The Definition of Short-Period Flying Qualities Characteristics via Equivalent Systems

David E. Bischoff*
Naval Air Development Center, Warminster, Pennsylvania

The high-order transfer functions representing the longitudinal dynamics of augmented aircraft were matched in the frequency domain with first- over second-order short-period models. Matching of the pitch rate to pilot input transfer function is shown to yield excellent time history matches. However, the resulting numerator term, L_α, takes on very large unrealistic values. The effect of simultaneously matching pitch rate and normal acceleration to restrict the variation of L_α is demonstrated. A control anticipation parameter is recommended to provide correlation between the high- and low-order system descriptions and the specification requirements.

Nomenclature

CAP = control anticipation parameter
CAP′ = attenuated CAP
F = stick force, lb
g = gravitational acceleration
K = system gain
L_α = lift curve slope, ft/s^2
M = mismatch parameter
n_z = normal acceleration, g
s = Laplace operator
t = time, s
T_{θ_2} = pitch rate numerator time constant, s
V = true airspeed, ft/s
α = angle of attack, rad
δ = cockpit control deflection, rad
δ_e = control surface deflection, rad
ζ = damping ratio
θ = pitch angle, rad
τ = time delay, s
ω = frequency, rad/s

Subscripts and Superscript

e = equivalent system
HOS = high-order system
LOS = low-order system
nd = nondimensional
sp = short period
ss = steady state
$(\dot{\ })$ = time derivative

Transfer Function Root Representation

$[\zeta, \omega]$ = imaginary root with damping ζ, frequency ω
(σ) = real root of value σ

Introduction

THE Military Specification for Flying Qualities of Piloted Airplanes, MIL-F-8785B,[1] was developed largely from flight tests of classically responding unaugmented aircraft. Its quantitative requirements are generally expressed in terms of modal approximations which can be described mathematically by first- or second-order linear expressions. Advancements in aerodynamics and complicated control system augmentation schemes, prevalent in modern aircraft designs, have resulted in responses which are described by high-order functions.

In an attempt to utilize the existing requirements in analyzing advanced aircraft/control system configurations, the concept of equivalent systems has been introduced.[2] A frequency domain equivalent system matching technique has been developed by Hodgkinson et al.[2] and applied to the high-order representations of numerous generic and experimental configurations.[3] The approach used was to approximate the high-order pitch rate to pilot control input transfer function of the subject aircraft with a classical low-order transfer function describing the specification requirements, augmented with a time delay. This equivalent time delay approximates the phase lag introduced by the high-frequency control system components. Within the scope of the initial investigations, it was determined that the linear modal requirements of MIL-F-8785B, when augmented by a requirement on time delay, are appropriate for specifying the handling qualities of the advanced high-order configurations of tomorrow's airplanes.[4] This approach has been incorporated in the latest revision to the MIL-SPEC, MIL-F-8785C,[5] which states: "The contractor shall define equivalent classical systems which have responses most closely matching those of the actual aircraft." The parameters defining the resulting equivalent system (frequency, damping ratio, etc.) rather than any modes of the high-order system, are to be compared with the specification requirements. However, no guidance is given as to how the contractor shall proceed with his equivalent system definition nor with what criteria its adequacy will be judged by the procuring agency.

This paper discusses some of the lessons learned from an equivalent systems investigation conducted by the Naval Air Development Center as part of its effort in identifying flying qualities criteria for manned aircraft. The purpose of this effort was to gain an understanding of the frequency matching technique and its usefulness in determining longitudinal short-period flying qualities characteristics. Not only are the effects of various control system components investigated but matching techniques are extended to additional aircraft parameters as well.

Method

The equivalent system approach to determining flying qualities characteristics utilizes frequency response matching techniques to determine low-order transfer functions which approximate the response of high-order systems. The technique[2] implements a direct Rosenbrock digital search algorithm to match the high-order system to an assumed low-order equivalent system. This match is obtained by minimizing the weighted sum of the squares of the differences in magnitude and phase angle between the low- and high-order systems at a number of discrete frequencies. The mismatch between the two systems is quantitatively expressed

Presented as Paper 81-1775 at the AIAA Guidance and Control Conference, Albuquerque, N. Mex., Aug. 19-21, 1981; submitted Sept. 15, 1981; revision received July 14, 1982.

