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Piloted Simulation of Helicopter Advanced Flight Control Systems and Tradeoff with Displays

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Final report

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16. Abstract

A piloted simulation was conducted on the NASA Ames Vertical Motion Simulator as part of a project to develop recommended minimum performance standards for helicopters with advanced flight control systems (AdFC).

Evaluations were conducted from two pilot stations. The right-seat pilot station consisted of a representative advanced display suite consisting of a Genesys® IDU 680 EFIS/FMS and sidestick controller. The left seat was representative of a legacy display suite with 3-inch round-dial instruments and a moving map display and standard center stick controller.

The math model consisted of a generic single rotor helicopter weighing 16,000 lb. Four flight control systems representative of AdFC designs were evaluated with two versions of autopilot. One backup system was evaluated as a preliminary look at failure modes.

Workload ratings and handling qualities ratings were obtained for each AdFC in light and moderate turbulence, single-pilot and dual-pilot instrument flight rules (IFR), and with advanced and legacy displays.

The evaluation tasks consisted of seven realistic high-workload IFR scenarios lasting between 40 minutes and 1 hour.
Three FAA pilots and one industry pilot served as subjects.

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Contents

Figures

Acronyms

Acronym	**Definition**
ACAH	Attitude-command-attitude-hold
AdFC	Advanced flight control system
AGL	Above ground level
AP	Autopilot
ASC/RTT	Airspeed command return to trim
ASRC/RTT	Airspeed rate command return to trim
BURS	Backup rate system
CFR	Code of Federal Regulations
CTE	Civil task element
DPIFR	Dual-pilot IFR
EFIS	Electronic Flight Instrument System
FAA	Federal Aviation Administration
FAF	Final approach fix
FCC	Flight control computer
FLI	First limit indicator
FMS	Flight management system
FTR	Force trim release
HQR	Handling qualities rating
IDU	Integrated display unit
IFR	Instrument flight rules
IMC	Instrument meteorological conditions
IVSI	Instantaneous vertical speed indicator
LNAV+V	Lateral guidance with recommended glidepath
LPV	Lateral guidance with vertical precision glidepath
MCH	Modified Cooper-Harper workload scale
MTE	Mission task element
RCAH	Rate-command-attitude-hold
RCAR	Rate command attitude retention
SAS	Stability augmentation system
SPIFR	Single-pilot IFR

Executive summary

A piloted simulation was conducted on the NASA Ames Vertical Motion Simulator as part of a project to develop recommended minimum performance standards for helicopters with advanced flight control systems (AdFC). Certification of AdFC can be comprised of two major elements:

1) Systems safety assessment
2) Handling qualities. This project is primarily concerned with the handling qualities of AdFC.

The objective of the FAA-sponsored program is to develop a methodology to use quantitative criterion boundaries for certification of rotorcraft for flight under instrument flight rules (IFR). It is recognized that the existing criteria in appendix B of Title 14 Code of Federal Regulations (CFR) parts 27 and 29 are outdated, and many of the requirements are not applicable to the augmented rotorcraft dynamics that can be achieved with AdFC. FAA evaluators are therefore required to make certification decisions based on subjective criteria, such as "No undue pilot fatigue or strain for duration consistent with normal operation." The goal of developing quantitative criteria is to minimize the need for such subjective judgments by Federal Aviation Administration (FAA) evaluators.

Whereas much of the supporting data necessary to develop quantitative criteria already exist, this simulation was conducted to fill in important gaps in the database. Specifically, the purpose of the simulation was to address the following issues:

- Lack of data regarding workload reduction (and therefore certification credit) for dual-pilot IFR (DPIFR) versus single-pilot IFR (SPIFR)
- Lack of data regarding workload reduction for advanced displays
- Lack of data on how divided attention plays a primary role in pilot workload in the IFR environment
- Need to develop civil task elements (CTEs) to standardize subjective evaluations of AdFC handling qualities during certification flight testing

Recognizing that quantitative criteria are never going to be perfect, and that some level of FAA pilot evaluation will be necessary, well-defined CTEs were developed and refined during this simulation.

This simulation focused on flight in instrument meteorological conditions (IMC) and flight in the un-failed state.

The data from this simulation project will be used to support recommended certification criteria for rotorcraft IFR.

1 Introduction

A piloted simulation was conducted on the NASA Ames Vertical Motion Simulator as part of a project to develop recommended minimum performance standards for helicopters with advanced flight control systems (AdFC). Certification of AdFC can be considered to be comprised of two major elements: 1) systems safety assessment, and 2) handling qualities. This project is primarily concerned with the handling qualities of AdFC. The following limitations are documented: there was no use of aircraft checklists during the simulations; during single pilot runs, the opposite side displays were not covered over and could be seen by the pilot; and obtaining airport weather as normal in actual flight was not performed.

The purpose of this simulation was to provide additional supporting data for recommended minimum performance standards for helicopters with AdFC in appendix A. Most of the proposed criteria in appendix A are based on the supporting data documented in appendix B.

The results reported herein expand the supporting data in appendix B to include the role of advanced displays and the role of a second qualified pilot as these factors affect the required AdFC architecture and dynamics.

Quantitative criteria are never going to be perfect and some level of FAA pilot evaluation will be necessary. It is proposed that such evaluations be conducted using well-defined CTEs. Six CTEs were developed and refined during this simulation.

Section 6 summarizes the results of this study. Background information regarding the details of the simulation setup and protocol are given in sections 7–9. Section 10 summarizes the raw pilot rating data.

1.1 AdFC and its impact on rotorcraft certification

For the purpose of this study, the term AdFC (advanced flight control) represents any flight-control system in which the flight-control actuators are driven by the output of a flight control computer (FCC). For this study, the term “flight-control system” refers to mechanical links and actuators, and AdFC refers to the control laws resident in the FCC. According to this definition, one type of AdFC is an autopilot (AP) and another is a stability augmentation system (SAS)[1].

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[1] Starting with the military rotorcraft handling qualities specification ADS-33E-PRF, any augmentation that is meant to be flown using the standard cockpit cyclic, collective, and pedals is termed a SAS. Augmentation that is flown using cockpit buttons and switches is defined as an autopilot (i.e., coupled flight director). Those definitions are adopted herein.

Because the certification requirements for APs are well established, the SAS version of AdFC is implied herein unless otherwise noted.

The insertion of an FCC between the pilot and flight controls requires consideration of systems issues and handling qualities issues. This work addresses handling qualities issues. Handling qualities and systems issues overlap when the probability of a system failure defines the allowable degradation in handling qualities.

This is the methodology used in military fixed- and rotary-wing aircrafts' handling qualities specifications. To use this methodology, it is necessary to have knowledge of the handling qualities of varying types of backup AdFC, because a failure of the primary AdFC means that the pilot must continue the flight on a backup AdFC. The probability of such failures results from the system safety analysis.

An extreme case is one in which the backup system is identical to the primary system, in which case there is no effect on the handling qualities. This is the basis for current rotorcraft instrument flight rules (IFR) certifications, which make IFR certification unrealistic for all but the most expensive helicopters. Most of the supporting data for such certifications consist of systems safety analyses to ensure that a failure of both APs is extremely improbable. One objective of this study is to determine the characteristics of an AdFC that are a suitable for use on Title 14 CFR part 27 and 29 aircraft.

This study also investigates the viability of an AdFC as the only means of controlling the rotorcraft for IFR and Visual Flight Rules (VFR). When augmented with an AdFC, rotorcraft are as stable, or more stable, than fixed-wing aircraft commonly flown IFR without an AP. The difference between fixed- and rotary-wing aircraft is that a failure of the AdFC can be far more critical for rotorcraft than for fixed-wing aircraft. Therefore, it is important to ensure that failure of the AdFC will not result in unacceptable handling qualities (i.e., a backup AdFC may be required).

1.2 Technical approach

This section summarizes outstanding issues regarding certification of AdFC in rotorcraft and the technical approach to address each issue.

Issue: Essentially, all existing handling qualities data are based on accomplishment of a single task in which division of attention is not required. It is well understood that division of attention away from the flight controls is an important element of the total IFR workload.

Technical Approach: Develop realistic very high workload IFR scenarios in the presence of light and moderate turbulence as the basis for piloted evaluations.

Issue: Essentially, all recent single-pilot IFR (SPIFR) rotorcraft certifications have been with fail operational three- or four-axis APs. Are simplified APs acceptable for SPIFR? Is fail operational a requirement, or is it acceptable to fail to a simpler AdFC?

Technical Approach: Simulate a three-axis AP with all upper modes and a simplified three-axis AP with only HDG and ALT (no altitude pre-select). Implement turn coordination augmentation in the directional axis under the assumption that this is essential for SPIFR. When the pilots expressed their opinion that an AdFC was not certifiable as a primary system, they were asked if the same AdFC would be certifiable as a backup system.

Issue: Is an AdFC acceptable for SPIFR without an AP?

Approach: Evaluate representative AdFC SAS types—rate-command-attitude-hold (RCAH) and attitude-command-attitude-hold (ACAH)—in a very-high IFR workload scenario. Evaluate the concept of incorporating what are usually considered "upper modes" into an AdFC SAS. The example used in this study was an airspeed command return to trim (ASC/RTT) SAS. With ASC/RTT, the longitudinal cyclic controlled airspeed and attitude were controlled only indirectly to achieve the commanded airspeed. This is equivalent to an airspeed select/hold mode in an AP.

Issue: Should certification of an AdFC take into account the effect of one versus two pilots (i.e., SPIFR versus DPIFR)?

Technical Approach: When the SPIFR evaluation of an AdFC resulted in poor numerical ratings, and therefore judged as uncertifiable, or exhibited at least one instance of potentially unsafe performance, it was flown again as DPIFR.

Issue: Can advanced Electronic Flight Instrument System (EFIS) displays be used for certification credit for SPIFR?

Technical Approach: Two evaluation stations were developed: one with legacy (round dial) displays and the other with a Genesys® state-of-the-art EFIS. The high-workload IFR scenarios were flown from both pilot stations. The legacy displays included a moving map and ability to input and revise flight plans. According to the author of this report, it is considered as essential for flying in the current IFR environment.

Issue: Handling qualities research conducted over the years has shown that turbulence plays a major role in pilot workload. Most company flight testing and FAA certification flight testing is conducted in light turbulence.

Technical Approach: Piloted evaluations were conducted in light and moderate turbulence. This was intended to expose AdFC deficiencies related to a lack of disturbance rejection.

Issue: Whereas the goal of this project is to develop quantitative criteria for certification, it is recognized that such criteria are not perfect and that some flight testing is necessary.

Technical Approach: Develop highly defined tasks that are representative of elements of IFR flight and designed to expose handling qualities deficiencies. These tasks are referred to as CTEs. That concept was successfully used in the military handling qualities specification, ADS-33E-PRF, in which the tasks are elements of military missions (e.g., mission task elements [MTEs]).

Issue: With fly-by-wire flight control systems, the possibilities for control/response characteristics are immense. It is not possible to develop quantitative criteria for each possible SAS type.

Technical Approach: This study looks at an ASC/RTT SAS as an example. ASC/RTT emulates a common airspeed command/hold AP mode, which is flown with cyclic and collective instead of AP buttons and knobs. This resulted in recommendations on what to look for when testing such a mode.

1.3 Phase A and Phase B defined

The simulation was conducted in two phases. This was a result of the fact that the motion system failed after 1 week of testing, and there was a 3-month delay before testing was resumed. The first week of testing is referred to as Phase A, and the subsequent 3 weeks of testing as Phase B.

2 Description of experiment

2.1 Pilot subjects

Four test subjects were used for the simulations. The four test pilot subjects accomplished evaluations over a 4-week period of formal motion base simulator testing. The number of test subjects was limited to allow time for training on the use of the Genesys advanced display system and to account for the fact that the runs lasted between 40 minutes and 1 hour.

2.2 Cockpit layout

Two sets of displays are provided: one to test advanced displays and one to test legacy displays. The right seat represents the advanced display suite, which includes a Genesys integrated display unit (IDU) 680, and backup instruments as required by the regulations. The legacy display suite is located in front of the left seat and consists of the commonly used 3-inch round-dial displays and a moving map display. The flight-management functions found in essentially all rotorcraft cockpits (e.g., Garmin® 400 through 5000 navigators) are available for the legacy and advanced display positons.

Figure 1 shows the cockpit layout.

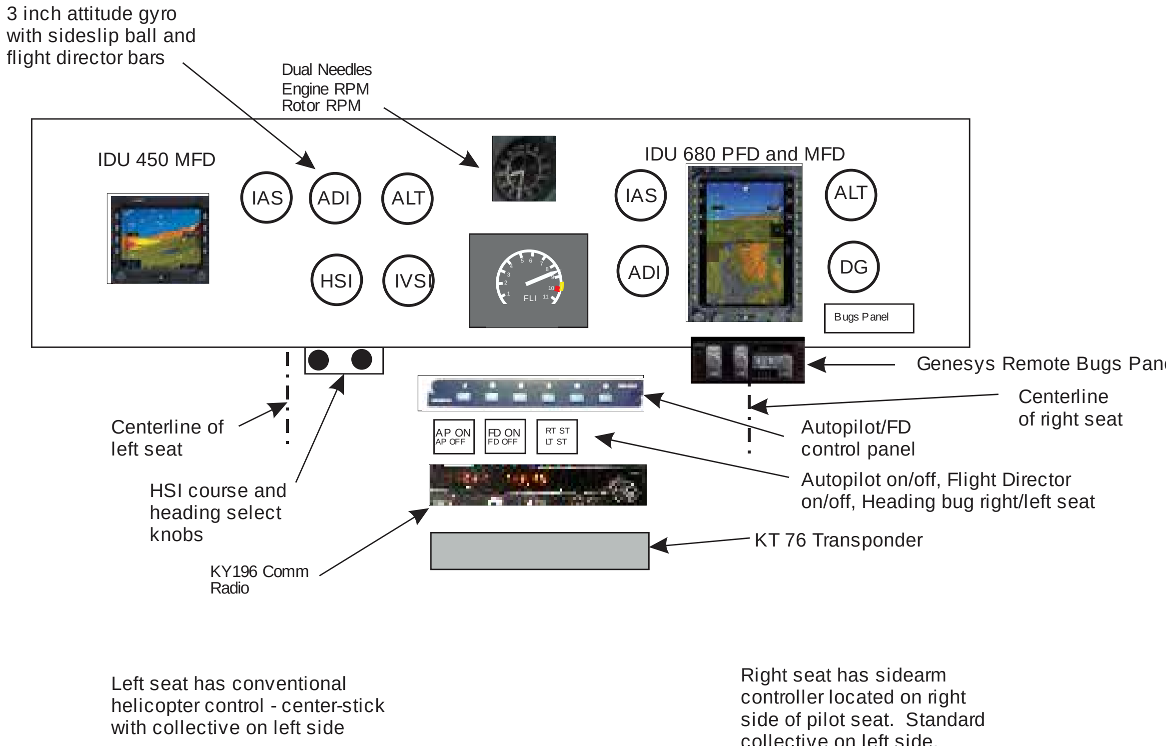

Figure 1. Instrument panel layout

The IDU 450 shown in Figure 1 was configured as a moving map display. When flying the legacy displays, all flight plan, approach, and holding data were input via the IDU 450. Inputting flight plan data on one side automatically populated to the other side.

The engine instruments consist of a conventional engine/rotor RPM display and a first limit indicator (FLI). The FLI defines the limit on power (collective), which is set by torque or temperature in a real helicopter and by the math model for this simulation.

Figure 2 shows an expanded view of the FLI. This is generated on a cathode ray tube and driven by the math model.

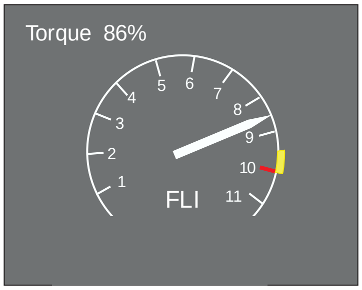

Figure 2. FLI

Flight director guidance in the form of longitudinal and lateral command bars were available for the legacy and advanced displays.

There was a communication radio (Bendix King KY196) on the center console (accessible to both pilots), which realistically simulated workload associated with changing communications frequencies. A transponder (Bendix King KT 76) was also included to provide the divided attention workload associated with entering transponder codes.

The cockpit controllers were as follows:

- Sidestick for right seat and conventional center stick for left seat. Buttons for AP DISC and force trim, and beep trim on both sticks.
- Standard collective and pedals for both pilots.
- Navigation functions
  - The IDU 680 and IDU 450 EFIS databases provided all required navigation functions. The simulator math model supplied latitude, longitude, airspeed, winds, track angle, heading, and pitch and roll attitude.
  - All IFR clearances were such that they could be flown with GPS only. This is intended to expose the workload associated with entering and modifying GPS/RNAV flight plans and approaches. This also avoids the need to simulate ILS and VOR signals.
- Legacy 3-inch round-dial displays in front of left-seat pilot.
  - Airspeed 0 to 220 knots with redline at 160 knots
  - Attitude indicator with flight director bars
  - Pointer drum altimeter
  - Instantaneous vertical speed indicator (IVSI)
  - Mechanical horizontal situation indicator (not back-driven by the flight management system [FMS])
  - Standard turn and slip indicator

2.3 Tested configurations

The AdFC configurations tested in this experiment were intended to represent typical systems that would be implemented in fly-by-wire rotorcraft. The configurations were designed so that the short-term dynamics met or slightly exceeded the Level-1 criteria defined in appendix A. This was done to isolate the effect of the shape of the response to cyclic and turbulence input as follows:

- ACAH—Response to cyclic input is a constant pitch or roll attitude that is proportional to the size of the input[2]. The response to an external disturbance was a return to the trim pitch or roll attitude. Pressing the force trim release (FTR) button reset the trim cyclic position and trim pitch and roll attitude. Activating the beep trim button on the cyclic causes the controller to move at 0.30 inches per second.
- RCAH[3]—Response to cyclic input is a linear pitch or roll rate that is proportional to the size of the input. Releasing the cyclic causes the SAS to hold the current pitch or roll attitude. The response to an external disturbance is a return to the trim pitch or roll attitude. The FTR button and beep trim were not functional. This is sometimes referred to as trim follow-up or unique trim.
- ASC/RTT—Response to cyclic was a commanded airspeed that was proportional to the size of the input. Releasing the cyclic caused the airspeed to return to the original trim speed. Pressing the FTR caused the airspeed and cyclic position to re-trim to the current values. Pressing the beep trim resulted in a 1 knot change in the trim airspeed per beep.
- Airspeed Rate Command Return to Trim (ASRC/RTT)—Similar to ASC/RTT, except that the airspeed trim did not take effect until the cyclic was returned to detent. Pressing the beep trim results in a change in trim airspeed of 1 knot per beep as long as the cyclic is in the detent. Because of time constraints, only a few runs were made with this AdFC.
- Backup Rate System (BURS)—A simple rate damper such as those used as a backup system on fly-by-wire military helicopters. There is no hold function, which results in noticeable coupling between axes.
- Yaw Damper/Turn Coordination—All evaluations were made with a yaw damper and turn coordinator that kept lateral acceleration near zero. All pilots agreed that the yaw axis was not a factor.

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[2] Attitude Command Velocity Hold (ACVH) is also very common. Because of time constraints, this was not tested.
[3] The pitch axis RCAH was mechanized as rate command attitude retention (RCAR). Functionally it is the same as RCAH.

- Three-axis AP—A three-axis AP that controls pitch and roll, with a yaw damper and turn coordination in the yaw axis. This provided a baseline as to the certifiability of a three-axis AP and a basis for comparison with the AdFC SAS systems. The AP was capable of heading select and hold, altitude pre-select and hold, vertical speed hold, airspeed hold, and lateral guidance with vertical precision glidepath (LPV) approaches. This AP was mechanized as a parallel system wherein the cyclic motion reflects motion of the swashplate. If the pilot attempted to override the AP, it was set to disengage (commanded and actual cyclic position differ by more than 0.5 inches), and the system reverted to ACAH SAS.
- A simplified version of the AP was also tested, in which the pilots were only allowed to use the heading select/hold, airspeed hold, and altitude hold modes (no altitude or airspeed preselect, or warning tones for altitude deviations).

ACAH, RCAH, ASC/RTT are defined here as AdFC SAS modes. This extends the classic definition of a rotorcraft SAS as a simple rate damper to any flight control system in which the pilot flies using the cyclic, collective, and pedals. An AP is defined here as flight by using cockpit switches and buttons.

The simulated AdFC SAS systems used full authority series servos.

The tested AdFC flight control systems are defined in section 8.

For cases that are not deemed certifiable by the test pilots for SPIFR, the following configurations were tested.

- Add a flight director.
- If that is still not deemed certifiable by the test pilots, add a second pilot.

3 Methodology

Each formal run consisted of a high-workload IFR scenario lasting between 40 minutes and 1 hour. Seven scenarios were developed to minimize the effect of learning on pilot workload. Each scenario included revised clearances, two LPV (or lateral guidance with recommended glidepath [LNAV+V]) approaches, the first of which required a missed approach, holding patterns, and altitude and speed changes from Air Traffic Control (ATC). One of the researchers acted as an air traffic controller and read clearances from the scripts, as presented in section 9. Runs were made in light and moderate turbulence. The ratings and comments were made after completion of the scenario.

The test pilots were in general agreement that these scenarios were realistic, although they produced a higher level of workload than exists for most IFR flights in the real world. The need to divide the pilot's attention away from rotorcraft control takes three basic forms: 1) ATC clearances, 2) obtaining weather and planning how to deal with it, and 3) non-normal or emergency checklists/procedures. The second and third of these are difficult to simulate in a research environment. Therefore, the first was used as a surrogate for all three. It is assumed that in the real world, the need to deal with the first and second forms of divided attention would be handled by advising ATC of a need for special handling. Such special handling can range from a "standby" request for a revised clearance, to a request for delay vectors or vectors-to-final to the nearest airport. It is asserted that if the FAA takes the position that pilots will not follow this strategy and must be able to handle two or all three types of divided attention simultaneously, the only possible solution is two-pilot IFR or dual fail-operational AP.

Turbulence was simulated using the FAA DRO model [1]. The FAA uses this model for all autoland and Cat III HUD certifications. Simulation runs were made in light turbulence above 1000 feet ($\sigma_H = 1$ ft/sec) and moderate turbulence ($\sigma_H = 4$ and 5 ft/sec). For altitudes below 1000 feet above ground level (AGL), the "DRO" turbulence is defined by the wind at 20 feet AGL. This was set as a 15-knot direct left or right crosswind for all runs. This strategy resulted in a decrease in turbulence when descending through 1000 ft. AGL, followed by steadily increasing turbulence and crosswind shear as the rotorcraft approached the ground. All evaluators agreed this was a challenging task.

Figure 3 shows representative gust profiles above 1000 feet for the three tested levels of turbulence ($\sigma_H =$ 1, 4, and 5 ft/sec).

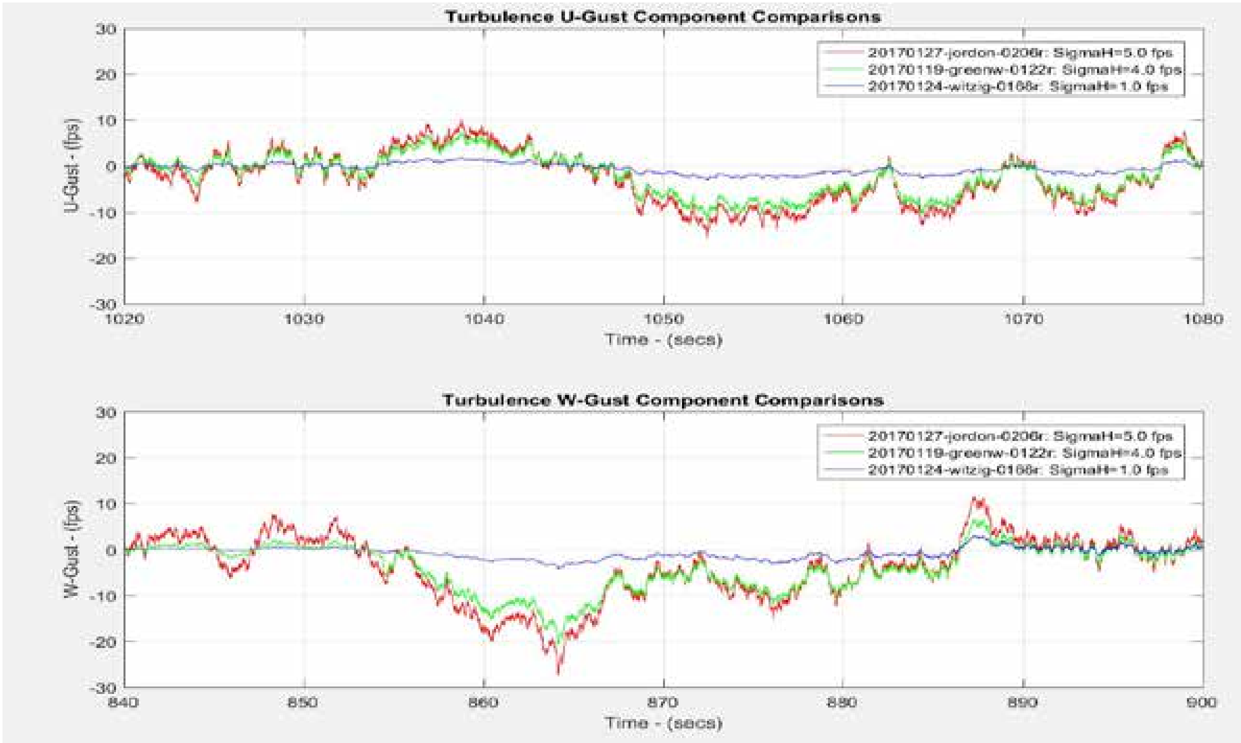

Figure 3. Example gust profile for tested levels of turbulence >1000 ft. AGL

Starting at run 205 (approximately two-thirds through the program), it was decided to increase the level of moderate turbulence from $\sigma_H = 4$ ft/sec to $\sigma_H = 5$ ft/sec based on test pilot comments to the effect that it would be useful to evaluate in a slightly higher level of turbulence. Most of the moderate turbulence runs were made during the last two weeks of the simulation.

There were some AdFCs in which this was seen to have an impact on the results, as noted in the results section of this report (see section 4).

Whereas advanced displays and FMS provide improved situational awareness, interfacing with such systems involves additional pilot workload. This tradeoff in workload was investigated by incorporating two pilot stations, one with an advanced FMS/EFIS display suite and the other with legacy displays. The legacy display suite included a moving map, and means to input and revise flight plans. Both display suites are described in section 2.2.

All subject pilots were provided with training on the Genesys advanced displays during the first day of the evaluation period. It was understood that this was not sufficient time to become IFR proficient on the display/FMS system. To compensate for that, the researchers provided the evaluation pilot with prompts if he or she experienced problems with entering revised clearances.

Such prompts were no longer offered when the pilot was considered proficient with the FMS/display interface.

The first evaluations were always done with the AP engaged, and using the advanced displays. The workload ratings and certification decision for this configuration were taken as a baseline that represents the lowest workload. This was done to confirm that a three-axis AP is adequate for SPIFR and to ensure that the IFR scenarios did not entail unrealistically high workload.

The second evaluation was done with legacy displays and a typical GPS navigation radio with a moving map display. This was done to determine if advanced displays are necessary (beyond the now-standard GPS map) for SPIFR when using a three-axis AP.

Subsequent evaluations were done with AdFCs to determine if full manual control is acceptable for IFR with such AdFC systems. Such manually flown systems are referred to interchangeably as AdFC or SAS modes.

A flight director was also included in the experiment, but was only used if a configuration was rated as uncertifiable and the evaluation pilot felt that a flight director could change that decision.

4 Results

Analysis of the data consists of the following:

- Workload ratings from the modified Cooper-Harper scale.
- Handling qualities ratings (HQRs) from the Cooper-Harper scale.
- Test pilot answer to the question—Is this configuration certifiable for the IFR scenario that you just completed? Assume that this is the only available flight control system. If not certifiable as a primary system, is it certifiable as a backup system? (Test pilots were chosen because of their experience in testing rotorcraft for certification; therefore, this question was used.)
- Pilot commentary associated with the ratings.
- Selective review of quantitative data and video taken for each run. The emphasis was on identifying any tendency for attitude excursions that could lead to loss of control. Divergences from assigned altitude or heading were noted, but not felt to threaten safety unless they were large (e.g., altitude deviation of 300 ft. or more)[4].

[4] Altitude deviations of greater than 300 ft could result in a “pilot deviation” with possible FAA enforcement action, especially if a traffic conflict is incurred. The pilots were very conscious of this, and worked hard to keep altitude deviations below 200 ft.

The pilot questionnaire and rating scales are presented in section 7.

The researchers monitored every run and noted incidences in which attitude excursions occurred that could lead to loss of control.

4.1 Workload rating results

As noted above, the pilots were asked to assign ratings to quantify workload using the modified Cooper-Harper scale. Those results are presented in this section.

The average modified Cooper-Harper (workload) SPIFR ratings for each of the tested configurations are shown in Figure 4. These averaged ratings combine data taken for the legacy and advanced displays.

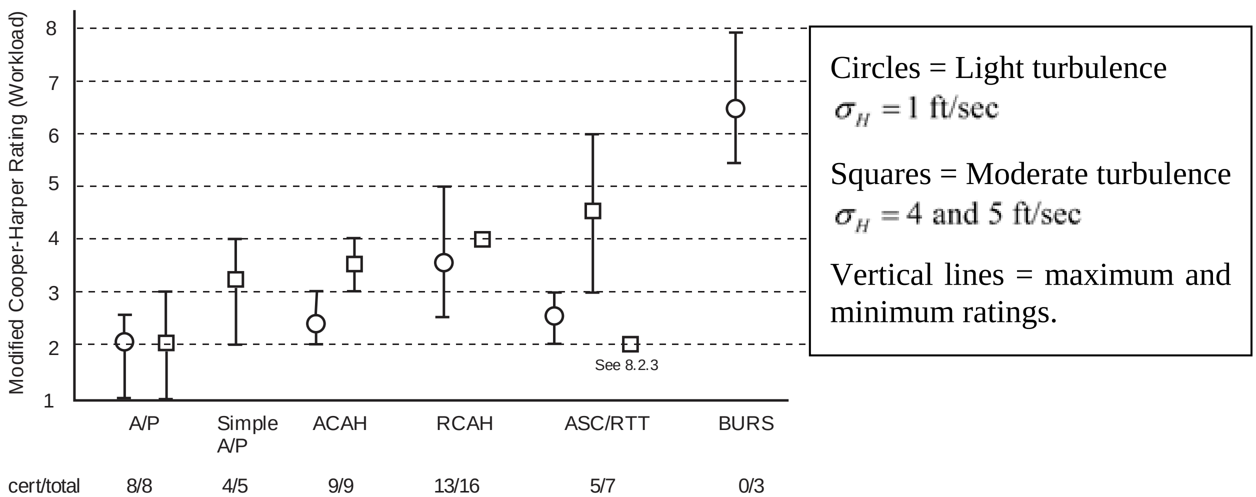

Figure 4. Modified Cooper Harper workload ratings in light and moderate turbulence

Figure 4 combines the effect of legacy and advanced displays to show the overall effect of turbulence. The results of the response to the question “Is this system certifiable for the scenario that you just completed?” is given as the cert/total line at the bottom of the plot.

The decision to certify a system as the only primary means for flight in instrument meteorological conditions (IMC) is correlated with the modified Cooper-Harper workload scale (MCH) workload ratings shown in Figure 5.

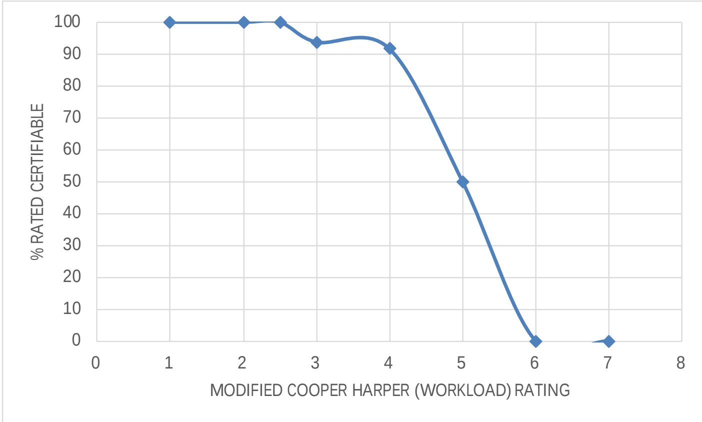

Figure 5. Correlation between workload rating and decision to certify

These data consist of 65 runs with three pilots and four different AdFC SAS configurations plus AP. The data for the fourth subject pilot were not included in this correlation because he held an opinion that certification of SPIFR in rotorcraft requires AP coupling, and rated all configurations without coupling as uncertifiable.[5] His decision to certify or not certify was preordained, and therefore not used when presenting results related to the response to the decision to certify question.

It is proposed that a workload rating of 4.5 or better should be considered as certifiable (75% of the ratings in that range were judged to be consistent with a certifiable SAS). On that basis, the data in Figure 4 indicate that all of the tested AdFC SAS types intended as a primary system for IFR were certifiable, albeit some with more margin than others.

The BURS was judged to be uncertifiable by three evaluators and rated in the uncertifiable workload range by all four evaluators. This is further discussed in section 4.1.8.

The effect of turbulence is seen to be more significant for some SAS types than others. The AP was effectively impervious to turbulence.

More detailed results for each of the tested AP, SAS systems, and display types are given in the following subsections.

[5] The ratings and commentary issued by this pilot are used throughout the analysis of the data. Only the decision to certify was excluded.

4.1.1 Autopilot

Figure 6 shows the workload rating data for the three-axis AP. Cert/total equals the number of pilots who certified versus the number of pilots evaluating this task.

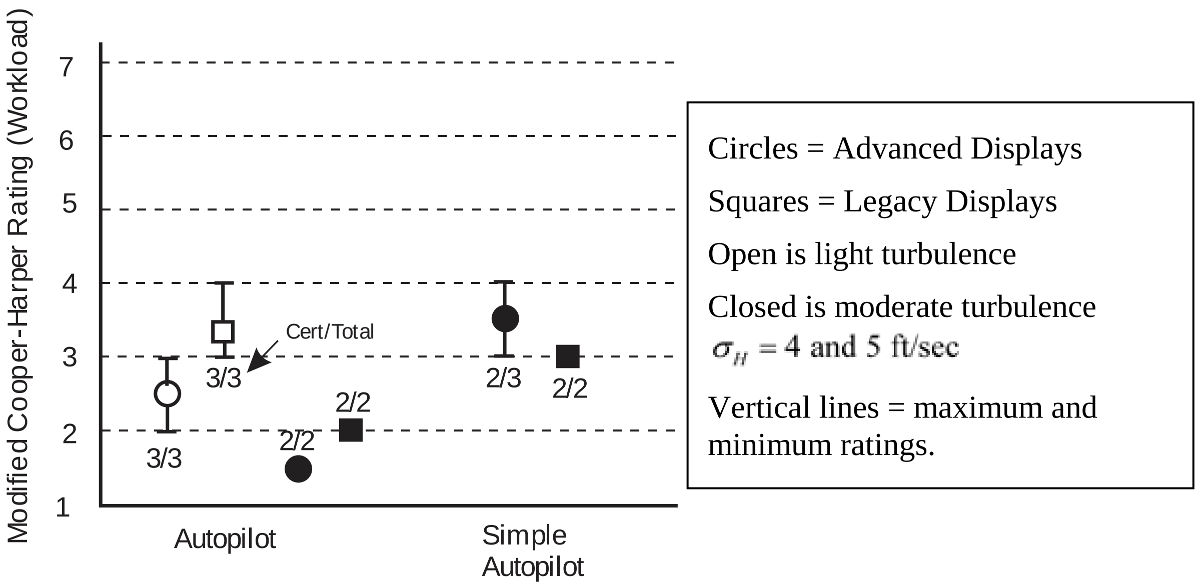

Figure 6. SPIFR workload ratings for three-axis AP

The AP and simple AP were both three-axis, in which the yaw axis provided yaw damping and turn coordination ($a_y \approx 0$). The AP upper modes included heading, altitude, airspeed, vertical speed pre-select and hold, lateral navigation, and LPV approach capability, and aural alerts for altitude deviations and minimums callout for IFR approaches. The simple AP only provided heading select and hold, and airspeed and altitude hold (no pre-select) with no aural annunciations.

For LPV approaches with the simple AP, the pilots were required to fly manually in the AP SAS mode, which is classified as an ACAH AdFC.

Conclusions from the data in Figure 6 are as follows:

- Both the AP and simple AP easily meet the MCH equal to or less than 4.5 criterion for SPIFR. The APs were not tested for DPIFR because they met the SPIFR requirements.
- The full AP showed especially low workload in moderate turbulence.
- The workload was slightly reduced with the advanced display suite relative to the legacy display suite.

- One pilot rated the simple AP as uncertifiable as a primary system in turbulence because of the workload associated with constantly changing the heading bug and engaging and disengaging altitude hold. He rated it as certifiable (albeit “barely”) on a repeat run that was accomplished later in the program.

The three-axis AP is seen to have provided a very low level of pilot workload in light and moderate turbulence. The pilot commentary strongly suggested that the AP provided significant workload relief compared to manual flying with a SAS.

4.1.2 Attitude-command-attitude-hold stability augmentation system (ACAH SAS)

The detailed workload rating data for the ACAH SAS are shown in Figure 7.

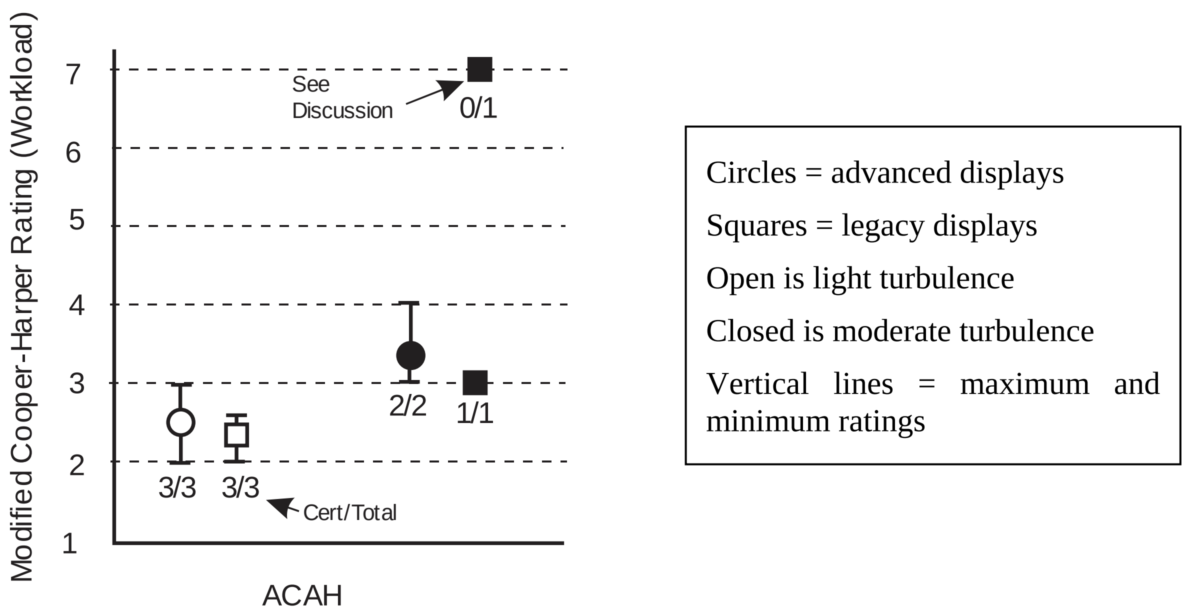

Figure 7. SPIFR workload ratings for ACAH SAS

With one exception, all the pilots noted that the IFR scenarios were safely accomplished with an acceptable level of workload with the ACAH SAS and were certifiable as the primary SPIFR system. Very importantly, there were no significant attitude excursions when the pilot’s attention was diverted away from the flying tasks.

When flying with the legacy displays, there were a few comments related to poor resolution of the pitch attitude scale on the 3-inch attitude indicator. However, the ratings show that this did not affect the overall workload.

There was one outlier (run 206) in which the MCH (workload) for the ACAH SAS was assigned a 7 when flying in moderate turbulence ($s_H = 5$ ft/sec) with the legacy displays (plotted separately in Figure 6). The following caveats apply:

- The HQR for this same run was 3. This indicates that the evaluator did not think that the handling qualities were a problem.
- This was the test pilot's first run with moderate turbulence (without the AP). The primary effect of turbulence on IFR flight tends to be difficulty maintaining altitude. Figure 3 shows that vertical gusts of 10 ft./sec (900 ft./min) were common, with some peaks at 15 ft./sec (1200 ft./min).
- The pilot noted that the workload for this run was "tremendous". A review of the data does show that there were more than normal altitude deviations for this run—standard deviation in altitude for level segments was 142 feet, compared to 53 feet on a subsequent run with the same pilot (run 257), also in moderate turbulence, but with the advanced display suite (MCH/HQR = 3/3)[6].
- There were no other runs with any pilot that produced unacceptable workload ratings (MCH>4.5) in light or moderate turbulence for ACAH in moderate turbulence (see Figure 7).

4.1.3 ACAH with reduced bandwidth

Appendix A limits on bandwidth were initially based on ADS-33E-PRF and were set at 1.5 rad/sec in pitch and 2.0 rad/sec in roll. Those limits are based entirely on testing that involved precise maneuvering in visual meteorological conditions. The test configurations were designed for a bandwidth of 2.5 rad/sec in pitch and roll to ensure that bandwidth was not a factor in the evaluations.

A comprehensive exploration of the minimum required bandwidth for flight in IMC was beyond the scope of this experiment. However, two runs were made with the ACAH bandwidth in pitch and roll reduced to 2.0 rad/sec ($s_H = 5$ ft/sec) with the result shown in Figure 8.

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[6] In general, there was not a strong correlation between the altitude deviations with advanced and legacy displays. There were some comments to the effect that it was easier to spot an altitude deviation with the round-dial altimeter and IVSI than with the advanced vertical tape format.

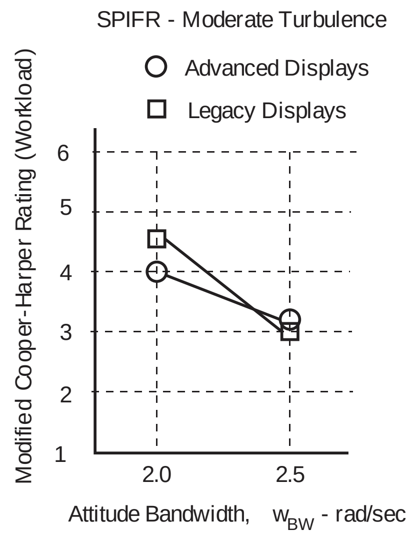


Figure 8. Effect of bandwidth on workload for SPIFR with ACAH SAS

This reduction in bandwidth increased the workload ratings to where certification would be marginal. The pilots noticed the reduction in bandwidth, and one noticed that the lower bandwidth system made it a little harder to set pitch and roll, and return to trim was slower (he was using the legacy displays). He rated it as uncertifiable as a primary system, but acceptable as a backup. This pilot previously noted that ACAH (with bandwidth of 2.5) was an acceptable alternative to an AP for 14 CFR Part 135 SPIFR.

4.1.4 Rate-command-attitude-hold stability augmentation system (RCAH SAS)

All the pilots commented that the RCAH AdFC had very desirable handling qualities, and specifically noted the very good attitude hold function when the cyclic was released and the lack of need to trim. It was also commonly noted that RCAH was not tolerant of divided attention. The pilots commented that it was necessary to take their hand off the cyclic when looking away from the displays to tend to non-flying tasks because any small force on the cyclic resulted in a linear divergence in pitch/ roll away from trim. An example of such a divergence is shown in Figure 9.

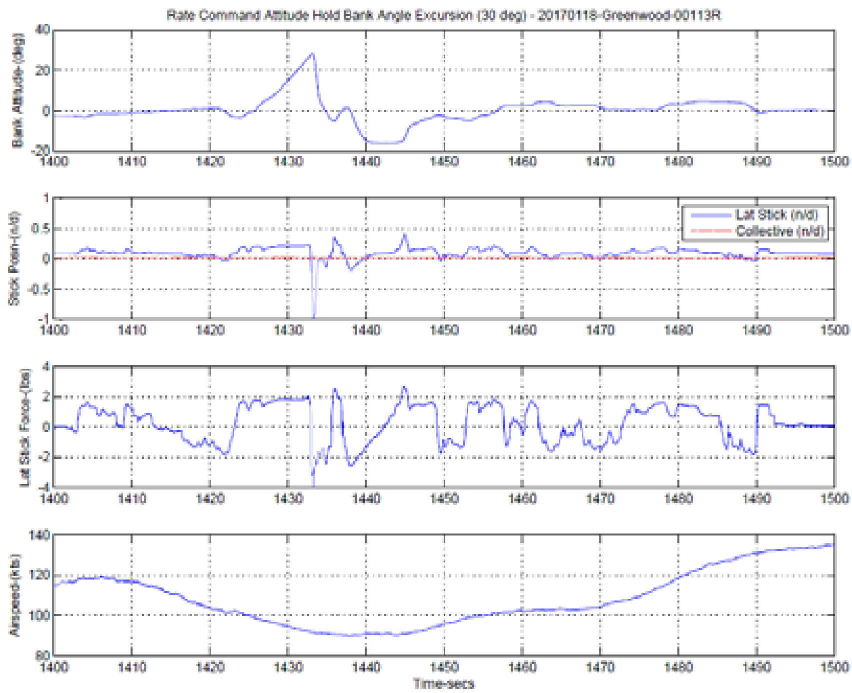


Figure 9. Typical roll excursion for run with RCAH SAS

A review of the video during this excursion showed that the pilot leaned to the left to change frequencies on the communications radio (mounted on the center console). It is seen that he applied a constant 2 lb. force on the cyclic during that time, resulting in a roll excursion of 30 degrees. Whereas such excursions were common for the RCAH SAS, there were no cases in which the bank angle exceeded 30 degrees.

Such excursions were not confined to roll, as shown in Figure 10.

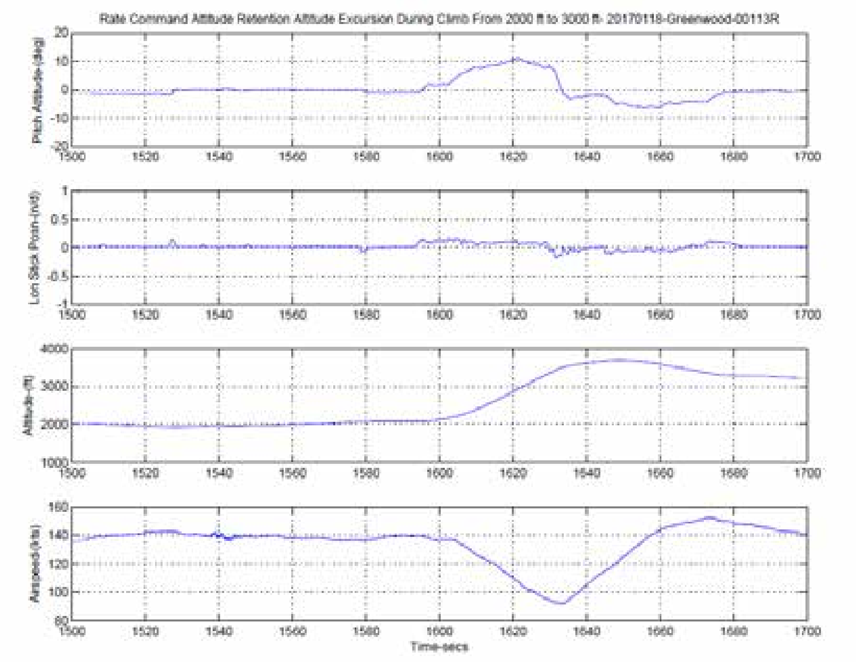
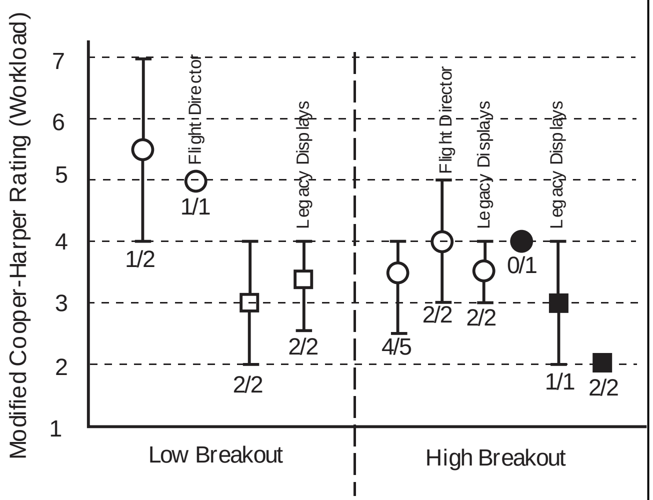


Figure 10. Large airspeed excursion with RCAH SAS

This 45-knot airspeed excursion occurred during a climb from 2000 ft. to 3000 ft. A review of the video showed that the pilot was looking away from the instruments while reviewing his clearance, and that his hand remained on the cyclic. The corresponding rapid increase in vertical speed resulted in a 700-ft. altitude overshoot. Such excursions never occurred with the other SAS types (excluding the backup SAS). The cyclic position shows a small constant displacement in pitch.

