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Mission Oriented Requirements for Updating MIL-H-8501 Volume II STI Background and Rationale

Warren F. Clement, Roger H. Hoh, David G. Mitchell, and Samuel W. Ferguson, III

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ABSTRACT

The structure of a new flying and ground handling qualities specification for military rotorcraft is presented in the first of two volumes. This preliminary specification structure is intended to evolve into a replacement for specification MIL-H-8501A. The new structure is designed to accommodate a variety of rotorcraft types, mission flight phases, flight envelopes, and flight environmental characteristics and to provide criteria for three levels of flying qualities, a systematic treatment of failures and reliability, both conventional and multiaxis controllers, and external vision aids which may also incorporate synthetic display content. Existing and new criteria have been incorporated into the new structure wherever they can be substantiated. A supplement to the new structure is presented in the second of the two volumes in order to explain the background and rationale for the specification structure, the proposed forms of criteria, and the status of the existing data base. Critical gaps in the data base for the new structure are defined, and recommendations are provided for the research required to address the most important of these gaps.

FOREWORD

This report comprises Volume II of a two-volume final report on Phase I of a program to develop mission-oriented flying and ground handling qualities requirements for military rotorcraft. Volume I presents a new preliminary specification structure which is intended eventually, following review and refinement, to replace the current specification MIL-H-8501A, Helicopter Flying and Ground Handling Qualities. Volume II supplements Volume I and explains some of the background and rationale for the new specification structure, the proposed forms of criteria, the status of the existing data base, and recommendations for enhancing the data base. Volume II should be read alongside Volume I. The recommendations contained herein have not been approved and should therefore be considered only tentative.

This report presents the results of work performed during the period from August 2, 1982, through May 31, 1984, under Contract NAS2-11304 from the Ames Research Center (ARC) of the National Aeronautics and Space Administration (NASA). The program of which this work is a part, however, is sponsored jointly by the U.S. Army and the U. S. Navy and is directed by the Army Aviation Research and Development Command (AVRADCOM). The technical responsibility for the program is shared between the Aeromechanics Laboratory of the U.S. Army Research and Technology Laboratories, located at Ames Research Center, Moffett Field, California, and the Directorate for Development and Qualification located at AVRADCOM, St. Louis, Missouri. Contributions to the program are also being made by representatives of NASA, the U.S. Air Force Wright Aeronautical Laboratories, and the Federal Aviation Administration through an ad hoc Technical Coordinating Committee which includes a variety of interested representatives of the U.S. Army and the U.S. Navy. The authors are particularly grateful to the co-chairmen and members of the Technical Coordinating Committee for their guidance, encouragement, and criticism throughout this effort.

Mr. David L. Key of the Aeromechanics Laboratory, a co-chairman of the Technical Coordinating Committee, served as the technical manager of this contract and was assisted initially by Mr. G. Dean Carico and subsequently by Mr. Christopher L. Blanken, also of the Aeromechanics Laboratory. The Systems Technology, Inc., (STI) technical director was Mr. Irving L. Ashkenas. Mr. Warren F. Clement served as the STI project engineer. The members of the Technical Coordinating Committee are as follows: Dr. Robert T. N. Chen, NASA ARC Flight Dynamics and Controls Branch; Messrs. Carmen Mazza and Ron Nave, Naval Air Development Center; Mr. James Hayden of the U.S. Army Aviation Engineering Flight Activity; Mr. Ralph Baker, U.S. Army Aviation Center; Mr. Robert Woodcook, AFWAL/FIGC, Wright-Patterson AFB; Mr. Jim Honaker, Federal Aviation Administration, Southwest Region; Maj. Tom Edwards, DAMA-WSA, Washington, D.C.; Dr. William White and Messrs. Gene Heacock and Robert Tomaine, U.S. Army Aviation R&D Command; Mr. Robert H. Bowes, Naval Air Test Center; Messrs. T. Lawrence and

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SECTION I

INTRODUCTION

A. SCOPE

This report is intended to supplement the preliminary revision to MIL-H-8501 entitled "Flying and Ground Handling Quality Requirements for Military Rotorcraft." This revision effort is being conducted in two phases. The primary objectives of Phase I have been to develop a new specification structure, to incorporate valid criteria where possible, and to identify gaps in the existing data base. In some cases where data are available, specific criteria have been presented. The level of confidence in this data is discussed in this background document, as well as gaps in the existing data base.

It is important to recognize that the proposed specification structure represents an instrument for organizing and unifying the collection of data necessary to write a viable specification for military rotorcraft. As these data become available, the proposed form of the criteria will probably be refined or, in some cases, be completed revised. Having reviewed the current data base as we prepared the proposed specification structure, we conclude that a substantial amount of simulation and flight test work is required as will be seen in Sections II and III of this volume. We recommend, therefore, that two objectives of the Phase II portion of this study should be to direct and unify the various experimental programs conducted over the next two years and to set the groundwork for unifying future efforts to develop specification data.

The primary objectives of Phase II are to develop (1) a usable Military Specification and (2) a Background Information and User's Guide (BIUG) which will support currently envisioned advanced rotorcraft programs, such as the LHX, as well as existing less sophisticated helicopters. While there are significant gaps in the data base for rotary-wing rotorcraft flying and ground handling qualities, we believe that it is possible to develop a reasonably valid specification if only the highest priority tests in Section III are completed.

The form of the flying and ground handling quality criteria to be used in the specification has been the subject of considerable discussion; however, the overriding consideration has been the lack of acceptance of frequency response methods by the helicopter manufacturing community. Therefore, all of the criteria in the specification are stated in terms of time responses to control inputs, atmospheric disturbances, and "other inputs" such as stores release, etc. In some cases it was possible to convert existing frequency response criteria into the time domain; unfortunately, some of the physical insight inherent in these criteria gets lost in the translation. It is our intention to include the original frequency response criteria (such as equivalent systems and the bandwidth criterion) in the BIUG in order to supplement the time response criteria in the specification for the purpose of design guidance. The present report is not the BIUG--which, as noted above is scheduled to be developed during the Phase II portion of this study--it is simply a supplement to the preliminary specification and explains the background and rationale for the specification structure, proposed criteria forms, and status of the existing data base.

B. OVERVIEW

The primary objective of the proposed specification is to ensure acceptable flying qualities for mission task elements and environments. In order to accomplish this objective, the methodology outlined in Fig. 1 has been developed. Figure 1 begins with a definition of rotorcraft maneuvering requirements which form the basic elements of all expected missions. These maneuvers, or "mission tasks elements," are defined in considerable detail, including specific control techniques and performance limits. In the preliminary specification, we have prepared tables of the expected mission task elements as well as detailed narrative descriptions (Appendix A of the specification). However, quantitative numbers for the performance requirements of these tasks need to be developed in a flight test study using operational pilots. This is discussed in more detail in Section II.3.2.

The next step in the specification methodology is to define the necessary "rotorcraft response characteristics" to control inputs in order to perform the maneuvers specified above. For example, some highly aggressive maneuvers requiring rapid movement with extreme precision will probably require an attitude response, whereas normal hovering and maneuvering in low winds and good visibility can be accomplished with today's helicopters, many of which have an acceleration-like response to control inputs. Flight testing is required to define the response type required for each of the mission tasks defined above. This is discussed in more detail in Section II.3.3.

The categorization of "mission task elements" under rotorcraft response type assumes that outside visual cues are not a limiting factor, although a moderate level of turbulence is assumed. Therefore, the next step in the specification methodology is to require a higher level of response (usually increased augmentation) with increasingly degraded outside visual cues. For up-and-away flight, the standard instrument meteorological conditions (IMC) versus visual meteorological conditions (VMC) definitions are applied. However, for flight where visual reference to the ground or ocean is required [i.e., nap-of-the-earth (NOE), takeoff, and landing] a special scale has been employed to develop a more fine-grained distinction between the various usable cue environments. The "outside visual cue" (OVC) environment noted in Fig. 1 does not include

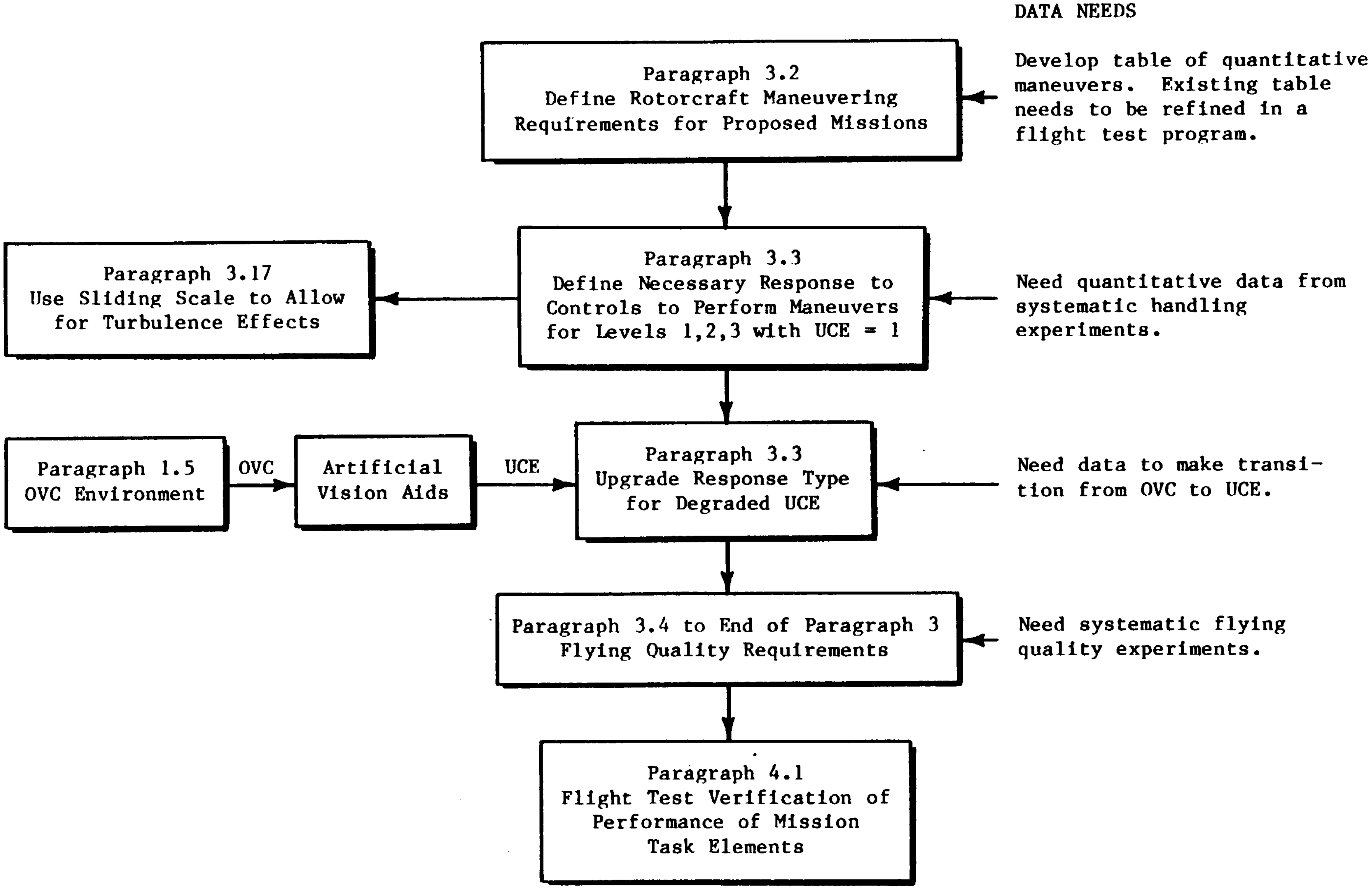

Figure 1. Basic Specification Methodology

the effects of any artificial vision aids and simply is representative of the mission environment. The "usable cue environment" (UCE) takes into account the effects of artificial aids on the OVC environment. The OVC/UCE scale in Paragraph 1.5 therefore combines the effects of the existing outside visual cues and artificial vision aids to define the total usable cue environment for the pilot. The use of certain basic display formats to modify the outside visual cues to an upgraded usable cue environment will require the development of a data base which currently does not exist. This is discussed further in Section II.3.3. The effect of the usable cue environment on the required rotorcraft response type is given in Table 2(3.3) of the specification.

Having associated each of the mission tasks with a given rotorcraft response characteristic, we proceed next in Fig. 1 is to provide the associated Levels 1, 2, and 3 flying quality boundaries for each response type (acceleration, rate, attitude, and translational rate command). This represents the bulk of the requirements section (Section 3) of the specification.

Finally, the prototype rotorcraft will be flight tested to ensure that it is capable of performing the mission task elements specified at the outset. Compliance will be based on the ability of most pilots to accomplish the maneuvers within the specified tolerances (Appendix A of the specification). It is emphasized that compliance with this part of the specification will not involve qualitative pilot opinion, since that has been insured by compliance with the time history parameters of Paragraph 3.

C. ORGANIZATION OF FLYING QUALITIES CRITERIA

The flying qualities criteria, starting with Paragraph 3.4, are organized in terms of response to the cockpit controllers, i.e., longitudinal, lateral, vertical, directional, and transition (for tilt wing or tilt nacelle configurations). Each of the controller sections considers all aspects of the rotorcraft response to the controller, as summarized below:

- Basic rotorcraft dynamic response including coupling and specialized modes, such as translational rate command (TRC)
- Pilot-induced oscillations
- Control power
- Controller force/displacement gradients
- Controller characteristics such as free play, break out, damping, and friction

- Trim characteristics.

Combined axis effects (control harmony, for example) are covered in a separate section as are miscellaneous topics, such as rotorcraft response to stores release and specific failure characteristics. The required response characteristics to turbulence are implicit in the response to a controller in that the flying quality boundaries are developed in a moderately turbulent environment. However, a separate section defining specific turbulence characteristics and required rotorcraft response characteristics not covered elsewhere is provided in Paragraph 3.17.

SECTION II

DISCUSSION OF SELECTED REQUIREMENTS

This section is organized with the identical paragraph numbering system utilized in the preliminary Flying and Ground Handling Qualities Specification; however, only selected criteria are discussed based on the need for providing background, rationale, and, wherever available, data correlations to support numerical requirements.

1.3 LEVELS OF FLYING QUALITIES

Where possible, the requirements of Section 3 of the preliminary specification have been stated in terms of three values of the stability and control parameter being specified. Each value is a minimum condition in order to meet one of the three levels of acceptability related to the ability to complete the operational missions for which the rotorcraft is designed. This has been common practice in other flying qualities specifications (i.e., MIL-F-8785C and MIL-F-83300). In past specifications, the levels of flying qualities were defined in terms of the ability to complete certain flight phases and/or in terms of mission effectiveness. However, in actual practice, the flying qualities boundaries were obtained by fairing lines of constant Cooper-Harper ratings. It was therefore necessary to develop equivalent definitions between the Cooper-Harper scale and the level definitions. In Ref. 1, a document intended to replace MIL-F-8785C, we suggested utilizing the Cooper-Harper scale directly in order to define levels of flying qualities. In that document the old level definitions were also retained, and the method for defining flying qualities levels was left to the procuring activity. In the present specification, we are recommending exclusive utilization of the Cooper-Harper pilot rating scale for defining the levels of flying qualities [see Fig. 1(1.3)]*. Retaining both definitions of flying qualities levels as was done in Ref. 1 seems undesirable in that it complicates the usage of the specification. The advantages of using the Cooper-Harper pilot rating scale directly in the definition of flying levels are as follows:

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*All figures and tables with this notation (parentheses) are found in the Flying and Ground Handling Qualities Specification (Volume I).

- It provides more precise definitions related to pilot workload and task.

- The use of faired experimental data (i.e., Level 1 = 3.5, Level 2 = 6.5, and Level 3 = 8) is consistent with the definition of levels in the specification. This is not the case in MIL-F-8785C and MIL-F-83300.

- The same standard is used when applying quantitative criterion boundaries for specification compliance as is used when showing compliance by flight demonstration.

- Test pilots are trained to assign Cooper-Harper ratings when performing tests and evaluations of military rotorcraft; for example, see Ref. 2.

The definition of Level 3 has been restricted to a pilot rating of 8 in order to retain the basic intention of Level 3, i.e., to allow Category A flight phases to be terminated safely and Categories B and C flight phases to be completed. Cooper-Harper pilot ratings of 9 and worse indicate that intense pilot compensation is required to retain control. This is thought to be outside the intent of Level 3. This interpretation was also made in the development of the MIL Standard and Handbook in Ref. 1.

An alternative to utilizing the Cooper-Harper pilot rating scale or the existing level definition in MIL-F-8785C was presented at a flying qualities workshop documented in Ref. 3. This definition of flying qualities levels is repeated here for convenience.

> Flying qualities such that [blank] task performance for the mission flight phase can be achieved with a workload that is [blank] to the pilot, under the set of environmental conditions (specified by the procuring activity) for which performance of the flight phase is required and such that Category A Flight Phases can be terminated safely and Category B and C Flight Phases can be completed safely in the most difficult set of environmental conditions required by the procuring activity to be considered in the design of the aircraft.
>
> Where:
>
> Level 1. Insert the words "desired" and "satisfactory" in the blanks.
>
> Level 2. Insert the words "adequate" and "tolerable" in the blanks.
>
> Level 3. Insert the words "not specified" in the blanks.

It is our opinion that the use of such definitions for flying qualities levels states the objective but does not indicate the method by which the objective should be achieved. It would, in fact, be necessary to fly the rotorcraft in all proposed missions, in the noted environmental conditions, under all failure states in order to determine the flying qualities levels if a definition similar to the one stated above were utilized. Such a task would involve an unreasonably large number of flight test hours. Finally, the connection between such definitions and the Cooper-Harper rating used to define the specification criteria seems vague at best.

1.4 FLIGHT ENVELOPES

The current MIL-F-8785C and MIL-F-83300 specify three flight envelopes: the operational flight envelope, the service flight envelope, and the permissible flight envelope. In preparation of the Ref. 1 MIL Standard and Handbook, a large volume of lessons learned information was obtained from the USAF special projects offices. Several comments indicated that the use of the service and permissible flight envelopes was very limited, and, in fact, it was noted that these two flight envelopes are rarely defined. Most of the lessons learned comments centered around the fact that military rotorcraft are routinely flown to their limits of performance and therefore should have Level 1 flying qualities up to these limits. The service flight envelope, as defined in MIL-F-83300 and MIL-F-8785C, sets <u>artificial limits</u> on the region of where Level 1 flying qualities are required; that is, the operational envelope is set by the defined mission, <u>not</u> the rotorcraft limits. In fact, it is the service flight envelope that is set by considerations of rotorcraft limits in MIL-F-8785C and MIL-F-83300. Since Level 2 flying qualities are allowed in the service flight envelopes, there can be substantial regions within the achievable flight envelope (set by performance and structural considerations) where degraded flying qualities are allowed. This has been eliminated in the proposed revised MIL-H-8501A by establishing the operational flight envelope based on rotorcraft performance and structural limits.* The permissible flight envelope has been retained in order to account for operation in "grey areas" such as retreating blade stall and the vortex ring state.

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*There was considerable resistance to this change at the second interim progress review (IPR-2) held at AVRADCOM in St. Louis, Missouri, on December 12 through 15, 1983. In particular, the issue of Level 1 values of control power was found to be difficult to support with this structure. This will be reviewed further during Phase II, and the original "operational," "service," and "permissible" flight envelopes will be retained if the new structure cannot be modified to be mutually acceptable to the contractors and to the government.

The operational envelope is subdivided into three specific regions in Paragraph 1.4 of the proposed specification. The hover region is defined as all operations occurring below the ground speed at which effective translational lift occurs in a no-wind condition. The rationale here is that the flying qualities task associated with hover, i.e., maintaining some position with reference to a fixed point on the ground, generally occurs at speeds below effective translational lift. After passing through the region of effective translational lift, the pilot is usually concerned with getting from one point to another rather than station-keeping with respect to a fixed point. The ground speed is used in the definition as opposed to airspeed in order to avoid the problems associated with hovering in high wind conditions.

The speed range between hover and 45 knots ground speed is labeled "low speed." Most operations in this speed range are associated with takeoffs, landings, and nap-of-the-earth (NOE) flight; hence, the flying qualities task is associated with maneuvering around objects on the ground or in the ocean as the case may be.

"Forward flight" is defined as all operations occurring when the ground speed is greater than 45 knots. The flying qualities task in this case is usually not associated with direct maneuvering with respect to objects on the ground, and the rotorcraft is flown more like a fixed-wing airplane. Even in high speed NOE operations, the rotorcraft is flown using the piloting techniques that would be utilized by a fixed-wing pilot on a terrain-following mission; hence, the requirements for forward flight are similar to those found in MIL-F-8785C. However, it is believed that the rotorcraft specification should be self-contained and that some special rotorcraft flying qualities make it impractical to utilize MIL-F-8785C (the fixed-wing specification) for forward flight.

1.5 DEFINITION OF USABLE CUE ENVIRONMENT

The usable cue environment (UCE) scale provides a reasonably fine-grained definition of visual cues available to the pilot in conditions of progressively decreasing visibility, such as may be caused by fog or darkness. This scale is a derivative of the outside visual cue (OVC) scale developed in Refs. 4 and 5. The prime difference between the UCE scale in Paragraph 1.5 and the OVC scales found in Refs. 4 and 5 is that the UCE scale accounts for the effect of artificial vision aids implicitly, where the OVC scale considered only the outside environment. In addition, the UCE scale utilizes the single adjectives "good," "fair," and "poor," whereas the OVC scale utilizes adjectival phrases. Previous studies involving the development of pilot rating scales have found that the adjectives "good," "fair," and "poor" tend to be linear (see Ref. 6) in terms of their semantic meaning to a large population of pilot/engineer subjects.

A review of the UCE scale reveals that the first three levels of usable cue environment involve good attitude cues with increasingly degraded translational rate cues. This accounts for flight in degraded visibility with a good artificial display of pitch and roll attitude. The lack of good attitude information results in the lowest UCE levels regardless of the translational rate cues (i.e., good to poor). This reflects the fact that the pilot cannot control the outer position loop without a good inner attitude loop closure (see Ref. 4). It is important to note that the "translational rate and position" cues refer to the rate of closure with outside objects; hence, a simple display of closure speed would not be acceptable if the object itself is not somehow represented.

The UCE scale in Paragraph 1.5 is based on discussions with operational pilots as well as the personal observations of one of the authors (and on Refs. 4 and 5) acting as a helicopter pilot in both simulation and flight in the presence of degraded outside visual cues. In addition, Systems Technology, Inc., (STI) is currently conducting an in-flight experiment to determine the fundamental elements of the reduced visual cue environment that are essential to accomplish low speed and hover flight. The results of this research are primarily intended to assist in upgrading current ground-based simulation visual display capability on the NASA Ames Research Center Vertical Motion Simulator (VMS). This research will be accomplished by selecting a range of visual environments over a dry lake bed at Edwards AFB as well as by degrading certain components of the visual field artificially with special lenses worn by the evaluation pilots in a Hughes 500 helicopter. It is believed that this research will have direct application to refinement of the present UCE scale [Fig. 1(1.5)] for use in the final specification.

3.1 GENERAL REQUIREMENTS

3.1.6.1 Probability Calculation. This requirement is included to provide a sound analytical method for accounting for the effects of failures and is patterned after the MIL Standard and Handbook (Ref. 1). It should be noted that the MIL Standard and Handbook is different from Ref. 7 (MIL-F-8785C) in that flight hours provide the basis for the calculation as opposed to the number of flights. This assures that the requirements are constant with operational time where, in the past (MIL-F-8785C), the requirements were easier to meet for rotorcraft with very short operational flight times and harder to meet for rotorcraft with very long flights.

3.1.6.3 Generic Failure Modes and Effects. This paragraph has been included to provide a way to specify the allowable degradation in handling qualities due to failures without making detailed probability calculations. Using this approach, it is assumed that a given component or series of components will fail. Furthermore, it is assumed that failures will occur in the most critical flight condition. Based on the lessons learned data used in developing the MIL Standard and Handbook, this approach is a reflection of the way things are frequently being done.

3.1.6.4 Artificial Vision Aids Failures. Inasmuch as artificial vision aids play a key role in determining the required rotorcraft response type, it is necessary to account for failures in the key display elements. In particular, the allowable probability of failure of an artificial vision aid is based on the degree of reliance placed on such aids in improving the usable cue environment [see Table 2(3.1)]. For example, if an artificial vision aid is utilized to improve the basic mission outside visual cues from a level of 5 (where attitude and translational rate cues are poor) to a usable cue environment of 1 (where these cues are both good), the probability of failure must be very low. We have assigned a maximum probability of 10^{-5} for this failure mode based on its being an "essential function."* The Civil Airworthiness Standards dictate that a system which has been determined to be "essential" must have a frequency of occurrence which is "improbable." Improbable failures are not expected to occur during the total operational life of a single airplane of a particular type but are expected to occur during the total operational life of all airplanes of a particular type. Such failures are required to have an estimated rate of 10^{-5} to 10^{-9} per flight hour. It is expected that there will be some question regarding the use of probability numbers taken from Civil Airworthiness Requirements (FAR 25.1309) in a military flying qualities specification. In particular, 10^{-5} may be overly conservative in that display systems with 10^{-5} reliability would be prohibitively expensive due to the triple or even quadruple redundancy necessary to achieve such performance.

The remaining probabilities in Table 2(3.1) are based on the existing MIL-F-8785C specification which requires that failures resulting in Level 3 flying qualities have a maximum probability of 10^{-4}, and failures resulting in Level 2 flying qualities should have a probability of no more than 10^{-2}. From Table 2(3.3) it can be seen that a failure to a UCE of 2 will result in a requirement for at least a rate system. Therefore, an artifical vision and failure resulting in a change in UCE from 5 to 2 would leave the pilot with a rate response in a situation where a

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*Essential functions are defined by the Civil Airworthiness Standards as functions which would reduce the capability of the airplane or the ability of the flight crew to cope with adverse operating conditions in the event of a failure.

translational rate command (TRC) response is necessary. This is estimated to result in Level 3 flying qualities if operating in the worst case condition (OVC = 5). Therefore a maximum probability failure of 10^{-4} is specified for this condition in Table 2(3.1). Likewise, a failure from a UCE of 4 (where an attitude system is required) to a UCE of 1 (where an acceleration system is allowed) is also estimated to result in Level 3 flying qualities and, hence, is assigned a maximum probability of failure of 10^{-4}. All other artificial vision aid failures are estimated to result in Level 2 flying qualities and, hence, are assigned a maximum probability of failure of 10^{-2} as seen in Table 2(3.1). Further refinements of these estimates will be made during the preparation of the final draft of the specification, to be accomplished in Phase II.

3.2 OPERATIONAL MISSIONS AND MISSION TASK ELEMENTS

a) Discussion. In order to develop a comprehensive mission-oriented specification, it was believed to be necessary to make a significant departure from the general category and class definitions used in MIL-F-8785C and MIL-F-83300. In place of the general category and class definitions, we have defined basic elements of rotorcraft missions in terms of specific flying qualities tasks which have been tabulated in Tables 1(3.2) and 2(3.2). These tasks are described in detail in Appendix A of the specification. The definition of well defined flying qualities tasks is entirely consistent with the use of the Cooper-Harper scale for specifying flying qualities levels [see Fig. 1(1.3)]. As has been noted in a great deal of recent flying qualities literature, as well as in the basic report defining the Cooper-Harper pilot ratings (Ref. 8), the definition of specific tasks is a key aspect to obtaining valid ratings. Therefore, it is important to emphasize that, by defining specific flying qualities tasks and using the Cooper-Harper scale as the basic level definition, we are indeed being responsive to the lessons learned during the past 15 years of flying qualities research.

It should be noted that some of the tasks in Table 1(3.2) are further broken down into categories of performance, i.e., moderate (M) and aggressive (A). The "moderate" tasks involve less stringent performance requirements and longer times to achieve the task than for the "aggressive" tasks. Large cargo helicopters would probably be in the moderate category, whereas attack helicopters would be in the aggressive category, although there may be some exceptions for certain maneuvers. An example of such an exception is the need for aggressive tactical maneuvering in hover for a large cargo helicopter. The ability of large helicopters to perform high agility maneuvers was demonstrated graphically in a film shown by Charles ("Cap") Parlier from Hughes Helicopters Incorporated showing a CH-53 performing 360-degree rolls.* One advantage of eliminating the class structure is that such exceptions are easily accounted for, i.e., the performance requirements are not linked to the size of the helicopter.

The way in which the mission task elements from Tables 1(3.2) and 2(3.2) fit into the overall picture is illustrated by the methodology to be utilized by the procuring activity which is summarized below.

1. Define detailed missions.
2. Select appropriate tasks from Tables 1(3.2) and 2(3.2) which represent elements of the above defined mission.
3. Determine the basic control response type required to attain Level 1 flying qualities for the above defined mission task elements from Table 1(3.3).
4. Define the worst-case outside visual cue environment for each element of the proposed mission in terms of Fig. 1(1.5).
5. Select the appropriate artificial vision aids and stability augmentation based on Table 2(3.3).
6. Settle on the final control/display configuration with the contractor.

It should be noted from Steps 5 and 6 above that there is a tradeoff between the sophistication of the artificial vision aids and the rotorcraft response type (sophistication of augmentation). The methodology of this specification allows the procuring activity to make quantitative tradeoffs between control and display sophistication in order to achieve Level 1 flying qualities for the specified mission task elements. The required probabilities of failure of augmentation [Table 1(3.1)] and displays [Table 2(3.1)] will have a strong influence on the cost of each potential control/display suite.

The mission task elements shall be used primarily as standardized flying quality tasks to be used in flight test and piloted simulation experiments conducted to determine Levels 1, 2, and 3 values of the time response parameters. It will be important to utilize highly experienced test pilots in order to insure valid and consistent pilot ratings in these experiments. In addition, the contractor shall be required to demonstrate

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*Shown at the Second Annual Flight Testing Conference, held in Las Vegas, Nevada, on November 17, 1983 (see Ref. 13).

that the specified performance requirements can be achieved in flight test. It is emphasized that this requirement (Paragraph 4.1.4) is intended only as an overall check to determine that the specified mission task elements can indeed be accomplished in flight. If the quantitative (time history) specification requirements are valid, the pilot effort in accomplishing the tasks should be Level 1, although there is no intent to require this. In the event that the flight tests reveal excessive pilot effort (Cooper-Harper ratings greater than 3), the pertinent quantitative requirements should be flagged for review and subsequent revision.

