

## NEW DEVELOPMENTS IN FLYING QUALITIES CRITERIA WITH APPLICATION TO ROTARY WING AIRCRAFT

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### Abstract

Some recent considerations and developments in handling quality criteria are reviewed with emphasis on using fixed wing experience gained in developing MIL-F-8785C and the more recent Mil Standard and Handbook. Particular emphasis is placed on the tasks and environmental conditions used to develop the criterion boundaries, SAS failures, and potential fixed wing criteria that are applicable to rotary wing aircraft.

### Introduction

Historically, the handling qualities of rotary wing aircraft have been vastly inferior to their fixed wing counterparts. For example, the pitch attitude control of many operational helicopters will not even meet the Level 3 requirements of MIL-F-8785C. (Level 3 is defined as a Cooper-Harper rating of worse than 6-1/2 or "Flying qualities such that the airplane can be controlled safely but pilot workload is excessive or mission effectiveness is inadequate or both."). An example is illustrated in Fig. 1 where it is shown that the time to double amplitude for several operational helicopters is in the extreme Level 3 region. The major deficiencies of rotary wing aircraft are nearly always associated with: excessive cross-axis coupling; inadequate dynamic stability; and unacceptable stick force gradients. Interestingly, the Cooper-Harper pilot ratings from many helicopter handling quality studies (for example, Refs. 1 and 2) indicate that rotary wing pilots are willing to accept much less than their fixed wing counterparts. This is shown in Fig. 2 where pilot ratings of 2 to 3-1/2 are found well into the Level 2 region defined for pitch control in MIL-F-8785C. (Level 2 corresponds to pilot ratings of 3-1/2 to 6-1/2 in MIL-F-8785C.) This is felt to occur for two reasons: 1) helicopter pilots are trained to cope with, and expect as "normal," severe instabilities and cross-axis coupling; and 2) the tasks used in the evaluations were not sufficiently demanding.

### Consideration of Handling Quality Evaluation Tasks

In recent years the task used in experiments to obtain handling quality pilot ratings has been found to have a profound effect on the results. For example, in the landing approach experiments of Ref. 4 the pilots were required to touch down at a

precise point on the runway. In a paper presented to the AGARD Flight Mechanics Panel in 1981 the authors of Ref. 4 cited a case where a pilot gave a surprisingly good rating to what should have been a particularly poor configuration. However, the landings were not in the prescribed touchdown area and the author (who was also the safety pilot) insisted that the evaluation pilot improve his performance. On the very next run, in an attempt to achieve the required precision, a severe PIO was encountered near touchdown. Needless to say, the

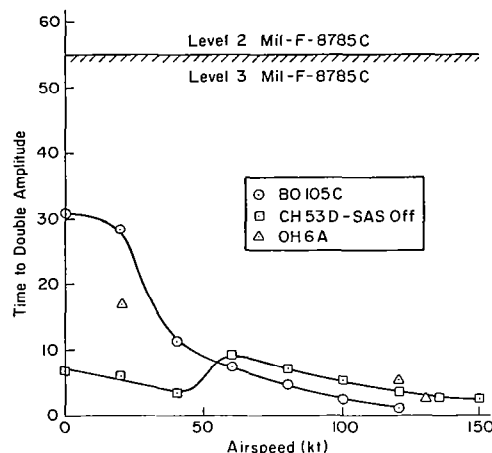


Fig. 1 Illustration that conventional unaugmented helicopters fall well below fixed wing standards even for a failed SAS (data from Ref. 3)

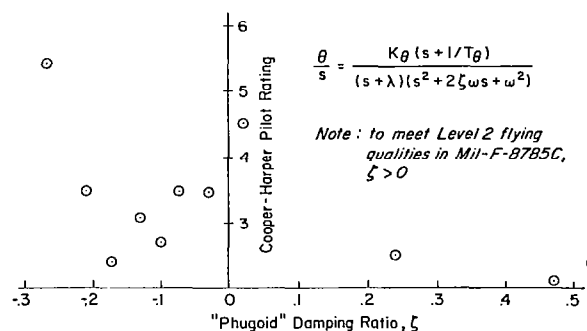


Fig. 2 Cooper-Harper pilot ratings vs. damping ratio in hover;  $\omega < 0.5$  rad/sec (data from Ref. 1)

evaluation pilot revised his rating downward considerably. The point here is that only by insisting on a precision task was the experimenter able to expose deficient handling qualities that would have otherwise gone unnoticed. In using existing data to develop boundaries for the helicopter handling qualities specification, we must critically evaluate the task. Some suggested evaluation factors might be:

1) Does the task require the same precision as required by operational missions?

