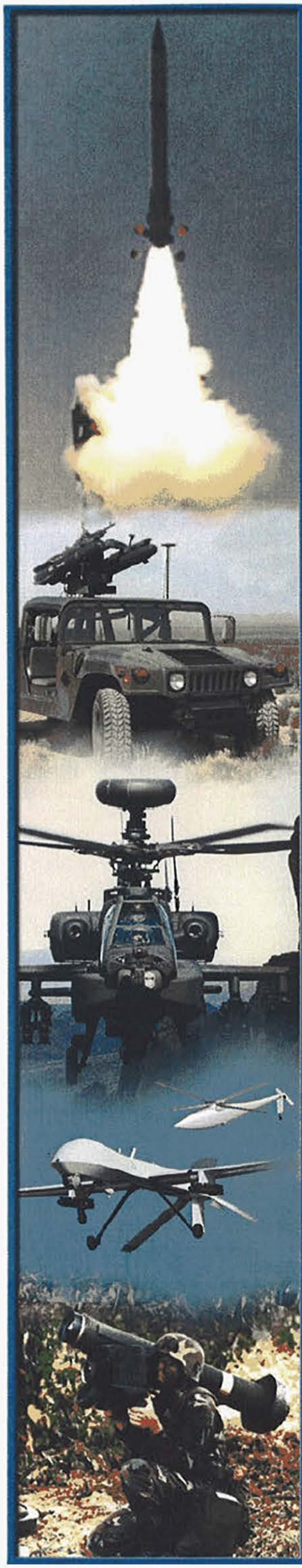

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TEST GUIDE FOR ADS-33E-PRF

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July 2008

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13. ABSTRACT (Maximum 200 Words)
This Test Guide provides guidance for testing to the requirements of ADS33E-PRF, Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft. Information is also provided for the gathering and analysis of the necessary data, including reference to more detailed sources as appropriate. In addition, guidance is provided for planning a flight test program, including selection of test conditions and estimating the overall scope. This Guide is intended to be of value for testing throughout the development cycle for a rotorcraft design, whether it is a new prototype or a modification to an existing design. It is expected that this Guide will be a reference source for both the developer of the rotorcraft and the procuring activity. Section I of the Test Guide provides an introduction and describes the overall scope. Section II provides detailed guidance for testing and data analysis, and interpretation for each requirement. Section III provides guidance for the selection of test conditions and rotorcraft Status for flight testing. An Appendix describes the input types required for applying the quantitative requirements of ADS-33E-PRF.

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Test Guide for ADS-33E-PRF

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ABBREVIATIONS AND SYMBOLS

ACAH	Attitude Command/Attitude Hold
AFCS	Automatic Flight Control System
AN/AVS-6	Aviator's night vision system, version 6
BIUG	Background Information and Users Guide
BW	Bandwidth
CIFER	Comprehensive Identification from Frequency Response
DVE	Degraded Visual Environment[1]
FCS	Flight Control System
FEBA	Forward Edge of the Battle Area
FMEA	Failure Modes and Effects Analysis
FPS	Flight Path Stabilization
GVE	Good Visual Environment
HQR	Handling Qualities Rating
IGE	In Ground Effect
IMC	Instrument Meteorological Conditions
MTE	Mission-Task-Element
NOE	Nap-of-the-Earth
NVG	Night Vision Goggles
OFE	Operational Flight Envelopes
OGE	Out of Ground Effect
ORD	Operations Requirements Document
PAE	Preliminary Airworthiness Evaluation
PFCS	Primary Flight Control System
PH	Position Hold
PIO	Pilot-Induced Oscillation
PIOR	Pilot-Induced Oscillation Tendency Rating
PNVS	Pilot Night Vision System
RCAH	Rate Command/Attitude Hold
RCDH	Rate Command/Direction (Heading) Hold
SAS	Stability Augmentation System
SCAS	Stability and Control Augmentation System
SFE	Service Flight Envelopes
SVR	System Verification Review
TRC	Translational Rate Command
TRCPH	Translational Rate Command plus Position Hold
UCE	Usable Cue Environment
VCR	Visual Cue Rating
V/STOL	Vertical/Short Takeoff and Landing
F_A	Lateral cockpit control force (lbs)

[1] ADS-33E and this design guide often (and incorrectly) use DVE as a shorthand for UCE>1. Strictly speaking, the DVE defines the environment (e.g. night), and UCE>1 refers to operation in the DVE with higher workload due to degraded vision aid performance.

F_B	Longitudinal cockpit control force (lbs)
F_C	Collective cockpit control force (lbs)
F_P	Pedal cockpit control force (lbs)
h	Altitude (ft)
$\dot{h}$	Altitude rate (rate of climb/descent) (ft/sec)
n_z	Normal acceleration at the center of gravity (g's)
p	Body-referenced roll rate (deg/sec or rad/sec)
p_{pk}	Peak roll rate for Attitude Quickness (deg/sec)
P	Period of oscillatory response (sec)
P_f	Probability of failure per flight hour
q	Body-referenced pitch rate (deg/sec or rad/sec)
q_{pk}	Peak pitch rate for Attitude Quickness (deg/sec)
r	Body-referenced yaw rate (deg/sec or rad/sec)
r^2	Coefficient of determination or correlation
s	Laplace variable
t	Time (sec)
T_2	Time to double amplitude of unstable mode (sec)
T_s	Time constant of spiral mode (sec)
V_H	Maximum level flight airspeed at maximum continuous power
V_{ne}	Never-exceed speed (kts)
V_T	True airspeed (kts)
x	Longitudinal position referenced to a fixed position on the ground (ft)
y	Lateral position referenced to a fixed position on the ground (ft)
β	Sideslip angle (deg)
δ_A	Lateral cockpit control position (in.)
δ_B	Longitudinal cockpit control position (in.)
δ_C	Collective cockpit control position (in.)
δ_P	Pedal cockpit control position (in.)
δ_{TR}	Tail rotor blade angle (deg)
$\Delta\phi_{min}$	Minimum change in bank angle for Attitude Quickness (deg)
$\Delta\phi_{pk}$	Peak change in bank angle for Attitude Quickness (deg)
$\Delta\theta_{min}$	Minimum change in pitch attitude for Attitude Quickness (deg)
$\Delta\theta_{pk}$	Peak change in pitch attitude for Attitude Quickness (deg)
ΔV_{ss}	Change in steady-state velocity (kts)
$\Delta\gamma_{ss}$	Change in steady-state flight path angle (deg)
ϕ	Bank angle (deg or rad)
θ	Pitch attitude (deg or rad)
θ_{TR}	Tail rotor collective pitch (deg)
ω_{BW}	Bandwidth frequency (rad/sec)
ω_{180}	Frequency where phase angle is –180 deg (rad/sec)
ψ	Heading angle (deg or rad)

I. INTRODUCTION

A. BACKGROUND

This document provides guidance for testing to the requirements of ADS-33E-PRF, *Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft* (Reference 1). Information is also provided for the gathering and analysis of the necessary data, including reference to more detailed sources as appropriate. In addition, guidance is provided for planning a flight test program, including selection of test conditions and estimating the overall scope.

The "E" version of ADS-33 is the most recent volume in a series of rotorcraft specifications that began in the mid-1980s. The ADS-33 series represents a significant departure from its predecessor, the helicopter specification MIL-H-8501A (Reference 2), and from the V/STOL specification MIL-F-83300 (Reference 3).

ADS-33E-PRF contains intermeshed requirements on not only short- and long-term response characteristics, but on expectations for Response-Types and Usable Cue Environments for all categories of rotorcraft and their missions. There are requirements on failures and the response to those failures, and there are both quantitative predictive requirements (criteria) and qualitative tasks (Mission-Task-Elements), which serve to spot-check areas not well addressed by the criteria.

Over the years several organizations have performed flight evaluations of rotorcraft against ADS-33 (e.g., References 4, 5, 6, 7, 8 and 9). Most of these programs were performed in collaboration with the research community responsible for developing ADS-33E-PRF, so it was possible to provide help, advice, and interpretation during the flight test programs. This will not always be the case, and these applications have made it increasingly obvious that a written guide is needed to aid in setting up and performing the tests.

Detailed discussion of the origins of most of the criteria of ADS-33E-PRF, and development of the related requirements, can be found in a 1989 Background Information and Users Guide (for ADS-33C), Reference 9.

B. APPLICATION OF THIS TEST GUIDE

This Guide is intended to be of value for testing throughout the development cycle for a rotorcraft design, whether it is a new prototype or a modification to an existing design. While final verification will in most cases require flight testing, initial checks can be performed through analysis and on ground-based simulators. Such checks may be conducted long before the first flight of the final article.

It is possible that some of the requirements of ADS-33E-PRF may continue to be tested in simulators even after the rotorcraft has started its flight tests, but final compliance is expected to be accomplished in flight. That is because there currently is no accepted standard to validate engineering flight simulators. The exception to this is when flight safety would be compromised by flight-test, simulator testing may be the only way to demonstrate compliance.

The manufacturer of the helicopter or system under test has the primary responsibility for safety. It is assumed that the rotorcraft will be appropriately instrumented to measure loads, and proper buildup techniques will be employed.

It is expected that this Guide will be a reference source for both the developer of the rotorcraft and the procuring activity. It should help define the scope of verification testing expected of a new rotorcraft or a modification to an existing design. It will aid the flight test engineer who may be familiar with the basic structure of ADS-33E-PRF but not with the specifics of testing or data reduction. It will also assist the test pilot whose job is to perform the proper tests.

This test guide does not provide detailed information regarding good practice for flight test instrumentation and data recording. It is assumed that the flight test activities in most helicopter companies have more expertise in that area than the authors of this guide. Reference 43 provides good information regarding frequency response testing.

The methodology for compliance with the specification criteria are given in Section 4 of ADS-33E-PRF (Verification). Table XIV provides the appropriate milestones to be met in analysis, simulation, and flight test. As noted in the specification, Table XIV is provided as guidance where such guidance is not available from the system performance specification. In the event that the system specification and Table XIV are in conflict, the system specification shall have precedence.

Considerable time has passed between the release of ADS-33E-PRF and the writing of this Guide. During that time both the government and manufacturers have gained experience with the ADS-33E-PRF criteria and we have attempted to incorporate that experience both as lessons learned, and interpretations of the criteria. In a few cases, it has been found that the criteria should be modified, or even deleted from the specification. Those cases are noted in this Guide along with recommended alternatives when available. Until such time as ADS-33 is updated, the manufacturer and procuring activity shall agree as to whether the recommended modifications/deletions should be incorporated into the version of the specification that is tailored for a specific application.

C. SPECIFICATION METHODOLOGY

ADS-33E-PRF testing can be part of the design and development process for a new rotorcraft, or an assessment of a modification to an existing system, Guidance for tailoring can usually be obtained from the Operations Requirements Document (ORD) and/or the system performance specification.

The structure of ADS-33E-PRF is illustrated in the schematic in Figure 1.

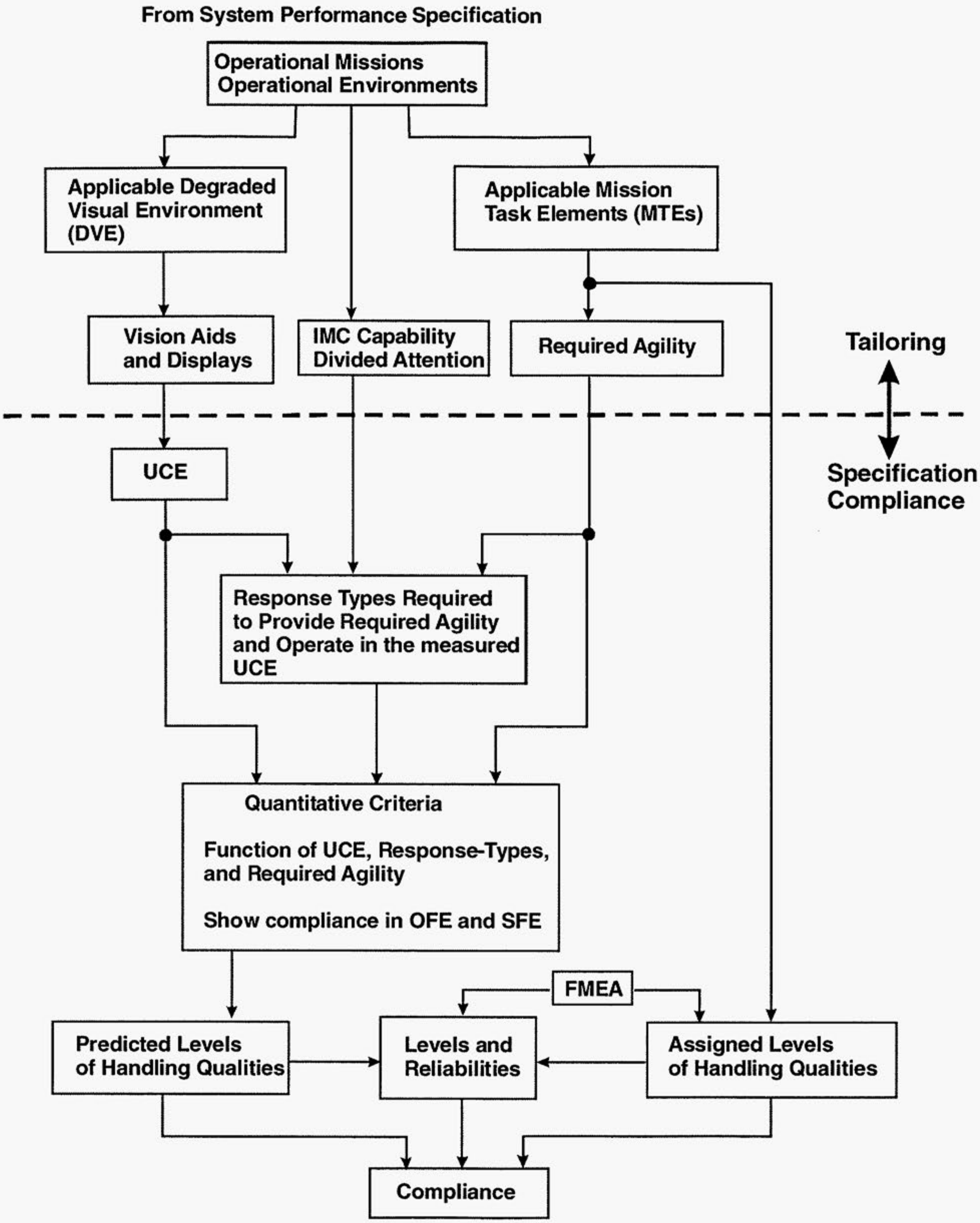

Figure 1 ADS-33E-PRF Structure

Salient points from Figure 1 are summarized as follows.

- Items above the dashed line consist of tailoring the generic specification to a specific rotorcraft. The items requiring tailoring are contained in 3.1.1, 3.1.2, and 3.1.3. The operational missions should have been defined by the user and included in the system specification for the rotorcraft. The system specification should also have defined the desired operational environment; specifically, Degraded Visual Environment (DVE), vision aids, IMC capability, slope landing capability, and degree of divided attention. Note that divided attention operation can result in a requirement for a Height Hold and Position Hold Response-Types even in the GVE (UCE = 1).

- Procedures are prescribed in 3.2.1 for determining the Usable Cue Environment (UCE) using the planned vision aids.

- The Response Types are determined explicitly by the UCE (Table IV in ADS-33E-PRF). They are also determined implicitly by the required agility. For example, it is usually necessary to implement a Rate Response-Type to meet the more aggressive quantitative criteria (e.g. Attitude Quickness in Para 3.3.3) and MTEs, whereas as UCE = 2 requires a more stable ACAH Response-Type.

- The quantitative criteria are functions of Response-Type and UCE (e.g., Bandwidth, Para 3.3.2.1), as well as required agility (e.g., Large Amplitude Attitude Changes, Para 3.3.4). The upper left and right sides of Figure 1 illustrate the classic conflict between good stability for UCE >1 and high agility for maneuvering in the GVE, for determination of the proper Response-Type. Conflicting requirements between these requirements often gives rise to the need for selectable Response-Types (modes).

- The failure modes and effects analysis (FMEA) in combination with a fault tree analysis defines probabilities of failures. These probabilities are used in Table II of the specification to define the Levels of Handling Qualities that must be demonstrated. The bottom of Figure 1 illustrates that this can be done by performing MTEs in the failed state (assigned Levels), or by determination of quantitative criterion parameters in the failed state (predicted Levels).

By the time the rotorcraft is ready for System Verification Review (SVR), the developer should have made analytical and simulation assessments, backed up with flight data. OFE and SFE boundaries should be defined and correlated with the structural and aerodynamic limits. Margins between the OFE and the SFE limits will have been assessed, and appropriate cautions and warnings developed. An FMEA/fault-tree analysis will have been accomplished and the handling qualities associated with the identified failed states will have been assessed according to the requirements in Table II of ADS-33E-PRF.

The requirements to be satisfied in verifying compliance with the specification are provided in ADS-33E-PRF Section 4, Verification.

The tester's activities related to the specification methodology are outlined in the schematic shown in Figure 2, and consist of four basic steps as follows:

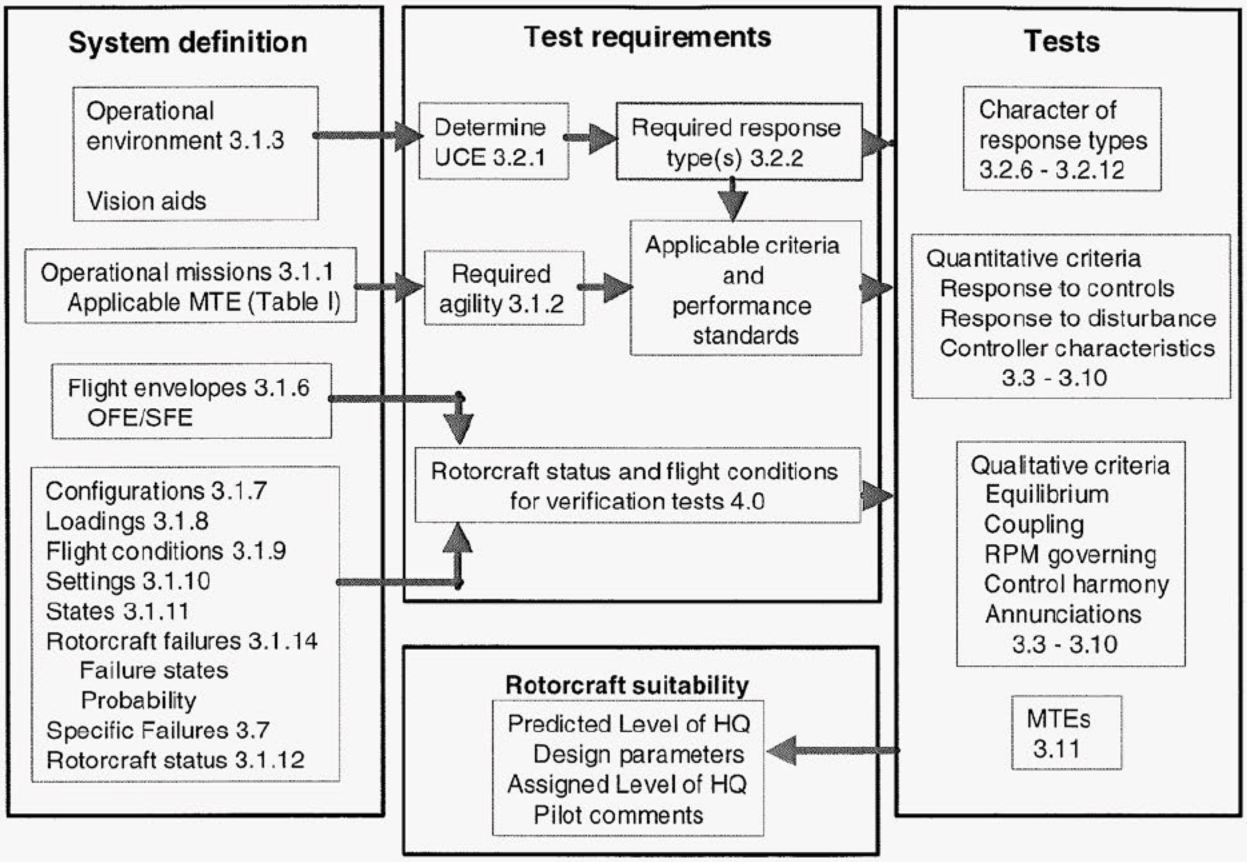

Figure 2 Overview of Specification

1. System Definition

ADS-33E-PRF is a generic specification that must be tailored for a specific application. Thus, unless the testing activity is presented with a tailored specification, the first step is to obtain the following system requirements and basic characteristics of the rotorcraft design.

Define the Mission-Task-Elements (MTEs) that represent the operational missions (3.1.1).

Define the operational environment (3.1.3). Specifically:

- Definition of the Degraded Visual Environment (DVE) and the Vision Aids that will be employed (e.g., overcast night over desert terrain with AN/AVS-6 night vision goggles),
- Are IMC operations required?,
- The angle and azimuth for slope take-offs and landings
- Is divided attention operation required? (See definitions in Paragraph 6.2.3 of ADS-33E-PRF

Flight envelopes (3.1.6). Define the Operational Flight Envelopes (OFEs) necessary to accomplish the intended missions. Define the Service Flight Envelopes (SFE) that are set by rotorcraft limitations.

Flight conditions (3.1.9). Define nominal and limiting flight conditions within the OFEs and SFEs.

Rotorcraft status (3.1.12), Rotorcraft Configurations (3.1.7), Loadings (3.1.8), Settings (3.1.10), States (3.1.11), Rotorcraft Failures (3.1.14), and Specific Failures (3.7). Sufficient information must be obtained to allow specific combinations for testing to be selected by the testing activity.

2. Test Requirements

Once the above information has been obtained, the testing activity can establish the following requirement standards and test conditions:

From the DVE and the vision aid performance determine the Usable Cue Environment (UCE) by assignment, or by performing a UCE evaluation (3.2.1). The UCE in turn determines the Required Response-Types (3.2.2) required for operation in the DVE.

Using the list of applicable MTEs determine the Required Agility (3.1.2 and Table I).

Determine the Response-Type required to achieve the agility defined above. If it is different than the Response-Type required for operation in the DVE, selectable modes will be required

From the combinations of Required Response Types and Required Agility, determine which of the criteria boundaries and MTE standards must be satisfied.

3. Testing

The actual testing can then be performed to accomplish the following:

Verify that the various SCAS modes meet the criteria for Required Response Types (3.2.6 – 3.2.12).

Determine the rotorcraft flying qualities relative to the quantitative criteria boundaries (3.3 – 3.10) (Obtain predicted level of handling qualities).

Evaluate the rotorcraft handling qualities while performing the applicable MTEs.

Assess the qualitative characteristics (3.3 – 3.10) while performing the MTEs and other flight tests (Obtain assigned level of handling qualities).

4. Rotorcraft Suitability

Based on the test results, the suitability of the rotorcraft handling qualities can be defined in terms of:

Predicted Level of handling qualities (based on design parameters) (3.1.5.1).

Assigned Level of handling qualities (based on pilot comments) (3.1.5.2).

D. LIMITED AUTHORITY FLIGHT CONTROL SYSTEMS

Position and rate limiting should be investigated for all tested rotorcraft, and will be most critical for limited-authority flight control systems. The recommended approach is to ensure that the Response-Types and criteria in ADS-33E-PRF are met for inputs that do not cause rate or position limiting of the servo-actuators. Until ADS-33E-PRF is updated to include explicit performance criteria for limited authority flight control systems, the effects of control saturation must be tested using the Mission-Task-Element tests given in Section 3.11 of the specification. Experience has shown that the Lateral Reposition and Acceleration and Deceleration MTEs are particularly valuable for testing the effects of flight control system saturation (see References 10 and 20). Even if the missions specified for the rotorcraft do not call for these MTEs, they are useful to determine the severity of the transient that occurs due to rate and/or position limiting.

Full authority flight control systems that utilize an architecture that includes software limits or "ports" that limit the position and/or rate commands to the actuators should be considered as a limited authority system. The now-cancelled RAH-66 and the V-22 tilt rotor aircraft are examples of such a control system architecture. Another clue that a system should be treated as "limited authority" is the need to backdrive the flight controls at low frequency as this usually indicates a need to center a series servo (which is not necessary for a full authority system).

All limited authority systems should receive special scrutiny with respect to control system limiting. The stop-to-stop V-22 PIO that occurred during shipboard landing trials is a good example of a lesson learned. That lateral PIO occurred when a software rate limit was encountered due to port saturation in software. Before the PIO occurred, there was considerable resistance to accomplishing the more aggressive MTEs on the basis that "the aircraft is not flown that way". This experience emphasizes the need to investigate limiting conditions even if the MTEs seem excessively aggressive compared to the mission. Limited authority control systems by definition involve lower rate and/or position limits than would be expected from the hardware actuator bandwidth, and therefore require special scrutiny.

Some limited authority flight control systems may backdrive the cockpit controller at mid-frequency to augment the limited authority series servo.[1] The UH-60 Blackhawk limited authority flight control system is an example. There are no specific provisions for limited authority flight control systems in ADS-33E-PRF. However, Army flight and simulator testing has shown that acceptable flying qualities may be achieved for this type of flight control system. Further research is required to determine whether response-types and criteria should be satisfied with cockpit control force and not position (see Reference 10). This has the following implications.

- The Bandwidth criterion may be met with stick force as the only input i.e., obtain the bandwidth from a Bode plot of attitude to stick force input and ignore stick position. Note, for the frequency-domain criteria in ADS-33E-PRF, all of the supporting data collection and processing techniques have used stick position.

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[1] The use of very low frequency motion of the cockpit controller to achieve trim does not fall in this category. As a rule of thumb, if the function of the input to the parallel servo is restricted to trim, the following bullets do not apply. They do apply, if the function of the feedback to the parallel servo is to augment stability.

- The Response-Type may be defined with a constant stick-force input, even though the cockpit controller may be moving during that input.
- Some criteria require that the aircraft response be within specified limits with the controller fixed, or fixed and free (e.g. Lateral Directional Oscillations (3.4.9.1)). For a limited authority system that backdrives the stick to achieve stability, the only way to meet such requirements is with the cockpit controller free.

These relaxations might be necessary to allow the use of limited authority systems as economical retrofits to existing rotorcraft flight control systems. However, this does not mean that they should be applied to a full authority fly-by-wire configuration where a higher standard should be achievable.

E. STRUCTURE OF THE TEST GUIDE

This test guide is organized as follows.

Section II, Test Guidance, provides detailed guidance for testing and data analysis and interpretation for each requirement in ADS-33E-PRF. Section III, Test Planning, provides guidance for the selection of test conditions and rotorcraft Status for flight testing.

The Appendix describes the input types required for applying the quantitative requirements of ADS-33E-PRF. While there are only a limited number of input types required, some (such as frequency sweeps) may not be familiar to all users of the Guide. This appendix provides a brief definition of the different types of inputs and includes examples.

II. TEST GUIDANCE

A. FORMAT

Data for most of the quantitative handling qualities criteria can be generated with just a few basic tests. These tests may, however, occur in each of the four control axes at flight conditions in both the Hover-Low Speed and the Forward Flight regimes. To reduce considerable duplication in the descriptions, this section is organized as follows:

- The principal test inputs, steps, pulses, doublets, and frequency sweeps, are discussed in general terms in the Appendix.
- In the discussions of the individual ADS-33E-PRF paragraphs, the first time a test input or method, or analysis method, is encountered, it is discussed in detail. In subsequent related paragraphs, the earlier paragraph is referenced, and only changes or special considerations are described.

For most paragraphs of ADS-33E-PRF, one or more of the following topics are presented.

Data Requirements: Lists the minimum test data or parameters required for the relevant requirements.

Input Type: The input form expected for each paragraph where a specific input is required is given here. The Appendix describes the control input formats in more detail.

Test Technique: Specific instructions for application of the test inputs, suggestions on initial conditions, important safety issues, etc., are provided. Indications of the typical amplitudes of output motion (angular attitudes or rates, linear velocities, etc.) and duration of the test are given. If there is a limitation on the applicability of a requirement, the first entry in Test Technique will identify that limitation in **bold text**.

Data Analysis and Interpretation: Provides tips on judging data quality and on extraction of parameters from the test data. Where it is possible to substitute one recorded parameter for another, suggestions on the process are provided.

Discussion: For some of the requirements, only general guidance is given, and the four topics are replaced by a single discussion.

Alternate Criterion: Experience with a few of the criteria in ADS-33E-PRF has shown that they are difficult to test, or for some reason are deficient in one or more areas. In such cases one or more alternate criteria are presented where available. The use of an alternate criterion in place of an ADS-33E-PRF requirement must be approved by the procuring activity. In some cases, the procuring activity may choose to specify one or more alternate criteria when tailoring ADS-33E for a specific application.

The alternate criteria contained in this test guide often are not supported by data, and require additional scrutiny before being included in the next upgrade to ADS-33E-PRF.

Where applicable the term Alternate Criterion will be replaced with a more appropriate heading such as Additional Criterion, or Modification to Criterion.

B. GUIDANCE FOR SECTION 3 "REQUIREMENTS" OF ADS-33E-PRF

It is expected that this Guide will be used side-by-side with ADS-33E-PRF. Figures and tables in that document are referred to in this report but, with a few exceptions, are not reproduced here. Paragraphs in ADS-33E-PRF are referred to by simply giving the paragraph number. For example, 3.3.1 refers to Paragraph 3.3.1 titled Equilibrium Characteristics in ADS-33E-PRF.

Each new requirement starts on a new page in this section.

3.1.5 Levels of handling qualities
3.1.5.1 Predicted Levels of handling qualities
3.1.5.2 Assigned Levels of handling qualities

Discussion: These requirements help to make a distinction between the methods used to evaluate quantitative requirements and qualitative requirements. For the quantitative requirements, the test objective is to obtain the necessary data to determine where the rotorcraft falls relative to specified criterion boundaries. It is not intended that formal pilot evaluations of handling qualities will be accomplished during these tests. The sole purpose of the tests is to generate data for determining Predicted Levels of handling qualities.

For the qualitative evaluations, the pilots are expected to accomplish precisely defined Mission-Task-Elements (MTEs) (3.11) and to assign Cooper-Harper Handling Qualities Ratings (HQRs), Reference 11. The pilot ratings are used to determine "Assigned Levels of handling qualities".

There is a natural tendency to place more emphasis on Assigned Levels of handling qualities than on the Predicted Levels. The two sets of information, however, are complementary, and the intent of the Assigned Levels is to provide an overall check of the quantitative criteria (Predicted Levels).

The quantitative criteria provide more comprehensive coverage of the helicopter flying qualities than the qualitative evaluations. It is therefore important to resist the temptation to compress the schedule by accomplishing only the qualitative evaluations.

It is recognized that the handling qualities criteria are not perfect. These criteria are an attempt to quantify what characteristics are acceptable, and which ones are not with a criterion boundary or number. Therefore, it is important to understand the intent of each of the criteria, and to be able to identify the basic reason that a configuration does not meet a criterion. In some cases, it makes sense to request a deviation if you believe that the intent of the criterion is met. Such a request should be backed up with flight test data from the conduct of appropriate MTEs from Section 3.11.

In cases where there is a conflict between the quantitative and qualitative flying qualities, for example if the criteria do not indicate a problem, and flying the MTEs does, the problem is most likely due to cockpit controller characteristics not covered by the criteria. In any event the basic reason for the discrepancy should be identified and reported.

Some requirements in ADS-33E-PRF involve both quantitative data and pilot opinion. These requirements will typically have a phrase such as "not objectionable to the pilot." In this case, no formal ratings are to be gathered, and assessment of compliance is based on subjective pilot opinion gathered in the form of comments.

3.1.6 Flight Envelopes
3.1.6.1 Operational Flight Envelopes
3.1.6.2 Service Flight Envelopes

Discussion: The Operational Flight Envelopes (OFE's) define a range of parameters over which the rotorcraft must be operated in order to accomplish the missions for which it has been designed. These envelopes are expected to be defined by the user. The OFE's are typically defined as limits on center of gravity, weight, airspeed, altitude, load-factor, rate-of-climb, and sideslip. The user of the specification is free to define the operational limits in terms of any other parameters. Sometimes the OFE is defined by the manufacturer based upon the Operations Requirements Document (ORD) or system performance specification.

The OFE boundaries are derived from mission requirements and are such that within these boundaries all operational missions can be accomplished. ADS-33E-PRF requires Level 1 handling qualities within the OFE's. It is common practice for rotorcraft manufacturers to accomplish most flight testing at the extremes of the OFE where handling qualities are most likely to degrade.

The SFE boundaries are derived from rotorcraft limits and are such that beyond these boundaries the rotorcraft should not and/or cannot be flown. For example, the airspeed for retreating blade stall represents an upper limit on forward speed. Adequate margin must exist between OFE and SFE boundaries to permit completion of the mission with Level 1 handling qualities, and with an adequate margin from rotorcraft limits. Mission requirements (OFE's) are normally established by the procuring agency, whereas rotorcraft limitations (SFE's) are usually established by the manufacturer to ensure that adequate margin is provided for strength and durability of components, and to provide a maneuver margin for the safety of the operator.

In most cases the SFE outer boundaries are defined by limitations other than handling qualities such as structural/dynamic loads, engine performance, etc. Nonetheless, it is possible (albeit not common) for the SFE boundary to be set by handling qualities considerations. Tests should be accomplished to ensure that it is possible to recover from excursions outside the SFE, although no handling qualities ratings are required for such tests.

One consequence of the connection between the OFEs, SFEs, and handling qualities Levels is that certain SAS failures can be accommodated by redefining the limits. For example, if a SAS failure results in continued Level 1 handling qualities below a certain airspeed, and Level 2 handling qualities above that speed, the OFE may be redefined accordingly. For example, V_{NE} for the CH-47 at a weight of 46,000 lbs on a standard day is 135 kts. If one AFCS channel is failed, this is reduced to 100 kts (see Reference 12, page 5-11).

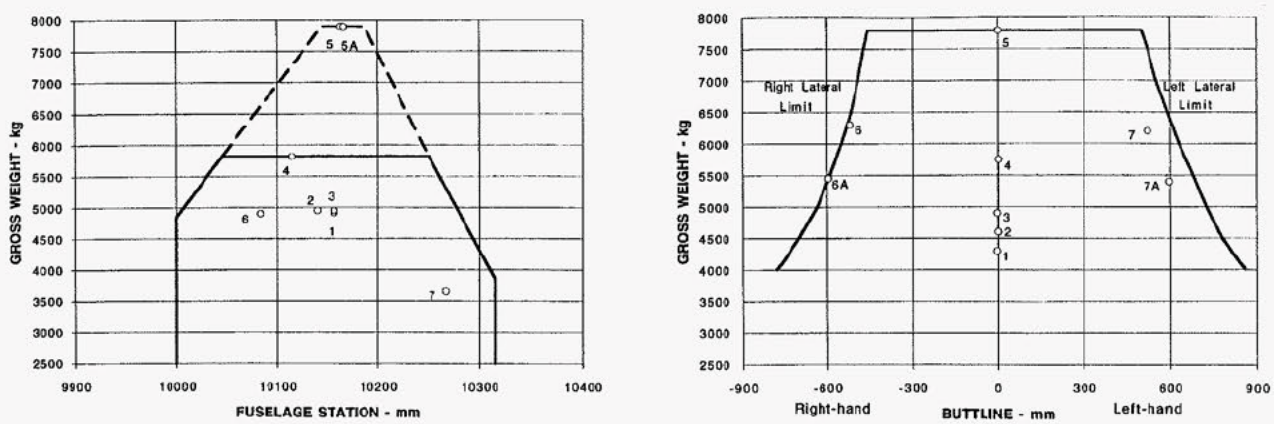
The final envelope definitions for the OFE and SFE are typically established in flight test.

Examples of flight envelopes for a scout-attack helicopter design are discussed in the following paragraphs.

Center of Gravity

Center of gravity envelopes represent the limits of allowable loadings. This normally takes into account body attitudes, rotor flapping restrictions, control range limitations, and stability issues.

An example of longitudinal and lateral c.g. limits for a scout attack helicopter design is given in Figure 3, taken from Reference13.



a) Longitudinal Center-of-Gravity vs Gross Weight

b) Lateral Center-of-Gravity vs Gross Weight

Figure 3 Example Center-of-Gravity Envelopes

The dashed line in Figure 3a represents a maximum alternate gross weight that may involve some flight restrictions. The lateral c.g. envelope is important because it represents the ability of the rotorcraft to carry asymmetric loads. These boundaries should be considered as OFE's as Level 1 handling qualities are expected. It would be acceptable to define SFE's for c.g. vs. weight to indicate that extreme conditions are possible, but with degraded handling qualities. However, that is rarely done.

The data points shown on the boundaries in Figure 3 indicate flight conditions that were tested and reported on in Reference 13.

Load Factor

An example of the OFE and SFE boundaries for load factor vs. airspeed for the example scout attack helicopter design (Reference 13) is given below in Figure 4.

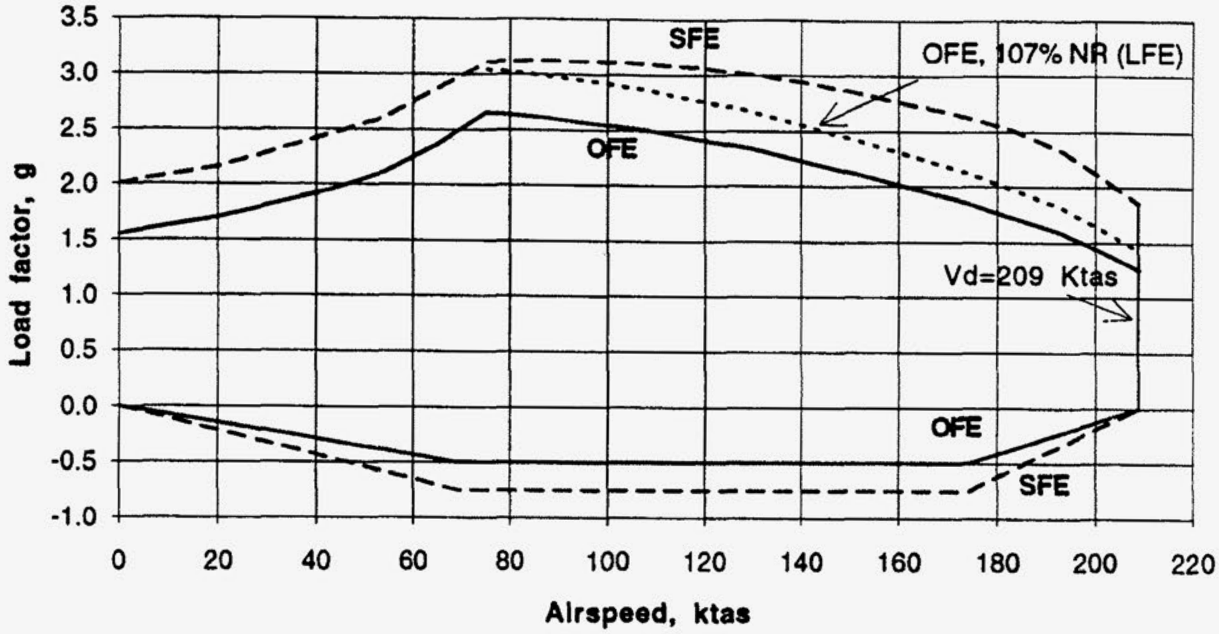


Figure 4 Example Load Factor Envelope

The OFE and SFE are clearly noted in Figure 4 along with an extended OFE that is available at 107% rotor RPM and termed "Load Factor Extension" or LFE. This extended OFE was included specifically to meet the more aggressive forward flight MTEs (e.g., Transient Turn (3.11.14), and Pullup/Pushover (3.11.15).

Load factor envelopes should be produced for nominal and limiting flight conditions that usually consist of a standard day as well as an upper limit on altitude, temperature, and gross weight. For the example scout attack design, the limiting conditions were defined as 4000 ft altitude and temperature of 95 deg F (4K/95) at both the nominal gross weight (solid line in Figure 3) and extended mission gross weights (dashed line in Figure 3). Setting the OFE at 4K/95 establishes a requirement for Level 1 handling qualities up to those conditions, and implicitly recognizes that operations beyond those conditions may be possible, but with degraded performance and handling.

Sideslip

An example of OFE and SFE boundaries for sideslip vs. airspeed is given below in Figure 5.

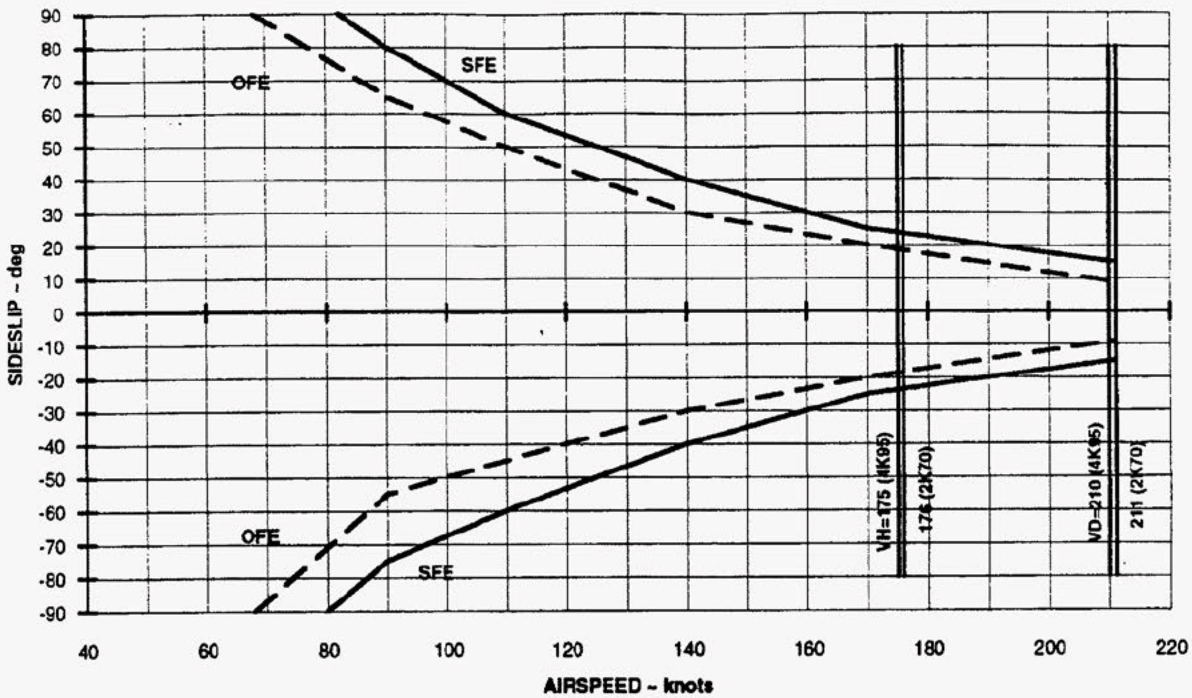


Figure 5 Sideslip vs. Airspeed Envelope

Rotor RPM

Other OFE and SFE envelopes should be defined based on unique capabilities of the subject rotorcraft. For example, the scout attack design used in this example included variation of rotor RPM to achieve a quiet mode and a load factor enhancement mode. The OFE and SFE for rotor speed are shown in Figure 6. In addition to OFE and SFE a transient operational flight envelope (TOFE) is defined to allow for a ± 3% governing tolerance applied to the rotor speed OFE.

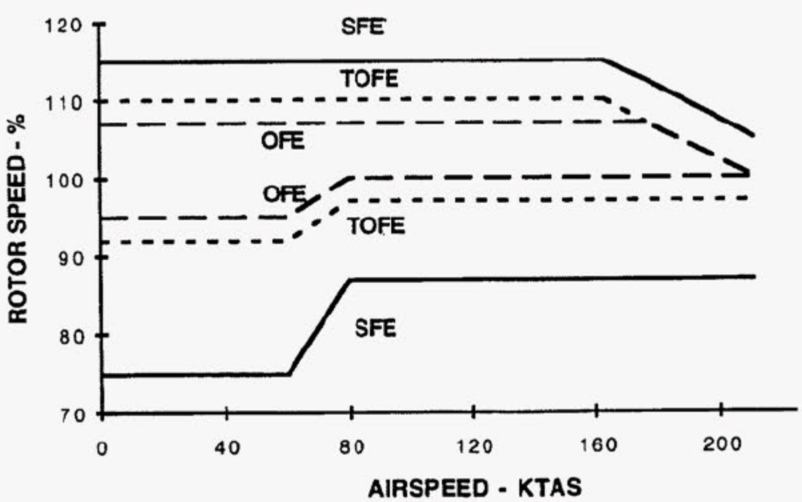


Figure 6 Example Rotor Speed Envelopes

3.1.14 Rotorcraft failures

3.1.14.1 Allowable Levels based on probability

Discussion: The Failure States to be tested will normally be supplied to the testing activity by the user and/or manufacturer. They will include all combinations of failures that have a probability of occurrence of greater than 2.5 x 10^{-7} per flight hour.

A Systems Safety Analysis (SSA), which includes a Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), will provide the calculated probability of occurrence of each failure state. The quantitative criteria in ADS-33E-PRF may then be used to determine the Level of handling qualities that is associated with each failure state. Flight testing of each failed state is required to obtain the data to determine criterion compliance (Level 1, 2 or 3).

As a result of testing, each failed state that is identified in the SSA will be associated with a Level of handling qualities. The tabulated failed states are to be grouped according to Level, and checked against the proper row in Table II of ADS-33E-PRF. For example, every Failure State resulting in Level 2 should be checked against the probability of failure listed in row 1 of Table II for the OFEs (i.e., must occur at a rate of $< 2.5\times10^{-3}$ per flight hr). Table II from ADS-33E-PRF is given below for reference.

Table 1 Levels for Rotorcraft Failure States (Table II in ADS-33E-PRF)

PROBABILITY OF ENCOUNTERING	WITHIN OPERATIONAL FLIGHT ENVELOPE	WITHIN SERVICE FLIGHT ENVELOPE
Level 2 after failure	$< 2.5\times10^{-3}$ per flight hr	
Level 3 after failure	$< 2.5\times10^{-5}$ per flight hr	$< 2.5\times10^{-3}$ per flight hr
Loss of control	$< 2.5\times10^{-7}$ per flight hr	

Table II may be interpreted as follows.

- Any failure state with a probability $\geq 2.5\times10^{-3}$ per flight hr must be demonstrated to result in Level 1 handling qualities.
- Any failure state with a probability such that $2.5\times10^{-3} > P_f \geq 2.5\times10^{-5}$ per flight hr must be demonstrated to result in Level 2 or better handling qualities criteria within the OFE.
- Any failure with a probability such that $2.5\times10^{-5} > P_f \geq 2.5\times10^{-7}$ per flight hr must be demonstrated to result in Level 3 or better handling qualities criteria within the OFE.
- Any failure with a probability $\geq 2.5\times10^{-3}$ per flight hr must be demonstrated to result in Level 2 or better handling qualities criteria within the SFE.

- Any failure with a probability $< 2.5\times10^{-3}$ per flight hr must be demonstrated to result in Level 3 or better handling qualities criteria within the SFE.
- Any failure with a probability $< 2.5\times10^{-7}$ per flight hr is not required to meet any ADS-33E-PRF criteria in the OFE or SFE.

Practically speaking, it is normally not possible to evaluate failures on a ground based simulator because most current simulation math models are not sufficiently accurate (especially for failure conditions), and the visual and motion cueing is almost always inadequate for the large amplitudes and rates that may occur with this task. While the simulator is a valuable tool to make initial estimates, and to perform buildup for flight testing, the final data should be obtained in flight.

Failure mode testing offers the opportunity to adversely affect safety more than any other part of ADS-33E-PRF. It is therefore recommended that any failures that are judged to be so severe that safety is compromised, even in the controlled flight-test environment, be assigned as "Uncontrollable". This has the effect of impacting the required flight control system redundancy to ensure that the failure will occur at a rate that is less than 2.5 x 10^{-7} per flight hour.

An Example

In order to comply with Table II, it is necessary to determine the Level of handling qualities for each defined Failure State. Consider four of the Comanche flight control modes as an example[1].

1. VELSTAB – Attitude Command with Velocity Hold and TRC near hover – for use in the DVE when UCE > 1.
2. Core AFCS – Rate Command – for use in the GVE
3. MISSION PFCS – Degraded rate command – a backup flight control system
4. Core PFCS – most reliable, but least capable backup system.

The VELSTAB is intended to be Level 1 when UCE = 2 or 3, and the Core AFCS is intended to be Level 1 in the GVE. The role of ADS-33E-PRF testing is to ensure that this is the case for all Normal states.

Flying qualities in these modes must be tested for all Failure States where a backup system is not to be automatically or manually selected (i.e., the pilot must keep flying in the failed mode). The System Safety Analysis will be used to determine the failure rate of the VELSTAB for comparison with the Table II requirement (System must not fail to Level 2 more often than 2.5 x 10^{-3} per UCE>1 flight hour, or once every 400 UCE>1 flight hours). Since the intended function of the VELSTAB is to achieve Level 1 for UCE>1, exposure time (time where UCE>1) may be factored into this failure rate (hence the term "UCE>1 flight hour")[2]. This is offset somewhat by the fact that failures of the vision aid must be included in the calculation of the probability of

[1] Even though the Comanche program was cancelled, the fly-by-wire flight control system architecture developed therein continues to be used by major helicopter manufacturers on other programs (e.g. V-22).

[2] For example, if it is estimated that the helicopter will fly 2 hours in the NOE with UCE>1 for every 100 flight hours, the probability of failure with UCE>1 is obtained by multiplying the overall probability of failure by 0.02.

failure, where UCE>1 defines the relevant exposure times. For example, using AN/AVS-6 night vision goggles on a full moon night does not count because the UCE = 1. The same vision aid on a moonless or overcast night results in UCE>1.

Testing of a given SCAS mode must account for all failures that are specified as "acceptable" while that mode is operational. An "acceptable failure" is one where the SAS mode is not automatically deselected, and the crew is not prompted or trained to switch to a backup mode. Using the Comanche design as an example, ADS-33E-PRF requires that VELSTAB remains Level 1 in the presence of acceptable failures. For example, if one attitude gyro out of three fails, VELSTAB continues to be operational. It must be demonstrated that VELSTAB continues to be Level 1 in the presence of this failure. Table 2 indicates a suggested format, using the Comanche flight control mode nomenclature, to determine the need for ADS-33E-PRF testing in the presence of each of the failures defined in the FMEA and fault tree analysis.

Table 2. Suggested format to define required ADS-33E-PRF testing

Mode	Failure (FMEA)	Continue in current mode?	Switch to backup mode?	HQ Level following failure (ADS-33E-PRF)	Probability of Failure, Pf (FMEA)	ADS-33E-PRF Test
VELSTAB	Loss of one Attitude Gyro	Yes	No	1	10^{-2}	None if remaining attitude gyros are of same quality. Otherwise test with backup attitude gyros.
	Loss of 2 Attitude Gyros	No	Yes - Core AFCS	1 in GVE 2 in DVE	10^{-5}	Core AFCS Level 1 in GVE Level 2 in UCE>1
Continue to list all identified failure states that affect VELSTAB						
Core AFCS	Attitude Gyro	Yes	No	1	10^{-2}	None - analysis
	2 Attitude Gyros	No	Yes - Mission PFCS	2 in GVE 3 in DVE	10^{-5}	Mission PFCS is Level 2 in GVE, and Level 3 in UCE>1
Continue to list all identified failure states that affect the Core AFCS						

Note: Probabilities in this table were selected to illustrate the point and do not represent data for any specific rotorcraft

The Failure and Probability of Failure columns would include all the Failure States defined in the fault tree safety analysis and their associated probabilities of occurrence. The strategy for handling each Failure State must be defined by the manufacturer (e.g., to switch modes or not to switch modes, manual vs. automatic, crew alerting strategy, etc.). This will entail an estimate of the Level of handling qualities that result following a failure, using the defined strategy. The role of ADS-33E-PRF is to check that the Level of handling qualities is as asserted, and the failure probabilities have been correctly applied in accordance with Table II.

Note that the only testing role for ADS-33E-PRF is to determine the Level of handling qualities of all the Normal and Failed States. It is intended that the manufacturer will specify the intended function of each state, and that the ADS-33E-PRF testing will be accomplished accordingly. For example, when accomplishing the Mission-Task-Element maneuvers (3.11) it would be expected that the Core AFCS would be tested to the GVE standards and the VELSTAB to the UCE>1 standards, based on the fact that the manufacturer specified that the intended function for VELSTAB is UCE>1 flight, and the intended function for Core AFCS is GVE flight.

Continuing the Comanche example, the MISSION PFCS is a simplified augmentation system that is inherently more reliable than the AFCS or VELSTAB. The manufacturer's intended function for the MISSION PFCS is to provide a mission-capable backup system with no worse than Level 2 handling qualities in the GVE. ADS-33E-PRF testing must therefore include the MISSION PFCS to ensure that it provides Level 2 handling qualities.

The Core PFCS is the "last resort" backup system and should provide at least Level 3 handling qualities (HQR < 8.5). It follows that failures that would cause the Core PFCS to become worse than Level 3 would be expected to result in loss of control in all but the most ideal circumstances. ADS-33E-PRF testing of failures that degrade the Core PFCS should be accomplished in flight, only to the extent possible considering safety. It is fully expected that some of the testing will be accomplished on a simulator. The simulator should be validated to the extent possible using flight test data.

Table II ofADS-33E-PRF is interpreted in terms of the Comanche flight control system states as follows:

Required Level of HQ	State (Flight Control System Mode)	Allowed Failure Probability Within Operational Flight Envelope	Allowed Failure Probability Within Service Flight Envelope
Level 1	Core AFCS (in GVE) VELSTAB (in DVE)	$<2.5 \times 10^{-3}$ per flight hr $<2.5 \times 10^{-3}$ per UCE>1 flight hr	NA
Level 2	MISSION PFCS in GVE Core AFCS in DVE	$<2.5 \times 10^{-5}$ per flight hr $<2.5 \times 10^{-5}$ per UCE>1 flight hr	$<2.5 \times 10^{-3}$ per SFE flight hr
Level 3	Core PFCS (in GVE) MISSION PFCS (in DVE)	$<2.5 \times 10^{-7}$ per flight hr $<2.5 \times 10^{-7}$per UCE>1 flight hr	NA

In the Comanche example, it is expected that the bulk of the ADS-33E-PRF compliance testing will involve Core AFCS, MISSION PFCS, and Core PFCS in the GVE, and VELSTAB in the DVE with UCE>1. It is expected that less extensive MTE testing will be accomplished to provide reasonable assurance that the Core AFCS is at least Level 2 in UCE>1, and that the MISSION PFCS is at least Level 3 in UCE>1. Any testing of the Core PFCS in UCE>1 would be confined to determination if survival is possible, and to publish the appropriate pilot technique in the Dash 10.

Generalizing beyond the Comanche example, full ADS-33E-PRF testing to determine handling qualities Levels is expected in the GVE for all modes except those specifically designed for operation in UCE>1. Flight control modes specifically designed for UCE>1 typically lack the agility to pass the requirements for GVE operation. As long as there are other more agile flight control modes for operation in the GVE, DVE-specific modes only need to be tested using the DVE performance standards.

Flight control failures in the DVE are partially handled by Table IV in ADS-33E-PRF. Table IV specifies the required Response-Type as a function of the Useable Cue Environment (UCE). The Degraded Visual Environment (DVE) is quantified by UCE>1. Table IV indicates that for UCE=2, at least ACAH is required for Level 1 and Rate for Level 2. Similarly, for UCE=3, at least ACAH is required for Level 2 and TRC for Level 1. Flight control failures that result in a switch to an operational backup system often result in a change in Response-Type (i.e., a system that is Level 1 in the GVE). Such systems do not require extensive testing as the result is known from Table IV. For example, the Comanche Core AFCS is intended to be a Level 1 rate system in the GVE. Table IV tells us that it will be Level 2 for UCE=2. That covers the "Core AFCS in UCE>1" entry in the above table. MTE maneuvers with the Core AFCS in UCE>1 can therefore be minimized, and would be accomplished as a sanity-check to ensure that there are no unexpected problems.

It is important not to allow the specification methodology to become excessively complex as we consider failures in the DVE, of modes designed to be Level 2 or 3 in the GVE. This is especially true if we consider that the results will be very different if UCE = 2 vs. UCE = 3. Such testing requires good engineering judgment and specific guidance is not possible because of the wide range of possibilities. Testing of Level 2 and 3 backup systems in UCE = 2 or 3 should be used primarily to develop survival strategies to be included in the Dash 10 as guidance to pilots. For example, it might be best to pull up into forward flight following a failure of the MISSION PFCS in UCE>1, rather than attempt a landing in a confined area.

3.1.14.2 Allowable Levels for Specific Failures

Discussion:

Specific failure requirements are contained in Paragraph 3.1.14.2 (Allowable Levels for Specific Failures) and 3.7 (Specific Failures). This paragraph provides a means for the procuring activity to define the required Level of handling qualities following a specific failure regardless of its probability. For example, Level 1 handling qualities may be specified for autorotation regardless of the probability of an engine or drive-train failure.

3.1.14.3 Rotorcraft Special Failure States

Discussion:

Some failures do not lend themselves to a handling qualities analysis. For example, the failure of a tail rotor is never demonstrated and is not part of the design of the flight control system or the helicopter.

3.1.14.4 Transients following failures

Discussion:

Based on current information, the values used in ADS-33E-PRF for pilot delay in Table III (Transients following failures) are judged to be unreasonably large. For example one large helicopter manufacturer noted that all their helicopters would be Level 3 based on Table III.

This table is not supported by data, and no data is currently available to update the table. Therefore, it is recommended that it not be included as a tailored specification requirement until data is obtained.

Alternate Criterion:

Until data becomes available, it will be necessary for the procuring activity to make a determination of the acceptability of failure transients in flight test for each tabulated failure and control system mode. The following guidance is suggested.

The allowable pilot delay time between failure and pilot takeover should be a function of the level of unattended operation that is specified for the rotorcraft missions. If unattended operation is envisioned, a 3 second delay time is a reasonable estimate. This may be reduced to as little as one second for fully attended operation.

The allowable magnitude of the transient should be based on the probability of its occurrence as specified in Table II. One interpretation of Table II in terms of failure transients is as follows. If the probability of the failure is $2.5\times10^{-7} < P_f \leq 2.5\times10^{-5}$ per flight hour, the failure may result in a transient that is limited only in that control should not be lost. If the probability of failure is $2.5\times10^{-5} < P_f \leq 2.5\times10^{-3}$ per flight hour, the transient should be described as no worse than "very objectionable but tolerable" (i.e., use the Cooper-Harper scale descriptors for Level 2, where Level 2 is defined as $3.5 \leq HQR \leq 6.5$). Finally if the probability of failure is $> 2.5\times10^{-3}$ per flight hour, the transient should be described as no worse than "some mildly unpleasant deficiencies" (i.e., HQR = 3).

Note that it is possible to modify the pilot delay time by placing restrictions according to flight condition. For example, a restriction for hands-on fully attended flight below a certain airspeed could reduce the delay time from 3 seconds to less than 1 second in that speed regime. This could be a practical constraint for utility helicopters where the autopilot is only engaged above 50 to 60 kts. This could be useful if certain SAS monitors are turned off at lower airspeeds (where larger and more rapid actuator motions may be necessary in turbulence) to avoid nuisance trips.

A shorter delay time might also be obtained if the procuring activity is willing to accept a restriction such that "the pilot must closely monitor the controls at all times". This effectively limits the degree of divided attention that would be allowed (see Paragraph 6.2.3 in ADS-33E-PRF).

The failure transient due to an engine failure depends heavily on the selected delay time that is allowed. This is not normally considered a handling qualities issue, and relates more to maintenance of rotor RPM following loss of engine power. However, coupling between pitch attitude and collective is a handling qualities issue and should be evaluated qualitatively and by the coupling criteria in Paragraph 3.4.5.1.2 Large Collective Inputs. This criterion was specifically developed to minimize the pitch attitude transient at entry into autorotation.