In the event that quantitative requirements are not available (because of data gaps), the mission task elements shall be used as flying quality tasks. Specification compliance in these cases shall be demonstrated through Cooper-Harper pilot ratings (Paragraph 1.3) wherein the consensus of the test pilots shall be used with appropriate averaging. Large spreads in the ratings between pilots should be considered as a warning of poor flying qualities.* In addition, the Cooper-Harper scale is known to be reasonably linear for pilot ratings from 1 to 6 (see Ref. 6); however, it is quite nonlinear between 7 and 10, so that averaging of ratings in this region is not valid.

The pilot ratings obtained in the above flight tests should be used to upgrade the quantitative criteria in the specification.

The proposed methodology for establishing compliance procedures as well as providing a basis for continually upgrading the specification is shown in Fig. 2.

b) Gaps in the Data. The general nature of the specified tasks in Tables 1(3.2) and 2(3.2) is well known; however, specific details of how the tasks should be performed and the exact performance limits will require interfacing with operational pilots. It is our opinion that simply discussing these tasks is not adequate, and some flight testing will be required. Such flight tests would involve flying the tasks noted in Section 3.2 using military instructor pilots--preferably with combat experience--and quantifying both the way in which the task is performed and the specific tolerances allowed by these instructor pilots in training new combat pilots. We envision a great deal of interaction between the specification writers, manufacturers' test pilots, and the military evaluation pilots in order to successfully accomplish this very important aspect of the specification development. It is estimated that approximately 40 to 50 flying hours would be required to quantify the tasks specified in Paragraph 3.2.

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*Unfortunately, no specific guidance is available for interpreting large spreads in pilot ratings at this time, except to note that the poor ratings should be investigated by reviewing pilot commentary carefully.

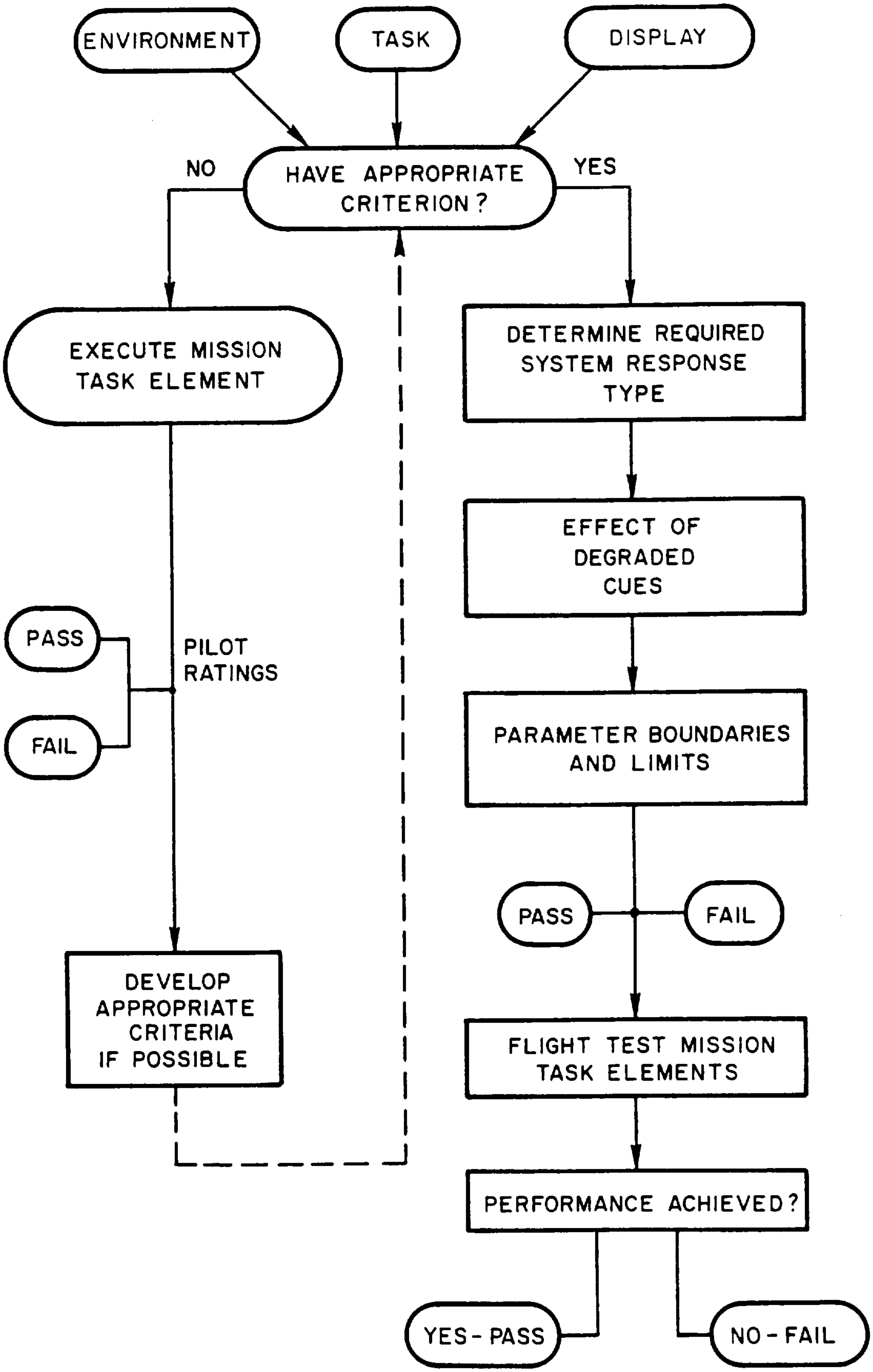

Figure 2. Alternate Methods of Specification Compliance

3.3 REQUIRED ROTORCRAFT RESPONSE TYPE

3.3.2 Required Response Type for Specified Mission Task Element.

a) Discussion. Using the mission task elements developed in the flight test described under Section 3.2, the level of augmentation required for Level 1 flying qualities with good outside visual cues (OVC = 1) is specified in Table 1(3.3). The example table shown in the preliminary specification is based purely on estimates utilizing a combination of past ground-based simulation data and our experience in dealing with rotorcraft flying qualities. This is considered to be inadequate for the final specification. The experimental work necessary to develop a relationship between the rotorcraft response type and the specific mission task elements is discussed below.

b) Gaps in the Data. There are some moving base piloted simulation data available utilizing the NASA ARC vertical motion simulator (VMS) which relates specific maneuvers to response types. This study was sponsored by the U. S. Army and is described in Ref. 9. A review of the results obtained in Ref. 9, as well as other referenceable results obtained on the VMS, indicates that the pilot rating data tend to be very conservative (i.e., high-order response types are required to perform what are known to be relatively simple tasks in the real world). For example, it is very difficult to do a precision hover on the VMS with a rate-type response--a task which is known to be very straight-forward in the real world. The conservative nature of the VMS results is thought to be attributable to the deficiencies summarized below.

- Excessive time delay in the computer generated imagery (CGI)
- Inadequate texture contrast and possibly field of view in the visual scene, again, a deficiency in the CGI
- Inappropriate motion washouts (in some cases the lack of correspondence between the visual and motion system has actually induced motion sickness in experienced pilots).

The net result is that it is impossible to do precision aggressive hovering with less than an attitude stability augmentation system (SAS) in the VMS, a situation which is clearly not representative of the real world.

Because of the above noted deficiencies, it is recommended that the data required to relate specific mission tasks to rotorcraft response types be generated using in-flight simulation (variable stability helicopters). Both the National Research Council (NRC) variable stability Bell 205 and the NASA ARC variable stability CH-47 helicopters represent candidate facilities for the necessary flight tests. For highly aggressive maneuvering, it will probably be necessary to use the NRC helicopter; however, for most tasks, the NASA ARC CH-47 will probably be adequate.

In general, the flight test experiment required to generate data for Table 1(3.3) will consist of setting up minimum response characteristics in each category (i.e., acceleration, rate, attitude, and TRC). This will require several configurations for each response type, because the minimum is defined by a number of parameters such as rise time, overshoot, time delay, stick sensitivity, and stick force displacement characteristics. It is expected that each of these parameters will define minimum acceptable flying qualities characteristics for specific groups of mission task elements. Therefore, the first phase of the experiment should be to define groups of tasks that are sensitive to certain flying qualities parameters. For example, nearly all maneuvers will be sensitive to rise time, whereas the maneuvers requiring aggressive precision will be more sensitive to the time delay or "dead time" parameter, τ_d. Such limiting factors, in addition to providing the necessary information to conduct the flight tests, would also be valuable design guidance information to be used in the BIUG.

3.3.3 Required Upgrading of Response Type in Conditions of Degraded Outside Visual Cues.

a. Discussion. It is well known that low speed and hover maneuvers become more difficult when visual cues are degraded, such as at night or in conditions of rain, snow, or fog. This is discussed in considerable detail in Ref. 4, where it is shown that the ability to accomplish precision maneuvering in low speed and hover depends on certain essential feedbacks. As shown in Ref. 4, these essential feedbacks consist primarily of attitude and translational rate quantities which must be perceived by the pilot accurately and quickly in order to make the appropriate control motions to stabilize the helicopter. In conditions of degraded outside visual cues, it is not possible for the pilot to make such accurate, rapid assessments of attitude and translational rate. In such cases it is necessary to have a certain amount of inherent stability depending on the severity of the degradation in usable visual cues. This requirement represents an important principle of the specification methodology, that is, required responses from Table 1(3.3) must be upgraded in the presence of degraded usable cue environments according to Table 2(3.3).

The methodology used for specification of the required rotorcraft response type as a function of the outside visual environment [Fig. 1(3.3)] was developed after considerable discussion and thought. The decision to require participation by both the procuring agency and the contractor in specifying the final (contractural) response type is believed to be extremely advantageous for several reasons. Cost and complexity of the control system should be minimized through joint participation. The outlined responsibility for the procuring agency should insure that the mission and mission task elements are included in the decision making process and that a conservative specification decision is always made during initial stages of development. This conservatism would be balanced by the contractor's ability to achieve a respecification of the minimum response type. Respecification of the response type would follow the contractor's demonstration of advanced outside visual aid or display technology that would make a change technically feasible and desirable. The requirement that final acceptance of a contractor request for respecification of the minimum response type insures that the procuring agency has control of the specification process (as well as responsibility for choice of the required response type).

The data in Table 2(3.3) is based on estimates, taking into account practical operational experience as well as piloted simulation results. However, this is not believed to be adequate for specification purposes, and the necessary additional data is discussed below.

It is possible that the contractor might decide to provide a more sophisticated flight control system than that required by Paragraph 3.3.2 and 3.3.3. If this should be the case, the requirements that apply to the more sophisticated system must be met. For example, it would be inappropriate to design an inadequate TRC system if attitude response is required. Regardless of the reasons for designing a TRC system, it still must have good characteristics.

b. Gaps in the Data. It is necessary to obtain data to determine the worst usable cue environment for each response type (acceleration, rate, attitude, and TRC) for Level 1 flying qualities. This can be accomplished via a combination of flight test and ground-based piloted simulations. However, it is necessary to understand the limitations of current state-of-the-art simulation in order to avoid obtaining overly conservative results. The primary deficiency in current moving-base rotorcraft simulation results has been a lack of fidelity in the computer-generated imagery (CGI). The primary culprits have been computational time delay and an apparent lack of texture and contrast in the computer-generated scene. These deficiencies lead experienced rotary wing pilots to find it difficult to manage a precision hover using a rate augmented helicopter. On this basis, it is recommended that flight tests be employed when making determinations which involve outside visual cues between 1 and 3. For outside visual cues of 4 and 5, it is believed that the simulator is probably adequate because of the minor role played by the CGI when simulating severely degraded visibility.

On the basis of the foregoing arguments, it seems reasonable to recommend the use of simulation to evaluate artificial vision aids designed to upgrade the usable cue environment from very low levels (say 4 or 5). These simulations should consider variations of basic display elements which present rotorcraft attitude and translational rate to the pilot. In addition to evaluating the content of the display, a systematic variation of format should also be included. A partial list of formats to be considered is given below.

- Helmet Mounted Display (HMD)
- Standard Head-Up Display (HUD)
- Forward Looking Infrared (FLIR)
- Computer-Generated Imagery (CGI)

Display variations involving usable cue environments between 1 and 3 should be accomplished in flight, inasmuch as a considerable amount of the usable cue involved comes from the outside world--a feature which currently cannot be simulated with sufficient validity. The major problem with conducting such full-scale flight tests will be to determine a method for accomplishing a systematic reduction in the outside visual cue environment. As discussed earlier, this is currently under study by STI in a flight test program designed to determine the outside visual cues needed to accomplish aggressive and precise maneuvering in hover. While this work is primarily aimed at upgrading the CGI displays in the NASA ARC VMS, it is not difficult to see that the ability to systematically vary the outside visual cues will have direct application to the flight test proposed herein.

It is estimated that approximately 5 to 6 weeks of simulation on the NASA ARC VMS and approximately 30 to 40 flight test hours will be required to obtain the necessary data for this section of the specification. These estimates assume that the displays, or emulations of the displays, would be available at the beginning of the flight test or simulation program. It can be seen, then, that a considerable number of engineering/programmer hours will be required to define, program, and check-out the desired display variations.

The level of atmospheric disturbance will, of course, have a major impact on the piloted evaluations of each tested display format and content. Therefore, all tests should be conducted in the "standard" level of turbulence to be used in this specification (i.e., "moderate" as defined in Paragraph 3.17.2). In addition, the allowable flying qualities degradations in moderate turbulence defined in Table 1(3.17) should be adhered to (i.e., Level 1 will be defined by a Cooper-Harper pilot rating of 5-1/2 in moderate turbulence) for acceleration and rate-type responses. However, it is important to note in Paragraph 3.17.1.2 that attitude and translational rate command responses require a pilot rating of 3-1/2 to define Level 1 flying qualities, even in moderate turbulence. This is based on the rationale that one of the primary reasons for going to such highly augmented configurations is to be able to perform precise and aggressive maneuvers in the face of severe environmental conditions which includes low visibility and moderate turbulence.

3.4 RESPONSES TO LONGITUDINAL CONTROLLER

The "longitudinal controller" is to be defined by the contractor and will usually take the form of the longitudinal cyclic stick. However, it is also intended that sidearm controllers and possibly other more exotic configurations may be specified by the contractor. Such unusual configurations will, of course, require agreement from the procuring activity. In addition, it will be possible to have separate longitudinal controllers. For example, the contractor may define the longitudinal controller as the pitch cyclic stick during low speed and forward flight and specify a separate sidearm controller for precision hover. This was done with the Heavy-Lift Helicopter (HLH), although separate crew men operated the two longitudinal controllers in that case. It is expected that the overwhelming majority of rotorcraft which will be required to meet this specification will have a single longitudinal controller and that, in most cases, this controller will consist of the cyclic stick with the most exotic controller expected in the foreseeable future being a four-axis sidearm controller.

3.4.1. Pitch Attitude Response to Longitudinal Controller in Low Speed and Hover. The required pitch attitude response to the longitudinal controller is separated into acceleration, rate, attitude, and translational rate response types. The response type to be utilized in complying with the specification will depend on the mission task elements [Table 1(3.3)] as well as the usable cue environment as defined by Table 2(3.3).

3.4.1.1. Required Pitch Attitude Dynamics When Acceleration Response is Allowed by Paragraph 3.3.

a. Discussion. The word "acceleration" here refers to the response in the region of piloted crossover which occurs approximately between 0.7 and 3 rad/sec. It refers to conventional unaugmented or lightly augmented rotorcraft. The requirements for such rotorcraft have been adapted from the current MIL-H-8501A as well as from Ref. 4.

The first part of this requirement ("short-term response") is intended to provide adequate pitch damping, and it replaces Paragraph 3.2.14 of the current MIL-H-8501A. In more general terms, the pitch damping is usually well represented by the first-order time constant of the classic hover cubic, e, from Ref. 10.

$$\frac{\theta}{\delta_{LONG}} = \frac{M_{\delta_{LONG}}}{(s + \lambda)\left[s + 2\zeta_n \omega_n s + \omega_n^2\right]}$$

The first-order time constant, λ, in the above equation is well approximated for most rotorcraft as $\lambda \doteq -M_q$. Various aspects of the hover cubic are discussed in detail in Ref. 4 (Section 4B).* The minimum acceptable values of λ for Levels 1, 2, and 3 flying qualities were obtained from Fig. 3. The references indicated in Figure 3 are from Ref. 4.

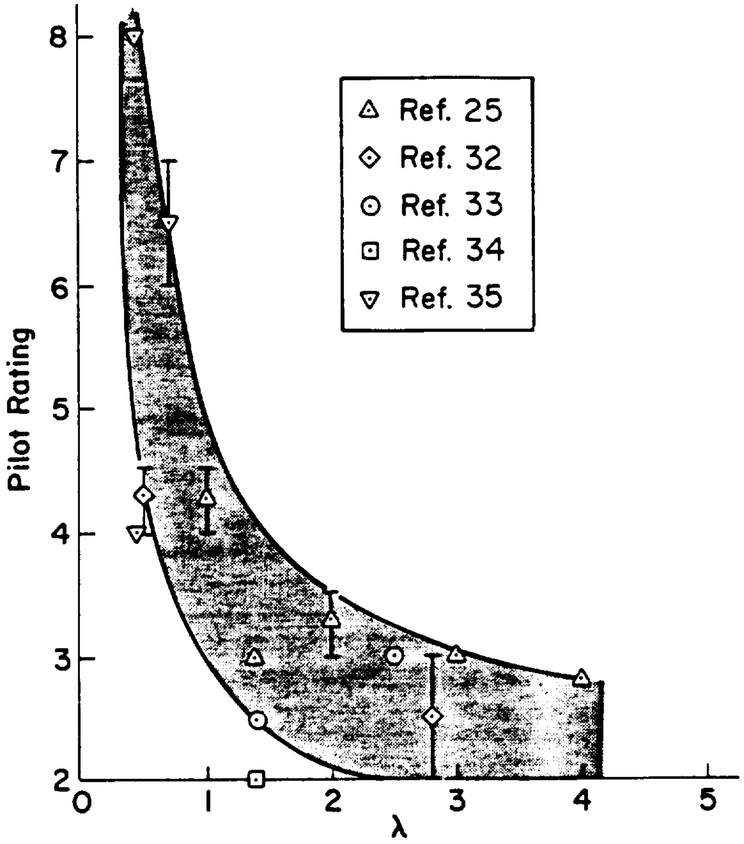

Figure 3. Pilot Ratings versus λ for Rate Augmented Configurations Where $\omega_n < 0.5$

The first of these references is based on an experiment using the NASA ARC S01 simulator which utilizes one-to-one motion and outside real world cues and, therefore, is considered to be highly reliable. The second reference is based on in-flight data taken from the X-14A variable stability short

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*There is an apparent discrepancy between the current specification and the terminology used in Ref. 4. Pure rate systems in Ref. 4 are equivalent to "acceleration systems" in the current specification. The reason for this is that the pure rate systems referred to in Ref. 4 were based on the very lightly augmented or unaugmented helicopters represented by the classic hover cubic. The rate systems referred to in the current specification refer to more highly augmented rotorcraft intended to operate in lower visibility conditions and to be used for more aggressive and precise maneuver requirements. In fact, many of the "rate systems" in Ref. 4 were actually acceleration type systems in the region of piloted crossover, as can be seen in Fig. 14 of Ref. 4.

takeoff and landing (STOL) aircraft. The last three references are based on variable stability data utilizing the CH-47 and the NRC Bell-205 rotorcraft. These data are considered to be reasonably reliable; hence, the confidence in the data in Table 1(3.4) is reasonably high. Utilizing the data in Fig. 3, the values of λ corresponding to Levels 1, 2, and 3 flying qualities were selected as 1.0, 0.7, and 0.5, respectively.

Following the basic philosophy of this specification, the parameter λ must be identified using a time response criterion. This works out reasonably well when the frequency ω_n is much less than λ so that the responses are well separated. The initial response of pitch rate to a step longitudinal controller input is seen to be first-order-like [Fig. 1(3.4)] and will have the time constant $1/\lambda$. Hence, the parameter $2/\lambda$ represents two time constants of the first-order response. When the frequency ω_n and the value of the inverse of the first-order time constant, λ, are not well separated, it is difficult, and sometimes even impossible, to identify the first-order portion of the response, making it impossible to identify the "short-term steady value" in Fig. 1(3.4). In these cases it will be necessary to identify λ using an equivalent system procedure as is done in MIL-F-8785C (Ref. 7) as well as in the proposed MIL Standard and Handbook (Ref. 1). Indeed, the very reason for going to the complexity of an equivalent system is to identify the parameters of a higher order response. However, the proposed preliminary specification does not dictate that λ be determined via equivalent systems, it only states that an "alternate method of demonstrating acceptable values of λ will be acceptable upon agreement with the procuring agency." It is our intent to include detailed instructions on how to identify λ using equivalent systems in the BIUG, to be generated during Phase II. It is believed that this will not only provide an alternate means of compliance, but will also be useful for design guidance. A requirement to utilize equivalent systems has intentionally been kept out of the specification in an effort to maintain simplicity. Special cases requiring frequency response methods such as this one will be dealt with by giving specific guidance on the recommended alternate method in the BIUG.

The mid- and long-term response requirements of this section are based on times to halve and to double amplitude and on the minimum period of oscillation, a format taken directly from MIL-H-8501A. The values specified in Table 2(3.4) are based on the data given in Fig. 4 taken from Ref. 4. These data are generated from variable stability helicopter in-flight simulation conducted at Princeton University as well as a moving-base simulations conducted at the Northrop Aircraft Corporation. This simulator is believed to have reasonable validity and is discussed in more detail in Ref. 4. The data in Fig. 4 indicate that a relatively large instability can be tolerated if the frequency of oscillation is low enough. Closed-loop pilot/vehicle analysis indicates that this is a

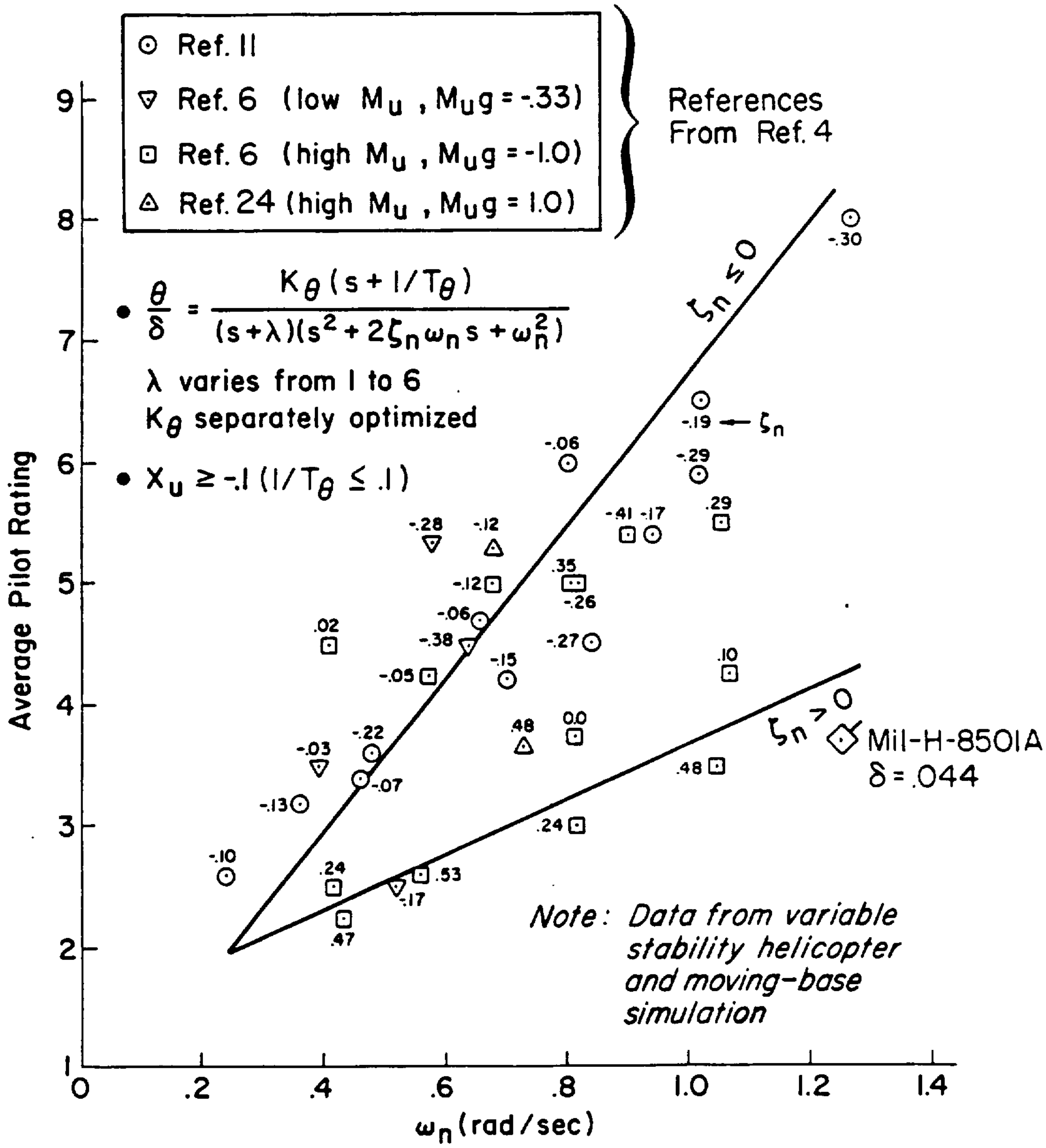


Figure 4. Pilot Rating versus Frequency for a Variety of ζ_n's and λ's (Longitudinal Axis)

direct result of the fact that instabilities at low frequencies are easily stabilized by a pilot with a minimum amount of lead equalization or gain.

The values in Table 2(3.4) were calculated directly from the frequencies and damping ratios noted in Table 1. A direct comparison of the criterion in Table 1 with MIL-H-8501A is given in Fig. 5 where the increased region of allowable instability is shown explicitly.

TABLE 1. LIMITS ON MID- TO LONG-TERM RESPONSE DERIVED FROM FIG. 4 [EQUIVALENT TO TABLE 2(3.4) IN SPECIFICATION]

Damping	Natural Frequency, ω_n (rad/sec)		
	Level 1	Level 2	Level 3
$-.15 < \zeta < 0.06$	0.50	0.90	1.20
$0.35 > \zeta > 0.06$	0.90	1.20	1.20
$\zeta > 0.35$	No Requirement		

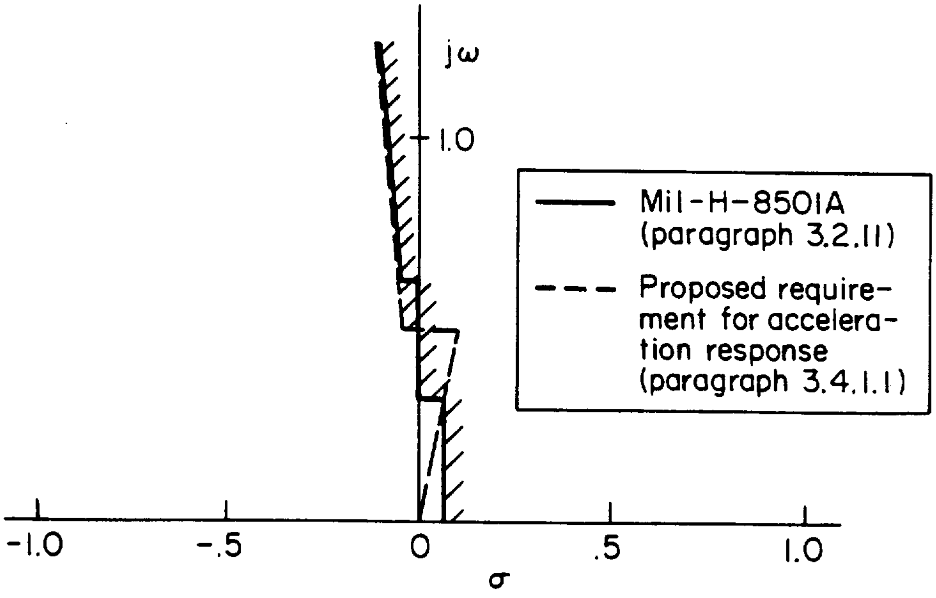


Figure 5. Comparison of MIL-H-8501A and Proposed Criterion

Fig. 5 also indicates that, for frequencies above 0.5 radians per second, the present requirement is slightly more stringent (at frequencies between 0.5 and 0.62). The minimum damping of 0.06 that is selected in Table 1 is based on the fact that it is equivalent to damping to half amplitude in two cycles, as required in MIL-H-8501A (for periods less than 5 seconds). The minimum damping allowable of -0.30 is based on the fact that very few damping ratios less than -0.30 appear in Fig. 2, an admittedly somewhat arbitrary selection. An upper value of damping ratio, where a minimum frequency no longer applies, was selected as 0.35, based on the fact that this is the minimum allowable in MIL-F-8785C for conventional aircraft; that is, for damping ratios of 0.35 or greater, there is insufficient oscillation to be considered a "nuisance mode."

b) Gaps in the Data. The frequency response data upon which the time response boundaries in Tables 1(3.4) and 2(3.4) are based are given in Figs. 3 and 4. Here it is seen that there are little data for damping ratios greater than zero as the frequency, ω_n, becomes greater than one in Fig. 4. This region should be investigated using a variable stability helicopter such as the CH-47 or the NRC Bell 205. Simulation is not recommended because of the insufficient visual cues available to hover lightly augmented or unaugmented helicopters. Fortunately, a good deal of the data in Figs. 3 and 4 is from flight test and only a few spot checks would be required to validate the data base. Aggressive maneuvering tasks should be emphasized to insure that such negative damping ($\zeta = -0.15$) is acceptable.

