: Mil Spec 8785C short period frequency requirements-Category A

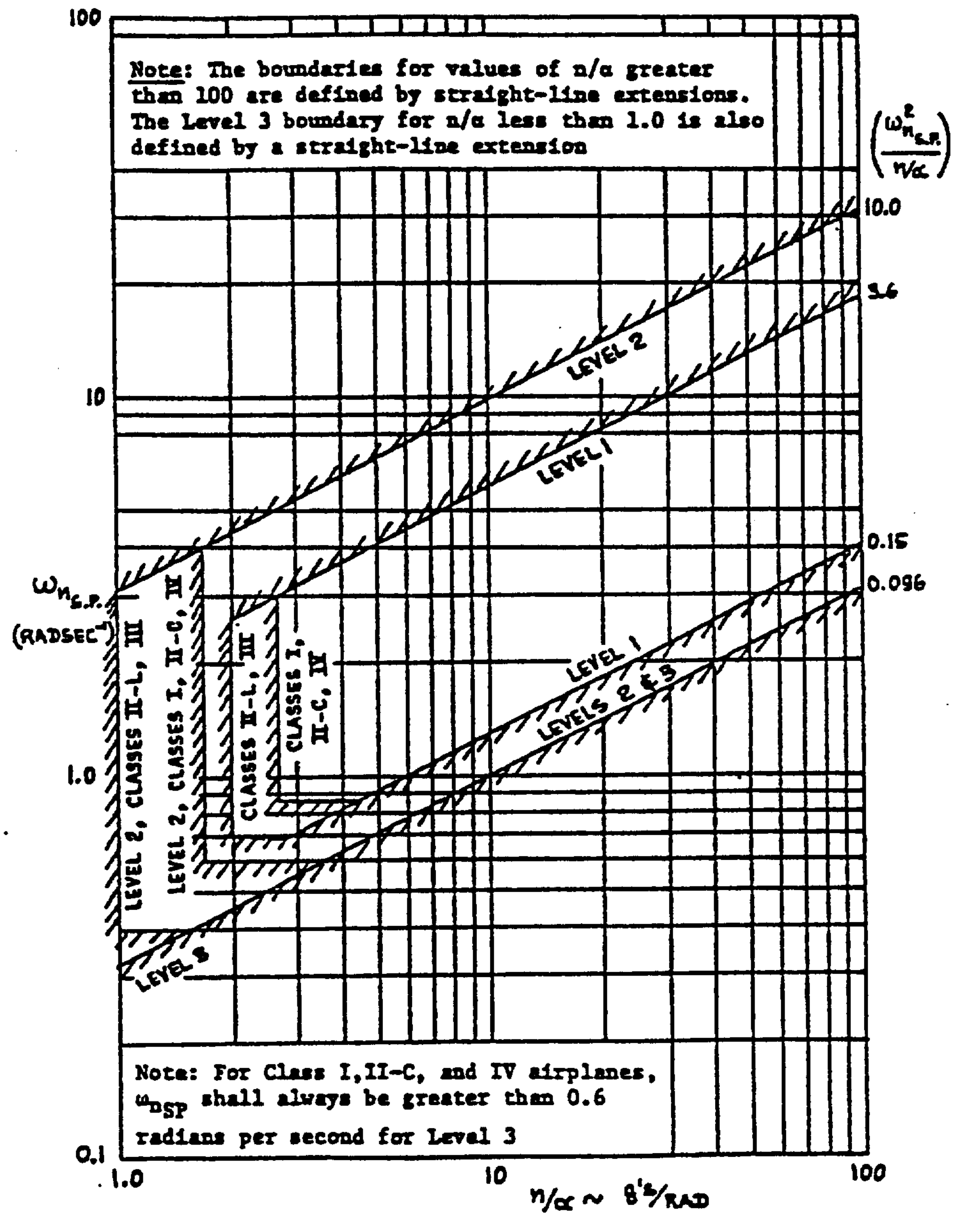


Figure 19: Mil Spec 8785C short period frequency requirements-Category C

Table 3: Allowable airplane response delay to stick force input

Level	Allowable Delay Sec
1	0.10
2	0.20
3	0.25

Table 4: Minimum Dutch roll frequency and damping

Level	Flight Phase Category	Class	Min ζ_{DR}	Min $\zeta_{DR}\omega_{DR}$ rad/sec	Min ω_{DR} rad/sec
1	A*	IV	0.4	-	1.0
	A	I, IV	0.19	0.35	1.0
		II, III	0.19	0.35	0.4
	B	All	0.08	0.15	0.4
	C	I,II-C,IV	0.08	0.15	1.0
		II-L, III	0.08	0.10	0.4
2	All	All	0.02	0.05	0.4
3	All	All	0	-	0.4

* Air-to-air combat and ground-to-air combat flight phases only.

Table 5: Maximum roll mode time constant, seconds

Flight Phase Category	Class	Level 1	Level 2	Level 3
A	I, IV	1.0	1.4	
	II, III	1.4	3.0	
B	All	1.4	3.0	10
C	I,II-C,IV	1.0	1.4	
	II-L, III	1.4	3.0	

Table 6: Spiral stability - minimum time to double amplitude

Flight Phase Category	Level 1	Level 2	Level 3
A & C	12 sec	8 sec	4 sec
B	20 sec	8 sec	4 sec

