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Developing Means of Compliance for eVTOL Vehicles: Phase 1 Final Report

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16. Abstract

The development of new air vehicles (e.g., personal air vehicles, urban taxis, etc.) has led to a proliferation of Vertical Takeoff and Landing (VTOL) vehicle concepts including electric vehicles, many of which are well funded and are in various stages of prototype development and test. The processes and requirements needed to certify these disparate vehicles for operation within the National Airspace System are still emerging. To aid in the requirements and certification process, a mission-oriented approach is being applied to define Handling Qualities Task Elements (HQTEs) that will serve as a means of compliance with Part 23 certification requirements. This report summarizes the Phase 1 work on this program, the primary focus of which was the defining of a new handling qualities certification process used in part for means of compliance that is designed to address the emerging markets for personal air vehicles and urban air taxis. The key element of this approach is the introduction HQTEs, which ultimately become part of the means of compliance with Federal Aviation Administration Part 23 regulations. A catalog of candidate HQTEs was created. While not comprehensive at this time, the defined HQTEs cover low speed/hovering flight, forward flight, and other Urban Air Mobility (UAM) mission relevant scenarios. The HQTEs are defined with desired and adequate performance requirements that facilitate direct use of the Cooper-Harper handling qualities rating scale. Selected HQTEs were evaluated with a representative eVTOL model in fixed-based engineering evaluations where initial viability of the candidate HQTE was demonstrated. The HQTE catalog is now well positioned for additional evaluation, validation, and expansion during Phase 2 work and related activities.

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Acronyms

Acronym	**Definition**
ACAH	Attitude Command Attitude Hold
ACS	Airman Certification Standards
CFR	Code of Federal Regulations
CHR	Cooper-Harper Ratings
CONOPS	Concept of Operations
eVTOL	Electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FMA	Failure Mode Analysis
FOV	Field-of-View
FQTE	Flying Qualities Task Element
HQR	Handling Qualities Rating
HQTE	Handling Qualities Task Element
KIAS	Knots of Indicated Airspeed
MOC	Means of Compliance
MTE	Mission Task Element
NASA	National Aeronautics and Space Administration
OFE	Operational Flight Envelope
PAV	Personal Air Vehicle
PFD	Primary Flight Display
PIO	Pilot-Induced Oscillation
PIOR	Pilot-Induced Oscillation Tendency Rating
PTS	Practical Test Standards
RCAH	Rate Command Attitude Hold
STI	Systems Technology, Inc.
UAM	Urban Air Mobility
UCE	Usable Cue Environment
VTOL	Vertical Takeoff and Landing

Executive summary

The development of new air vehicles (e.g., personal air vehicles, urban taxis, etc.) has led to a proliferation of Vertical Takeoff and Landing (VTOL) vehicle concepts including electric vehicles, many of which are well funded and are in various stages of prototype development and test. These vehicles will almost exclusively feature fly-by-wire flight control systems that may feature advanced response-types. The processes and requirements needed to certify these disparate vehicles for operation within the National Airspace System are still emerging. To aid in the requirements and certification process, a mission-oriented approach is being applied to define Handling Qualities Task Elements (HQTEs) that will serve as a means of compliance with Part 23 certification requirements.

This report summarizes the Phase 1 effort of this program. The primary focus of this phase was the defining of a new process used in part for certification means of compliance that is designed to address the emerging markets for personal air vehicles and urban air taxis. The key element of this approach is the introduction HQTEs, which ultimately become part of the means of compliance with Federal Aviation Administration Part 23 regulations. As part of this work, the process of HQTE development and the methods for conducting handling qualities evaluations with HQTEs was established, documented, and demonstrated.

While not yet comprehensive, a catalog of candidate HQTEs was created. These HQTEs cover low speed/hovering flight, forward flight, and other Urban Air Mobility (UAM) mission relevant scenarios. The HQTEs include maneuvers encompassing a range of precision, aggressiveness levels, allowing for a build-up test approach from non-precision, non-aggressive to precision, aggressive HQTEs. Furthermore, the HQTEs are defined with desired and adequate performance requirements that facilitate direct use of the Cooper-Harper handling qualities rating scale, noting that achieving adequate performance does not equate with adequate for certification. This will allow for greater discernment of handling qualities than can be achieved via a simple pass/fail assessment.

Selected HQTEs were evaluated with a representative electric Vertical Take-off and Landing (eVTOL) model in fixed-based engineering evaluations. The myCopter Personal Aerial Vehicle (PAV), which was provided to Systems Technology, Inc. (STI) for use on this program by the University of Liverpool, was utilized as the subject aircraft during these evaluations to assess whether the initial viability of the candidate HQTE was demonstrated. The HQTE catalog is now well positioned for additional evaluation, validation, and expansion during extension work, where formal piloted simulation evaluations of the candidate HQTEs will be conducted with suitable Urban Air Mobility (UAM) vehicle models. During the follow-on effort, the HQTE

catalog will be expanded to include additional mission-relevant areas of operation, including flight mode transitions, envelope protection, and automated modes.

1 Introduction

As described in [1], The FAA knows how to certify civilian fly-by-wire aircraft, as illustrated by the many models produced by Boeing, Airbus, Dassault, Gulfstream, Embraer, and Bombardier. Since the existing rules (i.e., 14 CFR Part 25) did not account for advanced fly-by wire technology, all of these certifications required a "patch" called special conditions. These special conditions were onerous and very time consuming to process. Furthermore, each special condition was different due to each design being unique.

Consequently, an alternative means to certify fly-by-wire aircraft without requiring special conditions for every single design would be beneficial and serves as the motivation for the work described in this report. At the same time, the FAA forecasts the proliferation of fly-by-wire technology to smaller aircraft. These smaller aircraft could use tailorable rules for special class aircraft (i.e., 14 CFR part 21.17b) or use rules adopted in 2017 for small airplanes (i.e., 14 CFR part 23, called the Part 23 Re-write). In either case, appropriate means of compliance to the rules that accommodated a broad category of fly-by-wire aircraft would be beneficial to replace unique special conditions.

Modern vertical take-off and landing aircraft could also benefit from an alternative means to certify fly-by-wire. Leveraging lessons learned from military helicopter certification, the FAA proposed to adapt military methodologies called Mission Task Elements outlined in the document ADS-33-PRF [2]. Mission Task Elements from ADS-33-PRF need to be modified appropriately for the civilian missions and the civilian certification rules. Military requirements are specified in terms of prescriptive key-performance parameters, whereas the FAA is seeking means of compliance, via a standard, to high-level performance-based rules.

The approach proposed by the FAA Small Airplane Standards Branch is outlined in this paper. The FAA launched a research project in 2018 with Systems Technology, Inc. (STI) to bridge the gap between military and civilian certification. The end goal of this research is to develop appropriate means of compliance to civilian rules and develop a catalogue of appropriate mission task elements. This paper outlines that approach with work done to date. As part of this work, the team will perform dry runs of the mission task elements written for eVTOL vehicles in various simulators, including the NASA AMES Vertical Motion Simulator and the NASA Langley Cockpit Motion Facility. The FAA Small Airplane Standards Branch conceived of and authored the cooperative agreements that are now in place between the FAA and NASA to facilitate these tests. Furthermore, the team plans to refine the mission task elements described herein with actual flight tests. Actual flight tests will be conducted with eVTOLs prior to certification as part of the NASA-FAA National Campaign for Advanced Air Mobility, previously known as the "Grand Challenge."

In a mission-oriented approach to aircraft handling qualities [3], means of compliance are based in part on realistic mission task elements (MTEs). Specific flight test demonstration maneuvers are defined for each MTE as a tool to assess if there are any handling qualities cliffs. Ultimately, a truly mission-oriented means of compliance will have quantitative requirements tied directly to appropriate MTEs. Thus, the MTE provides an explicit way of testing suitability for the identified mission, as well as satisfying some airworthiness requirements or rules. This is perhaps the most significant "mission-oriented" concept, and, as such, led to the research effort reported in [4]. This fixed wing research was based on the approach to handling qualities that was successfully established for military rotorcraft via ADS-33, the latest release of which is ADS-33E-PRF [2].

Aircraft size is not considered in a mission-oriented approach. A number of the requirements in the fixed wing military standard (i.e., MIL-STD-1797B), for example, have different values depending upon aircraft size, defined in terms of four Classes of aircraft. This includes in particular the modal requirements that were defined in MIL-F-8785B/C and that have remained through to the current fixed wing standard. This division is arbitrary and is sometimes irrelevant. For example, if a mission requires a high level of aggressiveness and precision, it should not matter if the airplane proposed for that mission is small or large. Only the mission requirements should set handling qualities. It is recognized that, in some cases, this may lead to unreasonable demands on very large airplanes. As an example, consider a vehicle that has been designated for the urban air mobility mission that includes VTOL operations in a dense urban air space. It is therefore reasonable to consider a precision hover MTE as a means of compliance with FAA Part 23 regulations, regardless of aircraft size, weight, or mode of operation (i.e., lift+cruise, multi-copter, tilt rotor, tilt wing, tail sitter, etc.).

A mission-oriented approach provides for the possibility of different dynamic response characteristics or flight control system response-types. One shortcoming of several of the requirements of MIL-STD-1797B, for example, is that they are not applicable to all response-types. Thus, aircraft with an attitude response-type such as pitch attitude command/attitude hold dynamics cannot be evaluated using the control anticipation parameter (CAP) criteria for short-term response. The number of different response types possible for VTOL airplanes is extensive, so this issue must be a consideration in the certification process.

Finally, one of the most significant features of the mission-oriented approach is the inclusion of MTEs as an integral part of the standard. This was done for rotorcraft in ADS-33 and an initial fixed wing catalog of maneuvers [5], but in the fixed wing case these maneuvers have not yet been incorporated into the military standard, though they are being considered for inclusion in the forthcoming MIL-STD-1797C. Qualitative flight test evaluations by trained evaluation test pilots that are familiar with the handling qualities rating process as established by Cooper and Harper [6] should be made an integral part of the handling qualities means of compliance evaluation process.

2 Flying and handling qualities

Historically, there has been a tendency to use the terms “flying qualities” and “handling qualities” interchangeably. For the engineering community, there is typically no recognized difference between these key words. To some, however, the terms have begun to take on different meanings, and this difference has been reflected, where possible, in this working paper. The terms are interpreted as follows from [1].

“Flying qualities” is taken to mean those analytical and empirical parameters or criteria that can be measured for a given airplane. All such parameters or criteria can be related to the demands the pilot places on the airplane to achieve desired performance. That is, they are *open-loop* metrics describing *pilot-in-the-loop* operations. Here we are talking about metrics such as Aircraft Bandwidth/Phase Delay as defined in [2] and elsewhere. This metric is based on crossover model theory [7] and, as such, the open-loop metric parameters derived from a flight test frequency response of attitude output to pilot inceptor input give a measure of the pilot-vehicle system bandwidth (i.e., crossover frequency) for a 45 degree phase margin closure. The phase delay parameter provides a measure of the higher frequency phase roll off, the magnitude of which quantifies effective time delay in the region of pilot-vehicle system control. Thus, parameters that are obtained via an open-loop test input can be used to predict closed-loop pilot-vehicle system performance.

By contrast, “handling qualities” is meant to describe operations while the pilot is actively in the loop. This includes the definition put forth by Cooper and Harper: “Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.”

In this context, the “flying qualities” criteria are measures from which we attempt to quantify the “handling qualities” of the airplane. By this definition, the criteria of ADS-33E-PRF and MIL-STD-1797B are flying qualities criteria, and the MTEs are handling qualities maneuvers. The flying qualities criteria are thus measures of *predicted* handling qualities, while Cooper-Harper Ratings (CHR) are measures of *actual* handling qualities. MTEs thus become the closed-loop pilot-vehicle system measure. The Cooper-Harper ratings assigned by an experienced test pilot using well-defined MTEs, including desired and adequate performance requirements that facilitate use of the CHR scale together with verification of task performance, measure actual handling qualities.

Flying qualities and handling qualities requirements are also reflected in Part 23 of the Airworthiness Standards: Normal Category Airplanes. As illustrated in Figure 1, the Part 23 requirements can be divided between flying qualities and handling qualities requirements using the above descriptions. First note that the list of flying qualities related requirements is longer than illustrated in the figure. Second, there will be some overlap in requirements as indicated by the complete lists provided in Table 1. For example, 23.2145 Stability appears on both lists, since airplane stability must be displayed via both open- and closed-loop pilot-vehicle system maneuvering. To meet these requirements, MTEs are applied as a means of compliance. Here, Flying Qualities Task Elements or FQTEs are the flight test maneuvers that measure flying qualities and related performance parameters. The FAA has long established flight test methodologies that serve as means of compliance with the Part 23 requirements [8]. Using the MTE template herein to the extent it is appropriate, FQTEs can be written in a format that is complimentary to the process described to aid in the development of a standardized means of compliance flight test methodology. Handling Qualities Task Elements or HQTEs are the flight test maneuvers that address closed-loop pilot-vehicle system performance. The remainder of this report will address the process to develop HQTEs.

Figure 1. Mission Task Elements as a Means of Compliance

Table 1. Breakdown of Part 23 Airworthiness Requirements

Flying Qualities	**Handling Qualities**
§23.2110 Stall speed. §23.2115 Takeoff performance. §23.2120 Climb requirements. §23.2125 Climb information. §23.2130 Landing. §23.2135 Controllability. §23.2140 Trim. §23.2145 Stability. §23.2150 Stall characteristics, stall warning, and spins. §23.2160 Vibration, buffeting, and high-speed characteristics. §23.2165 Performance and flight characteristics requirements for flight in icing conditions.	§23.2130 Landing. §23.2135 Controllability. §23.2145 Stability. §23.2155 Ground and water handling characteristics. §23.2165 Performance and flight characteristics requirements for flight in icing conditions.

3 Handling Qualities Task Elements

In flight test, it is desirable to categorize segments of aircraft missions into test maneuvers that address relevant Part 23 handling qualities requirements [1]. The ability of the aircraft to accomplish these tasks is predicted according to the appropriate criteria. Parameters for these requirements are generated first analytically, then via simulation, and finally via flight test. It is not practical, or necessary, to derive a separate set of criteria for every defined task. Instead, the tasks are grouped in terms of the criteria boundaries that apply to them, in this case the appropriate Part 23 requirement. As introduced previously, the handling qualities tasks in a mission-oriented specification are formally defined as Handling Qualities Task Elements or HQTEs. This approach has been well established for military rotorcraft in ADS-33E-PRF [2]. It is intended that the civilian HQTEs be specified in detail, including desired and adequate handling qualities performance requirements that facilitate use of the Cooper-Harper rating scale.

3.1 Definition

Building upon past work, the FAA Small Airplane Standards Branch has developed the following HQTE definition as it applies to Means of Compliance for the Part 23 Requirements listed above.

Handling Qualities Task Elements are repeatable tests based on vehicle Concept of Operations (CONOPS) and tailored to evaluate aircraft characteristics to assure:

- Safe operations within the flight envelope, and;
- The ability to perform the intended mission(s) with acceptable pilot workload/compensation and awareness.

The MTE should link to operationally relevant task (see notes) while accounting for:

a) environmental conditions and flight manual limits; and
b) expected failure conditions detailed in FMA (Failure Mode Analysis).

Notes:

1. Aircraft characteristics evaluated during development need to consider integration of flight control laws, displays, inceptors, and sensors.
2. Operational suitability determination may require additional testing. Linkage to ACS (Airman Certification Standards) or PTS (Practical Test Standards) may be relevant.
3. Level of precision and aggressiveness for a task may be contrived to uncover pilot-induced oscillations (PIO) and other handling qualities deficiencies.
4. HQTE MUST link to aircraft certification regulation(s) and can be used in partial fulfillment with respect to showing compliance to the regulation(s).
5. HQTEs may utilize Cooper Harper Ratings (CHRs) as a tool for correlating task performance and pilot compensation. Here, compensation is a factor in pilot workload. Compliance determination to regulations will need to consider more than just a CHR as a pass/fail criterion.
6. Uncovering the source of Handling Qualities deficiencies may require breaking out tasks in one axis at a time.

3.2 Required precision and aggressiveness

In a mission-oriented specification, the Flight Phase Categories are defined in terms of the level of *precision* and *aggressiveness* required of the pilot. Four HQTE categories under consideration are defined as follows:

- Non-Precision, Non-Aggressive
- Non-Precision, Aggressive
- Precision, Non-Aggressive
- Precision, Aggressive

The intent of the HQTE categories is that the requirements in a given category are sufficiently similar so that a single criterion boundary will apply. For example, the Aircraft Bandwidth/Phase Delay criteria [2, 7, 9] should have a form similar to that shown in Figure 2. Data will be required to properly define these boundaries for Part 23 aircraft applications.

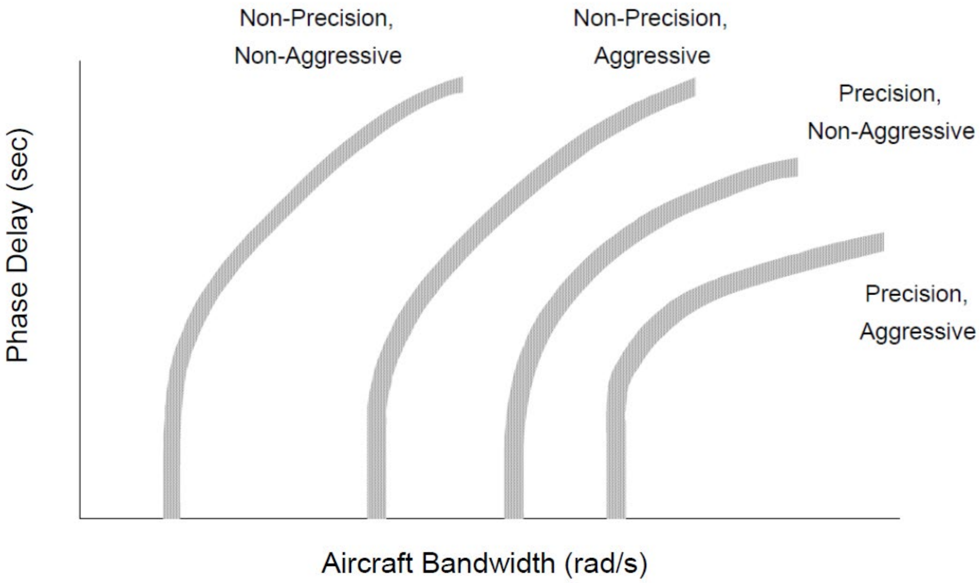


Figure 2. Relationship between HQTE categories and specification boundaries for Aircraft Bandwidth/Phase Delay criteria [3]

Non-Precision, Non-Aggressive: Non-precision tasks that require only a moderate amount of closed-loop control fall in this category. Examples include:

- Low speed tasks such as hover turn and landing.
- Cruise flight tasks such as heading changes, altitude (climb/descent) changes, and altitude rate (climb rate/descent rate) changes.

Non-Precision, Aggressive: This category is intended to include the large amplitude maneuvering HQTEs that emphasize control power over precise dynamic response. It is true, however, that a reasonably good dynamic response is inherently necessary to effectively utilize a large amount of control authority (i.e., to stop and start the large amplitude maneuvers with some precision). The moderate- and large-amplitude maneuvering requirements will be of primary interest for these HQTEs. Examples include:

- Low speed and transition tasks such as depart abort and obstacle avoidance.
- Cruise flight tasks such as collision avoidance with other aircraft.

Precision, Non-Aggressive: This category includes tasks where considerable precision is required, but without aggressive control activity. The dynamic response requirements for these tasks are expected to be less stringent than for *Precision, Aggressive*, but significantly greater than for *Non-Precision, Non-Aggressive*. Examples include:

- Low speed tasks such as precision hover, lateral reposition and hold, and pirouette.
- Cruise flight tasks such as pitch attitude captures, bank angle captures, and flight path regulation.

Precision, Aggressive: This category includes precision tasks, where an extremely crisp and predictable response to control inputs is required. Ride qualities are typically not a factor. The results of not achieving the required precision are usually significant in terms of accomplishing the mission or safety of flight. Examples include:

- Low speed tasks such as obstacle avoidance in a dense, urban environment.
- Cruise flight tasks such as flight path regulation in the presence of moderate to high turbulence.

4 HQTE development process

4.1 Process description

Figure 3 illustrates the process to develop HQTEs. In short, the first step in the HQTE development process is mission segment deconstruction of the Part 23 airplane. Since aircraft use cases may be unique for different Part 23 airplanes, there will not only be unique HQTEs based on these use cases, but also common HQTEs. For example, all fixed wing airplane will takeoff, land, climb, descend, loiter, etc. There will, however, be HQTEs that are specific to the unique use case. This may result in a common HQTE with separate performance requirements or a new HQTE. This section will describe the elements of the HQTE development process including a detailed HQTE template and evaluation questionnaire that can be used in the HQTE assessment process.

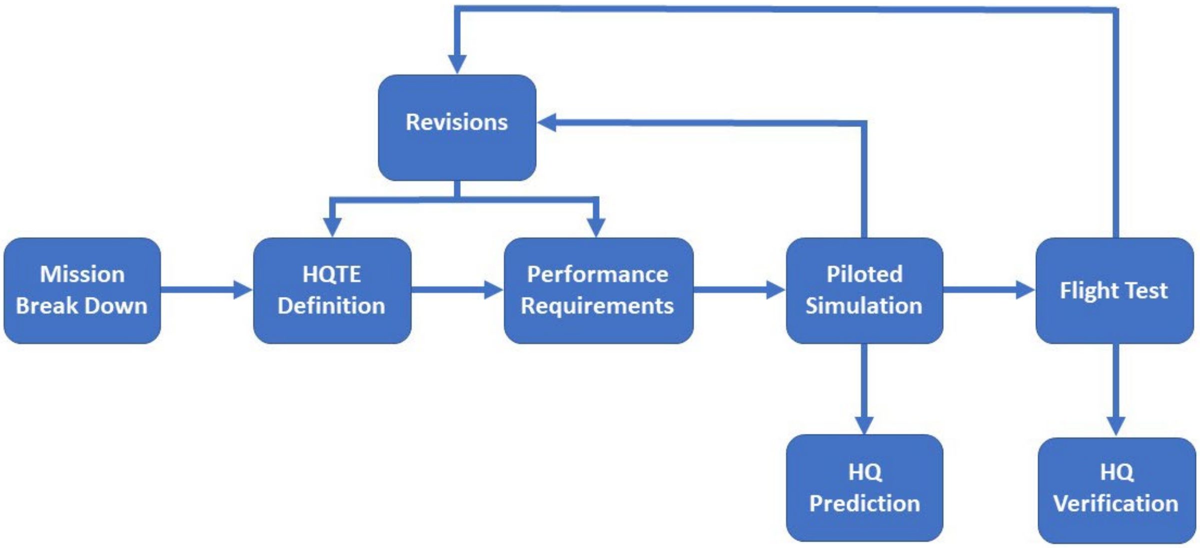


Figure 3. HQTE development process

4.1.1 Mission break down

As described above, the mission of the Part 23 Small Airplane will be dissected into elements that individually address the key components of the overall mission. For Part 23, this will include fixed wing airplanes and the great variety of emerging vertical takeoff and landing aircraft that are being developed for new urban air mobility and personal air vehicle use cases.

4.1.2 HQTE naming convention

Currently, the MTE naming convention is still being defined. The objective is to provide for a title that will allow users to extract information about configuration, test environment, etc., and provide a link to an operationally relevant maneuver. As stated elsewhere in this working paper, the HQTE is defined to consistently expose handling qualities deficiencies in a repeatable manner, not to provide operational relevance, per se.

4.2 HQTE template

This section defines the elements of a Handling Qualities Task Element that has been defined as means of compliance for FAR Part 23 requirements.

HQTE NAME

- Specify a name that clearly indicates the intention of the HQTE.

FAR Part 23 Requirement

- Identify Part 23 requirement to which the HQTE serves as a means of compliance.

- Handling qualities requirements apply to:
    - §23.2130 Landing;
    - §23.2135 Controllability;
    - §23.2145 Stability;
    - §23.2155 Ground and water handling characteristics; and
    - §23.2165 Performance and flight characteristics requirements for flight in icing conditions.

Link to Practical Test Standards

To the extent possible, the HQTEs should be linked to practical test standards [10]. It is recognized, however, that the primary role of the HQTE is to expose handling qualities. Thus, any linkage to airman proficiency standards may aid in a secondary role of pilot acceptance.