*Aerospace Engineer.

as

$$M=(20/n)\sum_{\omega_1}^{\omega_n}\left[(G_{\text{HOS}}-G_{\text{LOS}})^2+0.01745(\Phi_{\text{HOS}}-\Phi_{\text{LOS}})^2\right] \tag{1}$$

where G equals the gain in decibels and Φ is the phase in degrees. Summing the mismatch function over a number of frequencies, evenly spaced on a logarithmic scale, is similar to minimizing the integral of the square of the error on a Bode plot. As a result, it is possible to qualitatively compare the matches with the quantitative mismatch results. The frequency range over which the minimization was conducted was chosen to span the pilot's short-period frequency range of interest (nominally 0.1-10 rad/s).

The frequency response matching procedure enables the analyst to match any high-order system with any desired low-order system format. Restricting the scope of this analysis to the determination of short-period requirements establishes the desired form of the low-order system to be matched. The parameters describing the MIL-F-8785B short-period requirements $[\zeta_{sp},\omega_{sp},n/\alpha=V(1/T_{\theta_2})/g]$ are obtainable from the classical transfer function relating pitch rate response to control deflection:

$$\frac{\dot\theta(s)}{\delta(s)}=\frac{K_{\dot\theta}(s+1/T_{\theta_2})}{s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2} \tag{2}$$

Equation (2) is limited in its ability to match high-order system phase responses in that they may exceed the -90-deg phase asymptote of the classical system. Therefore the equivalent system procedure augments Eq. (2) through the addition of a time delay. This delay introduces phase lag without altering the gain characteristics. The resulting equivalent system may be expressed as

$$\frac{\dot\theta(s)}{\delta(s)}=\frac{K_{\dot\theta}(s+1/T_{\theta_2})e^{-\tau_\theta s}}{s^2+2\zeta_e\omega_e s+\omega_e^2} \tag{3}$$

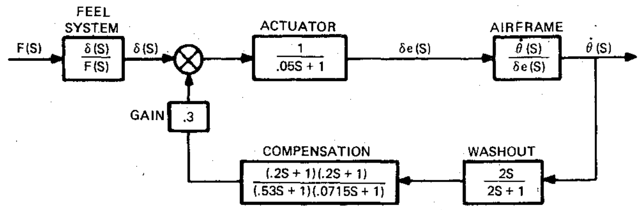
The equivalent system match was always performed with the system gain, damping ratio, frequency and time delay allowed to vary. The numerator root, $L_\alpha \doteq 1/T_{\theta_2}$, was initially held fixed at the aircraft value. If a good match (mismatch less than approximately 10) was not thus obtained, L_α was also allowed to vary.

In order to perform the matching procedure, the high-order system's frequency response characteristics must be known. The unaugmented aircraft's transfer functions were first computed from stability and control derivatives. Control system components were then added to obtain the high-order transfer function describing each aircraft, control system, flight condition combination to be analyzed.

Results and Discussion

Longitudinal short-period equivalent system models were determined for the A-6, A-7, F-14, F-18, and S-3 aircraft in both power approach and cruise flight conditions.[6] The results presented in this paper are for a representative configuration resulting from that tactical aircraft analysis. The approach taken is to begin with an augmented aircraft description, adding various control system components to illustrate their effect on the equivalent system methodology. The control system configurations investigated can be separated into three general categories—low, medium, and high frequency. Examples of each of these categories and how they are treated in the equivalent system analysis are demonstrated.

The example aircraft analyzed in this paper is a highly maneuverable, land and carrier based, supersonic fighter at 15,000 ft. A block diagram of the aircraft and control system is presented in Fig. 1.



.5M/15,000 FT:

$$\frac{\dot\theta(S)}{\delta e(S)}=\frac{-7.027(0)(.0103)(.773)}{[.043,\ .082]\ [.40,\ 2.17]}$$

$$\frac{\dot\theta(S)}{\delta(S)}=\frac{5.26(0)(.0103)(.773)(.5)(1.887)(13.986)}{[.016,\ .081]\ [.61,\ 2.78]\ (.418)(1.34)\ [.97,\ 17.04]}$$

$$\frac{\dot\theta(S)}{F(S)}=\frac{26.825(39.815)}{(3.366)\ [.46,\ 39.75]}\cdot\frac{\dot\theta(S)}{\delta(S)}$$

Fig. 1 Example aircraft description.

Low-Frequency Components

Low-frequency components are defined as those whose break frequency occurs below the minimum short-period frequency range of interest (i.e., $\omega<0.1$ rad/s). The effect of low-frequency components can be demonstrated by including only the aircraft's phugoid (0.082 rad/s) and short-period modes (2.17 rad/s) in the high-order system and determining the augmented aircraft's equivalent system.

