Technical Comments

C80-010

Comment on "Handling Quality Criterion for Heading Control"

Charles R. Chalk*
Calspan Corporation, Buffalo, N. Y.

Nomenclature

$C_{0,1,2,3}$ = coefficients
F_{RP} = rudder pedal force
g = acceleration of gravity
K = gain
L_i' = primed dimensional stability derivatives in roll where $i = \delta_{AS}, p$
N_i' = primed dimensional stability derivatives in yaw where $i = \delta_{AS}, p, r, \phi$
$N^{\beta}{}_{\delta_{AS}}$ = transfer function numerator
$N^{\beta}{}_{\delta_{RP}}$ = transfer function numerator
p = roll rate
r = yaw rate
S = Laplace operator
V = velocity
Y_{CF} = aileron-to-rudder crossfeed function
$Y_{\delta_{AS}}$ = side acceleration due to aileron stick
α_o = trim angle of attack
β = sideslip angle
$\Delta\beta_{max}/k$ = flying qualities parameter used in MIL-F-8785B
δ_{AS} = aileron stick displacement
δ_{r_c} = rudder command
λ_p = transfer function pole
λ_z = transfer function numerator factor
μ = crossfeed shaping parameter
ϕ = bank angle
$\psi_{\beta_{step}}$ = flying qualities parameter used in MIL-F-8785B

Introduction

THE sideslip excursion requirement ($\Delta\beta_{max}/k$ vs $\psi_{\beta_{step}}$) of MIL-F-8785B(ASG) was criticized by the authors of Refs. 1 and 2 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 Refs. 1 and 2 further claimed, "the fact that these criteria are not satisfactory is shown in Fig. 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 Fig. 1. Specifically, data points 4B, 5A, and 5B from Ref. 2 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 Fig. 1 are fictitious because these points have been plotted by the authors of Refs. 1 and 2 at the wrong values of $\psi_{\beta_{step}}$. The errors in locating these points relative to the specification boundaries are indicated in Fig. 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 are discussed in Ref. 3, the claim made by the authors of Refs. 1 and 2 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 $\psi_{\beta_{step}}$ is partly determined by this consideration.

Two different approaches to development of requirements for limiting sideslip during rolling and turning maneuvers have been proposed by the authors of Refs. 1 and 3. The time histories in Fig. 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 Fig. 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 response. In the approach described in

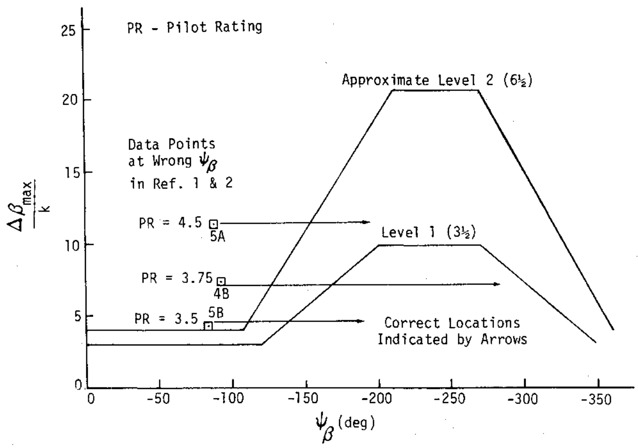

Fig. 1 Incorrect correlation of data made by authors of Refs. 1 and 2.

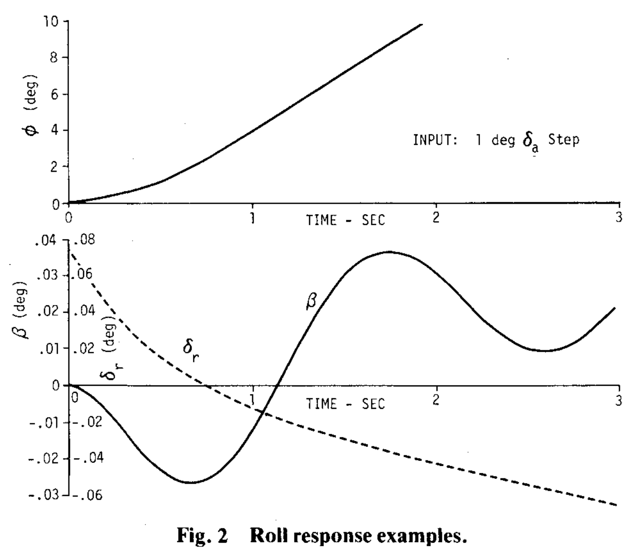

Fig. 2 Roll response examples.