Precision and Aggressiveness Level

- Identify specified level as linked to desired/adequate performance requirements.

- Levels to be specified are: 1) Non-Precision/Non-Aggressive; 2) Precision/Non-Aggressive; 3) Non-Precision-Aggressive; and 4) Precision/Aggressive.

Task Objectives

- Approximately two to four high-level bulleted items that will help the user determine why this HQTE should be used, as well as the expected outcomes.

Task Description

- Brief but explicit description of the task, including test course layout and specialized equipment/displays, if needed.
- Keep the HQTE simple in operation. If it becomes too elaborate, consider breaking it into two (or more) HQTEs.
- Be careful setting time as a task parameter. Consider whether time is a part of the task description (meaning it must be met) or a performance limit (meaning it is a measure of quality).
- Task description should read as a flight test card with precise instructions for the evaluation pilot.

Desired Performance

- Bullet list of the desired levels of task performance that can be achieved with appropriate level of pilot compensation (e.g., HQR $\leq$ 4).

- List primary task parameters and secondary measures that impact performance.

Adequate Performance

- Bullet list of the adequate levels of task performance that can be achieved with appropriate level of pilot compensation (e.g., $5 \leq \text{HQR} \leq 6$).
- List primary task parameters and secondary measures that impact performance.

Task Variations

1. Enumerate variations, if any, in HQTE execution (e.g., flight condition variations, unique entry/exit conditions, etc.).
2. Specify any variations in required environmental conditions (e.g., visual conditions, steady winds, turbulence, etc.).
3. Identify failure cases, if any, that will be considered.

4.3 HQTE considerations

4.3.1 Operational relevance

HQTEs should attempt to link to operationally relevant maneuvers; however, it is more important that they consistently expose the handling qualities associated with the Part 23 requirement. Other considerations that outweigh operational relevance include ease of use, repeatability, and ability to effectively expose handling qualities deficiencies, if they exist.

4.3.2 HQTE build-up

As certification seekers address HQTEs, a build-up approach will be applied that first introduces single-axis HQTEs. Precision and aggressiveness levels will then be increased. After successful completion of the single axis MTE set, multi-axis MTEs will be introduced that again build up the precision and aggressiveness levels.

4.4 Performance requirements

The desired and adequate performance requirements of the HQTEs are developed specifically for use with the Cooper-Harper Handling Qualities Rating Scale shown in Figure 4 [6]. The use of Cooper-Harper Handling Qualities Ratings or CHRs requires the definition of numerical values for desired and adequate performance. The performance limits are set primarily to drive the level of aggressiveness and precision to which the maneuver is to be performed. Compliance with the performance standards may be measured subjectively from the cockpit or by the use of chase aircraft or ground observers, if possible. It is not necessary to use complex instrumentation for these measurements. The evaluation pilot should be advised any time the desired or adequate performance limits are not met, immediately following the completion of the HQTE, as the pilot learns the task. Once proficiency in task performance is gained, however, the pilot should assign ratings based on perceived performance. Otherwise, the pilot may inappropriately rate a configuration higher or lower regarding handling qualities solely based on a performance parameter rather than other arguably more important factors, such as aircraft characteristics or required compensation.

In cases where the performance does not meet the specified limits, it is acceptable for the evaluation pilot to make as many repeat runs as necessary to insure that this is a consistent result. Repeat runs to improve performance may also expose handling qualities deficiencies. Such deficiencies should be an important factor in the assigned pilot rating. For those HQTEs that are by design very short in time (such as attitude captures and landings), at least two or three repeat runs should be encouraged. Desired and adequate CHRs do not, in and of themselves, equate to compliance and achieving adequate performance does not mean adequate for certification.

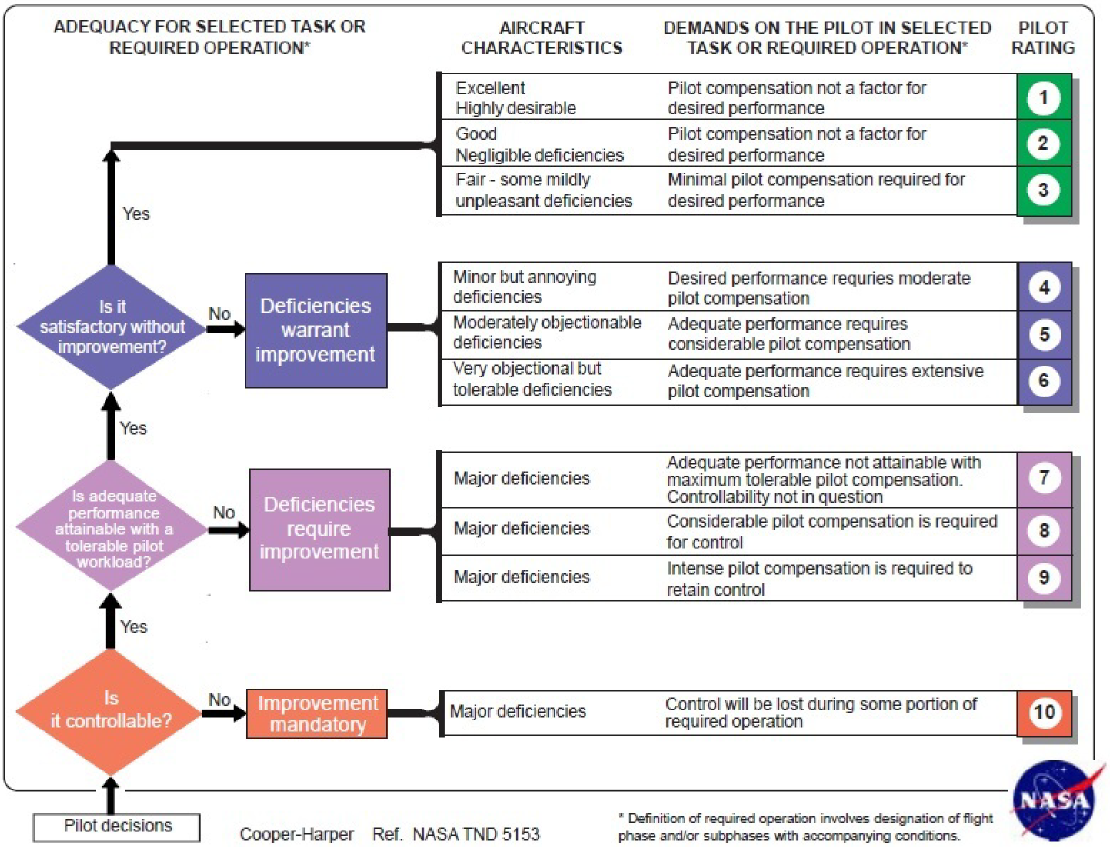


Figure 4. Cooper-Harper handling qualities rating scale [6]

For some maneuvers, the pilot may find it difficult to perceive actual performance. For example, in an offset landing task a limited field-of-view will restrict the pilot's ability to see the touchdown zone. Aircraft size, too, can play a part, since the pilot sits far ahead of the main landing gear in a large transport, yet the requirements for touchdown performance are referenced to the gear. In such instances, the pilot will frequently comment that better performance is simply not possible, since the target is not visible. The best remedy to this problem requires engineering judgment. If feasible, it is always preferable to find a better way of presenting the performance limits to the pilot. In the case of the landing, additional markers may be placed on or near the runway – located so that they are visible to the pilot – to indicate the correct reference for achieving desired performance. Alternatively, and especially if it is not feasible to increase the pilot's visual references, the best solution may be to accept minor excursions outside of desired performance. In this case, the pilot should be asked to comment specifically on the effects of the visual field – in addition to the handling of the airplane – on achievable performance.

The ultimate goal of the performance limits is to set the expected levels of aggressiveness and precision, and the intent of keeping the pilot informed about actual performance is to assure that occasional exceedances are due to lack of perception of the requirements, not lack of intensity on the part of the evaluation pilot. When assigning a rating, the pilot should begin at the bottom of the decision tree. From here, the pilot moves up through the question boxes until a "no" response or the last box is reached. Next, the pilot moves to the right and a rating is then assigned based on perceived performance and workload. It is important to remember that desired performance can still result in a Level 2 rating, if moderate compensation was required. Conversely, a configuration should not be down rated by an occasional exceedance of a performance requirement. In these cases, pilot comments should always accompany the numerical rating to provide the additional insight that may otherwise be missed.

5 Evaluating HQTEs

5.1 Piloted simulation

5.1.1 Aircraft model

It is critical to have a test aircraft model for HQTE development that can easily reflect a wide range of handling qualities from Level 1, in terms of the Cooper-Harper scale, to Level 3. Furthermore, an aircraft model that is known to have good handling qualities, based on predictions from validated criteria (e.g. [2]) and/or prior flight experience, is also required for the evaluation process. As one moves from piloted simulation to flight test evaluations, variable stability in flight simulators (e.g., Calspan Learjets, USAF VISTA, NRC Canada Bell 205 and 412 testbeds, and the VSS Navions) provide an effective means to develop and evaluate HQTEs.

5.1.2 Revisions

As the HQTE develops and is evaluated in the simulator using feedback from experienced test pilots, revisions to the task description (including visual display requirements, task performance requirements, and task variations) are expected. Pilot comments, ratings, and formal pilot questionnaire results should be used as part of the HQTE evaluation process. To the extent possible, feedback from multiple evaluation pilots should be considered as part of the HQTE revision process.

5.1.3 Predicted handling qualities

Given an accepted HQTE description, evaluations conducted in a piloted simulation can be used to predict handling qualities.

5.1.4 Flight conditions and aircraft states including failure conditions

There is typically no mention in the HQTE definition of applicable flight conditions, aircraft loadings (configurations), or aircraft States. These maneuvers are intended to be applicable throughout the Operational Flight Envelope (OFE) of the airplane under consideration, while operating in its normal configurations. The maneuvers should be performed at those Normal States within the OFE that are most critical from the standpoint of handling qualities. Aircraft performance is not meant to be an issue, and the flight conditions should be selected accordingly. It will, however, be necessary to demonstrate compliance with the Part 23 regulations under failure conditions. To ensure safety, these assessments may be made via piloted simulation.

5.2 Flight test

5.2.1 Revisions

Once an MTE has evolved via piloted simulation, revisions to the task description, including visual aids, task performance requirements, and task variations, are expected as the MTE is attempted in flight. Pilot comments, ratings, and formal pilot questionnaire results should be used as part of the MTE flight test evaluation process. To the extent possible, feedback from multiple evaluation pilots should be considered as part of the MTE revision process.

5.2.2 Verified handling qualities

Given an accepted HQTE description, evaluations conducted in a flight are used to verify handling qualities thereby serving as a demonstrated means of compliance for Part 23 requirements. This will represent a partial fulfillment of requirements, as other compliance measures will also be considered.

5.3 Pilot questionnaire for HQTE evaluations

Pilot questionnaires have been used effectively as part of the HQTE evaluation process. This includes the fixed wing handling qualities demonstration maneuvers work conducted in the mid 1990's [4]. More recently, pilot questionnaires were used to effectively evaluate HQTEs that were developed for high-speed rotorcraft evaluations [11, 12, 13, and 14]. The questionnaire shown in Figure 5 has been revised slightly for the Part 23 means of compliance application.

	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
The HQTE is linked to an operational relevant task.	○	○	○	○	○
The HQTE is well defined.	○	○	○	○	○
The HQTE is repeatable and easy to fly.	○	○	○	○	○
Entry/exit conditions for the HQTE were easy to establish.	○	○	○	○	○
The display used for the HQTE provided all the information required for performing it.	○	○	○	○	○
The HQTE provides a valid medium for handling qualities evaluations.	○	○	○	○	○
The HQTE provides a valid medium for PIO evaluations.	○	○	○	○	○
The HQTE is able to effectively expose the aircraft characteristics associated with the linked Part 23 requirements.	○	○	○	○	○

What changes would you recommend to the HQTE description and the desired and adequate performance requirements (e.g., cockpit displays, course layout, out-of-the-window cues, etc.)?

Comment on the factors other than the task that affected your ratings (e.g., aircraft characteristics, control force/displacements, cockpit displays, etc.).

Figure 5. Example HQTE assessment pilot questionnaire

5.4 Applying HQTEs early in the design process

In an ideal world, time and money would not influence the development of new aircraft. Unfortunately, in the real world, scheduling and costs drive the development process. As a result, some items, including handling qualities, often receive lower priority and they may not be addressed until a problem arises. On the other hand, aircraft model development including ground-based simulation begins early in the design process. Thus, one way to rectify the lack of attention paid to handling qualities is to employ HQTEs early in the development process. Common head-down or head-up displays are sufficient to exercise many of the maneuvers, so elaborate displays are usually not necessary. The process can begin with engineering workstations that use simple joystick type controls.

There are many benefits to this approach, including:

- Potential handling qualities problems may be identified early in the design process;
- HQTEs will provide repeatable evaluation techniques that can be applied to multiple configurations;
- Program test pilots will become more comfortable with the maneuvers heading into actual flight tests;
- HQTEs tend to expose flight control system discontinuities as well as poor response type transitions or even inadequate mode annunciations that could lead to mode confusion; and
- Valuable flight time will not have to be spent developing a pilot's learning curve.

The above benefits may also turn out to be a significant cost saver.

5.5 Use of other appropriate rating scales

In addition to Cooper-Harper ratings, additional ratings using other relevant scales may be collected to provide further insights into a given HQTE evaluation. The most significant of these is the Pilot-Induced Oscillation Tendency Rating (PIOR) Scale shown in Figure 6. Although not specifically designed to expose PIO tendencies, many of the precision HQTEs (e.g., attitude captures and fine tracking maneuvers) often reveal the handling qualities "cliffs" that can lead to PIO. Two scales are combined in Figure 6, one is a decision tree scale [15] and the other is the original "word" scale [16]. The decision tree should be applied by the pilot in a manner similar to that discussed for the Cooper-Harper scale. The additional dialog in the word scale, however, must be considered prior to assigning a rating. This will help the pilot distinguish between undesirable motions such as "pitch bobble" and oscillations (i.e., ~180° out-of-phase vehicle response to pilot control inputs as defined in [17]). Configurations are often rated too harshly when the decision tree scale alone is used to assign ratings.

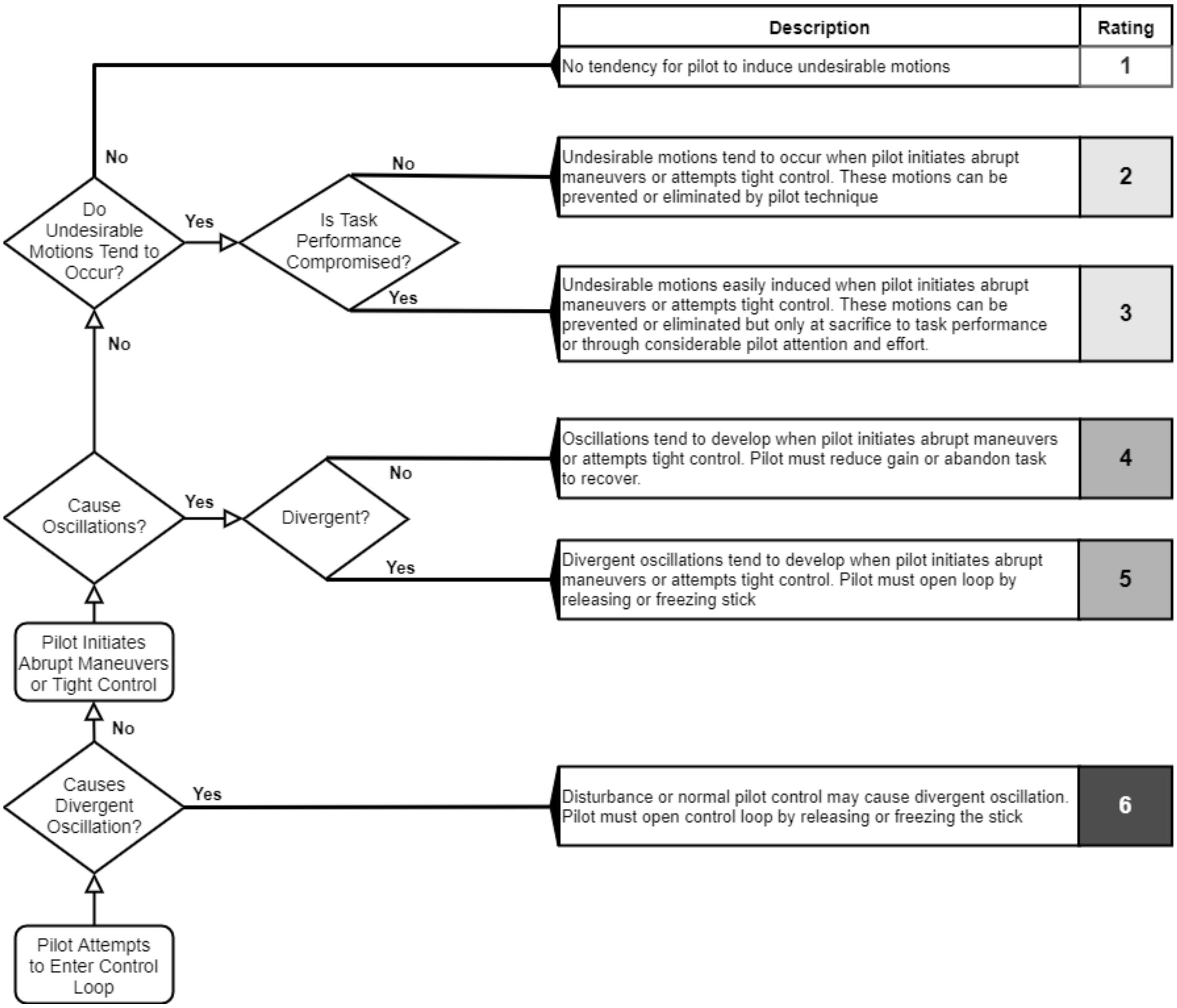


Figure 6. Pilot-Induced Oscillation tendency rating scale [15 and 16]

6 HQTE catalog

Descriptions of each of the candidate HQTEs developed during the Phase 1 effort are provided in this section. Each HQTE description uses the same template format defined in Section 4.2. A summary of each of the HQTEs is provided in Table 2. The HQTEs cover a wide range of different precision/aggressiveness levels and flight conditions.

These HQTEs are proposed for use in handling qualities Means of Compliance (MOC) assessments of new VTOL vehicles intended to operate as personal or urban commuter transports. Utilizing mission-oriented approach, these HQTEs were designed to be repeatable tests, based on vehicle CONOPS, and tailored to evaluate aircraft characteristics that assure:

- Safe operations within the flight envelope; and

- The ability to perform the intended mission(s) with acceptable pilot workload/compensation.

The MTEs from ADS-33E-PRF [2] provide tested and proven means to assess rotorcraft handling qualities. As such, the HQTE development was heavily influenced by the ADS-33E-PRF MTEs, and many of the HQTEs represented here are closely related to the ADS-33E-PRF MTEs, but they are now tailored to better suit the personal air vehicle/urban passenger transport CONOPS. The catalog also includes several new HQTEs, inspired by Urban Air Mobility CONOPS envisioned by the FAA [18], and forward flight HQTEs derived from high-speed MTE development work for advanced rotorcraft platforms [12].

Table 2. HQTE Catalog Summary

HQTE	Precision/Aggressiveness Level	Flight Condition(s)
Precision Hover HQTE	Precision/Non-Aggressive	Low Speed/Hover
Vertical Reposition and Hold HQTE	Precision/Non-Aggressive	Low Speed/Hover
Hovering Turn and Hold HQTE	Precision/Non-Aggressive	Low Speed/Hover
Lateral Reposition and Hold HQTE	Precision/Non-Aggressive	Low Speed/Hover
Pirouette HQTE	Precision/Non-Aggressive	Low Speed/Hover
Depart/Abort HQTE	Non-Precision/Aggressive	Low Speed/Hover – Forward Flight
Pitch Attitude Capture and Hold HQTE	Precision/Non-Aggressive	Forward Flight
Bank Angle Capture and Hold HQTE	Precision/Non-Aggressive	Forward Flight
UAM Heliport Approach HQTE	Precision/Non-Aggressive	Forward Flight –Low Speed/Hover
UAM Heliport Approach – Vertical Abort HQTE	Non-Precision/Aggressive	Forward Flight
UAM Heliport Approach – Horizontal Abort HQTE	Non-Precision/Aggressive	Forward Flight
Collision Avoidance – Vertical Escape HQTE (Forward Flight)	Non-Precision/Aggressive	Forward Flight
Collision Avoidance – Horizontal Escape HQTE (Forward Flight)	Non-Precision/Aggressive	Forward Flight

6.1 Precision Hover HQTE

FAR Part 23 Requirement

- Handling qualities requirements apply to:

    - §23.2130 Landing;
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The Precision Hover HQTE requirements and performance standards can be linked to several practical test standards (PTS) [19]. These PTSs include:

- Landings and Approach to Landings PTSs of FAA-S-8081-20 [20]
    - Normal and Crosswind Approaches and Landings
- Hovering Maneuvers and Takeoffs, Landings and Go-Arounds PTSs of FAA-S-8081-16B [21]
    - Hover Task and Air Taxi tasks
- Hovering Maneuvers and Takeoffs, Landings and Go-Arounds PTSs of FAA-S-8081-15A [22]
    - Hover Task and Air Taxi tasks

Precision and Aggressiveness Level

- Precision/Non-Aggressive

Task Objectives

- Check ability to transition from translating flight to a stabilized hover with precision and a mild amount of aggressiveness.
- Check ability to maintain precise position, heading, and altitude in the presence of a moderate wind from the most critical direction.
- Check for inceptor control harmony in all axes.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

Initiate the maneuver at a ground speed between 6 and 10 knots, at an altitude of 20 ft. The target hover point shall be oriented approximately 45 degrees relative to the heading of the rotorcraft. The target hover point must be a repeatable, ground-referenced point from which rotorcraft deviations can be measured. The ground track should be such that the rotorcraft will arrive over the target hover point after performing a 45 degree translation toward to hover point (see illustration in Figure 7a). For capturing the hover point, the pilot should apply a smooth deceleration. The pilot shall attempt to attain a stabilized hover within the specified performance times after the initiation of the deceleration. After capturing a stabilized hover, the pilot shall maintain a stabilized hover for 30 seconds while attempting to maintain the specified desired position tolerances.

In Figure 7, a suggested course for the Precision Hover HQTE is presented. The course includes several visual references that allow the pilot to perform the task and provide performance cues to the pilot. These visual references include:

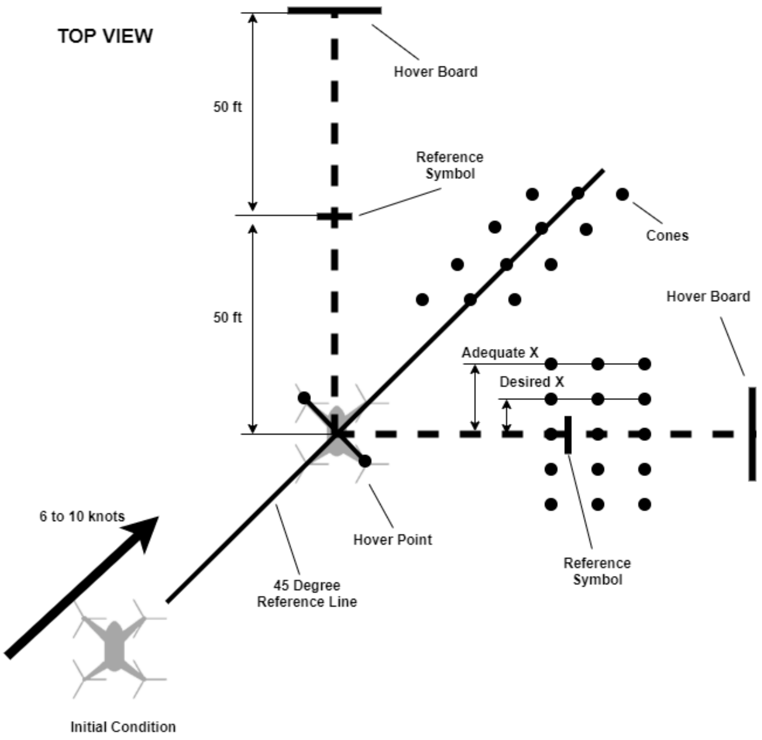
- 45 Degree Reference Line (e.g., painted lines and/or cones).
- A physical ground marker indicating the target hover point (e.g., painted "X" and/or cones).
- Two "Hover Boards" and "Reference Symbols." One set of these is positioned in front of the hover point and the other set is positioned 90 degrees laterally from the hover point. The Hover Board and Reference Symbol are used to provide the pilot position and altitude performance cues.
- Additional ground markers (e.g., cones) that provide added position cueing, especially fore/aft.

