Twenty-Five Years of Handling Qualities Research

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THIS paper reflects on 25 years (or more) of handling quality research and shares with the reader some of the author's resulting experiences and thoughts When reaching back so far and considering all that has been accomplished, there are many facets of handling or flying qualities which could be covered and considered However the author chooses to limit discussion to those aspects concerned with the *theory* of handling qualities in turn relating to closed loop pilot vehicle frequency domain analysis and its application to handling and flight control problems This is not to deny other aspects of handling qualities research which are beyond the scope of this limited exposition, such as: ground[1 8] and in flight[9 12] simulation; rating systems;[13 15] optimal control operator models;[16 19] workload concepts;[20 25] and data collection and codification [26 30] Rather, it is to emphasize those aspects that the author is personally most familiar with and which stress the design guidance role of handling qualities theory and practice This has always been important and it is especially important now because of increasing dependence on sophisticated flight control systems which can completely alter the way an airplane responds to the pilot's inputs In fact handling quality research has recently come up for its share of criticism as being inadequate to cope with some of today's design problems For example Berry [31] in a recent article in *Astronautics and Aeronautics* and Gibson,[32] in a paper before the AGARD Conference in Fort Worth both decried the fact that there have been a rash of generic handling problems associated with high performance aircraft having sophisticated flight control systems and that such systems have not always reached their full potential to provide handling qualities superior to much simpler aircraft of the past

Against this background first to be discussed are the basic aspects of handling or flying qualities and some of the early design problems that were solved; then the growth of handling qualities theory in response to design demands; and finally how that theory has been applied and expanded over the years to become a valuable tool especially useful in coping with new situations such as those that seem to be occurring almost daily

Getting down to basics then let handling qualities be briefly defined as those dynamic and static properties of a vehicle that permit the pilot to fully exploit its performance and other potential in a variety of missions and roles In other words the limitations on the airplane do not originate in any kind of a pilot vehicle control problem but rather are inherent in some other aspects to the design Discussed next are three recognized facets to handling

1) Trim and Unattended Operation

It is always necessary for the pilot to be able to *trim* the airplane in a hands off condition so that he can, in fact achieve an unattended state of operation Sometimes the trim characteristics themselves are such as to make the achievement of trim difficult and too time consuming *Unattended operation* concerns the features of the airplane and flight control system which determine whether the airplane is stable mildly, or perhaps, strongly divergent; and whether it can be left unattended for reasonable lengths of time while the pilot devotes some of his attention to tasks other than controlling the vehicle

2) Large Amplitude Maneuvers

These are sometimes restricted by control power sometimes by the nature of the response In any case the maneuver is a direct response to a programmed largely open loop pilot input triggered by some cue or imminent danger e g an attacking aircraft gust upset imminent collision etc

3) Regulation and Precision Flying

These mean that the pilot is now in closed loop control holding the airplane to whatever course or attitude he desires in the presence of wind and other disturbances and furthermore precisely maneuvering and controlling the vehicle down a given trajectory within whatever constraints are applicable

In the early classical airplane era before the advent of power boost control actuators artificial stability augmentation systems, etc , flying quality dynamic requirements were expressed in terms of modal response parameters e g , damping and frequency or response time constant Control power criteria were sometimes in nondimensional form e g a required roll helix angle pb/2U and stick force gradients reflected the realities of purely manual control systems Design guidance in these early requirements was mostly on the airplane geometry Accordingly handling quality requirements were used for sizing control surfaces (tail volume for specified damping and control or aileron geometry for achieving required nondimensional roll rates) in setting hinge moment parameters that were compatible with good handling e g in terms of stick force per kt or stick force per g and in establishing c g locations that were stable and controllable

Most of the early requirements starting with pioneering NACA work and going on through military specifications R 1815 and early versions of MIL F 8785 were largely based on

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direct flight experience with experimental prototype and production airplanes This experience was distilled into ac ceptable/unacceptable characteristics and criteria While it perhaps seems rather elementary such distillation and correlation of good to unsatisfactory characteristics of existing aircraft is still a very useful practice today and was even more so then The author can personally recall his own problems with the sizing of the B 25 aileron about this time and how delighted he was to find his problem solved by Gilruth s very early set of requirements for satisfactory flying qualities [33] which were as noted above based largely on experience with good and poor aircraft