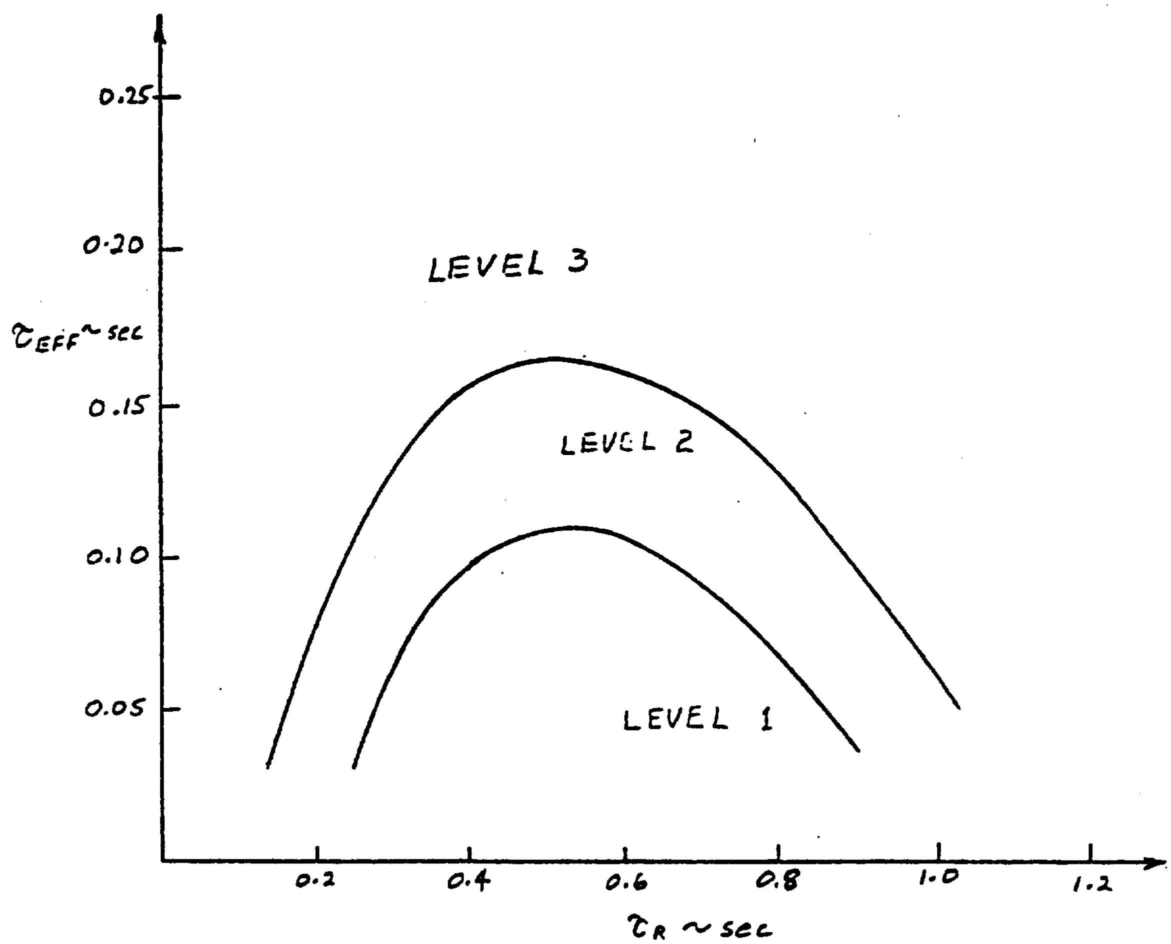


Figure 20: Recommended τ_R vs τ_{EFF} requirements, Catagory A
(LAHOS Ref. 13)

