AIAA 80-1592R

Handling Qualities Specifications for U.S. Military Helicopters

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Inadequacies in the military specification for helicopter handling qualities, MIL-H-8501A, have long been recognized, and the latest procurements by the U.S. Army used special Prime Item Development Specifications (PIDS). This paper assesses the efficacy of these PIDS and suggests that changes should be made. In particular, the structure developed in MIL-F-8785B (ASG) (the specification for flying qualities of piloted airplanes) should be incorporated. Improved requirements must be based on a systematic data base and concentrated on topics most important in preliminary design: static and dynamic stability, control power and sensitivity, and interaction with controllers and displays. Emphasis should be on current military helicopter missions and helicopter idiosyncrasies such as cross-coupling, nonlinearities, and higher-order dynamics.

I. Introduction

LIKE the old soldier, it seems that specification MIL-H-8501A, Helicopter and Ground Handling Qualities, will never die but just fade away. The current version[1] is a 1961 revision of a 1952 document. It gave good guidance in its early years, but by the late 1960s had many obvious deficiencies. For example, Ref. 2 provides a detailed analytical review of these shortcomings; empirical evidence can be seen in reports of flight-test evaluations by the Army Engineering Flight Activity (AEFA).[3-5] MIL-H-8501A is still used by AEFA, to some extent, as a yardstick for flight-test evaluation, but for procurement of the UTTAS and AAH, the Army Aviation Research and Development Command (AVRADCOM) developed a new set of handling qualities specifications and incorporated them into the Prime Item Development Specification (PIDS).[6,7] The Navy used essentially the same requirements for the LAMPS-III, and it is expected that if development of a new Advanced Scout Helicopter (AHS) were to go ahead, it also would use these requirements.[8]

There have been several formal attempts to revise MIL-H-8501A—a B version was proposed in 1968 but never developed and adopted. The V/STOL specification MIL-F-83300[9] was the culmination of a major effort by the Cornell Aeronautical Laboratory under the sponsorship of the Air Force Flight Dynamics Laboratory. It incorporated all the data available at that time and followed closely the structure and format of the recently revised specification for conventional aircraft—MIL-F-8785B.[10] The data and rationale for the requirements were presented in a background information and users guide (BIUG)[11] which was modeled after the equivalent BIUG for MIL-F-8785B.[12] MIL-F-83300 attempted to include helicopters and, in fact, was adopted for helicopter application by the USAF. However, the U.S. Navy and Army chose not to adopt it for helicopter application. Some of the reasons for this may be related to the type of criticisms provided by Green.[13] In an attempt to overcome the perceived shortcomings of MIL-F-83300, the Army and Navy jointly sponsored Pacer Systems, Inc. to attempt a revision of MIL-H-8501A. The resulting specification and an associated BIUG were drafted in March 1973. This effort included some of the concepts and structure used in MIL-F-8785B and 83300; many of the actual requirements were innovative though they lacked data for substantiation. The preliminary report of this effort had limited distribution and was never finally published.

This paper briefly assesses the contents of these various specifications and identifies certain shortcomings. No attempt is made to solve any of these shortcomings, but several of the topics are discussed to provide an illustration of the problems and to help focus future research efforts.

II. Review of Current Helicopter Specifications

An attempt was made to assess current specification by comparing the latest UTTAS and AAH system specifications[15,16] with MIL-H-8501A and MIL-F-83300. Three other specifications have been developed for VTOL aircraft: AGARD Reports 408 and 577-70[17,18] and Curry and Matthews.[19] Although these three references made notable contributions to the development of criteria, they were not included in the comparison because they made no claims to cover helicopters and were not written as contractual documents.

MIL-F-83300 shows clear advantages in its broad coverage of important handling qualities aspects and its systematic structure. Its disadvantages are that it is primarily based on V/STOL data, and explicit helicopter characteristics are only lightly covered. MIL-H-8501A and the PIDS do specifically address helicopters, and through long familiarity, the helicopter community is comfortable with them. However, they do have rather sparse coverage of many important topics. Even where topics are addressed, many shortcomings in the MIL-H-8501A requirements have long been recognized.[2] In addition, MIL-H-8501A and the PIDS lack a systematic treatment of flight envelopes and failures.