This early airplane era started changing with the advent of expanded performance aircraft which were being pushed into the high speed high altitude region, where some of them were exposed to a variety of compressibility effects To better cope with the attendant stability and control problems, designers began to install power actuated primary controls and rudimentary stability augmentation systems (SAS) The latter were intended to obtain the required or desired level of damping at high altitudes without outsize tail surfaces; they thus represented a design trade The power actuation systems were used to permit the attainment of desirable stick forces under high speed conditions without the excessive aerodynamic tailoring usually required at inordinate design cost in time and effort

Relative to this last point it is hard to believe the amount of calendar and flight time that in those days went into tailoring hinge moment characteristics to suit the operational demands on some early World War II aircraft The author distinctly recalls hundreds of hours of flying that went into a Vultee dive bomber then being developed for projected use in the Burma theater of operations, to test changes in the elevator overhang shape in tab gearing and spring rates, and in the control circuit itself This was not an isolated case The Curtiss C 46 elevator "Veetab" was a beautiful example of aerodynamic and mechanical system tailoring (Ref 34); and one of the early Douglas El Segundo airplanes was tested for very systematic changes in hinge location and nose shape (Ref 35)

At any rate, the advent of control surface power boost and rudimentary SAS were the first stirrings of a new design era Both forms of augmentation began to be routinely applied because they were design efficient No one asked whether the resulting improved handling qualities were cost effective—a question that had to be faced in pre SAS days when increased tail size was the only possibility Everyone including chief engineers was delighted by the prospect of reduced wind tunnel and flight test hours for hinge moment tailoring and by the elimination of high altitude damping as a tail sizing criterion

But as might be realistically expected troubles began to appear The original SAS idea was to augment an existing natural stability derivative, e g the yaw damping N_r When designers started using higher gains and feedbacks other than "natural" ones they encountered servo response stability and coupling problems that were not elementary in terms of old classical design tools Issues of stability adequate response control surface rate saturation etc also arose for fully powered surfaces but were balanced of course by their desirable elimination of compressibility induced surface "buzzing ' nonlinear or excessive stick forces and the need for stable hinge moments thereby allowing the use of very closely balanced surfaces which would reduce the hydraulic power requirements There were thus many design considera tions involved in setting up a modern" 1950's airplane with a power boost system and a SAS to augment the natural stability of the aircraft

To cope with these considerations airplane designers started adapting some of the extant missile technology and in particular began to apply servo analysis techniques to flight control system design issues They also had to establish design requirements on and corresponding designs to achieve, artificial feel and force feedback to the pilot Some other flight control innovations engendered by their new albeit still rudimentary tools were the use of accelerometers for augmentation feedback input command shaping and automatic trim all impinging on all interacting with handling qualities

At about the same time the early tail sitter VTOLs began appearing some propeller driven some jet driven but all without the benefit of any particular handling quality requirements or experience Finally there were already problems with some of the new gadgetry in terms of un desirable sensitivity parasitic effects on the stick forces and other characteristics leading in certain circumstances to pilot induced oscillations (PIO's) which are still with us along with sensitivity problems (Refs 36 37) In fact it was a PIO problem on the F 89 that climaxed all these pressures and led to the development of a handling qualities theory based on closed loop analysis of the pilot/vehicle system and on the notion that regulation and precision flying would reveal the crucial flight handling aspects of the system

However the F 89 PIO problems were not solved by the application of early closed loop handling quality theory Because the PIO was rather benign it was in fact eliminated by a pilot with a little finer touch The basic issue was just a question of pilot adaptation and this is still a problem with PIOs which very often are not really due to malignant aspects of the system but rather to overenthusiastic or aggressive pilot control

At any rate, now that the idea of closing the loop around the pilot and the vehicle had been advanced, the first problem was to characterize the pilot in servo analytic terms There was no sudden leap all at once into the present practice of describing function characterizations of the pilot nor into a crossover model nor into characterizations of the pilot's neuromuscular lag etc It was necessary to go out and get data and fit it with an isomorphic model which had direct ties with observed pilot behavior Furthermore it was desirable to obtain good reception and understanding of the model by the flight control design fraternity most likely to need it and hopefully to use it which meant it should be in servo analytic (frequency domain) form Accordingly experiments and means of reducing the data to measure and model the pilot's characteristics when excited by random inputs were designed Random inputs rather than sinusoidal were used to deter mine the frequency response of an inanimate object because the human operator s characteristics are different and more meaningful under such circumstances At any rate models were derived, and were applied to exploratory studies of closed loop pilot airframe analysis of longitudinal and lateral data on conventional classical aircraft It was concluded that the theory was practical and powerful and accordingly some early goals[38] were set for its application as shown in Table 1 It should be noted that some of these basic purposes are still very germane to present problems that is there is still need to consolidate existing knowledge and extend and apply it to new areas

