THE APPLICATION OF EQUIVALENT SYSTEMS TO MIL-F-8785B

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ABSTRACT

Equivalent systems allow analysis of augmented dynamics by building upon experience with unaugmented dynamics. Therefore, MIL-F-8785 requirements for augmented dynamics should likewise build upon existing requirements which describe essentially unagumented systems. This is simply achieved by retaining existing modal requirements, and adding a requirement restricting the equivalent delay caused by augmentation lags in both longitudinal and lateral dynamics.

Introduction

New data on the flying qualities of augmented aircraft have been analyzed using equivalent systems by a number of researchers. This is based on the generally held supposition that parameters such as equivalent frequency and damping adequately define the pilot's perception of the general response shape. This supposition has been upheld by preliminary data from a recent in-flight simulation, Reference 2. Available data also indicate that flying qualities problems due to frequency and damping deficiencies are indeed adequately predicted by these equivalent parameters and the requirements of MIL-F-8785B, Reference 1. This is covered more thoroughly in a forthcoming AGARD paper (Reference 3).

It is important to note that the great majority of our experience in analyzing augmented dynamics is with the equivalent system technique. A large number of studies have turned to order reduction as the first step in analysis of high order responses. References 4 through 15 are representative. These references discuss not only longitudinal short period flying qualities but also phugoid dynamics, approach power compensator effects, direct side force modes, direct lift blended dynamics, and lateral-directional fighter responses. Applications to V/STOL hover and transition effects are presently being carried out also. By using equivalents, flying qualities problems are parameterized for analysis and the insight gained with unaugmented aircraft is readily brought to bear on augmented dynamics. Ideally therefore, augmentation effects as identified by equivalents should be treated by adding to the existing requirements on unaugmented dynamics. This paper discusses and arrives at a recommendation on what this addition should be.

Longitudinal Control System Lag Effects

Augmentation systems deliberately modify response transfer function denominator effects to obtain improved frequency and damping, for example. They also add actuators and sensors, prefilters, compensatory networks and structural mode filters. Digital systems add computation delays together with other components which produce additional lag (Reference 16). In-flight simulations (Reference 4, 5, and 17) have all shown that this lag can dominate the pilot's opinion. Equivalent systems to date have modeled this lag in two ways. First equivalent $1/T_{\theta_2}$ in the pitch dynamics can be allowed to seek artifically high values in the matching process and interpreted as higher equivalent n_{z_α}. This effectively treats mid-frequency lags. Second, a delay term is generally added. This approximates high frequency lags.

MIL-F-8785B(ASG) in 3.5.3 limits control system phase lag to a maximum value at the aircraft natural frequency. This effectively allows larger delays if the aircraft response is already slow, or assumes that a given delay becomes more objectionable as the aircraft frequency increases. This was based on DiFranco's in-flight data (Reference 4). This latter concept is tested in Figure 1, using the somewhat later data of Neal and Smith (Reference 5). Only configurations possessing good (i.e. Level 1) damping and frequency are shown, thereby attempting to remove their effects from the experiments. The expected trend of worsened rating with jointly increased delay and frequency does not appear.

Figure 2 is another attempted correlation using Neal and Smith's data, in this instance between delay alone and pilot rating. Little correlation is apparent. However, the data do not preclude the expected trend of worsened rating with increased delay, within the scatter apparently caused by changes in the other experimental variables. This suggests a technique which accounts for simultaneous variation of a number of experimental parameters. The technique chosen (and described in Reference 7) was stepwise multiple linear regression. This was used to generate pilot rating prediction formulae such as that of Figure 3. Note that now a reasonably accurate predictor of rating is obtained, and that the delay term produces a linear, additive rating degradation of one Cooper-Harper point for roughly each .05 seconds of delay (18.5 rating points per second).