All of these specifications are sadly lacking in mission-oriented criteria and are basically for visual meteorological conditions (VMC) with only token recognition of separate instrument meteorological conditions (IMC) requirements.

It must be recognized that the task or mission to be performed by the helicopter can have a substantial impact on the requirements. For example, in MIL-F-83300 the requirements were divided into hover-low speed (i.e., less than 35 knots) and forward flight (i.e., for speeds from 35 knots to V_{con}). The idea was to convert to the fixed-wing requirements of MIL-F-8785B at speeds above V_{con}, but "V convert" became "V consternation," especially at the idea of making helicopters comply with the rigorous requirements in MIL-F-8785B. The data base for the hover and low-speed requirements were based largely on research investigations using a generalized hover and low-speed taxi task. No systematic investigations had been made of mission-oriented

Presented as Paper 80-1592 at the AIAA 7th Atmospheric Flight Mechanics Conference, Danvers, Mass., Aug. 11-13, 1980; submitted Oct. 8, 1980; revision received June 23, 1981.

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tasks, such as night NOE flying where precision of control is required in tasks such as hover-bobup (investigated by Aiken[20]), or shipboard landings in high sea state, where the ship motions and the wind and turbulence interactions result in an extremely taxing task.[21] Attention to such flight phases will necessitate significantly more stringent requirements.

For speeds greater than 35 knots the data and requirements were oriented at V/STOL approach and landing. The resulting requirements are probably good minimums for flight safety, but there is need to develop requirements to enhance performance of the operational missions that helicopters perform in this speed range. It is likely that the need for agility and maneuverability in daylight high-speed flight at very low altitudes will require maneuvering requirements similar to those for fixed-wing fighters, though of course, accounting for the capabilities provided by helicopter collective control. For example, in a ground simulator study of a lateral-directional maneuvering task, Tomlinson and Padfield[22] found that on a triple bend, with a radius requiring 2 g at 100 knots, crisp response was required to longitudinal and lateral control inputs: maximum roll rates exceeded 60 deg/s and rates of 80 deg/s were encountered; maximum pitch rates were typically 30-40 deg/s; and large attitude excursions were also encountered, with more than 60 deg being used in roll and 40-60 deg in pitch. These maneuvers are, of course, a function of the flight path defined for the task, and this leads to the idea that agility could be quantified by defining a range of maneuvers as a series of paths in space and an associated speed. A requirement of this nature was developed by AVRADCOM for inclusion in the UTTAS PIDS. This was a purely longitudinal requirement involving a pull-up and push-over.[25] The difficulty with this approach, of course, is in determining the maneuvers appropriate for the intended mission.

The real test for a specification, of course, is how well it does in producing a desirable helicopter. This is both a difficult and a very sensitive topic to assess. The flight-test evaluation reports for the UTTAS (YUH-60A) and the AAH (YAH-64), Refs. 23 and 24, respectively, conclude that their handling qualities represent a significant improvement over previous Army helicopters. However, a careful scrutiny of these reports does show some specification-related inconsistencies; some items that did not meet the specification, but were judged satisfactory, and some items that were considered shortcomings but had no specification coverage. These were minor problems, so the PIDS apparently produced a satisfactory product. However, there is need for a more systematic approach to the specification structure and for an expanded data base on which to base new requirements.

III. Recommendations for Modifications to Specification Structure

A general area of MIL-H-8501A and the PIDS that needs revising, and could be revised without an expansion of the data base, is to improve the structure by bringing it more into line with that of MIL-F-8785B. Two particular aspects of such a revision that will be discussed are 1) flight envelopes and 2) the concepts of levels as related to reliability and degradation due to failures.

A. Flight Envelopes

MIL-F-8785B and 83300 define three envelopes, the boundaries of which define 1) regions within which the aircraft must operate to accomplish its mission—operation flight envelope (OFE); 2) regions defined by the aircraft limitations that must include the operational flight envelope but also provide safe margins from dangerous flight conditions—service flight envelope (SFE); and 3) regions defining the extremes of aircraft operation with no margins—permissible flight envelope (PFE).

