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NEW CRITERIA FOR
ADVANCED AIRCRAFT DESIGN

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Abstract

The general problem is considered of how the tools of pilot-vehicle systems analysis may be used to develop handling quality specifications for systems design. A commentary is given with supporting analysis and data on the Cooper-Harper and the PIOR scales, their role in the design of experiments, and implications to pilot rating variability. A viewpoint is offered about the intent of MIL-F-8785B and the conflicting requirements posed by procurement versus system design. Elements from classic pilot-vehicle systems analysis methodology are distilled against a theoretical framework for the prediction of Cooper-Harper rating to develop a simplified and practical approach to handling qualities prediction that is directly applicable to the development of design specifications. Motion cue effects on handling qualities are included. The handling quality metrics proposed based on pilot-vehicle systems theory are evaluated against the Neal-Smith flight test data; the agreement is nearly 100 percent. Based upon these results five specific recommendations are offered for the revision of MIL-F-8785B in two areas: the longitudinal dynamic requirements and the flight path stability requirement in power approach. These revisions apply to aircraft incorporating direct lift control and digital flight control mechanizations. Modifications of the criteria proposed for longitudinal dynamics are proposed for the design of advanced display systems. Two additional recommendations are made which apply specifically to the design of digital flight control systems.

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A ROLE FOR PILOT-VEHICLE SYSTEMS ANALYSIS

For the conduct of pilot-vehicle systems research or even for the engineering design of an aircraft or FCS, matters of style and personal taste can dictate how one chooses to visualize and model the human pilot's role as an element in the system's dynamics. This is not a satisfactory basis for the development of design specifications for aircraft handling qualities. The rules of engineering conservation must apply, and the community of buyers, manufacturers, and users must all agree on the validity of the specifications to be imposed on the system design. In a practical sense this almost requires that any proposed handling quality specifications be independent of all explicit references to pilot modeling. The viewpoint of these authors is best expressed in the PIO specification based upon the theoretical development of Reference 3. In that work the study of pilot-aircraft system dynamics enabled the derivation of a physical theory for the PIO phenomenon which is independent of the analysis methodology or philosophy from which it is derived. The physical theory for PIO was then translated into a specification for engineering design. The validity of this or any other specification derived from a physical principal can be verified from a dedicated flight test experiment. A physical theory of this sort--once validated with reliable data--is independent of the analysis methods with which it originated.

We believe that handling quality specifications should be independent of pilot-vehicle systems analysis methodology; these are merely means to an end. The tools of analytical handling qualities may be used to understand or correlate data and to aid in the design of experiments; however, their only real use for the support of specification development is to assist ("bootstrap") in the evolution of physical principals on which the handling qualities technology is based.

It cannot be emphasized too greatly that the specification of aircraft design requirements for acceptable handling qualities is an altogether different problem from that of designing an aircraft to have acceptable handling. Any method is acceptable for the design and development of an

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aircraft-FCS so long as the results are acceptable. Any design approach will entail a certain number of iterations. Thus, methods for handling qualities prediction such as the Neal-Smith criterion, C* or TRP can all serve a useful function in the design process if they enable the transition of a FCS from the pencil and paper stage to hardware development.

An engineering specification for design acceptability must be right in an absolute sense. It is true that MIL-F-8785B is a design guide of sorts (it all depends upon one's concept of a design guide). But to view it only in those terms is to ignore the reasons for why such specifications exist at all. The intent of MIL-F-8785B is to provide a description of the desired functional performance of the pilot-vehicle system. This, however, is not easily possible to do in any direct quantitative sense without prior identification of a physical, measurable description of handling qualities. There is, as yet, no satisfactory measure for handling qualities other than pilot opinion rating; but that, for reasons that are well known, is not an acceptable metric for use in a design specification.

The philosophy of MIL-F-8785B rests upon the implicit use of pilot opinion rating to "map" airframe and FCS dynamic parameters into regions of acceptable or unacceptable handling qualities. This approach has never been entirely successful; exceptional cases, at both extremes, which violated MIL-F-8785B and its predecessor have always existed. The relationships between handling qualities and modal response parameters of the classic aircraft (ζ_{sp}, ω_{sp}, L_α, etc.) have been empirically derived with no substantial guidance from the technology of pilot-vehicle systems analysis. The problem, in essence, is that a reliable method for the <u>prediction</u> or unambiguous correlation of pilot opinion rating (POR) has not existed.

A UNIFIED, ANALYTICAL APPROACH FOR HANDLING QUALITIES SPECIFICATION DEVELOPMENT

The theory of Smith[2] provides the necessary physical and mathematical basis for the prediction of pilot opinion rating. John Arnold's[3] MSE thesis experiment provided the experimental data used by Smith for "calibration" of a pilot rating metric for pitch attitude tracking with a Class IV aircraft

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in Flight Phase Category A (fixed base simulation). The result is shown in Slide 2. The handling quality metric σ_{β_q} is hypothesized to represent a measure of pilot effort required for the stabilization of attitude rate q; it is a function of pilot dynamics, airframe and FCS dynamics, display dynamics and threshold (if IFR), and disturbance spectrum.

The estimation or prediction of σ_{β_q} requires an accurate pilot model for the estimation of $\hat{K}_q$ that is not tied too closely to any particular data base for its parameterization. Fortunately, a simpler criterion for handling qualities can be derived from it that is independent of how one models the human pilot.

It is shown in Reference 1 that for all of Arnold's data $\hat{K}_q$ can be treated as a constant value without significant error. This remarkable result suggests that for single-axis, fixed-base tracking of pitch attitude, Cooper-Harper rating is dependent only upon the rms value of q, the airplane's pitching velocity. This dependency is generally confirmed by Arnold's tracking results (Slide 3); quite a lot of scatter is evident at the greater POR. However, it can be seen that the data for each pilot, treated individually, is much more consistent than is the averaged data for all five subject pilots. Slide 4 further illustrates this observation. these data are representative of much of Arnold's data. The remarkable consistency demonstrated between POR and σ_q is more than chance.

Slide 5 shows data taken from Slide 3 for subject number 2. The power curve fit shown resulted from a least-squares fit; it yields an rms error of approximately one unit on the Cooper-Harper scale.

All the POR data for each of Arnold's subjects were fitted in a least-squared error sense with a curve of the form

$$R = K\sigma_q^n \qquad (1)$$

The metric K might be termed a "Cooper-Harper" gain. It appears to be approximately constant for each pilot and seems to represent how the individual subject perceives the control task requirements (stability and

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performance) against the adjectival descriptors of the Cooper-Harper scale. The results of the least-squares fit are shown in Slide 6. The rms error of fit of Equation (1) and the arithmetic average POR are also tabulated for each subject.

These results indicate that the Arnold data are more consistent on an individual pilot basis than on an average basis across all five pilots. The interpilot differences are systematic and could be interpreted to result from how each pilot interprets the task performance/control effort versus the Cooper-Harper scale.

