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Summary and Interpretation of Recent Longitudinal Flying Qualities Results

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Recently obtained longitudinal flying qualities data[1–4] are interpreted and analyzed with respect to their similarities, differences, relevance to particular tasks, and agreement or disagreement with other task-related results. In general, the recent data fall into line with and extend other, older results. Certain of these extensions re-emphasize the importance of spatial as well as time response characteristics for good terminal-area flying qualities.

Introduction

It is the author's purpose to try to consolidate the results of four recent papers[1–4] with respect to each other and to the literature in general. This consolidation and explanation role is a kind of self-imposed one that we at Systems Technology, Inc. (STI) have assumed over the years. Some of the resulting "explanations" may not stand the test of time, especially if the data involved are fragmentary or diverse, but they at least provide some timely food for thought pertinent to the next round of experiments. Naturally such thought-provoking analysis involves a number of us at STI; the authors would like therefore to acknowledge the particular contributions of S. Craig and R. Heffley to the present efforts.

To begin with, we will spend considerable time analyzing the A'Harrah, Lockenour data and the results thereof will tie in fairly directly with Bihrle's results. The Miller and Eney data are somewhat separate, but the former are shown to be consistent with the A'Harrah, Lockenour data; the latter are related to other similar results.

A'Harrah, Lockenour's Results

The setup utilized in the Ref. 1 investigation was rather unique in that independent variations in $1/T_{\theta_2}$, n_{z_α}, and CAP† were simulated by 1) assuming blended (variable) control of wing and fuselage incidence to provide an effective direct (wing) lift control (DLC) component geared to the elevator/stick motions and 2) using a large range in approach air speeds while maintaining constant (displayed) closing speed. With respect to the first artifice, we should note additionally that the simulation setup did not provide the pilot with angle-of-attack information on either the wing or the fuselage. Therefore it appears that he could have had no real appreciation for how the lift was being generated except, of course, his awareness of *attitude* changes and the corresponding changes in flight path (discussed more fully below). His main point of reference being an attitude change, he would probably be more interested in lift due to attitude than in lift due to an "artificial" α which he could not see. We expected, therefore, that n_{z_α} as "artificially" changed by the elevator/wing gearing was not, in fact, a parameter of importance to the pilot. The data tabulated in Fig. 1 reinforce this notion. Here the parameter $(n_{z_\alpha})_1$ is the gearing-modified parameter used in the Ref. 1 correlations, while n_{z_α} is the conventionally defined parameter of Eq. (1). The tabulation lists all the "raw" (pilot rating) data available to the author‡ for $1/T_{\theta_2} = 0.8$ and 0.2 for $\omega_{sp}^2 = 0.8$ and 1.6. The trends shown in this compact sample are exemplary of those exhibited by the complete set of data. We can see that the values of $(n_{z_\alpha})_1$ are not really indicative of any piloting problem or interaction. That is, wide variations in this parameter can occur without changing the pilot rating, provided the normally defined values of n_{z_α} and $1/T_{\theta_2}$ are held constant. Conversely, for constant values of $(n_{z_\alpha})_1$ and $1/T_{\theta_2}$, pilot ratings can vary between 2 and 10 as n_{z_α} changes (e.g., for $1/T_{\theta_2} = 0.8$). The conclusion we came to from these considerations was that the use of $(n_{z_\alpha})_1$ to correlate the Ref. 1 data was probably not valid. We therefore concentrated our examination of the data to considerations of the normally computed value of n_{z_α} given by

$$n_{z_\alpha} \equiv (U_o/g)(1/T_{\theta_2}) \tag{1}$$

The second interesting simulated effect noted previously was the maintenance of constant closure speed for a wide range in effective airspeeds as measured, for example, by the value of n_{z_α} defined previously. Closed-loop analyses (e.g., Ref. 8) and detailed observation of piloting behavior[11] indicate

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† Bihrle's "Control Anticipation Parameter"; see discussion under Altitude Control Comparisons.

‡ Obtained from notes on a briefing given by the Ref. 1 authors, Jan. 17, 1969. Some of these raw data points are not apparent in the correlations presented in Ref. 1.