Testing for failure transients should be conducted at the "worst-case" flight condition. For hardover and slowover failures, this would normally be at high airspeed and aft c.g. The manufacturer is tasked with determination of the worst-case flight condition for each defined failure mode.

3.1.14.5 Indication of failures

Discussion:

This paragraph was intended to allow flight control system designs that automatically deal with a failure and require no pilot action. In those cases, an annunciation could result in more of a distraction than a benefit, especially since no pilot action is required.

Even if the failure results in degradation in handling qualities, an annunciation during a period of high workload does not help the pilot. Some transport aircraft delay such failure annunciations until the aircraft is in cruise flight.

3.1.15 Rotorcraft Limits

Discussion:

This requirement is included to establish a requirement for warnings that the rotorcraft is approaching a limit. One example would be a collective shaker to warn the pilot that a torque limit is being approached.

Another form of warning is that a cockpit controller is approaching full travel. Numerous comments have been made that ADS-33E-PRF does not provide a criterion for control margin. The basic premise during development of ADS-33E-PRF was that the moderate and large amplitude criteria guaranteed adequate control margin.

Based on comments received, it is recognized that control margin is a standard design parameter, and should be included in the specification. Some background on the development of such a criterion is given in the following section.

Additional Criterion:

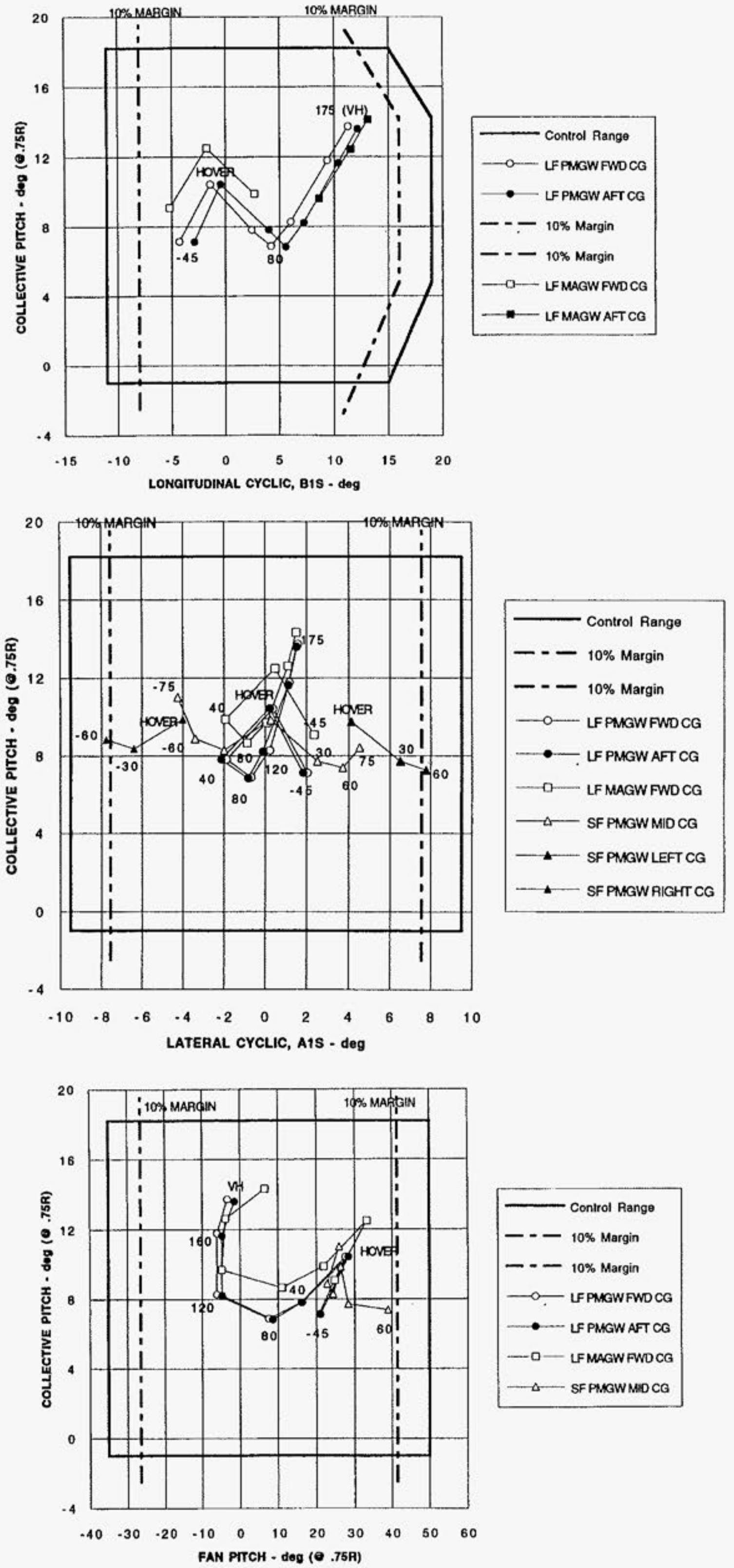
Until an update to ADS-33E is accomplished, it is recommended that a 10% control margin be shown to exist throughout the OFE. An example of this for an example scout-attack helicopter design is shown in Figure 7 and includes the control margin for the longitudinal and lateral cyclic and fantail as a function of collective position and airspeed. Until ADS-33E-PRF is updated, it is recommended that this format be used as a criterion on control margin.

The maneuvers that should be considered to define the control margins include the following:

- Forward longitudinal cyclic – high speed forward flight and maneuvering to achieve OFE load factor at aft c.g.

- Aft longitudinal cyclic – Rearward flight at forward c.g.
- Up collective – High speed and high weight
- Down collective – Rotor speed control in steady autorotation at light weight and low density altitude conditions.
- Right and left lateral cyclic – sideward flight and slope landings at extremes of lateral c.g.
- Left directional control – Transient Turn MTE for scout-attack helicopter
- Right directional control – Turn to target MTE in right sideward flight (or crosswind hover)

Of course the critical maneuvers used to define required control margin will vary with the rotorcraft category, e.g., Table I in ADS-33E as well as the OFE's (e.g., Figure 4 and Figure 5).



Notes:

PMGW = Primary Mission Gross Weight
MAGW = Maximum Alternate Gross Weight
Numbers by data points are airspeed in kts.

Figure 7 Example of Compliance with 10% Control Margin

3.1.16 Pilot-induced Oscillations

Data Requirements: Pilot comments about PIO tendencies, possibly augmented by pilot ratings from a PIO tendency rating scale

Test Technique:

PIO tendencies are most likely to be apparent while performing aggressive precision tasks. At some level of aggressiveness and precision, any rotorcraft may appear to be PIO-prone. This will occur in large, flexible rotorcraft at levels of aggressiveness and precision much lower than for small, agile rotorcraft. This is to be expected and is acceptable, since there should be no need to maneuver a cargo helicopter such as a CH-47 quite as aggressively as a scout-attack helicopter such as an AH-64. The question, then, is: how aggressively should the test pilot maneuver to assess the susceptibility to PIO? The MTEs have been designed with this question in mind. The levels of aggressiveness and precision have been tailored by teams of experimental test pilots with considerable operational experience. Each class of rotorcraft has a menu of appropriate tasks and performance standards. Pilots should be alert for PIO tendencies while performing the MTEs to the defined standards.

It may be most convenient to employ a PIO tendency rating scale. One such scale is shown below (from Reference14). This scale is a hybrid from two of the most familiar scales. It requires the pilot to march up the decision tree on the left and verify that the assigned rating is consistent with the words on the right. As with any pilot rating scale, the PIO tendency rating scale is intended to elicit pilot comments, and the comments should be given equal priority to the numerical rating. In general, however, experience has shown that ratings of 1, 2, and 3 indicate no PIO; ratings of 5 and 6 indicate PIO tendencies that require a fix; and a rating of 4 may reflect either a serious PIO or a more subtle "nuisance" oscillation such as a bobble. For the rating of 4, especially, pilot comments must be considered.

1. Commonly PIO tendency ratings (usually abbreviated PIOR) are assigned only if undesirable motions are observed by the pilot.
2. Small, almost-unnoticeable oscillations ("bobble") and oscillations resulting from the rotor, not from pilot inputs, are usually not considered PIO (see Reference15).

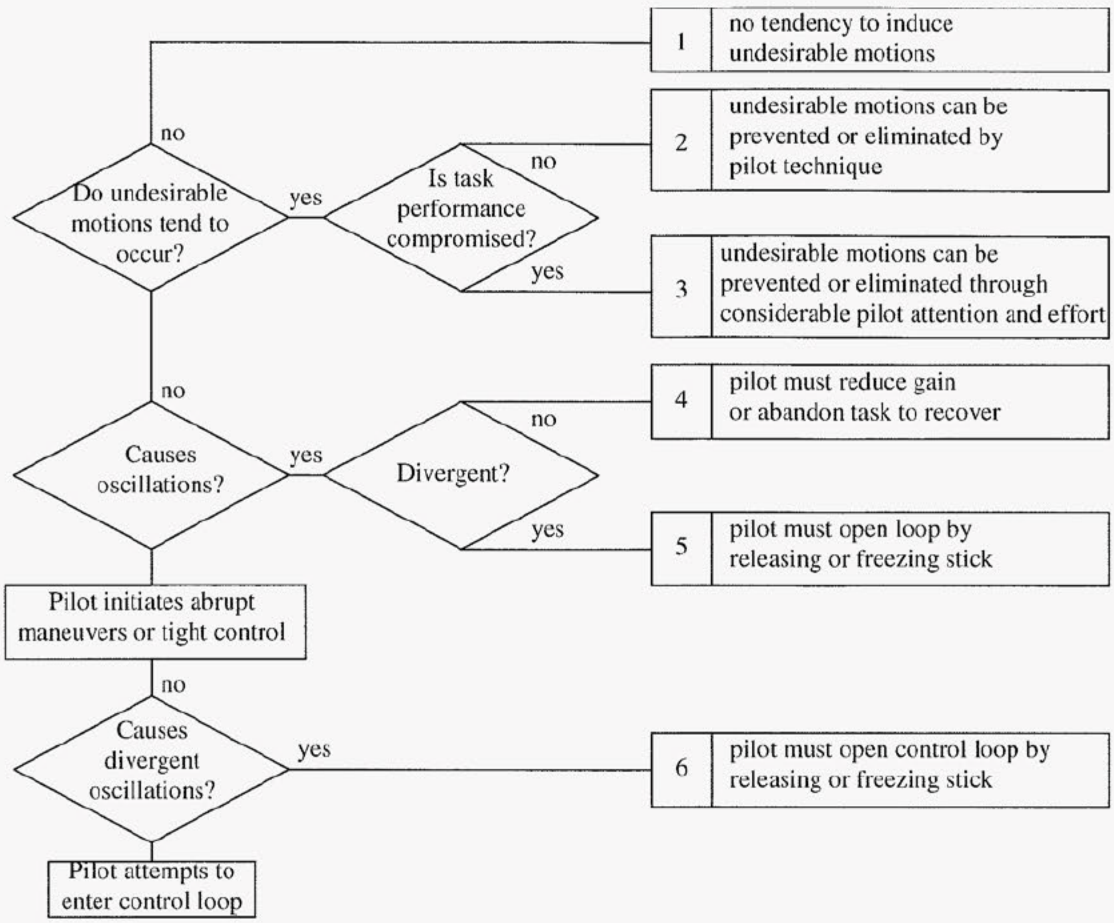


Figure 8 PIO Pilot Rating Scale

3.1.17 Residual Oscillations

Data Requirements: Controller input and attitude in axis where residual oscillation occurs. Pilot comments related to whether the residual oscillation is objectionable.

Test Technique: Pulse or doublet input to excite the oscillation. This should be the same input as used to show compliance with 3.3.5.2 (Mid-Term Response to Control Inputs)

Data Analysis and Interpretation:

Any oscillation that occurs well above the bandwidth frequency is considered to be a residual oscillation.

The specification limits in 3.1.17 are not very well supported by data. Therefore, if residual oscillations occur, pilot opinion of those oscillations is very important. If the oscillations are of greater magnitude than the criterion, but are not considered to be objectionable by the majority of evaluators, it would be prudent to request a deviation from this requirement.

An example of a residual oscillation is given in Figure 9 for the UH-60.

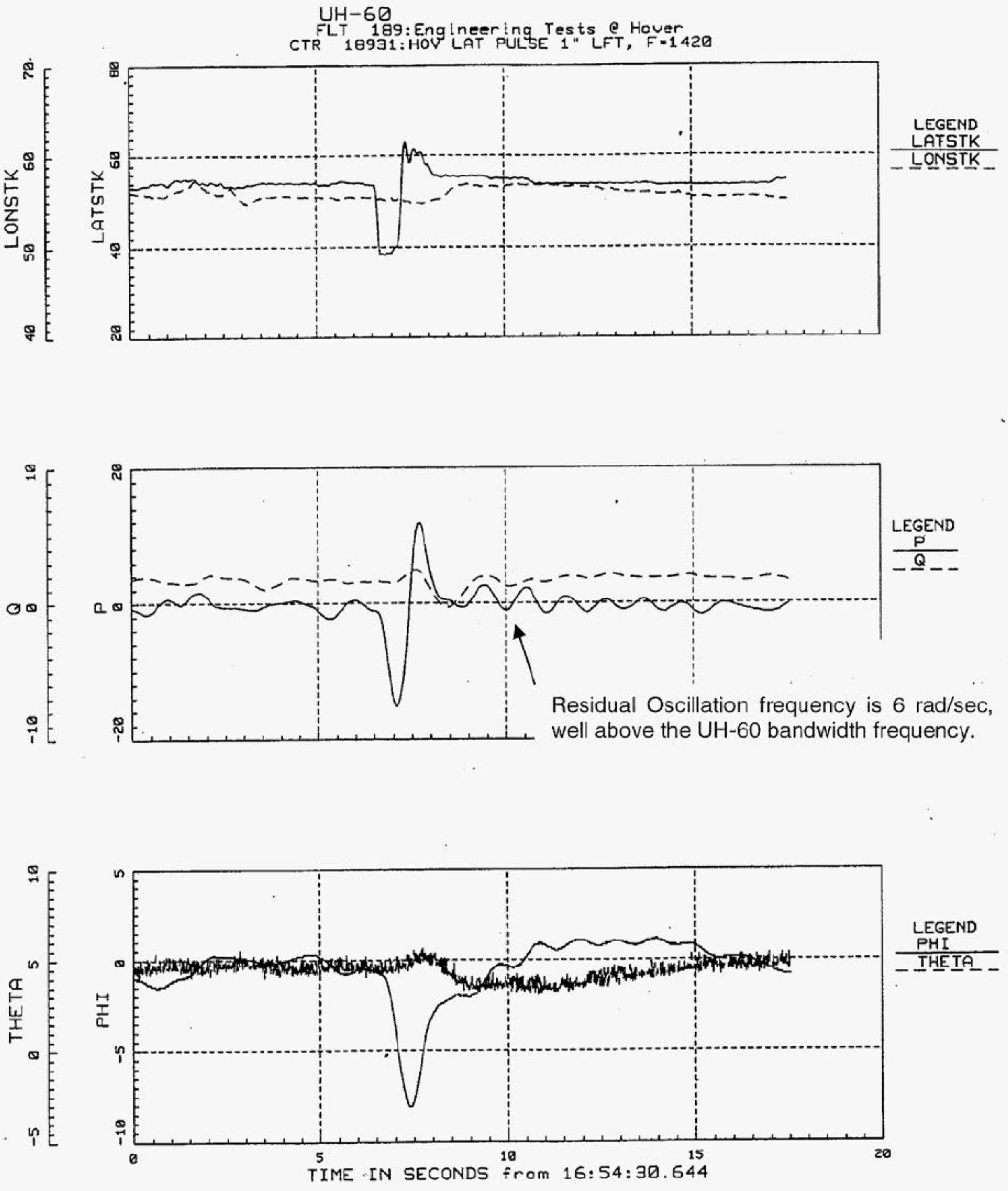


Figure 9 Example of Residual Oscillation

3.2 Response-Types

3.2.1 Determination of the Usable Cue Environment

3.2.1.1 Characteristics of test rotorcraft

3.2.1.2 Applicable Mission-Task-Elements

Data Requirements: The required data consist of the visual cue ratings for each specified task. These are to be plotted on Figure 3 of ADS-33E-PRF to determine the UCE.

If the flight control system design includes a translational-rate-command with position-hold (TRCPH) Response-Type, there is no requirement to conduct UCE tests to determine the Response-Type because TRCPH is the highest level of augmentation required by the specification. However, it will be necessary to simulate UCE = 2 or 3 to accomplish the 3.11 MTEs in the DVE[1].

Test Technique:

Paragraph 3.2.1 provides a detailed methodology for obtaining the Usable Cue Environment. The following paragraphs provide general guidance on the assignment of the Visual Cue Ratings (VCRs) that are used to define the UCE.

The sole purpose of determining the UCE is to specify what level of stabilization must be employed to operate in the DVE when using the supplied vision aid. The UCE is a measure of the quality of the vision aid to provide the cues needed for rotorcraft control (e.g., fine grained texture) in the DVE.

It is essential that the test rotorcraft have good handling qualities in a good visual environment (GVE) (as specified in 3.2.1.1) and have a Rate Response-Type according to 3.2.6. It is not necessary to use the rotorcraft under evaluation as the test rotorcraft to determine the UCE. Any rotorcraft with a Level 1 Rate Response-Type can serve as an acceptable test-bed to determine the UCE for a vision aid. That is because the UCE depends only on the vision aid and characteristics of the DVE (e.g., AN/AVS-6 NVGs on an overcast night over a grass field).

The evaluation pilots should fly the test courses enough times to ensure that training is not an issue, and that the markers that define desired and adequate performance are easily seen with the vision aid in place. Note that the UCE does not define how well pilots can see obstacles. Rather it defines how well the pilot can use the existing cues to stabilize the helicopter, which depends primarily on the ability to see fine-grained-texture (e.g., see Reference 16). The ability to see large objects is outside the purview of a handling qualities specification and is specified in terms of operational capability.

[1] It has become common practice to refer to UCE>1 as the DVE. For example all the performance standards in Paragraph 3.11 are labeled as GVE and DVE. This is technically not correct because the DVE refers to the environment without a vision aid (e.g. night with no moon). The useable cue environment (UCE) refers to the visual environment as affected by the vision aid. Therefore, it would be more correct to categorize the performance standards as UCE=1 and UCE>1 rather than GVE and DVE.

It is intended that the pilot relate his or her confidence in being aggressive and precise. Aggressive in this sense is best described as "hummingbird type agility" as opposed to large amplitude motions. It is important that the pilot does not try to make an estimate of the quality of the visual environment. It's not how well objects and texture can be seen, it's how confident the pilot can be in precisely maneuvering during performance of the required MTEs. It is very common to view a visual scene before liftoff and have the impression that hover will not be a problem, only to find that the task is elusive and requires the pilot to back out of the loop to keep from losing control.

It is not possible to make a distinction between a degraded visual scene and poor handling qualities. The purpose of the UCE methodology is to overcome this subtlety, so it is very important to strictly obey the ground rules in the specification and this Test Guide when assigning VCRs.

The VCR scale is intended to be linear, and the pilot should be encouraged to assign non-integer ratings, e.g., 2.3 is an acceptable VCR.

The specification requires that the pilots give separate VCR ratings for pitch, roll, and yaw attitude and horizontal and vertical translational rate for a total of 5 ratings. According to the requirement, these are to be averaged across pilots and the worst attitude and translational rate rating plotted on the UCE grid.

Experience has shown that good results are obtained if the pilots provide only three ratings, one for attitude, one for horizontal translation and one for vertical translation. The pilots should be instructed to give the rating for the worst axis for attitude (pitch, roll, or yaw), the worst axis for horizontal translational rate (X or Y), and the vertical axis.

The VCR scale assumes that the pilot can see all the objects required to accomplish the tasks. If such objects are not visible due to cockpit field-of-view problems, this is not a VCR/UCE issue. The pilot should not attempt to assign a degraded VCR due to problems with seeing the objects that define the limits for desirable and adequate performance for the task. An example of a misuse of the VCR scale occurred when a pilot assigned UCE = 2 to the AH-64 because the cockpit field-of-view did not allow him to see the end of the Accel/Decel course (in good visual conditions). In that case it would have been better to add more cones to the course. If there is still insufficient out-the-window visibility, an investigation should be performed to determine if the field of view of the rotorcraft is fundamentally deficient (i.e., it is not a handling qualities problem).

Visual Cue Ratings (VCRs) are a new concept for many test pilots, so there is a significant potential that the ratings could be assigned incorrectly. For example, there is often an initial tendency to want to rate the quality of the visual scene (field of view, richness of visual images, etc.), not the ability to maneuver using the visual scene. The UCE method in ADS-33E-PRF has evolved from over 15 years of research and testing. Avoid the temptation to "improve" the methodology. Such proposed improvements are often suggested without knowledge of the past work and resulting rationale. If such "improvements" are implemented they often result in invalid ratings.

Simulating the UCE in Flight Test

In order to comply with the mission task element (MTE) maneuver requirements (3.11) in the DVE, it is necessary to simulate the degraded UCE (UCE = 2 or 3). Several methods that have been used to accomplish this are discussed below.

There has been considerable experience with simulating UCE>1 in flight test. The flight testing that was accomplished to develop the supporting data for ADS-33E-PRF (e.g., References 9 and 19) was accomplished using the Canadian NRC variable stability Bell 205 helicopter. In those tests UCE = 2 was simulated by the use of daylight training filters on AN/AVS-6 NVGs. Initial results produced visual cue ratings that resulted in UCE = 1 because the daylight training filters simulated ideal night condition (e.g., full moon night). The visual scene was further degraded by defocusing the diopter adjustment on the NVGs while viewing a conventional Snellen eye chart that was placed 20 ft in front of the helicopter. A typical Snellen eye chart is shown in Figure 10.

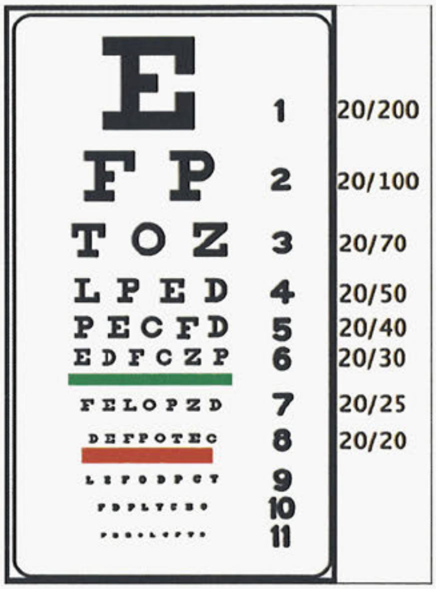


Figure 10 Snellen Eye Chart (not to scale)

When defocused to slightly worse than 20/70 vision, flight testing showed that the VCR ratings produced a solid UCE = 2. As lighting changed during the day, it was found necessary to readjust the diopter setting on the NVGs to maintain the UCE =2 environment.

The U.S. Army Night Vision Laboratory conducted flight tests that showed that NOE operations on a moonless night with NVGs resulted in a spatial frequency of 0.4 cycles/mrad. This environment resulted in degraded performance and increased pilot workload. The plot shown below in Figure 11 indicates that a spatial frequency of 0.4 cycles/mrad is equivalent to a visual acuity of 20/80. (Note that this is actually a plot of the visual acuity denominator vs. spatial frequency).

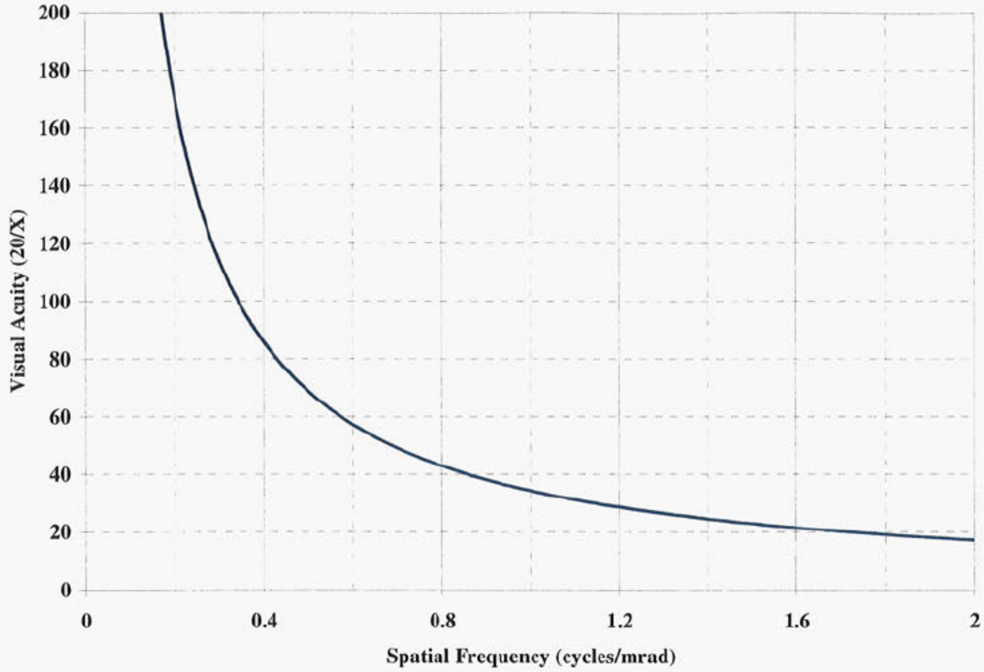


Figure 11 Relationship between Visual Acuity and Spatial Frequency

Testing accomplished in support of ADS-33 (Reference 9) showed that flight with NVGs when the visual acuity was equal to or better than 20/50 resulted in UCE = 1.

Using the above results, we can make the following approximations that are useful when simulating the UCE.

Rules-of-Thumb to Simulate UCE

- UCE = 1 if visual acuity is 20/50 or better or the spatial frequency (Ω) is equal to or greater than 0.70 cycles/mrad.
- UCE = 2 if visual acuity is between 20/60 and 20/80 or $0.40 \leq \Omega \leq 0.6$ cycles/mrad.[1]
- UCE = 3 if visual acuity is worse than 20/80 or $\Omega < 0.40$ cycles/mrad.

To put the above values in context, the visual acuity/spatial frequency of AN/AVS-6 NVGs as a function of light levels at night are shown in Figure 12 (taken from Reference 5).

[1] The region between 0.6 and 0.7 cycles/mrad is a "grey area" between UCE = 1 and UCE = 2.

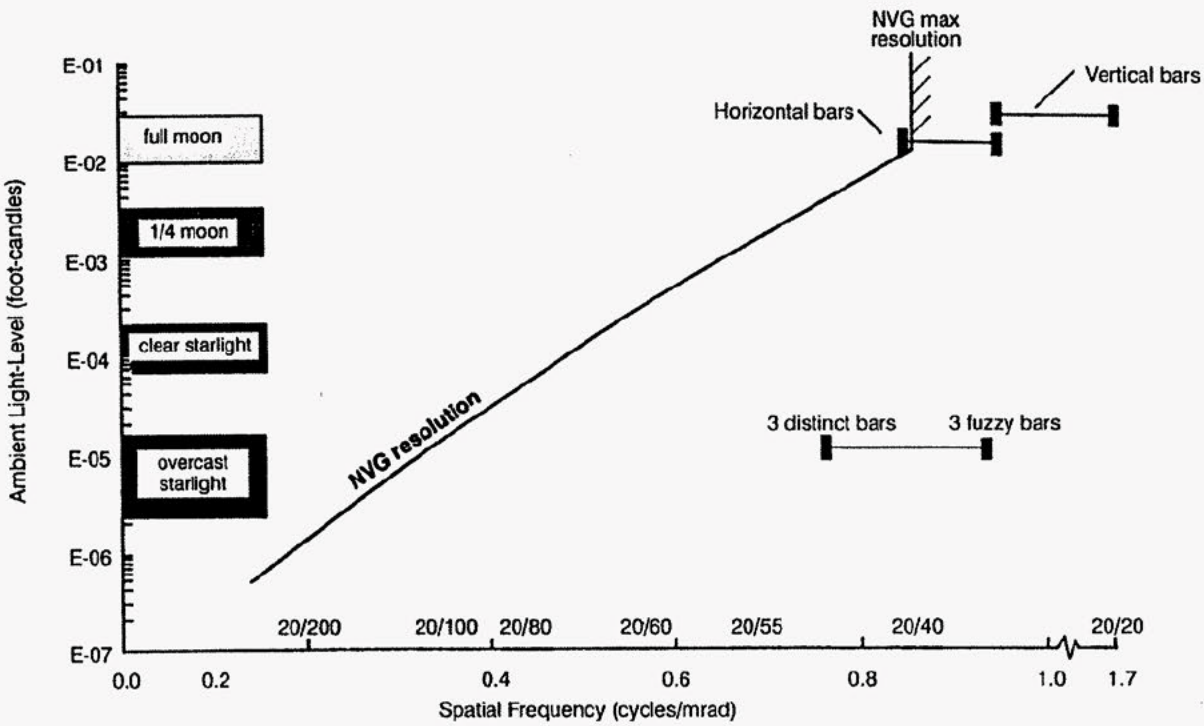


Figure 12 NVG Resolution as a Function of Light Level

It is cautioned that the above rules-of-thumb to simulate UCE are only approximate, and do not account for the level of contrast in the visual scene (depth of modulation). The test measurements used to obtain these approximations used a target to measure visual acuity with a contrast ratio of 1.0 (i.e., black on white).

It is possible to encounter UCE = 3 with a full moon over featureless terrain with little or no fine grained texture, e.g., some desert terrain, or over water. Therefore, if the DVE is simulated using a calibration target with a contrast ratio of 1, the testing for compliance with Paragraph 3.11 of ADS-33E should be accomplished in an area with good fine-grained texture. Use of an area with poor fine-grained texture could result in a UCE that is more degraded than the calibrated value from a black and white eye chart.

One should not use the simulated UCE rules-of-thumb to calculate the UCE for a night vision device to determine the proper Response-Type. The reason for that is that those approximations do not include the effect of the ability of the device to measure contrast (depth of modulation). The approximations are intended only to provide a means to simulate the DVE for MTE testing to show compliance with ADS-33E-PRF, Para 3.11. Testing to determine the UCE for a vision aid should be accomplished under actual DVE conditions.

Testing with a CH-47D (Reference 5) and an AH-64 (Reference 4) was accomplished in actual night conditions by the U.S. Army at Edwards AFB. The simulated UCE=2 was achieved with night vision goggles that were modified and calibrated using the Large Size Resolution Test Object shown in Figure 13.

Using the Large Size Resolution Test Object, or more commonly called the "3-bar chart", to measure visual acuity is very similar to using the Snellen chart except that spatial frequency (*SF*) is calculated from the results of the test and further calculations are required to determine visual acuity. Unlike the Snellen chart, the 3-bar chart may be used from any reasonable distance. The chart is set up with six groups (*K* varies from -6 to -1)) each containing six elements (*N* varies from 1 to 6).

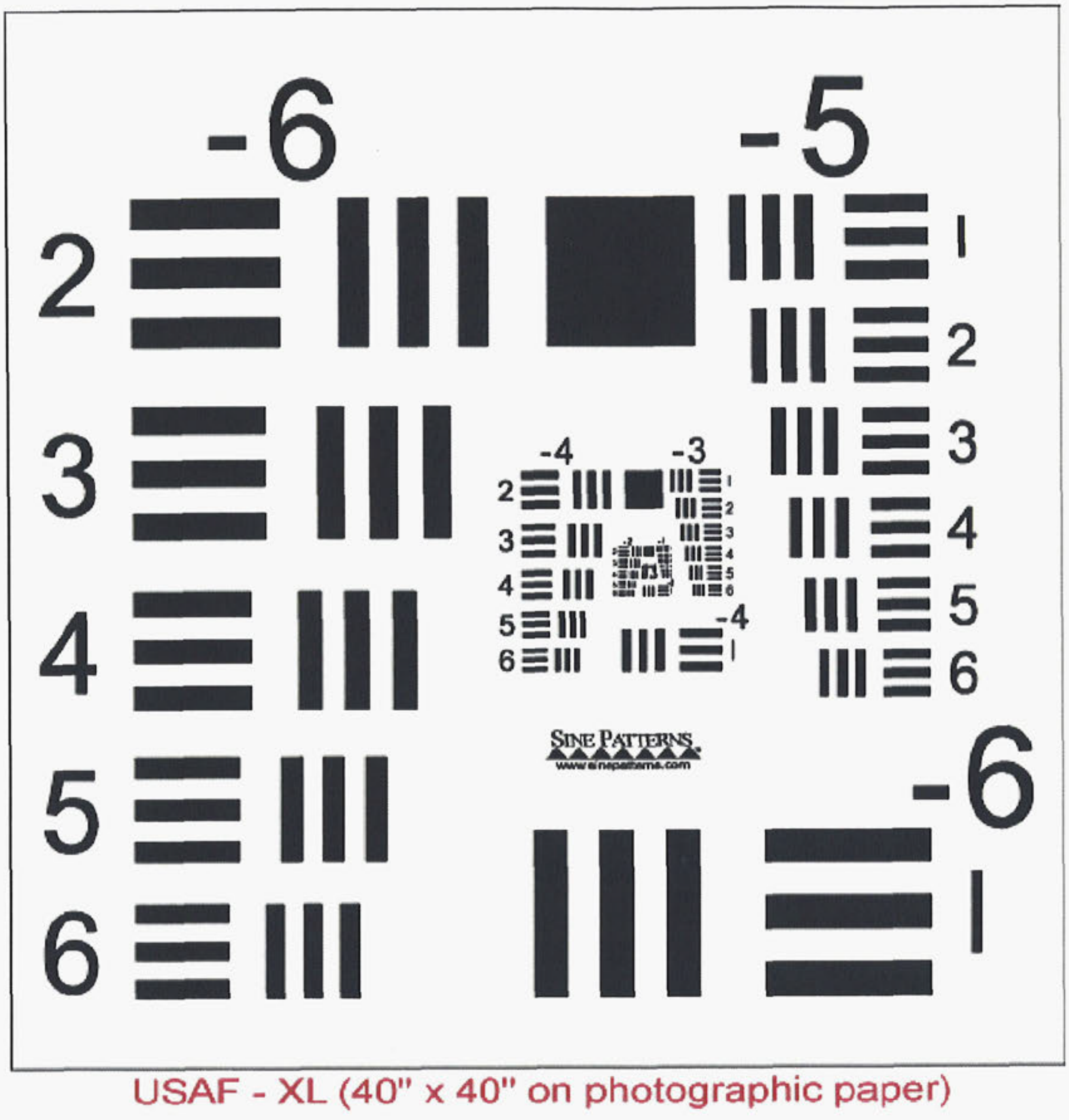


Figure 13 Large Size Resolution Test Object, RT-2-72, Type AB or 3-Bar Chart Used to Calibrate Night Vision Device

The three bar chart may be purchased from:

Rochester Institute of Technology
Technical and Education Center
One Lomb Memorial Drive
Rochester, NY 14623

To calculate visual acuity (VA) from the 3-bar chart, the group and element number are entered into the expressions below (taken from Reference 5).

Entering the group (K) and element (N) into equation 1 yields the resolution obtained in line pairs per mm. (Note that K is always negative and N is always positive).

$$R = \left(2^{-1/6}\right)\left(2^{K+\frac{N}{6}}\right), \text{ resolution, line pairs/mm} \qquad (1)$$

Knowing the distance to the chart (*D*), the spatial frequency (*SF)* and visual acuity (*VA)* can be calculated from the following expressions.

$$SF = 0.305(R \times D) \text{ , spatial frequency, cycles/mrad} \qquad (2)$$

$$VA = \frac{20}{34.38/SF} \text{ , visual acuity} \qquad (3)$$

With visual acuity measured directly from a Snellen chart or calculated using the method above, it is possible to modify the vision aids to simulate the desired UCE. Two methods have been used to degrade NVGs to UCE ≥ 2 while accomplishing the MTE evaluations in day or night conditions, as described below.

Neutral Density Filters

Army testers in the Reference 5 experiment were able to reach the target spatial frequency by testing at night and using special filters that reduced the spatial frequency from a range of 0.85-0.95 cycles/mrad to a range of 0.48-0.7 cycles/mrad. This was done through the use of neutral density filters that were placed over the AN/AVS-6 NVGs. (Note: A neutral density filter reduces the light transmittance without affecting the color). Because the AN/AVS-6 NVGs have an automatic gain control to compensate for varying ambient light levels, a trial and error approach was used to first filter the light down to a level where the automatic gain control could not compensate, and then adding more filters to lower the resolution as measured using the 3-bar chart (Figure 13). The final configuration used neutral density filters with a rating of 2.0 giving a spatial frequency of 0.48 cycles/mrad on a moonless night and 0.70 cycles/mrad with a full moon.

The horizontal bars shown in Figure 12 indicate the following:

- There was some variability in reading the 3-bar chart and the evaluators chose to bracket between 3 distinct bars and 3 fuzzy bars.
- The AN/AVS-6 NVGs were better able to distinguish vertical bars than horizontal bars in the good visual environment (full moon).

Reduced Apertures

In another flight test, the U.S. Army conducted acceptance testing of the digital flight control system incorporated into the CH 47F in simulated UCE = 3 conditions. These tests were conducted at night, and specially made apertures were added to the NVGs to degrade the pilot visual acuity below 20/80 and achieve UCE = 3 (see Reference 37). The concept of reduced apertures to simulate UCE>1 is based on the fact that less light reaches the NVGs as the opening is reduced (like increasing the f-stop on a camera).

Since these tests were conducted in actual night condition, the safety pilot also wore night vision goggles. The safety pilot's NVGs were not degraded with apertures.

Table 3 (from Reference 37) provides laboratory measurements relative to aperture diameter and the corresponding changes in resolution data.

Table 3 Aperture Effect on Acuity

Aperture Diameter (inches)	Snellen Acuity
0.875[a]	20 / 30
0.350	20 / 42
0.263	20 / 47
0.152	20 / 60
0.088	20 / 75
0.050	20 / 94
0.030	20 /120

The aperture of 0.875 inches represented an unobstructed NVG tube.

Each NVG tube was modified by inserting an aperture into the front end and, held in place with an o-ring and the light interference filter. A subsequent visual acuity reading was taken to confirm that visual acuity had been reduced to at least 20/80. Aperture diameter was iterated as necessary to achieve the desired acuity. The visual acuity of each subject pilot is presented in Table 4.

Table 4 Pilot Visual Acuity

Pilot	Normal NVG[a]	Modified NVG (apertures)
1	20/54	20/95
2	20/54	20/85
3	20/54	20/85
1[b]	20/54	20/85

These data indicate that the CH-47F evaluations were accomplished in UCE = 3 (based on above rules-of-thumb to simulate UCE).

Since ambient light levels are a factor with regard to NVGs, acuity, photometric measurements of both photopic and NVIS radiance were made before and during the flight test events to quantify any changes in light levels. Illumination at the test site was monitored throughout test execution and remained essentially constant.

Simulated UCE in Day Conditions Using filters and Apertures

The U.S. Army Aeroflightdynamics Directorate (AFDD) conducted an evaluation of a flight control system upgrade for the UH-60M at the NASA Ames Research Center. Those evaluations were conducted during the day. UCE = 2 was achieved through the use of apertures and neutral density filters.

The AFDD modified NVG setup, shown in Figure 14, consists of a set of AN/PVS-6 NVGs which are fitted with apertures and neutral-density filters, and a neoprene shroud to block excessive light from entering between the NVGs and the pilot's face and washing out the NVG image. The shroud is formed to allow the pilot to look down to view the primary flight display and other panel-mounted instruments that he would commonly use in a DVE. As this is usually the darkest part of the visual field in the cockpit, the ambient light from this direction is not enough to degrade the NVG performance. Although peripheral vision is sacrificed, many pilots report that they receive minimal peripheral vision cues in a UCE 2 or higher environment.

The UCE was calibrated by adjusting the amount of light entering the NVGs using an aperture disk (tin foil with a pin hole in the middle) and a stack of plastic (or gelatin) neutral density filters mounted between the objective lens and screw-on clear glass filters for the AN/PVS-6 goggles. The pin hole slightly reduced the field of view of the goggles, but greatly increased the depth of field, as well as reducing the number of neutral density filter disks required and sensitivity to imperfections in the filters. The composition of the filter stack was adjusted to achieve a light level yielding 20/60 to 20/80 visual acuity, which has been shown to correspond to a UCE=2 for the AN/PVS-6 goggles. The required filter stack varies with ambient light conditions, so it was checked immediately prior to each flight test.

Figure 14 AN/PVS-6 NVGs with neoprene shroud

The evaluation pilot's visual acuity was tested in the cockpit using the Air Force three-bar chart, as shown in Figure 15. The chart was placed 20 ft in front of the evaluation pilot's eye-point with the aircraft in the same orientation relative to the sun in which the maneuvers were flown. The required visual acuity was achieved when the evaluation pilot could clearly distinguish three horizontal and three vertical bars in the -4/3 range of the chart, shown in Figure 13. From equations 1, 2, and 3 the resulting spatial frequency was 0.48 cyc/mrad, and the visual acuity was 20/71. This corresponds to UCE = 2 based on the UCE rules-of-thumb noted above.

Verification of the UCE was achieved by collecting Visual Cue Ratings (VCRs) in an aircraft with known Level 1 handling qualities in a good visual environment. That is, from an earlier AFDD flight test to assess ADS-33 with a utility helicopter (UH-60A), the average Cooper-Harper pilot ratings for the daytime Hover MTE and the Vertical Maneuver MTE were Level 1. These two maneuvers were used to collect VCRs in an EH-60L in the simulated DVE with the filtered/shrouded AN/PVS-6 NVGs. The results of that testing are discussed in the following section and are summarized in Figure 17. These results verified that the simulated UCE was 2.

Figure 15 Verifying visual acuity in-situ from the evaluation pilot's station.

It is not necessary to accomplish this verification process to comply with the MTE maneuver requirements in 3.11. Use of the rules-of-thumb for simulating UCE is adequate.

Data Analysis and Interpretation:

The UCE methodology is summarized in Figure 16 below.

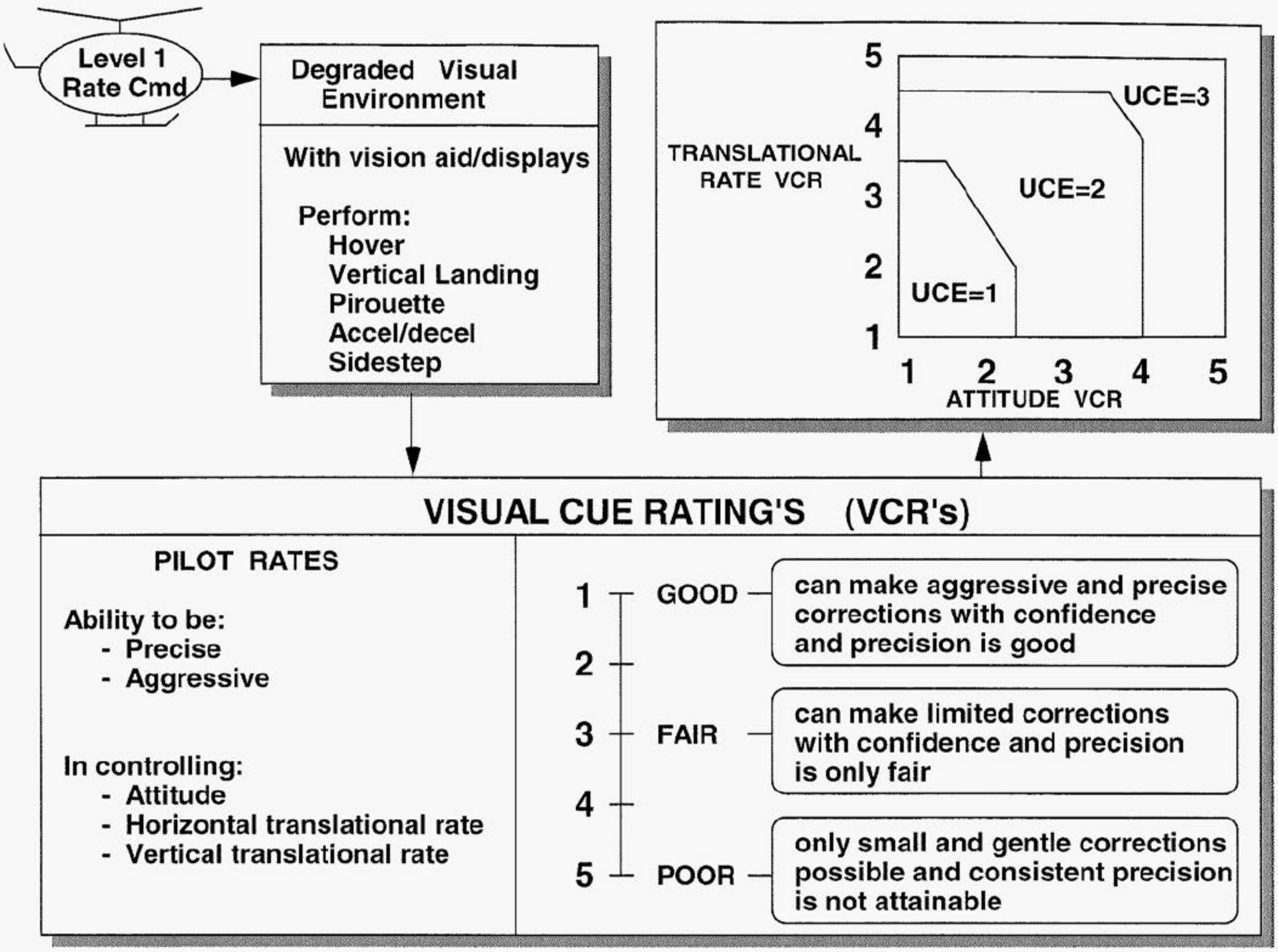


Figure 16 Illustration of UCE Methodology

The steps for combining the individual VCRs from each pilot into composite attitude and translational rate VCRs have evolved since ADS-33E was published. The modified method planned for the next update of ADS-33 is given as follows.

- Determine the VCR for each pilot
  - Take the worst VCR rating for pitch and roll attitude. This is VCR_θ. Yaw can almost always be ignored. (It is acceptable for the pilot to simply issue one attitude VCR to reflect his or her evaluation of the worst axis).
  - Take the worst VCR rating for horizontal X and Y translational rate. It is acceptable for pilots to rate X and Y translation as one rating, rather than give separate ratings. If that is done, ask the pilot to rate the worst axis. If he or she is compelled to give separate ratings, then tabulate the worst rating.
  - Always insist that the vertical axis be rated separately.

- Take the worst of the horizontal and vertical VCRs. This is VCR_X
- Tabulate the worst VCR_θ and VCR_X for each pilot

- Average the VCR_θ and VCR_X obtained above across the subject pilots.
- Plot the averaged worst-case VCRs on the UCE boundaries.

An example of this methodology is given for flight test data that was taken to determine the UCE for evaluations of a flight control upgrade for the UH-60M (see Figure 14). Night vision goggles were used as the night vision device. The tests were flown in the day, and both neutral density filters and apertures were used to achieve the degraded visual acuity (see above discussion regarding simulated UCE using apertures and filters).

The visual cue ratings for each pilot are given in Table 5. The averaged worst-case VCRs are tabulated along with the standard deviations. ADS-33E Paragraph 3.2.1.3 requires that the standard deviations be less than 0.75.

Table 5 Example of VCR Rating Results

	Attitude			**Translation**		
			Horiz	**Vert**	**Worst**	
Pilot A, 6/18/07						
Hover maneuver	3.8		**3.8**	2.0	3.8	
Vertical maneuver	4.0		**4.3**	2.0	4.3	
Pilot A, 8/9/07						
Hover maneuver	3		**4**	3	4	
Vertical maneuver	3		**4**	3.5	4	
Pilot B						
Hover maneuver	2		1.5	**3.5**	3.5	
Vertical maneuver	2		1.5	**4**	4	
Pilot C						
Hover maneuver	4		**4**	3	4	
Vertical maneuver	4		**5**	3	5	
	VCR_θ				VCR_x	
All Pilots	**Avg**	**Std Dev**			**Avg**	**Std Dev**
Hover maneuver	3.2	0.79			3.8	0.21
Vertical maneuver	3.3	0.83			4.3	0.41
	VCR_θ				VCR_x	
Without Pilot B	**Avg**	**Std Dev**			**Avg**	**Std Dev**
Hover maneuver	3.6	0.43			3.9	0.12
Vertical maneuver	3.7	0.47			4.4	0.42

A few comments regarding this data:

- Pilot A flew the evaluation twice – his VCR ratings were averaged as if they were different pilots, which is acceptable as long as there are two other evaluators (minimum of three).
- The pilots provided one VCR rating for pitch and roll attitude with the understanding that this was the worst VCR for pitch and roll.
- The pilots provided one VCR rating for longitudinal and lateral translation with the understanding that this was the worst VCR for X and Y.
- The standard deviation for the attitude VCRs is greater than the 0.75 limit required by 3.2.1.3. This is primarily due to the outlier ratings from Pilot B, who rated the attitude VCR as 2 and the horizontal VCR as 1.5 for both tasks.
- If pilot B's VCRs are removed, the standard deviations are well below 0.75, and the calculated VCRs are slightly higher.

The VCRs are plotted on the UCE requirement boundaries in Figure 17.

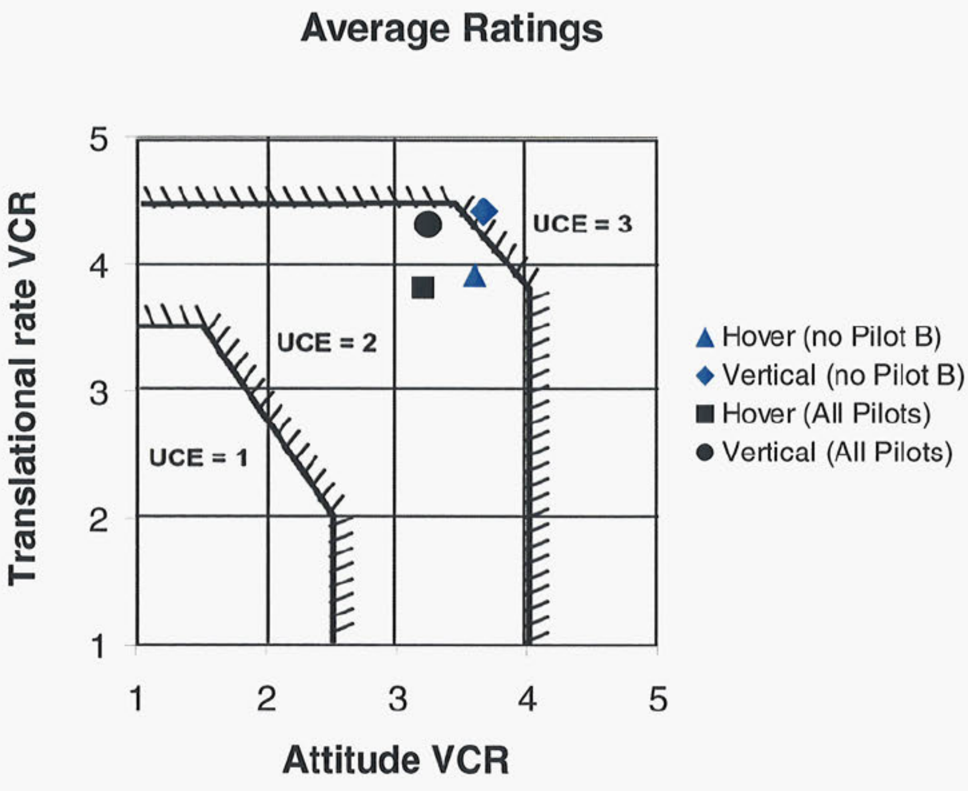


Figure 17 VCRs Plotted on UCE Criterion Boundaries

Without Pilot B, the vertical maneuver UCE is borderline UCE = 3. Otherwise the UCE is 2 with and without Pilot B. Because the UCE = 3 point is essentially on the 2/3 boundary and is a result of eliminating one pilot's ratings, the possible actions are:

- Set UCE = 2 since the point is so close to the boundary. Review Pilot B's comments regarding VCR to try to determine why he found the task much easier than the other two pilots. Ensure that Pilot B understood that his task was to rate agility and not his subjective evaluation of the scene.
- Obtain VCRs from a fourth pilot and take the average of all four pilots.

For the Control System Specialists

The background for the UCE methodology is given in References16 and 17.

Modification to Criterion:

ADS-33E-PRF requires that pilots provide a separate VCR for each of five axes of control (pitch, roll, yaw, vertical rate, and horizontal translational rate). Experience has shown that it is acceptable and more efficient for the pilots to provide separate ratings only for attitude, horizontal translation, and vertical translation. If desired, separate ratings may be given for pitch and roll attitude, and/or X and Y translation, in which case the worst rating is used.

ADS-33E requires that the average VCR in each axis be calculated, and the worst average rating for attitude and translational rate be used on the UCE criterion. Experience has shown that more meaningful results are obtained if the worst attitude and translational rate ratings are tabulated for each pilot and those worst-case ratings are averaged for plotting on the UCE criterion (see example in Table 5).

3.2.1.3 Dispersions among visual cue ratings

Discussion: Paragraph 3.2.1.3 is intended to place a limit on the allowed variability by requiring that the standard deviation of the VCRs must be less than 0.75. Although it is not stated explicitly, the standard deviation to be obtained is the *population* standard deviation, not *sample*. Though it may seem odd to consider three pilots a "population," the assumption is that there are no other pilots who have flown the particular combination of tasks and visual environment under consideration. More fundamentally, with a small data size, sample standard deviation (which divides by n-1) can be substantially larger than population standard deviation (which divides by n). The equation to be used to obtain standard deviation is as follows:

$$\sigma = \frac{\sqrt{n\sum x^2 - \left(\sum x\right)^2}}{n}$$

If there are significant outliers, it is probably because one or more pilots are not following the ground rules established above. It is best to catch this problem early in the evaluations. For example, if a pilot gives a VCR that seems unreasonable, it is best to stop and go over the ground rules rather than proceed and try to make sense of the ratings later. Comments that relate to the quality of the scene rather than ability to be precise and aggressive are a good clue that the pilot does not understand the process.

3.2.7 Character of Attitude Hold and Heading Hold Response-Types

Data Requirements: $\theta, \phi, \psi, \delta_B, \delta_A, \delta_P$

Input Type: Pulse in lateral (longitudinal) (directional) controller (if Hold function required)

Test Technique:

Testing is necessary if Attitude and/or Heading Hold modes are implemented, whether or not specified as a requirement by Table IV in ADS-33E-PRF.

This requirement can be tested with a cockpit control input for an ACAH Response-Type. A cockpit controller input is not appropriate for an RCAH Response-Type.

For a, RCAH Response-Type it is necessary to modify the test rotorcraft to allow a pulse input to be injected directly to the actuator.

While the specification calls for a "pulse" input, the intent is to disturb the helicopter from trim, and observe the response when the input is removed. The input can be injected slowly and removed in a stepwise fashion. Inputs used for this test should be accomplished by releasing the controller rather than returning the controller to zero.

Since the lower limit on all hold functions is one degree, inputs should be at least large enough to produce more than a one-degree perturbation from trim.

For some RCAH for RCDH Response-Types, it may be possible to disable or work-around the rate command part of the control loop to allow use of the cockpit controller. For example, if Heading Hold is switched OFF with feet on the pedals, pedal inputs cannot be used for compliance with this paragraph. One example of an acceptable work-around is the UH-60, where microswitches on the pedals disengage Heading Hold. Inputs on the edges of the pedals do not disengage the Heading Hold, and cockpit inputs could be used for compliance as long as the microswitches are not activated.

It is important to conduct this test with essentially no atmospheric turbulence to get valid results.

If it is found to be impossible to make inputs directly to the actuator in flight test, they should at least be done in simulation. If that is the case, qualitative evaluations in moderate turbulence by at least two pilots is acceptable as a last resort.

Data Analysis and Interpretation:

When computing the settling time, zero should be where the controls are released, at the peak of the pulse input, as sketched in part (a) of Figure 4 in ADS-33E-PRF and reproduced below.

Thresholds on allowable final attitude/heading deviations are shown in part (a) of the sketch to be functions of the peak change. In reality, the text requires 10% of peak *or one degree, whichever is greater.* Since one degree is *always* greater than 10% of peak (for changes of 10 degrees or less), the actual threshold is one degree in all axes.

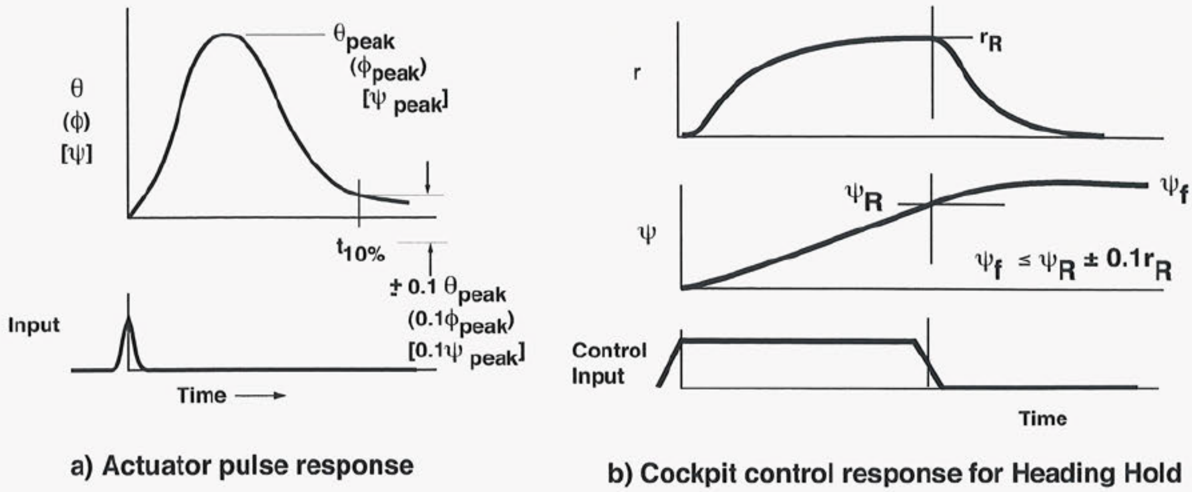


Figure 18 Illustration of Requirement for Hold Modes

If the response overshoots zero, the time to use is that for the last crossing of one degree, not the first (see sketch below). Such an oscillatory response is not desirable in any case, but small residual oscillations may exist that are well below the one-degree threshold.

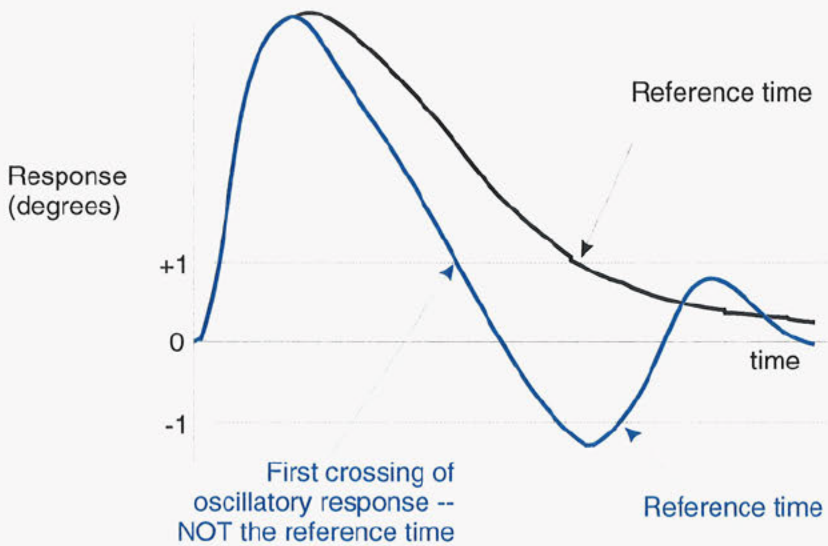


Figure 19 Interpretation of Requirement in presence of Overshoot

Alternate Criterion:

An alternate criterion for disturbance rejection is given in Section 3.3.2.2 of this Test Guide. That criterion requires that a frequency sweep be injected into the control loop at the attitude sensors, and allows for the calculation of a disturbance rejection bandwidth for Attitude Hold Response Types. Compliance with that criterion satisfies the intent of this criterion, and therefore obviates the need to include this criterion in the tailored specification.