Desired Performance

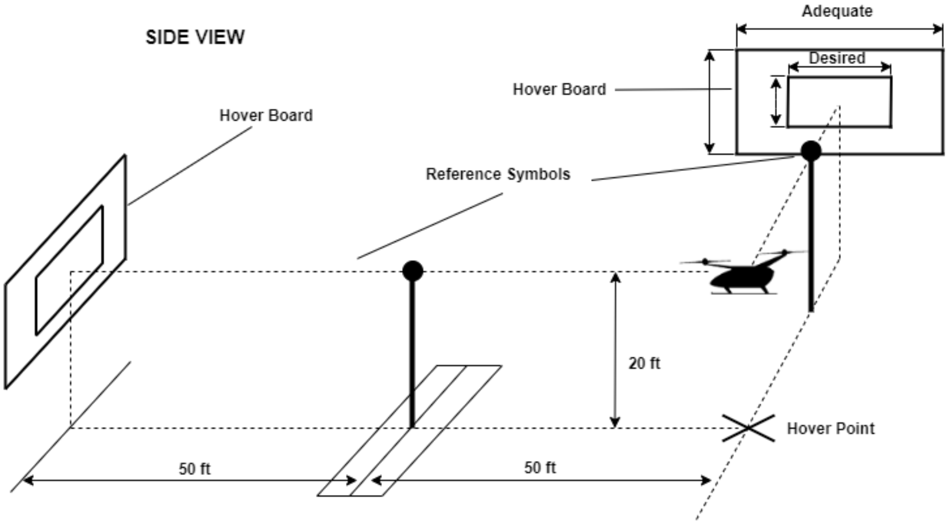
- Attain a stabilized hover within 5 seconds of initiation of deceleration.
- Maintain a stabilized hover for at least 30 seconds.
- Maintain the longitudinal and lateral position within ±3ft from a point on the ground.
- Maintain altitude within ±2ft.
- Maintain heading within ±5 deg.
- There shall be no undesirable motions (e.g., pitch or roll axis bobble) in any axis either during the transition to hover or the stabilized hover.

Adequate Performance

- Attain a stabilized hover within 8 seconds of initiation of deceleration.
- Maintain a stabilized hover for at least 30 seconds.
- Maintain the longitudinal and lateral position within ±6ft from a point on the ground.
- Maintain altitude within ±4ft.
- Maintain heading within ±10 deg.
- There shall be no objectionable oscillations in any axis either during the transition to hover or the stabilized hover.



a) Top View



b) Side View

Figure 7. Suggested Course for Precision Hover HQTE

Task Variations

- The precision hover should be performed in moderate wind conditions in the most critical direction for the test aircraft. If a critical direction has not been defined, the hover shall be accomplished with the wind blowing directly from the rear of the rotorcraft.

6.2 Vertical Reposition and Hold HQTE

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2130 Landing;
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The Vertical Reposition and Hold HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Landings and Approach to Landings PTSs of FAA-S-8081-20 [20]
    - Normal and Crosswind Approaches and Landings
- Hovering Maneuvers and Takeoffs, Landings and Go-Arounds PTSs of FAA-S-8081-16B [21]
    - Hover Task and Air Taxi tasks
- Hovering Maneuvers and Takeoffs, Landings and Go-Arounds PTSs of FAA-S-8081-15A [22]
    - Hover Task and Air Taxi tasks

Precision and Aggressiveness Level

- Precision/Non-Aggressive

Task Objectives

This maneuver is intended to assess the heave axis controllability with precision station keeping. The primary objectives include the following:

- Check for adequate heaving damping (i.e. ability to precisely start and stop a vertical rate).
- Check for adequate vertical control power.
- Check for undesirable coupling between collective (heave axis control inceptor) and the pitch, roll, and yaw axis.
- Check for any undesirable characteristics of the heave axis controller.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

From a stabilized hover at an altitude of 20 ft, initiate a vertical ascent of 25 ft to a new target altitude of 45 ft. Stabilized at new altitude for 5 seconds, then descend back to the initial hover position and stabilize again and hold for 5 seconds. The maneuver shall be accomplished in moderate winds from the most critical direction.

The test course shall include Hover Board and ground markings that provide visual cues that clearly define desired and adequate performance. It is recommended to use the Precision Hover course (Figure 7), with an additional Hover Board and Reference Symbol set to align with the upper altitude reference. A suggested course is shown in Figure 8.

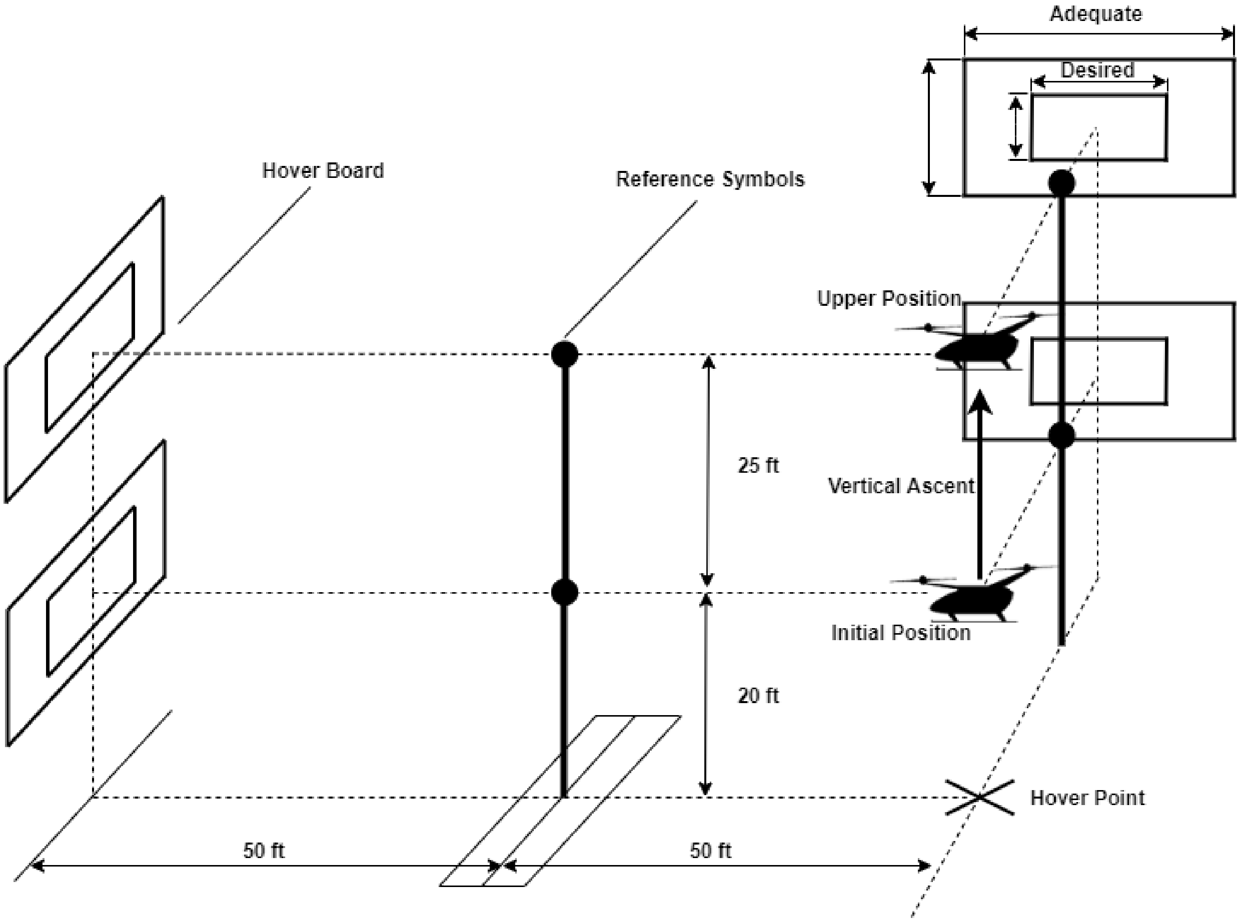


Figure 8. Suggested Course for Vertical Reposition and Hold HQTE

Desired Performance

- Maintain the longitudinal and lateral position within ±3 ft from the hover point.
- Maintain upper/final altitude within ±3 ft.
- Maintain heading within ±5 deg.
- There shall be no undesirable motions in the vertical axis during the altitude capture or hold.

Adequate Performance

- Maintain the longitudinal and lateral position within ±6 ft from the hover point.
- Maintain upper/final altitude within ±6 ft.
- Maintain heading within ±10 deg.
- There shall be no objectionable oscillations in the vertical axis during the altitude capture or hold.

Task Variations

- The Vertical Reposition and Hold HQTE should be performed in moderate wind conditions in the most critical direction for the test aircraft. If a critical direction has not been defined, the hover shall be accomplished with the wind blowing directly from the rear of the rotorcraft.

6.3 Hovering Turn and Hold HQTE

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The Hovering Turn and Hold HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Landings and Approach to Landings PTSs of FAA-S-8081-20 [20]
    - Normal and Crosswind Approaches and Landings
- Hovering Maneuvers and Takeoffs, Landings and Go-Arounds PTSs of FAA-S-8081-16B [21]
    - Hover Task and Air Taxi tasks
- Hovering Maneuvers and Takeoffs, Landings and Go-Arounds PTSs of FAA-S-8081-15A [22]
    - Hover Task and Air Taxi tasks

Precision and Aggressiveness Level

- Precision/Non-Aggressive

Task Objectives

- Check for any undesirable handling qualities during short and long duration mildly aggressive hovering turns.
- Check ability of aircraft to recover and stabilize from mild hovering turn rates with reasonable precision.
- Check for any undesirable inter-axis coupling.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

From a stabilized hover at an altitude of 20 ft, first complete a 90-degree turn while maintaining hovering position. After completing the 90-degree turn, stabilize and hold new position for 5 seconds. Next, perform a 270-degree turn in the same direction, returning and stabilizing back at the original aircraft heading for 5 seconds. Perform maneuver with both directions. The aircraft's initial heading will be aligned with one of the two Hover Boards, depending on which direction the maneuver is being performed. The maneuver shall be accomplished in moderate wind from the most critical direction.

It is suggested to use the test course described with the Precision Hover HQTE (Figure 7) shown again in Figure 9.

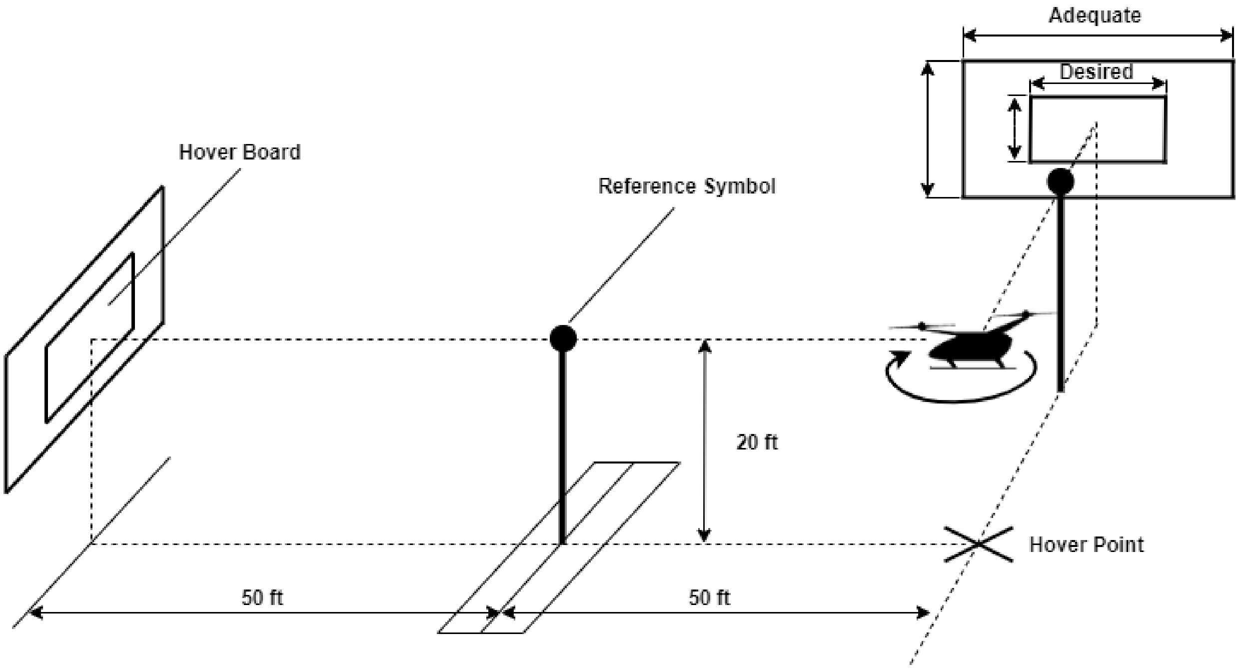


Figure 9. Suggested Course for Hovering Turn HQTE

Desired Performance

- Maintain the longitudinal and lateral position within ±3 ft from the hover point.
- Maintain altitude within ±4 ft.
- Stabilize the final rotorcraft heading at the 90-degree point and 270-degree point within ±5 deg.
- Complete turn (360-degree heading change) to a stabilized hover (within the desired position window) within 50 seconds from the initiation of the maneuver.
- There shall be no undesirable motions in the yaw axis during the heading capture or hold.

Adequate Performance

- Maintain the longitudinal and lateral position within ±6 ft from the hover point.
- Maintain altitude within ±4 ft.
- Stabilize the final rotorcraft heading at the 90-degree point and 270-degree point within ±10 deg.
- Complete turn (360-degree heading change) to a stabilized hover (within the desired position window) within 60 seconds from the initiation of the maneuver.
- There shall be no objectionable oscillations in the yaw axis during the heading capture or hold.

Task Variations

- The Hovering Turn HQTE shall be performed in moderate wind conditions in the most critical direction for the test aircraft. If a critical direction has not been defined, the hover shall be accomplished with the wind blowing directly from the rear of the rotorcraft.

6.4 Lateral Reposition and Hold HQTE

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The Lateral Reposition and Hold HQTE requirements and performance standards can be linked to several practical test standards (PTSs) [19]. These PTSs include:

- Hovering Maneuvers PTSs of FAA-S-8081-16B [21]

    - Hover Task and Air Taxi tasks
- Hovering Maneuvers PTSs of FAA-S-8081-15A [22]
    - Hover Task and Air Taxi tasks

Precision and Aggressiveness Level

- Precision/Non-Aggressive

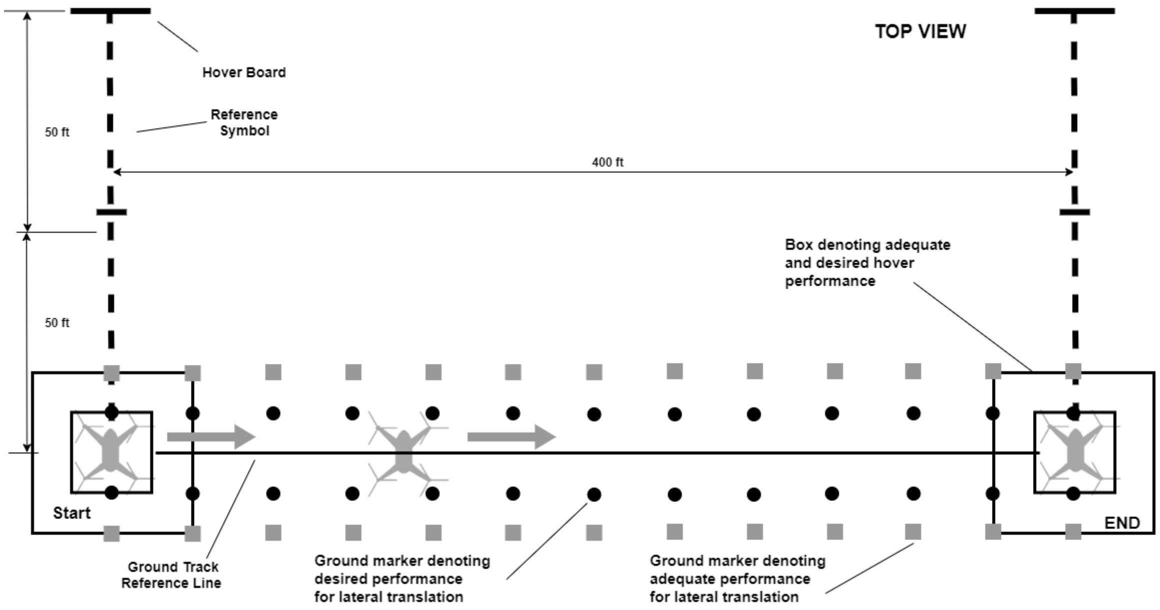
Task Objectives

- Check roll axis and heave axis handling qualities during mild low speed lateral maneuvering.
- Check for any undesirable coupling between the roll controller and other axes.
- Check ability to recover from mild lateral translation rate with reasonable precision.
- Identify pilot-induced oscillation tendencies, if present.

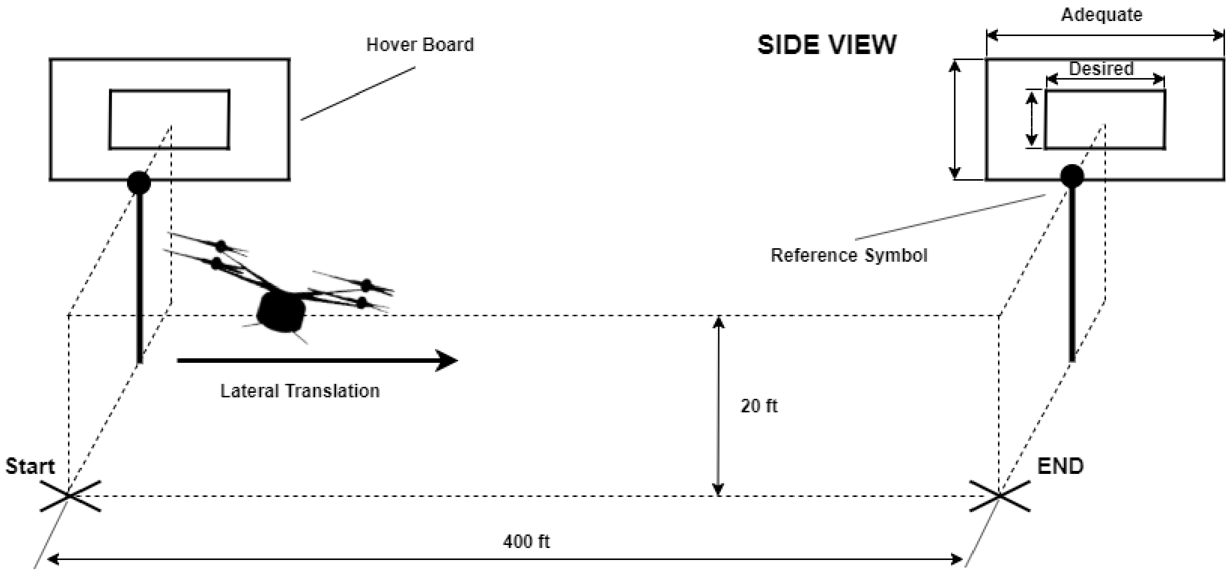
Task Description

Start in a stabilized hover at 20 ft altitude with the longitudinal axis of the aircraft oriented 90 degrees to a ground track reference line marked on the ground. Initiate a lateral acceleration up to a specified groundspeed followed by a deceleration to laterally reposition the aircraft in a stabilized hover 400 ft down the course. The acceleration and deceleration phases shall be accomplished as single smooth maneuvers. The aircraft must be brought to within ±6 ft of the endpoint during the deceleration, terminating in a stable hover within this band. A stabilized hover shall be maintained for 5 seconds and then the maneuver is repeated back in the other direction towards to original starting point, which is again held for 5 seconds. The maneuver is complete when a stabilized hover is achieved back at the maneuver start point.

The test course shall consist of a reference line and markers on the ground indicating the desired track and tolerances. It is recommended that the test course also include Hover Boards at each stabilization point. These Hover Boards provide lateral position and vertical performance cues to the pilot when attempting to stabilize at the endpoints of the course. A suggested course for the Lateral Reposition and Hold HQTE is shown in Figure 10.



a) Top View



b) Side View

Figure 10. Suggested Course for Lateral Reposition and Hold HQTE

Desired Performance

- Maintain the longitudinal position track within ±6 ft from reference line.
- Maintain altitude within ±5 ft.
- Maintain heading within ±10 deg.
- There shall be no undesirable motions in the lateral axis during the capture or hold.

Adequate Performance

- Maintain the longitudinal position track within ±12 ft from reference line.
- Maintain altitude within ±10 ft.
- Maintain heading within ±15 deg.
- There shall be no objectionable oscillations in the lateral axis during the capture or hold.

Task Variations

- In addition to calm winds, the Lateral Reposition and Hold HQTE may be performed in moderate wind conditions in the most critical direction for the test aircraft. If a critical direction has not been defined, the hover will be accomplished with the wind blowing directly from the rear of the rotorcraft.
- The maneuver may be performed at multiple translational rate rates, starting at 5 knots and up to 20 knots.
- The maneuver may be flown at higher stabilized altitudes to assess out-of-ground effect performance.

6.5 Pirouette HQTE

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The Pirouette HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Hovering Maneuvers PTSs of FAA-S-8081-16B [21]
    - Hover Taxi and Air Taxi tasks
- Hovering Maneuvers PTSs of FAA-S-8081-15A [22]
    - Hover Task and Air Taxi tasks

Precision and Aggressiveness Level

- Precision/Non-Aggressive

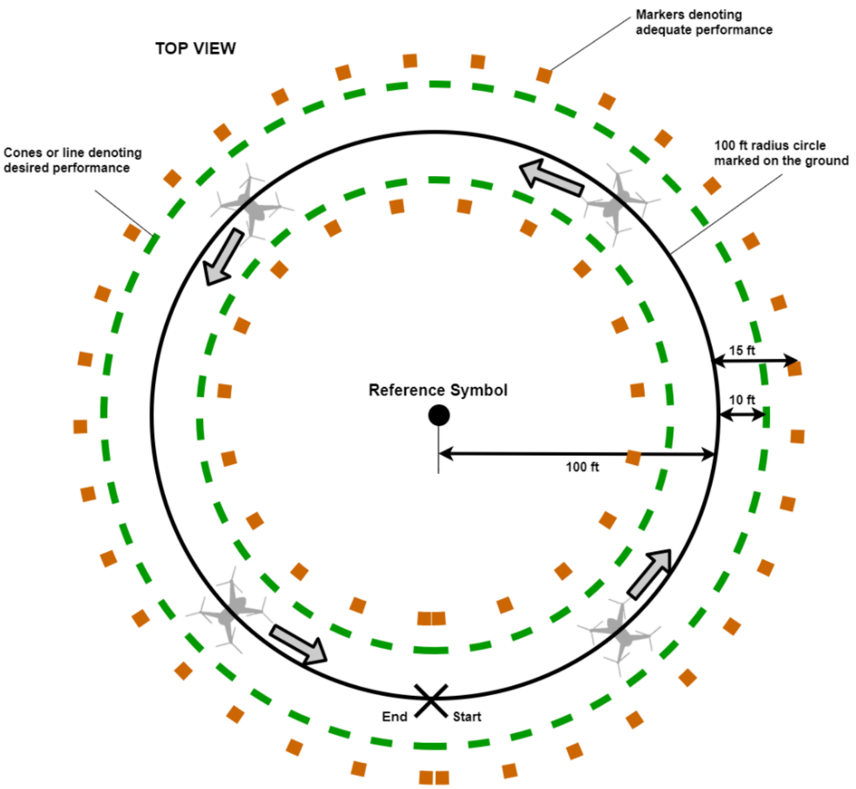
Task Objectives

- Demonstrated ability to accomplish precision control during multi-axis maneuvers (pitch, roll, yaw, and heave axes).
- Check for any undesirable coupling between the roll, pitch, yaw and heave axis controllers.
- Identify pilot-induced oscillation tendencies, if present.