A similar event occurred during a SPIFR missed approach with RCAH in which the pitch attitude diverged to 10 degrees nose-low, resulting in a momentary excursion in vertical speed from a climb to a 2000 ft./min descent. The rest of the 47-minute run was all within desired performance, and the pilot gave a workload rating (MCH = 4) and a marginal handling qualities rating (HQR = 5) but, in the end, said it was certifiable, albeit “right on the edge.”

Figure 11 shows the workload ratings for the RCAH AdFC.



Notes:

Advanced display unless otherwise noted

No Flight Director unless otherwise noted

Low Breakout = $\pm$ 0.25 lb No deadband

High Breakout = $\pm$ 0.50 lb 1% deadband

x/y at bottom of symbol is certifiable/total

Circles = SPIFR

Squares = DPIFR

Open = light turbulence

Filled = moderate turbulence

$\sigma_H = 4$ and 5 ft/sec for DPIFR

$\sigma_H = 5$ ft/sec all SPIFR runs

Figure 11. SPIFR and DPIFR ratings for RCAH SAS

The following observations apply.

- Increasing the pitch and roll cyclic breakout from 0.25 lb. to 0.50 lb. and adding a 1% deadband had a very favorable effect on the workload ratings. The additional force required to move the cyclic had the effect of mitigating the tendency to introduce inadvertent inputs during periods of divided attention. This was done early in the program, and most runs were made with the higher breakout.
- With increased breakout and DPIFR, RCAH received very good workload ratings.
- Adding a second pilot (DPIFR) was very effective in reducing workload for the low breakout case. This demonstrated that the addition of a second pilot mitigated a strong tendency to diverge during divided attention.
- The flight director was not effective in reducing pilot workload. This is not surprising given that the problem with RCAH is divided attention, and a flight director is only useful if the pilot is looking at it.
- For SPIFR in turbulence, two evaluators rated RCAH as uncertifiable. One of those evaluators rated all non-AP configurations as uncertifiable for SPIFR, but his comments for RCAH were especially strong.

- The advanced display did not result in significantly lower workload ratings compared to the legacy displays. However, all the evaluators' comments greatly favored the advanced display.

All pilots noted that the RCAH SAS was an ideal system to fly as long as the pilot was not required to divide his or her attention away from the flying task. The pilots also noted that divergences during divided attention could be eliminated by keeping one's hand off the cyclic when looking away. Nonetheless, during high workload, they often forgot to do that on one or more occasions during a 40-minute to 1-hour run. This usually occurred during a missed approach when workload was very high while receiving a clearance to the alternate airport.

In spite of this, the workload ratings in Figure 11 do not indicate that SPIFR workload is excessive with RCAH (with increased breakout) and suggest that it should be certifiable for SPIFR (average rating less than 4.5). It is hypothesized that the pilots did not highly weigh single excursions in bank angle or airspeed during the rating process because desired performance was achieved for the rest of the 40-minute to 1-hour flight. On that basis alone, it is difficult to conclude the RCAH is not certifiable for SPIFR.

Nonetheless, the unintended excursions in bank angle and airspeed that consistently occurred with RCAH represent a fundamental deficiency for SPIFR. Some of the pilot comments that accompanied a decision to certify provide further evidence that RCAH is marginal for SPIFR. Some of the comments included: "Certifiable but right at the limit;" "Some large excursions;" "Not tolerant of divided attention, lot of attitude errors;" "Had 30- to 40-degree bank excursion. Then later had 700 ft. altitude excursion."

When making a decision not to certify RCAH, the comments all related to problems with unattended operation. Some examples are as follows: "Not certifiable as primary system due to inadvertent large attitude excursions, okay as backup;" "Workload went up dramatically while programing EFIS and writing clearances;" "Very nice—sporty—IFR not so good;" "Attitude retention better than most helicopters, but let airspeed drift down to 60 kts on the missed approach."

No such comments were made for the ACAH or ASC/RTT types of AdFC.

In conclusion, whereas the majority of the runs with RCAH were rated as certifiable, and the workload ratings are in the certifiable range (less than 4.5), the pilot comments and time history data from the simulation suggest that the divided attention deficiency is significant for SPIFR. Therefore, the proposed criterion for SPIFR in appendix A states that a small force on the cyclic may not result in a continuous divergence in pitch or roll attitude. This is not proposed as a requirement for DPIFR.

4.1.5 Flight director

The experimental methodology was to add flight director guidance to the display mix for cases rated as not certifiable. This turned out to be not applicable for ACAH or ASC/RTT. Flight director guidance was tested as a means to mitigate problems with RCAH. The data in Figure 11 indicate that the flight director did not, on average, significantly reduce pilot workload. However, there were favorable comments. One pilot, when evaluating RCAH, commented that the flight director was "a tremendous help to lower workload" and gave very good ratings (MCH/HQR = 2.5/2.5)[7].

4.1.6 Airspeed command return to trim (ASC/RTT)

This AdFC was developed to obtain insight into the concept of incorporating what are usually AP upper modes into a SAS. It is described in detail in section 8.2.3 where it is noted that it is really an airspeed rate command system (i.e., a step cyclic commands an airspeed rate).

Several iterations were accomplished to develop the final version of this AdFC.

The workload ratings for the ASC/RTT SAS are shown in Figure 12.

[7] The pilot went on to judge RCAH with flight director was not certifiable as primary for SPIFR, but okay as a backup. That comment "did not count" because he was the evaluator that rated all non-AP cases as uncertifiable.

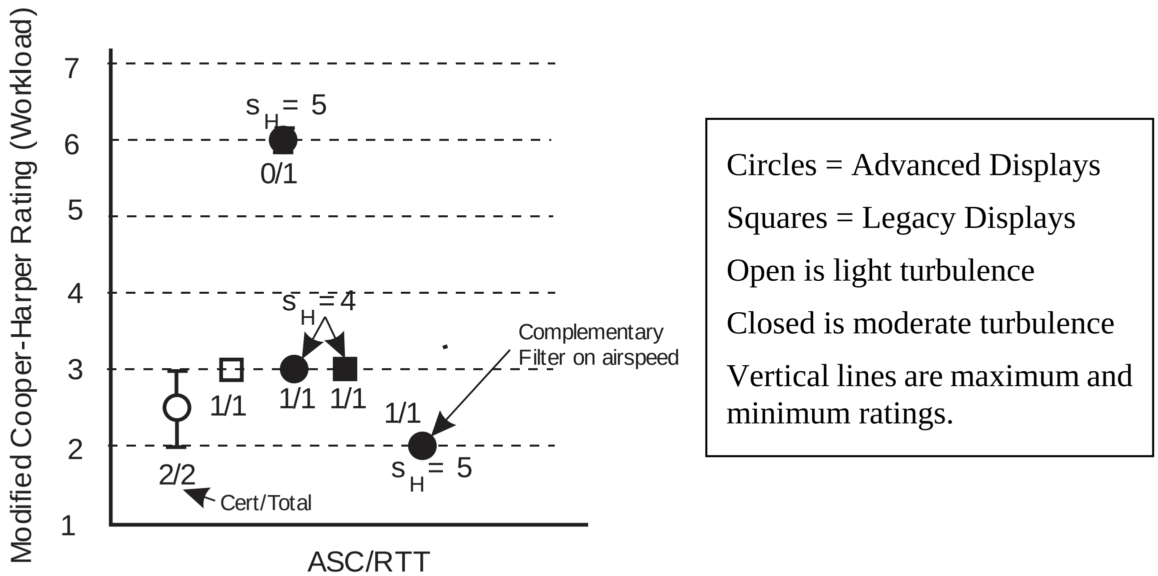


Figure 12. SPIFR workload rating for the ASC/RTT SAS

These data indicate that the workload for this AdFC is very dependent on the level of turbulence:

- For light turbulence ($s_H = 1$ ft/sec), the ratings indicate low workload.
- For moderate turbulence with $s_H = 4$ ft/sec, the workload was rated as low (MCH = 3) for one evaluation with advanced and one with legacy displays.
- For moderate turbulence with $s_H = 5$ ft/sec, the workload was rated as unacceptably high by two evaluators (MCH = 6).

A complementary filter was designed to sum lagged inertial speed with lagged airspeed (see description in section 8.2.3). This allowed heavy filtering of airspeed (T_{CF} = 10 seconds) without adding phase lag to the system. Because of the lack of remaining time, only one run was flown with this modified version of the system. The results for moderate turbulence ($s_H = 5$ ft/sec) were very good (MCH = 2, HQR = 3 and certifiable). The pilot (who earlier rated ASC/RTT at MCH = 6) noted that the pitch activity was much less, and that the airspeed holding ability was acceptable. He also noted that he never used the cyclic to control speed, electing simply to use the beep trim function to change airspeed at one knot per beep. This pilot said the workload was low, but that because of the special technique required to fly the system he would prefer (not necessarily require) that it be incorporated as a selectable mode with a more conventional SAS also available.

The main complaint was that the ability to use pitch attitude as a tradeoff between airspeed and altitude is lost with ASC/RTT. Any attempt to control altitude with pitch attitude resulted in what one pilot termed “mode confusion.” Strict adherence to the pilot technique in which cyclic controls airspeed and collective controls altitude was found to be necessary to avoid mode confusion. Finally, some pilots worried that the continuous large collective activity required to hold altitude in turbulence could have an adverse effect on the life of the engine and power train.

Using the FTR to reset the trim airspeed resulted in also re-trimming the roll attitude when ACAH was used in roll. This was found to be annoying, and pilots found it best to use beep trim for one axis and the FTR for the other.

The pilots noted that the airspeed being commanded by the SAS must be displayed on the EFIS. Otherwise, the pilot does not know what the SAS is trying to do. This is taken as a requirement for this type of SAS.

Because of the nature of this type of system, it would seem possible that any maneuver that required a constant acceleration or deceleration would be problematic. In particular, the deceleration to hover CTE was expected to produce less favorable results. However, it is shown in section 5.6 that the ratings are only slightly degraded over ACAH or RCAH (average HQR = 3.6 compared to 2.8 for RCAH and ACAH). None of the CTEs showed that ASC/RTT had a serious deficiency, and for some maneuvers it was found to be ideal (Deceleration on Glideslope and Missed Approach).

This type of system highlights the need to make a distinction between what is safe versus what is desirable. If properly designed, the ASC/RTT was found to be safe, if not ideal, as a stand-alone SAS.

4.1.7 Airspeed rate command/return to trim

As noted in the previous section, the ASC/RTT was really an airspeed rate command system. The ASRC/RTT represents a more direct way to implement airspeed rate command and is described in detail in section 8.2.4.

The primary difference between ASRC/RTT and ASC/RTT is that the former is based on unique trim (i.e., pilot must center the cyclic to set the trim point), and for the latter, the trim cyclic is a function of airspeed (resulting in effective speed stability). Specifically, cyclic position versus airspeed was zero for ASRC/RTT and 0.1 in/kt for ASC/RTT.

Because of time constraints, this system was only tested for three runs. Two pilots found it to be certifiable and the third pilot did not, saying it was the least desirable of all the AdFCs. The pilots that found it to be certifiable gave MCH/HQR = 3/3 (moderate turbulence - $\sigma_H = 4$ ft/sec) and 3/4 (light turbulence) and did not note any serious deficiencies.

The pilot that judged it to be uncertifiable rated it MCH/HQR = 4/3 (light turbulence). These ratings were surprising given the comments: "This is not a desirable system," and "Not even certifiable as a backup." This would indicate that, whereas the workload was not excessive, the pilot simply did not like the system.

4.1.8 Backup rate system (BURS)

The evaluation of the above SAS modes was accomplished as a primary system or as a backup system to an AP. For example, the RCAH SAS exhibited a deficiency that made it unacceptable as a primary system for SPIFR, but acceptable as a backup system for a SPIFR certification. (RCAH was judged to be acceptable as the primary system for DPIFR.)

One approach to dealing with primary system failures is to incorporate a simple but highly reliable rate damper as the backup following a primary system failure. The scope of this project did not allow a thorough investigation of what would be the minimum acceptable characteristics of such a backup system. However, it was possible to include one example as an exploratory study of minimum acceptable handling qualities for a backup system (i.e., a "get-home" system).

The BURS feedback gains were set to achieve Level 1 bandwidth in pitch and roll (2.5 rad/sec). However, the lack of an attitude hold function exposed the natural cross coupling between collective and roll and pitch, which increased pilot workload dramatically, as seen in Figure 13. Any collective change required a correction in pitch and re-trimming in pitch. This coupled into roll, which also required re-trimming. As a result, the trimming workload was very high[8].

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[8] A brief informal run with BURS with the force-trim-release button depressed (cyclic force gradients = 0) suggested that it was easier to fly (but still high workload).

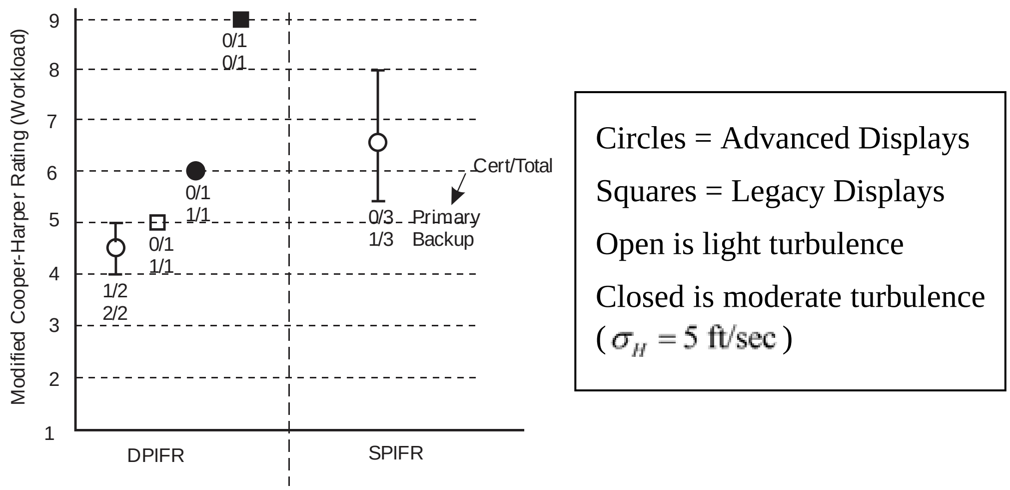


Figure 13. Workload ratings for BURS

The BURS SAS was found to be acceptable as a backup for DPIFR in light turbulence for the advanced and legacy displays. Increasing the turbulence level to moderate ($\sigma_H = 5$ ft/sec) showed that the advanced display was required for the pilot to judge the system as certifiable as a DPIFR backup. This was the only case in which the advanced display was found to have potential for certification credit for an AdFC (albeit a backup system).

For SPIFR in light turbulence, one of the three evaluators gave approval for certification as a backup, with the proviso that training would be required. One evaluator rejected it as uncertifiable as a backup with the caveat that it could be approved if credit could be given for the ability of the pilot to declare an emergency and get special handling. The third evaluator indicated that the BURS was unacceptable as a backup for SPIFR. However, that pilot flew an early version of BURS that had a roll bandwidth of 1.3 rad/sec.[9] Based on his evaluation, the bandwidth was increased to 2.5 rad/sec for all subsequent runs.

Large pitch and roll excursions were common for even the smallest amount of divided attention away from the flight controls. An example of such an excursion in a DPIFR scenario with light turbulence (Run 152) is shown in Figure 14. The workload MCH for this run was 8. A video of this event shows the pilot's attention was diverted away from the cockpit displays.

[9] The ADS-33E-PRF roll bandwidth requirement is 2 rad/sec for Level 1 and 1 rad/sec for Level 2.

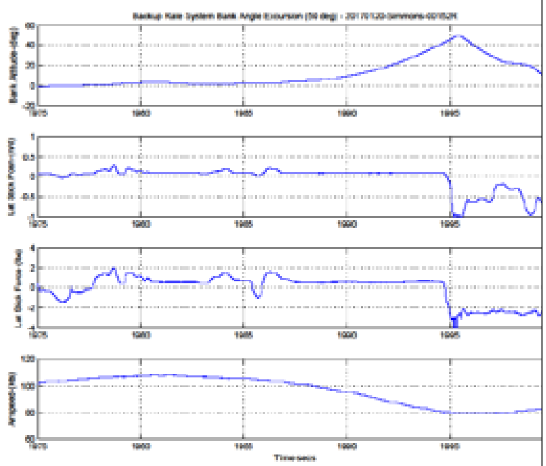
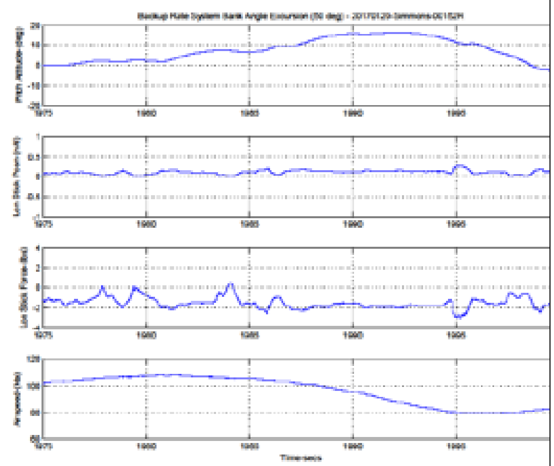
Roll Axis	Pitch Axis
	

Figure 14. Attitude divergence with BURS

These limited results provide some insight as to minimally acceptable backup systems.

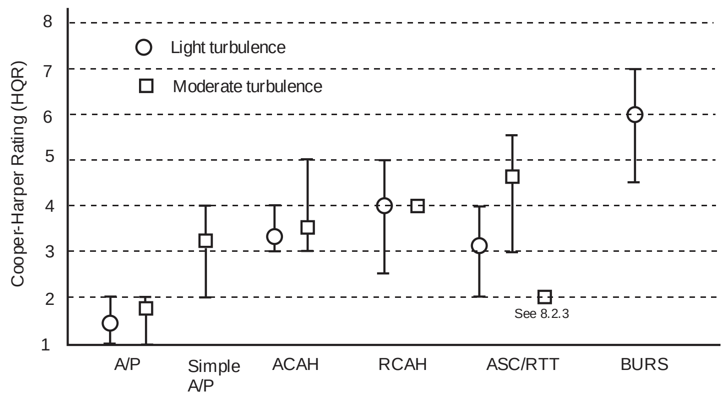
- Certification credit for advanced displays as part of a backup system solution may be viable.
- More degraded handling qualities can be tolerated for a backup system for DPIFR than for SPIFR.

4.2 Handling qualities rating (HQR)

Cooper-Harper HQRs were obtained at the end of each run. This was an unusual application of this rating scale because it is normally used to rate a single task, whereas the high-workload IFR scenarios incorporated a series of tasks. Desired and adequate performance limits were established for each subtask (e.g., altitude within 100 ft. for desired and glideslope within one dot). The rating scale and pilot briefing on use of the scale is given in section 7.

The averaged HQRs for SPIFR are shown for each AdFC as a function of turbulence level in Figure 15. These data lump together the effect of legacy and advanced displays.

For all plots, the upper end of the vertical line is the maximum HQR, and the lower end of the vertical line is the minimum HQR. The symbol is the average HQR.



Circles = Advanced Displays, Squares = Legacy Displays, (Open is light turbulence, Closed is moderate turbulence)

Figure 15. Summary of SPIFR HQRs

The workload rating results are very similar to the modified Cooper-Harper workload ratings in Figure 4. A detailed breakdown of the HQRs for each tested SAS is shown in Figure 16.

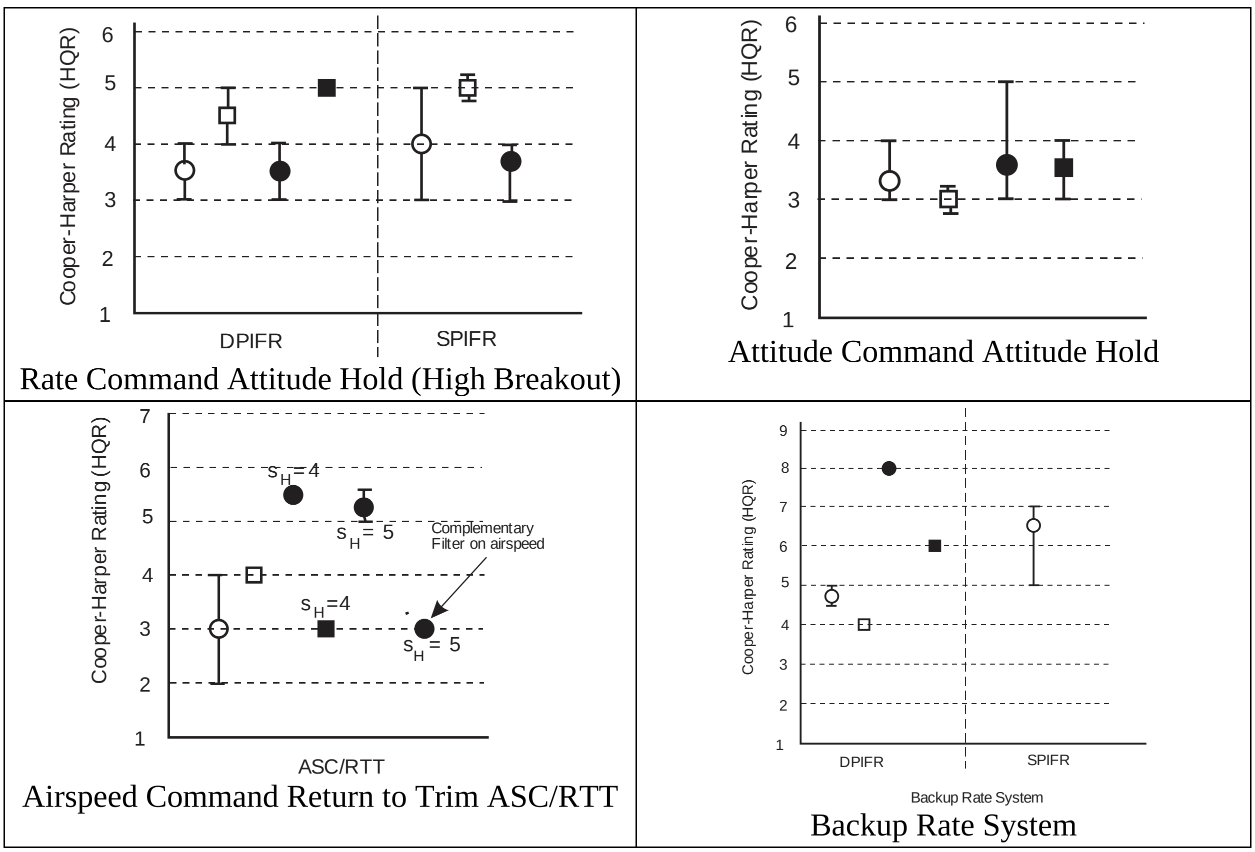


Figure 16. HQRs for tested AdFC SAS systems

The conclusions drawn in section 4.1 for the workload ratings apply to the HQRs, with the following additional comments:

- The handling qualities for the RCAH SAS were rated consistently better with the advanced displays than the legacy displays. That was not the case for the other AdFC types.
- For the single case in which ACAH was assigned a workload rating of 7, the HQR was assigned a 3, indicating that the reason for high workload for that run was not a handling qualities deficiency.
- The two workload ratings of 6 in moderate turbulence ($\sigma_H = 5$ ft/sec) for the ASC/RTT system were accompanied by HQRs of 5 and 5.5, suggesting a handling qualities deficiency that only existed in high levels of turbulence. With the improved version, the workload rating improved to 2 and the HQR to 3, suggesting that the complementary filter successfully eliminated the turbulence-induced handling qualities deficiency for this AdFC.

4.2.1 Longitudinal static stability

Longitudinal static stability was not a subject of this simulation program. It is useful to compare the longitudinal static stability of the tested configurations with the proposed minimum performance criteria in appendix A.

- The RCAH AdFC by definition has zero longitudinal static stability ($d\delta / dV = 0$). This created the possibility that RCAH would lead to a potential for large airspeed deviations during periods of divided attention, and that was the case for SPIFR but not for DPIFR.
- The ACAH AdFC had $d\delta / dV = 0.022$ in/kt and a force gradient of 4 lb/in. so that $dF / dV = .08$ lb/kt. ACAH was found to be acceptable for SPIFR, which is consistent with the NASA data in appendix B that support the proposed criterion in appendix A, which only requires that $d\delta / dV \geq 0$.

  The current 14 CFR Part 29 B29.4 requires that “stick force must vary with speed so that any substantial speed change results in stick forces clearly perceptible to the pilot.” What is “clearly perceptible” is a matter of opinion, which could vary among FAA evaluators. However, it is not likely that that a gradient of .08 lb/kt would meet the requirement. A requirement for compliance for static stability for an ACAH AdFC could lead to unnecessary band aids to the AdFC that would actually degrade the handling qualities.

- The ASC/RTT AdFC had $d\delta / dV = 0.1$ in./kt for small deflections (less than 0.3 inch), and 0.025 in./kt from 0.3 inch to 0.4 inch. For larger deflections, the airspeed continues to diverge, so $d\delta / dV = 0$, thereby not meeting the 14 CFR Part 29 Appendix B requirement for static stability. One of the enhancing features of this AdFC was the accuracy of airspeed control and the ability to hold airspeed during periods of divided attention. There were no cases in which airspeed control was anything but good for all evaluations with ASC/RTT.

These results emphasize that any requirement for static stability, other than it should be equal to or greater than zero, be limited to response types to which it has valid handling qualities implications. This is another way of saying that the existing requirements for static stability in 14 CFR parts 27 and 29 Appendix B are only applicable for a limited class of AdFC. The requirements in appendix A are updated to reflect this finding.

5 Civil task elements (CTEs)

The CTEs are included in the proposed certification process as an overall check on the quantitative criteria. This proposed certification procedure is identical to the procedure to comply with the military rotorcraft handling qualities criteria in ADS-33E-PRF, in which pilots are required to fly and assign Cooper-Harper HQRs for "mission task elements" or MTEs. The difference being that the CTEs are based on tasks that are consistent with civilian rotorcraft flight profiles.

The goal is to ensure that the subjective evaluation part of the certification process is consistent between and among Aircraft Certification Offices (ACO) and the Rotorcraft Directorate[10]. This is done by constraining the subjective evaluations of handling qualities to highly defined maneuvers with specified desired and adequate performance limits.

The CTEs and associated performance limits described in this section were flown and modified by the four pilot subjects and some guest pilots from the FAA and industry. All of the evaluators agreed that the tasks should be demanding to expose handling qualities deficiencies. For example, the LPV approach CTE that evolved during this simulation requires that the pilot fly off glideslope and localizer and then recapture within specified airspeed, space, and time limits.

[10] It is understood that the FAA is reorganizing, and the concept of ACOs and directorates is being eliminated. The intent here is to ensure that certification requirements are identical across all FAA pilots and organizations.

The pass-fail limits were discussed during the debriefs, and there was a general opinion that the HQR should be no worse than 5 for a pass. This was felt to be consistent with the FAA mandate to ensure that the system is safe, but not necessarily optimal.

The correlation between HQRs and decision to certify taken during the high-workload evaluations is shown in Figure 17.

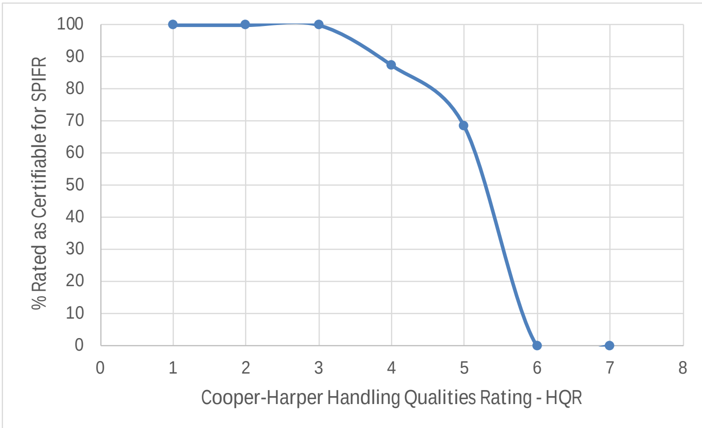


Figure 17. Correlation between decision to certify and Cooper-Harper HQR

This correlation confirms that an HQR of 5 is appropriate as a pass/fail criterion for the CTE evaluations.

It is not intended that CTEs be accomplished for a large number of test conditions. Rather, it is suggested that a few worst-case conditions be selected (e.g., aft c.g.).

Experience has shown that a valid average HQR requires at least three evaluation pilots (and more is better).

The evaluation pilots assigned Cooper-Harper HQRs just as they would when using the CTE for certification credit. The average, maximum, and minimum HQR assigned to each of the tested CTEs and SAS types are shown in Figure 18.

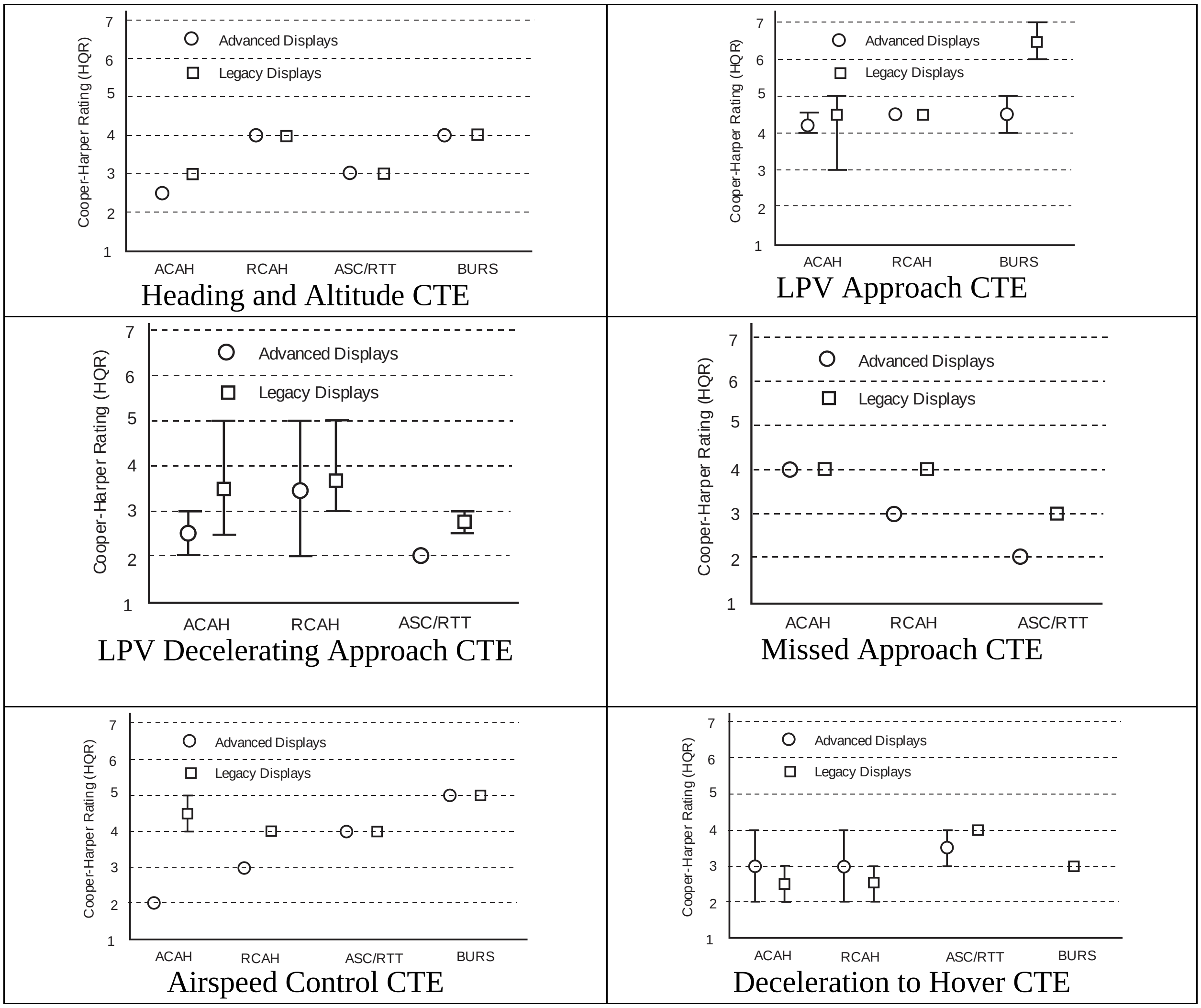


Figure 18. HQR data for CTEs

A comparison of the HQRs for the CTEs with those obtained during the high-workload IFR scenarios provides some interesting insights.

- BURS was found to be acceptable for SPIFR (albeit barely for the LPV task) for the CTEs but highly unacceptable when high levels of divided attention were introduced. This can be seen by comparing the HQRs for BURS in Figure 18 with those in Figure 16. This shows the importance of compliance with the quantitative criteria in which BURS would fail.
- The RCAH AdFC was found to be acceptable for all CTEs, whereas it was found to be unacceptable for SPIFR during the high-workload IFR evaluations. This would be caught in the quantitative criteria that require no divergence when the cyclic is displaced a small amount (i.e., for cases in which the pilot inadvertently leaves his or her hand on the cyclic during periods of divided attention).

5.1 Heading and altitude control

a. Objective

Verify good control of heading and altitude

b. Description of Maneuver

Accomplish 180-degree heading change while in a climbing turn to gain 500 ft. Use bank angle for standard rate turn (3 deg/sec). Hold new heading and altitude for 30 seconds, followed by 180-degree heading change in opposite direction while descending 500 ft. Hold new altitude and heading for at least 30 seconds. Accomplish at VY and VAPP. Make all climbs and descents at 500 ft./min.

c. Desired and Adequate Performance

DESIRED PERFORMANCE	
• Maintain target airspeed:	± 5 kts
• Capture and hold heading:	± 5 deg
• Maintain altitude within:	± 50 ft
ADEQUATE PERFORMANCE	
• Maintain target airspeed:	± 10 kts.
• Capture and hold heading:	± 10 deg
• Maintain altitude within:	100 ft

Rule of thumb: Standard rate turn bank angle = groundspeed divided by 10 and add 7 degrees.

5.2 LPV approach

a. Objective

Investigate ability to track glideslope and localizer and speed control.

b. Description of Maneuver

Start level on localizer and 100 kts airspeed outside the final approach fix (FAF)[11]. After established on the localizer and glideslope, and inside the FAF, turn to a heading of 30 degrees off the localizer course, and establish zero vertical speed to achieve two dots left or right and two dots high. In most cases, the localizer will reach two dots before the glideslope reaches two dots. In that case, turn to parallel the final approach course until the glideslope deviation reaches two

[11] The terms localizer and glideslope are intended to be applicable to RNAV glidepath and approach course.

dots. Initiate a correction back to the glideslope and localizer, and start a timer. Achieve a stable tracking solution on localizer and glideslope with 1/4 dot, and stop the timer[12]. If the glideslope reaches two dots before the localizer reaches two dots, establish a 500 ft./min rate of descent (3-degree flight path angle) until the localizer reaches two dots.

If the glideslope angle is greater than 4 degrees, it is acceptable to reduce the glideslope deviation to a value that does not result in entering autorotation as long as that deviation does not exceed one dot.

c. Desired and Adequate Performance

DESIRED PERFORMANCE	
• Maintain target airspeed:	± 10 kts
• Prior to glideslope intercept, maintain altitude within:	± 50 ft
• Maintain glideslope and localizer within:	1/2 dot
• Accomplish capture maneuver within:	1 minute
ADEQUATE PERFORMANCE	
• Maintain target airspeed:	± 15 kts
• Prior to glideslope intercept, Maintain altitude within:	± 100 ft
• Maintain glideslope and localizer within:	1 dot
• Accomplish capture maneuver within:	1.5 min

Airspeed excursions may exceed noted values by 5 kts in moderate turbulence.

This proved to be a challenging CTE, and both the ACAH and RCAH SAS types were rated as barely acceptable. The BURS was found to be acceptable with the advanced displays and not acceptable for the legacy displays. The ASC/RTT was not tested for this CTE.

5.3 ILS or LPV decelerating approach

a. Objective

Demonstrate ability to accomplish a decelerating approach while tracking the glideslope.

[12] It is intended that the capture be accomplished within ¼ dot prior to stopping the time. Subsequent tracking should be within the limits specified in the table.

b. Description of Maneuver

Start the maneuver in level flight on the localizer outside the FAF at VH. When established on glideslope and localizer, decelerate to 70 KIAS or Vmini, whichever is less, in 1 minute or less. Terminate the maneuver when stabilized on the localizer and glideslope at 70 KIAS (or Vmini).

c. Desired and Adequate Performance

DESIRED PERFORMANCE	
• Initial airspeed VH:	± 5 kts
• Final airspeed 70 kts:	5 kts ft
• Maintain glideslope and localizer within:	1 dot
• Prior to glideslope intercept maintain altitude within:	100 ft
ADEQUATE PERFORMANCE	
• Maintain final target airspeed:	± 10 kts
• Prior to glideslope intercept, maintain altitude within:	± 200 ft
• Maintain glideslope and localizer within:	2 dots

With the advanced displays, all the SAS types were acceptable, although one pilot rated RCAH a 5. The other two pilots rated this system as 3 and 4, for an average HQR of 3.5. This illustrates why at least three evaluators should be used. The ACAH and ASC/RTT SAS types were clearly optimal for this task. The ratings were slightly degraded for the legacy displays (but still acceptable).

5.4 Speed control task

a. Objective

Evaluate airspeed control.

b. Description of Maneuver

From trimmed level flight at 100 kts, decelerate to 70 KIAS, and retrim for zero force. Then accelerate to 100 kts and retrim for zero force. Finally, accelerate to 130 KIAS and retrim.

c. Performance Standards

DESIRED PERFORMANCE	
• Maintain altitude within:	± 100 ft
• Trim hands-off at target airspeed within:	± 5 kts
• Change from one trim speed to the next within:	30 sec
• Maintain heading within:	± 5 deg
ADEQUATE PERFORMANCE	
• Maintain altitude within:	± 200 ft
• Trim hands-off at target airspeed within:	± 10 kts
• Change from one trim speed to the next within:	1 min
• Maintain heading within:	± 10 deg

The ACAH SAS resulted in a dramatically different result for the advanced and legacy displays. For the advanced display, ACAH was the favored SAS with the advanced display (HQR = 2) and was barely acceptable for the legacy display.

5.5 Missed approach task

a. Objective

Test effect of large collective changes in a high-workload task.

b. Description of Task

Following an ILS approach to Decision Height (DH), 200 ft. AGL, initiate a climb on runway heading to 500 feet AGL by increasing power to maximum torque and pitch to maintain VY. If that results in a rate of climb greater than 2000 ft./min, use an airspeed that results in approximately 2000 ft./min rate of climb.

At 500 feet AGL turn right (or left) to a heading of 90 degrees from runway heading. Level off at 1000 feet AGL and accelerate to 100 kts. When steady at 100 kts, 1000 ft. AGL, and on heading, initiate a climbing right (or left) turn to a heading of 180 degrees from runway heading and climb to 2000 ft. AGL as rapidly as possible. Level off at 2000 ft. AGL while maintaining 100 kts. When established at 100 kts, 2000 ft., AGL and on heading, accelerate to VH.

c. Performance Standards

DESIRED PERFORMANCE	
• Maintain altitudes within:	± 100 ft
• Maintain target airspeeds within:	± 10 kts
• Maintain target heading within:	10 deg
ADEQUATE PERFORMANCE	
• Maintain altitudes within:	± 200 ft
• Maintain target airspeeds within:	± 15 kts
• Maintain target heading within:	20 deg

The ASC/RTT SAS was favored more than the others for this task. That is because the pilots simply had to pull power, while the SAS held speed, and the helicopter initiated a climb to execute the missed approach. ACAH and RCAH were also acceptable, with a one HQR improvement seen with the advanced display compared to the legacy display.

5.6 Deceleration to hover

a. Objective

Demonstrate ability to smoothly decelerate from forward flight to hover.

b. Description of Task

From an altitude of 300 ft. AGL and an airspeed of 100 kts, decelerate to hover over a defined point on the ground. Accomplish this maneuver at a nominal approach angle of approximately 3 degrees and an approach that is near the maximum achievable (steep approach).

c. Desired and Adequate Performance

It is difficult to put limits on desired and adequate performance because airspeed is constantly changing, and the flight path angle is determined visually by the pilot. Nonetheless, the evaluation pilots said they knew when they were on the desired glidepath and had no problem providing HQRs for this task (see Figure 17).

Some of the pilots noted a need for good peripheral vision.

This task was accomplished almost entirely looking outside, so display type was not expected to be a factor and in fact was not. All SAS types were found acceptable for this task. The pilots noted some issues with ASC/RTT regarding having to trim continuously, but it was not rated low enough to be unacceptable.

6 Summary of results

The results of this study are summarized as follows.

1. The seven IFR scenarios used in this experiment were judged by all the subject pilots to result in very high workload, and required significant divided attention away from control of the helicopter.

2. The tendency for the RCAH SAS to diverge if the pilot left his hand on the cyclic during periods of divided attention was judged to be a deficiency of sufficient magnitude to disallow this characteristic for SPIFR. The workload with RCAH in pitch and roll was found to be acceptable for dual-pilot IFR (DPIFR). In fact, RCAH was found to be highly desirable as long as the pilot could focus his attention on the flying task.

3. The ACAH SAS was found to be acceptable for SPIFR in light and moderate turbulence. A bandwidth of 2.5 rad/sec in pitch and roll was found to be necessary to ensure low workload.

4. A three-axis (pitch, roll, and yaw) AP resulted in low workload for SPIFR in light and moderate turbulence by all pilots. One of the three pilots indicated a need for a go-around button on the collective.

5. A simplified three-axis AP with only heading hold and altitude hold was found to be certifiable for SPIFR. However, it was noted that the workload associated with continuously setting the heading bug and engaging and disengaging altitude hold was a problem. One pilot voiced a preference for the ACAH SAS over the simplified AP.

6. An airspeed-command/return-to-trim (ASC/RTT) SAS was implemented and found to be acceptable with the following caveats:

   a. A special pilot technique was found to be necessary—use collective to control altitude and cyclic to control airspeed. Any attempt to hold altitude with cyclic resulted in "mode confusion" problems.

   b. Increasing turbulence from $\sigma_H = 4$ ft/sec to $\sigma_H = 5$ ft/sec caused a significant increase in workload and degradation in handling qualities for the ASC/RTT AdFC.

   c. The pitch attitude excursions to hold airspeed resulted in excessive workload to hold altitude with collective with the turbulence set to $\sigma_H = 5$ ft/sec. This was alleviated by using a complementary filter between inertial speed and airspeed.

d. When item b was not a factor (i.e., lower turbulence), the airspeed SAS resulted in low workload. Nonetheless, the pilots expressed a desire that a more basic SAS not requiring a special pilot technique be available as a selectable mode.

7. A simple backup rate system (BURS) was found to be unacceptable as a backup system by all of the pilots for SPIFR, even though it had Level 1 bandwidth. Three of four pilots found the BURS acceptable as a backup for DPIFR. However, one pilot said the workload was unacceptable even as a DPIFR backup (encountered a 50-degree bank angle excursion). The primary problem was due to cross coupling that occurs without an attitude hold function (or control crossfeeds).

8. These results indicate a need for a better understanding of what is minimally acceptable for a backup system. A study of minimally acceptable characteristics for a backup system was beyond the scope of this project. The need for such work is to answer what is acceptable as a backup system when the Functional Hazard Assessment and System Safety Analysis indicate that a failure of the primary AP/SAS does not allow continued IFR flight without a SAS or AP.

9. Advanced displays were found to be highly desirable but did not reduce workload sufficiently to justify certification credit for a primary system. However, there was evidence that the advanced display could reduce workload to an acceptable level for a backup system. The pilots especially liked the flight path symbol, floating waypoints, expanded pitch scale, and aural warnings. The pilots were not allowed to use the "highway in the sky function."

10. Six CTEs were developed and refined.

7 Pilot questionnaire

A Step 1—Provide a pilot rating for overall workload using the MCH shown in Figure 19. The following ground rules apply:

- Half ratings are OK except for 3.5 and 6.5.
- For high-workload divided-attention tasks, some errors/exceedances of desired performance are expected. Do not base a rating on a single error, but rather if there are many errors, and the level of difficulty to recover from an error. One or more errors that could lead to loss of control are expected to be rated very poorly.
- Always work the scale from lower left to upper right. It is very important to treat the scale as a decision tree.

- Provide comments to backup ratings that are worse than 4 to describe the deficiency. If possible, estimate what would be required to minimize or eliminate the deficiency.

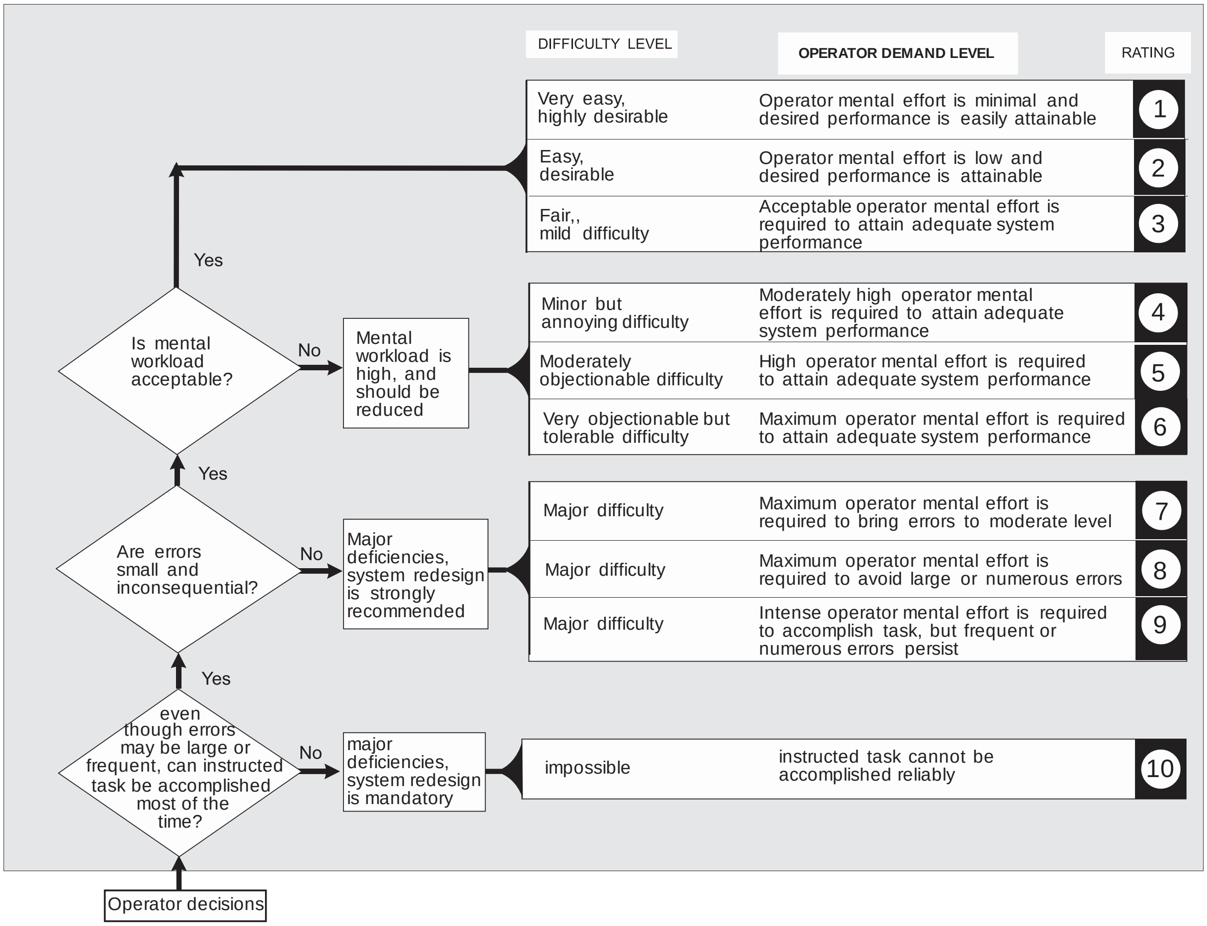
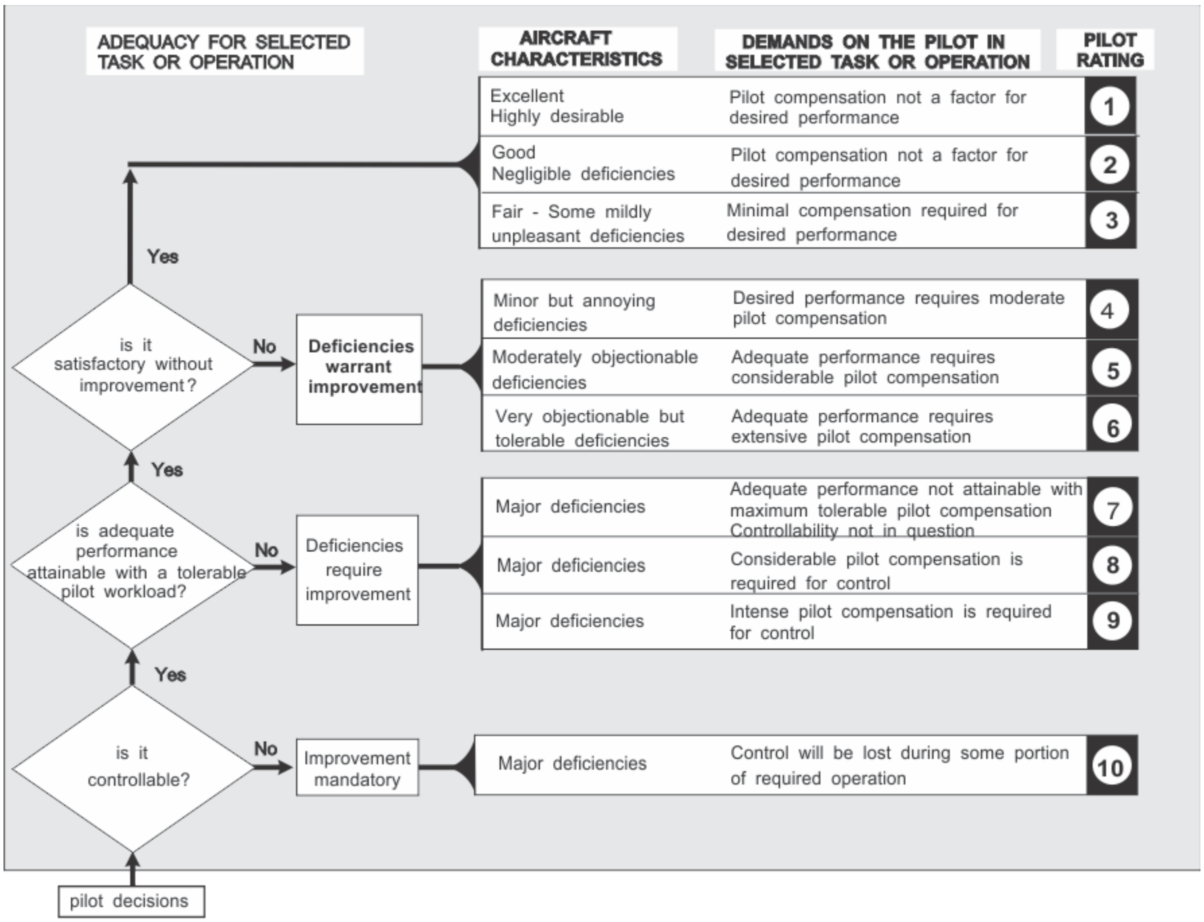


Figure 19. Modified Cooper-Harper scale

B Step 2—Provide a pilot rating for the AdFC flight control system using the Cooper-Harper HQR Scale shown in Figure 20. Use the same ground rules as above.