ω_{sp}^2	$1/T_{\theta_2}$	$M_{\delta_e}/\omega_{sp}^2$	U_o/g	n_{z_α}	$(n_{z_\alpha})_1$	PR	CAP
1.6	0.8	0.10	10	8	4	2*	0.2
			5	4		2.5	0.4
			2.5	2		6*	0.8
			1.25	1		10*	1.6
		0.05	20	16		7	0.1
			10	8		3	0.2
			5	4		2*	0.4
		0.025	40	32		10*	0.05
			20	16		4*	0.1
			10	8		4	0.2
			5	4		5	0.4
		0.10	5	4	2	2.5	0.4
					8	2.5	
					16	2.5	
0.8					2	2.8	0.2
					4	2.8	
					8	2.8	
1.6	0.2	0.40	10	2	4	3	0.8
		0.40	2.5	0.5		5*	3.2
		0.20	20	4		6	0.4
		0.20	5	1		1*	1.6
		0.10	20	4		4	0.4
		0.10	5	1		1*	1.6
		0.40	5	1	16	1*	1.6
					4	1	
1.6					1	1	
0.8					1	4	0.8
0.8		0.20	10	2	2	1*	0.4
		0.10	20	4	4	1*	0.2
		0.05	40	8	8	6*	1

*Minimum (near-optimum) PR for given n_{z_α}, $1/T_{\theta_2}$.

Fig. 1 Selected A'Harrah, Lockenour[1] basic data.

that, for elevator control of flight path, the pilot closes an inner attitude loop and wipes out altitude errors by attitude commands through the effective transfer function§

$$\frac{h}{\theta_c} = \frac{-Z_\alpha}{s(s + 1/T_{\theta_2})} = \frac{-Z_\alpha T_{\theta_2}}{s(T_{\theta_2}s + 1)} = \frac{U_o}{s(T_{\theta_2}s + 1)} \quad (2)$$

That is, assuming that the pilot has tight control of attitude, then his altitude response characteristics will be measured by the aforementioned transfer function form. This says that if U_o is made artificially high relative to the closing speed, the pilot may consider that the airplane is overly sensitive to changes in attitude; conversely, if U_o is artificially low, the configuration could be deemed too sluggish. Another way of viewing this effect is to consider that when the airspeed is much faster than the closing speed, the actual flight path angle through the air is, in fact, considerably smaller than the geometric path angle relative to the ground. This means that smaller changes in attitude than geometrically consistent with the pilot's view of the aiming point will be required to achieve control. In effect, the pilot's actions in aiming the airplane are scaled down so he can no longer "point" the airplane at the intended touchdown point in the way that he is used to. We suspected, based on such considerations, that the effects of the various simulated airspeeds would probably show up in the conventional, gain-type, sluggish and sensitive regions which would reflect corresponding pilot rating degradations. In fact, this turned out to be the case as shown by Fig. 2.

Here we have plotted only the raw data (available to us) corresponding to conditions for best opinion at given values of n_{z_α} and $1/T_{\theta_2}$ (e.g., the asterisked points of Fig. 1); and we see the familiar saddle-shaped variation of gain with pilot rating. That is, as gain is progressively reduced, pilot ratings improve up to a point, and then degrade beyond that point as gain is further reduced; the two extremes are usually characterized as being either too sluggish when the gain is too low or too sensitive when the gain is too high. Notice that for the larger values of $1/T_{\theta_2}$ ($1/T_{\theta_2} > 0.2$), the optimum situation is represented by a *constant airspeed* somewhere between $U_o/g = 5$ to 10. For "large" $1/T_{\theta_2}$ (i.e., $T_{\theta_2}s \ll 1$) Eq. (2) shows that the dynamics are approximately rate-ordering, i.e., $h/\theta_c \doteq U_o/s$. The data imply, therefore, that the principal gain of interest to the pilot for rate-ordering conditions is the rate-ordering gain, U_o. On the other hand, when $1/T_{\theta_2}$ gets quite low, the dynamics are approximately acceleration-ordering, i.e., $h/\theta_c \doteq -Z_\alpha/s^2$, so would expect the optimum gain to now be the acceleration gain, $-Z_\alpha$ or n_{z_α} Figure 2. shows that this is indeed the case for the two low $1/T_{\theta_2}$ conditions.

§ The expressions used here and in Ref. 1 are appropriate for short-period approximations to the equations of motion and for $Z_{\delta_e} \doteq 0$.