These envelopes are defined by multiple parameters. The usual: speed V, normal acceleration n_z, and sideslip β may have to be supplemented to include height, rate of climb, angular attitude rates and accelerations, weight, center of gravity (c.g.) position, and rotor rpm. Such envelopes are used as follows: The procuring activity defines the OFE based on the missions that are to be performed. The contractor designs the helicopter to encompass the OFE and then defines the SFE and PFE based on his own helicopter limitations. Specification compliance is required anywhere in the SFE, though degraded flying qualities are allowed outside the OFE (this is treated in the following section). Warnings that the SFE is being exceeded must be provided. This concept provides a systematic way of defining where and how the helicopter can be operated. In the Army combat environment it is frequently tempting to overload the helicopter, with c.g.'s outside the normal range, and to pull extreme maneuvers. Knowledge of the SFE and PFE provides the pilot with information on what to expect, and what his margins are.

In the past such definitions could perhaps have saved both lives and aircraft by making pilots more aware of the potential for "mast bumping" (see Burke[26]). Mast bumping arises as follows: In a teetering rotor helicopter (e.g., UH-1, AH-1, OH-58), as its name implies, the rotor is free to pivot at the hub over its full range of travel. There is no spring to restrain it relative to the rotor shaft. In flight, moment control is obtained by rotating the rotor plane, and hence thrust vector, about the hinge; being offset above the c.g., this provides a moment. In 1-*g* flight, thrust equals weight and provides a significant moment. In 0-*g* flight, thrust equals 0 so there is no moment, no control, and no way for the pilot to know where the rotor is relative to its flapping limits. If the flapping limits are exceeded in flight, the rotor contacts the mast and a few seconds of bumping can cause loss of the rotor. Mast bumping is now a well-known phenomenon, but helicopters with other rotor types have their own limitations which need defining. Envelopes and margins provide an excellent structure to ensure that they are defined by the contractor, and not by the Army pilot after the helicopter has entered service.

B. Levels of Flying Qualities

Three levels of flying qualities are defined in MIL-F-8785B. Level 1 corresponds to a Cooper-Harper pilot rating[27] of 1-3 and is termed satisfactory; level 2 corresponds to ratings of 4-6 and is termed unsatisfactory; and level 3 corresponds to ratings of 6-9 and is termed unacceptable.

The level concept is directed at achieving adequate flying qualities without imposing undue requirements that could lead to unwarranted system complexity or to decreased flight safety. The intent is to specify requirements that provide desirable flying qualities for normal operation (i.e., level 1 within the OFE and level 2 within the SFE). Equipment failures, however, either in the flight control system or in other subsystems, can cause a degradation in flying qualities. The emphasis is then on the effects of failures rather than on the failures themselves. Limited degradation of flying qualities (e.g., level 1 to level 2) is acceptable if the probability of encountering such degradation is acceptably low. Somewhat reduced requirements are imposed for flight within the service flight envelope. The numerical values for aircraft failure states can, of course, be chosen by the procuring agency to reflect specific requirements for a given weapon system.

The need for this type of treatment is relatively self-evident and becomes increasingly important as more advanced systems are developed. For example, with a fly-by-wire system there will be multiple failure modes and an efficient design philosophy may allow successive degradations in flying qualities. One systematic way of controlling these degradations is through the probability scheme outlined above. Interesting examples of the ambiguities that can arise with even a simple SAS occurred on the YAH-64 and YUH-60A. In Ref. 24 the AEFA test pilots considered that the YAH-64 handling qualities SAS-off deserved a handling qualities rating of 2. This 2 rating must have been in the context that the flying qualities SAS-off would be satisfactory for a failure situation, since some of the better SAS-on characteristics were rated 5 and 6. In Ref. 23, AEFA evaluated the YUH-60A AFCS-off mode as having a handling qualities rating of 6, but rationalized that since this is a degraded mode it would not be a "shortcoming." AVRADCOM headquarters did not concur in that assessment and the characteristics were subsequently improved. Clearly, a more systematic approach to the degradations allowed when augmentation systems are turned off or fail, will have to be developed; the structure developed in MIL-F-8785B appears to do this very well.