3.4.1.2 Required Pitch Attitude Dynamics When Rate Response is Required by Paragraph 3.3.

a) Discussion. In keeping with the general philosophy of the proposed Flying and Ground Handling Specification, the required rate response characteristics for Levels 1, 2, and 3 flying qualities are specified in terms of time response metrics. It is intended to utilize the time response parameters defined in Fig. 2(3.4) of the specification for lateral and longitudinal angular rate and attitude response types throughout the operational flight envelope. In general, these responses are well described by the following transfer function

$$\frac{\text{angular rate}}{\text{controller displacement}} = \frac{K(s + 1/T)\, e^{-\tau s}}{(s^2 + 2\zeta_n \omega_n s + \omega_n^2)}$$

and $1/T < \omega_n$. The four parameters chosen for defining this system are dead time, effective rise time, overshoot ratio, and settling time. These parameters serve to specify the bandwidth of the system, where bandwidth is defined as in Refs. 1 and 11 (see Fig. 6). Bandwidth is a measure of how tightly the pilot can control the rotorcraft without encountering closed-loop instabilities.

Open Loop Transfer Function

$$\frac{\theta}{\delta} = \frac{(s + 1/T)\,e^{-\tau s}}{s\left[s^2 + 2\zeta\omega s + \omega^2\right]}$$

Definition of Phase Delay

$$\tau_p = -\frac{\Phi_{2\omega_{180}} + 180^\circ}{114.6\,\omega_{180}}$$

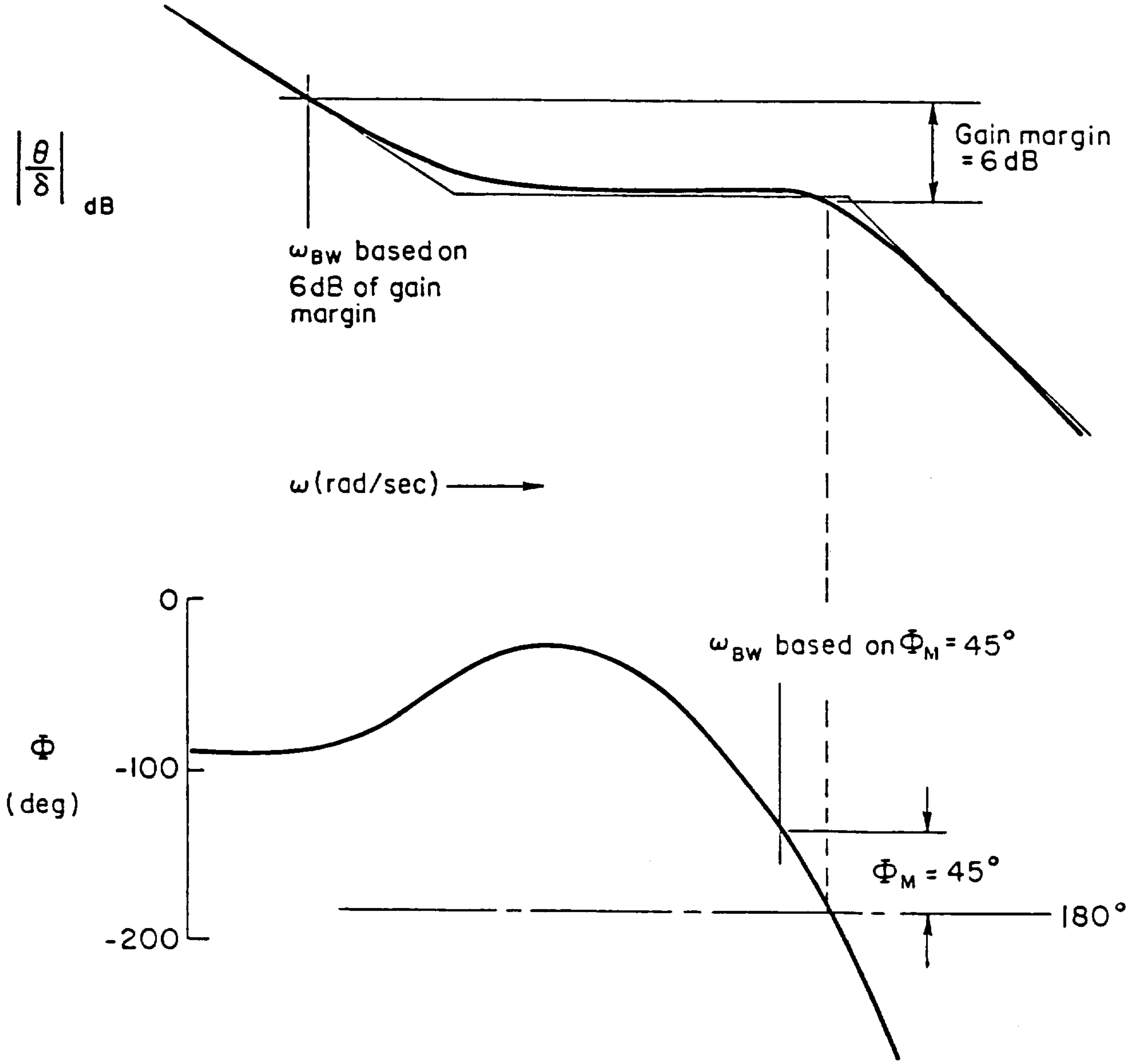


Figure 6. Definition of Bandwidth and Phase Delay from Ref. 1

The equivalence between the frequency response parameters of the above system and the time response parameters of Fig. 2(3.4) was verified by using a representative set of data. The data chosen were taken from Ref. 12, which contains step time responses for a large set of configurations of the form

$$\frac{q}{\delta_e} = \frac{20K_q\left(s + 1/T_{\theta_2}\right)}{(s + 20)\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}{}^2\right]}$$

These configurations were selected to fall on the boundaries of the longitudinal control criterion in MIL-F-8785C (ω_{sp} versus n/α). The bandwidth and phase delays (Fig. 6) of these systems were determined and correlated with the proposed time response metrics.

Dead time is found by drawing a straight line tangent to the maximum slope of the step time response [Fig. 2(3.4)]; τ_d is the point of intersection of this line with the zero-amplitude line. "Dead time" is preferred to describe this time period rather than "time delay," since the latter has taken on more specific connotations in the flying qualities community. As Fig. 7 shows, τ_d is linearly related to τ_{p_θ} for the Ref. 12 systems.

Effective rise time is defined as the difference between dead time and the time when the step response reaches 50 percent of its maximum value. This is similar to the rise time parameter recommended for use in the STOL flying qualities specification (Ref. 11) and is a measure of the system bandwidth (when bandwidth is defined by the phase margin, Fig. 6). Figure 8 shows the pitch attitude bandwidth, ω_{BW_θ}, versus $1/T_{R_q}$ for several of the Ref. 12 cases. The essentially linear relationship (obtained by linear regression fitting) which exists between ω_{BW_θ} and $1/T_{R_q}$ over a wide range of ζ represents good evidence that the selected rise time parameter is a good measure of bandwidth.

Overshoot ratio, x_m/x_o (where x is any response parameter, i.e., q, θ, ϕ, etc.), has been selected as a measure of the damping ratio for an oscillatory response, where x_o = any peak and x_m is any subsequent peak (m = 1, 2, 3, ...). It represents a convenient method of determining ζ for any oscillatory system, and Fig. 9 from Ref. 14 illustrates the relationship between x_m/x_o and ζ. Obviously, the first peak is the easiest to measure and hence has been chosen for the specification criterion

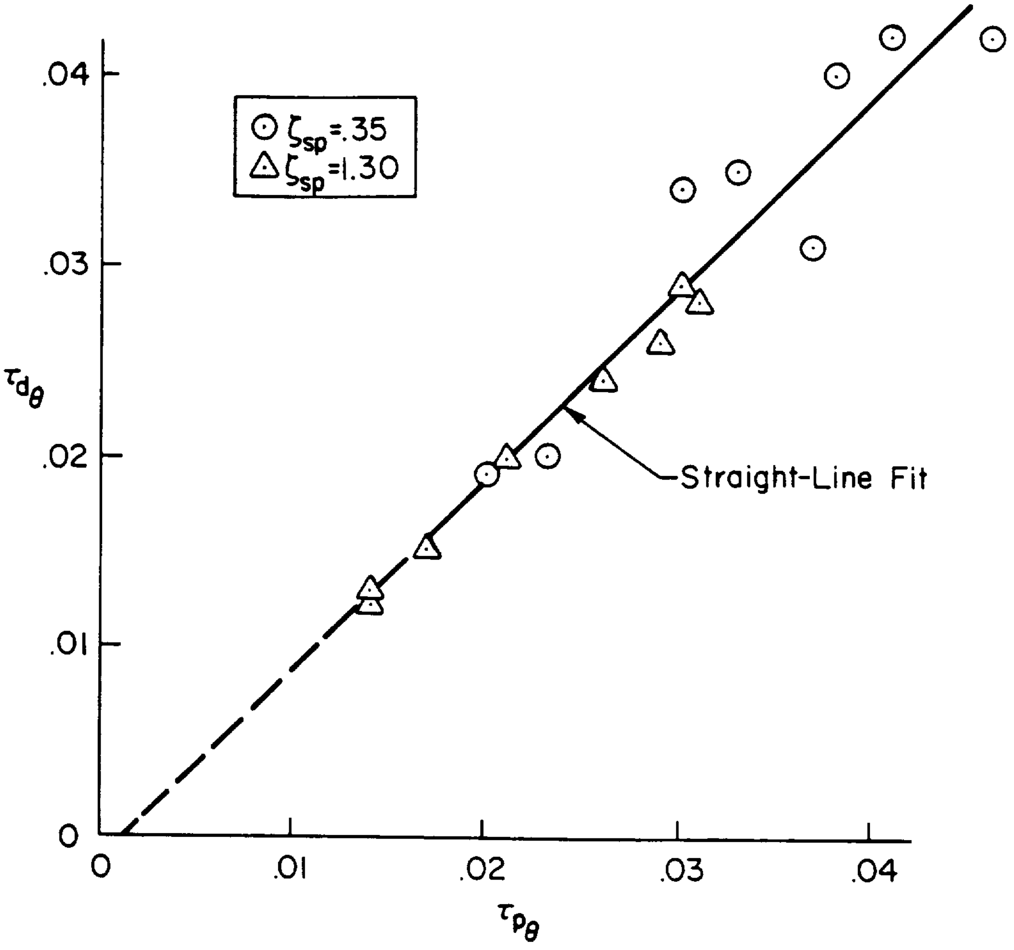


Figure 7. Correlation of Phase Delay and Dead Time

in Fig. 2(3.4). In addition to the three time response parameters (rise time, subsidence ratio, and dead time) the control sensitivities and control force gradients are also defined for each level of flying qualities [see, for example, Table 1(3.4)]. This provides a direct connection between control sensitivities, force gradients, and dynamic response characteristics, a connection that tends to be very vague in MIL-F-8785C as well as in MIL-F-83300. Center stick force gradient requirements have been developed subsequent to review of MIL-H-8501A, the Prime Item Development Specification (PIDS) (UTTAS, AAH, etc.), and fixed-wing flying qualities specifications.

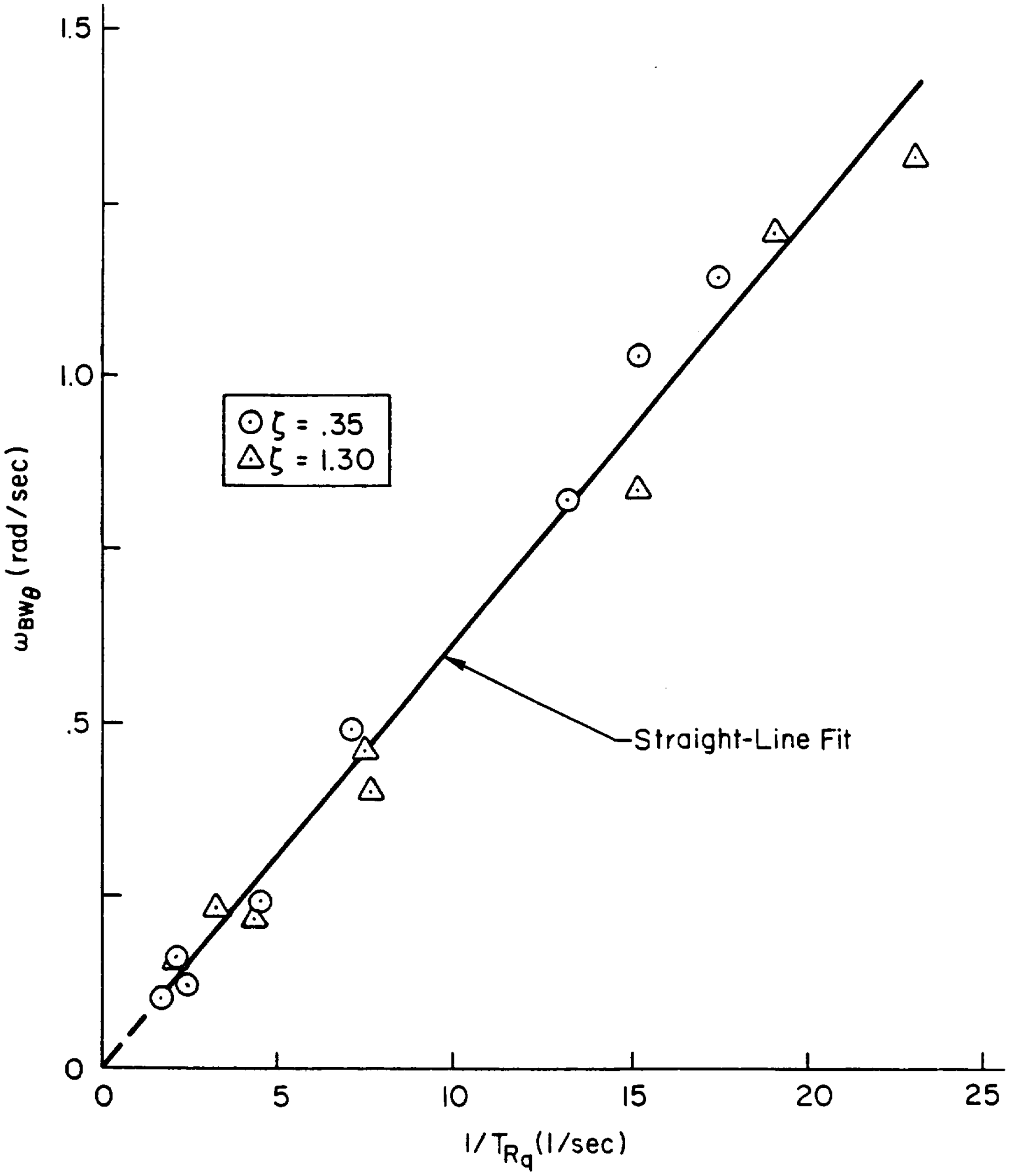
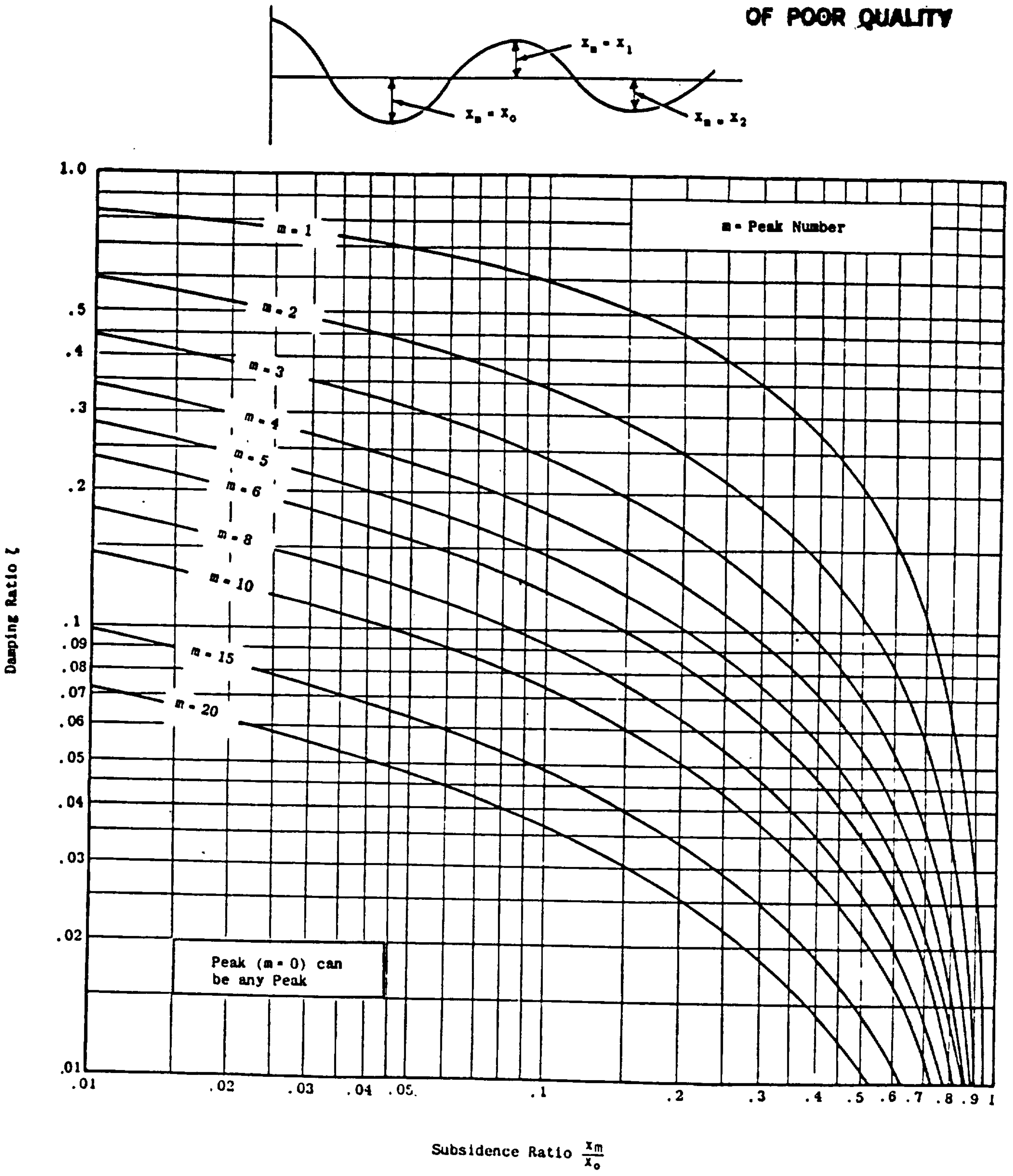


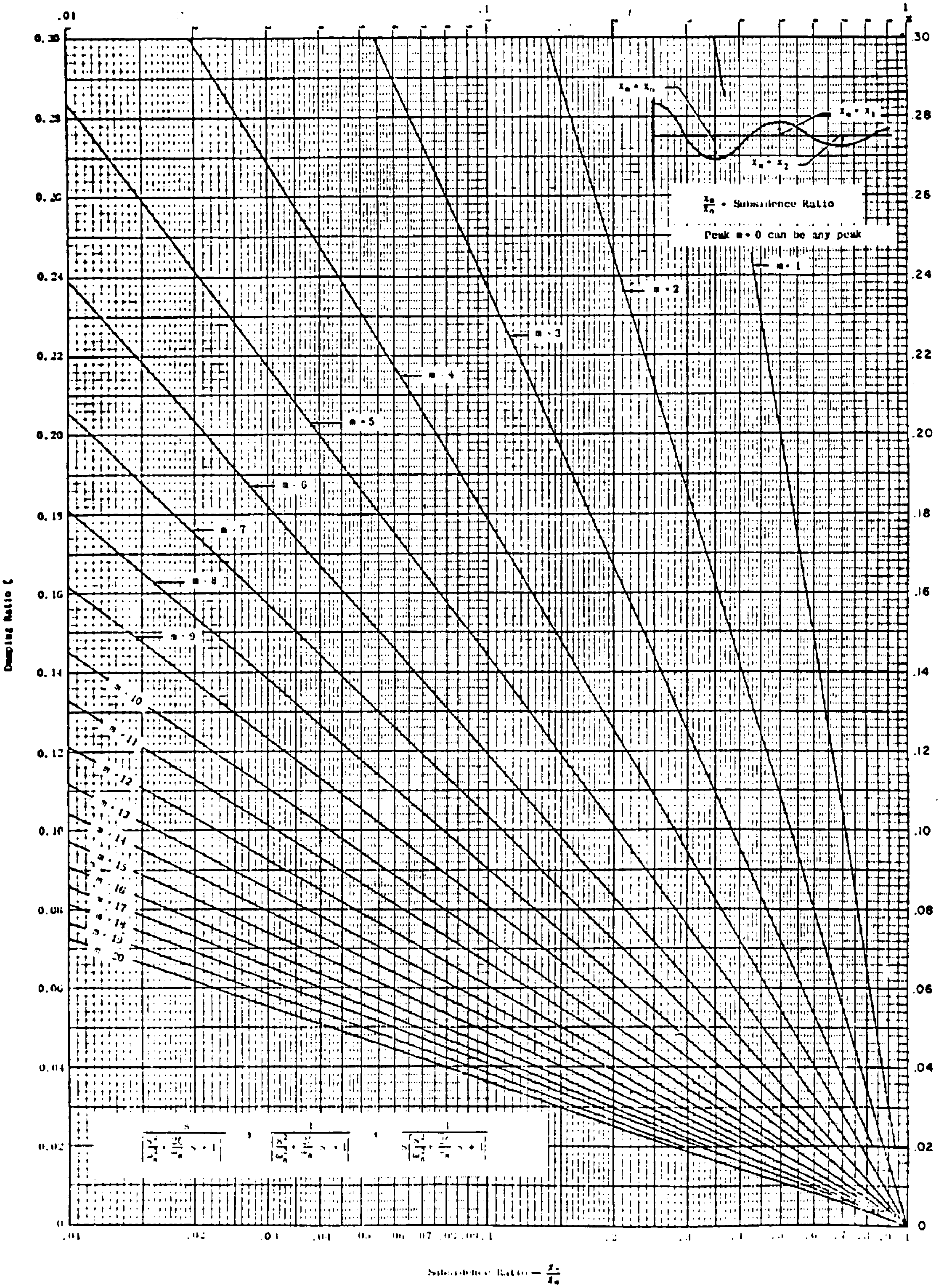
Figure 8. Correlation of Pitch Attitude Bandwidth and Pitch Rate Rise Time



$$\frac{s}{\frac{s^2}{\omega_n^2}+\frac{2\zeta}{\omega_n}s+1},\quad \frac{1}{\frac{s^2}{\omega_n^2}+\frac{2\zeta}{\omega_n}s+1},\quad \frac{1}{s\left[\frac{s^2}{\omega_n^2}+\frac{2\zeta}{\omega_n}s+1\right]}$$

a) $.01 \leq \zeta < 1.0$

Figure 9. Damping Ratio of Oscillatory Transients as a Function of Subsidence Ratio for Second-Order Systems (From Ref. 14)



b) $0 \leq \zeta \leq .30$

Figure 9. (Concluded)

If the actual response characteristics to a control input are not second order, or are nonlinear, the use of linear parameters constitutes an "equivalent system" in the time domain. This is common practice in MIL-H-8501A, where linear time response parameters such as cycles to half amplitude, damping ratio, and frequency are specified. Inasmuch as this has not caused any apparent problem with classical unaugmented helicopters (which tend to have more complex time response characteristics), it is not expected to be a problem in the current specification. However, the time response method of specifying flying qualities needs to be checked carefully for possible loopholes during the final specification development during Phase II. That is, every attempt should be made to contrive practical designs that would possess higher order response characteristics or nonlinear effects that could "fool the specification." In the event that such cases are found, the requirements will have to be modified in order to resolve the discrepancy or an alternate method of compliance will have to be defined for "special cases." Such alternate methods of compliance will probably be described in the BIUG in order to avoid making the specification overly complex just to account for a few special cases.

We have attempted to account for the effects of nonlinearities by including a requirement to vary the size of the input from barely perceptible up to the maximum that is safely possible. If nonlinearities degrade the response significantly, this requirement should expose the deficiency.

b) Gaps in the Data. There are very little systematic flying qualities data available for helicopters utilizing rate command augmentation systems. The data that is available is almost exclusively obtained from moving-base simulation experiments which have the deficiencies noted previously in this report. Therefore, many of the requirements in Table 2(3.4) come under the category of "to be determined" (TBD). Clearly there is a strong need for a systematic handling qualities experiment to cover rate command systems in low speed and hover utilizing a variable stability in-flight simulator. As discussed earlier, piloted moving-base simulation tends to give overly conservative results for rotorcraft with acceleration or rate response characteristics, hence the need for in-flight simulation.

The flying qualities tasks defined in Paragraph 3.2 of the specification should naturally be used in this experiment. As outlined in the discussion of Paragraph 3.2, the flight tests conducted to quantify the mission task elements should also break these elements into representative groups which require similar flying qualities characteristics. If this can be accomplished, the specific requirements for rate, attitude, and translational rate response types can be obtained from only one or two flying qualities tasks from each of the representative groups. This grouping will, in fact, be necessary to accomplish the required flight testing in a reasonable number of hours considering the large number of mission task elements contained in Paragraph 3.2.

3.4.1.3 Required Pitch Attitude Dynamics When Attitude Response is Specified by Paragraph 3.3.

a) Discussion. Attitude systems are defined by a time response boundary in Fig. 3(3.4). However, that boundary only specifies the nature of an attitude response to differentiate it from acceleration or rate responses, it does not specify the acceptability of that response.

Reference 4 reviewed several simulations (both ground-based and in-flight) of vertical takeoff and landing (VTOL) aircraft. The attitude systems of these aircraft were approximated by a pure second-order response, i.e.,

$$\frac{\text{attitude}}{\text{displacement}} = \frac{K}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Figure 10, from Ref. 4, shows correlations of $2\zeta\omega_n$ and ω_n with Cooper-Harper pilot ratings. The data show a degradation in pilot rating with low total damping (low $2\zeta\omega_n$ in Fig. 10) and a limit on minimum ζ. The lower limit on ω_n is not based upon pilot ratings, since configurations with $\omega_n = 0$ were Level 1. Instead, this represents a limit which defines the characteristics of attitude systems; i.e., aircraft that fall below the lower boundary of Fig. 10 will have rate-like responses, for which there are separate requirements. It should be noted that the limits in Fig. 3(3.4) are based on time responses along the lower boundary.

Because of the basic symmetry between longitudinal and lateral axes in hover, the criterion for roll attitude systems is identical to the Fig. 10 boundaries. This is verified in the roll response section (Paragraph 3.6.1) where it is shown that roll attitude data correlate well with the Fig. 10 limits. In addition, limits on attitude gain (measured as $K_\theta = \theta_{ss}/\delta_{LONG}$) are similar in both axes. Supporting data for these limits for Level 1 rotorcraft are shown in the roll attitude section.

Figure 11 summarizes the equivalent system boundaries recommended in Ref. 4 for attitude systems. These boundaries were converted to time domain parameters for the current specification as described in the following paragraphs.