- Desired performance is defined as:
  - Hold altitude within 100 feet.
  - Maintain glideslope and localizer within one dot for approaches.
  - Maintain crosstrack error within one dot for enroute and terminal navigation.
- Adequate Performance is defined as:
  - Hold altitude within 200 feet.

- Maintain glideslope and localizer within two dots for approaches.
- Maintain crosstrack error within two dots for enroute and terminal navigation.



Cooper Harper Handling Qualities Rating (HQR) Scale (Ref. NASA TND 5153)

Figure 20. Cooper-Harper HQR scale

C Step 3—Is this configuration certifiable for the IFR scenario that you just completed? Assume that this is the only available flight control system.

- Yes or no
- If no, what is your primary reason(s) to reject it?

D Step 4—If not certifiable as a primary flight control system, is this configuration certifiable as a backup system?

8 Detailed SAS configurations

High-level block diagrams are presented to show how each of the simulated AdFC systems functioned. The control laws were simulated in Simulink® during the simulation. The Simulink diagrams are considerably more complex than what is shown here.

8.1 Cyclic shaping

The command path shaping in pitch and roll for both the sidestick and center stick is shown in Figure 21.

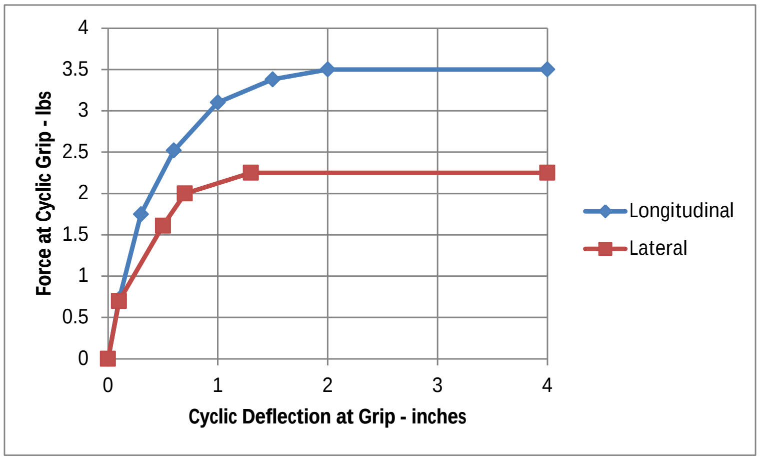


Figure 21. Cyclic shaping for sidestick and center stick

The maximum throw for both pitch and roll for the sidestick is ±3 inches and, for the center stick, ±4 inches.

This nonlinear shaping was found to be significantly better than linear shaping.

The breakout for each cyclic is 0.25 lb. in each direction for all AdFCs except for RCAH and rate command attitude retention (RCAR) where it was increased to 0.5 lb.

8.2 Longitudinal FCS

8.2.1 Attitude-command-attitude-hold (ACAH)

Where the cyclic position is normalized to unity at full travel in each direction for both the sidestick and center stick.

Pressing the FTR button resets the zero position of the cyclic force gradient shown in Figure 22.

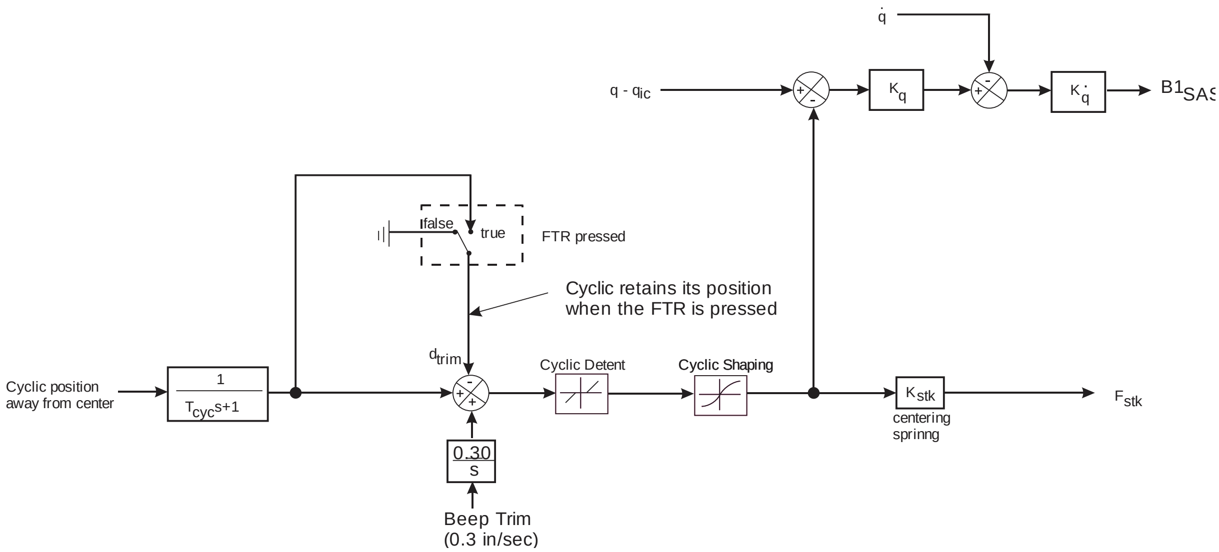


Figure 22. ACAH AdFC block diagram

Actuating the beep trim coolie-hat button causes the cyclic to move at 0.30 inches per second.

The first order lag on the cyclic input (T_{cyc}) was used to adjust the pitch attitude bandwidth to equal 2.5 rad/sec (slightly above the Level 1 boundary of 2 rad/sec). This low pass filter was used for all the AdFC configurations to tailor the bandwidth to 2.5 rad/sec in pitch and roll (Level 1 boundary is 2 rad/sec).

There was no cyclic dead-zone for ACAH.

Breakout was 0.25 lb for center and side sticks for all response types except for RCAH, which was increased to 0.5 lb on 9/1/2016.

$K_q = 1.0$ deg/ sec/ deg (Ktht)
$K_{\dot{q}} = -1.0$ deg/ deg/ sec (KthtDot)

T_{cyc} = 0.53 sec—to get bandwidth = 2.5 rad/sec ($T_{cyc}Th_{Secs}$)

T_{cyc} = 0.85 sec—to get bandwidth = 2.0 rad/sec

Stick shaping function is a linear gain = 35

Characteristics of pitch attitude response to longitudinal cyclic input for the longitudinal ACAH AdFC shown in Figure 23.

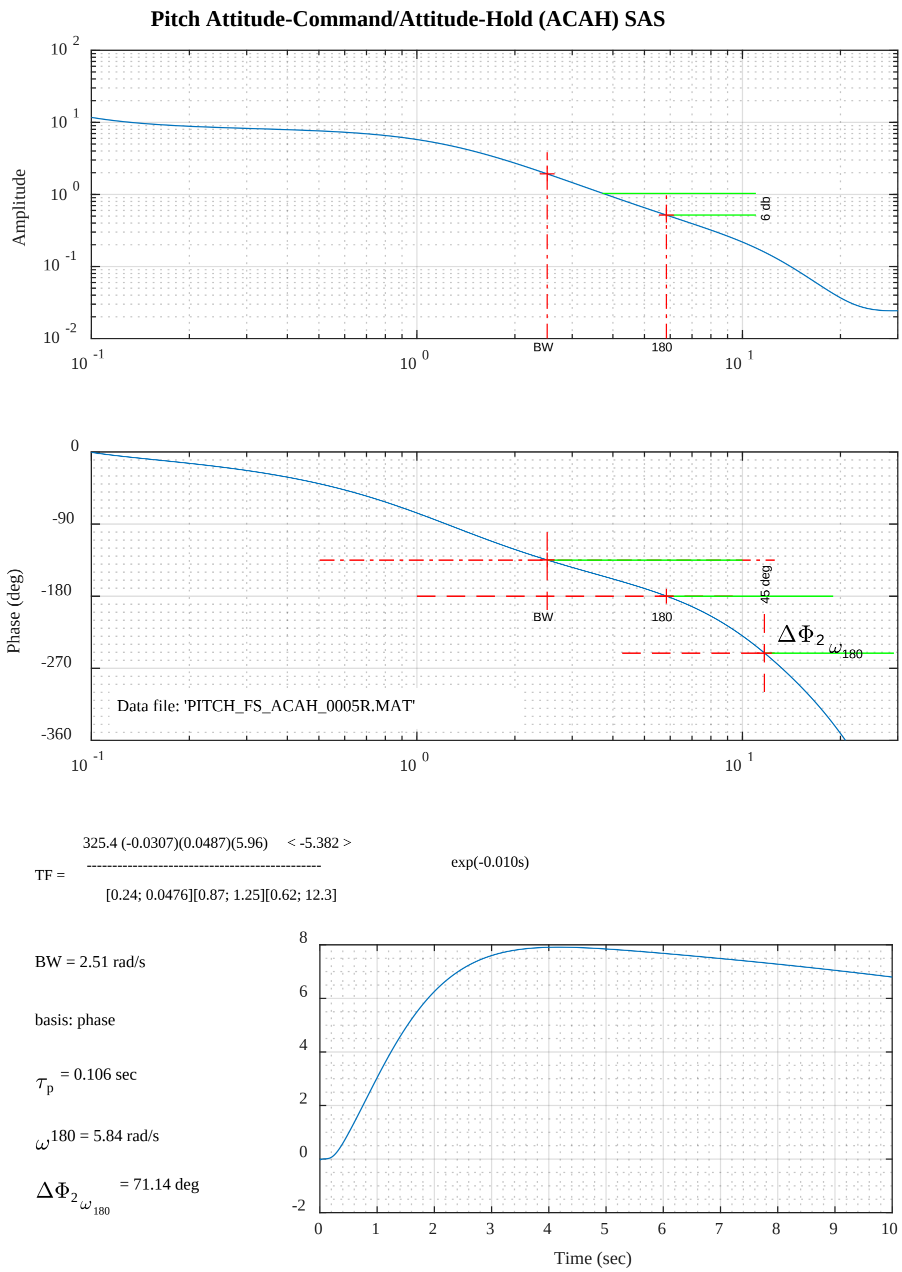


Figure 23. Pitch attitude frequency response and step input time response

Criteria for disturbance rejection have taken two forms: 1) time history of return to trim following a disturbance and 2) Bode plot that defines the frequency below which disturbances are rejected by the flight control system. Both are described in Figure 24, but only the time domain criterion is included in appendix A.

The frequency domain disturbance criterion is defined in appendix B (disturbance rejection bandwidth is defined when the pitch attitude magnitude curve is 3dB below the 0dB line).

ACAH pulse responses at 100 and 140 knots are shown in Figure 25 and Figure 26, respectively.

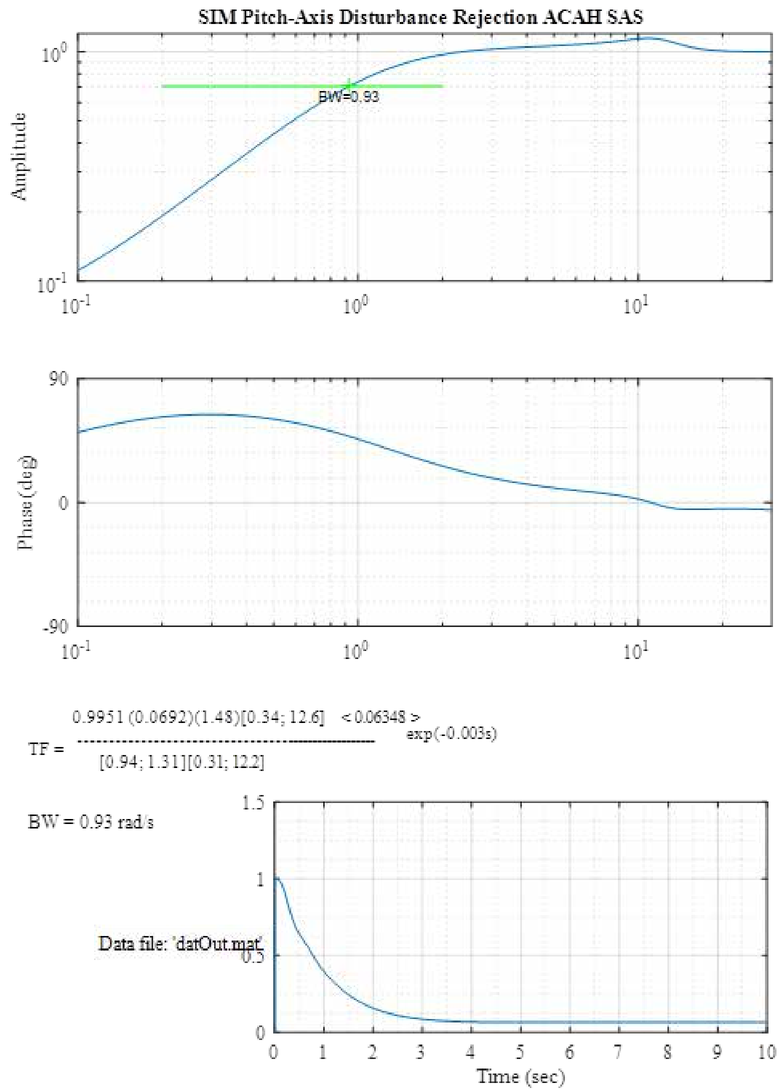


Figure 24. Pitch attitude disturbance rejection and attitude to initial condition offset

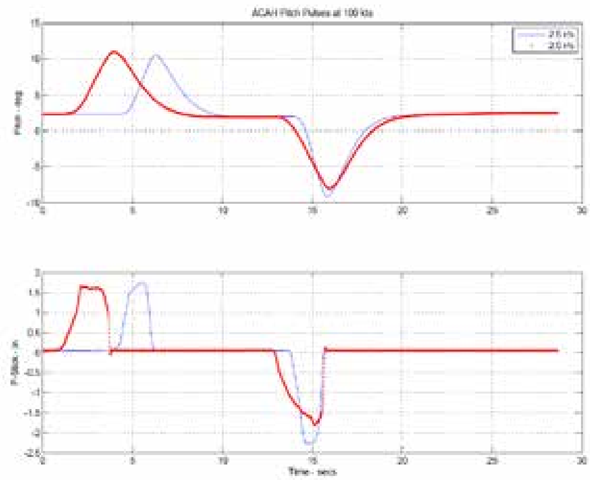


Figure 25. ACAH pulse response at 100 kts

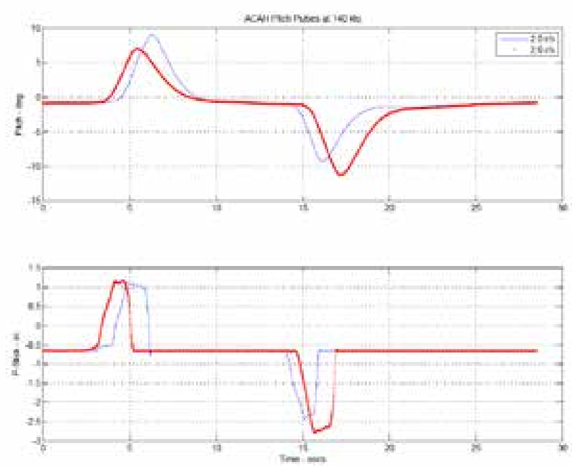


Figure 26. ACAH pulse response at 140 kts

8.2.2 Rate command attitude retention

During the Phase-A testing, RCAR RCAH AdFC was achieved by inserting an integrator in front of the ACAH system. K_q was increased from 1.0 to 2.0 in an attempt to compensate for the additional lag caused by the integrator. This resulted in a pitch attitude bandwidth of 1.8 rad/sec (i.e., less than Level 1).

The cyclic breakout was increased from 0.25 lb to 0.5 lb in pitch and roll during Phase-A testing.

For Phase-B testing, the architecture is changed to a pitch-rate command attitude-retention (RCAR) system. This eliminates the above-mentioned integrator allowing the bandwidth to be set at the target 2.5 rad/sec. The RCAR block diagram is shown in Figure 27.

The cyclic deadband was increased from zero for the other AdFCs to 4% when RCAR was active to minimize the effect on unintended inputs to the cyclic when looking away from the flight instruments.

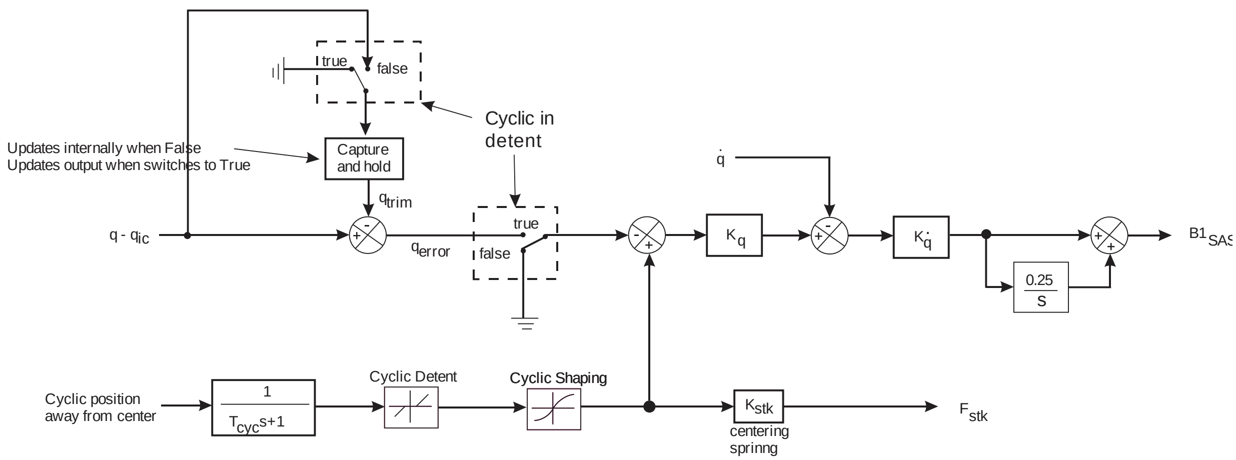


Figure 27. RCAR block diagram

The pitch attitude feedback is set to zero when the cyclic is out of detent. When the cyclic is returned to detent, the capture and hold function stops updating and outputs the last value of pitch attitude as the trim value. RCAR is functionally the same as RCAH.

The system parameters are as follows:

$K_q = 1.0\ \text{deg/sec/deg}$ (KthtRCAR)

$K_{\dot{q}} = -0.4\ \text{deg/deg/sec}$ (KthtDotRCAR)

T_{cyc} = 0.085 sec – to get bandwidth = 2.5 rad/sec (TcycThSecs)

The parallel integrator on the output of the control law was required to accurately hold the trim pitch attitude during collective or airspeed changes.

Stick shaping function is a linear gain = 25.

Cyclic breakout = 0.50 lb.

Characteristics of pitch attitude frequency response to cyclic for RCAR AdFC is in Figure 28.

The disturbance rejection bandwidth for RCAR in pitch is 0.85 rad/sec as shown in Figure 29.

The bandwidth data for RCAR are shown in Figure 30.

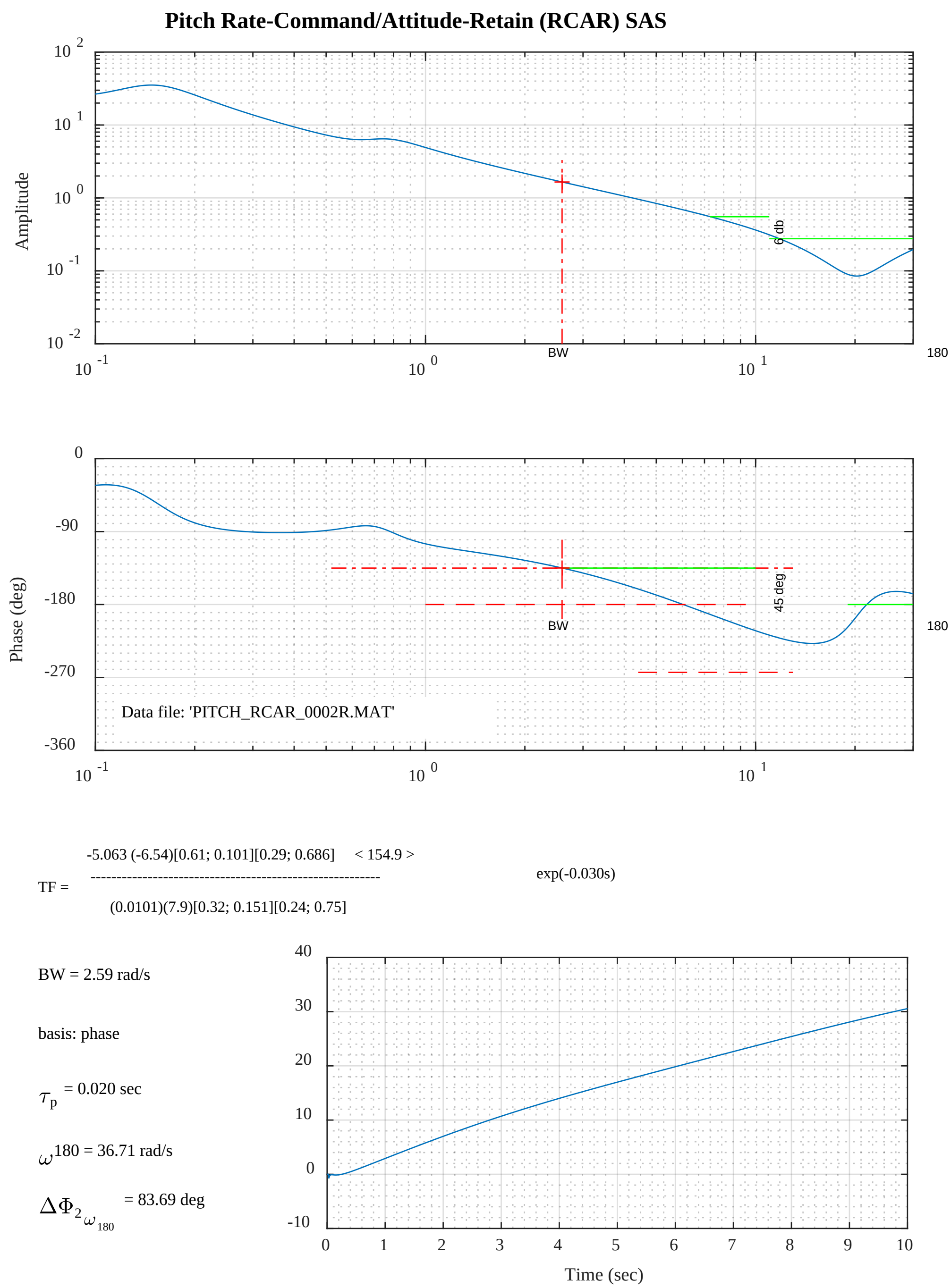


Figure 28. Pitch attitude frequency response to cyclic and step input time response

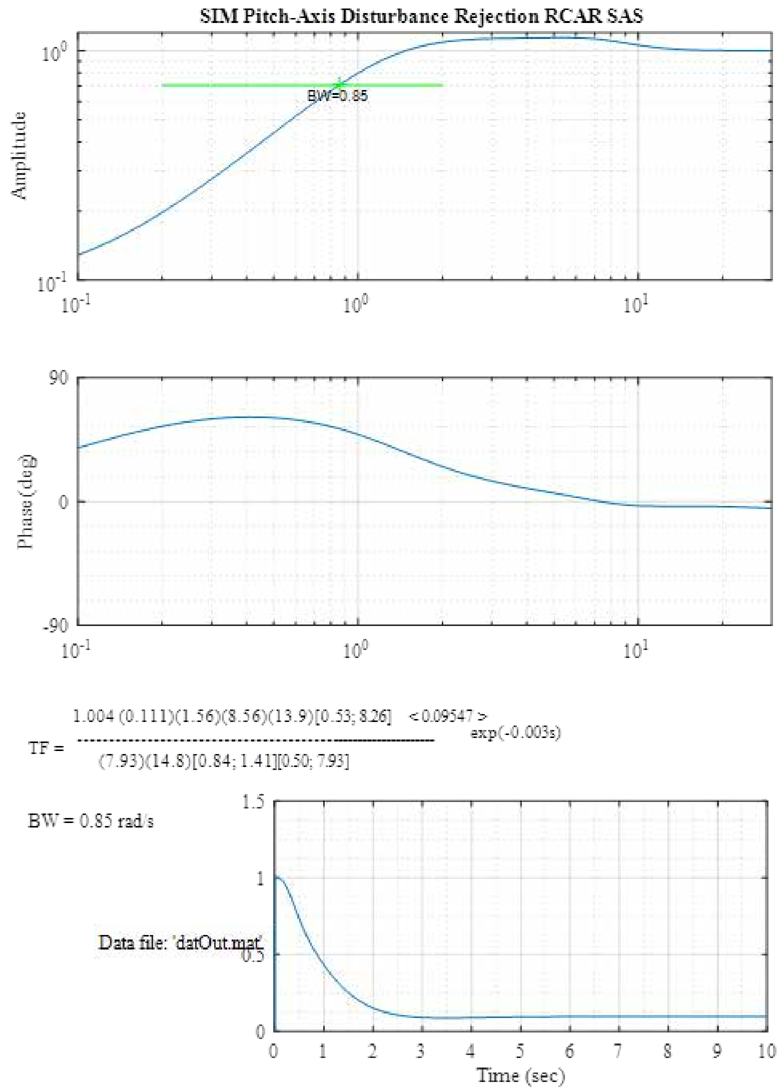


Figure 29. Pitch attitude disturbance rejection and attitude to initial condition offset

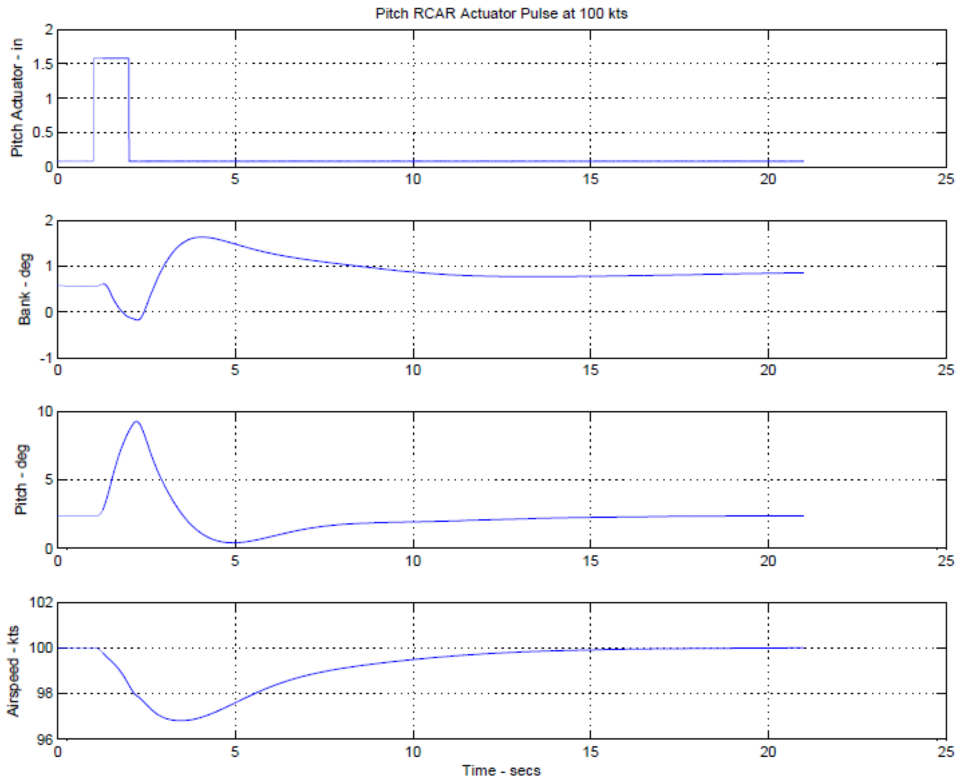


Figure 30. RCAR response to pulse input to actuator

8.2.3 Airspeed command return to trim (ASC/RTT)

For this type of AdFC, moving the cyclic out of detent results in an airspeed change that is proportional to cyclic displacement.

- Trimming with the FTR button results in a change in the airspeed reference and recentering the cyclic zero-force reference to the current cyclic position. The trim airspeed is reset by pressing and releasing the FTR button.[13]
- Using the beep trim causes the airspeed reference to change by 1 kt/beep, but has no effect on the trim cyclic position.

[13] For original design, the reference airspeed and cyclic position could only be reset if the rate change in airspeed was equal to or less than 2 kt/sec. This limitation was to prevent an abrupt pitch response if the pilot re-trims while airspeed is changing rapidly. If the trim is not reset, releasing the cyclic resulted in a return to the original trim airspeed. This logic was deleted during checkout with motion. It was found to increase workload when pilot expected new trim and did not get it. Further, deleting it did not cause a transient event with trimming while airspeed was changing rapidly.

- Holding the FTR button down removes the force on the cyclic, but has no effect on trim airspeed until the button is released.

The block diagram is shown in Figure 31.

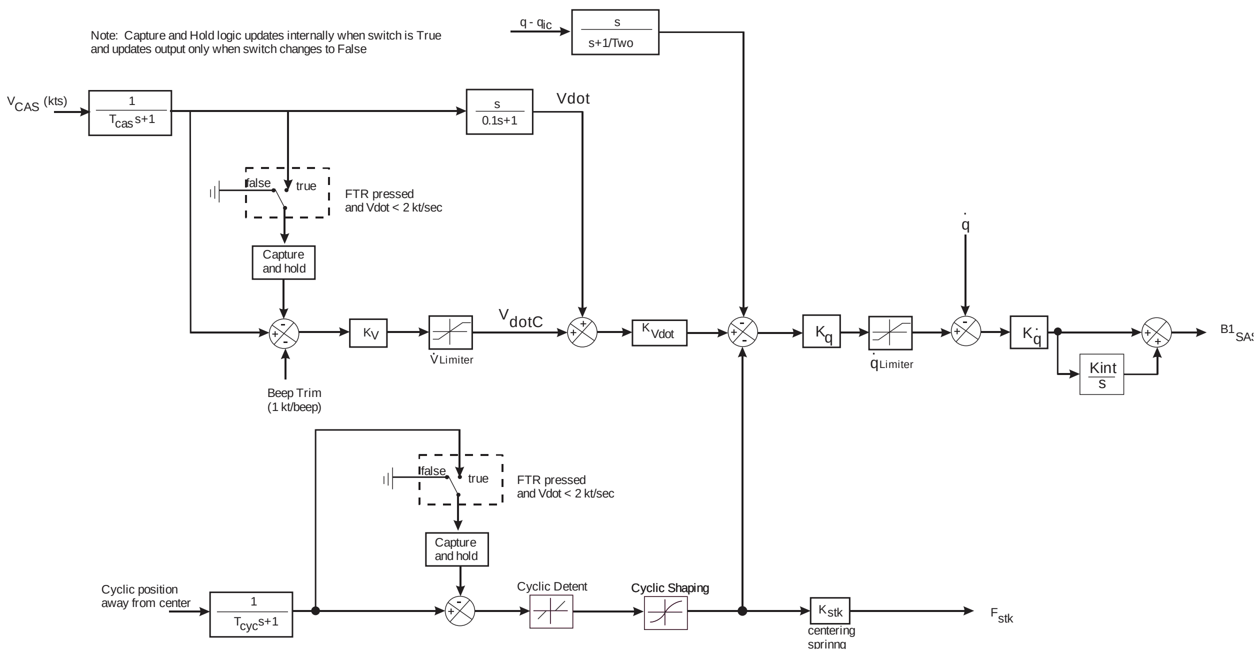


Figure 31. ASC/RTT block diagram

$KthtAS = 2$

$KthtDotAS = -0.4$

$TwoTheta = 5$ sec

$T_{CAS} = 3$ sec

KV=0.75 ft/sec/kt

KVdot=1.5 deg/ft/sec

VdotLim=2.5

ThetaDotLim=10

K_{INT}=0.33

Cyclic shaping is linear gain of 40.

Tcyc = 0.61 sec

Summing the cyclic input at the attitude feedback gives short-term control of pitch attitude and long-term control of airspeed. Because the pitch attitude is washed out, ASC/RTT is effectively an airspeed rate command system. Summing the cyclic input in front of the KV block provided a true airspeed command SAS. However, that was found to be unacceptable because the Vdot limiter severely restricted the pilot's short-term control of pitch attitude.

As noted above, the long-term response to a step change in cyclic is a change in airspeed rate that is proportional to the size of the step. However, in the short-term, the pilot still needs assurance that he or she has control of pitch attitude with the cyclic. Therefore, it is recommended that the bandwidth requirement for short-term pitch control be retained for airspeed SAS types of AdFC. The system parameters used in this study were adjusted to provide a pitch attitude bandwidth of 2.5 rad/sec, as shown in Figure 32.

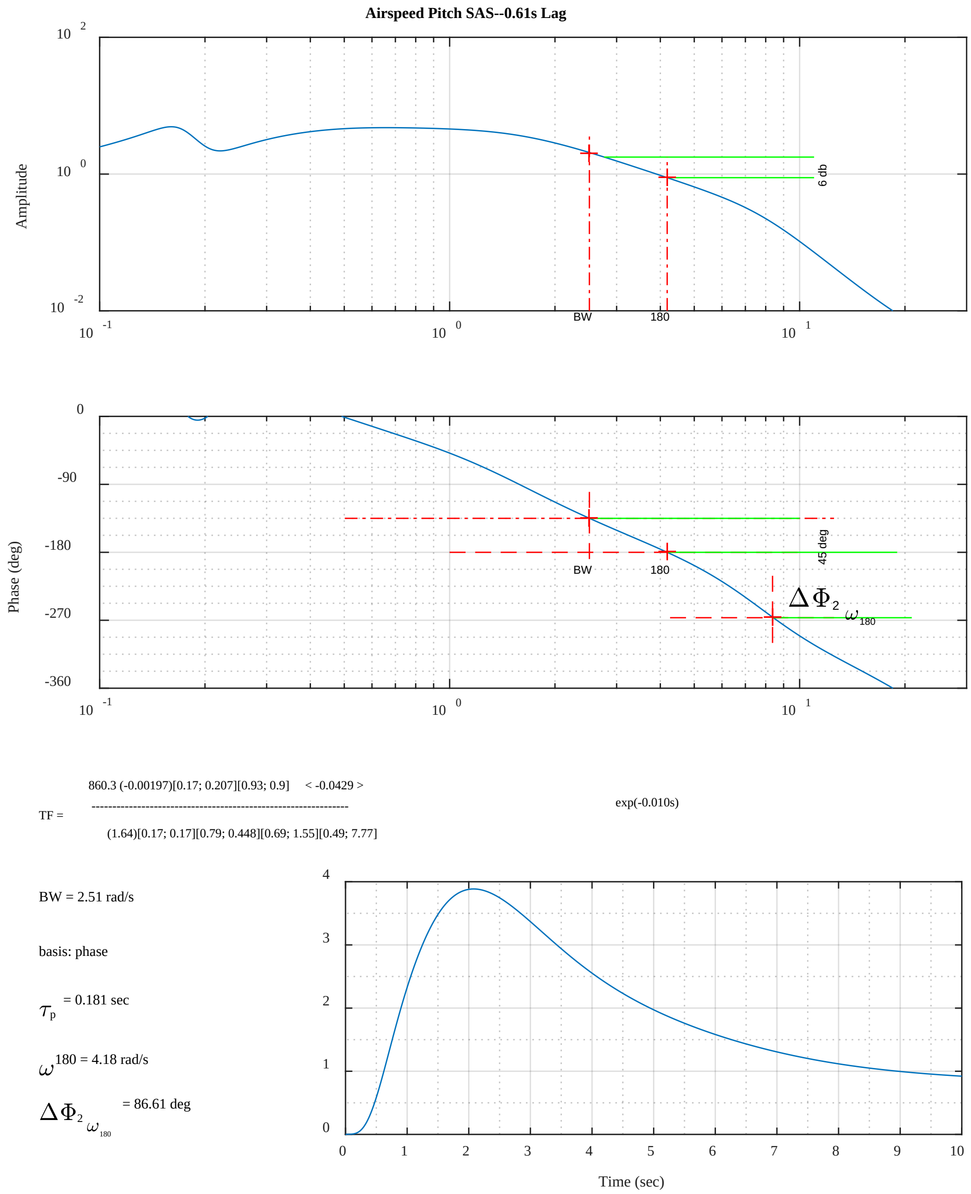


Figure 32. Pitch attitude bandwidth and theta response to cyclic step for ASC/RTT

The time response to a cyclic step shows an initial response in pitch attitude that is proportional to the cyclic input followed by a large drop back to control the rate change of airspeed.

Parameters were set as a compromise between good airspeed response and excessive pitch attitude activity in turbulence, as shown in Figure 33. The primary parameter for this is airspeed filter, T_{CAS}. Most runs were made with T_{CAS} set to 3 seconds. This worked well in light turbulence, but produced excessive pitch activity in moderate turbulence. A complementary filter on airspeed was developed to determine if that reduced the objectionable pitch excursions (see Figure 34).

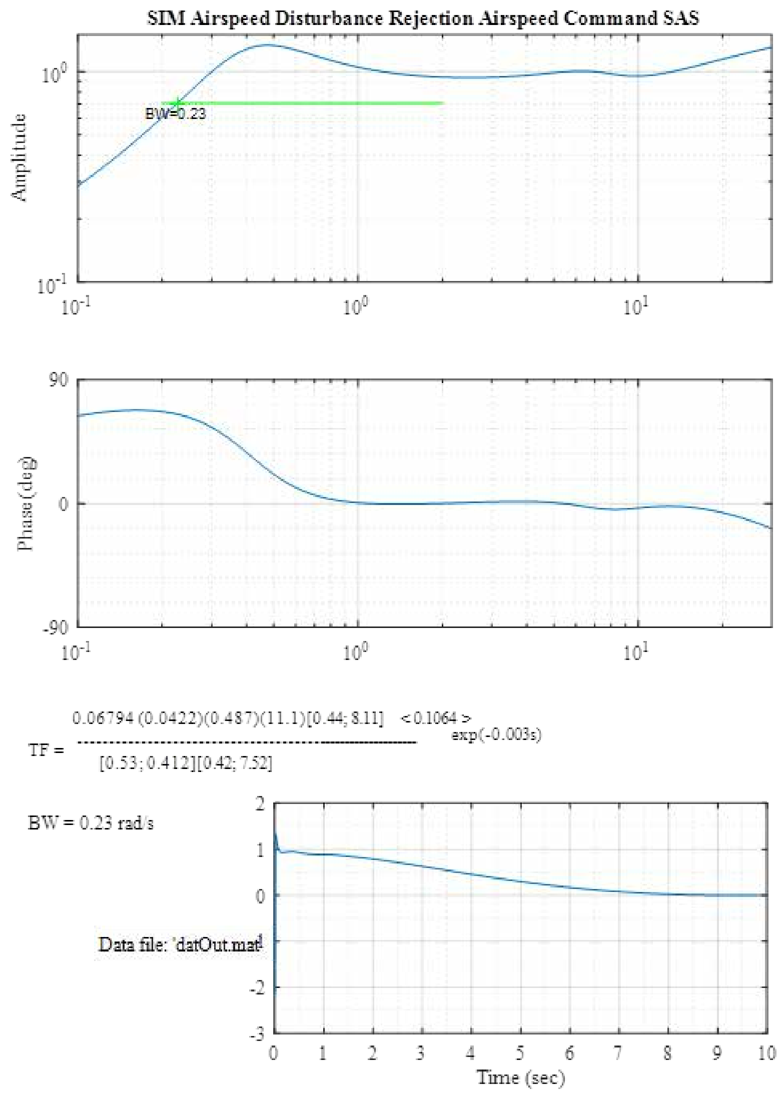


Figure 33. Airspeed disturbance rejection bode and airspeed response to initial condition offset

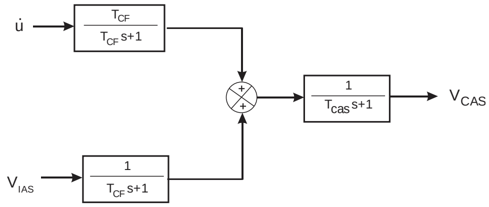


Figure 34. Complementary filter on airspeed

T_{CF} was set to 10 seconds and T_{CAS} was set to 0.10 seconds to effectively remove that low pass filter. Only one run was made with this complementary filter, as shown in Figure 35.

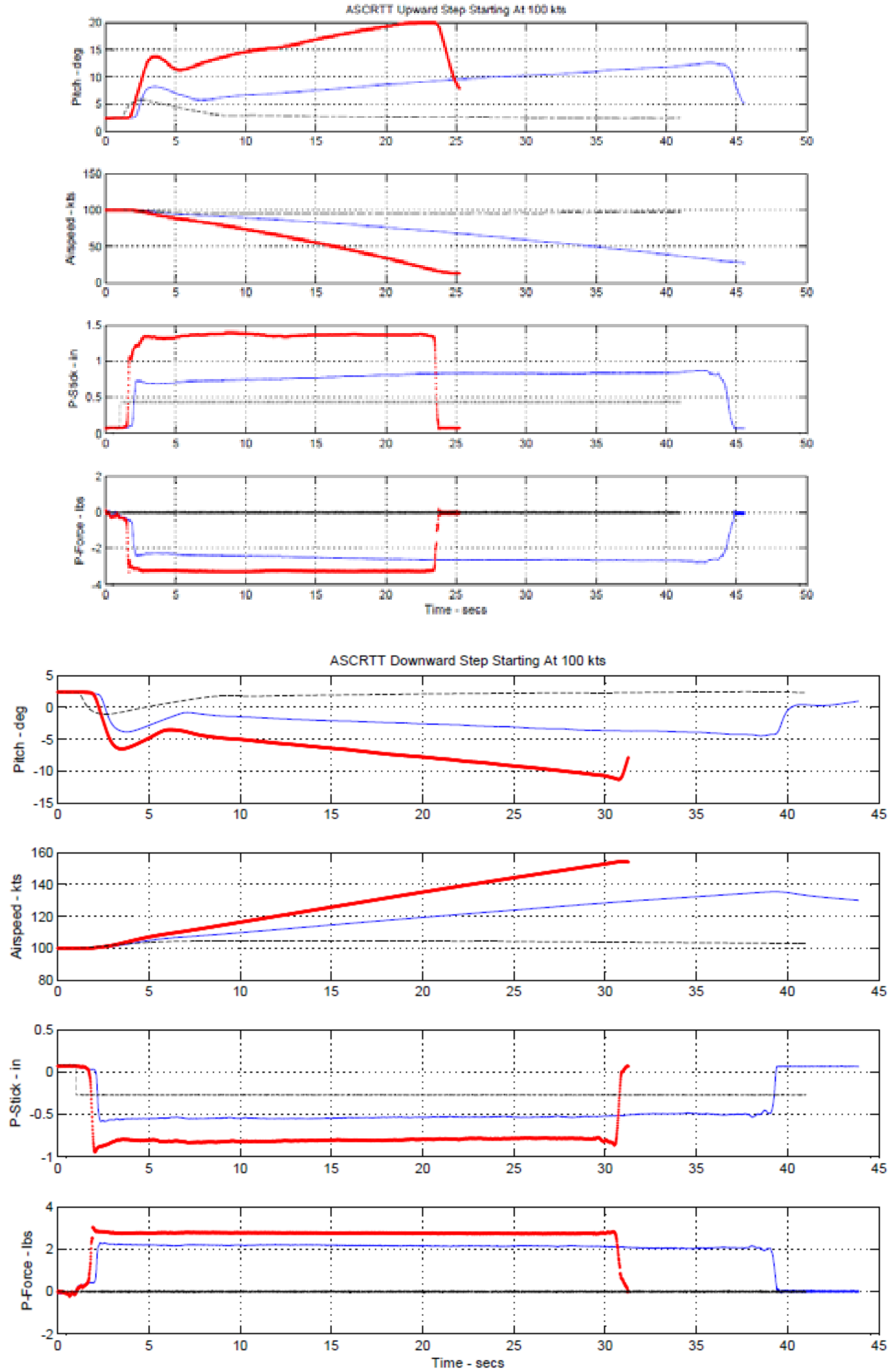


Figure 35. Response to cyclic step inputs—ASC/RTT

8.2.4 Airspeed ASRC/RTT

As noted in section 8.2.3, the ASC/RTT is really an airspeed rate command response type. The airspeed rate command systems described in this section represent an effort to investigate different types of trimming and a more direct command of airspeed rate. The large majority of airspeed system testing used the ASC/RTT system described in section 8.2.3.

This type of airspeed rate command is achieved by disabling the airspeed feedback on the airspeed command system when the cyclic is out of detent. For airspeed rate command systems, zero-force cyclic trim is always the cyclic center position. The following block diagram, in Figure 36, shows two types of airspeed rate command AdFC.