IV. Recommendations for Data Base Development

A primary objective of the U.S. Army Aeromechanics Laboratory (AVRADCOM) flight control program is to develop a data base for flying qualities criteria which can be used in a future specification revision. This program is being performed as a joint effort with the NASA Ames Research Center, using their extensive ground-based and in-flight simulator facilities. Some of the documentation that has resulted from in-house efforts are Refs. 20 and 28-30 and, from contracts, Refs. 31-33. However, there are many more topics that require an improved data base than can possibly be addressed with the available resources; as a result, priorities must be assigned to future efforts. In assessing similar priorities for future work on MIL-F-83300[34] it was found that during the specification review by industry most interest and comments on requirements addressed topics of 1) static and dynamic stability, 2) control power and damping, and 3) controller characteristics. Items 1 and 2 are naturally high priority since they can influence preliminary design parameters and have a major effect on the design of the helicopter. Controller characteristics are probably less critical early in design, but the topic does garner a lot of attention, as can be seen from the many items in MIL-H-8501A and PIDS that address control system characteristics. For the next generation of helicopters, data should be gathered on characteristics of side stick controllers; for example, the number of axes the controller should control (two, three, or even four), the helicopter response for each controller degree of freedom, and the relative advantages and disadvantages of force command or displacement controllers. A topic not treated well in any existing specification is the interaction of control and response characteristics with displays and vision aids; with current mission requirements for military helicopters this topic needs much more emphasis.

A. Control Power

At the present time, a critical need is for better information on control power, both moment controls and force controls. The UTTAS pull-up push-over maneuver forced considerable increases in controllability on the UTTAS and AAH. A helicopter can obtain control moments, in addition to those described above for a teetering rotor, by providing a hinge offset from the rotor hub and/or providing a spring restraint at the hinge. The more these hub moments due to flapping are increased, the more control moment and rate damping becomes available (Fig. 1); but these virtues are accompanied by bad features, such as cross-coupling (Fig. 2) and vibration. The control responses required to perform the agility maneuvers described by Tomlinson and Padfield[22] will require extremely high control power. Such maneuverability may be needed in future helicopters, especially if they are required to perform an air-to-air combat role. A requirement for high control power has not yet been defined by the Army, and in fact there is a trend by the manufacturers away from rotor systems that provide these high control powers; this is a critical problem that must be delineated and resolved.

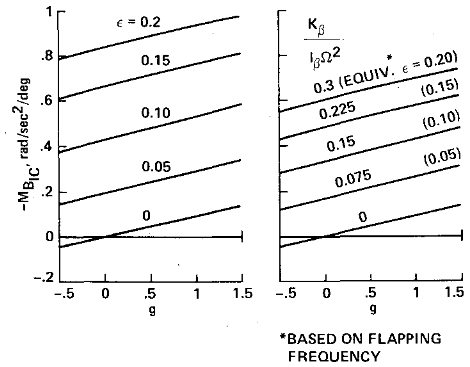

Fig. 1 The effect of hinge offset ϵ and hinge restraint K_β on pitching moment $M_{B_{1c}}$ at various load factors (hover) (from Ref. 28).

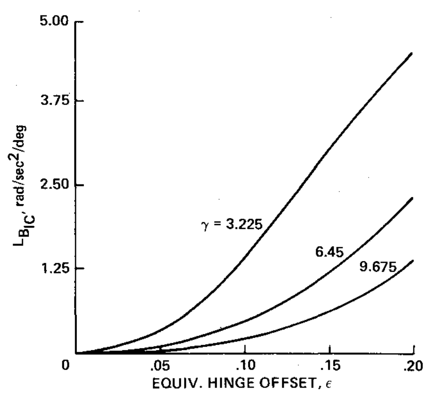

Fig. 2 Effect of hinge offset and Lock number γ on roll due to pitch control (at hover) (from Ref. 28).

