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PROPOSED REVISION TO THE LATERAL-DIRECTIONAL
COUPLING REQUIREMENTS OF MIL-F-8785

Prepared by:

C.R. Chalk
C. R. Chalk
Staff Engineer

A DIVISION OF CALSPAN CORPORATION
AN ARVIN COMPANY P.O. BOX 400 BUFFALO, NEW YORK 14225

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INTRODUCTION

The military flying qualities specification MIL-F-8785B(ASG) was adopted in 1968. In the intervening years the specification has been applied by designers, government procurement agencies and flight test organizations. The Air Force Flight Dynamics Laboratory has sponsored a number of contracts with airplane design organizations to make detail comparisons of existing aircraft F-4, C-5, F-5, and P-3 with MIL-F-8785B. Also a number of research contracts have been let to develop and propose revisions to the requirements. Under two of these contracts, attention was directed at the lateral-directional coupling requirements in MIL-8785 and revisions to those requirements have been proposed for consideration in References 1 and 2. The purpose of this paper is to present the proposed revisions developed by Calspan Corporation in Reference 1 and to compare the requirements for limiting sideslip proposed by Calspan with the aileron-rudder crossfeed requirement proposed by System Technology Incorporated in Reference 2.

DISCUSSION OF LATERAL-DIRECTIONAL REQUIREMENTS PROPOSED BY CALSPAN

The lateral-directional coupling requirements proposed by Calspan and the associated terminology definitions are included as Appendix A to this paper.

Bank Angle and Roll Rate Oscillatory Requirements

Requirements to limit bank angle and roll rate oscillations resulting from the pilot's use of aileron were introduced in MIL-F-8785B(ASG). These requirements have now been tested by additional data and have been subjected to the test of application. From this experience it is concluded that the requirements are basically valid and certainly should be retained, but certain

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problems in the present statement of the requirements have come to light which should be rectified.

1. It has been found that certain combinations of stability derivatives result in $\chi \frac{p}{\beta}$ of the Dutch roll mode between 180° and 270° . Because of this, the use of two ψ_β scales in the requirement and the rule for deciding which scale is to be used based on $\chi \frac{p}{\beta}$ has been re-examined and found to be an inadequate feature of the requirement. Both this problem and the problem identified in Item 2 can be remedied by using ψ_p rather than ψ_β in the requirement.
2. When $|\phi/\beta|_d$ is large, the amplitude of the Dutch roll oscillation in sideslip is quite small and measurement of the phase angle is difficult and inaccurate.
3. When the spiral root is not at the origin, the measures ϕ_{osc}/ϕ_{AV} and p_{osc}/p_{AV} are severely distorted and do not correlate with the flying qualities rating. This problem can be remedied by removing the spiral mode contribution to the ϕ and p time histories.
4. The symmetrical shape of the requirement boundary is inaccurate; additional data permit defining the boundary more accurately.
5. The requirements on roll rate oscillations require step aileron inputs to be held for $1.7 T_d$ sec in one case and until bank angle has changed 90° in another case. To avoid extreme roll attitude at the end of the test, it is desirable to start the maneuver from banked turning flight in one direction and to roll through wings level to bank in the opposite direction. The requirement that the rudder pedal be free during this maneuver prevents setting up zero-sideslip initial conditions or if the rudder is used to zero initial

sideslip and is then released when the aileron step is applied, the resulting response is not to the aileron input alone. This problem can be remedied by specifying that the rudder pedal be held fixed for the requirements that are based on aileron step inputs.

6. The large difference in the magnitude of p_{osc}/p_{AV} permitted by the requirement for $\psi_\beta = -240^\circ$ relative to that permitted for $\psi_\beta = -40^\circ$ is primarily a result of the fact that p_{AV} tends to zero for large adverse yaw due to aileron. This causes p_{osc}/p_{AV} to tend to infinity, but the pilot rating does not degrade nearly so rapidly, thus the gradient of pilot rating with p_{osc}/p_{AV} is shallow, making location of Level 2 boundaries imprecise. This situation can be alleviated by changing the denominator of the ratio to \hat{p}_1 and $\hat{\phi}_1$, respectively, in the definitions of \hat{p}_{osc}/\hat{p}_1 and $\hat{\phi}_{osc}/\hat{\phi}_1$.
7. The formula using two peaks to calculate p_{osc}/p_{AV} and ϕ_{osc}/ϕ_{AV} when $\mathcal{J}_d > .3$ has been found to have a characteristic which results in lack of discrimination for certain $\psi_{p_{step}}$ or $\psi_{\phi_{impulse}}$ phase angles. This situation can be avoided by using a formula based on three peaks for all cases regardless of the value of the Dutch roll damping ratio. When \mathcal{J}_d is high and there is no third peak, $p_3 = p_2$.

Sideslip Excursion Limit Requirements

The roll oscillation requirements are quite effective in limiting Dutch roll excitation resulting from control of roll rate and bank angle when the roll coupling derivatives L'_R and L'_β are significant. When these derivatives are small, however, the roll oscillation requirements are ineffective in limiting the Dutch roll excitation which will be manifested as a yawing oscillation with little roll. The flying qualities problems for configurations

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of this type are most serious if the Dutch roll frequency is low and the damping is light. For the situation of low roll-yaw coupling, it is important to limit the excitation of the Dutch roll mode in sideslip and yaw rate resulting from the pilot's use of aileron to control roll rate, bank angle and heading.

In MIL-F-8785B(ASG) the parameter $\Delta\beta_{\max}/k$ versus ψ_{β} step was introduced to limit the Dutch roll excitation in sideslip resulting from a step aileron input. The requirement has several undesirable features.

1. The requirement is based on step aileron inputs up to the magnitude that causes 60 degree bank change in a time of 2 sec or T_d sec, whichever is longer. For low frequency Dutch roll roots, it is necessary to restrict the size of the aileron input to quite small values.
2. For some configurations, the maximum sideslip occurring within T_d sec results from the residue of the spiral mode rather than the Dutch roll mode. For landing approach data, the resulting sideslip does not correlate with pilot rating data.
3. The definition of the parameter $K = \frac{\phi_{t \text{ command}}}{\phi_{t \text{ requirement}}}$ involves the roll performance requirement. Thus, the validity of the sideslip requirement depends on the validity of the roll performance requirements.
4. Permitting use of rudder to determine $\phi_{t \text{ command}}$ in a requirement based on rudder-pedal-free aileron inputs leads to confusion and additional work. This is a cumbersome aspect of the requirement because it requires a series of tests or analyses to define the roll performance as a function of aileron input amplitude and a separate series of tests or analyses to determine the sideslip excursions as a function

of aileron input amplitude. For analytical checks of the requirement there is no guidance as to how to calculate $\phi_{t \text{ command}}$. This aspect of the requirement is not substantiated in the BIUG because none of the data presented was treated in that way. The data were reduced in the form $\Delta\phi_{\text{max}}/\phi_{t=1}$ for step aileron inputs and then multiplied by what was considered to be the appropriate $\phi_{t=1}$ requirement for each experiment with no consideration being given to use of rudder to prevent adverse yaw.

5. Because the ϕ_t required values are different for Levels 1 and 2, it is necessary to calculate two separate values of $\Delta\phi_{\text{max}}/k$ for each data point to be compared with the requirements, one for Level 1 which is compared with the Level 1 boundary and one for Level 2 which is compared with the Level 2 boundary. This "double relaxation" of the requirement, i.e., lower required roll performance and a separate Level 2 boundary in the $\Delta\phi_{\text{max}}/k$ versus ψ/β plane, is involved and cumbersome and is not shown to be necessary by the available data.
6. Although the $\Delta\phi_{\text{max}}/k$ requirement in Figure 6 of MIL-F-8785B(ASG) has three boundaries, one for Level 2 and two for Level 1 as a function of Flight Phase Category, the requirement is actually the most complex and finely defined requirement in the entire specification. This is because the parameter k depends on the roll performance requirements which are specified as a function of Class, Flight Phase and Level. In the BIUG the parameter k is discussed as being the ratio of roll performance attainable from a specific aileron input to roll performance required by the specification and is presented as a replacement for the scaling rule in MIL-F-8785, paragraph 3.4.9. In paragraph 3.4.9, the sideslip resulting from a given input was scaled by the ratio of aileron deflection used to

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the aileron deflection required to meet roll performance requirements.

If the $\Delta\beta_{\max}/k$ parameter is written as $\phi_{t_{\text{required}}}$ $\frac{\Delta\beta_{\max}}{\phi_{t_{\text{command}}}}$ it seems that a better interpretation is that the ratio $\frac{\Delta\beta_{\max}}{\phi_{t_{\text{command}}}}$ must be multiplied by a weighting constant $\phi_{t_{\text{required}}}$ which makes the requirement a function of Class, Flight Phase, and Level. In other words, the requirement could have been written such that the measurement $\frac{\Delta\beta_{\max}}{\phi_{t_{\text{command}}}}$ is compared with a new Figure 6 which would have about 45 different curves on it, one for each $\phi_{t_{\text{required}}}$ value in 3.3.4 and 3.3.4.1. Some of the 45 curves would be coincident with Class I, Flight Phase Category A, Level 2 would be coincident with Class I, Flight Phase Category B, Level 1 because $\phi_{t_{\text{required}}}$ is 60° in 1.7 sec for both situations. If the sideslip excursion requirement had been presented in the latter format, it would no doubt have received much more criticism.

The $\frac{\Delta\beta_{\max}}{k}$ requirement of MIL-F-8785B(ASG) is tied to the bank angle response through a number of assumptions implicit in this requirement. The requirement assumes that a measure of the undesired response (sideslip excursion) resulting from an aileron input ratioed to the desired response (bank angle at a specific time) resulting from the aileron input will reflect flying qualities. The use of bank angle response as the measure of the desired response to aileron was intuitive, but to an extent arbitrary. In the roll oscillation requirements, the oscillatory component of roll rate or bank angle is ratioed to the average roll rate or bank angle resulting from the aileron input. This is a straightforward requirement relating an undesirable component of a response to the desirable component of the same response. In the case of the sideslip excursion requirement, the Dutch roll component of sideslip is identified as an undesirable component of the airplane's response

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to aileron commands but it is clearly an assumption to expect a measure of bank angle to be a universally valid parameter to use as the measure of the desired response to aileron. The situation is one of dividing "apples and oranges" so if a successful correlation parameter of this form does exist, its discovery will depend on intuition and empirical correlation. Using intuition one might argue that sideslip is a yawing motion and should therefore be ratioed with an aspect of the airplane heading or yaw rate response to aileron. Based on this intuition and examination of $\Delta\beta/\phi$ type measures from several experiments, it was determined that better correlation of several sets of data could be obtained by introducing the factor $\frac{g}{V_T}$. Specifically, the following parameter has been found to have potential as a flying qualities parameter.

For aileron impulse:

$$\frac{|\Delta\beta_{\max}|_{t < 1.2 T_d}}{\omega_d \left[\frac{g}{V_T} \hat{\phi}_1 \right]} \text{ versus } \psi_{\beta \text{ impulse}}$$

The Laplace transform for a step command is $1/s$ and the transform for an impulse command is unity. As a result the inverse transform of a variable to an impulse input is identical to the inverse transform of the derivative of the variable for a step input. Therefore,

For aileron step:

$$\frac{|\dot{\Delta\beta}_{\max}|_{t < 1.2 T_d}}{\omega_d \left[\frac{g}{V_T} \hat{p}_1 \right]} \text{ versus } \dot{\psi}_{\beta \text{ step}}$$

Advantage is also taken of this fact in stating the requirements for bank angle oscillations for an impulse input and the requirements for roll rate oscillations for a step input. In this example

$$\left. \frac{\hat{p}_{\text{osc}}}{\hat{p}_1} \right|_{\text{step}} = \left. \frac{\hat{\phi}_{\text{osc}}}{\hat{\phi}_1} \right|_{\text{impulse}} \quad \text{and} \quad \psi_{p \text{ step}} = \dot{\psi}_{\phi \text{ impulse}}$$

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For an impulse aileron input, the sideslip response will consist mainly of the Dutch roll component with no problems from the spiral mode unless it is highly divergent. Thus, the measure of sideslip is $\Delta\beta_{\max}$ defined as the maximum peak-to-peak excursion occurring within $1.2 T_d$ seconds. This time interval is stated to eliminate problems with an unstable Dutch roll mode or a highly unstable spiral mode. This measure of sideslip is divided by $\frac{g}{V_T} \hat{\phi}_1$, which can be viewed as a measure of the yaw rate response to the aileron input. $\hat{\phi}_1$ is the first peak of the bank angle response. A measure like $\hat{\phi}_{AV}$ could be specified to better reflect the yaw rate resulting from the steady bank angle but this was not considered likely to be significantly different from $\hat{\phi}_1$ for the low $|\delta/\beta|_d$ cases for which the sideslip excursion requirements are critical. The parameter $\hat{\phi}_1$ is proposed to eliminate the possibility that there would not be a peak if the spiral mode were unstable.