2) Does the task require the same degree of aggressive maneuvering as the proposed operational missions?

3) Are the tasks well defined, or does the task encompass a series of subtasks such as an entire approach, hover, and vertical descent? If the latter is true, can we identify what subtask has the most impact?

4) Are the data being used as a compromise because no better data are available?

5) Are the atmospheric disturbances of low enough frequency and large enough magnitude to displace the aircraft from its path?

6) Are the available outside visual cues consistent with the proposed mission?

Unfortunately, these factors may well eliminate most existing data. The last factor was found to be especially important for low speed and hover in Refs. 5 and 6 and is briefly reviewed in the following section.

Effect of Outside Visual Cues on Required Level of Augmentation and Display

Most of the available data for low-speed and hover handling criteria have been obtained with good visual outside references and with no requirement for unattended operation. The real-life existence of secondary tasks, and intermittent to total loss of visual references, places increased demands on the pilot -- an effect which is not discernible from such data. For example, pilot ratings for an unaugmented helicopter (Ref. 2) and a highly augmented translational rate command (TRC) system (Ref. 7) all fall within the acceptable region (pilot rating better than 3.5). This result is a consequence of experimental scenarios that tend to be tailored toward the systems being investigated. That is, with pure rate systems the scenario is usually benign, thereby usually allowing intense, full-time attention; whereas with a translational rate command system the task tends to be more demanding. The most critical contributor to the total pilot workload appears to be the quality of out-the-window cues for detecting aircraft attitudes, and, to a lesser extent, position and velocity. Currently, these cues are categorized in a very gross way by designating the environment as either VMC or IMC. A more discriminating approach is to classify visibility in terms of the detailed attitude and position cues available during the experiment (or proposed mission), and to associate handling qualities requirements with these finer-grained classifications.

The need for certain specific outside visual cues has been inferred from closed-loop considerations. These OVC levels have been logically quan-

tified in terms of a scale as shown in Fig. 3a. Certain specific closed-loop considerations, which were considered in formulating the scale, are summarized below and by the generic closed-loop structure in Fig. 3b.

1) A requirement for closure of the attitude loop implies VMC conditions and must prevail for adequate control.

2) If the equivalent system dynamics require closure of position and position rate, but not attitude, a minimum set of operating conditions quantified as OVC = 3 is defined.

3) OVC = 4 quantifies the operating condition where velocity and attitude cues are not available; that is, only the outer loop in Fig. 3b can be closed by the pilot.

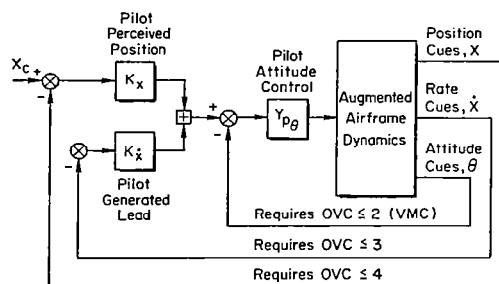
4) OVC = 5 indicates that no outside visual cues are available.

Pilot workload can also be reduced via improved displays. Recent work in the control/display tradeoff area includes the Calspan X-22 flight tests (Ref. 8) and the CH-46 variable-stability helicopter (Ref. 9).

Based on the above considerations, the required level of augmentation and cockpit displays can be related to the visibility levels associated with the missions defined for the helicopter. An initial attempt was made to establish a format for specifying the augmentation and displays required for various levels of outside visual cues in Refs. 1, 4, and 5 and is repeated in Table 1 for convenience.

	Attitude Cues	Position and Velocity Cues	OVC Level
VMC	Easily obtained.	Easily obtained.	①
	Somewhat obscured. Requires full concentration to obtain continuous attitude information	Easily obtained	②
Partial IMC	Inadequate in some sectors of the visual field.	Adequate position. Marginal rate cues.	③
	Inadequate over most of visual field.	Position and rate cues are marginal. Rate cues are intermittently unavailable.	④
IMC	Not available.	Not available.	⑤

a) Quantification of Outside Visual Cues (OVC)



b) Required Outside Visual Cues for Control

Fig 3 Development of outside visual cue scale

Table 1. Augmentation and displays required for various levels of outside visual cues