Choosing the frequency range of interest from 0.1 to 10 rad/s, the following equivalent system is obtained:

$$\frac{\dot\theta}{\delta}=\frac{7.721\,(0.773)}{[0.47,\,2.08]}\qquad M=89$$

The equivalent short-period damping ratio and frequency are somewhat different from that of the aircraft (0.40 and 2.17, respectively) and the mismatch is relatively high. This occurs since the phugoid roots are contributing both gain and phase components in the frequency matching range. The search algorithm is therefore attempting to not only match the dominant short-period mode, but to also minimize the mismatch at the low frequencies, without the benefit of additional parameters in the low-order system.

In order to reduce the mismatch and improve the system's modal characteristics, it is necessary to modify the frequency match range to exclude the phugoid's contributions. By reducing the frequency range to 0.3-10 rad/s, the following equivalent system is obtained:

$$\frac{\dot\theta}{\delta}=\frac{7.1\,(0.773)}{[0.41,\,2.16]}\qquad M=0.5$$

Not only is the mismatch improved, but the equivalent system accurately duplicates the aircraft's short-period mode. This was expected since modifying the frequency range left primarily short-period contributions in the high-order frequency response.

This technique of modifying the frequency match range works well for cases in which the short period and phugoid roots are not closely coupled. However, in some cases, such as power approach, the phugoid and short-period roots are not as well separated and less adequate results were obtained. In those cases, phase and gain characteristics of the low-frequency (phugoid) roots overlapped those of the higher-(short-period) frequency roots. Modifying the frequency range to eliminate the low-frequency contributions would also eliminate some of the short-period information, making it difficult to obtain an accurate short-period representation. In order to obtain the best match, it was necessary in such cases to remove the low-frequency roots from the high-order representation prior to performing the equivalent system match.

High-Frequency Contributions

High-frequency contributions may arise from numerous sources, including actuators, feel systems, and compensation networks. Their effect is very short lived. The magnitude of their response is not generally noticeable to the pilot. However, they may affect the phase characteristics, resulting in an apparent lag or delay in the desired aircraft response. The effect of high-frequency components can be demonstrated by adding the control surface actuator to the unaugmented aircraft's dynamics. When this is done for the example aircraft, the following equivalent system results:

$$\frac{\dot{\theta}}{\delta}=\frac{6.83(0.773)e^{-0.046}}{[0.40, 2.13]} \qquad M=1.4$$

The identified short-period frequency and damping ratio are very close to that of the high-order system. The high-frequency characteristics have been modeled by a time delay of 0.046 s which closely approximates the elevator actuator's time constant. The time delay parameter was included in all matches to account for the phase characteristics introduced in the short-period frequency range by high-frequency control system components.

Midfrequency Contributions

The midfrequency contributions (those roots which lie in the short-period frequency range) may be divided into two categories. The first consisting of those which are introduced through feedback control loops and the second consisting of feedforward control components. In the first case, both numerator and denominator roots are introduced into the high-order system. Each denominator root is accompanied by a numerator root of similar magnitude. These two roots effectively cancel each other, resulting in only local modifications of the frequency response. In the second case, it is possible to introduce a single numerator or denominator root, as in the case of a prefilter, which does not have a corresponding root in the denominator or numerator, respectively. Therefore the frequency response is affected over the entire short-period frequency range. The differences in the equivalent system technique for each of these cases will be demonstrated. Analysis of the example aircraft's response to control stick deflections, with the stability augmentation system (SAS) included, will provide examples of the first case. The response to stick force inputs, again with SAS included, will demonstrate the second.

Feedback Contributions

The effect of feedback terms on the determination of the equivalent systems can be analyzed from the expression for $\dot{\theta}/\delta$ of Fig. 1. The resulting low-order systems are

$$\frac{\dot{\theta}}{\delta}=\frac{0.277(0.773)e^{-0.052}}{[0.76, 2.36]} \qquad M=10.9$$

for L_α fixed, and

$$\frac{\dot{\theta}}{\delta}=\frac{0.245(1.334)e^{-0.039}}{[0.58, 2.74]} \qquad M=0.6$$

for L_α free. Freeing L_α improves the match, as evidenced by the mismatch parameter. However, both low-order systems have acceptable mismatch parameters and time history comparisons, as shown in Fig. 2.