Recently, in-flight data on augmented longitudinal dynamics in the landing approach (Smith, Reference 17) have become available. Figure 4 uses the equation developed from Neal and Smith's data to predict Smith's flare maneuver pilot ratings. Neal and Smith generally used a parallel feel system and Smith used a series system. However in spite of this the pilot ratings for the flare maneuver are broadly consistent with the up-and-away results. The equivalent delay due to the series feel system adds approximately one rating point to each estimate. This is indicated in Figure 4 by shifting the correlation line rather than each data point. (Ringland and Johnston noted this ability to predict a landing approach rating with the up-and-away equation in Reference 13. Since this was for a single configuration only, they deemed it to be fortuitous.) However, in contrast to Neal and Smith, Smith deliberately isolated lag effects. The results are shown in Figure 5. There is an apparent threshold in pilot's sensitivity to delay of about .07 seconds for good configurations, with a subsequent slope which is now around 35 rating points per second, double the value of the up-and-away prediction equation. This slope is also greater than the value of 25 obtained in a separate regression of the landing approach data. For already unsatisfactory configurations, the eventual degradation is similar but the threshold is larger. The data for these unsatisfactory configurations tend to contradict the current requirement on phase lag since rating degradation with delay is greater for the slowest configuration than for the fastest.

Therefore the two most recent in-flight experiments on high order systems are not consistent with the earlier data which formed the basis for the MIL-F-8785 lag requirement. A possible explanation for this is that high stick force levels adopted in the earlier study precluded the aggressive maneuvering and demanding task which are necessary to discriminate configurations with control lags. It is further possible that these stick forces were chosen to ameliorate the response abruptness following an initial delay.

Lateral-Directional Equivalent Systems

Since the great majority of basic research on augmented aircraft flying qualities has been on longitudinal dynamics, lateral-directional problems must at present be tackled partly by extrapolation. Reference 18 summarizes experience with obtaining lateral-directional equivalents reliably from given high order dynamics. Briefly, when lateral-directional coupling is present, the dutch roll is best identified from the sideslip to directional control response and the roll mode from the roll rate (or bank angle) to lateral control response. This is somewhat different from the methodology which has evolved for the longitudinal dynamics, in which coupling is ignored, if this is necessary to obtain an accurate parameterization of the primary pitch response.

Preliminary data are becoming available from a joint USN/USAF/MCAIR equivalent systems simulation using the USAF/CALSPAN variable stability NT-33 (Reference 2). The flying qualities effects of lag in lateral dynamics for the landing approach were examined. The data suggest that the MIL-F-8785B(ASG) requirements on roll mode are adequate, but a new requirement is needed for lags. (Note that no data were available as background to the current 3.5.3 requirements on lateral and directional lags.) Indications are again that a good configuration has a smaller threshold of rating degradation due to delay than a worse one. These thresholds are larger than for longitudinal dynamics. The subsequent sensitivity however is then roughly twice the value for longitudinal landing approach dynamics. These data have just become available as this is being written however, and in any case will be no substitute for the in-depth research which is needed on lateral-directional control system effects.

Recommendations for MIL-F-8785B Requirements

Longitudinal requirements - These should be stated in terms of equivalent systems. The matching process should retain $1/T_{\theta_2}$ at the basic value if possible; if not, the current $\omega_{n_{sp}}$ vs n/α requirement should be considered as a pitch criterion by calculating an equivalant n_{z_α} using the equivalent $1/T_{\theta_2}$ and the true speed. This is described and substantiated in References 3 and 7.

The particular effects of equivalent delay, the main topic of this paper, are adequately covered by substituting a Level 1 maximum of .1 seconds and a Level 2 maximum of .2 seconds for the current phase lag requirements of 3.5.3.

Lateral requirements - These also can be stated in terms of equivalent systems, as described and substantiated in Reference 18.

Delay effects can tentatively be covered by substituting a Level 1 maximum of .2 seconds and a Level 2 maximum of .25 seconds for the current requirements of 3.5.3.