3.2.7.1 Additional requirement for Heading Hold

Discussion: Experience has shown that this requirement is overly stringent, and needs to be modified. Suggestions for an alternate criterion that may be used until ADS-33E-PRF is updated are given below.

Alternate Criterion: Testing should show that the heading response following a pedal release from a constant yaw rate should be deadbeat as shown in Figure 18b above, but without the constraint to stop in $\Delta\psi \leq 0.10\dot{\psi}_0$.

In no case should the helicopter reverse the yaw rate to capture a reference heading.

In no case shall a divergence result from activation of the Heading Hold mode.

Test Technique for Alternate Criterion

Initiate a constant-yaw-rate turn in either direction and rapidly remove the input. If activation of Heading Hold requires further pilot action, such as removing feet from the pedals, take that action as the input is removed.

Perform the turns to the left and to the right with varying yaw rates, up to values representative of those required to perform applicable MTEs. For example, if the Hovering Turn is a required MTE, the task specifies a 180-degree turn in 10 seconds for desired performance. Therefore, compliance with this requirement should include yaw rates of at least 18 deg/sec (180 degrees/10 seconds). As noted above, the requirement to stop in 1.8 degrees is overly stringent. Simply test to ensure that the yaw rate is arrested in a "reasonable amount of time" without pilot intervention.

There is no data available to support a minimum yaw angle or time to arrest a yaw rate for a heading hold mode, hence the caveat that it must be "reasonable".

It is important to accomplish the increase in yaw rate with a slow buildup, and to release the pedals gently. That is, the pilot should not slide his or her foot off the pedal and allow it to "snap back" to center. This advice is based on a mishap at one of the test pilot schools.

Minimize excursions in the other axes, including altitude, but it is not necessary to maintain a specific ground position or altitude during the maneuver.

3.2.8 Character of Attitude Command Response-Types

Data Requirements: θ, ϕ, δ_B, δ_A, F_B, F_A, x and y groundspeeds

Input Type: Step in pitch (roll) control force

Test Technique:

Testing is required only if an Attitude Command Response-Type is required by Table IV of ADS-33E-PRF.

The specification requires that the input be a step force applied to the cockpit controller. For a passive controller (flight control system does not backdrive the controller) the input can be a step position change in the controller. That is because, for passive controllers, a step position input results in a step force input.

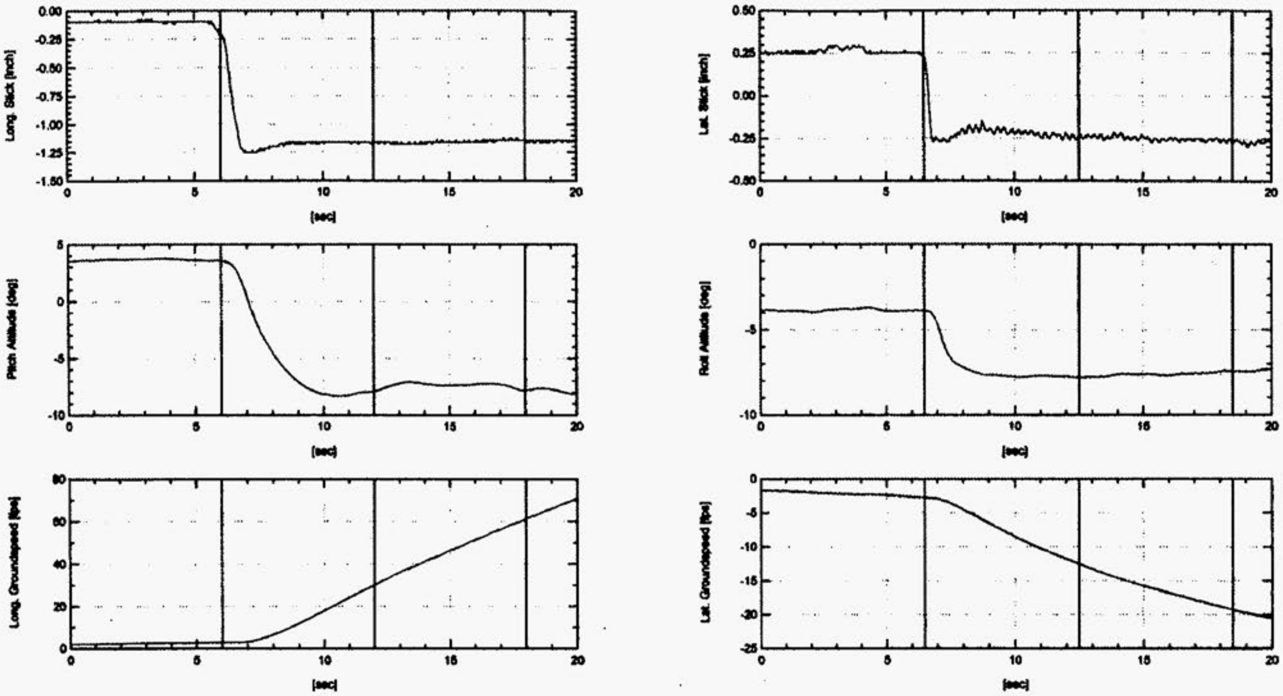
For controllers where the force is a function of deflection and aircraft state, a constant control *force* requires that the control *position* continuously vary during the run. This is common for limited authority systems where aircraft states are fed back to the controller through the parallel trim servo (e.g., UH-60 FPS). Since the controller is moving, it is difficult to hold a constant force on it. Experience has shown that using a hand-held force gauge, the pilot can keep the force sufficiently constant for the purpose of testing for this paragraph. This requires full concentration with head in the cockpit, however, so the other pilot should be monitoring the rotorcraft response very closely for flight safety.

The input must be maintained for at least 12 seconds. Input size should be varied from very small to as large as may be expected during operational use. Airspeed will necessarily change away from the trim condition following the input. For small and moderate attitude changes, typical of most low speed and hover tasks, this is not a problem. For example, for a rotorcraft with a 2 rad/sec bandwidth attitude system, a 5-degree attitude change initiated at hover will result in a groundspeed of approximately 15 kts, 12 seconds after initiating the input. For precise tasks in UCE>1, it is rare that larger attitude changes will be required.

The reason for requiring ACAH is for operations with UCE>1, so it is not particularly important to demonstrate that this criterion be met for large attitude changes. However, it is important to ensure that there are no objectionable characteristics if moderate or large attitude changes are commanded while in ACAH. Any tendency to "dig-in" and abruptly pitch up with no additional force on the controller is unacceptable. This tends to occur with limited authority systems that saturate at moderate pitch attitudes. This is discussed in detail in Reference 10 and 20.

Removal of the step can be viewed as simply another step, in this case going from a non-zero force to zero force. The removal of the step should be recorded and the 12-second response following the removal represents another data point. Aircraft with limited-authority augmentation systems have been known to have problems with saturation upon input removal, so this can be an important check of the dynamics of the system.

In the CH-47F ADS-33E compliance flight tests described in Reference 18, the pilots developed a test aid by stretching a rubber band across the gap of a U-shaped metal fixture. The copilot would hold the fixture so that the rubber band just touched the stick, at which time the pilot would drive the stick until it just contacted the bottom of the U. This method allowed sharp corners on the step input with a constraint to prevent over-driving the stick past the fixture. A sample of those results in given in Figure 20 taken from Reference 18.



a) Pitch ACAH Step Input

b) Roll ACAH Step Input

Figure 20 Illustration of Step Inputs With Simple Fixture

To check trim control, simply demonstrate that it is possible to change pitch attitude, activate the trim control, remove hands from the controller, and have the attitude remain essentially constant. While not required by the criterion, it is important that a "force-trim-release" [1] button result in immediate release of controller forces and negligible "stick jump". It should not be necessary to push the trim button numerous times or to hold it down for more than a fraction of a second while the trim takes effect.

Data Analysis and Interpretation:

The Response-Type is titled Attitude-Command-Attitude-Hold (ACAH) because that is the most common way to achieve the necessary dynamics for Level 1 handling qualities in UCE>1. (See Reference 19 for a more detailed explanation of the required dynamics to achieve Level 1 when the UCE ≥2). Linear acceleration command has been successfully demonstrated as an alternative to attitude command to meet this requirement.

Qualitatively, one can determine if the requirement is met by simply noting if the attitude holds constant or bleeds asymptotically towards trim in the steady-state (defined as 12 seconds for this requirement). If it does, compliance is assured. If the attitude continues to increase, then the

[1] The force trim release button has numerous names depending on the manufacturer. Its function is to remove all force from the controller and trim the aircraft at the current controller position.

detailed measurements specified by the requirement must be made to determine if the attitude increase with time is too large to allow the system to be considered an Attitude-Command Response-Type.

The 6 second and 12 second requirements are an admittedly crude way to quantify that the proper dynamics have been achieved using a criterion in the time domain. Furthermore the large changes in airspeed that can occur over 12 seconds can make it difficult to accomplish the test.

If there is doubt as to whether the Response-Type is ACAH, the alternative is to fly the MTEs in 3.11 in simulated UCE>1. If the pilot ratings are Level 1, the intent of the requirement has been achieved and a request for deviation is warranted. If accomplishment of the MTEs is used as a basis for deviation from this paragraph, it is necessary to take measurements of the UCE prior to making formal evaluations. <u>It is not adequate to simply put on NVGs and fly the courses, because it is often the case that the ambient lighting and course texture are such that the UCE = 1.</u> The UCE must be measured as 2, before MTE tests can be used to validate that the Response-Type meets the requirement in ADS-33E-PRF.

Finally, it is important to point out that the time response does not have to look like a pure attitude response (e.g., like that shown in Figure 31). Generally speaking, as long as the attitude does not continue to increase after the cockpit control is fixed following a step input, the Response-Type is Attitude Command[1]. Attitude "droop" is acceptable and in fact produces characteristics more akin to TRC.

Caveat for Separate Trim Control

The requirement for a separate trim control is based on the premise that an acceptable level of pilot workload requires an ability to quickly null control forces during acceleration and deceleration and when transitioning from one flight condition to another. For example, during the development of the digital flight control system upgrade for the CH-47F, the evaluation pilots insisted on having the ability to decelerate to hover by trimming nose-up and accomplishing the deceleration hands off.

Another lesson learned from the CH-47F DAFCS flight testing was that the ACAH trim control should be precise and immediate. The limited authority nature of the CH-47F mechanical flight control system resulted in a delay in achieving lateral trim after pressing the force trim release button. This was due to the need to re-center the series servo, and the delay was found to be unacceptable by the evaluation pilots. Plans are in the works to add a parallel actuator to handle lateral trim for the CH-47F. This result emphasizes the importance of an effective trim control for ACAH.

The need for a separate trim control can be circumvented by incorporating a trim follow-up, wherein the stick force to trim is slowly removed (usually with a washout or parallel integrator). This works very well in the GVE, but tends to make the response look more like a Rate Response-Type. The faster the trim follow-up, the more the system looks like Rate instead of the required ACAH Response-Type (see the Reference 9 BIUG for technical discussion). Running the trim follow-up sufficiently slow to meet the requirements of this paragraph has been found to

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[1] There are exceptions, such as with an acceleration command system wherein the attitude increases to hold linear acceleration constant. In those cases, it is necessary to show that the increasing attitude does not violate the 6 second and 12 second requirements in ADS-33E-PRF.

be a deficiency that requires improvement by some pilots who comment that the "aircraft is never in trim" and that the forces to hold the necessary attitudes are objectionable.

There has been considerable confusion when evaluating ACAH Response-Types in the GVE. The high stability and consequent sluggish response of ACAH can be objectionable in conditions of good visual cueing, whereas a Rate Response-Type with its more agile response is highly desirable. Adding a trim follow-up to an ACAH system would be viewed by pilots as an enhancing feature in the GVE because it makes ACAH look like Rate. However, in UCE ≥ 2 conditions this enhancement can become a deficiency for precision tasks.

This subtle but important distinction must be understood before accepting a trim follow-up in lieu of a separate trim controller. Furthermore, it is very important that any MTE testing to validate such a substitution must be accomplished in UCE ≥ 2. This usually means NVGs with the diopter or aperture adjustment used to simulate an overcast night (see discussion of means to simulate UCE>1 in Section 3.2.1). Simply flying with a FLIR or NVGs is not adequate because those devices produce UCE = 1 in ideal conditions. The UCE must be measured as equal to or greater than 2.

The Attitude Command Response-Type requirement in ADS-33E-PRF takes the conservative approach of requiring a separate trim control, which effectively disallows trim follow-up. This was done to ensure good handling in UCE>1 (which was the reason for requiring ACAH in the first place).

Since the publication of ADS-33E-PRF, cockpit sidestick controllers have been designed that do not have a provision for a separate trim controller, and are intended for use with ACAH Response-Types. Some manufacturers have insisted that the addition of a separate trim function to these sidestick controllers is not practical. By necessity, these controllers incorporate a very slow trim follow-up and obviously do not meet the requirement for incorporating a separate trim controller. As expected, the slow trim follow-up results in the need to hold stick force during periods of acceleration or deceleration. As of this writing, this has been judged as a shortcoming, but not a deficiency by evaluation pilots. Because, the trim follow-up is slow, the other requirements for ACAH are met, and the handling qualities in UCE>1 are Level 1 (based on simulation in UCE = 2).

Based on the above experience, it is recommended that a deviation from the requirement for a separate trim controller can be requested, providing that it can be shown in flight test that the control forces during acceleration and deceleration are acceptable, and that handling qualities in UCE>1 are Level 1. In such cases, emphasis should be placed on the Decelerating Approach MTE (Paragraph 3.11.20 of ADS-33E-PRF), and on the Precision Hover in the DVE MTE (Paragraph 3.11.1 of ADS-33E-PRF). While not given as an MTE, it should be demonstrated that the inability to manually trim during acceleration from hover to forward flight, and deceleration to hover from forward flight does not result in objectionably high control forces.

A note for the control systems specialist

This requirement is based on the knowledge that good handling qualities in UCE>1 can only be achieved if there are no poles near the origin of the attitude-to-stick transfer function. This somewhat abstract concept is the first-principle reason for requiring ACAH in UCE>1. The time domain requirement for ACAH was developed to achieve a testable way to ensure that there are no poles near the origin. It is based on the fact that the steady-state response of pitch attitude cannot keep increasing if there are no poles near the origin, and the system is stable. This is described in more detail in the Reference 9 BIUG as well as in References 16, 17, and 19.

Modification to Criterion:

The next modification to this requirement will include the following provisions:

- The criterion must only be met for attitude changes of $\pm$X degrees about trim (X is expected to be approximately 5 degrees).
- For larger attitude changes, the pitch attitude must be proportional to the force on the controller, and there shall not be a large increase in the gradient of attitude change with force input. Any deviation from this requirement shall require Level 1 pilot ratings for the Accel/Decel or Depart Abort and Lateral Reposition MTEs to GVE standards.
- A trim change shall occur within X seconds of pressing the force trim release button (X approximately 0.25 seconds).
- If a separate trim control is not supplied, a request for deviation should include Level 1 ratings for the following maneuvers:
    - Accel/Decel or depart abort
    - Hover in UCE=2
    - Slow decelerating approach from cruise to hover
    - Slow acceleration from hover to cruise.

3.2.9 Character of Translational Rate Response-Types

Data Requirements: θ, ϕ, δ_B, δ_A, x and y groundspeeds

Input Type: Step in longitudinal (lateral) controller position and force is recommended

Test Technique:

Testing is required only if Translational Rate Response-Type is required by Table IV of ADS-33E-PRF.

It is important to ensure that the controller input consists of a pure step with the following caveats.

- If the input "bleeds off", it can cause an attitude system look like a TRC system (i.e., this is cheating).
- If the input comes in too slow, any tendency for abruptness (due to excessive attitude response) will be masked. The speed of the input should be representative of the maximum rate that would be expected in operational use.

A series of step inputs should be made to achieve a range of steady translational velocities up to the maximum. For example, if the TRC blends to ACAH at 15 kts, the maximum controller step input should be that required to achieve a groundspeed of just under 15 kts.

It is important to avoid closed loop control of groundspeed to achieve these results. The controller steps should be open loop and take what you get, holding the controller constant. Using this technique, it will be necessary to iterate to find the right control input magnitude to achieve a desired groundspeed.

Apply steps in both directions. Return the controller to center, and observe that the rotorcraft smoothly decelerates to a hover.

Note that if the aircraft keeps accelerating with the controller held constant, the Response-Type is not TRC. An exception to this is given below for limited authority flight control systems.

Limited Authority Systems:

If TRC is mechanized as a limited authority system, it may be necessary to backdrive the cockpit controller to re-center the partial authority series servos. The basic concept of such systems is that the desired Response-Type is achieved by holding constant force on the controller. Experience has shown that, while not as good as a full authority system, this approach does provide some of the workload reduction that accrues from advanced Response-Types (e.g., see References 20 and 10). In this case, holding in a constant controller position input will defeat the system, and it is necessary to hold a constant force and allow the controller to move. An example of this is given for the CH-47F digital AFCS (DAFCS) longitudinal TRC in Figure 21, taken from Reference 18.

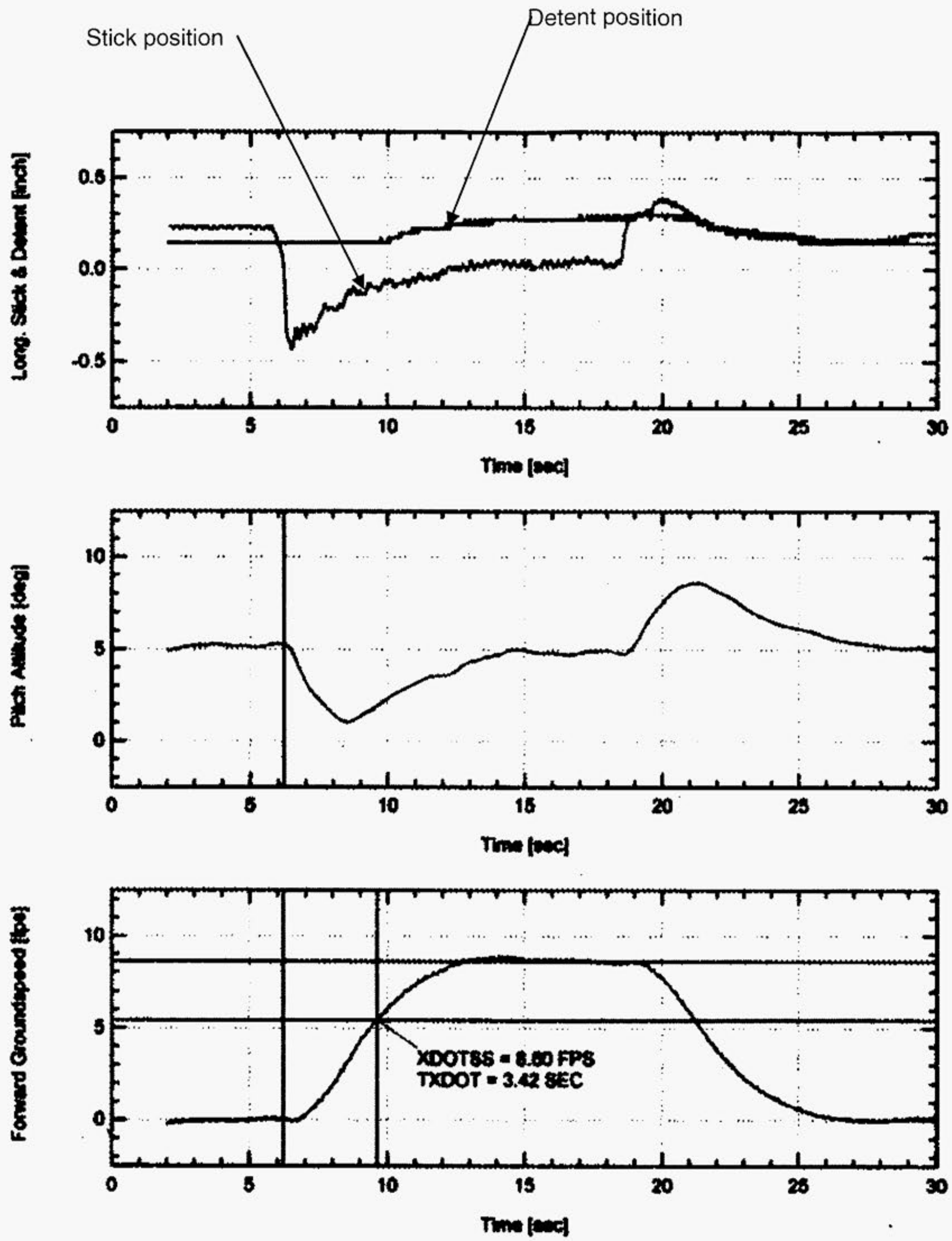


Figure 21 CH-47F DAFCS Longitudinal TRC Response

The pilot commentary for this test indicated that it was difficult to hold a constant force on the controller due to the moving backdrive zero-force position. Note that the stick position is not constant, but is steadily decreasing following the step the input. Experience has shown that it is best to focus primarily on the controller, while the second pilot looks outside. A handheld force gauge is very useful to keep force as constant as possible.

The results of this test may also be used to show compliance with the requirements in Paragraph 3.3.12 (Translational Rate Response-Type).

Data Analysis and Interpretation:

Given that the specification calls for constant force *and* constant stick position as the test input, the response shown in Figure 21 does not meet the requirement for a TRC. The criterion was written for a full authority fly-by-wire flight control system, whereas the CH-47F DAFCS is constrained to accomplish the result with a limited authority mechanical flight control system (adapted from the earlier analog system). In order to keep from running out of control authority, it was necessary to move the zero-force detent.

In the context that it is better to have TRC with force input rather than no TRC at all, this response is acceptable. Unfortunately, the control force was not measured, but it can be assumed that it was relatively constant given that it is noted in Reference 18 that the pilots were working hard to achieve that objective.

It is notable, that as of this writing, the CH-47F is the only operational helicopter to incorporate TRC.

For further discussion of handling qualities with TRC, see Section 3.3.12 (Translational Rate Response-Type).

3.2.10 Character of Vertical Rate Response-Type

Data Requirements: $\dot{h}, \delta_C$ (or F_C)

Input Type: Step in position (for position collective controller) or force (for isometric controller), as appropriate

Test Technique:

Pitch, yaw, and roll attitudes are to be held constant at their trim values, much as would be done in vertical bob-up maneuver.

Maintain the step input long enough to observe that vertical velocity is constant, or is becoming asymptotic to a constant value.

Apply both up- and down-collective steps of varying magnitudes, both IGE and OGE. For safety, it may not be possible to apply large down-steps, especially IGE.

Care must be taken to ensure that engine and power-train limits are not exceeded, especially when the power margin is small.

Data Analysis and Interpretation:

The intent of this requirement is to verify that the heave response looks rate-like. Detailed requirements on the vertical response to collective inputs are given in 3.3.10, "Response to Collective Controller."

It may not be practical to achieve a steady vertical rate because of the large altitude variations that result. This will always be true for the IGE down cases. The vertical rate response should, however, show a trend towards becoming asymptotic to a constant value during the run. An example of this is shown in Figure 22, taken from Reference 6.

The fitting process included in the quantitative requirement in 3.3.10 provides additional assurance that the response is sufficiently first-order.

Check the pitch, roll, and yaw attitude time histories to ensure they are reasonably constant at the trim values that existed at the beginning of the run.

Data obtained here should be directly applicable to the quantitative height response requirement in 3.3.10. The criteria in 3.3.10 are based on an ideal step collective input, so it is important to make the input as clean as possible. Some type of control fixture is desirable. As noted in the Appendix, time = 0 is taken at the halfway point between the beginning and end of the step input.

It may be necessary to synthesize an accurate $\dot{h}$ signal from other sources. Typically, $\dot{h}$ can be estimated by complementary filtering vertical acceleration and radar altitude (e.g., see Section 3.3.10 of this Test Guide).

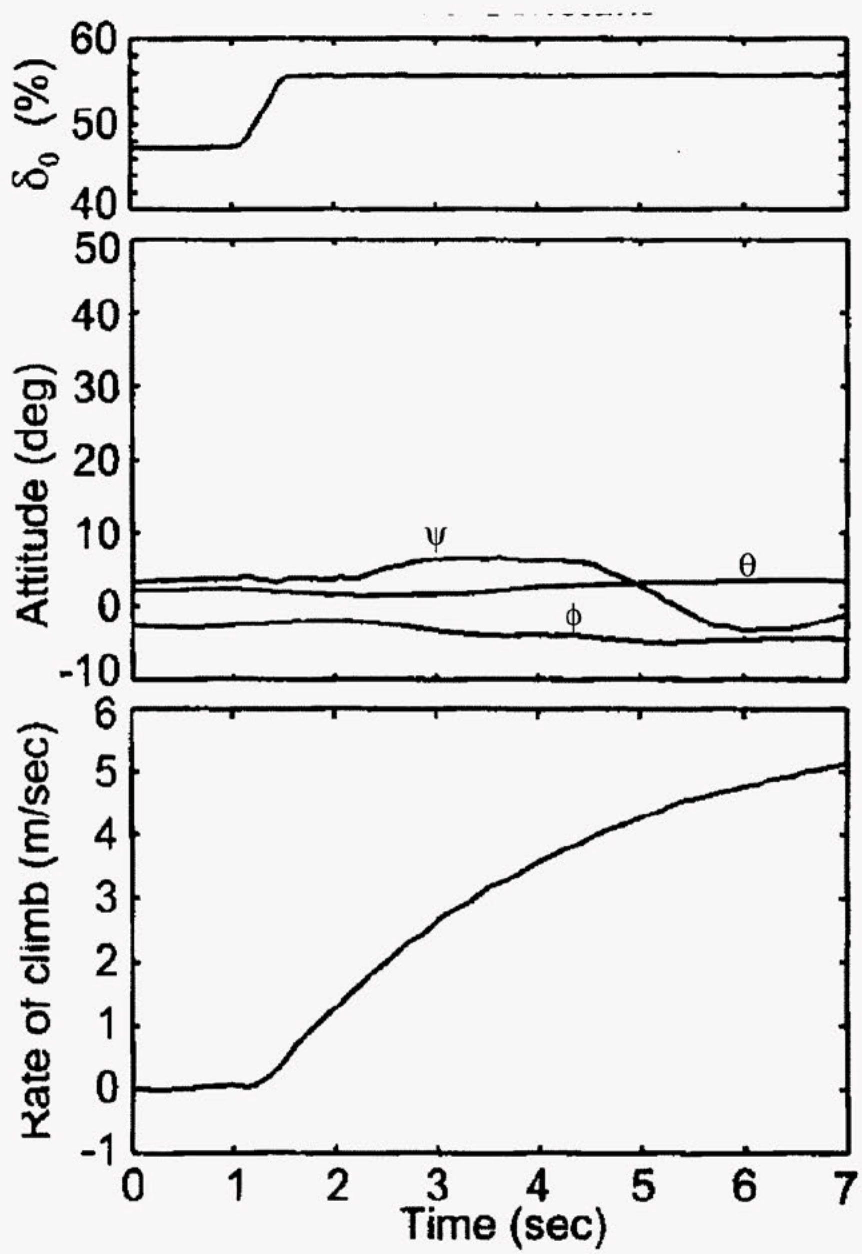


Figure 22 Response of BO 105 to Step Collective Input

3.2.10.1 Character of Vertical Rate Command with Altitude (Height) Hold

Data Requirements: h, δ_C (or F_C), vertical axis actuator position, Altitude Hold status, pilot comments

Input Type: Slowly apply an input directly into the vertical axis actuator, and remove the input after the rotorcraft exhibits the desired deviation from the reference altitude. Another possibility is to input a small step into the altitude sensor.

If radar altitude is used as the sensor, it is possible to use an abrupt change in terrain (such as a cliff or building with a flat roof) as the forcing function by moving across the edge with altitude hold engaged.

Test Technique:

Testing is required only if a Vertical Rate Command with Altitude (Height) Hold Response-Type is required by Table IV of ADS-33E-PRF.

There are three requirements imbedded in this paragraph that verify proper function of Altitude Hold. A discussion of recommended test procedures for each of these is given below.

1. *Altitude Hold function restores the rotorcraft to its original altitude following a perturbation*

It is recognized that inputs directly to an actuator or altitude sensor might represent an unacceptable level of complexity and raises safety issues. The objective is to disturb the rotorcraft from the reference altitude and observe the response. Any method that can be concocted to do that is acceptable, and it is important to note that the deviation from altitude can be accomplished very slowly.

If deviations are inserted into the altitude sensor, and that sensor is part of a redundant system, it will be necessary to take measures to avoid tripping safety monitors.

When this test is done, it is important to disturb the rotorcraft a significant amount from the reference altitude to ensure that the response does not lead to drive train over-torque or entry into autorotation. The flight control system should have limiting devices to ensure that the collective response to large altitude errors does not result in an unsafe flight condition.

We are reluctant to suggest the use of ground-based simulation to demonstrate compliance because of the problems that are associated with validating such a simulator. Nonetheless, if other measures are deemed impractical, and the vertical response of the simulation model matches flight test, it may be acceptable to demonstrate this part of the requirement via simulation. This is especially true in light of the fact that an altitude hold system that minimizes altitude excursions during the flight test demonstration maneuvers (see item 2 below) will most likely meet this portion of the requirement.

Pitch, roll, and yaw attitude excursions should be minimized during the test. Run the test long enough to verify that the rotorcraft has returned to initial trim altitude or until it has achieved no noticeable vertical drift.

2. *Altitude deviations during hover and low speed maneuvering must be within MTE limits*

This is most easily accomplished during testing for Section 3.11, "Mission-Task-Elements". The requirement specifies that the DVE (UCE>1) performance measures apply. As a result, altitude hold should be engaged to demonstrate compliance with 3.11, and additional runs to meet the requirements of this paragraph are therefore not required.

3. It must be possible to engage Altitude Hold with minimal pilot distraction.

The pilots should be requested to note any unacceptable transients associated with engagement or disengagement of Altitude Hold during NOE flight.

Verify proper engagement and disengagement of Altitude Hold by performing a series of altitude changes: from a stable hover with Altitude Hold ON, turn Altitude Hold OFF, climb or descend to another steady altitude, and turn Altitude Hold ON again. It should be possible to perform this maneuver without having to let go of the flight controls.

Data Analysis and Interpretation:

Little interpretation is required for parts 1 and 2 of this requirement as given above.

Experience gained during the development of the CH-47F DAFCS provided the following caveats regarding altitude hold in the low speed and hover flight regime.

- Radar altitude was not considered viable because of discontinuities that result when flying over obstacles. Inertial altitude hold was considered a better choice with the proviso that it does not protect the pilot from flying into rising terrain, especially in the DVE.
- It was desirable to automatically engage altitude hold when hover hold engaged.
- If automatically engaged, altitude hold should disengage automatically when the helicopter transitions from hover to forward flight.
- If manually engaged, altitude hold should remain engaged until manually disengaged.

Revised Criterion:

The ADS-33E-PRF criterion should be revised to include provisions for the following.

- Ensure that the response to an altitude excursion can not lead to drive train over-torque or entry into autorotation. The flight control system should have limiting devices to ensure that the collective response to large altitude errors does not result in an unsafe flight condition.
- Limit use of radar altitude to stationary hover.
- Require that automatic engagement of altitude hold in hover, include automatic disengagement at transition to forward flight.

3.2.11 Character of yaw response to lateral controller
3.2.11.1 Turn coordination
3.2.11.2 Rate command with direction hold

Data Requirements: Pilot comments; supporting quantitative data ($\phi, \psi, \delta_A, \delta_P$) are desirable

Discussion: These qualitative requirements are best verified by performance of relevant MTEs. The pilots should be instructed to comment specifically on the yaw response characteristics during maneuvering flight.

3.2.12 Limits on nonspecified Response-Types

Data Requirements: Pilot comments; supporting quantitative data are desirable

Discussion: The intent of this requirement is to provide the flexibility to incorporate novel Response-Types. In most cases, the basic dynamic requirements such as Bandwidth and coupling criteria will continue to apply. It will be up to the procuring activity and manufacturer to develop criteria to ensure that the Responses-Type meets its intended function.

For example, a flight path angle command and hold Response-Type should demonstrate dynamic response that ensures that the pilot can quickly capture a target flight path angle without overshoots or exceeding rotorcraft drive-train or torque limits.

The MTE testing in 3.11 will be particularly relevant when incorporating non-specified Response-Types.

3.2.14 Transition between airborne and ground operations

Data Requirements: h, $\delta_B, \delta_A, \delta_C, \delta_P$, and either actuator positions or rotorcraft states (accelerations, rates, attitudes) that can check transient responses

Input Type: Perform test maneuvers as described in the requirement

Test Technique:

This requirement is intended to test for unusual mode transition or switching problems during landing and takeoff. Most modern rotorcraft incorporate logic for determining when the vehicle is on the ground and flight control system functions can change dramatically between air and ground modes. Inputs should be planned so that operations with weight on only part of the landing gear or skids are emphasized. For example it should be possible to touch one wheel or one skid down, with the others in the air, and remain in contact for a prolonged period (several seconds) without adverse inputs from the flight control system.

Shipboard landings result in a unique set of requirements since the aircraft motions do not stop after touchdown. There is no data to develop a requirement for this, but as of this writing work is underway to develop such data.

Perform the transitions from air to ground and from ground to air in all possible combinations of gear and orientation to the slope.

The slope does not have to be too steep, since the area of concern is the initial transition itself. It should be possible to safely land and take off with normal effort.

Data Analysis and Interpretation:

The emphasis should be on operations with partial power and with one wheel or skid on the ground or landing platform.

Watch for unusual control motions required to maintain position. Vibrational modes will change, and so should notch filters or other systems intended to suppress the modes.

3.3 Hover and low speed requirements
3.3.1 Equilibrium characteristics

Data Requirements: Pilot comments; supporting quantitative data ($\theta, \phi, \delta_B, \delta_A$) are desirable

Input Type: Trim control inputs to achieve equilibrium

Test Technique:

The most common method to verify trim requirements in flight is to track a pace car or truck at varying azimuths to include the most critical azimuths.

Qualitative assessment should include control margins, ease of stabilization and trimmability, trim changes encountered, pitch and roll attitudes, power variations, control coupling, and vibrations.

Even though not required by ADS-33E, these tests are a good opportunity to take pilot comments and ratings to document pilot workload and aircraft stability as a function of wind azmuth.

Data Analysis and Interpretation:

Plots of trim pitch and roll attitudes, along with trim control positions, power required, rotor and engine torque, etc., are usually generated.

Document the most critical azimuths to determine where flight control system failures should be tested based on resulting control margins, pilot workload, and aircraft stability.

Note that control margins are suggested as an additional criterion in Section 3.1.15 "Rotorcraft Limits" of this Test Guide.

3.3.2 Small-amplitude pitch (roll) attitude changes

3.3.2.1 Short-term response to control inputs (bandwidth)

Data Requirements: The Bandwidth criterion parameters are derived from a Bode plot of pitch (roll) attitude resulting from longitudinal (lateral) cockpit controller inputs. Best results are obtained from measurement of the pitch (roll) angular rates. The attitude Bode plot is easily derived analytically from the angular rate data. Cockpit control position is required, and it is highly desirable to also measure the force on the cockpit controller so that Bode plots of pitch (roll) angle to pitch (roll) control force can be obtained. This is especially important if there is a possibility of significant lags in the feel system.

Input Type: Frequency sweep in longitudinal (lateral) cockpit controller (see description of frequency sweep in the Appendix for guidance on frequency sweep testing)

Test Technique: Experience has shown that piloted generated frequency sweeps work very well, and have the added benefit of keeping the rotorcraft in trim as long as the pilot is instructed to use low frequency inputs as necessary to stay on flight condition. The most difficult part of performing such sweeps is to get sufficient low frequency data. It is best to establish a cadence. For example, if a period of 8 seconds is desired, the cockpit controller should be at max travel in 2 seconds, pass through center at four seconds, etc.

An example of a well executed piloted-generated sweep for a UH-60 is shown in Figure 23, taken from Reference 21.

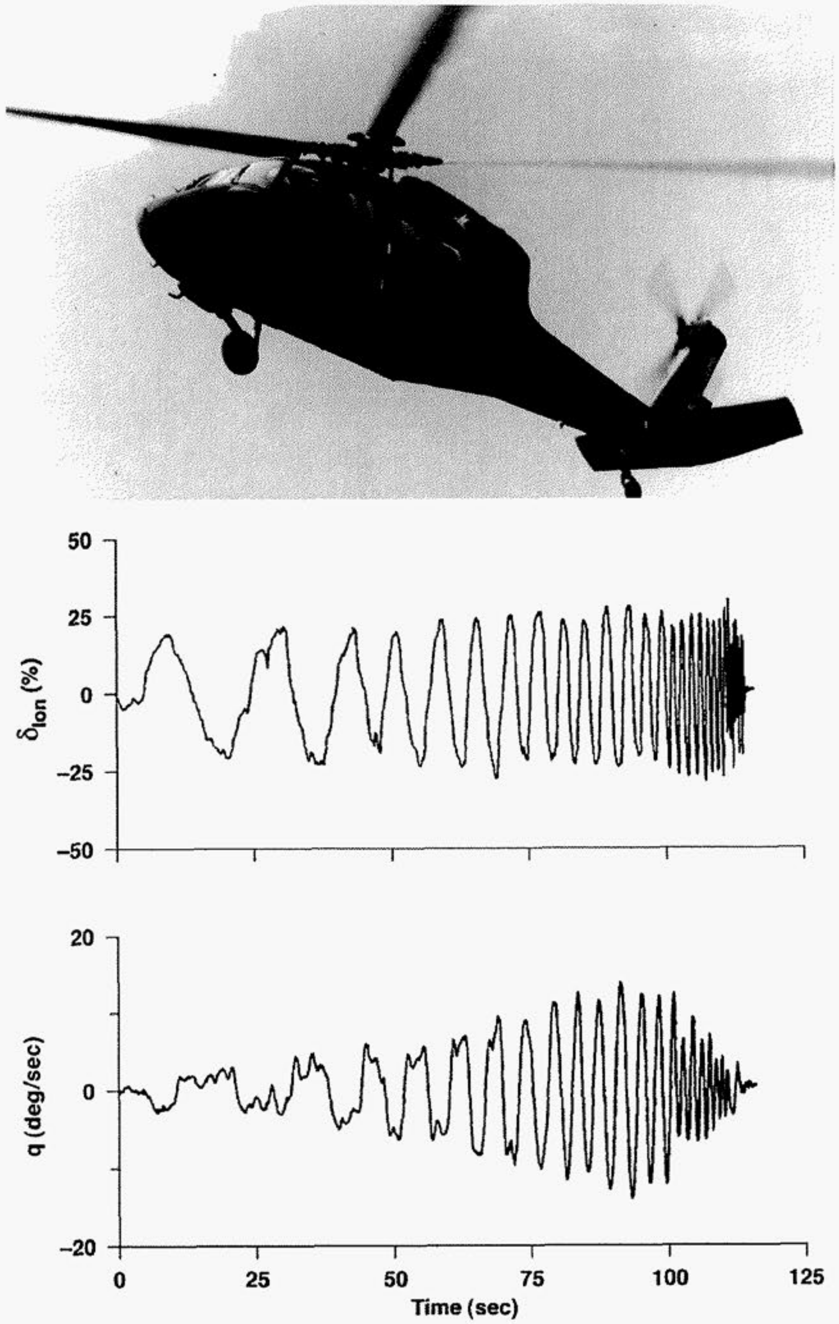


Figure 23 Example Frequency Sweep (Reproduced from Reference 21)

Automated sweeps also work well, and experience has shown that the pilot typically has no problem superimposing low frequency control inputs on top of the automated sweep to maintain trim without affecting the quality of the data. Safety considerations may dictate automated sweeps because the input amplitudes and frequencies can be tailored to ensure that excessive loads are not placed on the helicopter.

It is important to keep the inputs as close to on-axis as possible, except for low frequency inputs as necessary to maintain trim. If a test jig is not used, it is best for the pilot to look primarily at the cockpit controller when doing a manual sweep to avoid any instinctive tendency to close a loop to suppress mid and high frequency off-axis motions. Off-axis stick activity to maintain trim is acceptable, and such inputs should take the form of a "bias" on the sweep. For example, if the bank angle is increasing to the right, it is acceptable to bias the controller slightly left to slowly return to wings level while continuing the sweep.

Off-axis data that is obtained from the Bandwidth sweeps can be used to check 3.3.9.3 pitch-due-to-roll and roll-due-to-pitch coupling for Target Acquisition and Tracking. For example, roll-to-pitch coupling can be checked using the roll-rate response data to a pitch controller sweep. If the frequency sweep data for Bandwidth compliance is to be used to comply with 3.3.9.3 it is especially important to keep the inputs on-axis.

See the appendix of this test guide for more information regarding the conduct of frequency sweeps.

Data Analysis and Interpretation:

A fast Fourier transform (FFT) routine is necessary to process the frequency sweeps into Bode plots. An example of a Bode plot resulting from an FFT analysis is shown in Figure 24.

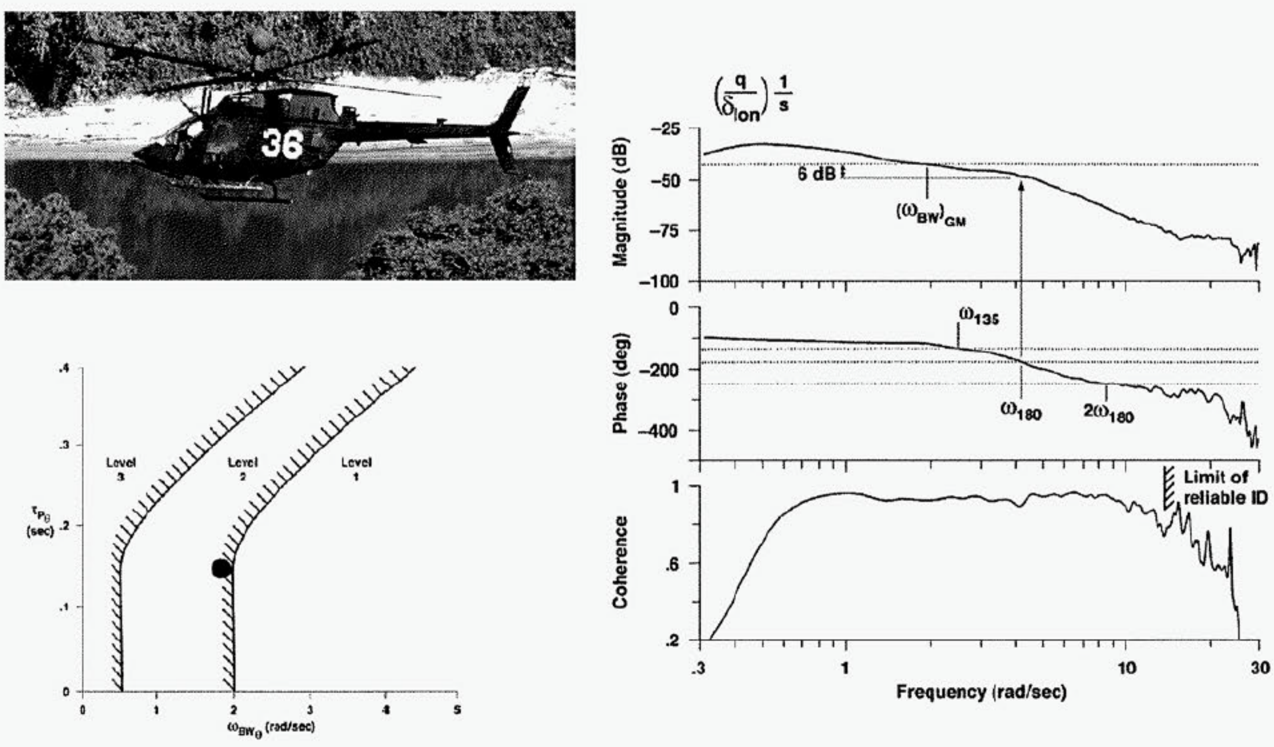


Figure 24 Example Bandwidth Compliance Data for OH-58D – SCAS-Off (Reproduced from Reference 21)

In this example, the gain margin definition is seen to apply because the gain margin bandwidth is less than the phase margin bandwidth. Note that the coherence data is plotted along with the magnitude and phase to provide a measure of the validity of the data. As a rule of thumb, the coherence should be at least 0.6 for the data to be used for compliance with the Bandwidth criterion.

An example of compliance with the Bandwidth criterion for a helicopter with an ACAH Response-Type is given in Figure 25.

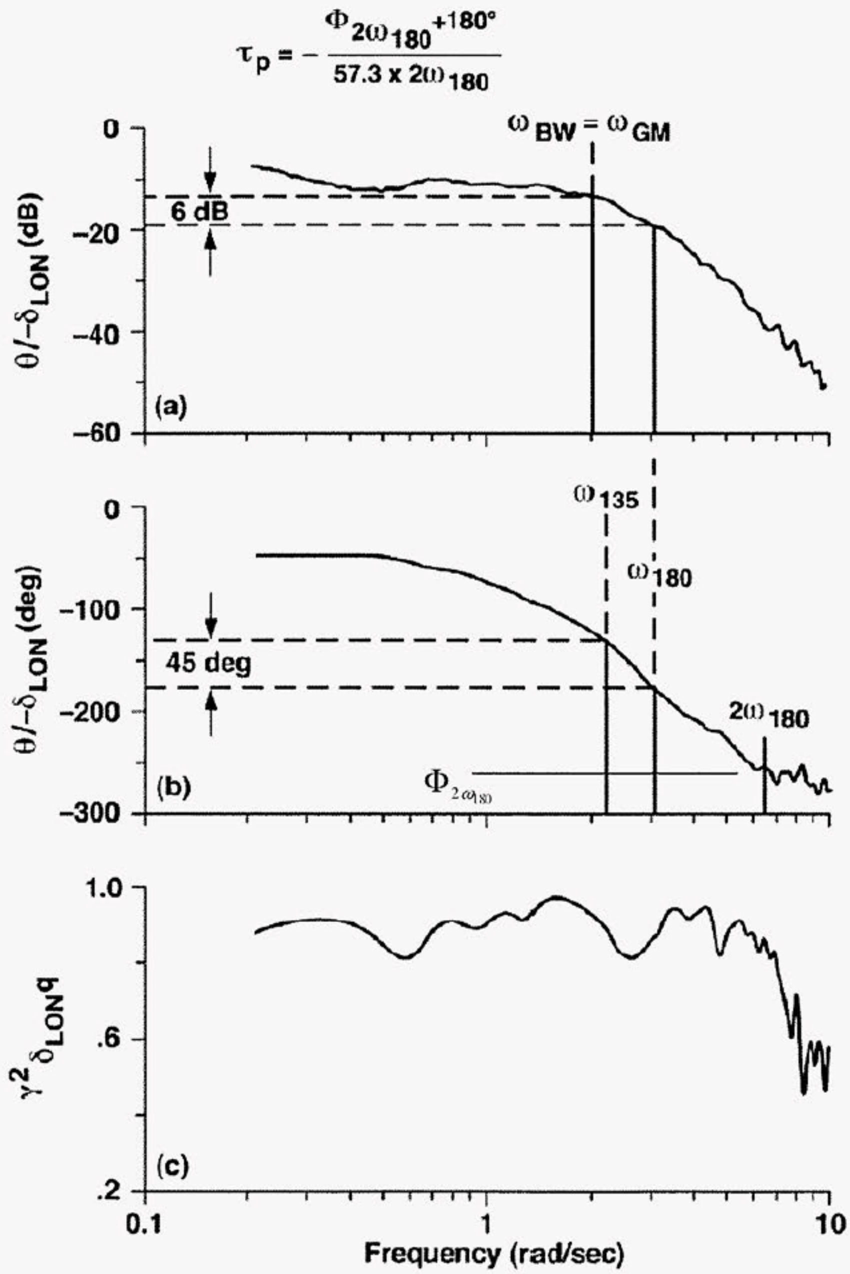


Figure 25 Frequency Response Data for Helicopter with ACAH Response-Type (Reproduced from Reference 21)

The bandwidth for this example is seen to be 2 rad/sec (Level 1) and is set by the gain margin definition. The phase margin bandwidth is only slightly higher; nonetheless, the caution note in ADS-33E-PRF applies. That note indicates that for ACAH, if $\omega_{BW_{gain}} < \omega_{BW_{phase}}$ the rotorcraft may be PIO prone for super-precision tasks or aggressive pilot technique. The Phase Delay parameter is calculated as $\tau_p = -\dfrac{-260+180}{2\times 3.05\times 57.3} = 0.223$ sec. This high value of phase delay combined with the gain margin limit should raise concern over tendencies for pitch bobble or PIO. Some development programs have concluded that ACAH systems have a generic tendency for pitch bobble where in fact it was the poor mechanization of the system that was the culprit. This reinforces the need to keep Phase Delay low for ACAH systems.

The Bandwidth and Phase Delay parameters from the Figure 25 example are plotted on the bandwidth boundaries in Figure 26.

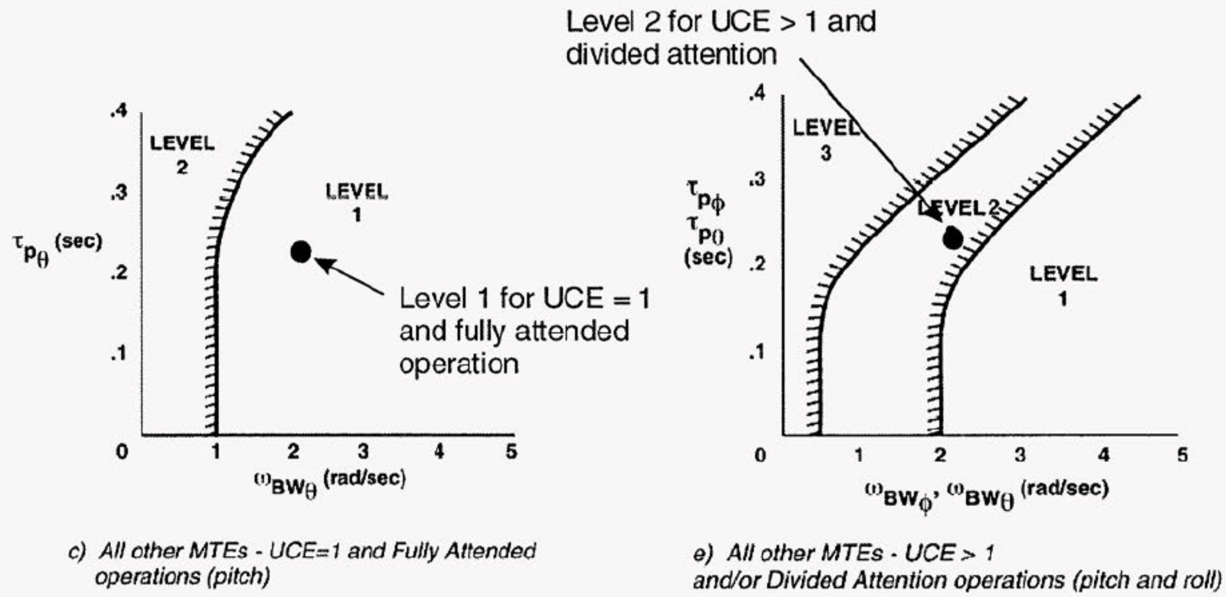


Figure 26 Example of Compliance with Bandwidth Criterion

This example illustrates how the UCE and divided attention factors into specification compliance in addition to setting the required Response-Type.

The two most popular tools for obtaining a Bode plot from frequency sweep data consist of the MATLAB® routines contained in The MathWorks' MATLAB® toolboxes, and a program developed specifically for this application by the US Army Aeroflightdynamics Directorate (AFDD) referred to as CIFER® (Comprehensive Identification from FrEquency Response), e.g., see Reference 32.

The primary difference between these FFT methods is the ability to correctly identify off-axis dynamics. The MATLAB® FFT routine is restricted to single-input-single-output (SISO) problems, whereas CIFER® has been developed to specifically handle the multi-input/single-output (MISO) problem. A second key feature of CIFER® is "COMPOSITE" windowing which combines the FFT results for multiple spectral windows to achieve a frequency response identification of acceptable quality and dynamic range.

The SISO and MISO solutions are discussed in detail in Chapter 9 of Reference 21. A brief overview is given as follows.

- A SISO method is satisfactory for on-axis frequency response calculations (e.g., p/δ_{lat}), such as is used to calculate Bandwidth and Phase Delay.
- A SISO FFT method will be satisfactory for off-axis frequency response calculations (e.g., q/δ_{lat}) such as would be used to calculate the coupling criterion parameter in 3.3.9.3 if at least one of the following conditions is satisfied (see Reference 21):
    1. Interaxis coupling is negligible (rare for helicopters).
    2. Secondary cockpit control inputs are uncorrelated with the primary input.

Since helicopters generally have significant interaxis coupling, the use of a SISO FFT technique requires that the second of the above two conditions be satisfied when accomplishing the frequency sweeps. Experience has shown that this is difficult to do in the presence of significant coupling. In theory it means that the pilot must not respond to off-axis aircraft motions except to bias his or her inputs to stay in trim. Such bias inputs must not be correlated with the primary input. As noted above, this is best accomplished by looking primarily at the cockpit controller during the sweep so as not to instinctively respond to off-axis aircraft motions, and to restrict controller movement to the desired axis. An occasional glance at the aircraft instruments is necessary to apply the required control bias to stay near the trim point. Note that the presence of a SAS will automatically result in correlations between the off-axis response and the primary input. In short, it is best to use a MISO solution when extracting the off-axis frequency response.

The examples in Figure 27 were taken from Chapter 9 in Reference 21 and are the result of using CIFER® to obtain Bode plots from a frequency sweep of a highly-coupled helicopter. It is possible to configure CIFER® to accomplish SISO and MISO solutions, and that was done to obtain the plots shown in Figure 27. The plots on the left show that the SISO and MISO FFT method provide essentially the same solution for the on-axis response (p/δ_{lat}). However, the plots on the right indicate that the solutions are quite different for the off-axis response (q/δ_{lat}) and that the MISO technique results in much better coherence. The difference in response for the off-axis indicates that the off-axis pilot inputs (δ_{lon}) were correlated with the on-axis inputs (δ_{lat}). That is, the pilot was intentionally or unintentionally trying to minimize the pitch response resulting from the lateral frequency sweep. In this case the MISO analysis must be used.

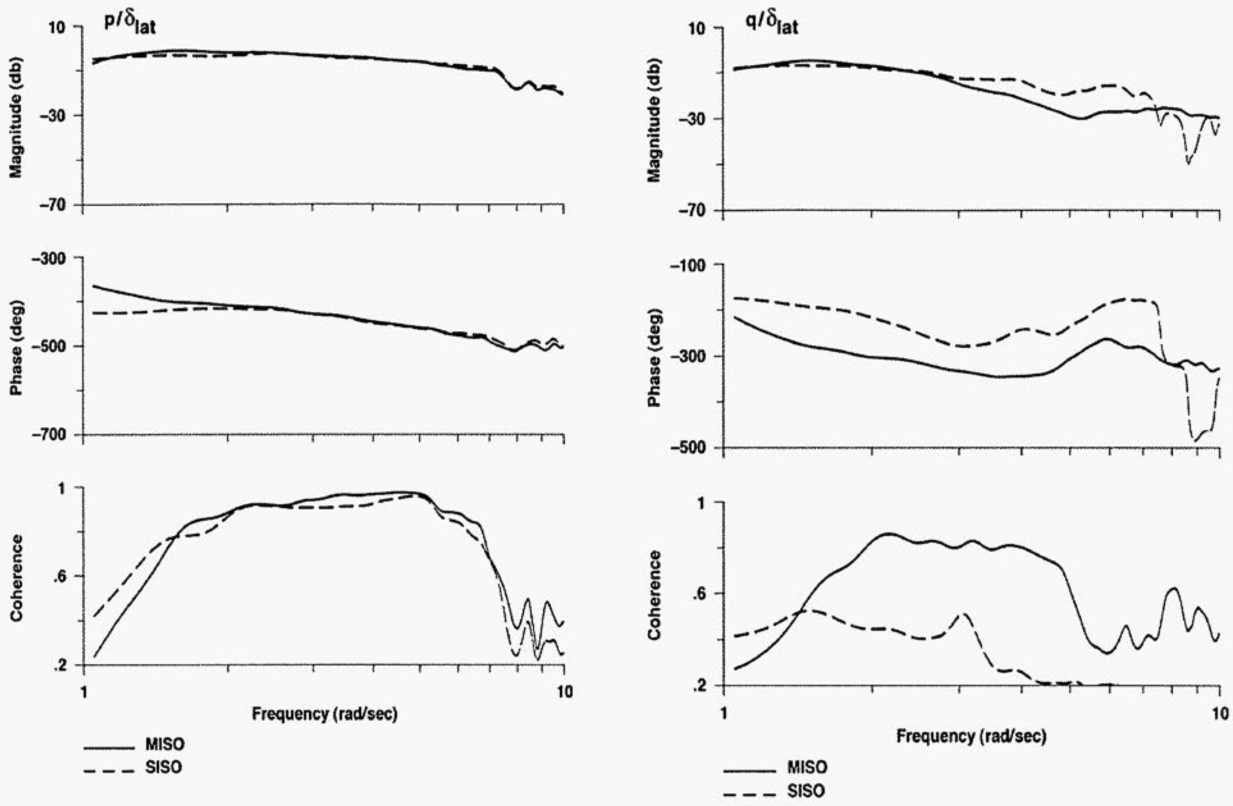


Figure 27 Comparison of SISO and MISO FFT Results (From Reference 21)

In summary the FFT method to obtain Bode plots is not critical for on-axis data that is used to calculate Bandwidth and Phase Delay. For off-axis Bode plots, the use of CIFER® eliminates the need for pure on-axis control inputs during the frequency sweeps, which are difficult to achieve for helicopter flight testing. SISO programs (e.g., MATLAB®) may be used for the on-axis responses, but it is critical to ensure that off-axis control inputs during the frequency sweep are restricted to low frequency trim or an occasional pulse to stay on flight condition.

In most cases, there is very little interpretation required for compliance with the Bandwidth criterion. However, there are exceptions such as illustrated by the results shown in Figure 28, taken from Reference 6. Here it is seen that for most conditions, the BO-105 easily meets the most stringent of the requirements from ADS-33E-PRF. However, the data points for 20-kt leftward and 15-kt rearward flight both show a marked reduction in pitch attitude Bandwidth and fail the criterion.

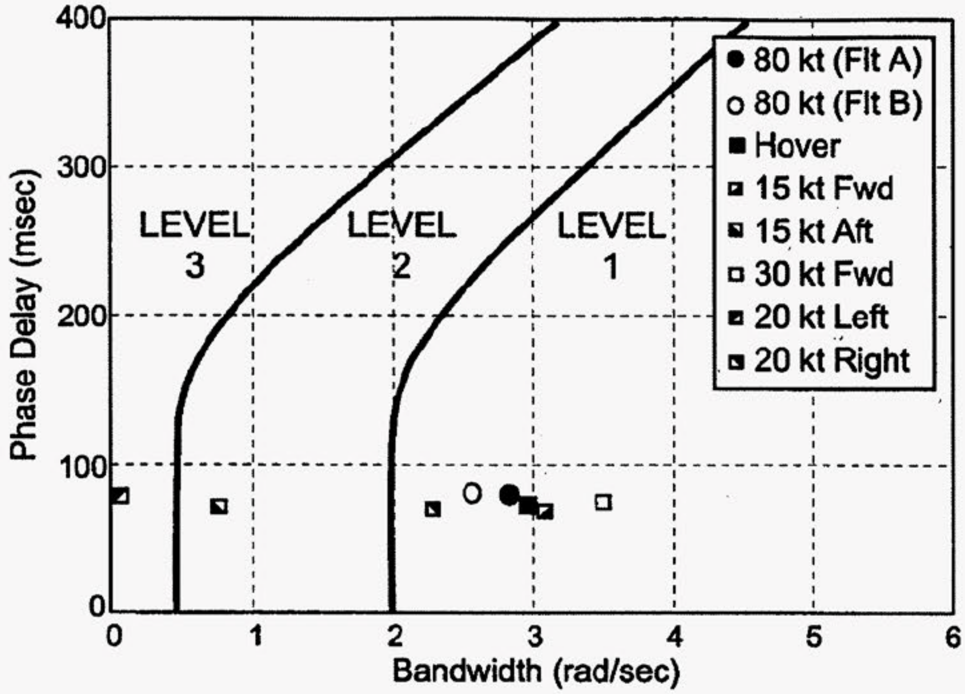


Figure 28 BO 105 Pitch Attitude Bandwidth from Reference 6

One conclusion from this data is that the BO 105 pitch attitude Bandwidth is very sensitive to wind direction. Before drawing such a conclusion, one must ask why a rotor system would be sensitive to wind direction. Degradation in directional control is expected due to tail-rotor effects, but it is not clear why the pitch attitude Bandwidth should be adversely affected to the extent shown in Figure 28, if at all. The first step in such a case should be to review the Bode plots used to extract the suspect data points. This is provided in Figure 29 for the rearward flight (tailwind) case.