It is also interesting that the error of fit between the formula $R = K\sigma_q^n$ and the actual pilot opinion rating seems to be strongly correlated with the average rating for each pilot. The connection between $\overline{\text{POR}}$ and rms error of fit σ_E can be summarized by the equation

$$\overline{\text{POR}} = 5.236 \sqrt{\sigma_E} \tag{2}$$

The rms error of fit of this equation to the data of Table 8 is 0.184 Cooper-Harper units. This relation is construed to represent the <u>expected variation of actual pilot opinion rating from the true nominal rating</u>. The "expected nominal" rating is given by $\overline{\text{POR}}$.

If this interpretation is correct, then Equation 2 indicates that increasing task difficulty will result in increased variability in Cooper-Harper ratings. By direct calculation the variation at the Level 1 and 2 boundaries is:

$(\text{POR})_{\text{avg}}$	σ_E
3.5	.404
6.5	1.626

We should <u>expect</u>, therefore, that the rms error of Cooper-Harper rating from the true average will be about four times greater at the Level 2 boundary

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than at the Level 1 boundary. This accounts for the increased spread in the data of Slide 3 at the greater POR.

The average value of the exponent in Equation 1, for all five pilots, equally weighted, can be computed to be $n = 0.497$.

In deference to Weber's Square Law, it is assumed that, in general, $n \equiv 0.5$ for all pilots. Thus, the general formula for pilot rating becomes $R = K\sqrt{\sigma_q}$ where K may be a constant but different value for each pilot. The average "rating gain" K across all five pilots for the Arnold experiment is determined to be $K_{avg} = 3.83$. It is therefore concluded that a general rating model for pitch attitude attitude control of Class IV aircraft in Flight Phase Categories A and C is

$$R = 3.83\ \sqrt{\sigma_q} \tag{3}$$

POR data from the Neal-Smith flight tests[4] are shown in Slide 7. The ratings of pilot M appear to be biased with respect to those of pilot W. This is indicated by the dashed line. Using the intersection of this bias line with POR = 1 for pilot W as an origin, the two radial lines are drawn to encompass the bulk of the data. The ratio Δ_2/Δ_1 shown is a measure of the relative POR variability at the Level 2 and Level 1 boundaries, respectively. The values used are the maximum of those indicated at each boundary. The result, $\Delta_2/\Delta_1 = 2.3$ is less than the value 4 which we estimated to exist based on the Arnold data. We conclude that the majority of the Neal-Smith data exhibit no more variability than should be expected in any test of this nature.

The 5 "spurious" data points shown in Slide 7 seem to result from interpilot differences in task interpretations--except for Case 6B where turbulence is a likely source. The pilot comments of Reference 4 provide valuable insight into the question of task. Pilot W, in general, seemed to emphasize factors related to air-to-air target acquisition. Pilot M's POR seem to have been based mostly on target tracking after the basic acquisition task had been solved.

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It is hoped that the comments made about the dependency between the expected value of pilot opinion rating and the rating variability will be further tested by simulation and flight test. Reference 2 hypothesized that such a relationship exists and that it exists for good physical reasons. The fact is that Cooper-Harper ratings vary because they reflect a physical phenomenon; the variability is systematic. These results indicate that this will be a practical consideration only for the determination of Level 2 boundaries for handling qualities.

Systematic differences between pilots exist. Again, this is no reason to doubt the utility of the Cooper-Harper scale. This effect must be considered when developing a data base or preparing a handling quality specification. The best available and practical solution to this problem at the present time is to use at least two pilot subjects and look for systematic rating differences.

We have proposed that Cooper-Harper rating is proportional to the square root of rms rate error: $R = 3.83 \sqrt{\sigma_q}$ (Slide 8). This result applies for the single axis regulation of pitch attitude with turbulence input in the absence of inertial acceleration cues.

Since the Cooper-Harper scale has a lower bound at 1, this result seems to indicate a contradiction. Note, however, that for $R = 1$, $\sigma_q = .068$ degrees/second = 1 milliradian/second. This value is generally presumed to equal the approximate threshold for visual perception of rate. There is, therefore, no conflict between formula (3) and the Cooper-Harper scale.

It follows that the optimization of handling qualities requires that σ_q approach the value corresponding to the perception threshold; i.e., <u>no tracking is performed</u>, and the Cooper-Harper rating is 1.

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THE NO-TRACKING HYPOTHESIS

Optimum handling qualities demands minimum closed-loop control by the pilot.

Application to Specification Development

If the features of open-loop aircraft response to control can be identified which promote pilot tracking, then these imply degraded handling qualities. The quantification of such response properties against available data will then lead in a natural manner to the development of handling quality specifications. This is the procedure that will be implemented in the remainder of this report.

QUANTIFYING THE EFFECTS OF MOTION

The pilot-centered normal acceleration a_{z_p} seems to dominate the effects of inertial motion cues on basic handling qualities. This provided the basis for the PIO theory of Reference 6.

Slide 9 is a typical variation of the parameter $\phi(j\omega)$ with frequency. ϕ is the approximate phase lag of the a_{z_p} loop dynamics (airplane plus pilot). The PIO theory says that if the pitch attitude dynamics (open or closed loop) are highly resonant at frequency ω_R then the susceptibility to PIO will depend upon whether ω_R is greater than or less than the frequency for which $\phi(j\omega)$ is $-180°$.

The acceleration loop phase margin ϕ_n is, we believe, a useful metric for identification and specification of adverse motion cue effects on handling qulaities--regardless of whether PIO is a potential problem.

For the single loop control of pitch attitude, the behavior of the crossover frequency ω_c with pilot adaptation provides a useful clue for decoding the Neal-Smith data base. The amplitude and phase properties of three stereotype controlled elements are shown on Slide 10. The zeroth order form of required pilot dynamic equalization is indicated for each. These dynamics are representative of a wide range of aircraft dynamics, θ/F_s.

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The sensitivity of crossover frequency ω_c to pilot lag T_I for the pure-gain controlled element is indicated in Slide 10. A comparison of ω_c with $\phi(j\omega)$ suggests that the regulation of normal acceleration would demand constant attention and significant precision of control when $\frac{\theta}{F_s}(s) \approx K$ (in violation of the No-Tracking Hypothesis, we note). This would not be true for the other controlled elements. the effect is parameterized by the slope:

$$\frac{d}{d\omega}\left|\frac{\theta}{F_s}(j\omega_c)\right|$$

Note that ω_c must be determined in some manner. The data of Reference 5 support the assumption that, to a good approximation, ω_c is parameterized by the slope parameter. Data from Reference 5 are shown in Slide 11. Note that the relation is an implicit one. This method for the estimation of the criterion frequency ω_c is assumed throughout the remainder of this presentation.

Slide 12 summarizes the four principal handling quality metrics that we have investigated. The time-to-first peak of q(t) was selected to discriminate important features of aircraft response during large amplitude maneuvering control that might escape our notice in a linear tracking experiment. The effects of sign convention on $\frac{\theta}{F_s}$ are removed by the division by $M_{\delta e}$.

QUANTIFYING THE METRICS

The Neal-Smith data were used to test the applicability of the above four metrics and to quantify their effect on POR.