As introduced in the previous discussion, several time response parameters can be measured to define the system characteristics. The most important of these, defined in the step response in Fig. 2(3.4), are rise time (T_{R_θ}), overshoot ratio (x_1/x_0), and effective time delay or dead time (τ_{d_θ}). The boundaries of Fig. 11a are based entirely upon frequency and damping of an equivalent second-order system and thus can be

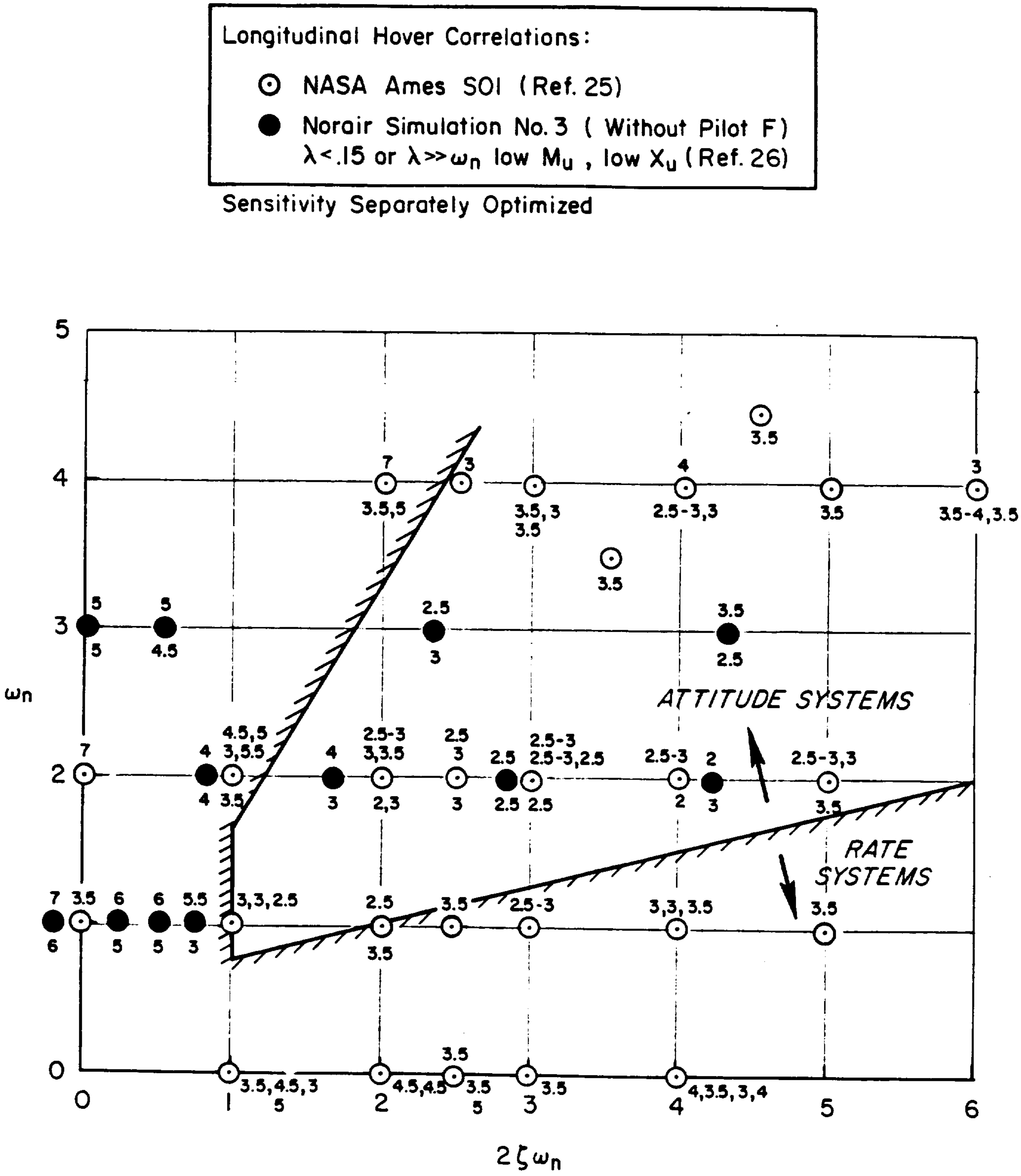
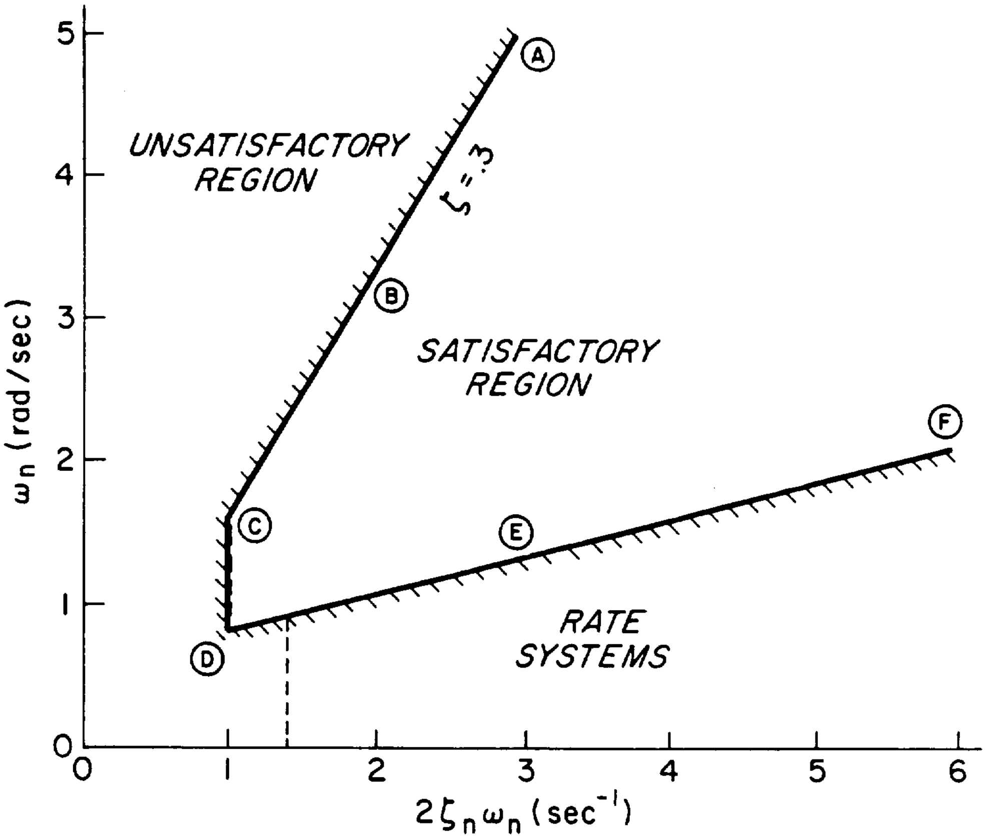
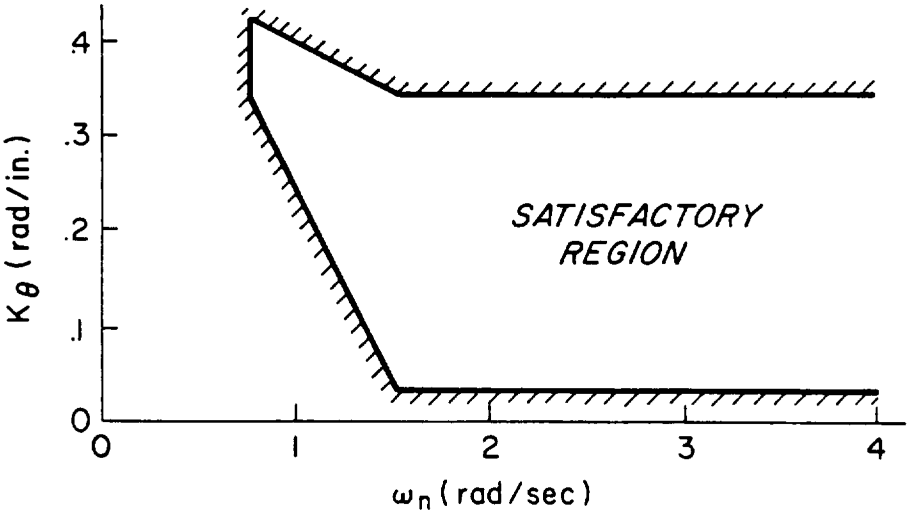


Figure 10. Pilot Rating Correlations with Ideal Second-Order System Responses -- Longitudinal Axis



a) Frequency and Damping



b) Gain, $K_\theta = \theta_{ss}/\delta_{es}$

Figure 11. Recommended Equivalent System Boundaries for Attitude Systems for Low Speed and Hover (from Ref. 4)

converted directly to the Fig. 2(3.4) time response parameters. For example, several points along the boundaries (A through F on Fig. 11a) were written as second-order systems, and time responses were generated. Figure 12 compares the impulse responses of these six cases with the attitude definition of Fig. 3(3.4). Cases A, B, and C represent the most oscillatory conditions allowed for Level 1 (i.e., lowest equivalent ζ). The normalized step responses for Cases A through F (Fig. 11a) are plotted in Fig. 13. These were used to measure the criterion parameters as defined in Fig. 2(3.4). The following table summarizes the results.

Case	τ_{d_θ}	T_{R_θ}	x_1/x_0
A	0.07	0.21	0.350
B	0.10	0.33	0.350
C	0.25	0.63	0.350
D	0.45	1.37	0.080
E	0.22	1.13	0
F	0.10	0.93	0

Rise time, T_{R_θ}, varies widely for the six cases. Since T_{R_θ} is related to bandwidth frequency (see Fig. 8), a lower limit on T_{R_θ} represents a lower limit on bandwidth. There is insufficient data to set an upper limit on ω_n, so no minimum T_{R_θ} has been specified. Such a limit would be a result of excessive abruptness. The Level 1 maximum on T_{R_θ} is set by the most sluggish case (Case D, Figures 11a and 13).

The time delay measure, τ_{d_θ}, is not the same as equivalent time delay, τ_e. To avoid confusion, it is preferable to refer to it as a "dead time" in the response. Hence, there is some τ_{d_θ} even when $\tau_e \equiv 0$. The Level 1 limit on τ_{d_θ} was taken from the largest value in the boundary cases (D), $\tau_{d_\theta} = 0.45$ seconds.

Overshoot ratio, x_1/x_0, is uniquely related to damping ratio as Fig. 9 showed. For a limit on ζ of 0.3 (see Fig. 11a) $(x_1/x_0)_{max} = 0.350$ and is therefore specified as the Level 1 limit. Work needs to be done to define criterion parameter values for Level 2.

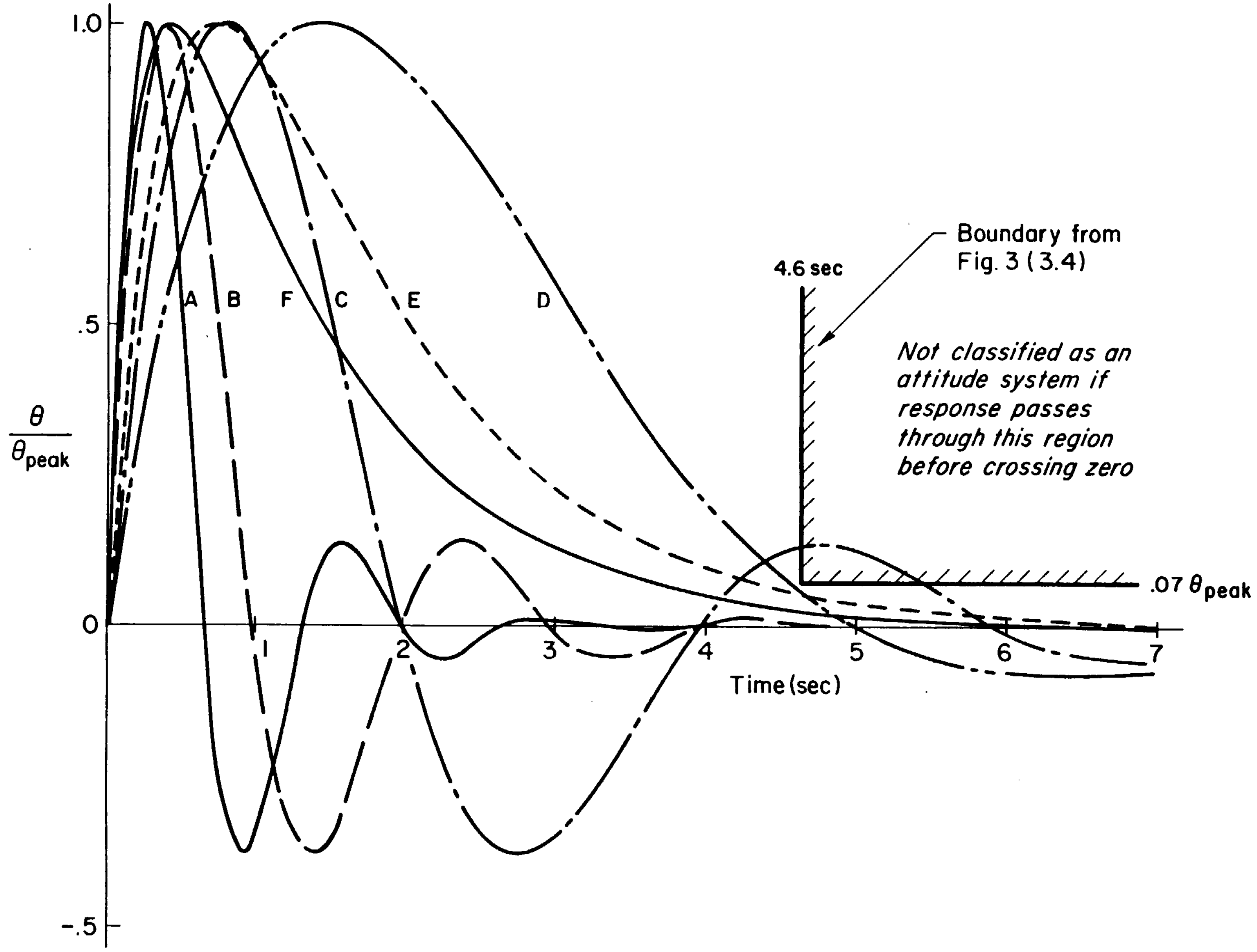


Figure 12. Comparison of Frequency and Damping Boundary Cases of Fig. 11 with Attitude Definition

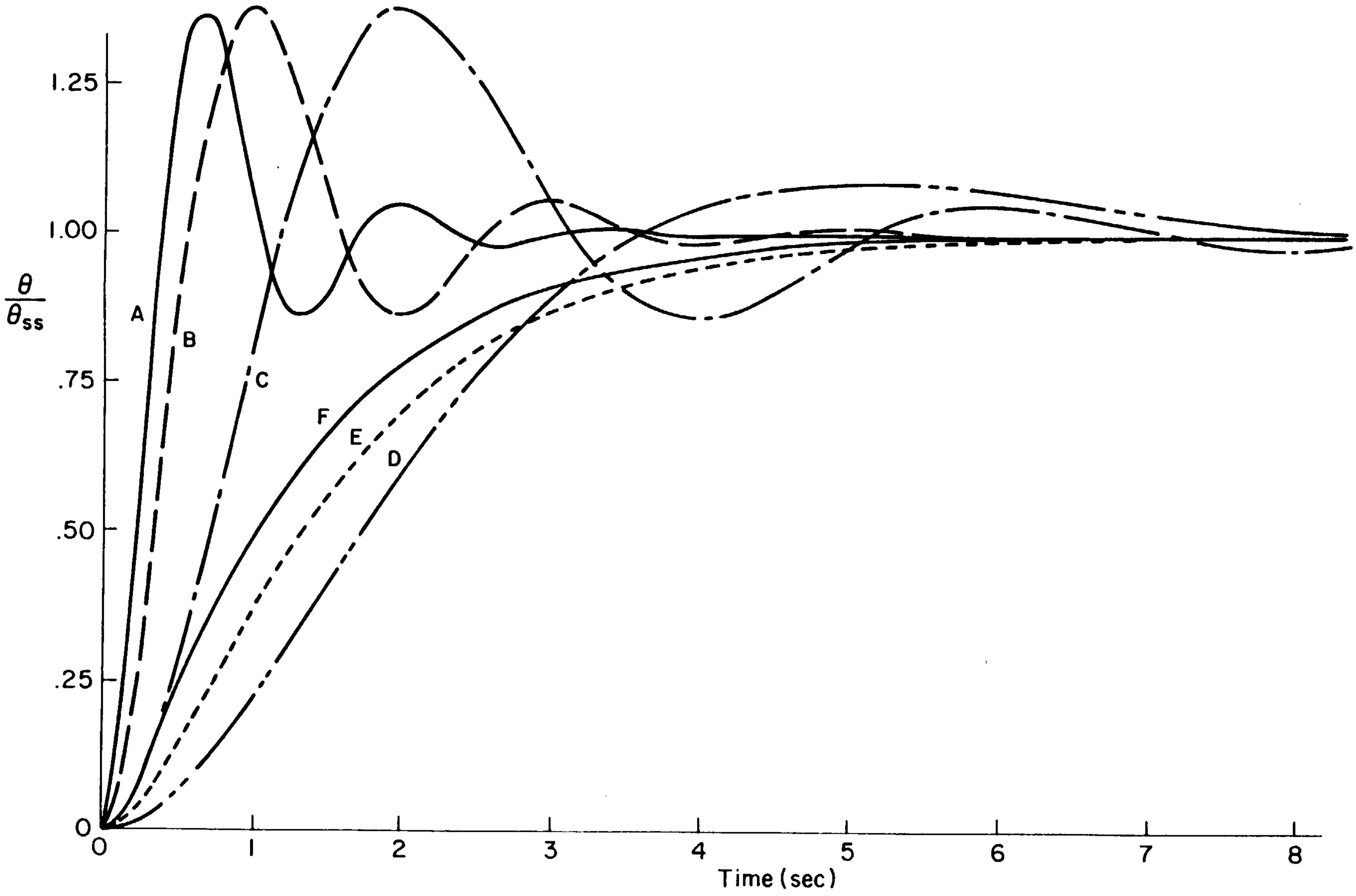


Figure 13. Step Responses of Boundary Cases From Fig. 11

Response gain, $K_\theta = \theta_{ss}/\delta_{LONG}$, can, for the most part, be read directly from Fig. 11b. For $\omega_n > 1.5$ radians per second, $K_{\theta_{min}} = 0.035$ radians per inch = 2 degrees per inch, and $K_{\theta_{max}} = 0.35$ radians per inch = 20 degrees per inch. The dependence on ω_n for $\omega_n < 1.5$ radians per second cannot be easily interpreted in the time domain. Tentatively we have based the Level 1 limits for K_θ on the values for $\omega_n > 1.5$ radians per second. The change in K_θ required for $\omega_n < 1.5$ radians per second needs to be investigated further. In addition, Level 2 limits must be defined.

b. Comparison with Recent Results. Several VTOL and helicopter studies conducted since publication of Ref. 4 add supporting data. These studies are: Ref. 15, in which a Type A VSTOL was simulated on the NASA ARC Flight Simulator for Advanced Aircraft (FSAA), flying shipboard approaches, hovering, and landings; Ref. 16, a simulation of various low-speed and hover tasks in day VMC and night IMC using the ADOCS helicopter model on Boeing Vertol's flight simulation facility; Ref. 17, a VTOL shipboard landing study conducted on the NASA ARC VMS; and Ref. 18, an investigation of control-display requirements for VTOL aircraft in terminal approach using the X-22A.

The following table documents the response characteristics of the attitude systems flown in each experiment.

Reference	Aircraft Simulated	τ_{d_θ}	T_{R_θ}	x_1/x_0
15	Type A VSTOL	0.1	0.3	1.0
16	ADOCS	0.3	0.8	1.0
17	VTOL	0.1	0.8	1.0
18	VTOL (1.0 ACAH)	0.2	1.6	1.0
18	VTOL (1.5 ACAH)	0.2	1.0	1.0
18	VTOL (2.0 ACAH)	0.2	0.7	1.0

With one exception, all of these configurations lie within the Level 1 limits. The first case from Ref. 18, 1.0 attitude command-attitude hold (ACAH), has the characteristics of a rate system and should not be compared with the attitude boundaries.

Pilot ratings for the Type A VSTOL (Ref. 15) were Level 1 in Sea State Zero [Pilot Rating (PR) = 3, 3, 4], and generally increased with sea state and wind over the ship's deck, Fig. 14. An attitude rate

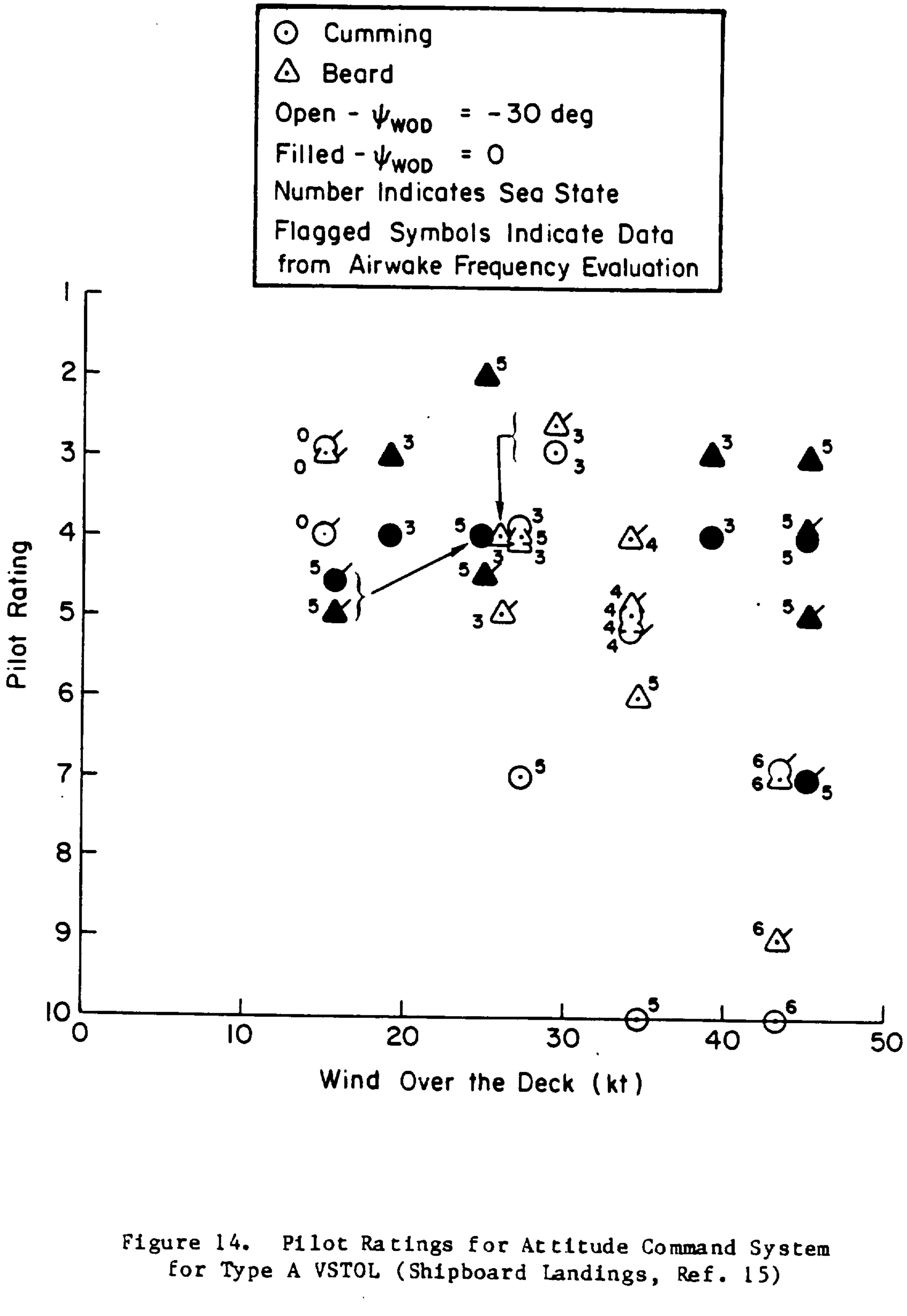


Figure 14. Pilot Ratings for Attitude Command System for Type A VSTOL (Shipboard Landings, Ref. 15)

command system provided good heave axis control. For the ADOCS experiment (Ref. 16), various side arm controller combinations were tried. For conventional controls (cyclic sidestick, collective, pedals) in day VMC, pilot ratings were as follows:

Stability Augmentation System Type	Task	PR
Attitude Command/Attitude Hold	NOE	3
	Accel-Decel	2-1/2
	Slalom	2-1/2
Attitude Command/Velocity Hold	NOE	2-1/2
	Bob-Up	3-1/2
	Accel-Decel	2-1/2
	Slalom	2-1/2

The VTOL experiment of Ref. 17 included a variety of head-up displays (HUDs) and Sea State 0, 4, and 6 conditions. Without a HUD, pilot ratings were 3 (Sea State 0), 4-1/2 (4), and 6-1/2 (6). For Ref. 18, the task consisted of a decelerating approach from 65 knots to hover over a landing pad. Pilot ratings may, therefore, be influenced by the higher speed portion of the task. However, pilots in the experiment assigned ratings for the overall task and for approach only; generally, the latter ratings were better, indicating that hover was the most demanding portion of the task. For 1.5 ACAH, ratings (for three different HUDs) were 3, 4, and 4; with 2.0 ACAH, a single rating of 5 was obtained.

The above data at least suggest that Level 1 flying qualities will be obtained by using the recommended requirements.

c) Gaps in the Data. The frequency response boundaries that form the basis for the Level 1 limits are relatively well-supported by existing data (Fig. 10 and Ref. 4). However, several areas require further study for validation and expansion of the requirements. These are:

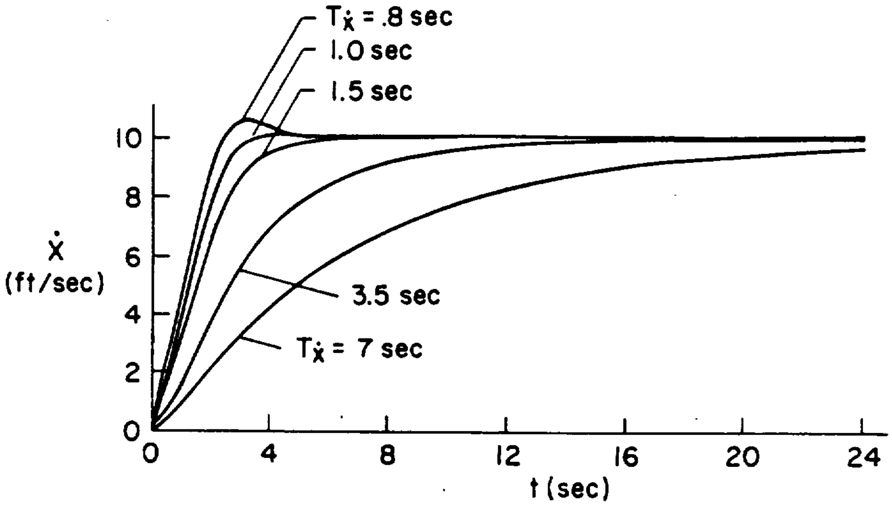
- Validation with flight data. Several marginal Level 1 cases should be flown on a variable-stability helicopter in order to verify the limits.
- Definition of Level 2 limits. Systematic variation of parameters should be performed in either ground-based or in-flight simulation in order to set the boundary for Level 2.

- Establishment of response gain (K_θ) requirement for $\omega_n < 1.5$ rad/sec. The dependency shown in Fig. 11b cannot be converted easily to the time domain.

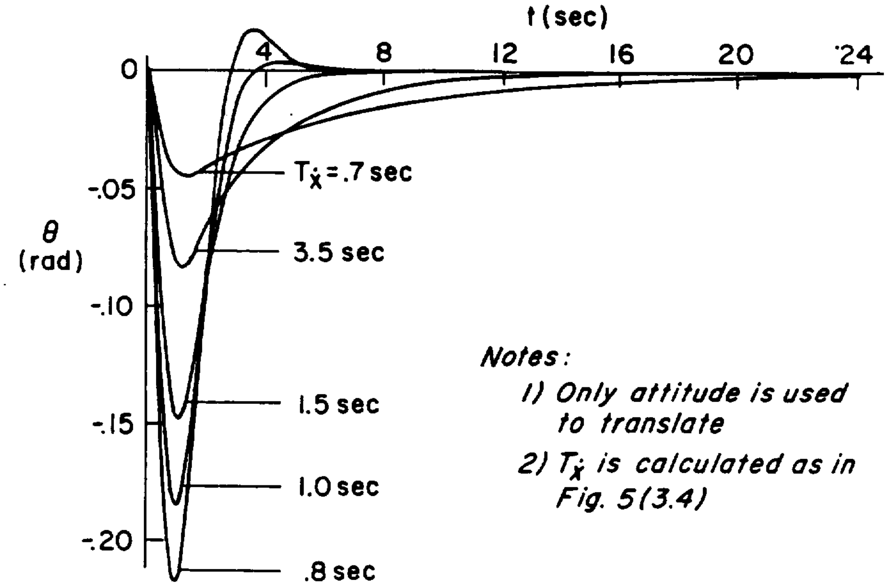
3.4.1.4 Allowable Pitch Attitude Excursions When Translational Rate Response is Required by Paragraph 3.3.

a) Discussion. Pitch attitude actually represents a secondary response to the longitudinal controller when a translational rate system is employed. For most rotorcraft the translational rate response is achieved with pitch attitude (i.e., $\ddot{x} \doteq g\theta$), and, hence, good translational rate bandwidth characteristics require fairly abrupt attitude responses. The connection between the translational rate rise time and the attitude response is shown in Fig. 15 taken from Ref. 4. As discussed in Ref. 4, the limiting factor on translational rate ($\dot{x}$) bandwidth is the peak attitude excursion required to accelerate the rotorcraft. This paragraph is included in the specification in order to limit these peak attitude excursions. It should be noted that this section would not be required if only pure attitude was used to translate because of the direct kinematic relationship between $\ddot{x}$ and θ noted above. However, it may be possible to disassociate to some extent the attitude and translational rate responses with tandem rotor helicopters utilizing differential collective or with tilt-rotor or tilt-wing configurations wherein a rotor system tilt is used to translate. In addition, this paragraph represents useful design guidance in developing translational rate command augmentation by reminding the designer that specific attitude limits must be adhered to for acceptable flying qualities.

b) Gaps in the Data. The maximum allowable attitude excursions for Levels 1, 2, and 3 for centerstick controllers and for Level 1 for a side arm controller were taken from Ref. 4. Piloted simulation is required to determine the remaining values in this table which are currently to be determined, "TBD." Moving-base piloted simulation using the NASA ARC VMS is believed to be adequate to obtain this data. As discussed earlier, the deficiencies in the CGI do not appear to be significant when evaluating highly augmented rotorcraft. The VMS should be utilized with the cab pointing down the track in order to obtain the maximum longitudinal motion fidelity available with this simulator. An experiment should also be conducted to consider the use of direct force (obtained by rotor tilting) as a means for providing the effector for a translational rate command system. This decreases or eliminates the attitude excursions. However, it must be cautioned that the use of direct force control results in undesirable surge motions which may actually degrade the higher bandwidth cases more than abrupt attitude motions (e.g., Ref. 15). Clearly, the investigation of this phenomenon will require good longitudinal motion



a) Path Response



Notes:

1) Only attitude is used to translate

2) $T_{\dot{x}}$ is calculated as in Fig. 5(3.4)

b) Pitch Attitude Response

Figure 15. Generic Time Responses to a 1 in. Step Longitudinal Control Input for a Translational Rate Response

cues which may or may not be available on the VMS. Therefore, it is recommended that, during the initial experiments to generate data for Table 4(3.4), some preliminary direct force control configurations be evaluated. In the event that the motion cues are inadequate, it will be necessary to go to in-flight simulation. Unfortunately, the variable stability helicopters currently available do not have direct force capability, although such capability could be generated on the variable stability CH-47 due to its tandem rotor configuration.

In summary, it appears that generating the data to complete Table 4(3.4) can be obtained easily on the NASA ARC VMS. In addition, at least preliminary estimates of the effect of using direct force control can be obtained in this facility. The use of variable stability in-flight simulation to generate the data required to specify limits on translational rate systems using direct force control is believed to be beyond the scope of Phase II due to the need for reconfiguring the CH-47.