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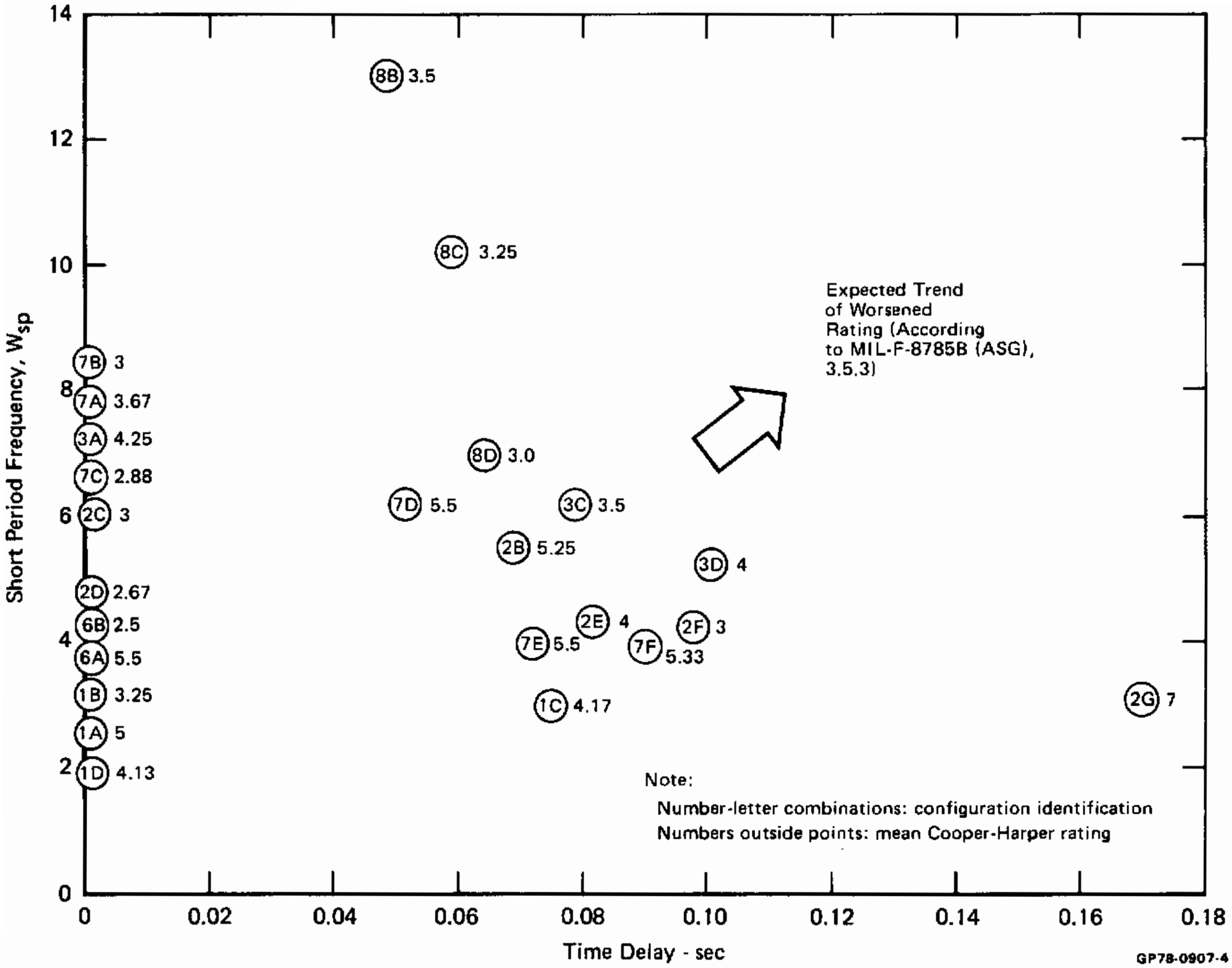


FIGURE 1
ATTEMPTED CORRELATION BETWEEN SHORT PERIOD FREQUENCY, TIME DELAY AND PILOT RATING
Neal and Smith's Data, MCAIR Equivalents, Level 1 Damping and Frequency