The impact of freeing L_α may be examined from the asymptotes presented in Fig. 3. The root at L_α influences only a small portion of the frequency range, while the numerator root influencing the high-order system near the short-period frequency arises from the control system. Fixing L_α at the aircraft value forces the equivalent system to identify airframe characteristics as modified by the control system. Allowing L_α to be free in the matching process effectively allows the airframe characteristic to be approximated by a denominator root. The control system root nearest the short-period frequency is then identified as the approximate numerator term rather than the airframe characteristic.

Feedforward Contributions

The effect of single feedforward components on the determination of equivalent systems can be analyzed from the response to stick force inputs. The equivalent system obtained with L_α fixed for the $\dot{\theta}/F$ equation of Fig. 1 is

$$\frac{\dot{\theta}}{F}=\frac{0.0278(0.773)e^{-0.171}}{[0.64, 1.74]} \qquad M=71$$

and, with L_α free,

$$\frac{\dot{\theta}}{F}=\frac{0.0172(4.48)e^{-0.122}}{[0.40, 2.88]} \qquad M=11$$

Fixing L_α, the feedback control roots are again approximately cancelled; however, the feel system root is now compounding the determination of the short-period frequency. Whereas the classical pitch rate to control transfer function gain falls off at 20 dB/decade at frequencies greater than the short-period frequency, the stick feel system root adds an additional 20 dB/decade in the range of short-period frequencies. With L_α fixed, ω_{sp} is reduced until an approximation to the gain characteristics is obtained. A large time delay is then necessary to match the high-order phase characteristics. Freeing L_α brings the short-period frequency more in line with that of the high-order system and the results of the control stick input analysis. However, both time delay and L_α have now assumed large values. In the example case, L_α has increased by nearly 600%. This condition has been referred to

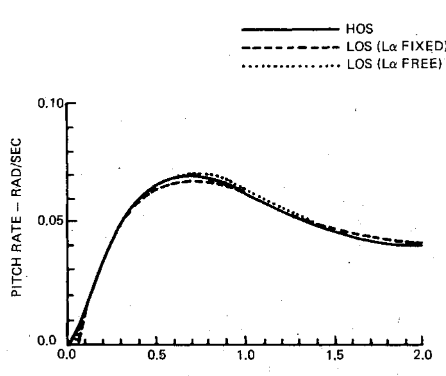


Fig. 2 Time history comparisons.

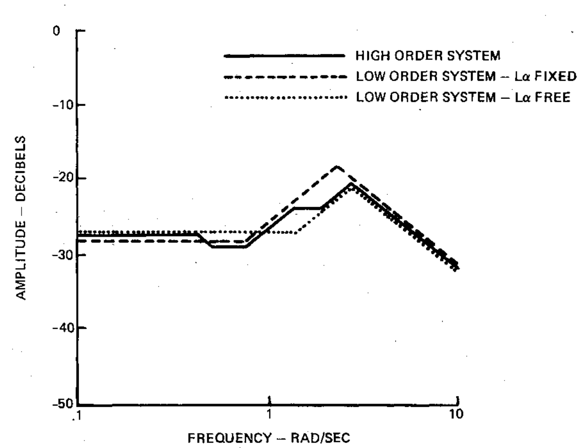


Fig. 3 Asymptotic approximations.

in the literature[3] as "galloping L_α." In this instance it is not possible to correlate the low-order system components with any of those of the high-order system. It is only known that the best overall match is obtained. Variation in L_α of such magnitude leads to questioning the validity of freeing L_α in the equivalent system search, especially when L_α is the parameter by which the short-period frequency is correlated with specification requirements $[n/\alpha = V(1/T_{\theta_2})/g = V(L_\alpha)/g]$. The lift curve slope of an aircraft is generally both easily and accurately obtained. While it may be possible to modify the effective L_α slightly by manipulation of the control system, variations of the magnitude obtained (200-600%) are inconceivable. Therefore it is desirable to determine if alternative methods of conducting the equivalent system search could alleviate this problem.

