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Recent Developments in Navy V/STOL Flying Qualities Criteria

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Recent developments in flying qualities criteria for fixed-wing V/STOL aircraft are reviewed and summarized. The criteria considered are limited to those applicable to hover and low-speed flight (airspeeds less than approximately 35 knots in any direction). Conclusions and recommendations resulting from development programs including equivalent system analyses and control/display system tradeoffs are presented. Results of both manned, ground-based simulations, and in-flight investigations are included. Comparisons with the existing V/STOL Flying Qualities Specification, MIL-F-83300, and selected full-scale data are made. Ongoing and future programs in the area are discussed.

Nomenclature

ES	= equivalent system
HOS	= high-order system
IFR	= instrument flight rules
IMC	= instrument meteorological conditions
K	= transfer function high-frequency gain
LOS	= low-order system
M	= mismatch [see Eq. (1)]
OVC	= outside visual cue
s	= Laplace operator, 1/s
T	= time constant, s
VFR	= visual flight rules
VMC	= visual meteorological conditions
$1/T$	= first-order transfer function factor of the form $s+1/T$
ζ	= second-order damping
ζ,ω	= second-order transfer function factor of the form $s^2+2\zeta\omega s+\omega^2$
λ	= first-order inverse time constant, 1/s
τ	= transport lag time, s
ω	= frequency, rad/s
ω_d	= damped natural frequency, rad/s

Introduction

THE current V/STOL Flying Qualities Specification, MIL-F-83300,[1] was adopted by the U.S. Navy and U.S. Air Force in December 1970. The specification was based, to a large extent, on helicopter flight experience due to a general lack of full-scale, fixed-wing V/STOL data. Since its adoption the specification has never been used in the procurement of a new airframe, but it has been applied/tested in several studies investigating the characteristics of existing and proposed fixed-wing V/STOL configurations. Included among these are the AV-8A, YAV-8B, and VAK-191B.[2-4] These investigations have identified some shortcomings in the existing specification—both in its quantitative requirements and its qualitative classifications. The more pertinent of these identified weaknesses include 1) considerable conservatism—particularly in yaw; 2) too much reliance on helicopter experience at low speeds; 3) inadequate consideration of IFR (IMC) flight requirements and the attendant information display requirements; 4) insufficient dynamic stability criteria for multimode control schemes; 5) difficulty in interpreting/applying some criteria to highly augmented systems; 6) inadequacy of some criteria for operation from small seaborne platforms.

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Recent exploratory development efforts[5-10] have attempted to provide data to alleviate the preceding deficiencies. This paper will provide an overview and results of some of these studies. Owing to both space limitations and data availability, only hover and low-speed flight criteria are included.

One particular area where the current specification exhibits what is probably its greatest shortcoming (from a Navy point of view) is in its lack of consideration for operations from small ships under adverse environmental conditions.[11] A manned simulation experiment at the NASA ARC in March 1979 investigated the effects of these extreme environmental conditions and the more significant results are presented herein.

Another area of significant concern (and proposed revision) is the application of low-order dynamic criteria to complex, high-order closed-loop aircraft/control dynamics of the type most likely to be exhibited by advanced V/STOL aircraft. Current thinking within the Navy and elsewhere tends to support the equivalent system (ES) approach developed by Hodgkinson and LaManna[12] and included in the revision to the CTOL Flying Qualities Specification, MIL-F-8785C.[13] A recent Navy sponsored effort[10] has attempted to develop guidelines for the application of this type of analysis to low-speed and hover flight. Several revised dynamic criteria have been proposed[8] utilizing the simplification afforded by an ES approach.

Navy sponsored as well as contractor supported work is continuing, particularly as applicable to the transition and conversion flight regimes. In-flight variable stability simulation is ongoing and planned to validate and further refine criteria as they are proposed. These programs are briefly reviewed herein.

Recent Studies and Results

Control/Display System Requirements

The complex interaction between displayed information and control augmentation available to the pilot has been known and studied over the years for CTOL aircraft. Research has concentrated on air-to-air tracking and, to some extent, on limited visibility, conventional approach, and landing. The Navy V/STOL mission strives to attain operational capability which includes extreme low visibility (700-ft range; zero ceiling) recovery aboard small ships in up to Sea State 5 conditions.[14] If this goal is to be achieved, the display systems [both head-up display (HUD) and head-down display (HDD)] must become an active, integrated part of the aircraft control system design.