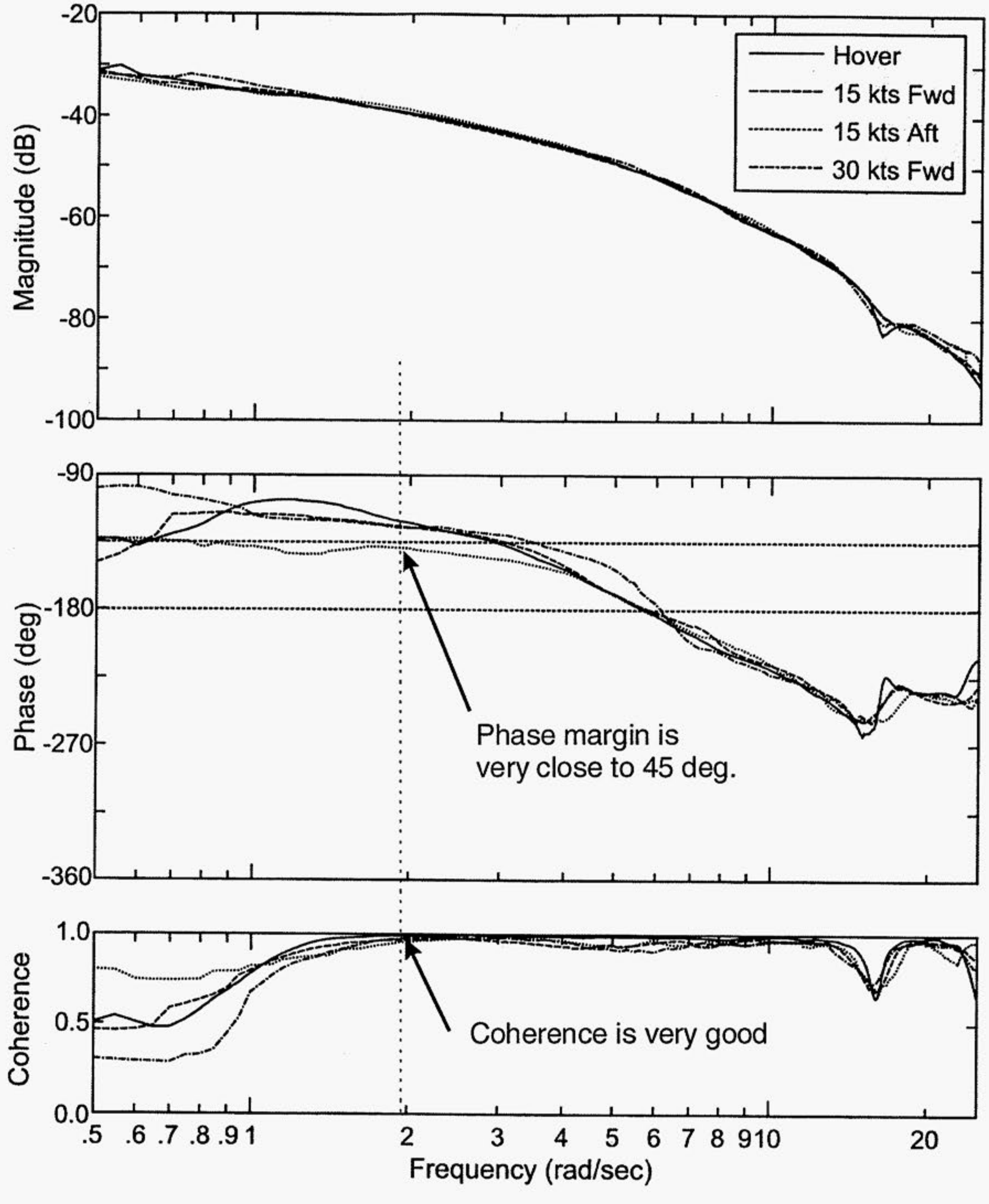


Figure 29 Bode Plot to Support BO 105 Bandwidth Calculations for Headwinds and Tailwinds (from Reference 6)

The coherence is shown to be acceptable (i.e., greater than 0.60) in the frequency range of interest, so there is no reason to believe that the frequency response plot is not a valid representation of the dynamics.

The data in Figure 29 indicates that the phase characteristics for the 15 kts aft case are such that 45 degrees of phase margin occurs at a very low frequency, hence the very low bandwidth shown in Figure 28. However, note that the phase remains very close to -135 deg (45 deg phase margin) and begins to roll off between 2 and 3 rad/sec.

The intent of the Bandwidth criterion is to determine if there is sufficient phase margin to allow the pilot to close the attitude loop at 2 rad/sec without threatening stability or using lead equalization. In order to convert this general intent to a criterion, it was necessary to pick a representative phase margin, which was selected as 45 degrees. The phase for 15 kts aft flight could be said to meet the intent of the criterion because the phase margin is very close to 45 degrees at 2 rad/sec. In this case, an argument could be made to request a deviation and plot the bandwidth at 2 rad/sec, with the caveat that Level 1 handling should be verified in flight test for this flight condition.

One of the objectives of including MTE maneuver requirements in ADS-33E-PRF was to check on quantitative requirements such as Bandwidth, especially for cases where compliance is marginal. It therefore is highly appropriate to focus on those MTEs that provide pilot rating data and commentary to support a request for a deviation from a quantitative requirement such as is suggested above. In this example, the request for a deviation from the pitch attitude Bandwidth criterion should be accompanied by the results of the Hover MTE in a tailwind of approximately 15 kts. Special emphasis should be placed on pilot commentary related to any change in the precision of pitch attitude control when this maneuver is conducted in a headwind, no wind, and a tailwind.

Consider now, the Bode plot for the 15 kts right flight condition as shown in Figure 30.

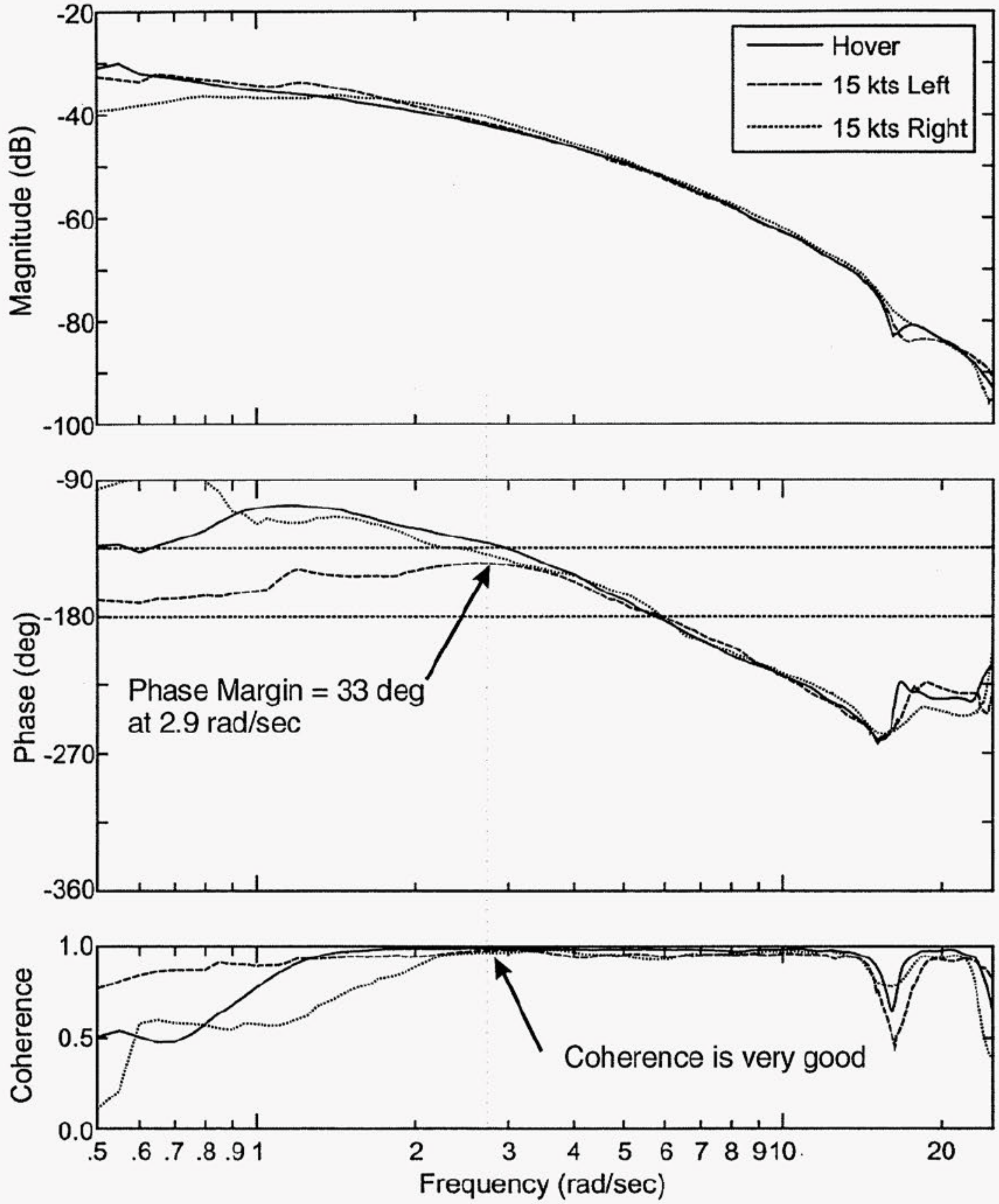


Figure 30 Bode Plot of Pitch Attitude Response to Longitudinal Stick Inputs (From Reference 6)

The coherence is shown to be acceptable (i.e., greater than 0.60) in the frequency range of interest so there is no reason to believe that the frequency response plot is not a valid representation of the dynamics.

The Bandwidth for this flight condition is plotted as zero because the phase margin never reaches 45 degrees. Nonetheless, one could argue that there is reasonable phase margin at frequencies as high as 2.9 rad/sec so that the handling qualities should be at least Level 2. Again, the intent of the Bandwidth criterion is to indicate the highest frequency that the pilot can close the loop without threatening stability. Unfortunately, the criterion does not account for conditionally stable systems, where the phase margin does not quite make it to 45 degrees.

The lack of phase margin at low frequency is not of great concern, and some unaugmented helicopters exhibit this characteristic and have Level 1 bandwidth. Because this flight condition results in a conditionally stable system with a maximum phase margin of 33 deg., a request for deviation would require that substantiating data be obtained from conduct of the MTEs as discussed above. A logical MTE would be the pirouette, wherein the evaluation pilots would be asked to comment on differences in their ability to precisely control pitch attitude when translating left vs. translating right. Note from Figure 28 that the pitch attitude Bandwidth is predicted to be Level 1 for right translation and Level 3 for left translation. It is important to focus on pitch attitude control, and not get "sidetracked" by other problems. For example, there may be a directional control power, or a tail rotor vortex ring-state issue for left translation that does not exist for right translation. The pilot comments for the BO 105 in Reference 6 show concern with low precision and predictability for pedal inputs, and there is no mention of pitch control problems.

The Bandwidth criterion contains a provision that in addition to controller position inputs, "it is desirable to also meet this criterion for controller force inputs". This is included because there are no requirements in this specification – or in any military flying qualities specification, for that matter – dealing with the dynamics of the cockpit force-feel system. When well-designed, the feel system is transparent to the pilot, but when implemented poorly, it can have a drastic impact on handling (e.g., see Reference 22). Therefore, as a check of the force feel system, it is desirable to obtain Bode plots with both position and force as the measured inputs. If the data are obtained from frequency sweeps, the same sweeps can and should be used, and FFT performed, with both force and position as the input parameter. This, of course, requires that the controls be instrumented with position and force sensors.

If the rotorcraft passes the criterion with position as the measured input and fails with force input, the paragraph requires "further flight testing," but is not specific as to exactly what should be accomplished. The intent is to utilize the applicable MTEs in Section 3.11, with special emphasis on perceived lags in the flight control system when making comments to support the assigned HQRs.

As noted above the Bandwidth criterion contains a provision for attitude Response-Types that states "if the bandwidth defined by gain margin is less than the bandwidth defined by phase margin, or is undefined, the rotorcraft may be PIO prone". This caveat is included in the criterion because bandwidth for Attitude Command Response-Types is defined only by the phase margin definition. A gain margin limit is not specified for Attitude Command Response-Types, because there was not sufficient data to set a limit, and the fact that gain margin can be undefined. The scenario that results in undefined gain margin bandwidth is illustrated in the sketch of the Bode plot of a generic Attitude Command system in Figure 31.

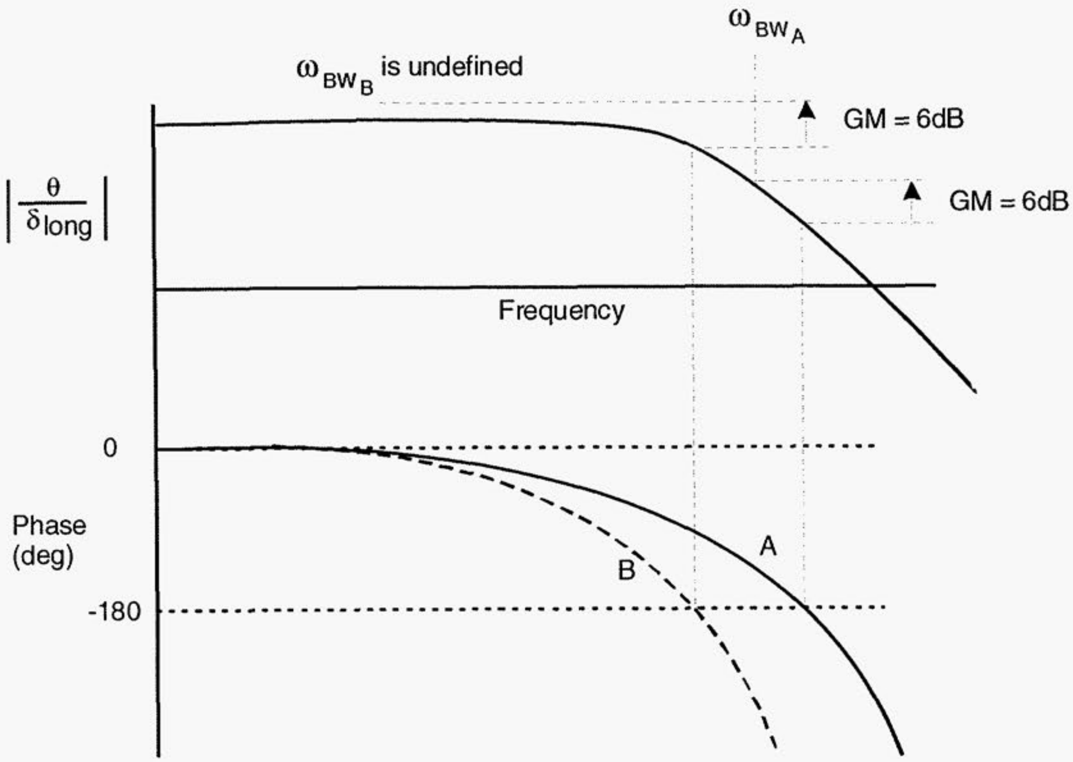


Figure 31 Illustration of the Effect of Gain Margin for ACAH Response-Type

If the phase roll-off is gradual as per phase curve A, then the gain margin bandwidth is defined as shown (ω_{BW_A}). However if the phase roll-off is more rapid as illustrated by phase curve B, the gain margin bandwidth becomes undefined. Experience has shown that a rapid phase roll-off (high phase delay) combined with a flat frequency response plot indicates a tendency for PIO at worst, and a tendency for pitch bobble at best.

The flat shape of the magnitude plot at frequencies below the bandwidth frequency is inherent to an ACAH Response-Type. Therefore it is very important to pay special attention to keep the Phase Delay parameter as low as possible for ACAH Response-Types. When the gain margin bandwidth is less than the phase margin bandwidth or is undefined, a tendency for pitch bobble or PIO is expected. This was kept as a recommendation instead of a requirement because of a lack of data that could be used to support a specific limit on gain margin or bandwidth degradation that defines where pitch bobble begins.

3.3.2.2 Short-term pitch and roll responses to disturbance inputs

Data Requirements: $q, p, \theta, \phi, \delta_B, \delta_A$; or if compliance is by analysis, the Bode Plot for pitch and roll attitude to controller input.

Input Type: Frequency sweeps in pitch (roll), inserted directly into the control actuators, or by analysis of cockpit controller frequency sweeps.

Discussion: When ADS-33 was first developed, it was anticipated the short-term response to control inputs (Bandwidth) would be achieved through feedback and this would also provide a benefit against atmospheric turbulence. The intent of the short-term pitch and roll responses to disturbance input criteria is to ensure that the required control response Bandwidth is not achieved with forward-loop shaping, thus neglecting the potential benefits for disturbance rejection associated with feedback. At the time of this writing, there is disagreement regarding the ADS-33E-PRF specification for regulation against disturbance inputs. Some contend that simply requiring some level of bandwidth with feedforward shaping excluded does not drive the design to achieve satisfactory gust rejection. It is in fact true that this requirement does not guarantee regulation against disturbances.

AFDD has developed a more comprehensive disturbance regulation requirement, and this is presented in this test guide as an alternative to the ADS-33E-PRF requirement. It is anticipated that at the next update to ADS-33E-PRF this alternative requirement will be implemented as the Disturbance Rejection Bandwidth ($\square_{drb}$) criteria and the current short-term pitch and roll response to disturbance input criteria will be dropped.

Until a revision to ADS-33E-PRF is accomplished, it is felt that providing an analytical method to comply with the current requirement as written provides a reasonable alternative to making inputs directly to the actuator. If this analytical approach is not practical for a given application, then the alternative AFDD requirement is recommended.

Test Technique:

The ADS-33E-PRF criterion for disturbance inputs requires a frequency sweep directly into the actuator. Frequency sweep inputs to the actuator are not always possible, and raise understandable concerns regarding flight safety, so an alternative analysis method is supplied below to meet the intent of the criterion.

If there is no feedforward shaping, this requirement does not apply as meeting the basic Bandwidth criterion in 3.3.2.1 is sufficient. This requirement also does not apply for an unaugmented rotorcraft (no feedback or forward loop shaping).

The following data analysis and discussion also applies to the ADS-33E-PRF disturbance rejection requirements in 3.3.7 and 3.4.11.

Data Analysis and Interpretation:

If a frequency sweep is injected into the actuator, the bandwidth is calculated in the usual way. Phase delay is not a factor for disturbance regulation, so it is not necessary to calculate τ_p.

It may be more practical to calculate the short-term pitch and roll response to disturbance inputs analytically in lieu of inserting a frequency sweep into the actuator. This analysis procedure requires that the user isolate the command shaping G_M and feed forward equalization G_a as defined in Figure 32. When properly done, this provides the same result as a frequency sweep into the actuator, as will be shown below.

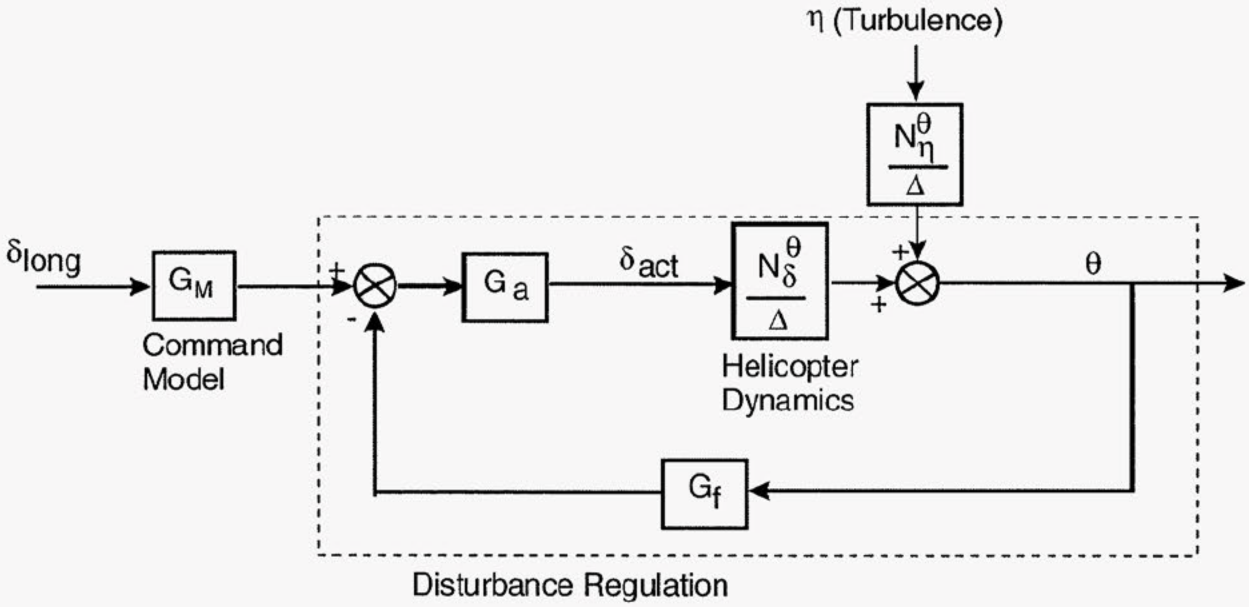


Figure 32. Generic Block Diagram of model following flight control system

G_a = Transfer function that represents forward loop equalization

G_f = Transfer function that represents feedback loop equalization

G_M = Transfer function that represents the command model.

θ / δ_{act} is obtained analytically by post processing the frequency sweep data used to comply with the control input Bandwidth criterion (e.g., 3.3.2.1), to remove the effect of the command model, G_M and to account for forward loop shaping, G_a.[1] Such post processing consists of multiplying the frequency response of the attitude response to longitudinal controller input $\left(\frac{\theta}{\delta_{long}}\right)$ by 1/ ($G_M G_a$), That is:

[1] This discussion uses nomenclature that represents the pitch attitude response to longitudinal controller and disturbance, but is intended to apply to the roll and yaw axes as well.

$$\frac{\theta}{\delta_{act}} = \frac{1}{G_M G_a} \frac{\theta}{\delta_{long}}$$

The Bandwidth of (θ / δ_{act}) is defined as short-term pitch response to disturbance inputs and is plotted on the same boundaries as the control input Bandwidth (Figures 5 and 9 in ADS-33E-PRF) assuming zero phase delay ($\tau_p = 0$). This can be construed as measuring the combined Actuator-Rotor Bandwidth. A vehicle with a high bandwidth rotor response can easily pass this criteria even with no attitude feedback to improve disturbance rejection.

The use of the same bandwidth criterion values for control input and disturbance input is not supported by data and is probably overly restrictive. The U.S. Army Aeroflightdynamics Directorate (AFDD) plans to accomplish a simulation on the NASA Ames Vertical Motion Simulator (VMS) to determine Level 1 and Level 2 limits for disturbance rejection bandwidth (the alternative AFDD criteria). In the interim, it seems reasonable to only require the lowest value of Bandwidth for disturbance inputs, which is 1.0 rad/sec (see Figure 5c in ADS-33E-PRF).

Only the phase margin definition of bandwidth should be used because the gain-margin definition of Bandwidth is based on human pilot loop closure characteristics that are not a factor in turbulence rejection.

The criterion allows the user to eliminate the need for testing if the bandwidth and phase delay can be shown to be equal for controller inputs and actuator inputs. This amounts to showing that G_M and G_a have no dynamics (i.e., are gains).

Identification of G_M and G_a can be accomplished with block diagram algebra. This might prove difficult for complex flight control systems with many feedforward paths. When that is the case, simply accomplish a manual or automatic frequency sweep at the cockpit controller while on the ground and measure the input to the actuator. That is, $\frac{\theta}{\delta_{act}} = G_M G_a$ because all feedback paths will be constant when the helicopter is on the ground (assuming that controller position itself is not used as a feedback). This procedure can also be accomplished in simulation (e.g. a Matlab® Simulink® model) with the aircraft states frozen, or feedback loops opened. If simulation is used, it is important to ensure that the flight control system is accurately modeled. Note that the aerodynamic model is irrelevant for the determination of G_M and G_a, which greatly simplifies the required simulator validation and/or Simulink model.

Rationale for Compliance by Analysis.

The rationale for this criterion is that requiring a minimum bandwidth in the feedback portion of the flight control system ensures that any augmentation used to achieve Level 1 Bandwidth to the cockpit controller input, also provides some level of disturbance regulation.

The linear relationship between the bandwidth to control inputs and to turbulence inputs is given as follows.

$$\frac{\theta}{\delta_{long}} = \frac{G_M G_a N_\delta^\theta}{\Delta + G_a G_f N_\delta^\theta} \quad \text{- attitude response to cockpit control input} \tag{1}$$

$$\frac{\theta}{\eta} = \frac{N_\eta^\theta}{\Delta + G_a G_f N_\delta^\theta} \quad \text{- attitude response to turbulence} \tag{2}$$

Where N_x^y is the numerator of the transfer function of the response of y to an input x and Δ is the characteristic equation (e.g., see Reference 23).

Note that the difference between the response to a gust input and to the longitudinal controller input lies entirely in the numerator transfer functions. That is, the characteristic roots are identical for turbulence and command inputs. The intent of this criterion is to ensure that the bandwidth of θ / δ_{long} is not strongly affected by the forward loop shaping, $G_M G_a$. That is achieved by setting a minimum value of bandwidth for $\frac{\theta}{\delta_{act}} = \frac{\theta}{\delta_{long}} \frac{1}{G_M G_a}$. Note that this gives "credit" for any bandwidth achieved through G_a as part of the feedback loop, but not as part of the forward loop shaping, and gives no bandwidth credit to G_M.

Alternative AFDD Criterion:

An alternative criterion for disturbance regulation has been developed by AFDD. The procuring activity may decide that this criterion should be employed as an alternative to the ADS-33E-PRF requirement in paragraph 3.3.2.2. This would be the case if there is reason to believe that the disturbance regulation characteristics of a flight control system under development may not be adequate.

This criterion has been successfully used as a design metric for the control system design and optimization program (CONDUIT®) developed by the Aeroflightdynamics Directorate (AFDD) at NASA Ames Research Center (References 24 and 25). Examples of its application are given in References 26, 27, and 28.

The criterion is a measure of the ability of the rotorcraft to reject external disturbances. For an attitude hold Response-Type (e.g., ACAH or RCAH) this amounts to a return to trim attitude, and for a Rate Response-Type a return to zero angular rate following a disturbance. This is characterized by the following block diagram.

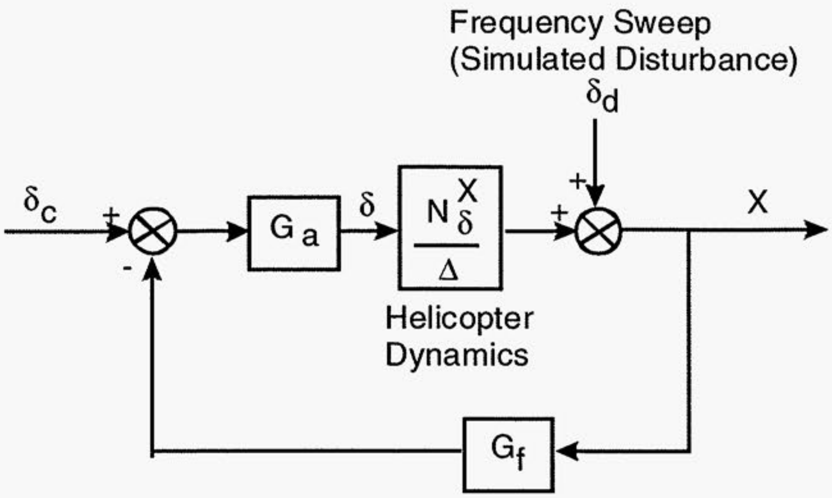


Figure 33 Disturbance Rejection Block Diagram

X in this block diagram depends on the Response-Type. If it is Rate, then X is angular rate and if it is Attitude Hold, then X is attitude.[1] The frequency sweep (δ_d) is added to X. An automated frequency sweep is the method of choice and it will be important to tailor that sweep to avoid exceeding aircraft limits. A suggested automated frequency sweep methodology is given in the appendix to this Test Guide.

Most helicopters that include forward loop shaping and a command model have redundant sensors and control lanes, and care must be taken so that injecting signals into a rate or attitude sensor does not trip a safety monitor. This may require disabling the safety monitors, or simultaneously injecting the frequency sweep into all of the redundant sensors.

This criterion can be interpreted as a direct measurement of how fast the system returns to trim after being disturbed from trim. For an attitude hold Response-Type (e.g., ACAH or RCAH) this amounts to a return to trim attitude, and for a Rate Response-Type a return to zero angular rate following a disturbance. The disturbance rejection bandwidth value is a direct measure of the tightness of the feedback loop. A higher value means a faster return to trim following a disturbance. Design for tighter disturbance response must be balanced by requirements for adequate closed-loop damping ratio.

A generic frequency response plot of the disturbance response to a frequency sweep into the sensor (see Figure 33) is given in Figure 34.

[1] Most Rate Response-Types consist of a simple SAS that would probably not have command shaping. Therefore, this criterion applies primarily to Attitude Hold Response-Types

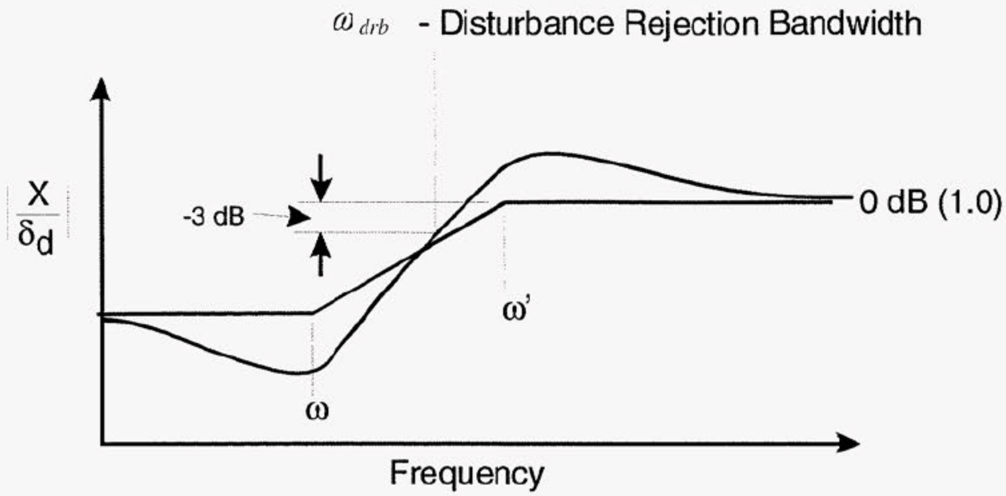


Figure 34 Typical Bode Magnitude Plot From Frequency Sweep at Output

This frequency response provides the expected result in that the high frequency asymptote shows no disturbance regulation ($|X/\delta_d|=1.0$) indicating that the disturbances are above the bandwidth frequency of the flight control system. The frequency below which the control system begins to regulate against the disturbances is taken as -3 dB from the 0 dB line and is called the Disturbance Rejection Bandwidth, ω_{drb}

Typical values for the Disturbance Rejection Bandwidth (ω_{drb}) are given in Table 6 from unpublished data for Attitude Hold Response-Types for four helicopters studied by the Aeroflightdynamics Directorate (AFDD). Qualitatively, the evaluation pilots felt that the handling qualities of these augmented helicopters were acceptable, but there was no data directly attributable to disturbance regulation. One of the four cases was from variable-stability flight test (UH-60 RASCAL) and the others from piloted simulation.

Table 6 Typical Disturbance Rejection Bandwidth Limits

Typical Values of Disturbance Rejection Bandwidth, ω_{drb} - rad/sec		
Pitch	Roll	Yaw
0.90	0.90	0.70

As noted above, AFDD has plans to conduct a simulation on the NASA Ames VMS to determine Level 1 and Level 2 values of the disturbance rejection bandwidth.

An example automated frequency sweep that was used as an input to the attitude sensors on the development of a fly by wire flight control system on the U.S. Army AFDD variable stability helicopter (RASCAL) is shown in Figure 35.

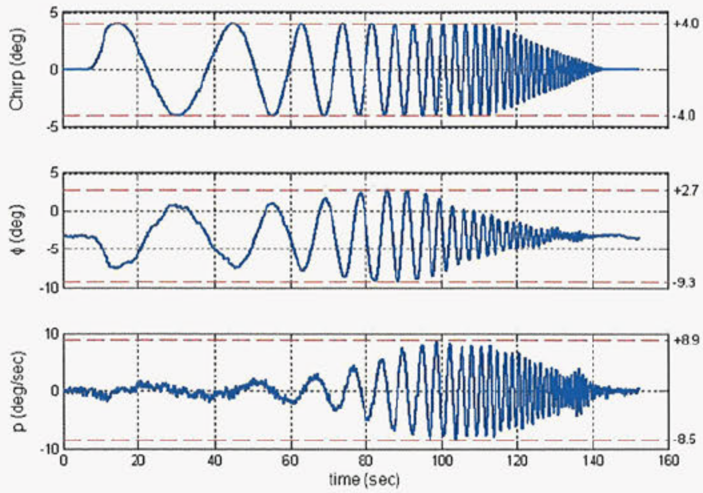


Figure 35 Automated Frequency Sweep into Roll Attitude Gyro

The data in Figure 35 was processed using CIFER® to produce the results shown in Figure 36.

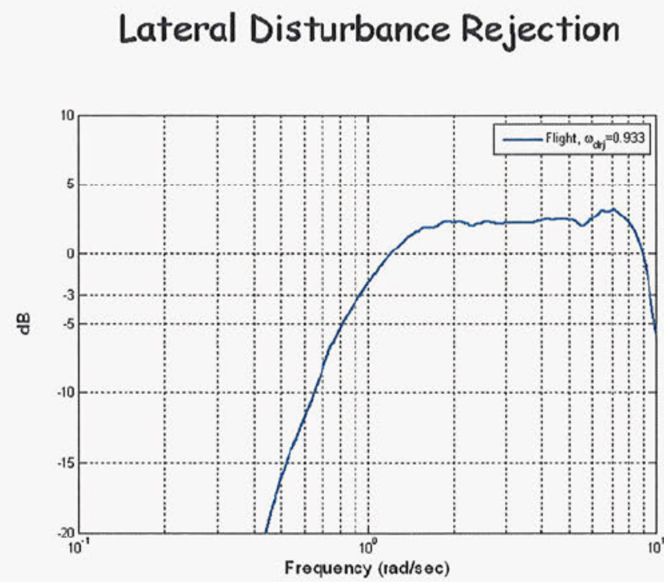


Figure 36 Disturbance Rejection Bode Plot from AFDD Flight Test

The disturbance rejection bandwidth is the frequency where the magnitude plot is -3bB, or 0.90 rad/sec for the example in Figure 36.

Rationale for alternate disturbance rejection criterion.

The response of the output X to the simulated disturbance (frequency sweep) δ_d is given as

$$\frac{X}{\delta_d} = \frac{1}{1 + G_a G_f \dfrac{N_\delta^X}{\Delta}} = \frac{\Delta}{\Delta + G_a G_f N_\delta^X} = \frac{\Delta}{\Delta'}$$

Where Δ is the characteristic equation of the helicopter response, and N_δ^X is the numerator of the X-to-δ transfer function (see block diagram in Figure 33). G_a and G_f represent feedforward and feedback equalization. Δ' represents the closed loop characteristic equation ($\Delta' = \Delta + G_a G_f N_\delta^X$).

The Bode plot in Figure 34 is defined by the ratio of the open loop and closed loop characteristic equations. The break frequency of the closed loop characteristic equation (ω') is the parameter that sets the disturbance bandwidth (see Figure 34). Note that ω' is always higher than the open loop break frequency (ω) by virtue of the fact that the natural frequency is increased by closing the control loop.

3.3.2.3 Mid-term response to control inputs
3.3.2.3.1 Fully attended operations
3.3.2.3.2 Divided attention operations

Data Requirements: q, p, δ_B, δ_A

Input Type: Pulse in longitudinal (lateral) cockpit controller is recommended

Test Technique:

It is recommended that a pulse input in lateral and longitudinal controllers be used to excite oscillations sufficiently to measure the damping ratio. Any input that excites an oscillation is acceptable, and a doublet may disturb the trim condition less, thus allowing a longer recording. Some examples are illustrated below in Figure 37.

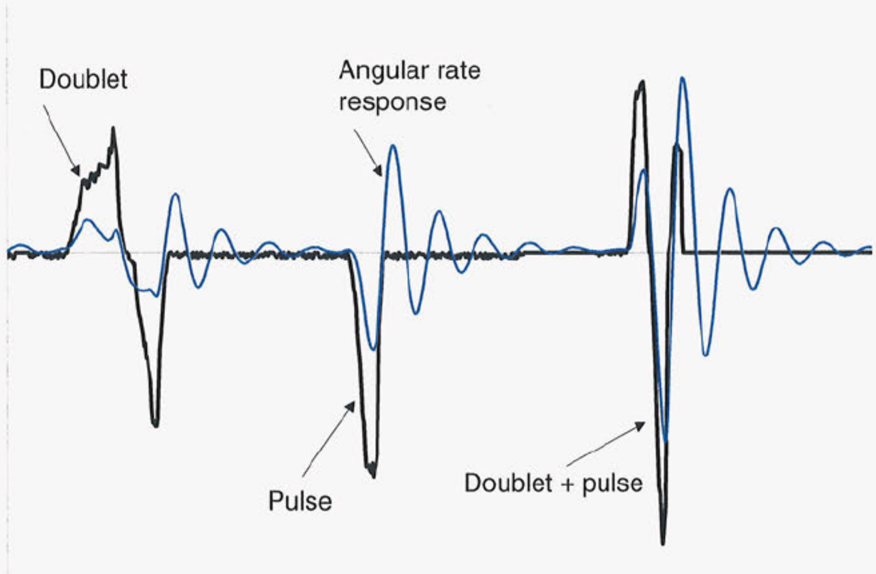


Figure 37 Doublet vs. Pulse Input to Excite Modes

It is important to establish precise trim in calm air for this test. Attain stabilized flight with all control forces trimmed to zero before making the control input.

While the requirements fall under "small-amplitude attitude changes," there should always be some concern about the possibility of an undesired oscillation for any size attitude change. Input size for most tests can be small (peak attitude change immediately following pulse rarely needs to exceed 5 degrees) but at least one large pulse input (peak attitude change on the order of 10 deg) should be applied in each axis as well, to verify that there are no nonlinearities that would cause responses that fail the criterion.

A large pulse input must be made with great care to avoid unsafe structural or dynamic load issues. Larger inputs can be made very gradually with the objective being to ensure that the response following the release of the controller is well damped.

No additional on-axis inputs should be made until oscillations have damped out. Preferably, the cockpit controller should remain hands-off for several cycles of the oscillation after the pulse is applied, although this may not be possible for some rotorcraft and flight conditions. If the controller cannot be released, it should be held fixed during the transient response. For example, one cannot release the cyclic stick on helicopters without powered controls because the swashplate feedback to the stick will cause it to go randomly hardover.

If the helicopter SAS backdrives the stick, it is important that the pilot allow the stick to remain free during the recovery transient. Such stick backdrives result when the SAS incorporates a parallel servo such as the UH-60 Flight Path Stabilization (FPS) system. The resulting stick motions may be unacceptable to the pilot. It is therefore important to look for this during the qualitative handling qualities testing of Mission Task Elements in Section 3.11.

The axes not being tested should be constrained to remain close to their initial condition values.

Data Analysis and Interpretation:

Different boundaries are invoked depending on the degree of divided attention that will be required of the pilot. The degree of divided attention required to accomplish the intended missions should be defined in the Systems Specification as required by 3.1.3. In the event that this information is not available, the following rule of thumb applies. If the rotorcraft is flown single-pilot for non-tactical missions, or dual-pilot in tactical mission scenarios, Divided Attention operations may be assumed. Operations with one pilot in instrument meteorological conditions (IMC) are always considered as divided attention. Also see the definitions in 6.2.3 of ADS-33E-PRF.

If information is taken directly from the time history, it is important to measure damping ratio and frequency from the free response, not the forced response. That is, the portion of the time history used to calculate the damping ratio should occur after the input is completed. Methods for determining damping ratio from time responses are documented in Section 3.4.7.1 (Figure 56) of this Test Guide and in Appendix B of the BIUG (Reference 9).

This requirement applies "at all frequencies below the bandwidth frequency obtained in 3.3.2.1." If there are low-damped modes near the bandwidth frequency, either bandwidth or phase delay will reflect the poor dynamic response. Low-frequency modes well below the bandwidth frequency may not impact the Bandwidth Criterion (3.3.2.1), though they can adversely affect rotorcraft handling qualities. An allowance for unstable oscillations below a natural frequency of 0.5 rad/sec reflects the knowledge that unaugmented rotorcraft may be Level 1 in the GVE.

Oscillations that occur well above the bandwidth frequency are considered to be residual oscillations and are covered under 3.1.17.

A note for the control systems specialist

The relaxation in damping allowed by this requirement is a reflection of the characteristics of the pilot in manual control. Pilots are much less sensitive to the dynamics of low-frequency modes than to those that occur near the region of piloted crossover (1 to 3 rad/sec).

3.3.3 Moderate-amplitude pitch (roll) attitude changes (attitude quickness)

Data Requirements: $q, p, \theta, \phi, \delta_B, \delta_A$

Input Type: Pulse in longitudinal (lateral) cockpit controller for Rate Response-Types; step for Attitude Response-Types

Test Technique:

This requirement is not intended to be applied to Response-Types designated specifically for use in UCE = 2 or 3. For example, if a rotorcraft has selectable AFCS modes that result in Rate and ACAH Response-Types, the Rate system is normally designated for use in the GVE and would be subject to this requirement. The ACAH AFCS mode would normally be delegated for use in UCE>1 or where divided attention is required.

From a practical standpoint, ACAH Response-Types emphasize stability for flight in UCE>1, and high agility is not judged to be necessary or even desirable. However, if an ACAH Response-Type is proposed for normal operation in the GVE, including aggressive maneuvering, compliance must be demonstrated with that system.

Testing involves large attitude changes that should be approached cautiously. Test input size should be increased slowly, starting with attempts to achieve the small-to-moderate attitude changes (10-15 degrees in pitch, 20 degrees in roll). Meeting the requirements for small attitude changes require inputs of short duration but quite large magnitude. The tests should be cleared for structural (mast bending) limits and main rotor tip-path-plane clearance from the empennage, especially in the pitch axis.

Attitude quickness testing should not be attempted without structural instrumentation. As a case in point, the RAH-66 Comanche exceeded its main rotor mast bending limit during longitudinal attitude quickness testing from hover. After significant command shaping changes (acceleration limiting) the endurance limit was still exceeded on the main rotor mast and damage tracking was required.

This experience points out the value of these tests not only to define handling qualities, but also to implicitly require input shaping such that the pilot cannot easily cause structural damage with an abrupt input.

For Rate Response Types, the proper input is a pulse in the lateral and longitudinal controllers, as illustrated by input #1 in Figure 38.

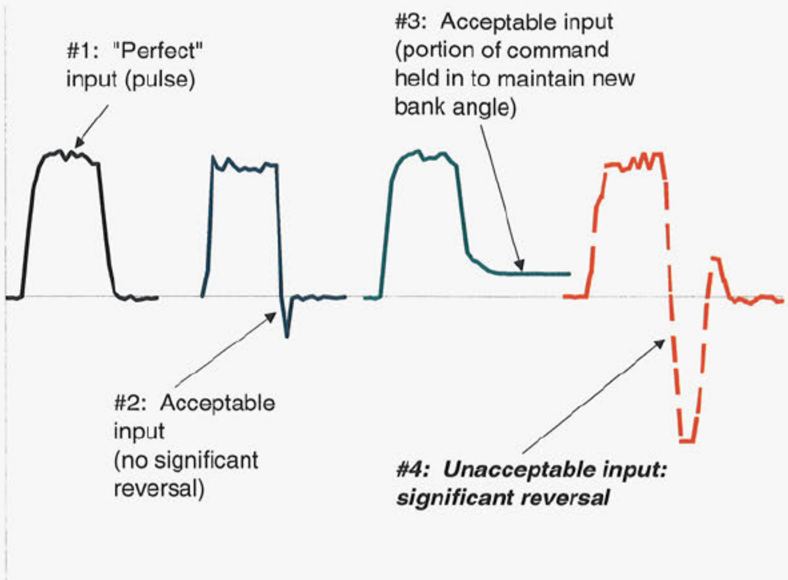


Figure 38 Illustration of Acceptable and Unacceptable Pulse Inputs

Apply pulses over a range of magnitudes to generate changes in attitude of between 5 and 30 deg in pitch, 10 and 60 deg in roll. The variation in attitude change from one maneuver to the next may be achieved through the magnitude of the pulse input. However, if the attitude change cannot be achieved with the maximum pulse, then the duration of the pulse will have to be increased. Note that increasing the duration of the input to achieve an attitude change reduces the peak angular rate, thereby making it more difficult to meet the requirement. Therefore, short duration pulses should be used wherever possible.

Avoid any tendency to make closed-loop attitude changes. It is best to look at the controller (not attitude) during the pulse. Make an effort to avoid targeting a new attitude when making the pulse input. Simply take what you get in terms of attitude change and if a larger attitude change is desired, increase the size or duration of the open-loop pulse input.

One approach that has been used successfully is to use a control fixture and target a cyclic deflection. Apply a rapid pulse control input to contact the fixture and then back to center. An example of one ingenious and simple fixture is discussed in Section 3.2.8 of this test guide.

Some small-amplitude control reversal may be unavoidable and is acceptable (see example input #2 in Figure 38).

In some cases the attitude may tend to slowly bleed back towards its initial value as the rotorcraft velocity deviates from trim. It is acceptable to hold in some of the pulse input to keep this from happening (input #3 in Figure 38).

Rapid control reversals are not acceptable (input #4 in Figure 38). Such control reversals act as stability augmentation (or pilot compensation) to improve the rotorcraft response, thereby resulting in misleadingly optimistic data. Unfortunately, it is not possible to place a specific limit on the amount of reversal that is acceptable. The only guidance that can be provided is to note that if there is a question about it, repeat the test with no reversal and see if that affects the ability to comply with the criterion.

Some types of low frequency compensation are acceptable (input #3 is an example).

It is important to accomplish the input close to the desired trim airspeed point. As an example, to achieve a large nose-up attitude change at hover (zero airspeed), initiate slow rearward flight, then pitch down to a target initial attitude causing the rotorcraft to decelerate to hover. When hover is reached, input the large nose up pulse. A similar technique is used for roll attitude changes. Since a steady initial bank angle results in a lateral translation, one technique is to start a translation, apply an input to generate a steady opposite bank angle and stop the translation, then apply the test pulse input as the translational rate goes through zero.

The requirement specifies that the attitude changes are "from one steady attitude to another." Once the roll rate is reasonably stabilized at zero, the maneuver is over. It is acceptable to make small low frequency corrections to hold the new bank angle. The "steady" period can be very short, (only a second or so) and a series of bank angle changes can be performed without going back to a steady condition between them. The initial and final angular rates must be near zero.

An example of attitude quickness testing that was accomplished during simulation of a scout attack helicopter design is shown in Figure 39. Note that the highest value of attitude quickness ($p_{pk} / \Delta\phi_{pk}$) occurs for the shortest duration pulse. Also note that $\Delta\phi_{MIN}$ is defined when the roll rate goes to zero and not several seconds later after the bank angle has drifted to a lower value. The intent of specifying $\Delta\phi_{MIN}$ is to penalize high frequency overshoots, not low frequency drift.

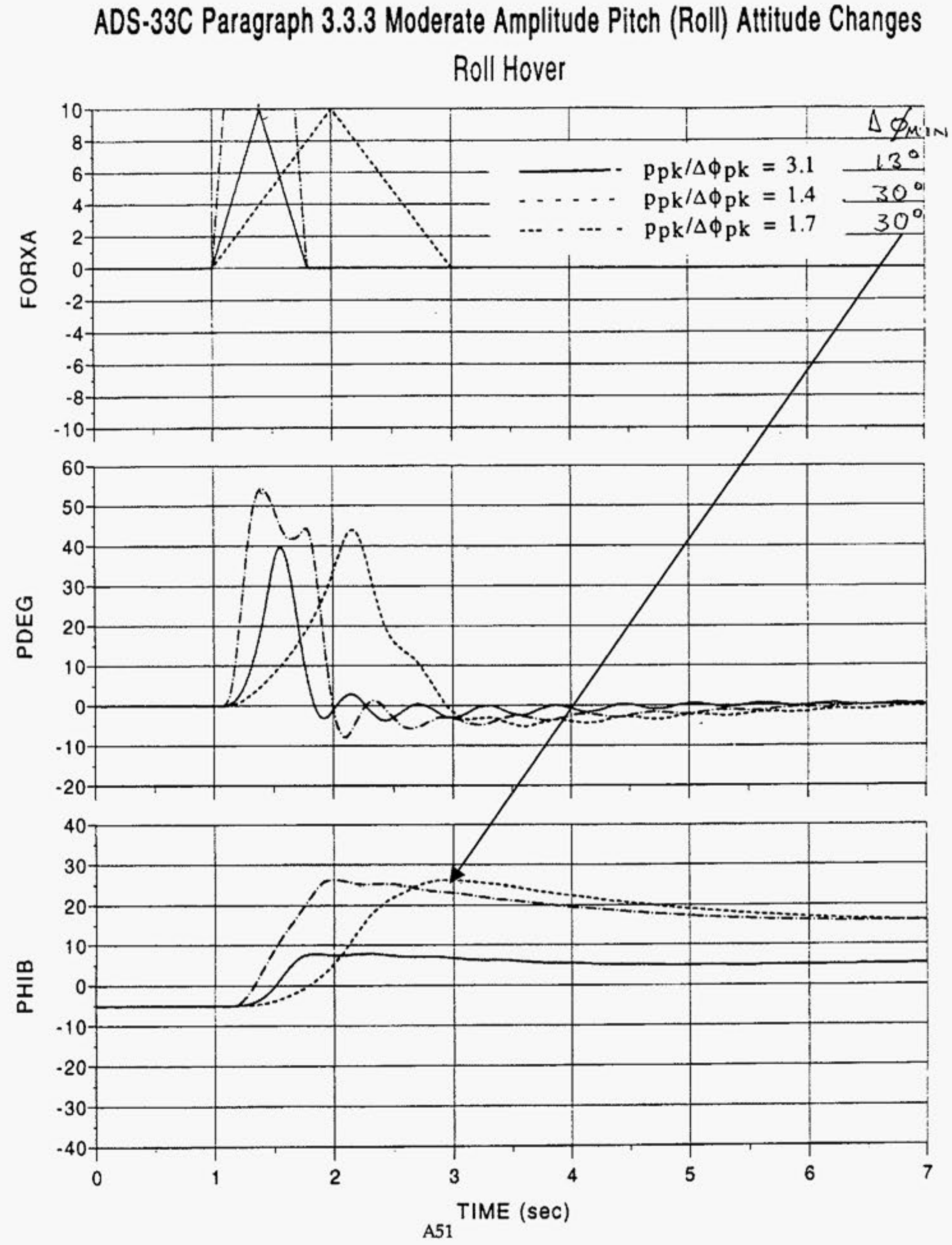


Figure 39. Moderate Amplitude Pitch (Roll) Attitude Changes: Roll Hover (RAH – 66 Simulation – Reference 29)

Additional examples that illustrate Attitude Quickness testing, starting from a hover are given in Figure 40. There are five lateral stick pulses in the sketches, labeled 1, 1a, 2, 3, and 4, for discussion purposes. All inputs are full-deflection, short-duration pulses – inputs that may not be practical in a real rotorcraft in flight. They are meant to exemplify the full response possible for a representative rotorcraft, in this case a large, cargo-class helicopter.

a. Input number 1 was applied to initiate a lateral translation. No attempt was made to regulate bank angle in the translation, but nevertheless data can be obtained from this input.

b. The input labeled 1a was applied once groundspeed reached 25 kts, to attain a bank in the opposite direction and start a deceleration.

c. Input number 2 was applied as groundspeed approached zero. This input produces a response similar to number 1, but in the opposite direction, and results in the rotorcraft reaching a near-hover flight condition. Again, there is no attempt to regulate the ending bank angle, so a small drift in bank angle is apparent. Still, the data are sufficiently good to obtain Attitude Quickness numbers.

d. Input number 3 is again from a hover to start a lateral translation.

e. Input number 4 stops the lateral translation, and there is an effort to maintain a steady final bank angle. The specific value of the bank angle was not pre-selected, but the pilot tried to hold the bank that was achieved when roll rate approached zero. This is acceptable as the maneuver is over once the new bank angle is achieved.

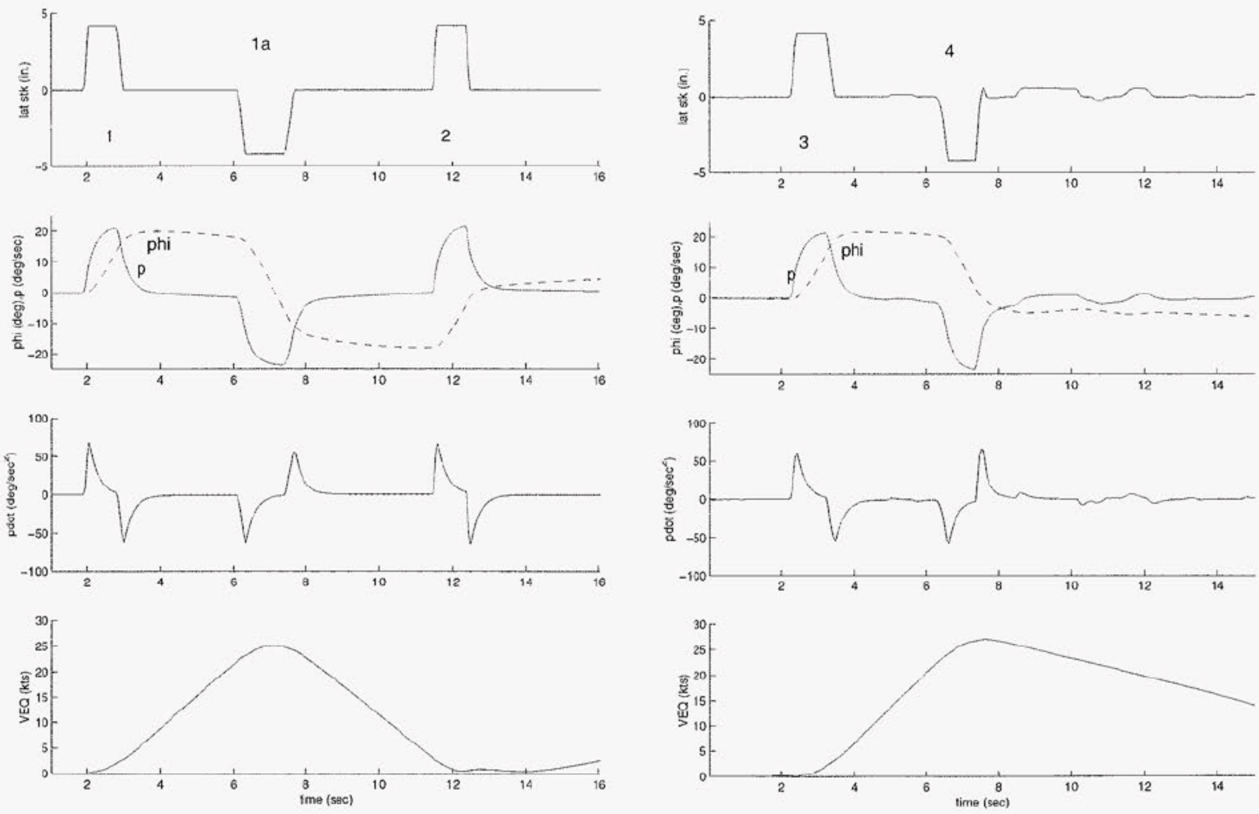


Figure 40 Illustration of Attitude Quickness Tests

Data Analysis and Interpretation:

The control inputs should be carefully reviewed in terms of the guidelines established above, as improper control application can make a deficient rotorcraft pass and a good one fail.

Once compliance is shown at some attitude change, the rotorcraft is considered to pass, even if other runs at that same attitude change do not show compliance. In other words, if there are six attempts to show compliance at a certain attitude change, and five of the six are below the limit but the sixth one is above it, the rotorcraft passes.

Compliance requires demonstration of Attitude Quickness across the range of attitude changes to the limits of the Operational Flight Envelope or 30 deg in pitch (60 deg in roll), whichever is less.

It is important to measure the proper parameters for this requirement: both *peak* and *minimum* attitude change are required, as sketched in Figure 41.

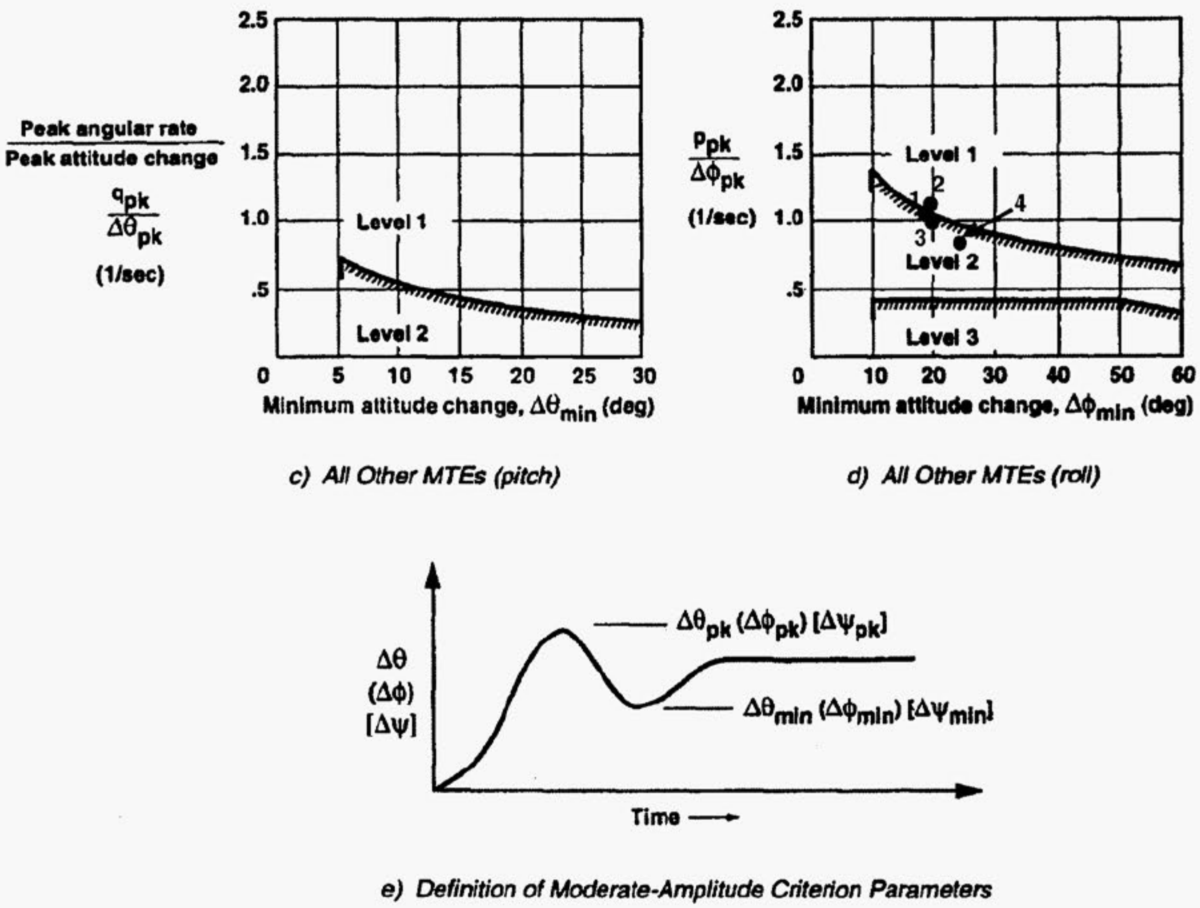


Figure 41 Attitude Quickness Criterion Excerpted from ADS-33E

As an example of data reduction, the Attitude Quickness parameters can be measured from the two sets of time histories shown in Figure 40. For the five inputs, labeled 1, 1a, 2, 3, and 4, , the following are the measured parameters:

- For input number 1, $p_{pk}/\Delta\phi_{pk} = 21/20 = 1.05$ deg/sec/deg (or 1/sec) and $\Delta\phi_{MIN} = 20$ deg.