The first application efforts were confined to single loop situations and to what would now be called *inner* attitude loops; these revealed the importance and role of numerator zeros as new parameters for handling characterization These efforts also showed that there was inadequate data on and understanding of, the pilot's crossover conditions and other elements of the pilot model; these revelations spawned flight test experiments on dynamic pilot measurements by Princeton University[39] and later by Cornell Aeronautical Labora tory [40 41] The importance of numerator zeros had already been confirmed by flights[42 43] on what was originally termed and is still called ω_ϕ/ω_d effects i e , the dipole effect in the roll/aileron transfer function which sometimes creates problems with oscillatory roll response Later analyses concerned with multiloop situations continued to show the prominence of the numerator zeros as significant handling parameters (Refs 44 48)

Table 1 Early goals of pilot vehicle analysis

Focus attention on and explain the connections between subjective pilot opinion and pilot vehicle system performance
Form a foundation for the insights required to determine airframe configuration variants which offer possible flying qualities improvement
Provide a basis for deriving handling criteria for configurations with novel dynamic characteristics
Provide a unifying structure for the large amount of dynamic data previously treated as unconnected

Table 2 Practical uses of pilot vehicle control and handling theory

Make preliminary assessments of closed loop piloting problems and estimated pilot ratings of new designs/situations
Devise 'crucial experiments to economically explore suspected or known problems
Analyze data resulting from such experiments
Troubleshoot and fix field encountered handling problems
Consolidate data from diverse sources/vehicles

Table 3 Operator models

Type, Features, Form	Use
1) Simple $Y_p = K_p e^{-\tau s}$ or $Y_p = K_p$	Search for C L problems Identify significant handling qualities parameters and effects and likely loop structure Use $e^{-\tau s}$ if at all on inner loops not on outer
2) Performance $Y_p Y_c = \frac{\omega_c e^{-\tau s}}{s}$ in crossover region + remnant	Estimate pilot adaptation C L dynamic performance and pilot opinion/commentary
3) Compleat = 2 plus as appropriate:	Evaluate effects of:
Neuromuscular model	Manipulator force display and filtering characteristics
Vestibular model	Motion cues
Biodynamic (acceleration) model	Limb bobweight and torso restraints
Display scanning model	Head down instrument scanning behavior available control capacity

Over the years the pilot model and pilot opinion rating correlates have been continually upgraded and applied to a rich variety of airplane flight control system display design problems such as those connected with controllability limits multiple loop control display design and evaluation workload estimates and correlates and multiple axis con siderations All this applies to a wide variety of vehicles including aerospace (CTOL VSTOL helicopters entry vehicles) land vehicles (autos tractor trailers trucks buses recreation vehicles tractors motorcycles mopeds) and water borne vehicles (submersibles hydrofoils surface effect ships) Table 2 lists the practical and routine uses of pilot vehicle theory

One might expect that a method powerful enough to do all this would be very complex but many of the extensions analyses etc used in implementing this list can be and have been accomplished with very simple pilot models and analysis procedures Others have been somewhat more complex The range of models utilized is shown in Table 3 (Refs. 49 52) Tables 2 and 3 are broadly indicative of much activity in this area and it is worthwhile now to illustrate the detailed coverage and later the generally applicable insights gained thereby; that is what pilots like, dislike the strategy em ployed etc So let us go first of all into the pilot vehicle application areas that have been covered over the years This will be done in three steps: applications to design problems to flight encountered problems and to simulation The first step Table 4a covers design and certain of the items shown deserve clarification and discussion as follows

Limits of Dynamic Control'' refers to the pilot's ability to control unstable situations; analysis shows that this is very strongly dependent on the pilot's time delay Therefore there is a variation in the limit of dynamic control depending on the latencies peculiar to a particular human operator This fact has been used to devise a so called critical tracking task which progressively degrades a first order control task making it more and more aperiodically unstable until the operator finally loses control The value of the instability where control is lost is a measure then of his time delay This task has been used in a number of different applications to show the degrading effects of alcohol marijuana fatigue etc on human ability to maintain effective control (Refs 53 61) Most recently it was used as an interlock test to prevent habitual drunk driving [62,63]