Slide 13 indicates that tq = 0.2 seconds is a lower limit. This is reasonable, based on human time delay estimated from closed loop tracking (generally near 0.2). When tq < 0.2, the response is "too abrupt" and, in effect, the pilot feels forced to track the results of his previous input--the No-Tracking Hypothesis again. It is possible that no upper limit should be placed on tq since large tq results from excessive phase lag. However,

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we have tentatively specified tq ≤ 0.9 as being consistent with most of the data.

Slide 14 shows a plot of pitch attitude phase (airplane including FCS) vs POR averaged for both pilots for each case tested. The results appear to be chaotic. Careful inspection, however, will reveal that the data may be generally grouped according to the slope parameter. The nominal bounds are shown for slope ≥ -2 decibels/octave (note that this is the alegebraic sense).

When those data cases for which $\frac{d}{d\omega}\left|\frac{\theta}{F_s}\right| \ge -2$ or which violate $0.2 \le t_q \le 0.9$ are removed, the results are as shown in Slide 15. The boundaries we believe, reflect the nonlinear nature of the Cooper-Harper scale. That is, the discontinuities in slope belong there until such time as a linear scale can be devised. The two "spurious" data points 7F (pilot W) and 1A can both be rationalized. Case 7F is especially interesting since grossly different POR were obtained for this case for pilot M (also shown). Both points 1A and 7F-W can be moved inside the boundaries when the criterion frequency ω_c is increased. As an a priori prediction, however, the combination of the three parameters tq, $\frac{d}{d\omega}\left|\frac{\theta}{F_s}\right|$ and $\measuredangle \frac{1}{M_{\delta e}} \frac{\theta}{F_s}$ yields 94 percent success.

The appropriate regions of level 1/2 handling qualities are indicated on Slide 15.

For the same cases, Slide 16 shows the variation of $\phi(j\omega_c)$ with pilot induced oscillation rating (PIOR). All except five cases exhibit a very consistent trend. These five, however, appear to be cases that would violate the proposed PIO specification (developed from Reference 6). All five cases would be correctly categorized by the boundaries shown in Slide 16 if the criterion frequency were increased to simulate a "more aggressive" piloting technique. Note that case 7F (pilot W) is one of the errant cases. The spurious cases are discussed in more detail in Reference 1.

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A DIRECT LIFT CONTROL CRITERION

Slide 16 omits those cases for which the slope criterion is violated; i.e., $\frac{d}{d\omega}\left|\frac{\theta}{F_s}\right| \geq -2$ db/oct. This was done on the presumption that such cases are those for which essential handling quality problems exist due to adverse normal acceleration cue effects. If we plot $\phi(j\omega_c)$ vs PIOR for only those aircraft-FCS cases which violate only the slope criterion (i.e., for which $\frac{d}{d\omega}\left|\frac{\theta}{F_s}\right| \geq -2$ db/oct) then the resulting trend will hopefully apply regardless of pitch dynamics. In particular, we suspect it will apply when a DLC system is employed--for which θ may be automatically controlled, for example. For these cases $\phi(j\omega_c)$ is plotted vs PIOR in Slide 17. A strong correlation exists. Note that there are no Level 1 cases. The Level 1 boundary is estimated by a slight extrapolation.

COMMENT ON THE PIOR SCALE

It has been suggested that the PIOR scale is redundant and that it be discarded. We do not believe this. The scale is highly compressed, truncated, and therefore nonlinear--this was seen in Slides 16 and 17.

We believe that the PIOR scale, as it has been used, quantifies the adverse effects of normal acceleration on handling qualities. It complements the Cooper-Harper scale which emphasizes the ability of a pilot to perform a control task without explicit consideration of motion cue effects. For advanced FCS with direct force control modes, the PIOR scale may prove valuable.

SUMMARY OF PROPOSED SHORT-PERIOD CRITERIA

The results of previous slides are summarized in Slide 19. It should be noted that these criteria would seem to apply equally well to advanced display design. When a display is used for a particular task (fire control, energy maneuvering, etc.) such that the pilot must track the error in a single cue x, then substitute x for r, $\overset{\circ}{x}$ for q and discard the motion

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criterion $\phi(j\omega_c)$. The result is a set of criteria for the preliminary design of display systems.

FLIGHT PATH STABILITY

A new criterion for flight path stability in power approach can be developed in a manner completely analogous to that for attitude control. The essentials are listed on Slide 20.

The time response measure $t_{\dot{\gamma}}$ was defined as the time to 90 percent peak because of the near-aperiodic nature of the $\dot{\gamma}$ responses for many aircraft. The simplified treatment used for addressing the difficult question of control technique effects in power approach is fully justified in Reference 1. Here, we note that when an aircraft-FCS demands a level of control complexity significantly greater than the simple use of F_s or δ_t to correct γ errors, then the pilot is forced to track; by the No-Tracking Hypothesis, the handling qualities will be degraded.

The peculiar damping parameter D is defined in the manner indicated in Slide 20 because it is a "pilot-centered" perspective of flight path stability and is probably more flight testable than a more conventional, linear measure of response damping.

The proposed criteria for flight path stability are tabulated in Slide 21. These results were empirically determined from an analysis of 17 aircraft. Slide 22 is a comparison between flight experience (as best as can be estimated from personal experience or from published data sources) and the criteria proposed. The agreement is complete except at the Level 1 boundary where some minor uncertainty occurs.

Observe that the NATOPS-prescribed carrier approach task falls into the "Throttle" column. The F-111B is seen to be much more poorly rated for the carrier approach task than it is predicted to be for field landing (the USAF approach seems to, more often than not, emphasize a "point the nose at the end of the runway and come in hot" technique). Both predictions concur with

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USN and USAF experiences. Conversely, the F-4B gets rave reviews for carrier approach but is a more difficult airplane when flown with a technique that emphasizes elevator control of flight path angle.

The effect on handling qualities of the F-4 of direct lift control are also indicated. The DLC airplane is shown in the elevator column. This assessment is supported with flight test experience with this airplane. One problem with DLC that must be solved is the design of a cockpit manipulator. We suggest that an attitude-hold FCS would be appropriate with stick (center or side) used for DLC command. Thumbwheels on top of control sticks, with all systems integration being done within the pilot's skull hardly seems like the way to fly in the computer age.

DFCS REQUIREMENTS

Slide 23 shows some specific requirements proposed in Reference 1 for digital FCS. Time does not permit a discussion of these here beyond noting that DFCS hardware choices can have a potentially significant effect on handling qualities. This is particularly true of A-D and D-A conversion techniques. The handling qualities impact must be carefully evaluated for each specific system before the hardware design becomes immutably frozen.

OTHER TOPICS

Slides 24 and 25 indicate the maximum tolerable values of short-period damping ratio and equivalent systems time delay for Level 1 handling qualities. These results were derived by using the proposed phase criterion

$$\measuredangle \frac{1}{M_{\delta_e}} \frac{\theta}{F_s}(j\omega_c) \geq -130^\circ$$

and solving for τ_E to give a phase of -130° for the cases shown.