- For input number 2: $p_{pk}/\Delta\phi_{pk} = 22/20 = 1.10$ 1/sec and $\Delta\phi_{MIN} = 20$ deg.
- Input number 3 has $p_{pk}/\Delta\phi_{pk} = 21/21 = 1.00$ 1/sec and $\Delta\phi_{MIN} = 20$ deg.
- For input number 4, $p_{pk}/\Delta\phi_{pk} = 22/25 = 0.88$ 1/sec and $\Delta\phi_{MIN} = 24$ deg.

These Attitude Quickness results are plotted in Figure 41. Points 1, 2, and 3 all represent data for a bank angle change of approximately 20 deg. Points 1 and 3 are slightly below the Level 1 boundary, but point 2 passes. As noted above, criterion compliance at a given pitch or bank angle only requires that one point pass. Point 4 fails the criterion, so a need for additional testing at larger bank angles is indicated. In this case, efforts should be made to increase the amplitude of the pulse, and minimize the duration (i.e., get the most roll rate for a given bank angle).

3.3.4 Large-amplitude pitch (roll) attitude changes

Data Requirements: q, p (Rate Response-Types) or θ, ϕ (Attitude Command Response-Types)

Input Type: Recommended input is a step, but any control input that generates a large angular rate or attitude may be used

Test Technique:

Response-Types that are designated for use only in UCE of 2 or 3 have to meet only the Limited agility limits in Table VI of ADS-33E-PRF. As a typical example, if a rotorcraft has selectable AFCS modes consisting of Rate and Attitude Response-Types, the Attitude mode would likely be designated for use in UCE>1. From Table VI, the large-amplitude requirement for this AFCS mode would be plus or minus 15 degrees of attitude from trim.

Other tests will usually generate the necessary data for this requirement, e.g., Attitude Quickness (3.3.3) or MTE evaluations, such as the Slalom. If more data are required in flight, unusual attitude recoveries should be practiced using a build-up technique. The inputs do not have to be as abrupt as for the Attitude Quickness criterion (3.3.3), since the objective is only to achieve a target angular rate or change in attitude. Also, unlike 3.3.3, control reversals can be used in the recovery if required.

The control input has to be applied only long enough to show compliance with the relevant limit. It is helpful to know the target angular rate or attitude change.

Perform the maneuver in both directions (nose up and down or left and right, as appropriate).

Limit excursions in the other axes as needed.

As with attitude quickness testing, there is a structural loads concern with this type of testing, especially during recovery from extreme attitudes and the aircraft should be instrumented accordingly.

3.3.5 Small-amplitude yaw attitude changes

3.3.5.1 Short-term response to yaw control inputs (bandwidth)

Data Requirements: r, ψ, δ_P, F_P; other states, such as airspeed and altitude, are useful

Input Forms: Frequency sweep in directional controller (see description of frequency sweep in the Appendix for detailed instructions)

Test Technique:

See discussion for 3.3.2.1 for bandwidth guidance.

During testing of the RAH-66 Comanche serious structural problems with the fan tail, specifically torque limit exceedances occurred. Care has to be taken to avoid exceeding structural limits when accomplishing flight tests in support of Sections 3.3.5 through 3.3.8.

For dual-piloted rotorcraft such as the UH-60 Black Hawk, it has been found that improved data quality can be obtained by segregating the control inputs, especially for directional axis sweeps. That is, one pilot performs the pedal sweep while the other pilot monitors and controls the cyclic and collective. This minimizes correlated off-axis inputs and improves the resulting data.

Data Analysis and Interpretation:

See discussion for 3.3.2.1 for bandwidth guidance.

During development of the heading bandwidth criterion boundaries it was difficult to find realistic tasks that required tight closed loop heading control. The target acquisition and tracking requirement is based on a pointing task with fixed guns (Reference 30. If the gun is mounted to a turret (e.g., AH-64) there is no requirement for the very high yaw bandwidth for Target Acquisition and Tracking ($\omega_{BW} \geq 3.5$ rad/sec). Therefore, it is acceptable to request a deviation for relaxed heading bandwidth if the procuring activity agrees that there is no yaw task to justify the requirement. A request for such a deviation should be accompanied with pilot rating data from related MTEs such as Hovering Turn (3.11.4), Pirouette (3.11.5), and Lateral Reposition (3.11.8) or Sidestep (3.11.12) and Turn to Target (3.11.17). Only maneuvers specified in 3.1.1, Operational Missions and MTEs need be included.

3.3.5.2 Mid-term response to control inputs
3.3.5.2.1 Fully attended operations
3.3.5.2.2 Divided attention operations

Data Requirements: r, δ_P

Input Type: ADS-33E-PRF specifies a pulse in the directional controller. Any input that excites an oscillation is acceptable, and doublets may be preferable to pulses

Test Technique:

This requirement is equivalent to the pitch/roll requirement of 3.3.2.3. See the discussion for that requirement.

Data Analysis and Interpretation:

See discussion for 3.3.2.3.

3.3.6 Moderate-amplitude heading changes (attitude quickness)

Data Requirements: r, δ_P

Input Type: Pulse in the directional controller

Test Technique:

See discussion for the pitch/roll equivalent, 3.3.3.

Data Analysis and Interpretation:

See discussion for 3.3.3.

3.3.7 Short-term yaw response to disturbance inputs

Data Requirements: r, θ_{TR} or δ_{TR}; other states, such as airspeed and altitude, are useful.

Input Type: Frequency sweep inserted into the directional control actuator

Discussion:

See discussion for 3.3.2.2 for proposed revised criterion for disturbance inputs.

3.3.8 Large-amplitude heading changes

Data Requirements: r, δ_P

Input Type: Recommended input is a step, but any control input that generates a large yaw rate may be used

Test Technique:

This requirement applies only for hover.

See discussion for 3.3.4.

Data Analysis and Interpretation:

See discussion for 3.3.4.

One flight test organization noted that the heading response was sluggish for small inputs with increasing yaw rate for larger inputs. As the pedal deflection increased past one inch, it was not possible to hold a step pedal input because the yaw rate kept increasing. For compliance with this criterion, it is not necessary to hold a pure step input. Any directional controller input that achieves the desired yaw rate is acceptable.

However, if the yaw rate keeps increasing with constant pedal deflection, the helicopter may not meet the Bandwidth criterion for yaw.

3.3.9 Interaxis coupling
3.3.9.1 Yaw due to collective for Aggressive agility

Data Requirements: pilot comments; $r, \dot{h}, \theta, \phi, \delta_C$

Input Type: Step in collective controller

Test Technique:

This test applies only for those rotorcraft required to perform Aggressive maneuvering, as defined in 3.1.2 Required agility.

Apply both up- and down-collective steps of varying magnitudes. For safety, it is not possible to apply large down-steps IGE. Ideally the up collective steps should be up to maximum rated power.

The critical flight condition exists when the helicopter is light on a cold day at sea level, thereby resulting in the maximum power change before reaching the limit.

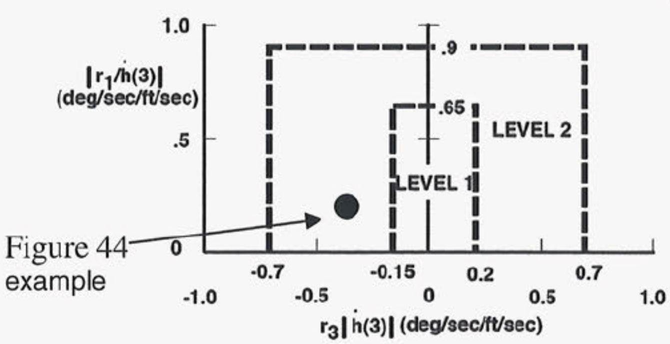
Even though the test required to obtain the criterion data is short (the primary criterion require only 3 seconds worth of data after the step is applied), it is necessary to run the test for a longer time to look for any objectionable yaw oscillations (see below).

If the rotorcraft is not equipped with Heading Hold, or if Heading Hold is deactivated for this test, hold the directional controller fixed throughout the test. If the rotorcraft is equipped with Heading Hold, the directional controller may be free.

The pitch and roll attitude should be held essentially constant during the maneuver. No attempt should be made to hold constant position or translational rate.

Data Analysis and Interpretation:

The criterion is repeated from the specification in Figure 42 for convenience.



Where:

r1 = first peak (before 3 seconds)
r3 = r(3) - r1 (for r1 > 0)
r3 = r1 - r(3) (for r1 < 0)

r(1) and r(3) = yaw rates at 1 and 3 seconds

$\dot{h}$(3) = rate of climb at 3 seconds

Figure 42 Yaw Due to Collective Coupling Criterion from ADS-33E-PRF

Some examples of how the above criterion parameters are obtained from the yaw-rate time histories are given in Figure 43.

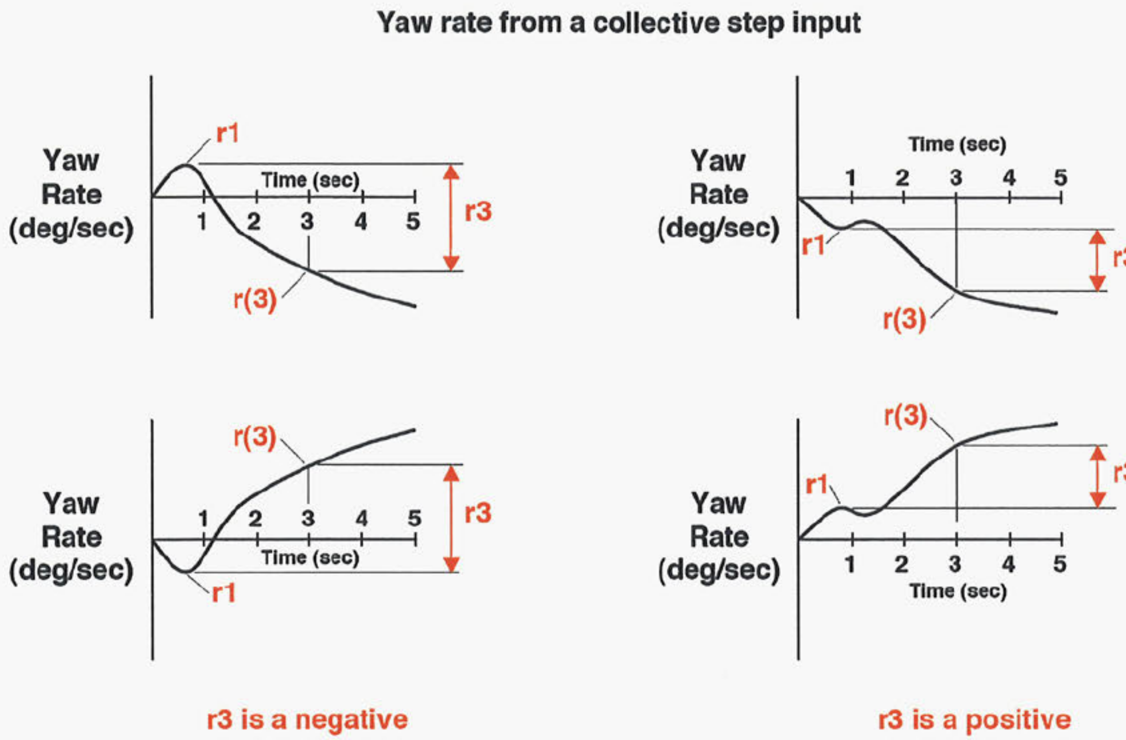


Figure 43 Example of Criterion Parameters From Time Histories

An example from an actual time history taken from a UH-60 flight test is given in Figure 44. From that example, the criterion parameters are calculated as:

$\dot{h}(3) = 10.5$ ft/sec

r_1 = -2 ft/sec

r(3) = 1.5 ft/sec

$r_3 = r_1 - r(3) = -3.5$ ft/sec

The criterion parameters for plotting are:

$\left| r_1 / \dot{h}(3) \right| = 0.19$ deg/sec/ft/sec and $r_3 / \left| \dot{h}(3) \right| = -0.33$ deg/sec/ft/sec

Plotting these on the criterion boundary in Figure 42 shows that the UH-60 is Level 2.

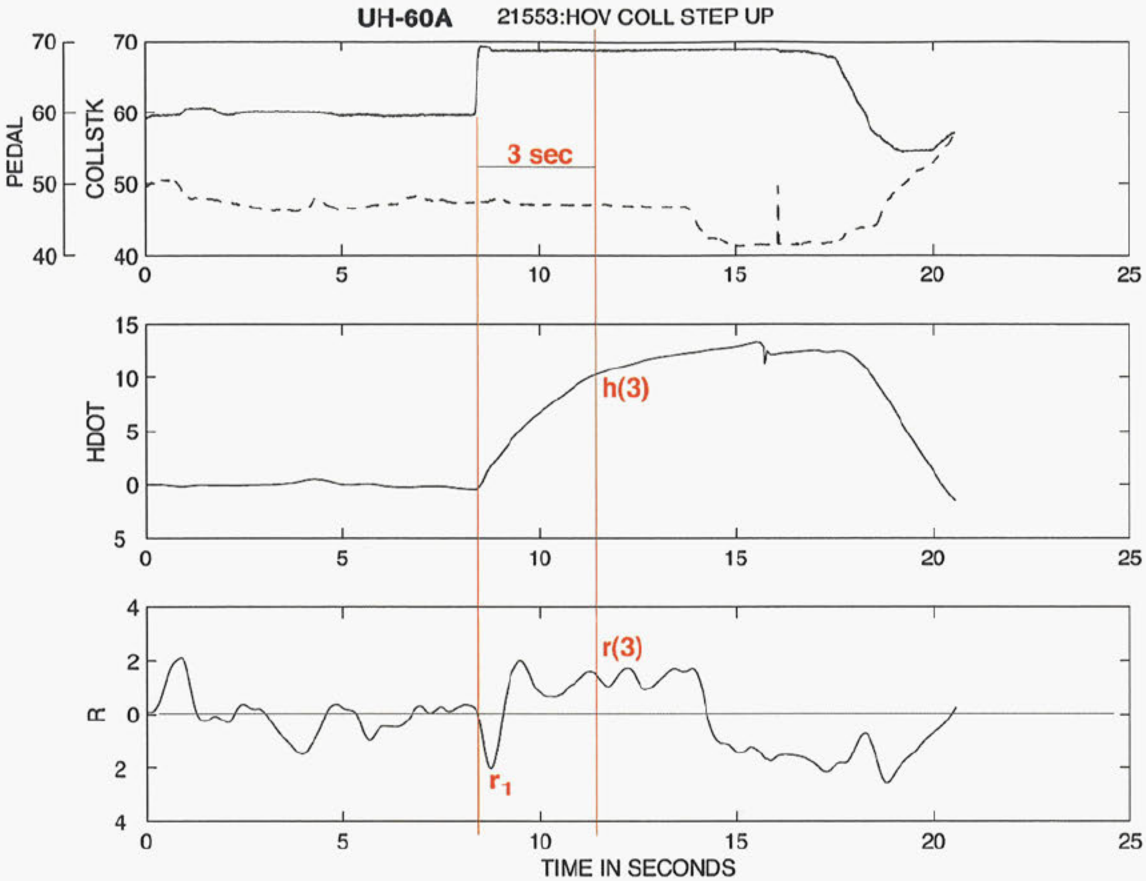


Figure 44 Time History of Maneuver to Obtain Yaw-Collective Coupling Data

As with most time-response requirements, it is important to determine when the "step" input really began. The assumption for this specification is that time = 0 occurs at the point where the step has reached its midway value, or 50% of final amplitude. If the step is suitably abrupt, choice of the initial time should not make a big difference (e.g., see Figure 44).

It may be necessary to synthesize an accurate $\dot{h}$ signal by complementary filtering radar altitude and normal acceleration as described in Section 3.3.10.1 of this Test Guide.

Check the yaw response for objectionable oscillations following the input. Any oscillations in yaw rate greater than 5 deg/sec are automatically classified as "objectionable" – nonetheless, it is acceptable to rate the oscillations as objectionable for lower magnitudes. Unfortunately, there are no criteria to define what is objectionable, so that is up to the judgment of the test pilot. If there is a question about what is objectionable, it is recommended that the Acceleration/Deceleration Maneuver (3.11.11) and/or the Vertical Maneuver MTE (3.11.6) be used to make that determination (i.e., if those MTEs are not Level 1 due to yaw oscillations, it is objectionable).

If yaw coupling in response to collective inputs is large, monitor engine and rotor RPM response to determine if coupling is the result of vehicle dynamics or engine/rotor response. The requirement on yaw oscillations was motivated by experience gained during development of the AH-64 Apache, wherein an objectionable yaw oscillation was encountered following an aggressive collective pull at the end of an acceleration/deceleration maneuver. This oscillation was induced by oscillations in the engine-rotor RPM governor.

The data used to develop the boundaries for this criterion indicated that the effect of collective-to-yaw coupling was a strong function of the aggressiveness of the task. For non-aggressive tasks, coupling that fails this criterion will probably not be objectionable. This is an important caveat to bear in mind when interpreting the results of testing for this criterion. It is the reason that this criterion is only required for rotorcraft that are required to accomplish Aggressive Maneuvering.

3.3.9.2 Pitch due to roll and roll due to pitch coupling for Aggressive agility

Data Requirements: $\theta, \phi, \psi, \delta_B, \delta_A$

Input Type: Step in pitch (roll) controller

Test Technique:

This test applies only for those rotorcraft required to perform Aggressive maneuvering, as defined in 3.1.2 Required agility.

Apply steps in both directions. Vary amplitudes from almost imperceptible to as large as practical. Depending upon the abilities of a particular rotorcraft, "as large as practical" may be quite small (on the order of one inch or less), since the input is to be applied and held for 4 seconds.

For the largest inputs, attitudes and resulting groundspeeds may come close to operational limits. If necessary, start the tests from a non-zero attitude.

Make no inputs in other axis of cyclic control except as noted below.

The requirement includes a statement that "heading shall be maintained essentially constant". This is reasonable for very low forward speeds, but has been found to be impractical for lateral inputs at forward airspeeds greater than approximately 20 kts. Therefore, if forward speed is greater than about 20 kts, it is acceptable to use the directional controller to maintain essentially zero sideslip for lateral inputs.

It is important that the amplitude of the input be held as constant as possible for the full 4 seconds. A control input test fixture will be of value when performing this test. An in-cockpit control position indicator, or a command generator, can significantly improve the quality of the data obtained.

Airspeed will naturally vary during the 4 second input in either axis. Keep track of the maximum airspeed excursion from trim for each maneuver.

If the step input in pitch results in large airspeed variations from trim, start the maneuver at an airspeed so that the trim airspeed is achieved approximately 2 seconds into the maneuver. This will minimize the deviation from the trim airspeed during the evaluation – an important factor since coupling can depend on airspeed.

For the larger inputs, recovery from large attitudes might result in the largest structural loads and therefore proper recovery techniques should be briefed and should be practiced before conducting this test.

Data Analysis and Interpretation:

The peak attitudes for on-axis and off-axis response will usually occur at different times. For example, for a typical helicopter, a longitudinal cyclic step will generate a pitch rate that will decrease as the low-frequency dynamics (phugoid mode) begin to dominate. It is possible, then, that the peak pitch attitude (on-axis) response will occur before 4 seconds, or at least that pitch attitude will not be increasing very rapidly at the end of the 4 seconds. Bank angle (off-axis response), however, may not peak in those 4 seconds. The relevant parameter is the ratio of peak bank angle *in the first 4 seconds* over the pitch attitude *at 4 seconds*.

Example time histories from a UH-60A flight test to demonstrate compliance with this criterion are shown in Figure 45.

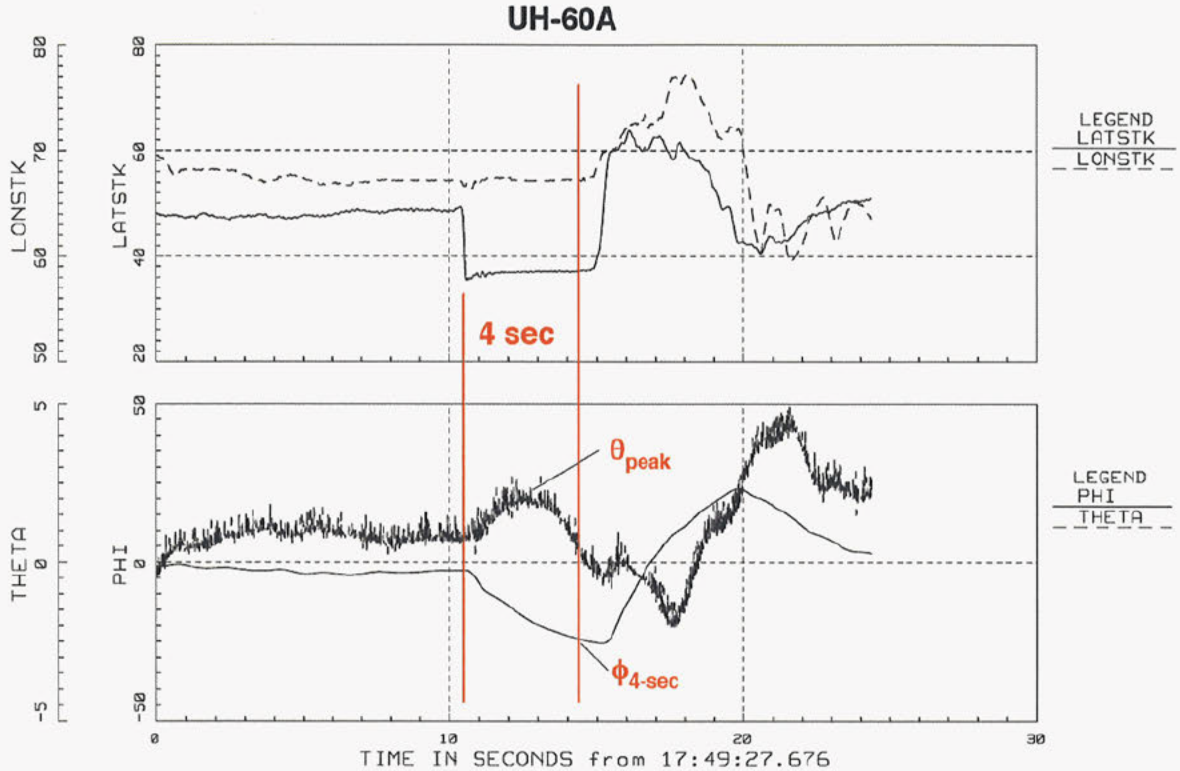


Figure 45 Time Histories of Maneuver to Show Compliance with Pitch Due to Roll

For this example, the parameter $\frac{\Delta\theta_{peak}}{\Delta\phi_4} = \frac{1.2}{23} = 0.052$ compared to the Level 1 boundary of ± 0.25. Therefore it is Level 1.

An example, from a simulation model of a small single-main-rotor helicopter, is shown below in Figure 46. This model illustrates the typical response for a nose-up step (the on-axis pitch parameters are shown by dashed lines, off-axis roll parameters by solid lines): pitch attitude peaks about 4.5 seconds after the input. Roll angle continues to increase over the period so that $\Delta\phi_{pk} = \Delta\phi_4$ so that $\Delta\phi_{pk}/\Delta\theta_4 = 18/24 = 0.75$, which is Level 3 by ADS-33E-PRF.

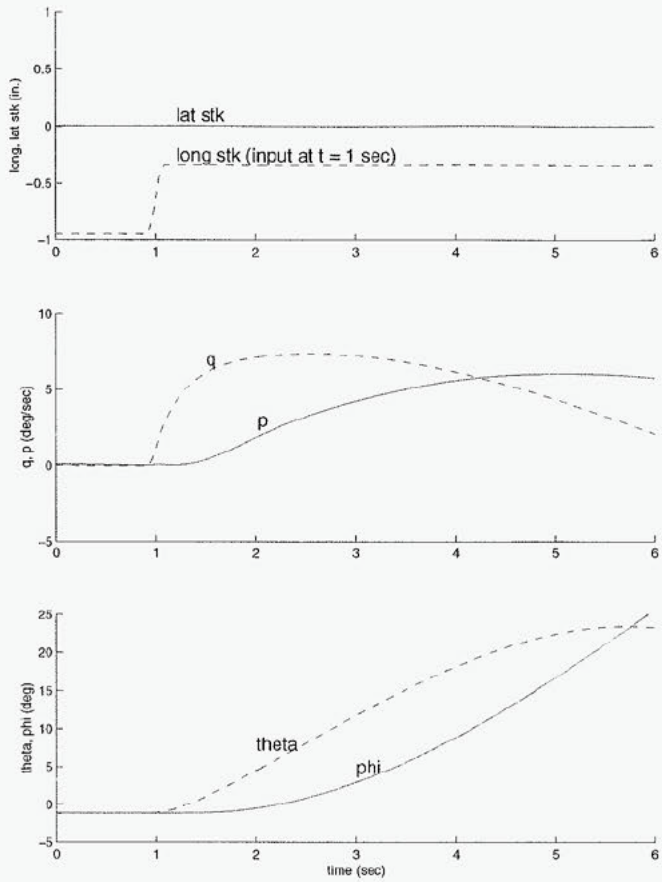


Figure 46. Illustration of Pitch-to-Roll Coupling

If the step is not quite perfect over the 4 seconds, inaccurate numbers can result. A slow increase in amplitude may give a misleadingly large on-axis response (resulting in a ratio that is lower than it should be). Conversely, if the input amplitude decreases over the 4 seconds the peak on-axis response may be incorrectly small (and the ratio will be larger than it should).

Two examples, for the same simulation model discussed above, are shown in Figure 47 . As above, the on-axis pitch parameters are shown by dashed lines, off-axis roll parameters by solid lines. As shown above, the correct value of roll-due-to-pitch coupling is 0.75.

For the plot shown in Figure 47 (a), the input magnitude decreased during the run, and pitch rate decreases to zero during the 4 seconds after input. For this example, $\Delta\phi_{pk}/\Delta\theta_4 = 11/13 = 0.85$, slightly worse than the correct value of 0.75.

For the plot shown in Figure 47 (b), the input magnitude was allowed to slowly increase during the 4-second run, resulting in an effective increase in pitch command. This results in the expected decrease in the criterion parameter: $\Delta\phi_{pk}/\Delta\theta_4 = 8/14 = 0.57$, well below the 0.75 achieved with a perfect step.

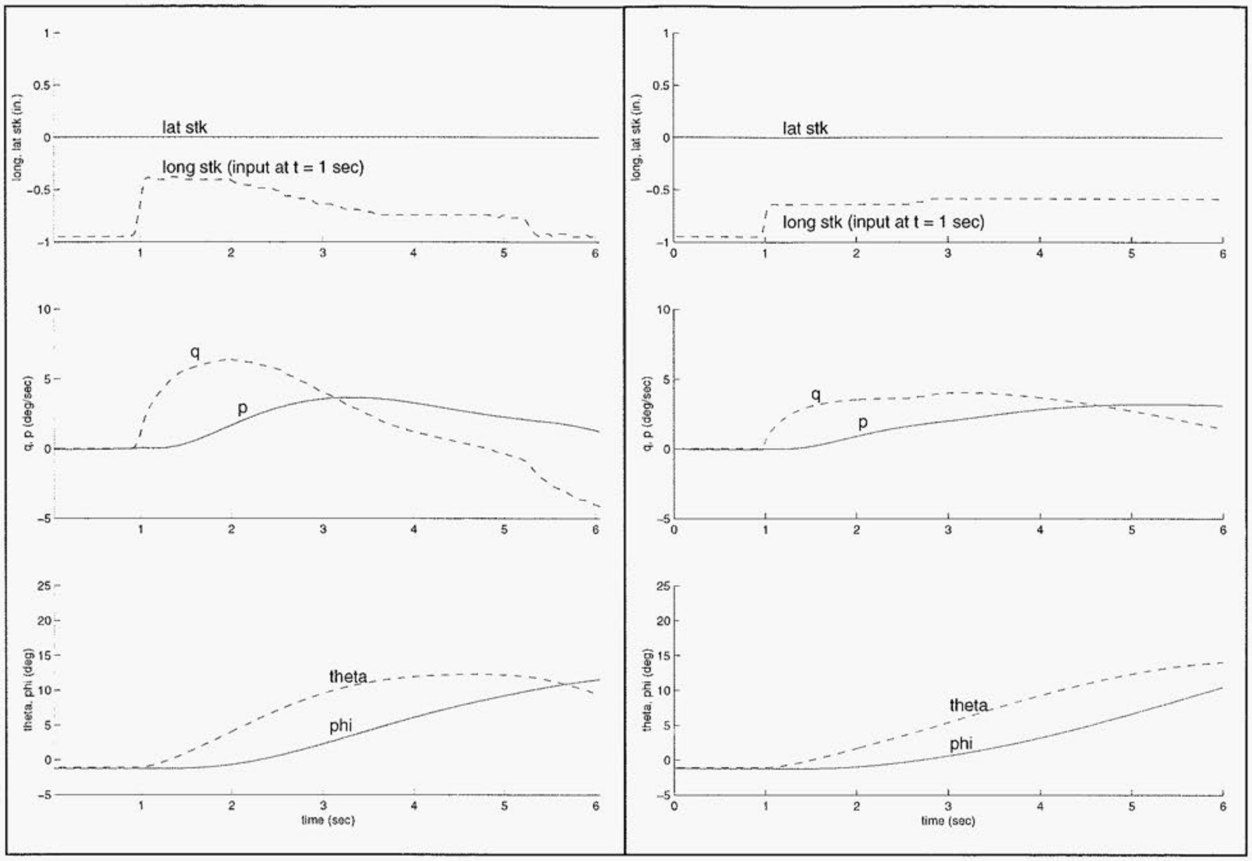


Figure 47(a). Decreasing Input

Figure 47(b). Increasing Input

Figure 47. Small Single Main Rotor Helicopter Simulation 2 ….

It is not unusual for conventional helicopters to demonstrate different levels of cross-coupling depending upon direction of the input. If nose-up pitch commands, for example, generate coupling ratios that meet Level 1, but nose-down commands do not, the helicopter is not Level 1. The worst of the response sets will apply to the criteria.

Modification to Criterion:

Experience with this criterion has shown that it is difficult to test for. This stems from problems with holding the input constant for 4 seconds, as well as the large change in flight condition that occur during the 4 second period. Therefore, future versions of ADS-33 will consider implementing the frequency domain criterion for target acquisition and tracking (3.4.5.4) in lieu of this time domain criterion.

3.3.9.3 Pitch due to roll and roll due to pitch coupling for Target Acquisition and Tracking

Data Requirements: q, p, δ_B, δ_A

Input Type: Frequency sweep in pitch (roll) cockpit controller (see description of frequency sweep in the Appendix for detailed instructions)

Test Technique:

This test applies only for those rotorcraft required to perform Target Acquisition and Tracking, as defined in 3.1.2 Required agility.

The frequency sweep data generated for the pitch and roll Bandwidth requirements (3.3.2.1) can also be used for this requirement. However, it is important to ensure that the off-axis inputs are minimized, and most importantly, are not correlated with the on-axis inputs. This is discussed at some length in the discussion of the Bandwidth criterion (3.3.2.1).

If specific testing is to be conducted, the appropriate input is a control-input frequency sweep. Consult the test technique information provided for 3.3.2.1.

Data Analysis and Interpretation:

See Reference 31 for a detailed discussion of this criterion.

The required frequency responses p/q and q/p *are* computed indirectly from the frequency responses of p/δ_B and q/δ_B (to obtain p/q) and of q/δ_A and p/δ_A (to obtain q/p). As discussed in Section 3.3.2.1, it is necessary to use multi-input FFT methods to obtain the correct off-axis frequency response (p/δ_B and q/δ_A). Multi-input frequency response determination comes with most advanced flight data analysis programs such as CIFER® (Reference 32).

The criterion parameters are calculated as an average q/p and an average p/q between the bandwidth and neutral stability frequencies of the off-axis response. The average q/p is a linear average of the q/p ratio at the available discrete frequency points between the pitch-axis bandwidth and pitch-axis neutral stability frequencies. Likewise, the average p/q ratio is a linear average at the available discrete frequency points between the roll-axis bandwidth and roll-axis neutral stability frequencies. The rationale for using the off-axis bandwidth and neutral stability points is that the pilot must regulate in the off-axis to minimize the effects of coupling (see Reference 31).

Figure 48 and Figure 49 show Bode plots of q/p and p/q for an attack helicopter at 60 kts with SCAS on and a BO 105 helicopter at 80 kts respectively. For the attack helicopter, there seems to be little variation of the coupling ratio with frequency. For the BO 105 helicopter, the p/q response shows a decrease from about 0 dB (100% coupled) at low frequencies to about –15 dB at 6 rad/sec. Beyond 6 rad/sec, there is an increase in roll-due-to-pitch coupling as a result of a decrease in q/δ_{lon} and an increase in p/δ_{lon} (resulting from rotor/body interactions). The averaging process tends to neutralize the detrimental effect of noisy data and simplifies the criterion.

The coherence for the off-axis frequency responses can be quite poor, something which can be primarily attributed to the phase plot. As would be expected, the coherence tends to be low for aircraft with small amounts of coupling since, by definition, there is little off-axis output that is correlated with the on-axis input.

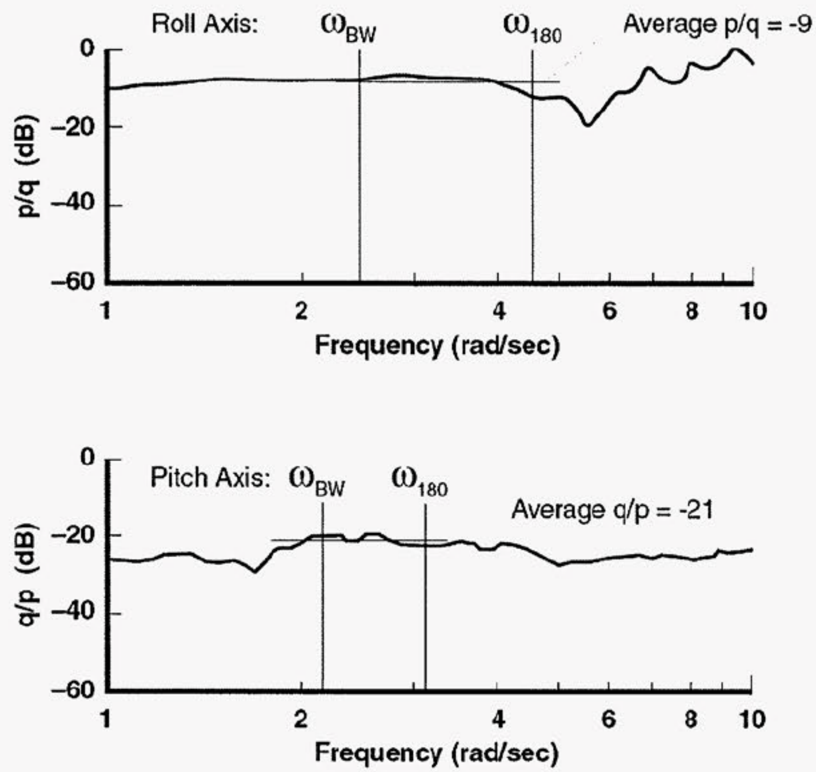


Figure 48. Amplitude of p/q and q/p ratios for an attack helicopter at 60 knots

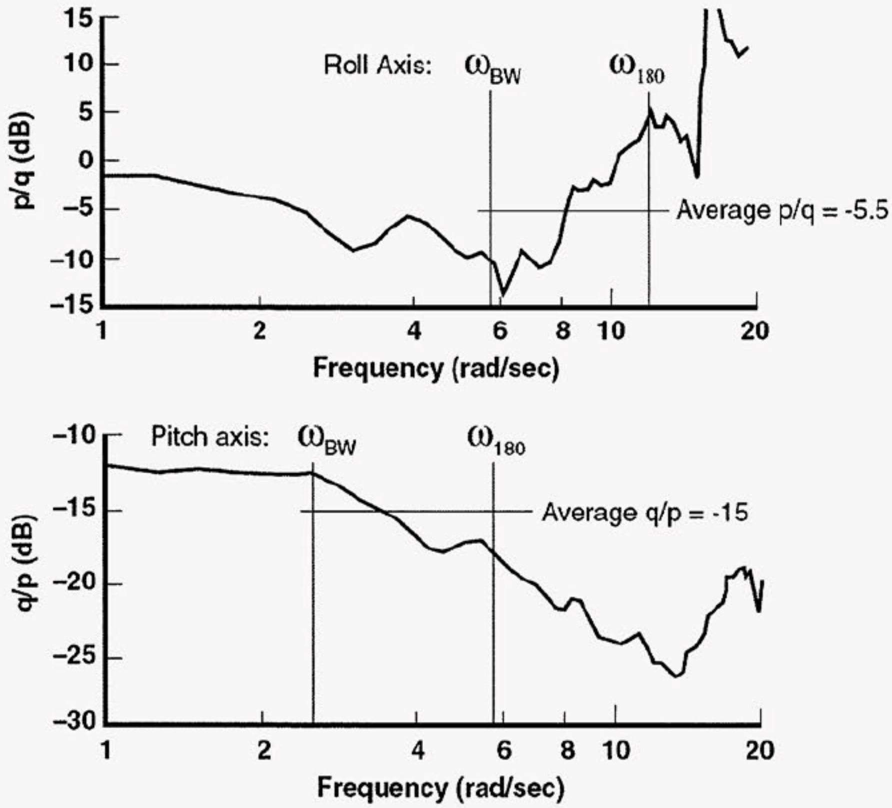


Figure 49. Amplitude of p/q and q/p ratios for a BO 105 helicopter at 80 knots

Alternate Criterion:

This criterion may be specified as an alternate to 3.3.9.2. However, it should be recognized that it is significantly more stringent than that time domain criterion. For example, the Apache data in Figure 48 is shown to be Level 2 using the frequency domain criterion, while it is Level 1 according to the 3.3.9.2 time domain criterion (see Reference 33). The pilot commentary in Reference 33 indicates that the off-axis response to control inputs was not found to be objectionable. It should be noted that the evaluators in Reference 33 did comment of problems of holding the input for 4 seconds for inputs over 0.75 inches. This is also discussed in Reference 31.

3.3.10 Response to collective controller

3.3.10.1 Height response characteristics

Data Requirements: $\dot{h}$, δ_C

Input Type: Step in collective controller

Test Technique:

Data obtained for Para 3.2.10 (Character of Vertical Rate Response-Type) may be used here. In addition, the data generated for this requirement may be applied to Para 3.3.10.2 and Para 3.3.10.3. (For Para 3.3.10.2 an additional parameter, displayed torque, must be recorded.)

Initiate the test from a steady hover, both IGE and OGE.

Apply both up- and down-collective steps of varying magnitudes. For safety, it may not be possible to apply large down-steps, especially IGE.

Minimize pitch, roll, and heading excursions. Collective-to-pitch coupling can become a significant factor as the airspeed increases. Pitch attitude should be held reasonably constant during the 5 second step. This should not require large or aggressive longitudinal controller activity.

Maintain the step for 5 seconds.

For more recommendations on the preferred test technique, consult the discussion for 3.2.10.

Data Analysis and Interpretation:

The shape of the collective input must be as step-like as possible. Any significant ramping of the input will affect the equivalent time delay.

The number of points used in the match is an important parameter. A sample rate less than 20 samples per second on a response showing high-order effects can impact the value of equivalent time delay. If the response is clearly first-order in appearance, sample rate will have less impact.

It may be necessary to synthesize an $\dot{h}$ signal from other sources to obtain the best estimate of vertical rate, $\dot{h}_{est}$. For example, $\dot{h}_{est}$ can be estimated from radar altitude or inertial altitude, and vertical acceleration using the following complementary filter

$$\dot{h}_{est} = h_{cf}\left(\frac{s}{T_{cf}s+1}\right) + N_z\left(\frac{T_{cf}}{T_{cf}s+1}\right)$$

where $h_{cf} = h_{rad} + \dot{h}_{est}\dfrac{T_{rad}}{T_{rad}s+1}$

Where h_{rad} is the output of a radar altimeter and Nz is vertical acceleration. The time constant T_{rad} should be set equal to the break frequency that represents the lag in the radar altimeter (or inertial altitude source). The time constant T_{cf} determines how the instantaneous vertical speed is calculated as a function of frequency as follows.

$$\dot{h}_{est} = \int N_z dt \text{ for } \omega > \frac{1}{\mathrm{T_{cf}}} \text{ and}$$

$$\dot{h}_{est} = \frac{dh_{cf}}{dt} \text{ for } \omega < \frac{1}{\mathrm{T_{cf}}}$$

T_{cf} is normally set to a value of about 5 seconds so that $\dot{h}_{est}$ is the integral of normal acceleration for all frequencies above 0.20 rad/sec. Due to the short duration of these tests it may be adequate to simply integrate N_z. This was done successfully at the Navy Test Pilot School. The only danger with this simplified approach is that the filters normally used to eliminate accelerometer noise could introduce additional time delay resulting in an artificially high value of $\tau_{h_{eq}}$.

If the radar altimeter or inertial altitude lags are very small, it may be possible to take the slope of altitude vs. time. Again this has the danger of introducing additional time delay.

Barometric altitude can be used in lieu of radar altitude for up and away, but is not reliable IGE, due to the effects of rotor wash on the static ports.

A coefficient of determination, r^2, is to be computed and must be between 0.97 and 1.03. If r^2 is not between these values, the rotorcraft does not meet the requirement. This is true even if the computed values of rise time and time delay are Level 1. In such a case, the data should be inspected for possible problems with the input or with the quality of the data.

It is rare for helicopters to have difficulty with this requirement.

3.3.10.2 Torque response

Data Requirements: displayed torque, δ_C

Input Type: Step in collective controller

Test Technique:

This requirement applies if there is a displayed parameter that represents the maximum power that can be commanded to prevent the pilot from exceeding engine or transmission limits (e.g., torque). If no such parameter exists, for example if torque limiting is performed by software, testing is not needed.

The parameter to be measured is that *displayed* to the pilot, not just the signal sent to a display. Thus it includes the dynamics of the display.

Data for 3.3.10.1 Height response characteristics may be used here as well.

While not called out in the specification, it is recommended that heading be held constant with the yaw controller during this maneuver. Experience has shown that holding heading constant results in torque overshoots due to tail rotor thrust requirements.

Size of the inputs in the up direction must be at least to the torque limit or maximum continuous power, whichever is less. Run the test long enough to observe one cycle of response in the display, if overshoot occurs.

Data Analysis and Interpretation:

The biggest challenge will probably be verifying that the output data represent the output of a cockpit display. It may be necessary to resort to some unusual test methods (such as a high-speed camera mounted in the cockpit) to obtain the data.

If the torque display clearly does not have overshoots, or if the overshoots are small and occur within the first fraction of a second of the input, this requirement will have been met.

If the torque overshoots fall in the Level 2 region and near the Level 1/2 boundary, and if those overshoots are a result of holding heading constant, it is recommended that the Vertical Maneuver MTE (Para 3.11.6) be accomplished. If the HQRs for that maneuver are Level 1, a deviation from this requirement is justified.

The intent of this requirement is to disallow large torque overshoots that might result from unusual rotor RPM governing methods or poor engine transmission characteristics. The variation of torque due to tail rotor thrust requirements is unavoidable, and should only result in non-compliance if the overshoots are very large which would be a cause for Level 2 ratings for the Vertical Maneuver MTE.

3.3.10.3 Vertical axis control power

Data Requirements: $\dot{h}$, δ_C

Input Type: Collective input as required

Test Technique:

Input form is not critical for this requirement, since the primary interest is in the achievable vertical rate 1.5 seconds after initiating the input. The input must be applied rapidly, however, to maximize the response. The test can be terminated any time after 1.5 seconds. If the input is a step that can be maintained for at least 5 seconds, data obtained for this requirement can also be used for 3.3.10.1 and 3.3.10.2.

Initiate the maneuver from a spot OGE hover at a critical density altitude. The rotorcraft is to have the most critical loading.

Only collective inputs in the up direction are of interest because this test is a measure of vertical axis control power.

Testing is to include inputs while in a wind of the most critical speed (up to 35 kts) from the most critical direction from the standpoint of power required. It is possible that the worst case will be calm winds. Another critical case for single rotor helicopters may be in a 35-kt wind from the side, since power will be required by the tail rotor to maintain heading constant in the hover.

The input should not exceed any applicable engine and transmission limits.

Data Analysis and Interpretation:

This requirement has one important difference from any other in ADS-33E-PRF: vertical rate is to be measured 1.5 seconds after *initiation* of the collective input, that is, the clock starts as soon as the pilot makes a noticeable change in collective. For all other requirements that involve defined inputs such as a step, the initial time ($t = 0$) is assumed to occur at the mid-point of the step (see the Appendix).

See the discussion in Section 3.3.10.1 of this regarding accurate measurement of vertical rate.

While this may seem like an engine test rather than a handling qualities test, experience has shown that vertical axis control power is an important handling qualities parameter. It is a function of both T/W (engine) and heave damping (see Reference 9).

3.3.11 Position Hold

Data Requirements: x, y, θ, ϕ, ψ

Input Type: Step in directional controller

Test Technique:

This requirement must be tested if Position Hold is a required Response-Type in Table IV of ADS-33E-PRF.

There are three parts to this requirement. The first involves a specific test for verifying functionality, the second assures that activation of Position Hold does not adversely affect the hands-on characteristics of the rotorcraft, and the third requires a clear annunciation to the pilot of status of Position Hold.

For the first part of the requirement:

It is recognized that it is nearly impossible to find a steady wind of 35 knots. Ideally the test would be conducted in a "reasonably strong wind". This would be followed up in a simulator that repeated the conditions observed in flight. If agreement between flight and simulation is good, the 35 kt wind requirement can be demonstrated on the simulator.

Experience has shown that the pitch and roll attitudes required to hold the required position tolerance in a 35 kt wind can be objectionable. It may be necessary to relax the position hold requirement or reduce the level of wind to avoid unacceptably large or abrupt changes in pitch and roll attitude during the 360 degree turn. In such cases, a request for deviation from this requirement should be accompanied with pilot ratings and comments to support the reduced standards.

For the second part of the requirement (pitch and roll attitude responses):

ADS-33E-PRF specifies that all of the requirements of 3.3.2 be met with Position Hold engaged.

The intent of this is to allow the pilot to easily override or "fly through" the position hold to make adjustments without having to disengage the mode. As noted in the Reference 9 BIUG, this feature allows the pilot to make minor adjustments without feeling that he or she is "fighting the system".

Experience during the development of the CH-47F digital automatic flight control system (DAFCS) confirmed that position hold (PH) should transition to ACAH if the stick is moved out of detent. Such a mechanization automatically meets this requirement as long as the transition is transient free.

Alternatively compliance with this part of the requirement could be demonstrated by accomplishing the hover turn as specified, and demonstrating that the pilot can make minor adjustments by overriding the position hold function with an acceptable level of pilot workload.

For the third part of the requirement

The best check of clear annunciation of Position Hold status will be through testing in an operational environment. The CH-47F DAFCS low speed and hover display included a circle located at the end of a horizontal translation acceleration vector. An armed PH mode was indicated by a dot in the middle of the circle, and an active PH mode was indicated when the fill was solid white. If PH was not armed or active the circle was not filled. If translational rate command (TRC) was active the circle was crosshatched, and if PH was armed with TRC active the dot was located in the middle of the crosshatched circle. This advised the pilot that the system would automatically switch to PH when the groundspeed became less than 1 kt.

Data Analysis and Interpretation:

Since it is not always easy to accurately record ground track, especially when the requirements are stringent (in this case, stay within a 10-ft diameter circle), it may be most convenient to use ground-based or airborne cameras to visually record the rotorcraft's position.

A specific location on the rotorcraft will be used for reference during the pedal turn. It obviously benefits the testing agency most if the reference point is near the center of rotation during the pedal turn.

The TRC system mechanized on the CH-47F utilized different TRC bandwidth when the cockpit controller was in or out of detent. A higher bandwidth was used when the controller was in detent and Position Hold captured. This allowed a more crisp capture of Position Hold, without excessive attitude overshoots while maneuvering in TRC. This can be seen in Figure 50 (see next section on TRC) where the translational rate response to the controller input is slower than when the controller is returned to detent.

There has been experience to show that position hold should be an inherent part of TRC (i.e., TRCPH). Any time the cockpit controller is returned to detent, it is required to hold zero translational rate. The intent of that is to hold the position that exists when the rotorcraft comes to a stop. Adding position hold simply reinforces the ability to satisfy that intent.

Adding the capability to "beep" the position with the trim controller allows the pilot to make minor modifications without transitioning in and out of Position Hold.

Additional Position Hold Requirements:

Other lessons learned from the development of the CH-47F digital automatic flight control system (DAFCS) are presented below and will be included in future upgrades to ADS-33.

It should be demonstrated that the transition in and out of position hold does not result in unacceptable transients and can be accomplished with low workload. Experience with the CH-47F DAFCS indicated that it is desirable to be able to arm position hold, and automatically transition to that mode when groundspeed becomes less than 1 kt. It should be possible to arm position hold at any point in the flight envelope.

If position hold can be armed while on the ground, it is important that there are no transients during a vertical liftoff. This should be tested in the following conditions.

- Varying wind magnitudes and direction
- Extremes of longitudinal and lateral c.g. position.

Position hold should not result in excessive attitude variations due to changing winds. Such attitude changes can be disorienting especially in UCE>1. It may be necessary to relax the 10 ft diameter requirement to avoid excessive attitude excursions. The PH gain was reduced in the CH-47F DAFCS based on a pilot preference for reduced attitude excursions (see Reference 18).

Engagement of PH should be rapid and predictable. The delay in engagement of PH from when the pilot expects it to engage (aircraft in hover and PH armed) and when it actually engages should be under 2 seconds. Problems with the mechanical control system detent resulted in a 5 second delay for the CH-47F, and that was found to increase workload considerably (see Reference 18).

CH-47F DAFCS testing indicated that it is unacceptable for the system to disengage from position hold without being commanded to do so by the pilot (say by commanding a translation). Such disengagements can result in undetected drift in UCE>1 or conditions of high pilot workload.

3.3.12 Translational Rate Response-Type

Data Requirements: δ_B, δ_A, x and y groundspeeds, pilot comments

Input Type: Step in longitudinal (lateral) controller position or force

Test Technique:

This requirement must be tested if Translational Rate Response-Type is required by Table IV of ADS-33E-PRF.

The test technique used to show compliance with this criterion is identical to that used to show compliance with the TRC response type in Paragraph 3.2.9. In addition to the rise time criterion, there are three additional qualitative requirements and these are discussed below.

a) Pitch and roll attitude shall not exhibit objectionable overshoots in response to a step cockpit controller input. This requirement is included because the only way to mechanize a translational rate command (TRC) system for a conventional helicopter is through pitch and roll attitude. Increasing the bandwidth of the TRC, comes at the cost of increasing attitude overshoots (discussed in more detail in References 9 and 18). Such attitude activity has been shown to be disorienting and therefore may be the limiting factor for TRC bandwidth. Future versions of ADS-33 will include a criterion to limit the pitch and roll attitude response to stick inputs. Until that is accomplished, it is recommended that the Hover MTE (3.11.1) be accomplished to qualitatively evaluate the pitch and roll activity with TRC activated. Use the maximum run-in speed of 10 kts to maximize the aggressiveness of the maneuver.

b) Zero cockpit control force and deflection shall correspond to zero translational rate with respect to fixed objects or to the landing point on a moving ship. This requirement ensures that the translational rate is inertially based, but stops short of requiring position hold. Position Hold is required separately in 3.3.11. If TRC is to be used on a moving ship, it must be relative to the ship. An earth-referenced TRC is unacceptable on a moving platform. For example, if TRC is engaged at liftoff, it will immediately command a translation that is the negative of the ship speed, and could result in collisions with objects that are stationed on the deck.

c) There shall be no noticeable overshoots in the response of translational rate to control inputs. This subjective requirement is intended to further enforce the first-order appearance of a TRC system. The Hover maneuver, noted above, is one way to determine if overshoots in translational rate should be rated as objectionable. This would be most noticeable during the run-in portion of the task when trying to capture a target groundspeed.

Data Analysis and Interpretation:

The first step in analysis of the data is to scrutinize the controller input to ensure that it is constant. A good example of an acceptable step controller input is shown in Figure 50 and was done to show compliance with this criterion for the CH-47F digital automatic flight control system (DAFCS) as reported in Reference 18.

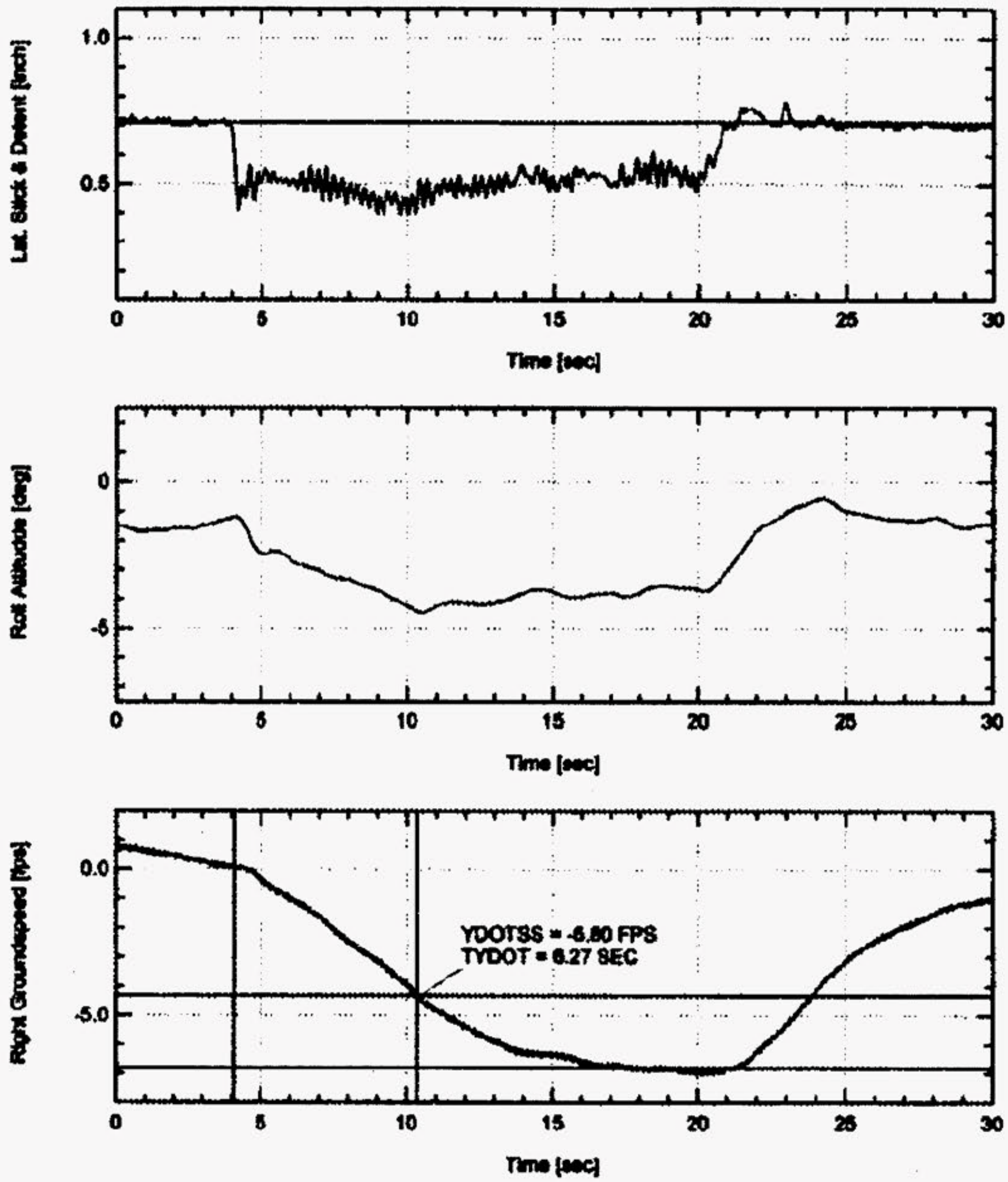


Figure 50 Response to Lateral Step Input – CH 47F DAFCS

The criterion requires that the translational rate response should have a "qualitative first order appearance". The intent of this requirement is to ensure that the response is monotonic and predictable. It should be possible to do this by eye without accomplishing a mathematical fit. A good example is the CH-47F TRC response to a step roll controller input shown in Figure 50.

The translational rate response in Figure 50 is not classical first order, but is adequate for the purpose of this requirement. The calculated rise time (6.27 sec) following the control input does not meet the ADS-33E requirement for being under 5 seconds, which may be one reason why the TRC mode did not provide the expected workload relief in UCE>1 (see Reference 37). Nonetheless, the TRC did provide some measure of workload relief in UCE>1, which is a significant accomplishment given the limited authority nature of the CH-47F DAFCS.

The specification provides recommended control sensitivity gradients and notes that those gradients are nonlinear. Supporting data from both flight and simulation for the recommended sensitivities are given in Reference 9. The TRC developed for the CH-47F used a control gradient that was linear, and much higher than the gradient recommended in ADS-33E as shown in Figure 51.

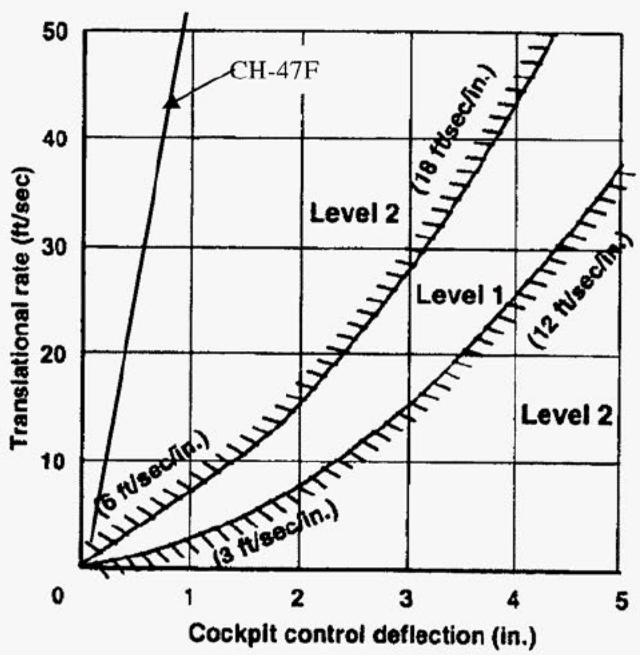


Figure 51 CH-47F TRC Control Sensitivity Compared to ADS-33E Recommendation - Centerstick

As discussed in Reference 18, the rationale for using such a high gradient was that lower gradients produced objectionably high stick forces. The all-mechanical flight control system of the CH-47F did not allow tailoring of the stick force gradients, so one gradient had to fit all Response-Types. However, even with this very high gradient (pitch = 72 ft/sec/in, and roll = 63 ft/sec/in), all of the evaluation pilots indicated that the TRC Response-Type produced a good deal of pilot workload relief.