The Carrier Landing Aids'' work started with a model of the pilot controlling a vehicle on the back side of the power curve and ended up with a fairly complete picture of how a carrier landing proceeds and how it can be improved by modification of the optical guidance stabilization system These ideas were eventually implemented in an actual system which is now deployed on two aircraft carriers and is about to become standard for the rest of the carriers in the United States Navy

Table 4b continues to flight encountered problems As indicated earlier ' Pilot Induced Oscillations'' (PIOs) have been a problem for a long time Most appear to be single loop problem situations but there is at least one example of a flight encountered two loop PIO problem [36]

Carrier Landing has already been alluded to in terms of its effect on design but arriving at an understanding of this flight encountered problem led to an interesting multiple loop limitation What happened was that on the back side of the drag curve where it is necessary to use throttle to control altitude (and elevator to control attitude) there is a calculable speed below which increasing loop tightness or gain *degrades* performance; i e the system bandwidth is actually reduced by increasing gain This is termed a performance or dynamic reversal in the path response and the speeds at which it occurs correspond with pilot chosen carrier approach speeds[64] for airplanes suffering from inability to arrest rate of sink

The analysis of certain High Angle of Attack Depar tures'' indicated that it was possible to get an adverse numerator term which would cause one of the airplane's closed loop poles to diverge as the pilot regulated attitude and slowly increased his angle of attack The attitude regulation feature actually promoted rapid departures above a certain point due to the presence of the coupling numerator zero

The Six Degrees of Freedom Control Situation' is one in which in addition to the normal elevator aileron rudder and thrust controls there are direct lift and direct side force controls as well Under these circumstances there is the possibility of direct translational control and maneuvers other than banking as a means of executing turns The significant

Table 4 Some past applications of pilot vehicle display system analyses to a) design

Situation	Analysis results	References
Basic airframe and primary control system	Predict multiple closed loop pilot vehicle system problem areas and assess possible solutions	44 48 75 77 80 82 90 111
Limits of dynamic control	Strongly depends on pilot time delay	44 98 53 54 112 124
Stability augmentation tradeoffs	Candidate stability augmentation systems pilot behavior and work load system performance and compromises reliability redundancy etc	125 133
SAS failure effects	Pilot actions and resulting air craft excursions	134 140
Competing pilot display formats Manual control AFCS monitoring	Information requirements scan patterns workload assessment factors and criteria	141 155
Flight director	Command display laws status information requirements flight director/pilot/stability augmentation tradeoffs	142 156 167
Carrier landing aids	Optimum FLOLS control and stabilization	44 168 173
Categories II and III landing system	Probability of approach success decision state windows touchdown statistics manual/automatic trade offs guidance sampling	174 177
Energy trim management	Simplified controls/displays	178 181
Actuation systems	Permissible lags non linearities rate limits	182 183

thing about these kinds of control situations is that they are usually contaminated to some extent by control coupling due to impure side force or lift generating surfaces The effective bandwidth for piloted control can be increased or decreased by such contamination It was hypothesized and then shown experimentally that the details of such deleterious effects are unimportant the effect on total system bandwidth being of prime significance to the pilot

Table 4c delineates simulation applications Here the most significant and most usual form of analysis is that conducted first to plan experiments and then to analyze them Exercising the pilot vehicle model to predict those areas likely to be critical allows a considerable reduction in the matrix of ex periments without loss of generality The same thing is true in interpreting and generalizing the results Once the basic cause of the problem is understood it is relatively easy to generalize and to predict future problems and solutions more effectively

Although the context of the foregoing tables and the discussion concerning them was in respect to airplane or flight encountered problems as indicated earlier there is a universal quality to handling requirements in general, regardless of the vehicle type Of course this quality depends on the presence in all cases of the human operator in an active control role This universality can be illustrated with two pertinent examples as follows

Figure 1 is a plot that may be familiar to many readers It stems basically from some quite old but classic roll simulator data taken by Creer[65] and shows the variation of pilot rating (numerical and adjectival) with roll time constant and gain The numerical scale (Ref 66) is such that 3 5 and 6 5 are the boundaries between satisfactory and unsatisfactory and unsatisfactory and unacceptable respectively Overlaid with a dotted line is the corresponding plot from experimental data taken in a number of various automobiles with different turning dynamics [67] It shows that the region considered "best" for a car in terms of turn rate vs gain fits nicely within the desirable airplane region However because one of the purposes of steering control in a car is to take evasive action against adjacent and oncoming vehicles in heavy and sometimes erratic traffic a faster response than that needed in an airplane is called for; the reduced time constant reflects this.