The residue of the Dutch roll mode in the sideslip response to a step aileron input is roughly proportional to ω_{nd}^{-2} , however, the residue for an impulse input is roughly proportional to ω_{nd}^{-1} . Because of this characteristic, it is necessary to divide $\Delta\beta_{\max}$ measured from an impulse input by ω_{nd} in order to preserve the empirically demonstrated correlation between pilot rating and the $\Delta\beta_{\max}/k$ criterion in MIL-F-8785B(ASG). To clarify this point, assume that pilot rating is found by experiment to be a function of $\Delta\beta_{osc}$ for a step aileron input, P.R. = $f(\Delta\beta_{osc})_{step}$. Then it follows that pilot rating should be correlated with $\Delta\beta_{osc} \times \omega_{nd}$ when an impulse aileron input is used, P.R. = $f\left(\frac{\Delta\beta_{osc}}{\omega_{nd}}\right)_{impulse}$. This is the rationale for including ω_{nd}^{-1} in the definition of the new sideslip parameter proposed by Calspan.

COMPARISON OF CALSPAN SIDESLIP REQUIREMENT AND STI AILERON-RUDDER CROSSFEED PARAMETERS

The $\Delta\beta_{\max}/k$ vs $\psi_{\beta}/\omega_{step}$ requirement of MIL-F-8785B(ASG) was criticized by the authors of References 2 and 3 as being "...based on aileron-only parameters and the effects of rudder control are only indirectly apparent as they may have influenced individual pilot ratings." The authors of

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References 2 and 3 further claimed, "the fact that these criteria are not satisfactory is shown in Figure 10 where several configurations which violated boundaries based on aileron-only parameters were given good to excellent pilot ratings." The data and figure referred to are reproduced herein as Figure 1. Specifically, data points 4B, 5A and 5B from Reference 4 were singled out as gross violations of the $\Delta\beta_{\max}/k$ requirement and held up as proof that the $\Delta\beta_{\max}/k$ requirement was inadequate to handle cases which required the pilot to use the rudder for coordination. In fact, however, the violations of data points 4B, 5A and 5B illustrated in Figure 1 are fictitious because these points, and others in Figure 1, have been plotted by the authors of Reference 2 at the wrong values of $\gamma_{\beta}^{\prime}/\text{step}$. The errors in locating these points relative to the specification boundaries are indicated on Figure 1. It is seen that when the points are properly plotted, they are not in gross violation but are quite well accommodated by the specifications requirement boundary. Although there are many reasons for making revisions to the $\Delta\beta_{\max}/k$ requirement which were discussed elsewhere in this paper, the claim made by the authors of References 2 and 3 that the requirement does not account for the pilot's use of rudder to coordinate turns is quite unfounded. The evaluation pilots were free to use the rudder during all of the experiments and their ratings reflect the feasibility of using rudder to coordinate maneuvers. The shape of the requirement boundary as a function of $\gamma_{\beta}^{\prime}/\text{step}$ is partly determined by this consideration.

Calspan in Reference 1 and STI in Reference 2 have taken two different approaches to development of requirements for limiting sideslip during rolling and turning maneuvers. The time histories in Figure 2 illustrate two aspects of the problem and suggest the two approaches. Figure 2 shows the bank angle and sideslip responses for a given configuration that result from a step aileron input with rudder zero. Also shown on Figure 2 is the rudder input that must accompany an aileron step input in order to maintain zero sideslip. The bank angle response to the combination aileron and rudder input is identical to that for the aileron step alone for this configuration because the roll yaw coupling is very low. The Dutch roll mode is excited by

the aileron-alone input and has a residue in the sideslip, yaw rate and heading responses. The Calspan approach, described previously, is to develop requirements to limit the magnitude of the oscillatory component of the sideslip response to an impulse aileron input as a function of the phase angle of the oscillation. The STI criterion is based on the aileron-rudder sequencing required to achieve coordinated turns, defined as turns with zero sideslip. The ideal aileron-rudder crossfeed is the ratio of transfer function numerators

$$Y_{CF} = - N'_{\delta_{AS}} / N'_{\delta_{RP}}$$

The STI criterion is based on the assumption that the ideal rudder crossfeed transfer function can be adequately represented by a first order lead-lag form

$$Y_{CF} \approx - \frac{K(s + \lambda_z)}{(s + \lambda_p)}$$

Under this assumption (which will later be shown to be invalid for the YF-16) a parameter, μ , is defined as the ratio of the separation of the zero from the pole normalized by the value of the pole of the lead-lag network. The STI criterion consists of empirical boundaries drawn on a plane defined by the μ parameter and the ratio of $N'_{\delta_a} / L'_{\delta_a}$ calculated for stability axes. Under the assumption that the crossfeed transfer function can be approximated by a lead-lag, the μ parameter can be defined in terms of the initial and final values of a time history of rudder pedal for a step aileron stick input to the simplified lead-lag transfer function,

$$\mu = \frac{\text{final value}}{\text{initial value}} - 1.$$

In general the ideal aileron-rudder crossfeed transfer function will not be a first order lead-lag. For an unaugmented airplane the transfer function can be the ratio of third order polynomials and for the augmented YF-16 airplane the crossfeed is the ratio of sixth order polynomials. The authors of Reference 2 define a set of rules for simplifying higher order crossfeed transfer functions to the first order form. These simplification rules will be illustrated and the STI requirement will be compared with the Calspan requirement through application to two examples.

The first example is configuration P-8 taken from Reference 5. The ideal crossfeed transfer function for this example, together with a time

history for a step aileron wheel input, is shown on Figure 3. Following the rules for simplifying this transfer function given in Reference 2, the simplified transfer function and time history shown on Figure 3 is obtained. Evaluation of the μ parameter from the simplified transfer functions and time history is also shown on Figure 3.

The effect of the simplified crossfeed on the sideslip response of configuration P-8 is illustrated in Figure 4. In this case, the simplified crossfeed is effective in eliminating excitation of the Dutch roll mode and in constraining the sideslip to be nearly zero for the first seven seconds. After seven seconds the effect of eliminating the low frequency factors of the crossfeed is seen to result in an increase in the sideslip.

The roll rate and sideslip rate responses of configuration P-8 to a step aileron stick input without the crossfeed are shown in Figures 5 and 6. In Figure 5 it is seen that the p response exhibits a significant residue of the unstable spiral mode and measurement of \hat{p}_{os}/p_{AV} of MIL-F-8785B(ASG) would be severely influenced by the spiral mode. The \hat{p} time history has been calculated by subtracting the contribution of the spiral mode as was described earlier. The reduced time history has been analyzed to calculate the parameters

$$\frac{\hat{p}_{os}}{\hat{p}_1} \text{ vs } \psi_{p\text{step}}$$

recommended by Calspan in Reference 1. The calculations are illustrated in Figure 5. In Figure 6 it is seen that the $\dot{\beta}$ response to the step aileron stick input is dominated by the excitation of the Dutch roll mode whereas the β response to the step input illustrated in Figure 4 was highly influenced by the spiral mode residue. The calculations to evaluate the new sideslip coupling requirement recommended by Calspan are illustrated on Figure 6.

Now that the Calspan and STI recommended flying qualities parameters have been calculated for configuration P-8, they can be compared to the criteria boundaries in Figures A4, A5 and 7. Configuration P-8 was evaluated

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by three different evaluation pilots and was rated as follows: Pilot A PR = 8, Pilot B PR = 9-10, Pilot C PR = 6-6.5. Unfortunately, none of the requirements are successful in screening out this configuration. It should be pointed out that a configuration that is rated PR > 6.5 does not have to appear outside the 6.5 boundary on all the flying qualities parameter plots; it only need exceed that boundary on one plot to have been properly screened out. In this case, the pilot complaints were directed at the sideslip and heading control difficulties and the large and difficult-to-accomplish rudder inputs required to prevent these problems. Therefore, one should not expect the \hat{p}_{os}/\hat{p}_1 requirement to screen out this case but it should be screened out by the Calspan sideslip requirement or the STI aileron-rudder crossfeed requirement. Actually this case was chosen by the author because it was anomalous in the Calspan data correlations reported in Reference 1 and was considered to be a test case of interest in comparing the STI and Calspan requirements. Extensive data correlations treating the data from fifteen flying qualities experiments are shown in Reference 1 but are too voluminous to report here.

The second example chosen to compare the Calspan and STI requirements is the YF-16 as it was known to Calspan at the time Calspan simulated the aircraft in the T-33 VSS airplane prior to its first flight, Reference 6. This aircraft is augmented in a manner which results in higher order transfer functions and for this reason it is an interesting case to use in exploring the applicability of the proposed flying qualities requirements. The ideal aileron-rudder crossfeed transfer function for the YF-16 is the ratio of two sixth order polynomials in S. The rudder pedal force required for a step aileron stick force is shown in Figure 8. This is a complex time history involving a rapid rudder pedal force reversal within the first tenth of a second followed by a dip at $t \approx .4$ sec and then a fairly steady growth with time. The complete crossfeed transfer function is noted on Figure 8. Using the STI rules for simplifying that transfer function, the reduced transfer function and time history illustrated on Figure 9 is obtained and $\mu = -.408$. It should be recalled that the parameter was defined under the assumption that the crossfeed transfer function could be approximated by a first order lead-lag. Obviously the simplified YF-16 crossfeed which is third order in numerator

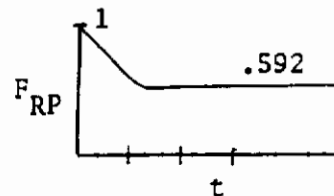
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and denominator does not meet that assumption. Also, because of the second order complex factors in the numerator which cause a notch effect, the shape of the YF-16 crossfeed is quite different than that implied by a $\mu = -.408$ value for the first order lead-lag model. The first order model would imply a rudder pedal time history that starts at unity initial value and decays exponentially to the steady state value of .592. The time constant of the exponential decay is normally the roll mode time constant but in the case of the augmented YF-16, it is not obvious which of the three factors in the simplified crossfeed transfer function should be considered to be the roll mode. To make an extreme interpretation, the author assumed that the root at $s + 1$ should be used to relate the $\mu = -.408$ value to a first order crossfeed model. Then

$$\mu = \frac{\lambda_z}{\lambda_p} - 1 = \frac{.592}{1} - 1$$

The first order crossfeed model implied by $\mu = -.408$ then would be

$$Y_{CF} = \frac{.262 (s + .592)}{(s + 1)}$$



where the gain has been calculated by rules given in Reference 3. This crossfeed was used to calculate the sideslip rate response illustrated in Figure 10. Obviously this crossfeed does not constrain sideslip to be zero and, in fact, by comparison with the sideslip rate time history in Figure 10 which was calculated for an aileron stick force step input with no crossfeed, it is seen that the first order crossfeed for which $\mu = -.408$ has aggravated the sideslip response. It is the author's opinion that this case demonstrates that the assumption that the crossfeed can be adequately represented by a first order lead-lag in the frequency band $.33 < \omega < 6$ is not valid and can lead to meaningless values of the μ parameter. This, of course, does not invalidate the aileron-rudder crossfeed approach to analyzing and evaluating flying qualities; it simply means that the first order model and the μ parameter are an oversimplification.

Although the YF-16 is highly augmented and the lateral-directional transfer functions are higher order, the p and $\dot{\beta}$ time histories in Figure 11 are amenable to evaluation of the flying qualities parameters recommended by Calspan in Reference 1. The calculations are illustrated on Figure 11. The parameters evaluated fall within the Level 1 requirement boundaries in Figures A4 and A5.