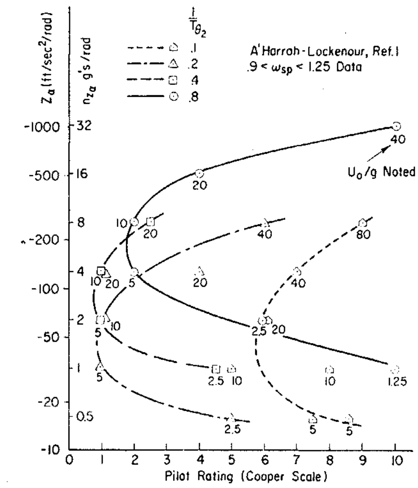


Fig. 2 Ref. 1 effects of altitude gain on "best" pilot rating.

These observations are quite consistent with those made relative to other similar dynamic situations; for example, first-order roll control systems[9] or hovering attitude control.[10] Furthermore, the correlations contained in the cited references show that the optimum gains are consistent with a constant value of the pilot's gain at the crossover frequency, and with a constant displacement response for a given time interval and unit step control input. We might also note that, although not shown, the optimum values of $M_{\delta_e}/\omega_{sp}^2$ as a function of $1/T_{\theta_2}$, as obtained from the complete Ref. 1. data, are consistent with other work and with the general observations made previous.

Altitude Control Comparisons with Other Data (Including Bihrle's)

For comparison with other data we selected the A'Harrah, Lockenour altitude control results for $U_o/g = 5$ because: 1) for this condition, closing speed equals airspeed, thus avoiding speed mismatch questions raised earlier; 2) the aforementioned equality also prevailed in the conditions tested by Bihrle,[2] Barnes,[5] and others in connection with the simulation and flight testing of longitudinal requirements for

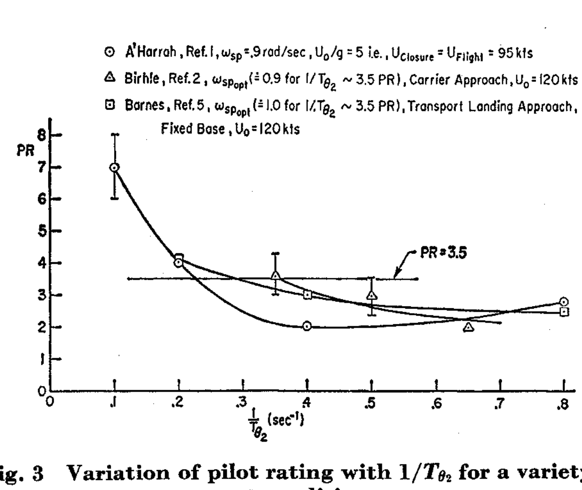


Fig. 3 Variation of pilot rating with $1/T_{\theta_2}$ for a variety of test conditions.

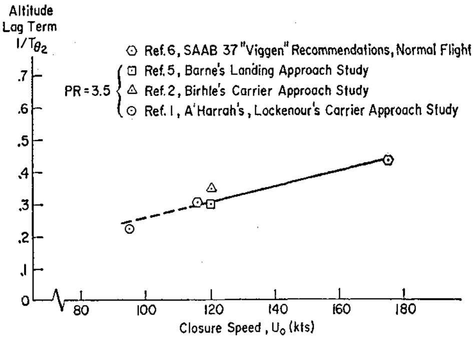


Fig. 4 Relation between minimum satisfactory $1/T_{\theta_2}$ and closure speed.

approach conditions; and 3) the $U_o/g = 5$ results generally yield near-optimum pilot ratings (e.g., Fig. 2).