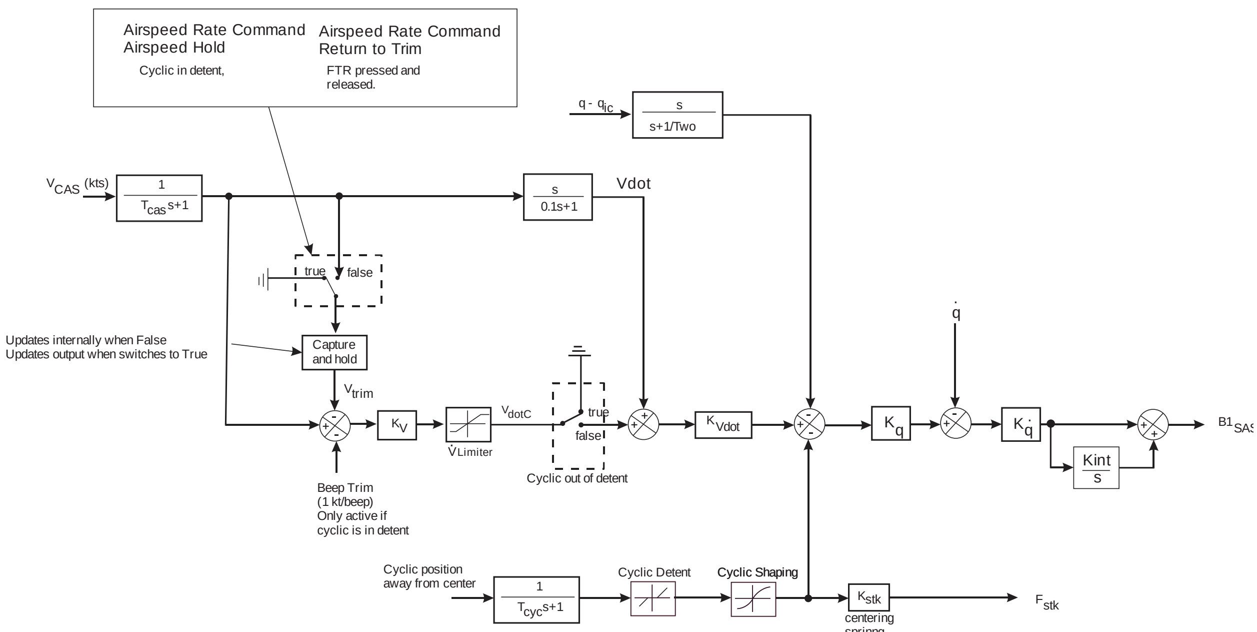


Figure 36. Airspeed rate command/return to trim block diagram

The difference between the two airspeed rate systems depends on how the trim airspeed is achieved.

- For Airspeed Rate Command with Return to Trim (Figure 37):
  - The trim airspeed is set by pressing and releasing the FTR button on the cyclic. The new trim airspeed is not activated until the cyclic is centered.
  - The beep trim is always active
- For Airspeed Rate Command with Airspeed Hold (Figure 38):

- The trim airspeed is set when the cyclic is returned to the detent. The FTR button is disabled.
- The beep trim is only active when the cyclic is in the detent.

The parallel integrator implemented on the $B1_{SAS}$ signal is included to ensure precise control of the trim speed.

Cyclic shaping is linear with gain of 30.

The cyclic deadband for this system was $\pm 4\%$.

$KthtAS = 2$

$KthtDotAS = -0.4$

$TwoTheta = 5$ sec

$TCAS = 3$ sec

KV=0.75 ft/sec/kt

KVdot=1.5 deg/ft/sec

VdotLim=2.5

ThetaDotLim=10

K_{INT}=0.33

Tcyc = 0.00

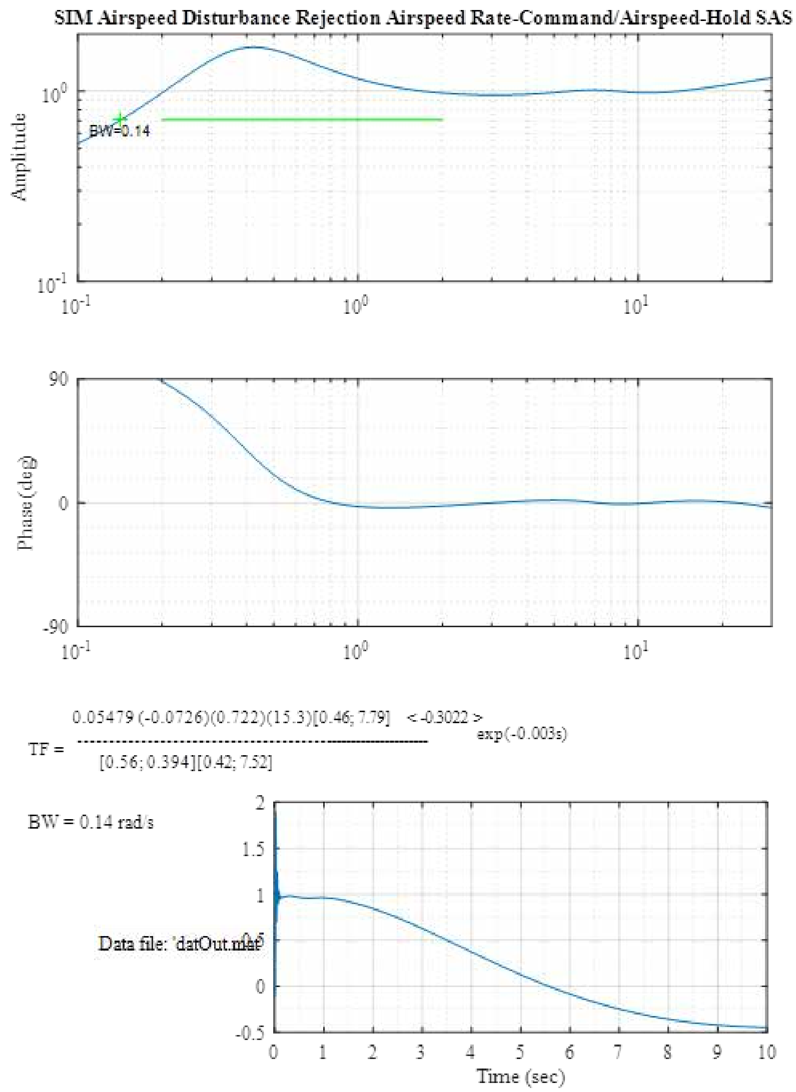


Figure 37. Airspeed response to disturbance input Bode and to initial condition offset

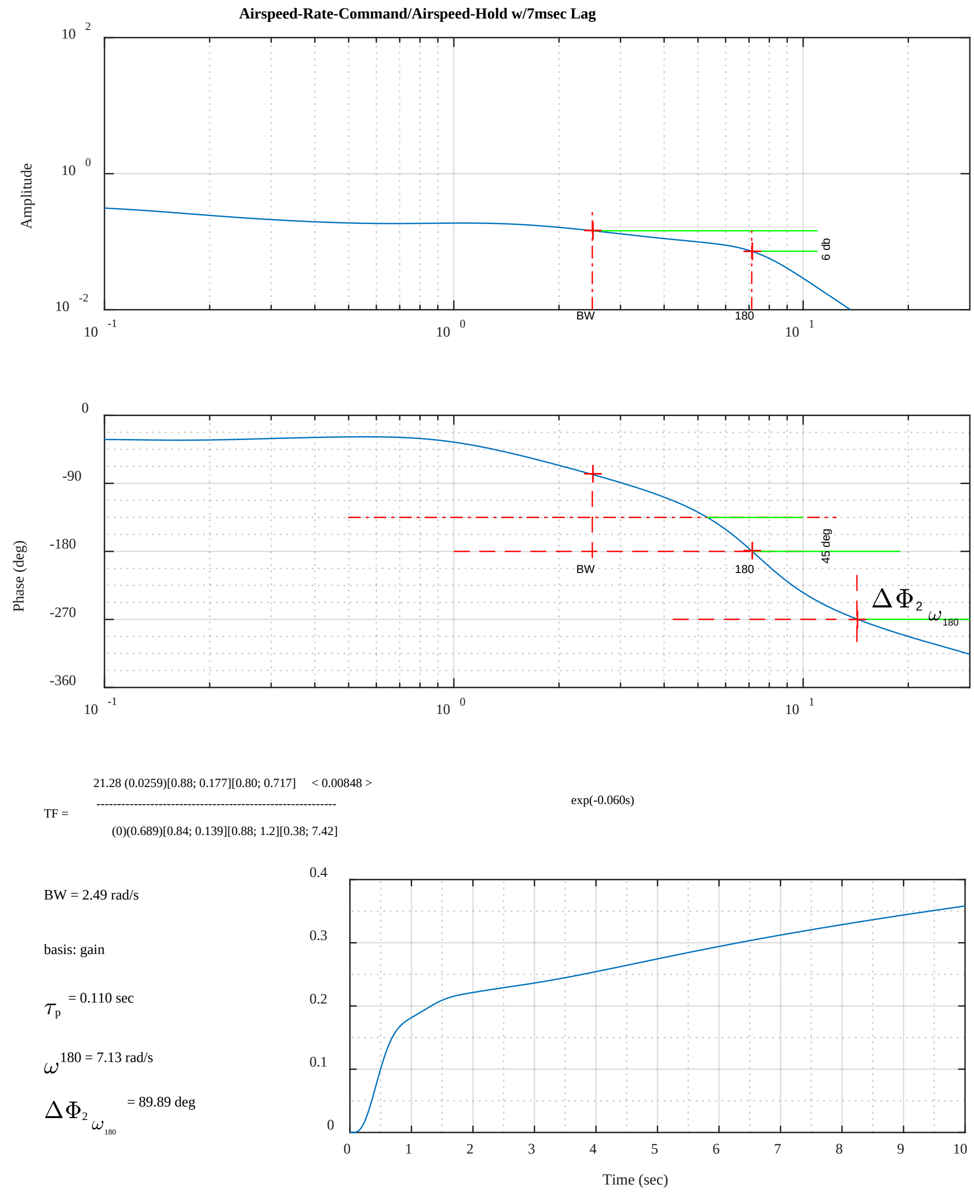


Figure 38. ASRC/RTT pitch attitude bandwidth and airspeed response to cyclic step input

8.2.5 Backup pitch rate SAS

This consists of simple Euler pitch rate feedback. For Phase A, the cyclic lag time constant was set to 0.53 seconds to achieve a bandwidth near the originally proposed Level 1 limit of 1 rad/sec (BW = 1.06 rad/sec). For Phase B, the pitch cyclic time constant was set to 0.134 seconds to give a pitch bandwidth of 2.44 rad/sec.

The stick shaping function was a linear gain of 50 deg/sec/% (full cyclic travel normalized to unity). KthtDotRate = -0.40.

The response characteristics from VMS frequency sweeps are given as follows:

- For Phase A, the bandwidth was as shown in Figure 39.

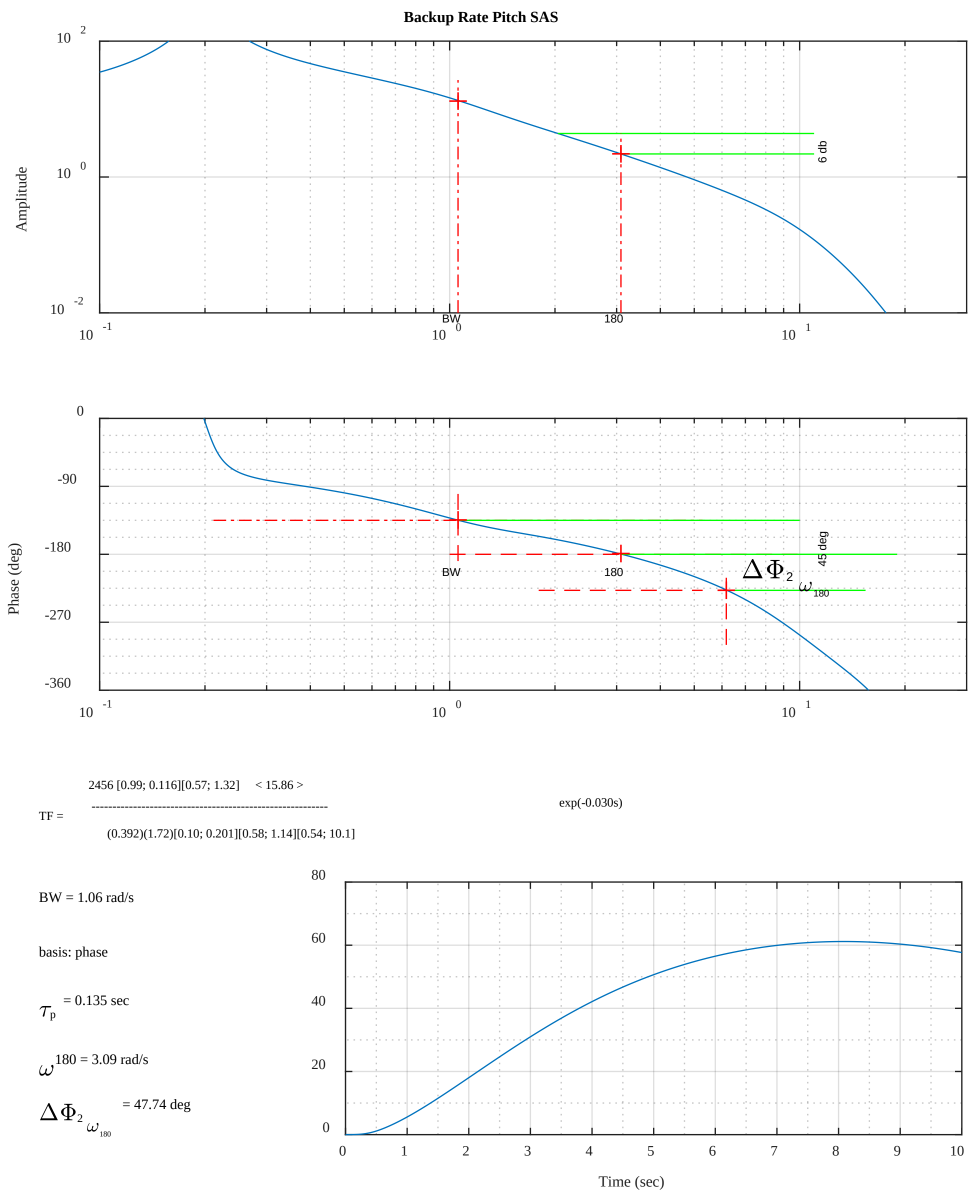


Figure 39. BURS attitude bandwidth and attitude response to step cyclic input—Phase A

· For Phase B, the pitch bandwidth was increased to 2.44 for the BURS, as shown in Figure 40.

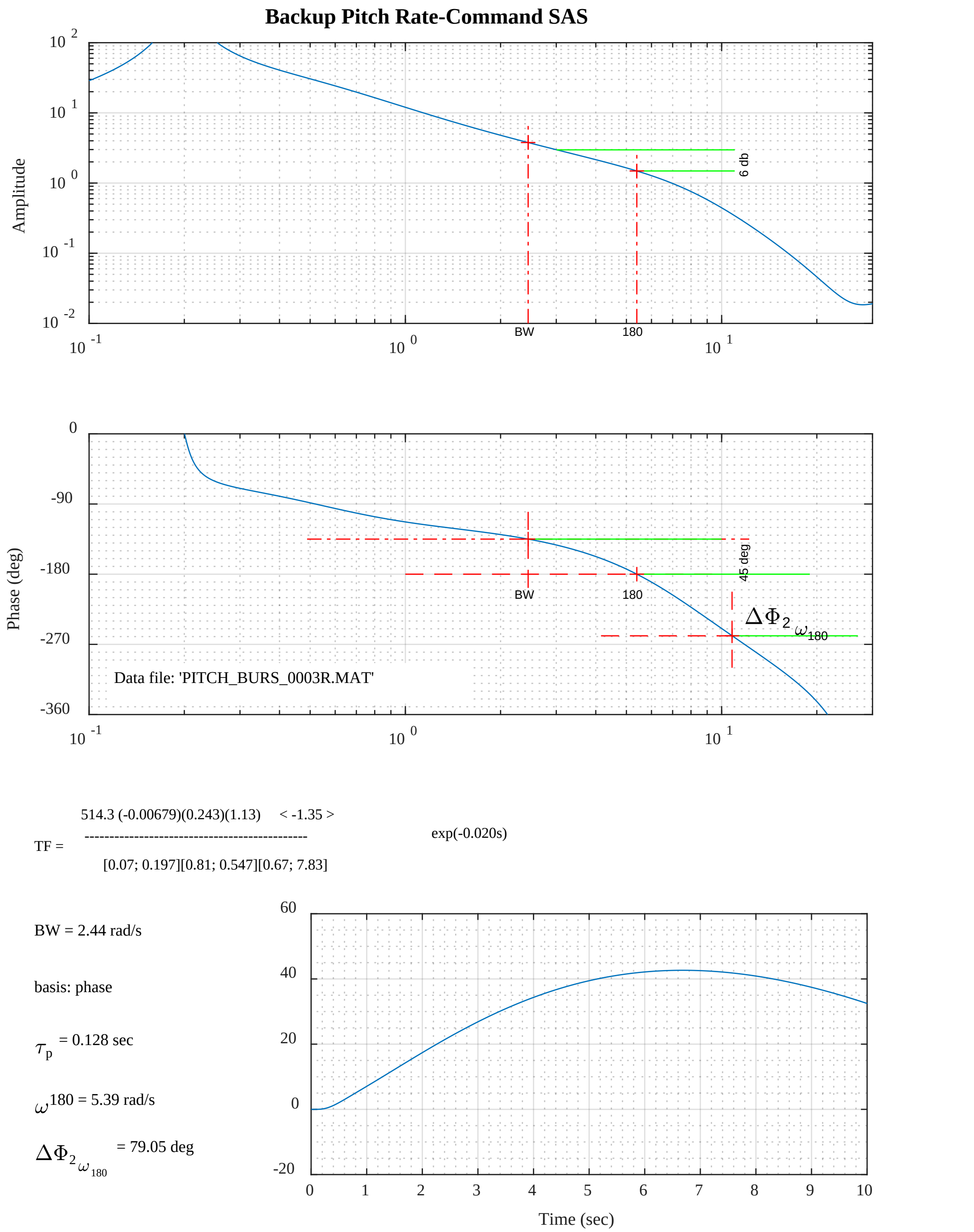


Figure 40. BURS attitude bandwidth and attitude response to step cyclic input—Phase B

8.3 Lateral FCS

8.3.1 Attitude-command-attitude-hold (ACAH)

The roll axis ACAH block diagram is shown in Figure 41.

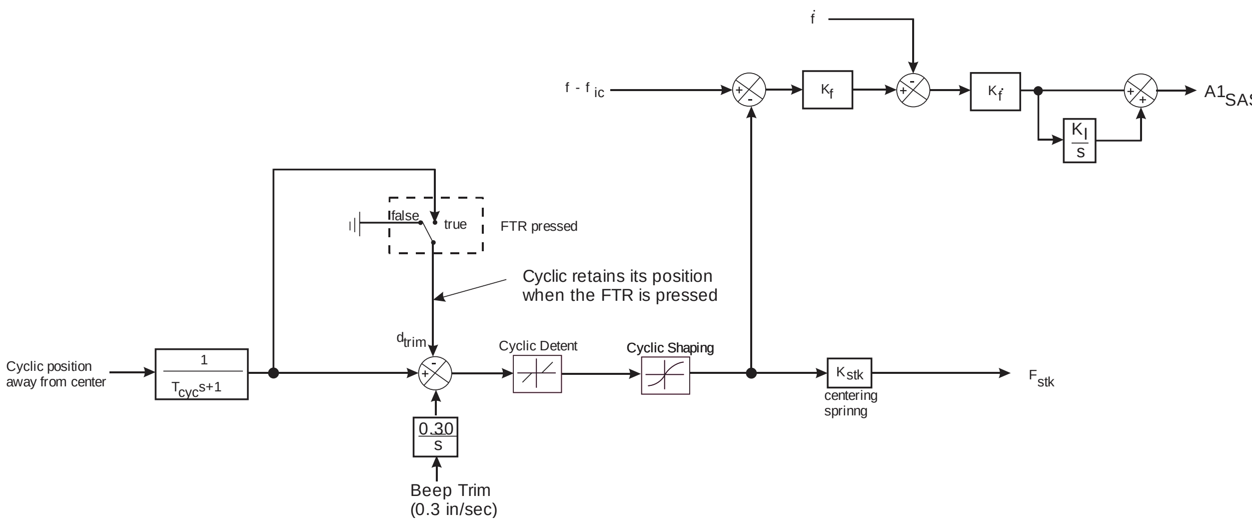


Figure 41. Roll axis ACAH block diagram

The system parameters are as follows:

$K_{f} = 2.0$ deg/ sec/ deg (KPhi)

$K_{\dot{f}} = 0.1$ deg/ deg/ sec (KPhiDot)

T_{cyc} = 0.45 sec – to get bandwidth = 2.5 rad/sec (TcycThSecs).

T_{cyc} = 0.73 sec – to get bandwidth = 2.0 rad/sec

K_I = 0.33

The response characteristics for cyclic step input for roll attitude bandwidth and bank angle-ACAH is in Figure 42. The responses of roll ACAH to lateral cyclic steps are shown in Figure 43 and the roll attitude responses to pulse inputs are shown in Figure 44.

The disturbance rejection bandwidth for ACAH in roll is 0.83 rad/sec and is shown in Figure 45.

The lateral cyclic shaping function is linear with a maximum value of ± 75 degrees.

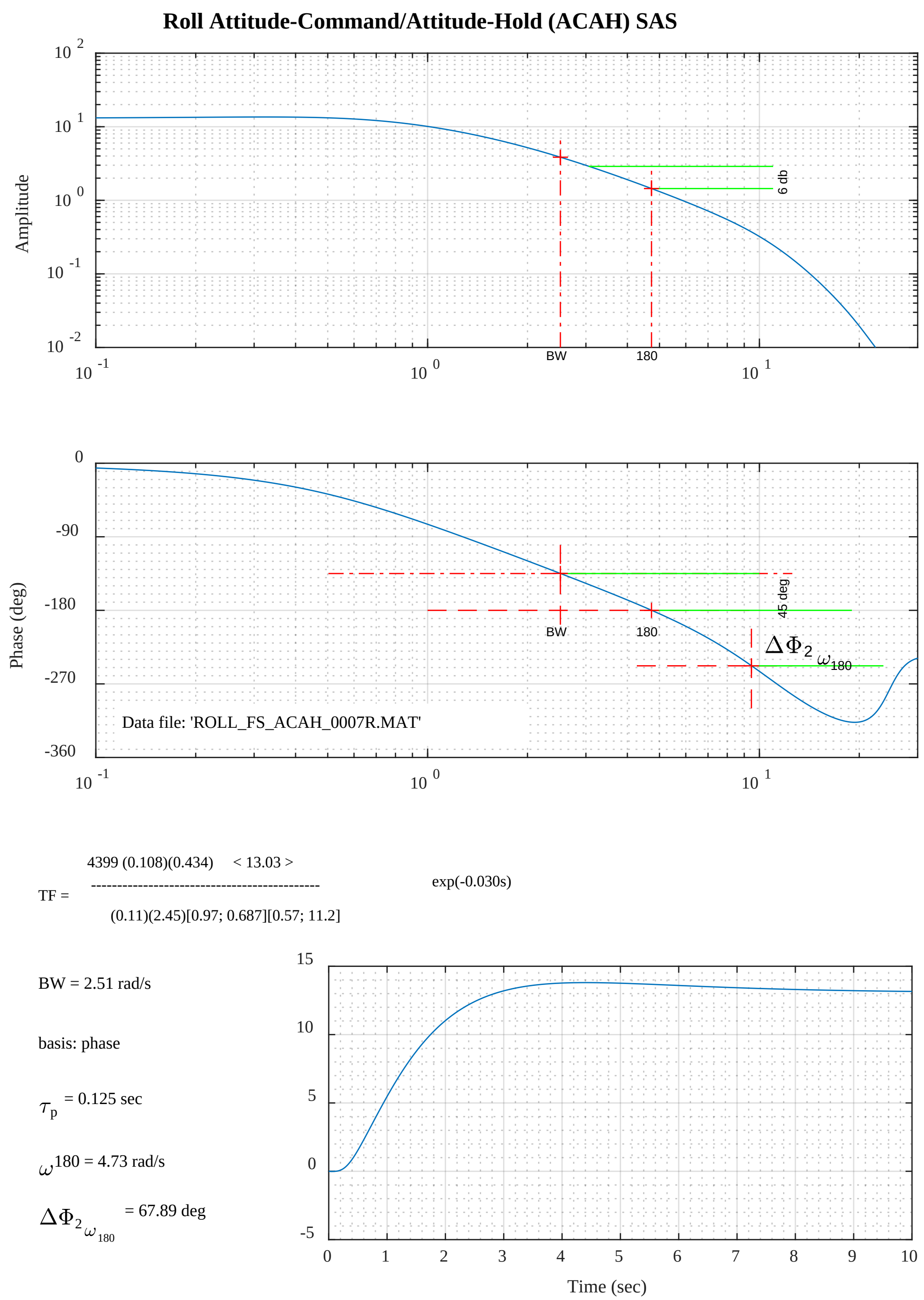


Figure 42. Roll attitude bandwidth and bank angle response to cyclic step input—ACAH

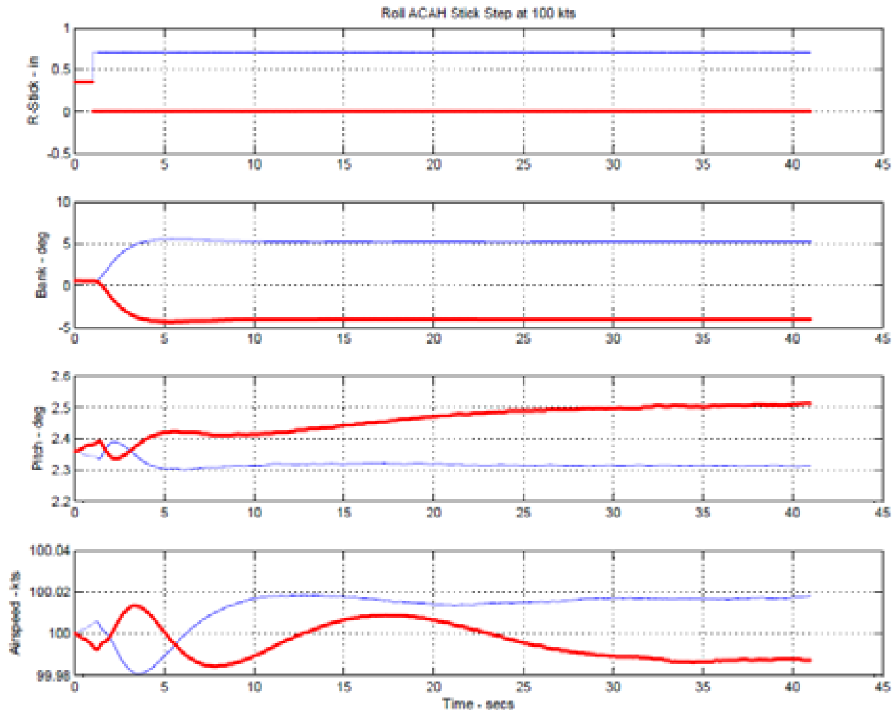


Figure 43. Response of roll ACAH to lateral cyclic steps

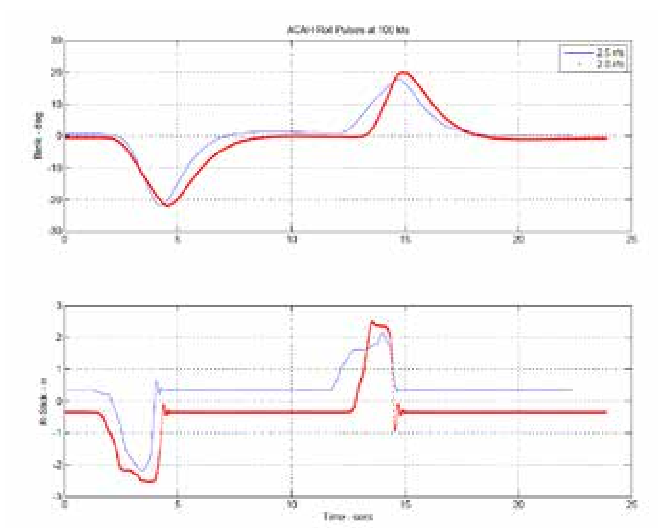


Figure 44. Roll attitude response to pulse inputs—ACAH

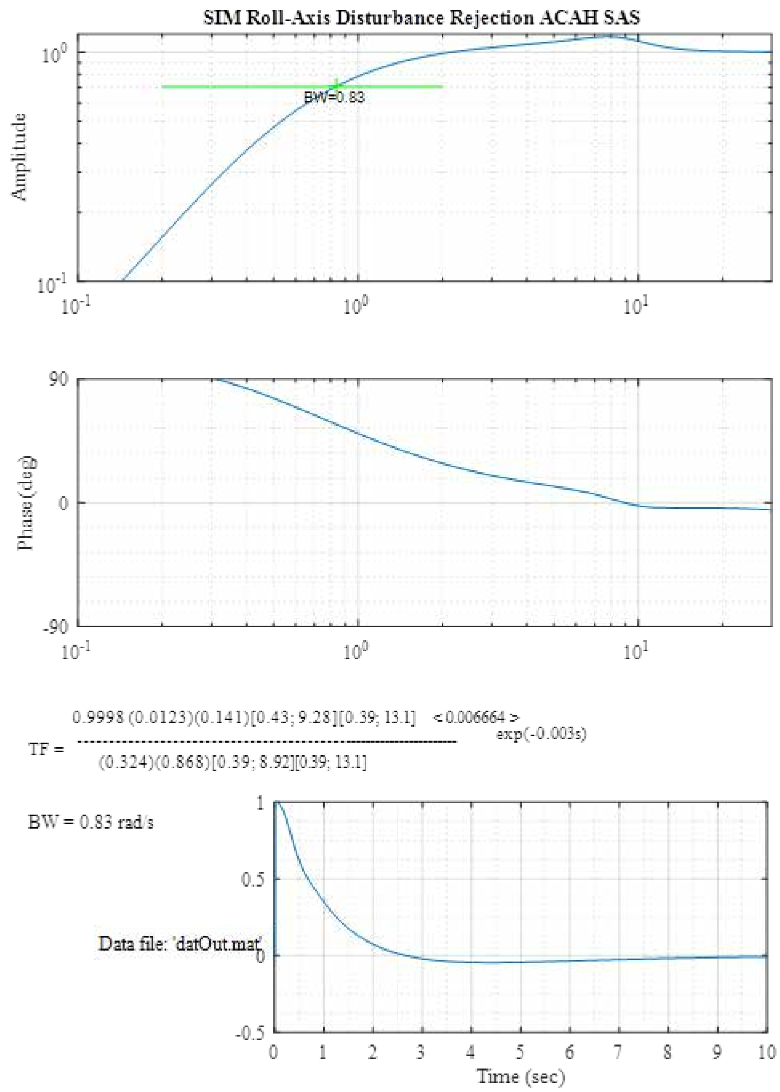


Figure 45. Bank angle response to disturbance to initial condition offset

8.3.2 Rate command attitude hold (RCAH)

A model-following architecture was implemented for this AdFC, as shown by the following block diagram in Figure 46. This architecture was employed to avoid the large phase lag introduced by modeling RCAH as an integrator in front of an ACAH system.

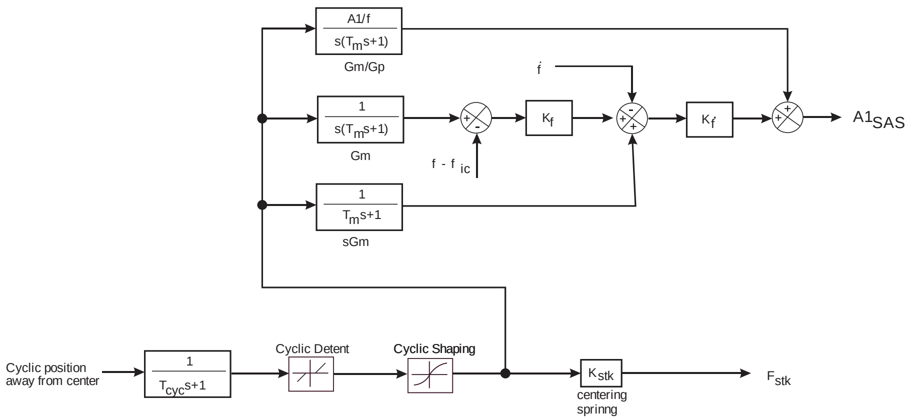


Figure 46. Lateral rate-command-attitude-hold block diagram

The system parameters are as follows:

$$G_m = \frac{1}{s(T_m s + 1)}$$

$$G_P = \frac{43.32}{(s + 0.068)(s + 3.71)}$$

Tm = 0.25 sec.

$K_{\phi} = 2.0$ deg/sec/deg (KPhi)

$K_{\dot{\phi}} = 0.1$ deg/deg/sec (KPhiDot)

Cyclic shaping is linear with a peak value of ± 50 deg/sec.

T_{cyc} = 0.098 sec – to get bandwidth = 2.5 rad/sec (TcycThSecs).

The lateral cyclic deadzone was ± 4% when RCAH was active in roll.

Figure 47 shows the response characteristics for roll attitude bandwidth to cyclic step input for RCAH. The SIM RCAH roll axis disturbance is shown in Figure 48. The response of the pulse input to roll actuator at 100 kts is shown in Figure 49.

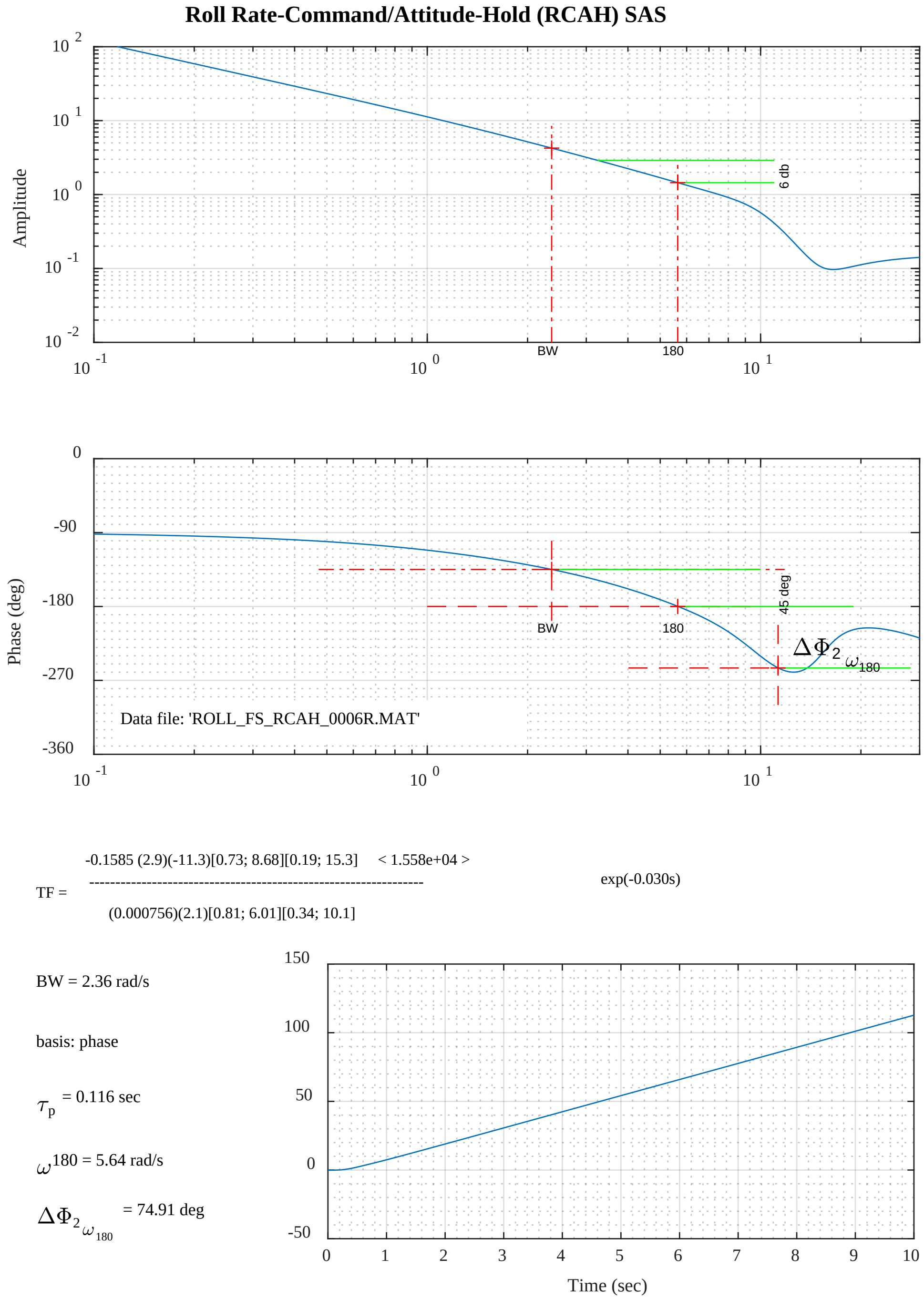


Figure 47. Roll attitude bandwidth and response to cyclic step input—RCAH

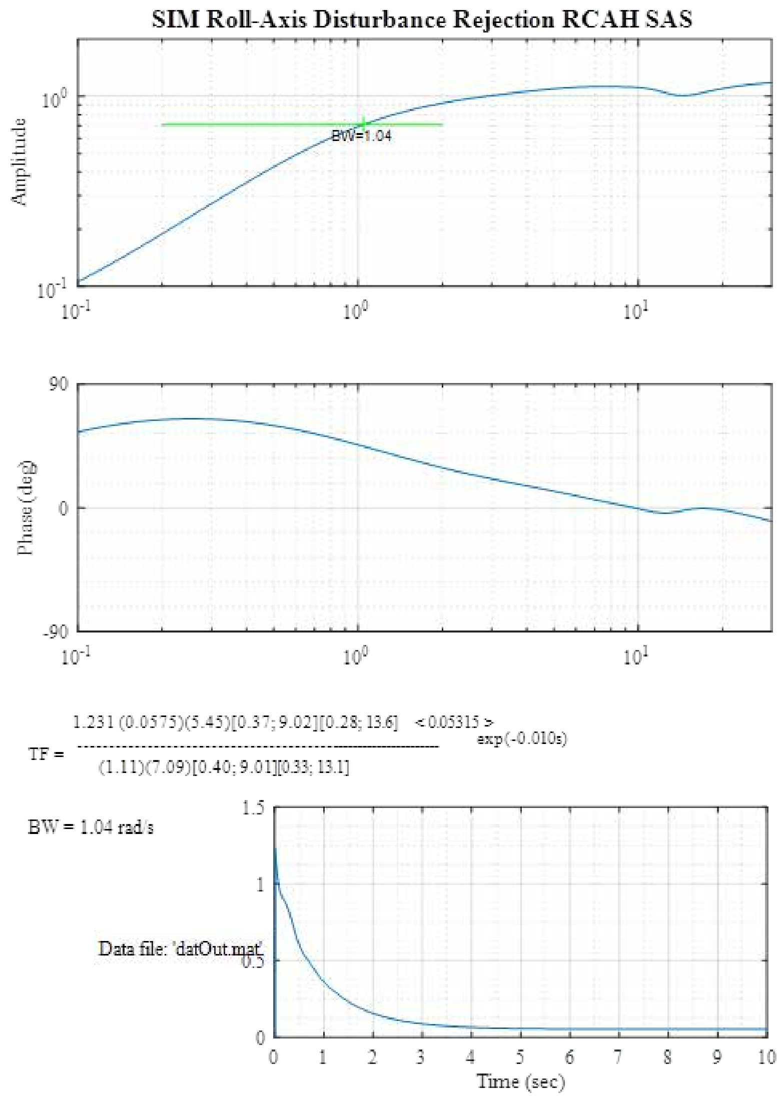


Figure 48. RCAH roll axis disturbance regulation

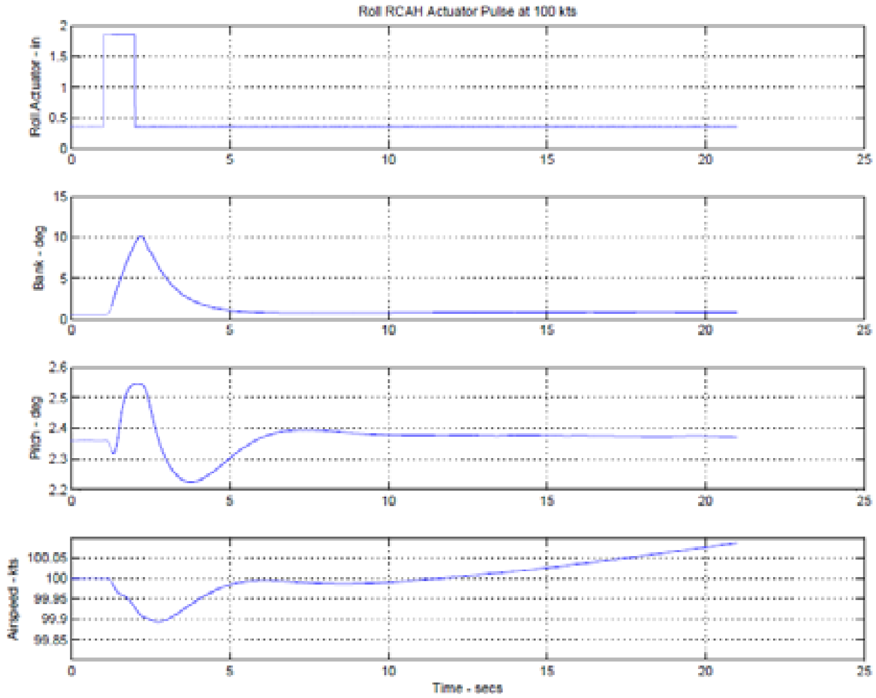


Figure 49. Response of pulse input to roll actuator—RCAH

8.3.3 Backup roll rate SAS

The backup roll rate SAS consists of simple Euler roll rate feedback. The loop gain is KPhiDotRate = 0.05 deg/deg/sec. The cyclic lag time constant was set to 0.45 seconds to achieve a bandwidth of 1.3 rad/sec (near the proposed Level 2/3 limit of 1 rad/sec). The stick shaping function was a linear gain of 100 deg/sec/% (full cyclic travel normalized to unity). The response characteristics from VMS frequency sweeps are given as follows for Phase A in Figure 50 (these also apply to Phase B starting at run 104).

Tcyc was reduced to 0.22 seconds to achieve a bandwidth of 2.5 rad/sec for run 161 to the end of the program.

The cyclic dead zone was ± 4% when BURS was active.

The cyclic breakout was left at 0.25 lb under the assumption that this would not change following a failure of the higher-level system (e.g., ACAH).

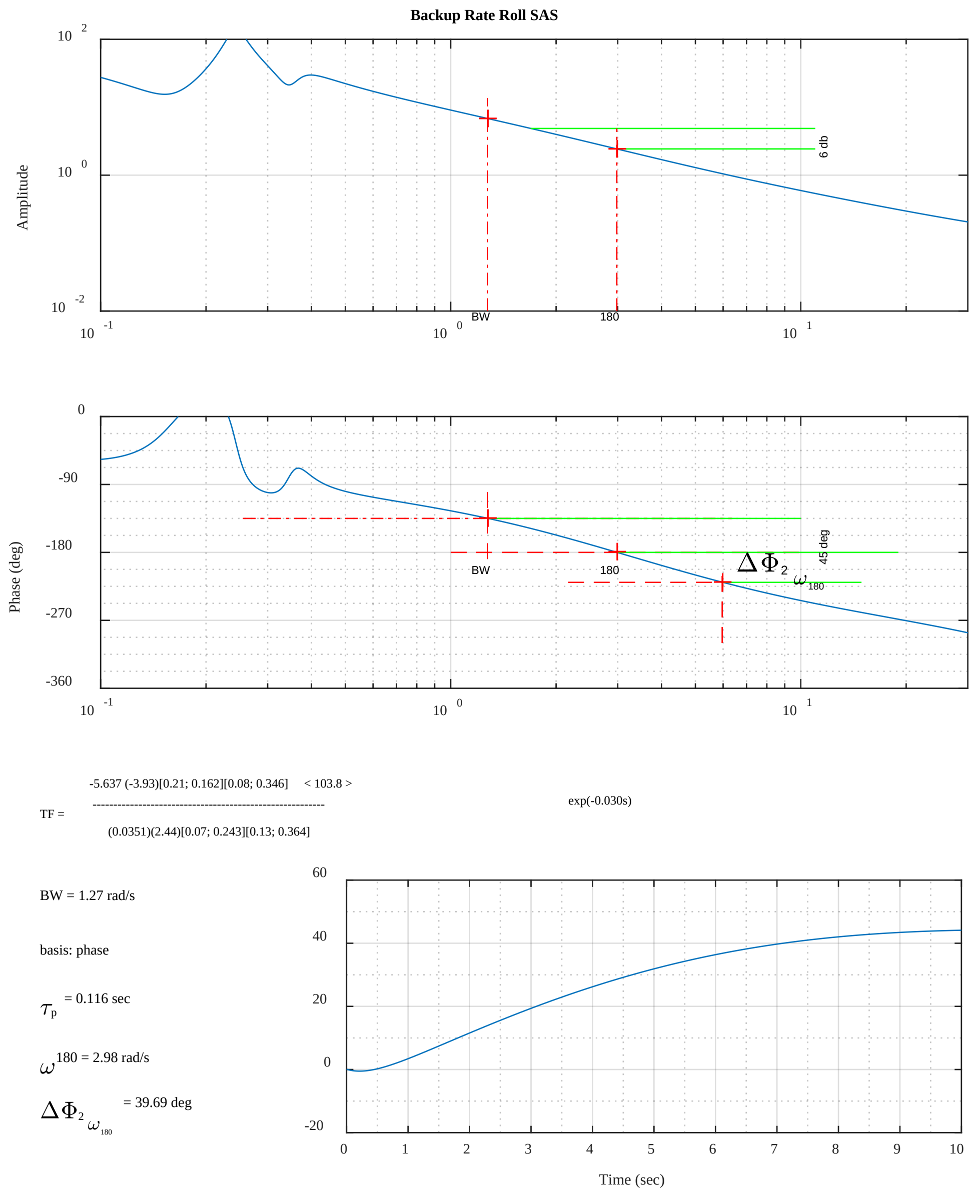


Figure 50. Roll attitude frequency response and response to cyclic step input

For Phase B, the bandwidth was increased to 2.5 rad/sec, as shown in Figure 51:

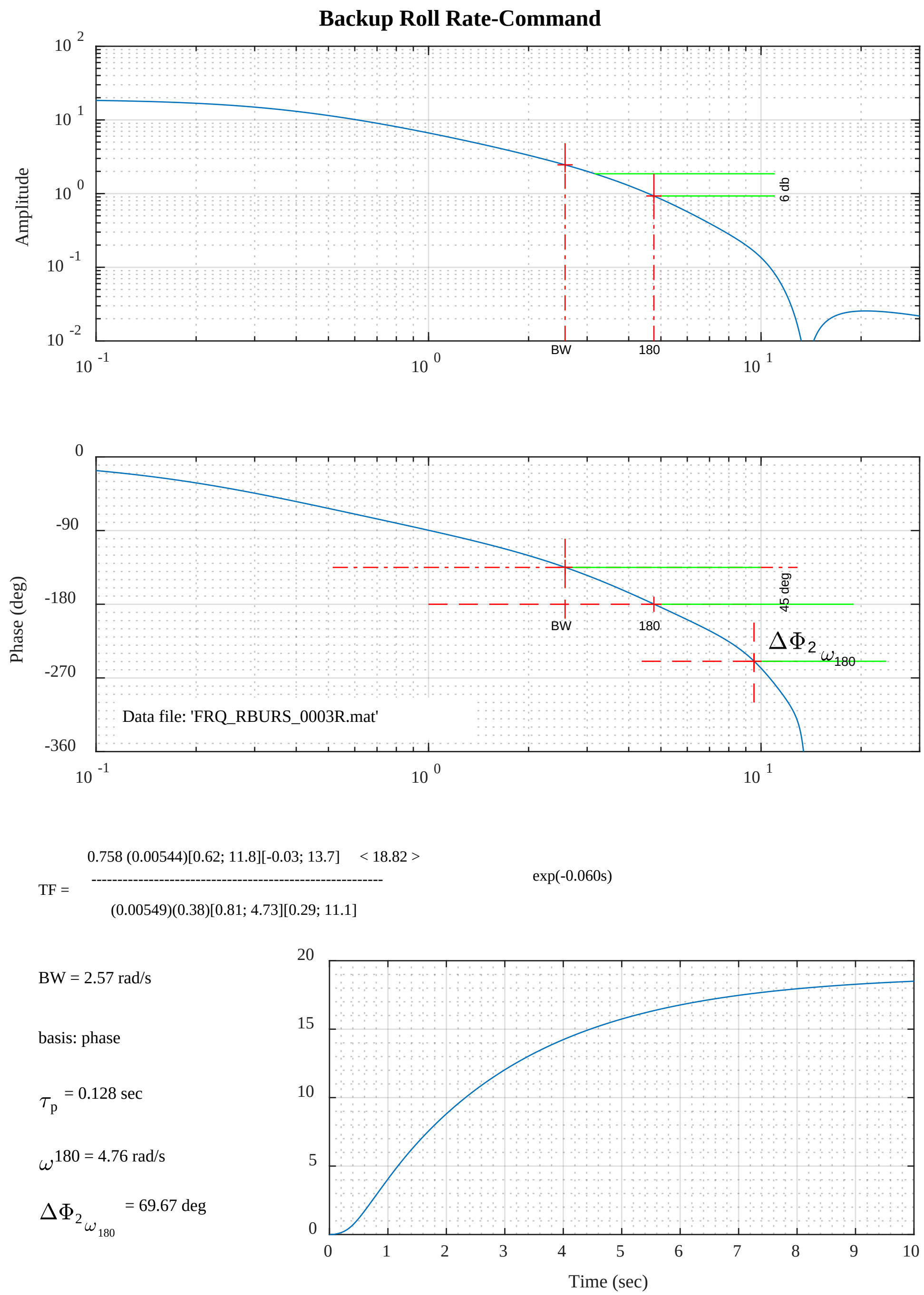


Figure 51. Backup roll rate command

8.3.4 Yaw damper/turn coordination

Yaw damping is achieved by feeding back yaw rate that is not due to bank angle $R = r - g\sin f / V_{TAS}$ to tail rotor. Turn coordination is achieved by feeding back lateral acceleration to tail rotor (i.e., keep the ball centered).