When constraints such as noted above do not allow meeting of the TRC criteria, it is recommended that the Hover, Depart Abort, and Lateral Reposition MTEs be flown (see 3.11). If the pilots do not object to the control sensitivity, a request for deviation from the recommended gradients is warranted.

The recommended control gradients in ADS-33E are different for centerstick and sidestick controllers because those controllers have different ergonomic characteristics. To make matters worse, not all sidestick controllers are the same and different gradients will apply. The best advice regarding control sensitivity is to accomplish MTEs that are known to be sensitive to controller sensitivity. Good examples of these are Hover, Depart/Abort, and Lateral Reposition.

3.4 Forward flight requirements

3.4.1 Pitch attitude response to longitudinal controller

3.4.1.1 Short-term response (bandwidth)

Data Requirements: q, θ, δ_B, F_B; other states, such as airspeed and altitude, are useful

Input Type: Frequency sweep in longitudinal cockpit controller (see description of frequency sweep in the Appendix for detailed instructions)

Test Technique:

This requirement is the forward-flight equivalent of 3.3.2.1. See the discussion for that requirement.

Data Analysis and Interpretation:

See discussion for 3.3.2.1.

3.4.1.2 Mid-term response to control inputs

3.4.1.2.1 Fully attended operations

3.4.1.2.2 Divided attention operations

Data Requirements: q, δ_B

Input Type: Pulse in longitudinal cockpit controller is recommended

Test Technique:

1. See discussion for 3.3.2.3, 3.3.2.3.1, and 3.3.2.3.2.

Data Analysis and Interpretation:

1. See discussion for 3.3.2.3, 3.3.2.3.1, and 3.3.2.3.2.

3.4.1.3 Mid-term response – maneuvering stability
3.4.1.3.1 Control feel and stability in maneuvering flight at constant speed
3.4.1.3.2 Control forces in maneuvering flight

Data Requirements: n_z, V_T, F_B, pilot comments

Input Type: As required for specific test

Test Technique:

These criteria require two specific tests.

1. Obtain stick force gradient with normal acceleration (stick force per g)
2. Obtain frequency response of control deflection/control force (δ / F)

The data should be obtained with collective held constant. Collective inputs will generate load factor changes, resulting in erroneous values of F_s/n.

It is nearly impossible to obtain accurate normal acceleration data with a hand-held force gauge under dynamic conditions. Automatic data recording equipment should be used. The pilot should have an event marker button on the controls to note the points at which discrete data points should be collected (to create plots of stick force vs. normal acceleration). Time history data should also be collected.

Stick force per g

One method for generating the required data is a wind-up turn. This is accomplished by slowly increasing bank angle while holding airspeed constant with pitch attitude. A descending turn results. The advantages of this maneuver are that it can produce data for a range of g's in one run, and it allows the pilot to sustain a given load factor for a prolonged period (compared to a pullup or pushover). Large sideslip can contaminate the data, so careful control of sideslip is also important.

For low airspeeds (below about 90 kts), it may not be practical to use the windup turn because excessive rates of turn are required to achieve any significant load factor. The pullup/pushover maneuver is better suited for lower airspeeds. As a practical matter, load factors less than one g must be obtained using the pushover maneuver. If desired, the pullup/pushover maneuver may be used for the entire speed range.

One technique for accomplishing the pullup maneuver is as follows.

- Initiate the maneuver near zero pitch attitude and below the target airspeed.
- Enter a dive. As the airspeed approaches the target speed, accomplish a pullup at constant load factor. Record the speed, control force and position, and load factor as the pitch attitude passes through zero (± 5 degrees). Higher load factors are accomplished by increasing the dive angle.
- Repeat the maneuver at different rates of pullup to obtain data for a range of values of load factor at a given airspeed.

The pushover maneuver is accomplished as follows.

- Initiate the maneuver near zero pitch attitude above the target airspeed.
- Enter a climb. As the airspeed approaches the target speed, accomplish a pushover. Record the speed, control force, and position, and load factor as the pitch attitude passes through zero (± 5 degrees). Decreased load factor requires a steeper initial climb.
- Repeat the maneuver at different rates of pushover to obtain data for a range of values of load factor at a given airspeed.

The pullup/pushover maneuvers are usually accomplished back-to-back as each one sets up the initial condition for the other one.

In all pull-ups and pushovers, minimize excursions in roll and yaw using the lateral and directional controllers as needed. Collective must be held constant.

Experience has shown that this test can be especially critical in any flight region where AFCS mode transition takes place, or actuator position or rate limiting may occur. Testing should always include evaluations in such areas.

The test matrix should include the most aft and most forward c.g. regardless of weight.

Pilots should be instructed to make comments relating to any tendency for the aircraft to "dig in," that is, for the attitude to increase without an increase in force on the cockpit controller. This is especially critical for aft c.g.

Any restrictions on low-g maneuvers must be strictly adhered to. This is especially important for teetering rotor helicopters where mast bumping may be an issue.

Feel System Frequency Response

The frequency sweep data used to generate data for the longitudinal bandwidth criterion (3.4.1.1) can be used to satisfy this requirement. This requires that control system force and deflection be measured during the sweep.

Data Analysis and Interpretation:

The data resulting from windup turns and pull-up/pushover maneuvers should be plotted on the same grid. This will result in a range of data from near zero load factor (or less if the OFE specifies negative load factor) to the upper g limit of the Operational Flight Envelope. The data for load factors less than 1 g will necessarily result from pushover maneuvers.

It is useful to analyze the time history of windup turns and pull-up/pushover maneuvers to determine if control system friction has a significant impact on the results. For example, if the normal acceleration remains nearly constant, but the control force is decreasing, it usually is a result of friction (fixed swash plate with decreasing controller force). This phenomenon usually is associated with very low stick force gradients (e.g. at aft c.g.).

The plots of controller force vs. normal acceleration should be analyzed to check the part of the requirement that disallows zero local gradients and changes in gradient that are abrupt or excessive (more than 50%). Nonlinear regions that are marginal should be cause for careful investigation during performance of the appropriate MTEs (Pullup/Pushover and Slalom).

Compliance with the second part of this criterion can be accomplished analytically by showing that there are no dynamics between controller force and position that could lead to stick force lightening (position leads force) at any frequency. The origin of this part of the criterion comes from fixed-wing aircraft that utilize a bobweight. Poor location of the bobweight can result in position leading force, or stick force lightening.

Modification to Criteria:

Some flight control systems are designed to automatically provide the needed body-axis pitch rate in turns to achieve zero stick force per g at moderate bank angles. An example was the AH-66 Comanche that held level flight up to 30 deg bank (1.15g) without the need for applying aft control force. The evaluation pilots considered this an enhancing feature and future upgrades of ADS-33E-PRF will provide criteria to account for this possibility. In the interim, a deviation from this requirement should be granted to allow this feature as long as it can be shown to provide its intended function.

3.4.2 Pitch control power

Data Requirements: V_T, n_z δ_B, δ_C, torque

Input Type: As required to perform turns, pullups, pushovers, and airspeed changes

Test Technique:

To check for Level 1 handling qualities, turns or pull-up/pushover maneuvers should be performed to the limits of the OFE for load factor at various airspeeds and c.g. locations, e.g., see Figure 4 of this Test Guide. The forward c.g. limit is usually the most critical loading for this test.

Demonstrating the aircraft's ability to generate load factor to it's envelope limits is usually done as part of the structural demo, therefore extreme caution should be taken when performing this maneuver. The aircraft should be structurally instrumented in case of "overshoots" that might result in structural load exceedances.

Data Analysis and Interpretation:

None required.

Additional Criterion:

ADS-33E does not include requirements on control margin under the assumption that meeting the requirements throughout the OFE for Level 1 and SFE for Level 2 (see example envelopes in Section 3.1.6 of this guide) cannot be accomplished without adequate control margin. In addition, no data could be found that supports a given level of control margin. Nonetheless, a 10% margin is generally accepted as a safe control margin and should be included in the specification. This is discussed in more detail in Section 3.1.15 of this Test Guide.

3.4.3 Flight path control

Data Requirements: γ (or $\dot{h}$), V_T

Input Type: As required in longitudinal cockpit controller to collect data

Test Technique:

There are two flight path response requirements, 3.4.3.1 and 3.4.3.2. The applicable requirement depends upon the slope of steady-state flight path angle, $\Delta\gamma_{ss}$, for steady-state changes in airspeed, ΔV_{ss}.

The standard flight test technique of making small pitch attitude changes away from trim, and noting the resulting change in airspeed and vertical rate may be used to obtain the necessary data.

If the ratio $\Delta\gamma_{ss}/\Delta V_{ss}$ is less than zero, the rotorcraft is operating on the frontside of the power required curve and flight path can be controlled effectively by pitch attitude changes alone, 3.4.3.1 applies.

If $\Delta\gamma_{ss}/\Delta V_{ss}$ is zero or positive, the rotorcraft is on the backside of the power required curve where the best controller for flight path is collective, and 3.4.3.2 applies. In addition, even if the ratio is negative, if pitch attitude is not a good flight path controller (that is, if the requirement of 3.4.3.1 cannot be met), 3.4.3.2 should be applied.

Data collected while performing speed-stabilized tests for verifying longitudinal static stability (3.4.4) can be applied here as well, as long as accurate readings of rate of climb/descent relative to the air – not the ground – were obtained. Flight path angle (in radians) is then $\sin^{-1}$((rate of climb)/airspeed).

Compliance should be demonstrated in climbs, descents, and level flight.

It is not necessary to demonstrate compliance with this criterion in autorotation because there is no long-term flight path control in that maneuver. That is autorotations are accomplished at a selected airspeed and collective used to modulate rotor RPM (not flight path).

There is no flight path control requirement for autorotation because this is considered to be a performance issue. Good attitude control is required in autorotation by ADS-33E-PRF. However, the rate of descent and ability to arrest the sink rate with collective are a function of rotor design and not considered in the purview of a handling qualities specification.

Data Analysis and Interpretation:

None.

3.4.3.1 Flight path response to pitch attitude (frontside)

Data Requirements: $\dot{h}$, θ (or q)

Input Type: Frequency sweep or single sinewaves in longitudinal controller

Test Technique:

This requirement applies only if the rotorcraft is operating on the frontside, defined as a negative slope of the steady-state response of flight path angle versus airspeed, $\Delta\gamma_{ss}/\Delta V_{ss}$, obtained for 3.4.3.

A frequency sweep applied for this requirement must start at quite a low frequency but does not have to go to very high frequency. The requirement applies at frequencies below 0.40 rad/sec. Experience has shown that obtaining data of high quality from a low-frequency sweep is very challenging: the time required to perform several cycles of a sweep at such low frequencies will be measured in minutes rather than seconds. Input size must of necessity be small to avoid large changes in trim.

A more practical approach is to apply a few single-frequency sinewaves. Since compliance requires that the flight path angle must lag attitude by less than 45 degrees at 0.40 rad/sec (for Level 1), a logical input is a constant-frequency sinewave at 0.40 rad/sec. Such a sinewave will have a period of 15.7 seconds, and perhaps as many as three or four full cycles may be required to assure a steady response. Checking for Level 2 will require that the sinewave will have a frequency of 0.25 rad/sec, or a period of 25.1 seconds. Three cycles will require about 75 seconds to run.

Excursions in roll and heading should be minimized while testing for this requirement.

Data Analysis and Interpretation:

The requirement applies to the frequency response of the ratio $(\dot{h}/\theta)$ and may be assembled from a variety of sources.

For analysis and simulation, the ratio $(\dot{h}/\theta)$ is best obtained by a ratio of frequency responses, $\dot{h}/\theta = (\dot{h}/\delta_B)/(\theta/\delta_B)$. Because pitch attitude tends to have lower power than pitch rate, it is common to use body axis pitch rate, q, and adjust for 1/s. Then the ratio of responses would be $\dot{h}/\theta = (\dot{h}/\delta_B)/(q/\delta_B) * \frac{1}{s}$.

With the proper computer software, it may be possible to assemble the desired frequency response directly, rather than as a ratio of frequency responses.

A significant advantage of single sinewaves is that data reduction does not require sophisticated software and can be accomplished based on the time history data.

An illustration of the parameters for determining the phase angle between $\dot{h}$ and θ from a single sine wave input at the pitch cyclic controller is shown in Figure 52. The phase shift is calculated as $\Delta\phi(\text{deg}) = \Delta t / P \times 360$.

For a sinusoidal input of frequency ω rad/sec:

Period = $P = 2\pi/\omega$, seconds

Phase = $\Phi = (\Delta t/P) * 360$, degrees

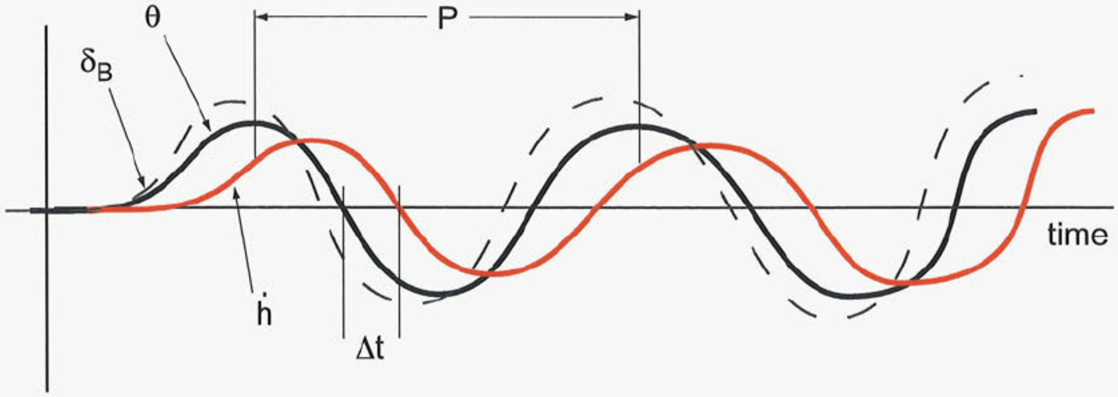


Figure 52. Determining Phase Angle From $\dot{h}$ and θ From a Single Sine Wave Input

3.4.3.2 Flight path response to collective controller (backside)

Data Requirements: $\dot{h}$, δ_C (or F_C)

Input Type: Step in collective position or force, as appropriate

Test Technique:

This requirement applies only if the rotorcraft is operating on the backside, defined as zero or positive slope of the steady-state response of flight path angle versus airspeed, $\Delta\gamma_{ss}/\Delta V_{ss}$, obtained from 3.4.3.

This requirement is equivalent to the height response to collective controller for low speed and hover (3.3.10.1). See the discussion for that requirement.

Data Analysis and Interpretation:

When checking for compliance with 3.4.3.2 (backside), scrutinize the pitch attitude time response during the maneuver to ensure that it varies only a negligible amount from trim. Variations in a direction to counter the step collective input (e.g., pitch down following an up-step of collective) tend to degrade the response, so are acceptable if Level 1 performance is demonstrated.

Also see discussion for 3.3.10.1.

3.4.4 Longitudinal static stability

Data Requirements: V_T, δ_B F_B ($\dot{h}$ can be collected for 3.4.3)

Input Type: As required for appropriate test

Test Technique:

The recommended test for longitudinal static stability is described below.

- Trim the rotorcraft in level flight at a selected airspeed.
- Make small (typically 5 to 10 knots) changes in airspeed using the longitudinal controller alone. Hold collective constant, minimize roll and yaw excursions, and do not retrim in pitch. Record longitudinal control position and force at each stabilized airspeed point.
- It is best to approach each test point from the same direction. That is, for decreasing airspeed points, approach the test point with a pull. Otherwise, the effect of control system friction will result in apparent noise in the data.
- Evidence of friction in the controls should be checked by slowly relaxing control force to zero. The speed at which the aircraft stabilizes will normally be different from the initial trim speed because of control system friction. Record this speed.
- Allow altitude to vary but try to limit such variations to less than 5000 ft.
- Repeat the test at a range of airspeeds.

Experience has shown that it is easier to conduct this test in two steps. First trim the aircraft at a given airspeed, altitude, and flight condition. Then perform the high-airspeed data points and recover the aircraft. Second, retrim at the initial flight conditions and an altitude slightly above that used for the high-airspeed points. Then perform the low-airspeed data points. This will help decrease the altitude variation.

Data Analysis and Interpretation:

The requirement addresses only stick-free static stability (controller force changes with airspeed), not stick-fixed (control position changes). It does not require positive stability about a trim point, only that there be no instability (force changes must be no worse than zero).

Control force and airspeed information obtained from the recommended test described above are plotted as sketched below in Figure 53. Positive static stability will be demonstrated with a negative slope as sketched.

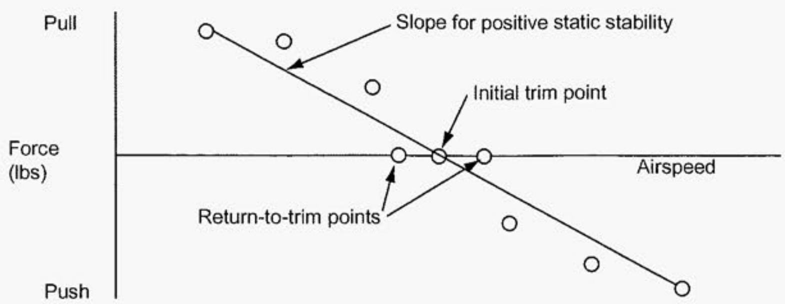


Figure 53. Control Force and Airspeed in the Determination of Static Stability

Altitude rate should be recorded to support determination of flight path stability for application of the requirements under 3.4.3.

Modification to Criterion:

The current requirement allows zero stick free stability ($d\delta_{long} / dV = 0$) and does not constrain stick fixed stability at all. This is based on the concept that longitudinal static stability is not required for some modern Response-Types (e.g. RCAH).

Experience obtained since ADS-33E-PRF was published has resulted in evidence that positive stick fixed and stick free stability should be a requirement for Level 1 handling qualities for helicopters. This experience was gained during the development of the CH-47F digital flight control system upgrade. Simulation showed that the stick position vs. airspeed gradient could be close to zero, whereas flight test showed that those values were not acceptable and a good level of stick fixed stability is important. This difference between flight test and simulation was especially surprising given that tasks were created on the NASA Ames VMS Simulator specifically to expose the need for longitudinal static stability.

The need for static stability is at odds with the fixed-wing transport aircraft experience wherein many fly-by-wire aircraft have zero stick fixed and stick free stability. This is inherent to aircraft with Rate or RCAH Response-Types.

Another caveat is that many fixed-wing aircraft have zero stick fixed stability ($d\delta_{long} / dV = 0$) and augment stick free stability ($dF_{long} / dV < 0$) to achieve acceptable handling qualities.

The most conservative approach is to require stick fixed and stick free stability and allow for a deviation if it can be demonstrated that Level 1 handling qualities can be achieved without meeting one or both of these parameters. Such a demonstration should include high workload IFR tasks such as the MTEs in 3.11.20 through 3.11.23. Based on the above noted experience, these tasks must be demonstrated in flight-test, as simulation is known to give misleading results.

There currently is no data to support the magnitude of stick fixed and stick free stability that is necessary for Level 1 flying qualities. The FAA regulations for civil helicopters simply require that the slopes be negative. Experience has shown that most helicopters meet this with slopes that are so small that to a pilot they look like zero. This is based on unpublished simulation results from the NASA Ames VMS simulator that showed that small amounts of stick-fixed and stick free stability do not decrease pilot workload for IMC tasks.

Commercial fixed wing transports are required to have a stick fixed stability of at least 0.166 lbs/kt. (Some fly-by-wire transports deviate from this requirement via a Special Condition).

It can be seen that work needs to be accomplished to develop a meaningful requirement on longitudinal static stability. In the interim, it will be necessary to rely on pertinent forward flight MTEs to define whether the longitudinal static stability is adequate. Applicable MTEs are Decelerating Approach (3.11.20), ILS Approach (3.11.21), Missed Approach (3.11.22), and Speed Control (3.11.23).

3.4.5 Interaxis coupling
3.4.5.1 Pitch attitude due to collective control
3.4.5.1.1 Small collective inputs
3.4.5.1.2 Large collective inputs

Data Requirements: n_z, θ, δ_C, pilot comments

Input Type: Step in collective

Test Technique:

For the general requirement of 3.4.5, pilot comments will be collected in flight while performing all required MTEs.

Vary the magnitude of the collective control step inputs from barely perceptible up to the maximum achievable without exceeding maximum continuous power, or torque, load factor, structural, or rotor-mast clearance limits. Apply steps in both the up and down directions. If the ratio $\left|\Delta\theta_{peak}/\Delta n_{z_{peak}}\right|$ shows little variation with input direction or amplitude, it is not necessary to run a large number of steps.

The aircraft should be structurally instrumented for these tests, unless previous testing or calculations have shown that the collective inputs required by these tests do not exceed any structural limitations.

Maintain the step for at least 3 seconds.

Allow the longitudinal controller to be free for the 3 seconds. If this results in an excessive pitch divergence, the longitudinal control may be held fixed at its trim value.

Roll and yaw excursions should be minimized.

Compliance should be checked for forward flight conditions above 45 KIAS. To keep the number of test points manageable, it is recommended that a test pilot qualitatively check for coupling throughout the flight envelope. This should include climbs and descents throughout the speed range. Once the worst-case points are known, obtain data for those points. Pilot comments should be documented to the effect that the coupling is subjectively no worse throughout the OFE than as recorded for the selected points.

Data Analysis and Interpretation:

The parameters for this requirement are defined as changes from trim. Their measurement from time histories is relatively straightforward.

At some flight conditions, load factor will peak during the 3 seconds but pitch attitude will not. In this case the relevant measures are change in pitch attitude at 3 seconds and peak change in load factor during the 3 seconds.

In the event that the input is not a clean step, starting time is defined as the midpoint in the input (see the Appendix).

Example time histories from flight test of the UH-60A are given in Figure 54.

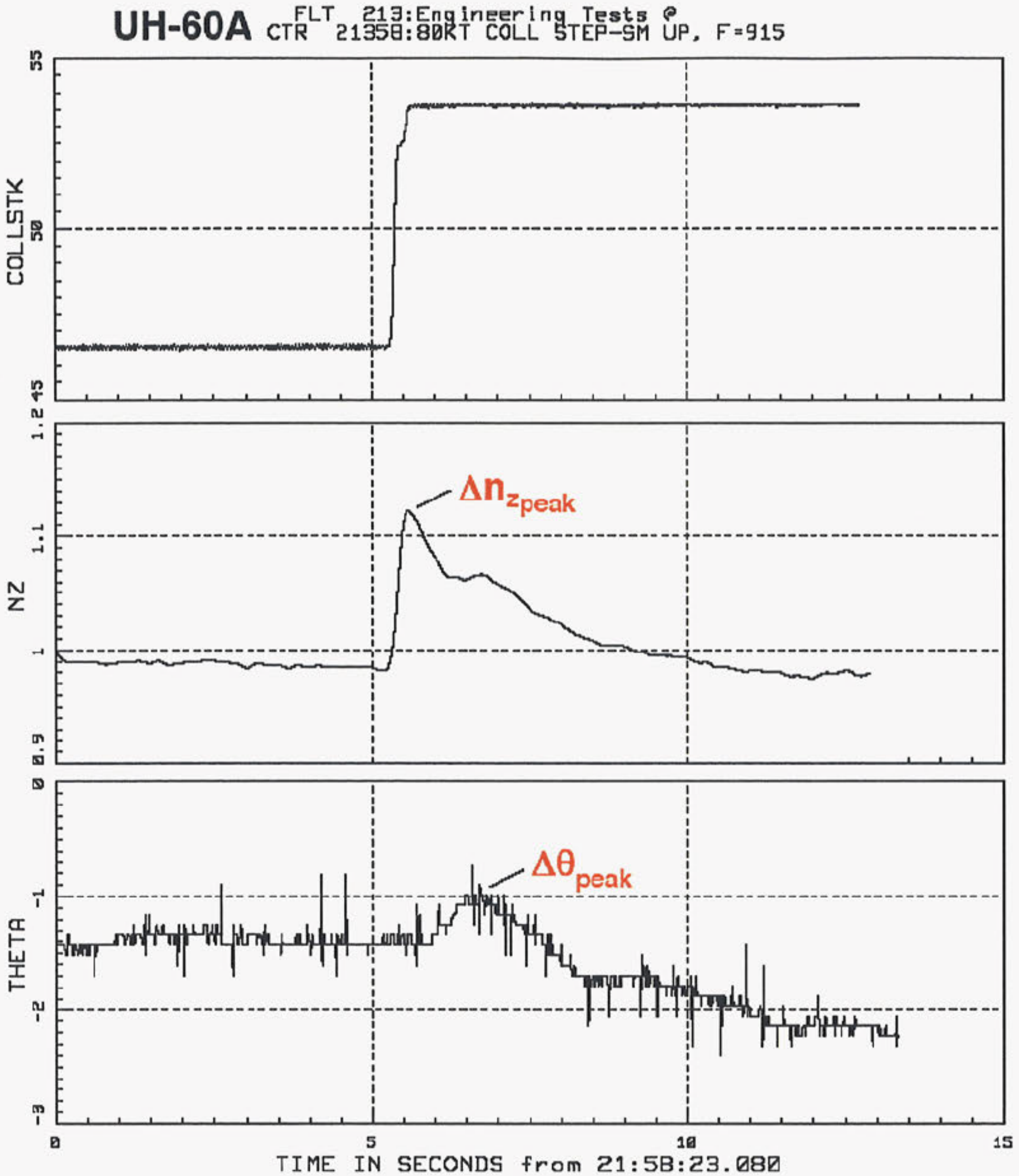


Figure 54 Data to Show Compliance with Collective to Pitch Coupling Criterion

For this example the criterion parameters are:

$$\left|\frac{\Delta\theta_{peak}}{\Delta n_{z_{peak}}}\right| = \frac{0.45}{0.14 \times 32.2} = 0.10 \text{ deg/ft/sec}^2$$

Assuming that the collective change was "small" (less than 20% torque change), the Level one boundary is 1.0 deg/ft/sec^2, so this example would be Level 1.

3.4.5.1.3 Pitch control in autorotation

Data Requirements: δ_B

Input Type: As appropriate for performing autorotation

Test Technique:

This requirement is included to ensure adequate pitch control power in autorotation (where collective changes are very large. It is almost certainly redundant with operational testing where autorotation capability must be demonstrated. It is not intended that this requirement will incur any additional testing beyond what is required to demonstrate autorotation capability.

Data Analysis and Interpretation:

A controller travel margin of 5 percent applies to the total stop-to-stop travel. If, for example, the controller travel limits were ±4 in. (8 in. total travel), a margin of at least 0.4 in. (8 * 0.05) must be demonstrated during the autorotation.

Modification to Criterion:

Since ADS-33E-PRF was published there have been numerous comments that 10% control margin is the accepted standard (also see Section 3.1.15 of this guide). This will probably be incorporated into ADS-33E-PRF at the next upgrade.

3.4.5.2 Roll due to pitch coupling for Aggressive agility

Data Requirements: θ, ϕ, δ_B, δ_A, δ_{Ped}

Input Type: Step in longitudinal controller

Test Technique:

This test applies only for those rotorcraft required to perform Aggressive maneuvering, as defined in 3.1.2 Required agility.

Apply steps in both directions. Vary amplitudes from almost imperceptible to as large as practical. Depending upon the abilities of a particular rotorcraft, "as large as practical" may be quite small (on the order of one inch or less), since the input is to be applied and held for 4 seconds.

For the largest inputs, attitudes and load factors may come close to operational limits. It may be useful to start the tests from a non-zero attitude. For example, for nose-up pitch inputs:

- Trim in level flight at the target altitude and airspeed.
- Decelerate and climb to an airspeed lower than, and an altitude higher than, the target conditions.
- Pitch over to a desired nose-down attitude.
- As airspeed/altitude approach the target conditions, apply a rapid nose-up longitudinal controller step.
- Reverse the process for nose-down pitch inputs.

Make no inputs in other axis of cyclic control and heading.

Hold the step for 4 seconds before recovering to normal flight.

It is important that the amplitude of the input be held as constant as possible for the full 4 seconds. A control input test fixture will be of value when performing this test. An in-cockpit control position indicator, or a command generator, can significantly improve the quality of the data obtained.

Compliance should be checked for all forward flight conditions above 45 KIAS. However, in order to keep the number of test points manageable, it is recommended that a test pilot qualitatively check for coupling throughout the flight envelope. This should include climbs and descents throughout the speed range. Once the worst-case points are known, obtain data for those points. Pilot comments should be documented to the effect that the coupling is subjectively no worse throughout the OFE than as recorded for the selected points.

Data Analysis and Interpretation:

The guidance for this criterion is identical to that used for the low speed and hover version in 3.3.9.2.

Modification to Criterion:

Experience with this criterion has shown that it is difficult to test for. This stems from problems with holding the input constant for 4 seconds as well as the large change in flight condition that can occur in the 4 second period. The latter factor restricts the criterion to small control inputs.

If such problems occur when attempting compliance with this criterion, it is acceptable to use the frequency domain criterion for target acquisition and tracking (3.4.5.4) in lieu of this time domain criterion. However, it should be noted that the frequency domain criterion boundaries are more stringent than the time domain boundaries.

The frequency domain criterion may replace the time domain criterion at the next specification upgrade.

3.4.5.3 Pitch due to roll coupling for Aggressive agility

Data Requirements: Pilot comments

Input Type: As appropriate for maneuvering

Test Technique:

This test applies only for those rotorcraft required to perform Aggressive maneuvering, as defined in 3.1.2 Required agility.

This qualitative requirement (coupling "shall not be objectionable to the pilot") applies during bank-to-bank maneuvering. While there are no specific tests required, coupling can be checked while performing Aggressive maneuvering MTEs of 3.11, including the Slalom at low speeds and the Transient Turn and Roll Reversal at high speeds.

Data Analysis and Interpretation:

None.

Modification to Criterion:

Plans are to delete this requirement from future versions of ADS-33. There is no point to having such a requirement when the MTE maneuvers noted above can be used to obtain pilot opinion.

3.4.5.4 Pitch due to roll and roll due to pitch coupling for Target Acquisition and Tracking

Data Requirements: q, p, δ_B, δ_A

Input Type: Frequency sweep in longitudinal controller

Test Technique:

This test applies only for those rotorcraft required to perform Target Acquisition and Tracking, as defined in 3.1.2 Required agility.

This requirement is the forward flight equivalent of 3.3.9.3. See discussion for that requirement.

Data Analysis and Interpretation:

See discussion of the low speed version of this requirement in 3.3.9.3 for specific guidance on data analysis.

It is acceptable to use this criterion in lieu of the time response criterion in Para 3.4.5.2, and the qualitative time domain requirement in Para 3.4.5.3. Compliance with this criterion will be accepted as compliance with the Para 3.4.5.2, and 3.4.5.3. However, it should be noted that the frequency domain criterion boundaries are more stringent than the time domain boundaries.

3.4.6 Roll attitude response to lateral controller

3.4.6.1 Small-amplitude roll attitude response to control inputs (bandwidth)

Data Requirements: p, ϕ, δ_A, F_A; other states, such as airspeed and altitude, are useful

Input Type: Frequency sweep in roll cockpit controller (see description of frequency sweep in the Appendix for detailed instructions)

Test Technique:

This requirement is the forward-flight equivalent of 3.3.2.1. See the discussion for that requirement.

Consideration should be taken as to whether any rotor modes will be in the frequency range of interest. If so, appropriate structural instrumentation should be required and it may be necessary to tailor the frequency sweep to account for such modes. For example, Comanche's regressive lag mode was at 1.8-2.0 hz and was usually excited during this test. The frequency sweep was tailored with appropriate limitations on control amplitude at specific frequencies to avoid exciting this mode.

Data Analysis and Interpretation:

See discussion for 3.3.2.1 (Short Term Response to Control Inputs (Bandwidth)).

3.4.6.2 Moderate-amplitude attitude changes (attitude quickness)

Data Requirements: q, p, $\theta, \phi, \delta_B, \delta_A$

Input Type: Pulse in roll controller for Rate Response-Types; step for Attitude Response-Types

Test Technique:

This requirement is the forward flight equivalent of 3.3.3. See discussion for that requirement.

Similar data are required for the roll-sideslip coupling requirement, 3.4.7. The two tests should therefore be considered together.

One large helicopter manufacturer has noted that this maneuver has structural implications, particularly main rotor mast bending as large accelerations result in high bending loads.

Data Analysis and Interpretation:

See discussion for 3.3.3.

3.4.6.3 Large-amplitude roll attitude changes

Data Requirements: q, p (Rate Response-Types) or θ, ϕ (Attitude Command Response-Types)

Input Type: Recommended input is a step, but any control input that generates a large angular rate or attitude may be used

This requirement is the forward flight equivalent of 3.3.4. See discussion for that requirement.

Data Analysis and Interpretation:

See discussion for 3.3.4.

3.4.6.4 Linearity of roll response

Data Requirements: Pilot comments

Discussion: Compliance with this requirement can be determined from pilot comments while performing the relevant MTEs for the rotorcraft. The pilots should be asked if there are any undesirable roll response characteristics. Such characteristics could be due to nonlinearities and further measurements may be needed.

Experience has shown that nonlinear shaping can be favorable, so linearity is not an issue here. The key word is "objectionable".

3.4.7 Roll-sideslip coupling
3.4.7.1 Bank angle oscillations

Data Requirements: p, β, ϕ, δ_A

Input Type: Pulse (Rate Response-Type) or step (Attitude Response-Type) in lateral controller

Test Technique:

The same data can be used for both 3.4.7.1 and 3.4.7.2.

Initiate the test from trimmed flight. For large bank angle changes, it may be appropriate to initiate a turn and apply the input opposite the direction of the turn.

Make the input as abrupt as practical. Apply inputs to both the left and the right.

Input size is required by 3.4.7 to be "up to the magnitude required to meet the roll performance requirements of 3.4.6.2," the attitude quickness requirements. This means bank angle changes of up to the lesser of the OFE limits (if any are defined for bank angle) or 60 degrees.

Testing for 3.4.6.2 Moderate amplitude attitude changes (attitude quickness) should be coordinated with the tests for this requirement. The needed data are essentially the same, though a much longer recording of the free response is required here.

Use of augmentation, either rate or attitude, may suppress the oscillatory response for small inputs. If the augmentation has limited authority, inputs large enough to saturate the SAS should be applied if practical, to assure that there are no anomalous responses.

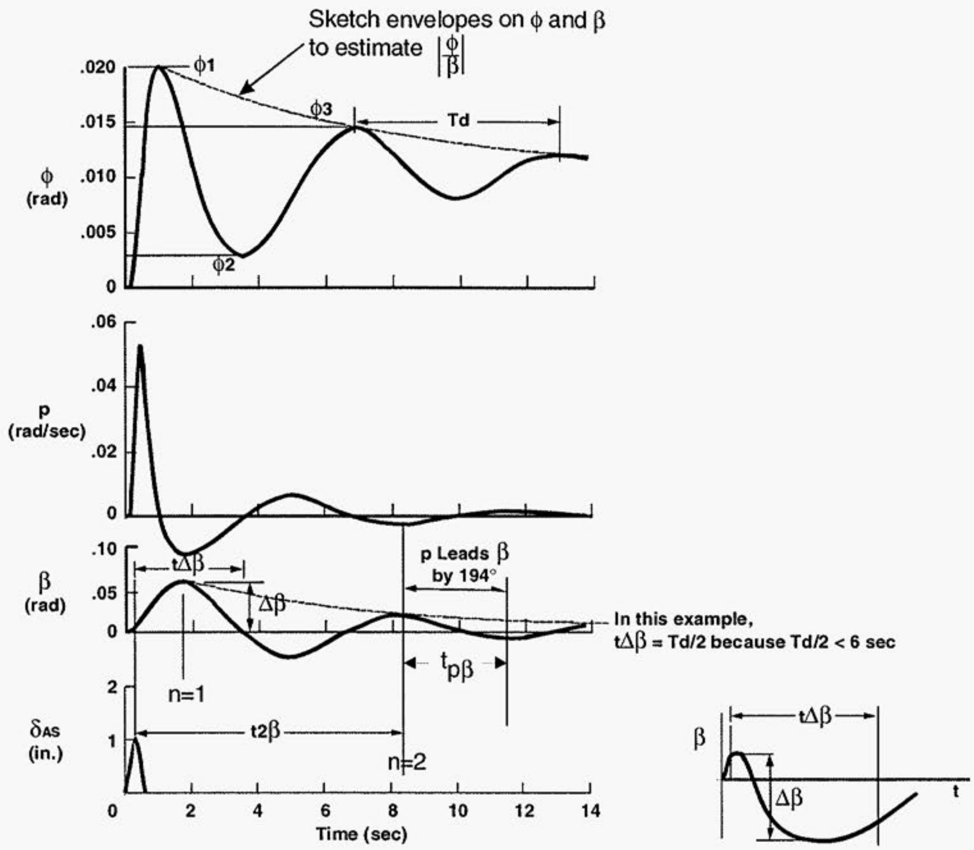
ADS-33E-PRF requires that the yaw controller remain free during the test. For some rotorcraft this may not be practical, and it may be necessary to hold the controller fixed (e.g., helicopters with reversible control system).

Obtain at least 6 seconds worth of data after the pulse is removed. In some conditions, less will be required, but it may not be possible to determine this until the data are analyzed.

Compliance should be checked for all forward flight conditions above 45 KIAS. It is realized that it is not practical to obtain detailed data at all flight conditions within the OFE. It is therefore acceptable to qualitatively check for excessive bank angle oscillations throughout the flight envelope and to obtain detailed data for selected worst-cases. Pilot comments should be documented to support the qualitative findings. This should include the points flown and the results (e.g., no significant sideslip or bank angle oscillations observed). The tested points should include some points during autorotation, albeit with bank angles that are no greater than would be used for a normal 180 deg autorotation maneuver.

Data Analysis and Interpretation:

Parameters and their definitions are given in Figure 19 of ADS-33E-PRF, repeated below in Figure 55 for reference. Note that this figure shows a pulse input, appropriate for Rate Response-Types. For Attitude Response-Types, the input will be a step. In addition, the figure illustrates measurement of parameters for inputs to the right only, and inputs should be applied both to the right and to the left.



Example to illustrate definition of Δβ in a response with sideslip reversal at t < tΔβ

$$Td = \frac{2\pi}{\omega_n \sqrt{1-\zeta^2}}$$

ζ, ω_n from paragraph 3.4.9.1

$$\frac{\phi_{osc}}{\phi_{av}} = \frac{\phi 1 + \phi 3 - 2\phi 2}{\phi 1 + \phi 3 + 2\phi 2} \quad (\zeta \leq 0.2) \qquad = \frac{\phi 1 - \phi 2}{\phi 1 + \phi 2} \quad (\zeta > 0.2)$$

ϕ, β, δ_{AS} change in roll attitude, sideslip, and lateral control position from trim.

$\Delta\beta$ the maximum change in sideslip following an abrupt roll control pulse command within time $t\Delta\beta$

$t\Delta\beta$ the lesser of 6 sec or Td/2.

$t_n\beta$ time for the lateral-directional oscillations in the sideslip response to reach the nth local maximum for a right command.

$\psi\beta$ phase angle expressed as a lag for a cosine representation of the lateral-directional oscillation in sideslip, where:

$$\psi\beta = -360\, t_n\beta / Td + (n-1)\, 360 \quad \text{(degrees)} \quad \text{with n as in } t_n\beta \text{ above}$$

$|\phi/\beta|_d$ at any instant, the ratio of amplitudes of the bank angle and sideslip angle envelopes in the lateral-directional oscillatory mode.

Figure 55 Figure 19 From ADS-33E-PRF

Using the time histories in Figure 55 as an example, the criterion parameters are calculated as follows.

The first step is to estimate the damping ratio. This can be done by a number of methods, e.g, see Appendix B in Reference 9. For convenience a version of the transient peak ratio method is provided in Figure 56, where:

$$TPR = e^{-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}} \quad or \quad \zeta = \frac{-2\ln(TPR)}{\sqrt{4\pi^2 + [2\ln(TPR)]^2}}$$

TPR is the ratio of any two successive peaks of the oscillation, e.g., $\Delta\phi_3 / \Delta\phi_2$ where $\Delta\phi_3$ occurs ½ cycle later than $\Delta\phi_2$ (see Figure 55)

For a second order system, TPR is a constant.

The transient peak ratio method is considered to be valid for damping ratios between -0.5 to +0.5

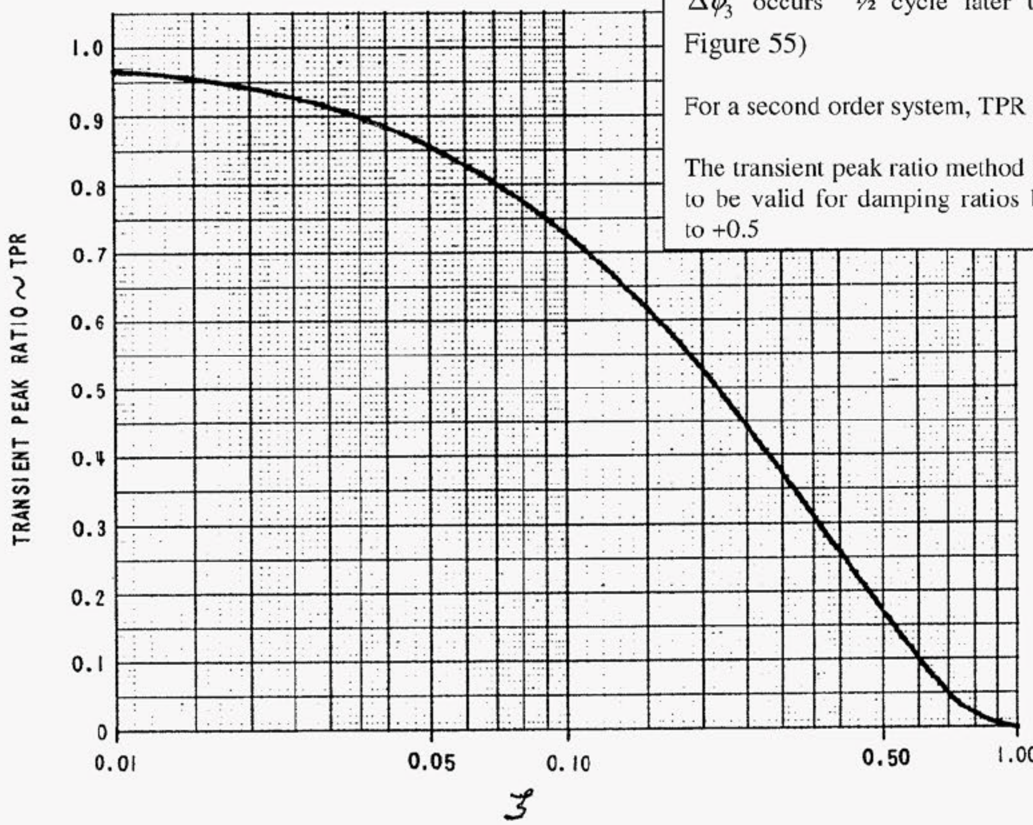


Figure 56 Transient Peak Ratio Method to Estimate Damping Ratio

From the bank angle time history in Figure 55, the transient peak ratio is 0.50 ($\Delta\phi_3 / \Delta\phi_2 = .50$)[1]. Using this in Figure 56 yields a damping ratio (ζ) of 0.21.

Calculate the ϕ_{OSC} / ϕ_{AV} criterion parameter as:

$$\frac{\phi_{OSC}}{\phi_{AV}} = \frac{\phi_1 - \phi_2}{\phi_1 + \phi_2} = \frac{0.02 - 0.003}{0.02 + 0.003} = 0.74$$

[1] Where $\Delta\phi$ refers to the bank angle with respect to the steady state value

Measure T_d from time history of bank angle, roll rate, or sideslip:

$T_d = 6.5$ sec.

Use the second local maximum so that n = 2. Then $t_{n\beta} = 8.3$ sec.

Calculate the amount that p leads β as follows:

$$\omega_d = \frac{2\pi}{T_d} = \frac{6.28}{6.5} = 0.966\ rad/\sec$$

$$\Delta\phi = T_{p\beta}\omega_d = 3.5 \times 0.966 \times 57.3 = 194^o$$

Calculate ψ_β:

$$\psi_\beta = -360\frac{t_{n\beta}}{T_d} + (n-1)360 = -360\frac{8.3}{6.5} + 360 = -99.7^o$$

Plot on criterion boundary in Figure 57, noting that p leads β by 194°. For this contrived example, the helicopter falls in the Level 2 region of the criterion. This is unusual for helicopters which are almost always Level 1 for this criterion as shown by examples in Reference 9.

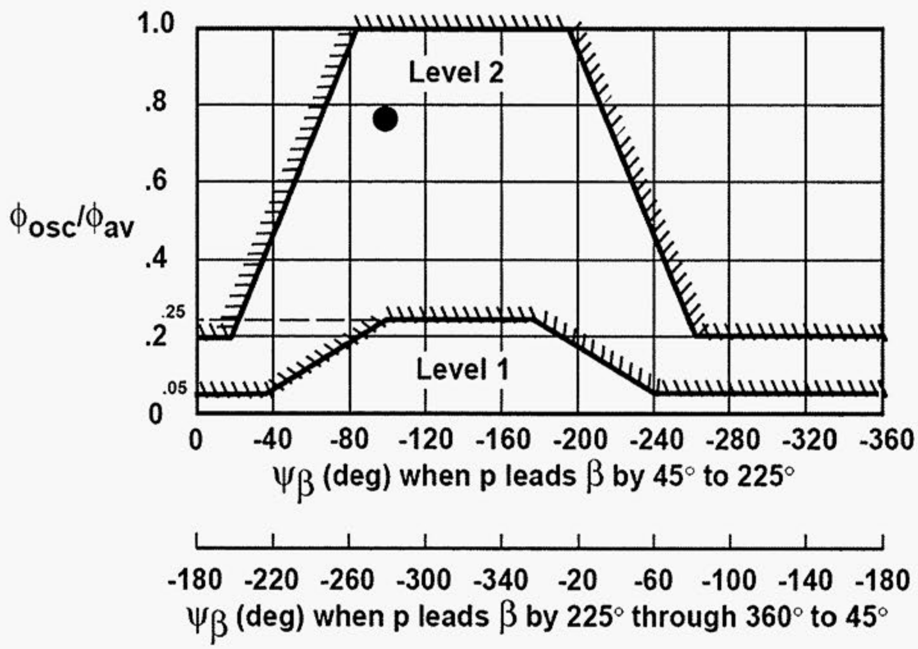


Figure 57 Example Data Point Plotted on Paragraph 3.4.7.1 Criterion Boundary

Measurement of the parameters required for this requirement can be complicated by the dynamics of the rotorcraft. While the criteria are most easily applied to a response dominated by a first-order roll mode and a Dutch roll oscillation, effects of roll/flap and spiral modes, and interaxis coupling, can produce a higher-order response. An example for the BO-105 is shown in Figure 58, reproduced from a report by Ockier, see Reference 6. The bank angle response, especially, differs from that given in Figure 19 of ADS-33E-PRF. Ockier found it necessary to use curve matching, using the procedure described by Chalk *et al.* (Reference 34) to extract the bank angle parameters.

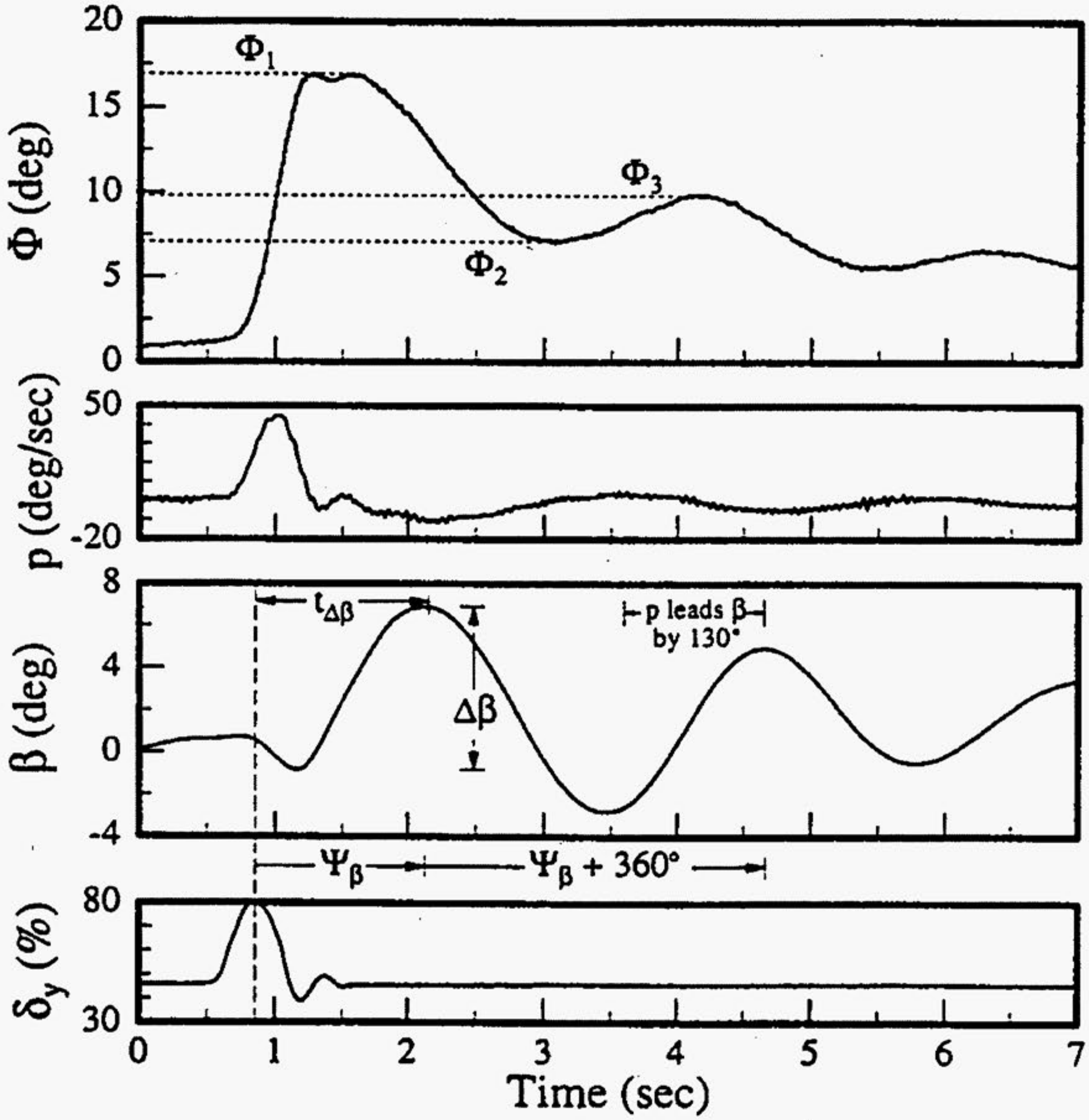


Figure 58. Lateral Response of BO-105 to Pulse Input

Stability augmentation will usually suppress the Dutch roll mode so that it is not apparent in the bank angle response. If an oscillation is not observable, compliance has been achieved.

3.4.7.2 Turn coordination

Data Requirements: p, β, φ, δ_A, pilot comments

Input Type: Pulse (Rate Response-Type) or step (Attitude Response-Type) in lateral controller

Test Technique:

Tests can be run for both 3.4.7.1 and 3.4.7.2 at the same time.

See discussion for 3.4.7.1.

Compliance should be checked for all forward flight conditions above 45 KIAS. However, it is not practical to obtain detailed data at all flight conditions within the OFE. It is acceptable to qualitatively check for excessive sideslip and/or adverse/proverse yaw throughout the flight envelope and to obtain detailed data for selected worst-cases. Pilot comments should be documented to support the qualitative findings. This should include the points flown and the results (e.g., no significant sideslip or bank angle oscillations observed). The tested points should include some points during autorotation, albeit with bank angles no greater than would be used for a normal 180 deg autorotation maneuver.

Data Analysis and Interpretation:

Continuing the example from Section 3.4.7.1 of this Test Guide, calculate the criterion parameters for turn coordination as follows.

$\Delta\beta = .07$ rad

$\dfrac{\Delta\beta}{\phi_1} = \dfrac{.07}{.02} = 3.5$ (Where $\Delta\beta$ and ϕ_1 are obtained directly from Figure 55)

$\left|\dfrac{\phi}{\beta}\right|_d = \dfrac{.008}{.055} = 0.15$ (draw envelopes around the ϕ and β oscillations and take ratio at any point)

Since this ratio is less than 0.20 it is not necessary to calculate $0.20 \times \left|\dfrac{\Delta\beta}{\phi_1}\right| \times \left|\dfrac{\phi}{\beta}\right|_d$

Plot on criterion boundary (ADS-33E-PRF, Figure 21, repeated below as Figure 59), noting that p leads β by 194° and from the example in Section 3.4.7.1, $\psi_{\beta} = -99.7^{o}$.

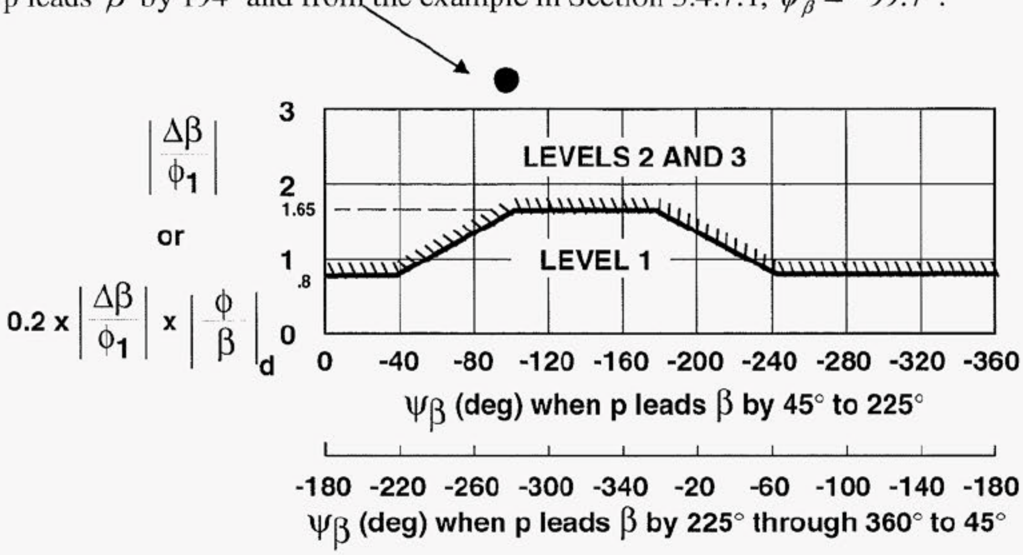


Figure 59 Example Data Point Plotted on 3.4.7.2 Criterion Boundary

For this contrived example, the turn coordination plots well into the Level 2 and 3 region so that some type of turn coordination augmentation would be required.

3.4.8 Yaw response to yaw controller

3.4.8.1 Small-amplitude yaw response for Target Acquisition and Tracking (bandwidth)

Data Requirements: r, ψ, δ_P, F_P; other states, such as airspeed and altitude, are useful

Input Forms: Frequency sweep in directional controller (see description of frequency sweep in the Appendix for detailed instructions)

Test Technique:

This test applies only for those rotorcraft required to perform Target Acquisition and Tracking, as defined in 3.1.2 Required agility.

Caution should be taken and loads in the drive train should be monitored during this test as overshoots in tail rotor (or fantail) torque can result.

See discussion for 3.3.2.1.

Data Analysis and Interpretation:

See discussion for 3.3.2.1.

Throughout the development of ADS-33, it was difficult to find realistic tasks that required tight closed loop heading control. The target acquisition and tracking requirement is based on a pointing task with fixed guns conducted in the NASA Ames VMS. If the gun is mounted to a turret (e.g., AH-64) there is no requirement for the very high yaw bandwidth that is required for Target Acquisition and Tracking ($\omega_{BW} \geq 3.5$ rad/sec). Therefore, it is acceptable to request a deviation for relaxed heading bandwidth if the procuring activity agrees that there is no yaw task sufficiently aggressive to justify the requirement. A request for such a deviation would ideally be accompanied with pilot rating data from related MTEs that require heading control with the yaw axis controller (e.g., the Transient Turn (3.11.14).

3.4.8.2 Large-amplitude heading changes for Aggressive agility

Data Requirements: β, δ_P

Input Type: Step in directional controller

Test Technique:

This test applies only for those rotorcraft required to demonstrate Aggressive agility, as defined in 3.1.2 Required agility.

Apply and hold the step for at least 1 second. Because time for measuring sideslip is so short, the input should be as abrupt as practical.

The input may be removed after 1 second or after sideslip achieves the limit of the Operational Flight Envelope, or 16 degrees, which ever is less.

Apply inputs to the left and to the right.

Other controls should remain fixed, but they may be used as necessary to reduce excursions in pitch and roll.

Sideslip envelopes are usually set based on structural loads and overshoots of the OFE into the SFE can approach structural limits. Therefore the structural sideslip envelopes (OFE and SFE, e.g., see Figure 5) should be known and accounted for when conducting this handling qualities test. Tail rotor or fantail torque should be monitored along with airframe loads.

Data Analysis and Interpretation:

The start time for step inputs is defined as the midpoint between zero and full input (see Appendix). If the "step" is applied at a slow rate, the rotorcraft will be penalized.

3.4.8.3 Linearity of directional response

Data Requirements: Pilot comments

Discussion: Compliance with this requirement can be determined from pilot comments while performing the relevant MTEs for the rotorcraft. If those comments indicate problems that might be traced to a nonlinear response, the sideslip response should be plotted as a function of directional control input.

There is no data to determine how linear is good enough, so it is necessary to rely on pilot commentary.

3.4.8.4 Yaw control with speed change

Data Requirements: V_T, h, $\phi, \psi, \delta_A, \delta_B, \delta_P$, F_P, pilot comments

Input Type: As required to perform speed changes at constant power (altitude varies) and constant altitude (power varies).

Test Technique:

Trim at the selected airspeed and altitude (or altitude rate).

Rapidly vary pitch attitude to increase or decrease speed by 30 percent from trim, or 20 kts, whichever is less, at constant power while maintaining heading and bank angle constant. There is no criterion on how constant but ± 3 deg of heading and bank angle would be a reasonable expectation.

Repeat the test by varying power and holding altitude constant by varying pitch attitude. Altitude should be held to within ± 50 ft.

If the directional controller is a three or four axis sidestick, twisting motion using the pilot's wrist is required. The specification only requires that the forces not be objectionable. The wrist muscles are generally not well developed, so it is possible that forces that are acceptable for an occasional yaw input would be unacceptable for tasks where frequent yaw control is required. Therefore, the testing activity should determine a worst-case forward flight mission as a task to determine if the yaw forces are acceptable. An example might be prolonged steady heading sideslips.

These tests should be accomplished at trim airspeeds from 65 kts to the maximum level flight speed (V_H). It is not necessary to go below 45 kts or above V_H.

Data Analysis and Interpretation:

For a helicopter with an irreversible flight control system, the directional controller forces are a known function of displacement and can easily be calculated.

If the forces are light, it is acceptable for the pilot to estimate that they are under the values in Table XIII. This is easy to do for forward flight as the maximum allowable force is 75 lbs, a value that is rarely if ever approached by helicopters.

3.4.9 Lateral-directional stability
3.4.9.1 Lateral-directional oscillations

Data Requirements: p (or ϕ), r (or β), $\delta_A, \delta_B, \delta_C, \delta_P$

Input Type: Doublet in directional controller; pulse in lateral controller

Test Technique:

This requirement applies to any oscillation in the lateral-directional degrees of freedom. The most common is the low-damped Dutch roll oscillatory mode. If one or more lightly damped oscillations exists at frequencies above the Dutch roll mode, they should be plotted on the criterion boundary.