GENERAL OBSERVATIONS

It should be observed that the Calspan sideslip requirement and the STI crossfeed requirement are both related to the numerator of the β/δ_{AS} transfer function. Both requirements are aimed toward achieving airplanes that can be maneuvered in rolling and turning flight without sideslip. The information required to accomplish that objective is contained in the coefficients of the β/δ_{AS} transfer function numerator. The Dutch roll component of the sideslip response is minimized when the factors of the numerator cancel the Dutch roll roots of the characteristic equation. The sideslip response is completely eliminated when each of the numerator coefficients is zero. The following equations are derived by setting each coefficient of s in the β/δ_{AS} numerator to zero. The numerator polynomial being considered does not account for servo dynamics, sensor dynamics or electronic shaping networks. The equation applies to linearized equations of motion with augmented stability derivatives, including the artificial derivatives N'_{ϕ} , L'_{ϕ} and Y_{ϕ} which would result from feedback of bank angle to the rudder and aileron $N'_{sAS} = C_3 s^3 + C_2 s^2 + C_1 s^1 + C_0$.

$$\begin{aligned}
 C_3 = 0 & \text{ when } Y_{\delta_{AS}} = 0 \\
 C_2 = 0 & \text{ when } N'_{\delta_{AS}} \approx \alpha_o L'_{\delta_{AS}} \\
 C_1 = 0 & \text{ when } N'_p \approx \frac{g}{V} + \alpha_o (L'_p - N'_r) + Y_{\delta_{AS}} \frac{L'_p N'_r}{L'_{\delta_{AS}}} \\
 C_0 = 0 & \text{ when } N'_{\phi} = - \frac{g}{V} N'_r
 \end{aligned} \tag{1}$$

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These equations indicate that independent control of side force and yawing moments is required to eliminate the sideslip response to aileron stick. Side force control is necessary to cancel the side force due to aileron stick commands. This component is not normally a significant consideration and, for practical augmentation design, can be ignored. The remaining coefficients, C_2 , C_1 , C_0 can all be set to zero through generation of yawing moments with the rudder that are proportional to δ_{AS} , p and ϕ . Expressed in equation form, the rudder augmentation required to constrain sideslip to be zero is:

$$\delta_{r_c} = \frac{\delta_{r_c}}{\delta_{AS}} \delta_{AS} + \frac{\delta_{r_c}}{p} p + \frac{\delta_{r_c}}{\phi} \phi \quad (2)$$

The augmentation gains in this equation can be calculated from Equation 1. An example will be used to illustrate that an equation of this form will accurately represent the rudder time history calculated from the ideal aileron-rudder crossfeed transfer function. This process is illustrated in Figure 12. Note that it is necessary to have time histories for the p and ϕ (or at least ϕ) responses to the aileron stick step which are calculated with the ideal aileron-rudder crossfeed included.

This interpretation of the rudder augmentation required to constrain sideslip to be zero suggests that crossfeed of aileron stick through a shaping network is an idealization that does not properly represent the task the pilot must accomplish. If he could fly the airplane in smooth air using only aileron stick inputs, then crossfeed of the stick inputs through the crossfeed filter to the rudder would prevent excitation of sideslip. The pilot, however, must fly the airplane in rough air and he may occasionally "miscoordinate" with the rudder. In these circumstances, the airplane motions are the result of more inputs than just the pilot's aileron stick commands. In this situation, the pilot must resort to the control law of Equation 2 which requires independent observation of δ_{AS} , p and ϕ . In many cases that task is too demanding and the pilot may decide the best way to fly the airplane is not to attempt to use the rudder.

CONCLUSIONS

1. Although the lateral-directional coupling requirements of MIL-F-8785B(ASG) are generally valid, application experience and additional data has revealed deficiencies. These deficiencies have been addressed by Calspan in Reference 1 and revisions to the definitions of the parameters involved have been proposed which are designed to alleviate the observed deficiencies.
2. The sideslip requirement recommended by Calspan and the aileron-rudder crossfeed analysis proposed by STI are both useful in understanding the cause of flying qualities deficiencies. The μ parameter used in the STI heading control criterion, however, is based on the assumption that the aileron-rudder crossfeed transfer function can be adequately represented by a first order lead-lag network. This assumption is not generally valid and in some cases the magnitude of the μ parameter resulting from the assumption implies quite different rudder coordination from that actually required to restrain sideslip to be zero.
3. It is shown that the following rudder control law will constrain sideslip to be zero during rolling and turning maneuvers.

$$\delta_{r_c} = \frac{\delta_{r_c}}{\delta_{AS}} \delta_{AS} + \frac{\delta_{r_c}}{p} p + \frac{\delta_{r_c}}{\phi} \phi$$

The gains in this control law can be evaluated by setting the coefficients of $N_{\delta_{AS}}^{\beta}$ to zero.

4. Both the Calspan and STI requirements can be applied during the design phase of an aircraft development. The STI crossfeed criterion, however, would be difficult to evaluate

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during the flight test phase. Evaluation would require identification of a complete set of stability derivatives from flight test data and use of these derivatives to show compliance through calculations. The Calspan requirements can be evaluated directly from recorded time histories of responses to step or impulse control inputs applied by the pilot.

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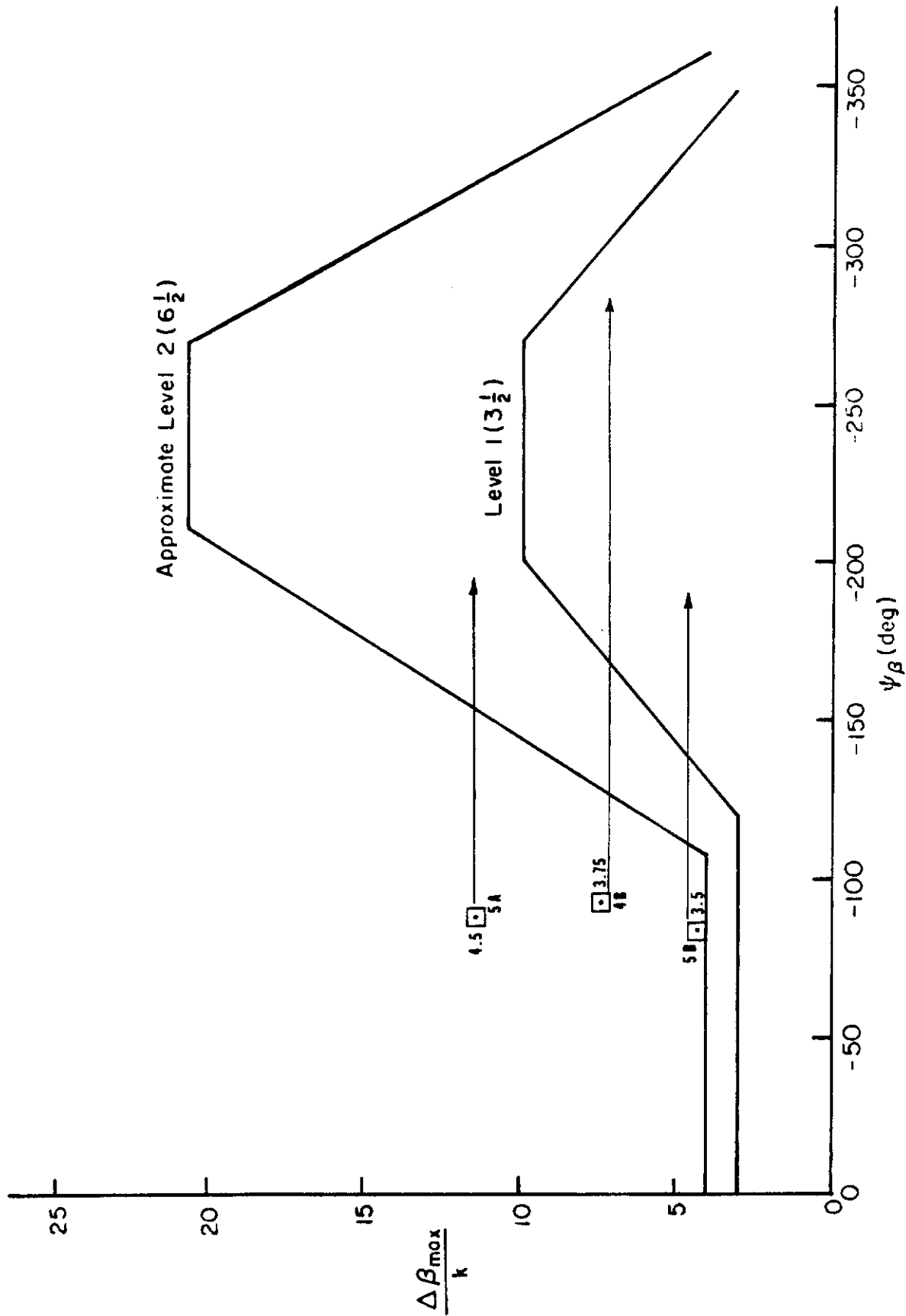


Figure 1 CORRELATION DATA ON $\Delta\beta_{\max}/k$ vs ψ_{β} PLOT

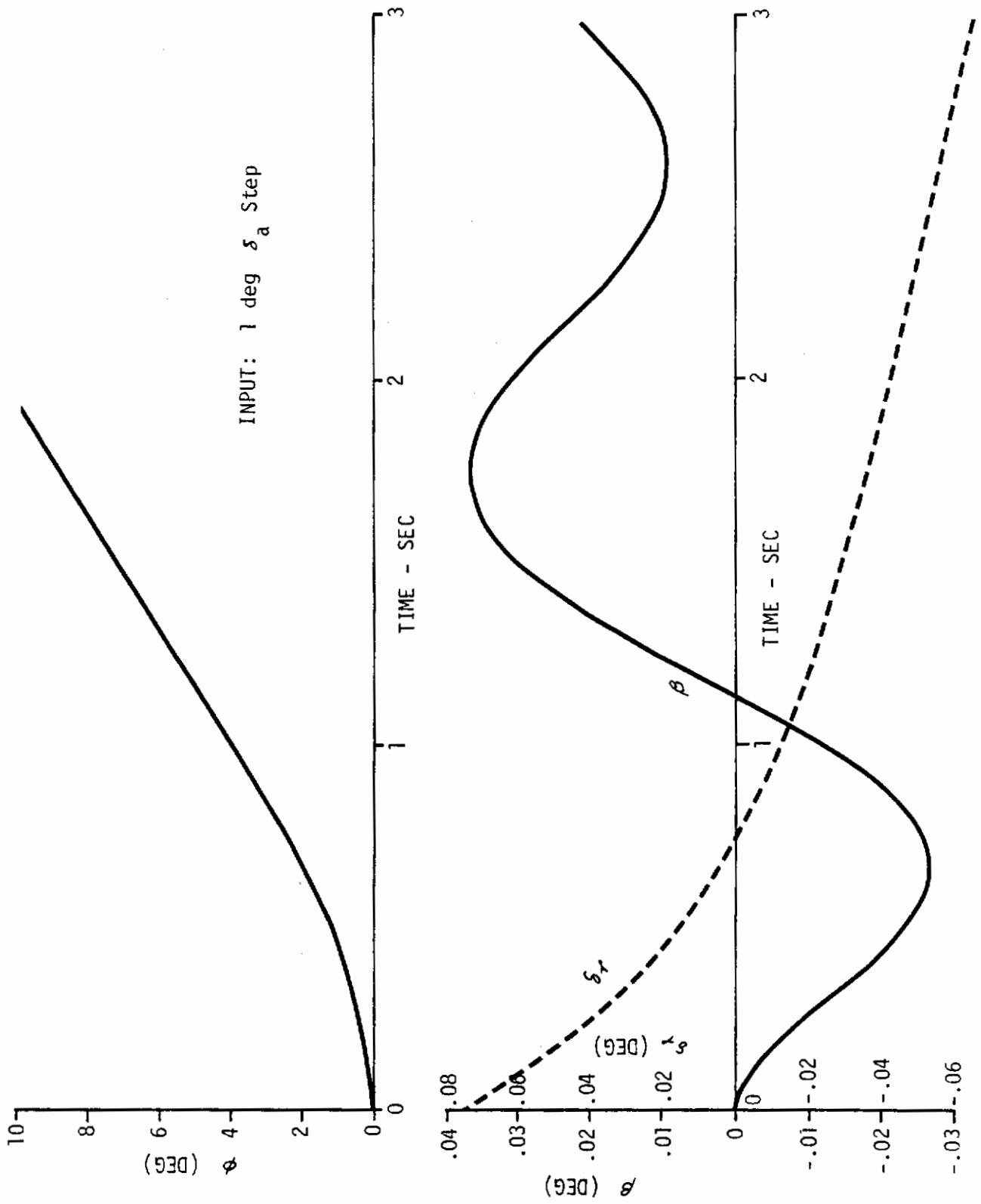


Figure 2 ROLL RESPONSE EXAMPLES

$$\text{--- } \delta_{RP} = \frac{.177(S+.0799)(S-5.80)(S+23.59)}{(S-.0264)(S+3.40)(S+11.66)} \cdot \frac{\delta_w}{S}$$