The other example Fig 2 is one recently formulated in connection with cross control coupling effects The basic plot is for airplane heading control[68] and shows the cross control parameter in this case aileron yawing/rolling acceleration vs a phasing parameter μ that indicates whether the rudder sequencing with aileron is critical or not As shown in the basic plot the least critical area one that can accommodate the biggest cross coupling is in the region where μ is ap proximately equal to minus one That also happens to be the region where some crew opinions on cross coupling due to multiple surfaces on a submersible were recently obtained [69] In this case the secondary (lifting) surfaces were in the pitch plane and were either large or small and located near the bow or on the vertical (fair water) sails " There was a required degree of coordination between these and the aft pitch control surface in order to accomplish a seakeeping task successfully The differential rating between the two sets of data was about two points on a five point scale which fits in fairly well with the spread in the basic data Therefore although in a com pletely different surrounding and task, the results are very consistent with those for the coordination effort required to control an airplane

Table 4 (Continued) Some past applications of pilot vehicle display system analyses to b) flight encountered problems

Situation	Control problem	Causes	References
Pilot induced oscillations	Pitch (single loop)	Sensitivity; bobweight/feel spring; loss of pilot lag; elevator rate limiting	36
	Roll (single loop)	ω_ϕ/ω_d effect; lateral bobweight	
	Pitch and altitude (2 loops)	Excess time delay in control loop; adverse pilot location	184 190
Weapon delivery	Heading aim wander (3 loops)	Loss of roll loop; lateral directional multiloop cross coupling	191 194
Carrier landing	Path control inability to arrest rate of sink (2 and 3 loops)	Dynamic reversal in path	45 84 93 195 199
Attitude control	Pitch (single loop)	Improper pilot/stability augmenter matching; high control sensitivity	199 202
High α departures	Pitch and roll (2 loops)	Adverse pitch roll (coupling) numerator	48 203 208
6 DOF control	Adverse control coupling	Reduction in effective system bandwidth	209 210

Table 4 (Concluded) Some past applications of pilot vehicle display system analyses to c) simulation

Situation	Analysis results	References
Pre experimental analysis	Predict critical areas and parameters guidance for experimental design pilot briefing questionnaire	45 211 214 217 220
Post experimental analysis	Interpretation and generali zation of results	211 221
Competing piloting techniques	Pilot control procedures system performance and safety margin differences Control system refinements to simplify piloting technique	211 216 221
Motion cue simulation	Task dependent motion sensi tivity, optimum washout design	222 236

The foregoing examples which are only a few of many in the literature illustrate the power and applicability of closed loop man/machine analysis to the revelation understanding and simulation of handling related design problems During the past 25 years the theory and practice has broadened to include new and novel and even old and classical system configurations This has occurred through improved un derstanding of operator adaptation in the closed loop context and of the adjustment and loop closure rules necessary to predict and utilize such adaptations for example Ref 49 Furthermore it can be anticipated that such understanding will gradually increase by virtue of some lately developed methods for obtaining pilot identification in routine flying tasks without the requirement for specialized disturbing inputs (Refs 70 74) Such techniques are currently being used for instance, to help validate simulation relative to full scale flying That is identifying exactly what the pilot is doing in a given flight control situation and comparing that with his behavior in a simulator can establish that the simulator is in fact mimicking flight The significant point is that a valid simulator should reproduce the pertinent in flight pilot control behavior

At any rate, deriving from this improved understanding and the long list of applications are a number of observations and catalogs of desirable or undesirable closed loop quan tities Table 5 lists some generally desirable closed loop features There are not too many surprises here for those who have been following the literature

Relative to the first item past multiple loop problems where either a parallel or series loop structure was considered have shown the series loop structure to make much more sense where a single control was being utilized In that case the leads developed in the inner loop are propagated to the outer loop and are very helpful in effecting a good outer loop closure