Some type of equivalent system matching technique would be required to identify the frequency and damping of more than one second order mode. This has not been shown to be an issue for rotorcraft developed to date, so no guidance is available. However, the recommended procedure would be to use frequency sweep methods to develop a Bode plot of the response, which would be the basis for identification of the frequency and damping of the modes.

High-frequency, low-amplitude oscillations, such as structural modes, that do not affect the pilot's ability to control the rotorcraft, are not the target of this requirement. An example of such an oscillation was given in Section 3.1.17 of this Test Guide, Figure 9.

Both roll and yaw test inputs are specified to assure that both the lateral and directional degrees of freedom are checked.

Some of the lateral control pulse data generated for 3.4.7.1 can be used here as well.

Testing is required with controls both fixed and free. For a reversible flight control system a controls-free input may not be practical due to swashplate feedback into the controller.

If the rotorcraft is equipped with limited-authority augmentation, inputs large enough to saturate the augmentation should be applied, if practical. This will verify that there are no unusual oscillatory responses resulting from the saturation.

Data Analysis and Interpretation:

An example response of the BO 105 to a pedal doublet in forward flight is shown in Figure 60 as taken from Reference 6.

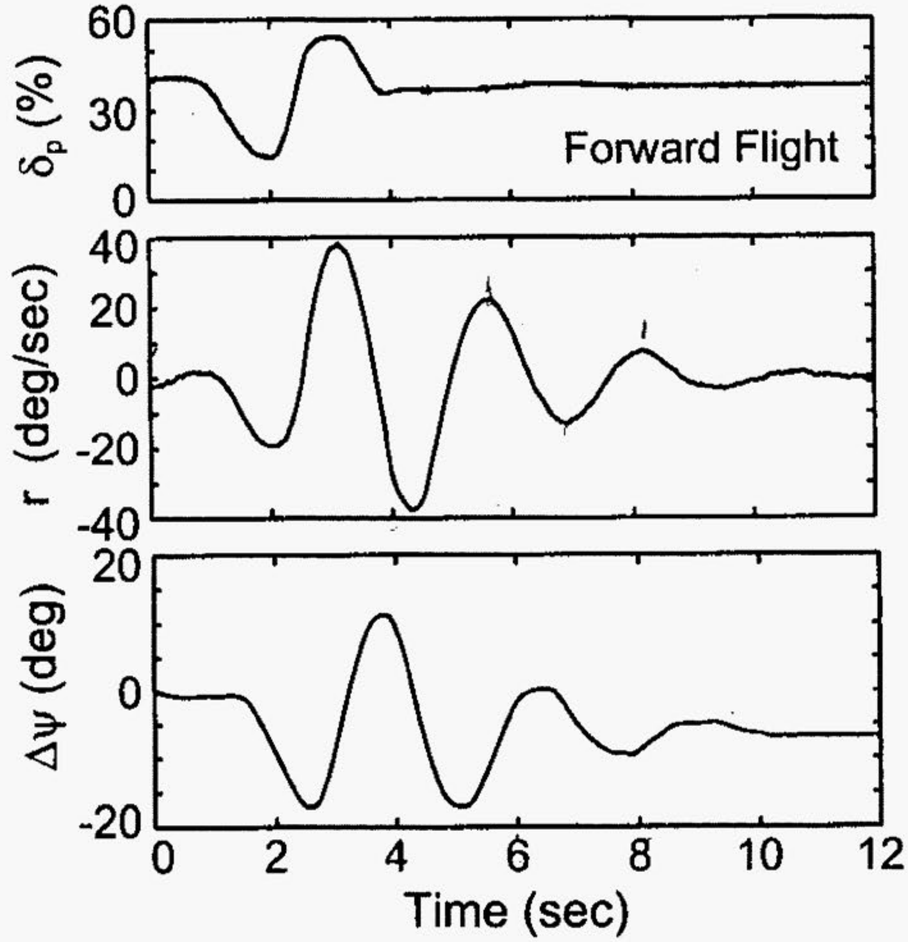


Figure 60 BO 105 Response to Pedal Doublet in Forward Flight (Reference 6)

It is important to measure the free response that occurs after the input has been completed (e.g., after 4 seconds in the above example). The period of oscillation is measured as 2.8 seconds and the frequency is calculated as

$$\omega_d = \frac{2\pi}{T} = \frac{6.28}{2.8} = 2.24 \text{ rad/sec}$$

The damping ratio may be obtained using the Transient Peak Ratio method shown in Figure 56 as follows. Using successive peaks of the yaw rate response at approximately 6 seconds and 7 seconds results in a ratio of 15/21 = 0.71. From Figure 56 this results in a damping ratio of 0.105 so that, $\zeta_n \omega_n = 0.24$ and $\omega_n \sqrt{1-\zeta^2} = 2.24$ rad/sec. These parameters are plotted on the ADS-33E-PRF criterion boundaries (filled circle) in Figure 61, and indicate that the BO 105 is Level 2 for the All Other MTEs category and Level 3 for Target Acquisition and Tracking.

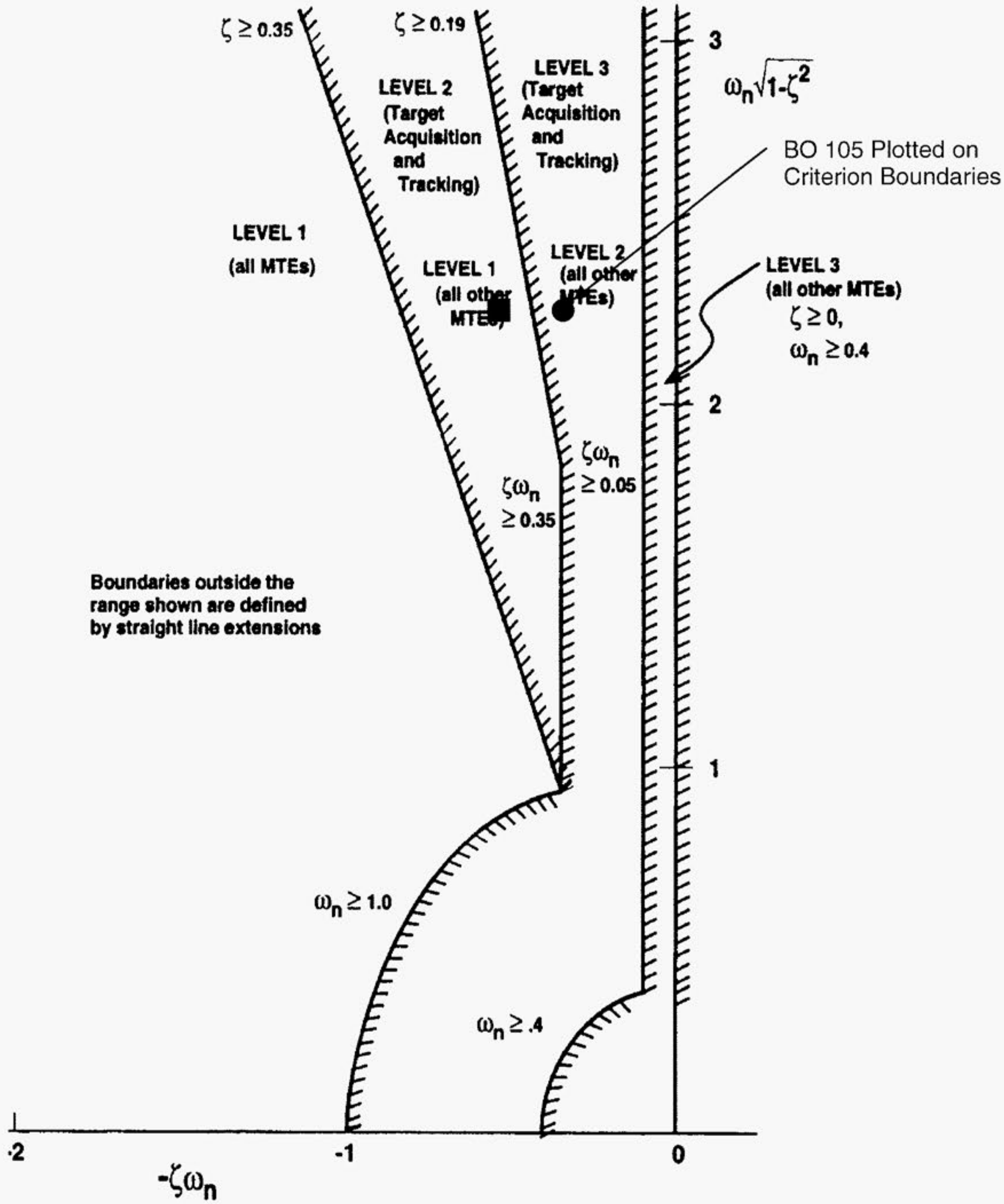


Figure 61 Lateral Directional Criterion (ADS-33E-PRF Figure 23)

To check for linearity, the ratio of the yaw rate peaks at approximately 7 and 8 seconds are obtained giving a transient peak ratio of 8/15 = 0.53. Since this is different than the ratio of the two previous peaks, the response is seen to be nonlinear, and therefore the requirement applies to each cycle. Carrying out the above calculations for this cycle results in a damping ratio of 0.20, and this is plotted on the criterion boundaries as a filled square. The criterion must be met for each cycle of the response, so the worst case applies (Level 2 for all other MTEs).

If an oscillatory response cannot be observed, more elaborate methods may be required to extract the parameters (for example, Appendix B of Reference 9). Figure 23 of ADS-33E-PRF requires a minimum value of modal frequency even if damping is high. Damping ratios above about 0.6 may be difficult to observe in the time responses. In this case damping is not as important since Figure 23 of ADS-33E-PRF places a limit on modal frequency independent of damping if the damping ratio is greater than 0.35.

3.4.9.2 Spiral stability

Data Requirements: ϕ ; other states such as airspeed and altitude are useful.

Input Type: Pulse in lateral controller

Test Technique:

Initiate the test from trimmed, straight and level flight. It is important that the aircraft be carefully trimmed prior to initiating the pulse. The test must be accomplished in calm conditions (no turbulence).

ADS-33E-PRF requires that the test be conducted with cockpit controls free. If such a test results in a potentially dangerous condition, the controls may be fixed during the test. This might be the case for a reversible control system, wherein the swashplate can backdrive the cyclic.

It may be necessary to let the response develop for several seconds (perhaps 30 or more) to gather sufficient data.

It can be difficult to apply a pure lateral controller pulse because control system friction will cause a small amount of controller input to remain, if the pulse is accomplished by releasing the controller after the input. Responses due to this residual input are often misinterpreted as part of the free response, resulting in misleading conclusions. The solution to this is to use a fixture that provides a reference for the controller trim position. Rather than release the controller, return it to the starting position where it just contacts the fixture. The importance of returning the controller exactly to trim is emphasized.

The purpose of the pulse input is to excite the spiral mode. The size of the pulse input should be just large enough to initiate a roll disturbance. If the aircraft returns to the original bank angle, the spiral mode is stable. If the pulse results in a new constant bank angle, the spiral stability is neutral. A concave-up divergence indicates an unstable spiral mode.

The specification only requires testing from straight and level flight. The reason is that the purpose of this requirement is to ensure that the rotorcraft will not rapidly diverge in bank angle during periods of divided attention. Pilots rarely divide their attention away from aircraft control while in a turn. Nonetheless, it may be desirable to accomplish the pulse input at a small steady bank angle (say 15 degrees) in addition to the required level flight condition. In most cases, spiral mode stability is independent of bank angle.

For an attitude-command-attitude-hold (ACAH) Response-Type the spiral mode will always be stable (i.e., the response to a pulse will be to return to the trim attitude). For a rate-command-attitude-hold (RCAH) Response-Type, the helicopter will seek a new trim attitude, indicating a neutrally stable spiral mode. These responses are fundamental to the ACAH and RCAH Response-Types and any deviation indicates that the flight control system is not performing its intended function.

Data Analysis and Interpretation:

Time to double amplitude is a standard measure of spiral instability. Application of this requirement involves a substantial amount of bank angle time-history data. There must be enough data to observe spiral stability, or to accurately measure the instability, and to distinguish the spiral response from oscillatory modes that may contribute local minima in the time history.

Example time histories for stable, neutral, and unstable spiral are shown in Figure 62.

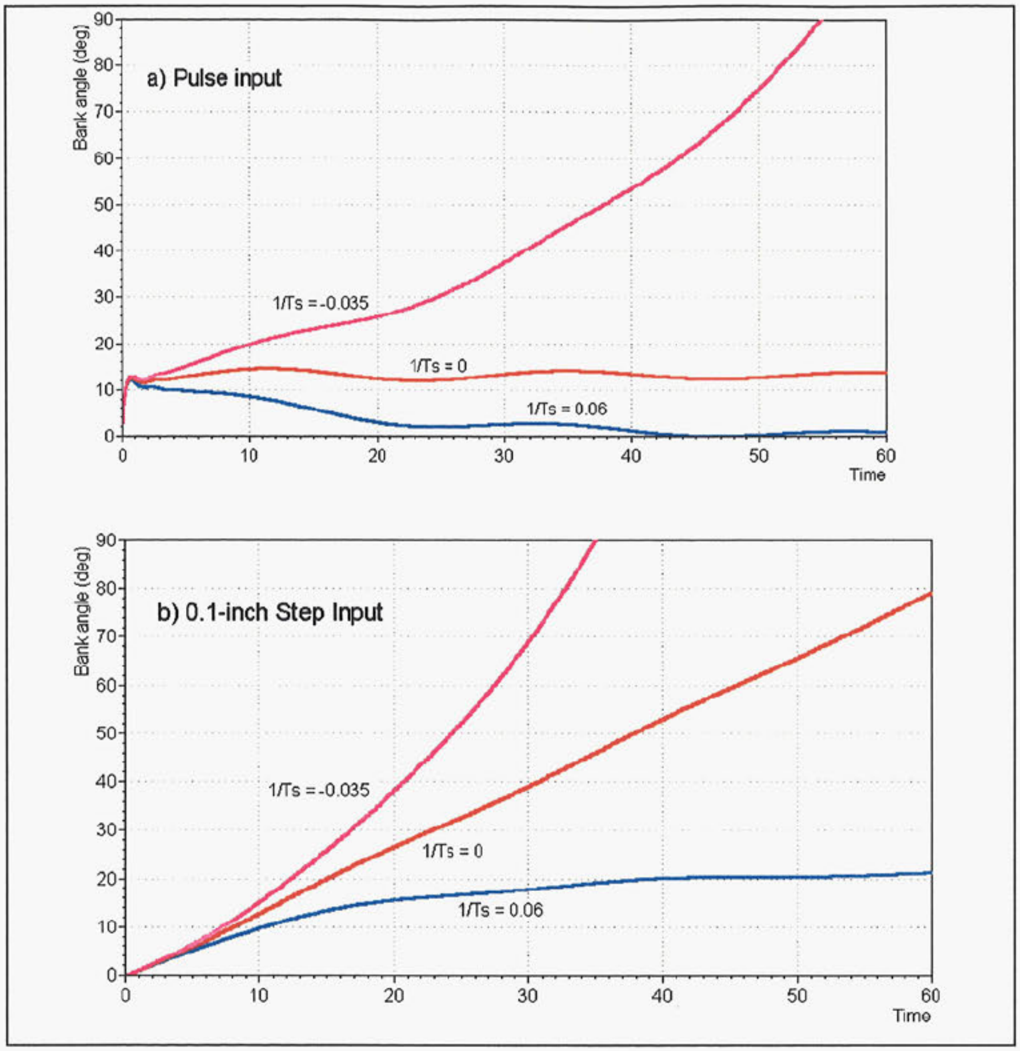


Figure 62. Stable, Neutral, and Unstable Spiral Modes

The responses represent an analytical model of a single main rotor helicopter (the OH-6A at 80 kts) with the spiral mode pole, $1/T_s$, set to 0.06 (stable) , 0 for the neutral case, and to –0.035 for the unstable case (units are 1/seconds). The latter gives a time to double amplitude, based on the spiral mode alone, of approximately 20 seconds, since $t_2 \cong 0.693/(1/T_s)$. (Note - time to double amplitude for a first order divergence is calculated as: $t_2 = T_s \log_e 2$).

- For a one-inch pulse input (Figure 62a) the response with a stable spiral mode gives the expected result wherein the bank angle returns toward zero. A neutrally stable spiral is seen to result in an essentially constant bank angle response, and with an unstable spiral there is an obvious concave upward response.
- The 0.1 inch step input (Figure 62b) is shown to illustrate the effect of friction, wherein the control does not return to center after the pulse input. Note that the neutral spiral case

continues to diverge, which could easily be interpreted as an unstable spiral. These responses would add to the response to the pulse input (i.e., part (a) of the figure).

- In the pulse example, the test could have been stopped well before the 60 seconds, but notice that a test of only 20 seconds might have given the wrong impression: there is a low-frequency oscillation that causes a "hump" in all three responses and that could fool the tester into thinking that the spiral was stable.

With the pulse input, if bank angle tends to return to trim or to attain a new trim during the run, compliance is assured and detailed analysis to determine the spiral mode is not required.

A common method for extracting the time constant of an unstable spiral mode is to plot the bank angle response on semi-log paper (for example, Reference 34). The spiral component is the time-averaged response after the first few seconds (the roll and Dutch roll modes dominate the initial response). An example is shown in Figure 63. This plot shows the first 20 seconds of the unstable spiral case from the pulse response (top of Figure 62), replotted on a semilog scale.

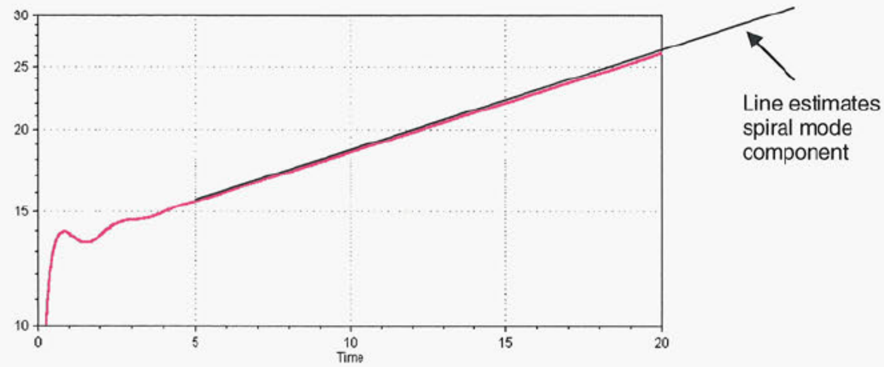


Figure 63. Extraction of the Spiral Mode Using Bank Angle

As long as there are no nonlinearities in the response, the spiral is well-approximated by a straight line drawn through the time history after five seconds or so, as shown.

Measure the values of the average line, $\hat{\phi}_1$ and $\hat{\phi}_2$, at two times, t_1 and t_2. The spiral mode time constant is given by the following equation:

$$T_s = \frac{-(t_2 - t_1)}{\ln\dfrac{\hat{\phi}_2}{\hat{\phi}_1}}$$

Time to double is as defined above, $T_2 \cong -0.693 * T_s$.

For the example case, $\hat{\phi}_1 = 18.5$ degrees at 10 sec and $\hat{\phi}_2 = 26.3$ degrees at 20 sec. This gives $T_s = -0.035$ sec and $T_2 = 19.7$ sec, accurately estimating the actual values.

3.4.10 Lateral-directional characteristics in steady sideslips
3.4.10.1 Yaw control in steady sideslips (directional stability)
3.4.10.2 Bank angle in steady sideslips
3.4.10.3 Lateral control in steady sideslips
3.4.10.3.1 Positive effective dihedral limit

Data Requirements: $\beta, \phi, \delta_P, \delta_A, F_P, F_A$

Input Type: Steady directional controller inputs

Test Technique:

Data for all of the sideslip requirements can be generated from one series of tests. It is possible that the data may be obtained from the performance of other tests, including the relevant requirements from 3.6 Controller characteristics.

Testing requires yaw-control-induced, steady heading (zero-yaw-rate) sideslips with the rotorcraft trimmed for straight and level flight.

Perform the sideslips to the right and to the left up to at least the limits of the Operational Flight Envelopes.

An example of data produced to show compliance with 3.4.10.1 Yaw Control in Steady Sideslips (directional stability) is given in Figure 64.

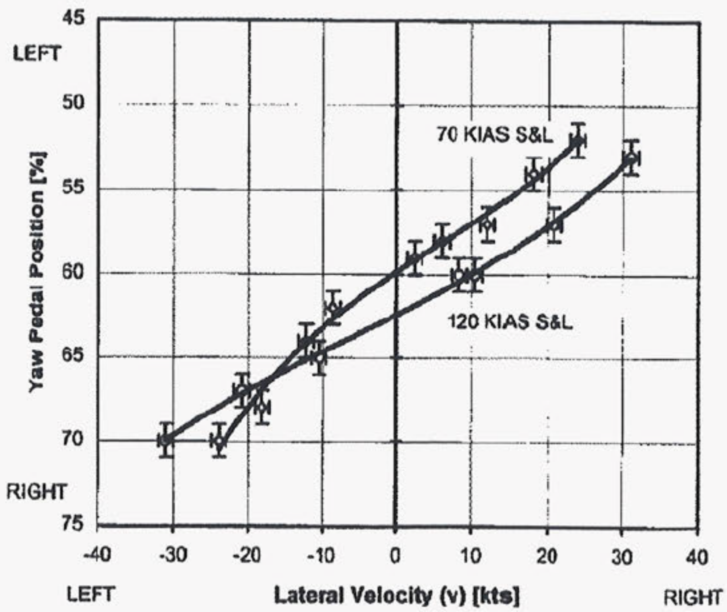


Figure 64 Example of Data to Show Compliance with Directional Stability

This data is plotted against lateral velocity instead of sideslip. To convert to sideslip use the following formula.

$$\beta = \sin^{-1} \frac{v}{V_{CAS}}$$

For the 120 KIAS curve, the required sideslip angle of 15 degrees occurs at a side velocity of 31 kts, and for the 70 KIAS curve the side velocity corresponding to a 15 degree sideslip is 18 kts.

The curves in Figure 64 are judged to be sufficiently linear as to meet the intent of 3.4.10.1.

An example of data to show compliance with 3.4.10.3 Lateral Control in Steady Sideslips (Lateral Static Stability) is given in Figure 65.

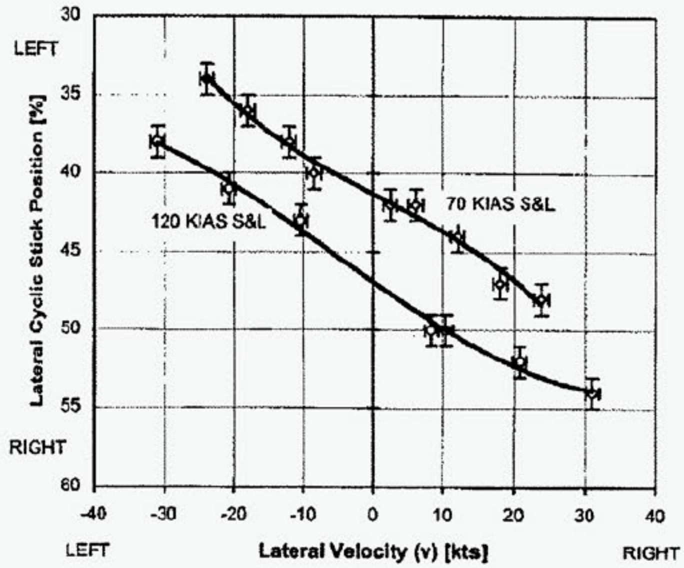


Figure 65 Example of Data to Show Compliance with Lateral Static Stability

These curves are also judged to be sufficiently linear to meet the requirements in 3.4.10.3.

Note that the data for Figure 64 and Figure 65 were taken from the same series of inputs.

Data Analysis and Interpretation:

For some helicopters, the pedal force gradient with deflection is zero. In those cases, it will be necessary to demonstrate that Level 1 handling qualities can be achieved for the mission MTEs assigned in 3.1.1.

A simple feel spring is often used so that force is a direct function of displacement. In those cases the requirements on force may be satisfied by calculating the force from displacement data.

The requirement in 3.4.10.3.1 (Positive Effective Dihedral Limit) places a limit that specifies that no more than 75% of available roll control power be required to maintain zero roll rate at the sideslips required by the MTEs. This is problematic because roll control power is stated in terms of maximum roll rate, not controller deflection.

To comply with this requirement, determine the roll controller deflection required to reach 75% of the specified roll rate or bank angle in 3.4.6.3 (Table IX). That deflection sets the limit on allowable roll controller input for this requirement. For Level 2 this is increased to 90% .

If a yaw-rate command direction hold (RCDH) system is mechanized (e.g. Comanche three axis sidestick design), it will not be possible to meet Para 3.4.10.1 (Directional Stability). That is because an RCDH Response-Type has no directional stability and will trim at any sideslip angle. While this may be acceptable, there is no data to support it, and a deviation from ADS-33E-PRF would be the only avenue to show compliance. Unfortunately, for forward flight only the Transient Turn MTE (3.11.14) involves intentional sideslip. Other maneuvers would have to be developed to show that zero directional stability is acceptable when implementing RCDH in forward flight.

3.4.11 Pitch, roll, and yaw responses to disturbance inputs

Data Requirements: q, p, r, $\theta, \phi, \psi, \delta_B, \delta_A, \theta_{TR}$ or δ_{TR}

Input Type: Frequency sweep inserted into the appropriate actuator

Discussion:

This is the forward flight equivalent of 3.3.2.2 and 3.3.7.

See discussion for 3.3.2.2 for revised and alternate versions of this criterion for response to disturbance inputs.

3.6 Controller characteristics

Data Requirements: $\delta_B, \delta_A, \delta_P, \delta_C, F_B, F_A, F_P, F_C$, pilot comments

Input Type: No specific inputs

Test Technique:

The criteria in these paragraphs are all for conventional center stick, pedals, and collective controllers. For any other type of controller, it will be necessary to identify deficiencies during compliance with the MTE maneuvers in Para 3.11 of ADS-33E-PRF. One of the primary motivations for developing the MTE maneuver requirements was to account for possible deficiencies in controllers for which there are not sufficient data to develop quantitative criteria.

For conventional helicopters the control centering and breakout can be measured on the ground. Breakout shall be taken as the force that is required to start the controller moving and is the sum of any mechanical detent and friction. This can be determined with a hand-held force gauge.

If ground-to-flight similarity cannot be assured then the controller breakout can be determined in flight using the same technique as noted above. However, for augmented helicopters that use feedback to a parallel servo (e.g. UH-60 FPS) the gradient may be a function of angular rates or attitude and in those cases cannot be measured in flight.

For augmentation that is implemented with series-servos and a feel spring, the breakout and gradient will be the same on the ground as in flight.

Any potential problems with controller characteristics, including dynamic responses, harmony, lack of centering, hysterysis, and force/deflection gradients should be identified during performance of the MTE maneuvers in Section 3.11.

The caveat that the collective breakout force can be measured with adjustable friction set will be removed from future upgrades to ADS-33E and can be ignored.

Data Analysis and Interpretation:

A hand-held force gauge and ruler are usually adequate to measure the controller characteristics on the ground.

Definitions of control system parameters are given in Figure 66

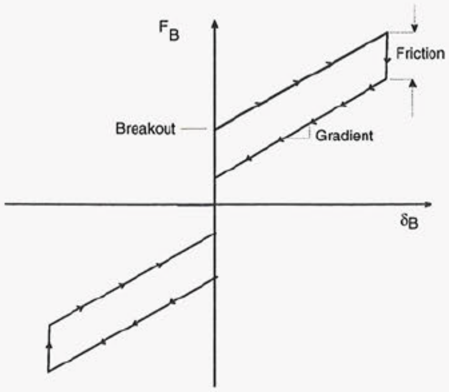


Figure 66 Control System Parameter Definitions

3.7 Specific failures

Data Requirements: As required to demonstrate compliance

Input Type: As required

Discussion:

The testing activity is tasked to assess whether the flying qualities after failure are "dangerous or intolerable." Worse-than-Level-3 may be used as equivalent to dangerous or intolerable.

Pilot recovery delay times and allowable recovery techniques should be specified prior to initiating any test. Unless delay times are specified by the procuring activity, for fully attended flight, it is recommended that the pilot be required to wait for 1.5 seconds after the failure before initiating a recovery. The aircraft must stay within the SFE during the entire event. However, the pilot is allowed to make control inputs consistent with maintaining the flight condition after the failure is input. For example, when the S-76 experiences an engine failure it has a tendency to pitch up and roll. The pilot is allowed to immediately make cyclic inputs to maintain pitch and roll attitude, but not collective inputs. The delay requirement on collective inputs is intended to simulate the time required for the pilot to diagnose the engine failure and then begin to take proper corrective action.

For divided attention operations (e.g. single pilot IFR), it is suggested that the 1.5 second delay time would refer to all control inputs.

Relief from these requirements cannot be granted on the basis of probabilities or the inclusion of redundant protections.

The testing activity should be provided with a list of the specific failures to be evaluated. It will be the task of the testing activity to determine those failures that will be (or have already been) verified by other specifications and those that are too hazardous to perform in flight.

Some of the requirements, such as autorotation following engine failure, will almost certainly be specified in a system specification or similar document. Most of these will eventually require flight verification. If the requirements of the system specification are more stringent than those of ADS-33E-PRF, the more stringent requirements apply. Compliance with one verifies compliance with the other.

In some instances, such as complete loss of a function of the flight control system, the testing for verification may be impractical or prohibitively dangerous to be performed in flight. In this case, a validated ground-based simulator, preferably with flight hardware in the loop, will be used.

See related discussion under 3.1.14 Rotorcraft failures.

Application of the Cooper-Harper Handling Qualities Rating Scale to failures can sometimes be difficult. Large transients following the failures, for example, can lead to momentary out-of-control flight that would warrant an HQR of 10. Immediately after the transient, however, the rotorcraft may again be flyable and be no worse than Level 2. Researchers have addressed this dilemma by developing alternative rating scales based solely on the failure, its transients, and the requirements on the pilot to recover. One such scale, from a 1990 technical paper by Hindson *et al.* (Reference 35), is reproduced in Figure 67 with some modifications (see Reference 36).

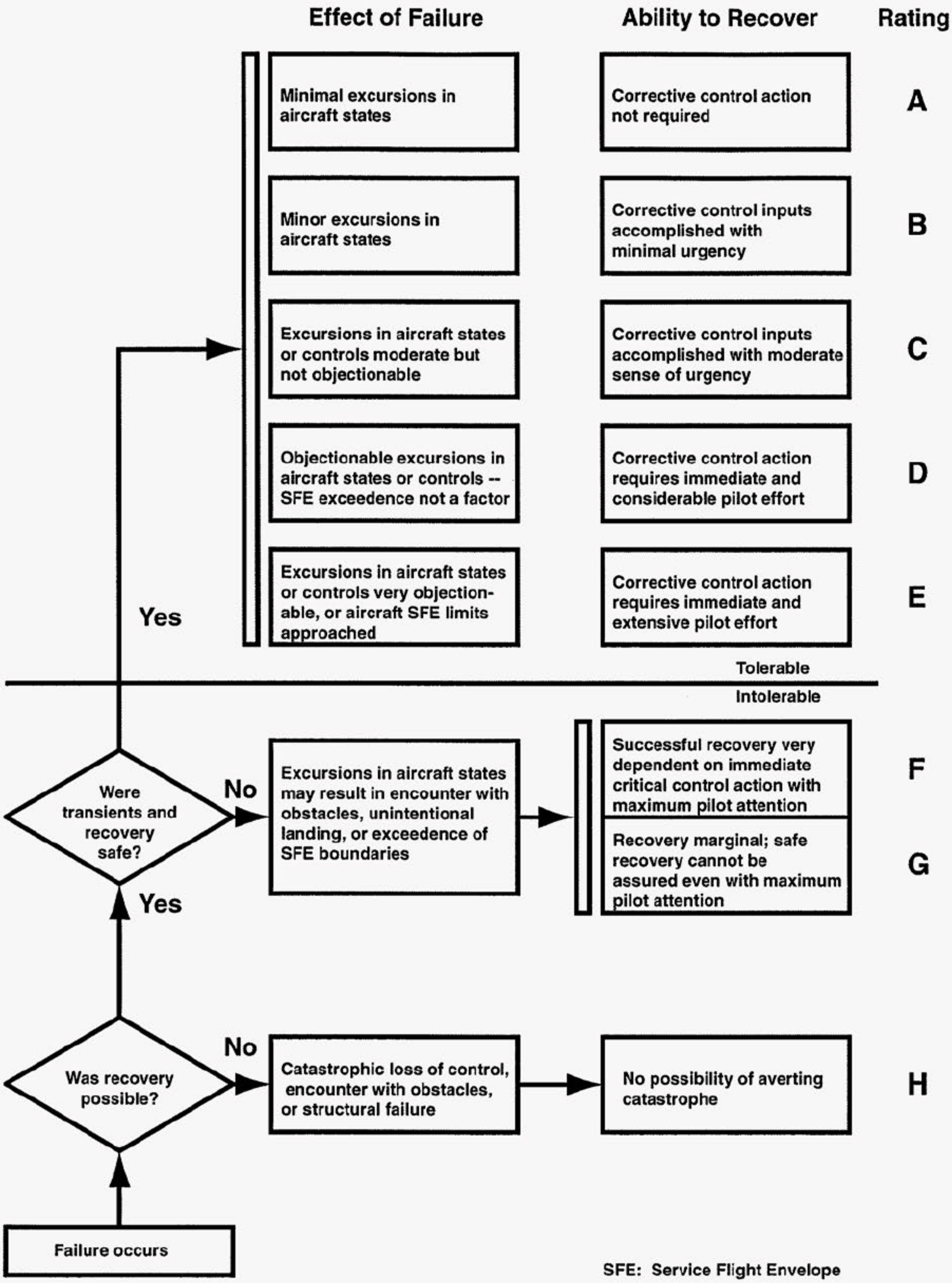


Figure 67. Alternative Rating Scale used for Large Transients

With the following caveats, this scale should be considered as a possible replacement for the HQR scale when rating failure effects.

- There is relatively little practical experience with the Failure/Recovery Rating Scale, so any potential limitations have not been fully explored.
- The scale as developed by Hindson *et al.* referred to exceeding the Operational Flight Envelopes (OFEs), but ADS-33E-PRF expects that specific failures will lead to flight in the Service Flight Envelopes (SFEs). The scale in Figure 67 has been amended to refer to the SFE, not the OFE.
- Hindson *et al.* used different questions to lead the user up the decision tree. The first (lowest on the scale) question formally asked, "Was recovery impossible?" The second (higher) question asked, "Was safety of flight compromised?" Answering "Yes" to either question led the user to branches to the right. In the more familiar Cooper-Harper scale, "No" answers lead the user to branches. The two questions have been revised in Figure 67 to be more consistent with the format of the Cooper-Harper scale.
- It is up to the procuring activity to determine the minimum acceptable rating on the Figure 67 scale. Without such guidance, assume that a rating of E or better would satisfy the intent of 3.7.

The intent of this paragraph in ADS-33E-PRF is to allow the procuring activity to insist on better flying qualities than would be required by the probability methods of Para 3.1.14.1. For example, the probability method may allow Level 2 handling qualities in autorotation following an engine failure (Pf < 2.5E-3 per flight hour). This might be considered as unacceptable for a training helicopter with only one engine. Therefore the procuring activity would be able to specify that the handling qualities in autorotation shall be Level 1 using this section of ADS-33E-PRF.

The intent of this paragraph is not to circumvent the probability methods for multiple failures. For example it would have taken two failures for the Comanche design to revert from Core Automatic Flight Control to Mission Primary Flight Control and a further third yaw rate sensor failure to revert to Core Primary Flight Control. The probability of this happening at the extremes of the OFE where it would be catastrophic (e.g., high speed and elevated load factor) are less than 2.5E-7 per flight hour, and therefore adequate redundancy was provided. It is not intended that such improbable multiple failures in rare flight conditions be survivable using this section of ADS-33E-PRF.

Careful consideration should be given to those failures that are deemed too dangerous to be evaluated in flight test and have a reasonable probability of occurring. If it is too dangerous to be flown in a controlled environment, with an experienced test pilot and an instrumented aircraft when that pilot knows the failure is going to happen, then perhaps it is too dangerous for operational pilots. If the probability of such a failure can be shown to be less than 2.5E-7 per flight hour, it is deemed an acceptable risk according to ADS-33E-PRF and flight testing should not be required.

The engine failure testing required by 3.7.2 is usually found in other places such as the rotorcraft systems specification. These high-level requirements were included in ADS-33E-PRF for completeness. When developing the specification it was assumed that autorotation, or single engine operation for a multi-engine rotorcraft is within the OFE or SFE. Therefore, the handling qualities requirements following an engine failure are implicitly required to be Level 1 or Level 2 depending on which flight envelope is invoked by the tailored specification (which should be based on the probability of that failure). As with other failures, the transient following an engine failure must be subjectively evaluated until quantitative requirements are developed.

The height-velocity curve that defines safe airspeeds as a function of altitude following a power train failure is considered to be a performance issue and therefore that subject is not addressed in ADS-33E-PRF.

Modification to Criterion:

Specific failure requirements are contained in Paragraph 3.1.14.2 (Allowable Levels for Specific Failures) and 3.7 (Specific Failures). Future upgrades to ADS-33E-PRF will combine these so all failures are handled under 3.1.14 (Rotorcraft failures).

If data are available, delay times for pilot takeover will be specified in future upgrades to the specification.

3.8 Transfer between Response-Types

Data Requirements: As required to show compliance, including pilot comments

Input Type: As required

Test Technique:

This set of requirements applies to any augmentation mechanization that involves a change of Response-Types, either automatically or by pilot action. If there are no switchable modes, or if mode switching does not produce a change in Response-Type, these requirements do not need to be tested. Most of these requirements are subjective due to a lack of data, and due to the fact that there are a very large number of ways that the transfer between Response-Types can be accomplished.

Following are some examples of transfers between Response-Types:

- Hover Hold that engages and disengages automatically based on cockpit control position and groundspeed. (see discussion of Para 3.3.11, Position Hold).
- Selectable Attitude Hold for cruise flight.
- A SCAS that blends between Heading Hold (or no yaw augmentation) and Turn Coordination.

An example of the strategy used to transition between Response-Types as developed for the CH-47F digital automatic flight control system (DAFCS) is given below in Figure 68 (Taken from Reference 37.

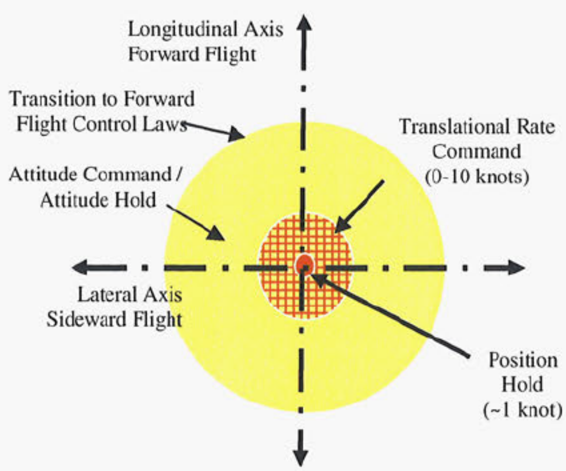


Figure 68 Transition Logic Used for CH-47F DAFCS

The CH-47F DAFCS transitions from Rate in forward flight, to ACAH for low speed, to translational rate command (TRC) below 10 kts, to position hold (PH) below 1kt. Some caveats to these transitions are as follows:

- TRC is activated/armed via a 4-way switch on the collective.
- The pilot can remain in ACAH all the way to hover by not arming TRC.
- The switch between ACAH and TRC was found to be seamless by the pilots.
- The criteria to transition from TRC to PH are groundspeed one knot or less and stick in detent.
- The criterion to transition out of PH is to move the stick out of detent. If the stick was moved past a threshold, the system transitions from PH directly to ACAH.
- Selecting PH, automatically results in TRCPH. It is also possible for the pilot to select TRC, in which case PH is not armed. For some versions of the CH-47F (built for a foreign government) it is only possible to select TRCPH (TRC without PH is not available).

Following are some examples of transfers for which the requirements do not apply:

- Pilot-selectable SAS that does not change the basic Response-Type, such as a rate damper.
- A limited-authority rate damper that saturates momentarily during maneuvering flight. (Saturation changes the dynamic response of the rotorcraft, however, and it should be verified that the effective vehicle dynamics are not significantly adversely affected. This should be checked during the testing of the applicable MTEs.)

The most critical transfers occur when the pilot is actively controlling the rotorcraft, for example, blending from Attitude Command in hover to Rate Command during acceleration to forward flight, where a displacement of the pitch controller changes from commanding an attitude to commanding a pitch rate.

An acceleration command velocity hold (ACVH) Response-Type was rejected for the CH-47F DAFCS because of an uncommanded pitch down that occurred as the helicopter decelerated through the transition speed where the Response-Type switched from ACAH to ACVH. The pitch down occurred because ACVH tries to hold the airspeed constant, whereas the pilot almost without exception wanted to continue the deceleration to hover. For that reason, the ACVH mode was eliminated in favor of using ACAH for all low airspeed operations where TRC was not active.

A transfer between Response-Types can occur following a failure. The effect of such a transfer should be handled as a transient in 3.1.14.4 (Transients Following Failures).

Data Analysis and Interpretation:

Most of the requirements are subjective. Therefore it is important to include as many pilots in the evaluation as possible.

3.9 Ground handling and ditching characteristics

Data Requirements: As required to show compliance, including pilot comments

Modification to Criterion: Most industry comments indicated that compliance with the ditching paragraph (3.9.4.1) is not practical and is out of scope of a handling qualities specification. Further, none of the requirements in 3.9 are related to handling qualities and should be specified elsewhere. Therefore, consideration will be given to elimination of Paragraph 3.9 at the next specification update.

3.10 Requirements for externally slung loads

Discussion: The requirements in 3.10 are most probably redundant with detail specifications for rotorcraft that are required to carry external loads. It is implicit in ADS-33E-PRF that the rotorcraft meet the specification with no slung load. Explicit allowances for HQR degradations with very large load mass ratios were developed in Reference 38, and are stated in 3.1.5.2 Assigned Levels of handling qualities.

Quantitative requirements for external loads have been developed, but not tested sufficiently to be included in a specification. Those requirements are contained in Reference 38.

3.11 Mission-Task-Elements (MTEs)

Data Requirements: Cooper-Harper Handling Qualities Ratings; measures of task performance

Input Type: As required to perform MTEs

Test Technique:

Mission-Task-Elements (MTEs) to be evaluated will be specified by the system specification according to 3.1.1 Operational missions and Mission-Task-Elements (MTEs).

A summary of what is expected for compliance testing for the MTE maneuvers is given as follows.

- Where MTE performance limits are not met, it is acceptable to make as many repeats as necessary to ensure consistent results. Repeat runs to improve performance may expose handling qualities deficiencies
- Maneuvers shall be accomplished by at least three test pilots. The assigned HQRs shall be averaged and Level 1 requires that the average HQR$\leq$3.5. Level 2 requires that the averaged HQR$\leq$6.5 and Level 3 exists if the HQR is between 6.6 and 8.5.
- The evaluation pilot is to be advised if his or her performance falls outside of desired or adequate limits after maneuver completion and before the rating is assigned.
- All individual ratings and associated comments shall be documented and provided to the procuring activity.
- The MTEs are intended to provide answers to handling qualities issues, not performance. It is acceptable to offload weight if necessary to accomplish the MTEs.

MTEs were included in the specification in recognition of the fact that quantitative criteria are never perfect. Several examples are given in this test guide that demonstrate how the MTEs can be used as supporting data to justify a deviation from a quantitative criterion, e.g., see Section 3.3.2.1. In some cases there are no applicable quantitative criteria and it is necessary to rely on the MTEs to determine compliance. Various types of sidestick controllers are a good example as there is not sufficient data to support criteria for all the possible implementations of these devices.

There is a temptation to move directly to the MTEs and shortcut the quantitative requirements. This is a mistake as the two sets of requirements are complementary. MTEs are intended to be a check of the overall flying qualities. As such, they do not address all of the issues that lead to good handling qualities.

The MTEs are defined in ADS-33E-PRF. There is a considerable amount of relevant material in the specification that should be consulted.

The test courses described in ADS-33E-PRF are provided as the recommended test environment. Testing activities have found it convenient to modify the details of the courses (though not the dimensions) as needed to achieve adequate visual cueing to perform the maneuvers. An example of this is shown in Figure 69 where the turf was plowed to outline the pirouette course as opposed to using traffic cones that tend to be blown away (see Reference 39).

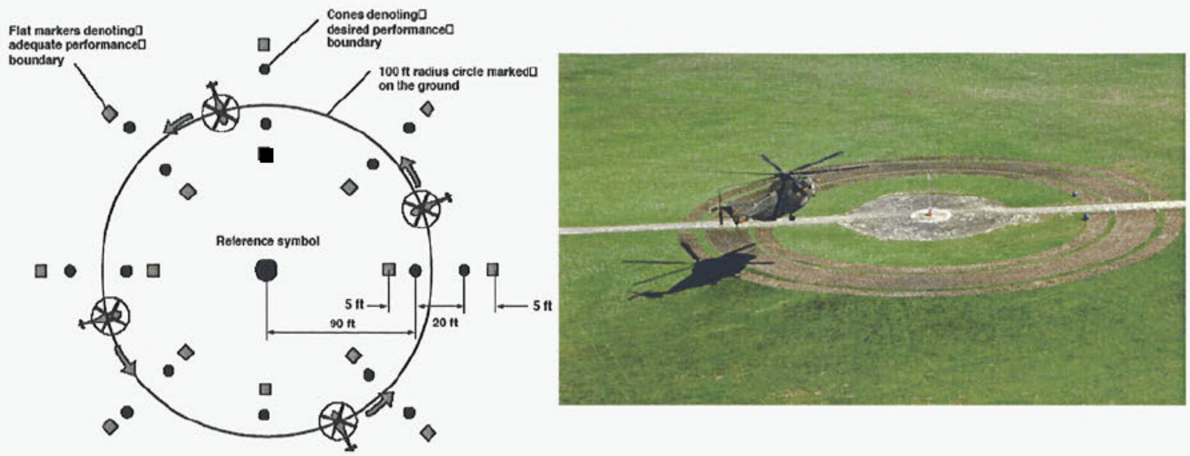


Figure 69 Modification of Test Course for Pirouette

The U.S. Army Aeroflightdynamics Directorate at NASA Ames developed the hover cues shown in Figure 70 to allow several tasks to be performed with and without an external load.

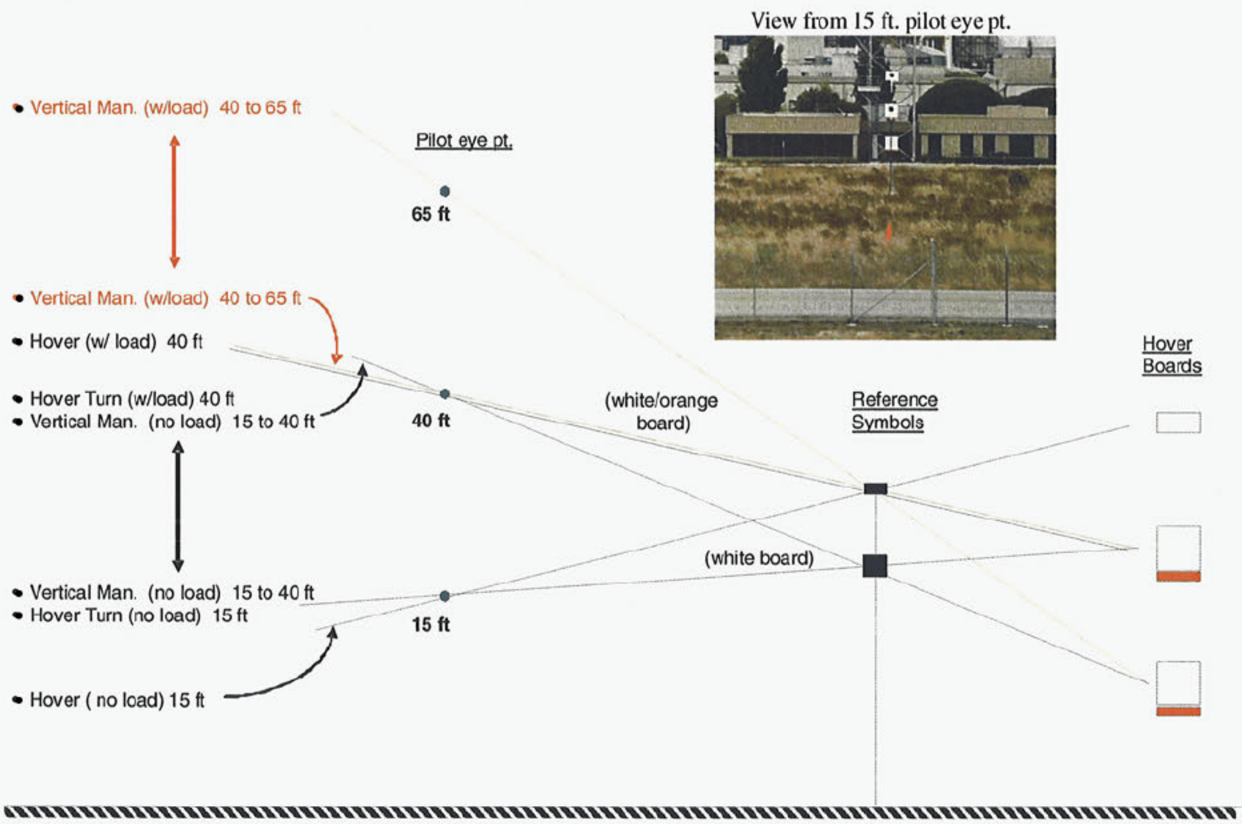


Figure 70 Cueing for the Hover, Hover Turn, and Vertical Maneuver with and without an external load

Finally, the slope landing course (a.k.a., Strecker Mountain) developed by the WTD 61 in Germany is shown in Figure 71 (From Reference 39).

Figure 71 Example Slope Landing Course

Evaluation pilots should practice each maneuver sufficiently to assure that training effects are minimized. This can be done in any rotorcraft with reasonably good handling qualities. It is also a good time to determine if the visual cues on the test course are adequate to accomplish the task. For example, if the pilot cannot see the endpoint of the Depart/Abort course during the deceleration due to limited cockpit visibility at high pitch attitudes, additional markers should be installed to resolve that deficiency.

Specification compliance for the piloted evaluations (in either simulation or flight) is evaluated through the assignment of Cooper-Harper Handling Qualities Ratings (HQRs), Reference 11. The rating scale is reproduced in Figure 72.

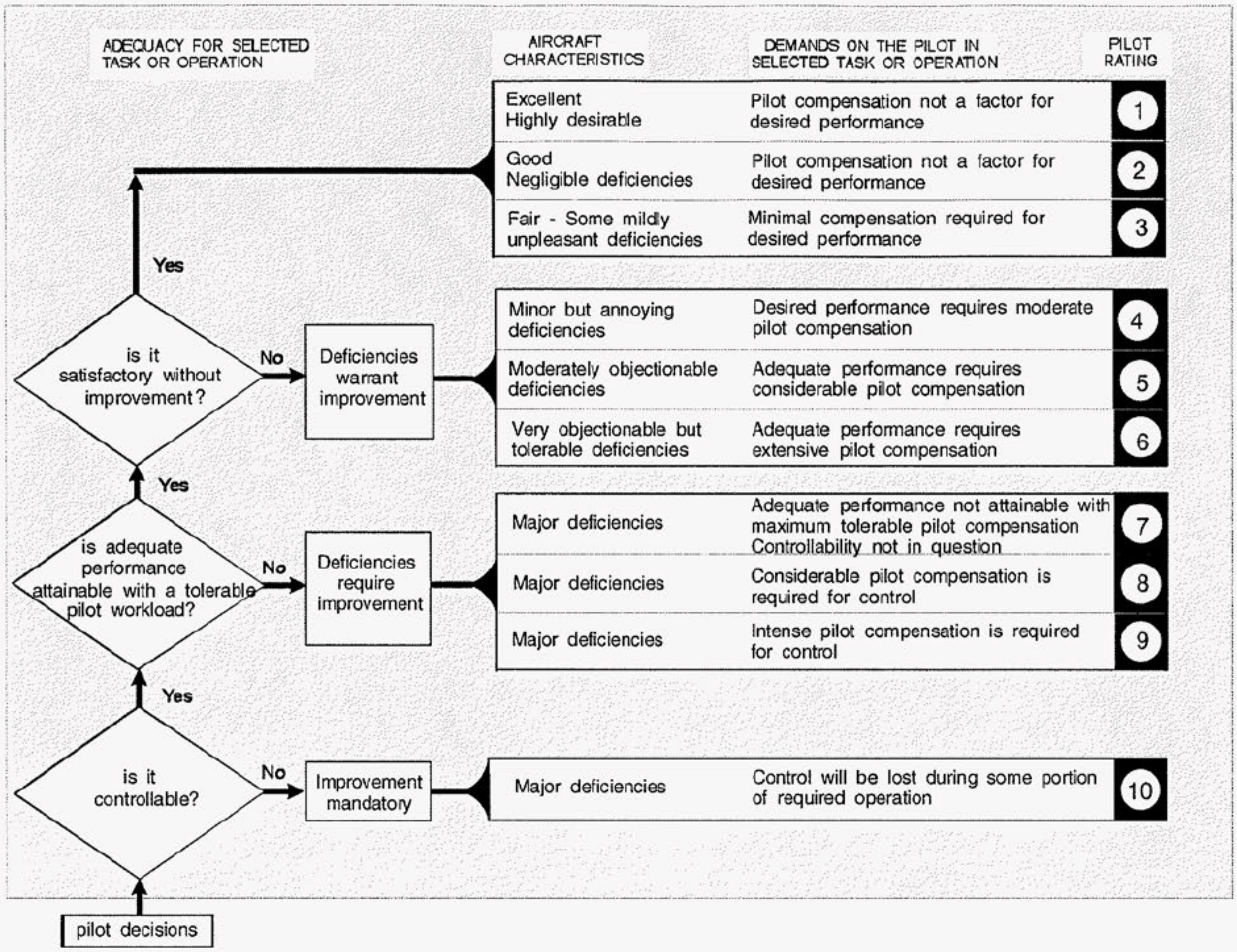


Figure 72. The Cooper-Harper Rating Scale

Groundrules for using the Cooper-Harper rating scales for compliance with 3.11 are provided below and should be part of the pilot briefing. Additional insights in the use of the Cooper-Harper rating scale can be found in Reference 40

- Always start at the lower-left and work up and to the right. Experience has shown that dispersions between pilots can be minimized by always enforcing adherence to this somewhat tedious, but very important decision process.

- The major decisions on both scales do not allow half ratings. That is, ratings of 3.5, 6.5, and 9.5 cannot be assigned. It is otherwise okay to assign half ratings, e.g., a rating of 2.5 is acceptable. Justification for this can be found in References 41 and 42

- When using the Cooper-Harper Handling Qualities scale, emphasize workload over performance. For example, if desired performance is achieved, but considerable compensation was required it is okay to give an HQR of 5. Be sure to note that is what you are doing in your commentary.

- It is not okay to assign an HQR that is not warranted by your performance. For example, if it is not possible to achieve desired performance, the rating must be 5 or worse. If workload is only low or moderate, and desired performance is not achieved, the correct procedure is to re-fly the task and increase aggressiveness in an attempt to achieve desired performance.

- The desired and adequate performance limits have been established to drive the level of aggressiveness when accomplishing the maneuvers. Occasional drift out of desired is acceptable as long as you can maneuver back into the desired limits at will. This is a judgment call on the part of the pilot.

- Always fly the task at least three times before assigning a rating. If in doubt, it is acceptable and even desirable, to fly additional trials.

- When attempts to achieve "desired performance" result in problems, repeat the MTE attempting to meet only the "adequate performance" limits. If that improves the assigned HQR, that result should be noted. This procedure is intended to be similar to normal procedures in dealing with handling qualities deficiencies. That is, it is preferable to back out of the loop and achieve a performance degradation to Level 2 rather than continue tight closed-loop control and risk the danger of loss of control (Level 3 or worse).

- A number of MTEs require that the pilot determine when the helicopter is "stable" after decelerating to a hover. This is intended to define the transition from hover capture to tracking.

  Call "Stable" when you have mentally transitioned from hover-capture to maintaining desired or adequate hover performance. This is normally occurs when the following conditions are met.

  1. The pitch and roll attitudes are approximately at the hover values and angular rates are small.

  2. The helicopter position is in the designated hover box to at least adequate performance standards, and translational rates are small.

It should be possible for the pilot to determine if desired or adequate performance has been achieved using the cueing that is available on the test course. It is acceptable to inform the pilot if he or she achieved desired or adequate performance, but repeated questions about this are good reason to consider modifying the course. The purpose of the tests is not to determine cockpit visibility limitations, but to assess the handling qualities given that the visual cues are not a factor in the evaluations.

Additional background regarding the use of the Cooper-Harper rating scale is given in References 40, 41, and 42.

Simulating UCE>1

Compliance with ADS-33E Para 3.11 requires that the MTEs be flown in a good visual environment (GVE), and in the degraded visual environment (DVE). When flying in the DVE, it should be under actual or simulated worst-case conditions, where the UCE>1. Separate standards are provided for the GVE and DVE for each MTE.

If the vision aid can produce UCE = 1 in the worst-case DVE, it is not necessary to simulate UCE>1. At the time of this writing, no such vision aid exists, unless the specified worst-case DVE is benign (e.g., a full moon night with good texture).

As an example, the CH-47F digital automatic flight control system (DAFCS) was designed to achieve Level 1 handling qualities in a DVE consisting of an overcast night with little or no texture, using night vision goggles. This results in UCE = 3. Therefore, all MTE testing in the DVE was accomplished in a simulated UCE = 3.

In order for the evaluation pilot to perform the MTEs in conditions of UCE>1 without compromising safety, it is desirable for the safety pilot's environment to be UCE = 1. This can either be done by flying in the daytime using daylight training filters, or in actual night conditions where the safety pilot's vision aid produces a UCE that is close to 1. In either case, some means to detune the evaluation pilot's night vision device to the desired UCE is required. Methods for accomplishing this with night vision goggles are discussed in detail in Section 3.2.1 of this test guide.

Data Analysis and Interpretation:

The primary outcome of this testing is pilot opinion in the form of HQRs and pilot comments. Besides the Cooper-Harper Handling Qualities Rating Scale, it may be necessary for the pilots to have access to a PIO Tendency Rating Scale, such as presented in Section 3.1.16 of this test guide. The PIO scale will not be required unless a tendency to PIO is noted. If the pilot notes a tendency (or, in the worst case, reports an actual PIO), the PIO scale should be consulted and the PIO Tendency Rating obtained.

As noted above, the test course cueing should be adequate for the pilot to determine if desired or adequate performance standards have been met. Otherwise how can he or she maneuver the helicopter to remain within those standards? Nonetheless, it may be desired to document the performance achieved during MTE testing as a backup to pilot commentary and ratings. The level of sophistication of such quantitative data will be at the judgment of the testing activity. Techniques that have been employed are summarized below.

- Use ground observers
- In the DVE use ground observers with night vision device
- Strategically mounted cameras
- Ground tracker instrumentation or differential GPS

A pilot questionnaire should be used to gather comments about relevant responses. For example, the pilots should be asked to comment about response predictability, objectionable cross-coupling, controller characteristics, etc. Responding to the questionnaire may sometimes seem a bit tedious, and sometimes it will be suggested that the pilots complete such questionnaires after the flight (or simulator session) is over. Verbal comments immediately after completing an MTE should be recorded with a ground transmission, on-board recorder, or, at least, with a hand-held, pocket-sized audio cassette recorder. An example pilot comment card is shown below. This was taken from the CH-47F Digital Automatic Flight Control System (DAFCS) flight tests to show compliance with ADS-33E-PRF. The pilots should review their recorded verbal comments and written notes when preparing post flight write-ups.