The block diagram is as follows in Figure 52:

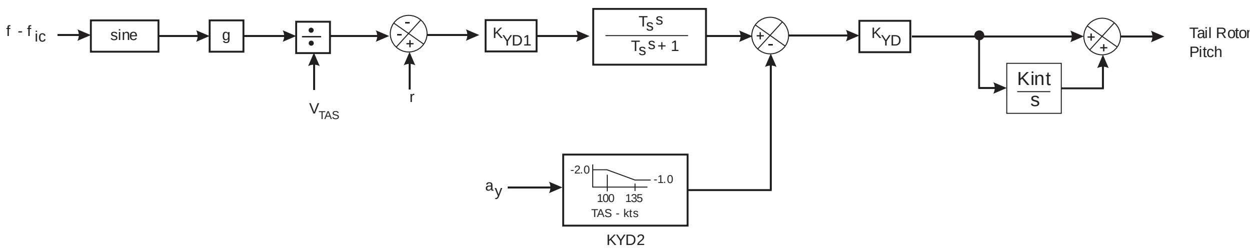


Figure 52. Yaw damper/turn coordination block diagram

K_{INT} = 0.10 required to account for large changes in trim tail rotor thrust with airspeed changes.

KYD2 = per gain schedule - deg/ft./sec^2

KYD1 = 0.25 deg/deg/sec

KYD = 1.0

T_s = 7 seconds (4 seconds also seemed okay—did not optimize this parameter).

Kint = 0.10

Lateral accelerometer is at the c.g.

Tail rotor thrust is positive to the right.

Feeding back just ay damped the Dutch-roll, but not enough to eliminate the need for yaw rate feedback.

The yaw rate feedback consisted of residual yaw rate $(r - g\sin f / V_{TAS})$, which is the yaw rate not needed for a coordinated turn. This term was washed out to account for non-zero bank angle in straight flight for helicopters.

Note that:

$$a_{y_{cg}} = \dot{v} + ru - pw = g\cos\theta\sin\phi = Y/m$$

$$a_{y_{cg}} \approx \dot{v} + rV_{TAS} - g\sin\phi$$

8.4 Flight directors

The longitudinal and lateral flight directors consisted of the AP outer loop command plus washed out attitude feedback as shown in Figure 53.

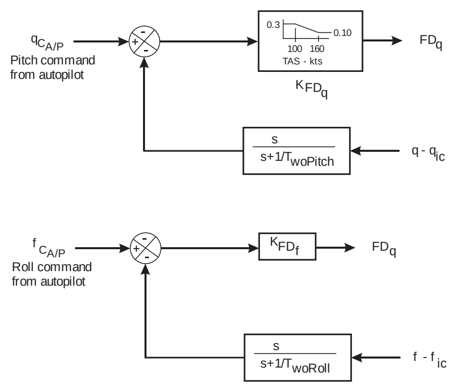


Figure 53. Flight director block diagram

The flight director parameters are as follows:

K_{FD_θ} scheduled with airspeed between 100 and 160 kts (0.4 V<100 and 0.3 for V>160).

$T_{woPitch} = 0.50$ sec For all modes except airspeed hold

$T_{woPitch} = 5.0$ sec For airspeed hold mode

$K_{FD_\phi} = 0.10$ (display scale factor)

$T_{woRoll} = 0.50$ sec

Following the pitch flight director with the airspeed SAS engaged was found to be confusing. For example, if ALT mode is selected, following the pitch flight director does control altitude but results in large airspeed variations. What worked best was to think of the command bar as a collective flight director. That worked very well, but could be confusing to have the same cue apply to different controllers depending on the SAS mode. The best solution would be to have a separate collective flight director cue. That is out of scope for this testing. No flight director evaluations were accomplished with the airspeed SAS systems.

8.5 Autopilot

AP functionality was achieved with a hardware-in-the-loop HeliSAS® AP FCC (Version 52 software). This provided the following upper modes:

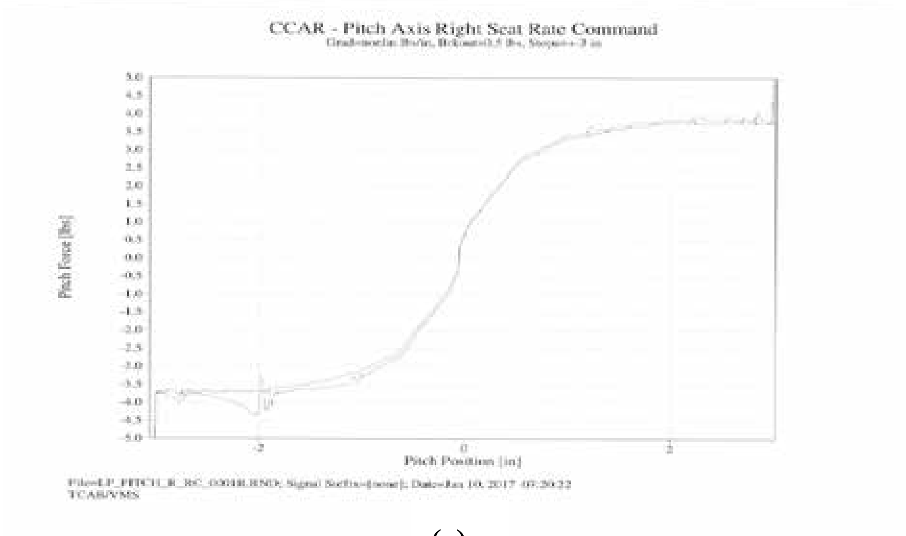
- Longitudinal—Altitude select and hold, airspeed select and hold, vertical speed select and hold, LPV glideslope tracking.
- Lateral—Heading select and hold, LNAV tracking, LPV localizer tracking.

HeliSAS is a parallel system that back-drives the controls. This was converted to a series mechanization for the VMS simulation.

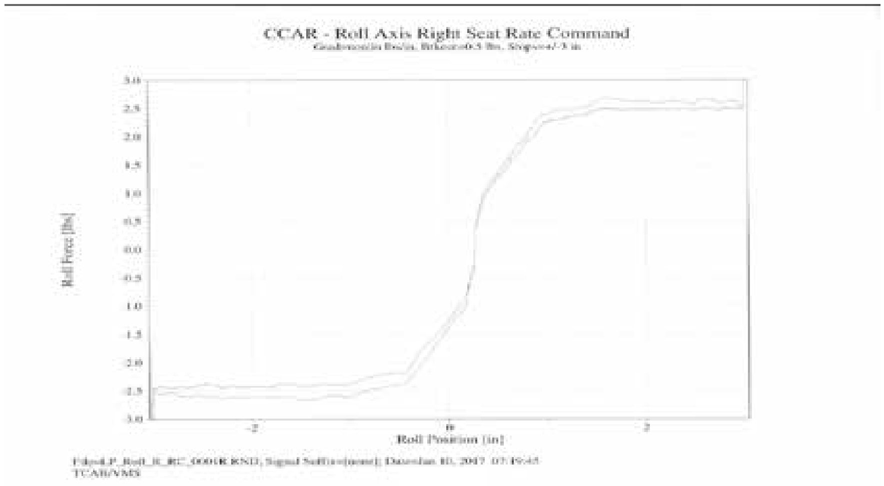
8.6 VMS control loaders

The figures that follow in sections 8.6.1 and 8.6.2 document the force vs. displacement characteristics of the sidearm controller in the right seat (Figure 54a-54d) and center stick controller in the left seat (Figure 55a-55d). They were obtained by slowly moving the controller from full displacement in one direction to full displacement in the other direction and then back to the initial position. This provides a quantitative measure of force gradients, breakout, and hysteresis.

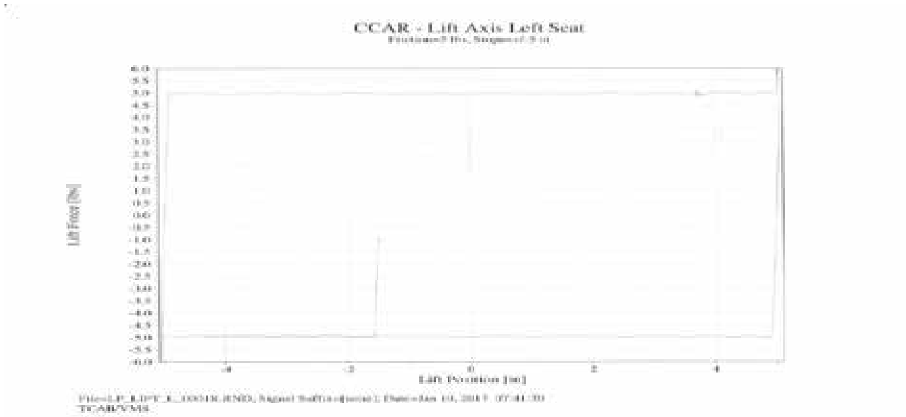
8.6.1 Sidearm controller (right seat)



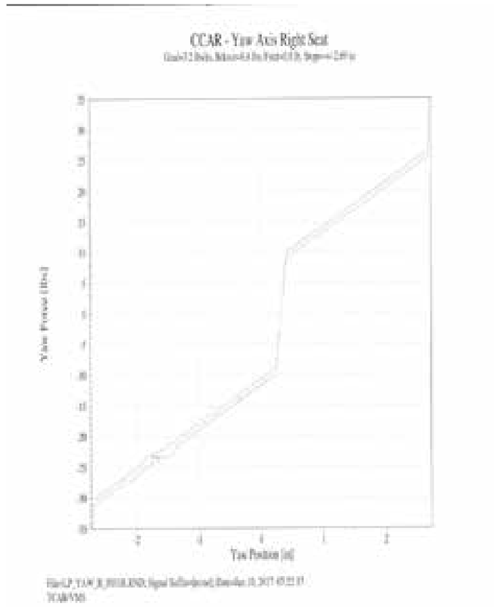
(a)



(b)



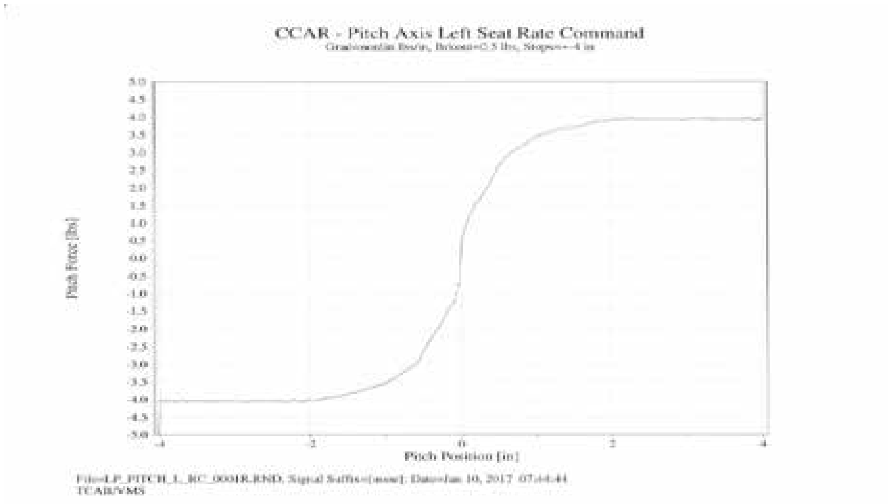
(c)



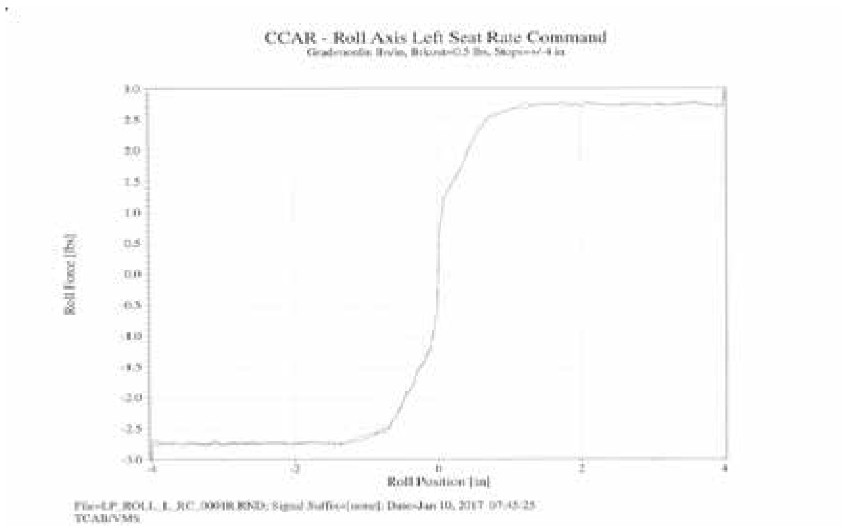
(d)

Figure 54. Force vs displacement sidestick right seat

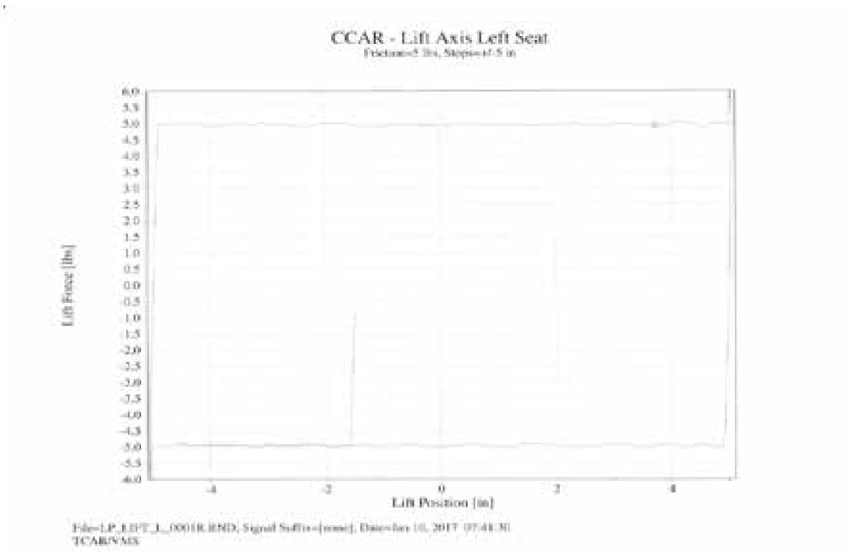
8.6.2 Center stick controller (left seat)



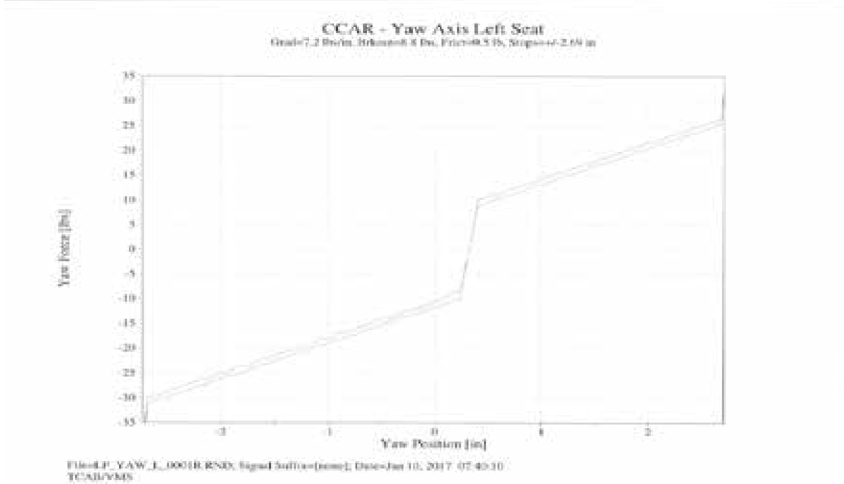
(a)



(b)



(c)



(d)

Figure 55. Force vs displacement center stick left seat

9 Simulation scenarios

The following are the seven simulation scenarios that the pilots used on the NASA Ames VMS to gather the data provided in this report and are shown in Figure 56 through Figure 62.

Sigma H is 1 ft./sec; the initial airspeed is 100 kts for all runs.

Steady wind above 1000 ft. is zero. V20 is always 15 kts, but direction varies during the scenarios (to provide a crosswind at the airport).

SCENARIO 1

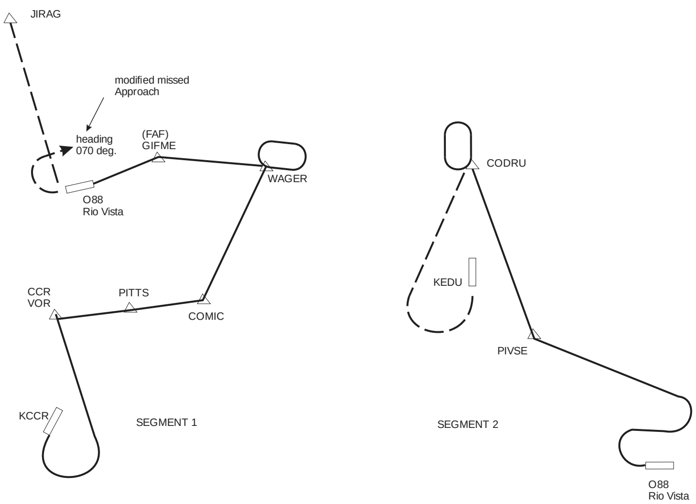


Figure 56. VMS scenario #1

Initial Condition: At Concord airport (KCCR), heading 190 degrees at an altitude of 125 feet MSL.

Weather: Ceiling at Concord is 500 ft. Lower ceiling to 50 ft. after pilot goes IMC. V20 = 170 degrees at 15 kts.

Pilot Brief: You have submitted an IFR flight plan from Concord (CCR) direct to Rio Vista (O88) at 4000 ft. Your filed alternate airport is Davis University (KEDU). You call Concord tower for clearance on 119.7. Rio Vista Weather is 500 overcast 3 miles visibility with winds from 270 deg at 15 kts.

ATC: VMS 1 is cleared to Rio Vista airport via the Buchanan Nine Departure, Pitts transition, Direct Wager intersection, Direct. Cross Pitts at 2000 and maintain 3000. Contact Travis Departure 119.9 airborne. Squawk 0351. VMS 1 is cleared for takeoff.

After crossing the Concord VOR—

ATC: We have a revised clearance, advise ready to copy.

When pilot advises ready to copy—

ATC: VMS 1 is cleared to Rio Vista via direct COMIC direct Wager, climb and maintain 4000 ft. Contact NorCal approach 125.4 crossing COMIC.

After pilot reads back clearance—

ATC: Clearance correct. Maintain heading of 080 degrees and proceed direct COMIC when able.

After leveling at 4000 ft.—

ATC: If able, increase airspeed to 140 kts.

After passing COMIC and established toward WAGER—

ATC: Cleared for the RNAV Runway 25 approach to RIO Vista Airport. Switch to advisory frequency after crossing the GIFME intersection. (Verify switch to 122.725 on KY196). In the event of a missed approach, contact Travis Approach on 119.9.

When pilot calls Travis Approach to advise of missed approach (verify 119.9)—

ATC: VMS 1 turn left, heading 350 degrees, climb and maintain 4000 ft. and advise when ready to copy clearance to Davis University airport.

When pilot reports ready to copy—

ATC: VMS 1 is cleared to the Davis University Airport, Echo Delta Uniform, via direct PIVSE, direct CODRU Direct. Cross CODRU at 3000 ft. Squawk 4247. Maintain maximum forward speed to CODRU.

Weather: Set V20 = 260 deg at 15 kts. Set ceiling to 700 ft. AGL and visibility to 2 miles.

Crossing CODRU—

ATC: VMS 1 is cleared for the RNAV Runway 17 approach to Davis University. Contact advisory frequency after passing HAPAX intersection. In the event of a missed approach, contact Travis Approach Control on 126.6 and hold as published.

End scenario when pilot advises runway is in sight.

SCENARIO 2

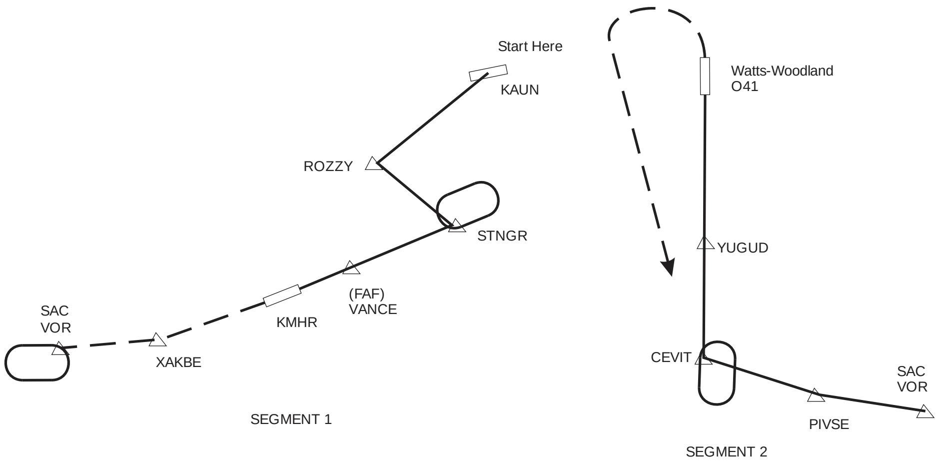


Figure 57. VMS scenario #2

Initial condition: Auburn airport (KAUN) heading 250 deg at an altitude of 1700 ft. MSL. (200 ft. AGL) and visibility to 5 miles.

Weather: Lower ceiling to 50 ft. after pilot goes IMC. V20 = 310 deg at 15 kts.

Pilot Brief: You have filed an IFR flight plan from Auburn airport (KAUN) to Mather Airport (KMHR). Your filed alternate is Woodland airport O41. You will announce your departure from AUN on the local advisory frequency and contact NorCal departure on 125.4 when established in the climb. A check of Woodland weather shows 300 overcast, visibility .5 mile in fog. Wind is from 220 deg at 10 kts.

When pilot contacts NorCal Approach via cell phone—

ATC: VMS 1 is cleared to the Mather airport via direct ROZZY direct STNGR direct. Climb and maintain 4000 ft. Squawk 3521. Contact NorCal approach on 125.5 airborne.

When pilot crosses Rozzy—

ATC: VMS 1 expect RNAV Runway 22 Left approach to Mather Airport. Report inbound out of procedure turn.

When pilot crosses STNGR—

ATC: VMS 1 is cleared for the RNAV Runway 22 Left approach to the Mather airport. Contact Mather Tower 120.65 crossing VANCE.

When pilot calls tower at VANCE—

ATC: VMS 1 is cleared to land runway 22 Left. Ceiling is 200 overcast with .5-mile visibility, wind 310 deg at 15 kts.

When pilot calls the tower to advise of the missed approach—

ATC: Contact NorCal approach on 127.4 and squawk 5464.

When pilot calls ATC on 127.4—

ATC: VMS 1 is cleared to hold as published at the Sacramento VOR. Maintain 4000 ft. and expect further clearance to the Woodland airport when established in holding.

After one turn in holding and inbound to the Sacramento VOR—

ATC: VMS 1 is cleared to the Woodland airport via direct PIVSE, direct, expect the RNAV Runway 36 approach. Contact Travis approach 126.6.

Weather: Ceiling is 700 ft. MSL, visibility 5 miles. V20 to 270 deg at 15 kts.

Half way between PIVSE and CEVIT—

ATC: VMS 1 is cleared for the RNAV Runway 36 approach. Contact advisory frequency at CEVIT. Return to this frequency in the event of missed approach.

End scenario when Woodland airport is in sight.

SCENARIO 3

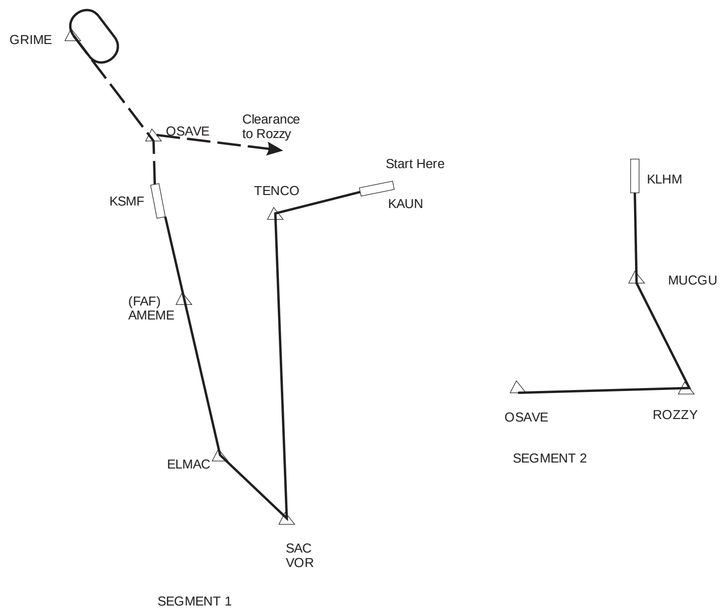


Figure 58. VMS scenario #3

Initial Condition: Auburn airport heading 250 deg at 1700 ft. MSL and 100 KIAS.

Weather: Ceiling is 2300 ft. MSL. Lower ceiling to 50 ft. after pilot goes IMC. V20 = 070 degrees at 15 kts.

Pilot Brief: You have submitted an IFR flight plan from Auburn (KAUN) to Sacramento International Airport (KSMF) at 4000 ft. Weather at AUN is a ceiling of 500 ft. AGL and visibility 3 miles. Your alternate is Lincoln (KLHM). You call ATC on your cell phone for clearance and announce departure on Unicom, 122.7.

ATC: Via Cell Phone—

VMS 1 is cleared to the Sacramento International Airport via direct to the Sacramento VOR, direct COUPS, direct ISYOH direct, and Maintain 4000 feet. Weather at Sacramento is 200 overcast visibility is .5 mile, winds from 320 degrees at 15 knots. Contact NorCal departure 125.4 airborne, squawk 0321.

Weather: Change ceiling to 100 ft. MSL and visibility .5 mile.

When pilot contacts NorCal Departure on 125.4—

ATC: VMS 1 expect the RNAV Yankee approach to runway 34 Left. Change squawk code to 5631

Approximately 5 miles before reaching the Sacramento VOR—

ATC: VMS 1 is cleared for the RNAV Yankee Approach to Runway 34 Left. Via direct ELMAC, descend and maintain 3400 ft.

When pilot crosses ELMAC—

ATC: VMS 1 Contact Capitol tower on 125.7 crossing AMEME

When pilot calls the tower—

ATC: "VMS 1 is cleared to land Runway 35 Left, report field in sight."

When pilot calls tower to announce missed approach—

ATC: Contact NorCal approach on 127.4.

After pilot contacts NorCal on 127.4—

ATC: Roger. We have your clearance to Lincoln, advise ready to copy.

When pilot advises ready to copy—

VMS 1 is cleared to Lincoln direct Rozzy, direct. Climb and maintain 3000 ft. Expect RNAV Runway 33 approach to Lincoln. Contact NorCal departure on 125.4 and squawk 2715.

Weather: V20 to 250 at 15 kts. Set ceiling to 600 ft. AGL and visibility to 3 miles.

When pilot contacts NorCal approach (verify 125.4)—

ATC: VMS 1, climb and maintain 4000 ft.

5 Miles from Rozzy—

ATC: VMS 1 is cleared for the RNAV Runway 33 approach to Lincoln. Weather at Lincoln is 500 overcast, visibility 2 miles. Contact advisory frequency at MUCGU.

Scenario ends when runway is in sight.

SCENARIO 4

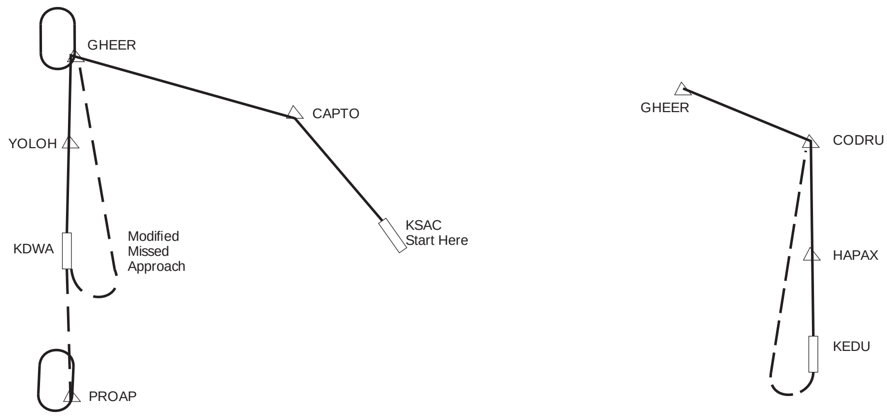


Figure 59. VMS scenario #4

Initial Condition: At SAC airport heading 340 degrees at an altitude of 200 feet MSL

Weather: Ceiling at SAC is 500 ft. AGL. Lower ceiling to 50 ft. after pilot goes IMC. V20 = 120 degrees at 15 kts.

Pilot Brief: You have submitted an IFR flight plan from Sacramento Executive airport (KSAC) direct to Yolo County Airport (KDWA) at 3000 ft. Your filed alternate airport is Davis University (KEDU). You call Sacramento tower for clearance on 119.5. Weather at Davis is 500 ft. ceiling, 1 mile visibility, wind south at 15 kts.

ATC: VMS 1 is cleared to the Yolo County airport via a climbing left turn direct CAPTO, direct GHEER, direct, Cross CAPTO at 2000 ft. and maintain 4000. Contact NorCal Departure 119.9 airborne and squawk 4610.

After reaching 2000 ft.—

ATC: We have a revised clearance, advise ready to copy.

When pilot reports ready to copy—

VMS 1 is cleared direct to the GHEER intersection, expect the RNAV Runway 16 approach to the Yolo County Airport, climb and maintain 4000 ft. Change squawk code to 5341 and contact Travis Approach Control 126.6.

When pilot calls on 126.6—

ATC: VMS 1 is cleared for the RNAV Runway 16 approach, report inbound out of procedure turn.

When pilot calls inbound—

ATC: VMS 1, change to advisory frequency crossing YOLOH, report this frequency in the event of a missed approach.

When pilot calls to report a missed approach (verify radio is set to 126.6,)—

VMS 1 Turn left direct to the GHEER intersection and hold as published, maintain 3600 feet. Expect the RNAV Rwy 17 approach to Davis University

When passing 3000 ft.—

ATC: VMS 1 advise ready to copy clearance to Davis University airport.

When pilot advises ready to copy—

ATC: VMS 1 is cleared to the Davis University airport via direct to the CODRU intersection, direct. Maintain 3000 ft. and contact Travis approach control on 119.9 and squawk 0312.

When pilot contacts Travis approach control—

ATC: VMS 1 is cleared for the RNAV Rwy 17 approach to Davis University, report inbound out of procedure turn.

When pilot reports inbound—

ATC: VMS 1 is cleared for the RNAV Runway 17 approach. Switch to advisory frequency passing HAPAX. In the event of a missed approach contact NorCal approach on 126.7.

End scenario when airport is in sight.

SCENARIO 5

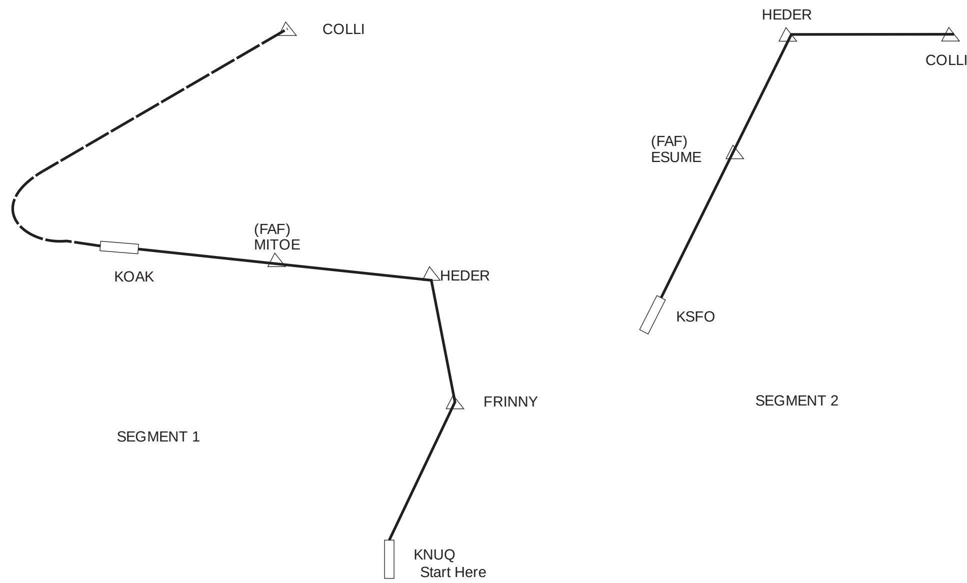


Figure 60. VMS scenario #5

Initial Condition: Moffett field (NUQ) at 200 ft. MSL heading 320 deg and 100 KIAS.

Weather at NUQ: Ceiling = 500 ft. MSL. Winds are calm.

Pilot Brief: You have submitted an IFR flight plan from Moffett field to Oakland with San Francisco as the alternate. Weather at SFO and OAK is IFR with a ceiling of 300 ft. and visibility 1 mile, wind 240 deg at 15 kts. You call Moffett tower for clearance on 119.55.

ATC: VMS1 is cleared to the Oakland airport via direct CYMBL intersection, direct, climb and maintain 5000 ft. Contact NorCal Departure 125.35, squawk 3701.

Climbing out of 2000 ft.—

ATC: VMS 1 expect the RNAV Y Runway 28 Left approach to Oakland.

Weather: Ceiling 100 ft., visibility .5 mile. V20 010 degrees at 15 kts.

Climbing out of 4000 ft.—

VMS 1 is cleared for the RNAV Y Runway 28 Left approach to Oakland via direct HEDER Intersection, descend and maintain 2800 ft. Contact Oakland tower 118.3 at VODSY. Oakland weather is 300 overcast with visibility 1 mile.

When pilot contacts Oakland tower on 118.3—

ATC: VMS 1 is cleared to land runway 28 Left.

When pilot calls tower to advise of missed approach—

ATC: Contact NorCal Departure on 127.45.

When pilot contacts NorCal—

ATC/NorCal: Advise ready to copy clearance to San Francisco.

When pilot advises ready to copy—

VMS 1 is cleared direct COLLI intersection direct BERKS, maintain 5000 ft. Expect RNAV Runway 19 Left approach to San Francisco airport.

Change wind V20 = 15 kts from 100 deg.

When over BERKS—

ATC: VMS 1 is cleared for the RNAV Runway 19 Left approach to San Frisco.

End scenario when SFO is in sight.

SCENARIO 6

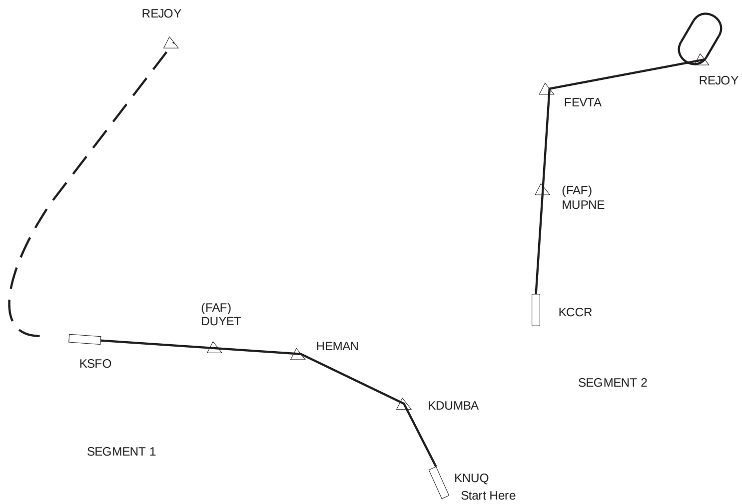


Figure 61. VMS scenario #6

Pilot brief: You have filed IFR from Moffett field (NUQ) to San Francisco (SFO) direct at 3000 ft. You call Moffett tower on 119.55 for clearance. Your filed alternate is Concord (KCCR).

Initial Condition: At NUQ heading 140 deg at 100 ft. AGL.

Weather: Ceiling 500 feet AGL and visibility 1 mile. V20 = 0.

ATC: Clearance in IC. VMS 1 is cleared to the San Francisco airport via runway heading to 2000 ft. and then left turn direct MENLO intersection direct, climb and maintain 4000 ft., squawk 7308. Contact NorCal departure on 120.1 San Francisco weather: 300 overcast, .5-mile visibility in fog, wind is 260 deg at 15 kts.

Passing 2000 ft.—

Weather: Ceiling 100 ft. V20 = 15 kts from 190 deg.

ATC: VMS 1 expect the RNAV Runway 28 Left approach to San Francisco airport. San Francisco weather is ceiling 300 ft. with RVR 2400 ft.

Crossing MENLO—

ATC: VMS 1 is cleared for the RNAV Runway 28 Left approach, contact San Francisco tower on 120.5 passing DUYET.

When pilot calls the tower on 120.5—

ATC/Tower: VMS 1 is cleared to land Runway 28 Left.

When pilot reports missed approach—

Contact NorCal Departure 134.5

ATC: Advise ready to copy clearance to Concord.

When pilot advises ready to copy—

VMS 1 is cleared to the Concord airport via REJOY intersection direct, climb and maintain 5000 ft. Turn right to a heading of 040 degrees, cleared direct REJOY when able.

Weather: V20 = 280 deg at 15 kts. Ceiling = 1200 ft. MSL. Visibility = 1.5 miles.

When REJOY is entered into the flight plan and pilot is established direct to REJOY—

VMS 1 Contact Travis Approach 119.9, squawk 4352.

When pilot calls Travis Approach—

ATC: VMS 1 Expect the RNAV Runway 19R approach to Concord Airport.

When approximately 7 miles from Rejoy—

ATC: VMS 1 is cleared direct to FEVTA intersection, descend and maintain 2000 ft.

When pilot is established direct to FEVTA intersection at 2000 ft.—

ATC: VMS 1 is cleared for the RNAV Y Runway 19R approach to Concord.

End Scenario when airport is in sight.

SCENARIO 7

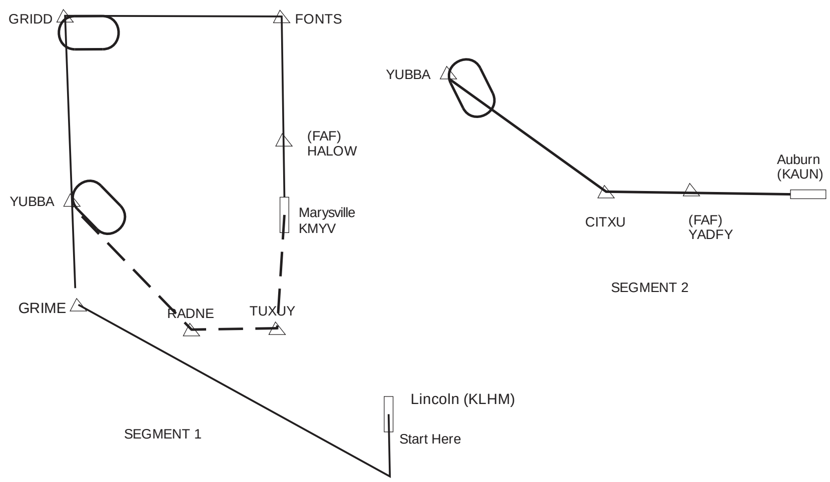


Figure 62. VMS scenario #7

Pilot brief: You have filed an IFR flight plan from Lincoln (LHM) airport direct to Yuba County airport Marysville (MYV). Your alternate is Auburn (AUN). You call NorCal approach on your cell phone for clearance. You depart Lincoln using advisory frequency of 123.0. Weather at Marysville is 400 overcast, visibility 1 mile, winds south at 15 kts.

Initial Condition: At LHM on Runway 14 heading 140 deg at 100 ft. at 100 kts.

Weather: Ceiling is 500 ft. Lower ceiling to 50 ft. after pilot goes IMC. V20 = 040 degrees at 15 kts.

ATC: VMS 1 is cleared to Marysville airport via runway heading to 2000 ft., then right turn direct to Grime intersection, V23 GRIDD intersection, FONTS, direct. Maintain 5000 ft., squawk 2364, contact NorCal on 125.9 out of 500 ft.

After crossing GRIME intersection northbound—

ATC: We have a revised clearance, advise ready to copy.

When pilot advises ready to copy—

ATC: VMS1 is cleared to hold east of GRIDD intersection on the 75-degree radial, left turns. Expect further clearance to Marysville established in holding. Expect the RNAV Runway 14 approach to Marysville.

After entering hold and crossing GRIDD westbound—

ATC: VMS 1 is cleared for the RNAV runway 14 approach to Marysville via direct Fonts. Contact advisory frequency crossing HALOW. In the event of a missed approach, contact NorCal on 124.55.

When pilot reports missed approach to NorCal (confirm 124.55 is dialed on com radio)—

ATC: VMS 1 is cleared to execute the published missed approach, report entering hold at YUBBA.

When pilot crosses RADNE (enroute to YUBBA)—

ATC: Advise when ready to copy clearance to Auburn Airport.

ATC: VMS 1 is cleared to Auburn via direct CITXU, direct. Maintain 6000 ft., squawk 3571 and contact NorCal departure on 128.75.

When pilot call NorCal—

VMS 1 Maintain 5000 ft. to CITXU.

Crossing CITXU—

VMS 1 is cleared for the RNAV Runway 7 approach to Auburn.

Weather: V20 = 160 deg at 15 kts. Ceiling = 500 ft. Visibility 2 miles.

End scenario when runway is in sight.

10 Pilot rating data

The pilot test data are shown in Figure 63.

Date	Run	Pilot	SAS	Displays	MCH	HQR	Certifiable?	SPIFR/DPIFR	FD		Sigma H	
8/30/2016	11	A	AP	Advanced	1	1	Yes	SPIFR	off	Motion	1	
30-Aug	12	B	AP	Advanced	2	2	Yes	SPIFR	off	Motion	1	
30-Aug	13	A	AP	Legacy	2	1	Yes	SPIFR	off	Motion	1	
30-Aug	14	B	AP	Legacy	2	2	Yes	SPIFR	off	Motion	1	
30-Aug	15	A	ACAH	Advanced	3	4	Yes	SPIFR	off	Motion	1	
30-Aug	16	B	ACAH	Advanced	3	3	Yes	SPIFR	off	Motion	1	
31-Aug	17	A	RCAH	Advanced	4	5	Yes	SPIFR	off	Motion	1	Repeated in Run 28
31-Aug	18	B	RCAH	Advanced	7	7	No	SPIFR	off	Motion	1	Airspeed got below 40 kts Repeated in Run 29
31-Aug	19	A	RCAH	Advanced	2	3	Yes	DPIFR	off	Motion	1	
31-Aug	20	B	RCAH	Advanced	4	4	Yes	DPIFR	off	Motion	1	
1-Sep	23	B	RCAH	Advanced	5	5	Yes	SPIFR	on	Motion	1	
1-Sep	24	A	ACAH	Legacy	2.5	3	Yes	SPIFR	off	Motion	1	
1-Sep	25	B	ACAH	Legacy	2	3	Yes	SPIFR	off	Motion	1	
1-Sep	26	A	RCAH	Legacy	2.5	4	Yes	DPIFR	off	Motion	1	
1-Sep	27	B	RCAH	Legacy	4	5	Yes	DPIFR	off	Motion	1	
2-Sep	28	A	RCAH	Advanced	2.5	4	Yes	SPIFR	off	Motion	1	First run with BO increased from 0.25lb to 0.50 lb and added deadband of 1% travel (pitch and roll both sticks)
2-Sep	29	B	RCAH	Advanced	4	5	Yes	SPIFR	off	Motion	1	Run 28 is repeat of run 17 Run 29 is a repeat of run 18
2-Sep	30	A	RCAH	Legacy	3	5	Yes	SPIFR	off	Motion	1	
6-Sep	31	B	RCAH	Legacy	4	5	Yes	SPIFR	off	Motion	1	
6-Sep	32	B	RCAH	Advanced	3	3	Yes	SPIFR	on	Motion	1	
8-Sep	56	B	BU Rate	Advanced	5.5	5	No	DPIFR	off	Fixed base	1	ok as BU
8-Sep	57	A	BU Rate	Advanced	6	5	No	DPIFR	off	Fixed base	1	ok as BU
8-Sep	58	A	BU Rate	Legacy	6	6	No	DPIFR	off	Fixed base	1	ok as BU
8-Sep	59	B	BU Rate	Legacy	6	7	No	DPIFR	off	Fixed base	1	ok as BU
8-Sep	65	B	Airspeed	Advanced	5	4.5	Yes	SPIFR	off	Fixed base	1	
8-Sep	66	B	Airspeed	Legacy	2	2	Yes	SPIFR		Fixed base	1	Added 1 kt per beep
	PHASE B											
17-Jan	104	B	ASC/RTT	Advanced	3	4	yes	SPIFR	off	Motion	1	Sigma H = 1 all runs Phase A. This is first run in Phase B
17-Jan	105	A	AP	Advanced	1	2	yes	SPIFR	off	Motion	4	
17-Jan	106	B	AP	Legacy	2	2	yes	SPIFR	off	Motion	4	Last scenario for Tuesday 1/17
18-Jan	113	A	RCAH	Advanced	4	4.5	yes	SPIFR	off	Motion	1	Some large excursions. See data
18-Jan	114	B	RCAH	Advanced	3	4	No	SPIFR	off	Motion	1	Okay as Backup system.
18-Jan	115	A	ASC/RTT	Advanced	2	3	yes	SPIFR	off	Motion	1	
18-Jan	116	B	RCAH	Advanced	5	5	No	SPIFR	on	Motion	1	Trouble with flight director logic
18-Jan	117	A	RCAH	Advanced	3	4	yes	SPIFR	off	Motion	1	Fly CTEs while Glen Knaust is here
18-Jan	119	B	ACAH	Advanced	3	3	yes	SPIFR	on	Motion	4	Look at RCAH, ACAH, ASC/RTT
19-Jan	122	A	ACAH	Legacy	3	4	yes	SPIFR	off	Motion	4	First run 1/19 1 Heading and Altitude Control
19-Jan	123/24	B	ASC/RTT	Legacy	3	3	yes	SPIFR	off	Motion	4	Vertigo due to pitching in turbulence 2 LPV Approach
19-Jan	125	A	ASC/RTT	Advanced	3	5.5	yes	SPIFR	off	Motion	4	3 LPV Decelerating Approach
19-Jan	126	B	ASRC/RTT	Advanced	3	3	Yes	SPIFR	off	Motion	4	4 Deceleration to Hover
20-Jan	152	B	BUB	Advanced	8	7	No	SPIFR	off	Motion	1	NG as BU D=2.5 pitch and 1.3 in roll 5 Speed Control Task
20-Jan	153	A	BUB	Advanced	4	5	Yes	DPIFR	off	Motion	1	D=2.5 pitch and 1.3 in roll 6 Missed Approach Task
20-Jan	154	B	RCAH	Advanced	2	3	Yes	DPIFR	off	Motion	4	
20-Jan	155	A	RCAH	Legacy	4	5	Yes	DPIFR	off	Motion	4	Might be better with advanced displays
24-Jan	161	C	AP	Advanced	2.5	1	Yes	SPIFR	off	Motion	1	First run 1/24/17 Standby gyro is not certifiable
24-Jan	162	D	AP	Legacy	2	3	Yes	SPIFR	off	Motion	1	
24-Jan	163	C	ACAH	Advanced	3	3	No	SPIFR	off	Motion	1	Certifiable for this task. We would not certify on principal (see notes) We would certify as backup system.
24-Jan	164	D	ACAH	Advanced	2	3	Yes	SPIFR	off	Motion	1	Better than some APs we have flown Okay for Part 135.
24-Jan	165	C	ACAH	Legacy	2	3	No	SPIFR	off	Motion	1	Must have coupled AP for SPIFR (to handle continencies).
24-Jan	166	D	ACAH	Legacy	2.5	3	Yes	SPIFR	off	Motion	1	Okay for SPIFR Part 135 (even tho A/P is written policy)
25-Jan	169	C	RCAR	Advanced	3	2.5	No	SPIFR	off	Motion	1	Okay as Backup system. Like attitude hold. Problems with divided attention.
25-Jan	171	D	RCAR	Advanced	4	4	Yes	SPIFR	off	Motion	1	
25-Jan	173	C	RCAR	Advanced	2.5	2.5	No	SPIFR	on	Motion	1	Okay as backup. Not as primary because WL is less if coupled
												Reduced FD theta gain and scheduled with true airspeed
25-Jan	174	D	RCAR	Advanced	5	5	Yes	SPIFR	on	Motion	1	Not tolerant of divided attention. Lot of altitude errors.
25-Jan	175	C	simple AP	Advanced	2	2	Yes	SPIFR	off	Motion	4	This is minimum acceptable for IFR if had go-around switch on collective.
25-Jan	176/177	D	simple AP	Legacy	3	4	Yes	SPIFR	off	Motion	4	Confusing on how to use combination of manual and AP but is certifiable
												Simple autopilot is HDG and ALT
1/26/2017	178	C	ASC/RTT	Advanced	2.5	2	No	SPIFR	off	Motion	1	First run 1/26 Need altitude hold for SPIFR
26-Jan	179	D	ASC/RTT	Legacy	3	4	Yes	SPIFR	off	Motion	1	Hi workload on collective due to attitude changes to hold airspeed
26-Jan	182	C	ASRC/RTT	Legacy	4	3	No	SPIFR	off	Motion	1	Not certifiable as backup system. Least desirable of all systems.
26-Jan	183	D	ASRC/RTT	Advanced	3	4	Yes	SPIFR	off	Motion	1	Had surplus attention left for additonal tasks
27-Jan	201	D	BUB	Advanced	5.5	5	No	SPIFR	off	Motion	1	D=2.5 Not certifiable as backup either (unless can declare emergency and get special handling)
27-Jan	202	C	BUB	Advanced	6	6	No	SPIFR	off	Motion	1	D=2.5 Certifiable as backup but training required. Mike Hardy copilot
27-Jan	203	D	BUB	Legacy	5	4.5	No	DPIFR	off	Motion	1	Okay for backup system DPIFR
27-Jan	204	C	BUB	Advanced	5	4.5	No	DPIFR	off	Motion	1	Okay for backup system DPIFR
27-Jan	205	D	ACAH	Advanced	4	5	Yes	SPIFR	off	Motion	5	Considerable pilot compensation due to turbulence.
27-Jan	206	C	ACAH	Legacy	7	3	No	SPIFR	off	Motion	5	Not certifiable as backup
30-Jan	207	C	AP	Advanced	2	1	Yes	SPIFR	off	Motion	5	
30-Jan	208	D	AP	Legacy	2	2	Yes	SPIFR	off	Motion	5	
30-Jan	209	C	simple AP	Legacy	3	3	Yes	SPIFR	off	Motion	5	
30-Jan	210	D	simple AP	Advanced	4	4.5	No	SPIFR	off	Motion	5	Not certifiable as primary. OK as backup - "clugy" ACAH is better
												Found problem with sidestick loaders - repeat this run
31-Jan	216	C	ASC/RTT	Advanced	6	5	No	SPIFR	off	Motion	5	Certifiable as backup - "maybe"
31-Jan	217	D	simple AP	Advanced	4	4	Yes	SPIFR	off	Motion	5	Repeat run 210 A marginal yes. Would rather have ACAH
31-Jan	218	D	ASC/RTT	Advanced	6	5.5	No	SPIFR	off	Motion	5	Not certifiable as backup. Too much theta in turbulence leading to excessive collective
1-Feb	255	C	RCAH	Advanced	4	4	No	SPIFR	off	Motion	5	Okay as backup. Not certifiable due to inadvertent large attitude excursions.
1-Feb	256	D	RCAH	Advanced	4	4	No	SPIFR	off	Motion	5	Okay as backup. Very close to being certifiable. Good FCS
1-Feb	257	C	ACAH	Advanced	3	3	No	SPIFR	off	Motion	5	Okay as backup. Not as primary because average pilot needs at least HDG+ALT A/P
2-Feb	258	C	ACAH2	Advanced	4	3	No	SPIFR	off	Motion	5	D=2.0 pitch and roll. Okay as backup. Half FAA pilots might say certifiable, but average pilot needs upper modes
2-Feb	259	D	ACAH2	Legacy	4.5	4	No	SPIFR	off	Motion	5	Okay as backup. Sluggish ACAH response. Poor pitch scale on AG.
2-Feb	271	D	RCAH	Advanced	2	4	Yes	DPIFR	off	Motion	5	Definitely certifiable
2-Feb	272	C	RCAH	Legacy	2	5	No	DPIFR	off	Motion	5	Not suitable for IFR Okay for backup
3-Feb	273	C	BUB	Advanced	6	8	No	DPIFR	off	Motion	5	Certifiable as backup DPIFR only if restrict airspeed to 120 kts. HQ very bad at high airspeed Model only good to 140.
3-Feb	290	D	BUB	Legacy	9	6	No	DPIFR	off	Motion	5	Not certifiable as backup. Several instances of large bank angle
3-Feb	291	D	RCAH	Advanced	3	3	Yes	SPIFR	on	Motion	5	Certifiable as primary system
3-Feb	292	D	ASC/RTT	Advanced	2	3	Yes	SPIFR	off	Motion	5	Complementary filter on airspeed Much better than previous ASC/RTT

Figure 63. VMS Test Results

11 References

1. Barr, N. M, Gangsas, D., and Schaffer, D. (1974). *Wind Models for Flight Simulator Certification of Landing and Approach Guidance and Control Systems*. Paper 1st Annual Meteorological and Environmental Inputs to Aviation Systems Workshop. (FAA -RD-74-206).