The point of the second item is that where a crossfeed is helpful in ' purifying'' the effective control the trained pilot will adapt one

The next two items are somewhat better known and ac cepted That is first that the closed loop low frequency performance is optimum in some sense corresponding to the minimization of rms error By that it is meant that the gain crossover frequency phase margin etc adapted are reasonably close to those required to effect minima among a variety of errors—control usage primary response and secondary responses as well Second the fact that the pilot adapts to make the complete open loop transfer function from input to output look like K/s in the crossover frequency region is an observable experimental fact

If the lead required to effect such K/s ness is greater than one second the pilot's opinion will be degraded as will his workload capacity

When operating in a multiple loop situation the inner loop's crossover frequency is generally on the order of three to four times that of the outer loops In that way there is a frequency separation of say the inner attitude from the outer path response In some cases there is even a further distinc tion among trajectory response parameters; that is speed response is even slower than altitude response So the progression is from attitude to altitude to speed

In all cases it appears that an adequate closed loop damping ratio is in the range of 0 35 0 5

Good performance requires closures without midfrequency droop (closed loop gain 3 dB or so less than unity in the region below crossover frequency) This along with others of the above, may be recognized as the basis for the original Neal Smith criterion for short period control [75]

A final point is that in all cases increasing the gain or the pilot lead should produce a favorable effect on performance and bandwidth and damping If it does not then the system is unsuitable There are a number of instances where that is the case The carrier approach performance reversal has already been mentioned; in that case increasing gain decreases the system's bandwidth There are similar cases among some marginally controllable VTOL aircraft where sensitivity to *lead* is very poor i e despite increasing pilot lead there is no net gain in performance

To be more specific and detailed good path regulation properties are indicated below

Good Path Regulation Properties

Inner Loop (e g Attitude) Control Integrity and Equalization Potential

The inner attitude loop is fundamental to path control regardless of piloting technique and should have response characteristics generally faster better damped etc than the primary path loop A minimum open loop crossover frequency of the order of 2 rad/s[76] with adequate gain and phase margins is desirable Closing the inner loop should improve the phugoid mode damping to inhibit airspeed fluctuations and provide overall path mode equalization insensitive to and tolerant of the 'tightness'' or 'looseness' of attitude control

Adequacy and Ordering of Path Control Loop Bandwidths

The h loop (with θ closed) should have faster response than the u loop by at least a factor of 3; its minimum crossover with adequate gain and phase margins and without equalization should be of the order of 0 5 rad/sec [77]

Uncoupled or Complementary Control Responses

It should be possible to control h without exciting excessive excursion in u and vice versa However if some degree of coupling exists the responses should be complementary i e control actions required to regulate one path variable help in regulating the other

Minimum Depletion of Safety Margins

During path regulation and control limits due to stall buffet, control comfort etc must never be exceeded and excursions into the available margins should be minimized

Control Economy

The pilot desires to use the minimum number of non sensitive feedback loops with little or no equalization and/or crossfeeds Such 'economical'' control allows him sufficient excess capacity for other functions

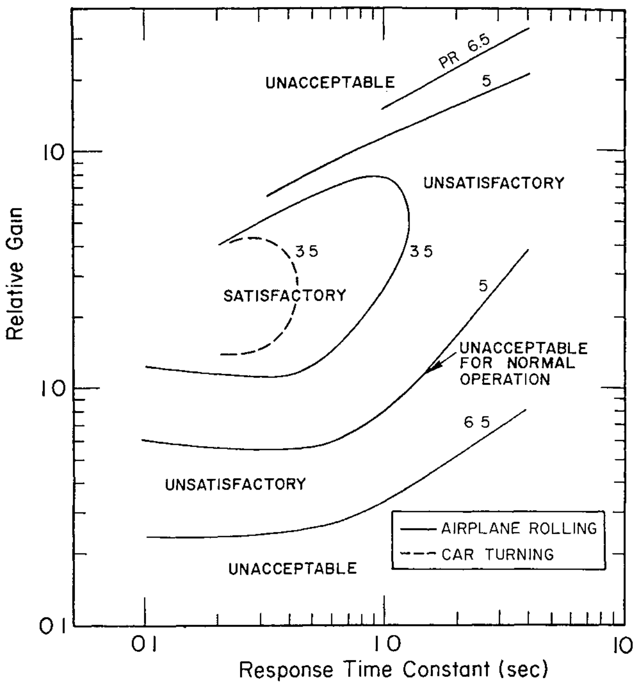

Fig 1 Comparison of good handling boundaries for airplane rolling and car turning