The point of this exercise is to indicate that the phase criterion seems to be quite powerful, easily applied, and yields results consistent

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with other evidence. For instance, the $(\zeta_{sp})_{max}$ values are in reasonable agreement with MIL-F-8785B; based on these results, the Level 1 limit of the specification seems to be conservative as Mayhew has suggested (Proposed Revisions to MIL-F-8785B). Various investigators have suggested that $\tau_E = 0.1$ might be used as a handling qualities boundary. The examples of Slide 25 support that to a certain extent, but suggest that such a requirement is too simplistic and restrictive.

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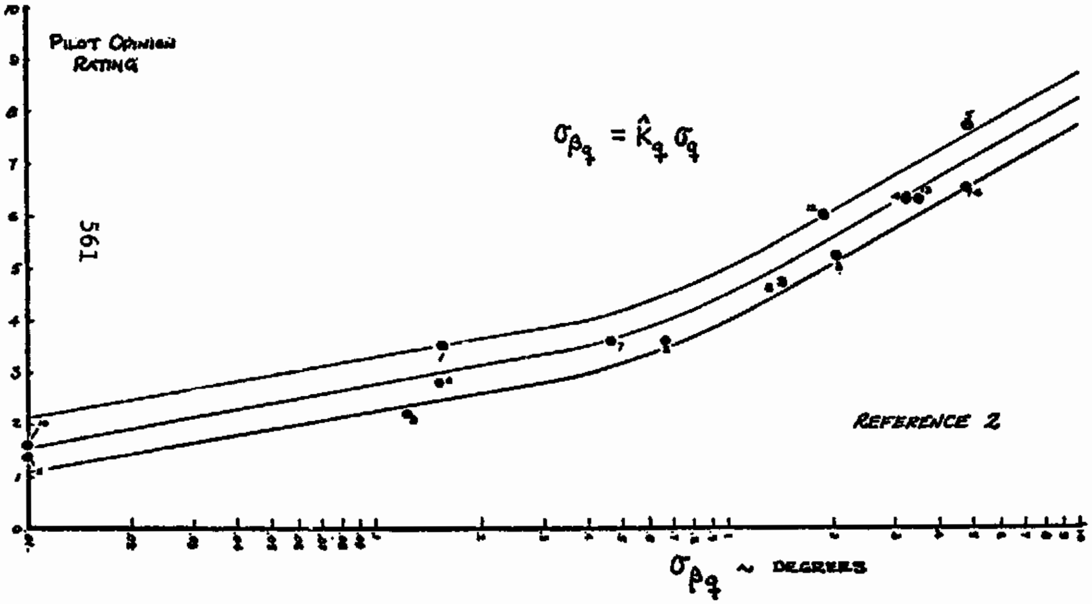
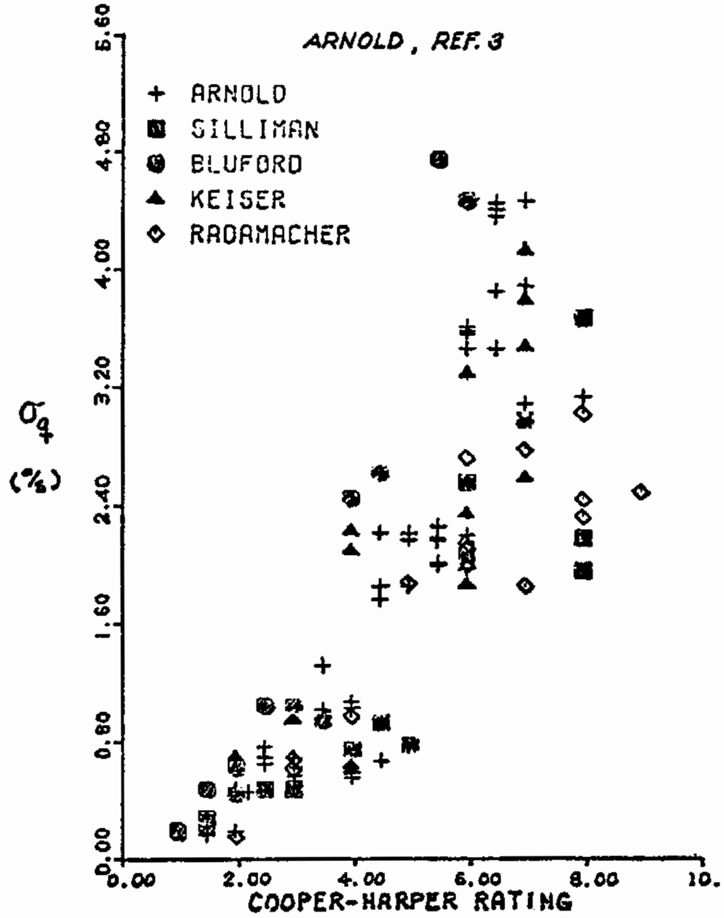


Slide No. 2



Slide No. 3

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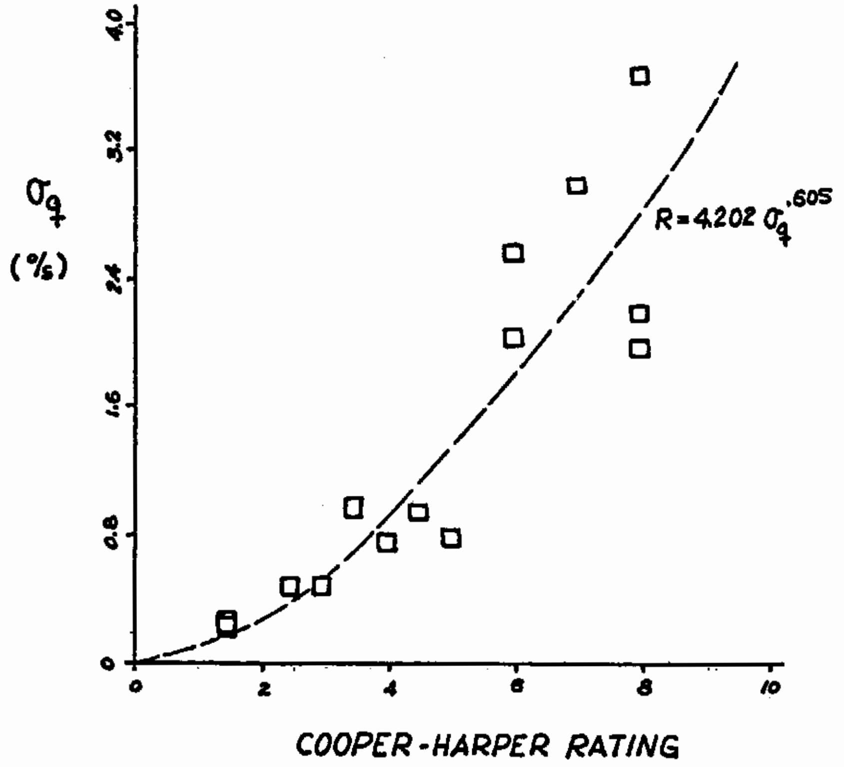
SUBJECT NO. 5