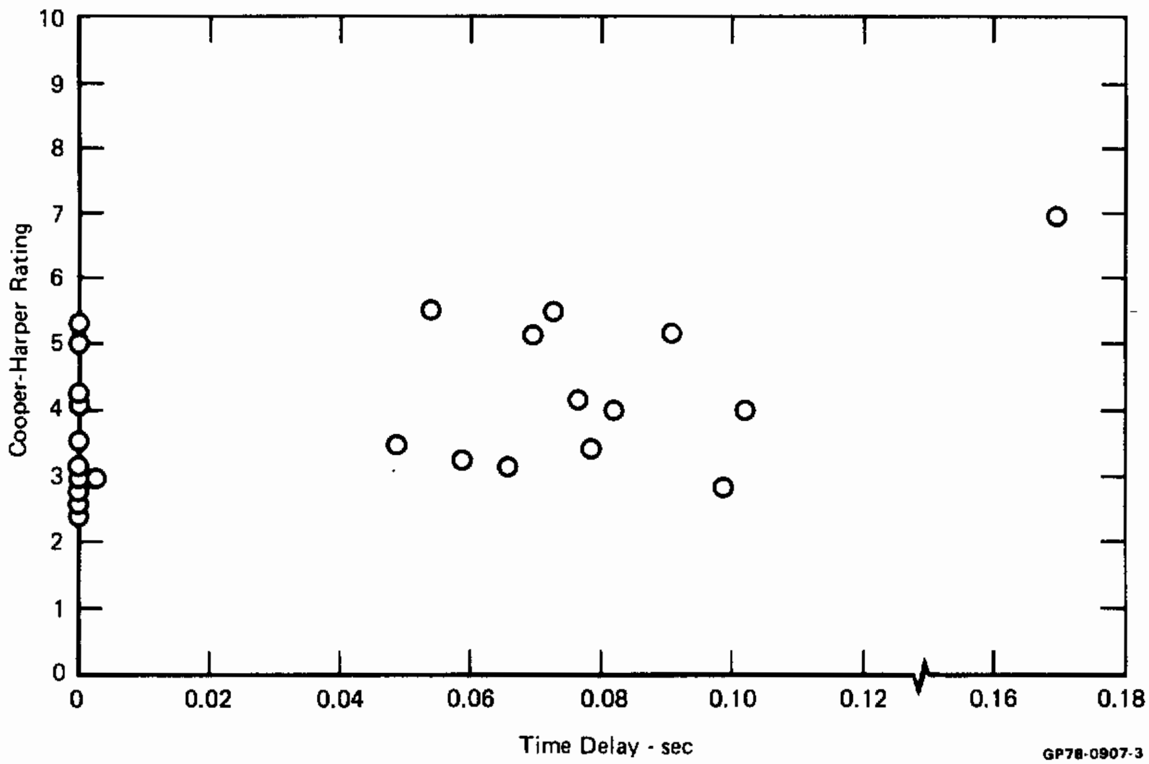
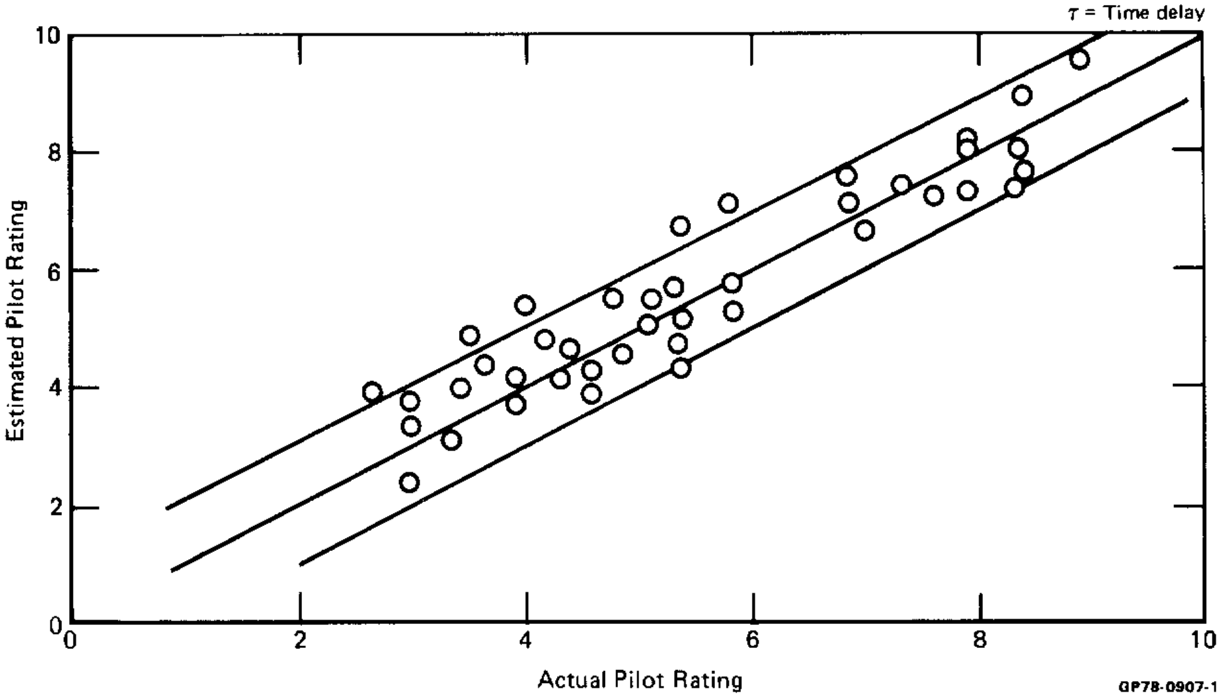