In Fig. 3 we have accordingly plotted the comparable data from both the Bihrle and A'Harrah, Lockenour moving-base simulations, together with the Barnes data obtained in a fixed-base simulation. The A'Harrah, Lockenour data plotted are only those where the short-period frequency was around 0.90 rad/sec. The reason for confining the data to this latter frequency was that the additional available data at $\omega_{sp} \doteq 1.3$ rad/sec seemed much less consistent, and also because the 0.90 rad/sec frequency is close to the values found optimum for the other two investigations. Although the data are far from definitive, they do show a trend for the minimum acceptable ($PR = 3.5$) value of $1/T_{\theta_2}$ to vary directly with closing speed. That is, as closing speed increases and the available time to execute maneuvers decreases, the value of $1/T_{\theta_2}$, which is a measure of the speed of response in altitude (e.g., Ref. 8), has to increase, and vice versa. This trend therefore suggests the notion of requiring completion of a given correction or maneuver within a given *distance*. There have been similar suggestions concerning, for example, the distance required to recover from a gust-induced roll upset.[9] In fact, the old roll-power requirement for a given $pb/2U_o$ translates directly into requirements based on the preservation of spatial rather than time responses. The preservation of spatial relationships is also suggested in Ref. 19 and is the explanation given for the Ref. 6 speed-dependent, minimum $1/T_{\theta_2}$ data (not shown in detail) trends observed in ground-based simulation studies directed at establishing SAAB "Viggen" requirements. These latter data, combined with the PR = 3.5 boundary values of $1/T_{\theta_2}$ taken from Fig. 3, are shown in Fig. 4. The obvious conclusion is that the data are all consistent and point to a dependence of the minimum required value of $1/T_{\theta_2}$ with airspeed, in this case taken to mean closing speed.

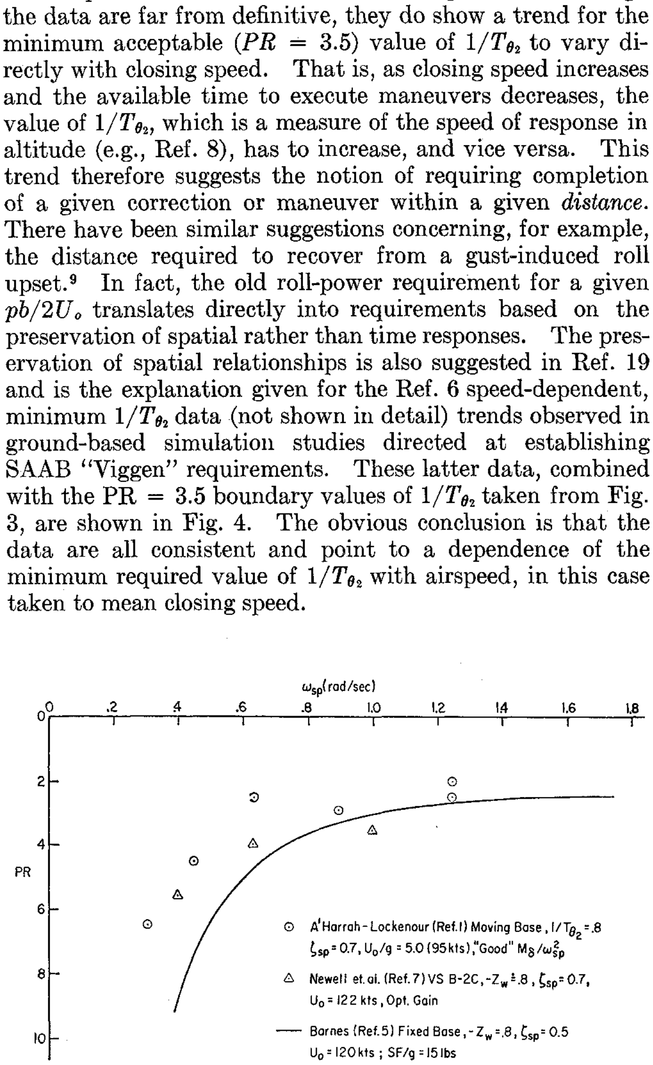


Fig. 5 Comparison of selected data for $1/T_{\theta_2} \doteq -Z_w \doteq 0.8$.

Even if it is eventually more thoroughly verified for the data region shown in Fig. 4, it is doubtful that the trend depicted will extend unbroken to much lower speeds. One reason for this expectation is the observation that there is probably some maximum maneuver *time* that a pilot will tolerate. For example, the degradation of pilot rating for estimated outer-loop crossover frequencies less than about 0.3 to 0.4 rad/sec (noted in Ref. 9) has also been found to apply to spot hovering conditions.[21] Since closing speed or distance considerations cannot be important for such conditions, this may represent some maximum allowable response time. Incidentally, such numbers are compatible with Newell's[16] observation that a maximum allowable time for a response outcome to be manifested is 3 to 4 sec.