$$\text{--- } \delta_{RP} = \frac{(S-5.80)}{(S+3.40)} \cdot \frac{\delta_w}{S}$$

$$\mu = \delta_r(3) - 1$$

$$= -1.706 - 1$$

$$= -2.706$$

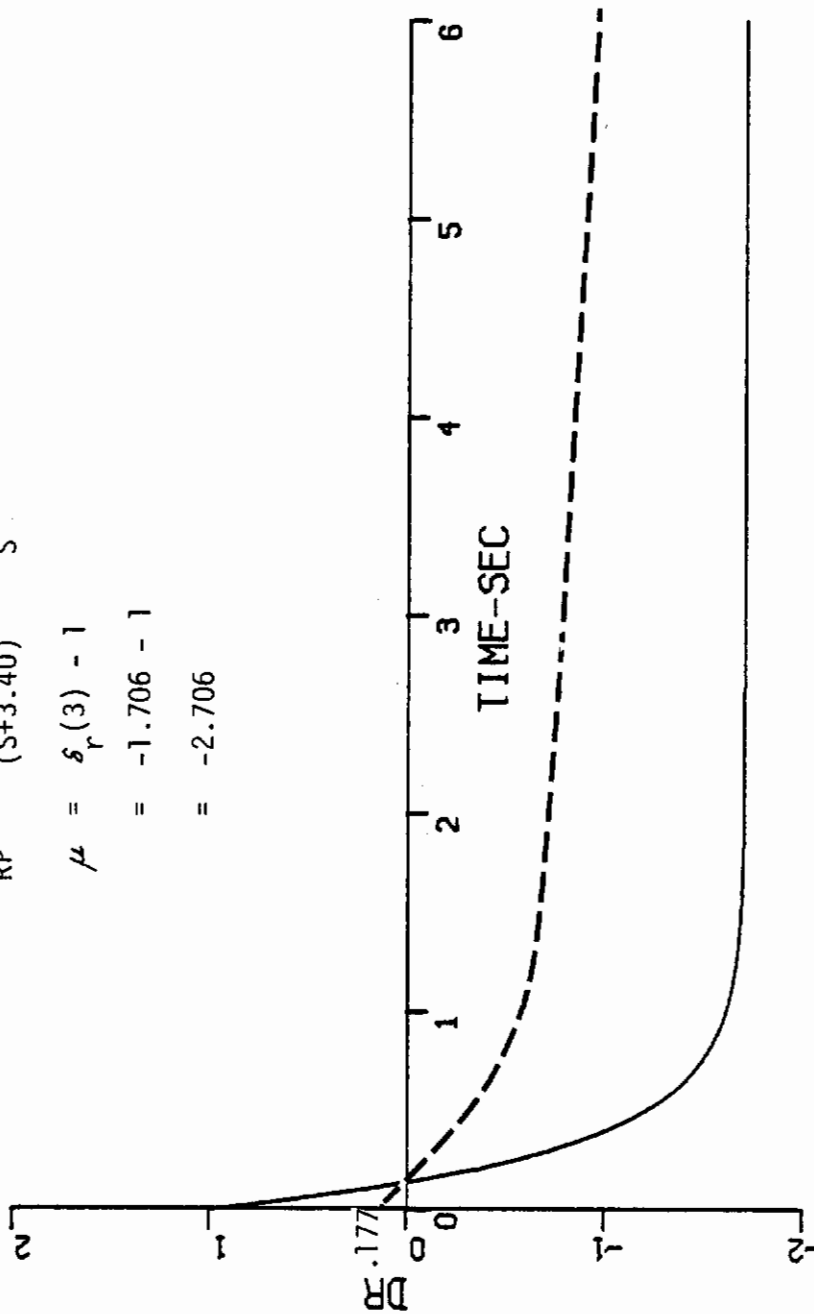


Figure 3 RUDDER PEDAL CROSSFEED FOR CONFIGURATION P-8

$$\beta(s) = \left[\frac{\beta}{\delta_w} + \frac{\beta}{\delta_{RP}} Y_{CF} \right] \delta_w(s)$$

$$Y_{CF} = \frac{.357(S-5.8)}{(S+3.4)} \quad \text{Simplified} \sim \text{STI rules}$$

$\delta_w \sim$ Unit Step

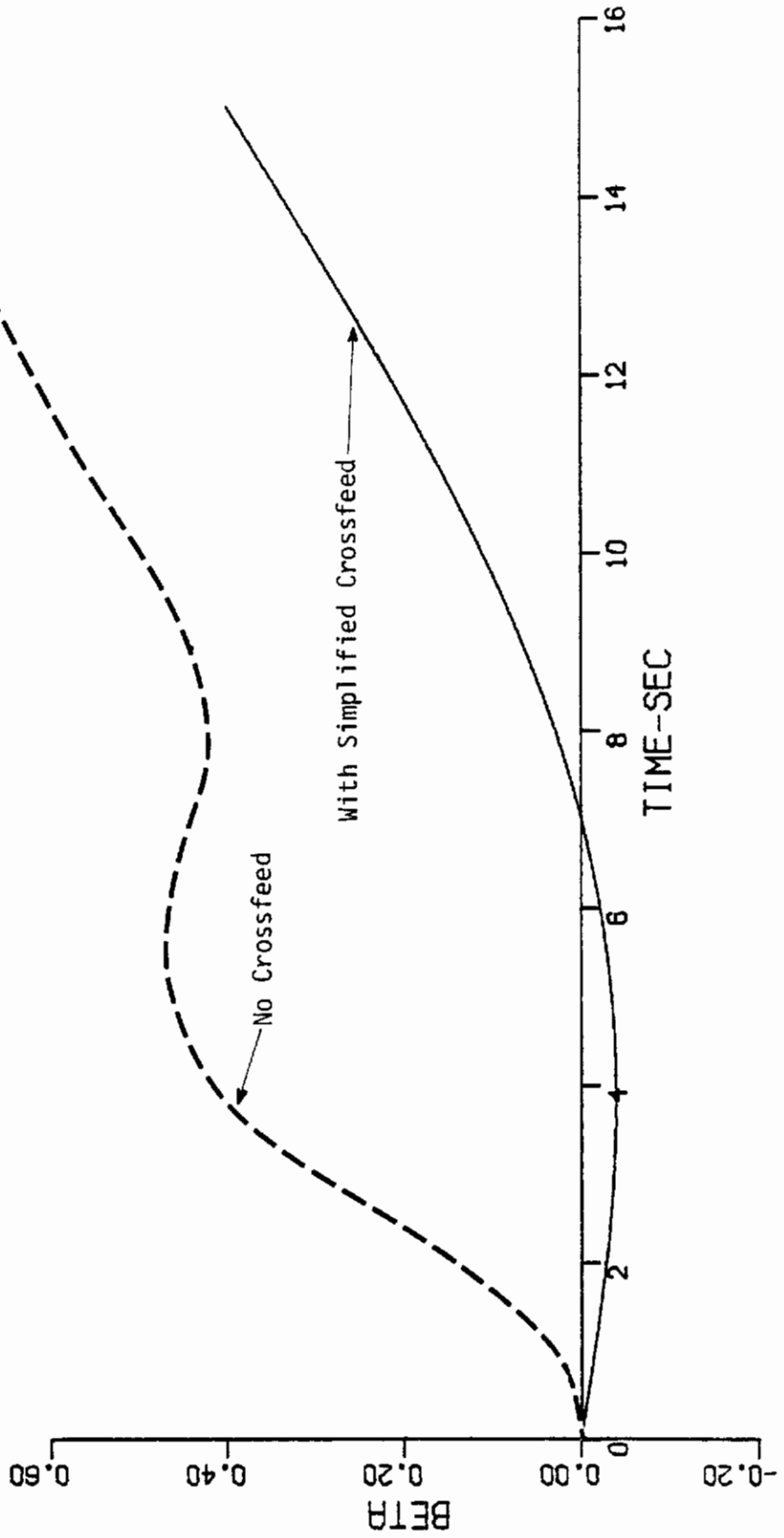
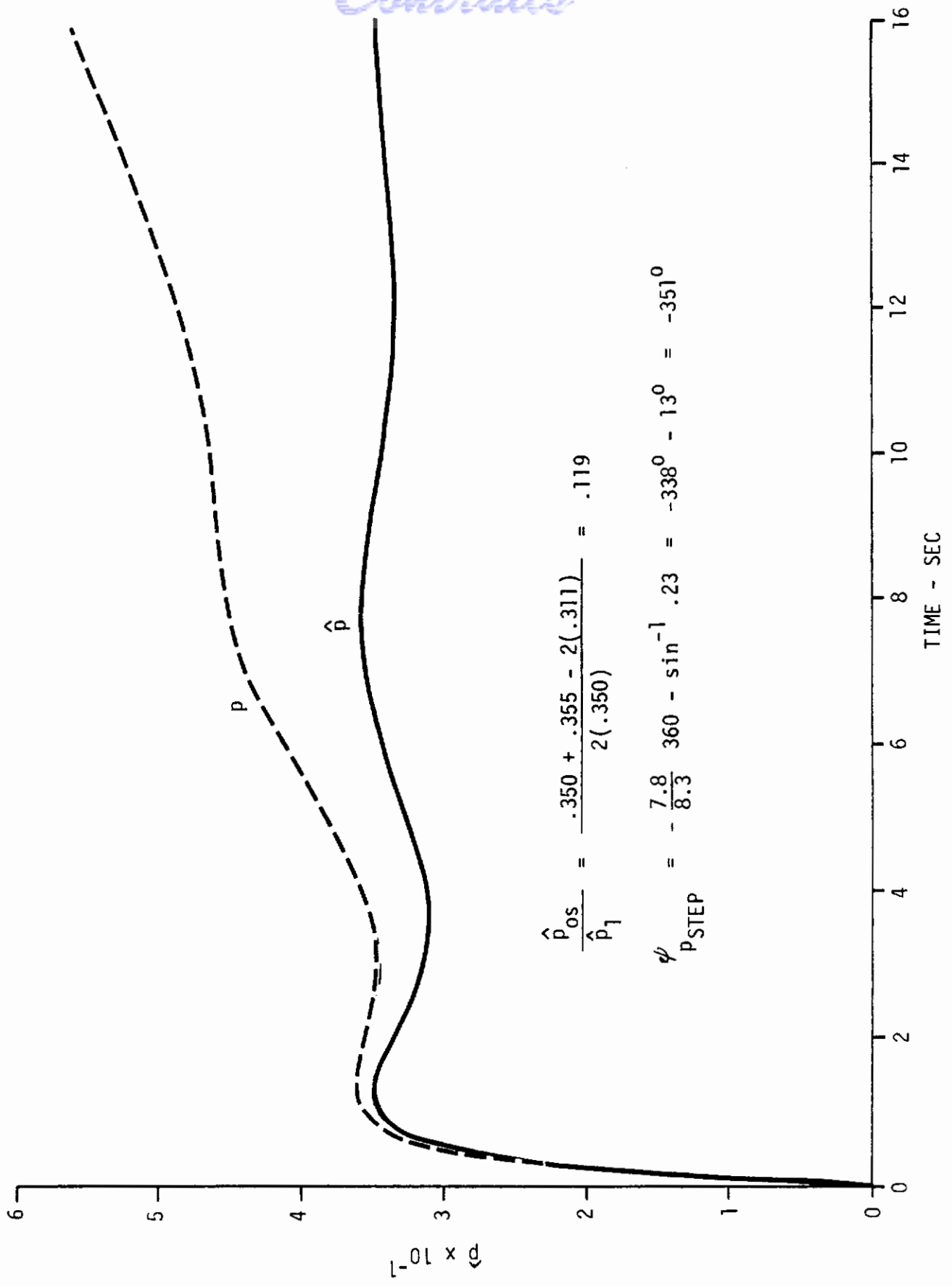


Figure 4 SIDESLIP RESPONSE OF CONFIGURATION P-8



$$\frac{\hat{p}_{os}}{\hat{p}_1} = \frac{.350 + .355 - 2(.311)}{2(.350)} = .119$$

$$\psi_{PSTEP} = -\frac{7.8}{8.3} 360 - \sin^{-1} .23 = -338^\circ - 13^\circ = -351^\circ$$

Figure 5 ROLL RATE FOR STEP AILERON STICK (CONFIGURATION P-8)

$$\frac{|\Delta \dot{\beta}_{MAX}|_{t < 1.2 T_d}}{\omega_d \left[\frac{g}{V_T} \hat{p}_1 \right]} = \frac{228 \cdot .182}{.773 \cdot 32.2 \cdot .350} = 4.76$$

$$\psi_{\beta STEP} = -360 \left(\frac{10.8}{8.3} + 1 - 2 \right) - \sin^{-1} .23 = -108^\circ - 13^\circ = -121^\circ$$