Augmentation	MIL-F-8785C flying quality level	Pilot display		
		Raw data	Mechanical flight director	Integrated display-flight director plus aircraft velocity information
Rate	Level 1	1	2	3
	Level 2	2	4	5
Rate command/ attitude hold	Level 1	2	3	3
	Level 2	2	5	5
Attitude (response feedback)	Level 1	2	3	3
	Level 2	2	5	5
Attitude (model following)	Level 1	2	4	4
	Level 2	2	5	5
Translational rate with attitude	Level 1	3	5	5
	Level 2	3	5	5
Translational rate with direct force control	Level 1	3	5	5
	Level 2	3	5	5

SAS Failures

The concept of "Levels" is used in MIL-F-8785C to specify the allowable degradation in handling qualities in the presence of failures. The specification of Level 2 and 3 handling qualities will tend to be more critical in rotary wing aircraft in terms of driving the cost and complexity of the SAS. This is a result of the relatively poor handling qualities of the unaugmented helicopter and hence the large change in dynamics before and after a failure of the SAS. This is illustrated in Fig. 4, which shows a dramatic shift in the characteristic modes after a SAS failure in the CH-53D. Clearly, the specification of Level 2 handling qualities that are better than most unaugmented helicopters would have significant implications on complexity and cost.

Potential Fixed Wing Criteria Applicable to Rotary Wing Aircraft

The mission requirements for rotary wing aircraft have become increasingly severe to the point where marginal handling qualities can no longer be tolerated. In most cases satisfactory inherent stability and coupling cannot be obtained without some level of stability augmentation. Indeed, many modern helicopters employ a stability augmentation system. It is therefore not unreasonable to expect the same quality of response (to control inputs and turbulence) in helicopters that is currently enjoyed by fixed wing pilots. In fact, the rapid and precise maneuvering required in some NOE missions may make it necessary to impose more stringent requirements than are necessary for fixed wing aircraft.

The applicability of some requirements currently proposed for the fixed wing Mil-Standard to

rotary wing aircraft are reviewed in the following paragraphs.

Lower-Order Equivalent Systems

The basic intent of lower-order equivalent systems is to define a very high-order system in terms of a few variables that describe the fundamental response characteristics important to the pilot (see Ref. 10). This can be done in the time domain or in the frequency domain, although all work done to date has been in the frequency domain. Equivalent systems are a viable concept for defining Level 1 flying qualities for helicopters.

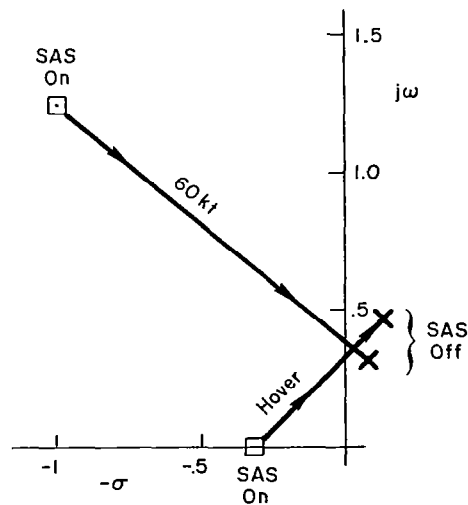


Fig 4 Effect of SAS failure on key response modes of CH-53D (Data from Ref. 3)

However, the complexity of the responses of unaugmented helicopters, due to inter-axis coupling, makes it unlikely that useful equivalent system forms of sufficient generality can be defined for the Level 2 and 3 boundaries.

### Bandwidth Criterion

The bandwidth criterion was developed originally for fixed wing aircraft with direct force control. Because of the almost infinite variety of responses that can occur due to inter-axis coupling, it was difficult to define a lower-order equivalent system form for aircraft with direct force control. In looking for an alternative solution it was hypothesized that the coupling itself was incidental, and mattered only to the extent that it interfered with the pilot's ability to adequately perform tight closed-loop tracking. This of course is directly related to the bandwidth, which was defined in Ref. 11: "The bandwidth of the specified response to a particular control input is defined as the lowest frequency for which the (open-loop) phase margin is at least 45 deg and the gain margin is at least 6 dB." (See Fig. 5 for a graphical description.)

The Ref. 11 variable-stability in-flight simulation results indicated that the Bandwidth Hypothesis was indeed valid, i.e., the coupling itself mattered only to the extent that it affected bandwidth. These results were extended to pitch attitude control in Ref. 12.