An equally important control-power question is control power in the thrust axis. Much NOE flight time is spent near or below the speed for minimum power. In such conditions maneuvers such as a level turn require higher thrust, which if not available, results in decreased velocity, which can only be compensated by rotor rpm bleed-off and/or settling of the helicopter. The Army user is currently requesting more thrust control power; however, it is possible that at least part of the requirement could be satisfied by increased thrust response rate, rather than greater steady-state thrust. Providing increased thrust through increased power can have a significant effect on the design of the engine, transmission, and rotor system; as a result, it is important to know exactly how much increased power is required.

B. Engine Coupling

Piston-engine helicopters required the pilot to compensate for the modified torque demand whenever he changed the collective control position. On turbine-powered helicopters this function is performed automatically by the engine governor, which senses rpm drop and modifies the fuel flow to compensate. The closed-loop system consisting of engine-governor-transmission-main and -tail rotors must be stable, but may or may not do an adequate job of holding rpm within tolerance. If it does not perform this task adequately, a significant amount of pilot attention may be required to compensate. This can be a particularly severe problem in NOE flight. Both the YUH-60A and YAH-64 achieved an excellent control of rpm, and this feature was picked out as an enhancing feature, but quantitative tolerances should be established for such speed control and, in the case of two engines, torque matching.

There is another phenomenon, both intriguing and not widely recognized, that is related to the engine governing system: coupling between the yaw response and the rotor rpm

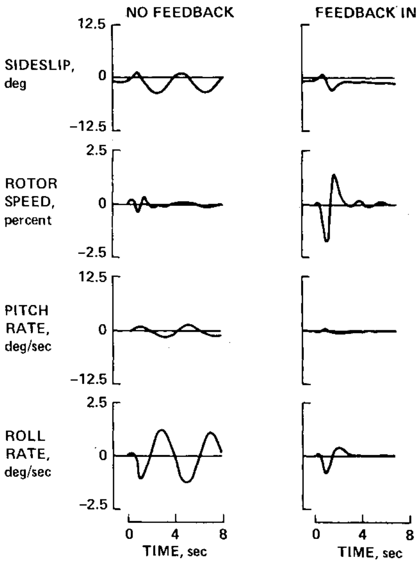

Fig. 3 Effect of roll rate feedback to fuel control on Dutch-roll mode response (from Ref. 36).

control. This subject is well described by Kuczynski et al.[36] Briefly, the situation occurs as follows: The engine fuel control governor senses a yaw rate as an rpm perturbation and tries to correct to the reference value. This changes the rotor torque, which has to be reacted through the fuselage. Depending on the engine fuel control system dynamics, the phasing can result in amplifying or damping the fuselage yaw response. Kuczynski et al. discuss an example in which deliberate feedback of roll rate can be used to augment Dutch-roll damping (see Fig. 3). It is not suggested that requirements should be developed to require Dutch-roll damping using fuel control; however, some reference to rotor and airframe coupling could be made to alert the designer to the possible potential and pitfalls.

C. Cross-Coupling

The inherent asymmetry of single-rotor helicopters causes them to have several features that complicate analysis and specification of handling qualities criteria. In particular, there is strong cross-coupling between longitudinal- and lateral-directional responses; they exhibit static and dynamic nonlinearities, and they inherently involve more than classical rigid body modes used to represent the responses of conventional fixed-wing aircraft.

The response of the YAH-64 to a lateral doublet at 125 knots,[35] (Fig. 4) illustrates the coupling that typically exists between longitudinal- and lateral-directional degrees of freedom. MIL-F-83300 (3.8.7) requires that such coupling be not objectionable, and limits cross-axis-coupling to requiring not more than 10% of the cross-axis control to compensate. MIL-H-8501A and the PIDS for the AAH and UTTAS only address longitudinal and lateral trim changes with collective or power changes. Unfortunately, dynamic coupling is inevitable in helicopters and unlikely to be made zero, so some benchmark is required. Chen and Talbot[28] suggested a requirement based on the ratio L_q/L_p (Fig. 5). Heffley[31] shows that some insight can be obtained from $M\delta_B L_q/M_q L_p$, or the peak bank angle ϕ following a unit step in commanded pitch. Figure 6 shows a plot of these parameters vs speed for the UH-1H. Yet a third perspective on the problem is provided by White and Blake.[37] Figure 7 shows the variation of roll rate to pitch rate for longitudinal cyclic inputs as a function of frequency for the YUH-61A, BO-105, and CH-47, all with pitch and roll SCAS off. Both the YUH-61A and BO-105 have very high couplings; in fact, the response to longitudinal control input is greater in roll than pitch from