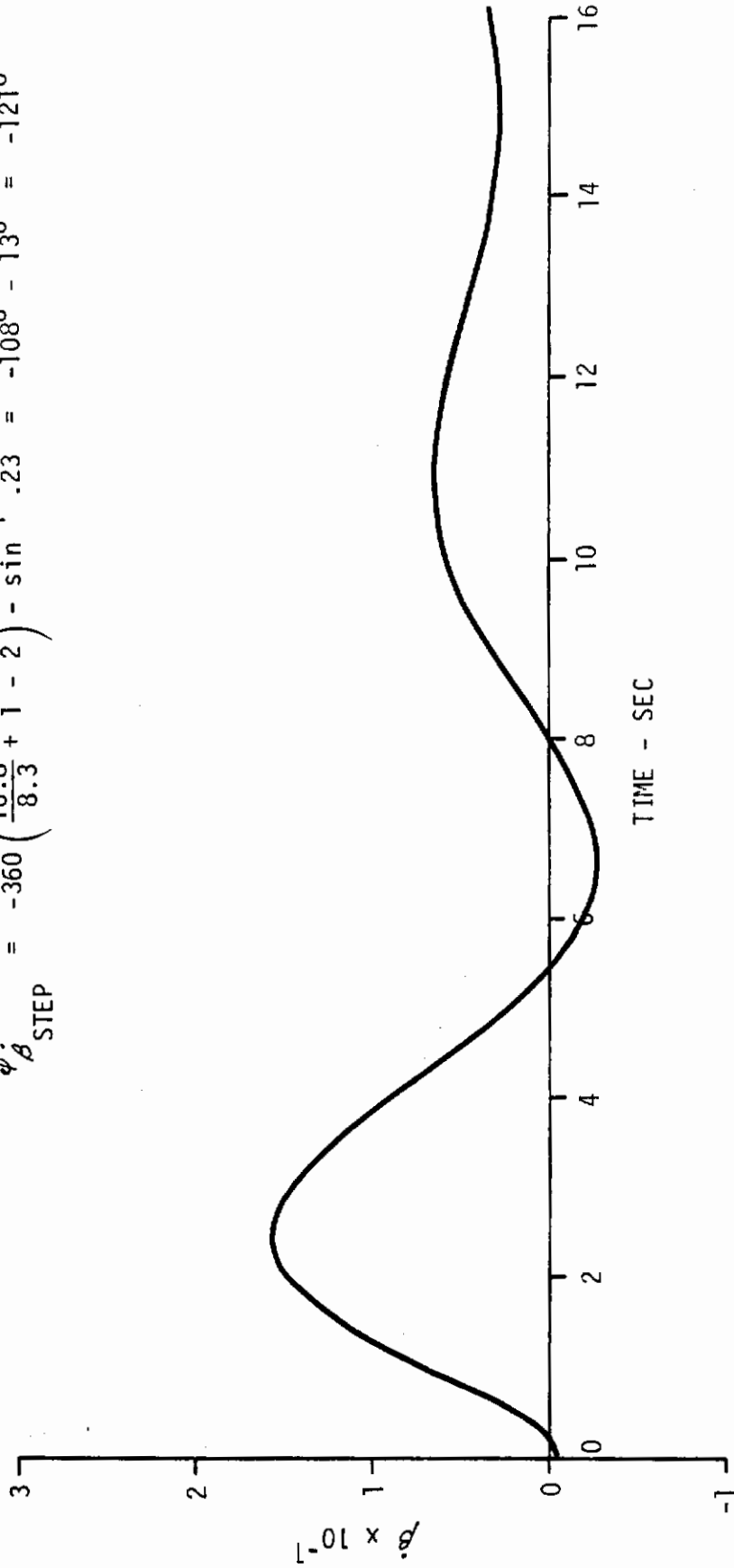


Figure 6 SIDESLIP RATE FOR STEP AILERON STICK (CONFIGURATION P-8)

Contrails

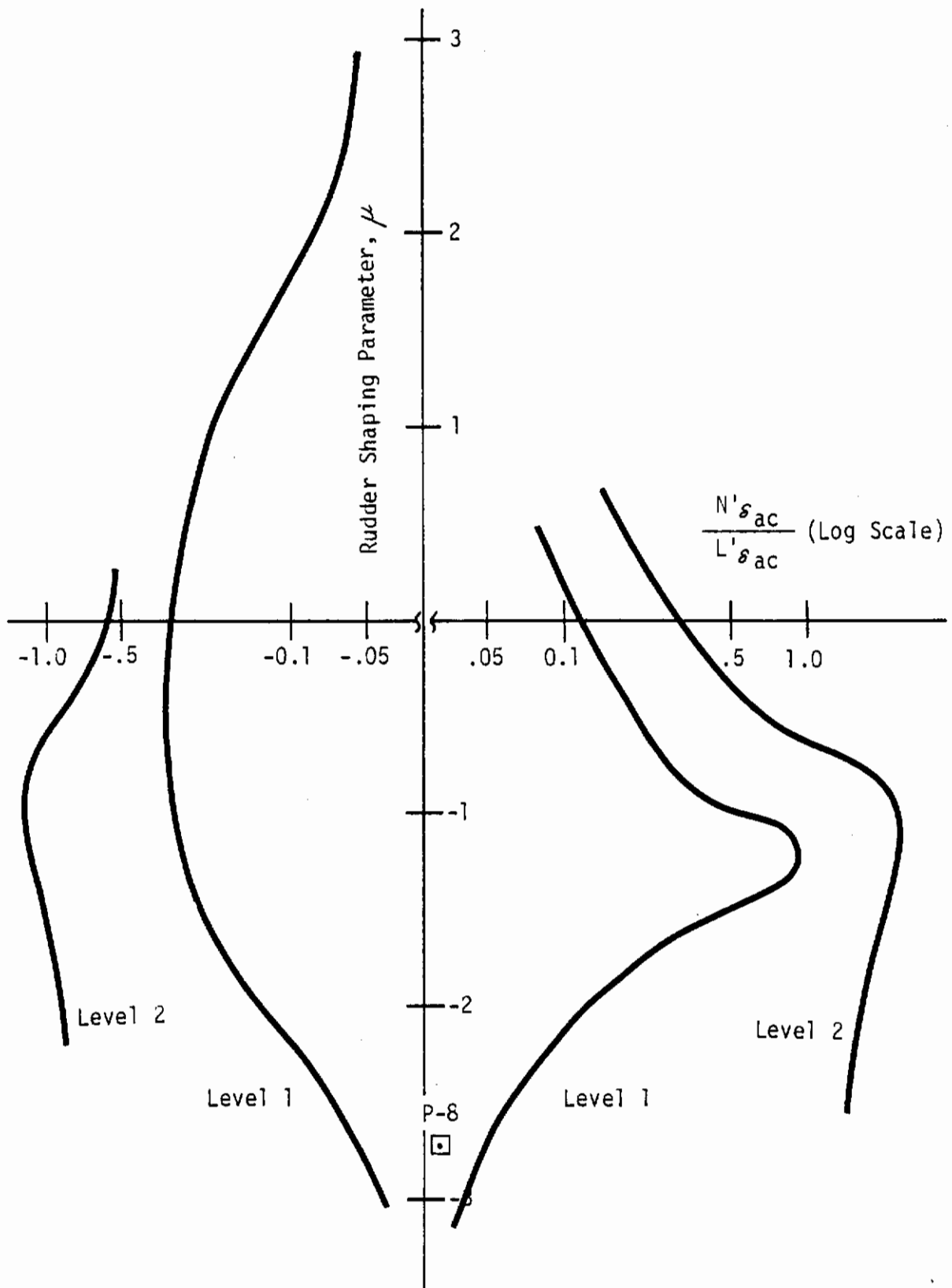


Figure 7 AILERON-RUDDER COORDINATION LIMITS

$$F_{RP} = \frac{-0.292(S+1.178)[S^2+0.995S+3.748](S+4)(S+12.87)(S-42.9)}{(S-0.245)(S+1)(S+2.35)(S+10)(S+15)(S+41)}$$

$$\mu = \frac{F_{RP}(3)}{K} - 1 \quad K = \frac{-0.0129(12.87)(-42.9)}{0.0441(15)(41)}$$