We should also recognize that some of the data points on Fig. 4 were obtained in the absence of random gustiness (Bihrle simulated a carrier air wake disturbance); some of the data (e.g., A'Harrah, Lockenour) represent very idealized control dynamics, i.e., constant airspeed, short-period control with stick only. The conditions under which the SAAB data were taken are unknown at present. The point is that the trends of Fig. 4, while fairly convincing, need better qualification as to the conditions for which they apply.

Attitude Control Comparisons

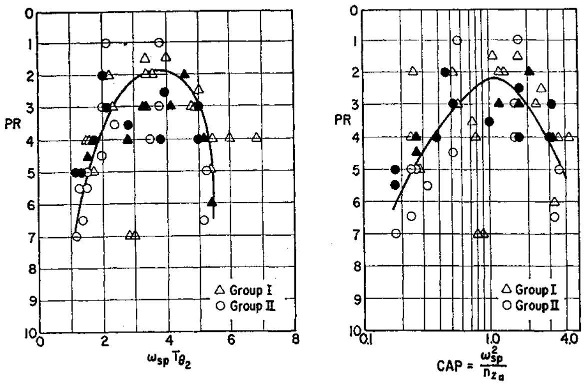
Turning now to aspects of the data concerned specifically with attitude control, we will confine our attention to those situations in which the value of $1/T_{\theta_2}$ is high enough so that altitude control is no particular problem. With this in mind, let us look at the A'Harrah, Lockenour data for $1/T_{\theta_2} = 0.8$. For this particular value, there was a greater range of short-period frequencies investigated than for any other value of $1/T_{\theta_2}$. Accordingly, we have plotted these data in Fig. 5, which also shows some other data for $1/T_{\theta_2}$ (or equivalent) $\doteq 0.8$. The obvious conclusion is that all the data are fairly consistent as to general shape and level. These results, taken with others at various values of good $1/T_{\theta_2}$ (e.g., Refs. 5, 8, 12, 20), show that there is a frequency region for a given value of $1/T_{\theta_2}$ which results in the best opinion. In other words, as the value of $1/T_{\theta_2}$ changes, so does the corresponding best short-period frequency, and the range of $\omega_{sp}:1/T_{\theta_2}$ for the acceptable region is roughly constant independent of the value of $1/T_{\theta_2}$. Constant values of acceptable $\omega_{sp}T_{\theta_2}$ are simply, but not universally, related to constant values of Bihrle's CAP parameter, given by $\omega_{sp}^2/n_{z_\alpha}$, which is also indicative of good pilot opinion regions.[11] Without trying to decide which of these forms is really the better for correlation purposes, we can make some distinctions as follows:

1) The good values of $\omega_{sp}T_{\theta_2}$ (and ζ_{sp}) are those which yield a rate-ordering, K/s-like attitude control characteristic near the expected crossover region (e.g., Ref. 13). Therefore, the pilot can control these without adapting lead equalization. Furthermore, since the primary quantitative effect of motion is to permit easier pilot lead-generation[14] which, however, is not required for K/s-like dynamics, we would expect the pilot's adaptation, ratings, performance, etc. to be essentially the same whether in a fixed or moving simulator.

2) The value of $\omega_{sp}T_{\theta_2}$ (for a given ζ_{sp}) is a measure of the pitch overshoot characteristics. For good values of $\omega_{sp}T_{\theta_2}$ between about 1 and 4 to 5, and reasonably good short-period damping, ζ_{sp} approximately equal to or greater than 0.5, the overshoot ratio is fairly constant, varying between about 1 and 2.

3) Too much pitch rate overshoot is accompanied by a hangup or hesitation in the attitude response to an elevator step which is not only a function of the $\omega_{sp}T_{\theta_2}$ value, but also of the short-period damping. Too little rate overshoot implies a sluggish dynamic response in attitude.

4) The effect of variations in the CAP parameter, which had its origins in the notion that the pilot perceived and responded to properly scaled pitch acceleration motions,



Group	n_{z_α}(g/rad)	U_0(ft/sec)	$1/T_{\theta_2}$(sec^{-1})	ζ_{sp}	ω_{sp}(rad/sec)
I	16.5	411	1.29	0.7	2 to 8
II	56.2	685	2.65	0.7	3 to 14

Fig. 6 Pilot rating for two pilots for two data groups (from Ref. 12): filled points are those for pilot-selected *SF/g*.

i.e., CAP $= \ddot{\theta}_o/\Delta n_{ss}$, would seem to be fairly dependent on the presence of valid motion effects. Accordingly, we might suspect difficulties in correlating mixed batches of fixed, moving-base and in-flight simulation on the basis of such a parameter.