Normal Acceleration Equivalent Systems Analysis

A second parameter of interest in longitudinal short-period analysis is the aircraft's normal acceleration. It is related to the aircraft pitch response by a lag parameter which can be shown to be approximately equal to the pitch rate numerator term. Therefore the normal acceleration response can be approximated by

$$\frac{n_z(s)}{\delta(s)} = \frac{K_{n_z} e^{-\tau_{n_z} s}}{s^2 + 2\zeta_e \omega_e s + \omega_e^2} \tag{4}$$

The denominator of this response is the same as that of the pitch rate response. It may be useful in determining which of the pitch rate equivalent system models (L_α fixed or L_α free) yields the appropriate response. The high-order normal acceleration to stick force transfer function for the example case may be expressed as

$$\frac{n_z}{F} = \frac{35.86(0.5)(1.887)(13.986)}{[0.61, 2.78](0.418)(1.34)(3.366)}$$

(plus phugoid and high-frequency roots), where normal acceleration is measured at the center of rotation. The center of rotation was chosen since at that point, the normal acceleration numerator roots are the farthest removed from the short-period roots. At other locations, such as the center of gravity or pilot's position, the pitch acceleration component arising from the force on the vertical tail introduces two nonminimum phase roots in the short-period frequency range. In such cases, a zero- over second-order transfer function only approximates the total response and does not contribute to an understanding of the proper low-order model. Determining the equivalent normal acceleration model for the example aircraft yields

$$\frac{n_z}{F} = \frac{0.356e^{-0.151}}{[0.63, 1.75]} \qquad M = 68$$

This low-order system is almost identical to that obtained for the pitch rate response with L_α fixed. Based on the similarity of these responses it appears feasible to introduce the normal acceleration as a method of constraining L_α when matching the pitch rate response. Therefore pitch rate and n_z were matched simultaneously while constraining the equivalent denominators to be identical. The following equivalent systems resulted:

$$\frac{\dot{\theta}}{F} = \frac{0.0264(0.978)e^{-0.165}}{[0.60, 1.81]} \qquad M = 60$$

$$\frac{n_z}{F} = \frac{0.364e^{-0.151}}{[0.60, 1.81]} \qquad M = 71$$

The effect of simultaneously matching the two transfer functions is to greatly reduce the variation in L_α (25% increase as opposed to nearly 600% increase with $\dot{\theta}$ alone). Comparing the mismatch parameters, this case is seen to be a compromise on the previous best matches—the pitch rate mismatch is considerably higher than that for pitch rate alone (with L_α free) and the normal acceleration mismatch is higher than that for n_z alone. However the variation in L_α has been restricted to a reasonable value with respect to the known aircraft value.

To this point, the determination of acceptable equivalent systems has been primarily related to the mismatch parameter. The conclusions of Ref. 7 indicated that pilots were insensitive to mismatches as high as 200. Such results would seem to make all of the matches achieved thus far acceptable, including those with galloping L_α. It is therefore necessary to investigate additional methods of interpreting the equivalent system.

Comparison with MIL-SPEC Requirements

MIL-F-8785C places requirements on damping ratio, undamped natural frequency, and time delay for equivalent longitudinal short-period responses. The requirements are applied directly to ζ_{sp} and τ, while ω_{sp} is correlated as $\omega_{sp}^2/n/\alpha$ as summarized in Table 1.

The results for the example aircraft's response to stick force inputs are compared against these requirements in Fig. 4.

The identified damping ratio and time delay are levels 1 and 2, respectively. However, discrepancies occur in the definition of frequency levels. Depending on the method utilized in determining the low-order system, the frequency characteristics range from level 1 to worse than level 3. In order to understand these apparent discrepancies, the time history responses were further analyzed in terms of their control anticipation parameters.

Control Anticipation Parameter Development

The control anticipation parameter (CAP), developed by Bihrle,[8] is defined as the ratio of initial pitch acceleration to steady-state normal acceleration in response to a step longitudinal control input. Bihrle further showed that for the classical short-period approximation, CAP is related to the aircraft's short-period frequency:

$$\mathrm{CAP} = \frac{\ddot{\theta}(t=0^+)}{n_{z_{ss}}} = \frac{\omega_{sp}^2}{n/\alpha} \tag{5}$$

Additionally, pilot opinion data on short-period frequency responses can be correlated by lines of constant CAP, as outlined in Table 1. DiFranco[9] showed that when actuators or feel system dynamics are included in the system description, the initial pitch acceleration is identically zero building to a maximum at some time greater than $t = 0^+$. This maximum

Table 1 MIL-F-8785C short-period requirements

	Time delay		Damping ratio		$\omega_{sp}^2/n/\alpha$	
Level	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	0.0	0.1	0.35	1.3	0.28	3.6
2	0.1	0.2	0.25	2.0	0.16	10.0
3	0.2	0.25	0.15	...	0.16	...