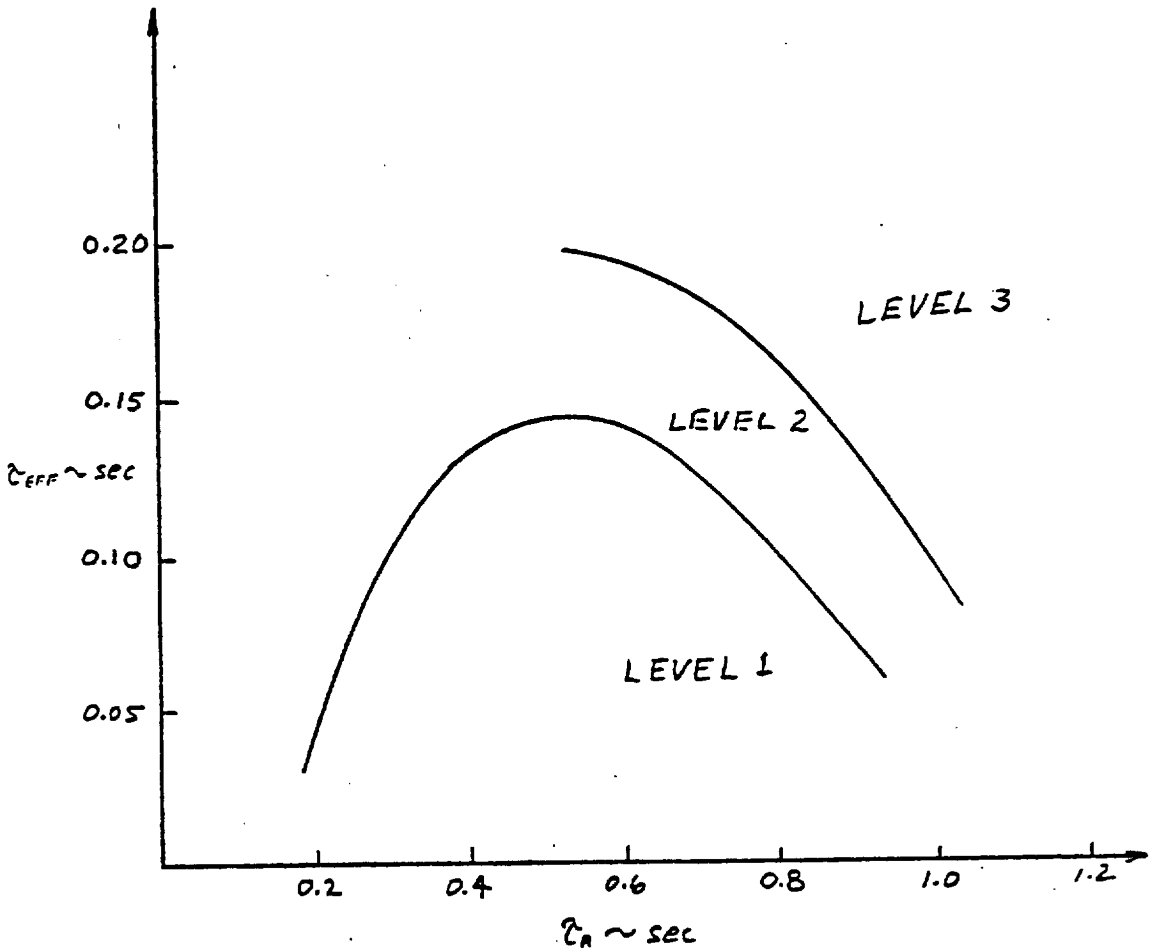


Figure 21: Recommended τ_R vs τ_{EFF} requirements, Catagory C (LAHOS Ref. 13)

Table 7: F-8 DFBW flight configurations

Flight Config.	Velocity (KIAS)	Altitude (ft)	Task	Pilot Ratings Long	Pilot Ratings Lat
A	300	20,000	wing formation	3	3
B	400	20,000	wing formation	4	4,5
C	280	35,000	wing formation	2-2.5	2,3
D*	300	20,000	wing formation	-	5
Time Delay Study					