PILOT QUESTIONNAIRE FOR CH47F DAFCS FLIGHT TESTS

1. Were aircraft attitude and translational velocity responses to cyclic and collective control inputs predictable?
2. Describe cyclic and collective controller characteristics:
   - control forces desirable, too light, or too heavy?
   - control displacements desirable, too large, or too small(overly sensitive)?
   - any comments relative to breakout, friction, or deadband?
   - was stick backdrive objectionable?
3. Did undesirable oscillations occur? If so, were they pilot induced oscillations (PIO)? Which axis?
4. Describe frequency of use of the force-trim-release trim button. Any "stick jump" when trim button is depressed?
5. For TRC and Position Hold modes, did the aircraft hold velocity and position as expected? Did you observe uncommanded pitch and roll attitude activity? Was it excessive?
6. Describe any objectionable transients or delays when transitioning from one mode to another.
7. If applicable, describe any unique pilot technique that you found necessary to accomplish the task.
8. If applicable, describe undesirable responses to winds or turbulence.
9. Were DAFCS mode annunciations clear and unambiguous?
10. Were the DAFCS flight control modes easily selected?
11. Describe any adverse attitude and/or control sensitivity changes during DAFCS mode transitions.

11\. Assign HQR (see Figure 72). Then answer one of the following questions.
   - <u>If HQR is Level 1 (between 1 and 3)</u>, briefly describe any enhancing features of the DAFCS
   - <u>If HQR is Level 2 (between 4 and 6)</u>, briefly summarize the deficiencies that make this configuration unsuitable for normal accomplishment of this task.
   - <u>If HQR is Level 3 (HQR > 6)</u>, briefly summarize the deficiencies that make this configuration unsuitable to accomplish this task with adequate performance following a flight control system failure.

12\. If assigned HQR is Level 2 or 3, categorize the handling qualities deficiencies as one of the following.
   - <u>Suggested Improvement</u> – Problem is such that improvement is desirable but not imperative – developer is under no obligation to implement an improvement.

- Shortcoming –Must be corrected to render the helicopter as completely serviceable, but does not have an effect on safe operation or materially affect usability.
- Deficiency – Seriously impairs the equipment's operational capability
- Hazard – Will result in loss of the helicopter or a safety hazard to operating personnel.

The pilot is asked to summarize the deficiencies that make the configuration unsuitable to accomplish this task with adequate performance following a flight control system failure. This question is to determine the specific deficiency that would disallow this configuration to be used as a backup system.

Question 12 is included to put the rating in the context of verbiage that is used by the Army to conduct operational evaluations of new or modified systems.

4. Verification

Verification requirements are spelled out in ADS-33E-PRF Section 4, which includes detailed paragraphs and tables addressing analysis, simulation, and flight. The following guidance is an interpretation of the intent of ADS-33E-PRF, but if conflicts arise, the requirements govern.

4.1 General

Tables XIV and XV are provided in the specification as guidance where such guidance is not available from the systems specification.

Table XIV presents proposed goals for typical project milestones such as the preliminary design review (PDR) and the critical design review (CDR). When tailoring the specification, the procuring activity is free to modify the methods of verification suggested in this table as well as the suggested milestones.

It is important to understand that when simulation is given as the method of verification, it is necessary to specify criteria to validate the simulation. This is less important for early milestones where simulation validity is not critical and the intent is to demonstrate the basic functionality of the flight control system modes.

Modification to Criterion:

Table XV presents a summary of flight conditions and rotorcraft states for verification. A proposed modification of Table XV for the next specification upgrade is given below in Table 7.

Table 7. Rotorcraft status, flight conditions, and test requirements for verification (Revised Table XV)

Rotorcraft Status[a]		Flight Condition[g]	Test Requirements		HQ Level Reqd
Settings	States		FQ Criteria	Applicable MTE	
Primary SCAS	Normal	GVE and IMC	All for rotorcraft category	All for mission	1
Primary or Augmented SCAS		UCE>1 and IMC	All for rotorcraft category	All for mission	
Primary SCAS		UCE>1	All for rotorcraft category [b]	All for mission	2
Secondary SCAS	Failed	GVE	Mission critical [c]	Mission critical [d]	
		UCE>1 and IMC	None [b]	Mission abort [d]	3
Primary SCAS		GVE SFE	None [f]	Investigate limits [e]	2
Backup		GVE	None	Mission abort [d]	3
		UCE>1 and IMC	None	Flight safety [f]	Controllable

NOTES:

a. Configurations and Loadings to be selected as appropriate for missions

b. Use the UCE=2 handling qualities criteria data

c. Mission critical handling qualities criteria and MTEs may be a subset of all applicable

d. Mission abort: only selected MTE that are elements of a mission abort apply

e. Investigate envelope limits to assure adequate warnings, safe margins, and easy return to the OFE

f. Flight safety implies that the rotorcraft is controllable in UCE>1 or IMC, and can be flown to a landing or an escape out of the UCE>1 or IMC.
g. Flight envelope is OFE unless otherwise specified.

The definitions of the example SCAS types in Table XV are presented below along with the definitions used for the V22 and RAH-64 Comanche designs (in parenthesis).

- Primary SCAS – Rate system intended to provide Level 1 handling qualities in the GVE and IMC (Core AFCS)
- Augmented SCAS – Attitude Command or TRC system intended to provide Level 1 handling qualities in UCE>1 (Core AFCS with VELSTAB engaged)
- Secondary SCAS – Backup system intended to provide Level 2 handling qualities in the GVE (MISSION PFCS)
- Backup – Very simple system with highest level of reliability. Intended to provide at least Level 3 handling qualities in the GVE. Could be the bare airframe. (Core PFCS)

For the Secondary SCAS in GVE, Table 7 indicates that a "mission critical" subset could be acceptable. For example, the flying qualities criteria and MTEs related to Target Acquisition and Tracking would not be required for this mode.

For Level 2 in the SFE, it is not necessary to flight test the flying qualities criteria since SFE flight is assumed to be a transient situation. Qualitative assessment of adequate margins, the approach to limits, warnings, and ease of recovery to controlled flight in the OFE should be made in both the GVE and UCE>1.

The Backup system is a "get home anyway you can" mode and requires only Level 3 handling qualities in the GVE. Testing in this mode clearly involves risk and it is acceptable to rely on analysis, simulation, and selected benign MTE flight tests.

For Level 3 in UCE>1 with Secondary SCAS or Level 3 in GVE with Backup, Table 7 indicates that only MTEs deemed essential for mission abort need be tested. Such mission abort MTEs could include hover, vertical maneuver, acceleration and deceleration, and sidestep. Helicopter categories not expected to operate in hostile NOE environments may only need to demonstrate the ability to perform up and away egress. MTE-type definitions for such a maneuver have not yet been developed, but ability to perform a typical traffic pattern, starting from hover, climbing to about 500 ft and 60 kt and terminating in a landing, would seem appropriate.

To check controllability with Backup control system in UCE>1 or IMC, the ability to accomplish a traffic pattern would also seem appropriate. If in IMC, it would be necessary to accomplish an instrument approach, albeit with very high workload.

4.1.2 Simulation

Since ADS-33E-PRF was published, it has become clear that adequate methods to validate a simulator for the purpose of compliance with a flying qualities specification do not exist. Therefore, Section 4.1.2 should be taken as a recommended, but not required part of compliance with the specification. Unless otherwise specified, it is recommended that final ADS-33E compliance be accomplished in flight test.

The procuring activity may require simulation during development, in which case the methodology given by Paragraph 4.1.2 should be followed. If this is the case, that should be specified during the ADS-33E-PRF tailoring process for a specific project.

Until a specification to guide the validation of engineering simulators is developed, such validation will be up to mutual agreement between the Government and Contractor. Validation specifications for training simulators are not considered to be adequate for this application because they do not explore the edges of the flight envelope, nor do they emphasize handling qualities.

All simulation validation efforts must include comparisons between simulation and flight data. This may include reasonable extrapolations based on engineering judgment. Validation based on wind tunnel data or physics based derivations are not acceptable.

When validating a simulator, it is not acceptable to claim that a large percentage of validation criteria have been met as substantiation of compliance. Any failure to meet a validation criterion should result in an appropriate limitation on the simulator. For example, if the simulator does not adequately represent the flight dynamics at high sideslip angles, the simulator demonstrations should not include any maneuvers that require large sideslip angles.

4.1.3 Flight

It is intended that the requirements of this specification be met in flight test. The only exception is the demonstration of failure modes which are considered to be unacceptably hazardous to test in flight. An example of a test that would be restricted to ground-based simulation is the Apache backup flight control system, which involves breaking a shear pin when the controls jam.

ADS-33E-PRF requires that "the DVE MTEs shall be tested in the real DVE when evaluating the primary or augmented SCAS in normal state. The secondary SCAS may be tested in simulated DVE".

Modification to Criterion:

As discussed in Section 3.2.1 of this test guide, techniques have been developed to accurately simulate UCE>1. Future upgrades to ADS-33E-PRF will allow all testing to be accomplished in simulated UCE. In the interim, evaluations of the primary SCAS may be accomplished in simulated UCE>1 with concurrence between the Government and Contractor.

All testing to determine the Response-Type associated with a vision aid must be accomplished in the actual DVE. The actual DVE should specify the conditions that are critical to the sensors used in the vision aid. For example, for night vision goggles, the DVE should specify lighting conditions as well as texture (e.g. no moon over flat desert terrain).

General Guidance for Section 4

There are four primary topics to consider in developing a compliance verification plan:

1. What to test, i.e., the rotorcraft status (combinations of configuration, loading, setting, and state).
2. Where to test, i.e., the flight conditions.
3. Which requirements to test, i.e., the requirements to be satisfied.
4. How to test, i.e., how to perform the various tests against the criteria.

Item 4 is the subject of Section II of this Guide.

Items 1, 2, and 3 are the primary subjects of Section III of this test guide.

6. Notes and Definitions

This section provides some clarification of the definitions provided in this portion of the specification.

Status (defined in 6.2.13)
The Rotorcraft status is a unique combination of Configurations, Settings, States, and Loadings (defined in 6.2.9).

Configurations (defined in 6.2.2) may include characteristics such as gear up or down, weapon bays open or closed, external weapon or equipment installations such as missiles/rockets on AH-64, the External Stores System developed for the UH-60 or the LONGBOW radar on the AH-64 and OH-58.

Settings (6.2.14) include the functionality of any pilot selectable components or systems that affect the handling qualities. Examples are the various SCAS modes referred to in Table XV of ADS-33E-PRF may be described as follows (see Table 7 above for modified version of Table XV).

> Primary SCAS – Rate system intended to provide Level 1 handling qualities in the GVE
>
> Augmented SCAS – Attitude Command or TRC system intended to provide Level 1 handling qualities in UCE>1
>
> Secondary SCAS – Backup system intended to provide at least Level 2 handling qualities in the GVE

Backup – Very simple system with highest level of reliability. Intended to provide at least Level 3 handling qualities in the GVE. Could be the bare airframe.

States (6.2.17) include Normal States (flight with all systems working as designed). Failure States define the helicopter dynamics in the presence of single or multiple failures of any of the systems that affect handling qualities. Unlike Settings, the Failure States to be considered are not limited to pilot-selectable functions. Degradations due to failures within the flight control system are prime examples, and failures to the vision aid system would also be included for UCE>1 operations such as night NOE with no moon. Two classes of failures must be considered (3.1.14) in complying with the requirements. Specific Failures (3.7) are designated conditions that must be evaluated regardless of their likelihood. The other class of Failure States to be considered depends on the probability of being encountered. These Failure States and associated probabilities are normally provided by the Failure Modes and Effects Analysis (FMEA).

III. TEST PLANNING

A. WHERE TO TEST (FLIGHT CONDITIONS)

In selecting the flight conditions for the quantitative testing, the critical guidance from 4.1.3 is that:

> Emphasis shall be on data points that are critical from the standpoint of handling qualities and safety, but shall also demonstrate performance at important nominal mission conditions.

It should be quite apparent from simulation and previous flight testing which selections of rotorcraft Status are critical and at what flight conditions (see Table 7). In addition, much insight will be gathered from performing the MTE flight tests and other qualitative assessments, so it may well be preferable to perform them first, **before the quantitative data collection**.

Examples of flight conditions that may be critical from the point of handling qualities include the following:

- Hovering in a wind from the critical direction.
- Speeds where the SCAS functionality changes.
- Aft c.g. limit and lateral c.g. limit
- Conditions close to limits such as torque, power, control, structural or aerodynamic.

B. WHICH REQUIREMENTS TO TEST (REQUIREMENTS TO BE SATISFIED)

The Guide Introduction lays out the steps that must be taken to tailor the generic ADS-33E-PRF for a specific application. This process results in the designation of criteria boundaries and MTE standards that must be satisfied.

For ease of review and laying out a test plan, the following three tables provide a listing of all the requirements grouped by test input similarity.

Table 8 gathers miscellaneous requirements, most of which are qualitative and may be satisfied by pilot observations during flight testing for other purposes, especially during the MTE evaluations. Some quantitative criteria, such as controller force-displacement characteristics and the tests required for Response-Type verification, are included. Failure paragraphs are referenced but no testing guidance is provided. This complex topic needs the much more detailed treatment that can be found above under the subheading "Status".

Table 9 lists the hover and low speed test requirements.

Table 10 lists the forward flight test requirements.

All of these are quantitative criteria that must be tested at a selection of flight conditions and with a selection of rotorcraft status, as discussed above. Not all of the requirements need to be tested at every set of rotorcraft status and flight condition.

Table 8. Miscellaneous tests and qualitative requirements

Test	Axis/ Control	ADS-33E-PRF Requirement	Para.	Control inputs	Remarks
Response-Types	All	Determine UCE	3.2.1	Designated MTE	Perform designated DVE MTE
		Required Response-Types	3.2.2	No special inputs required	Designated by UCE and applicable MTE
		Character of Response-Types	3.2.6 – 3.2.12	In accordance with required Response-Type	Assess if required Response-Types are achieved
Failures		Probable failures	3.1.14	To be determined	Requires detailed tailoring for specific rotorcraft
		Specific Failures	3.7		
Transfer between Response-Types		Annunciation of Response-Type	3.8.1	Mode transfer actuations whether automatic or manual	Qualitative assessment during mission/performance flight testing, especially during performance of applicable MTE
		Control forces during transfer	3.8.2		
		Control system blending	3.8.3		
		Transition from air to ground	3.2.14		
Warnings, indications, and preventions		Rotorcraft limits	3.1.15	Flight near limits of OFE and SFE	
Engine governing	RPM	Rotor RPM governing	3.3.10.4 3.4.3.3	No special inputs required	
Undesired oscillations	All	Pilot induced oscillations	3.1.16		
		Residual oscillations	3.1.17		
Controller characteristics	Pitch roll yaw collective	Sensitivity and gradients	3.6.3		
		Cockpit control free play	3.6.4		
		Control harmony	3.6.5		
		Dynamic coupling	3.6.7		
		Trimming characteristics	3.6.6	Trim checks in unaccelerated flight	
Cockpit control forces	Pitch roll yaw collective	Centering and breakout	3.6.1.1	Controller inputs across available range	Applies throughout speed range
		Limit control forces	3.6.1.3		
	Pitch roll yaw	Force gradients	3.6.1.2		
Ground handling and ditching	All	Rotor start-stop	3.9.1	Rotor start-stop in wind	
		Shipboard operation	3.9.1.1		Applicability to be determined in accordance with 3.1.3.
		Parked position	3.9.2	Normal takeoff	
		Wheeled rotorcraft	3.9.3	Taxi tests	
		Ditching characteristics	3.9.4	Requires special tests outside scope of this manual	Applicability to be determined in accordance with 3.1.3.
Externally slung loads		Externally slung loads	3.10		
Mission-Task-Elements		Mission-Task-Elements	3.11	Perform MTE at flight conditions specified	Applicability of each MTE to be determined in accordance with 3.1.1

Table 9. Hover and low speed tests

Test	Axis/ control	ADS-33E-PRF Requirement	ADS-33E-PRF Para.	Control Inputs	Remarks
Bandwidth	Pitch Roll Yaw	Short-term response	3.3.2.1 3.3.5.1	Frequency sweeps in pitch, roll, and yaw	Input frequency range approximately 0.05 to 2.0 Hz; control amplitude approximately ± 1 inch about trim
Actuator inputs	Pitch Roll Yaw	Response to disturbances	3.3.2.2 3.3.7	Frequency sweeps in pitch, roll, and yaw	See discussion in Section 3.3.2.2.
Damping ratio	Pitch Roll Yaw	Mid-term response	3.3.2.3 3.3.5.2	Pulse in pitch, roll, yaw	Pulse amplitude approximately 1 inch from trim
Attitude quickness	Pitch Roll Yaw	Moderate attitude response	3.3.3 3.3.6	Attitude quickness pulses in pitch, roll, yaw	Inputs increased to achieve approximately 10 deg attitude increments
Maximum angular rate	Pitch Roll Yaw	Large attitude response	3.3.4 3.3.8	Steps in pitch roll and yaw	Input amplitude and duration are limiting extensions from attitude quickness tests.
Interaxis coupling	Pitch Roll	Pitch/roll roll/pitch coupling	3.3.9.2	Steps in pitch and roll	For Aggressive agility rotorcraft only
			3.3.9.3	Frequency sweeps in pitch and roll	For Target Acquisition and Tracking agility rotorcraft only
	Collective	Yaw due to collective	3.3.9.1	Steps in collective	For Aggressive agility rotorcraft only
Linearity of height response	Collective	Height response	3.3.10.1	Steps in collective	Requires rate of climb data
Torque display response	Collective	Torque response	3.3.10.2	Steps in collective	Requires measurement of the torque meter response
Rate of climb in 1.5 sec	Collective	Vertical axis control power	3.3.10.3	Steps in collective	Requires rate of climb data
Turns in wind	Yaw	Position hold capability	3.3.11	360 degree yaw controller turn in wind	Applies only if Position Hold is required
Translational rate response	Pitch roll	Translational rate command	3.3.12	Steps in pitch and roll	Applies only if TRC is required

Table 10. Forward flight tests

Test	Axis/ Control	ADS-33E-PRF Requirement	ADS-33E-PRF Parag	Control inputs	Remarks
Attitude Bandwidth	Pitch Roll Yaw	Short term response	3.4.1.1 3.4.6.1 3.4.8.1	Frequency sweeps in pitch, roll, yaw cockpit control	Sweep range 0.05 to 2.0 Hz, amplitude approximately ±1 inch (±20%)
Pitch-roll cross coupling.	Pitch roll	Pitch-roll coupling	3.4.5.4	Frequency sweeps in pitch, roll, yaw cockpit control	Required for Target Acquisition and Tracking Agility rotorcraft only
Actuator inputs		Response to disturbances	3.4.11 3.2.13	Frequency sweeps in pitch, roll, and yaw actuator	See discussion in Sections 3.3.2.2
Damping ratio	Pitch	Mid term response	3.4.1.2	Pulse inputs in pitch	Pulse amplitude approximately 1 inch
Damping ratio and frequency	Yaw	Lateral-directional oscillations	3.4.9.1	Doublet inputs in yaw	Doublet amplitude ± 1 inch
Control stability and forces in maneuvers	Pitch	Maneuvering stability	3.4.1.3	Steady turns, pull-ups, and pushovers	Observe OFE limits
Control authority	Pitch	Pitch control power	3.4.2	Achieve OFE limits from trimmed flight.	
Rate of climb lag to attitude	Pitch	Flight path response-front-side	3.4.3.1	Frequency sweep in pitch	Need to first determine front-side back-side speed regions
Linearity of climb rate response to collective	Pitch	Flight path response-backside	3.4.3.2	Step collective input	Need to first determine front-side back-side speed regions
Control force gradients	Pitch	Longitudinal static stability	3.4.4	Incremental pitch forces from trim	
Directional static stability	Yaw	Yaw control in steady sideslip	3.4.10.1	Steady heading sideslip	
Bank angle in sideslip	Yaw/roll	Bank angle/sideslip	3.4.10.2	Steady heading sideslip	
Dihedral effect	Yaw/roll	Lateral control in sideslip	3.4.10.3	Steady heading sideslip	
Roll attitude quickness	Roll	Moderate amplitude response	3.4.6.2	Attitude quickness pulses	
Maximum roll rate/attitude	Roll	Large amplitude	3.4.6.3	Step roll inputs	
Bank angle oscillations and turn coordination	Roll Yaw	Roll-sideslip coupling	3.4.7	Pulse roll inputs	
Time to double amplitude	Roll	Spiral stability	3.4.9.2	Pulse roll inputs	
Pitch due to collective	Pitch	Pitch due to collective	3.4.5.1	Step collective inputs	
Roll due to pitch	Roll	Roll due to pitch	3.4.5.2	Step pitch control	For Aggressive agility rotorcraft only
Pitch due to roll	Pitch	Pitch due to roll	3.4.5.3	Rapid bank angle changes	For Aggressive agility rotorcraft only
Sideslip limits	Yaw	Large amplitude heading changes	3.4.8.2	Step inputs to yaw	
Yaw control and forces	Yaw	Yaw control with speed change	3.4.8.4	Speed change with constant power/altitude	

C. SCOPE OF HYPOTHETICAL ADS-33E-PRF FLIGHT TEST VERIFICATION

Using the guidance provided along with Table 7, a verification test program for a utility helicopter such as UH-60 could be developed as summarized in Table 11.

- Rotorcraft status: Select at least one set of Configuration and Loading. Assume Normal States, and two SCAS Settings, Primary and Augmented, and the Backup system.
- Speeds: Hover, a low forward flight speed such as 60 kt, and a high forward flight speed such as the lesser of 120 kt or 0.8 $V_{H.}$. In reference 8, a slightly higher low-forward speed of 80 kt was found to make data collection more efficient and possibly more mission relevant.
- Altitude: A modest but safe altitude of 1000 to 3000 ft agl.
- Rate of climb: Level flight, descent at reduced power, climb at maximum continuous power.

Table 11. Scope of a hypothetical ADS-33E-PRF test evaluation

<table>
<tr><th rowspan="2">Tests and visual environment</th><th colspan="2">Rotorcraft status</th><th colspan="3">Flight condition</th><th colspan="2" rowspan="2">Flight time hrs TOTAL 62</th></tr>
<tr><th>Config/Loading/ States</th><th>Setting</th><th>Speed</th><th>Altitude</th><th>Climb rate</th></tr>
<tr><td rowspan="9">Quantitative Flying Qualities Criteria – GVE</td><td rowspan="13">Configuration
- Primary mission

Loading
- Mission gross
- aft cg

State
- Normal</td><td rowspan="7">SAS
(Primary SCAS for GVE)</td><td>0</td><td rowspan="9">2000</td><td rowspan="3">0</td><td>4</td><td rowspan="3">12</td></tr>
<tr><td>60</td><td>4</td></tr>
<tr><td>120</td><td>4</td></tr>
<tr><td rowspan="2">60</td><td>climb</td><td>3</td><td rowspan="4">12</td></tr>
<tr><td>descent</td><td>3</td></tr>
<tr><td rowspan="2">120</td><td>climb</td><td>3</td></tr>
<tr><td>descent</td><td>3</td></tr>
<tr><td rowspan="2">SAS+FPS (Augmented for DVE)</td><td>0</td><td rowspan="2">0</td><td>4</td><td rowspan="2">8</td></tr>
<tr><td>60</td><td>4</td></tr>
<tr><td>MTE-GVE</td><td>SAS</td><td colspan="3">Applicable MTE (Utility 13 in calm + 4 in wind)</td><td>17</td><td rowspan="4">30</td></tr>
<tr><td>MTE-DVE</td><td>SAS+FPS</td><td colspan="3">Applicable MTE (Utility 7)</td><td>7</td></tr>
<tr><td>MTE-IMC</td><td>As applicable</td><td colspan="3">Applicable MTE (4)</td><td>4</td></tr>
<tr><td>Egress-DVE</td><td>SAS off (Backup)</td><td colspan="3">Applicable MTE (1)</td><td>2</td></tr>
</table>

The exact rotorcraft states and flight conditions should be selected to satisfy the requirement that: "Emphasis shall be on data points that are critical from the standpoint of handling qualities and safety, but shall also demonstrate performance at important nominal mission conditions".

Applicable MTEs are defined in Table I of ADS-33E-PRF. Selection of flight condition is simple for the MTEs since speeds and maneuvers are detailed along with the maneuver descriptions.

The estimated flight hours listed in Table 11 are based on data gathered by Blanken *et al.* in testing a UH-60A Black Hawk (Reference 8). They found it took two flights or about 4.0 flight hours to perform all the hover-low speed or forward flight quantitative tests at one flight condition. This has been used for the basic level flight conditions. Since not all of the tests are strictly repeated by flight condition, it is assumed that the climbs and descents would only require an additional 3.0 hours per condition. In the same test program, the MTEs required an average of 15 to 20 minutes per evaluation. Assuming that three pilots evaluate each MTE, then approximately one hour is required per MTE. The Utility class of rotorcraft requires 13 MTEs to be evaluated in GVE and calm air, with repeat of four MTEs in moderate wind. These evaluations would be performed with the Primary SCAS. Seven MTEs apply in DVE with the Augmented SCAS. It is assumed that the highly reliable Backup system would be evaluated in a simple maneuver such as a take-off, flight around a typical traffic pattern, and landing. Two hours are assumed for this.

The total flight hours estimated to perform such an evaluation is 62. Some additional flight time would no doubt be required to prepare the test facilities and train the participants. Examples include setting up the MTE evaluation courses and training the pilots and observers, and calibrating the MTE courses to ensure the DVE achieves UCE = 2 or 3, as appropriate. Some of this additional flight time can be performed in a surrogate rotorcraft that is more available and less expensive to fly than the test candidate.

A verification program for a cargo helicopter such as the CH-47 could be smaller by about 5 hours since the list of applicable MTEs is five less than for the utility. External load testing will add to the test program and must be accounted for.

A program for a scout or attack helicopter would be longer than the basic utility by at least 4 hours since it must satisfy four extra MTEs. If the scout helicopter used a modern fly-by-wire flight control system with multi-mode SCAS, the testing would have to include the Secondary SCAS mode. This might be scoped as follows:

Three speeds, level flight at 4 hours per condition = 12 hours
Full set of GVE MTEs (17 at 1.0 hr/MTE) = 17
Half of the DVE MTEs (4 at 1.0 hr/MTE) = 4
Total increase = 33 hours.
Total test = 62 + 4 + 33 = 99 hours

The data in Figure 73 provide an example in terms of the flight time required to conduct each of the MTEs during testing of a UH-60A by the Aeroflightdynamics Directorate at NASA Ames.

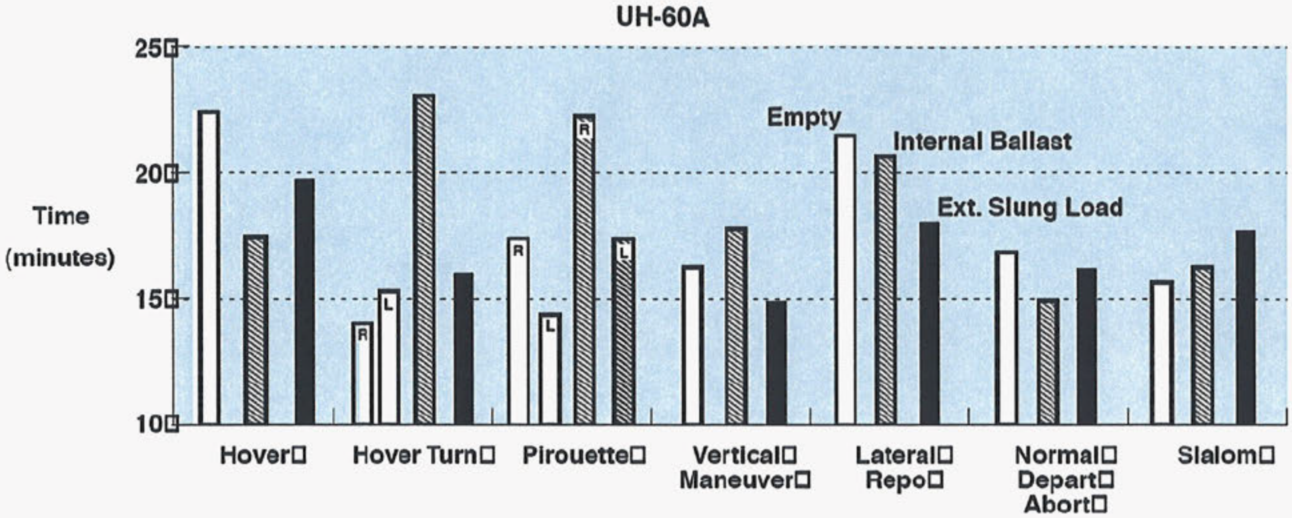


Figure 73 Time Required to Complete Testing of MTEs

Each MTE test consisted of the following:

- Practice runs to familiarize pilots with course cuing, performance standards, and aircraft response.
- At least three data runs (more if not consistent)
- Pilot questionnaire and assign HQR from Cooper-Harper scale
- Approximately 15 to 20 minutes per MTE

D. INSTRUMENTATION REQUIREMENTS

Table 12 lists the parameters that must be available to assess compliance with the quantitative requirements. Also listed are other parameters that can provide some redundancy for use in data consistency analysis, and other parameters that should be monitored for safety.

Accurate measurements of several of the critical parameters can be difficult to obtain. Measurement of low airspeed requires special devices. Some of these devices can also provide velocity components, and will operate throughout the speed range, but otherwise boom mounted vanes may be required. All of the air data measurements will be influenced by the rotor wake, particularly at low speeds, so require particularly careful calibration. These measurements should also be corrected for position errors related to aircraft angular rates.

Redundant or complementary measurements can be used for checking data consistency and improving the overall accuracy. For example, the rigid body angles can be differentiated to compare with the body rate measurements, and complementary filtering of the radar altitude and normal acceleration signals may be used to obtain the rate of climb measurements.

Every effort should be made to instrument the test rotorcraft to determine pilot control forces, not just the displacements. This is especially important if the flight control feel system contains any active elements so that control force at a given displacement can vary with flight condition.

Sensor dynamic response, and recording system filtering and digitizing characteristics, must be well understood and documented. Static accuracy through calibration and scaling is important throughout. Dynamic accuracy is also very important, especially for the frequency response testing. As a minimum, the dynamic characteristics of the sensors, and filtering of the signal, should be documented along with sample rates and other characteristics of the data recording system. Guidelines suggested in Reference 32 are that the bandwidth of any filtering be at least five times the highest frequency of interest, and the sampling rates be at least five times the filtering frequency (twenty-five times the highest frequency of interest).

Table 12. Basic instrumentation parameters

Parameter	Comments
Air data Airspeed Pressure altitude Sideslip angle Angle of attack	
Temperature	
Inertial data Ground speed Longitudinal velocity Lateral velocity Rate of climb Radar altitude Pitch angle Bank angle Yaw angle (heading) Pitch rate Roll rate Yaw rate Linear normal acceleration	
Controls Longitudinal control position Lateral control position Yaw control position Collective control position Pitch actuator position Roll actuator position Yaw actuator position Collective actuator position Longitudinal control force Lateral control force Yaw control force Collective control force	If a control mixer is utilized, the input to the mixer unit in pilot control axes should be measured.
Engine/rotor parameters Main rotor RPM Torque Pilot's torque gauge reading	
Miscellaneous Time marker Rotorcraft status indicators: Configuration, Loading, Setting, State Weight on wheels indication	

Table 12. **(Concluded)**

Parameter	Comments
Additional useful parameters	
Miscellaneous Outside air temperature Longitudinal linear acceleration Lateral linear acceleration Pitch acceleration Roll acceleration Yaw acceleration Aircraft position tracking	
Aircraft limits Main rotor mast/hub moments Tail rotor mast/hub moments Blade flapping Blade pitch	

Real-time monitoring of the tests via telemetry provides a significant safety benefit and can add to the efficiency of testing. During frequency sweeps, as a minimum the input and output parameters should be monitored so that the flight test engineer can observe the quality of the inputs and help to alert the test pilots when the target frequency is reached. In addition, aircraft structural or other limits should be monitored to provide warnings in the event critical modes are approached and the test needs to be terminated. During all of the requirement testing the pilot's controls and aircraft's responses can be monitored to assess the quality of the inputs and the need for repeats, while ensuring that predetermined limits are not exceeded.

ADS-33E-PRF leaves to the testing authority the choice of data taking for documenting compliance with the MTE performance standards. During development of ADS-33E-PRF and the flight testing to assess its validity, a range of instrumentation was used. The Apache tests (Reference 4) relied on observations from the cockpit, and strategically located observers on the ground. This can be somewhat cumbersome, and to some extent hazardous, especially at night during DVE testing, and may not be sufficient in a contractual compliance situation. In subsequent tests (References 5, 6, and 8), the rotorcraft's ground position was monitored using a laser tracking device, and video cameras were mounted in the cockpit to provide a view of the instrument panel and of the outside targets. In addition, the laser tracking information was monitored real-time so that the pilots could be informed immediately if, and how well, they had met the desired performance standards. Other methods of position tracking such as differential global position system, or an onboard inertial system, could be used if laser tracking is not available. Such measurements and onboard video recording provides a much more satisfactory arrangement than relying on just observers, and is recommended.

APPENDIX: INPUT TYPES

Frequency sweep

Applicable Paragraphs:

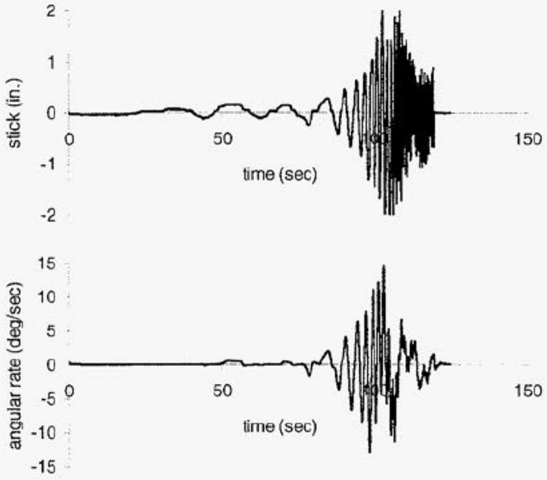
3.3.2.1 Short-term response to control inputs (bandwidth)
3.3.2.2 Short-term pitch and roll responses to disturbance inputs (disturbance bandwidth)
3.3.5.1 Short-term response to yaw control inputs (bandwidth)
3.3.7 Short-term yaw response to disturbance inputs (disturbance bandwidth)
3.3.9.3 Pitch due to roll and roll due to pitch coupling for Target Acquisition and Tracking [hover and low speed]
3.4.1.1 Short-term [pitch, forward flight] response (bandwidth)
3.4.3.1 Flight path response to pitch attitude (frontside)
3.4.5.4 Pitch due to roll and roll due to pitch coupling for Target Acquisition and Tracking [forward flight]
3.4.6.1 Small-amplitude roll attitude response to control inputs (bandwidth)
3.4.8.1 Small-amplitude yaw response for Target Acquisition and Tracking (bandwidth)
3.4.11 Pitch, roll, and yaw responses to disturbance inputs (disturbance bandwidth)

Description: ADS-33E-PRF relies heavily on frequency-domain measures of basic flying qualities parameters. The majority of these parameters are taken directly from frequency-response plots that describe the output/input relationships between a specified state and a cockpit controller. These plots describe the amplitude ratio and phase difference between the output and input as functions of frequency.

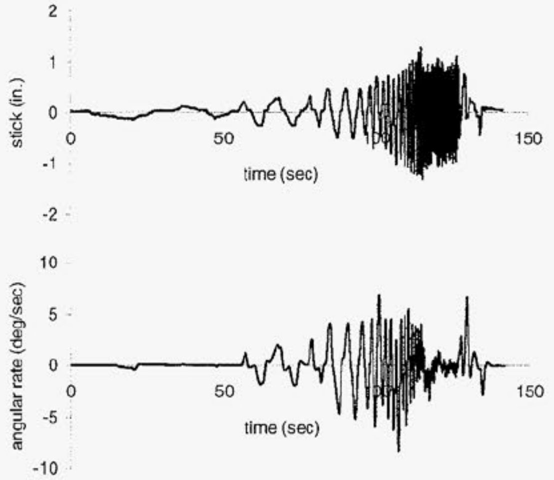
Frequency sweeps are intended to encompass the frequency range over which we require data for ADS-33E-PRF. This is a rather small range compared to other uses – for identifying structural modes, for example. They may be generated by software, or by a pilot through the cockpit controls.

Several reports (for example, References 21,43, and 44) contain additional background discussion, practical examples, and some safety considerations.

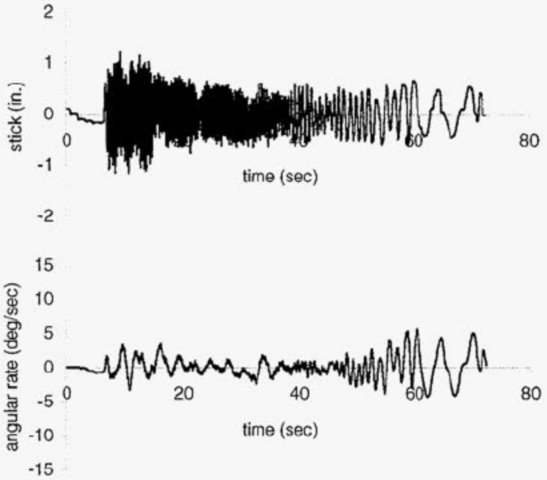
Examples of different types of frequency sweeps are shown in Figure 74.



a) Typical frequency sweep



b) Frequency sweep with input amplitude maintained approximately constant



c) High-to-low-frequency sweep

Figure 74. Example Frequency Sweeps

Rules for Generating Manual Frequency Sweeps (summarized from Reference 21):

- Initial and final conditions must be in steady trim, and several seconds of this trim must be included in recorded data. The frequency sweep is considered to be a "transient" in the FFT analysis.
- Maximum on-axis responses should be in the range of:
  - Attitudes within ± 10 degrees
  - Angular rates within ± 10 deg/sec
  - Airspeed should remain with ± 10 kts of trim

  - Responses will naturally decrease in magnitude as frequency increases
- Frequency Sweeps should be a single-axis input, and multi-axis response
  - On-axis inputs should be around ± 0.5 to ± 1.0 inches
  - Smaller inputs may be necessary at low frequencies to maintain flight condition
  - Bias on-axis inputs as necessary to maintain trim
  - Off-axis inputs should be kept to a minimum
- Off-axis responses should only be regulated to maintain flight condition
  - Keep off-axis inputs at as low a frequency as possible
  - Bias off-axis control as necessary to maintain flight condition
- The range of frequencies necessary for specification compliance is less than required for system identification. It is never greater than 0.10 to 10 rad/sec.

Some additional caveats are given in the following paragraphs.

It is useful for the pilot flying to focus primarily on the cockpit controller and to include airspeed, altitude and heading in his or her scan at lower frequency to maintain the flight condition.

At the very low frequencies it will be impossible to produce an ideal "sinewave" command (see the examples in Figure 74), but don't be too concerned as long as the input is generally one-sided for the entire half of each cycle. High-frequency corrections on top of the low-frequency input simply generate more high-frequency data.

Each cycle of the sweep should be at about half the period of the previous cycle. There should be no rush to complete the sweep. Rushed sweeps do not provide sufficient input power across all frequencies and the resulting frequency response data are very poor.

Sweep from low to high frequencies. There are some who suggest a high-to-low sweep, starting at the highest input frequency and slowly decreasing input frequency (example c in the sketch above), is best. They argue that the most important data (for flying qualities) are obtained before the rotorcraft can deviate far from trim. Attempts to perform pilot-generated high-to-low sweeps, however, have revealed some problems. First, it is essential that the pilot's initial sinewave be carefully monitored to assure that it is not too high. Second, the pilot seems to have a greater tendency to dwell at a single frequency rather than smoothly reducing frequency of inputs. Third, it is difficult to know when the copilot or flight test engineer should start coaching the pilot to assure that very low-frequency data are obtained. By starting at low frequency and working up, all of these problems are avoided, or at least minimized. A final key consideration is that the overall low frequency dynamics must be persistent for 4-5 periods (Reference 21). So, when the sweep starts at low-frequency, these dynamics continue during the course of the sweep. This is not the case when the sweep is conducted from high to low frequency.

In hover, lateral stick inputs may cause significant coupling to the directional axis. Heading excursions should be reduced (to roughly ±20 deg) with directional control inputs. This should be considered a low-frequency and low-priority piloting function.

Small off-axis excursions from trim can be tolerated, but large changes in trim should be minimized by the appropriate control inputs. Such inputs, if they are infrequent and not in phase with the sweep, will be uncorrelated with the primary sweep input and will not adversely impact the quality of the results. If the rotorcraft is multi-crew, it may be easiest if the pilot not flying applies controls to minimize off-axis excursions. This technique has been found to work well when performing directional frequency sweeps.

In forward flight, lateral stick inputs may cause sideslip excursions. Pedals should not be used during lateral sweeps unless sideslip operational limitations are encountered. It is preferable to reduce the magnitude of the lateral inputs if sideslip excursions are too great, rather than to use large pedal inputs.

Cockpit control position indicators are very useful for aiding the pilot in maintaining symmetrical wave forms.

Coaching by a flight test engineer looking at the on-line data may help the pilot to perform the proper sweeps at proper input periods. It is very easy to remain at one frequency too long; having the engineer tell the pilot to dwell on a specific frequency longer or increase frequency during a data run aids data acquisition. This assumes the engineer has real time data.

The copilot or flight test engineer should coach the pilot for the low frequency responses by counting seconds for timing the quarter periods. This should only be done for the lowest frequencies. It was found that if the copilot tried counting at higher frequencies it only mixed up the pilot and resulted in the pilot following the copilot's counting rather than increasing the frequency as required by the test.

For a given test condition, sweeps should be performed at least twice to improve the quality of the reduced data. Engineers at the German DLR (Reference 6) reported greatly improved data quality from three sweeps, each about 30-50 seconds in length, performed in one data sequence with a brief return to trim between sweeps. Some analysis software, such as CIFER®, is designed to concatenate multiple sets of sweep data. An example of two runs concatenated by CIFER that were not flown in a single flight test maneuver is given in Figure 75.

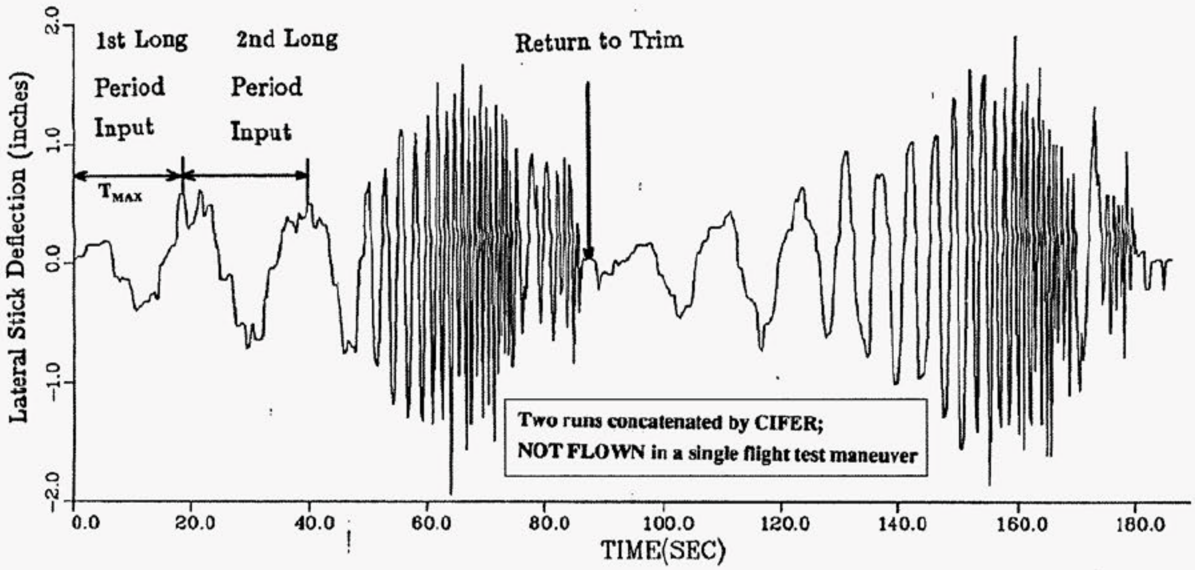


Figure 75 Frequency Sweep Data from Bell 214ST Testing as Analyzed by CIFER

If an instrumented airspeed boom is used, during flights that require longitudinal inputs the boom must be monitored closely for deflection beyond limits, or it should be removed.

There are numerous texts and tutorials on the theory behind the Fast Fourier Transform and similar methods for reduction of time history data to frequency responses. Commercially available software, such as CIFER® (Reference 32), can be used to perform the data reduction. Reference 21 contains a wealth of information and data regarding the conduct and analysis of frequency sweeps. Reference 43 provides additional detailed background including theoretical definitions and calculations of frequency responses, as well as safety and other considerations.

Reference 21 contains excellent guidance for instrumentation requirements when accomplishing frequency sweeps. Guidance that is excerpted from that reference is as follows:

- The break frequency for filters on input and output signals should be approximately 5 times the maximum frequency used in the sweep, and should be the same for input and output measurements.
- The data sample rate should be at least 5 times the filter break frequency.

Automated Frequency Sweeps

It is sometimes desirable to use an automated frequency sweep, and some guidelines for that are presented herein.

Automated frequency –sweep generation begins with the assignment of key variables that define sweep duration, sweep amplitude, and the range of frequencies that are of key interest. As an example Reference 21 section 5.11, provides an example frequency sweep with a 90 second duration, mean amplitude of one inch (± 0.5in), and with a range of 0.3 to 12 rad/sec.

$T_{rec} = 90s$	*frequency sweep duration*
$A = 1.0in$	*mean sweep amplitude*
$\omega_{min} = 0.3rad / s$	*low frequency limit*
$\omega_{max} = 12rad / s$	*high frequency limit*

A generic frequency progression over a defined range is given as:

$$\omega(t) = \omega_{min} + K(\omega_{min} - \omega_{max})$$

Where $K = f(t)$. To ensure that ample time during the sweep is spent at low frequencies, an exponential frequency progression can be used as shown in Reference 21, equation 5.15).

$$K = C_2(e^{C_1 \frac{t}{T_{rec}}} - 1)$$

From Reference 21 it is suggested that $C_1 = 4.0$ and $C_2 = 0.0187$. It is also suggested that the frequency progression fades in and out to prevent sending discontinuous signals to the model and/or hardware. This is accomplished by holding ω_{min} constant for the first few seconds of the sweep. Also, as Tischler points out, to prevent time modulation of the sweep input, the frequency should be integrated discretely as a function of time:

$$\theta(t) \equiv \int_0^t \omega(t)dt$$

$$\theta(t_n) = [\omega(t_{n+1}) + \omega(t_{n-1})]\frac{\Delta t}{2} + \theta(t_{n-1})$$

This can be accomplished with the use of Simulink or a few lines of code:

```
for i = 1:length(t)
    theta(i) =  (w(i) + w(i-1))/2*dt +theta(i-1);
end
```

At this point the resulting sweep input can be generated as seen in Figure 76:

$$\delta_{sweep} = A\,sin[\theta(t)]$$

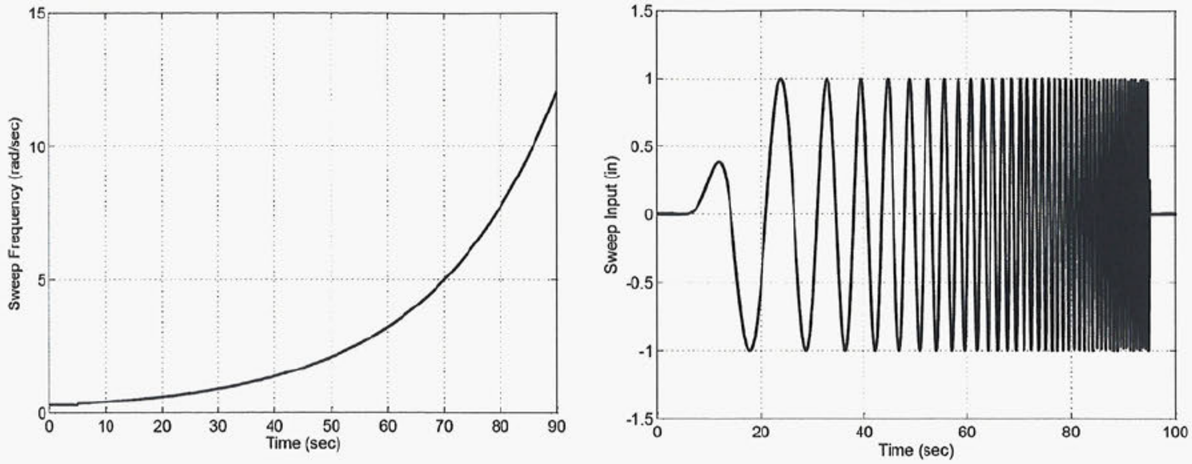


Figure 76. Exponential sweep frequency and resulting computer generated frequency-sweep

This sweep input contains trim and fade durations for 3 to 5 seconds by zeros before and after the sweep progression, as well as, parabolic shaping at the beginning and end to remove any remaining discontinuous data.

Pulse ("Rap" or "Spike")

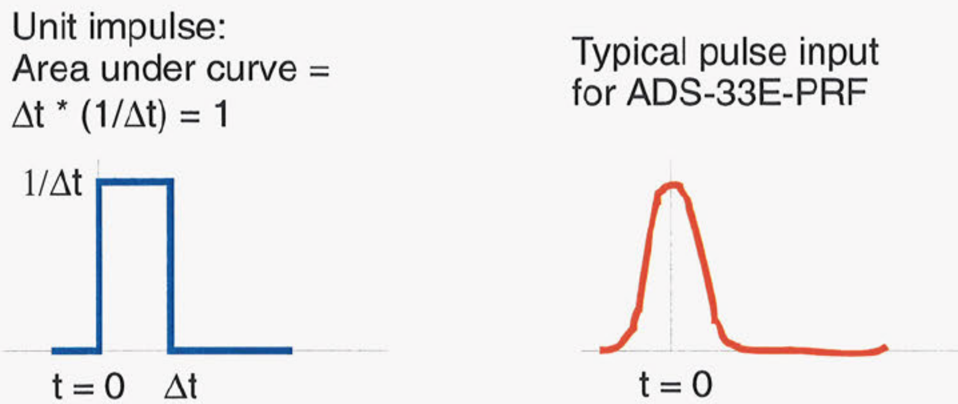
Applicable paragraphs:

3.2.7 Character of Attitude Hold and Heading Hold Response-Types
3.3.2.3 Mid-term response to control inputs
3.3.3 Moderate-amplitude pitch (roll) attitude changes (attitude quickness)
3.3.5.2 Mid-term response to control inputs
3.3.6 Moderate-amplitude heading changes (attitude quickness)
3.4.1.2 Mid-term response to control inputs [pitch, forward flight]
3.4.6.2 Moderate amplitude attitude changes (attitude quickness) [pitch, forward flight]
3.4.7.1 Bank angle oscillations
3.4.7.2 Turn coordination
3.4.9.1 Lateral-directional oscillations
3.4.9.2 Spiral stability

Description:

Pulse inputs – sometimes referred to as "stick raps" or "spikes" – are used to excite a physical system without generating a large transient from trim. They are meant to be very brief, generating data for the free response of the rotorcraft. We choose to call this a *pulse* as opposed to an *impulse* input. An impulse has a strict mathematical definition of an input size approaching infinity for a vanishingly small input time (see left side of the sketch below). While an impulse might be the ideal forcing function, it is neither achievable nor necessary for the purposes of this specification.

Instead, the relevant requirements of ADS-33E-PRF use a pulse input: an input of finite time and magnitude, usually resembling more of a triangle than a spike (right side of the sketch below). The input should be applied as quickly as possible within any constraints on rotorcraft response, such as excitation of flex modes. Magnitude of the pulse is usually stated within the applicable requirement, and if not, is inferred by the subject of the requirement (that is, small, moderate, or large amplitude).



In most cases, a pulse is used to perturb the aircraft so the free response can be identified. When that is true, it is even less important that the input look like a stick rap. Instead, the input should be more of a ramp that is tuned to the rotorcraft's natural response frequency. For those requirements that are based on the forced response, or on the ratio of angular rate to angular attitude, there is an obvious benefit to making the pulse as rapid as possible. This is especially true for the Attitude Quickness tests, where a slow ramp-like input and/or removal of the input can penalize measured handling qualities. For these requirements there is a dedicated discussion about the best form of input (see 3.3.3 Moderate-amplitude pitch (roll) attitude changes (attitude quickness)), including provision for leaving a portion of the input in, if needed, to maintain a new trim attitude.

Experience has shown that the quality of discrete time domain inputs can be significantly enhanced through the use of control fixtures. An example of such a fixture is given in Figure 77.

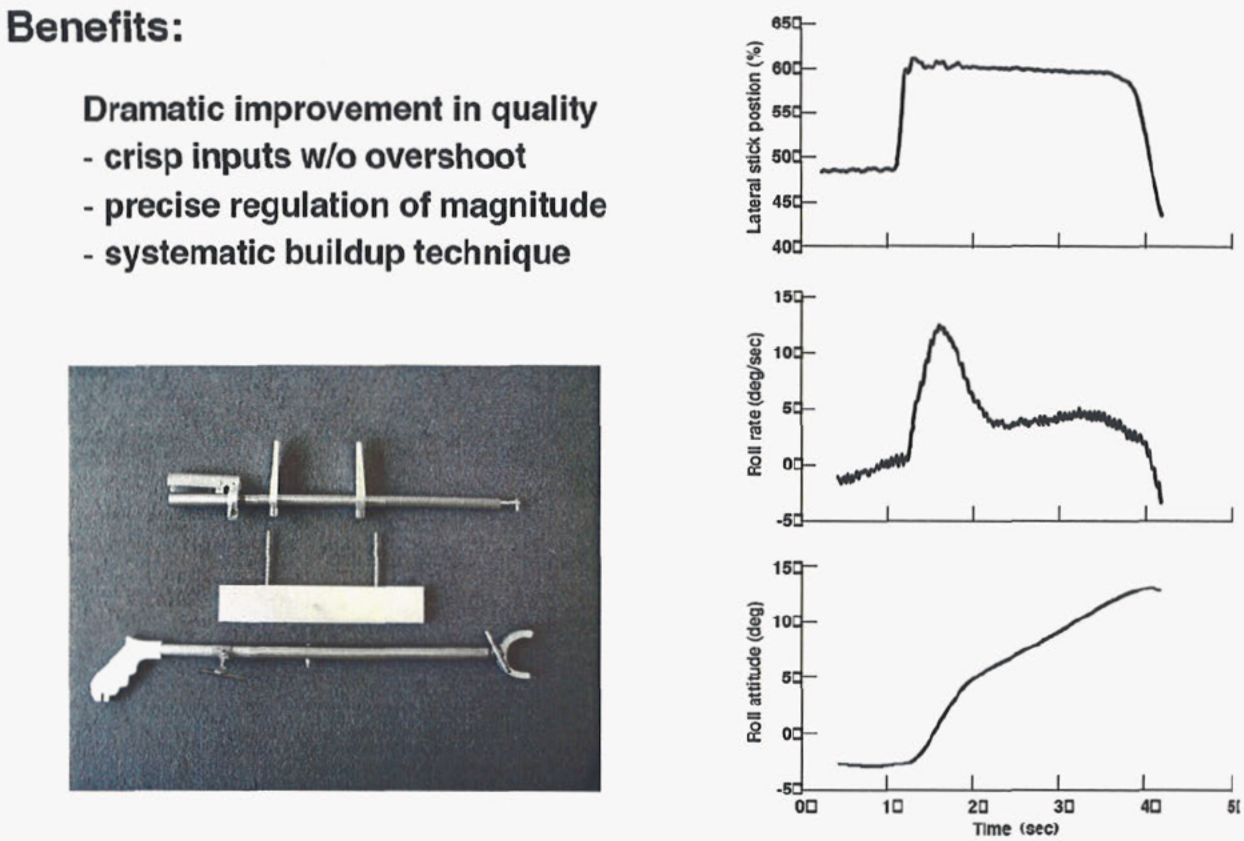


Figure 77 Example Test Fixture for Enhanced Control Over Discrete Inputs

An example of a much simpler fixture was developed for the ADS-33E compliance flight tests described in Reference 18. In that program the pilots developed a test aid by stretching a rubber band across the gap of a U-shaped metal fixture. In flight, the copilot would just touch the rubber band to the stick, at which time the pilot would drive the stick until it just touched the bottom of the U. This method allowed sharp corners on the step input with a constraint to prevent over-driving the stick past the fixture. An example of a test input using that device is given in Section 3.2.8 of this test guide.

Square wave

Applicable paragraphs:

3.2.7.1 Additional requirement for Heading Hold

Description:

A square wave input is simply a long pulse, or a short step. The input amplitude and duration are adjusted to develop an appropriate angular rate and attitude change.

t = 0 (midway pt of input)

Step

Applicable paragraphs:

3.2.8 Character of Attitude Command Response-Types
3.2.9 Character of Translational Rate Response-Types
3.2.10 Character of Vertical Rate Response-Types
3.3.4 Large-amplitude pitch (roll) attitude changes (attitude quickness)
3.3.8 Large-amplitude heading changes
3.3.9.1 Yaw due to collective for Aggressive agility
3.3.9.2 Pitch due to roll and roll due to pitch coupling for Aggressive agility
3.3.10.1 Height response characteristics
3.3.10.2 Torque response
3.3.11 Position Hold
3.3.12 Translational Rate Response-Type
3.4.3.2 Flight path response to collective controller (backside)
3.4.5.1.1 Small collective inputs [pitch attitude due to collective control]
3.4.5.1.2 Large collective inputs [pitch attitude due to collective control]
3.4.5.2 Roll due to pitch coupling for Aggressive agility
3.4.6.3 Large-amplitude roll attitude changes
3.4.7.1 Bank angle oscillations
3.4.7.2 Turn coordination
3.4.8.2 Large-amplitude heading changes for Aggressive agility

Description:

For some of the requirements, the most important consideration in the application of a step is that it be as true a step as possible. That is, a rapid input followed by a period with the input held constant. There should be no "drift" in input with time, either increasing or decreasing the magnitude of the input. For a number of the requirements, the final result is not overly sensitive to small changes in the input size. For a few, however, the answer may change depending upon whether the "step" really is a step, or if it has a slow increase or decrease of magnitude. Examples of this sensitivity to step quality – and where more discussion may be found in this Guide – include 3.3.10.1 Height response characteristics and 3.4.5.2 Roll due to pitch coupling for Aggressive agility. Use of a fixture in the cockpit to limit inputs will greatly enhance the quality of the step response, since it can facilitate a rapid displacement with a clear stop at the desired amplitude, and a subsequent constant displacement for as long as needed.

As with the square wave input, discussed above, the step does not have to be applied in zero time, that is, the initial input may be a rapid ramp. In this case, "zero time" for the step is when the displacement has achieved half its amplitude (see sketch for square wave).

Doublet

Applicable paragraphs:

3.4.9.1 Lateral-directional oscillations

Description:

A doublet is specified when there is a concern about perturbing the rotorcraft too far from trim with any other input form. The doublet should effectively look like two pulses of approximately equal amplitude but opposite sign. For the purposes of flight testing, the doublet can be pilot-generated and does not have to be perfect in application. See discussion of pulse above for more information. An example doublet used during UH-60 flight testing is given in

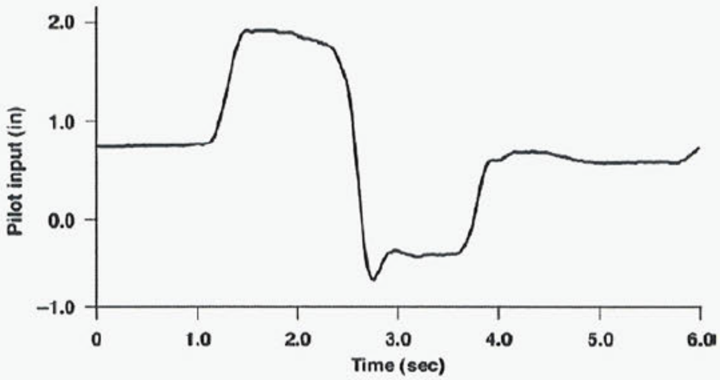


Figure 78 Example of a Doublet

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