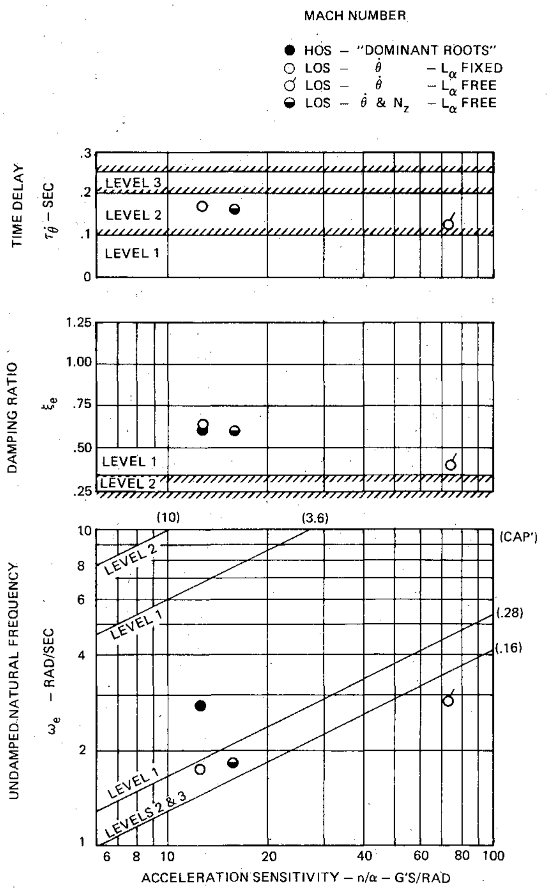


Fig. 4 Comparison with MIL-F-8785C requirements.

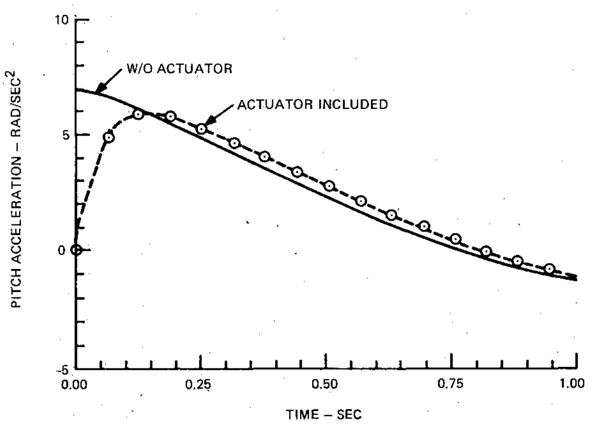


Fig. 5 Control system attenuation effects.

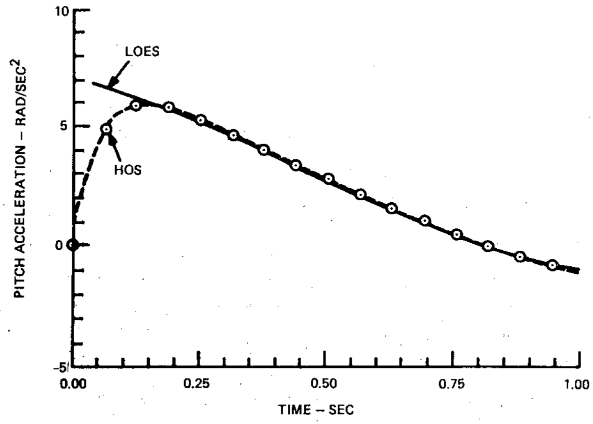


Fig. 6 Equivalent system time history comparison.

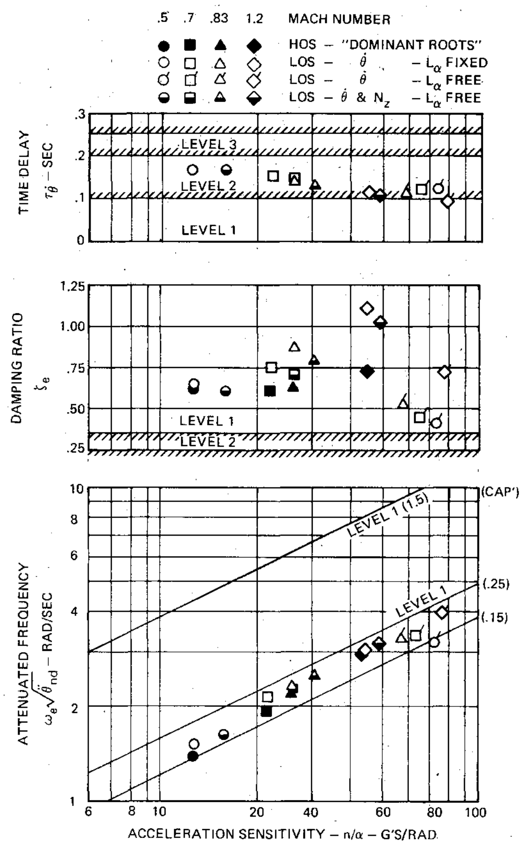


Fig. 7 F-14 short-period characteristics.