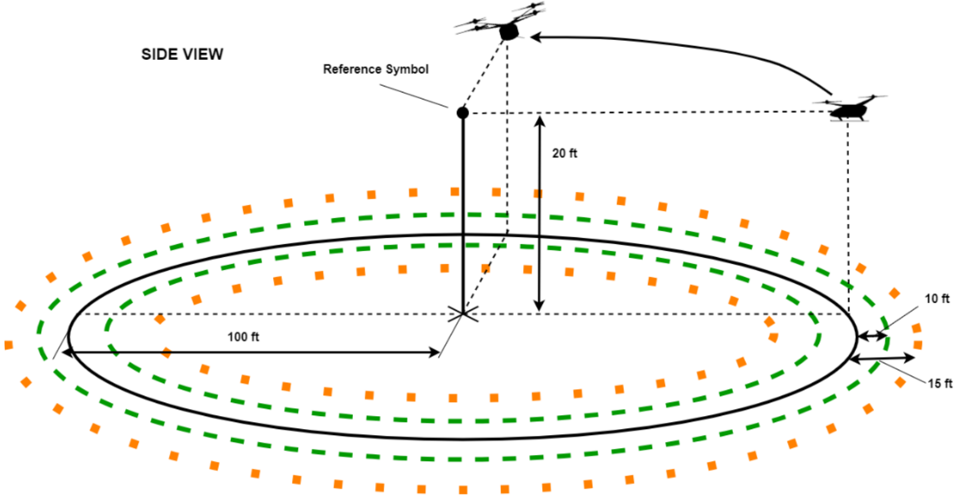
Task Description

Initiate the maneuver from a stabilized hover over a point on the circumference of a 100 ft radius circle with the nose of the rotorcraft pointed at a reference point at the center of the circle, and at a hover altitude of approximately 20 ft. Accomplish a lateral translation around the circle, keeping the nose of rotorcraft pointed at the center of the circle, and the circumference of the circle under a selected point on the rotorcraft. Maintain essentially constant lateral groundspeed throughout the lateral translation (note: nominal lateral velocity will be approximately 8 knots for the 45-sec and 6 knots for the 60-sec time around the circle). Terminate the maneuver with a stabilized hover over the starting point. Perform the maneuver in both directions.

The test course shall consist of markings on the ground that clearly denote the circular pathways that define desired and adequate performance. The suggested course shown in Figure 11 is considered adequate for the evaluation. Typically, ground markers include painted lines (of varied color) and cones. It is also recommended to add objects to assist the pilot with vertical cueing, such as a post at the center of the circle with a reference symbol at the top.



a) Top View



b) Side View

Figure 11. Suggested Course for Pirouette HQTE

Desired Performance

- Maintain a selected reference point on the rotorcraft within ±10 ft of the circumference of the circle.
- Maintain altitude within ±5 ft.

- Maintain heading so that the nose of the rotorcraft points at the center of the circle within ±10 deg.
- Complete the circle and arrive back over the starting point within 45 seconds.
- Achieve a stabilized hover, at the original starting position, within 5 seconds after returning to the starting point.
- Maintain the stabilized hover for 5 seconds.
- There shall be no undesirable motions in the lateral axis during the capture and hold at the termination of the maneuver.

Adequate Performance

- Maintain a selected reference point on the rotorcraft within ±15 ft of the circumference of the circle.
- Maintain altitude within ±10 ft.
- Maintain heading so that the nose of the rotorcraft points at the center of the circle within ±15 deg.
- Complete the circle and arrive back over the starting point within 60 seconds.
- Achieve a stabilized hover, at the original starting position, within 10 seconds of returning to the starting point.
- Maintain the stabilized hover for 5 seconds.
- There shall be no undesirable motions in the lateral axis during the capture and hold at the termination of the maneuver.

Task Variations

- The Pirouette HQTE shall be performed in calm wind and then moderate wind conditions that continuously vary in direction relative to the rotorcraft heading.

6.6 Depart/Abort HQTE

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Normal and Crosswind Takeoff PTSs of FAA-S-8081-20 [20].
  - Normal and Crosswind Approaches and Landings.
  - Rejected Takeoff.
- Takeoffs, Landings, and Go-Arounds and Performance Maneuvers PTSs of FAA-S-8081-16B [21].
  - Normal and crosswind takeoff and climb.
  - Maximum performance takeoff and climb.
  - Rapid Deceleration.
- Takeoffs, Landings, and Go-Arounds and Performance Maneuvers PTSs of FAA-S-8081-15A [22].
  - Normal and crosswind takeoff and climb.
  - Maximum performance takeoff and climb.
  - Rapid Deceleration.

Precision and Aggressiveness Level

- Non-Precision/Aggressive

Task Objectives

- Check pitch axis and heave axis handling qualities during moderately aggressive maneuvering.
- Check for undesirable coupling between the longitudinal and lateral-directional axes.
- Check for harmony between the pitch axis and heave axis controllers.
- Check for any undesirable flight mode transitions.
- Check for overly complex power management requirements.
- Check for ability to re-establish hover after changing trim.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

From a stabilized hover at 35 ft and 800 ft from the intended endpoint, initiate a longitudinal acceleration to perform a normal departure. At 40 to 50 knots groundspeed, abort the departure and decelerate to a hover such that at the termination of the maneuver, the cockpit shall be within 50 ft of the intended endpoint. It is not permissible to overshoot the intended endpoint and move back. If the rotorcraft stopped short, the maneuver is not complete until it is within 50 ft of the intended endpoint. The acceleration and deceleration phases shall be accomplished in a single smooth maneuver. For rotorcraft that use changes in pitch attitude for airspeed control, a target of approximately 20 degrees of pitch attitude should be used for the acceleration and deceleration. The maneuver is complete when control motions have subsided to those necessary to maintain a stable hover.

The test course shall consist of at least a reference line on the ground indicating the desired track during the acceleration and deceleration, and markers to denote the start point and endpoint of the maneuver. The course should also include reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate longitudinal tracking performance, such as the example shown in Figure 12.

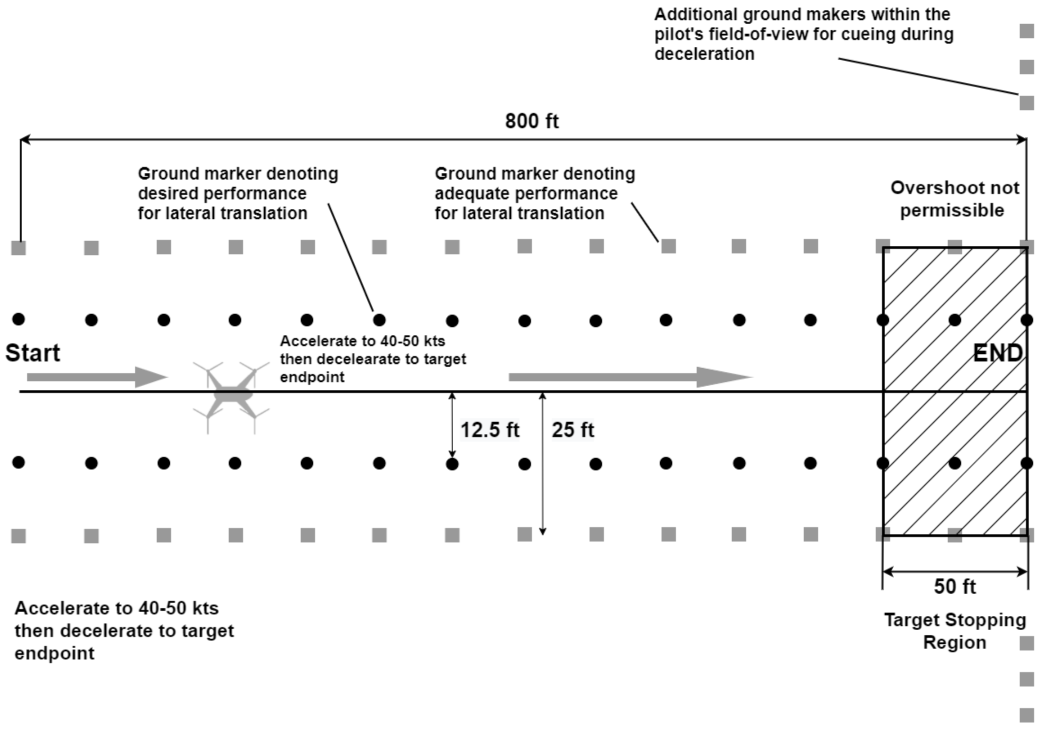


Figure 12. Suggested Course for Depart/Abort HQTE

Desired Performance

- Maintain the lateral position track within ±12.5 ft from reference line.
- Maintain altitude below ±50 ft.
- Maintain heading within ±10 deg.
- Complete maneuver within 25 seconds.

- Aircraft must be brought to within 50 ft of the endpoint; overshooting target hover region is not permitted.
- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

Adequate Performance

- Maintain the lateral position track within ±25 ft from reference line.
- Maintain altitude below ±75 ft.
- Maintain heading within ±15 deg.
- Complete maneuver within 30 seconds.
- Aircraft must be brought to within 50 ft of the endpoint; overshooting target hover region is not permitted.
- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

Task Variations

- The Depart/Abort HQTE shall be performed in calm wind and moderate wind conditions.

6.7 Pitch Attitude Capture and Hold HQTE

This HQTE was developed as part of National Rotorcraft Technology Center FY15 Program "Rotorcraft Handling Qualities Requirements for Future Configurations and Missions" [12] and was proposed as a high-speed MTE for advanced rotorcraft platforms. Here the MTE is redefined as an HQTE.

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

No direct links to Practical Test Standards (PTSs)

Precision and Aggressiveness Level

- Precision/Non-Aggressive

Task Objectives

- Evaluate ability to pitch and capture a desired attitude angle.
- Identify maneuverability limitations and Pilot-Induced Oscillation (PIO) tendencies.

Task Descriptions

This task is driven by an automated command signal selected by the flight test engineer (see Figure 13).

From steady, wings level flight pitch and capture the commanded pitch angle of ±5° from trim and maintain this pitch attitude within the specified tolerance for 5 seconds. Then capture and hold the next commanded pitch angle (0° or ±5°) from trim and maintain this pitch angle within the specified tolerance for 5 seconds. Continue with captures until the flight test engineer calls the run complete. Maintain wings level flight throughout the maneuver.

This task represents a precision, non-aggressive MTE that features 2 seconds for each 5° (from trim) pitch capture and 5 seconds for the hold.

Two examples of the pitch attitude command signal are shown below. Alternating the initial pitch attitude command minimizes pilot shaping from anticipated commands.

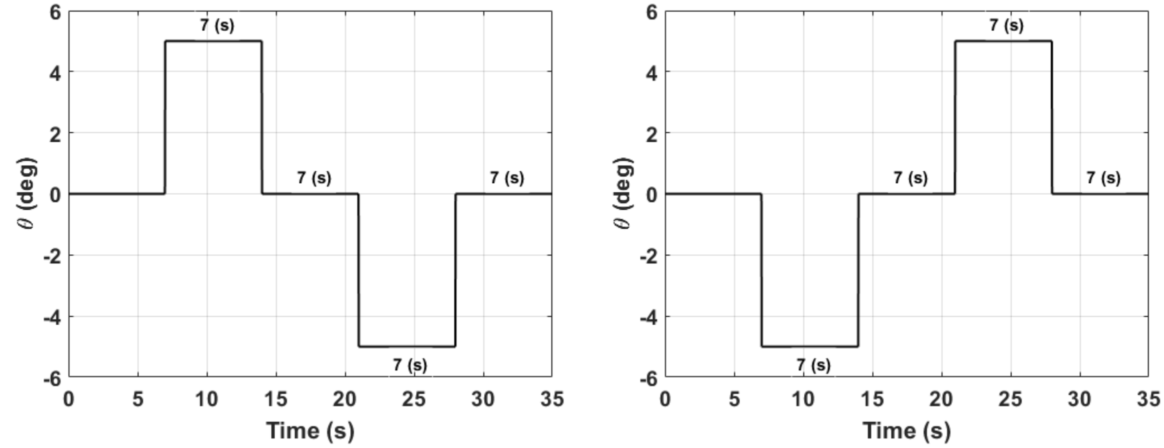
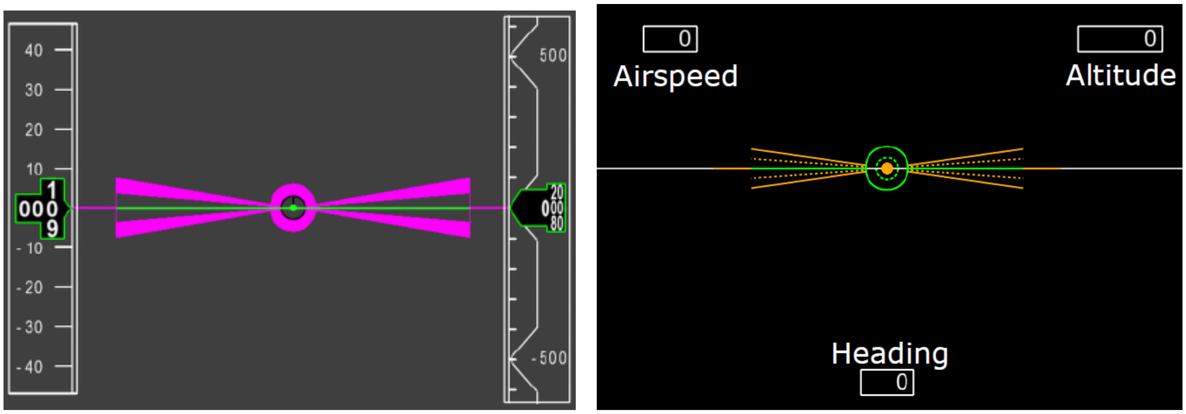


Figure 13. Example Pitch Attitude Capture and Hold Command Signals [12]

The cockpit display symbology designs for this HQTE are inspired by the evaluation pilot displays that have been used by Calspan Corporation in their Learjet In-Flight Simulators [23] and [24]. Two essentially equivalent display variations (see Figure 14) are shown below, the bowtie and the whiskers display variations. For the pitch evaluations with the bowtie display, the objective is to capture and hold the green dot within the magenta circles for each commanded pitch attitude. For the roll evaluations with the same display, the objective is to capture and hold the green line within the diagonal bowtie bounds for each commanded bank angle. Similarly, with the whisker display, the objective is, for each commanded attitude, to maintain the orange dot within the green reticles for pitch and to capture and hold the green lines within the diagonal whisker bounds for roll. The display can be displayed in either a Head-Down or Head-Up format.



a) Bowtie Display b) Whisker Display (with labels)

Figure 14. Cockpit Displays [12]

Desired Performance

- Maintain pitch angle error within ±1° from command.
- Maintain airspeed within ±5 kts from initiation airspeed.
- No more than one pitch attitude overshoot on the initial capture of each attitude. Magnitude of overshoot shall be less than 1°.
- There shall be no PIO tendencies.
- Inter-axis coupling shall not be undesirable.

Adequate Performance

- Maintain pitch angle error within ±2° from command.
- Maintain airspeed within ±10 kts from initiation airspeed.
- No more than one pitch attitude overshoot on the initial capture of each attitude. Magnitude of overshoot shall be less than 2°.
- There shall be no divergent PIO tendencies.
- Inter-axis coupling shall not be objectionable.

Task Variations

- Task can be flown as varied initial airspeeds.
- Variations of this HQTE can be made to increase the level of aggressiveness. For example, the capture angles can be increased to ±10° from trim. Alternatively, given the same commanded attitudes as shown in Figure 13, the capture time can be reduced. With reduced capture time, it is important to maintain the 5 seconds for the hold as this preserves the precision portion of the HQTE.

6.8 Bank Angle Capture and Hold HQTE

This HQTE was developed as part of National Rotorcraft Technology Center FY15 Program "Rotorcraft Handling Qualities Requirements for Future Configurations and Missions" [12] and was proposed as a high-speed MTE for advanced rotorcraft platforms. These the HQTE is redefined as an HQTE.

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The HQTE requirements and performance standards can be linked to several practical test standards (Ref. 19). These PTSs include:

- Performance and Ground Reference Maneuvers PTSs of FAA-S-8081-5F [25].
    - Steep Turns
- Performance and Ground Reference Maneuvers PTSs of FAA-S-ACS-7A [26].
    - Steep Turns
- Performance and Ground Reference Maneuvers PTSs of FAA-S-ACS-6B [27].
    - Steep Turns

Precision and Aggressiveness Level

- Precision/Non-Aggressive

Objectives

- Evaluate ability to roll and capture a desired bank angle.
- Identify maneuverability limitations and Pilot-Induced Oscillation (PIO) tendencies.

Task Description

This task is driven by an automated command signal selected by the flight test engineer (see Figure 15).

From steady, wings level flight roll and capture the commanded bank angle of ±30° and maintain this bank angle within the specified tolerance for 5 seconds. Then capture and hold the next commanded bank angle (0° or ±30°) and maintain this bank angle within the specified tolerance for 5 seconds. Continue with captures until the flight test engineer calls the run complete. There is one capture of a 60° bank angle change in each command set.

This task represents a precision, non-aggressive HQTE that features 3 seconds for each 30° capture and 5 seconds for the hold. An additional 2 seconds is included in the capture time associated with the 60° bank angle change. The hold remains at 5 seconds.

Two examples of the bank angle command signal are shown below in Figure 15. Alternating the initial bank angle command minimizes pilot shaping from anticipated commands.

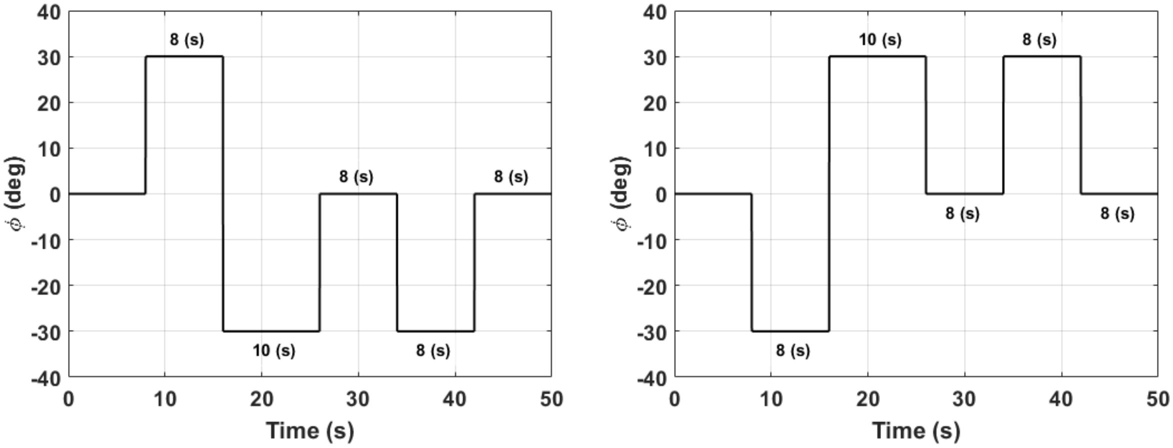
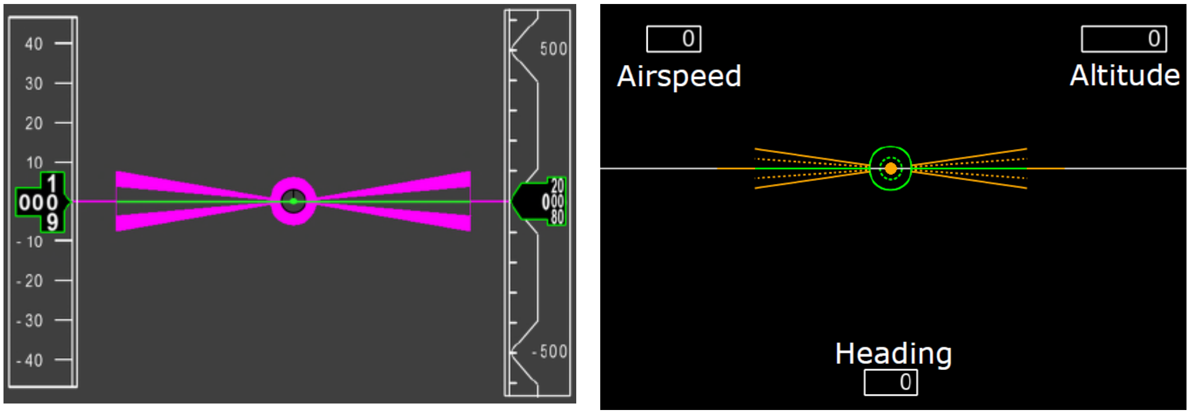


Figure 15. Example Bank Angle Capture and Hold Command Signals [12]

The cockpit display symbology designs for this HQTE are inspired by the evaluation pilot displays that have been used by Calspan Corporation in their Learjet In-Flight Simulators [23] and [24]. Two essentially equivalent display variations (see Figure 16) are shown below, the bowtie and the whiskers display variations. For the pitch evaluations with the bowtie display, the objective is to capture and hold the green dot within the magenta circles for each commanded pitch attitude. For the roll evaluations with the same display, the objective is to capture and hold the green line within the diagonal bowtie bounds for each commanded bank angle. Similarly, with the whisker display, the objective is, for each commanded attitude, to maintain the orange dot within the green reticles for pitch and to capture and hold the green lines within the diagonal whisker bounds for roll. The display can be displayed in either a Head-Down or Head-Up format.



a) Bowtie Display

b) Whisker Display (with labels)

Figure 16. Cockpit Displays [12]

Desired Performance

- Maintain bank angle error within ±5° from command.
- Maintain airspeed within ±5 kts from initiation airspeed.
- No more than one bank angle overshoot on the initial capture of each attitude. Magnitude of overshoot shall be less than 5°.
- There shall be no PIO tendencies.
- Inter-axis coupling shall not be undesirable.

Adequate Performance

- Maintain bank angle error within ±10° from command.
- Maintain airspeed within ±10 kts from initiation airspeed.
- No more than one bank angle overshoot on the initial capture of each attitude. Magnitude of overshoot shall be less than 10°.
- There shall be no divergent PIO tendencies.
- Inter-axis coupling shall not be objectionable.

Task Variations

- Task can be flown as varied initial airspeeds.
- Variations of this HQTE can be made to increase the level of aggressiveness. For example, the capture angles can be increased to ±45° with one 90° change. Alternatively, given the

same commanded attitudes as shown in Figure 15, the capture time can be reduced. With reduced capture time, it is important to maintain the 5 seconds for the hold as this preserves the precision portion of the HQTE.

6.9 UAM Heliport Approach HQTE

This HQTE, including graphic elements in the maneuver description, are based on the nominal UAM Heliport approach profile developed by David Webber as part of NASA Advanced Air Mobility (AAM) National Campaign work [28]. This HQTE is meant to simulate a nominal UAM approach to landing at a Heliport.

FAR Part 23 Requirement

- Handling qualities requirements apply to:
  - §23.2130 Landing;
  - §23.2135 Controllability; and
  - §23.2145 Stability.

Link to Practical Test Standards

The HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Landings and Approach to Landings PTSs of FAA-S-8081-20 [20].
  - Normal and Crosswind Approaches and Landings
- Hovering Maneuvers, Takeoffs, Landings and Go-Arounds, and Special Operations PTSs of FAA-S-8081-16B [21].
  - Hover Task and Air Taxi tasks
  - Normal and crosswind approach
  - Steep Approach
  - Pinnacle/Platform Operations
- Hovering Maneuvers and Takeoffs, Landings and Go-Arounds PTSs of FAA-S-8081-15A [22].
  - Hover Task and Air Taxi tasks
  - Normal and crosswind approach
  - Steep Approach
  - Pinnacle/Platform Operations

Precision and Aggressiveness Level

- Precision/Non-Aggressive

Task Objectives

- Check pitch axis and heave axis handling qualities during precise maneuvering.
- Check for harmony between the pitch axis and heave axis controllers.
- Check for any undesirable flight mode transitions.
- Check for overly complex power management requirements.
- Check for ability to maintain steady approach to landing.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

Begin maneuver in straight and level flight at 70 knots of indicated airspeed (KIAS), at an altitude of 500 ft above and > 0.6 nmi downrange of the target landing area. Capture and maintain the target approach glidepath angle of 9 degrees, for the specified capture height of 500 ft, this approximately corresponds to 0.5 nmi from the target landing area. While maintaining the approach glidepath angle, begin a smooth deceleration profile. Altitude and groundspeed at the landing area threshold shall be approximately 10 ft and 10 kts, respectively. Then complete hover to landing at center of landing area.