Table 5 Desirable closed loop features

Series loop structure for single control
Crossfeeds to directly negate subsidiary responses
Closed loop low frequency performance optimum ~ minimum RMS error
Pilot adaption to make $Y_p Y_c \to K/s$ in the crossover frequency region
Pilot lead $T_L < 1$ to avoid degraded opinion workload capacity
Frequency separation of inner outer loops e g $\omega_{c_i} = 2$ 3; $\omega_{c_0} = 0$ 5 1 0
Adequate closed loop damping $\zeta_{CL} \geq 0$ 35 0 50
Avoid closed loop mid frequency droop for good opinion
Favorable sensitivity to increasing K_p T_L

Control Harmony

An otherwise dynamically good airplane can be seriously degraded if control sensitivities are too high or too low and/or if the relative sensitivities are disproportionate

Some specific pilot centered path regulation 'problems'' representing deviations from the ''good properties listed above are useful in pinpointing known sources of pilot complaints or in suggesting aircraft and/or flight control system modifications to improve pilot acceptance

Attitude Control

Inadequate Bandwidth

Such problems are often associated with low short period stiffness where the attitude response is dominated by the phugoid mode These situations require excessive pilot lead compensation (Refs 76 and 78)

Inner Outer Loop Equalization Conflict

This results when pilot lag T_{I_θ} is required in the attitude loop [76] thereby restricting the path mode bandwidth

Low Static Attitude Gain

These properties are another manifestation of back sidedness Sufficiently low values of static gain limit the