Just to put all this in better perspective, a recent in-flight simulation study by Hall[12] compares a number of correlation parameters, including the two we have just been talking about, and Fig. 6 presents samples of his results pertinent to the foregoing discussion. We can see that, for these data at least, either parameter seems to offer equivalent correlation, as also concluded by Hall. However, we should note that the $\omega_{sp}T_{\theta_2}$ correlations indicate sharper, more distinct cutoffs (especially for large values) than do the $\omega_{sp}^2/n_{z_\alpha}$ correlations (recognize that the scales are linear and logarithmic, respectively). That is, the pilot appears more sensitive to the former than to the latter parameter. Based on the Fig. 6 correlations, Hall established the following limits for acceptable (PR $\leq$ 3.5) ratings:

$$0.43 \leq \omega_{sp}^2/n_{z_\alpha} \leq 2.4 \qquad 2.2 \leq \omega_{sp}T_{\theta_2} \leq 5.3$$

Note that from Fig. 5, the lower limit for acceptable $\omega_{sp}T_\theta$ could be shifted to about 1.0 (for $1/T_{\theta_2} \doteq 0.8$).

Miller's and Eney's Data

Considering now Miller's[3] results, it appears that they (as well as the other data cited by Miller) are consistent with the previous data, although they do not agree with the CAP boundary suggested by Bihrle's results. Incidentally, Bihrle's data plotted for constant values of $1/T_{\theta_2}$, as in Fig. 5, show a much narrower optimum region than other investigators, i.e., his data also would not agree with the $\omega_{sp}T_{\theta_2}$ boundary values cited previously. These discrepancies could possibly be due to the constant, non-optimized control-feel characteristics used in Bihrle's studies, as suggested by Miller.

Relative to Eney's data, there are two main points of interest, one being the conditions prone to pilot-induced oscillations (PIO); the other being the fact that one of the points has better than the Ref. 11 required ζ_{sp}, yet does not have an acceptable rating. On the first point, we have taken the trouble to replot some of the data and to show that they compare well with other low speed, PIO-prone data in Fig. 7. The parameter against which these data are plotted is $\zeta\omega - 1/2T_{\theta_2}$, indicative of increased linear PIO tendencies as the positive value approaches zero.[17] Moderate-to-large positive values of this parameter, while plotted to establish trends, have no particular significance as a correlating parameter because qualities other than incipient PIO are involved. In part this can be seen in the way the Eney data scatter for such large values, but tend to coalesce as the parameter approaches zero.

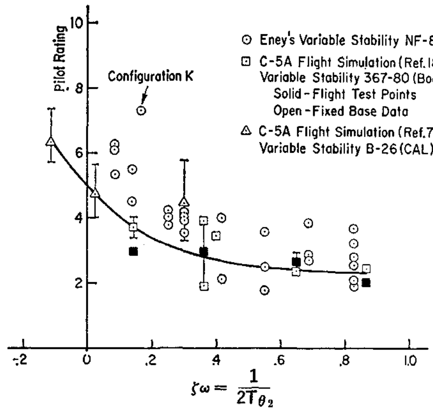


Fig. 7 Comparison of Eney's and C-5A landing approach results using linear PIO parameter.

We can see, too, that his condition K, which is the point that does not fit the proposed specification boundaries, is also somewhat out of line with these trends; nevertheless, considering the trends, its rating should definitely be worse than about a 5, whereas the spec boundaries would make it no higher (worse) than 3.5 based on a required $\zeta_{sp} > 0.35$ (configuration K had $\zeta_{sp} = 0.39$). The issue of whether or not the specification should be in terms of constant ζ_{sp} has been, and continues to be, a very arguable point. The specification was drafted on the basis of constant ζ_{sp} cut-offs because they appeared to correlate as well as anything else with the available data, and were simple. However, there were objections to such cutoffs based on the feeling that response times and decay times which are measured by ζ/ω and $\zeta\omega$ could be equally as important as ζ. In fact, if we go to the backup document[11] for MIL-F-8785B(ASG) and look at the data pertinent to Eney's discrepant point, Fig. 8, we can see that it fits right in with the other available data. The only discrepancy is in the cutoffs used to establish the specification boundaries which, in hindsight and reflecting Eney's additional point, should perhaps be established along constant $\zeta\omega$, ζ/ω lines.