Received Oct. 5, 1978; revision received April 23, 1979.

Index category: Handling Qualities, Stability, and Control.

*Staff Engineer, Flight Sciences Department. Member AIAA.

Ref. 3, requirements limiting the magnitude of the oscillatory component of the sideslip response to an impulse aileron input are stated as a function of the phase angle of the oscillation. The approach described in Refs. 1 and 2 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

$$Y_{\mathrm{CF}} = -N^{\beta}{}_{\delta_{\mathrm{AS}}} / N^{\beta}{}_{\delta_{\mathrm{RP}}}$$

The Refs. 1 and 2 criterion is based on the assumption that the ideal rudder crossfeed transfer function can be adequately represented by a first-order lead-lag form

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

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 Ref. 1 criterion consists of empirical boundaries drawn on a plane defined by the μ parameter and the ratio of $N'_{\delta_{\mathrm{AS}}}/L'_{\delta_{\mathrm{AS}}}$ 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,

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

This expression is further approximated by assuming that the final value will be reached before 3 s.

$$\mu = \frac{\text{value at } t=3}{\text{initial value}} - 1$$

The ideal aileron-rudder crossfeed transfer function generally will not be a first-order lead-lag. It is usually the ratio of third-order polynomials for unaugmented airplanes and for augmented airplanes, the crossfeed can be the ratio of higher-order polynomials. The authors of Refs. 1 and 2 define a set of rules for simplifying higher-order crossfeed transfer functions to the first-order form.

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 Fig. 3. This is a complex time history involving a rapid rudder pedal force reversal within the first 0.1 s followed by a dip at $t \approx 0.4$ s and then a fairly steady growth with time. The complete crossfeed transfer function is noted on Fig. 3. The reduced transfer function, time history, and value of $\mu = -0.408$ illustrated on Fig. 4 are obtained by using the rules in Ref. 2 for simplifying the complete transfer function. The simplified YF-16 crossfeed is third order in numerator and denominator and therefore does not meet the assumption that the crossfeed transfer function can be approximated by a first-order lead-lag under which the μ parameter was defined. Because of the second-order complex factors in the numerator, which cause a notch effect, the rudder time history of the YF-16 crossfeed is quite different from the time history implied by the first-order lead-lag model with $\mu = -0.408$. The first-order model would imply a rudder pedal time history in response to a step input that starts at unity initial value and decays exponentially to a steady-state value of 0.0592. 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 denominator factors of 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 $\mu = -0.408$ value to a first-order crossfeed model. Thus, for $\lambda_p = 1.0$ and $\mu = -0.408$, the value of $\lambda_z = 0.592$ is found from the definition relating μ to the first-order model:

$$\mu = \frac{\lambda_z}{\lambda_p} - 1 = \frac{0.592}{1} - 1 = -0.408$$

The first order crossfeed model implied by $\mu = -0.408$ then would be

$$Y_{\mathrm{CF}} = \frac{0.262(s+0.592)}{(s+1)}$$

where the gain has been calculated by rules given in Ref. 1. The time response of this crossfeed for a step input is illustrated in Fig. 5. This time history is not the same shape as

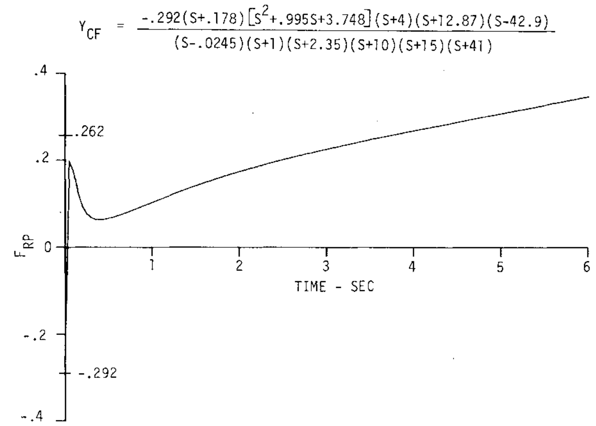

Fig. 3 Rudder pedal crossfeed for YF-16.