A Appendix A—Recommended minimum performance standards for rotorcraft with AdFC systems

HOH
AERONAUTICS
INC.

HANDLING QUALITIES FLIGHT CONTROLS FLIGHT TEST SIMULATION

Recommended Minimum Performance Standards for Rotorcraft With Advanced Flight Control (AdFC) Systems

Hoh Aeronautics, Inc. -- FAA Tech Paper 1186-1 (Rev 5)[1]

DRAFT

Roger H. Hoh

March 2016.

[1] Formerly titled Tech Paper #1

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. SCOPE

This document provides recommended minimum performance criteria that account for the flight characteristics of helicopters with advanced flight control systems (AdFC). Current CFR 14 Part 27 and Part 29 requirements do not address many of the flight characteristics that become possible with fly-by-wire flight control systems. The criteria presented herein apply to all helicopters regardless of the level of augmentation.

This document addresses the forward flight regime where AdFC would be used to obtain certification for IFR flight with one or two pilots. Certification requirements for AdFC in the nap-of-earth (NOE) low speed and hover regime are not addressed. Additional work is required to develop quantitative criteria for AdFC in the low speed and hover flight regime.

The objectives of this document are summarized as follows.

- Provide quantitative handling qualities criterion boundaries based on Cooper Harper pilot rating data from past simulations and flight tests. These ratings have been taken during research programs wherein the pilots had no vested interest in the outcome, and wherein there were highly structured tasks with well-defined desired and adequate performance limits. Wherever possible, the boundaries are based on averages from ratings by at least three pilots. The Cooper-Harper rating scale is given in Figure 18.
- Develop a methodology to use quantitative criterion boundaries for certification. The rationale for this objective is that such boundaries:

    - Provide well-defined pass-fail requirements for AdFC control laws for primary and backup flight control systems, and
    - Provide applicants with quantifiable design guidance for flight control system development, and
    - Eliminate the variability in pass-fail criteria that exists between different FAA ACOs, certification pilots, and engineers.

- Define certification flight testing deemed necessary as a sanity check on the quantitative criteria. Such testing will be accomplished using highly structured Civil Task Elements (CTEs). It is intended that certification flight testing for credit shall consist of CTEs that are agreed upon between the applicant and FAA at the outset of the program and documented in the Project Specific Certification Plan (PSCP).

    - The CTEs shall have the following characteristics.

        § Each task shall be defined in detail.

        § At least three pilots shall fly each task, and shall assign a Cooper-Harper pilot rating. The average HQR will be used to determine pass/fail.

        § Specific values of “desired performance” and “adequate performance” shall be specified for each CTE. These shall be used ensure a common level of control aggressiveness to accomplish the task. For example, if desired performance on an ILS is ± 1 dot, the evaluation pilots are forced to "tighten-up" if that deviation is exceeded. This has been shown to be a highly effective way to expose handling qualities deficiencies.

- It is intended that the certification process be primarily focused on the quantitative criteria and that the roles of CTEs are:

  - A spot-check verification of the quantitative results.
  - An evaluation method where sufficient quantitative criteria are not available (e.g., sidestick controllers).

Demonstration of compliance using quantitative criteria requires that the applicant calculate criterion parameters such as Bandwidth and Phase Delay. Such parameters are calculated from data obtained from standard test maneuvers (e.g., frequency sweeps, steps, and pulses). These may be accomplished in actual flight test or offline simulation using a validated math model of the aircraft and flight control system.

Model validation procedures used to accept Level D training simulators are considered as a viable way to verify computer models. This has the economic advantage of simultaneously providing the math model to support training simulators and for certification. The usual correlation of flight test data with the computer model is also acceptable.

The FAA establishes the minimum for safety, and it is up to the manufacturer to go beyond that to optimize the flight control system.

Separate criterion boundaries are provided to reflect what is acceptable for normal and failed states.

Separate boundaries are provided for single pilot IFR (SPIFR) and dual pilot IFR (DPIFR) in recognition of the fact that the workload reduction with a second qualified pilot allows the pilot flying to devote most of his or her attention on aircraft control. DPIFR requirements are considered as also applicable to VFR certifications. Data that supports making a distinction between SPIFR and DPIFR is given in Reference 1.

The requirements provided herein are intended to be applicable to any helicopter, whether it has AdFC or not.

IFR is intended to mean flight in IMC in this report. The category DPIFR is intended to represent IMC flight with two qualified pilots, or flight with one pilot that is technically VFR, but with marginal cueing (e.g. at night).

The requirements provided herein are to be integrated with the quantitative criteria currently in 14 CFR Part 27/29 and Part 27/29 Appendix B. It is intended to remove qualitative assessments that exist in the existing regulations, e.g., "exceptional piloting skill or alertness" and "No undue pilot fatigue or strain for duration consistent with normal operation". This is in accordance with the goal of this work to remove disparities in what is acceptable and what is not between Aircraft Certification Offices and certification pilots and to eliminate the variability with time (e.g., what was okay yesterday is not okay today).

2. REQUIREMENTS

2.1 GENERAL

Minimum performance standards for advanced flight control systems consist of two equally important elements.

1. Workload associated with closed-loop pilot control. This relates to the rotorcraft dynamics as defined by handling qualities metrics (e.g., short period frequency and damping or bandwidth and phase delay). Acceptable values of these metrics are given by the quantitative criteria in this document.

2. Workload to accomplish non-flying tasks. This is a function of the tendency of the rotorcraft to diverge from steady flight when the pilot's attention is diverted away from control of the helicopter. This includes the effect of inadvertent control inputs, e.g., the pilot leans on the cyclic when looking at an approach chart or copying a clearance. Single pilot IFR requires a high level of divided attention whereas the requirements for division of attention are less with a second qualified pilot and/or an autopilot.

Autopilot requirements are outside the scope of this document, where autopilot is defined as control of the helicopter via cockpit knobs and buttons as opposed to the cyclic, pedals, and collective. The terms autopilot and "coupled flight director" are considered to be synonymous.

2.2 BACKGROUND

The supporting data for the requirements in this document are contained in References 1–7.

While it is not intuitively obvious that handling qualities and overall workload are directly related, past research has shown that in fact they are. The argument and logic are provided in Section 2.3 of Reference 1.

Intuition tells us that having a second pilot to accomplish non-flying tasks will significantly reduce the required EWC for the pilot-flying. This was verified in a NASA-supported simulation and flight test program to study single pilot IFR workload in the mid-1980s. That research conclusively showed that IFR workload with a single pilot is significantly higher than with a qualified co-pilot. The results of that work are summarized in Reference 1 and are the basis for making a distinction between SPIFR and DPIFR in the proposed minimum performance criteria.

Advanced displays and integrated cockpits have the potential to reduce the requirement for SPIFR workload. All currently available data is based on legacy displays and flight director guidance. Work is in progress (simulation on NASA Ames VMS) to determine the effect of more advanced displays and controls. Until such data becomes available, the requirement for EWC for SPIFR and DPIFR must be based on past simulations and flight testing.

An important application of existing data is to define the minimum acceptable handling qualities for certification. In those tests, the FAA evaluation pilots were asked to provide Cooper Harper ratings as well as a decision to certify for SPIFR and DPIFR. The results of that testing are discussed in detail in Reference 1, where it is established that:

- For SPIFR the HQR should be no worse (greater) than 3.5.
- For DPIFR the HQR should be no (worse) greater than 5.

It is emphasized that compliance with the quantitative criteria is the primary method of compliance, and that FAA test pilots will only be required to provide subjective Cooper-Harper ratings as a spot check. Such ratings will be assigned using a highly structured rating procedure. The tasks will consist of well-defined Civil Task Elements (CTEs) as discussed in more detail in Section 15. The only flying to support the quantitative criteria will include pulses, steps, and frequency sweeps, or any other structured maneuvers necessary to calculate the criterion parameters.

2.3 LEVELS

The required handling qualities in normal and failed states are defined in terms of “Levels” as follows.

- Level 1 is required for the unfailed state and for failures with a “frequent” or “reasonably probable”[2] probability of occurrence (frequent is defined by $P_f > 10^{-3}$ and reasonably probable is defined by $10^{-5} < P_f \le 10^{-3}$). All probabilities are per flight hour.
- At least Level 2 is required for failures with a “remote” probability of occurrence. (Remote is defined by $10^{-7} < P_f \le 10^{-5}$).
- At least Level 3 is required for failures with an “extremely remote” probability of occurrence (extremely remote is defined by $10^{-9} < P_f \le 10^{-7}$).
- If the failure results in handling qualities that plot outside the Level 3 criterion boundaries, the failure must be “extremely improbable” ($P_f \le 10^{-9}$).

These probabilities are consistent with the values used to define the allowable flight control system failure rates for current rotorcraft certifications (see AC 29.1309 and AC 27.1309). If at a later time it is decided to relax the requirements to encourage the use of advanced displays and controls for smaller helicopters (e.g., as is done for fixed wing aircraft), that can be easily done by simply revising the above probability ranges.

The formulation of quantitative minimum performance boundaries for certification requires that a rationale be developed to associate a range of handling qualities corresponding to each of the above Levels. This is provided in Table 1.

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[2] The terms frequent, reasonably probable, remote, and extremely remote are defined in AC 29-2C, Chg 1 Subpart F – Equipment, Systems, and Installations (page F-14). See excerpt in Figure 19, Section 19.

Table 1. Definition of Levels

Level	Certifiable for Single Pilot IFR	Certifiable for Dual Pilot IFR and VFR
1	HQR $\le$ 3.5	HQR $\le$ 4.5
2	$3.5 < HQR \le 5$	$4.5 < HQR \le 6$
3	$5 < HQR \le 6$	$6 < HQR \le 7$

This table is used to develop criterion boundaries using HQR data from past and future research experiments. For example, the criterion boundary for Level 1 SPIFR is created by fairing a line midway between HQR ratings of 3 and 4. Level 1 DPIFR would be defined by fairing a curve through HQR = 4 and 5 points on the grid of criterion parameters.

The rationale to support the Table 1 definitions is provided as follows.

The Level 1 requirements are based on the supporting data in Reference 1).

The Level 2 requirements apply to failed states resulting from flight control system failures whose probability of occurrence is “remote” ($P_f \le 10^{-5}$ per flight hour). From AC 29.1309 page F18, (repeated herein as Figure 19) this probability applies to failures that are classified as “Major”. The semantics of the Major failure classification are related to Cooper-Harper scale semantics in Table 2.

Table 2. AC 29.1309 and Cooper-Harper Semantics for Major Failure

AC 29.1309 Semantics			**Cooper-Harper Semantics**	
Effect on Rotorcraft	Effect on Occupants	Effect on flight crew	**SPIFR** Applicable HQR=5 (see Table 1)	**DPIFR** Applicable HQR=6 (see Table 1)
Significant reduction in functional capabilities or safety margin	Physical distress, possibly including injuries	Physical discomfort or a significant increase in workload or in conditions impairing crew efficiency	Moderately objectionable deficiency. Adequate performance requires considerable pilot compensation.	Very objectionable but tolerable deficiencies. Adequate performance requires extensive pilot compensation

For SPIFR it is asserted that “moderately objectionable deficiencies” are acceptable (i.e., CHR = 5) in the context that it applies to a backup system that is expected to be used no more than once every 100,000 flight hours. With DPIFR, it is asserted that the pilot flying can safely accomplish the IFR tasks with very “objectionable but tolerable deficiencies” (i.e., CHR = 6), given that his or her only task is control of the helicopter.

The Level 3 requirements apply to failed states resulting from flight control system failures whose probability of occurrence is “extremely remote” ($P_f \leq 10^{-7}$ per flight hour). From AC 29.1309 (also see Figure 19) this probability of failure applies to failures that are classified as “Hazardous”. The semantics of the Hazardous failure classification are related to Cooper-Harper scale semantics in Table 3.

Table 3. AC 29.1309 and Cooper-Harper Semantics for Hazardous Failure

Effect on Rotorcraft	Effect on Occupants	Effect on flight crew	**SPIFR** Applicable HQR=6 (see Table 1)	**DPIFR** Applicable HQR=7 (see Table 1)
Large reduction in functional capabilities or safety margins (Note 1)	Serious or fatal injury to a passenger or a cabin crew member	Physical distress or excessive workload impairs ability to perform tasks accurately or completely	Adequate performance requires extensive pilot compensation	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question

Note 1. Hazardous failure conditions can include events that are manageable by the crew by use of proper procedures which, if not implemented correctly or in a timely manner, may result in a catastrophic event.

For a single pilot it is asserted that the adequate performance requires extensive pilot compensation (i.e., HQR = 6) is acceptable in the context that it applies to a backup system that is expected to be used no more than once every 10,000,000 flight hours. With two pilots, it is asserted that controllability is not in question (i.e., HQR = 7), is acceptable3 given that his or her only task is control of the helicopter.

2.4 QUANTIFICATION OF FAILURE CLASSIFICATIONS

Hazard classifications are defined in AC 29.1309 and have historically been interpreted by safety experts for each certification. As such they are subject to the background and personal opinions of such experts. It is proposed that the potential for dependence of hazard classifications on personal opinion or vested interest can be circumvented by quantifying them in terms of the minimum performance criterion boundaries. To accomplish this we assert the following.

- Failures that result in calculated handling qualities parameters that meet Level 1 criterion boundaries are classified as Minor. It is not necessary to calculate the probability of failures that result in handling qualities that meet the Level 1 criterion boundaries. AC 29.1309 (AC 29.1309-2 page F-18 – also see Figure 19) does not require the calculation of probabilities for Minor failures.

- Failures that result in one or more calculated handling qualities parameters that fall outside the Level 1 but inside the Level 2 criterion boundaries are classified as Major. This means that a failure that results in handling qualities that fall in the Level 2 region of a criterion must have a probability of occurrence of $\leq 10^{-5}$ per flight hour.
- Failures that result in calculated handling qualities parameters that fall in the Level 3 region of one or more criterion boundaries are classified as Hazardous. This means that a failure that results in handling qualities that fall in the Level 3 region must have a probability of occurrence of $\leq 10^{-7}$ per flight hour.
- Failures that result in handling qualities that fall outside the Level 3 region of one or more criterion boundaries are classified as Catastrophic. This means that a failure that results in handling qualities that fall outside the Level 3 region must have a probability of occurrence of $\leq 10^{-9}$ per flight hour. There is very little data to support a boundary between Level 3 and loss of control. In most cases a rating of Catastrophic is based on policy rather than data. For example, a full authority hardover failure or jammed flight controls are essentially always rated as Catastrophic. Where there is a question or disagreement, it will be necessary to accomplish ground-based simulation (flight test being impractical due to safety considerations).

These definitions provide a quantitative methodology to assign FHA hazard classifications for each specified AdFC failure mode. This only applies to AdFC failures that are seen by the pilot as degraded handling qualities, and does not account for other factors that might affect the hazard rating. For that reason, the hazard levels determined from this methodology are considered minimum. For example, if the handling qualities parameters for a failed state fall in the Level 2 region of the criterion parameters the assigned hazard is at least major. If there are other factors resulting from the failure (e.g., loss of some displays), it may be necessary to upgrade the hazard level to Hazardous, or even Catastrophic.

These concepts are summarized in Table 2.

Table 4. Failure Classification as Function of Handling Qualities Level

Minimum Failure Classification	Failure Classification Description (AC 29.1309)	Required Levels and Corresponding Cooper Harper Semantics. (Reference Table 1 and Figure 18)	Probability of Failure per flight hour
Minor	Failure conditions that would not significantly reduce aircraft safety, and would involve crew actions that are well within their capabilities. Minor failure conditions may include, for example: a slight reduction in safety margins or functional capabilities, a slight increase in crew workload, such as, routine flight plan changes, or some inconvenience to occupants	**Level 1** VFR and dual pilot IFR Between “minor but annoying” and “moderately objectionable deficiencies”. Single pilot IFR Between “minimal” and “moderate” pilot compensation required for desired performance”	No requirement
Major	Failure conditions that would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example: a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries	**Level 2** VFR and dual pilot IFR “Very objectionable but tolerable deficiencies” “Adequate performance requires extensive pilot compensation” Single pilot IFR “Moderately objectionable deficiencies” “Adequate performance requires considerable pilot compensation”	$P_f \leq 10^{-5}$
Hazardous	Failure conditions that would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be: (1) A large reduction in safety margins or functional capabilities. (2) Physical distress or higher workload such that the flight crew could not be relied on to perform their tasks accurately or completely. (3) Adverse effects on occupants, including serious or potentially fatal injuries, to a small number of those occupants.	**Level 3** VFR and dual pilot IFR “Major deficiencies” “Adequate performance not attainable with maximum pilot compensation” “Controllability not in question”. Single pilot IFR “Very objectionable but tolerable deficiencies” “Adequate performance requires extensive pilot compensation”	$P_f \leq 10^{-7}$
Catastrophic	Failure conditions that would prevent continued safe flight and landing.	Ranges from “Considerable pilot compensation required to retain control” to “control will be lost”	$P_f \leq 10^{-9}$

These definitions are in the context that the goal is to define the minimum performance standards for safe operation. Ideally, manufacturers will produce systems that exceed these minimums, especially for the Level 1 primary flight control system.

Two common ways that this table would be used in practice are illustrated below.

1. Determine the Level of handling qualities following the failure (i.e., when a backup system is active), and use the table to determine the allowable probability of that failure, This means:

   a. If the backup system parameters[3] plot in the Level 1 region of the quantitative criteria, the failure is classified as at least minor and the probability of the failures that lead to this backup system can be greater than 10^{-5}.
   b. If the backup system parameters plot in the Level 2 region of the quantitative criteria, the failure is classified as at least Major and the probability of the failures that lead to this backup system must be equal to or less than 10^{-5}.
   c. If the backup system parameters plot in the Level 3 region of the quantitative criteria, the failure is classified as at least Hazardous and the probability of the failures that lead to this backup system must be equal to or less than 10^{-7}.
   d. If the backup system results in points that fall outside the Level 3 boundary on any criterion it is classified as Catastrophic and failures that lead to this backup system must be equal to or less than 10^{-9}

2. The corollary to 1 is: Given the probability of failure leading to reversion to the backup system, determine the required handling qualities Level. This means:

   a. If $P_f > 10^{-5}$ the handling qualities of the backup system must be Level 1. (i.e., the backup system parameters must plot in the Level 1 region of the quantitative criteria).
   b. If $P_f > 10^{-7}$ the handling qualities of the backup system must be Level 2 or better.
   c. If $P_f > 10^{-9}$ the handling qualities of the backup system must be Level 3 or better.
   d. If $P_f \le 10^{-9}$ there is no requirement

Note that the "backup system" could be the unaugmented helicopter.

2.5 SUMMARY OF METHODOLOGY

1. Using flight test or simulation data, calculate the handling qualities parameters for flight conditions that represent the entire flight envelope and loadings in the unfailed state. Emphasize critical conditions such as maximum aft and forward center of gravity points.
2. Plot the parameters on the boundaries specified in Sections 3 through 14. This defines the Level. Note that some cases the Level 1 boundaries are different for SPIFR and DPIFR.
3. All primary flight control systems must be Level 1.
4. Determine if the Level for each backup flight control system meets the probability of failure requirement in Table 4.

[3] Backup system parameters refer to the handling qualities metrics (e.g., Bandwidth or short period frequency and damping) that are calculated from rotorcraft responses when the backup system is active

5. Accomplish flight evaluations of the CTEs defined in Section 15 (sanity check). The pass/fail criteria are defined in Table 1. Such flight evaluations should consist of a small subset consisting of worst-case conditions.

3. RESPONSE CHARACTERISTICS

Quantitative criteria are given in this section and sections 4 through 14. The source of supporting data is given for each criterion. In many cases the origin of the criterion is the military rotorcraft flying quality specification ADS-33E-PRF and its Background Information and User Guide (BIUG) (Reference 3). The paragraph number in ADS-33E-PRF may not exactly correspond to the section number in the BIUG. That is because the paragraph numbers changed slightly with revisions of the specification subsequent to Rev C when the BIUG was published. Additional information regarding ADS-33E-PRF criteria can be obtained from Reference 2, "Test Guide for ADS-33E-PRF".

Criteria are taken from ADS-33E-PRF only when the supporting data are applicable to civil rotorcraft operations.

3.1 REQUIRED RESPONSE TO CYCLIC INPUTS—LEVEL 1 SPIFR

This requirement is to satisfy the need for unattended operation wherein the pilot's attention is diverted away from control of the rotorcraft. This includes the possibility that the pilot may inadvertently lean on the cyclic while looking at an approach plate, copying a revised clearance, etc.

> A step cockpit pitch or roll controller force input shall produce a time response with respect to the trimmed pitch attitude or bank angle that reaches steady state, or peaks in 6 seconds or less, and asymptotically approaches a constant value, that is equal to or less than the peak value and has the same sign as the peak value. This requirement shall apply for cyclic force inputs equal to at least three pounds or a deflection of one inch, whichever is less.

An example of pitch or roll attitude responses that satisfy and do not satisfy this requirement is given in Figure 3.

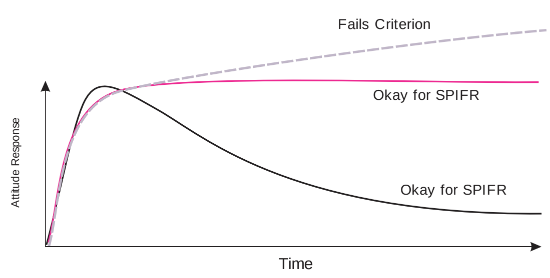

Figure 3. Example Attitude Responses to Step Cyclic Controller Input

Meeting the longitudinal cyclic position and force gradient and return to trim requirements for Level 1 SPIFR in Section 4.1 is acceptable in lieu of meeting this requirement.

This requirement was taken from ADS-33E-PRF, paragraph 3.2.8. Support for this requirement can be found in Reference 1 and in Reference 3.

3.2 REQUIRED RESPONSE TO ATMOSPHERIC TURBULENCE (LEVEL 1 SPIFR)

Experiments have shown that safe flight in IMC with moderate or greater turbulence requires that the flight control system provides turbulence rejection. The following requirements provide turbulence rejection for flight control systems that are designed to hold bank angle, pitch attitude, heading, or airspeed.

3.2.1 Roll Attitude Disturbance Response – Level 1 SPIFR

The time response of bank angle response to a pulse input shall be as illustrated in Figure 4.

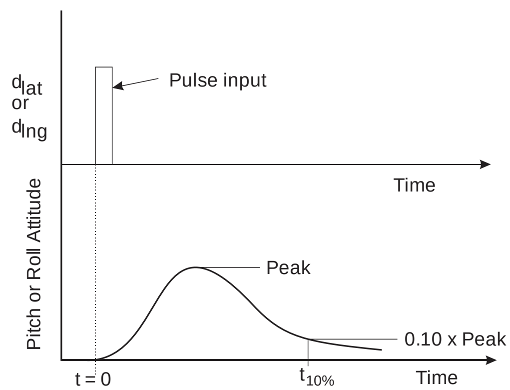

Figure 4. Response to Pulse Input for.

Starting at a trimmed bank angle, the pulse input shall be inserted directly into the control actuator, unless it can be demonstrated that a pulse cockpit controller input will produce the same response[4]. The bank angle shall return to the trimmed state within 10% of the peak or one degree whichever is greater in less than 10 seconds. The size of the input shall be such that the peak bank angle excursion is at least 10 degrees away from trim.

This requirement is taken from ADS 33E-PRF, Para 3.2.7 (see Reference 3, (Section 3.2.6) for supporting data).

The disturbance rejection criterion of Section 4.3 must be also be complied with. Support for the Section 4.3 criteria is found in Reference 2.

[4] For example, if there is no command-path shaping in the flight control system, the response to the cyclic and actuator would be the same.

3.2.2 Airspeed Hold

Following a displacement from the trim airspeed, the rotorcraft must return to trim within 10% of the trim airspeed when displaced by the amounts specified in Section 4.1.1 (a) through (e). The time required to return to trim is implicit in the dynamic criteria in Section 4.4.

The displacement from trim airspeed to test for compliance cannot be made with cyclic. It will be necessary to accomplish the deviation from trim airspeed with collective, or by using offline simulation.

This requirement is taken from the existing FAA criterion in CFR 14 Part 29 Appendix B, paragraph B29.4.

The disturbance rejection criterion of Section 4.4 must be also complied with. Support for the Section 4.4 criteria is found in Reference 2.

3.2.3 Heading Hold with Pedals

Heading hold with pedals is normally confined to low speed and hover. However, there are examples where the AdFC may employ heading hold with pedals in forward flight. For instance, heading hold may be employed during the final portion of a decelerating ILS or LPV approach to very low groundspeeds (e.g., V_{mini} = 20 kts has been tested). The flight control system architecture for this task is to convert from turn coordination to wing-low to compensate for a crosswind. The advantage of this is that the landing area will appear straight ahead at breakout.

There are currently no data to support the dynamics of this Response-Type. It is characterized by minimal change in heading in response to changes in bank angle. It is recommended that this be evaluated by FAA test pilots as the decelerating precision approach CTE.

3.3 AUTOPILOT AS AN ALTERNATE MEANS OF COMPLIANCE

Autopilot (aka coupled flight director) modes are an acceptable alternative to meeting the SPIFR response characteristics. However, it must be demonstrated that the pilot interface with the autopilot modes is intuitive and meets all current FAA requirements for autopilots.

In practice it is expected that most applicants will supply an autopilot as the primary system for IFR. The probability of failure of a single-string autopilot is on the order of 10^{-4}. It follows from Table 4 that failure of the autopilot must be followed by a reversion to a backup system that meets the Level 1 quantitative criterion boundaries. This could be achieved with any flight control system that meets the Level 1 performance criteria (e.g., attitude command attitude hold with Level 1 dynamics for SPIFR and simple rate damping for DPIFR). The reversion from flight with a full autopilot to a manually flown AdFC is a degradation, but one that is acceptable by this methodology.

As an example, consider a single string autopilot with no backup system. While no existing helicopter could pass the SPIFR level 1 criteria, some helicopters might fall in the Level 1 criteria for DPIFR. A piloted simulation is planned to determine the impact of advanced displays on this process.

4. REQUIRED ROTORCRAFT DYNAMICS – PITCH AXIS

4.1 SMALL AMPLITUDE PITCH RESPONSE TO LONGITUDINAL CONTROLLER INPUT

The requirements on short term dynamics are defined by limits on Bandwidth and Phase Delay parameters as shown in Figure 5 and by the limits in Table 5.

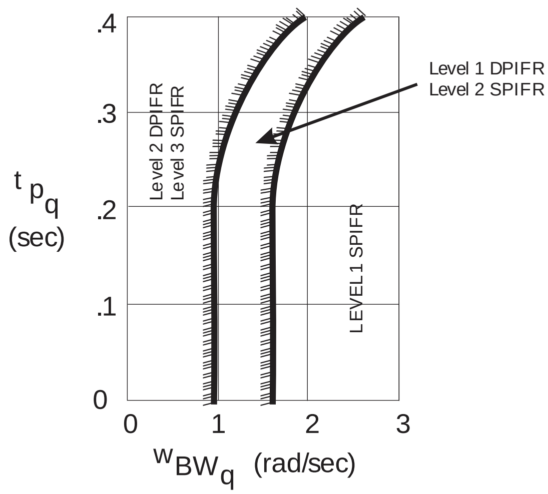

Figure 5. Requirements for small amplitude pitch attitude changes

Table 5. Small Amplitude Pitch Axis Requirements

	Level 1 SPIFR	Level 1 DPIFR and Level 2 SPIFR	Level 2 DPIFR and Level 3 SPIFR
Bandwidth (w_{BW_q}) and Phase Delay (t_{p_q})	Figure 5	Figure 5	Figure 5
Short Term Damping, z	³ 0.35	³ 0.25	³ 0.25
Phugoid frequency, w_p - rad/sec	None	w_p <0.50 rad/sec for z_p < 0.25	w_p <1.00 rad/sec for z_p < 0.25
Phugoid damping, z_p	³ 0.35	See time to double.	See time to double.
Time to double amplitude following small cyclic pulse - seconds	NA	14	8
Cyclic positon gradient – in/kt[5]	³ 0.045*	³ 0	³ 0
Cyclic force gradient – lb/in	³ 0.50*	³ 0	³ 0
Return to trim when cyclic is released at an airspeed away from trim.	10% of trim speed	None.	None.

[5] Based on sign convention that forward cyclic is positive.

* These gradients are based on test data with a center mounted cyclic. Until such data is obtained with a side-stick it will be necessary to verify acceptability during performance of CTEs. It is recommended that in the interim, use of these values provides a reasonable starting point for design purposes.

The bandwidth values are for the pitch attitude-to cyclic position frequency response.

Short term damping refers to oscillations that occur in the vicinity of the Bandwidth frequency.

Phugoid frequency and damping refers to any oscillations that occur well below the bandwidth frequency. If such oscillations are nonlinear, the requirement applies to each cycle of the oscillation.

The time to double amplitude criterion assumes that the cyclic is constrained by the pilot's hand following the pulse input.

The sources of support for these requirements are provided below.

- Supporting data for the Bandwidth criterion is found in the ADS-33 BIUG, (Reference 3, section 3.4.1.1). The rationale for a revision of the Level 2 ADS-33E-PRF boundary is given in Reference 1.
- Short Term Damping is from ADS-33E-PRF Paragraph 3.4.1.2 for Level 1. The requirement of the Level 2 damping ratio of 0.25 is taken from the fixed-wing specification Mil-Std 1797A, paragraph 4.2.1.2. This also confirms 0.35 as the minimum damping ratio for Level 1. That specification and supporting data is Reference 4.
- Cyclic position and force gradients are from Reference 1. There it is shown that the need for the required cyclic position gradient is exposed with flight in turbulence. Flight in smooth air does not exhibit a strong need for a cyclic position gradient.
- The return to trim requirement is the current IFR regulation for Appendix B, Paragraph 29.4 "Static Longitudinal Stability".
- The time to double amplitude and restrictions on phugoid frequency for $z_p < 0.35$ requirements are derived in Reference 1.

See Appendix A for the definition of Bandwidth.

These requirements must be met for the following flight conditions. (These are identical to 14 CFR Part 27/29 Appendix B Paragraph B29.4).

(a) Climb – must show stable force gradient for $\pm$ 20 kts about trim when:

(1) Trimmed at VYi

(2) Landing gear retracted

(3) Power for limit climb rate (at least 1000 ft/min) at VYi or max continuous power whichever is less.

(b) Cruise – 0.7 to 1.1 VH or VHi not to exceed 20 knots from trim with power to achieve 0.9VH

(c) Slow Cruise – 0.9 to 1.3 Vmini or 20 knots above trim speed with power to achieve 1.1 Vmini

(d) Descent – $\pm$20 knots from trim when trimmed at 0.8Vnei with power set to achieve sink rate of 1000 ft/min and gear down

(e) Approach – 0.7Vapp to 0.7Vapp+20 knots when trimmed at Vapp for three degree glideslope and for steepest glideslope for certification.

4.2 MODERATE AMPLITUDE PITCH RESPONSE TO LONGITUDINAL CONTROL INPUTS (ATTITUDE QUICKNESS)

The ratio of peak pitch rate to change in pitch attitude, $q_{pk}/\Delta\theta_{pk}$, shall meet the limits specified in Figure 6. The required attitude changes shall be made as rapidly as possible from one steady attitude to another without significant reversals in the sign of the cockpit control input relative to the trim position. The attitude changes required for compliance with this requirement shall be at least 10 degrees.

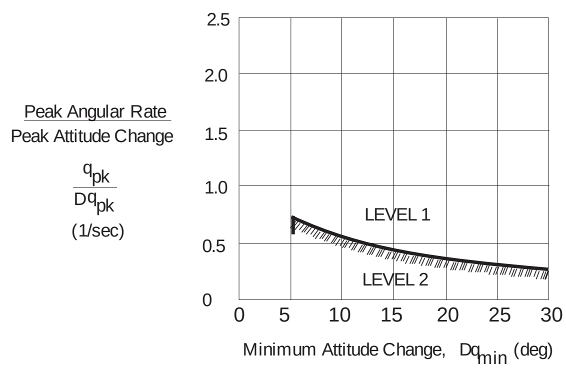

Figure 6. Moderate Amplitude Pitch Response Requirement

The purpose of this "attitude quickness" criterion is to ensure that there is no rate limiting in the AdFC. Such rate limiting has been identified as a common cause of pilot induced oscillations (PIO) in highly augmented aircraft (e.g., V22 lateral PIO). This requirement was taken from ADS-33E-PRF, paragraph 3.3.3. It is the least stringent boundary from that specification, and is judged to be applicable to civil helicopters as a means to minimize the possibility of PIO due to rate limiting. Supporting data for this requirement is found in Reference 3.

This requirement was restricted to groundspeeds below 45 kts in ADS-33E-PRF. However, experience gained since the publication of ADS-33E-PRF has shown that the attitude quickness requirement is a powerful tool to minimize the potential for PIO. On that basis it is included herein at all speeds.

An illustration of the time response parameters in Figure 6 is given in Figure 7

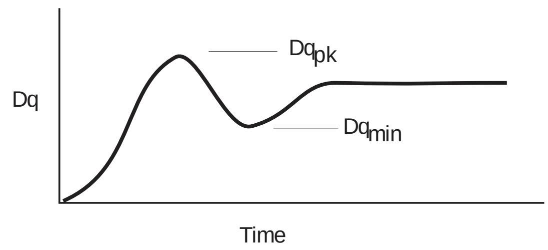

Figure 7. Attitude Quickness Parameters

4.3 DISTURBANCE REJECTION FOR ATTITUDE HOLD (AH) RESPONSE TYPES – (SPIFR)

The disturbance rejection bandwidth (DRB) and disturbance rejection peak (DRP) for pitch attitude shall be:

$DRB_{\theta} \geq 0.5$ rad/sec
$DRP_{\theta} \leq 5\, dB$

See Appendix B for definition of DRB and DRP.

Reference 2 provides support for this requirement.

4.4 DISTURBANCE REJECTION FOR VELOCITY (AIRSPEED) HOLD RESPONSE TYPES – (SPIFR)

The disturbance rejection bandwidth (DRB) and disturbance rejection peak (DRP) for airspeed shall be:

$DRB_{V} \geq 0.34$ rad/sec
$DRP_{V} \leq 5\, dB$

See Appendix B for definition of DRB and DRP.

Reference 2 provides support for this requirement.

5. MANEUVERING STABILITY (LEVEL 1 SPIFR)

The following maneuvering stability requirements shall apply at all airspeeds greater than 45 knots.

These requirements are taken from ADS-33E-PRF paragraph 3.4.1.3 and supporting data and rationale is found in Reference 3.

5.1 CONTROL FEEL AND STABILITY IN MANEUVERING FLIGHT AT CONSTANT SPEED

In steady turning flight at constant airspeed, and in pull-ups and push-overs, for Levels 1 and 2 there shall be no tendency for the rotorcraft pitch attitude or angle of attack to diverge aperiodically. For the above conditions, the incremental control force required to maintain a change in normal load factor and pitch rate shall be in the same sense (aft force – more positive load factor, forward force – more negative load factor) as those required to initiate the change. These requirements shall apply for all local gradients.

5.2 CONTROL FORCES IN MANEUVERING FLIGHT (LEVEL 1 SPIFR)

During past flight testing, pilots have commented that positive maneuvering stability in term of cyclic stick force per g provides a necessary cue that is missing in many helicopters. That testing resulted in the following quantitative criteria.

The variations in longitudinal cockpit control force with steady-state normal acceleration shall meet the following requirements.

a. For centerstick controllers, the local force gradient, Fs/n, shall be at least 3 lb/g and no greater than 15 lb/g.
b. For sidestick controllers, the local force gradient shall be at least 3 lb/g and no greater than 6 lb/g.
c. The local slope of Fs vs. n should be relatively constant over a range of normal accelerations from -.5 to positive 2 g's. A variation of more than 50 percent shall be considered as excessive. If pushovers are prohibited (e.g., due to mast bumping with teetering rotors), demonstration is only required from -0.8 to 2 g's.

In addition, the phase of the longitudinal cockpit controller position shall not lead the phase of the control force at any frequency below 5 rad/sec.

This requirement was taken from ADS-33E-PRF, Paragraph 3.4.1.3.2. Supporting data may be found in the ADS-33 Background Information and User Guide - Reference 3.

6. PITCH ATTITUDE-COLLECTIVE COUPLING – (LEVEL 1 SPIFR)

This requirement is based on data that indicates that excessive pitch-to-collective coupling adversely affects workload for precision instrument approaches.

Small Collective Inputs

The peak change in pitch attitude from trim, $\Delta\theta_{peak}$, occurring within the first 3 seconds following a step change in collective causing less than 20% torque change shall be such that the ratio $\left|\Delta\theta_{peak}/\Delta n_{z_{peak}}\right|$ is no greater than 1 deg/ft/sec^2. $\Delta n_{z_{peak}}$ is the peak change in normal acceleration from 1g flight.

Large Collective Inputs

The peak change in pitch attitude from trim, $\Delta\theta_{peak}$, occurring within the first 3 seconds following a step change in collective resulting in greater than or equal to 20% torque change shall be such that the ratio $\left|\Delta\theta_{peak}/\Delta n_{z_{peak}}\right|$ is no greater than 0.5 deg/ft/sec^2 in the up direction and 0.25 deg/ft/sec^2 in the down direction.

These requirements are taken from ADS-33E-PRF Paragraph 3.4.5.1. Supporting data may be found in Reference 3, Paragraph 3.4.4.1.

7. FLIGHT PATH CONTROL—(LEVEL 1 SPIFR)

When operating at airspeeds on the frontside of the power required curve Section 7.1 shall apply. For operation at airspeeds on the backside of the power required curve, or when the requirements of Section 7.1 cannot be met, Section 7.2 shall apply. For the purpose of this requirement, frontside operation shall be defined when the slope of the steady-state response of flight path angle vs. airspeed, $\Delta\gamma_{ss}/\Delta V_{ss}$, resulting from a step change in pitch attitude, with collective held fixed, is negative. Backside operation shall be defined when this slope is positive or zero.

Alternatively, the applicant may set the airspeed for backside to frontside transition. This allows the autopilot or AdFC control laws to be tailored to the rotorcraft flight characteristics. For example, an autopilot or AdFC may be programmed to control flight path with collective at airspeeds well above where $\Delta\gamma_{ss}/\Delta V_{ss}$, transitions from positive to negative.

7.1 FLIGHT PATH RESPONSE TO PITCH ATTITUDE (FRONTSIDE)

The vertical rate response shall not lag the pitch attitude response, with the collective controller held fixed, by more than 45 degrees at all frequencies below 0.40 rad/sec for Level 1 and 0.25 rad/sec for Level 2. This requirement ensures adequate flight path response to pitch attitude changes.

This requirement is taken from ADS-33E-PRF paragraph 3.4.3.1. Supporting data is found in Reference 3 paragraph 3.4.3.1.

For frequencies at and above the bandwidth frequency the vertical rate response shall lag the pitch attitude response by at least 52 degrees for Level 1 and 37 degrees for Level 2. This part of the requirement ensures that the flight path response to a pitch attitude change is not overly abrupt[6].

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[6] This effect has historically been taken into account with the Control Anticipation Parameter ($CAP = \omega_{sp}^2/(n/\alpha)$) or equivalently $\omega_{sp}T_{\theta 2}$ (e.g. see Reference 4, paragraph 4.2.1.2). It is defined here as a minimum lag between pitch attitude and flight path to avoid the necessity for defining a short period frequency (which may not exist for many AdFC architectures).

This requirement was taken from Reference 5. The data in that reference is based on fixed wing STOL aircraft in the power approach flight condition, but is judged to be applicable to any aircraft in the approach-to-landing flight condition.

7.2 FLIGHT PATH RESPONSE TO COLLECTIVE CONTROLLER (BACKSIDE)

The vertical rate response shall have the form specified by the following equation for at least 5 seconds following a step collective input with hands off the cyclic control.

$$\frac{\dot{h}}{\delta_c} = \frac{K e^{-(\tau_{\dot{h}_{eq}} s)}}{T_{\dot{h}_{eq}} s + 1}$$

The requirements on the criterion parameters are as follows.

$$T_{\dot{h}_{eq}} \le 5.0 \text{ sec}$$

$$\tau_{\dot{h}_{eq}} \le 0.20 \text{ sec}$$

These parameters may be obtained by means of an equivalent system fit as defined in Appendix C. The coefficient of determination, r^2, shall be greater than 0.97 and less than 1.03 for compliance with this requirement. This fitting process may be accomplished using other methods with concurrence by the FAA.

This requirement is taken from ADS-33E-PRF, paragraph 3.4.3.2, and the supporting data is found in Reference 3, paragraph 3.4.3.

8. REQUIRED ROTORCRAFT DYNAMICS – ROLL AXIS

8.1 ROLL RESPONSE TO SMALL AMPLITUDE ROLL CONTROLLER INPUTS

Short Term Dynamics

The requirements on short term dynamics are defined by limits on Bandwidth and Phase Delay parameters as shown in Figure 8.

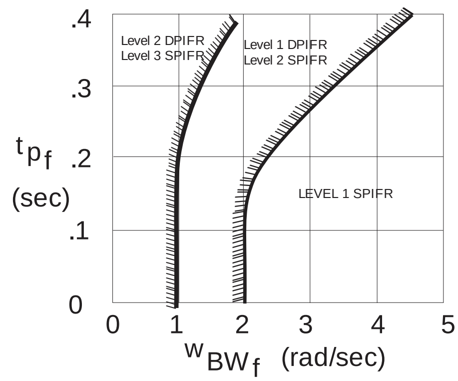


Figure 8. Requirements for small amplitude roll attitude changes

These Bandwidth requirements are taken from ADS-33E-PRF, paragraph 3.4.5.4. Supporting data is found in Reference 3, paragraph 3.4.5.1. The rationale for revising the Level 2 boundary from ADS-33E-PRF is given in Reference 1. The bandwidth values are for the frequency response of the roll attitude response to cyclic position.

Long Term Dynamics

For Level 1 SPIFR, the longer term response to a roll controller pulse must have the characteristics defined in Section 3.1.

For DPIFR and Level 2 SPIFR the time for the bank angle to double amplitude following a small lateral controller pulse shall be greater than 14 seconds.

For Level 2 DPIFR or Level 3 SPIFR or DPIFR the time for the bank angle to double amplitude following a small lateral controller pulse shall be greater than 6 seconds.

The time to double amplitude requirements are derived in Reference 1.

8.2 MODERATE AMPLITUDE ROLL RESPONSE TO LATERAL CONTROLLER INPUT (ATTITUDE QUICKNESS)

The ratio of peak roll rate to change in roll attitude, $(p_{pk}/\Delta\phi_{pk})$, shall meet the limits specified in Figure 9. The required attitude changes shall be made as rapidly as possible from one steady attitude to another without significant reversals in the sign of the cockpit control input relative to the trim position. The roll attitude changes required for compliance with this requirement shall be at least 20 degrees.