pitch acceleration is attenuated from that obtained from pure short-period approximation, as shown in Fig. 5.

DiFranco introduced an attenuated control anticipation parameter (CAP′) as the ratio of this maximum pitch acceleration to steady-state normal acceleration and showed its relationship to CAP as

$$CAP' = \frac{\ddot{\theta}_{\max}}{n_{z_{ss}}} = \frac{\omega_{sp}^2}{n/\alpha}\ddot{\theta}_{nd} \tag{6}$$

where $\ddot{\theta}_{nd}$ is a nondimensional pitch acceleration. It is the ratio of the maximum pitch acceleration, including the attenuation affects of actuator or feel system dynamics, to the maximum acceleration excluding those components. Utilizing CAP′ as the correlating parameter, DiFranco showed that pilot opinion ratings could be correlated as

$$\text{Level 1} = 0.25 < CAP' < 1.5$$

$$\text{Level 2} = 0.15 < CAP' < 0.25$$

For the aircraft example under consideration, CAP′ of the high-order system is determined to be equal to 0.150, which lies on the level 2 boundary and not in the middle of the level 1 region, as would be predicted by determining CAP from the high-order system dominant oscillatory root (Fig. 4). The use of CAP′ indicates the problems associated with directly analyzing the short-period component of the high-order system responses with respect to MIL-F-8785C requirements. The "dominant root" frequency can be plotted as a function of n/α. However, the resulting control anticipation parameter does not represent the actual response in terms of $\dot{\theta}$ and n_z experienced in the airplane.

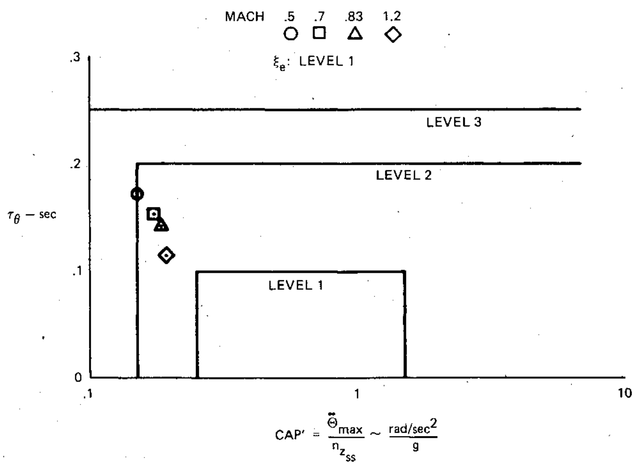


Fig. 8 Alternate criteria format.

Correlation of Equivalent Systems via CAP′

The control anticipation parameter is easily determined for the low-order systems since both CAP and the equivalent system were defined from the same short-period approximation. CAP values for the three equivalent systems are 0.238, 0.112, and 0.204 for the $\dot{\theta}(L_\alpha$ fixed), $\dot{\theta}(L_\alpha$ free), and simultaneous $\dot{\theta}$ and n_z matches, respectively. These values differ from CAP′ for the high-order system by as much as 40-60%.

Comparing Figs. 5 and 6, the high-order pitch response is found to be attenuated from the equivalent response in much the same way the total response is attenuated from the short-period response. Following DiFranco's development, it becomes possible to define an attenuated equivalent CAP, CAP_e' as

$$CAP_e' = \frac{\omega_e^2}{n/\alpha}\frac{\ddot{\theta}_{max_{HOS}}}{\ddot{\theta}_{max_{LOS}}} = \frac{\omega_e^2}{n/\alpha}\frac{\ddot{\theta}_{max_{HOS}}}{K\dot{\theta}} \tag{7}$$

The Neal-Smith[10] and LAHOS[11] data were analyzed via this technique.[12] Correlation with the high-order system was shown to be greatly improved for CAP_e' as opposed to CAP_e.