$$= \frac{0.226}{0.262} - 1 = 0.262$$

$$= 0.865 - 1$$

$$= -0.135$$

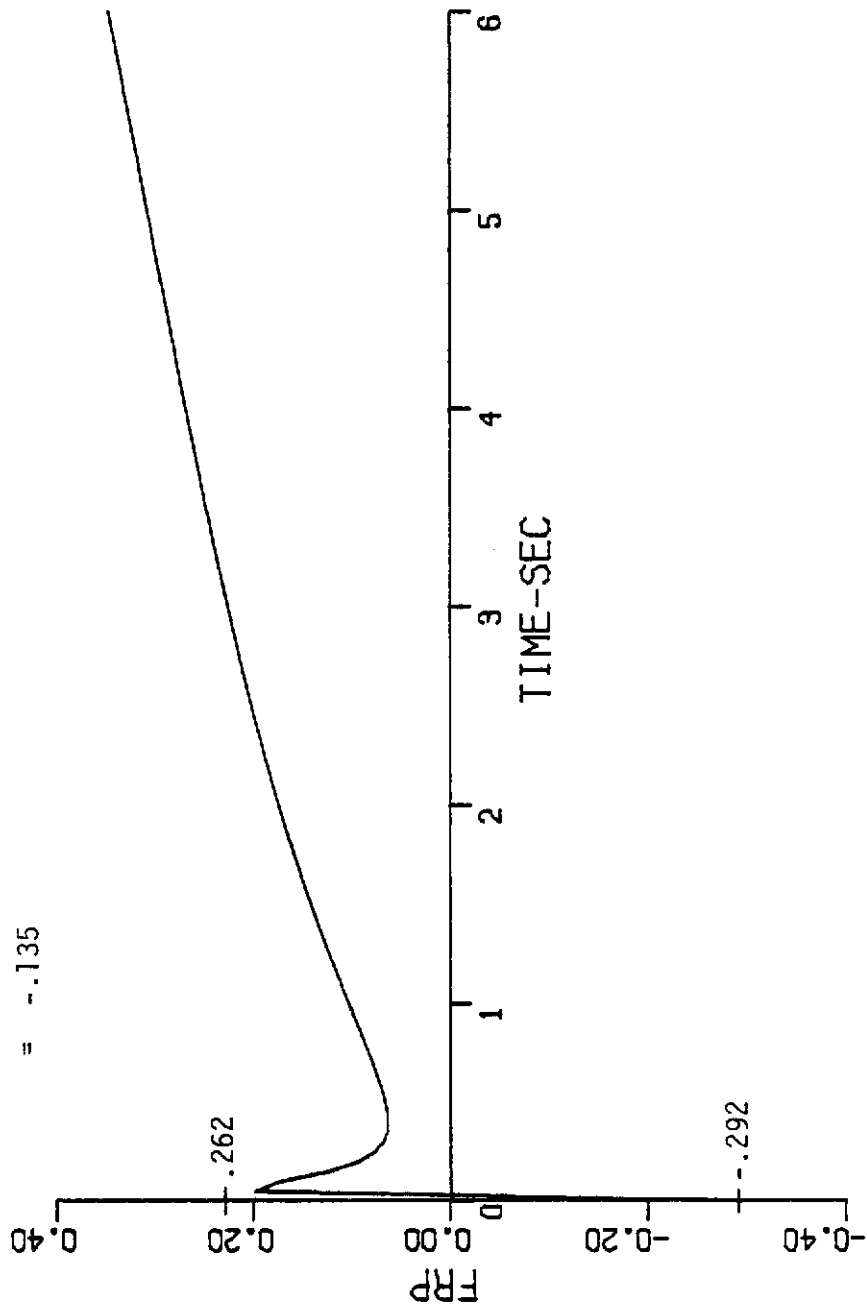


Figure 8 RUDDER PEDAL CROSSFEED FOR YF-16

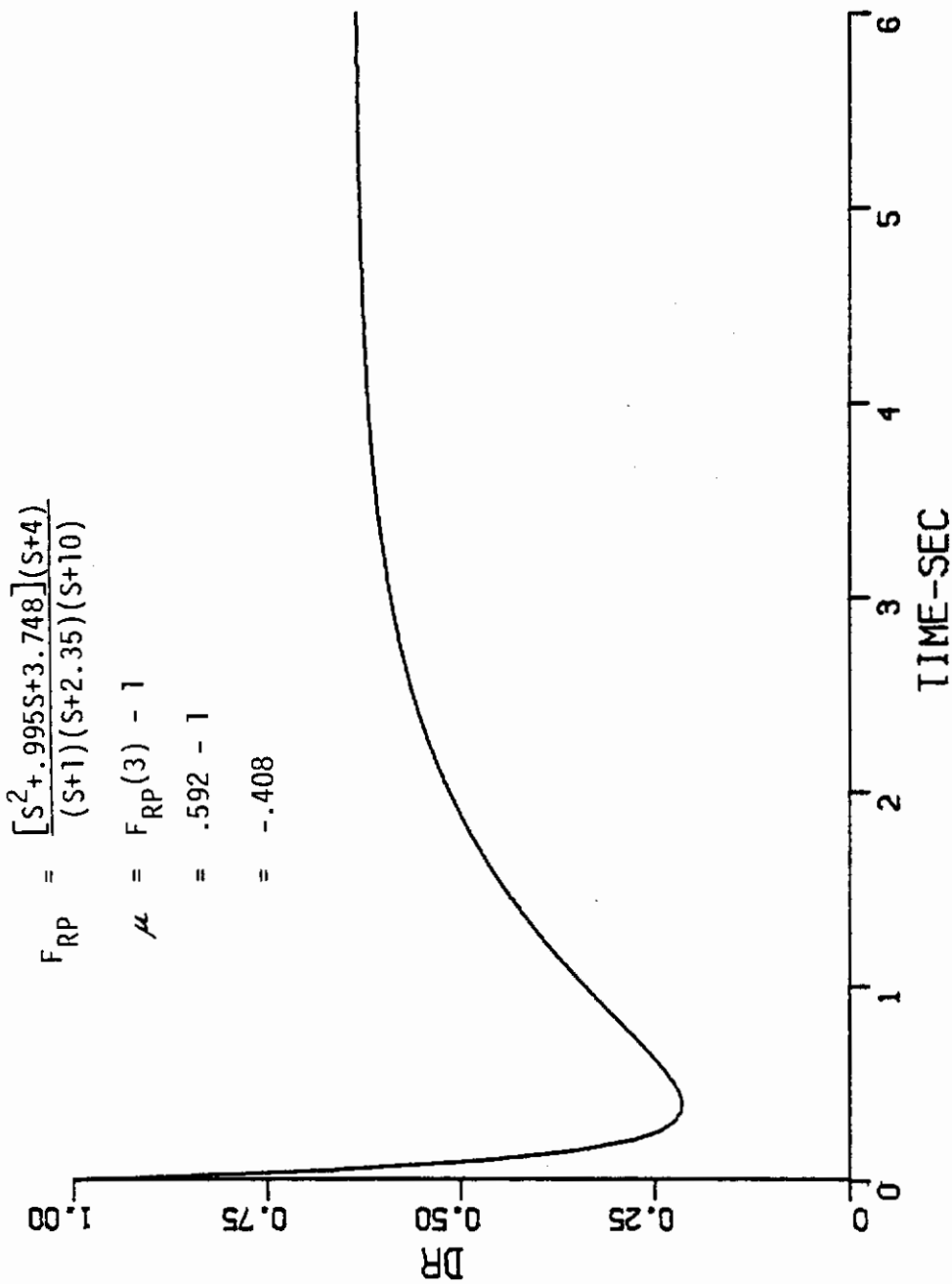


Figure 9 SIMPLIFIED RUDDER PEDAL CROSSFEED FOR YF-16

$$\dot{\beta} = \left[\frac{\dot{\beta}}{S_{AS}} + Y_{CF} \frac{\dot{\beta}}{S_{RP}} \right] \delta_{ASc}$$

$$Y_{CF} = \frac{.262(S+.592)}{(S+1)}$$

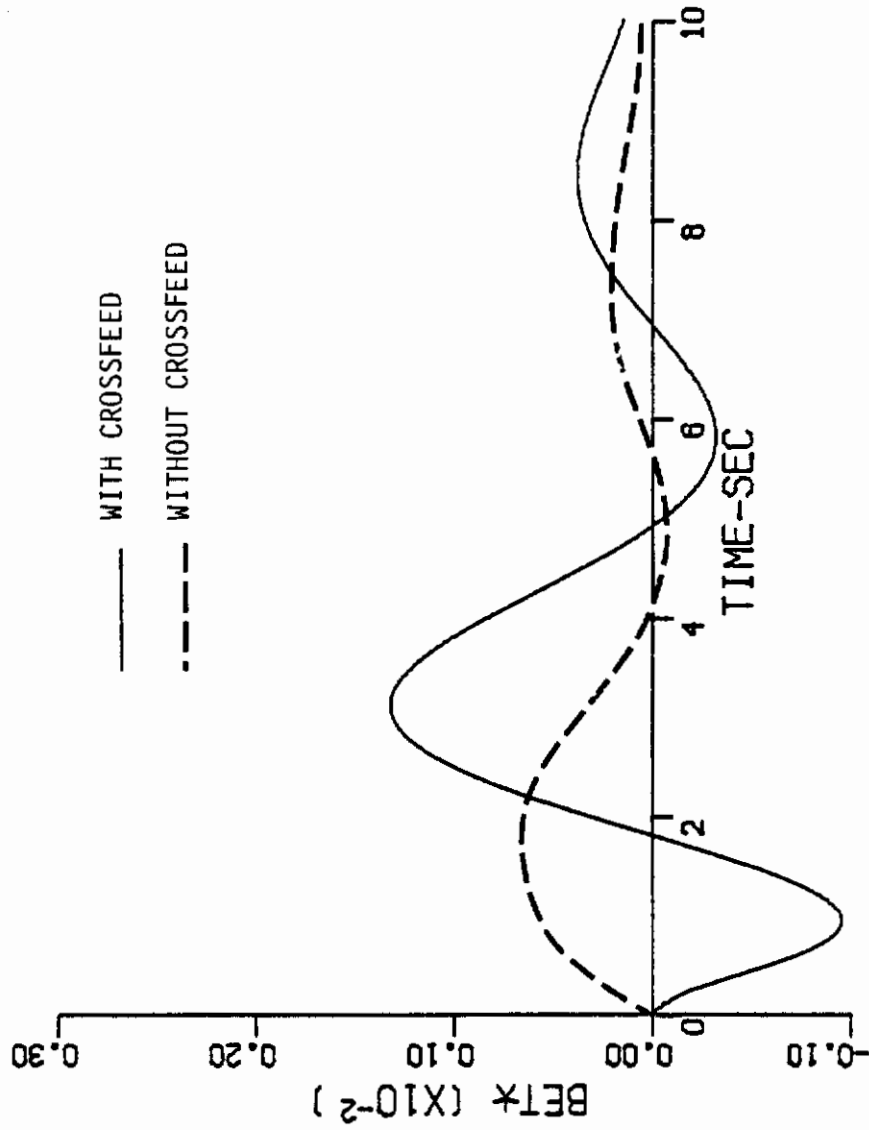
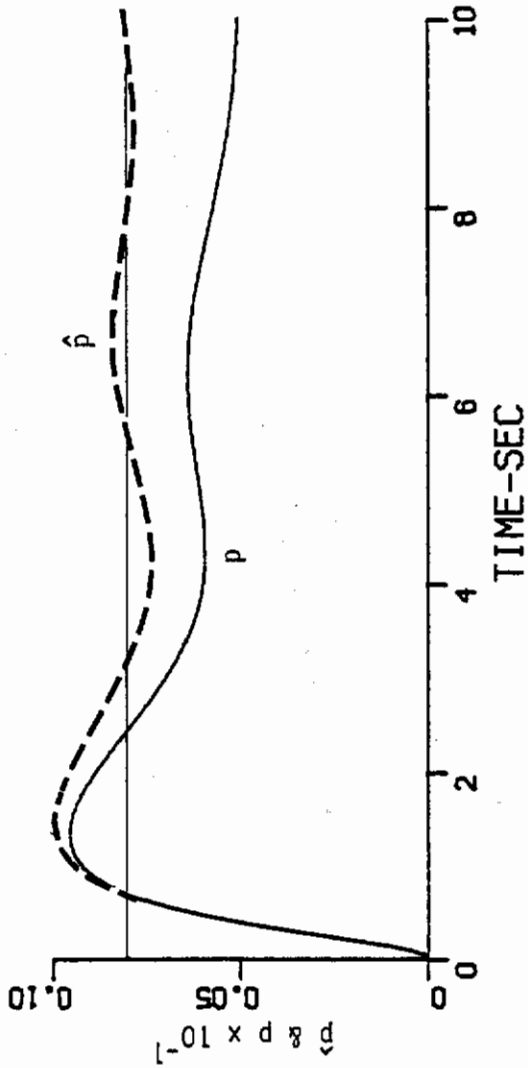
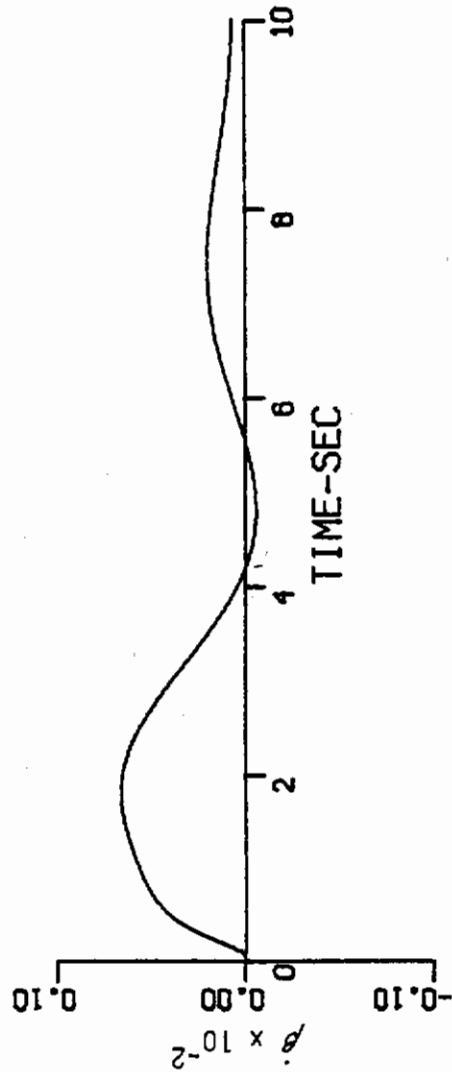


Figure 10 SIDESLIP RATE RESPONSE FOR YF-16 USING CROSSFEED IMPLIED BY $\mu = -.408$



$$\frac{\hat{p}_{05}}{\hat{p}_1} = \frac{.010 + .00828 - 2(.00739)}{2(.010)} = .176$$

$$\psi_{p_STEP} = -360 \left[\frac{6.3}{5.3} + 1 - 2 \right] - \sin^{-1} .25 = -83^\circ$$



$$\frac{1}{\omega_d} \frac{V_T}{g} \frac{\Delta \hat{\beta}_{MAX}}{\hat{\phi}_1} = \frac{1}{1.22} \frac{223}{32.2} \frac{1.20 \cdot 10^{-4}}{10.0 \cdot 10^{-3}} = .409$$

$$\psi_{\hat{\beta}_STEP} = -360 \left[\frac{7.4}{5.3} + 1 - 2 \right] - \sin^{-1} .25 = -158^\circ$$

Figure 11 ROLL RATE AND SIDESLIP RATE RESPONSES TO STEP AILERON FORCE, YF-16

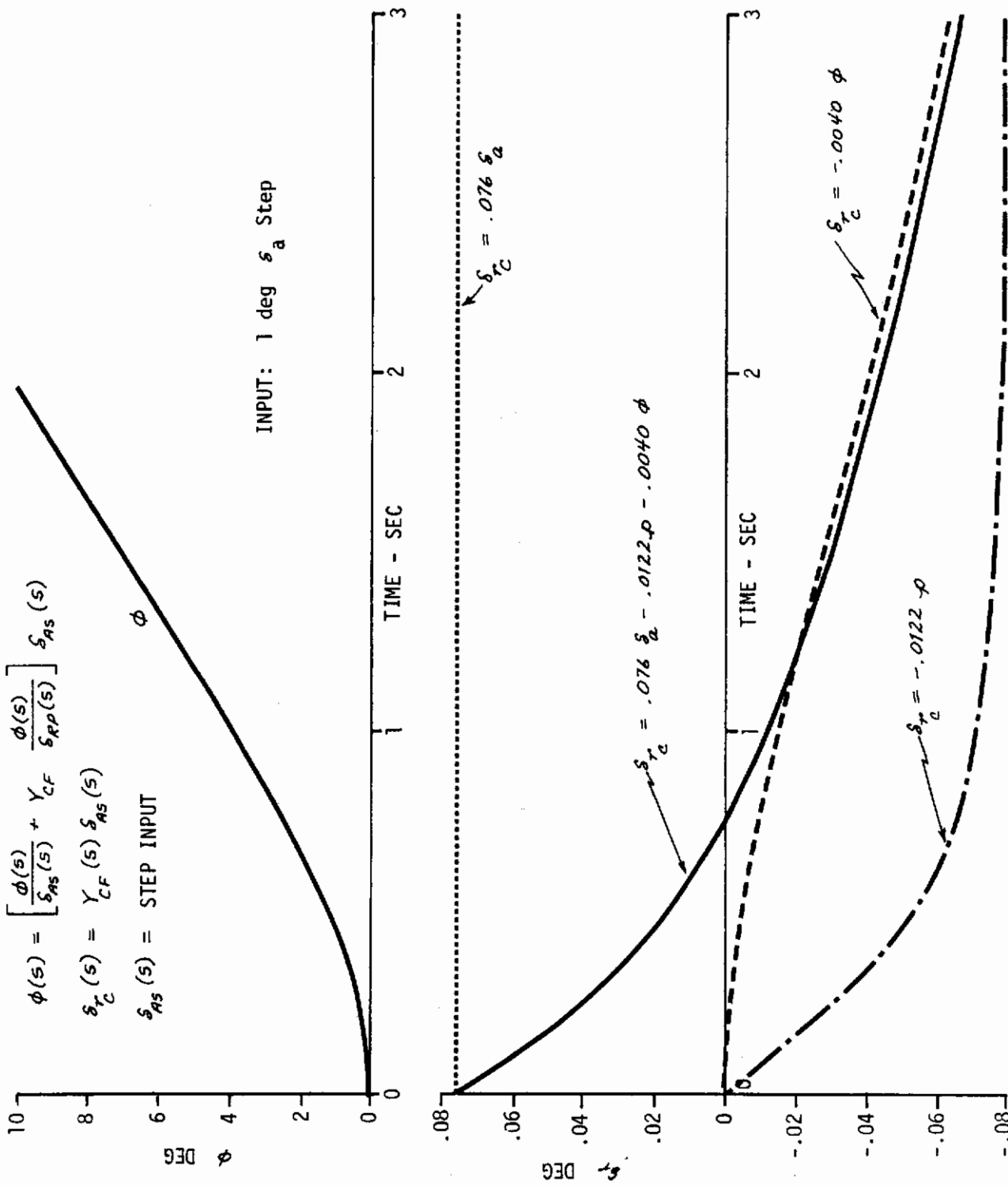


Figure 12 APPROXIMATION OF CROSSFEED TIME HISTORY

Appendix A

REVISED LATERAL-DIRECTIONAL COUPLING REQUIREMENTS PROPOSED BY CALSPAN

3.3.2.2 Bank angle oscillations. The value of the parameter $\hat{\phi}_{osc}/\hat{\phi}_1$ following a rudder-pedals-free impulse aileron control command shall be within the limits in Figure A4 for Levels 1 and 2. The impulse shall be as abrupt as practical within the strength limits of the pilot and the rate limits of the aileron control system. For all Levels, the change in bank angle shall always be in the direction of the aileron control command.