CASE	RMS PITCH RATE °/s	POR
2	1.035	4
	1.015	3.5
	1.012	3.5
	1.012	3.5
3	1.852	5
	1.845	4.5
	1.761	4.5
4	2.193	6
	2.152	6
	2.160	5.5
	2.172	5.5
	2.254	5.5
5	3.129	8
	3.007	7
	3.081	7
	2.962	7
10	.162	1.5
	.175	1.5
	.141	1.5
	.168	2
	.171	2

Slide No. 4

SUBJECT 2



Slide No. 5

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$$R = K\,\sigma_q^{\,n}$$

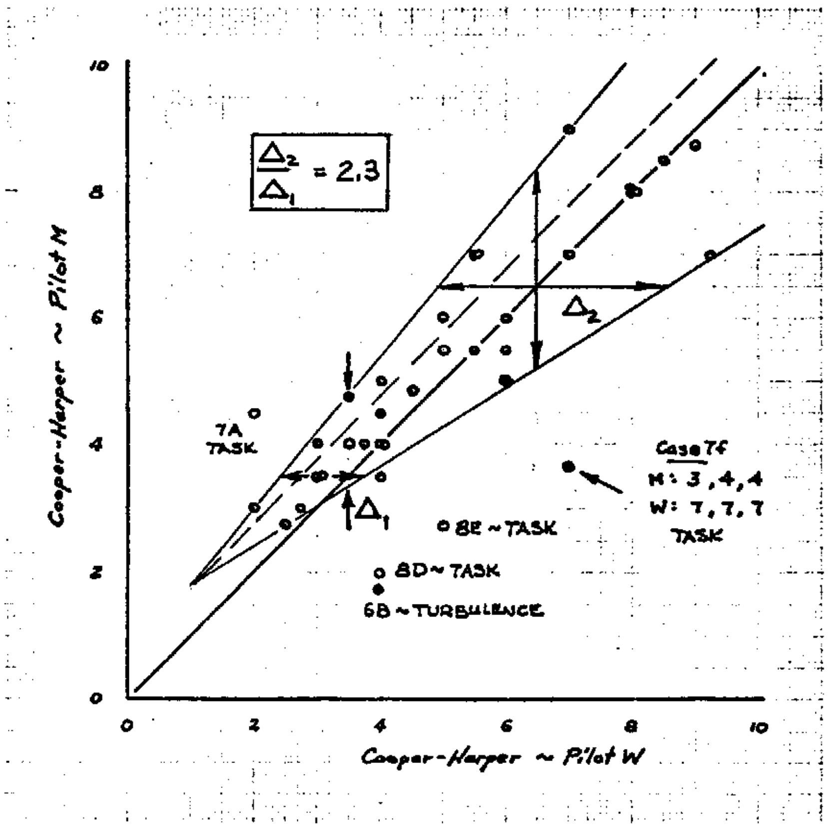
SUBJECT	K^3	n	σ_ϵ'	$\overline{POR}^2$
BLUFORD	2.606	.527	.218	2.6
ARNOLD	3.559	.450	.588	4.4
KEISER	3.844	.431	.906	5.1
SILLIMAN	4.202	.605	.983	4.9
RADAMACHER	4.391	.474	.982	5.2

$$R = 3.83\sqrt{\sigma_q}$$

$$\overline{POR} = 5.236\sqrt{\sigma_\epsilon}$$

1. σ_ϵ = RMS (POR – R)
2. $\overline{POR}$ = ARITHMETIC AVERAGE (EACH SUBJECT)
3. K = COOPER-HARPER GAIN
4. $\dfrac{(\sigma_{POR})_{6.5}}{(\sigma_{POR})_{3.5}} \cong 4$

Slide No. 6



Slide No. 7

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THE NO-TRACKING HYPOTHESIS

$$R = 3.83\sqrt{\sigma_q}$$

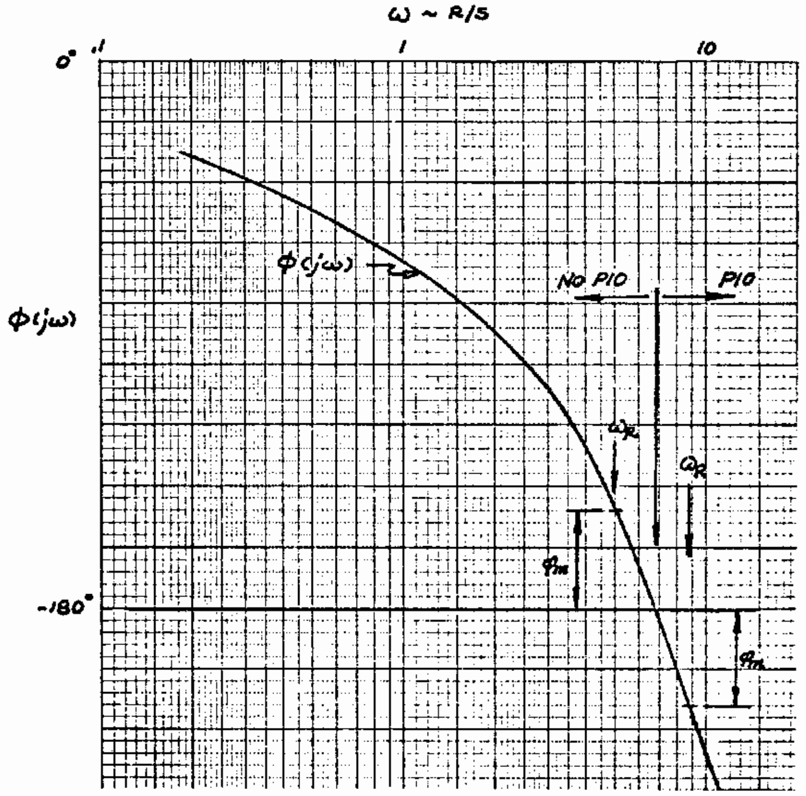
$$\sigma_q \rightarrow 1 \text{ mR/s} \Rightarrow R \rightarrow 1$$

OPTIMUM HANDLING QUALITIES REQUIRES
NO UNNECESSARY TRACKING

THE SPEC PROBLEM:

IDENTIFY FEATURES OF AIRCRAFT-FCS RESPONSE WHICH FORCE A PILOT TO TRACK

Slide No. 8



$$\phi(j\omega) \triangleq \measuredangle \frac{a_{z_p}}{F_s}(j\omega) - 14.3\,\omega$$

$$|\phi(j\omega_R)| < 180^\circ \quad \text{FOR NO PIO}$$

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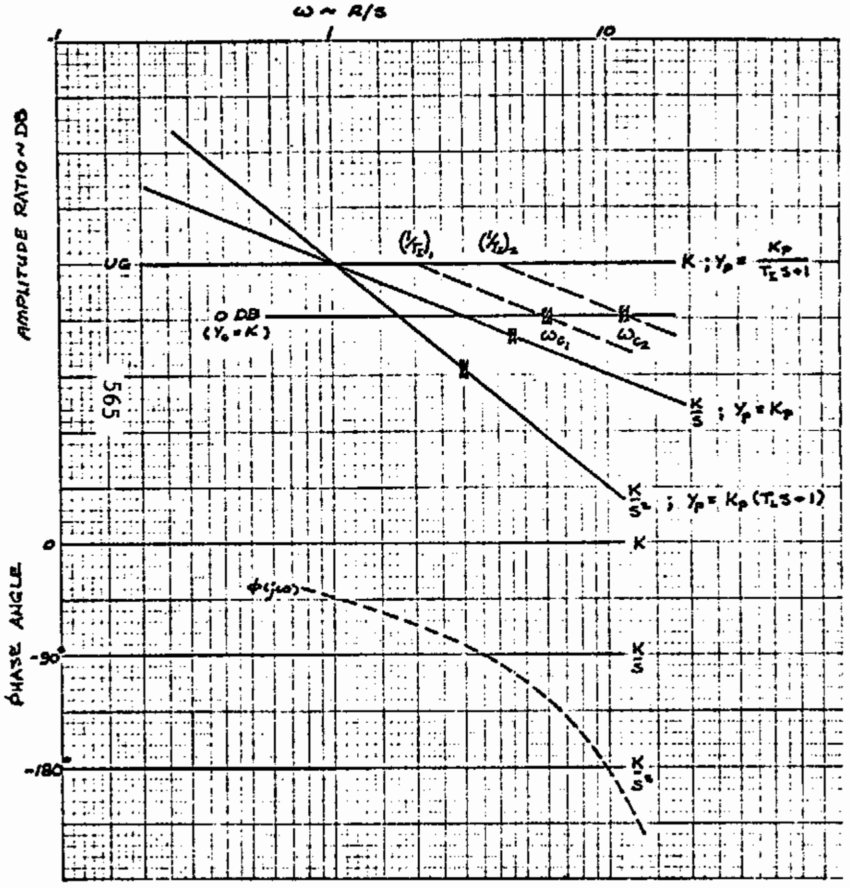
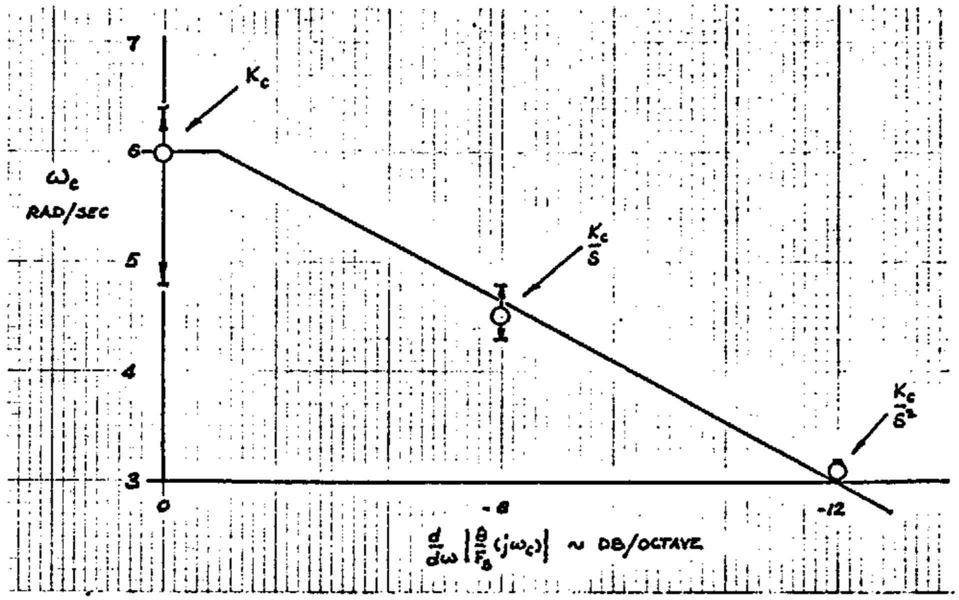


Slide No. 10



Slide No. 11

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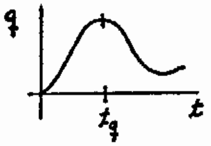
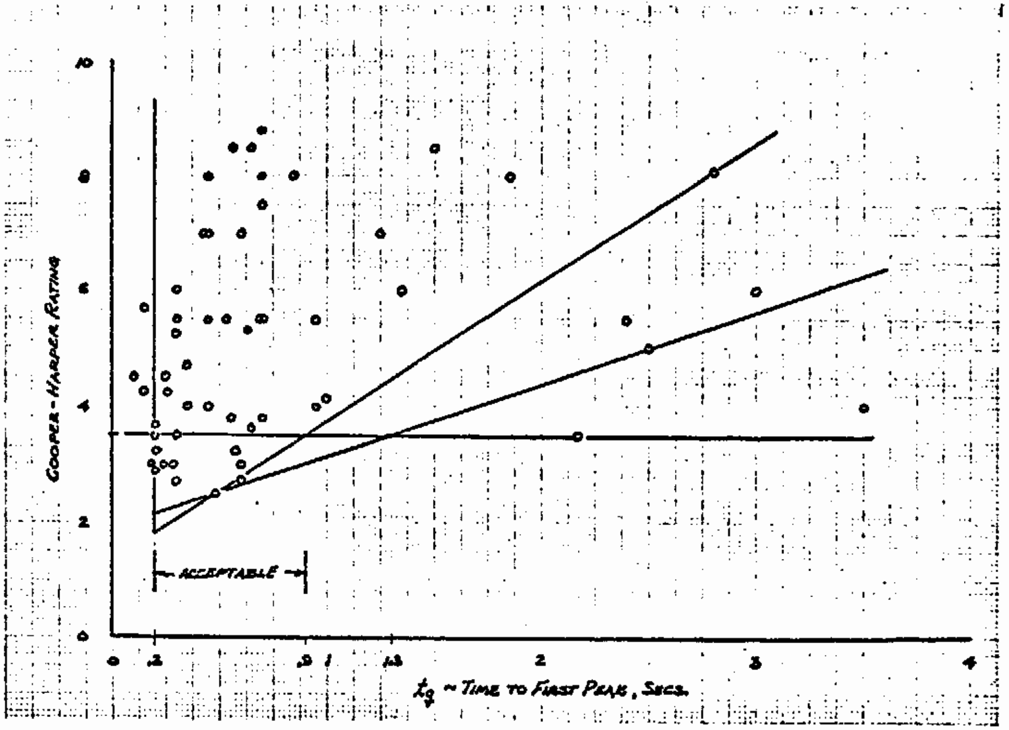
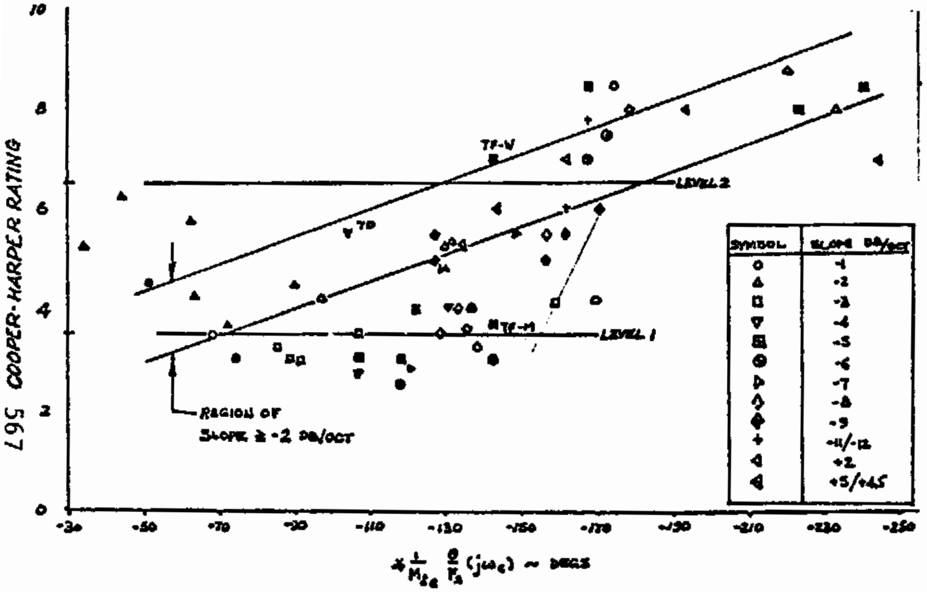
METRIC	HANDLING QUALITY COMPONENT
t_q	 INITIAL RESPONSE TO STEP F_s
$\frac{d}{d\omega}\left\|\frac{\theta}{F_s}(j\omega_c)\right\|$	ADVERSE MOTION CUE DESIGNATOR & METRIC FOR CRITERION FREQUENCY
$*\frac{1}{M_{\delta e}}\frac{\theta}{F_s}(j\omega_c)$	DESIGNATOR FOR REQUIRED PILOT EQUALIZATION
$\phi(j\omega_c)$	ADVERSE MOTION CUE DESIGNATOR