The approach profile and suggested test course is shown in Figure 17. The test course shall at least consist of ground markers clearly indicating the center and boundaries of the target landing area. Specific course markers indicating performance during the approach are not required. Glidepath tracking performance shall be monitored via the cockpit primary flight display (PFD).

Desired Performance

- Maintain glidepath angle with ±1.5 deg.
- Maintain lineup with ±1.75 deg.
- Maintain heading within ±10 deg.
- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

Adequate Performance

- Maintain glidepath angle with ±3.0 deg.
- Maintain lineup with ±3.5 deg.
- Maintain heading within ±15 deg.

- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

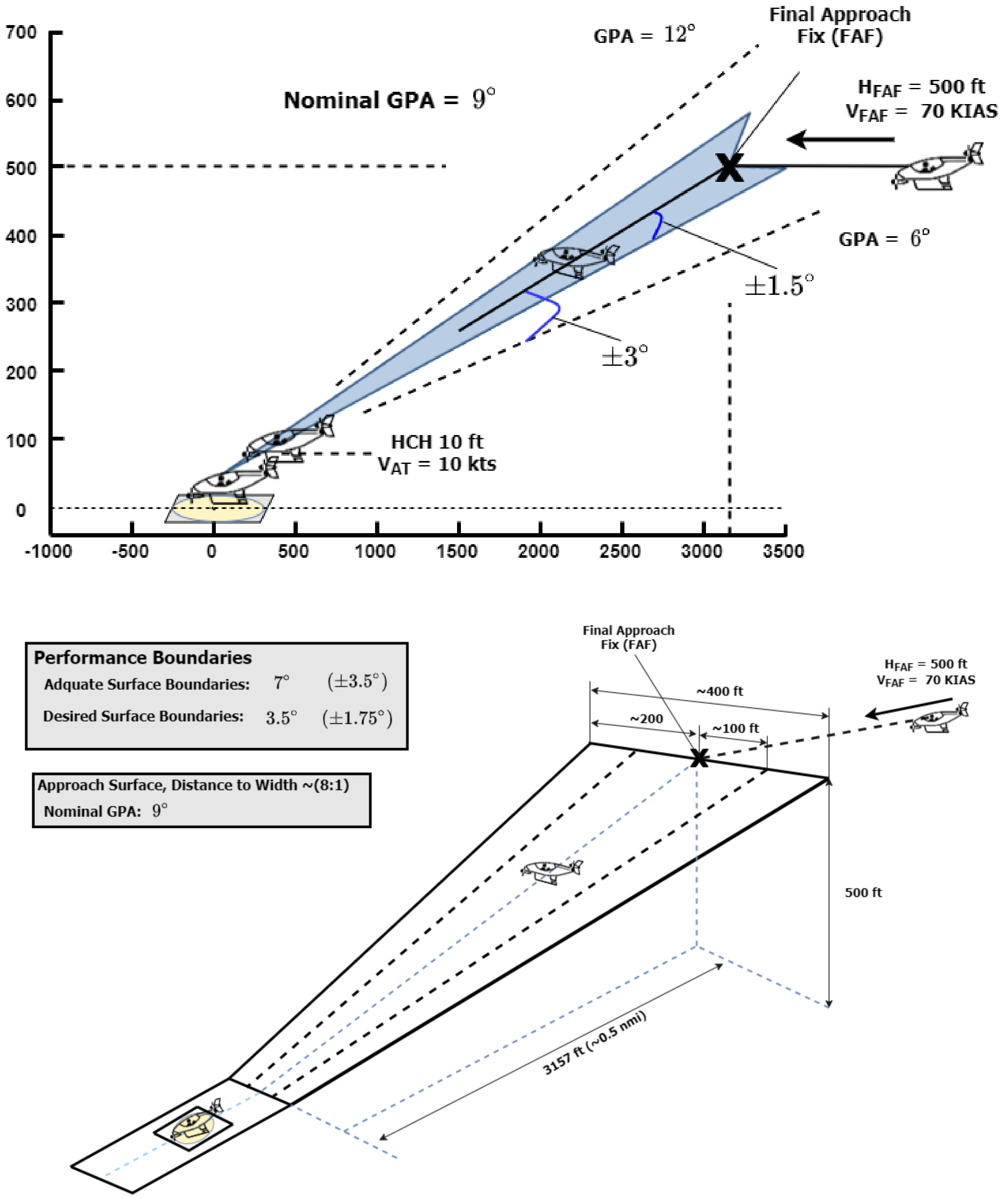


Figure 17. Suggested Approach Profile & Test Course for UAM Heliport Approach HQTE

Task Variations

The UAM Heliport Approach HQTE shall be performed in calm wind and moderate wind conditions.

6.10 UAM Heliport Approach – Vertical Abort HQTE

This HQTE, including graphic elements in the maneuver description, are based on the nominal UAM Heliport approach profile developed by David Webber as part of NASA Advanced Air Mobility (AAM) National Campaign work [28]. This HQTE is meant to simulate an aborted UAM approach to landing. In this variation, a vertical abort maneuver is specified, where the pilot rapidly arrests the descent and climbs out of the approach path to a new altitude.

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Landings and approach to landings PTSs of FAA-S-8081-20 [20]
    - Normal and Crosswind Approaches and Landings
    - Rejected Landing
- Takeoffs, Landings and Go-Arounds, Airport Operations, and Special Operations PTSs of FAA-S-8081-16B [21]
    - Normal and crosswind approach
    - Go-Around
    - Steep Approach
    - Traffic Patterns
    - Pinnacle/Platform Operations
- Takeoffs, Landings and Go-Arounds and Airport and Heliport Operations PTSs of FAA-S-8081-15A [22]
    - Normal and crosswind approach
    - Go-Around
    - Steep Approach
    - Pinnacle/Platform Operations

    - Traffic Patterns

Precision and Aggressiveness Level

- Non-Precision/Aggressive

Task Objectives

- Check ability to resolve tactical conflicts (e.g., obstacles including non-cooperative UAM) during flight operations within a nominal UAM approach to Heliport.
- Check ability to rapidly transition from approach to tactical avoidance.
- Check heave and pitch axis handling qualities during aggressive maneuvering near rotorcraft limits of performance.
- Check for objectionable inter-axis coupling during aggressive heave/pitch axis maneuvering.
- Check vertical rate response and vertical flightpath change to aggressive control inputs when transitioning from a descent to a climb.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

Begin maneuver in straight and level flight at 70 KIAS, at an altitude of 500 ft above and > 0.6 nmi downrange of the target landing area. Capture and maintain the target approach glidepath angle of 9 degrees, for the specified capture height of 500 ft, this approximately corresponds to 0.5 nmi from the target landing area. While maintaining the approach glidepath angle, begin a smooth deceleration profile. At an altitude of approximately 200 ft above the landing area, rapidly arrest the descent and begin climb out of approach profile. Establish a positive rate of climb and the appropriate airspeed/V-speed within ±5 knots. Maintain climb until an altitude of at least a 400 ft above the landing area is captured. During the descent arrestment, the aircraft shall not sink below 150 ft AGL (or altitude above landing area).

The approach profile and suggested test course is shown in Figure 18. The test course shall at least consist of ground markers clearly indicating the center and boundaries of the target landing area. Specific course markers indicating performance during the approach are not required. Glidepath tracking performance shall be monitored via the cockpit PFD.

Desired Performance

- Maintain glidepath angle with ±1.5 deg.
- Maintain lineup with ±1.75 deg.
- Maintain heading within ±10 deg.
- Overshoots of 400 ft target abort altitude shall not exceed 50 ft.

- Aircraft shall not drop below 150 ft altitude above target landing area.
- Maintain appropriate airspeed/V-speed within ±5 knots
- No exceedances of OFE normal load factor limit.
- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

Adequate Performance

- Maintain glidepath angle with ±3.0 deg.
- Maintain lineup with ±3.5 deg.
- Maintain heading within ±15 deg.
- Overshoots of 400 ft target abort altitude shall not exceed 75 ft.
- Aircraft shall not drop below 150 ft altitude above target landing area.
- Maintain appropriate airspeed/V-speed within ±10 knots.
- No exceedances of OFE normal load factor limit.
- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

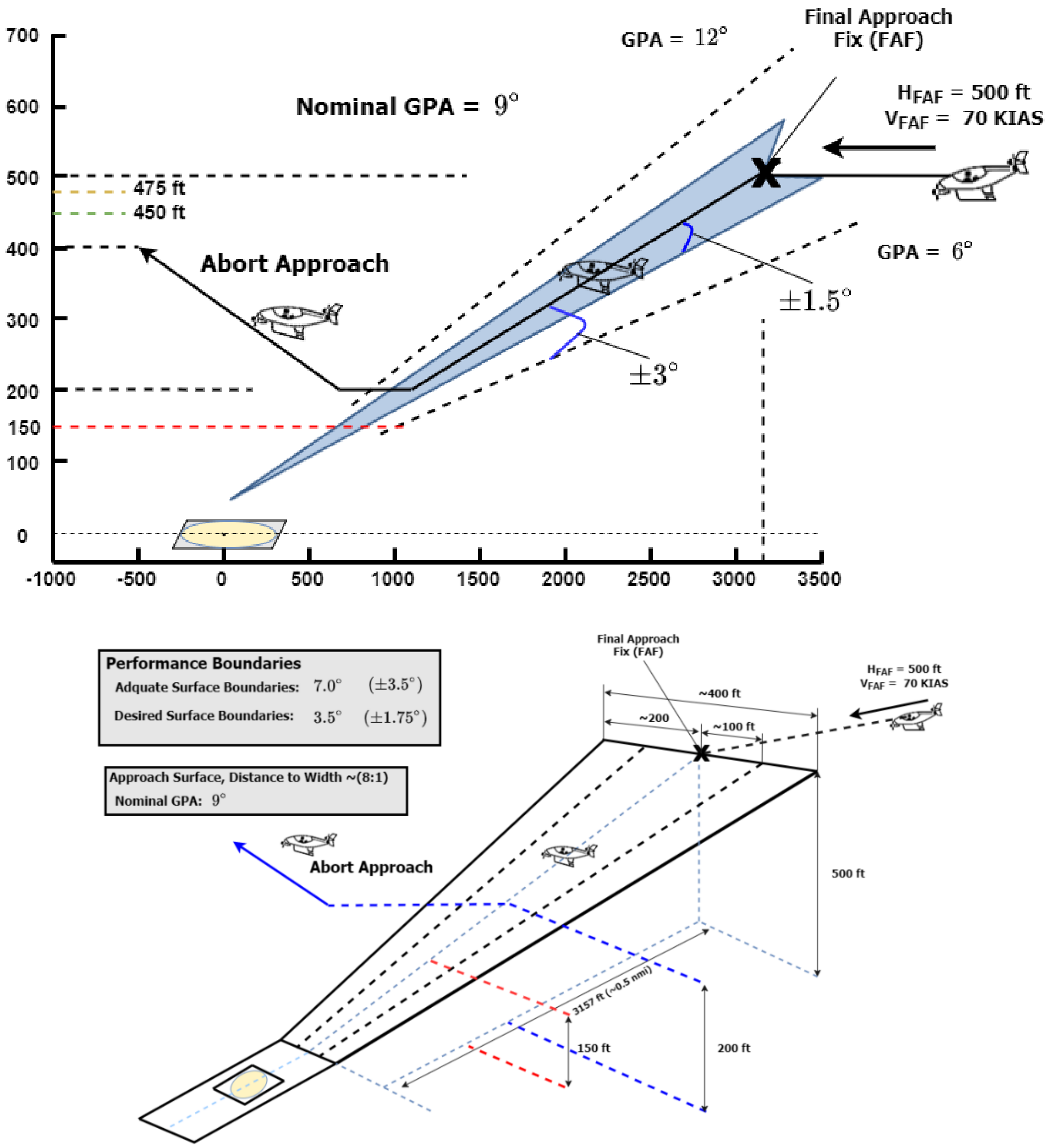


Figure 18. Suggested Approach Profile and Test Course for the UAM Heliport Approach – Vertical Abort HQTE

Task Variations

- Shall be performed in calm wind and moderate wind conditions.

6.11 UAM Heliport Approach – Horizontal Abort HQTE

This HQTE, including graphic elements in the maneuver description, are based on the nominal UAM Heliport approach profile developed by David Webber as part of NASA Advanced Air Mobility (AAM) National Campaign work [28]. This HQTE is meant to simulate an aborted

UAM approach to landing. In this variation, a horizontal abort maneuver is specified, where the pilot rapidly arrests the descent and aggressively turns out of the approach path.

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Landings and Approach to Landings PTSs of FAA-S-8081-20 [20]
    - Normal and Crosswind Approaches and Landings
    - Rejected Landing
- Takeoffs, Landings and Go-Arounds, Airport Operations, and Special Operations PTSs of FAA-S-8081-16B [21]
    - Normal and crosswind approach
    - Go-Around
    - Steep Approach
    - Traffic Patterns
    - Pinnacle/Platform Operations
- Takeoffs, Landings and Go-Arounds and Airport and Heliport Operations PTSs of FAA-S-8081-15A [22]
    - Normal and crosswind approach
    - Go-Around
    - Steep Approach
    - Pinnacle/Platform Operations
    - Traffic Patterns

Precision and Aggressiveness Level

- Non-Precision/Aggressive

Task Objectives

- Check ability to resolve tactical conflicts (e.g., obstacles including non-cooperative UAM) during flight operations within a nominal UAM approach to Heliport.
- Check ability to rapidly transition from approach to tactical avoidance.

- Check heave and lateral axis handling qualities during aggressive maneuvering near rotorcraft limits of performance.
- Check for objectionable inter-axis coupling during aggressive heave/lateral axis maneuvering.
- Check vertical rate response and horizontal flightpath change to aggressive control inputs when exiting a descent.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

Begin maneuver in straight and level flight at 70 KIAS, at an altitude of 500 ft above and > 0.6 nmi downrange of the target landing area. Capture and maintain the target approach glidepath angle of 9 degrees, for the specified capture height of 500 ft, this approximately corresponds to 0.5 nmi from the target landing area. While maintaining the approach glidepath angle, begin a smooth deceleration profile. At an altitude of approximately 200 ft above the landing area, rapidly arrest the descent and aggressively turn out of the approach profile. For the turn, a bank angle of 45 degrees shall be captured and an appropriate airspeed/V-speed within ±5 knots shall be established. Maintain bank angle, altitude, and speed until a heading change of at least 90 degrees is achieved. Upon completion of the turn, return to level flight. This maneuver shall be performed in both directions, turning to left and right.

The approach profile and suggested test course is shown in Figure 19. The test course shall at least consist of ground markers clearly indicating the center and boundaries of the target landing area. Specific course markers indicating performance during the approach are not required. Glidepath tracking performance shall be monitored via the cockpit PFD.

Desired Performance

- Maintain glidepath angle with ±1.5 deg.
- Maintain lineup with ±1.75 deg.
- Maintain heading within ±10 deg, before and after horizontal escape.
- Aircraft shall not drop below 150 ft altitude above target landing area.
- Overshoots of 400 ft target abort altitude shall not exceed 50 ft.
- Maintain bank angle during horizontal escape turn within +10 degrees.
- Maintain appropriate airspeed/V-speed within ±5 knots.
- No exceedances of OFE normal load factor limit.
- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

Adequate Performance

- Maintain glidepath angle with ±3.0 deg
- Maintain lineup with ±3.5 deg
- Maintain heading within ±15 deg, before and after horizontal escape
- Aircraft shall not drop below 150 ft altitude above target landing area
- Overshoots of 400 ft target abort altitude shall not exceed 75 ft
- Maintain bank angle during horizontal escape within +15 degrees
- Maintain appropriate airspeed/V-speed within ±10 knots
- No exceedances of OFE normal load factor limit.
- There shall be no undesirable motions during the capture and hold at the termination of the maneuver.

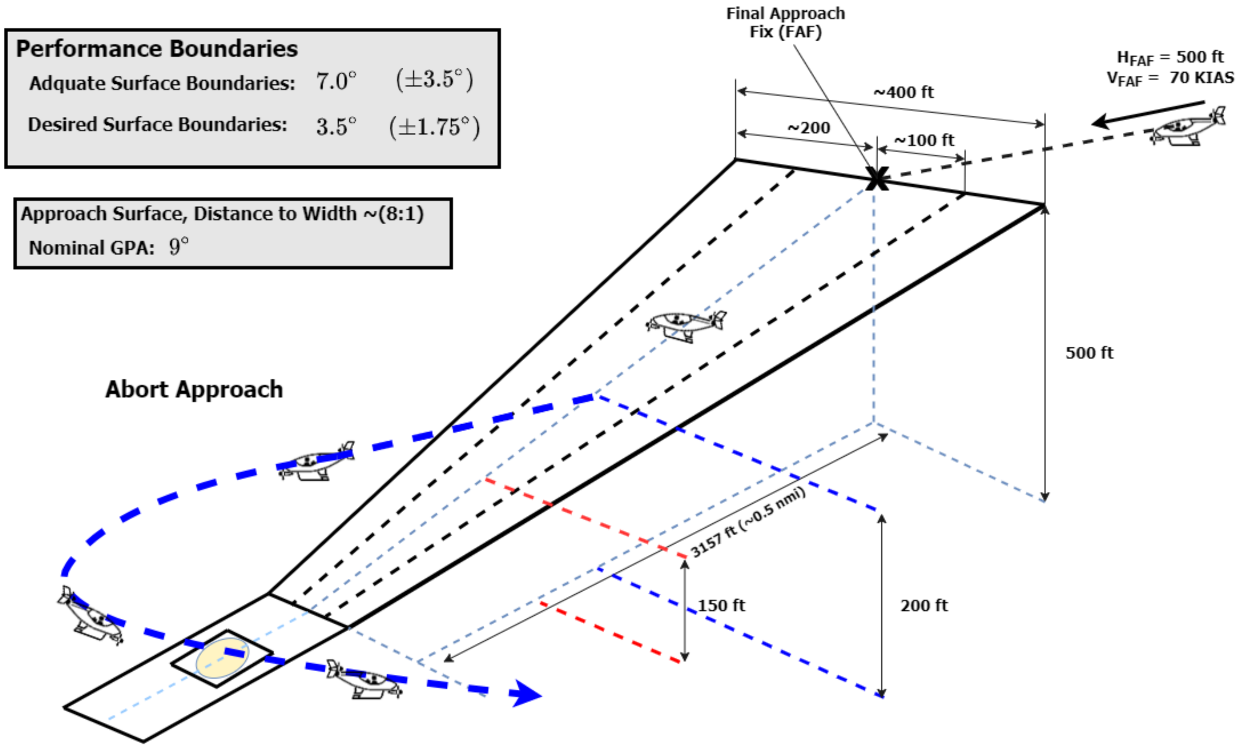


Figure 19. Suggested Approach Profile and Test Course for the UAM Heliport Approach – Horizontal Abort Approach HQTE

Task Variations

- Shall be performed in calm wind and moderate wind conditions.
- Shall be performed in both directions, turns to the left and right.

6.12 Collision Avoidance – Vertical Escape HQTE (Forward Flight)

Notes Regarding HQTE

This collision avoidance HQTEs is defined for operations within UAM Corridors as envisioned in the FAA's "Concept for Operations v1.0 for Urban Air Mobility (UAM)" [18].

FAR Part 23 Requirement

- Handling qualities requirements apply to:
  - §23.2135 Controllability; and
  - §23.2145 Stability.

Link to Practical Test Standards

The HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Airport Operations PTSs of FAA-S-8081-16B [21]
  - Traffic Patterns
- Heliport Operations PTSs of FAA-S-8081-15A [22]
  - Traffic Patterns

Precision and Aggressiveness Level

- Non-Precision/Aggressive

Task Objectives

- Check ability to resolve tactical conflicts (e.g., obstacles including non-cooperative UAM) during forward flight operations in a UAM corridor.
- Check heave and pitch axis handling qualities during aggressive maneuvering near rotorcraft limits of performance.
- Check for objectionable inter-axis coupling during aggressive heave/pitch axis maneuvering in forward flight.
- Check vertical rate response and vertical flightpath change to aggressive control inputs.

Task Description

This task is representative of a vertical collision avoidance maneuver occurring during UAM operation within a UAM Corridor. From steady level forward flight, perform an aggressive vertical climb at the vehicle's maximum climb rate to escape an imagined obstacle (e.g., non-cooperative UAM). Since the obstacle is imagined, the avoidance maneuver can begin on a count or suitable reference point. (In a simulator, a non-cooperative vehicle or other obstacle can be placed in the visual scene). The climb shall be sustained until an altitude change of at least one full UAM Corridor width is achieved. Once the target altitude is reached, steady level flight shall be reestablished.

This maneuver does not require a test course. It can be flown up and away as depicted in Figure 20.

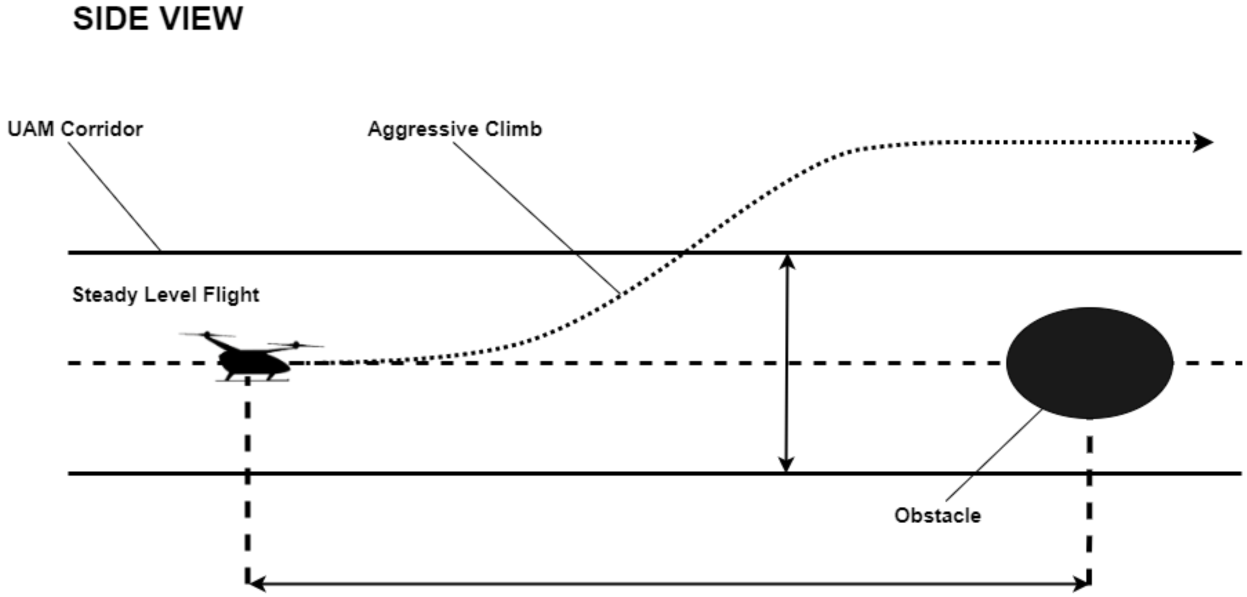


Figure 20. Depiction of Collision Avoidance Vertical Escape HQTE

Desired Performance

- Reach maximum climb rate within X seconds from initiation of climb.
- Maintain angular deviations in roll within ±X degrees from the initial unaccelerated level flight condition to the completion of the maneuver.
- Maintain heading within ±X degrees from the initial unaccelerated level flight condition to the completion of the maneuver.
- Capture the target altitude within +X feet (overshoots are permitted, but no undershoots are allowed).
- No exceedances of positive OFE normal load factor limit.

Adequate Performance

- Reach maximum climb rate within X seconds from initiation of climb.
- Maintain angular deviations in roll within ±X degrees from the initial unaccelerated level flight condition to the completion of the maneuver.
- Maintain heading within ±X degrees from the initial unaccelerated level flight condition to the completion of the maneuver.
- Capture the target altitude within +X feet (overshoots are permitted, but no undershoots are allowed).
- No exceedances of positive OFE normal load factor limit.

Task Variations

Specific task variations not anticipated.