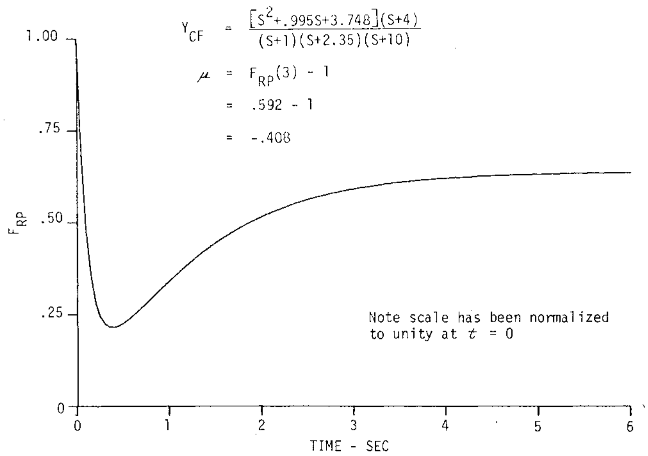

Fig. 4 Simplified rudder pedal crossfeed for YF-16.

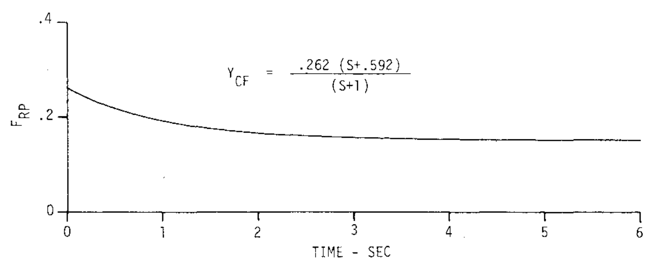

Fig. 5 Rudder pedal force time history for lead-lag crossfeed with $\mu = -0.408$.

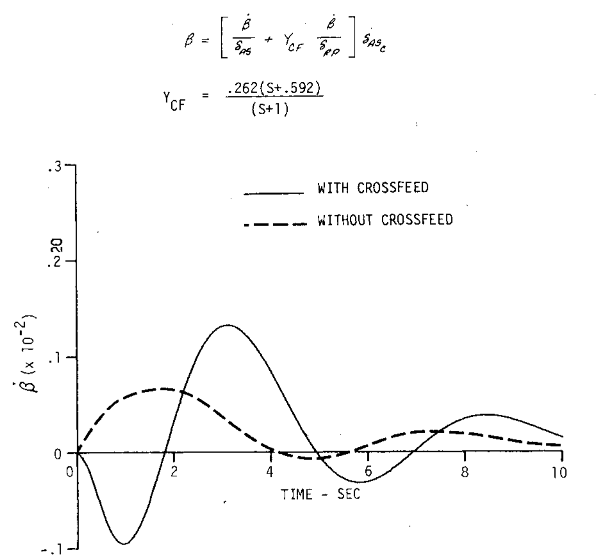

Fig. 6 Sideslip rate response for YF-16 using crossfeed implied by $\mu = -0.408$.

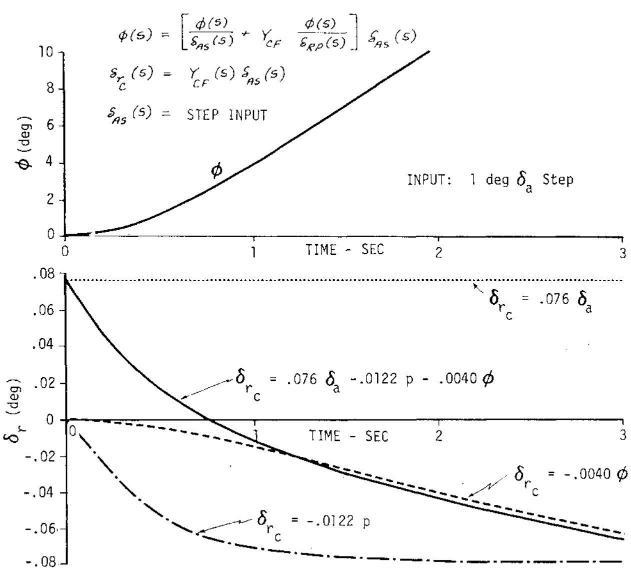

Fig. 7 Approximation of crossfeed time history.