Slide No. 12



Slide No. 13



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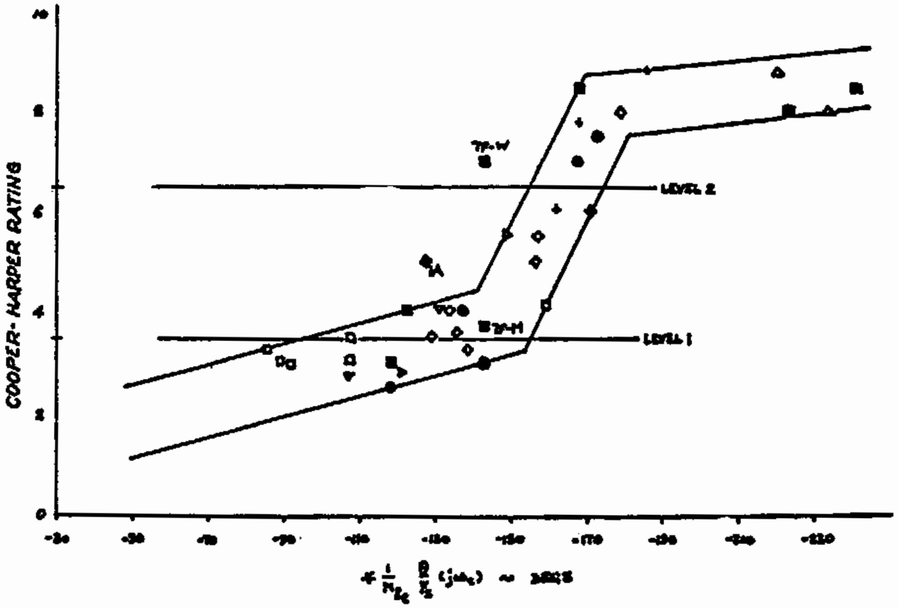

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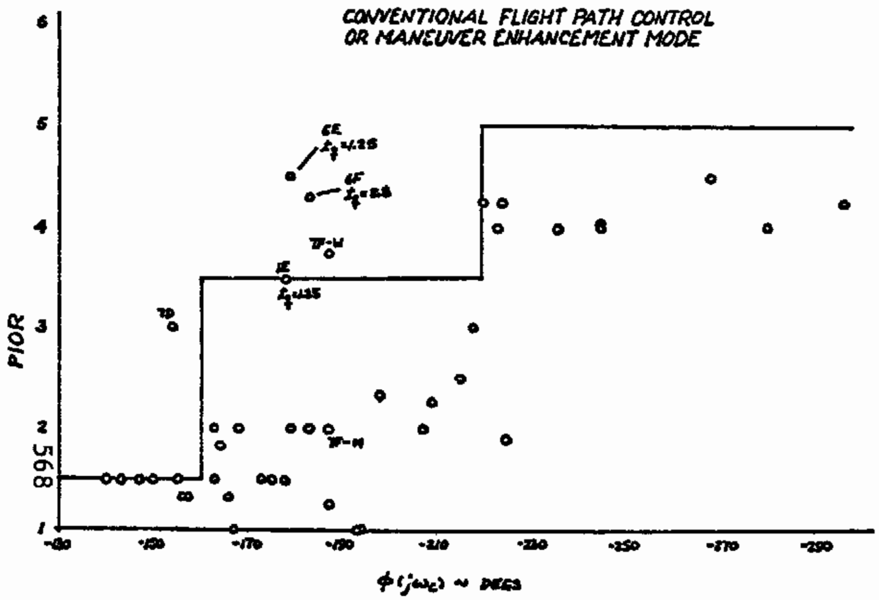
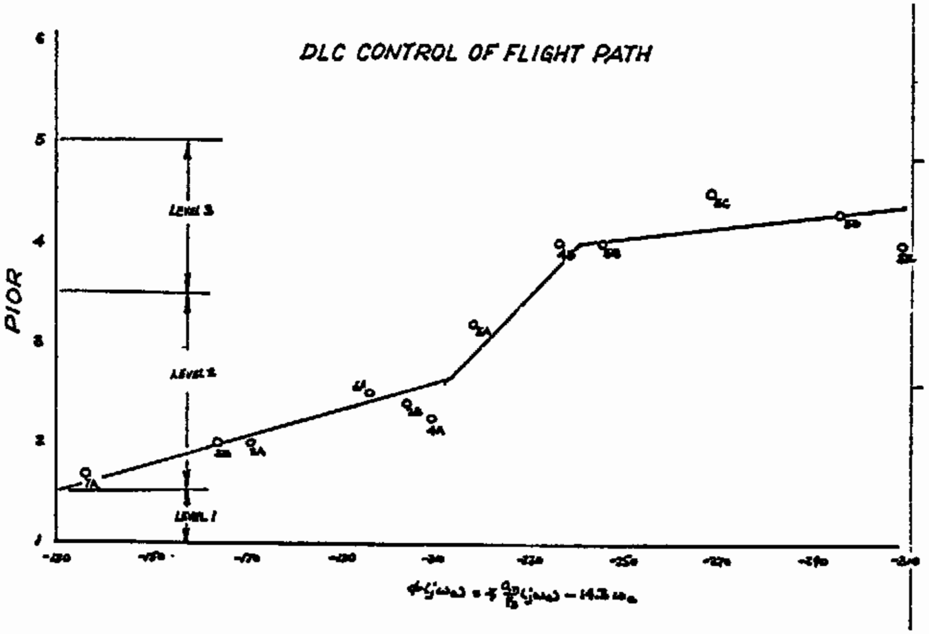


Slide No. 16.