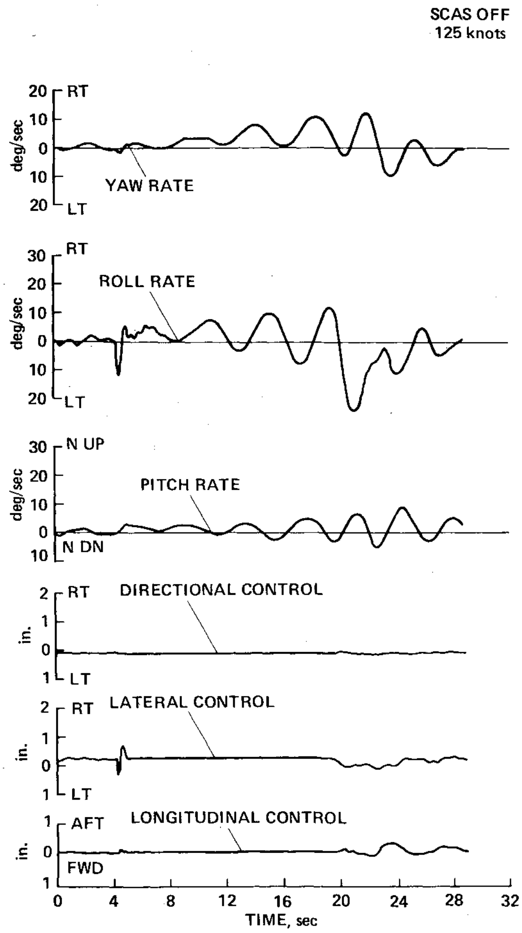

Fig. 4 Response of YAH-64 to roll control doublet (from Ref. 35).

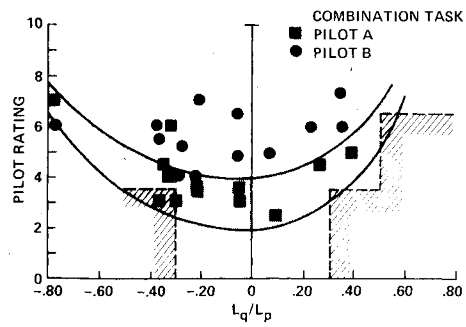

Fig. 5 Pilot rating vs L_q/L_p (from Ref. 28).

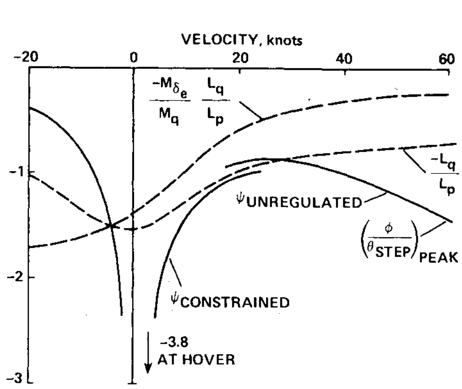

Fig. 6 Variations of roll-due-to-pitch coupling parameters (UH-1H) (from Ref. 31).

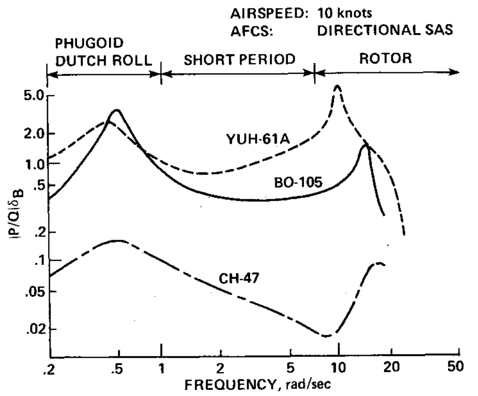

Fig. 7 Comparison of roll-to-pitch coupling for different aircraft (from Ref. 37).