the ideal crossfeed time history illustrated in Fig. 3. This crossfeed was used to calculate sideslip rate response illustrated in Fig. 6. Obviously this crossfeed does not constrain sideslip to be zero and, in fact, by comparison with the sideslip rate time history in Fig. 6, which was calculated for an aileron stick-force step-input with no crossfeed, it is seen that the first-order crossfeed for which $\mu = -0.408$ has aggravated the sideslip response. In the author's opinion, this case demonstrates that the assumption the crossfeed can be adequately represented by a first-order lead-lag in the frequency band $.33 < w < 6$ 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 in oversimplification.

General Observation

It should be observed that the sideslip requirement of Ref. 3 and the crossfeed requirement of Refs. 1 and 2 are both related to the numerator of the β/δ_{AS} transfer function. Both the 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 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 in this explanation 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 derivative N'_ϕ which would result from feedback of bank angle to the rudder and aileron.

$$
\begin{aligned}
N^{\beta}{}_{\delta_{AS}} &= C_3 S^3 + C_2 S^2 + C_1 S + C_0 \\
C_3 &= 0 \text{ when } Y_{\delta_{AS}} = 0 \\
C_2 &= 0 \text{ when } N'_{\delta_{AS}} \cong \alpha_o L'_{\delta_{AS}} \\
C_1 &= 0 \text{ when } N'_p = (g/V) + \alpha_o (L'_p - N'_r) \\
&\quad + Y_{\delta_{AS}} (L'_p N'_r) / (L'_{\delta_{AS}}) \\
C_0 &= 0 \text{ when } N'_\phi = -(g/V) N'_r
\end{aligned}
\tag{1}
$$

These equations indicate that independent control of side force and yawing moments is required to make all of the coefficients be zero. Side force control is necessary to cancel the side force due to aileron-stick commands but this component is not normally a significant consideration and 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 control law required to constrain sideslip to be zero is:

$$\delta_{rc} = \frac{\delta_{rc}}{\delta_{AS}} \delta_{AS} + \frac{\delta_{rc}}{p} p + \frac{\delta_{rc}}{\phi} \phi \tag{2}†$$

The gains in this equation, which are constants for a given flight condition, can be calculated from Eq. (1). The time histories in Fig. 7 illustrate that an equation of this form will accurately represent the rudder time history calculated from the ideal aileron-rudder crossfeed transfer function.

This interpretation of the rudder control 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 Eq. (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) The sideslip requirement recommended in Ref. 3 and the aileron-rudder crossfeed analysis proposed in Refs. 1 and 2 both are useful in understanding the cause of flying qualities deficiencies. The μ parameter used in the heading control criterion of Ref. 1, however, is based on the assumption that

†This control law also is applicable to airplanes with complex augmentation systems, but in that case the expressions for calculating the gains are more complex than those shown in Eq. (1).

the aileron-rudder crossfeed transfer function can be represented adequately 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.

2) It is shown that the following rudder control law will constrain sideslip to be essentially zero during rolling and turning maneuvers.

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

The gains in this control law can be evaluated by setting the coefficients of $N^{\beta}{}_{\delta_{AS}}$ to zero. (A) C77-001

no ref

References

[1] Hoh, R.H. and Ashkenas, I.L., "Handling Quality Criterion for Heading Control," *Journal of Aircraft*, Vol. 14, ~~Feb. 1977~~ 2, pp. ~~143~~ 142-150.

[2] Ashkenas, I.L., Hoh, R.H., and Craig, S.J., "Recommended Revisions to Selected Portions of MIL-F-8785B(ASG) and Background Data," AFFDL-TR-73-76, Aug. 1973.

[3] Chalk, C.R., DiFranco, D., Lebacqz, J.V., and Neal, T.P., "Revisions to MIL-F-8785B(ASG) proposed by Cornell Aeronautical Laboratory under Contract No. F33615-71-C-1254," AFFDL-TR-72-41, April 1973.

00017

C80-011

Reply by Authors to C. R. Chalk

Roger H. Hoh* and Irving L. Ashkenas†
Systems Technology, Inc., Hawthorne, Calif.

In the Calspan critique, an example configuration is used to question the viability of the μ parameter. This reply is presented in rebuttal and also to illustrate proper application of the parameter.