3.4.2. Pitch Rate Response to Longitudinal Controller in Forward Flight.

a) Discussion. The requirements for the pitch rate response to the longitudinal controller in forward flight have been broken down into visual meteorological conditions (VMC) and instrument meteorological conditions (IMC). This logical distinction was also made in MIL-H-8501A. As in MIL-H-8501A, the requirements for hover have been retained for Level 1 flying qualities in forward flight in VMC for the presently proposed specification. The IMC flying qualities specified in MIL-H-8501A (Ref. 18) are believed to be excessively lenient, allowing a damping ratio as low as 0.11 for the short-term response and an unstable divergence for the long-term response. By comparison, MIL-F-8785C (Ref. 7) requires a damping ratio of 0.35 for the short-term response and a phugoid, or long-term, damping ratio of 0.04 (i.e., slightly stable).

For operation in IMC conditions, we have elected to utilize the short-term attitude requirements specified in the proposed MIL Standard and Handbook (Ref. 1). These requirements are based on the pitch attitude bandwidth of the aircraft (see the definition and discussion in Paragraph 3.4.1.2). As Fig. 8 showed, bandwidth frequency (ω_{BW_θ}) is linearly related to rise time [Fig. 2(2.3)]. This is true for phase-margin-limited configurations (generally $\zeta > 0.25$). Therefore, a specification based on T_{R_q}* will define limits on ω_{BW_θ}.

---

*Note that T_{R_q}, measured from the pitch rate response to a step input, is identical to T_{R_θ} measured from the pitch attitude response to an impulse input.

The proposed MIL Standard and Handbook (Ref. 1) limits for ω_{BW_θ} versus phase delay, τ_{p_θ} (Fig. 6), are shown in Fig. 16. These limits were developed in Ref. 1 for Category C (terminal operation) tasks. They are applicable to rotorcraft in forward flight because of the similar piloting technique used for precise short-term path and attitude control (cyclic-to-pitch in order to control flight path). The Level 1 limits on T_{R_q} in Table 6(3.4) are based on the Fig. 16 boundaries. From the linear regression fit in Fig. 8, $\omega_{BW_\theta} = 2.5$ radians per second corresponds to $T_{R_q} \doteq 0.250$ seconds and $\omega_{BW_\theta} = 4.5$ radians per second (an approximation of the upper limit) corresponds to $T_{R_q} \doteq 0.125$ seconds.

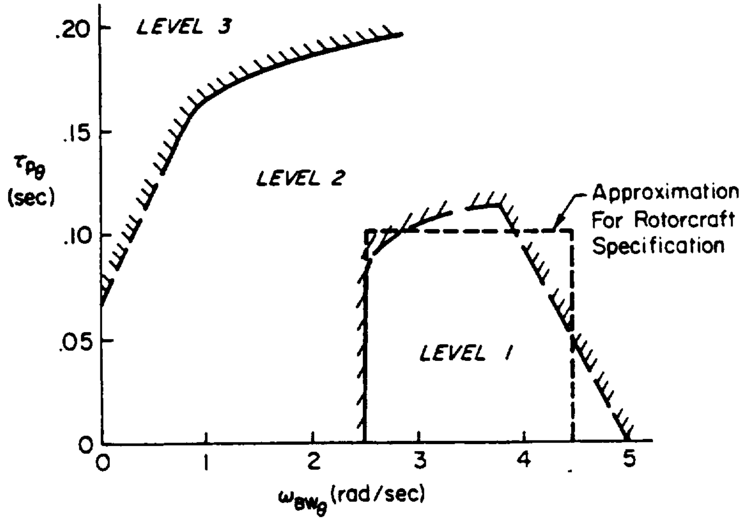


Figure 16. Bandwidth Requirements from Proposed MIL Standard and Handbook (Ref. 1). Category C (Takeoff/Landing) Operations.

The limits on the overshoot ratio, x_1/x_0, set lower bounds on damping ratio (Fig. 11). The MIL-F-8785C Level 1 limit is $\zeta = 0.35$ ($x_1/x_0 = 0.306$); Level 2, $\zeta = 0.25$ ($x_1/x_0 = 0.444$). For Level 3, MIL-F-8785C allows first-order (non-oscillatory) instabilities to exist as long as the time to double amplitude, T_2, is greater than or equal to 6.0 sec. We have adopted this as the Level 3 limit.

As Fig. 7 illustrates, phase delay (τ_{p_θ}) is linearly related to dead time (τ_{d_θ}). Based on this, the upper limits of τ_{p_θ} from Fig. 16 were used to define the Level 1 limits on τ_{d_θ}; these are consistent with limits on τ_e in MIL-F-8785C.

b) Gaps in the Data. As noted above, the limits specified for up-and-away flight in VMC conditions are based on those for hover. It would be desirable to validate this assumption in a flight test program. It is recommended that a variable stability helicopter be employed because of the large amplitude maneuvers which probably set the critical handling quality boundaries for VMC up-and-away maneuvering. Considering the expanded role of rotorcraft to conduct at least limited air-to-air combat, this should be part of the investigation.

We have recommended utilizing the Category C Levels 1, 2, and 3 boundaries from Ref. 1, based on the rationale that rotary-wing aircraft should have at least as good handling qualities as fixed-wing aircraft for instrument flying. However, it should be noted that the limits specified in Ref. 1 are not based on instrument flying tasks, although experience has shown them to be valid limits for this case. Nonetheless, it would be desirable to test these limits utilizing moving-base simulation. There is no need for in-flight testing for the instrument flying task. Additionally, some simulation data is already available from studies conducted by the NASA Ames Research Center in support of the Federal Aviation Administration (FAA) certification of helicopter IMC operations. While this data does not provide systematic variations of the handling qualities parameters, it does yield considerable insight into the required response types and control systems characteristics required for rotorcraft IMC operations. These data are documented in Ref. 20, which should be utilized as the baseline for completing the simulation studies necessary to develop helicopter IMC flying quality requirements.

3.4.3 Longitudinal Speed Response to Longitudinal Controller--Low Speed and Hover.

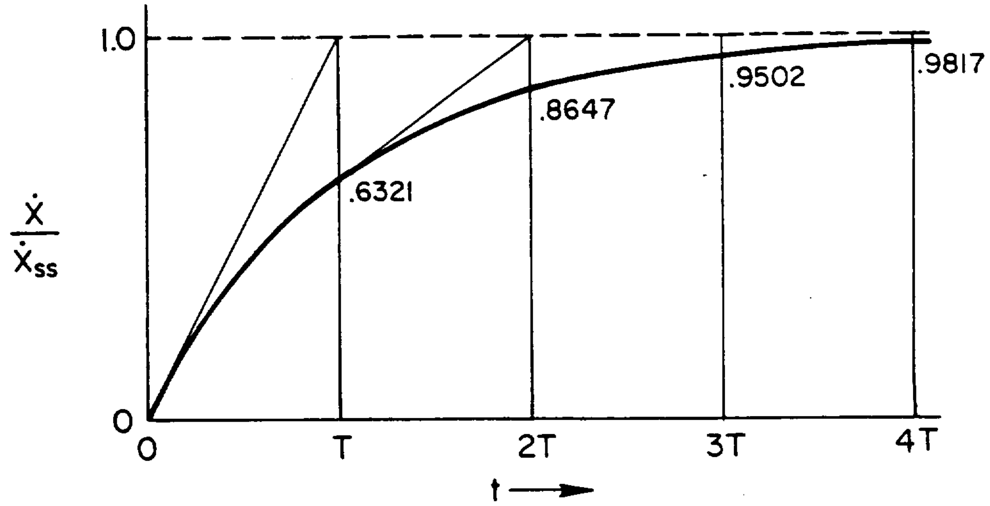
a) Discussion. No requirement is necessary in this section for acceleration, rate, and attitude systems inasmuch as the forward speed characteristics are simply a matter of the kinematics between longitudinal acceleration and pitch attitude (i.e., $\ddot{x} \doteq g\theta$). Therefore, this section, for all practical purposes, applies only to the required speed response when a translational rate response is required by Paragraph 3.3.

3.4.3.1. Required Speed Response When Translational Rate Response is Specified by Paragraph 3.3

a. Discussion. Requirements for translational rate command (TRC) systems were investigated in Ref. 4. It was shown there that response of inertial velocity ($\dot{x}$) to a longitudinal control input (δ_{LONG}) could be adequately represented by a first-order model, i.e.,

$$\frac{\dot{x}}{\delta_{LONG}} = \frac{K_{\dot{x}_c}}{T_{\dot{x}_{eq}} s + 1} \qquad (1)$$

such a model has the response characteristics shown in the following sketch



where $T \equiv T_{\dot{x}_{eq}}$, defined as the time $\dot{x}/\delta_{LONG}$ reaches 63.2 percent of its steady-state value. Level 1 limits were developed for $K_{\dot{x}_c}$ versus $T_{\dot{x}_{eq}}$ in Ref. 4.

The ideal first-order model, Eq. 1, has the shortcoming of not accounting for the effects of time delay, which have been shown to be significant (see Refs. 21 and 22). In addition, $T_{\dot{x}_{eq}}$, as defined above, is based on only one point (at which $\dot{x}/\dot{x}_{ss} = 0.632$) on the time response. The authors of Ref. 23, using results of their flight test program with the variable-stability X-22A, recommended a slightly different model consisting of two time-response parameters:

$$\frac{\dot{x}}{\delta_{LONG}} = \frac{K_{\dot{x}_c} e^{-\tau s}}{T_{\dot{x}_2} s + 1} \qquad (2)$$

In this case, $T_{\dot{x}_2}$ is defined as the time for $\dot{x}/\delta_{LONG}$ to go from 63.2 percent to 86.5 percent of steady state. Time delay, τ, is calculated as

$$\tau = T_{\dot{x}_2} - T_{\dot{x}_{eq}}$$

for a pure first-order system with no time delay, $\tau = 0$ and $T_{\dot{x}_2} = T_{\dot{x}_{eq}}$.

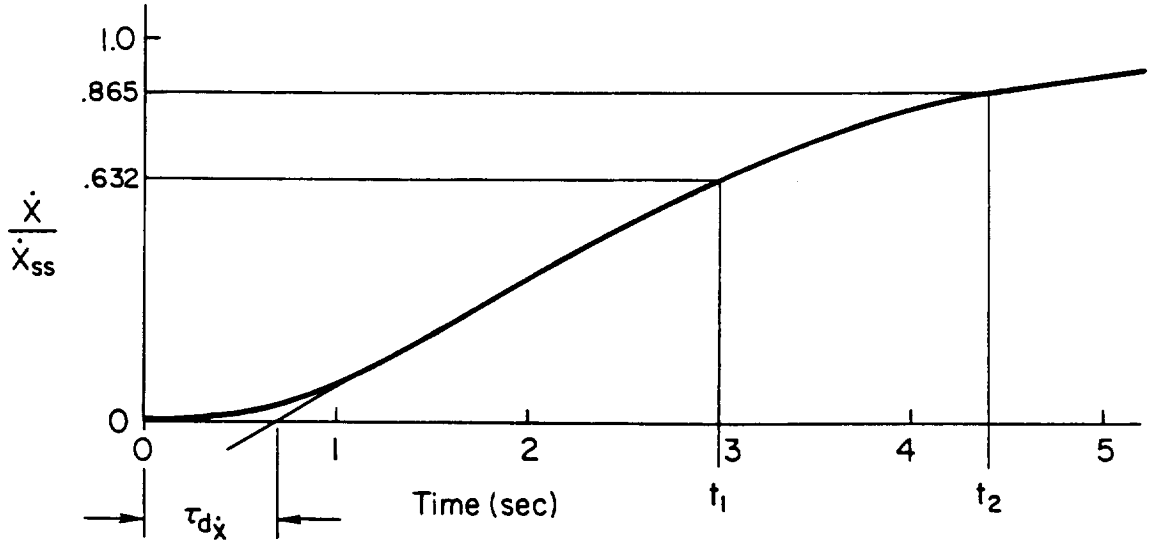
The first-order model proposed for this specification is identical in form to Eq. 2, although the parameters are defined differently:

$$\frac{\dot{x}}{\delta_{LONG}} = \frac{K_{\dot{x}_c} e^{-\tau_{d_{\dot{x}}} s}}{T_{\dot{x}} s + 1} \qquad (3)$$

This model is compared with those of Eqs. 1 and 2 in Fig. 17. Time delay (or "dead time") is found by extending the slope of the initial response (starting where the response is generally greater than about 10 percent of steady state) to the time axis; $\tau_{d_{\dot{x}}}$ is that time. Time constant $T_{\dot{x}}$ is based purely on how long it takes the response to reach 86.5 percent of steady state, or $T_{\dot{x}} = t_2/2 - \tau_{d_{\dot{x}}}$, Fig. 17.

The three first-order models discussed above are all very similar in form, yet the characteristics of the equivalent systems described by each look very different. Examples of this are sketched in Fig. 18. The example in Fig. 18a is from Ref. 23; the configuration in Fig. 18b is from Ref. 24. Both have almost identical equivalent responses based on Eq. 1 ($K_{\dot{x}_c} \doteq 12$ feet per second per inch for both). In Fig. 18a, the two-parameter model of Ref. 23 matches the actual response slightly better than the Eq. 3 model. Here $T_{\dot{x}_2} = T_{\dot{x}}$, but τ is twice $\tau_{d_{\dot{x}}}$. For Fig. 18b, the two-parameter model uses a rapid time constant but a large time delay to match the actual response. The proposed model has a slightly lower time constant and much less delay. While the two-parameter model matches the response for a longer time, the initial time delay is excessive--the actual response is 25 percent of steady state at $t = \tau$. Therefore, we have chosen to adopt the proposed model of Eq. 3 for this specification. Further work in this area is warranted, including comparison testing (in-flight or ground-based simulation) of the high-order system and resulting low-order models for a configuration such as that shown in Fig. 18b.

Data for defining the limits on $K_{\dot{x}_c}$ and $T_{\dot{x}}$ come from Refs. 23 and 24. The Ref. 23 data, obtained from the NASA ARC S01 six-degree-of-freedom simulator, are for rapid maneuvering in calm air under good visual conditions. Figure 3 from Ref. 23 presents the data on a crossplot of $K_{\dot{x}_c}$ versus $T_{\dot{x}}$ (Eq. 3). The Level 1 boundary shown in Fig. 19 is based on these data.



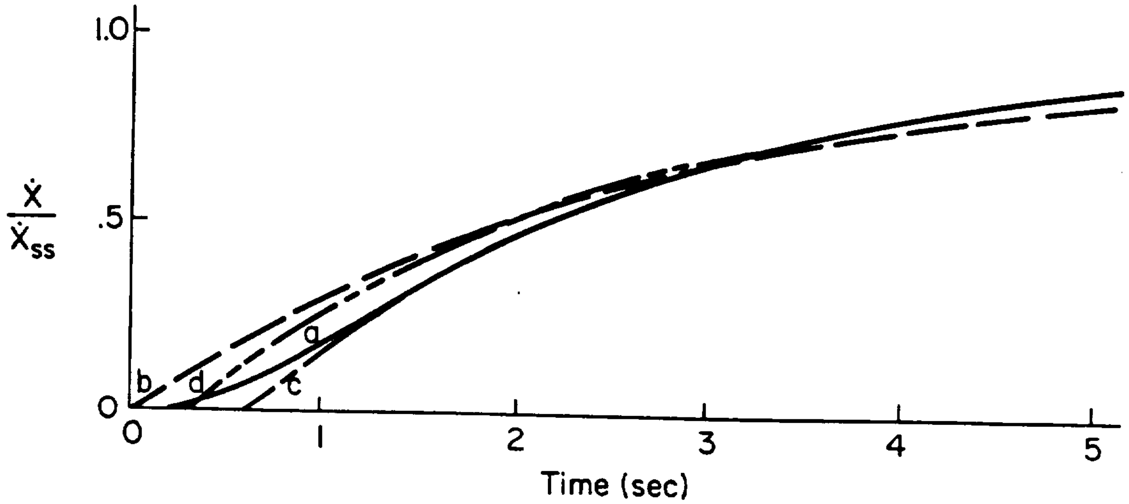
<u>Response Forms:</u>

First Order — $\frac{1}{T_{\dot{X}_{eq}} s+1}$ $T_{\dot{X}_{eq}} = t_1$
(Ref. 4)

Two-Parameter — $\frac{e^{-\tau s}}{T_{\dot{X}_2} s+1}$ $T_{\dot{X}_2} = t_2 - t_1$
(Ref. 23) $\tau = t_1 - T_{\dot{X}}$

Proposed — $\frac{e^{-\tau_{d\dot{X}} s}}{T_{\dot{X}} s+1}$ $T_{\dot{X}} = t_2/2 - \tau_{d\dot{X}}$
$\tau_{d\dot{X}}$ = Time-axis intercept of slope of response

Figure 17. Definitions of Candidate First-Order Models Based upon Step Response



Response Forms:

a) Actual — $\frac{.390(9.12)}{(.46)[.98, 2.78]}$

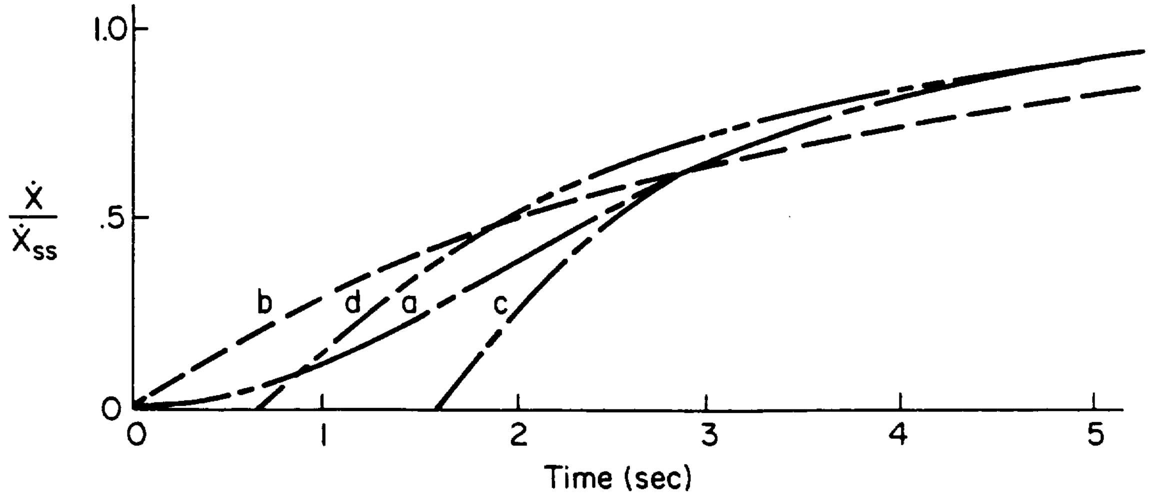
b) First Order (Ref. 4) — $\frac{1}{2.8s+1}$

c) Two-Parameter (Ref. 23) — $\frac{1e^{-.65}}{2.2s+1}$

d) Proposed — $\frac{1e^{-.35}}{2.35s+1}$

a) Configuration from X-22A Flight Test Program (Ref. 23)

Figure 18. Examples of Application of Competing First-Order Models for TRC Systems



Response Forms:

a) Actual — $\frac{1.331}{(1.1)^3}$

b) First Order (Ref. 4) — $\frac{1}{3s+1}$

c) Two-Parameter (Ref. 23) — $\frac{1e^{-1.6s}}{1.4s+1}$

d) Proposed — $\frac{1e^{-.7s}}{1.85s+1}$

b) Configuration from NASA Simulation on SO1 (Ref. 24)

Figure 18. (Concluded)

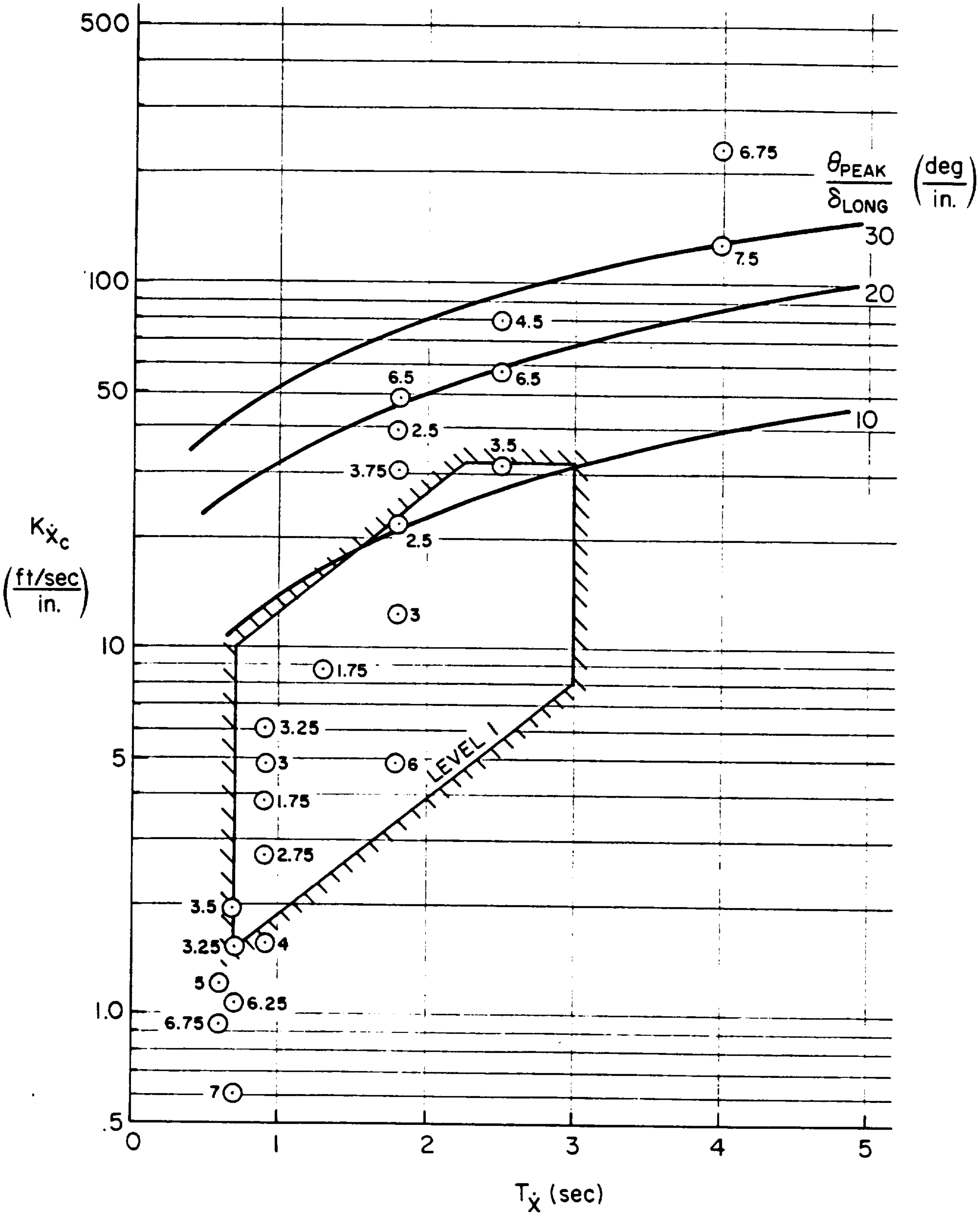


Figure 19. Pilot Rating Correlations for TRC Systems from Ref. 23 (NASA Ames S01 Simulator)

Results of the X-22A flight tests (Ref. 24) suggest more stringent limits on $T_x^{\bullet}$, Fig. 20. Included on Fig. 20 is the Level 1 limit from Fig. 19. However, there are several significant differences between the simulation of Ref. 23 and the Ref. 24 flight tests. While the simulation was conducted with no disturbance inputs (i.e., in calm air), the X-22A tests included both simulated random atmospheric turbulence (through the pitch, roll, yaw, and thrust flight control systems) and an artificial steady wind of 25 knots. In addition, of course, natural turbulence would influence the results in flight. The tasks in Ref. 23 consisted of tracking a hover pad symbol on the HUD and simulated vertical landings.

The major difference between the two studies is the possible effects of steady wind on the flight results. Since neither of the studies included an inertial position hold capability, a steady wind would give rise to the necessity for holding a trim bias on the controller in hover. This has been shown to be highly undesirable in TRC systems, i.e., a primary advantage of such systems is that zero controller position is a reference for zero groundspeed. We have interpreted the data of Fig. 20 as being applicable when position hold is used, and the data of Fig. 19 are applicable when there is no position hold. In the latter case, sluggish TRC response ($T_x^{\bullet} > 1.7$ sec) makes correction for winds difficult.

Requirements for translational rate responses using centerstick controllers [Fig. 4a(3.4)] are based on the Figs. 19 and 20 data; the sidearm controller limits [Fig. 4b(3.4)] were developed by shifting the Fig. 4a(3.4) boundaries to require higher control sensitivities. This was shown in Ref. 4 to be necessary for sidearm controllers.

b. Gaps in the Data. Several areas in the definition of requirements for translational rate response systems must still be investigated. As mentioned above, it would be worthwhile to evaluate the differences in the low-order equivalent models and to identify the most representative form for the specification. Because of the large time delays inherent in these models, motion-based simulation (for example, the NASA ARC VMS) could be used as long as the simulation-induced delays (e.g., CGI rates, etc.) are quantified. It is possible that a task such as HUD tracking might suffice, since the evaluation is a comparative one to determine which low-order model looks most like the high-order system.

The possible discrepancy between the no-wind, simulator results (Ref. 23, Fig. 19) and the simulated-wind, flight results (Ref. 24, Fig. 20) should be studied. This would require flight test in calm air and in windy conditions, and would validate the assumed value of position hold. TRC systems with and without position hold would be flown.

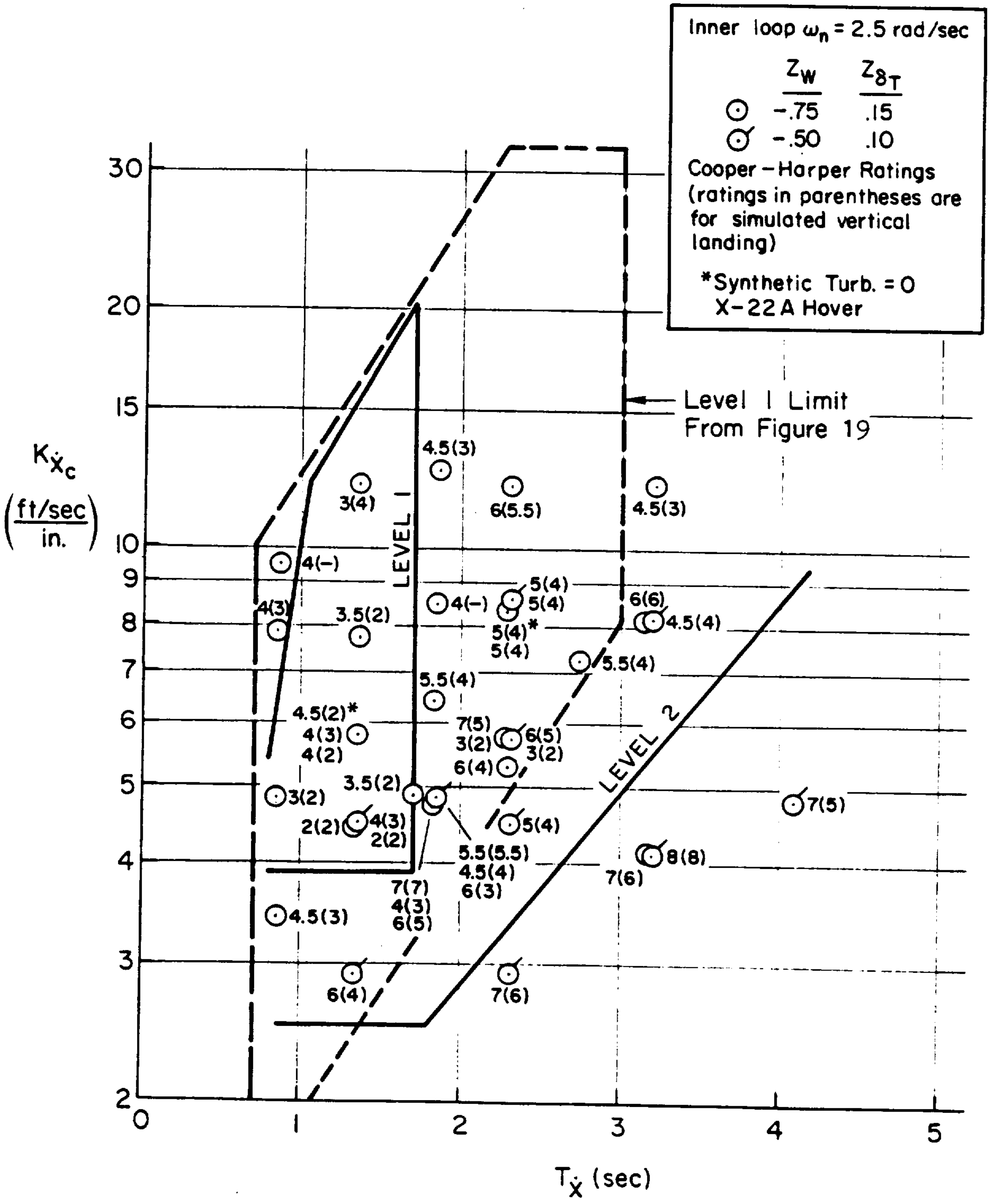


Figure 20. Pilot Rating Correlations for TRC Systems from Ref. 24 (X-22A Flight Tests)

No information exists to specify limits on $\tau_{d_{\dot{x}}}$. This could be studied using the VMS, since it is known that Level 1 ratings are obtainable there with TRC (e.g., Ref. 16). A systematic increase in $\tau_{d_{\dot{x}}}$ to define Levels 1 and 2 limits could be done with a very modest effort.

Level 2 limits must be determined for TRC with position hold.

3.4.5 Pilot-Induced Oscillations. Most of the dynamic response criteria are oriented towards preventing closed-loop pilot/vehicle instabilities. Hence it seems redundant to include an additional quantitative requirement on pilot-induced oscillations. However, it seems reasonable to include at least a qualitative requirement regulating against any pilot-induced oscillation. This approach has also been taken in MIL-F-8785C.