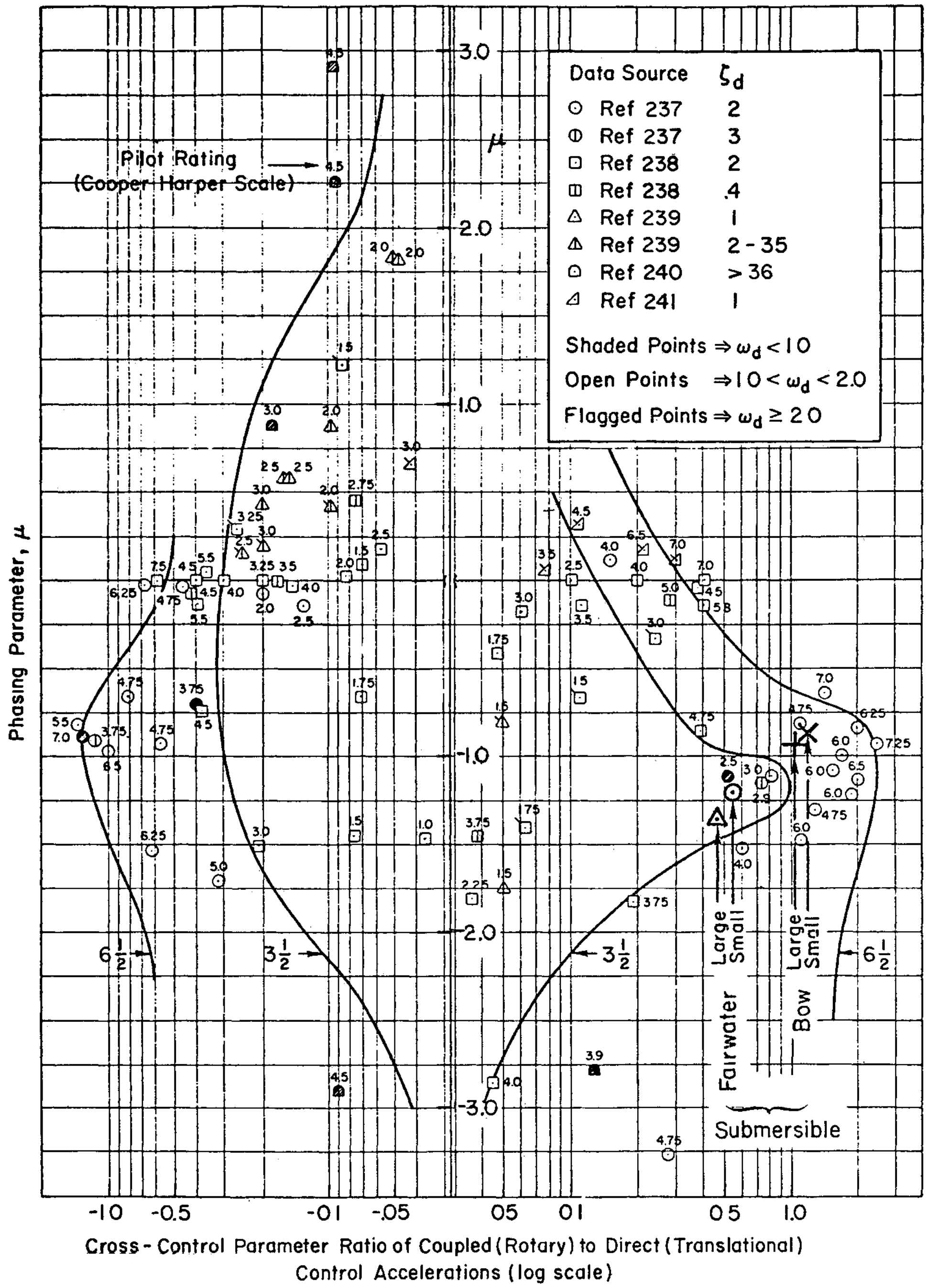

Fig 2 Comparison of allowable control coupling effects for airplanes and submersibles

pilot s ability to separate u and $\dot{h}$ responses Also attitude trimmability and the use of attitude as a speed reference are degraded resulting in increased attentional demands on the pilot [79 80]

Oversensitivity to Gain/Equalization

Attitude gain[64] and lead equalization[80] sensitivity are underlying control problems affecting path regulation

Path Control

Performance Reversals

These occur when increased pilot gain and/or lead cause a net *loss* in performance Typically closure of the innermost loop restricts the path mode bandwidth [64 79] Other boxed in ' reversal situations[80] constrain the pilot not only to a given control strategy but also to narrowly confined values of gain and/or lead Increasing *or* decreasing gain equalization causes an undesirable performance degradation

Inadequate Bandwidth

This is primarily an altitude loop (with attitude closed) problem When the loop crossover frequency is less than about 0 3 to 0 4 rad/s [77] the pilot rating will be un satisfactory

Inadequate Response Separation

This refers to undesirable ' mixing' of u and $\dot{h}$ response If u is faster than $\dot{h}$ the ' mixing'' is especially bad; in general u responses faster than about half the $\dot{h}$ response (assuming the latter is adequate as above) are undesirable

Difficult or Conflicting Crossfeeds

These have already been discussed relative to dynamic problems Additional difficulties arise when the necessary or required control actions are too large are unnatural (e g reversed sign), or when they limit regulation performance (e g by reducing effective gain or bandwidth)

Excessive Depletion of Safety Margins

This can be caused by any combination of the above deficiencies In extremo cases the type and smallness of the available margin may dictate the control strategy e g if stall margin is small control h with throttle rather than with elevator

Low (High) Effective Path Gains

Departures in either direction from desirable gain levels result in degraded ratings and poorer pilot acceptance Analysis of the regulation control activity in terms of rms control deflections or forces can sometimes provide a clue to degrading gain levels [81 82]

Although these lists are not exactly short anyone who has been exposed to the large variety of open loop parameters which can be involved in specifying handling qualities will recognize that this is a much abbreviated list of *pilot* centered requirements and problems as opposed to an *airplane* or systems centered set which would be much more diverse and diffused

As already mentioned some of these desirable qualities have been translated directly into flying qualities requirement terms for example by Neal Smith[75] and also in the proposed new prime standard replacement[83] for 8785 which recognizes the existence of lower-order equivalent system bandwidth criteria stemming from pilot vehicle analysis considerations

Also some of the pilot model adjustments and closure rules have been incorporated into computer programs e g Mc Pilot [84] Drivem [85 86] and Paper Pilot [87 89] These programs are of course intended to help make man/machine closed loop analysis routine but routine'' can become a synonym for thought avoidance To be a good designer one cannot be routine and the same is true for a good flying qualities analyst One must learn to think in closed loop terms and about what the pilot is trying to do This and taking ad vantage of and extending the quantitative and qualitative knowledge about what human operators like and do not like and can and cannot do as in the above listings will go far toward eliminating recurring teething problems with new untried systems and configurations

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