3.3.2.2.1 Additional roll rate requirement for small step inputs. The value of the parameter \hat{p}_{osc}/\hat{p}_1 following a rudder-pedals-fixed step aileron command shall be within the limits shown on Figure A4 for Levels 1 and 2. This requirement applies for step aileron control commands up to the magnitude which causes a 60 degree bank angle change in $1.7 T_d$ seconds. For all Levels, the change in bank angle shall always be in the direction of the aileron control command.

3.3.2.3 Sideslip excursions. Following a rudder-pedals-fixed step aileron control command, the sideslip increment, $\Delta\beta$, shall be less than the values specified herein. The aileron command shall be held fixed until the bank angle has changed at least 90 degrees.

<u>Level</u>	<u>Flight Phase Category</u>	<u>$\Delta\beta$</u>
1	A	6 degrees
	B&C	10 degrees
2	All	15 degrees

3.3.2.3.1 Additional sideslip requirement. The amount of (sideslip) (rate of change of sideslip) following a rudder-pedals(-free) (-fixed) (impulse) (step) aileron control command shall be within the limits shown on Figure A5 for Levels 1 and 2. The impulse shall be as abrupt as practical within the strength limits of the pilot and the rate limits of the aileron control system. The requirement shall apply for step aileron control commands up to the magnitude which causes a 60-degree bank angle change within T_d seconds.

Lateral-Directional Parameter Definitions

ϕ bank angle measured in the $y_s - z_s$ plane, between the y_s - stability axis and the horizontal

p roll rate about the x_s stability axis

$\hat{\phi}(t) \equiv \phi(t) + K_{s\phi} (1 - e^{-\lambda_s t}) \delta_{AS, IMPULSE}$ Bank angle response to an impulse aileron input with the spiral component subtracted.

$\hat{p}(t) \equiv p(t) + K_{sp} (1 - e^{-\lambda_s t}) \delta_{AS, STEP}$ Roll rate response to a step aileron input with the spiral component subtracted.

$\frac{\hat{p}_{osc}}{\hat{p}_1}$ a measure of the ratio of the oscillatory component of roll rate to the roll rate at the first peak following a rudder-pedal-fixed aileron control command.

$$\frac{\hat{p}_{osc}}{\hat{p}_1} = \frac{\frac{1}{2} [(\hat{p}_1 - \hat{p}_2) + (\hat{p}_3 - \hat{p}_2)]}{\hat{p}_1}$$

where \hat{p}_1 , \hat{p}_2 and \hat{p}_3 are roll rates at the first, second and third peaks, respectively (Figure 126).

$\frac{\hat{\phi}_{osc}}{\hat{\phi}_1}$ a measure of the ratio of the oscillatory component of bank angle to the bank angle at the first peak following a rudder-pedal-free impulse aileron control command.

$$\frac{\hat{\phi}_{osc}}{\hat{\phi}_1} = \frac{\frac{1}{2} [(\hat{\phi}_1 - \hat{\phi}_2) + (\hat{\phi}_3 - \hat{\phi}_2)]}{\hat{\phi}_1}$$

where $\hat{\phi}_1$, $\hat{\phi}_2$, and $\hat{\phi}_3$, are bank angles at the first, second, and third peaks, respectively. (Figure 126)

$\Delta\beta_{max}$ maximum sideslip excursion at the c.g., occurring within $1.2 T_d$ sec following a rudder-pedals-free impulse aileron control command. Usually the peak to peak amplitude (Figure 127)

Contrails

$\dot{\Delta\beta}_{max}$ maximum sideslip rate excursion at the c.g. occurring within $1.2 \tau_d$ sec following a rudder-pedals-fixed step aileron control command (Figure 127)

proposed flying qualities parameter to limit sideslip excited by roll commands.

$$\frac{|\Delta\beta_{max}|_{t < 1.2 \tau_d}}{\omega_d \left[\frac{g}{V_T} \hat{\phi}_1 \right]}$$

ψ_x IMPULSE OF STEP phase angle expressed as a lag for a cosine representation of the Dutch roll oscillation in the (x) response resulting from an aileron impulse or an aileron step input

$$\psi_x \text{ IMPULSE OF STEP} = -360 \left[\frac{t_{nx}}{T_d} + 1 - n \right] - \sin^{-1} \zeta_d \text{ deg}$$

with n as in t_{nx} , below. Where (x) is bank angle, roll rate, yaw rate, yaw^x acceleration, sideslip or sideslip rate response with the spiral residue subtracted (Figures 126, 127)

ψ_z IMPULSE OF STEP phase angle expressed as a lag for a cosine representation of the Dutch roll oscillation in the (x) response resulting from an impulse or step aileron-control command

$$\psi_z \text{ IMPULSE OF STEP} = \sum \theta_z - \sum \theta_p$$

where:

θ_z angles of line segments from zeros of $\frac{x(s)}{\delta_{AS}(s)}$ transfer function numerator to the positive conjugate Dutch roll root, for δ_{AS} impulse or step.

Contrails

θ_p angles of line segments from poles of $\frac{x(s)}{\delta_{AS}(s)}$ transfer function denominator to the positive conjugate Dutch roll root, for δ_{AS} impulse or step.

t_{nx}

time for the Dutch roll oscillation in the (x) response to reach the n^{th} local maximum for a right step or impulse aileron-control command, or the n^{th} local minimum for a left command. In the event a step command is employed, the control shall be moved as abruptly as practical and, for purposes of this definition, initial time, t_0 , shall be defined as the instant the cockpit control deflection passes through half the amplitude of the commanded value. For pulse inputs, time shall be measured from the point halfway through the duration of the pulse. Only peaks occurring after $t = 3\tau_R$ should be used to avoid distortion resulting from the roll mode.

K_{Sx}

Residue of spiral root in the (x) time history response to aileron impulse or aileron step input.