6.13 Collision Avoidance – Horizontal Escape HQTE (Forward Flight)

Notes Regarding HQTE

This collision avoidance HQTEs is defined for operations within UAM Corridors as envisioned in the FAA's "Concept for Operations v1.0 for Urban Air Mobility (UAM)" [18].

FAR Part 23 Requirement

- Handling qualities requirements apply to:
    - §23.2135 Controllability; and
    - §23.2145 Stability.

Link to Practical Test Standards

The HQTE requirements and performance standards can be linked to several practical test standards [19]. These PTSs include:

- Airport Operations PTSs of FAA-S-8081-16B [21]
    - Traffic Patterns
- Heliport Operations PTSs of FAA-S-8081-15A [22]
    - Traffic Patterns

Precision and Aggressiveness Level

- Non-Precision/Aggressive

Task Objectives

- Check ability to resolve tactical conflicts (e.g., obstacles including non-cooperative UAM) during forward flight operations in a UAM corridor.
- Check lateral-directional axis handling qualities during aggressive maneuvering near rotorcraft limits of performance.
- Check for objectionable inter-axis coupling during aggressive lateral-directional maneuvering in forward flight.
- Check roll response and heading change to aggressive control inputs.
- Check for harmony between the longitudinal and lateral-directional response as altitude is maintained.

Task Description

This task is representative of a horizontal collision avoidance maneuver occurring during UAM operation within a UAM Corridor. From steady level forward flight, roll and capture a bank angle of at least 45 degrees while maintaining altitude and speed to escape an imagined obstacle (e.g., non-cooperative UAM). Since the obstacle is imagined, the avoidance maneuver can begin on a count or suitable reference point. (In a simulator, a non-cooperative vehicle or other obstacle can be placed in the visual scene). Maintain bank angle, altitude, and speed until a heading change of at least 45 degrees is achieved. Upon completion of the turn, return to wings level flight.

This maneuver does not require a test course. It can be flown up and away as depicted below in Figure 21.

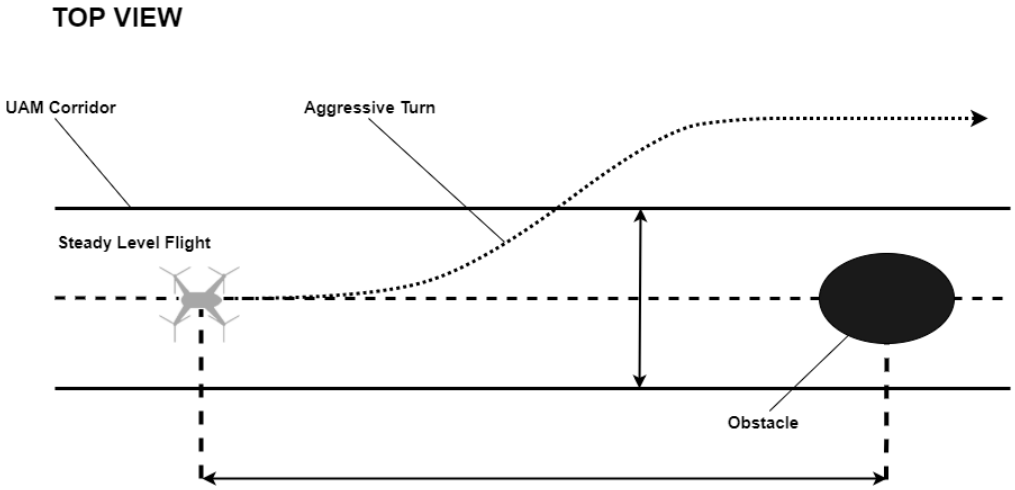


Figure 21. Depiction of Collision Avoidance Horizontal Escape HQTE

Desired Performance

- Obtain required heading change within X seconds.
- Maintain bank angle during horizontal escape within +X degrees.
- Maintain Altitude within ±X ft.
- Maintain speed within ±X ft.
- Capture final heading within +X degrees.
- No exceedances of OFE normal load factor limit.

Adequate Performance

- Obtain required heading change within X seconds.
- Maintain bank angle during horizontal escape within +X degrees.
- Maintain Altitude within ±X ft.
- Maintain speed within ±X ft.
- Capture final heading within +X degrees.
- No exceedances of OFE normal load factor limit.

Task Variations

- Specific task variations not anticipated.

7 Next steps

During the Phase 1 effort, engineering evaluations of some of the proposed HQTEs were conducted. These evaluations focused on the low-speed/hover HQTEs, and were conducted utilizing the myCopter Personal Aerial Vehicle (PAV) model developed by the University of Liverpool [29, 30 and 31]. Details of these evaluations are presented in Appendix B and additional background on the myCopter PAV model is presented in Appendix C. The evaluations were conducted with an engineer pilot. As such, only task performance data were collected with no pilot rating or commentary. Although the engineering evaluations demonstrated the initial validity of the hover/low speed HQTEs as appropriate handling qualities MOC tasks for a representative eVTOL vehicle, formal piloted evaluations are still required as revisions to the maneuver descriptions, performance requirements, and task variations are anticipated.

As part of extension work for this project, STI will support formal piloted simulation evaluations of candidate HQTEs, including those defined herein, which will take place at NASA Ames using the Vertical Motion Simulator. This is a critical step, as it is anticipated that the description of the HQTEs defined in this report and others under development will evolve as they are exercised via piloted simulation and ultimately flight test.

As part of the Phase 2 work, STI will be identifying suitable control law transitions modes (hovering flight to forward flight), envelope protection schemes, and automation flight modes. The selected modes will be integrated into a suitable UAM model (e.g., a lift+cruise configuration) for use during evaluations. The HQTE/FQTE catalog will then be expanded to included mission-relevant scenarios that assess the handling qualities associated with these flight modes and control architectures. A suitable UAM model with these features integrated will be used as the subject vehicle during fixed-based simulator piloted evaluations at STI, which will include assessment of flight mode transitions, envelope protection, and automation.

Appendix A contains a summary of best practices for piloted simulation evaluations and lessons learned during the development and testing of the proposed HQTEs. During the extension work, the lessons learned material will be updated and maintained to capture key insight or observations made during the development and testing of additional HQTE/FQTEs.

8 Summary

This report introduced a new handling qualities certification process used in part for means of compliance that is designed to address the emerging markets for personal air vehicles and urban air taxis. A key element of this approach is the introduction of mission task elements, redefined here as Handling Qualities Task Elements (HQTEs), which ultimately become part of the means of compliance with Federal Aviation Administration Part 23 regulations. HQTEs are defined based on levels of precision and aggressiveness required that naturally allow for a build-up test approach from non-precision, non-aggressive to precision, aggressive HQTEs. Furthermore, the HQTEs are defined with desired and adequate performance requirements that facilitate direct use of the Cooper-Harper handling qualities rating scale, noting that achieving adequate performance does not equate with adequate for certification. This will allow for greater discernment of handling qualities than can be achieved via a simple pass/fail assessment.

A catalog of candidate HQTEs is presented in this report. The HQTEs cover a wide range of flights conditions and precision, aggressiveness levels. The catalog includes several low speed/hover HQTEs that are influenced by legacy ADS-33E-PRF MTEs, newer HQTEs that are representative of envisioned UAM mission scenarios, and forward flight HQTEs derived from high-speed MTE development work for advanced rotorcraft platforms [12]. It is anticipated that the description of these HQTEs and others under development will evolve as they are exercised via piloted simulation and ultimately flight test. The HQTE catalog is listed below.

Low Speed/Hover HQTEs:

1. Precision Hover HQTE
2. Vertical Reposition and Hold HQTE
3. Hovering Turn and Hold HQTE
4. Lateral Reposition and Hold HQTE
5. Pirouette HQTE

Forward Flight HQTEs:

6. Depart/Abort HQTE
7. Pitch Attitude Capture and Hold HQTE
8. Bank Angle Capture and Hold HQTE

UAM Mission Representative HQTEs:

9. UAM Heliport Approach (Forward Flight to Hovering Flight)
10. UAM Heliport Approach – Vertical Abort HQTE (Forward Flight)
11. UAM Heliport Approach – Horizontal Abort HQTE (Forward Flight)
12. Collision Avoidance – Vertical Escape HQTE (Forward Flight)
13. Collision Avoidance – Horizontal Escape HQTE (Forward Flight)

Initial engineering evaluations of the Low Speed/Hover HQTEs were conducted in STI's fixed-based simulator using the myCopter PAV model as the subject vehicle. The evaluations demonstrated the initial viability of the proposed low speed/hover HQTEs as suitable handling qualities MOC tasks. The results were used to make modifications and updates to the performance criteria for some of the HQTEs and provided valuable "lessons learned." Details of the evaluations are presented in Appendix B.

The myCopter PAV model [31] was integrated into STI's fixed based simulator. As mentioned previously, the myCopter model was used as the subject vehicle in engineering evaluations of the proposed HQTEs. The myCopter model provided models of varied response-types and predicted levels of handling qualities, making it the perfect reference model with which candidate HQTEs could be evaluated. Additional background on the myCopter model is provided in Appendix C.

A "Lessons Learned" document was created and maintained. This document captures key insights or observations made during the HQTE development and testing process. In addition to HQTE development lessons learned, general best practices for conducting handling qualities evaluations with HQTEs were also documented. The best practices and lessons learned are summarized in Appendix A.

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A Simulation best practices and lessons learned

This appendix summarizes best practices identified by Systems Technology, Inc. and elsewhere for piloted simulations that address, first, development and evaluation of HQTEs, and second, evaluation of vehicle handling qualities using the verified HQTEs. The appendix also provides considerations for assigning ratings with the Cooper-Harper Handing Qualities Rating Scale. The final section provides "lessons learned" for some of the proposed HQTEs presented in Section 6 of the main body of this report. The lessons learned are derived from:

1. Insights gained during the original development and use of the ADS-33E-PRF [1] MTEs that form the basis for several of the HQTEs; and
2. Insights gained during the development and initial evaluation of the proposed HQTEs.

A.1 Best practices – simulation checkout

Prior to formal piloted evaluations, typically up to one week of simulation time should be set aside for checkout. Further, a cushion of several weeks or more should separate the checkout from formal evaluations such that checkout data can be evaluated, and any identified issues can be resolved. Specific best practices for the simulation checkout are as follows:

- Verify vehicle configurations and response modes.
  - Use standard system ID inputs (steps, pulses, sweeps, etc.) and vehicle response data to verify that the dynamic model has been integrated as intended.
    - Verify using appropriate criteria/metrics that handling qualities levels for each vehicle configuration remain as predicted from computer simulation models.
    - Anticipated differences may arise from added effective time delays present in the piloted simulation environment. If significant differences are found, the configurations may need to be adjusted.
  - The dynamics model should be checked at all relevant flight conditions, for each vehicle configuration, and for all flight control modes that will be used in the formal evaluations:
    - Flight conditions include airspeed/altitude, turbulence levels, steady winds, and visual conditions (e.g., visual flight rules (VFR) and instrument flight rules (IFR)).
    - For VTOL aircraft, vehicle configurations include helicopter mode, airplane mode, transition, etc., as well as variations within modes due to, for example, variations in center of gravity location.

        - Flight control modes may include Rate Command Attitude Hold, Attitude Command Attitude Hold, Translational Rate Command, Nz Command, C* Command, etc.
    - Verify that the inceptor characteristics (e.g., breakout, gradient, soft stops, etc.) and trim features are as intended.
- Verify visual setup for out-of-the-window HQTE courses.
    - Ensure that there are enough visual cues available to accurately estimate lateral, vertical, and especially fore/aft position. Adequate fore/aft visual cueing is very important for evaluations in fixed-base simulators.
    - Make liberal use of cones, tarmac markings, and other visual references to define the individual courses.
- Verify that required parameters and, if needed, custom HQTE symbology (e.g., tracking task attitude indicators that are tied to desired/adequate performance requirements) are available from the primary flight displays and/or head-up display (HUD) to execute each HQTE.
- Establish trimmed starting points for each HQTE with a known position relative to key course references (e.g., hover boards).
    - This will allow more rapid run-to-run resets after an individual run is complete.
    - The known positions will allow for task performance trajectories to be created for each run to aid the assessment of task performance.
    - Desired and adequate performance boundaries can be added to the trajectories to further enhance the utility of the trajectory plots.
- To the extent it may be needed, assign and practice engineering roles for the formal evaluations.
    - Flight Controls Engineer (FCE):
        - Brief pilots on control laws (CLAWS), inceptor mechanical characteristics, trim functions, etc.
        - Monitor CLAWS performance through aircraft performance and pilot ratings/comments.
        - Assist with monitoring task performance during HQTE evaluations.
    - Handling Qualities Engineer (HQE):
        - Brief pilots on selected HQTE descriptions and requirements.
        - Brief pilots on selected rating scales (e.g., Cooper-Harper Handling Qualities Ratings (HQR), Bedford Workload, NASA TLX, Pilot-Induced Oscillation Tendency).
        - Assist with monitoring task performance during HQTE evaluations.

    - Record pilot comments as pilots are giving ratings.
    - Facilitate use of pilot run-to-run or debrief questionnaires.
- Simulation Evaluation Engineer (SEE):
    - Fill in run log/knee card during HQTE evaluations.
    - Operate timer as required for HQTE performance measurements.
    - Record pilot ratings when given.
    - Work with Simulator Operations Engineer to ensure run log is consistent.
    - Work with Simulator Operations Engineer to ensure correct simulation location (HQTE course) and visual condition is set.
    - Assist in performing post-run analysis of recorded data at workstation computer.
- Simulator Operations Engineer:
    - Set specified simulation location (HQTE course) and visual condition.
    - Set up datafile and run number for recording data.
    - Start and stop data recording during HQTE evaluations.
    - Transfer data from Simulation Computer to the Engineering Workstation Computer for post-run data analysis.
- The team should have at least one experienced pilot fly through the courses following the procedures outlined in the test plan to:
    - Verify efficacy evaluation test procedures and adjust, as necessary.
    - Test the data recording process (time series data and pilot comments).

A.2 Best practices – developmental evaluations of MTEs (i.e., HQTEs, FQTEs, STEs)

Specific best practices for developmental evaluations of handling qualities task elements (HQTEs), flying qualities task elements (FQTEs), and system task elements (STEs) are as follows (outlined for an HQTE evaluation):

- The evaluation session will begin with a pilot brief in which the team will review session objectives, simulator features, cockpit displays/inceptors, and HQTE descriptions.
- Evaluation pilots will be familiarized with the HQTEs using vehicle configurations with known “good” handling qualities.
- Formal HQTE evaluations will be made using vehicle configurations with predicted handling qualities that cover the range from Level 1 to Level 3, including borderline cases (i.e., Level 1/Level 2 and Level 2/Level 3).

  - When practicing the task or becoming familiar with a new configuration, the pilot may be given task performance information at the end of a run. For the formal evaluations, however, the pilot will provide ratings based on perceived performance.
  - An effective HQTE will allow the pilot to clearly discern the handling qualities between the diverse configurations.
  - As the pilot is evaluating and assigning ratings for each configuration, the configuration should not be specified to the pilot (i.e., blind evaluations). This will avoid potential bias from prior knowledge of the configurations. Configurations should be repeated as feasible to insure consistency.
- When performing a formal handling qualities evaluation of a given HQTE, the pilot will be asked to perform the selected HQTE a minimum of two times and as many times as necessary (within reason) with each configuration before providing pilot comments and ratings.
  - Cooper-Harper handling qualities ratings will be collected using the complete rating scale including the decision tree. Evaluation pilots will be strongly encouraged to talk through the rating scale decision trees as a means of extracting additional commentary.
  - As part of the evaluation process, a pilot questionnaire may be used to extract further pilot comments that add clarity to the numerical ratings.
  - Additional rating scales/methods may also be used to assess PIO tendencies and pilot workload (e.g., Bedford or NASA TLX).
- At the completion of a given HQTE evaluation, the pilot should complete a pilot questionnaire that allows the pilot to rapidly assess HQTE objectives, description, performance requirements, repeatability, ease of execution, etc.
- To the extent possible in a session, repeat runs should be conducted to verify evaluations of previously seen configurations. Known “good” configurations should be used liberally, especially after several “poor” handling configurations in a row.
- A detailed run log will be kept, and all pilot comments will be recorded.
- For lengthy pilot evaluation sessions, breaks should be given approximately every 45 minutes or when the pilot is clearly showing signs of fatigue.

A.3 Best practices – formal evaluations of handling qualities

Specific best practices for formal evaluations are as follows (note that many of these are repetitive of the best practices identified in the previous section):

- The evaluation session will begin with a pilot brief in which the team reviews session objectives, simulator features, cockpit displays/inceptors, flight control modes, and HQTE descriptions.
- Evaluation pilots will be familiarized with the HQTEs using vehicle configurations with known "good" handling qualities as predicted by appropriate criteria.
    - An appropriate level of familiarity will be met when the pilot can routinely achieve desired performance with the selected HQTE when presented the "good" configurations.
    - When practicing the task or becoming familiar with a new configuration, the pilot may be given task performance information at the end of a run. For the formal evaluations, however, the pilot will provide ratings based on perceived performance.
- When performing a formal handling qualities evaluation with a given vehicle configuration, the pilot will be asked to perform the selected HQTE a minimum of two times and as many times as necessary (within reason) before providing pilot comments and ratings.
    - Cooper-Harper handling qualities ratings will be collected using the complete rating scale including the decision tree. Evaluation pilots will be strongly encouraged to talk through the rating scale decision trees as a means of extracting additional commentary.
    - If part of the evaluation process, a pilot questionnaire may be used to extract further pilot comments that add clarity to the numerical ratings.
    - Additional rating scales/methods may also be used to assess PIO tendencies and pilot workload (e.g., Bedford or NASA TLX).
- To the extent possible in a session, repeat runs should be conducted to verify evaluations of previously seen configurations. Known "good" configurations should be used liberally, especially after several "poor" handling configurations in a row.
- A detailed run log will be kept, and all pilot comments will be recorded.
- For lengthy pilot evaluation sessions, breaks should be given approximately every 45 minutes or when the pilot is clearly showing signs of fatigue.

A.4 Considerations when using the Cooper-Harper Handling Qualities Rating Scale

In addition to the above-mentioned formal evaluation best practices, included here are some other items to consider when using the Cooper-Harper Handing Qualities Rating Scale. Many of these are directly pulled or summarized from the Test Guide for ADS-33E-PRF [2] with additional commentary from the STI authors.

- It is acceptable to make as many repeat runs as necessary to obtain consistent performance results [2].
    - STI: Adequate time for the pilot to familiarize themselves with the HQTE should be provided. A lack of experience with a particular HQTE should not be the driving factor in a pilot's evaluation of the vehicle and can be largely avoided through training runs. These can be conducted just prior to a simulation, providing the pilot the opportunity to fly the HQTE's under nominal conditions to better understand the general piloting technique and task requirements. Repeat runs are always encouraged, as they provide for a period for the pilots to "warm up" and they may expose handling qualities deficiencies. Repeat runs, as warranted during formal evaluations, are also encouraged. If the pilot is unsure of a rating or notices a potential issue, he/she should be allowed to repeat the task to provide not only a more confident rating, but also additional and valuable pilot commentary.
    - STI: When a pilot is becoming familiar with a particular HQTE, he/she can be alerted to desired and adequate task performance results. For best results, the pilots should base their formal evaluations on perceived performance. Past simulations and flight test experience have shown that pilots will color their ratings based on the quantified performance call outs. Ratings based on perceived performance yield a more pure assessment of the exposed handling qualities.
- HQRs should not be assigned on performance alone; the required compensation/workload also must be considered. In following the Cooper-Harper Handling Qualities Rating Scale, if desired performance is not obtained the rating must be a 5 of worse. However, if the pilot workload was only low or moderate, an HQR 5 is not necessarily justified. In such a case, the task should be flown again with increased aggressiveness to attempt to get desired performance [2].
- When assigning HQRs, workload should be emphasized over performance. For example, if desired performance is achieved but the pilot had to use what he considered to be considerable pilot compensation, it is okay to assign an HQR of 5 [2].
    - STI: As mentioned above, the pilot commentary must be captured during the ratings process. The comments will provide those key insights for the test engineer or regulating authority, along with the supporting data, to assess the underlying issues or lack thereof.

- The desired and adequate performance limits not only allow the pilot to assign ratings, but also drive the level of aggressiveness required for accomplishing the maneuver. When assessing task performance, occasional drifts out of desired are acceptable if the pilot can maneuver back into the desired limits at will. In such cases, the determination of task performance is a judgment call from the test pilot [2].
- STI: There should be sufficient visual cueing and course markings to allow the pilot to properly complete the task and assess each of the associated metrics. This does not require the pilot be provided a clock to ensure the maneuver was completed in a particular time, this is driven by his/her perceived performance. Alternatively, if the pilot is required to hover in a location, there should be sufficient cueing to allow the pilot to maintain fore/aft, lateral, and vertical position. These issues should largely be caught during the HQTE development and addressed at that phase. Alternative cueing may be required dependent upon the resources available and the specific test environment. If this is true, the intent and spirit of the course layout should be maintained, and the variation noted during the test phase.
- Generally, the pilot should be able to determine desired and adequate performance based on cueing from course markers. If asked by the pilot, it is acceptable to inform the pilot if he/she was able to achieve desired or adequate performance. However, if the pilot must repeatedly ask for this information, then the course should be modified to provide additional cues needed for the pilot to determine performance [2].

A.5 HQTE lessons learned

A.5.1 Precision Hover HQTE

- This HQTE is based on the Hover MTE from section 3.11.1 of ADS-33E-PRF.
  - STI: This maneuver is included to provide an overall check of the handling qualities as the pilot translates to and maintains a steady hover.
- Helicopter handling qualities typically degrade in winds over 15 knots [3].
  - STI: This is a reasonable wind condition to expect that UAM are likely to experience during normal operations. In keeping with ADS-33E-like language, it is recommended to perform the task in wind-speeds above 20 knots (moderate winds) with the wind in the most critical direction. A build up approach is suggested to demonstrate this ability. The maneuver should first be demonstrated in calm winds prior to testing in moderate winds.
- For a conventional helicopter, a tailwind usually represents the worst-case wind direction due to its destabilizing effect on the tail rotor and its reduction to airspeed [3].

  - STI: For other less traditional rotorcraft configurations (especially new VTOL concepts), the critical wind azimuth may be in a different direction. If this direction is known, it should be tested; otherwise, the task should be performed in a tailwind.
- It is also recognized that the magnitude and direction of the wind may vary during testing; this is not deemed to be critical if the average wind speed is at least 20 knots [3].
  - Calm winds: “Winds with a steady component of less than 5 knots” [1].
  - Moderate winds: “Winds with a steady component of between 20 and 35 knots” [1].
- As stated in the Background information users guide (BIUG) [3], the performance requirements are based on experience in testing helicopters with known Level 1 and Level 2 handling qualities. Most of the performance limits are derived from variable stability testing at the National Research Council (NRC) and US. Army Engineering Flight Activity (AEFA) tests [4].
- The HQTE should be performed with all combinations of displays and flight control modes that would normally be provided to the pilot in the given rotorcraft [2].
  - STI: Flight displays can be very helpful in providing cueing during simulation evaluations where field-of-view (FOV) and simulator graphics are limited. In such cases, some simulator graphics may fail to provide high fidelity attitude change and translational rate cues; a well-designed flight display can make up for some of these deficiencies. Regarding flight modes, a Height Hold mode, for example, can drastically reduce the required workload for performing the Precision Hover HQTE by eliminated the need to monitor and control the vertical axis. Introducing these modes to overcome simulation deficiencies must also ensure that all required workload is not removed from the task.
- STI: The 45-degree translation (or “run-in” portion of the hover task) is a critical maneuver as it forces the pilot to activate both the lateral and longitudinal axes and causes the aircraft to exit a stabilized trim condition. The 45-degree translation also supports assessment of the aircraft’s ability to transition from translating flight to a stabilized hover, a critical task in any VTOL aircraft CONOPS. The 30-second hover maintenance portion of the task would be far less effective in assessing the aircraft ability to maintain a precision hover if the aircraft started from a trim hover condition.
- STI: A 20-foot maneuver altitude was selected to simulate Near-Earth Operations (NEO). NEO describes “...operations that are sufficiently close to the ground or fixed objects on the ground… …where flying is primarily accomplished with reference to outside objects” [5]. A 20-foot altitude allows the pilot to reference course markers on the ground (i.e., cones, painted lines, etc.) and eases the requirements for creating any physical “Hover Boards.” The maneuver altitude can be modified based on safety needs and the reference

objects available, if the pilot has the cueing required for performing the task and NEO is still established.