The trade between increasing display sophistication and increasing control complexity was hypothesized in a 1972 AGARD report[15] and is shown here as Fig. 1. As is evident from the figure, system capability can be increased by either "sophisticating" the display (increasing information/ in-

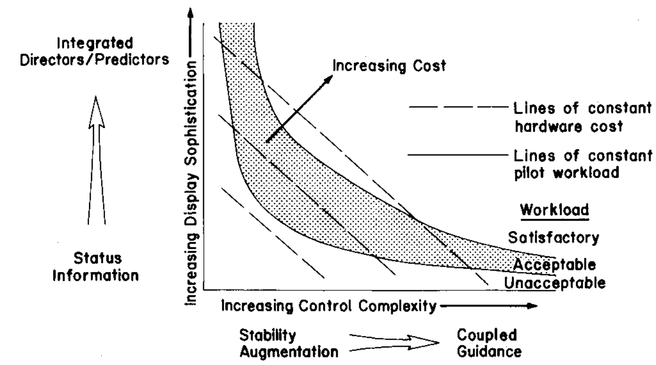

Fig. 1 **AGARD control/display tradeoff.**

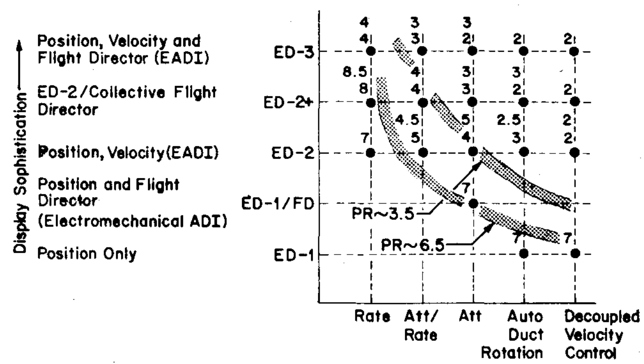

Fig. 2 **X-22A Task IV flight research results (Ref. 5).**

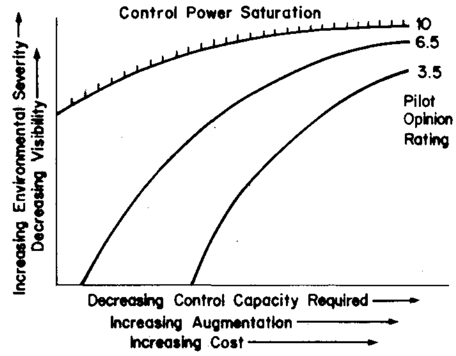

Fig. 3 **Proposed control augmentation/environmental severity tradeoff (Ref. 7).**

	OVC LEVEL	CUE AVAILABILITY ATTITUDE	POSITION/VELOCITY
VMC	1	Easily obtained	Easily obtained
	2	Full concentration is required to obtain continuous attitude information	Easily obtained
	3	Inadequate in portions of the visual field	Position is obtainable, velocity information is marginal.
	4	Inadequate over most of visual field	Position information is marginal, velocity information is unavailable at times
IMC	5	Unavailable	Unavailable

Fig. 4 **Proposed outside visual cue (OVC) scale (Ref. 8).**

tegration) or "sophisticating" the control system (successively augmenting outer loops). Inherent in this hypothesis is increased system cost regardless of the approach taken. Note that the axes of Fig. 1 are not quantified in any way and therefore give little specific guidance to the system designer.

Two recent research programs performed by Calspan Corp. using the Navy's X-22A Variable Stability V/STOL Research Aircraft attempted to quantify the control/display tradeoff. The first of these[5] studied decelerating, descending transition to hover under IMC conditions utilizing a HDD. Control complexity varied from a basic rate augmentation system to decoupled velocity control. The display formats were varied from basic position situation information to integrated flight director information. Figure 2 summarizes the results. The general conclusion of the study, as evidenced by Fig. 2, is that the hypothesized interaction between control augmentation and display content is exhibited in flight. Several key specific conclusions also resulted.

1) The minimal level of displayed information must include translational velocity information to obtain acceptable performance, regardless of the level of control augmentation. This requirement is primarily hover-oriented and reflects the pilot's dislike of having to obtain translational rates implicitly from the movement of symbols on the display.

2) Rate augmentation alone is unacceptable for the task investigated unless full control director information is provided. Performance with the rate system in crosswinds became unacceptable even with full director information.