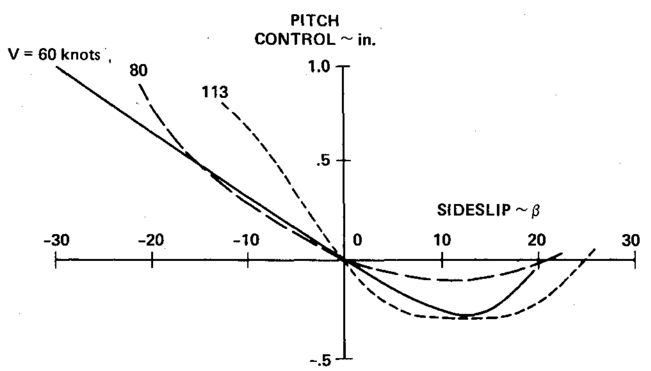

Fig. 8 Pitch control to trim steady sideslip (YAH-64) (from Ref. 24).

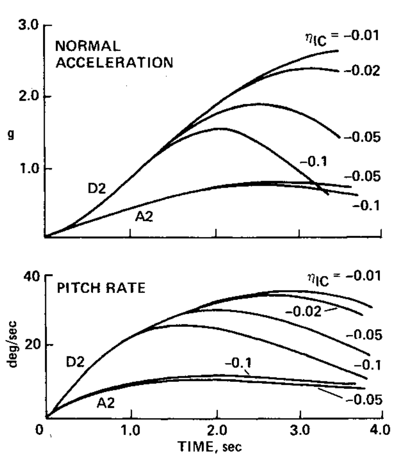

Fig. 9 Response to different levels of longitudinal cyclic at 100 knots (from Ref. 22).

about 0.3 to 1.0 rad/s. Changing the cyclic phasing can have a marked effect, but a compromise has to be made with the steady-state lateral stick migration with speed.

Clearly, much work will have to be performed to determine just how much coupling is acceptable to the pilot, in what part of the frequency band, and for what tasks.

D. Nonlinearities

Several forms of nonlinearity are manifested on helicopters, both statically and dynamically. An example of static nonlinearity showed up in the YAH-64 pitching moments due to sideslip[24] (Fig. 8). This pitch-to-sideslip coupling causes problems in turning maneuvering flight and was determined to be a shortcoming for maneuvering flight.

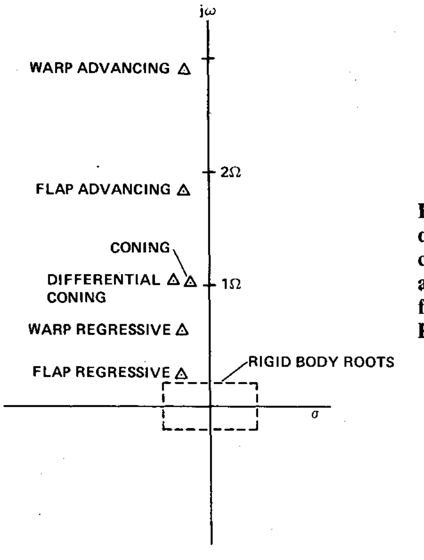

Fig. 10 Illustrative diagram showing typical characteristic root location for a six-bladed flapping rotor (from Ref. 40).

Tomlinson and Padfield[22] illustrate other forms of nonlinearities, especially for helicopters with stiff hingeless rotors. For example, the changes in normal acceleration and pitch rate responses as input size is increased are quite nonlinear (Fig. 9). They point out that linear theory would predict the type of response produced by small inputs, hence handling qualities criteria based on such linear models may not reflect pilot opinion, at least in tasks involving large maneuvers.

E. Higher-Order Responses

Examples used in the discussions of engine governing topics and cross-coupling illustrated situations in which rotor modes can affect the responses in the frequency range of interest to the pilot. Figure 10 shows the frequency range of some typical main rotor modes. Instead of merely ignoring these higher-order modes in handling qualities analysis, the helicopter would appear to be a natural candidate to which to apply the techniques of equivalent systems developed to account for control system effects in fixed-wing aircraft.