E**	260	10,000	refueling	5	-
F	260	10,000	refueling	2,4	-
G	260-190	7000-1200	landing approach	3	-

* Lateral SAS includes aileron feed feed forward loop.

** Configuration is in direct mode i.e. no longitudinal SAS.

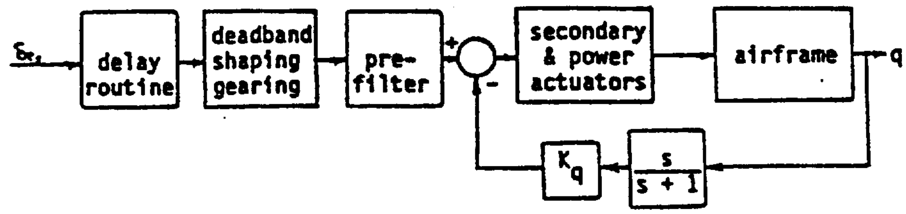
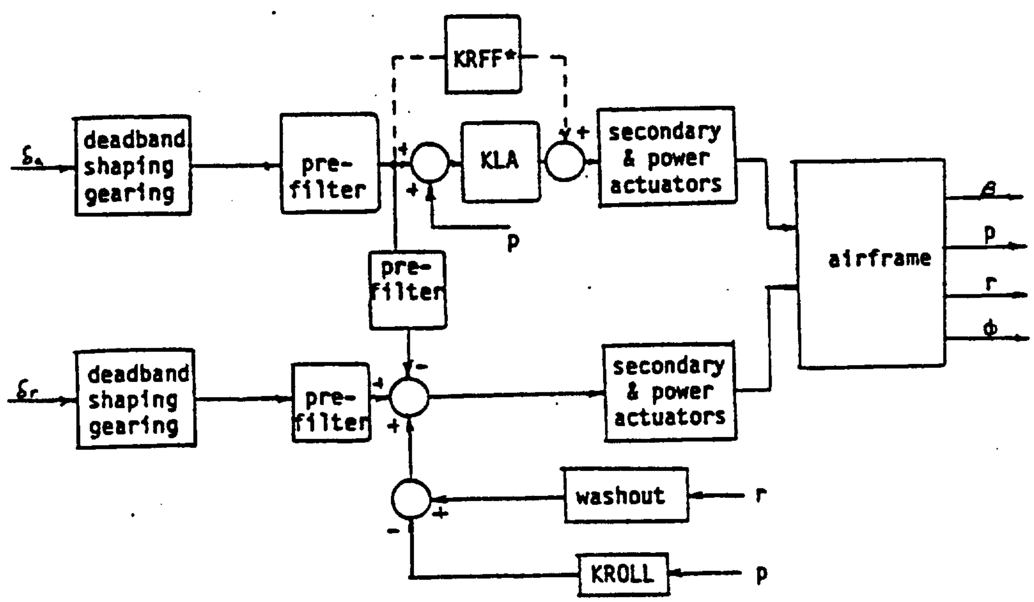


Figure 22: F-8 DFBW pitch SAS



* Feedforward loop was activated for flight configuration "D" only.