3.4.7 Longitudinal Control Power--Low Speed and Hover. The requirements on the control power of the longitudinal controller have been broken into two basic portions of the operational envelope. One set of requirements has been written for low speed and hover and the other for forward flight. Based on analysis of all existing control power data, it is our conclusion that the requirements for hover and for low speed will be essentially identical in that the tasks required in these two portions of the flight envelope are very similar.

3.4.7.1 When Acceleration, Rate, or Attitude Response Type is Required by Paragraph 3.3.

a) Discussion. An extensive review of control power requirements conducted in Ref. 4 indicated that the attitude achieved 1 second after a maximum control input represents the best criterion for all response types except translational rate. It should be noted that the attitude in 1 second criterion, $\theta(1)$, was used in MIL-F-83300 (Ref. 27).

The data in Ref. 4 indicate that acceleration and rate response types require considerably more control power than the attitude response type. The data supporting this conclusion, as well as the Levels 1, 2, and 3 boundaries in Table 7(3.4), are given in Figs. 21 and 22. While these data were taken for lateral maneuvering in the NASA ARC S01 simulator, it is believed that they are valid for the longitudinal axis as well due to symmetry in hover. It should be noted that the S01 simulator utilizes the real world visual scene and one-to-one monitor and, hence, does not have the CGI problems noted earlier.

The distinction between aggressive and moderate maneuvering defined in Paragraph 3.2 is utilized explicitly in the control power criteria used in the specification. The maneuvers conducted in the S01 simulator consisted of rapid lateral quick stops involving bank angles of up to 25 to 30 degrees and, hence, are classified as "aggressive." The control power limits specified for "moderate" maneuvering were taken from Ref. 27 (MIL-F-83300). These data are based on experiments which involved moderate to gentle maneuvering in hover utilizing rate and acceleration

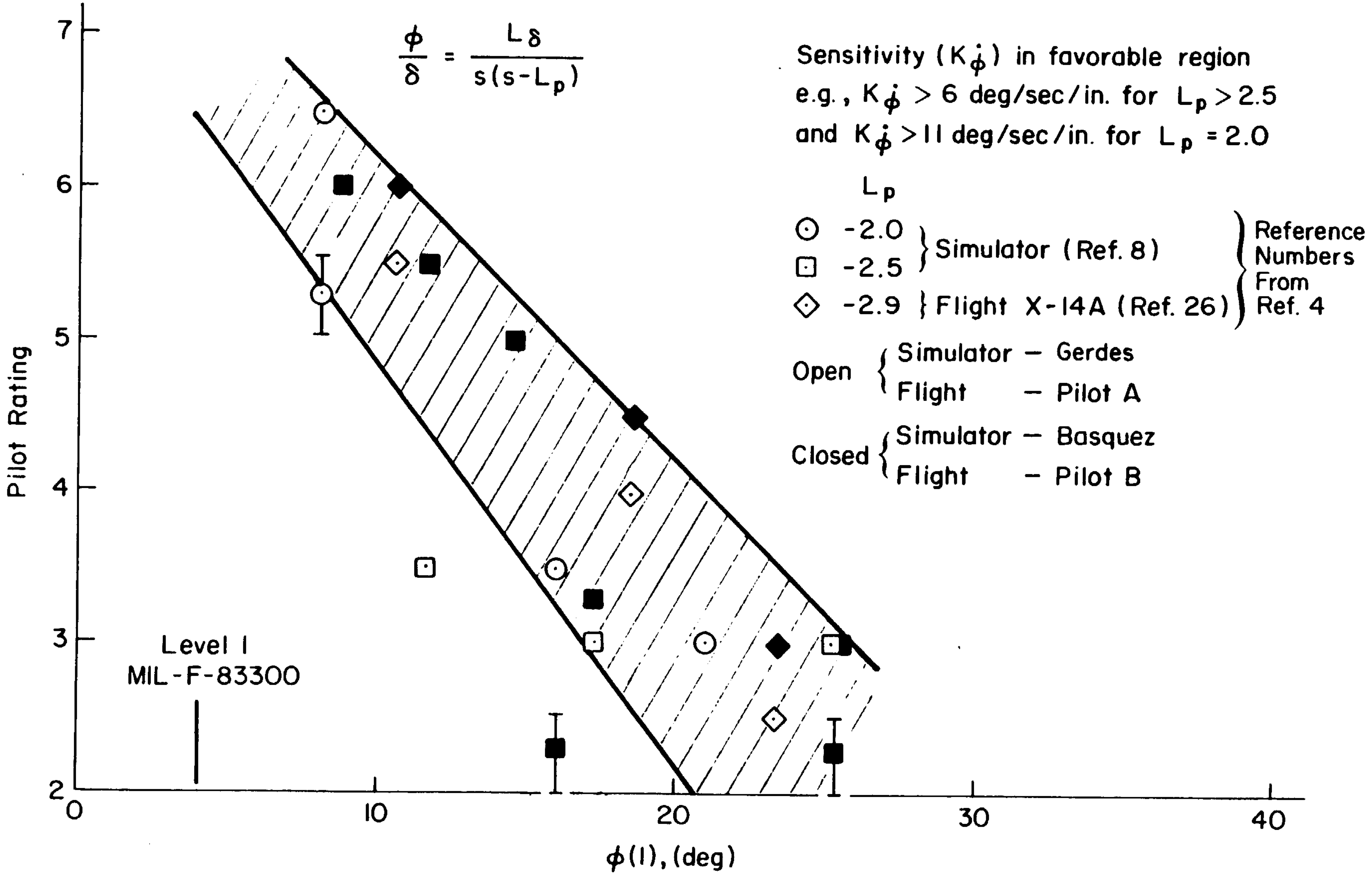
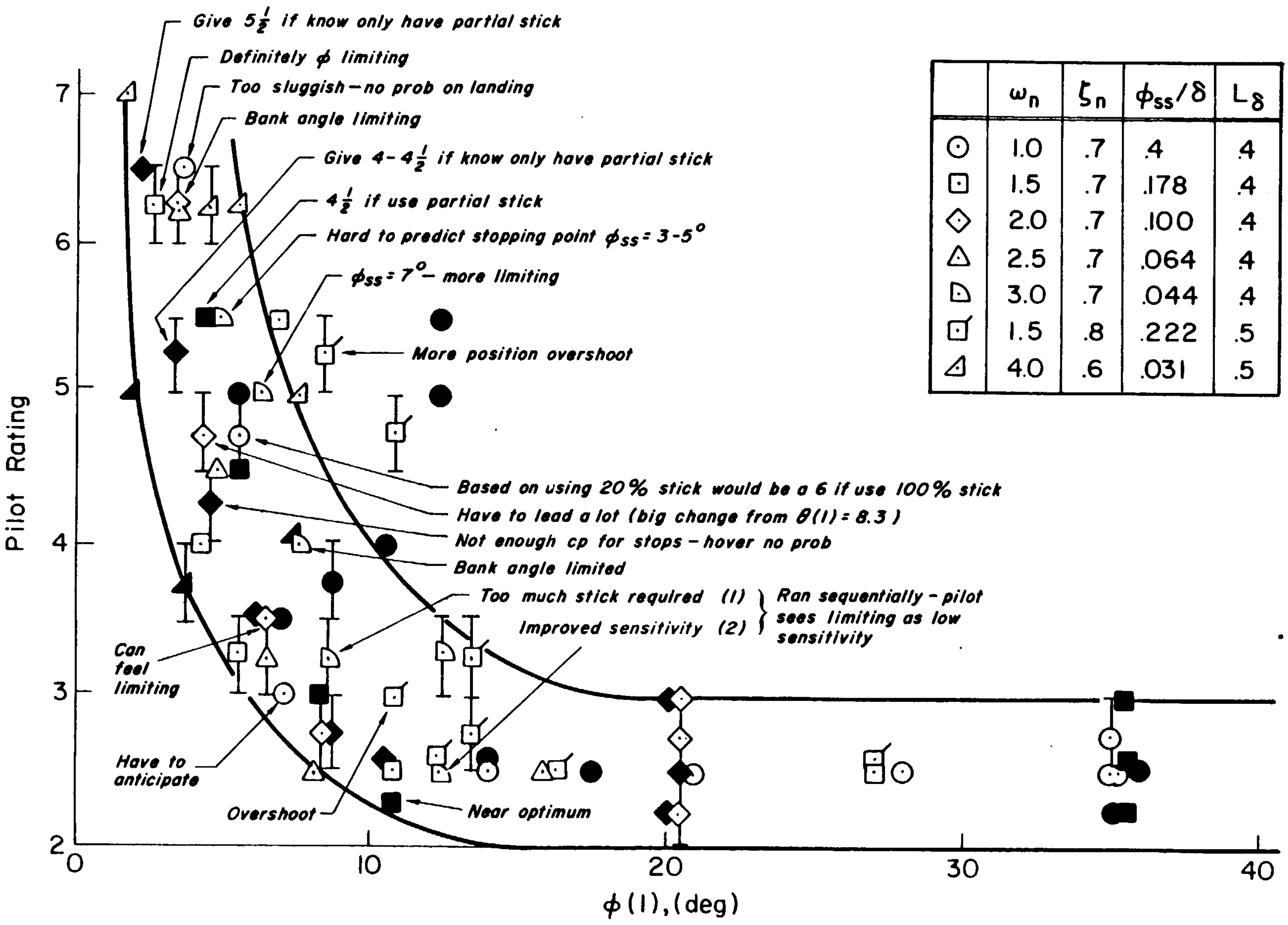


Figure 21. Control Power Data for Rate Systems (from Ref. 4)



	ω_n	ζ_n	ϕ_{ss}/δ	L_δ
⊙	1.0	.7	.4	.4
⊡	1.5	.7	.178	.4
◈	2.0	.7	.100	.4
◬	2.5	.7	.064	.4
◗	3.0	.7	.044	.4
⊡	1.5	.8	.222	.5
◿	4.0	.6	.031	.5

Figure 22. Control Power Data for Attitude Systems (from Ref. 4)

]

type responses. There are currently no data available for the minimum level of control power allowed for attitude systems for "moderate" maneuvering.

b) Gaps in the Data. It would be desirable to obtain control power data for the "moderate" maneuvering mission task elements defined in Paragraph 3.2. This should be done as a minimum for attitude systems and, if possible, for acceleration and rate systems to check the "moderate" maneuvering values obtained from MIL-F-83300. The hover tasks used in the experiments which defined this data may be excessively benign, resulting in the very low values noted in Table 7(3.4).

3.4.7.2 When a TRC Response is Required by Paragraph 3.3.

a) Discussion. For the purpose of this specification, the control power of a translational rate response is defined as the maximum steady-state velocity achieved with full control input in a zero wind condition. The Level 1 values of 45 knots for aggressive maneuvering and 35 knots for moderate maneuvering, shown in the preliminary specification, are based purely on estimates and were obtained from flying such systems in several simulations. However, there is no hard data to support these numbers. Another rationale for selecting 45 knots is that it would be desirable to hover in a 35-knot wind with gusts to 45 knots with a rotorcraft designed for aggressive maneuvering.

In addition to specifying "to be determined" levels of steady-state velocity for full controller inputs, we have also required that the rotorcraft maintain its longitudinal position over a fixed point on the ground in a steady wind. This implies a position hold feature that is inherent to the translational rate response type. Experiments reported in Refs. 4 and 15 have indicated that the primary advantage of a translational rate response is that the relative velocity between the rotorcraft and the ground (or ship) will be zero when the pilot releases the control force. Such a characteristic allows the pilot to be very aggressive, knowing that he can attain zero relative velocity with any obstacle or with any desired hover point simply by releasing the control force. It cannot be over emphasized that this feature is the overwhelmingly most important aspect of a translational rate system. In fact, the results of a recent in-flight evaluation (Ref. 24) of a translational rate system without position hold using the Navy X-22 VSTOL aircraft resulted in a limit cycle when attempting hover in steady winds (Ref. 28). These limit cycles varied in amplitude from ± 4 to ± 9 degrees with a frequency of about 0.9 radians per second. Requiring a position hold feature for all translational rate systems is somewhat restrictive; therefore, we have defined a small region of the $T_{\dot{x}}$ versus $K_{\dot{x}_c}$ region where the Ref. 24

flight tests indicated Level 1 flying qualities could be achieved without position hold in a steady wind.

b) Gaps in the Data. There are no data from which we can make a quantitative determination of the control power required for translational rate response types. It is recommended that this data be obtained on the NASA ARC VMS. As noted previously in this report, the validity of this simulator is adequate for highly augmented response types. Aggressive and moderate maneuver tasks should be selected from those listed in Paragraph 3.2. The tests should also involve steady winds up to 35 knots from all quadrants as well as critically timed wind shears. An example of a critically timed wind shear would be a decreasing headwind shear occurring during an aggressive quick stop which must be terminated at a fixed point due to an obstacle. The decreasing headwind shear will appear to make the rotorcraft decelerate more slowly requiring maximum control power to stop without hitting the obstacle (or bobbing up).

The above noted experiment should be combined with the experiment required to obtain data for longitudinal control force gradients with translational rate systems (Paragraph 3.4.9.3). As discussed in Paragraph 3.4.9.3, nonlinear controller force gradients will be required to obtain the appropriate sensitivity around zero without giving up the necessary control power at maximum controller deflections.

3.4.8 Longitudinal Control Power in Forward Flight and Sideslipping Flight.

a) Discussion. The requirements for longitudinal control power in forward flight are based upon pitch rate attained in 1.5 seconds following a full control deflection. A distinction is made between aggressive and moderate maneuvering; however, it is not thought to be necessary to make a distinction between acceleration, rate, and attitude responses in forward flight when specifying control power. The data presented are based upon PIDS requirements (UTTAS, AAH; Refs. 30 and 31).

b) Gaps in the Data. There is currently no valid data base which will support numerical requirements for aggressive or moderate maneuvering control power in forward flight. The use of fixed-wing criteria from MIL-F-8785C was eliminated based on the large differences in normal acceleration capability between fixed- and rotary-wing aircraft. It is believed that a special set of experiments needs to be conducted in order to determine the control power necessary for rotary-wing aircraft in forward flight. This is especially true for tasks involving air-to-air combat.

3.4.9 Longitudinal Controller Gradients and Forces.

a. Discussion. Different feel characteristics are required depending on the rotorcraft response type. This is accounted for in the specification by organizing the criteria into three separate subparagraphs: When acceleration response type is allowed, when rate or attitude is required, and when translational rate response is required. Finally, a separate requirement is specified for steady maneuvering in low speed and forward flight to insure adequate maneuver margin or dF_s/dn.

The requirements of MIL-H-8501A are invoked when an acceleration response is allowed by Paragraph 3.3 (see Paragraph 3.4.9.1). This allows all existing rotorcraft to be accounted for in the present specification.

When a rate response is allowed, the control force gradient with speed, by definition, is zero; hence, the requirements of MIL-H-8501A, which requires a stable gradient, would not apply. However, the higher quality response of a rate system eliminates the need for a stable control force gradient with speed (see, for example, Ref. 20). The control force and position gradients specified in Table 3(3.4) will insure proper feel for rate systems, and, likewise, the gradient specified in Table 4(3.4), for attitude systems.

The control force gradient for translational rate response types are specified in terms of a linear gradient for precision tracking [see Table 9(3.4)] as well as in terms of the maximum acceptable nonlinearity required to get adequate control power. A typical nonlinear force gradient for a translational rate command system is shown in Fig. 6(3.4). This gradient was taken from Ref. 4 which documents the heavy-lift helicopter.

b) Gaps in the Data. Longitudinal controller feel characteristics for acceleration, rate, and attitude response types have been investigated in simulations at NASA ARC (see Ref. 20). However, these investigations were based primarily on instrument approaches at 60 knots. Further experiments are needed to obtain force/deflection data for rate command, attitude command, and translational rate command systems for low speed and hover in order to provide data for Tables 3(3.4) and 4(3.4) as well as Table 9(3.4). For the rate command and, preferably, for the attitude command response types, it would be desirable to obtain this data utilizing variable stability in-flight simulation.

The systematic variation of force gradient parameters should be conducted during the basic rate and attitude dynamic response flight tests to be conducted in support of Paragraph 3.4.1.

It would be desirable to include side arm controllers as well as center sticks during these investigations.

3.4.9.5.4 Longitudinal Controller Free Play. The requirements presented in this paragraph were taken from the PIDS (UTTAS, AAH; Refs. 30 and 31) and are considered to be appropriate for the controller types described within the proposed specification.

3.4.9.5.5 Cockpit Longitudinal Controller Centering and Breakout Forces. The requirements presented in this paragraph were incorporated following a review of the PIDS (UTTAS, AAH; Refs. 30 and 31), MIL-H-8501A (Ref. 19), and fixed-wing specifications MIL-F-8785 and MIL-F-83300

(Refs. 7 and 27) and are considered to be appropriate for the controller types described within the proposed specification.

3.5 RESPONSE TO VERTICAL CONTROLLER

3.5.1 Pitch, Roll, and Yaw Response Coupling to Vertical Controller Inputs.

a) Discussion. This requirement is intended to limit the amount of coupling due to vertical controller inputs into the pitch, roll, and yaw axes. For acceleration and rate systems, such coupling is likely to result in divergences, whereas, with attitude and translational rate response types, the coupling will always take the form of a peak excursion which returns to some steady value. Therefore the requirement on acceleration and rate responses is based on the maximum control force and displacement required to eliminate the coupling, whereas the requirement on attitude and translational rate is based on the peak attitude excursions with the controls free [see Tables 1(3.5) and 2(3.5) respectively]. With lower order response types (i.e., acceleration and rate), it is expected that the pilot will have to use some control deflection in order to eliminate coupling; hence, placing limits on these forces and deflections is a logical form for the criterion. Attitude and translational rate response types are required for relatively severe operating conditions wherein the pilot will not have the excess workload capacity to regulate against coupling; therefore, peak attitude excursions represent a logical criterion for coupling for these cases.

b) Gaps in the Data. A review of Table 1(3.5) indicates that there is very little data available to place quantitative limits on coupling. The data that is shown for acceleration systems has been taken directly from MIL-H-8501A. Some additional insights into the effects of coupling can be obtained from Ref. 29. Unfortunately, this data comes from a ground-based simulation of acceleration and rate augmented rotorcraft which is deemed to be unreliable because of the considerations mentioned earlier in this report. Therefore, a systematic study of coupling for all response types is warranted in order to obtain the data required in Tables 1(3.5) and 2(3.5). The experimental matrix utilized in Ref. 29 can be applied directly to the variable stability flight test with modifications to account for the mission task elements specifically noted in Paragraph 3.2.

Some additional insights into the effects of coupling can be obtained from Ref. 20 wherein the different rotor types tested in those simulation experiments resulted in significant variations in the coupling response to collective inputs. This was especially noticeable in the missed approaches studied in that experiment.

3.5.2 Vertical Response to Vertical Controller Input.

a) Discussion. The vertical or height response characteristics to a vertical controller input is linked to the required response type in Table 3(3.5). The parameters selected to define the vertical axis response are rise time, path overshoot, and control sensitivity. The rationale behind the values selected for each of these parameters in Table 3(3.5) is given below.

Reference to Table 2(3.3) indicates that an acceleration response type is allowed only when the proposed mission is to be accomplished in good outside visual cues [i.e., usable cue environment (UCE) = 1 or 2)]. There is considerable good flight test data to indicate that zero heave damping is acceptable in this environment. Some of this data is summarized in Fig. 23, taken from Ref. 4, where it is shown that zero heave damping results in pilot ratings of 3-1/2 or better as long as the control power (T/W) is equal to or greater than 1.1. This level of control power is required in Paragraph 3.5.3.

Rise time is defined as the time to one-half peak amplitude following a step vertical controller input following the rationale utilized in Ref. 11 for STOL flying qualities. This is illustrated graphically in Fig. 1(3.5) of the proposed specification. When an acceleration response is allowed in the vertical axis following a step vertical controller input, the corresponding value of the rise time is infinity, which is reflected in Table 3(3.5) for acceleration and rate response types. The rationale for lumping acceleration and rate response types for the purpose of categorizing the vertical response is based on the fact that rate response is allowed when the usable cue environment is only slightly degraded [i.e., UCE = 2, in Table 2(3.3)].

More stringent rise time requirements are dictated for the attitude and translational rate response types inasmuch as they are designed to operate in considerably more severe conditions of restricted visibility. Data from a recent FSAA experiment involving transitions to hover in outside visual cue environments of 4 indicates that a rise time of 3 seconds is adequate for Level 1 when a good attitude command system is employed. This data is shown in Fig. 24 and should be considered preliminary, as it is still being analyzed at the time of this writing. The data in Fig. 24 also reveal that there is no large degradation in Cooper-Harper pilot rating as the rise time increases to as much as 7 seconds for attitude or rate command systems. Therefore, until better data can be obtained, a rise time of 7 seconds is allowed for Level 2, and an acceleration response is allowed for Level 3 (i.e., $T_{R_{h_T}}$ = infinity). It should be noted that, while the outside visual cue environment in this experiment was on the order of 4, a good attitude display on the HUD resulted in an improved UCE of about 3 (i.e., good attitude cues but poor translational rate cues, particularly in the vertical axis).

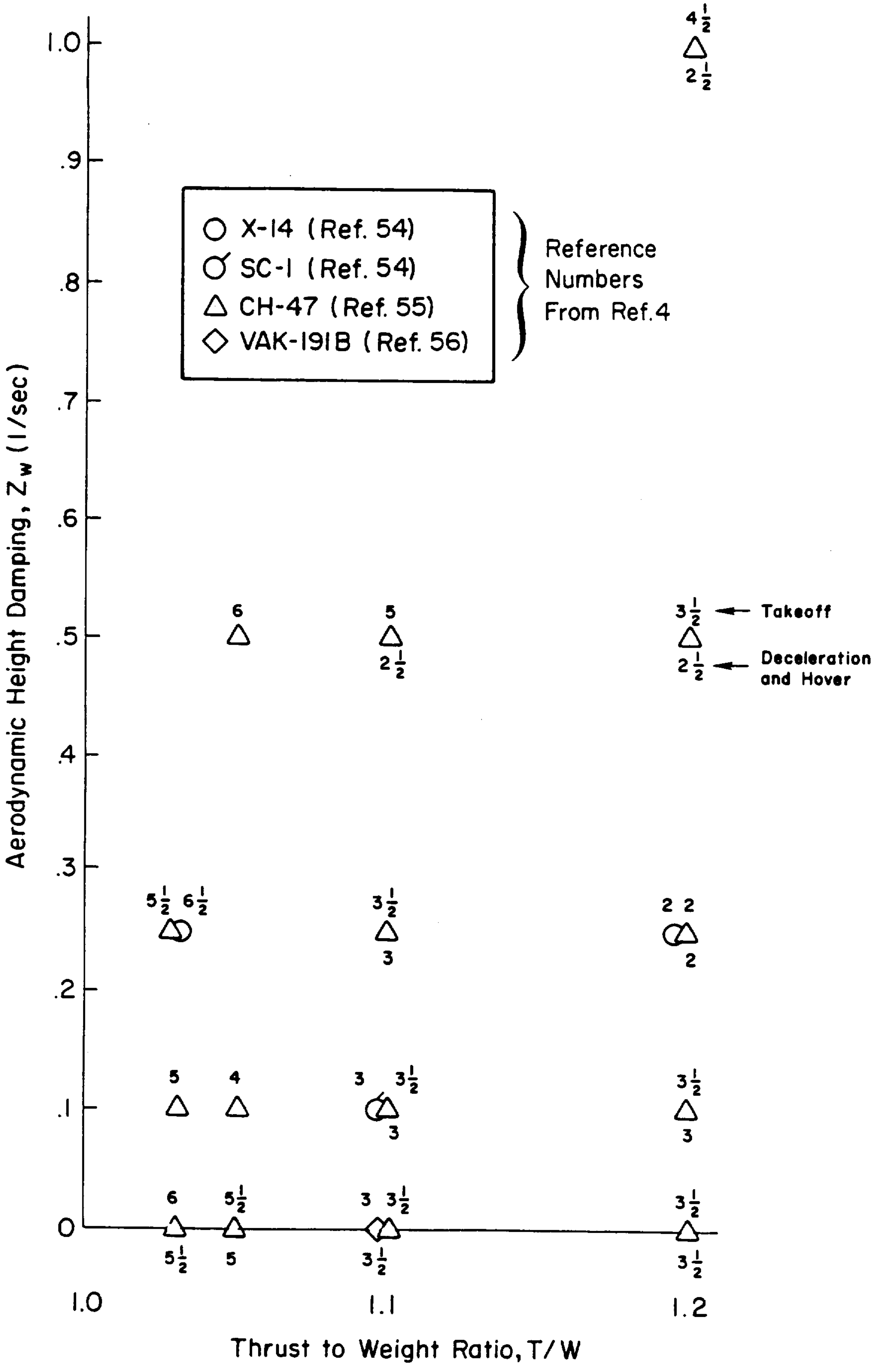


Figure 23. Flight Data for Vertical Axis Control
(from Ref. 4)

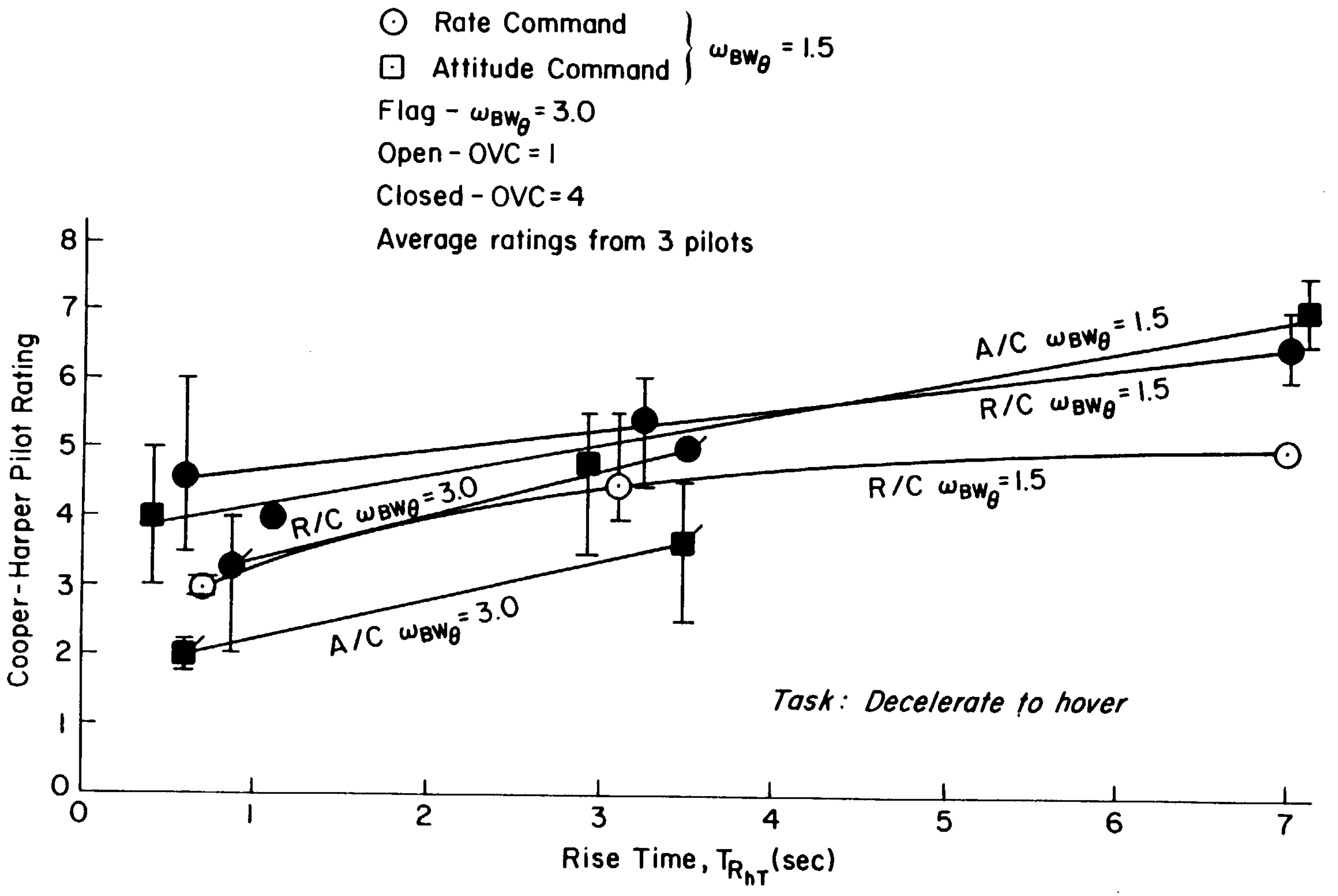


Figure 24. Interrelated Effects of Heave Damping, Attitude Bandwidth, and Outside Visual Cues (from recent FSAA experiment; data not published)

The control sensitivity values shown in Table 3(3.5) were taken from Fig. 25 (from Ref. 4) which indicates that sensitivities above 1300 feet per minute per inch are too sensitive and below 400 feet per minute per inch are too sluggish. However, quantitative Cooper-Harper ratings to quantify the magnitude of sluggish and sensitive are not available from that experiment which was conducted at NASA-Langley Research Center in the variable stability CH-47.