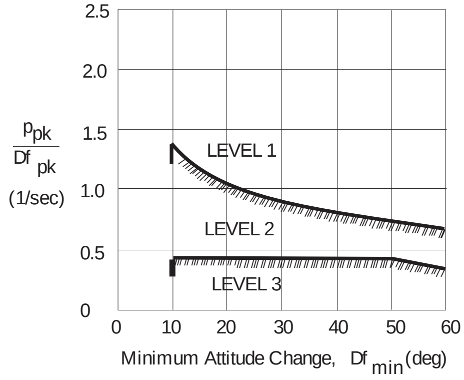


Figure 9. Moderate Amplitude Roll Response Requirement

This requirement was taken from ADS-33E-PRF, paragraph 3.4.6.2. Supporting data is found in Reference 3, paragraph 3.4.5.2.[7] The primary objective of this "attitude quickness" criterion is to prevent PIO due to actuator rate limiting.

8.3 LARGE AMPLITUDE ROLL ATTITUDE CHANGES

The achievable attitude change from trim shall be at least as specified in Section 8.3.1 for bank angle command flight control systems, and the achievable roll rate shall be at least as specified in Section 8.3.2 for other Response-Types. Yaw control may be used to reduce sideslip that retards roll rate but not to produce sideslip that augments roll rate.

These requirements are adapted from ADS-33E-PRF, paragraph 3.4.6.1. Supporting data is found in Reference 3, paragraph 3.4.5.3.

8.3.1 For Bank Angle Command Flight Control Systems

The achievable bank angle shall be at least ± 25 degrees for Level 1 and ± 15 degrees for Level 2.

A bank angle command system is defined when the steady state bank angle is proportional to lateral cyclic deflection.

8.3.2 For all other Flight Control Systems

The achievable roll rate shall be at least ± 15 deg/sec for Level 1 and ± 12 degrees for Level 2.

8.4 ROLL AXIS DISTURBANCE REJECTION – (LEVEL 1 SPIFR)

The disturbance rejection bandwidth (DRB) and disturbance rejection peak (DRP) for roll attitude shall be:

---

[7] Paragraph numbers sometimes differ between the ADS-33 BIUG and ADS-33E-PRF due to revisions in ADS-33 after the BIUG was written at the revision C level.

$DRB_{\phi} \geq 0.9$ rad/sec

$DRP_{\phi} \leq 5\,dB$

See Appendix B for definition of DRB and DRP.

This requirement is taken from Reference 2.

9. REQUIRED ROTORCRAFT DYNAMICS – YAW AXIS

9.1 YAW RESPONSE TO YAW CONTROLLER INPUT

The requirements specified in Part 29 are adequate for AdFC with the caveat that the turn coordination requirements of Section 12.2 and the lateral directional requirements of Section 10 must be met.

9.2 YAW AXIS DISTURBANCE REJECTION – (LEVEL 1 SPIFR)

See Appendix B for definition of DRB and DRP.

The disturbance rejection bandwidth (DRB) and disturbance rejection peak (DRP) for sideslip shall be:

$DRB_{\beta} \geq 0.7$ rad/sec

$DRP_{\beta} \leq 5\,dB$

This requirement is taken from Reference 2.

9.3 HEADING HOLD DISTURBANCE REJECTION (LEVEL 1 SPIFR)

This applies for the heading hold Response-Type (Section 3.2.3).

The disturbance rejection bandwidth (DRB) and disturbance rejection peak (DRP) for heading shall be:

$DRB_{\psi} \geq 0.7$ rad/sec

$DRP_{\psi} \leq 5\,dB$

This requirement is taken from Reference 2.

10. LATERAL DIRECTIONAL STABILITY

The frequency, ω_n, and damping ratio, ζ, of lateral-directional oscillations following a yaw control pulse shall meet the Figure 10 criterion boundaries. This requirement shall also be met for a roll control pulse input. For SPIFR the requirement shall be met with the controls fixed and with them free. For DPIFR the requirement shall be met with the controls fixed. If the oscillation is nonlinear with amplitude, the requirement shall apply to each cycle of the oscillation.

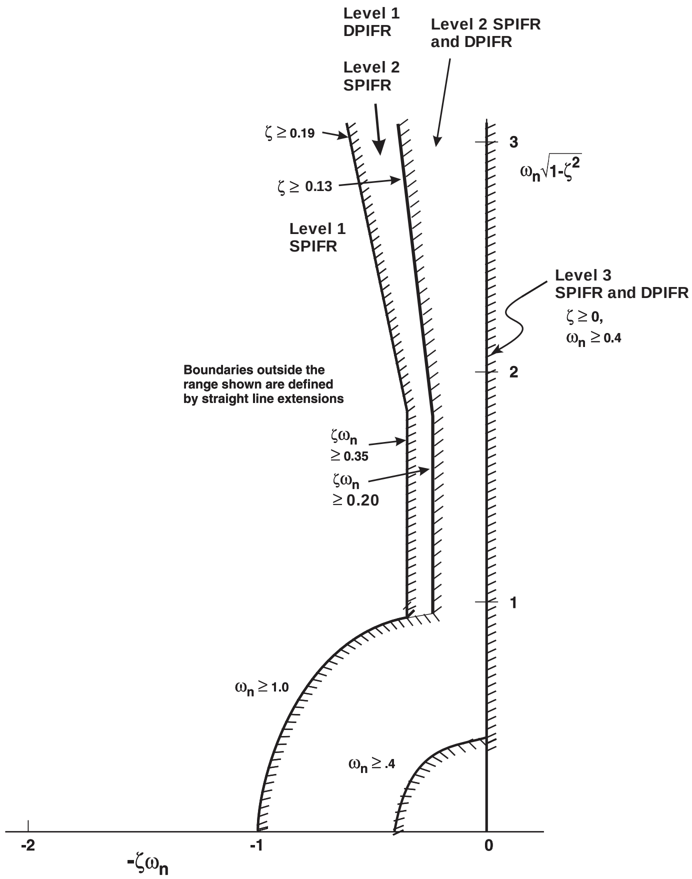


Figure 10. Limits on Lateral Directional Oscillations

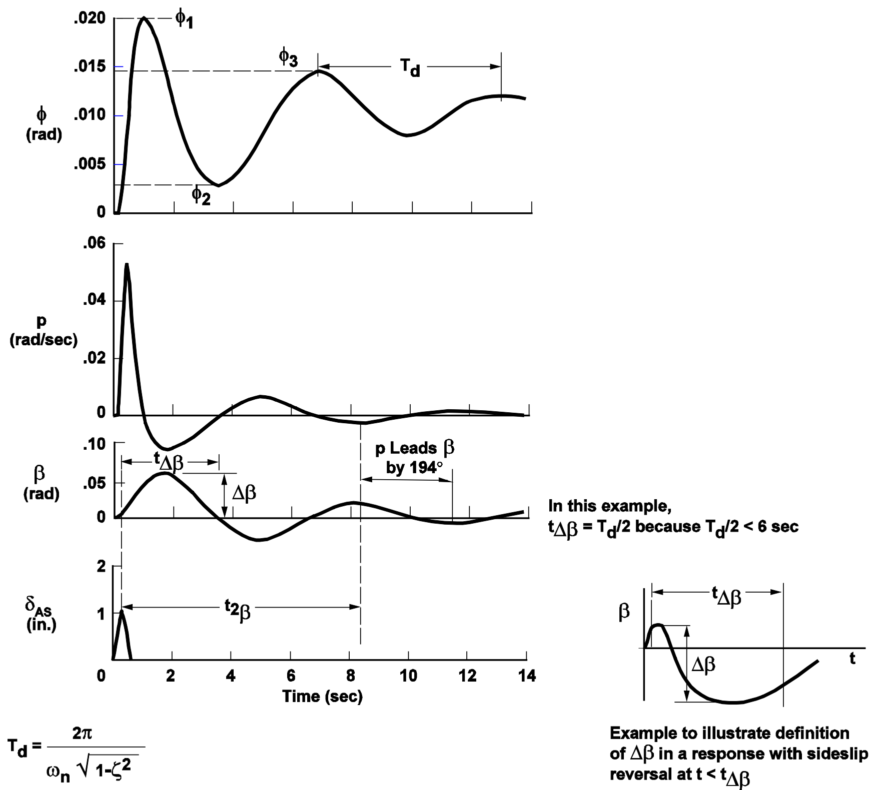
This requirement is taken from ADS-33E-PRF, paragraph 3.4.9.1. Supporting data is found in the ADS-33 BIUG (Reference 3) paragraph 3.4.8.

11. YAW DUE TO COLLECTIVE COUPLING

This type of coupling is found on all single rotor helicopters. Testing in support of ADS-33 showed that pilots did not find this coupling objectionable for non-aggressive tasks (See Reference 3. Since all IFR tasks for civil helicopters may be classified as “non-aggressive”, there is no quantitative criterion for yaw-to-collective coupling.

12. ROLL SIDESLIP COUPLING

The requirements on roll-sideslip coupling shall apply for both right and left lateral control commands of all magnitudes up to the magnitude required to meet the roll performance requirements of Section 8.3 The cockpit yaw controller shall be fixed. The parameters for the criteria in this section are defined in Figure 11.



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

ζ, ω_n from paragraph 3.4.9.1

$$\frac{\phi_{osc}}{\phi_{av}} = \frac{\phi_1 + \phi_3 - 2\phi_2}{\phi_1 + \phi_3 + 2\phi_2} \quad (\zeta \le 0.2) \qquad = \frac{\phi_1 - \phi_2}{\phi_1 + \phi_2} \quad (\zeta > 0.2)$$

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 $T_d/2$.

$t_{n\beta}$ time for the lateral-directional oscillations in the sideslip response to reach the n[th] local maximum for a right command.

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

$\psi_\beta = -360\, t_{n\beta} / T_d + (n-1)\, 360$ (degrees) with n as in $t_{n\beta}$ 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 11. Roll-Sideslip Parameter Definitions

12.1 BANK ANGLE OSCILLATIONS

The value of the parameter ϕ_{OSC}/ϕ_{AV} following a step command for Attitude Command Response-Types and a pulse lateral control input for all other Response-Types shall be within the limits specified in Figure 12. The input shall be as abrupt as practical. ϕ_{AV} shall always be in the direction of the lateral control command.

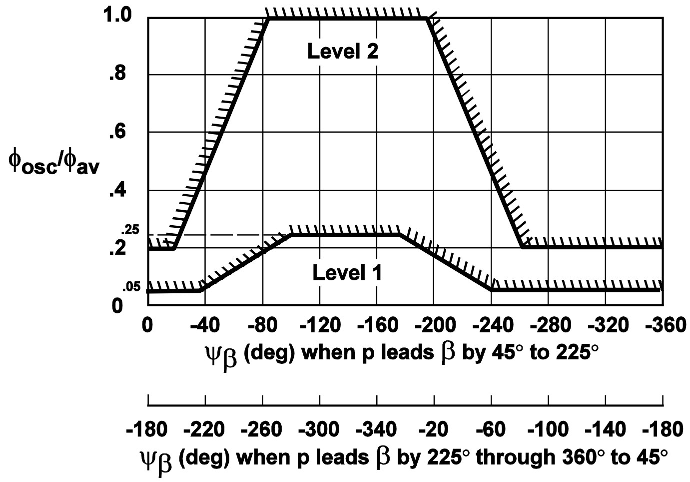


Figure 12. Limits on Bank Angle Oscillations

This requirement is taken from ADS-33E-PRF, paragraph 3.4.7.1. Supporting data is found in Reference 3.

12.2 TURN COORDINATION (LEVEL 1 SPIFR)

The ratio of the maximum change in sideslip angle to the initial peak magnitude in roll response, $|\Delta\beta/\phi_1|$, for a lateral controller step input for Roll Attitude Command Response-Types or a lateral controller pulse input for other response shapes, shall fall within Level 1 in Figure 13. In addition, if the ratio $|\phi/\beta|_d$ exceeds 0.20, the product $0.20 \times |\Delta\beta/\phi_1| \times |\phi/\beta|_d$ shall fall within Level 1 in Figure 13.

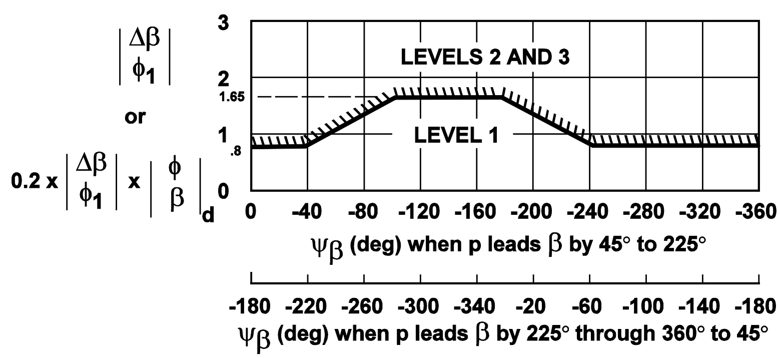


Figure 13. Limits on Sideslip Excursions

This requirement is taken from ADS-33E-PRF, paragraph 3.4.7.2. Supporting data is found in Reference 3.

13. PILOT INDUCED OSCILLATIONS (PIO)

PIO is addressed in this specification by the Bandwidth criterion in Sections 4.1 and 8.1 and the Attitude Quickness criterion in Sections 4.2 and 8.2. The rationale for this is as follows.

- Bandwidth: Exceedance of the phase delay limits on the Bandwidth criterion boundaries has been shown to result in a tendency for PIO due to excessive phase lags in the flight control system.
- Attitude Quickness: Exceedance of the Attitude Quickness criterion boundaries has been shown to result in a tendency for PIO due to actuator rate limiting.

Supporting data for these PIO criteria may be found in Reference 3).

14. TRANSFER BETWEEN CONTROL MODES

14.1 ANNUCIATION OF CONTROL MODE TO THE PILOT

If more than one control mode can be selected in a given axis, there shall be a clear and easily interpretable annunciation to the pilot indicating which of the control modes are currently engaged or armed. For near-earth operations, the annunciation shall be located so that it is not necessary for the pilot to significantly shift his eye point of regard from the forward near-field or to look around, or refocus any vision aid.

14.2 CONTROL SYSTEM BLENDING

Blending between control modes shall be essentially linear with time and shall occur within the time limitations specified below.

Blending During Deceleration: 2 sec $< t_{blend} <$ 10 sec

Blending During Acceleration: 2 sec $< t_{blend} <$ 5 sec

When blending from a series to a parallel trim system, a longitudinal, lateral, or directional trim follow-up may be used as long as the cockpit controller does not move more than 20 percent of its travel in either direction during the blend.

This requirement is taken from ADS-33E-PRF, paragraph 3.8.3. Supporting data is found in Reference 3.

15. CIVIL TASK ELEMENTS (VERY PRELIMINARY)

These CTEs are included as an overall check on the quantitative criteria. They should not be evaluated for credit until the applicant has demonstrated compliance with the quantitative criteria.

The CTEs in this section are provided to give an idea of the concept. A catalog of CTEs will be developed using simulation and/or flight test. One objective of the upcoming VMS simulation is to provide FAA test pilots an opportunity to develop and refine CTEs for inclusion in this section.

For each certification project, the FAA will indicate if any of the CTEs do not apply. For example, if there is no credit being sought for decelerating ILS/LPV approaches, that CTE would not be required. Similarly, the FAA or applicant may designate a new CTE for a given program. Such CTEs must consist of an element of the flight profiles that are expected to exist in service. They must be well defined and include desired and adequate performance limits.

An example of a “tailored” CTE occurred during early Army simulator evaluations of the CH-47F Digital advanced flight control system. In that case there was controversy regarding Attitude-Command-Attitude-Hold (ACAH) vs. Attitude-Command-Velocity-Hold (ACVH) for low speed maneuvering. The tailored CTE consisted of a constant attitude deceleration from forward flight to hover. This CTE exposed a deficiency in the ACVH flight control system wherein an uncommanded pitch down occurred when the system transitioned to the low speed ACVH mode. All evaluation pilots found this to be unacceptable and ACAH was down-selected as the final system.

It is emphasized that all CTEs must be mutually agreed on between the applicant and FAA, and documented in the PSCP early in the program, and in no case used to allow evaluation pilots to “make up” maneuvers late in the program.

The CTEs should be accomplished in representative normal and failed states. The CTEs are intended to be a spot check of the quantitative criteria. It is not intended that CTEs be accomplished for a large number of test conditions. Rather, it is suggested that a few worst-case conditions be selected (e.g., aft c.g.).

At least three pilots shall accomplish the CTEs specified by the FAA. The average HQR shall be calculated and compared with Table 1.

The concept of Civil Task Elements (CTE) is taken from the “Mission-Task-Elements” (MTE) in ADS-33E-PRF. Paragraph 3.11. The CTEs are to be comprised of a completely new set of tasks that are defined in terms of civil helicopter flight profiles. Guidance for accomplishment of CTEs is given below.

- Each CTE shall be accomplished by at least three FAA test pilots. The assigned HQRs shall be averaged and the results compared with the requirements in Table 1.
- All individual ratings and associated comments shall be documented.
- The CTEs are intended to provide answers to handling qualities issues, not performance. It is acceptable to offload weight if necessary to accomplish the CTEs.

Ground-rules for using the Cooper-Harper rating scale for compliance with the CTEs 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 4.

- Always start at the lower-left of the scale 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 5 and 6.
- When using the Cooper-Harper Handling Qualities scale, emphasize workload over performance. For example, if desired performance is achieved, but considerable compensation was required <u>it is okay to give a HQR of 5.</u> Be sure to note that is what you are doing in your commentary.

- It is not okay to assign a 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 CTE 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).

15.1 HEADING CONTROL AND ALTITUDE CONTROL

a. Objective

Evaluate control of heading and altitude

b. Description of Maneuver

Accomplish 180 degree heading change while in climbing turn to gain 500 feet. Hold new heading and altitude for 30 seconds followed by 180 degree heading change in opposite direction while descending 500 ft. Hold new altitude and heading for at least 30 seconds. Accomplish at 70, 90, and 120 KIAS.

c. Desired and Adequate Performance

DESIRED PERFORMANCE	
• Maintain target airspeed:	± 5 kts
• Capture and hold heading	± 5 deg
• Maintain altitude within:	± 50 feet
ADEQUATE PERFORMANCE	
• Maintain target airspeed:	± 10 kts.
• Capture and hold heading	± 10 deg.
• Maintain altitude within	± 100 ft

15.2 ILS OR LPV APPROACH IN TURBULENCE

a. Objective

Evaluate ability to track glideslope and localizer and speed control

b. Description of Maneuver

Start on a heading to intercept the localizer and an airspeed that is at least 20 kts faster than the final approach speed. Intercept the localizer and slow the helicopter to the final approach speed prior to glideslope intercept. Track the ILS to a 200 ft decision height.

c. Desired and Adequate Performance

DESIRED PERFORMANCE	
• Maintain target airspeed within:	± 5 kts
• Prior to glideslope intercept, Maintain altitude within:	± 50 ft.
• Maintain glideslope and localizer within:	± 0.5 dot
ADEQUATE PERFORMANCE	
• Maintain target airspeed:	± 10 kts.
• Prior to glideslope intercept, Maintain altitude within:	± 100 ft.
• Maintain glideslope and localizer within:	± 1.0 dot

In moderate turbulence, increase allowable tolerances by the following amounts:

- Airspeed by 5 kts
- Altitude by 50 ft.
- Glideslope and localizer by 0.5 dots

15.3 ILS OR LPV DECELERATING APPROACH

a. Objective

Demonstrate ability to accomplish decelerating approach

b. Description of Maneuver

Repeat 14.2 with deceleration on glideslope.

Applicant specifies Vmini and the maximum approach speed to initiate a decelerating approach. Require demonstration of maximum approach speed to Vmini when on glideslope.

If applicable, switch from turn coordination to heading hold when approaching hover.

c. Desired and Adequate Performance

TBD

<u>15.4 SPEED CONTROL TASK</u>

a. Objective

Investigate airspeed control.

b. Description of Maneuver

From trimmed level flight at 100 kts, decelerate to 70 kts and retrim for hands off flight. Then accelerate to 100 kts and retrim for hands off flight. Finally, accelerate to 110 kts and retrim.

c. Performance Standards

DESIRED PERFORMANCE	
• Maintain altitude within:	100 ft.
• Trim hands-off at target airspeed within:	3 kts.
• Change from one trim speed to the next within:	1 min
• Maintain heading within:	5 deg.
ADEQUATE PERFORMANCE	
• Maintain altitude within:	200 ft.
• Trim hands-off at target airspeed within:	5 kts.
• Change from one trim speed to the next within:	2 min
• Maintain heading within:	10 deg.

15.5 MISSED APPROACH TASK

a. Objective

Test longitudinal flight control variations for high workload divided attention task.

b. Description of Task

Following an ILS approach to DH, (200 ft), initiate a climb on runway heading to 500 ft at 80 kts.

At 500 feet, turn right to a heading of 90 degrees from runway heading. Level off at 1000 feet and accelerate to 100 kts. Once steady at 100 kts, and 1000 ft, turn right to a heading of 180 deg from runway heading and climb to 2000 ft. Once level at 2000 ft, and steady on 100 kts, accelerate to 130 kts.

c. Performance Standards

DESIRED PERFORMANCE	
• Maintain altitudes within:	100 ft.
• Maintain target airspeeds within:	5 kts.
ADEQUATE PERFORMANCE	
• Maintain altitudes within:	200 ft.
• Trim hands-off at target airspeed within:	10 kts.

15.6 DECELERATION TO HOVER

a. Objective

Demonstrate ability to smoothly decelerate from forward flight to hover.

b. Description of Task

From an altitude of 500 ft a.g.l., and an airspeed of 100 kts, decelerate to hover over a defined point on the ground. Accomplish this maneuver at a nominal approach angle of approximately 3 degrees, and an approach that is near the maximum achievable (steep approach).

c. Desired and Adequate Performance

TBD

16. APPENDIX A DEFINITION AND TEST PROCEDURE FOR BANDWIDTH CRITERION

The Bandwidth (ω_{BW}) and Phase Delay (τ_p) parameters shall be obtained from frequency responses as defined in Figure 14. For Attitude Command Response-Types, if the bandwidth defined by gain margin is less than the bandwidth defined by phase margin, or is undefined, the rotorcraft may be prone to pitch bobbling or even be PIO prone.

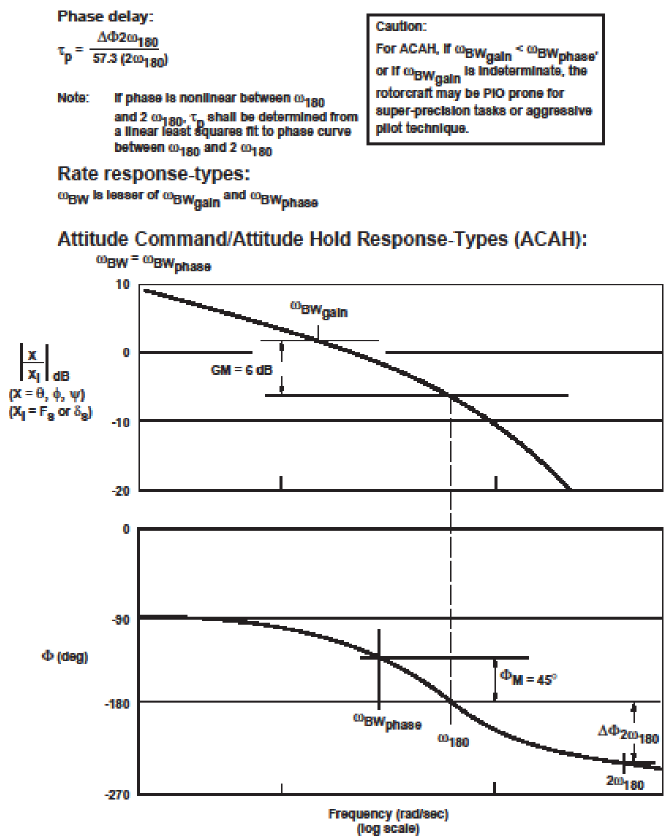


Figure 14. Definition of Bandwidth and Phase Delay

17. APPENDIX B DEFINITION AND TEST PROCEDURE FOR DISTURBANCE REJECTION CRITERION

The disturbance rejection criterion is based on frequency domain analysis of the response to a disturbance injected as a frequency sweep and added to the measured hold response variable (see Reference 2.) For example, the attitude disturbance response is characterized by the frequency response f / f_d as shown in Figure 15.

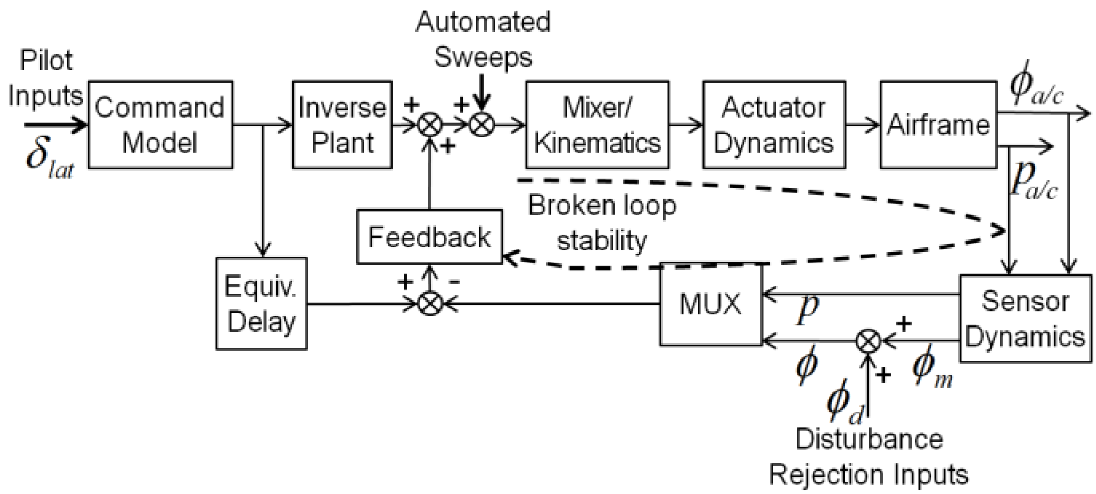


Figure 15. Block Diagram for Disturbance Response (Taken from Reference 2)

There are two requirements based on this disturbance frequency response: Disturbance Rejection Bandwidth (DRB) and Disturbance Rejection Peak (DRP) magnitude. These metrics are defined from the magnitude response as shown in Figure 16.[8]

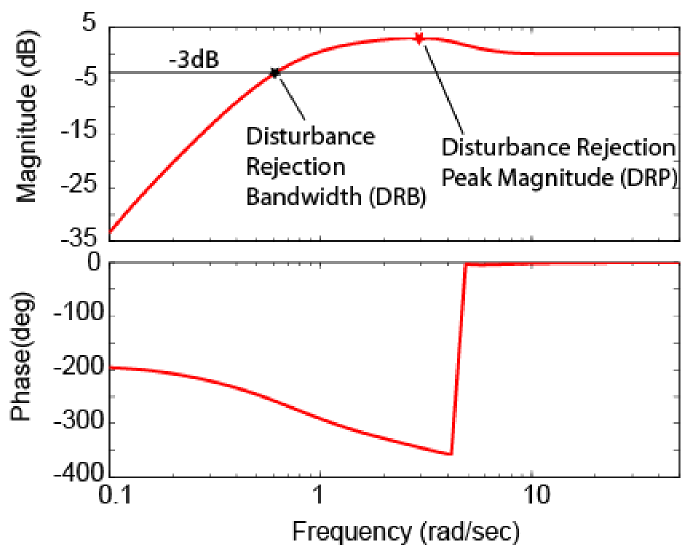


Figure 16. Definition of DRB and DRP

For an Attitude Hold Response-Type the Magnitude is defined by pitch, and roll, attitude with respect to trim and for a Velocity Hold Response-Type it is defined by airspeed with respect to the trim airspeed. For the Turn Coordination Response-Type the appropriate parameter is sideslip angle (or lateral acceleration), whereas for Heading Hold it is heading.

[8] This criterion was developed by the U.S. Army Aeroflightdynamics Directorate at NASA Ames. See Reference 2.

If there are multiple crossings of the -3dB line, the lowest frequency is taken as the DRB frequency.

The Bode plot is obtained in the same fashion as used for the Bandwidth Criterion discussed in Appendix A, except that the frequency sweep is superimposed on the aircraft state. For example for an ACAH system in roll, a frequency sweep is added to the roll attitude gyro output.

For redundant systems, it is necessary to either superimpose the frequency sweep on the output of each channel, or to turn off the monitor for this test. Otherwise the monitors will trip.

If safety of flight is judged to be compromised by adding a frequency sweep into the airspeed or attitude sensor output, it is acceptable to accomplish this by analysis using a validated model of the augmented rotorcraft. A validated model must consist of comparisons between simulated data and flight test data at the applicable flight condition.

18. APPENDIX C PROCEDURE TO CALCULATE HEIGHT RESPONSE (REF SECTION 7.2)

The vertical rate response shall have a qualitative first-order appearance for at least 5 seconds following a step collective input. If the most rapid input achievable is not a clear step, the time zero shall be defined as shown in Figure 17.

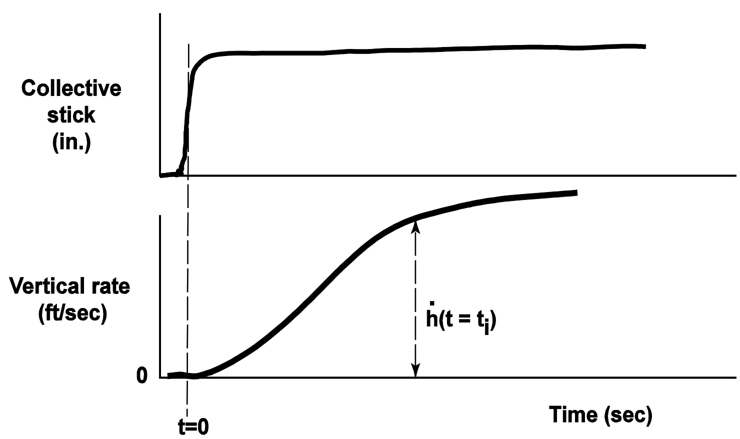


Figure 17. Procedure for obtaining equivalent time domain parameters for the Section 7.2 criterion on height control

The first order model is given as:

$$\frac{\dot{h}}{\delta_c} = \frac{K e^{-(t_{\dot{h}_{eq}} s)}}{T_{\dot{h}_{eq}} s + 1}$$

The equivalent system parameters may be obtained using the time domain fitting method defined below. The coefficient of determination, r^2, shall be greater than 0.97 and less than 1.03 for compliance with this requirement.

Obtain readings ft/sec from response to step collective input at intervals of no greater than t = 0.05 sec for a time span of 5 sec – a total of $n = 5/\Delta t + 1$ data points (minimum n = 101).

Use a three variable nonlinear least squares algorithm to obtain a best fit curve to this data in the time domain using the following form for the estimated $\dot{h}\left(\dot{h}_{est}\right)$

$$\dot{h}_{est}(t) = K\left[1 - \exp\left[-(t - \tau_{\dot{h}_{eq}})/T_{\dot{h}_{eq}}\right]\right] \text{ for } t > 0$$

where t is time (sec) and K, $1/T_{\dot{h}_{eq}}$ and $\tau_{\dot{h}_{eq}}$ are the variables. (Note: $\tau_{\dot{h}_{eq}}$ may be less than zero.)

The function to be minimized is the sum of squares of the error (e), defined as,

$$e^2 = \sum_{i=1}^{n} \left[\dot{h}(t = t_i) - \dot{h}_{est}(t = t_i)\right]^2$$

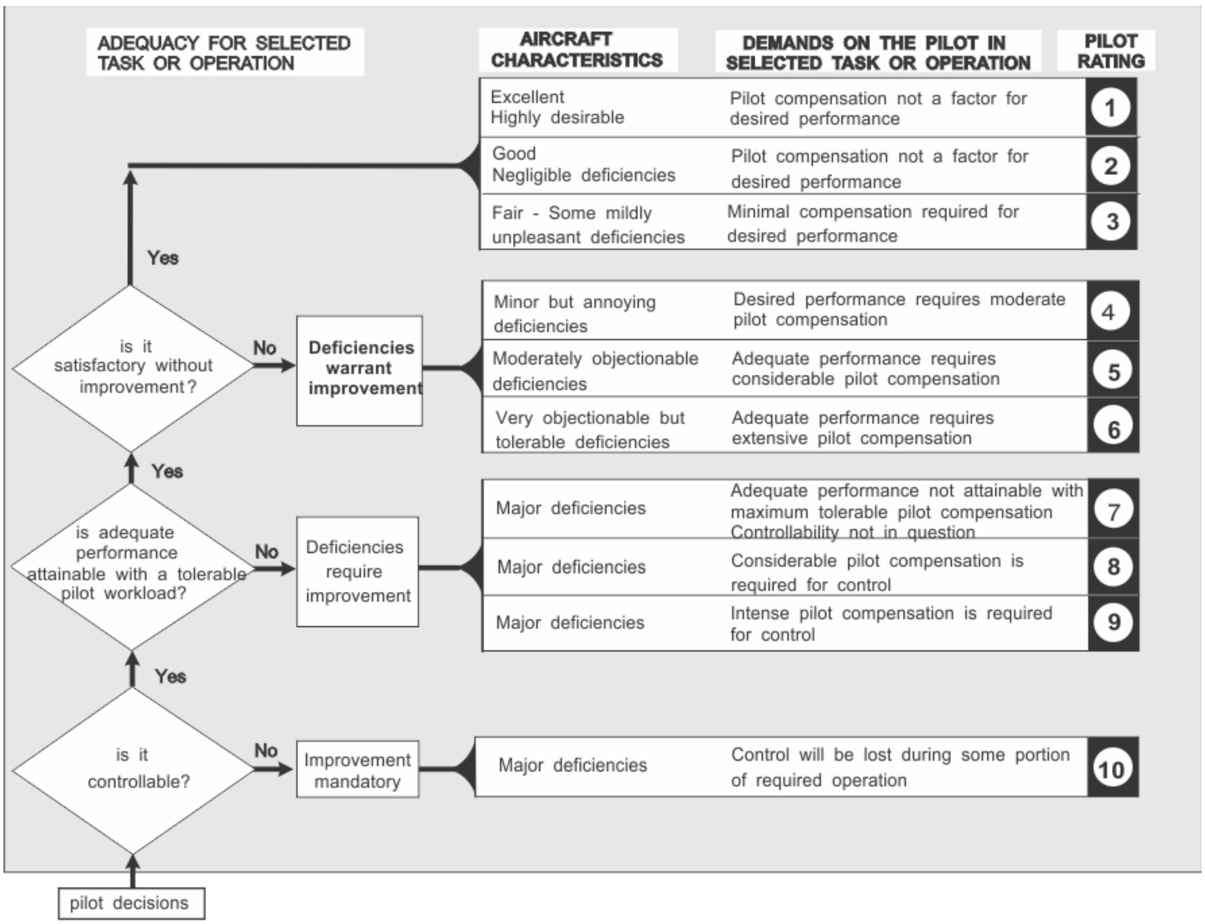
where t_i is the time (sec) at the ith observed data point.

The goodness of fit of the estimated curve shall be determined by the coefficient of determination

(r^2) which is defined as $r^2 = \dfrac{\sum_{i=1}^{n}\left[\dot{h}_{est}(t = t_i) - \dot{h}_m\right]^2}{\sum_{i=1}^{n}\left[\dot{h}(t = t_i) - \dot{h}_m\right]^2}$

where $\dot{h}_m$ is the mean of the observed $\dot{h}$, $\dot{h}_m = \sum_{i=1}^{n} \dfrac{\dot{h}(t = t_i)}{n}$

19. APPENDIX D COOPER HARPER SCALE AND HAZARD CATEGORY SCALE



Cooper Harper Handling Qualities Rating (HQR) Scale (Ref. NASA TND 5153)

Figure 18. Cooper-Harper Rating (HQR) Scale

Table for Failure Condition Categories and Probability Definitions					
Effect on rotorcraft	**No effect on operational capabilities or safety**	**Slight reduction in functional capabilities or safety margins**	**Significant reduction in functional capabilities or safety margin**	**Large reduction in functional capabilities or safety margins(Note 4)**	**Loss of rotorcraft**
Effect on occupants excluding flight crew	**Inconvenience**	**Physical discomfort**	**Physical distress, possibly including injuries**	**Serious or fatal injury to a passenger or a cabin crew member (NOTE 2)**	**Multiple Fatalities**
Effect on flight crew	**No effect on flight crew**	**Slight increase in work load which involve crew actions well within crew capabilities such as routine flight plan changes**	**Physical discomfort or a significant increase in workload or in conditions impairing crew efficiency**	**Physical distress or excessive workload impairs ability to perform tasks accurately or completely**	**Fatalities or incapacitation**
DO-178B Software Level (Note 3)	**E**	**D**	**C**	**B**	**A**
Failure Condition Category	**No Effect**	**Minor**	**Major**	**Hazardous / Severe-Major**	**Catastrophic**
Qualitative Probability	**Frequent**	**Reasonably Probable**	**Remote**	**Extremely Remote**	**Extremely Improbable**
Quantitative Probability :	**No probability requirement**	$\leq 10^{-3}$ (Note 1)	$\leq 10^{-5}$	$\leq 10^{-7}$	$\leq 10^{-9}$
Note 1: A numerical probability range is provided here as reference. The applicant is not required to perform a quantitative analysis, or substantiate by such an analysis, that this numerical criterion has been met for Minor Failure Conditions.					
Note 2: This is true if it can be shown that the given failure condition can be contained to a fatal injury of one occupant only.					
Note 3: This is not intended to imply that the identified software levels are assigned a probability value, but instead, shows a correlation to the Failure Condition Category.					
Note 4: Hazardous/Severe-Major failure conditions can include events that are manageable by the crew by use of proper procedures which, if not implemented correctly or in a timely manner, may result in a Catastrophic event.					

Figure 19. Failure Condition Categories and Probability Definitions (Figure AC 29.1309-3 Page F-18)

20. REFERENCES

[1.] Hoh, Roger H., Supporting Data and Rationale for the Definition of Criterion Boundaries for Rotorcraft With AdFC, Hoh Aeronautics, Inc. Tech Paper 1186-2, Rev 2.

[2] Blanken, Chris L., Roger H. Hoh, and David G. Mitchell, et. al., “Test Guide for ADS-33E-PRF, U.S. Army Aeroflightdynamics Directorate (AMRDEC), Special Report AMR-AF-08-07, July 2008.

[3] Mitchell, David G., and Roger H. Hoh, “Development of a Unified Method to Predict PIO”, AIAA-1996-3435 AIAA Atmospheric Flight Mechanics Conference, San Diego, CA, July 1996, pp 611-622.

[4] Hoh, Roger, H., *Lessons Learned Concerning the Interpretation of subjective Handling Qualities Pilot Rating Data*, AIAA Atmospheric Flight Mechanics Conference, Portland, OR, AIAA-90-2824, August 20-22, 1990.

[5] McDonnell, John, D., *Pilot Rating Techniques for the Estimation and Evaluation of Handling Qualities, AFFDL* TR 68-76, March 1968.

[6] Mitchell, David G. and Bimal L. Aponso, *Reassessment and Extensions of Pilot Ratings with New Data*, AIAA Paper 90-2823, August 1990.

B Appendix B—Supporting data and rationale for the definition of criterion boundaries for rotorcraft with AdFC

HOH
AERONAUTICS
INC.

HANDLING QUALITIES FLIGHT CONTROLS FLIGHT TEST SIMULATION

Supporting Data and Rationale for the Definition of Criterion Boundaries for Rotorcraft with AdFC

Tech Paper 1186-2 Rev 2[1]

February 5, 2016

DRAFT

[1] Formerly titled Working Paper 1186-4

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

1. BACKGROUND

This technical paper provides supporting data for the quantitative minimum performance criteria and pilot evaluation methodologies for FAA certification of advanced flight control (AdFC) systems in rotorcraft (Reference 1).

Quantitative criteria for civil rotorcraft certification must necessarily be based on the same fundamental human-pilot-centered requirements as apply to military rotorcraft. It follows that the structure of many of the criteria in the military specifications (e.g., Bandwidth vs. Phase Delay in ADS-33E-PRF, Reference 2) is directly applicable to civil helicopters. Ground rules for redefining criterion boundaries, to be applicable to civil certification are:

- Avoid correlating any data that involves aggressive or tactical maneuvering that is unique to military missions.
- Be consistent with minimum required for safety. This is different from the military specifications that establish requirements to ensure that pilots can complete specified missions with acceptable workload.

The existing data to support development of criterion boundaries for civil rotorcraft AdFC consists of the following sources.

- Experiments accomplished by NASA Ames and the Canadian National Research Council (NRC) during the late 1970s and 1980s. NASA used mostly motion based simulation with some flight testing on a variable stability Bell UH-1H (References 7 13 and 14). The NRC testing was all conducted on their variable stability Bell 205 (12, 13 and 16). Both of these projects were funded by the FAA to support the development of IFR certification criteria. Subsequent to the completion of the NASA and NRC projects, the FAA added IFR rotorcraft criteria in the form of Appendix B to CFR14 Part 27 and Part 29. However few, if any of the results of the NASA and NRC programs are reflected in those criteria. Section 3 of this Tech Paper presents an analysis of the data from the NASA and NRC testing resulting in criteria that are included in Tech Paper #1 (Reference 1).
- Criteria developed for the U.S. Army Aeronautical Design Standard ADS-33E-PRF (Reference 2). While some of these criteria support aggressive maneuvering, many are typical rotorcraft maneuvers that are common to civil and military flight profiles. The Background Information and User Guide for ADS-33E-PRF (Reference 3) contains an extensive review of essentially all helicopter handling qualities data that was available at the time of its publication in 1989. More recent refinements and test guidance can be found in the Test Guide for ADS-33E-PRF (Reference 20).
- Other sources result from research funded or conducted by various government organizations, e.g., References 7, 11, 12, 19, and 20.

A detailed description that points to the origin of the supporting data is included for each requirement in Tech Paper #1 (Reference 1).

2. PASS-FAIL CRITERIA

2.1 APPLICABILITY

The pass fail criteria and resulting criterion boundaries apply to augmented (AdFC) and unaugmented helicopters. This is based on the rationale that pilot workload depends solely on the response that occurs when the pilot moves the controls or encounters turbulence. In terms of actual flying, the source of handling qualities (e.g., AdFC, aerodynamic design, or anything else) is irrelevant. In that context, experience has shown that a flight control system that requires "special pilot technique" that is not intuitive after minimal training is generally not acceptable.

AdFC allows modification of rotorcraft dynamics from marginally stable or unstable to highly stable through the use of feedbacks and feedforwards to the flight controls. This introduces the need to include the effect of failure modes as an integral element of the pass-fail criteria.

2.2 PASS-FAIL CRITERIA DEVELOPMENT

The acceptability rotorcraft flying characteristics depend on two equally important elements.

1. Workload associated with closed-loop pilot control. This relates to the rotorcraft dynamics as defined by handling qualities metrics (e.g., short period frequency and damping or bandwidth and phase delay). Acceptable values of these metrics are given by the quantitative criteria in Reference 1.
2. Workload to accomplish non-flying tasks. This is a function of the tendency of the rotorcraft to diverge from steady flight when the pilot's attention is diverted away from control of the helicopter. This includes the effect of inadvertent control inputs, e.g., the pilot leans on the cyclic when looking at an approach chart or copying a clearance. Single pilot IFR requires a high level of divided attention whereas the requirements for division of attention are less with a second qualified pilot and/or an autopilot.

Most available data is based on testing in support of Item 1, and is based on handling qualities evaluations using the Cooper-Harper scale in Figure 1. It follows that the quantitative criterion boundaries must necessarily be based on Cooper-Harper Ratings (CHRs) obtained from past research programs. Essentially all of this data has resulted from government sponsored simulator and flight tests where the evaluators had no vested interest in the outcome. Interpretation of such data requires some understanding of the correct use of the CHR scale.

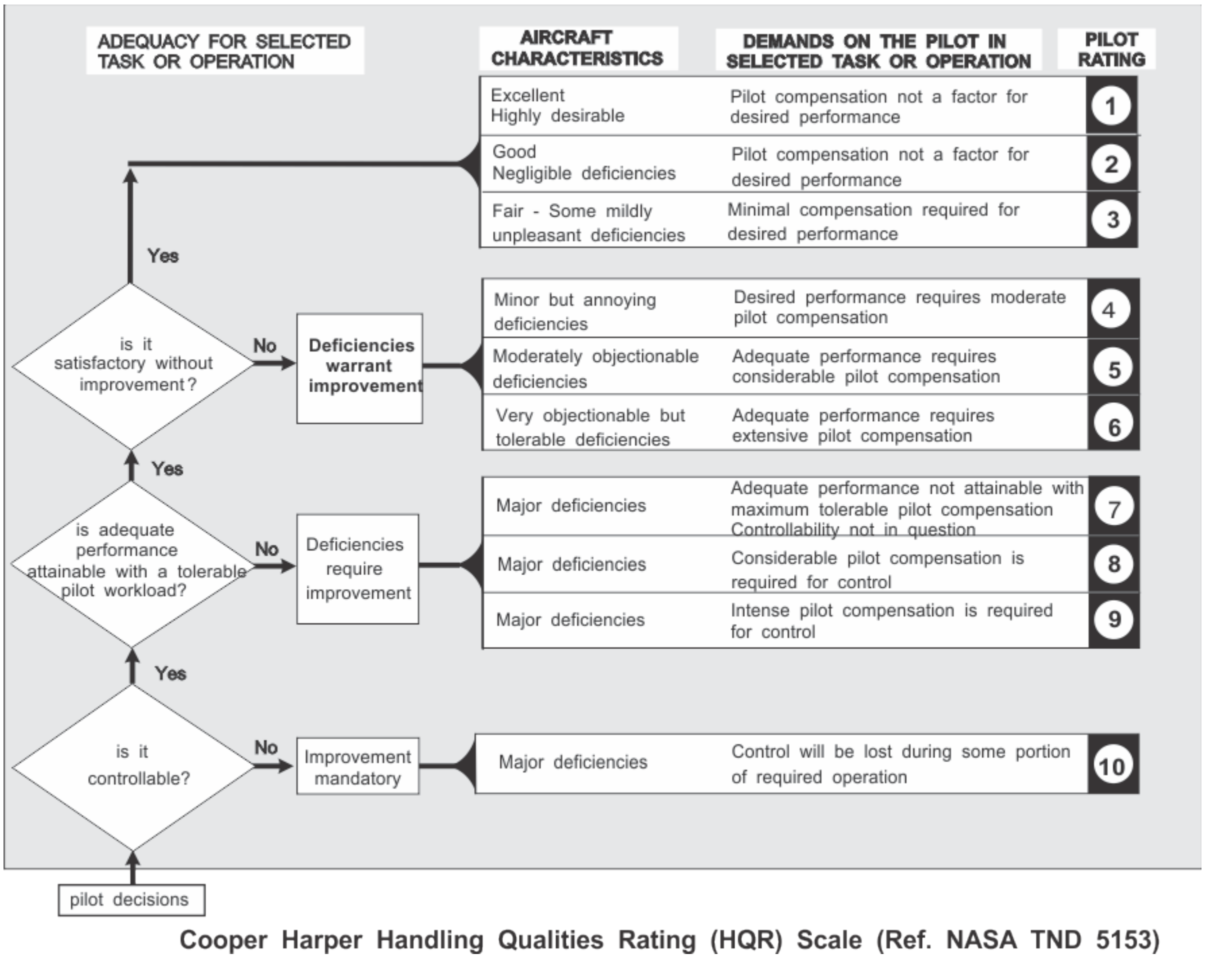


Figure 1. Cooper Harper Handling Qualities Scale

All handling qualities experiments set specific values of “desired performance” and “adequate performance”. Such performance standards force pilots to increase tracking aggressiveness to a defined level (e.g., keep glideslope and localizer error less than ½ dot and airspeed within 5 kts).

The intent of the Cooper Harper scale is to quantify the pilot workload that is required to achieve the specified level of performance. If the pilot is able to achieve desired performance the CHR normally (but not always) falls between 1 and 4. However, if the workload to achieve desired performance is excessive, higher ratings are assigned to reflect that fact.

If desired performance cannot be achieved, the rating must be 5 or higher, and the workload to achieve only adequate performance is quantified by ratings between 5 and 7. Finally, if it is not even possible to achieve adequate performance, the workload to maintain control is defined by ratings between 8 and 10. Additional insight into the use of the Cooper-Harper rating scale is given in Reference 4.

As discussed in Reference 6, the use of half ratings is acceptable (despite what is often taught in test pilot schools). The caveat being that pilots may not assign ratings that fall between the major decision points in the Figure 1 scale (3.5, 6.5, 9.5). Furthermore, contrary to what is often taught, it is acceptable to average the ratings, for example equal numbers of ratings of 3 and 4 results in an average of 3.5. This in fact is how all handling qualities boundaries are developed (i.e., by fairing lines midway between ratings of 3 and 4 on a criterion grid). Studies have shown that the semantic meanings of the Cooper-Harper Scale phrases are indeed linear, and therefore may be averaged (References 5 and 6). This is less true at the ends of the scale. Fortunately, the ratings that correspond to a pass/fail decision occur near the middle of the scale.