Figure 23: F-8 DFBW lateral SAS

Table 8: Neal-Smith criteria results

Flight Config.	n/α	BW_{min} = 2.5	HQ Levels 3.0	3.5
F-8 DFBW				
A	20	1	1*	1-2
B	48	1	1	2*
C	18	1	2*	2
E	16	3+	3+*	3+
F	20	1	1*	2
G	6.6	1	2*	2
YF-12	51	1	1	1*
AFA				
1	16	1	1*	1-2
2	21	1	1*	2
3	10	1	2*	2
4	9.7	1	1-2*	2

* HQ level according to bandwidth recommended by Neal-Smith

Table 9: Bandwidth criteria results

Flight Config.	τ_p (sec)	ω_{BW} (rad/sec)	HQ Level
F-8 DFBW			
A	0.075	4.6	2
B	0.072	4.8	2
C	0.076	4.7	2
E	0.063	3.1	2
F	0.076	3.6	2
G	0.120	2.3	2
YF-12	0.029	5.0	2
AFA			
1	0.052	3.9	2
2	0.061	3.7	2
3	0.089	3.2	2
4	0.083	3.4	2

Table 10: Equivalent Systems and Mil Spec criteria results

Flight Config.	Equivalent Parameters L_α	ω_{sp}	ζ_{sp}	t_θ	M	HQ Levels
F-8 DFBW						
A	0.952	3.48	0.830	.0996*	3.1	1-2
B	1.770	6.22	0.620	.0937*	1.4	1-2
C	0.695	3.85	0.827	.1010*	3.4	1-2
E	1.080	2.54	0.320*	.0940	2.4	2
F	1.300	3.10	0.920	.0995*	1.9	1-2
G	0.603	1.75	0.990	.1400*	6.3	2
YF-12	1.147	3.75	0.791	.0484	9.2	1
AFA						
1	1.16	3.37	0.895	.084	27.2	1
2	1.26	3.41	0.876	.102*	13.2	1-2
3	0.911	3.00	0.713	.135*	19.4	2
4	0.845	3.23	0.814	.138*	14.7	2

* HQ level according to bandwidth recommended by Neal-Smith

Table 11: Summary of longitudinal rating levels

Flight Config.	Pilot Rating	Rating Level	Predicted HQ Levels: Bandwidth Criteria	Equivalent Systems	Neal-Smith Criteria
F-8 DFBW					
A	3,4	1-2	2	1-2	1
B	4	2	2	1-2	2
C	2-2.5	1	2	1-2	2
E	5	2	2	2	3+
F	2,4	1-2	2	1-2	1
G	3	1	2	2	2
YF-12	-	1	2	1	1
AFA					
1	-	2	2	1	1
2	-	2	2	1-2	1
3	-	2	2	2	2
4	-	2	2	2	1-2

Table 12: F-8 DFBW lateral Equivalent Systems results

Flight Config.	ζ_{dr}	ω_{dr}	$\zeta_{dr}\omega_{dr}$	τ_R	T_{double}	t_ϕ	t_β	HQ Level
A	0.38	1.66	0.63	0.29	19.2	0.08	0.05	1
B	0.74	1.78	1.32	0.20	51.3	0.07	0.06	1
C	0.38	1.75	0.67	0.39	31.5	0.08	0.07	1
D	0.40	1.60	0.64	0.23	20.2	0.08	0.05	1

Table 13: F-8 DFBW LATHOS results

Flight Config.	τ_{EFF}	τ_R	HQ Level
A	0.08	0.29	2
B	0.07	0.20	2
C	0.08	0.39	1
D	0.08	0.23	2

Table 14: Summary of lateral rating levels for the F-8 DFBW

			Predicted Levels	
Flight Config.	Pilot Rating	HQ Level	Equiv. Systems	LATHOS
A	3,3	1	1	2
B	4,5	2	1	2
C	2,3	1	1	1
D	5	2	1	2