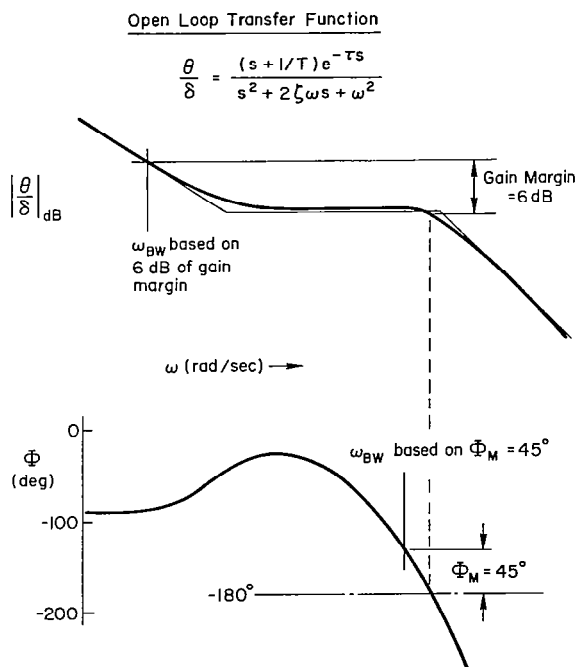


Fig. 5 Effect of using gain and phase margins to define bandwidth

From a pilot's point of view, a high-bandwidth response would be described as "crisp" or perhaps "rapid and well damped." Typical commentary for a low-bandwidth response might be "sluggish response to control input" or "tends to wallow." There is a long history of correlating such commentary with basic aircraft stability derivatives and/or parameters made up of such derivatives (e.g.,  $\omega_{sp} = \sqrt{Z_w M_q - M_{\alpha}}$ , etc.). The term bandwidth comes more naturally into play when feedbacks and crossfeeds are combined to produce aircraft responses that are unconventional in that the classical modes are no longer appropriate definitions.

The advantage of this approach is that it does not assume a particular form of response. Hence it may be suited for helicopters, where coupling tends to mask the classical response forms. The deficiency of the bandwidth criterion in its present form is that it does not directly account for the pilot's ability to supply crossfeeds to counteract coupling. It seems intuitively obvious that responses requiring only a simple crossfeed (such as pure gain) would be more acceptable than those requiring complex shaping. This concept was investigated in Refs. 13 and 14 for the turn coordination problem in fixed wing aircraft and is reviewed briefly in the following section.

### Inter-Axis Coupling

Inter-axis coupling is well recognized as one of the most severe handling quality problems with unaugmented rotary wing aircraft. While fixed wing aircraft tend to be much less affected by such coupling, a significant amount of yaw response to roll control inputs is not uncommon at high angles of attack. In such cases the pilot must use rudder coordinated with aileron inputs to eliminate the undesirable heading excursions that occur. It was hypothesized in Ref. 14 that the pilot opinion of roll-yaw coupling would be directly related to the magnitude and shaping of the rudder control required. Such an approach is expected to be directly applicable to the inter-axis coupling characteristics of helicopters. Because of its possible direct application to helicopter coupling, the results of Ref. 13 are briefly described below.

While the use of "coordinated" aileron and rudder is accepted as common piloting technique, a quantitative measure of what exactly is acceptable or desirable is not known. The purpose of this study was to provide a quantitative measure of the aileron-rudder sequencing required to eliminate roll-yaw coupling and thereby achieve coordinated turns, and to correlate this with pilot opinion ratings from available data. To achieve this end Ref. 13 considered the aileron-to-rudder crossfeed necessary to exactly cancel the inter-axis coupling. This idealized crossfeed provides a measure of pilot acceptability of heading control because it is indicative of: the complexity of the rudder activity necessary to achieve perfectly coordinated turns; and the heading excursions that occur when the pilot does not use rudder. Note that these considerations apply equally well to the known coupling between pedal, power, cyclic and collective in an unaugmented helicopter.

Two parameters are defined in Ref. 13:  $\mu$ , which defines the shaping of the rudder crossfeed; and  $N'_{\delta_{ac}}/L'_{\delta_{ac}}$ , which defines the magnitude. The frequency response characteristics of the aileron-to-rudder shaping as a function of the sign of  $\mu$  are shown in Fig. 6 in terms of literal expressions for the Bode asymptotes. These asymptotes indicate that the magnitude of the rudder required to coordinate is a function of  $N'_{\delta_{ac}}/N'_{\delta_{ac}}$  at all frequencies and that the shaping of the rudder response is determined by  $\mu$ . These parameters are summarized in terms of their analytical and pilot-centered functions in Table 2.