3) Decoupling and augmenting the longitudinal and vertical velocity responses to control inputs considerably enhanced task performance and tended to eliminate the variation of pilot rating with display sophistication in the configurations where ground velocity was explicitly displayed.

The second program[6] investigated control/display tradeoffs for a vectored-thrust, jet-lift V/STOL aircraft performing a "one-step" deceleration, descending transition to hover. The primary conclusions of the previous study were supported by the results of this study.

A study by Ringland and Clement[7] reached somewhat different, though consistent, conclusions. Their findings revealed that varying the display complexity (for a fixed display medium) would not significantly alter the overall system cost. For this reason, they suggested that the optimum display is dictated by the chosen level of control augmentation and the control/display tradeoff variation therefore disappears. Required level of control augmentation is still a strong function of environmental factors and a control augmentation/environmental severity tradeoff, such as that of Fig. 3, appears reasonable. In general, the more severe the operating environment the more augmentation is required and the greater the cost.

An attempt has been made to quantify the total concept of acceptability of combinations of levels of control augmentation, display and visibility level. Hoh and Ashkenas[8] have proposed a categorization scheme in terms of a visibility scale which quantifies the mission oriented environmental conditions in a (hopefully) more precise manner than merely stating IMC or VMC conditions. This outside visual cue (OVC) scale, depicted in Fig. 4, subdivides visibility conditions between *total* VMC and *total* IMC into five levels—each level being defined by the degree of availability of visual attitude, position, and rate cues. Using the OVC scale, Table 1 defines the minimal acceptable level of control augmentation for a given level of visibility and display information content. This table correlates reasonably well with available data and deserves further consideration as a handling qualities specification tool for hovering and low-speed V/STOL flight.

Equivalent System Criteria

Potential flight control augmentation systems for V/STOL aircraft at hover and low-speed involve a variety of control philosophies which can be broadly categorized as attitude, attitude rate, and translational rate systems (see Table 1). Practical implementation of such systems through feedback and feedforward mechanization normally results in high-order models of the aircraft dynamic response to pilot and

Table 1 Allowable OVC level (from Ref. 8)

System type	Flying quality level	Information display: Raw data	Mechanical flight director	Integrated director plus velocity information
Rate	1	1	2	3
	2	2	4	5
Rate command	1	2	3	3
Attitude hold	2	2	5	5
Attitude	1	2	3	3
(response feedback)	2	2	5	5
Attitude	1	2	4	4
(model following)	2	2	5	5
Translational	1	3	5	5
rate	2	3	5	5

disturbance inputs. The existing flying qualities specifications are, for the most part, quantified in terms of simple, low-order classical dynamic models (which pilots seem to prefer). Highly augmented system models must be simplified in some manner if they are to be realistically compared to these specifications. If the range of V/STOL augmented dynamics can be reduced to forms which are completely identifiable by a few key equivalent parameters, they could readily be parameterized for analysis, design, and evaluation.

The frequency response (Bode) matching technique developed by Hodgkinson and LaManna[12] has been applied to highly augmented CTOL vehicles with reasonable success. It shows promise for application to V/STOL systems and is being considered for this purpose. Briefly, the approach used is to match the frequency response (amplitude and phase) of the high-order system (HOS) over a given frequency range with a preselected low-order system (LOS) model which minimizes the cost function or mismatch (M) defined by Eq. (1),

$$M = 20/n \sum_{l}^{n} [(\text{gain}_{HOS} - \text{gain}_{LOS})^2 + 57.3(\text{phase}_{HOS} - \text{phase}_{LOS})^2] \quad (1)$$

where gain is in decibels and phase is in radians. Large amounts of high-frequency lag are accounted for by including a transport lag (delay) in the equivalent system model.