A'Harrah et al.[38] discussed the equivalent systems approach. Based on some applications to various higher-order system dynamics and to a recent fighter aircraft design, they concluded that the method is useful, and that the ability of the requirements in MIL-F-8785B to discriminate the level of flying qualities of higher-order systems is relatively insensitive to the equivalent system methodology or to the quality of the match. Current revision efforts on MIL-F-8785B propose to include equivalent system matching using a second-order system with a time delay.[14]

F. Displays and Vision Aids

Since the adoption of MIL-F-83300, considerable work has been done in the area of how displays interact with stability and control augmentation systems in determining flying qualities. In the civil world the critical instrument flight phase is approach and landing into an area where ground-based references are available. This scenario leads to instrumentation, such as flight directors, for which a considerable body of data is now available.[29]

To a large extent the Navy helicopter mission has the same landing approach situation as the civil, in the sense of having a well-defined ground-based aim point. However, a very different situation exists for the Army. The current doctrine of NOE implies prolonged operations close to the ground in a combat zone where there will not be a ground-based beacon to home in on. Rather, the Army pilot has to find an arbitrary path from point to point and avoid obstacles on the way. At night and in poor weather this necessitates some form of vision aid such as a light intensification device (low-light-level TV), infrared sensors, or radar. Presentation of this out-of-the-window view to the pilot can be through a helmet-mounted device or through a display on the instrument panel. In either case it appears that symbology providing flight control information has to be superimposed onto the real-world imagery to enhance the pilot's ability to perform his flying tasks. Reference 39 describes efforts performed by the Avionics Research and Development Activity (AVRADA) to develop symbols and appropriate drive logic that could be implemented while minimizing the necessity for special sensors for the translational position velocity and acceleration information. This design has been incorporated into the AAH Pilot Night Vision System (PNVS). Aiken and Merrill[20] report results of an investigation of how the symbology and drive logic interacts with the SCAS to influence handling qualities in an NOE hover and bobup task. The symbology, particularly the drive logic, or the SCAS, or both, can be varied to obtain satisfactory handling qualities, but in moderate turbulence a horizontal velocity command system and some form of vertical axis augmentation are required. Failures of the SCAS can result in a system inadequate for the task. The SCAS required for hover and bobup tasks is unsuitable for the higher-speed flight segments so a multimode SCAS and corresponding multimode display are required. Definition of these modes, mode switching control, and the limitations of panel-mounted vs helmet-mounted displays, are design features that need thorough investigation so that appropriate design criteria and specifications can be developed.

V. Conclusions and Recommendations

The current military specification for handling qualities of helicopters, MIL-H-8501A, is inadequate and long overdue for revision. Recent attempts to develop a revision have been unsuccessful, not because of lack of ideas, but because of a shortage of dependable well-conditioned data to use as basis for substantiation. Efforts to build such a data base are underway at Ames Research Center in a joint Army NASA program. However, with the present level of effort it is likely to be several years before the picture is changed significantly.

The current approach of developing a specification for a particular helicopter has apparently worked well for the YUH-60A and the YAH-64, but there are several areas where a more systematic approach is desirable. One important feature that could be incorporated into a revision without waiting for further data base development is a structure similar to that used in the fixed-wing flying qualities specification, MIL-F-8785B. Of primary concern is a systematic treatment of levels of flying qualities, flight envelopes, and reliability.

In developing the future data base, priorities must be chosen carefully, and it is recommended that efforts concentrate on those characteristics influencing the basic vehicle during preliminary design: static and dynamic stability, and moment and thrust control power and sensitivity. These topics need developing with emphasis on current military helicopter missions, with adequate recognition of important helicopter idiosyncrasies, such as longitudinal-to-lateral directional cross-coupling, nonlinear responses, and dynamics in the frequency range pertinent to the pilot that are cross-coupled, nonlinear, and of higher order than the classical representations for fixed-wing aircraft.

In the 11 years since the adoption of MIL-F-8785B (ASG), the fixed-wing aircraft flying qualities community has not been idle. Many new ideas, both in requirements and in structure, have been developed and are on the verge of being adopted into a Revision C of the specification. Of these, only the equivalent systems approach for handling higher-order systems was mentioned in this paper. However, many of these ideas are worthwhile and should be assessed for possible integration into a revised specification for helicopter handling qualities.

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