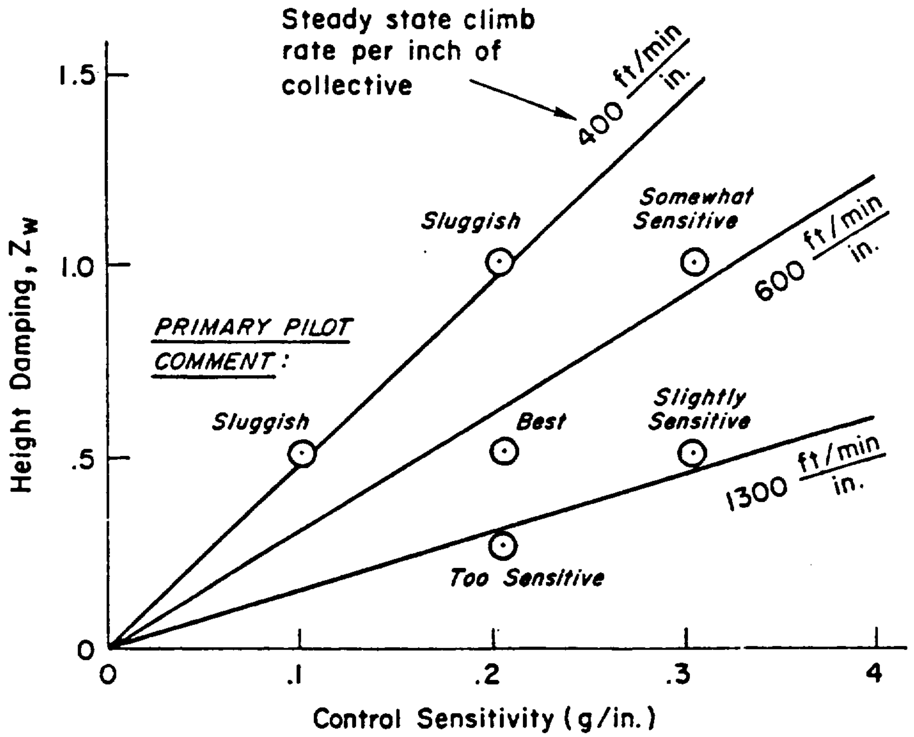


Figure 25. Combinations of Control Sensitivity and Height Damping from Variable Stability CH-47 (From Ref. 4)

b) Gaps in the Data. A review of Table 3(3.5) indicates that the primary areas of missing data for height control are vertical rate overshoot in hover and Levels 2 and 3 values for rise time and control sensitivity. In addition, the minimum value of rise time noted as 0.5 for Levels 1, 2, and 3 is based on an estimate of abruptness. Actual experimental data are required to refine this number.

It would be highly desirable to obtain the data required to complete the height control specification requirements using a variable stability rotorcraft, because the lags in current visual display systems are probably excessive for obtaining high confidence level height response data.

A moderate level of turbulence should be employed to provide a substantial handling qualities task in the horizontal axis in order to avoid allowing the pilot to concentrate solely on height control. This is consistent with the turbulence model defined in Paragraph 3.17, wherein it is required to conduct all flying qualities experiments to support specification data utilizing a "moderate" level of turbulence.

3.5.3 Vertical Response Using Vertical Controller.

a) Discussion. The required vertical response was obtained primarily from MIL-F-83300 with supporting data from Ref. 4, such as Fig. 23. The requirement is stated in terms of incremental vertical acceleration for low speed and hover and in terms of a minimum steady vertical speed for forward flight. The data for forward flight was obtained from Ref. 11. Past exerience in analyzing data for VSTOL and rotorcraft indicate that, when operating in the vicinity of the ground, the ability to generate incremental vertical accelerations to change the flight path for the purpose of avoiding obstacles is of primary importance. Likewise, for forward flight, the ability to effect changes in the steady flight path angle or vertical speed are of primary importance. These considerations are reflected in Table 4(3.5).

b) Gaps in the Data. Control power requirements for low speed and hover are fairly well substantiated by the data in Fig. 23. There is little or no data for forward flight directly applicable to rotorcraft; there is, however, a substantial body of data for STOL aircraft which may applicable. These numbers have been included in Table 4(3.5) and have been taken directly from a recently completed STOL amendment to the MIL Standard and Handbook (Ref. 11). The applicability of these data can be judged by reviewing Section 5 of Ref. 11 in the context of the mission task elements defined in Paragraph 3.3 of the preliminary specification. Such an investigation will reveal that the numbers from Ref. 11 are applicable to power approach and landing and do not apply to such up-and-away tasks as air combat, which may require significantly larger values of flight path control power. These considerations will be expanded in the Phase II portion of this study. An extremely important aspect of these expanded considerations will be the applicability of utilizing rotorcraft in the air-to-air combat mode. If, indeed, this is deemed to be a viable flight phase, the flight path control power aspects of air-to-air combat should be tested during the flight test recommended for Paragraph 3.2 (i.e., specific definition of mission task elements).

3.6 RESPONSE TO LATERAL CONTROLLER

All the responses to the lateral controller--including coupling into heave, pitch, and yaw--are included in this section. The lateral controller can consist of the conventional cyclic stick as well as side arm controllers.

3.6.1. Roll Response to Lateral Controller.

3.6.1.1 Hover. Based on the assumption of symmetry in hover, the limiting response characteristics in roll are assumed to be identical to those specified for the pitch axis in Paragraph 3.5. Therefore, no separate requirement is specified for the hover mode.

3.6.1.2 Low Speed and Forward Flight.

a) Discussion. The lateral response characteristics in low speed and forward flight are assumed to be identical (i.e., the desired response characteristic in bank angle to a lateral controller input is rate). This conclusion is based on numerous piloted experiments wherein it was found that bank angle stability tends to interfere severely with the lateral maneuverability of the rotorcraft during low speed as well as during up-and-away mission tasks. It should be noted that this fact implicitly sets a requirement for control system blending in the lateral axis from rate to attitude as the rotorcraft transitions into the hover mode. The characteristics of such blending have been studied at some length in Ref. 4, as well as in the recently completed work for VSTOL transition conducted on the FSAA (report to be published). Criteria related to this necessary control system blending are to be developed.

Inasmuch as the roll response to the lateral controller is primarily a rate response, the step time response criterion in Fig. 2(3.4) is directly applicable and is reflected by Table 1(3.6).

b. Gaps in the Data. There is not a great deal of data available to define the minimum acceptable lateral response characteristics of rotorcraft in low speed and forward flight [i.e., Table 1(3.6)]. Consideration was given to utilizing the fixed-wing specification from MIL-F-8785C; however, this was rejected on the basis that the mission task elements for rotorcraft in low speed and forward flight are considerably different than those for fixed-wing aircraft. Therefore, specific experiments need to be conducted. It is believed that these experiments could be successfully conducted on the NASA ARC VMS inasmuch as deficiencies in the CGI will not seriously degrade ratings taken for low speed and forward flight. However, a few data points obtained from simulation should be compared with data obtained from identical maneuvers taken in flight. In the event that the flight test data does not agree with simulation, it is recommended that the remaining data be taken in flight until the state-of-the-art of computer-generated imagery can be increased to the point where valid data can be obtained. Therefore these "anchor points" should be obtained early in the program. Additionally, current work being conducted to validate the Black Hawk simulation being run on the VMS should be directly applicable to this assessment. Fortunately this data will be available before the initiation of Phase II of this program.

3.6.1.3 Roll Attitude Response to a Roll Disturbance.

a. Discussion. The requirements of this paragraph are included for the purpose of providing spiral mode design guidance. References 30 and 31 were used as the basis for criteria specification.

b. Gaps in the Data. Verification of the Table 2(3.6) requirements through flight test with the use of a variable stability helicopter would be most desirable. No data exists to determine whether this form of criteria is acceptable for all mission tasks.

3.6.3 Yaw Response to Lateral Controller.

3.6.3.1 Hover.

a) Discussion. The pedal force and pedal deflection required to eliminate coupling due to lateral controller inputs serve as the basis for the specification of maximum allowable crosscoupling. MIL-H-8501A (Paragraph 3.3.14) requires that "lateral control displacement shall not produce pedal forces in excess of 100 percent of the associated lateral force" (i.e., one pound of pedal per pound of lateral control force). Our interpretation of this requirement is that it must not require more than one pound of pedal to hold a constant heading following a one pound input of lateral stick and that the 1:1 ratio specified represents Cooper-Harper pilot ratings of 3-1/2 or better. On this basis, we have specified one pound for Level 1 in Table 3(3.6). MIL-H-8501A does not place a requirement on the amount of pedal deflection required to counter any existing cross-coupling. However, we believe that excessive pedal deflection would, in itself, be limiting and therefore needs to be specified separately.

Zero crosscoupling is specified for Level 1 flying qualities when attitude and translational rate responses are required. This somewhat arbitrary decision is based on MIL-H-8501A, which specifies that no longitudinal control forces shall be developed in conjunction with lateral or directional control displacements for helicopters employing power-boosted or -operated controls. This requirement, in addition to the fact that the stringent mission requirement is implied when attitude and translational rate responses are mandated, is thought to form a strong argument for requiring zero coupling in these cases.

b) Gaps in the Data. Considering the large number of "TBDs" in Table 3(3.6), it is clear that there is a definite need for coupling data. The discussion of data gaps in Section 3.5.1 applies to this section.

3.6.3.2 Low Speed and Forward Flight.

a) Discussion. We have tentatively allowed two separate means for compliance in this paragraph. The first requirement is somewhat qualitative in that the pedal deflections and forces required to achieve acceptable heading control during rolling maneuvers induced by lateral stick deflection "shall not be objectionable." It is intended that these characteristics be checked in flight test or simulation, or by analysis using the turn coordination parameter (μ), specifically designed to place limits on the shaping and magnitude of rudder required to coordinate rolling maneuvers (see Paragraph 3.6.2.1.2 of the proposed MIL Standard and Handbook, Ref. 1.) The μ parameter is believed to provide excellent design guidance, but it is not included in the proposed specification, because it is not a time response parameter. However, the μ parameter will be included in the BIUG in order to provide guidance for design and for quantitative compliance with the first part of this paragraph.

The alternative requirement in this paragraph indicates that, in the event that the pedal forces required to coordinate rolling maneuvers are questionable, the ratio of the maximum change in sideslip angle to the initial peak magnitude or roll response shall not exceed the specified limits. This criterion is used in MIL-F-83300 and in a slightly different format in MIL-F-8785C. It is utilized here primarily because it is a time response criterion. As noted in Ref. 1, it is believed to have some drawbacks in that it does not quantitatively account for the amount of pedal required to coordinate rolling maneuvers. Nevertheless, the parameter appears to work most of the time and is therefore included in the proposed specification.

b) Gaps in the Data. While it would be desirable to refine some of the boundaries which form the basis for the turn coordination criteria further, there appears to be sufficient data to write a reasonably valid specification at this time. It is therefore believed that obtaining additional data for these criteria should have a relatively low priority in the experiments specifically conducted for the revised specification.

3.6.4 Pitch Response to Lateral Controller Inputs. The discusison for yaw response to lateral controller (Paragraph 3.6.3) applies to this section as well. The value for Level 1 flying qualities for the acceleration response in Table 4(3.6) was taken from Paragraph 3.3.14 in MIL-H-8501A.

3.6.8 Lateral Controller Power--Forward Flight

a) Discussion. The primary distinction for control power in this proposed specification is the "aggressiveness" of the mission task elements defined in Table 1(3.2), that is "moderate" and "aggressive".

It is thought that the lateral control power required for a rotorcraft in forward flight has the same basic considerations as fixed-wing aircraft. This is reflected in Table 9(3.6) wherein the minimum time to roll to a bank angle of 30 degrees is taken directly from MIL-F-8785C. The numbers used for the "aggressive" classification were taken from the Class 4, Category A requirements (precision maneuvering of fighter-type aircraft) operating at low speed (less than 1.8 V_{min}). The values used in the "moderate" classification were taken from the Class 3, Category A requirements of MIL-F-8785C (large aircraft having precision maneuver requirements) operating at medium speeds (between $1.8V_{min}$ and $0.7\ V_{max}$). These numbers will be refined during Phase II.

b) Gaps in the Data. No specific data gaps requiring simulation or flight test are perceived for this paragraph. However, the numbers should be refined based on discussions with test pilots representing the manufacturers as well as with operational pilots.

3.7 RESPONSE TO DIRECTIONAL CONTROLLER

3.7.2 Sideslip Response to Directional Controller in Forward Flight.

a) Discussion. This requirement represents the classical Dutch roll oscillation (i.e., sideslip excitation following a pedal-pulse input). The nature of the Dutch roll oscillation for helicopters in forward flight is believed to be identical to fixed-wing aircraft and, therefore, no distinction is required. The values specified in Table 3(3.7) were taken directly from MIL-F-8785C, Paragraph 3.3.1.1, "Lateral Directional Oscillations (Dutch Roll)." The values specified for rate, attitude, and translational rate responses represent the most stringent requirements from MIL-F-8785C, i.e., Category A (combat and ground attack). The requirements specified when an acceleration response is required are based on the MIL-F-8785C Category C requirements (i.e., approach and landing). The values specified for Category B are thought to be excessively lenient, even for fixed-wing aircraft in cruise.

The frequency response parameters stated in MIL-F-8785C were converted to time response parameters for the present specification where

- T_β is a measure of ω_d
- $T_{1/2}$ is a measure of $\zeta_d \omega_d$
- x_1/x_o and x_3/x_o are a measure of ζ_d

b) Gaps in the Data. No data gaps are perceived in this section aside from the usual desire to further refine existing criteria.

3.8 RESPONSE TO TRANSITION CONTROLLER

This section of the specification sets limits on the responses of variable configuration rotorcraft where wing tilt or pylon tilt is employed. The controller utilized to vary the rotor configuration is referred to as the transition controller. In addition, limits on rotorcraft responses due to control system blending or discrete changes in the rotorcraft's configuration are also established in this section.

3.8.1 Pitch Response to Transition Controller.

a) Discussion. For the purpose of this specification, the primary objectives of the transition controller are to:

1. Reconfigure the rotorcraft for operation in different ranges.
2. Change speed rapidly.

Rapid changes in the transition controller to achieve the above objectives should not result in undesirable pitch attitude or altitude excursions. Pitch attitude excursions are limited in terms of the peak attitude excursion per unit deflection of the transition controller. This metric was found to be the best parameter for defining transition controller coupling in a recently completed transition study accomplished for VSTOL aircraft (report to be published). The values noted in Table 1(3.8) are obtained from the preliminary results of that VSTOL study which should apply equally well to rotary-wing aircraft.

b) Gaps in the Data. The coupling data for rate and attitude systems in Table 1(3.8) need to be augmented with coupling data for acceleration-type systems. Acceleration systems were not investigated in the above noted VSTOL transition study. It is believed that such data could be obtained on a simulator, because precision hover using the computer generated imagery is not required for the transition maneuver.

3.8.2 Height Response to Transition Controller.

There is currently no data available to indicate the allowable heave response to a change in transition controller. However, during the above noted VSTOL transition study, it was hypothesized (although not experimentally justified) that the amount of pitch attitude required to cancel the altitude excursions due to a transition controller change would be an appropriate metric. The format of Table 2(3.8) should be considered tentative, therefore, until data can be generated to determine whether the metric is appropriate and until specific numbers can be obtained. An experiment is currently being conducted at the NASA ARC in order to investigate the transition of variable tilt-rotor configurations. It is hoped that the information required for this paragraph will be obtained during that study.

3.8.3 Transient Handling Quality Degradations in Transition.

a) Discussion. Transient handling quality degradations are included to allow short periods of instability to occur in regions where steady-state operation is not contemplated. The recent VSTOL transition study indicated that the instabilities noted in Table 3(3.8) could be tolerated for Levels 2 and 3 flying qualities. However, a Level 1 region was not defined due to the lack of time to investigate a sufficient number of configurations. However, based on the pilot comments received, it is expected that such a region may not exist. Therefore, unless data is received to the contrary, we will probably not allow any region of instability or degradation in the Level 1 requirements during transition when rate, attitude, or translational rate responses are required by Paragraph 3.3. For the relatively benign conditions that exist when an acceleration response is allowed by Paragraph 3.3, it is expected that some degradation in flying qualities would be allowed over a small portion of the transition envelope. It should be remembered that acceleration responses are only allowed in conditions of good visibility and that a number of highly unstable current day helicopters operate without apparent problems.* As noted in Table 3(3.8), the allowable degradations in handling qualities during transition when acceleration response is allowed is not defined and should be the subject of a simulation experiment.

3.8.4 Response to Configuration Change (i.e., Flaps, Landing Gear, etc.).

a) Discussion. This paragraph is intended to limit the rotorcraft attitude excursions due to discrete changes in the rotorcraft configuration or when the stability and control augmentation system (SCAS) control mode is changed.

b) Gaps in the Data. While no specific data is available for Table 4(3.8), there are a number of sources of data from which estimates might be made. For example, control system blending was considered in some detail in Ref. 4 and in the recently completed VSTOL transition study. The results of these references should be considered in detail

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*These highly unstable rotorcraft do not meet the Level 1 requirements of the proposed Flying and Ground Handling Specification due primarily to the reversible nature of their flight control system; that is, the feedback from the swash plate to the cyclic stick tends to drive the cyclic stick hard over in random directions such that stick-free flying qualities are nonexistent. The fact that such helicopters (for example, the Hughes 300) are successfully operated both as civilian and military trainers indicates that such instabilities can be tolerated in conditions of good visibility.

during the Phase II portion of this study in order to make estimates of the forces and deflections required for Table 4(3.8). Of course, experimental data would be highly desirable but difficult to justify in the face of the many items of higher priority noted previously in this report, for example, basic longitudinal, lateral, rate, and attitude response characteristics.

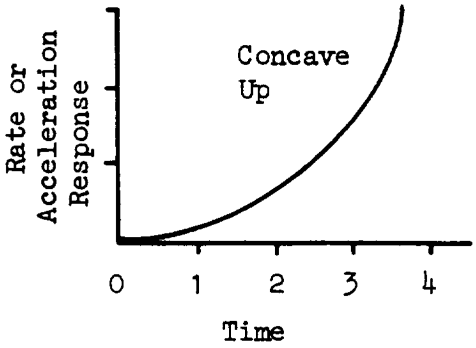
The manufacturers are expected to perform simulations of proposed configurations which would include any control system blending and configuration changes. The BIUG will include information which will serve as guidance for compliance via demonstration. Until more data are made available, such a qualitative requirement may have to suffice for the first draft of the proposed specification.

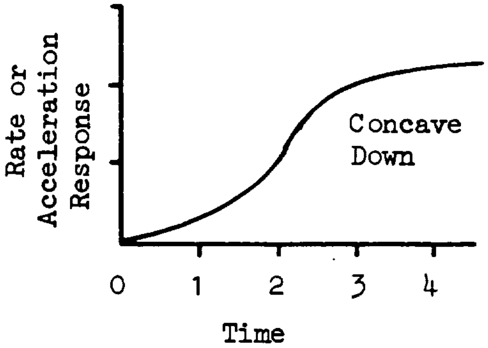
3.10 RESPONSE TO FAILURES

3.10.2 Failures of the Automatic Flight Control System(s).

a. Discussion. Safe recovery from any single failure of the automatic flight control system is an extremely important requirement, especially in light of the advanced cockpits, the fly-by-light/fly-by-wire controls, and the high levels of maneuverability which will be demanded from the next generation of rotorcraft. A two-fold approach is taken in specification of this paragraph. Separate requirements are provided for the maximum allowable rotorcraft response following any single failure (independent of corrective pilot action) and for the minimum allowable time in which the pilot is allowed to respond to any single failure. Previous criteria used in rotorcraft specifications have been based on a minimum allowable pilot response time which is independent of the workload or the attention the pilot is giving to control of the rotorcraft. This form of criteria is considered to be undesirable for future specification purposes.

A rotorcraft which exhibits a concave upward response to a failure (see sketch on following page) may be recoverable following the appropriate pilot intervention delay time by a test pilot who is familiar with a specific rotorcraft type and has practiced the failure by building up to it (e.g., from a slower airspeed to higher airspeeds). The operational pilot who may have never experienced the failure or practiced it may be involved simultaneously with other tasks (e.g., navigation, communication) and may not demonstrate the same educated or practiced response to a failure. Therefore, the intent of the requirement presented in Paragraph 3.10.2.1 of the specification is to provide an upper bound on what is believed to be a tolerable rotorcraft response following any single failure in trimmed level flight (where the pilot will most likely not be active in the control loop). The quantitative requirements, as listed in Table 1(3.10), are intended to insure that, when the pilot enters the control loop to initiate recovery from the failure, a reasonable chance of recovery exists. A rotorcraft response following a failure that does not exceed 10 degrees per second or 0.5 g's or TBD by 3 seconds will either be a slowly divergent response or a concave downward response (see sketch).





A similar specification for flight phases such as climb, autorotation, approach to landing, etc., is not considered germaine, because the pilot will probably already be active in the control loop; therefore, the requirements of Paragraph 3.10.2.2 are considered sufficient for these flight phases. Quantitative requirements in Table 1(3.10) are drawn from the UTTAS and AAH PIDS (Refs. 30 and 31).

The intent in the proposed specification of Paragraph 3.10.2.2 on pilot intervention delay time is to develop reasonable criteria for testing the acceptability of any single failure of the automatic flight control system. The criteria are based on the premise that failures should be tested in their appropriate flight mode (e.g., cruise, landing, climb), and the pilot should be allowed to respond with corrective control action following a period of time appropriate to that mode. The concept of pilot intervention time delay originated in the proposed specification of Ref. 38 and is composed of the sum of 2 components: the rotorcraft response time and the pilot response time. Those variables are defined in Table 2(3.10).

Pilot response time is especially critical in defining a reasonable minimum pilot intervention delay time to a failure. The status of the pilot in the overall task of controlling the rotorcraft can be described as active or attended control operation, divided attention control operation (both hands on the controls and hands off), or unattended control operation such as in autopilot mode (both hands on and hands off the control). For example, if the pilot is making a final approach to a landing, he would be considered to be in an attended operation mode of rotorcraft control with his hands on the control. Should an automatic flight control failure occur, the minimum pilot response time for corrective control input following recognition of the failure would be quite small, approximately half a second. Therefore, for testing the acceptablilty of failures in this mode of flight, it would be unreasonable to require testing (or specification) of a minimum allowable response time any greater than 1/2 second. However, for cross country flight at cruise airspeeds, it is very possible that the pilot will not have his hands on the control if an autopilot is engaged. For failures which have a significant probability of occurrence in this flight mode, the specification of a

1/2 second pilot response time for test purposes would be unreasonable and unsafe. In this specification, therefore, the minimum allowable pilot response time would be adjusted to 2-1/2 seconds following any single failure.

In applying the proposed criteria, the contractor would first be expected to identify critical single failures of the automatic flight control system. The probability of the failure occurring in various modes of flight should then be identified. For example, some logic or switching failures might only be capable of occurring at low speed or in a final approach. Other failures might be capable of occuring in any flight mode. Following this identification, each failure should be tested in accordance with the associated pilot delay times specified in Table 2(3.10). Engineering consultation with project pilots should be sufficient to determine the appropriate pilot modes of control attentiveness for the types of failures to be tested.

3.13 RESPONSES TO STORES RELEASE, ARMAMENT DELIVERY, AND MISSION EQUIPMENT OPERATION

The specification criteria presented in this section are based almost exclusively on the UTTAS and AAH PIDS (Refs. 30 and 31). The delay times (following intentional or inadvertent release of stores) which are specified in Paragraphs 3.13.2 and 3.13.3 and during which the rotorcraft must not exceed certain load factors or flight limits with the controls held fixed have been questioned by numerous sources as being unreasonably restrictive. It is recommended that these times be reviewed and documented in the BIUG to the final draft of the specification.

3.15 WATER HANDLING CHARACTERISTICS

Research and interviews which were conducted during the drafting of this specification indicated that a significant need existed for specification of ditching criteria. British Civil Authority (CAA) criteria (Ref. 38), which has been accepted for the civil use of rotorcraft, is considered adequate for the proposed specification.

3.16 VIBRATION AND RIDE QUALITY CHARACTERISTICS

a. Discussion. While it is accepted that the proposed specification should not emphasize criteria for general vibration and ride qualities purposes, it is nevertheless a fact that pilots and crew members are affected by these rotorcraft characteristics. MIL-H-8501A placed constant acceleration limits on frequencies up to 32 Hertz. There is considerable disagreement with these limits in the low frequency range where pilots respond to displacement amplitude rather than acceleration. MIL-H-8501 also does not take into account the length of the mission (as discussed in Ref. 32) or the effect of noise. In an assessment of vibration criteria in 1981 (Ref. 33) it was stated by Kidd that a large body of literature dealing with vibration comfort criteria existed but only a relatively small portion of that reported work had direct applicability to helicopter ride quality. Since that time a considerable amount of research has been published which deals specifically with rotorcraft ride quality (Refs. 26, 34, 35, 36, and 37). This work ties analytical, flight test, and simulation data together into a ride quality model which should be extremely useful for developing and specifying rotorcraft criteria. Results from this research indicate strong interactive effects among noise and vibration components in defining overall ride quality. In looking toward the development of advanced cockpits and possibly a single pilot cockpit for the LHX, it will be important to account for these interactive effects if mission effectiveness is to be maximized while minimizing pilot fatigue. Proposed ride quality criteria for this specification (based on Ref. 34) are designed primarily to acknowledge that the interaction of noise and vibration exists. The exact form of criteria needs to be studied further; however, the proposed curves of A-weighted noise level (dB) versus root mean squared (rms) acceleration (g) are considered to be quite representative of what final criteria would look like.

b. Gaps in the Data. Subjective human discomfort contours, as presented qualitatively in Figs. 1(3.16) through 3(3.16), have been established quantitatively using pilots as subjects. However, the data was acquired with each subject pilot as a passenger and not while the subject pilot was actually flying a helicopter. Research will therefore be required in order to establish the effect that various comfort contours have on the piloting task workload and the overall mission effectiveness. Both simulator and flight data will be required.

Portable equipment does exist to measure subjective human discomfort, and analytical models exist which predict contours of subjective human discomfort quite accurately. Therefore, instead of experimentally repeating all of the possible vibration/noise combinations, data need only be obtained for establishing correlation between the present data base and piloting effectiveness. Final contours for specification purposes can be generated subsequently using the available subjective discomfort data base and analytical models with a high degree of confidence in the results.

3.17 FLYING QUALITY REQUIREMENTS IN ATMOSPHERIC DISTURBANCES

3.17.1 Allowable Flying Quality Degradations in Turbulence.

a. Discussion. The bounds on the flying quality levels are to be adjusted to reflect the documented degradation in pilot opinion ratings of flying qualities caused by atmospheric turbulence. Table 1(3.17) merely limits this degradation; it does not require degradation. The only exception applies to attitude response and to TRC systems required by Paragraph 3.3: No degradation in the flying qualities levels is allowed for turbulence up to and including "moderate," because attitude response and TRC systems should provide consistent flying qualities in light to moderate disturbances.

b. Data Base Sources.

Jewell, W. F., et al., Powered-Lift Aircraft Handling Qualities in the Presence of Naturally-Occurring and Computer-Generated Atmospheric Disturbances, FAA-RD-79-59, May 1979 (STI TR-1099-3), also J. of Aircraft, Vol. 16:6, June 1979, pp. 388-392.

Sinclair, S. R. M., and LTC. T. C. West, "Handling Qualities of a Simulated STOL Aircraft in Natural and Computer-Generated Turbulence and Shear," in Piloted Aircraft Environment Simulation Techniques, AGARD CP-249, October 1978.

Jacobson, I. D., and D. S. Joshi, "Investigation of the Influence of Simulated Turbulence on Handling Qualities," J. of Aircraft, Vol. 14, No. 3, March 1977, pp. 272-275.

Jacobson, I. D., and D. S. Joshi, "Handling Qualities of Aircraft in the Presence of Simulated Turbulence," J. of Aircraft, Vol. 15, No. 4, April 1978, pp. 254-256.

Moorhouse, D. J., and R. J. Woodcock, Background Information and User Guide for MIL-F-8785C, Military Specification--Flying Qualities of Piloted Airplanes, AFWAL-TR-81-3109, July 1982, Section XII, pp. 199-207.

Moorhouse, D. J., and R. J. Woodcock, Proceedings of AFFDL Flying Qualities Symposium Held at Wright State University, 12-15 September 1978, AFFDL-TR-78-171, Dec. 1978.

3.17.2 Definition of Atmospheric Disturbances.

a. Discussion. To specify allowable flying quality degradations in turbulence requires definition of atmospheric disturbances. The definition must also recognize that compliance may be demonstrated by simulation or by flight test. Simulation will require a "model" of atmospheric disturbances. Flight tests may require "surrogates" for atmospheric disturbances if naturally-occurring disturbances are not appropriate for the demonstration. For rotorcraft tasks in up-and-away flight, authoritative models of homogeneous isotropic turbulence, wind shear, and steady winds in Refs. 1 and 7 are acceptable. For near-earth and near-ship operations of rotorcraft, however, authoritative models of anisotropic turbulence which incorporate the effects of surface shape and roughness are still being developed and have not yet been sufficiently well validated to gain wide acceptance. It is therefore deemed inappropriate at this time to invoke models of atmospheric turbulence within the specification itself, although models for wind shear and steady winds from Ref. 1 have been included. Instead, some relevant references will be offerred here for turbulence models appropriate for near-earth and near-ship operations.

b. Data Base Sources. (Each document provides a comprehensive list of sources.)

Moorhouse, D. J., and R. J. Woodcock, Background Information and User Guide for MIL-F-8785C, Military Specification--Flying Qualities of Piloted Airplanes, AFWAL-TR-81-3109, July 1982, Section XI, pp. 161-198.

Hoh, Roger H., David G. Mitchell, Irving L. Ashkenas, et al., Proposed MIL Standard and Handbook--Flying Qualities of Air Vehicles. Volume II: Proposed MIL Handbook, AFWAL-TR-82-3081(II), November 1982.

Turner, Robert E., and C. Kelly Hill (Compilers), Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1982 Revision, NASA TM 82473, 1982.

3.17.2.1 Random Turbulence.

a. Discussion. The qualitative definitions of light, moderate, severe, and extreme turbulence levels are from Ref. 1, which, in turn, based the definitions on those given by the Federal Aviation Administration in the Airmen's Information Manual. The quantitative definitions of light, moderate, and severe turbulence in terms of root-mean-squared longitudinal gust velocity (σ_{u_g}) are also from Ref. 1, which, in turn, based the definitions on qualitative experience reported in the MIL-F-8785C BIUG.

b. Data Base Sources. (Refer to Appendix A)

c. Gaps in the Data. Credible models of anisotropic turbulence for nap-of-the-earth (NOE) and near-ship operations of rotorcraft are needed. Models which incorporate the effects of surface shape and roughness are being developed but have not yet been sufficiently well validated to gain wide acceptance. Full scale measurements of turbulence are required to validate scale model measurements. The NRC (Ottawa, Ontario) model 205 Variable Stability helicopter is equipped to measure turbulence and has been used as a probe in Ref. 39.