As discussed in the paper, the numerators of the aileron-rudder cross-feed cannot be generalized. To overcome this, a two point curve fit of the rudder time response was suggested as a way to define μ in the frequency range of interest. Such lower order equivalent system (LOES) approximations to complex higher order systems (HOS) have shown considerable promise as a method of specifying handling qualities criteria (see Refs. 1 and 2). In fact, the referenced works have shown that an HOS which cannot be fit by an LOES form is predictably unsatisfactory to the human pilot.

Coming back to μ, it must be understood that the corresponding first order LOES form does *not* represent an assumption that *all* airplanes respond in this manner. Rather it implies that:

1) Responses which can be adequately fit by the LOES form can be classified as acceptable or unacceptable according to values of μ and $N_{\delta_w}/L_{\delta_w}$ or $\delta_r(3)$.

2) Responses which are higher order in nature and cannot be fit by the first order LOES form in the frequency range of control will be unacceptable to the pilot.

The example cited in Mr. Chalk's critique (an early version of the YF-16) turns out to be quite interesting in terms of lending additional insight into application of the μ parameter. In this case the required rudder time-history to coordinate is extremely complicated and not well matched by the lower-order equivalent system defined by μ, as shown in Fig. 3 of the technical comment. The extreme mismatch between the HOS and LOES precludes even a cursory evaluation of μ. However, the complex nature of the required rudder to coordinate a step aileron input would in itself lead one to suspect very poor pilot opinion of heading control. While Mr. Chalk was not able to produce a pilot rating for this configuration, it is well known that the original version of the YF-16 was an extremely poor airplane (pilot ratings of 9 and 10). These results, rather than invalidating μ, actually provide the first available data which tend to support the assumed extension of the results of Refs. 1 and 2, i.e., that complex higher order responses are unacceptable to the pilot.

Finally, Mr. Chalk states that "crossfeed of aileron stick through a shaping network is an idealization that does not properly represent the task the pilot must accomplish." We could easily take issue with this statement by noting the lack of positive evidence experimentally quantifying the pilot's auxiliary rudder activity, e.g., in describing function or other terms. However, what seems most significant is the characteristic shape and magnitude of the rudder required to coordinate stick inputs, no matter how the pilot manages to generate it. If the magnitude is large, or the shape complex, he will not like it. In fact, he may not use the rudders at all, in which case the complex shaping or large magnitude required will show up as a lack of consonance between bank angle and yaw rate.

As noted by Mr. Chalk, some of the ψ_β values used in the paper were in error. This issue was covered in correspondence between Calspan and STI nearly two years ago. However, correcting these points has no effect, considering all the available evidence, on our basic conclusion that the $\Delta\beta_{max}$ parameter is overly conservative—a conclusion in line with Mr. Chalk's (Ref. 3) "thought that the $\Delta\beta/k$ requirement is in need of revision...." Rather than "revise" it, we devised a different and perhaps a better set of correlating parameters; whether better or not would be an issue more worthy of consideration than worrying about inadvertent data handling errors which do not affect the final result. In connection with such errors, as noted in Ref. 4, the tendency to miscalculate ψ_β is perhaps an inherent deficiency in the parameter. Witness the discrepancies for the values of ψ_β listed in Table 1 for the same flight conditions which appear in two separate Calspan authored reports.

No attempt has been made to determine which of these represents the "correct" values of ψ_β.

Table 1 Discrepancies in calculated values of ψ_β

	ψ_β, deg	
Configuration	Ref. 5	Ref. 6
2P2	−295	−254
3N0	−189	−224
3P2	−344	−290
4P2	−332	−208
12A2	−207	−159
12A1	−210	−167
12P2	−356	−291

Received June 18, 1979.

Index category: Handling Qualities, Stability and Control.

*Senior Research Engineer.
†Vice President and Technical Director. Fellow AIAA.

References

[1] Hodgkinson, J., LaManna, W.J., and Heyde, J.L., "Handling Qualities of Aircraft with Stability and Control Augmentation Systems—A Fundamental Approach," *Aeronautical Journal*, Vol. 80, Feb. 1976.

[2] Hodgkinson, J., "Equivalent Systems Approach for Flying Qualities Specification," presented at SAE Aerospace Control and