General Implications and Conclusions

A basic conclusion of the consolidation efforts described above is that, when properly considered, all the data are

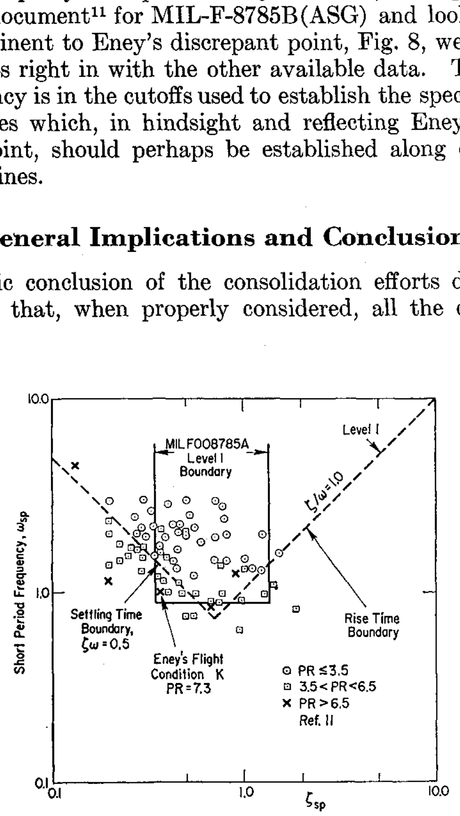


Fig. 8 Damping data for landing approach short period conditions (from Ref. 11).

compatible among themselves and with other results in some important respect. Some implications of these compatible data, for the low-speed approach conditions studied, are:

1) Altitude control with elevator (e.g., assuming no speed-stability or phugoid problems): a) appears to be characterized primarily by the h/θ transfer properties [i.e., Eq. (2)]; b) requires a minimum value of $1/T_{\theta_2}$ which is dependent on the approach (and closing) speed (Fig. 4). However, the desirable spatial response properties inferred thereby are not expected to necessarily apply to airspeed reductions below the range investigated; and c) can be improved by lift-control geared to the elevator only if the effective value of Z_{δ_e} is altered thereby. Such alteration can have a direct effect on the complete h/θ transfer function as it influences

$$1/T_{\theta_2} \doteq -Z_w + (Z_{\delta_e}/M_{\delta_e})M_w$$

and also the "high-frequency" zeros which govern the initial h response to elevator.

2) Assuming good altitude control as characterized previously, good pilot ratings will then depend on good *attitude* control, viz: a) proper $\omega_{sp}T_{\theta_2}$ and ζ_{sp}, ζ_{sp}/ω_{sp} or $\zeta_{sp}\omega_{sp}$ values to minimize attitude-rate overshoot and achieve proper response and settling times. For ζ_{sp} of the order of 0.5 or better, values of $\omega_{sp}T_{\theta_2}$ which appear appropriate for low speed approach conditions range from about 1 to 5; b) CAP $\equiv \omega_{sp}^2/n_{z_\alpha}$ while a possible alternative correlating parameter is not as directly related to attitude control as is $\omega_{sp}T_{\theta_2}$. Resolution of the possible conflict here depends to some extent on the final validity of the altitude control implications drawn above—i.e., through h/θ rather than through h/δ_e; and c) PIO-proneness, assuming no important control system dynamics or nonlinearities, seems to follow a consistent trend with the parameter $\zeta_{sp}\omega_{sp} - 1/2T_{\theta_2}$.

3) A general implication of the tuning inherent in optimum values of $\omega_{sp}T_{2\theta}$ and in the speed dependence of minimum acceptable $1/T_{\theta_2}$ is that spatial rather than only time response characteristics need to be carefully considered in terminal-area handling qualities problems.

4) Other means of achieving altitude control, e.g., with throttle (as in powered-lift STOLs) or with separate direct lift control, are expected to modify the aforementioned conclusions. However, conclusions 2, relative to good attitude control, are expected to apply regardless of the mode of altitude control.

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