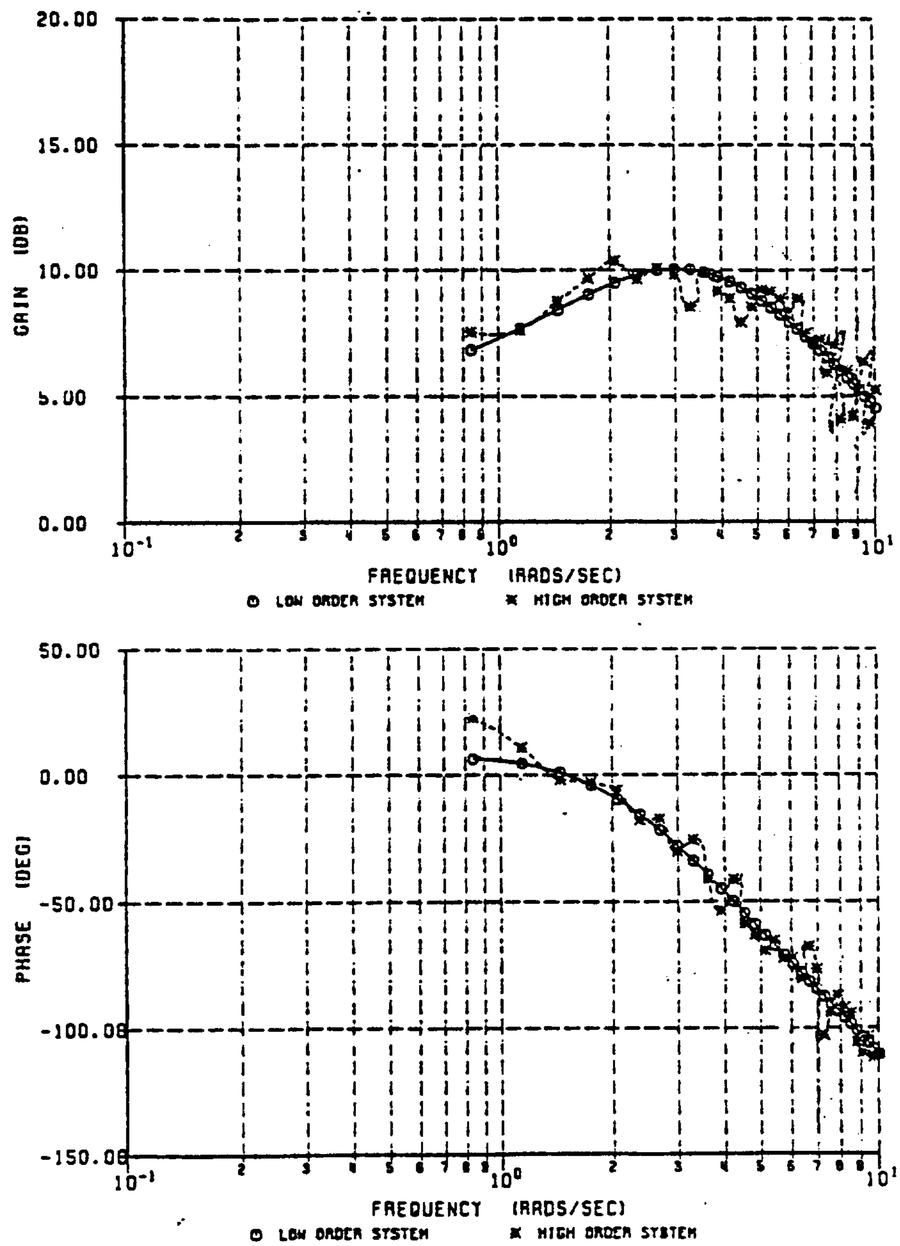


Figure 24: q / δ_{e_s} Bode plot of HOS and LOS (Advanced Fighter Aircraft, mismatch = 27.2)