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THE PIOR SCALE

- HIGLY NONLINEAR -- COMPRESSED
- QUANTIFIES EFFECTS OF NORMAL ACCELERATION ON HANDLING QUALITIES
- COMPLEMENTS COOPER-HARPER
- SHOULD BE REVISED & USED--NOT SCRAPPED

PROPOSED
SHORT-PERIOD CRITERIA
(SUMMARY)

(1)	$0.2 \leq t_q \leq 0.9$	ALL LEVELS
(2)	$\frac{d}{d\omega}\left\lvert \frac{\theta}{F_s}(j\omega_c) \right\rvert < -2$ DB/OCT	LEVELS 1 & 2
(3)	$\measuredangle \frac{1}{M_{\delta_e}} \frac{\theta}{F_s}(j\omega_c) \geq -130^\circ$	LEVEL 1
	$-130^\circ > \measuredangle \frac{1}{M_{\delta_e}} \frac{\theta}{F_s}(j\omega_c) \geq -170^\circ$	LEVEL 2
	$-170^\circ > \measuredangle \frac{1}{M_{\delta_e}} \frac{\theta}{F_s}(j\omega_c)$	LEVEL 3
(4)	$\phi(j\omega_c) \geq -160^\circ$	LEVEL 1
	$-160^\circ > \phi(j\omega_c) \geq -220^\circ$	LEVEL 2
	$-220^\circ > \phi(j\omega_c)$	LEVEL 3

FOR CONTROL-DISPLAY INTEGRATION:

(1) SUBSTITUTE: x FOR θ , $\dot{x}$ FOR q
(2) DISCARD CRITERION #4

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FLIGHT PATH STABILITY

$\dot{\gamma}$ ANALOGOUS TO q

$t_{\dot{\gamma}}$ " " t_q

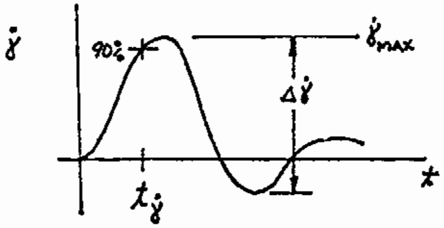
CONTROL TECHNIQUE :

(1) STEP F_s @ U_0 = CONSTANT

(2) STEP δ_T @ θ = CONSTANT

INVOKE THE NO-TRACKING HYPOTHESIS

DEFINITIONS :



$D \triangleq \Delta\dot{\gamma}/\dot{\gamma}_{MAX}$ …. "DAMPING"

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	AUTHORITY	TIMELINESS	PRECISION
	$\dot{\gamma}_{MAX}$	$t_{\dot{\gamma}}$	D
LEVEL 1	.4	3.5	1.5
LEVEL 2	.2	6.0	2.0
LEVEL 3	.1	NA	3.0

FLIGHT PATH STABILITY CRITERIA
(PROPOSED)

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DATA COMPARISON:
POWER APPROACH

PROPOSED CRITERIA

	CONTROL TECHNIQUE		
	ELEVATOR	THROTTLE	FLT. EXPERIENCE
LEVEL 1	F-8 DLC P-3B T-2C DC-8 A-3B YF-16 NT-33 F-111 A A-6E	F-4B F-5A/E/F T-2C A-6E	P-3B F-4B (USN) F-8DLC T-2C YF-16 F-111A (AF) A-6E DC-8 F-5A/E/F F-4C (AF) N-T33 A-3B
	C-5 RA-5C	A-3B	C-5
LEVEL 2	F-8D F-5A F-4B	YF-16 F-111A C-5 RA-5C DC-8 P-3B F-8D F-4M	RA-5C F-111A (USN) F-8 F-4M
LEVEL 3			

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DFCS REQUIREMENTS

FRAME RATE :

LOW FREQUENCY LIMIT $\ast \frac{1}{M_{\delta_e}} \frac{\theta}{F_s}(j\omega_c)$

HIGH FREQUENCY LIMIT $f < \frac{\theta_o \omega_c}{10R/2^n}$, Hz

CONTROL ROUGHNESS :

$$\left|\frac{q}{\delta_e}(j\omega_c)\right| \Delta\delta_e \leq .001 \text{ R/S}$$

$$\left|\frac{a_{z_P}}{\delta_e}(j\omega_c)\right| \Delta\delta_e \leq .01 \text{ G}$$

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MAXIMUM ζ_{SP}

(CLASSIC AIRPLANE)

$\frac{1}{T_{\theta_2}}$	ω_{SP}	$(\zeta_{SP})_{MAX}$
0.5	2.0	2.1
1.5	6.0	2.1
2.0	9.0	2.5

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EQUIVALENT SYSTEM:

TIME DELAY

$$\frac{\theta}{F_s}(s) = \frac{K\,(s + 1/T_E)\; e^{-\tau_E s}}{s\,(s^2 + 2\zeta_E\omega_E s + \omega_E^2)}$$

$\zeta_E = 0.5$, $1/T_E = 1.$

ω_E	$(\tau_E)_{MAX}$
2	-,042
4	,009
6	,089
9	.205

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Dwight Schaeffer, Boeing: What was the basis for your expression

$$R = 3.83\sqrt{\sigma q} \ ?$$

Answer: The simple formula $R = 3.83\sqrt{\sigma q}$ was derived from data for fixed-base simulation of pitch tracking in turbulence. The formula appears not to address task performance but, in fact, does since q & θ are linearly related. If the task requirements were completely changed, this would be reflected by a change of gain constant. In general, for pitch tracking with no adverse effects of normal acceleration, $R = K\sqrt{\sigma q}$ seems to reasonably approximate the relation between σq & Cooper-Harper ratings. I have termed K the "Cooper-Harper" gain. Based on Arnold's data K is a constant of the individual pilot and seems to establish how the individual calibrates his task performance and the degree of difficulty with the adjectives of the Cooper-Harper scale. The rating formula is not proposed for applications; it was used by me to identify $q(t)$ as the essential response of importance to handling qualities and to develop the No Tracking Hypothesis as a philosophy to guide the search for handling quality parameters.

Bill Rickard, Douglas: In the Cooper-Harper rating versus phase criterion, at 130° what is the rating?

Answer: The boundaries shown merely illustrate the tightness of fit between the phase angle criterion and the data. As a specification, I suggested the mid-point of the data lying along the 3.5 rating line. In the region of the "knee" of the data, a small change in pilot technique may yield a large change in pilot opinion rating. This is suggested by the correlation shown and constitutes what Rogers Smith has termed a "handling qualities cliff".

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