2.3 SINGLE VS. DUAL PILOT IFR

Intuition tells us that the existence of a second pilot significantly decreases the workload for the pilot flying in the IFR environment. This was quantified in Reference 7, “The Effects of Display and Autopilot Functions on Pilot Workload for Single Pilot Instrument Flight” with the result shown below in Figure 2 .

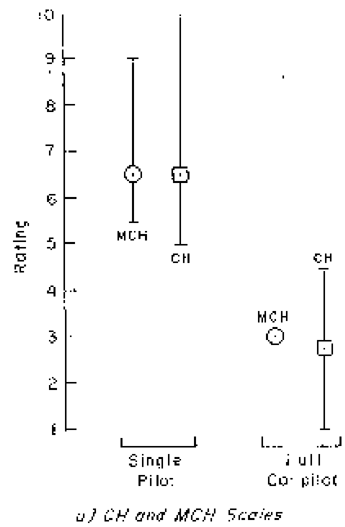


Figure 2. Workload Ratings With and Without a Co-Pilot from Reference 7

Both Cooper Harper ratings (CHR) and Modified Cooper Harper (MCH) pilot ratings were taken. The MCH scale is shown in Figure 3. It is patterned after the CHR scale, but is couched in terms of human factors workload considerations by Wierwilli and Casali (see Reference 8). Single pilot IFR (SPIFR) is clearly seen to require higher workload than dual pilot IFR (DPIFR).

The Reference 7 study consisted of simulation and flight testing to investigate requirements for displays and autopilots for SPIFR. The testing consisted of realistic high workload IFR tasks, and was conducted at NASA Langley (flight test), Flight Safety International (simulation). The Flight Safety portion of the testing allowed inclusion of system failures. While that study was conducted using fixed wing aircraft, the results apply equally for any type aircraft for IFR tasks.

Finally, the summary report for a NASA test program conducted specifically to develop criteria for FAA IFR rotorcraft certification (Reference 15) concluded that: “A difference in requirements for single and dual pilot operations was shown to be warranted”.

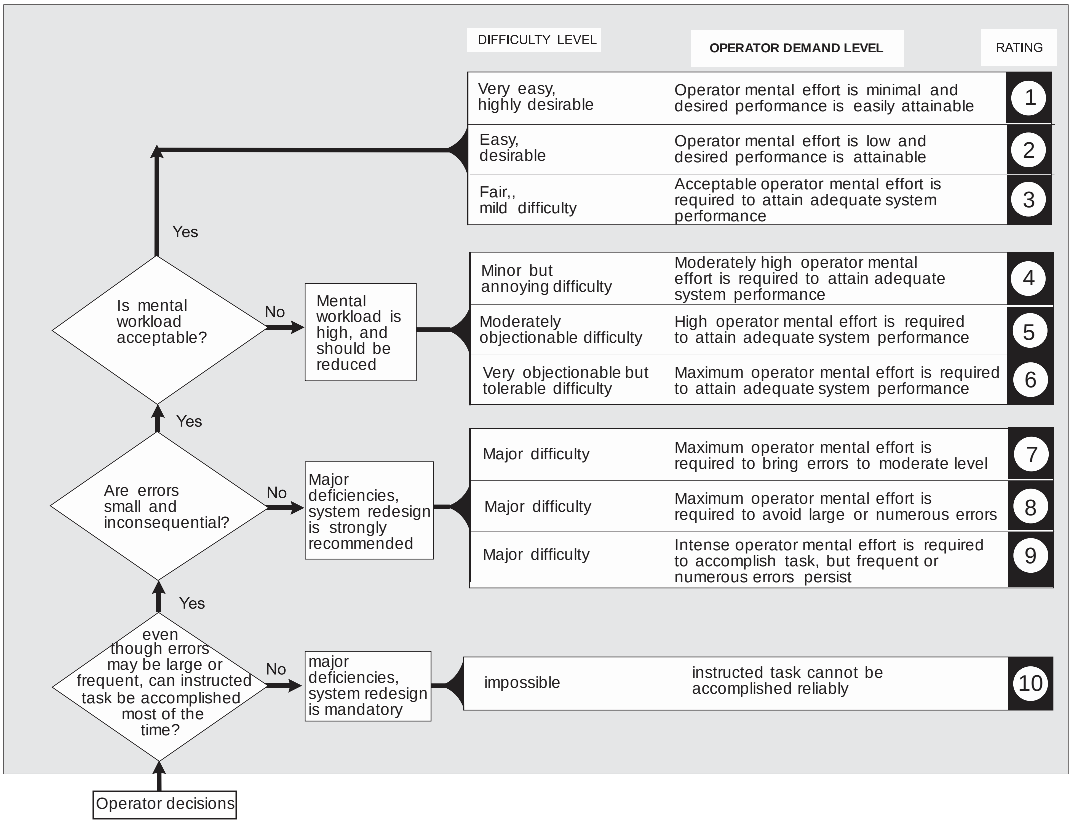


Figure 3. Modified Cooper Harper Scale to Measure Pilot Workload

2.4 DECISION TO CERTIFY VS. COOPER HARPER RATING (CHR)

Cooperative research efforts between the FAA and the Canadian National Research Council (NRC) in the 1980s resulted in several flight test experiments on the NRC Variable Stability Bell 205. Two of these tests required the evaluation pilots to provide Cooper-Harper ratings as well as a decision to certify as: SPIFR, DPIFR, or Uncertifiable. All approaches were flown as SPIFR and the DPIFR decision was an estimate made by the evaluation pilot.

This data provides a basis to correlate the relationship between Cooper-Harper pilot rating and certifiability as discussed below.

Experiment #1 (Reference 9)

This test was conducted on the NRC variable stability helicopter to gain insight into the acceptability of manually flown and coupled decelerating rotorcraft approaches in simulated IMC, to an airspeed of 20 kts and a decision height of 50 feet, using a three cue flight director. Various display combinations and levels of autopilot coupling were tested. In addition to assigning CHRs the pilots were asked to make a decision as to whether the configuration was certifiable with one pilot, with two pilots, or not at all. The raw data from those flight tests was re-analyzed for the present work with the result shown below in Figure 4.

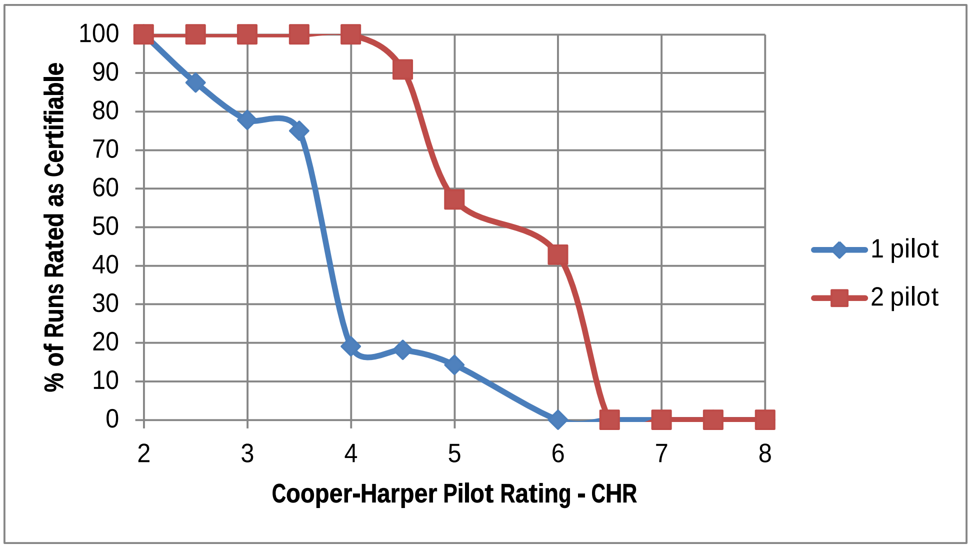


Figure 4 Relationship Between Decision to Certify and Cooper Harper Rating CHR From Reference 9

These results are based on evaluations of 92 approaches by five pilots consisting of two FAA test pilots from FAA Southwest Region, one FAA test pilot from FAA New England region, One Transport Canada test pilot, and one NRC test pilot.

Experiment #2 (Reference 13)

This was an extensive series of experiments (150 hours of flight time) with FAA, Transport Canada, and NRC pilots (8 total pilots). The data from these tests is given in Figure 5.

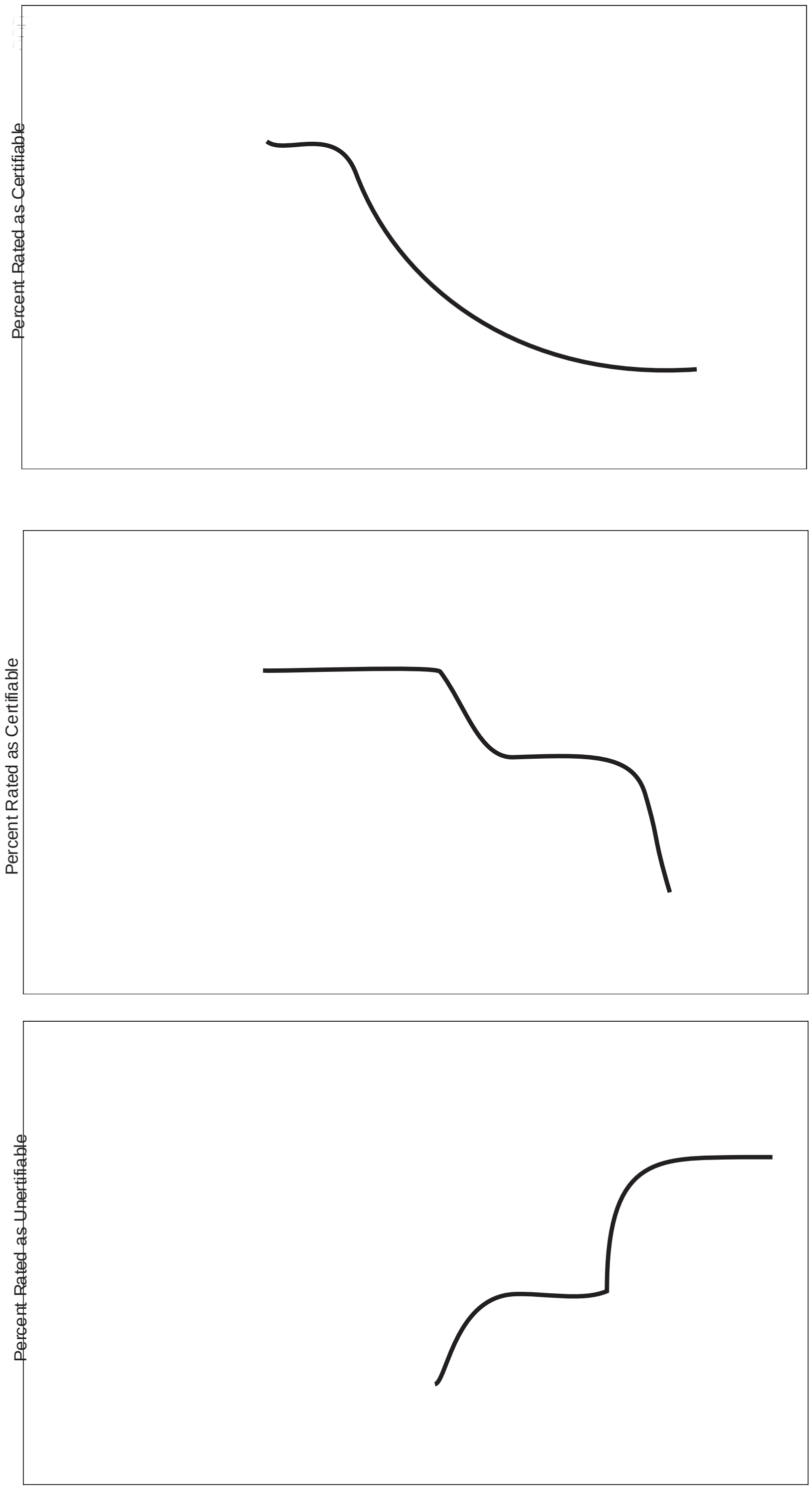


Figure 5. Relationship Between Decision to Certify and Cooper Harper Rating (CHR) From Reference 13

The data in Figure 4 and Figure 5 are interpreted as follows:

- For SPIFR both sets of flight tests indicate a clearly defined reduction in the decision to certify for CHRs greater than 3.5. This indicates that a CHR of 3.5 or better[2] represents the pass/fail boundary for single pilot IFR certifications.
- For DPIFR, the data from both experiments indicate a high probability of certification for ratings of 4.5 and better. The decision to certify/not certify is approximately 50/50 for ratings between 4.5 and 6. Any rating above 6 was judged as uncertifiable. Based on this data, a conservative upper limit for two-pilot IFR is CHR = 5.

The data for two pilots is representative of tasks where the pilot's attention can be primarily focused on flying the helicopter, i.e., VFR or IFR with a two pilot crew.

2.5 CORRELATION BETWEEN COOPER-HARPER RATING AND PILOT WORKLOAD

The relaxation of criterion boundaries for DPIFR is based on the concept that the Cooper-Harper rating (CHR) is a measure of the workload required to control the helicopter. If the workload for control is high, the pilot must devote more his or her attention to the flying task than if the workload is low. High workload for control translates to less excess workload capacity for situational awareness. This concept is used to interpret data from experiments wherein all of the pilot's attention is available for control (which is the vast majority of all handling qualities tests), to set boundaries for SPIFR and DPIFR.

The data in Section 2.4 quantifies this concept to indicate that the appropriate CHR for SPIFR is 3.5 and for DPIFR is 5.

The following rationale supports the concept that CHR ratings are a measure the Attentional Demand required for control (AD).

The attentional demand required for aircraft control was experimentally obtained as a function of CHR in Reference 10 with the following result.

$$AD = \frac{CHR - 1}{8.33}$$

Equation 1

100% of the pilot's workload capacity is allocated to the sum of the "attentional demand" required for aircraft control (AD) and excess workload capacity (EWC).

AD + EWC = 1.0. (or 100%)

This is illustrated in Figure 6.

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[2] Better meaning a lower number.

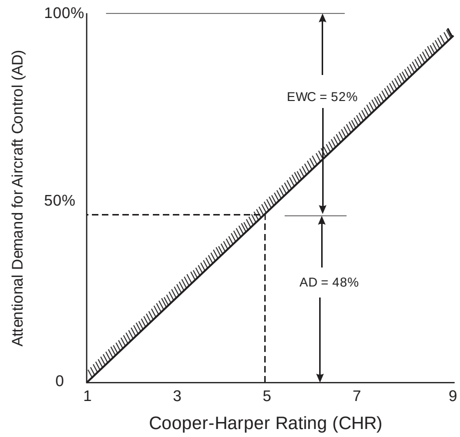


Figure 6. Effect of CH Rating on Attentional Demand for Aircraft Control

The example in Figure 6 illustrates that for CHR = 5, the attentional demand required for control is estimated to be 48%, leaving 52% of the pilot's workload capacity to attend to non-flying tasks. To put this in context, if the CHR from a typical handling qualities experiment (no side-task) is 5, this infers that in the "real world", the pilot-flying would be able to devote 52% of his or her attention to non-flying tasks.

For single pilot IFR, the required CHR is 3.5. This corresponds to AD = 30% leaving 70% of the available workload (EWC) for non-flying tasks.

2.6 SUMMARY

To summarize, analysis of existing data to develop criterion boundaries will utilize the following ground rules.

· Requirements for Single Pilot IFR (SPIFR) in the unfailed state.

  - CHR £ 3.5 for closed loop control.
  - Response-Type[3] that eliminates the tendency of the rotorcraft to diverge from steady flight if left unattended.

· Requirements for Dual-Pilot IFR (DPIFR) in the unfailed state.

  - CHR £ 5 for closed loop control
  - No requirement on Response-Type

As a final note, highly stabilized flight control systems that are required for SPIFR are often not suitable when agility is required. In particular, some pilots do not like a wing leveler when maneuvering in VMC conditions. Unlike the military, civil certification does not take into account

[3] Response-Type is used in this report to indicate the shape of the pitch or roll attitude response to a cockpit controller input.

a need for high agility. Therefore, the incorporation of selectable flight control system modes is a matter of manufacturer choice.

3. SUPPORTING DATA

This section provides support for criteria that define the required dynamics in forward flight, utilizing data that heretofore has not been applied to the development of criteria. The rationale for using existing criteria (e.g., from Reference 2) is also presented in cases where further clarification is required.

3.1 RESPONSE-TYPE FOR LEVEL 1 SPIFR

Response-Type is defined as the shape of the attitude response to a cyclic input. The "shape" of the response is expressed as a time response of rotorcraft attitude following a step or pulse input of the cockpit controller. The applicant is free to use any flight control system architecture that results in the required shape of the response.

A NASA report summarizing the results of 6 simulator and flight test experiments that were conducted to support the development of FAA certification criteria (Reference 15) showed that CHR less than 3.5 could only be achieved with an Attitude Command SCAS. Those results are shown below in Figure 7.

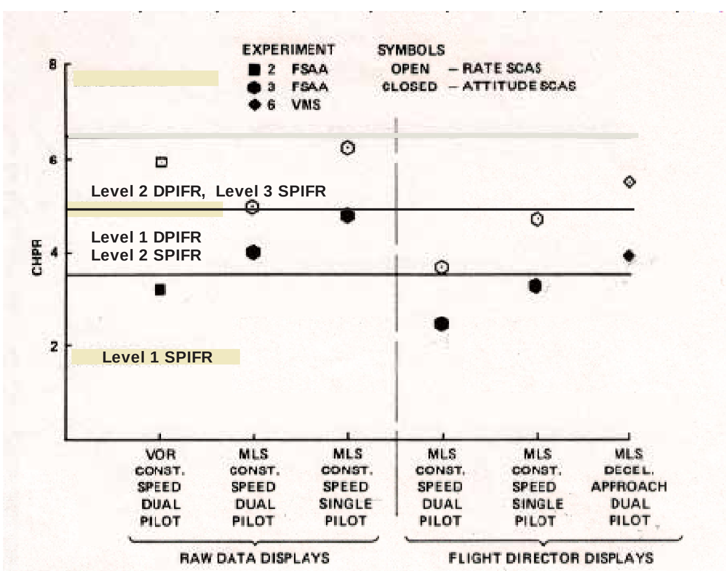


Figure 7. Effect of SCAS Type and Flight Director

These data reveal that attitude command attitude hold (ACAH) in pitch and roll was the only tested flight control system architecture that met the criterion for SPIFR for several tasks. The single pilot data were obtained by introducing divided attention tasks such as tuning radios and copying clearances. The tasks consisted of a steep (6 degree glideslope) precision approach (microwave landing system) followed by a missed approach procedure and a VOR non-precision approach (no vertical guidance).

These results imply that flight director guidance is also necessary to achieve Level 1 SPIFR. This is at odds with other data during these tests (e.g., Reference 16 – see Figure 11), as well as NRC tests as shown in Figure 9 (specifically, Configurations 3 and 3A). The need for flight director guidance will be a subject of an upcoming VMS simulation in the fall of 2016.

The need for an attitude command response is consistent with the NRC tests where the FAA subject pilots indicated that for SPIFR, the helicopter must not diverge if left unattended. Experience has shown that "unattended" means not only hands-off, but hands on the cyclic with an inadvertent input while looking away from the flight instruments.

Finally, an undocumented VMS simulation conducted by Hoh Aeronautics, Inc. in 2001 showed conclusively that attitude command was necessary for safe IFR operations in a very high workload environment.[4]

For the purpose of this specification, the above results are interpreted to mean that ACAH is one way to satisfy the requirement for unattended operation. This interpretation is in the context that a ground-rule for writing certification criteria is that they do not specify a flight control system architecture.

Reference 3 Section 3.2.7 provides rationale and analysis that show that the generic feature of ACAH that provides pilot workload relief can be captured by the following time response criterion.

> A step cockpit pitch or roll controller force input shall produce a time response with respect to the trimmed pitch attitude or bank angle that reaches steady state, or peaks in 6 seconds or less, and asymptotically approaches a constant value, that is equal to or less than the peak value and has the same sign as the peak value. This requirement shall apply for cyclic force inputs equal to at least three pounds or a deflection of one inch, whichever is less.

This requirement is illustrated graphically in Figure 8.

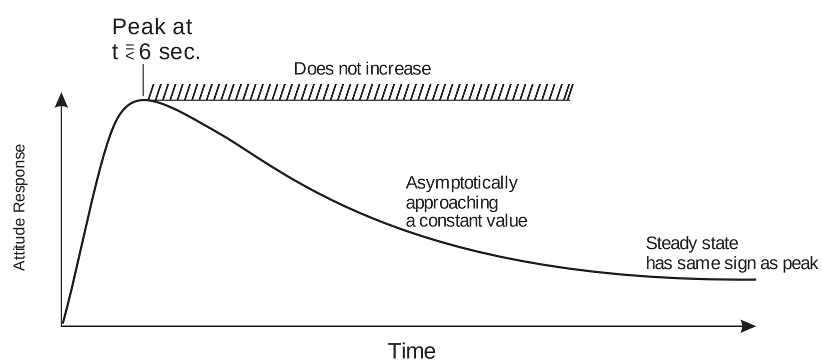


Figure 8. Requirement on Response-Shape to Step Cyclic Input for Level 1 SPIFR

[4] That experiment was intended to be an exploratory simulation to determine the minimum acceptable augmentation for IFR rotorcraft certification. The planned follow-on formal simulation was cancelled when all rotorcraft funding was cut from the NASA budget.

This criterion was developed for low speed and hover in Reference 3, but the underlying principle applies equally to forward flight. The criterion is modified slightly from Reference 3 to accommodate the possibility of a flight control system architecture that transitions from an ACAH to RCAH at moderate cyclic deflections. A force of three pounds is judged to be representative of the maximum inadvertent force that would be applied, and is low enough to allow a smooth transition from attitude to rate.

3.2 BANDWIDTH

The concept of a criterion based on the bandwidth of the rotorcraft responses to controller input has been successfully employed in the fixed and rotary wing military handling qualities specifications: Mil Std-1797A (or B) (Reference 11) and ADS-33E-PRF (Reference 2).

The Bandwidth criterion is a measure of how well a system output follows the input (e.g., accuracy and crispness of the rotorcraft attitude response to cockpit controller inputs). This is very generic in nature and applies to any dynamic system. The phase delay (t_p) portion of the criterion is a measure of the slope of the phase curve as it crosses through -180^o. Excessive phase delay has been shown to result in a tendency for pilot induced oscillations. Such oscillations occur when a small increase in pilot gain results in a rapid loss of phase in the pitch or roll attitude frequency response (i.e., when the slope of the phase curve is negative and large). It is important to understand that while t_p has the units of seconds, it is not a time domain parameter. It must be determined from the frequency response (i.e., Bode plot). A more complete definition of Bandwidth and Phase Delay is given in Appendix A of Reference 1.

The criterion boundaries used for the Reference 1 Bandwidth requirements are derived from the data in Reference 3, Section 3.4.1.1. for the longitudinal axis and Section 3.4.5.1 for the lateral axis. The Level 1 SPIFR boundaries are taken directly from ADS-33E-PRF, whereas the Level 1 DPIFR boundary is adjusted to account for the change from CHR = 6.5 in ADS-33E-PRF to CHR = 5 in the FAA criteria.

Since the publication of Reference 3, there have been numerous correlations with the Bandwidth criterion (e.g. see Reference 12). Reference 12 shows that the published Bandwidth criterion boundaries apply to control position inputs (not force).

3.3 SUPPORTING DATA FOR PITCH AXIS RESPONSE CRITERIA IN SECTION 4.1 OF REFERENCE 1

Support for the static stability and phugoid[5] response criteria are derived in this section, and is based on testing conducted by NASA and the Canadian National Research Council (NRC).

The short term response that is classically defined by the short period frequency is represented herein in terms of the Bandwidth criterion. This is done because the Bandwidth criterion also

[5] Phugoid is used here as representing the low frequency pitch axis response.

includes the phase delay parameter, which is deemed essential to eliminate PIO tendencies due to excessive phase lag in the flight control system.

<u>NRC Flight Tests 1979 through 1981</u>

This was an extensive series of experiments (150 hours of flight time) with FAA, Transport Canada, and NRC pilots (8 total pilots). There were three experimental scenarios as follows.

1. Basic IMC maneuvering and evaluation of response to control pulses.
2. Maneuvering for ILS approach, ILS approach and missed approach
3. Same as 2 but with the aid of co-pilot

The testing was done for three separate experiments that are documented in References 13 and 14. Most of the published data was for scenario #2 during the third flight test experiment, which is documented in Reference 14. The pilots provided Cooper-Harper ratings, and an opinion as to certifiability for SPIFR, DPIFR, or uncertifiable for IFR (UC). The rating for DPIFR was based on the evaluator's extrapolation from flying the single pilot task (scenario #2). No data from the actual 2-pilot task (scenario #3 was published).

Artificial turbulence was introduced during the ILS approach and missed approach. The report defines the level of turbulence as "moderate".

Tested configurations for all three experiments had longitudinal dynamics that were characterized by well-defined phugoid and short period modes (classical dynamics). Such characteristics are common for most unaugmented rotorcraft in forward flight and the parameter variations were all a result of modifications of the basic Bell 205. This was achieved by augmenting stability derivatives by means of feedbacks to the pitch and rolls series servos, resulting in the following test configurations.

- Two short term dynamics cases. (Estimated short period frequency and damping were obtained from root locus plot and time histories of pulse responses in the report.)
  - ω_{sp} = 0.9 rad/sec (basic Bell 205)
  - ω_{sp} = 1.9 rad/sec (achieved by increasing Mq where $M_\alpha \approx 0$).[6]
  - $\zeta_{sp} \geq 0.70$ for all cases

- Varied $d\delta/dV$ as: 0, .025, .045 in/kt. (Achieved by variations in Mu).
  - $d\delta/dV$ = 0 and .045 in/kt and ω_{sp} = 1.9 rad/sec
  - $d\delta/dV$ =.025 in/kt had ω_{sp} =0.9 rad/sec (the only way to get this $d\delta/dV$ was to reduce Mq.)

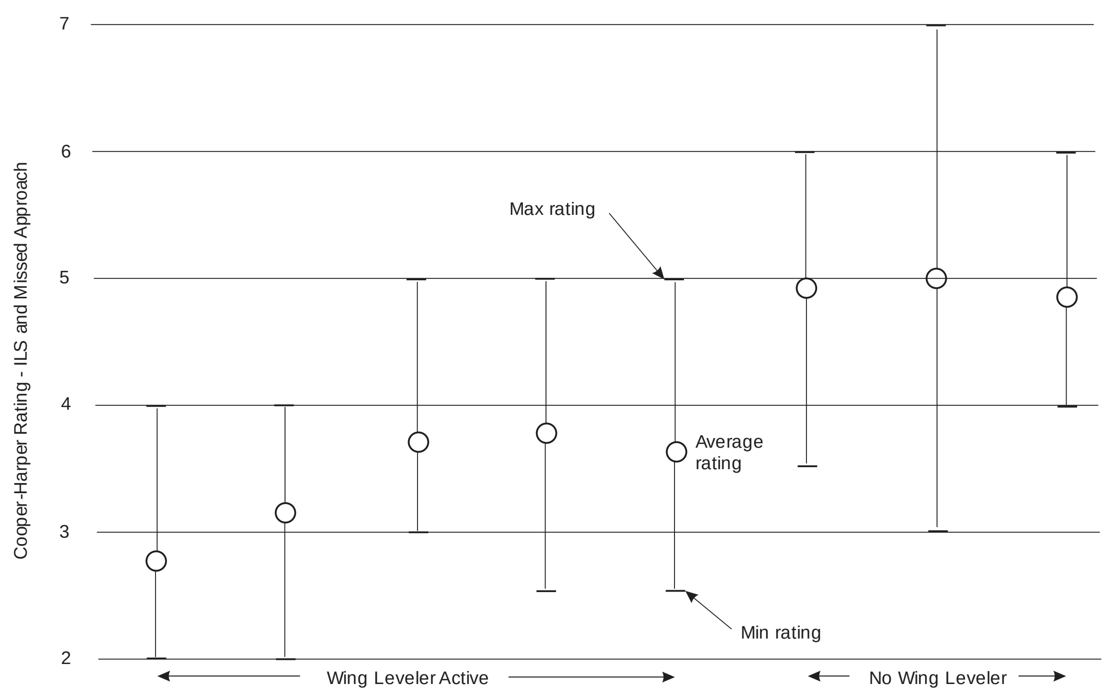
[6] Note that $\omega_{sp} \approx -M_\alpha + Z_w M_q$

- Phugoid damping was tested as un-damped (V_p= 0) and damped (V_p=0.44). w_p = 0.23 rad/sec.
- Case with dd/dV = 0 and w_{sp} = 1.9 has characteristics of a good Rate response-type, where the shape of the response is quantified as a linear ramp attitude change to a cyclic step input. The phugoid mode was completely suppressed for this configuration.

Cyclic force gradient was 0.5 lb/inch with 0.5 lb breakout in pitch and roll for all configurations.

Five cases had a “wing leveler” and three did not. The directional dynamics were the unaugmented Bell 205. Verbal summaries of experiments 1 and 2 were provided, but no data was included.

Cooper-Harper ratings for maneuvering for an ILS approach, ILS approach, and missed approach with no divided attention requirement are given in Figure 9. This data was obtained for Experiment 3, Scenario #2 (Reference 14).



Configuration	3	3A	2	2A	1	3B	2B	1B
dd/dV - in/kt	0.045	0.045	0.025	0.025	0	0.045	0.025	0
w_{sp} - rad/sec	1.9	1.9	0.9	0.9	1.9	1.9	0.9	1.9
z_p - ND	0.44	0	0.44	0	undefined	0.44	0.44	0.44
Certifiable? ILS (SPIFR/DPIFR/No Cert)	4/1/0	3/2/0	3/2/0	4/0/1	3/1/1	0/3/2	1/2/2	0/4/1
Certifiable? IFR Maneuvers (SPIFR/DPIFR/No Cert)	4/1/0	2/1/1	4/0/1	1/2/1	1/3/1	0/1/3	0/1/3	0/1/3

Figure 9. Cooper-Harper Pilot Rating Data for ILS Approach/Missed-Approach – NRC Data

NRC uses the NASA sign convention where aft cyclic is positive so that a stable cyclic position vs. airspeed gradient is defined as $dd/dV < 0$. FAA and many manufacturers define forward cyclic as positive so that a stable gradient is defined as $dd/dV > 0$. We have converted the NRC data to be consistent with the FAA convention (i.e., all the cyclic positon vs. airspeed gradients in Figure 9 are stable or zero).

Effect of Wing Leveler (ACAH in roll)

- Average CHR without wing leveler for the ILS approach and missed approach task was approximately 5 regardless of the longitudinal characteristics. The wing leveler was by far the most dominant aspect of the tested flight control systems.
- Configurations 3 and 3B are identical except for the wing leveler. Configuration 3 is judged as acceptable for SPIFR by most pilots, compared to configuration 3B (no wing leveler), which is judged as marginal for DPIFR by approximately half the pilots and uncertifiable for IFR by the other half.

Static Stability, Short period, and Phugoid (Wing leveler active)

- Adherence to the criterion that the average CHR must be 3.5 or better for single pilot IFR indicates that only Configurations 3 and 3A would pass for SPIFR certification. These configurations are described as follows.
    - Static stability and short period damping: dd/dV = .045, and w_{sp} =1.9 rad/sec. This short period frequency is very close to the Level 1 SPIFR Bandwidth specified in Reference 1, Section 4.1 ($w_{BW_q} = 2.0$ rad/sec)
    - Zero phugoid damping was found to be acceptable.
        - § Configuration 3 - V_p = 0.44
        - § Configuration 3A - V_p = 0
- Configurations 2 and 2A are acceptable for IFR with two pilots
    - These are characterized as w_{sp} = 0.9 rad/sec, dd/dV = .025 in/kt). This short period frequency is very close to the Level 1 DPIFR (also the Level 2 SPIFR) Bandwidth specified in Reference 1, Section 4.1 ($w_{BW_q} = 1.0$ rad/sec)
    - Changing the phugoid damping between 0 and 0.44 made no difference in pilot opinion.
- Configuration 1 represents a good longitudinal rate response (characterized by dd/dV = 0 and w_{sp} = 1.9 rad/sec) where the lateral flight control system is attitude command attitude hold. The average Cooper-Harper rating is 3.6 (i.e., borderline SPIFR). This suggests that it may be acceptable to employ a rate command system in pitch (where by definition $dd/dV = 0$) as long as the roll axis is attitude command. However, the NASA data in Figure 11 (discussed later) show a clear need for a stable cyclic position vs. airspeed gradient for instrument approaches in turbulence. Furthermore, the Rate response-type

does not meet the stated requirement for SPIFR made by the evaluation pilots that the rotorcraft attitude must not diverge if left unattended. Specifically, if the pilot inadvertently leans on the cyclic while accomplishing a non-flying task, a Rate response-type will diverge.

Experiments 1 and 2

Experiment 1 was accomplished primarily to set up the configurations and tasks, and to achieve some preliminary results. This is the only experiment where attitude hold in pitch was tested. This consisted of a very limited authority attitude hold that could be selected on and off with a cyclic-mounted button. Due to the very limited authority, pilots were instructed not to use it as a fly-through system (albeit, it would hold attitude if left unattended). The report states that this Response-Type was found to be suitable for SPIFR. It further concludes that for SPIFR the pilots demanded that the helicopter could be left unattended for periods of time required for “non-control housekeeping tasks”.

Experiment 2 did not include attitude hold for any of the configurations. The primary variables were static stability (dd/dV) and short period frequency (w_{sp}). The results are summarized below.

- All of the evaluators indicated that a stable cyclic position vs. airspeed gradient was of no value without a corresponding force gradient (often referred to as a “force-feel system”). Cyclic force/position gradient was found to be useful even if dd/dV = 0. The cyclic characteristics were fixed at 0.5 lb breakout and 0.5 lb/in gradient (pitch and roll).
- A damped or un-damped phugoid with an unusually high frequency of 0.5 rad/sec was found to be a significant problem for cases with low short period frequency (w_{sp} = 0.9 rad/sec). The high frequency phugoid resulted from airspeed feedback used to achieve a large value of stick fixed static stability (dd/dV = 0.1 in/kt.) The evaluation pilots noted that the helicopter felt to be “digging-in” in turbulence. Increasing the short period frequency from 0.9 to 1.9 eliminated this problem, and the configuration was rated as “good for single pilot IFR”. This result is important because it suggests that increased static stability requires increased short period frequency.

NASA/FAA Simulation and Flight Tests – 1981 through mid-1983

This FAA sponsored project consisted of 6 experiments. Two were conducted on the NASA Ames Flight Simulator for Advanced Aircraft (FSAA), four on the Vertical Motion Simulator (VMS), and one flight test on a variable stability Bell UH-1H (VSTOLAND).

The results of all testing was reported in a series of papers and journal articles as well as two Technical Memorandums. References 15 and 16 are judged to capture the essence of the NASA results and are used herein as supporting data. Reference 15 provides a summary of all 6 experiments. The evaluation pilot’s affiliations were: 3 NASA, 4 U.S. Army, 4 FAA, 2 NRC, and 1 UK Civil Aviation. The testing included over 800 evaluations. The tasks included VOR and steep (6 degree) MLS approaches and missed approaches. Most of the data used herein is for the MLS task.

The nature of rotorcraft dynamics is such that longitudinal static stability as characterized by a lack of restoring pitching moment due to changes in angle of attack (i.e., M_a » 0). Augmentation of angle of attack is very difficult in rotorcraft due to the downwash created by the rotor. It follows that the only practical way to achieve "airspeed stability" (i.e., tendency to return to trim airspeed following a perturbation) is by augmentation of M_u via feedback of airspeed to the longitudinal swash plate. Such augmentation also increases the phugoid frequency. A significant portion of the NASA testing was done to investigate the effect of variations in M_u as characterized by the gradient of steady-state cyclic with airspeed (dd/dV). This was motivated by the fact that the proposed FAA criteria for IFR helicopters (Appendix B) required a stable dd/dV gradient.

A wide range of stick-fixed longitudinal static stability (cyclic position gradient) was tested on the NASA Simulators with spot checks in flight test with a variable stability UH-1H helicopter (V/STOLAND). All tests included input decoupling and were rate damped. As with the NRC experiments, the tested augmentation was limited to feedbacks that augment the basic rotorcraft dynamics, i.e., no forward loop shaping or model following architecture was employed. Input decoupling consisted of interaxis crossfeeds. Pitch and roll augmentation was accomplished by augmenting Mq and Lp to achieve a good short term response in both axes (see Reference 16).

Cyclic force vs position gradient was achieved with a control loader to achieve a constant gradient of 0.5 lb/in and 1.0 lb breakout and 0.75 lb hysteresis (Reference 16).

The frequency response plot for the baseline case with the highest level of stick gradient (Config L01S) is given in Figure 10.

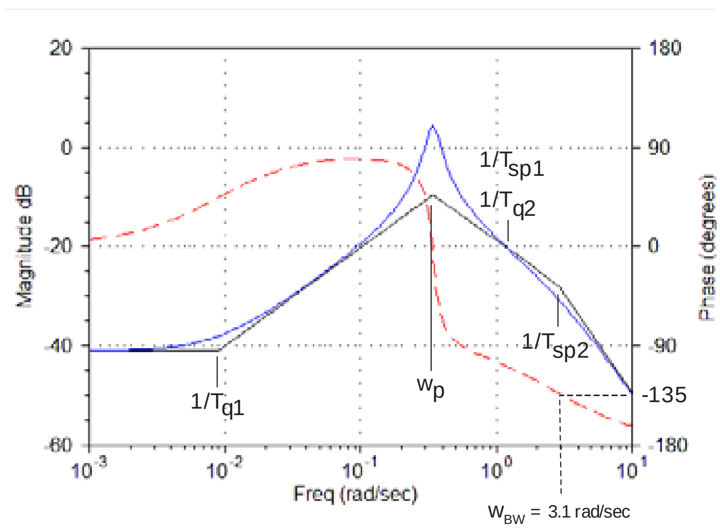


Figure 10. q/d **Configuration L01S - High Mq** dd/dV **= -.067 in/kt**

This is seen to be a classical response with a well-defined phugoid mode and a short period mode consisting of two real roots. The bandwidth is 3.1 rad/sec, which is high when compared to the requirements in ADS-33E-PRF and Reference 1 (where a maximum of 2 rad/sec is required). The airspeed to pitch-axis series actuator feedback augmented Mu considerably to achieve the static cyclic gradient of -0.067 in/kt, resulting in a phugoid mode frequency at 0.34 rad/sec.

The effect of augmenting Mu to vary dd / dV on pilot opinion is shown in Figure 11. In all cases the lateral augmentation was a high gain rate-command-attitude-hold (RCAH). This plot was developed from the data in Reference 14, which consisted of a piloted simulation on the NASA Ames VMS.

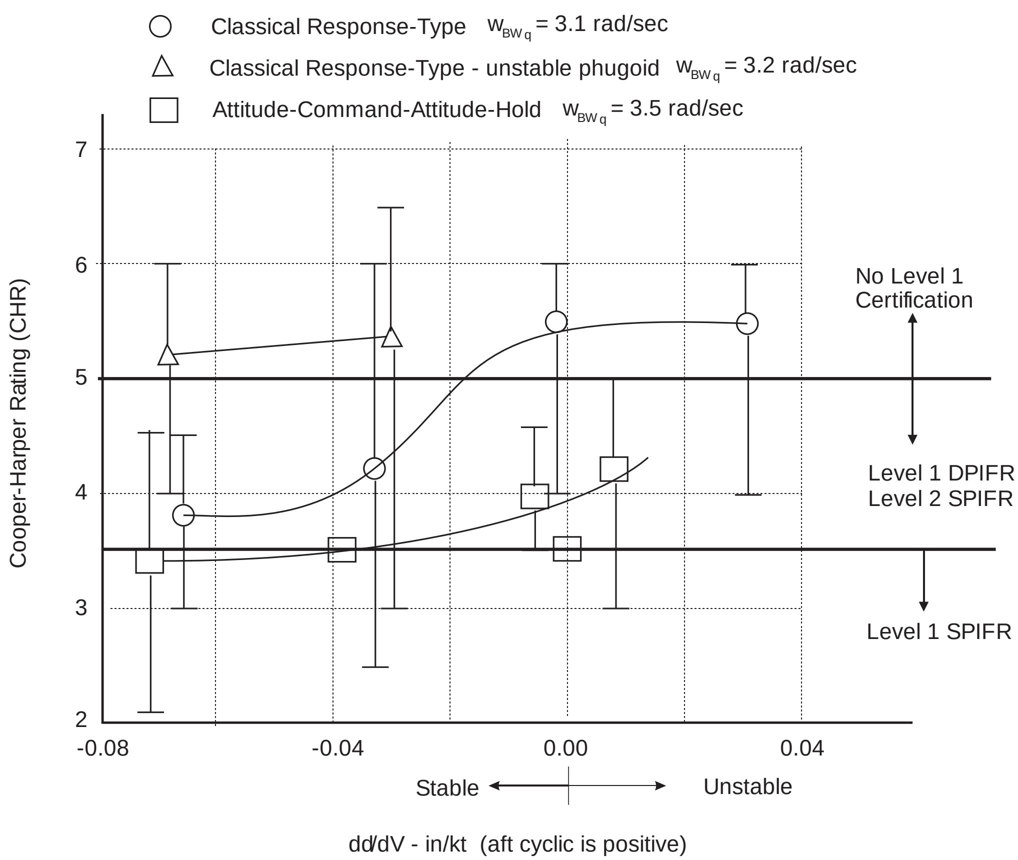


Figure 11. Cooper-Harper Pilot Rating as a Function of longitudinal cyclic gradient – NASA Data

This plot employs the NASA convention for cyclic positon where aft cyclic is positive so that a stable gradient is indicated in Figure 11 when $dd / dV < 0$. As previously noted, some helicopter manufacturers and the FAA use the opposite convention so that aft cyclic is negative (stable gradient is defined as $dd / dV > 0$. The FAA convention is used in the Reference 1 requirements document.

All of the configurations had a Bandwidth well above the required 2 rad/sec for Level 1 SPIFR.

The simulated turbulence was moderate as defined by $\sigma_{ug} = \sigma_{ug} = 3.0$ ft/sec and $\sigma_{wg} = 1.5$ ft/sec. The task was to fly an MLS approach with a 6 degree glideslope followed by a missed approach. No division of attention away from rotorcraft control was required.

The data in Figure 11 indicates that stick-fixed static stability is required for both of the tested response types (classical and ACAH) to achieve Level 1 SPIFR. As an aside, it is notable that for ACAH augmentation, a requirement for static stability equates to some "droop" in the time response, e.g. as illustrated in Figure 8).

The NRC data (Figure 9) and the NASA data (Figure 11) both support a limit on stick-fixed static stability for Level 1 SPIFR as $d\delta / dV \geq .045$ in/kt (where forward cyclic is positive). Pilot commentary for cases with lower values of stick-fixed static stability relate to problems with airspeed control in turbulence.

The data in Figure 11 are slightly at odds with the NRC data in Figure 9, in that the NRC data indicate that Level 1 SPIFR is possible with the classical response-type (see configurations 3 and 3A in Figure 9), whereas the NASA data do not quite make it into the SPIFR Level 1 region (CHR $\leq$ 3.5). It is possible that this is due to the lack of a wing leveler in the NASA experiment.

3.4 UNSTABLE LOW FREQUENCY DYNAMICS

Some level of divergent dynamics has been found to be acceptable for DPIFR as long as it occurs at a low frequency. This is reflected in the time-to-double amplitude and restrictions on phugoid frequency for $\zeta_p < 0.35$ requirements in Table 5 of Reference 1.

The cases with unstable phugoid in the NASA tests (Reference 16) resulted in the following characteristic equations for the longitudinal axis.

(3.24)(1.35)[-0.13, 0.34] for $d\delta / dV = -.070$ in/kt [7] (Configuration L01U)

(3.26)(1.35)[-0.21, 0.24] for $d\delta / dV = -.030$ in/kt (Configuration L02U)

The times to double amplitude for these unstable phugoid modes are:

- T_2 = 15.7 seconds for Configuration L01U
- T_2 = 13.8 seconds for Configuration L02U

Both of these configurations are assigned CHR greater than 5 (Figure 11), meaning they would only be acceptable as Level 2 backup system dynamics.

The pilot commentary for configurations with an unstable phugoid damping indicated problems with airspeed and glideslope steady state tracking, especially in turbulence (Reference 16).

[7] Aft cyclic positive.

ADS-33E-PRF restricts the divergence as illustrated by the "mid-term response" requirement illustrated in Figure 12, which applies only to divided attention tasks (i.e. DPIFR)[8]. This is seen to allow a damping ratio of -0.20 for frequencies below 0.50 rad/sec, which results in a more rapid divergence than was found to be acceptable in the NRC and NASA flight tests[9]. Therefore, the damping ratio of -0.20 was replaced with the times to double amplitude shown in Table 1. These times to double amplitude are based on the results of NRC flight tests that are reported in Reference 17.

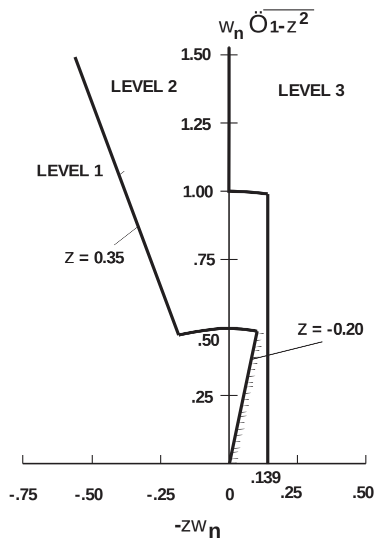


Figure 12. ADS-33E-PRF Requirement on Low Frequency Divergence (Section 3.4.1.2.1)

Table 1 Limits on Time to Double Amplitude for IFR Certification from Reference 17

	Single Pilot	Two Pilots
Lateral	$T_{2f} > 14$ sec	$T_{2q} > 6$ sec
Longitudinal	$T_{2f} > 14$ sec	$T_{2q} > 8$ sec

The results in Table 1 are slightly at odds with the NASA results in Figure 11 that showed an unstable phugoid with time to double amplitude equal to or greater than 14 seconds resulted in CHR > 5. While this is technically not acceptable for DPIFR, the CHR ratings are only slightly worse than 5, and the NRC flight test results did indicate such cases were found to be acceptable, even for SPIFR. On that basis a time to double amplitude of 14 seconds or greater is taken as acceptable for DPIFR and Level 2 SPIFR. The NRC limits for DPIFR are taken as the criteria for Level 2 DPIFR and Level 3 SPIFR. (See Table 5 in Reference 1).

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[8] Supporting data for the ADS-33E-PRF requirement can be found in Reference 3, Section 3.3.2.2.2.

[9] For example, the time to double amplitude if $z_p = 0.20$ and $w_p = 0.5$ rad/sec is 6.9 seconds.

4. FLIGHT PATH CONTROL

4.1 FLIGHT PATH RESPONSE TO PITCH ATTITUDE (FRONTSIDE)

These requirements are based on simulator experiments conducted to support criteria for STOL aircraft (Reference 18), and are judged to be applicable to rotorcraft in forward flight.

It should be noted that the requirement that the vertical rate response shall not lag the pitch attitude response by more than 45 degrees at all frequencies below 0.40 rad/sec for Level 1 and 0.25 rad/sec for Level 2 is equivalent to setting lower limits on $1/T_{q2}$, where:

$$\frac{g}{q} \text{ » } \frac{1}{T_{q2}s+1}$$

Flight path lags that deviate from this requirement result in poor glideslope tracking with pitch attitude.

There is also a lower limit on the lag between pitch attitude and flight path. This is done to ensure that the flight path response to a pitch attitude change in not excessively abrupt. The requirement states that at frequencies at and above the bandwidth frequency, the vertical rate response shall lag the pitch attitude response by at least 52 degrees for Level 1 and 37 degrees for Level 2, which is equivalent to setting a lower limit on $w_{BW}T_{q2}$ at 1.3 for Level 1 and 0.75 for Level 2. This requires that for Level 1 the flight path response frequency ($1/T_{q2}$) is less than the pitch response frequency (i.e., bandwidth), and for Level 1, it is restricted to no more than 25% above the bandwidth frequency.

5. CIVIL TASK ELEMENTS (CTES)

The concept of CTEs was introduced in ADS-33E-PRF (Reference 2) as Mission-Task-Elements (MTEs). The purpose of the MTEs was to provide an overall check on the quantitative criteria. The MTEs were initially developed by U.S. Army test pilots using the NRC variable stability Bell 205 as well as the AH-64 Comanche. The MTEs have undergone several iterations to meet the needs of rotorcraft development programs. For example, the MTEs were tailored to the needs of a large helicopter during the development of the CH-47F Digital AFCS (see Reference 19). Also see the ADS-33E-PRF test guide (Reference 20).

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