- STI: The desired 5-second hover stabilization time performance standard is included to tailor pilot aggressiveness. The desired stabilization, combined with the 6-10 knots groundspeed requirement, requires the pilot use a mild amount of aggressiveness to transition from translating flight to a hover. An inability of the aircraft to meet this requirement typically suggest poor harmony between the lateral and longitudinal axes and sluggish lateral/longitudinal response characteristics.
- STI: For the determination of the stabilization times, this HQTE requires the pilot to call "Mark" at the beginning of the deceleration to hover and "Stable" when he or she establishes a stable hover (i.e., the vehicle has entered the adequate performance bounds at a minimum and can be maintained within these bounds). Defining what is a stable state is often a point of contention during simulation or flight tests. The Test Guide for ADS-33E-PRF [2] defines this well in stating that "Stable" is established when "…the pilot has mentally transitioned from hover-capture to maintaining desired or adequate performance." This normally occurs when the following conditions are met:
  - "The pitch and roll attitudes are approximately at the hover values and angular rate are small" [2].
  - "The rotorcraft position is in the designated hover box to at least adequate performance standards and translational rates are small" [2].
- ADS-33E recommends different control gradients depending on the response-type and inceptor (center stick or sidestick). However, it is known that not all sidestick controllers are the same and different gradients may apply. The Test-Guide for ADS-33E [2] recommends the used of MTEs for checks of control sensitivity. The Hover MTE is a great task to check control sensitivity for low-speed precision flight.
  - STI: The Precision Hover HQTE can also be utilized for control sensitivity checks of UAM vehicles in low-speed precision flight. However, control sensitivities deemed appropriate for the low amplitude/precision inputs of hovering flight may not be deemed appropriate for more non-precision/aggressive inputs tasks. The inverse of this also hold true, control sensitivity well suited for more gross acquisition, non-precision/aggressive maneuvering may not be appropriate for precision, non-aggressive maneuvering. Given this, control sensitivity should be checked during both precision, non-aggressive maneuvering (e.g., Precision Hover HQTE) and non-precision, aggressive maneuvering (e.g., Depart/Abort HQTE).

A.5.2 Vertical Reposition and Hold HQTE

- This HQTE is based on the Vertical Maneuver MTE from section 3.11.6 of ADS-33E-PRF.
    - STI: The repositioning and hold elements of this HQTE exercises the aircrafts ability to precisely start and stop a vertical rate (adequate heave damping). Specifically, exceedances of the target altitudes (±3 ft for desired performance) suggests inadequate heave damping and/or deficient heave axis controller characteristics. The specific angle change is to be determined based on further study and flight test.
    - STI: Exceedances of the desired heading requirements (±5 deg) could suggest undesirable coupling between the collective and yaw axes. For example, if the pilot experienced a yaw rate greater than 5 deg/s this could be considered "objectionable" coupling [2]. The specific angle change is to be determined based on further study and flight test.
    - STI: The 5-second hold time was established to allow ample time for the pilot to assess any and all coupling between the collective and pitch, roll, and yaw axes. The original Vertical Maneuver MTE from section 3.11.6 of ADS-33E-PRF used a 2-second hold time. Although that time was appropriate for a military attack helicopter that may have to rapidly accent and descend to engage and evade a target, it was deemed to be inappropriate and overly aggressive for a VTOL/urban air taxi aircraft. Hence, the overall maneuver completion time requirement was removed from the Vertical Reposition and Hold HQTE.
    - STI: Although there are not completion time requirements for the Vertical Reposition and Hold HQTE, excessively long completion times suggest a lack of vertical axis control power and poor heave damping (excessively long time to stabilize at target altitudes).

A.5.3 Hovering Turn and Hold HQTE

- This HQTE is based on the Hovering Turn MTE from section 3.11.4 of ADS-33E-PRF.
    - STI: The Hovering Turn and Hold HQTE includes a shorter (90-degree) heading change and longer duration heading change (270-degree). This allows the HQTE to check for any undesirable handling qualities during short and long duration, mildly aggressive heading changes.
    - STI: The Hovering Turn and Hold HQTE specifies a 50-second maneuver completion time. This timing metric was included to tailor the pilot's aggressiveness level. The task is intended to require mild yaw rates. It is not necessary to require an aggressive

yaw rate, like the 18-20 deg/sec yaw rate required for the Hovering Turn ADS-33E-PRF MTE. Rather, a milder yaw rate suitable for urban air taxi CONOPS is appropriate for assessing the yaw-axis handling qualities. The 50-second timing metric required for the Hovering Turn and Hold HQTE would require about an 8-10 second yaw rate for obtaining desired performance.

  - STI: The mid-maneuver heading capture and hold (after the 90-degree heading change) was included to assess the aircraft's ability to precisely command and recover from mild hovering turn rates.
  - STI: An inability to meet the desired heading capture and hold requirement (±5 deg) indicates deficiencies within the yaw axis controller characteristics. The specific angle change is to be determined based on further study and flight test.
  - STI: When determining the reference position, it is important to make it in reference to the aircraft's eyepoint and not the aircraft's C.G. This is especially important for the Hovering Turn and Hold HQTE because the aircraft is going to rotate about its C.G. and not the eyepoint (See example in Figure 22).

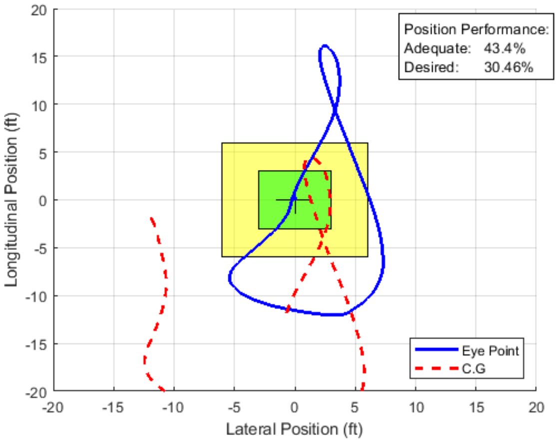

Figure 22. Example Hovering Turn and Hold HQTE (eyepoint vs. C.G.)

- With large pilot offsets, on the order of 30 ft or more, yaw axis maneuvering can confer large, sudden, lateral accelerations, or side-forces, at the pilot station, which can severely interfere with the ability of the pilot to capture a precise heading [5].
  - STI: Pilot station offset from the center of gravity (C.G.) of the vehicle can have a dramatic impact on yaw axis handling qualities. Although a 30-ft offset is more typical of large rotorcraft, larger than those expected for eVTOL Urban Air Mobility vehicles, the effect of pilot station offset should still be considered.

    - STI: Tail rotors of traditional helicopter configurations induce side forces during yaw-axis maneuvering in hover. To meet the desired position threshold, pilots often must immediately and continuously compensate for this force using cyclic inputs for the duration of the maneuver. This is often a driving factor when determining task performance and levels of pilot compensation.
    - STI: Having a limited FOV makes this task difficult to perform within a simulator. To achieve desired performance levels for this HQTE, it is suggested to include additional cueing elements that may not be required for performing the task during actual flight test. One suggested addition is including additional hover boards at 90 degree heading intervals around the hover point. These provide positional cueing to the pilot for the duration of the maneuver.

A.5.4 Lateral Reposition and Hold HQTE

- This HQTE is based on the Lateral Reposition MTE from section 3.11.8 of ADS-33E-PRF.
    - STI: The original Lateral Reposition MTE from ADS-33E-PDF included a timing metric that required aggressive lateral groundspeeds (about 35 knots) to achieve desired performance. This level of aggressiveness is beyond the scope of VTOL/urban air taxi CONOPS. For the Lateral Reposition and Hold HQTE, the focus is on checking for undesirable coupling between the roll controller and other axes by assessing the ability to recover from mild lateral translation rates. As such, the timing metric was removed and was replaced with suggested groundspeeds up to 20 knots.
    - STI: For the Lateral Reposition and Hold HQTE, the most difficult portions of the maneuver are the hover captures at the ends of the course. During this portion of maneuver, the highest amount of inter-axis coupling occurs, especially between the lateral and longitudinal axes. An ability to smoothly arrest lateral translation rates while maintaining desired longitudinal position tolerances (±6ft) indicate highly desirable lateral-longitudinal axis coupling.

A.5.5 Pirouette HQTE

- This HQTE is based on the Pirouette MTE from section 3.11.5 of ADS-33E-PRF.
- This maneuver was first developed and refined during several flight tests using the NRC variable stability Bell 205A. Testing at NRC with various sidestick controllers has shown that the pirouette tends to expose deficiencies in multiple axis manipulators that do not shown up in other task [3].

- When performing the maneuver in winds over 10 knots, the pirouette tends to magnify handling qualities deficiencies [3].
- Although the Pirouette MTE does not directly correspond to a military mission element (or in this case an urban air taxi CONOPS), it was included in ADS-33E-PRF because it is a proven maneuver known to expose handling qualities deficiencies, especially those associated with manipulators and feel systems [3].
  - STI: For this reason, the Pirouette maneuver is a perfect candidate as an HQTE, as it is a repeatable, multi-axis task, which can check for desirable coupling between all axes of control and gain insight into the feel system and manipulators.
  - STI: Given the potential wide variety of inceptor types and control strategies, an HQTE that provides insight into these systems is of critical importance.
  - STI: The Pirouette HQTE requires coordinated control between all of the cockpit inceptors. If pilots are able to achieve desired performance with low levels of workload, it indicates harmony between all axes of control.
  - STI: The Pirouette HQTE requires about an 8-knot lateral groundspeed to meet the desired timing performance metric as defined in ADS-33E-PRF. This speed is specified to tailor the desired level of aggressiveness. Reaching the 8-knot speed requires only a mild level of aggressiveness, thus creating a precision/non-aggressive task.
  - STI: During flight test or piloted simulation, pilots often exceed the recommended 8-knot groundspeed. This can result in faster maneuver completion times, usually at the cost of ground track and hover capture performance. In such a case, the pilot should re-fly the task at slower groundspeeds before determining if desired performance can be achieved.
  - STI: Typically, the most difficult portion of the task is the hover capture at the end of the maneuver. Performing the maneuver at groundspeeds greater than what is recommended further increases the difficulty of the hover capture.
  - STI: The pilot can use any reference position on the rotorcraft for positioning the rotorcraft over the 100 ft radius course marker. Since this reference position may not be the C.G of the aircraft, the reference position offset must be accounted for when determining ground track performance during data processing.

A.5.6 Depart/Abort HQTE

- This HQTE is based on the Depart/Abort MTE from section 3.11.7 of ADS-33E-PRF.

- STI: The Depart/Abort HQTE is representative of an aborted departure scenario. In the case of the UAM mission, this could simulate an abort scenario for a collision avoidance required when departing a heavily trafficked heliport.
- STI: The specified 40-50 knot capture airspeed of the Depart/Abort HQTE allows the task to capture any handling qualities deficiencies resulting from transitions from hovering flight to forward flight. This is important for UAM vehicles. UAM vehicles can vary dramatically in configuration and method for facilitating flight mode transition.
- STI: The Depart/Abort HQTE is a great method of checking an aircraft's ability to re-establish a trimmed hover from forward flight. This is of particular interest for the UAM mission, where vehicles can vary dramatically in configuration and ability to re-established hover after transition.

A.6 References

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1. Anon., *Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft*, US Army Aviation and Missile Command, ADS-33E-PRF, Mar. 2000.
2. Blanken, C. L., R. H. Hoh, D. G. Mitchell, and D. L. Key, *Test Guide for ADS-33E-PRF*, Special Report AMR-AF-08-07, July, 2008.
3. Hoh, Roger H., David G. Mitchell, Bimal L. Aponso, David L. Key, and Chris L. Blanken, *Background Information and User's Guide for Handling Qualities Requirements for Military Rotorcraft*, USAAVSCOM TR-89-A-008, Dec. 1989.
4. Nagata, J. I., et al, Report, *Evaluation of the Light Helicopter Family (LHX) Specification Demonstration Maneuvers*, USAAEFA Project No. 85-22, Jan. 1986.
5. Malpica, C. A., Theodore, C.R, Lawrence, B.; and Blanken, C.L., "Handling Qualities of Large Rotorcraft in Hover and Low Speed," *NASA/TP—2015–216656*, March 2015.

B HQTE simulator demonstrations

Selected HQTEs were demonstrated via informal HQTE engineering evaluations conducted using STI's in-house flight simulator. The evaluations were conducted with an engineer pilot performing the HQTEs. As such, only HQTE performance data was collected and pilot ratings (i.e., Cooper-Harper Handling Qualities Ratings (HQRs)) were not. Evaluations of the Precision Hover, Hovering Turn, Vertical Reposition and Hold, Lateral Reposition and Hold, and Pirouette HQTEs were performed. Detailed descriptions of each HQTE evaluated are provided in Section 6 of the main report. These tests were strictly engineering evaluations intended to: 1) provide data for the development of analysis tools; 2) inspect the simulation environment created for the HQTE courses; and 3) make an initial assessment of the proposed low speed/hover HQTEs. Analysis of the recommended HQTEs is presented and recommendations for HQTE improvements are provided.

B.1 Simulator description

B.1.1 Hardware

The STI flight simulator has been developed as a research tool to strengthen the capabilities of STI in the field of real-time, pilot-in-the-loop flight simulation and pilot-vehicle system identification. The key elements of the simulator, including the pilot, are identified in Figure 23. The STI simulator is comprised of a center stick, pedals, collective, head-down display, and an out-the-cockpit view, all of which can be seen in Figure 24. The simulator can be set up to use a projected display or a 3-view monitor configuration with forward, right 45-degree, and 90-degree cockpit views. The 3-view monitor configuration was used for these evaluations. Due to the monitor configuration, the HQTEs were only evaluated in one direction, to the right. For example, the Lateral Position and Hold and Pirouette HQTEs were only flown translating to the right and the Hovering Turn and Hold HQTE was flown turning to the right. The full flight simulator and operator station can be seen in Figure 25.

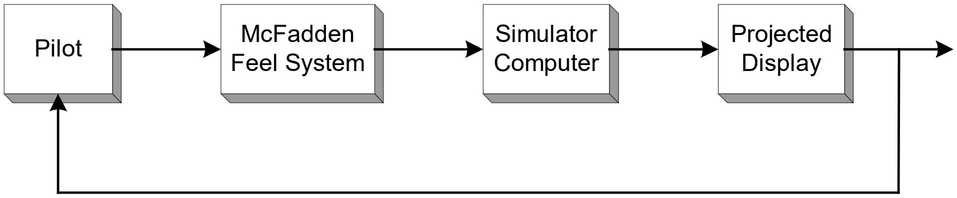


Figure 23. Pilot-in-the-loop simulator elements

STI's McFadden feel system is comprised of a McFadden Series 292A 2-axis (pitch and roll) fighter stick and McFadden Control Loader shown in Figure 26a and Figure 26b, respectively. The system provides a wide range of control-stick force characteristics that are typical of traditional aircraft, including linear and nonlinear spring gradients, damping, breakout, deadband, Coulomb friction, and travel limits. These characteristics may be used in any combination and changed "on the fly" via the McFadden Control Loader. The roll and pitch axes are independent of each other and therefore can be tuned to different performance characteristics.

Figure 24. Simulator setup and control inceptors

Figure 25. Flight simulator operator station and control loader

a) McFadden Series 292A 2-axis (pitch and roll) fighter stick

b) McFadden electronic control unit

Figure 26. McFadden feel system

No active feel-system is included for the pedal and collective inceptors. The current pedal inceptor contains only a simple spring feedback, and the collective inceptor is purely position-based and does not include any force-feedback. As such, they are much lower fidelity in comparison to the McFadden Feel System center stick. The in-house constructed simulation computer is a 64-bit Windows machine with an Intel i7-6700K processor, 32 GBs of memory, and an Nvidia GeForce RTX 2070 graphics card.

B.1.2 Software

STI's flight simulator primarily leverages two pieces of software, FlightGear and MATLAB/Simulink. FlightGear is a free, open source, customizable flight simulation framework that STI has used extensively in other related work. Although FlightGear contains flight dynamics components, FlightGear is used purely as a graphical platform in this simulator. MATLAB/Simulink hosts the flight dynamics for the simulations and provides the data to drive any displays, including the out-of-the-cockpit view. UDP communications protocols are used to transmit data from Simulink to FlightGear.

B.1.3 Simulation setup

The simulation settings used for the informal HQTE testing are:

- 3-monitor out-of-the-cockpit view. Each monitor shows a field of view of 45 degrees.
- Clear skies at dusk.
- No winds
- The McFadden Feel System stick forces were set to be very light, typical of smaller rotorcraft systems.

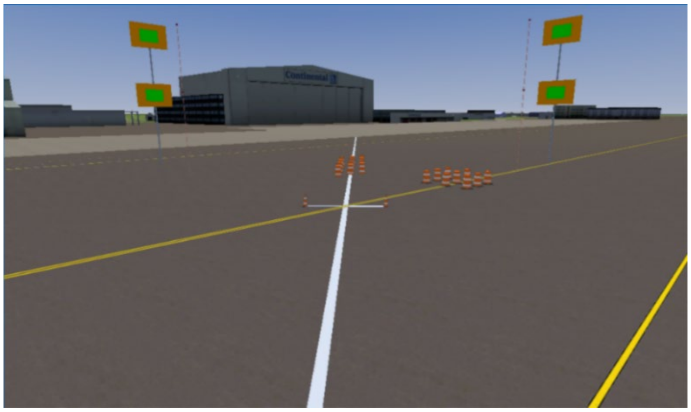
B.2 HQTE Courses

B.2.1 Hover Course

The "Hover Course" (Figure 27) is the HQTE course used for the Precision Hover, Vertical Reposition and Hold, and Hovering Turn HQTEs. The Hover Course is based off the recommended course description for the Precision Hover and the Vertical Reposition and Hold HQTEs provided in Section 6 (see Figure 28). The course includes the following cueing elements:

- **Hover Boards** – Two sets of hover boards for longitudinal/lateral and altitude performance cueing. When in a stable hover over the target hover point, the nose of the aircraft would be aligned with the front hover board, and the second hover board would be oriented out the right window (90 degrees clockwise relative to the nose of the aircraft). The lower hover boards provide altitude performance cueing for the Precision Hover and the Hovering Turn and Hold HQTEs. The higher boards cue the target altitude capture for the Vertical Reposition and Hold HQTE.

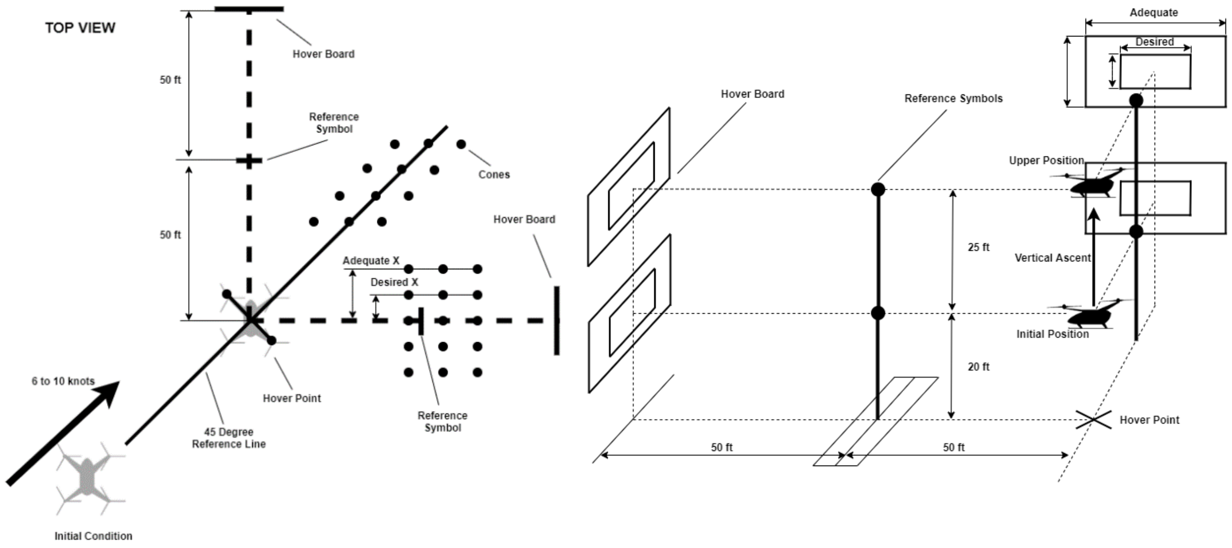
- **45-degree Reference Line –** A white line that provides the pilot a ground track cue to follow when performing the 45-degree forward translation (run-in) during the Precision Hover HQTE.
- **Target Hover Point –** The “X” that is formed by the intersection of the 45-degree reference line and the second white line at the target hover point. The formed “X” included cones that are positioned at each tip for added clarity. This “X” serves as a reference of the target hover point.
- **90-degree Reference Line –** A yellow 90-degree reference line that is oriented 90-degrees relative to the reference heading of the forward hover board. It is aligned with the side hover board and provides additional longitudinal position and drift cueing.
- **Reference Cones –** Cones that are placed to provide ground cues of the adequate and desired position performance bounds. Cones are also placed along the 45-degree reference line to provide additional position and translation drift cues.



a) Hover board

b) Hover Board within 3-View Monitor Setup at the Hover Location

Figure 27. Hover course



a) Top View b) Side View

Figure 28. Course for the Precision Hover and the Vertical Reposition and Hold HQTEs

B.2.2 Lateral Reposition and Hold Course

The "Lateral Reposition and Hold Course" used for the Lateral Reposition and Hold HQTE is shown in Figure 29. The course is based off the recommended course description for the Lateral Reposition and Hold HQTE provided in Section 6 (see Figure 30). The course includes the following cueing elements:

- **Hover Boards –** One hover board is positioned in front of the start point, and the other is positioned in front of the end point. These boards provide hover capture and position maintenance performance cueing.
- **Start Point Reference –** An "X" outlined with cones that provides a reference position of the Lateral Reposition and Hold HQTE start point.
- **Course Reference Line –** A yellow course reference line positioned along the length of the Lateral Reposition and Hold Course. This line provides a lateral translation ground track performance cue to the pilot.