Figure 5 shows the results of applying this procedure to the hover roll attitude command transfer function of the VAK-191B. In this case the HOS is first/fifth order and the LOS is first/third order with a transport lag. The figure shows that, for this case, the HOS is matched very well ($M=2.0$) by the specified LOS form. Note that in order to obtain a good high-frequency match, a transport lag of 0.094 s was required in the LOS model. This case is a perfect example of the potentially erroneous system dynamic information which might be gained by considering only the dominant oscillatory mode of the HOS. Here the dominant (only) oscillatory mode of the HOS has a damping and frequency of 0.89 and 8.59 rad/s, respectively; whereas the corresponding parameters of the oscillatory mode of the LOS are 0.95 and 3.58. The time domain responses are essentially identical (except for the first 0.1 s). Applying a frequency domain criteria based on a third-order type response to the HOS dominant oscillatory mode would most probably be in error. Many questions remain to be answered, however, before this type of frequency domain equivalent system approach can be considered to be totally viable. Among these are the following questions: 1) Over what frequency range should a match be accomplished and to

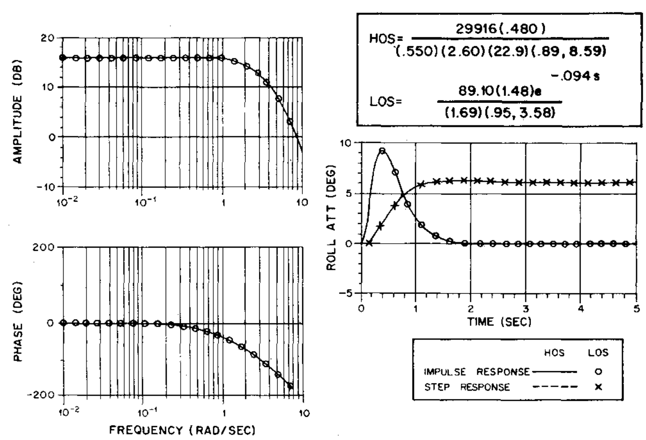

Fig. 5 VAK-191B roll dynamics in hover.

what tolerance (mismatch)? 2) Is transport lag a reasonable approximation to high-frequency dynamics (lag) and what is the acceptable level? 3) To what extent do pilots actually require a low-order-appearing response in hover and low-speed flight?

A recent study by Carpenter and Hodgkinson[10] has addressed these questions. The study determined through simulation and analysis that, for hovering flight with attitude control, the pilot's frequency range of interest is 0.5-4.0 rad/s and that an acceptable (unnoticeable) mismatch in this range is 100 or less, as defined by Eq. (1). The study further concluded that suitable limits on time delay for Level 1 and Level 2 flying qualities are 0.1 and 0.3 s, respectively. Additional research is still required for translational-rate-type dynamics and transition flight, and all results should be verified through in-flight research.

Proposed equivalent system forms and attendant criteria for hover and low speed are presented in a latter section of this paper.

Piloted Simulation Results

A piloted simulation was conducted in March 1979 to assess the complex interaction between the flying qualities and performance of varying combinations of V/STOL aircraft characteristics, flight control systems (FCS), and displays in the Navy seaborne terminal area operating environment. The environment consisted of operation onboard a DD963 Spruance class destroyer in Sea States up to and including 5 in a realistic unsteady airwake environment. The simulation was conducted on the 6 degree-of-freedom motion base Flight

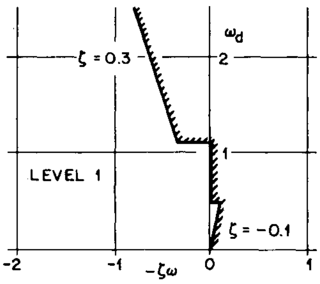

Fig. 6 Current "oscillatory mode" criterion.

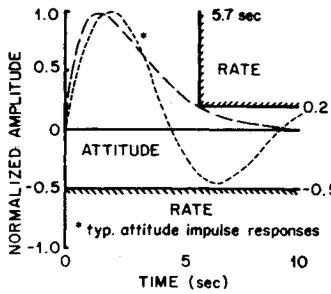

Fig. 7 Proposed attitude vs attitude rate response classification criterion.

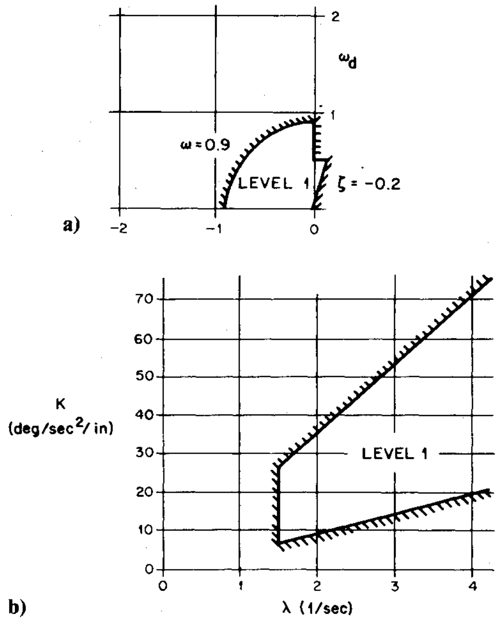

Fig. 8 Proposed rate response criteria. a) Frequency and damping. b) Gain.