The resulting CAP_e' values for the example equivalent systems are 0.182, 0.139, and 0.162, respectively. The complete results thus obtained for the F-14 airplane at 15,000 ft are presented in Fig. 7. Excellent agreement exists between the high- and each of the low-order systems for all conditions investigated. In addition, the discrepancies noted in defining the frequency level for each of the system descriptions associated with the presentation in Fig. 4 no longer exist. Each of the identified systems now falls in the level 2 category.

The last result leads to the observation that the method of obtaining the equivalent system is inconsequential in the specification of longitudinal short-period flying qualities requirements. Each method investigated provided similar measures of the physical response of the aircraft to step control inputs, as evidenced by the resulting attenuated control anticipation parameters. Freeing L_α in the search routine does not provide any specific information about the nature of the system. The large increase in L_α serves only as an indicator of a potential problem with the configuration being analyzed: a condition which may also be inferred from the relatively high mismatch obtained with L_α fixed and with simultaneous pitch rate and normal acceleration matching.

The attenuated control anticipation parameter may be obtained from either the high- or low-order equivalent system. The low-order equivalent system (LOES) has the advantage of providing additional parameters of interest in specifying the performance of the system in classical terms; namely, the equivalent time delay and damping ratio. These parameters can generally be related to pilot comments regarding airplane response to control inputs and overshoot characteristics.

This analysis then suggests that for those configurations in which the equivalent damping ratio is satisfactory (i.e., $0.35<\zeta_e<1.3$, a condition which is generally achievable in highly augmented aircraft) that dynamic longitudinal flying qualities be examined via CAP′ and τ, as shown in Fig. 8. This approach has the advantage of providing the parameters of primary interest to the pilot, in performing a maneuver, in a single presentation.

Summary

The results of applying an equivalent system methodology to typical Navy tactical aircraft have been demonstrated. Simultaneously matching pitch rate and normal acceleration at the center of rotation restricts the amount of variation in L_α obtained when matching pitch rate alone.

The short-period frequency vs acceleration sensitivity relationships obtained from either of these methods do not directly correlate with the response parameters describing the high-order system. It is necessary to consider the attenuation affects of the control system. The high- and low-order systems can be correlated via an attenuated control anticipation parameter which can be related to pilot opinion ratings. This attenuated control anticipation parameter should be further investigated as the basis for longitudinal handling quality requirements.

The demonstrated examples indicate that the approach of utilizing equivalent systems to identify MIL-SPEC short-period frequency requirements is basically sound. However, the resulting parameters must be properly interpreted in their representation of the high-order system.

References

[1] "Military Specification, Flying Qualities of Piloted Airplanes," MIL-F-8785B, Aug. 7, 1969.

[2] 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, No. 782, Feb. 1976, pp. 75-81.

[3] Johnston, K.A. and Hodgkinson, J., "Flying Qualities Analysis of an In-Flight Simulation of High Order Control System Effects on Fighter Aircraft Approach and Landing," McDonnell Aircraft Company, St. Louis, Mo., Report MDC A5596, Dec. 22, 1978.

[4] A Harrah, R.C., Hodgkinson, J., and LaManna, W.J., "Are Today's Specifications Appropriate for Tomorrow's Airplanes?" AGARD Flight Mechanics Symposium on Stability and Control, Ottawa, Canada, Sept. 1978.

[5] "Military Specification, Flying Qualities of Piloted Airplanes," MIL-F-8785C, Nov. 5, 1980.

[6] Bischoff, D.E., "Development of Longitudinal Equivalent System Models for Selected U.S. Navy Tactical Aircraft," NADC Report 81069-60, Aug. 1, 1981.

[7] Hodgkinson, J. and Johnston, K.A., "Initial Results of an In-Flight Simulation of Augmented Dynamics in Fighter Approach and Landing," AIAA Paper 79-1783, Aug. 1979.

[8] Bihrle, W. Jr., "A Handling Qualities Theory for Precise Flight Path Control," AFFDL-TR-65-198, June 1966.

[9] DiFranco, D. A., "Flight Investigation of Longitudinal Short Period Frequency Requirements and PIO Tendencies," AFFDL-TR-66-163, June 1967.

[10] Neal, T.P. and Smith, R.E., "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes," AFFDL-TR-70-74, Dec. 1970.

[11] Smith, R.E., "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities," AFFDL-TR-78-122, April 1978.

[12] Bischoff, D.E., "The Control Anticipation Parameter for Augmented Aircraft," NADC Report 81186-60, May 15, 1981.