The details of the criterion are presented in Refs. 13 and 14. The criterion boundaries and the data used to support these boundaries are given in Fig. 7. It is interesting to note that the ideal crossfeed was not a pure gain ( $\mu = 0$ ). Actually, a little proverse yaw ( $\mu = -1$ ) is seen to be desirable. Similar results could be expected with helicopters, i.e., the coupling can actually be favorable.

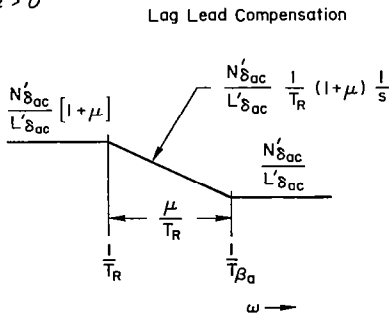
### Conclusions

A great deal of the experience gained in developing handling quality criteria for fixed wing aircraft is directly applicable to rotary wing aircraft as well. In this paper we have reviewed a

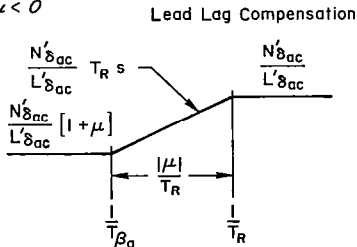
Table 2. Parameters defining the aileron-rudder crossfeed

Parameter	Analytical function	Pilot-centered function
$\mu$	Defines shape of $Y_{CF}$	Determines complexity of rudder activity necessary for ideally coordinated turns; also defines phasing of heading response when rudder is not used.
$N'_{\delta_{ac}}/L'_{\delta_{ac}}$	Defines magnitude of $Y_{CF}$	Determines magnitude of required and/or high-frequency yawing induced by aileron inputs.

For  $\mu > 0$



For  $\mu < 0$



$\delta_{rc}$  = normalized rudder control  
 $\delta_{ac}$  = normalized aileron control

Fig. 6 Asymptotes of aileron-rudder crossfeed

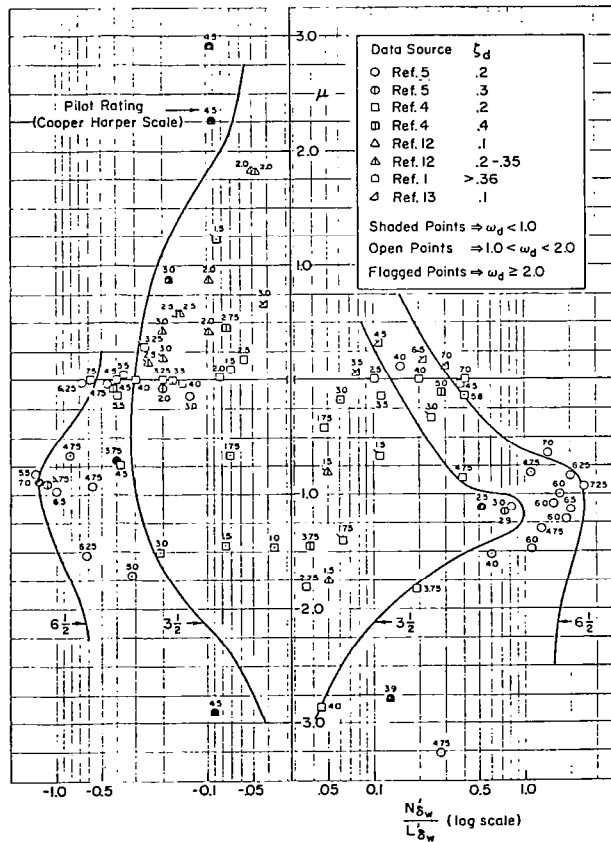


Fig. 7 Pilot rating correlation with crossfeed parameters

few areas that seem particularly salient. Summarizing, these are:

1) The piloting task and environment are overriding considerations in developing and using handling quality criterion boundaries.

2) Helicopter pilots have historically been willing to put up with considerably more degraded handling qualities than have fixed wing pilots. The increasing severity of helicopter missions is reversing this trend.

3) Outside visual cues and cockpit displays must be considered when structuring a helicopter handling quality specification.

4) The poor inherent handling qualities of rotary wing aircraft make SAS failures more critical than for fixed wing aircraft. Attempting to impose fixed wing requirements for Levels 2 and 3 is probably not practical in terms of cost and complexity.

5) Many handling qualities criteria developed for fixed wing aircraft should be directly applicable to helicopters with appropriate revisions in the numerical limits and boundaries.

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