Simulator for Advanced Aircraft (FSAA) at the NASA Ames Research Center. Three FCS were simulated. These included a "baseline" attitude command system, a "backup" attitude rate command system and a velocity command/position hold (VCPH) system. Sea State, airwake characteristics, and propulsion-induced ground effects were varied throughout the simulation.

Detailed descriptions and results of this simulation are presented in the final report[9] and are too numerous to review herein. The more significant flying qualities oriented conclusions are, however, listed below.

1) Vertical landings can be accomplished manually on a DD963 if the pilot is provided with adequate position information. There is an important tradeoff between operational environment limits and FCS complexity.

2) The backup FCS (rate command about all three axe,· but with no heave augmentation) was adequate for 15-20 knots wind over deck.

3) Altitude rate command in heave was considered by the pilots to be one of the best (if not the best) features of the baseline system.

4) The VCPH system with excellent command and status information provided by the HUD was rated no worse than 3 on the Cooper-Harper scale for winds over the deck up to 45 knots.

5) While hovering over the deck, the pilot requires very good position data with fore/aft data being the most important (and probably the most difficult to provide).

6) The most significant environmental parameters in the simulation were wind-over-deck magnitude and direction. Task difficulty was due mainly to the severity of the disturbances produced by ship's airwake. Operational requirements should specify wind over deck in addition to Sea State.

7) Ground effects (as modeled in this simulation) were not an important flying qualities consideration. They were primarily masked by the FCS and the landing technique—a rapid letdown from 10-15 ft above the deck. Ground effects might be more significant if a different landing procedure was used or if the attitude FCS augmentation were lessened.

8) Major configuration changes should be accomplished prior to the final approach. The pilots desired to complete major configuration changes prior to acquiring terminal guidance (5-n.mi. range) so that transients would be stabilized before localizer and glide slope tracking.

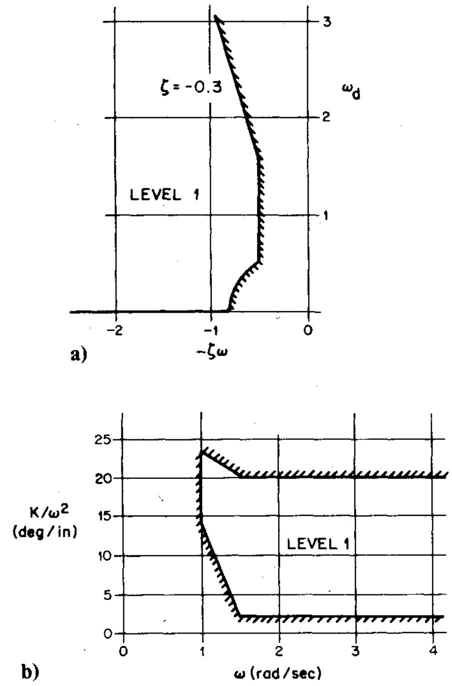

Fig. 9 Proposed attitude response criteria. a) Frequency and damping. b) Gain.

Proposed vs Existing Criteria

A number of criteria revisions have been proposed as a result of the studies described in the preceding sections. While they are too numerous to allow description of all of them herein, a few of the more significant areas will be addressed. The following sections of this paper will attempt to describe several of the proposed criteria and compare them with their counterparts in MIL-F-83300. Examples of their application to existing full-scale aircraft data are also presented.

Criteria Comparison

The current specification, MIL-F-83300, poses dynamic response and stability criteria in terms of dominant model parameters (frequency and damping) with no differentiation between various types of augmentation systems. For example, the Level 1 pitch and roll attitude dynamic response criterion (paragraph 3.2.2.1) limits the "oscillatory mode" parameters, as shown in Fig. 6, and requires all aperiodic modes to be stable. Little guidance is given to facilitate determining which mode, or modes, should satisfy this requirement. In fact the paragraph implies that all modes should satisfy the requirements. This has been found to be overly restrictive, particularly for extremely low-frequency modes.