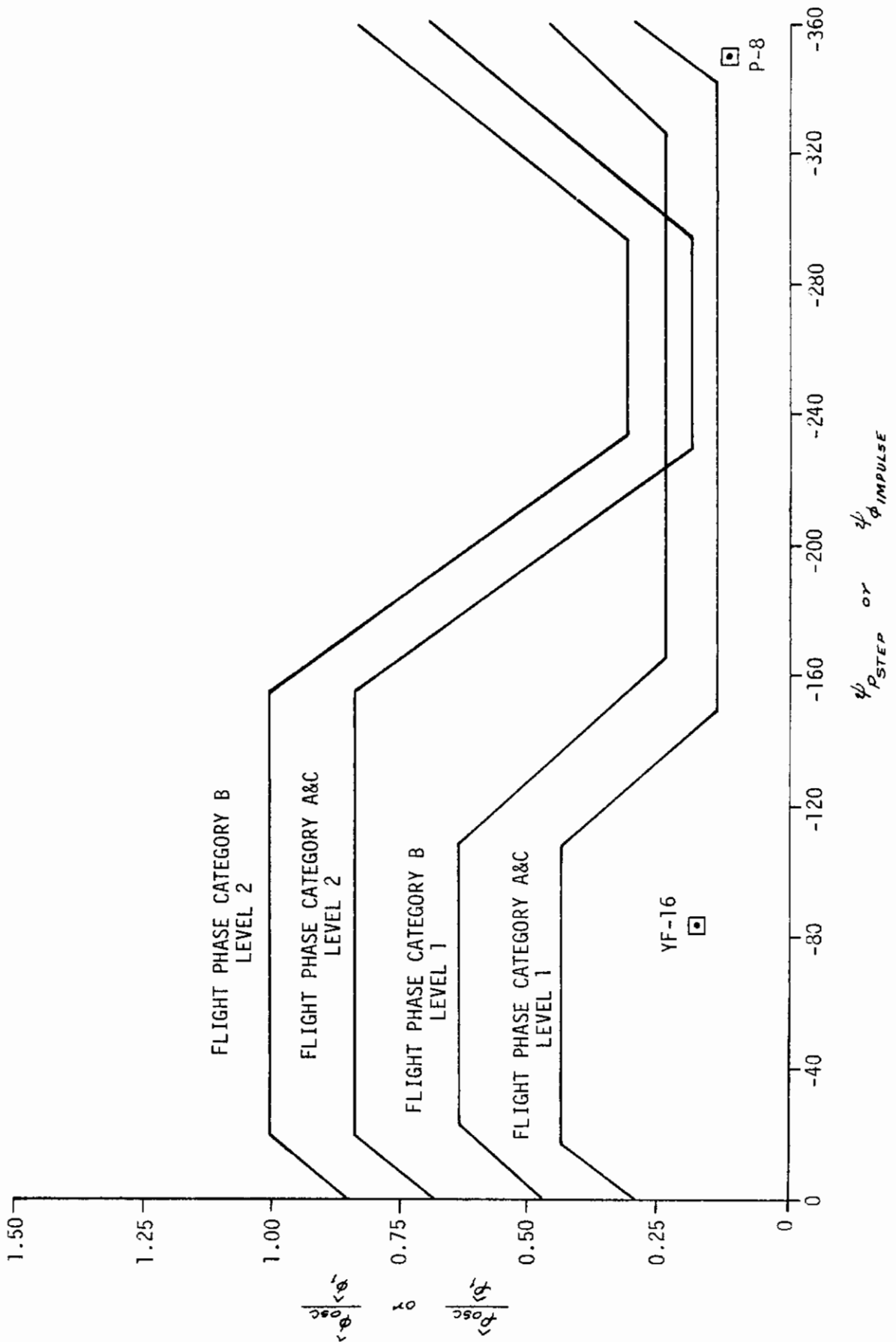


Figure A4 ROLL RATE AND BANK ANGLE OSCILLATION LIMITATIONS

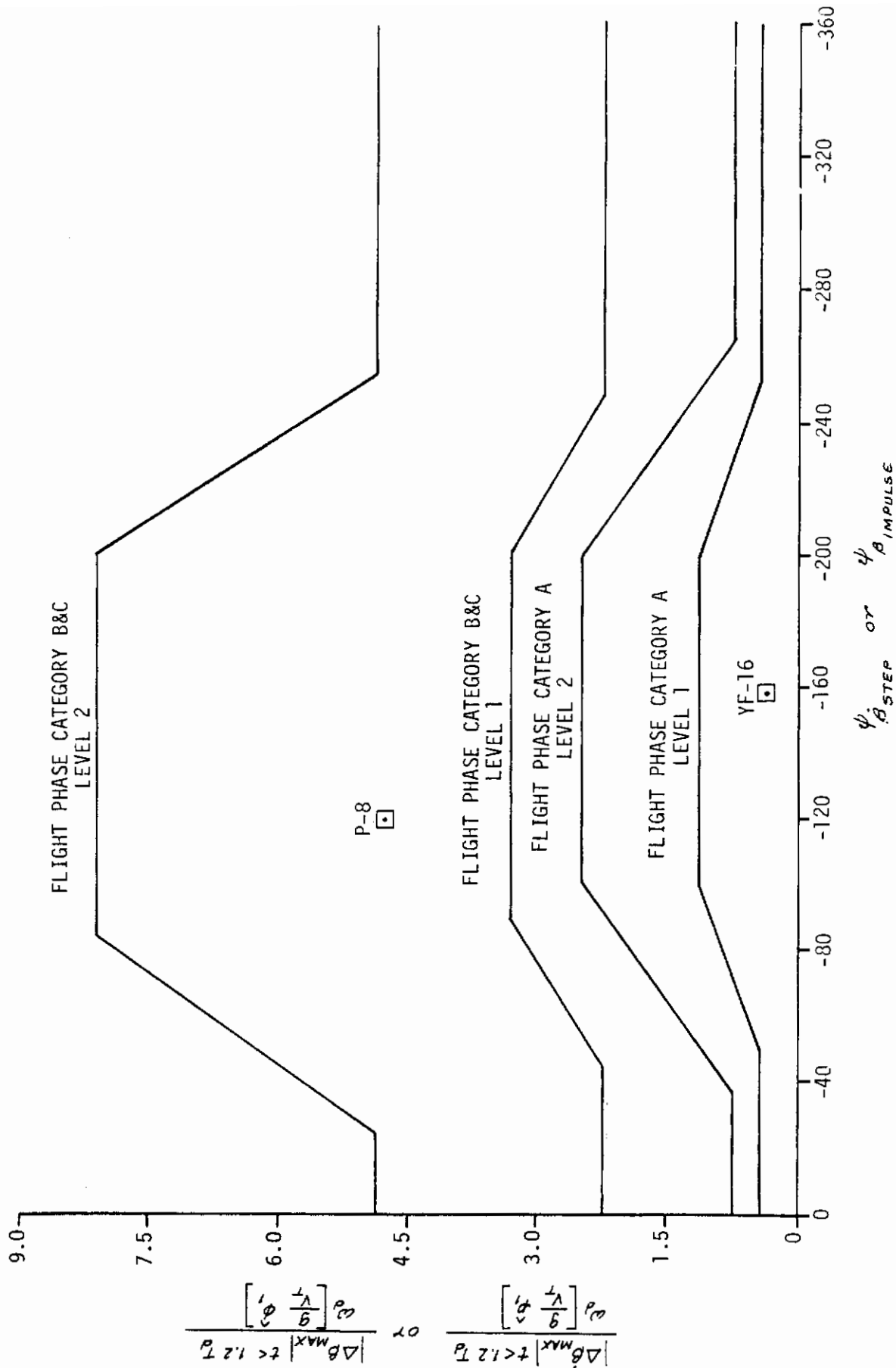


Figure A5 SIDESLIP EXCURSION LIMITATIONS

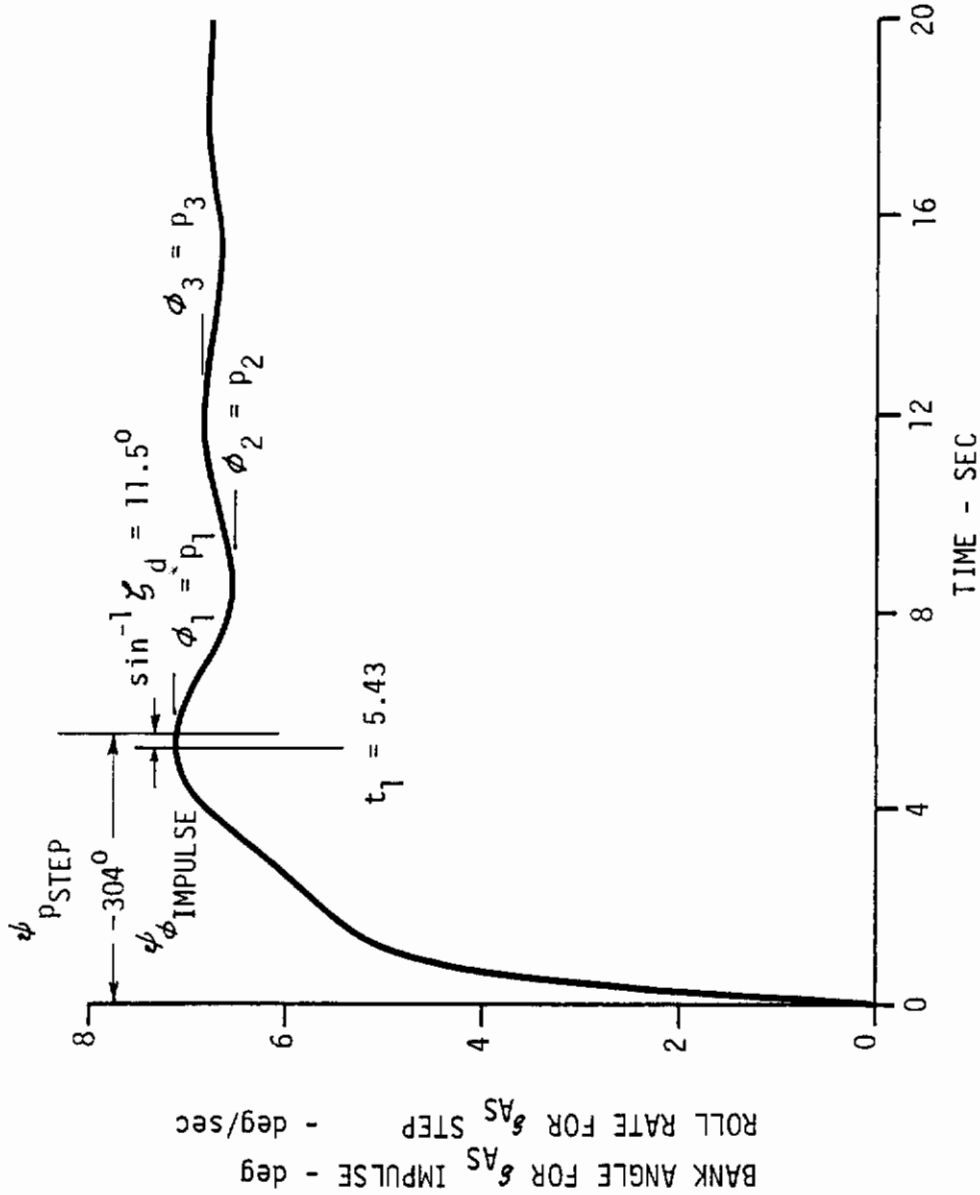


Figure 126 BANK ANGLE OR ROLL RATE RESPONSE TOAILERON IMPULSE OR STEP COMMAND

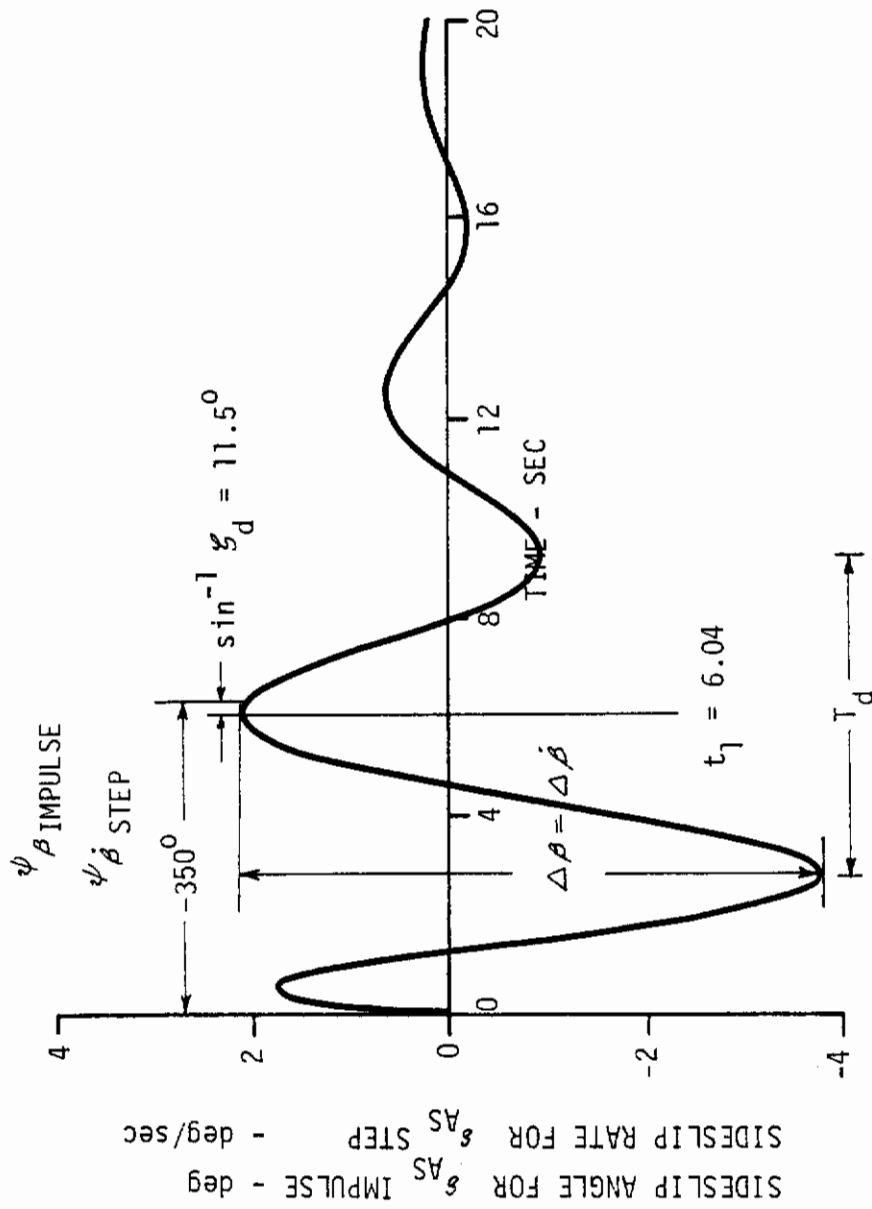


Figure 127 SIDESLIP OR SIDESLIP RATE RESPONSE TOAILERON IMPULSE OR STEP COMMAND

Contrails

Roger Hoh, STI: 1. Your primary argument with the μ parameter appears to be the simplification of the crossfeed. We no longer recommend that high or low frequency roots be removed and that the crossfeed (with unity high frequency gain) be used in its raw form to calculate $\delta_r = (3)$. How does this affect your objections?

2. You show a rudder time history which is non-monotonic. This is an important piece of data because such large departures from the assumed monotonic shape are expected to result in poor pilot ratings. What was the pilot rating for that configuration? (Original YF-16) What was the value of $\frac{N_{\delta\omega}}{L_{S\omega}}$ for the original YF-16? (Obtain $N_{\delta\omega}$

as high frequency gain of $(N_{\delta\omega}^P)_{aug}$ respectively).

3. What was $\frac{N_{\delta\omega}}{L_{\delta\omega}}$ on the configuration that met both criteria and

was bad?

Answer: 1. If the rules for measuring $\delta_r = (3)$ are different from those published in the STI AIAA article and the AFFDL report, then why didn't Mr. Hoh describe these new rules in his presentation before lunch today? I believe I have shown that cases can exist for which the μ parameter as defined in the written reports, implies a crossfeed time history that is not at all shaped like the rudder time history required to restrain sideslip to be zero and in fact will cause larger sideslip excursions than would occur if no rudder was used.

It is not clear to me what the new measurement rule is; therefore, I am not prepared to comment on its utility.

Examination of the stick to rudder crossfeed required to constrain sideslip is certainly worthwhile, and as I indicated in my paper, the rudder time history can be interpreted in terms of crossfeed and feedback gains δ_r / δ_w , δ_r / p and δ_r / ϕ which can be used to diagnose the coordination problem of a given airplane. These gains are also effective augmentation loops. Whether or not an adequate flying qualities criterion can be developed which uses rudder amplitude conformation at only one or two instants in time is not clear to me. The STI approach does not seem to treat cases where the pilot chooses not to use the rudder.

2. I do not know what pilot rating the YF-16 has been given for the flight condition the transfer function represents. The ratings from the NT-33A simulation should not be used because there was no attempt to mechanize the details of the YF-16 lateral directional control system. The ratio of high frequency coefficients in r/δ_w and p/δ_w transfer functions is $(-.111)$.

3. For configuration P-8 the value of $N'_{\delta_w} / L'_{\delta_w}$ was $t.035$.

Dwight Schaeffer, Boeing: Do the feedbacks to rudder employed to make $\beta/\delta_w = 0$ adversely affect steady turn (hands off) coordination or response to turbulence?

Contrails

Answer: The feedbacks δ_r/p and δ_r/ϕ and the crossfeed δ_r/δ_w are designed to help keep sideslip zero in steady turns and rolling maneuvers. The δ_r/ϕ feedback will effect the spiral root and it may be necessary to use yaw rate feedback to the aileron δ_a/r to keep the spiral root neutral or stable. The feedback signals are inertial, therefore the airplane tends to be stabilized and to reject turbulence upsets.