FIGURE 2
ATTEMPED CORRELATION OF TIME DELAY WITH PILOT OPINION RATING
Neal and Smith's Data, MCAIR Equivalents,
Level 1 Damping and Frequency

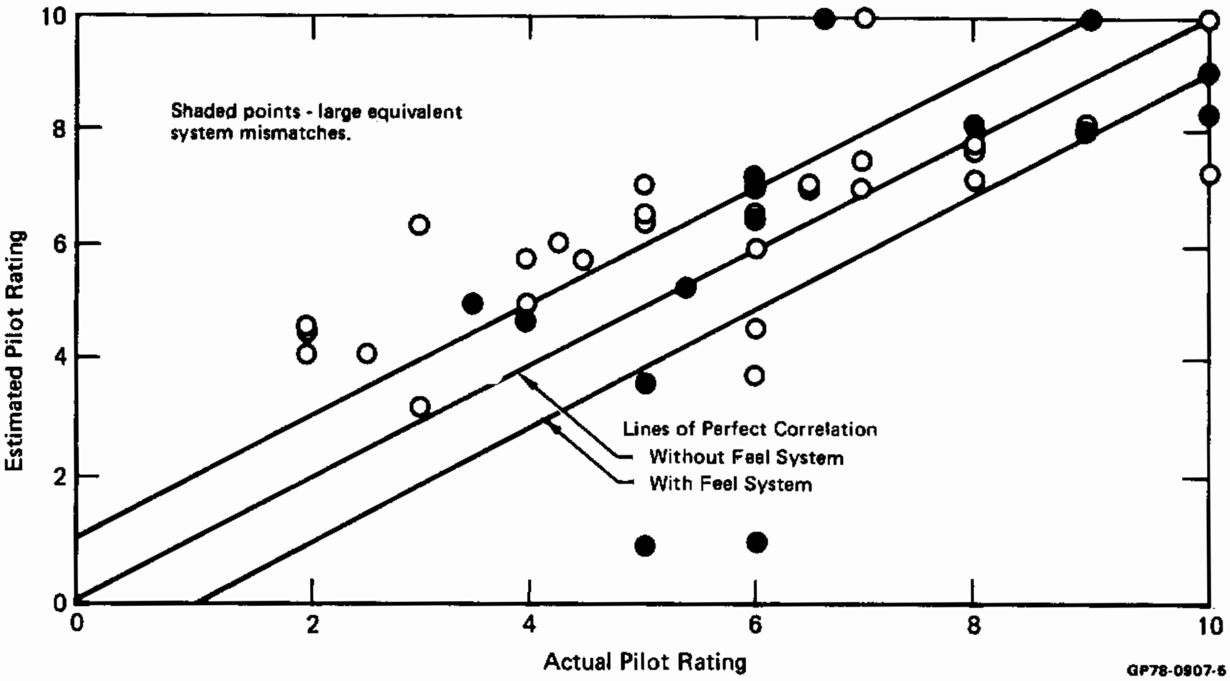


Note:

Equation developed by regression from Neal and Smith's data, ref. 5

Pilot rating = $5.16 + 18.50\,\tau + 0.56\,(L_{\alpha_e}/2\zeta_e\omega_e) - 0.61\,(\zeta_e\omega_e) + 0.02\,(\omega_e^2)$
(Cooper-Harper)

FIGURE 3
EXAMPLE OF PILOT RATING PREDICTION USING EQUIVALENT SYSTEM PARAMETERS



Note:

Equation developed by regression from Neal and Smith's data, ref. 5
Data from Smith, ref. 17

Pilot rating = $5.16 + 18.5\,\tau + 0.56\,(L_\alpha/2\zeta_e\omega_e) - 0.61\,(\zeta_e\omega_e) + 0.02\,(\omega_e^2)$
(Cooper-Harper)

FIGURE 4
PREDICTION OF PILOT RATING FOR LANDING APPROACH USING EQUATION DEVELOPED FROM UP-AND-AWAY SIMULATION

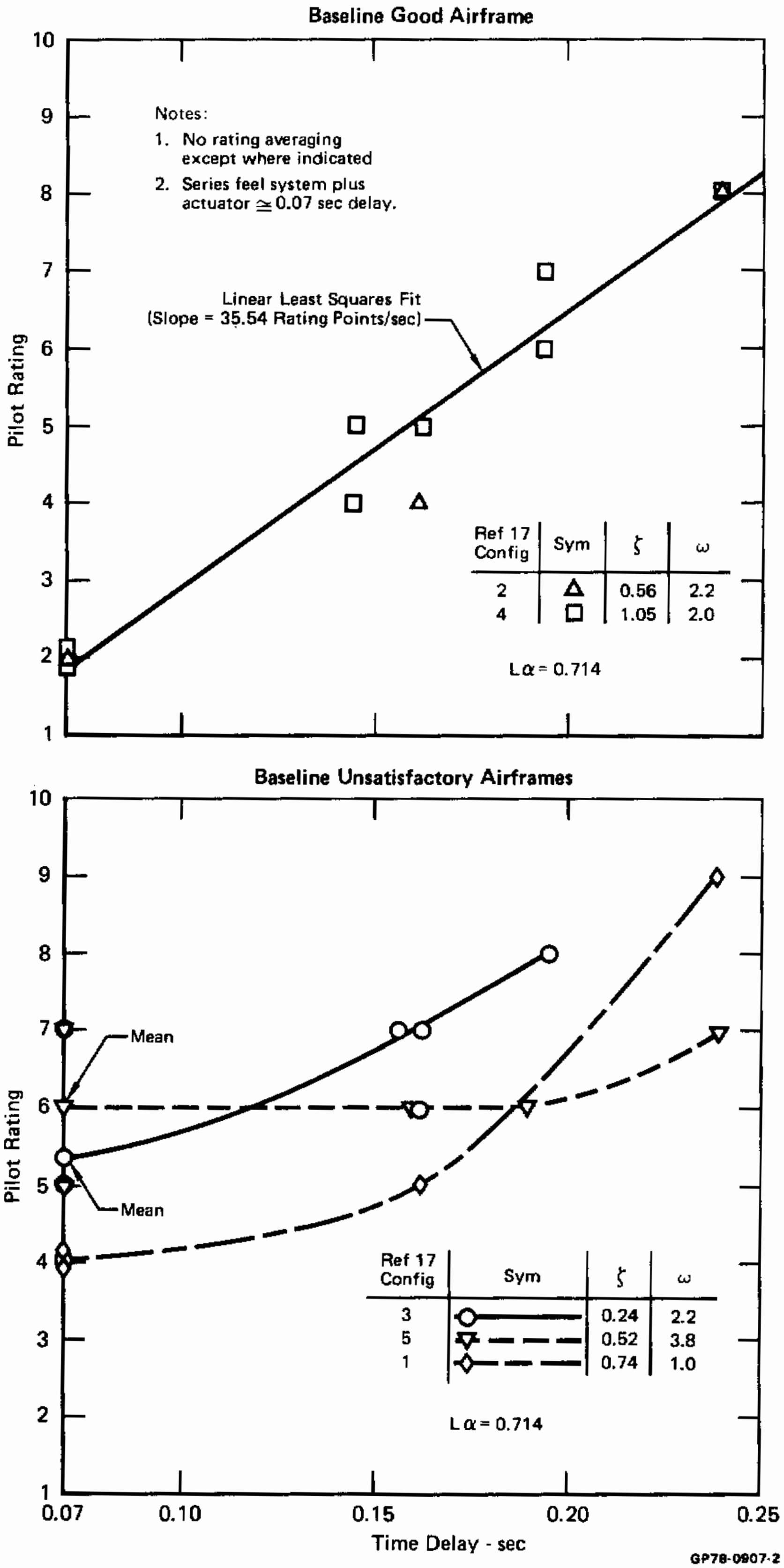


FIGURE 5
DEGRADATION OF PILOT OPINION RATING DUE TO EQUIVALENT TIME DELAY
LAHOS Data, MCAIR Equivalent Systems

- Dwight Schaeffer, Boeing - Why independently specify limits on equivalent transport lag?

  The effect of equivalent delays on flying qualities is additive and adequately covered by independent limits for the various levels of flying qualities. This is the simplest way to update the current specification to ensure that recent data, showing the very deleterious effects of lag, are considered by both manufacturers and procuring activities.
- Dwight Schaeffer, Boeing - Why specify short period pitch response as a classical first order over second order?

  The first function of equivalents is to parameterize the response for analysis and insight, using a low order model. This low order model approximately quantifies those bandwidth, damping and delay characteristics which all designers actually or intuitively use. It so happens that the majority of augmented responses can be reduced to equivalents of quasi-classical form. This enables the equivalents to perform a valuable second function, namely of relating augmented dynamics to our wide background with unaugmented dynamics.
- John Schuler, Boeing - Why match in the frequency domain?