The ES approach is being considered to improve definition of this requirement. As proposed, both attitude-rate- and attitude-command-type responses are assumed to have an LOS form, as described by Eq. (2),[8]

$$\frac{\text{attitude}}{\text{control displacement}}=\frac{K(s+1/T)e^{-\tau s}}{(s+\lambda)\,(s^2+2\zeta\omega s+\omega^2)} \tag{2}$$

Criteria are defined for the LOS parameters ($K, 1/T$, etc.) dependent upon whether the response is attitude or rate in nature. The delineation between the two general types of response is provided by the time domain criterion of Fig. 7. If the impulse response of the system lies within the boundaries of Fig. 7, it must satisfy the attitude criteria. If it violates the boundaries at any point, it is considered to be a rate system.

Once the response type is classified, and its LOS equivalent is determined as previously described, the following proposed modal parameter criteria are applied. For Level 1 rate systems,

$$\lambda \geq 1.5 \quad \text{and} \quad 1/T \leq 0.1$$

ζ, ω are defined by Fig. 8a and K is defined by Fig. 8b. For Level 1 attitude systems,

$$\lambda \simeq 1/T$$

ζ, ω are defined by Fig. 9a and K is defined by Fig. 9b. Acceptable levels of time delay have been previously defined. Close comparison of Figs. 8a and 9a and Fig. 6 reveals that the combined proposed criteria cover roughly the same region of acceptability as the existing specification does but with better system definition. Further experimentation is required to validate the proposed criteria and define consistent requirements for Levels 2 and 3.

The hover directional criterion of the specification (paragraph 3.2.2.2) limits the allowable first-order time constant for Level 1 yaw rate response to less than 1 s. This requirement may be applied directly in the ES format if the following LOS form is assumed.

$$\frac{\text{yaw rate}}{\text{control displacement}}=\frac{K}{s+1/T} \tag{3}$$

Acceptable levels of the gain (K) in Eq. (3) are defined by Fig. 10. The requirement of Fig. 10 is merely a reformulation of the yaw criterion of paragraph 3.2.3.2 of MIL-F-83300.

A nonattitude-type augmentation showing great promise as a hover control mode is that of translation rate control (TRC). MIL-F-83300 does not cover this type of response but an ES criteria has been proposed to specify satisfactory TRC dynamics. The proposed LOS form is given by

$$\frac{\text{translational velocity}}{\text{control displacement}}=\frac{K}{(Ts+1)} \tag{4}$$

The Level 1 boundaries for K and T are given by Fig. 11. These boundaries are based on preliminary results from a recent in-flight simulation using the X-22A Variable Stability Research Aircraft.[16] Further analysis of these data are required to validate the preliminary boundaries and also to determine whether inclusion of a transport delay is required in the ES format.

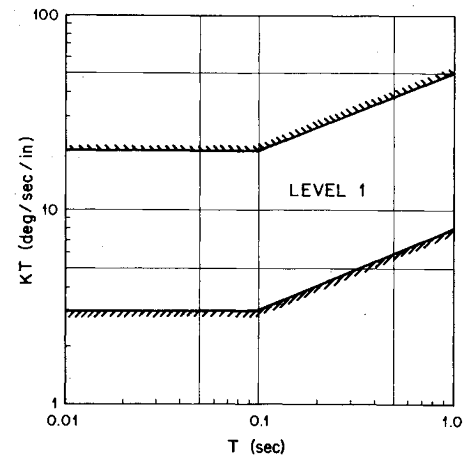

Fig. 10 Yaw response gain criterion.

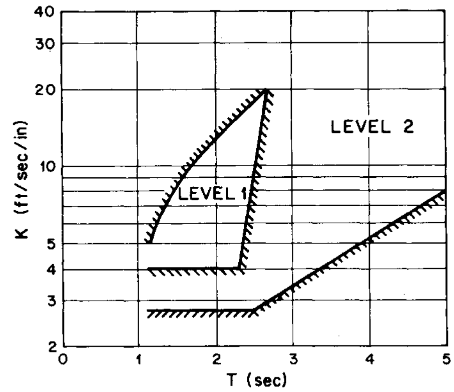

Fig. 11 Proposed translational rate response criterion.

Full-Scale Data Comparison

Two cases are presented to indicate how the previously discussed proposed criteria might be applied. The first case considers the roll dynamic response in hover for a VAK-191B lift plus lift/cruise jet-lift aircraft. The second case is that of the hover pitch dynamic response of the YAV-8B advanced Harrier.