3.17.2.2 Windshear.

a. Discussion. The quantitative definitions of wind shear are from Ref. 1.

b. Data Base Sources.

Moorhouse, D. J., and R. J. Woodcock, Background Information and User Guide for MIL-F-8785C, Military Specification--Flying Qualities of Piloted Airplanes, AFWAL-TR-81-3109, July 1982, Section XII, pp. 199-207.

Hoh, Roger H., David G. Mitchell, Irving L. Ashkenas, et al., Proposed MIL Standard and Handbook--Flying Qualities of Air Vehicles. Volume II: Proposed MIL Handbook, AFWAL-TR-82-3081(II), November 1982.

Turner, Robert E., and C. Kelly Hill (Compilers), Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1982 Revision, NASA TM 82473, 1982.

3.17.2.3 Steady Crosswind.

a. Discussion. The qualitative and quantitative definitions of steady crosswinds are from Ref. 1.

b. Data Base Sources.

Moorhouse, D. J., and R. J. Woodcock, Background Information and User Guide for MIL-F-8785C, Military Specification--Flying Qualities of Piloted Airplanes, AFWAL-TR-81-3109, July 1982, Section XII, pp. 199-207.

Hoh, Roger H., David G. Mitchell, Irving L. Ashkenas, et al., Proposed MIL Standard and Handbook--Flying Qualities of Air Vehicles. Volume II: Proposed MIL Handbook, AFWAL-TR-82-3081(II), November 1982.

Turner, Robert E., and C. Kelly Hill (Compilers), Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1982 Revision, NASA TM 82473, 1982.

3.17.3 Atmospheric Disturbances When Demonstrating Compliance Via Flight Test or Piloted Simulation.

a. Discussion. This requirement insures that effects of light and moderate turbulence on flying qualities will be included in compliance demonstrations (by flight test or simulation) which employ mission tasks.

b. Gaps in the Data. This issue is a data gap at this point. This requirement is designed to fill a data gap while at the same time improving the practical basis for demonstrating compliance.

3.17.4 Atmospheric Disturbances for New Specification Data.

a. Discussion. This requirement insures that effects of light and moderate turbulence on flying qualities will be included in data acquired to support new specifications.

b. Gaps in the Data. This issue is a data gap at this point. This requirement is designed to fill a data gap while at the same time improving the practical basis for demonstrating compliance.

3.17.5 Sensitivity of Trim Attitude to Steady Winds.

a. Discussion. This requirement limits the gust-sensitivity represented by stability derivatives X_u and Y_v for rotorcraft that change attitude to translate. An attitude-speed gradient of 0.6 degrees per knot is equivalent to X_u (or Y_v) of -0.2 per second based on calculations using the homogemeous perturbed equilibrium equation.

$$X_u u - g\theta = 0$$

This requirement is from Ref. 27.

b. Data Base Sources.

Chalk, Charles R., David L. Key, John Kroll, Jr., et al., Background Information and User Guide for MIL-F-83300-Military Specification--Flying Qualities of Piloted V/STOL Aircraft, AFFDL-TR-70-88, March 1971.

McCormick, R. L., VTOL Handling Qualities Criteria Study Through Moving-Base Simulation, AFFDL-TR-69-27, October 1969.

3.17.6 Sensitivity of Equilibrium Control Power to Steady Winds.

a. Discussion. This requirement limits the gust-sensitivities represented by stability derivatives L_v, M_u, N_v, Z_u, and Z_w based on calculations using the control power represented in the following homogeneous perturbed equilibrium equations:

$$-L_v v - L_{\delta_A}\delta_A = 0$$

$$-M_u u - M_{\delta_B}\delta_B - M_{\delta_s}\delta_s = 0$$

$$-N_v v - N_{\delta_p}\delta_p - N_{\delta_c}\delta_c = 0$$

$$-Z_u u - Z_{\delta_c}\delta_c = 0, \text{ provided } w = 0$$

$$-Z_w w - Z_{\delta_c}\delta_c = 0, \text{ provided } u = 0$$

This requirement, as well as that in Paragraph 3.17.5, may be involved in lieu of those in Paragraphs 3.17.7 through 3.17.12, because it does not require measurement of the specific dynamic responses to gust velocities in the context of the precision hovering or stationkeeping tasks (Tasks A.1.1.2 or A.1.1.6, respectively) in Appendix A.

b. Data Base Sources. The necessary trim control data are available from equilibrium flight tests of control displacements as functions of the respective velocities. The necessary control derivatives must be identified from indepedent flight tests of control effectiveness using transient control inputs. The following reference is a typical source of data.

Abbott, William Y., John O. Benson, Randall G. Oliver, and Robert A. Williams, Validation Flight Test of UH-60A for Rotorcraft Systems Integration Simulator (RSIS), USAAEFA Project No. 79-24, September 1982.

3.17.7 through 3.17.12 Specific Responses to Gust Velocities.

a. Discussion. These requirements provide alternate ways of limiting the gust-sensitivity represented by stability deratives M_u, X_u, L_v, Y_v, N_v, and Z_w, respectively, in the context of the precision hovering or stationkeeping tasks (Tasks A.1.1.2 or A.1.1.6, respectively) in Appendix A. The step function in each gust velocity can readily be provided by simulation. If specification compliance is to be demonstrated by flight test, the step function in gust velocity can be provided by the wind generators described in Ref. 40 for precision hovering IGE. In either case, it is essential to enforce the cited standards of task performance in Appendix A.

b. Data Base Sources.

Klein, Richard H., Henry R. Jex, Arthur A. Blauvelt, and Irving L. Ashkenas, Development and Calibration of an Aerodynamic Disturbance Test Facility. Volume I: Executive Summary, NHTSA DOT HS-803 616, June 1978.

Klein, Richard H., Irving L. Ashkenas, and Henry R. Jex, Development and Calibration of an Aerodynamic Disturbance Test Facility. Volume II: Development of Requirements and Preliminary Design, NHTSA DOT HS-803 617, June 1978.

Klein, Richard H., Arthur A. Blauvelt, and Paul G. Van Valkenburgh, Development and Calibration of an Aerodynamic Disturbance Test Facility. Volume III: Construction, Calibration, and Operation, NHTSA DOT HS-803 618, June 1978.

3.17.13 Requirements for Rotorcraft Failure States in Atmospheric Disturbances.

a. Discussion. This is the more practical requirement from Ref. 1.

b. Data Base Sources. (Refer to alternate Paragraph 3.9.4, MIL Prime STD, AFWAL-TR-82-3081, Ref. 1.)

SECTION III

SUMMARY OF DATA GAPS AND PRIORITIES OF REQUIRED EXPERIMENTS

The data gaps have been discussed throughout this volume together with the necessary flight test or simulation experiments required in order to resolve the noted gaps. This latter information is summarized in Table 2, which includes recommended priorities for the data necessary to turn the structure of the Flying and Ground Handling Qualities of Volume I into a viable specification.

TABLE 2. EXPERIMENTS REQUIRED TO PROVIDE DATA FOR REVISED MIL-H-8501A

Priority	Specification Paragraph	Data Requirements	Required Experiments
1	Paragraph 3.2, combine with Paragraphs 3.3.2 and 3.4.1.2 in unified program	Define mission tasks elements (MTEs) in Tables 1(3.2) and 2(3.2) ● Details of maneuver execution ● Definitions of performance limits (desired and adequate) Step 1--Develop tentative MTEs on paper Step 2--Evaluate performance requirements using computer simulation of tactical environments Step 3--Group obvious similar tasks Step 4--Flight test MTEs Step 5--Agree on performance limits Step 6--Write tentative MTE descriptions Step 7--All review (government and manufacturers) Step 8--Revise as necessary	Flight Test ● Operational rotorcraft (Ft. Rucker, AH-64) ● Operational and instructor pilots, representative contractor test pilot ● Variable stability helicopter when attitude and TRC are required ● Approximately 40 to 50 hours
1	Paragraph 3.3.2, combine with Paragraphs 3.2 and 3.4.1.2 in unified program	● Define required response type for Level 1 handling for each mission task element or element group (See Fig. 26) ● Determine effect of turbulence and resulting need for attitude hold	Flight test ● Variable stability helicopter ● CH-47 and NRC Bell 205, most tasks ● NRC Bell 205 for high agility tasks ● Preliminary tests to scope range of base response type--20 hours ● Complete tests--100 hours

TABLE 2 (Continued)

Priority	Specification Paragraph	Data Requirements	Required Experiments
1	Paragraph 3.4.1.2, combine with Paragraphs 3.2 and 3.3.2 in unified program	Determine specific limits on time response criterion parameters for rate response in low speed and hover (Levels 1, 2, and 3). Vary systematically: (see Fig. 26) - T_{R_q} - K_q - τ_{d_q} - K_{q_F} - X_1/X_o	Flight test ● Variable stability CH-47 or NRC Bell 205 ● Pick most critical tasks from results of Paragraph 3.3 tests ● Approximately 40 hours
2	Paragraphs 3.3.3 and 3.1.6.4	● Define worst usable cue environment (UCE) for each response type to achieve Level 1 ● Define acceptable display formats for attitude and translational rate information* ● Determine effects of vision aid failures in critical flight conditions	Flight test ● Outside visual cue (OVC) = 1 to 3 ● Use vision degrading lenses ● Approximately 40 hours simulation ● OVC = 4 to 5 ● All forward flight ● Evaluation of display formats ● Effect of vision aid failure ● Require two five-week periods

*The context is the type of display, e.g., helmet mounted, head-up, etc. The content is the information on display, e.g., pitch ladder, closure rate, or range display with given field of view, contrast texture, etc.

TABLE 2 (Continued)

Priority	Specification Paragraph	Data Requirements	Required Experiments
3	Paragraph 3.8.2	- Determine maximum heave coupling due to transition controller	Simulation - Vertical Motion Simulator (VMS)--adequate for transition work--two-week period
3	Paragraphs 3.4.4, 3.5.1, 3.6.3.1, 3.6.4, and 3.7.2	- Determine maximum allowable inter-axis coupling	Flight test - Variable stability for acceleration rate and attitude responses (50 hours) Simulation - VMS for TRC (one five-week period)
4	Paragraph 3.4.2	- Validate applicability of hover criteria for up and away--VMC - Define required response characteristics for IMC - Extend FAA results to include systematic flying qualities evaluations	Flight test - Variable stability for large amplitude up-and-away flight--CH-47 Simulation - Instrument flying tasks on VMS - Two weeks using ICAB - Four weeks with motion
5	Paragraph 3.4.1.1	Fill in small amount of missing data for low speed and hover of lightly augmented helicopters	Flight Test - Variability stability CH-47 or NRC Bell 205 - Vary ω_n, ζ_n, and λ systematically - Approximately 15 hours

TABLE 2 (Continued)

Priority	Specification Paragraph	Data Requirements	Required Experiments
5	Paragraph 3.18	● Determine allowable control system blending characteristics	Simulation ● VMS simulator ● Five-week period
6	Paragraph 3.8.3, combine with Paragraph 3.18	● Determine allowable transient instabilities in roll and yaw in transition	Simulation ● VMS--adequate for transition work--three-week period
7	Paragraph 3.10.2	● Determine allowable excursions in attitude and velocity following stability and control augmentation system failures	Simulation ● Use VMS ● Five-week period
8	Paragraph 3.4.1.3	Expand existing data base to include Levels 2 and 3 for attitude response in low speed and hover	Flight test ● Variable stability CH-47 or NRC Bell 205 ● Approximately 20 hours
9	Paragraph 3.4.1.4, combine all TRC, i.e., Paragraphs 3.4.3, 3.4.6.2, and 3.4.8.3	Fill in data base to augment existing TRC flight and simulation results	Simulation ● Use VMS ● Two weeks on ICAB ● Four weeks with motion Flight test ● Simulation validation ● Approximately five hours with CH-47

TABLE 2 (Concluded)

Priority	Specification Paragraph	Data Requirements	Required Experiments
9	Paragraph 3.4.3, combine all TRC, i.e., Paragraphs 3.4.1.4, 3.4.6.2, and 3.4.8.3	See previous entry (for Paragraph 3.4.1.4)	
9	Paragraph 3.4.6.1	● Determine control power needed for attack and cargo rotorcraft using TRC	Simulator ● VMS or FSAA ● FSAA terrain board may give better speed cues
9	Paragraph 3.4.8.3, combine all TRC, i.e., Paragraphs 3.4.1.4, 3.4.3, and 3.4.6.2	● Determine envelopes for acceptable nonlinear force gradients	Same as above
In Progress	Paragraph 3.4.6.1	● Existing data base is adequate if using $\theta(1)$, $\phi(1)$	● Currently have contrast in force to look at roll control power

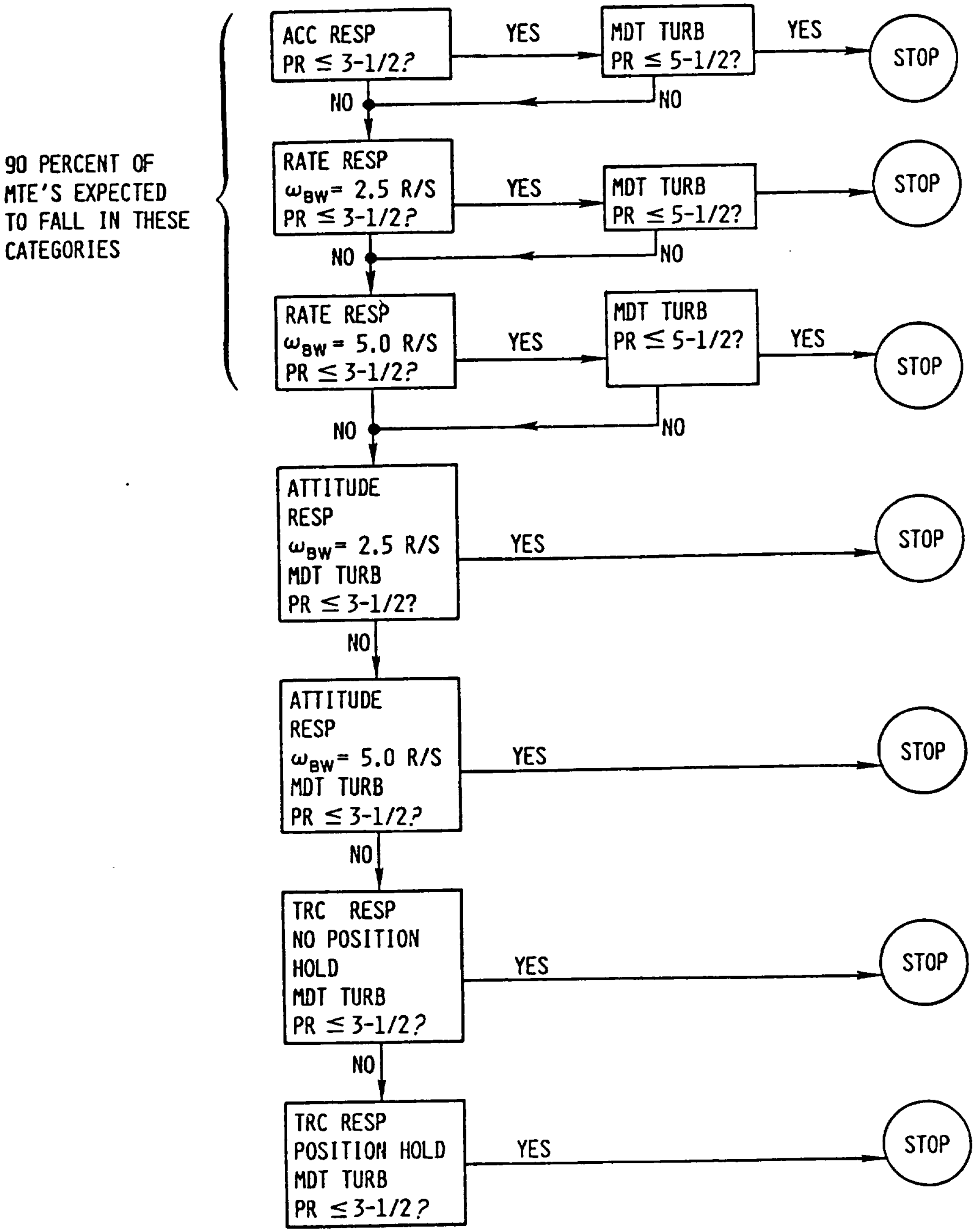


Figure 26. Flight Test to Determine Minimum Response Type for Each Mission Task Element (MTE)

SECTION IV

PLAN FOR PHASE II

A. FINALIZATION OF SPECIFICATION STRUCTURE AND PREPARATION OF BACKGROUND DOCUMENT

Although execution of Phase II will await completion of Phase I and a final contractor selection, it is desirable to plan its approach in advance. We plan, therefore, to minimize the effort spent on finalization of the specification structure and to maximize that spent on developing a comprehensive and useful background document. The exact proportion of effort, however, will depend largely on how much new data must be integrated into the specification as a result of other research activities.

If awarded the Phase II program, STI will begin with a planning effort during which we will revise the statement of work task emphasis as needed. This planning will, of course, necessarily involve active participation by both government and industry; and all four manufacturers represented at IPR-2 will be consulted for advice and recommendations during this period. The initial planning effort in Phase II will also integrate all desirable aspects of Phase I.

1. Selection of the Final Format and Structure of the Specification

Following the initial planning effort, the first step in Phase II will be the selection of a final specification format and structure. As a result of frequent and close contact with government and industry personnel during Phase I--through subcontracting, interim progress reviews, and visits--STI expects to have a substantial level of acceptance going into Phase II. The level of effort devoted to this task, therefore, should be modest.

This task will consist of a review of all government and industry input, resolution of differences where feasible, and preparation of a specification structure working paper suitable for government and industry review.

2. Incorporation of New Data

Performance of this task will depend on the emergence of new data during the early period of Phase II. STI expects that most new data generated during this time will be geared to this program. In fact, is is hoped that the specific priorities identified in Table 2 of Section III will have a very direct and powerful influence on any associated research programs. The ultimate responsibility for insuring an efficient feedback of new research to the proposed effort is, of course, that of the sponsoring agencies. Research efforts based on the plans and facilities are recommended in Section III.

3. Preparation of Background Information and User's Guide

The intent of the Background Information and User's Guide (BIUG) is to explain the concept, history, and philosophy underlying the structure of the new specification, to discuss the purpose of each requirement, to present and interpret some of the data on which the requirements are based, and to offer a defense of those requirements for which the data may be sparse or non-existent, so that critical gaps in the data can be identified and filled subsequently.

As noted in Section I, where frequency domain criteria have been converted to the time domain in the specification proper, it is our intention to include the original frequency response criteria in the BIUG for the purpose of design guidance.

The BIUG will discuss analytical techniques for interpreting operational requirements in terms of specific task-oriented mission requirements from which "outer-control-loop" requirements on the pilot-rotorcraft system evolve. These analytical techniques, in turn, provide the basis for designing effective controlled elements or "inner-control-loop" requirements to support task requirements in specific flight environments and thereby render the mission task elements in Appendix A of the specification structure (Volume I) more useful for design guidance.

Finally, the BIUG will summarize necessary supporting technology for analytical models of the environment, surrogates for atmospheric disturbances, and models for the human pilot which are useful for interpreting operational requirements during preliminary design.

B. GOVERNMENT AND INDUSTRY REVIEW AND WORKSHOP

1. Interim Program Review-3 (IPR-3)

STI will present a report of progress made in and plans for continuing Phase II at the third interim program review to be convened at AVRADCOM, St. Louis, Missouri, approximately six months after authorization of Phase II. This will be an oral briefing with distribution of copies of briefing material at the conference. Anticipated topics will include (a) criteria development and rationale therefor, (b) specification language, and (c) the content for the BIUG. STI will review the results of its analyses of comments from its subcontractors as well as from the Phase I workshop and will indicate the revisions resulting therefrom.

2. Interim Program Review-4 (IPR-4) and Phase II Workshop

This review is also expected to be at AVRADCOM, St. Louis, Missouri, approximately twelve months after authoirzation of Phase II. STI will present a detailed review of the proposed specification and BIUG, including the rationale for the structure and a description of the criteria. The format will include an oral briefing after advance distribution of copies of the proposed specification and BIUG for solicitation of comments at the workshop.

C. SCHEDULE FOR PHASE II

Figure 27 shows the schedule for Phase I as well as the proposed schedule for Phase II.

SCHEDULE

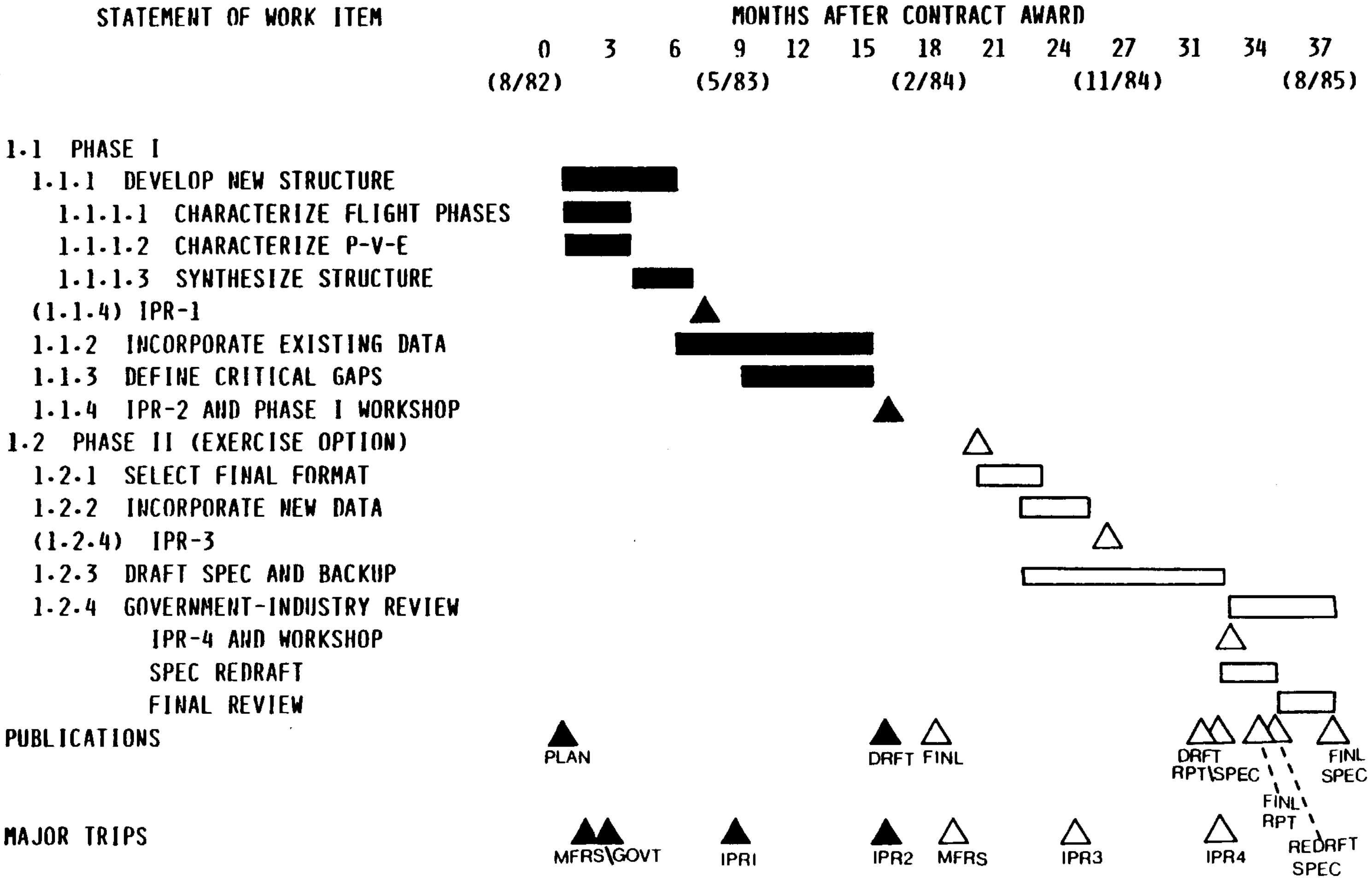


Figure 27. Schedule

APPENDIX A

PUBLISHED SOURCES FOR CHARACTERIZING THE ENVIRONMENT

A. Naval Ship Motion

Fortenbaugh, R. L., Application of the NAEC Ship Motion Simulation Program for Starboard Approaches to DD-963 Class Ships, (A Vought Corporation Working Paper for Type A V/STOL Flying Qualities and Flight Control Requirements Study), May 5, 1978.

B. Navy Airwake Turbulence

1. Wind tunnel work for FF-1052 was scaled to represent a DD-963 for the Type A V/STOL simulation

Garnett, Theodore S., Jr., Investigation to Study the Aerodynamic Ship Wake Turbulence Generated by an FF 1052 Frigate, Boeing Vertol Company of Philadelphia, Pennsylvania, December 1976.

Fortenbaugh, R. L., Application of the Vought Small Ship Airwake Model for Starboard Approaches to DD-963 Class Ships, (A Working Paper for Type A V/STOL Flying Qualities and Flight Control Requirements Study, Vought Corporation), March 5, 1978.

Fortenbaugh, R. L., Mathematical Models for the Aircraft Operational Environment of DD 963 Class Ships, Vought Corporation Report No. 2-55800/BR-3500, September 26, 1978.

Nave, Ronald L., Development and Analysis of a CVA and a 1052 Class Fast Frigate Air Wake Model, NADC-78182-60, September 30, 1978.

2. Wind tunnel work for DD-963; Simulation Model for MIL-H-8501 Revision

Garnett, Theodore S., Jr., Investigation to Study the Aerodynamic Ship Wake Turbulence Generated by a DD963 Destroyer, NADC-77214-30, October 1979.

Hanson, Gregory D., Airwake Analysis, Systems Technology, Inc., Working Paper No. 1198-3, September 1983.

3. On-going programs at Naval Air Development Center concerned about distributed interaction of turbulence with aircraft and rotorcraft

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4. No full-scale correlation, yet, though planned

C. Army turbulence

1. Aiken's model for isotropic turbulence (Dryden model, RMS values modified)

Moorhouse, David J., and Robert J. Woodcock, Background Information and User Guide for MIL-F-8785C, Military Specification--Flying Qualities of Piloted Airplanes, AFWAL-TR-81-3109, July 1982.

Aiken, E. W., A Mathematical Representation of an Advanced Helicopter for Piloted Simulator Investigations of Control System and Display Variations, NASA TM-81203, 1980.

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Turner, Robert E., and C. Kelly Hill (Compilers), Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1982 Revision, NASA TM 82473, 1982.

Colmer, M. J., Some Full Scale Measurements of the Flow in the Wake of a Hangar, ARC C.P. 1166, November 1970.

Tomlinson, B. N., Developments in the Simulation of Atmospheric Turbulence, RAE TM FS-46, September 1975, also in Flight Simulation/Guidance Systems Simulation, AGARD CP-198, June 1976.

Reid, Lloyd D., "STOL Aircraft Response to Turbulence Generated by a Tall Upwind Building," Journal of Aircraft, Vol. 19, No. 7, pp. 601-603.

Gerlach, O. H., van de Moesdijk, G. A. J., and van der Vaart, J. C., "Progress in the Mathematical Modeling of Flight in Turbulence," Flight in Turbulence, AGARD-CP-140, 1973, pp. S-1 through S-38.

Reeves, P. M., et al., Development and Application of a Non-Gaussian Atmospheric Turbulence Model for Use in Flight Simulators, NASA CR-2451, September 1974.

Jewell, Wayne F., and Robert K. Heffley, A Study of Key Features of the RAE Atmospheric Turbulence Model, NASA CR-152194, October 1978.

D. Terrain

1. Flight Systems Incorporated terrain modeling (for Monte Carlo batch/interactive computer programs)

2. AFFDL-TR-65-119 includes terrain models for high speed together with models for the amplitude fluctuation and angle scintillation of radar return signals

   Weir, David H., Compilation and Analysis of Flight Control System Command Inputs, AFFDL-TR-65-119, January 1966.

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Stapleford, Robert L., Warren F. Clement, Robert K. Heffley, et al., Flight Control/Flying Qualities Investigation for Lift/Cruise Fan V/STOL. Volume II: Piloted Simulation, NADC-77143-30, August 1979.

Stapleford, Robert L., Warren F. Clement, Robert K. Heffley, et al., Flight Control/Flying Qualities Investigation for Lift/Cruise Fan V/STOL. Volume III: Simulator Model, NADC-77143-30, August 1979.

16. Landis, Kenneth H., and Edwin W. Aiken, "An Assessment of Various Side-Stick Controller/Stability and Control Augmentation Systems for Night Nap-of-Earth Flight Using Piloted Simulation," Helicopter Handling Qualities, NASA CP 2219, April 14-15, 1982, pp. 75-96.

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16. Abstract

The structure of a new flying and ground handling qualities specification for military rotorcraft is presented in the first of two volumes. This preliminary specification structure is intended to evolve into a replacement for specification MIL-H-8501A. The new structure is designed to accommodate a variety of rotorcraft types, mission flight phases, flight envelopes, and flight environmental characteristics and to provide criteria for three levels of flying qualities, a systematic treatment of failures and reliability, both conventional and multiaxis controllers, and external vision aids which may also incorporate synthetic display content. Existing and new criteria have been incorporated into the new structure wherever they can be substantiated. A supplement to the new structure is presented in the second of the two volumes in order to explain the background and rationale for the specification structure, the proposed forms of criteria, and the status of the existing data base. Critical gaps in the data base for the new structure are defined, and recommendations are provided for the research required to address the most important of these gaps.

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