  The original intent was to mechanize hand matching, which is easiest with Bode plots. We have found that good Bode matches produce good step time response matches, and suspect that the reverse is not always true. However, any method with reasonable precision and discrimination of high frequency (or initial response) characteristics should be a useful aid to a competent engineer.
- John Stigal, NASA JSFC - Does time lag imply a sample rate?

  Equivalent time delay approximates all the high frequency phase lags from all sources, continuous or discrete. The sample rate contributes lag, so there is an indirect correspondence.
- Chick Chalk, CALSPAN - Some time ago we investigated equivalent systems for V/STOL dynamics, and saw a need for a mismatch function. This was unacceptable to Ron Anderson, who then proposed Paper Pilot as an alternative.
- Bob Woodcock, AFFDL/FGC - Even if a good match to an equivalent classical system is necessary for level 1, more difficulty would be expected in fitting level 2 and 3 responses to an equivalent model. What do you think the prospect is?

  As you point out, "unmatchable" configurations have flying qualities problems.

However, the equivalent parameters for the level 2 and 3 cases we have analyzed are consistent with MIL-F-8785, while accepting the high mismatch. Analysis of data from the recent simulation on equivalent systems should answer some of our questions on mismatch.

- Chick Chalk, CALSPAN - What do you think of the boundaries for equivalent systems proposed by Mayhew for MIL-F-8785?

  [See AFFDL-FGC - Working Paper, Proposals for Revising MIL-F-8785B, Vol. I, February 1978, pages 86 and 87].

  They are too complex and unwieldy. Equivalent systems instead should be used to demonstrate compliance with all the current modal requirements, and an updated requirement on lags or delays should be added. This is consistent with available data and is an expeditious way of screening out:

  (1) misleading 'dominant root' models

  (2) configurations with large delays, which are unsafe.