The ES match for the VAK-191B has already been presented in Fig. 5. This particular match was accomplished over a range of frequencies from 0.1 to 10.0 rad/s with a mismatch less than 2.0. It is readily apparent from the impulse response that this system is definitely an attitude system based on the criteria of Fig. 7. The first-order numerator and denominator factors are approximately equal, as required, and the second-order factor characteristics (0.95, 3.58) are seen to be well within the Level 1 boundary of Fig. 9. The steady-state gain of the LOS (6.1 deg/in.) also satisfies the Level 1 requirement of Fig. 9. The LOS transport lag (0.094 s) is less than 0.1 s and is, therefore, also satisfactory. All of this is very consistent with flight test results in which this configuration was given Cooper-Harper PR's (Pilot Rating) of 2-3 in roll (in hover).[17]

For the YAV-8B case, the ES match is given in Fig. 12. Here the match was achieved over a frequency range of 0.4-5.0 rad/s to a mismatch level of 0.008! The corresponding LOS modal characteristics are also shown in Fig. 12. The time response here clearly indicates that the system is rate in nature and, therefore, must satisfy the previously outlined rate response requirements. The first-order numerator term (0.033) is less than 0.1 and the first-order denominator term (1.74) is greater than 1.5, as required for Level 1. The second-order denominator mode characteristics (0.10, 0.129) meet the Level 1 criterion of Fig. 8a; however, the gain value (7.66 deg/s/in.) falls slightly below the criterion of Fig. 8b. LOS

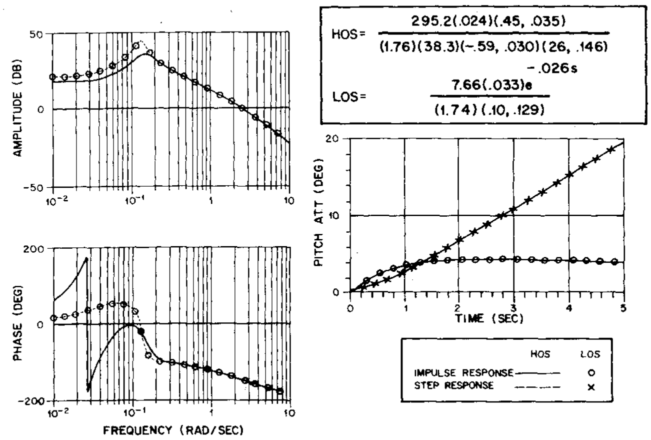

Fig. 12 YAV-8B pitch dynamics in hover.

transport lag (0.026) is well within the 0.10-s limit. The configuration was given a PR of 3 in flight test indicating that the gain criterion may be too restrictive.

This example is particularly interesting in that the HOS has an unstable mode $(-0.59, 0.030)$ which would not satisfy the MIL-F-83300 requirement of paragraph 3.2.2.1. The LOS, on the other hand is relatively unaffected by this mode and, in fact, meets the Level 1 ES criteria. Flight test results support the conclusions reached through the ES approach.

The previous examples are representative of a number of cases which have been examined for these aircraft. In all cases the ES results were in agreement with available pilot ratings. This by no means constitutes validation of the ES approach and proposed criteria but the results are positive enough to warrant continued study in the area.

Ongoing and Planned Programs

One Navy sponsored programs, as yet unfinished, in the field of V/STOL Flying Qualities is worthy of note at this point. It is just getting underway and is planned to assess the requirements of paragraphs 3.3 and 3.4, "Forward Flight and Transition," of MIL-F-83300 in light of recent analysis and experience. This study will attempt to extend the ES criteria approach to transition and forward flight.

Conclusions

Since the acceptance of MIL-F-83300, sufficient insight has been gained to warrant the revision of some sections and the addition of others to the specification. This revision process must be an interactive one including inputs from all elements of the V/STOL community—both government and industry. This paper has presented the status of recent developments in the establishment of revised criteria. Specifically, 1) available visual cue information level must be adequately defined and included within the specification of minimum control augmentation and display levels; 2) equivalent, low-order system definition appears to be a viable approach to the specification of levels of hover stability and response of highly augmented V/STOL configurations; and 3) unique specification of response parameters for attitude rate, attitude and translational rate augmentation is required.

Continuing work is planned to validate proposed criteria revisions through in-flight simulation. Other areas of the V/STOL flight envelope (i.e., transition and conversion) are also being examined.

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