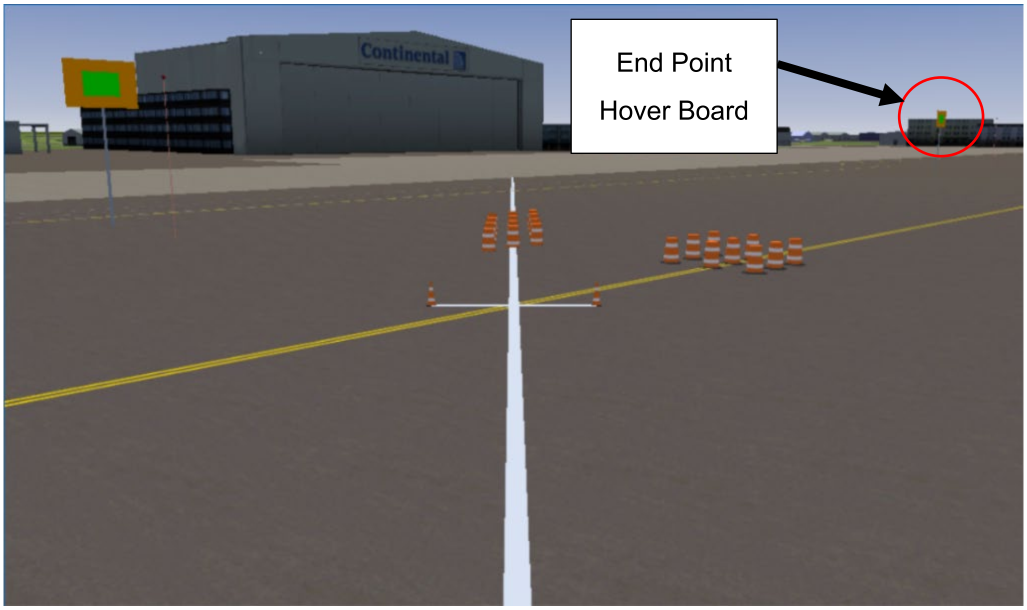
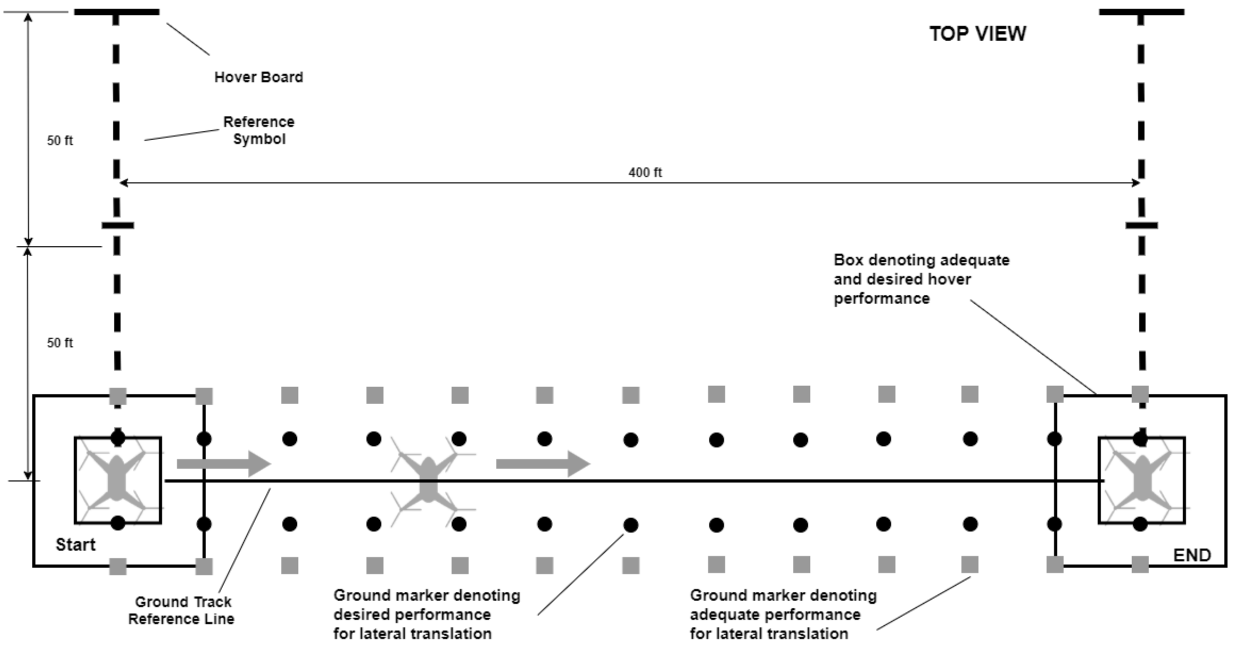
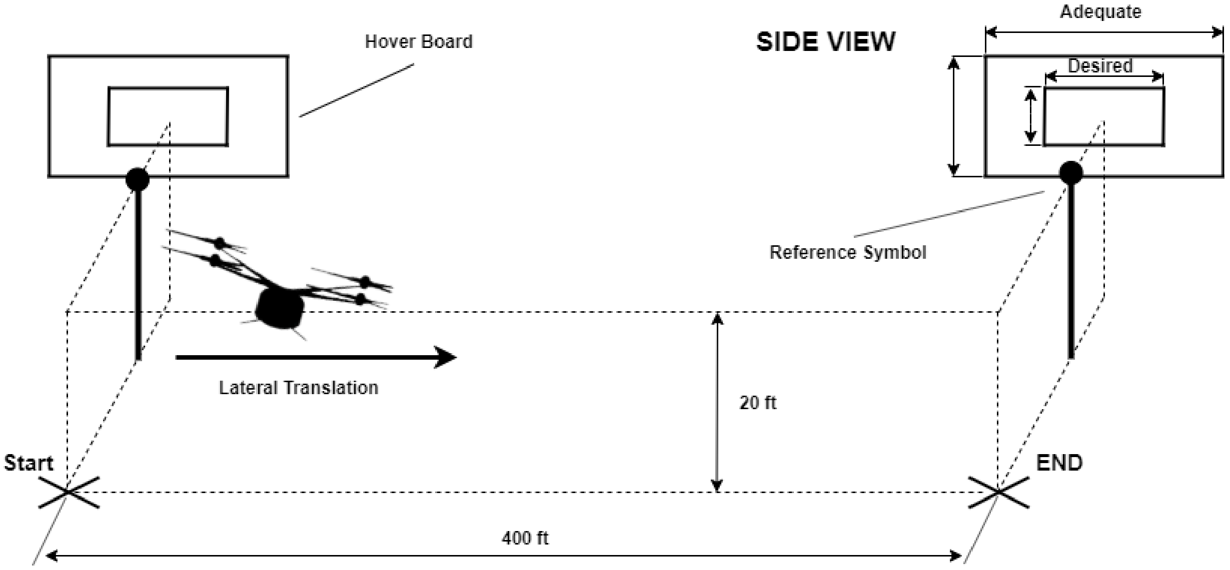


Figure 29. Lateral Reposition and Hold course



a) Top view



b) Side view

Figure 30. Course for Lateral Reposition HQTE

B.3 Aircraft configurations

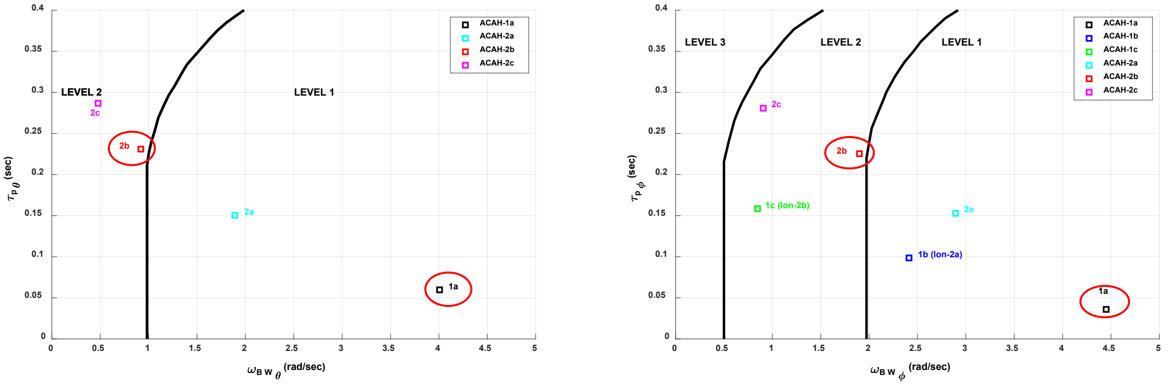
This evaluation used the myCopter Personal Aerial Vehicle (PAV) model. The myCopter PAV models were created as part of European Commission funded University of Liverpool work on the myCopter project [1]. The PAV dynamics model was developed to enable the simulation of a range of tasks that are representative of a typical PAV commuting role. The models have been configured to provide a range of predicted handling qualities and a range of response types including, Rate Command Attitude Hold (RCAH) and Attitude Command Attitude Hold (ACAH) response types. Additional details on the myCopter models, including a complete survey of the predicted handling qualities and system responses of the different myCopter configurations, is provided in Appendix C.

B.3.1 Lateral, longitudinal, and directional axes

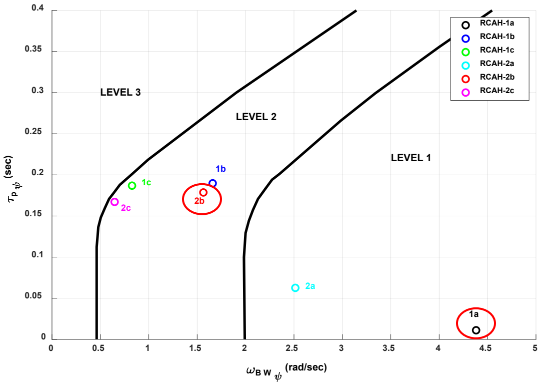
Two different myCopter configurations were used during the engineering evaluations. Each configuration used an Attitude Command Attitude Hold (ACAH) system in the longitudinal and lateral axes and a Rate Command Attitude Hold (RCAH) system in the directional axis. Each configuration had matching predicted handling qualities across the lateral (roll), longitudinal (pitch), and directional (yaw) axes. The Hover and Lateral Reposition HQTEs were also evaluated with Rate Command Attitude Hold (RCAH) configurations in the longitudinal and lateral axes. The two configurations, which are described in detail in [2] (and Appendix C), used for this evaluation are designated as:

1. ACAH-1a (also RCAH-1a, with Hover and Lateral Reposition)
2. ACAH-2b (also RCAH-1b, with Hover and Lateral Reposition)

Based upon aircraft bandwidth and phase delay values computed for each configuration [2], the ACAH-1a configuration was predicted to be a highly responsive configuration with solid Level 1 handling qualities. The ACAH-2b configuration was predicted to be less responsive with borderline Level 1/Level 2 handling qualities. For completeness, the bandwidth and phase delay for every myCopter configuration available are shown in Figure 31. These plots are the requirements for the small-amplitude pitch, roll, and heading attitude changes from ADS-33E-PRF [3]. The configurations used for the evaluations are circled in red. The lateral and longitudinal RCAH configurations that were used during additional evaluations of the Hover and Lateral Reposition HQTEs are circled in red in Figure 32.

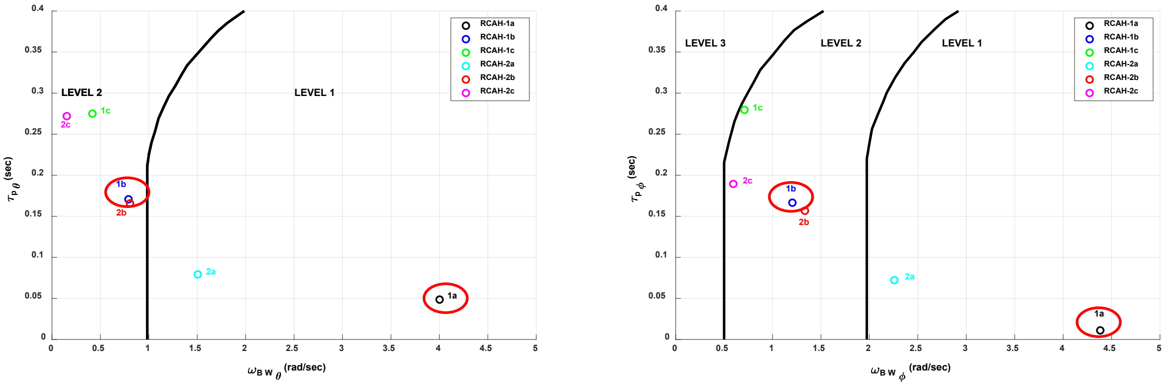


a) ACAH – Longitudinal Axis b) ACAH – Lateral Axis



c) RCAH – Directional Axis

Figure 31. Requirements for small-amplitude changes



a) RCAH – Longitudinal Axis b) RCAH – Lateral Axis

Figure 32. RACH – Longitudinal and lateral requirements for small-amplitude changes

B.3.2 Vertical axis

The vertical axis is controlled via a vertical rate command system and it was varied with the changing configurations (ACAH-1a, ACAH-2b). A first-order lag with varied time constant and time delay values was implemented into the vertical axis to create the degraded vertical configurations [4]. The myCopter vertical axis response to a maximum step command for each of the three configurations is shown in Figure 33. Vertical axis 1a and 1b configurations were used with ACAH-1a and 2b configurations, respectively. For completeness, Figure 33 also includes the 1c vertical axis configuration. This configuration is the most degraded vertical axis configuration created, but was not used during the evaluations. The myCopter autopilot includes a height hold mode; however, this was not engaged during the evaluations.

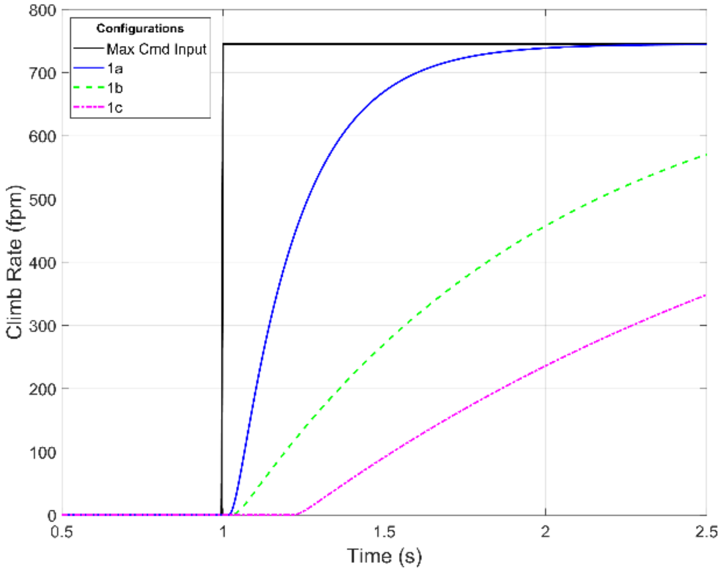


Figure 33. Vertical axis response to maximum step command

B.4 HQTE evaluation results

This section includes some example HQTE analysis results using data collected during the informal engineering evaluations. The results presented here provide examples of the HQTE analysis process as well as an initial look at the HQTE requirements. The evaluations also provide valuable insight into the utility and deficiencies of the HQTE course visual cues.

B.4.1 Precision Hover HQTE

The following metrics, based off the HQTE requirements described in Section 6 of the main report, were used to assess the Precision Hover HQTE task performance:

- Percentage of time within desired and adequate position relative to the target hover point.
    - Recording of this metric began once the aircraft entered a circle with a radius equal to the adequate position performance value about the target hover point. Total position performance (when simultaneously within both the desired and adequate boundaries) and individual axis position performance were measured.
- Percentage of time within desired and adequate altitude limits.
- Percentage of time within desired and adequate heading limits.

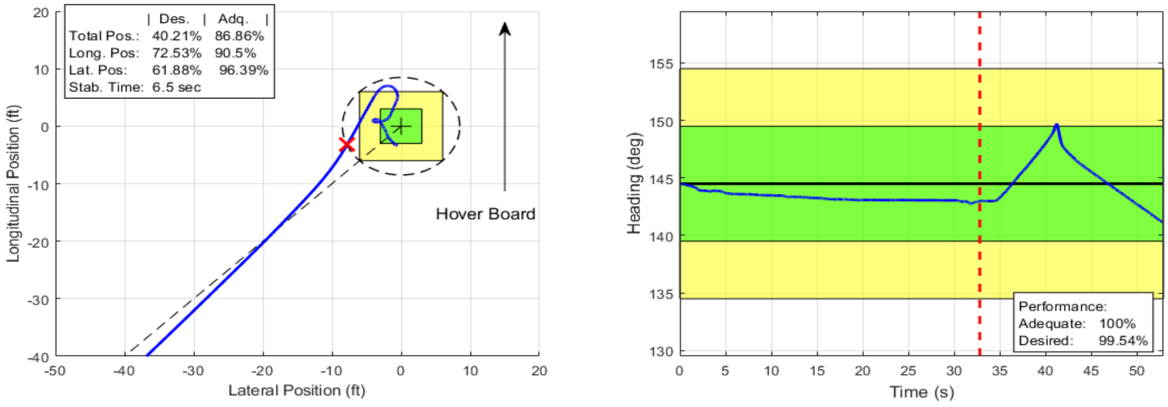
For reference, the Precision Hover HQTE requirements are listed in Table 3.

Table 3. Precision Hover HQTE Performance Requirements

Requirement	**Desired Performance**	**Adequate Performance**
Attain a stabilized hover within X seconds of initiation of deceleration.	5	8
Maintain a stabilized hover for at least 30 seconds.	30	30
Maintain the longitudinal and lateral position within ±X feet from a point on the ground.	3	6
Maintain altitude within ± X feet.	2	4
Maintain heading within ±X degrees.	5	10
There shall be no objectionable oscillations in any axis either during the transition to hover or the stabilized hover.	N/A	N/A

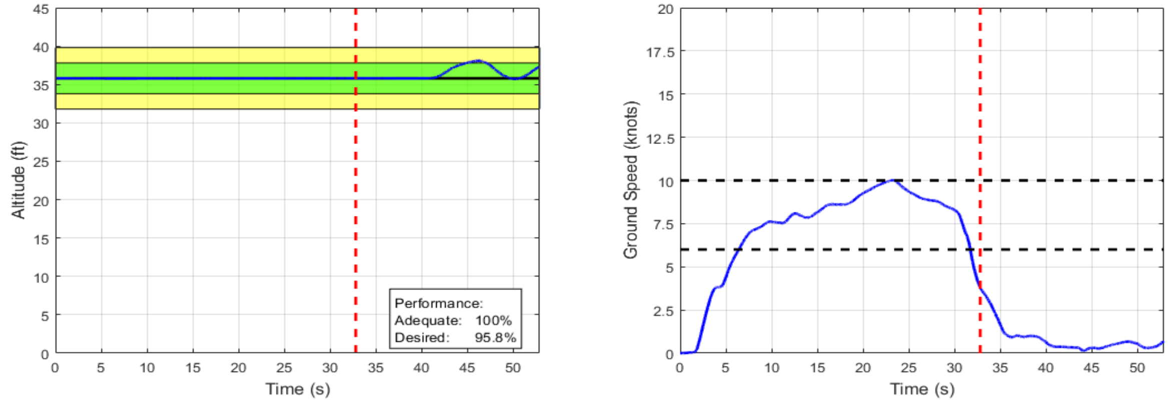
Example Precision Hover analysis plots for the ACAH-1a and ACAH-2b configurations are shown in Figure 34 and Figure 35, respectively. Each set of analysis plots includes a longitudinal and lateral position plot and time history plots of heading, altitude and groundspeed with the desired and adequate performance limit boundaries indicated in green and yellow, respectively. In the hover performance plots, Figure 34a for example, the desired and adequate boundaries are inscribed by a circle. When the rotorcraft entered this circle, indicated by the red “x”, scoring of position performance started. The vertical dashed red lines on the time histories also indicates this point. The entry circle was added to account for any off ideal approach angles towards the hover point and to provide a consistent base from which scoring performance could be measured.

In Figure 34 the pilot achieved near desired performance in the ACAH-1a configuration. After a slight overshoot, the engineer pilot backed into the desired region and settled at the lateral desired/adequate position border. This pilot then essentially maintained this position for the duration of the 30-second hover maintenance portion of the task. Heading remained within the desired boundaries; however, when performing the deceleration to hover, it appears that the pilot inadvertently commanded an approximate 1 deg/s yaw rate. This indicates an overly sensitive pedal control and the need for either an increased force gradient in the pedal (which is not possible with the current pedal used in the STI Flight Simulator) or the addition of a positional “breakout” so that these unintended inputs are mitigated. The altitude performance remained within the desired region, an unsurprising result for the idealized myCopter model. Minor deviations in altitude, within desired, occurred during hover capture and maintenance. The pilot did not achieve the desired stabilization time in the ACAH-la configuration, meeting only the adequate limit of under 8 seconds. In Figure 34d, during the 45-degree run-in towards the hover point, the max groundspeed was just under the recommended max limit of 10 knots. A minor decrease in groundspeed would result in reduced deceleration and thus reduced stabilization time. With more practice and a minor decrease in approach speed, the desired stabilization time could have been achieved. Overall, the performance boundaries are appropriate. This configuration achieved desired, or near desired, performance with an engineer pilot. A minor decrease in approach groundspeed may be warranted to make the task more suitable for urban/civilian transport applications.



a) Hover Point Offsets

b) Heading vs. Time



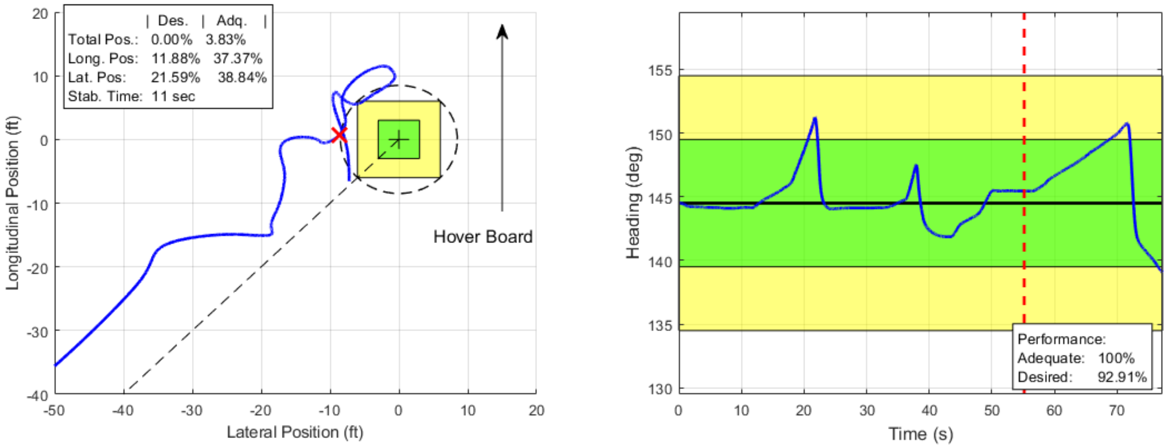
c) Altitude vs. Time

d) Groundspeed vs. Time

Figure 34. Precision Hover performance, configuration: ACAH-1a, Run ID: 103700

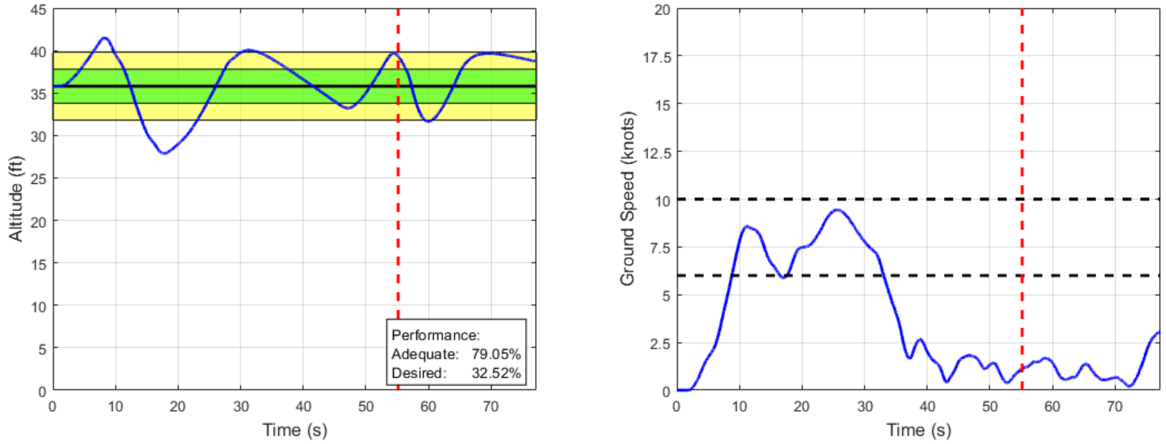
In comparison to the ACAH-1a results, the ACAH-2b results, shown in Figure 35, reveal a dramatic drop in performance. Adequate performance was not achieved. After a long stabilization period (11 seconds), the pilot stopped to the left of the hover point and was not able to make the small corrections necessary to correct back into the desired region. The degraded configuration, in combination with the lack of low-speed transitional rate cueing in the simulator, made it very difficult to make minor position corrections. In the heading performance (Figure 35b), consistent heading rates were repeatedly corrected by the pilot. This again reveals the tendency for the pilot to unintentionally apply yaw—rate inputs that would go unnoticed when the pilot was not monitoring heading indicators within the PFD. There is also a dramatic increase in altitude deviations, where the pilot “bounced” between the upper and lower adequate boundaries. The reduced bandwidth and added phase delay of this configuration is clearly impacting task performance. These degradations were exacerbated by the limited simulator FOV and the low fidelity pedal and collective inceptors. The Precision Hover HQTE is clearly revealing the degraded handling qualities of the ACAH-2a configuration. The ACAH-2a configuration is predicted to have Level 2 HQ. As such, adequate performance should be attainable with tolerable pilot workload. This is clearly not the case for this evaluation; however, with improved visuals (increased FOV), higher fidelity collective/pedal inceptors, and the use of a formally trained pilot, adequate performance would likely be achievable.

The Precision Hover HQTE was also evaluated with a RCAH system. Results from a RCAH-1a evaluation are shown in Figure 36. In comparison to the ACAH-1a configuration, the performance is clearly degraded. Although the RCAH-1a configuration is predicted to have Level 1 HQ, the reduced inherent augmentation of the response-type clearly impacted performance. For a RCAH system, to maneuver or stabilize in pitch and roll, the pilot must close the attitude loop by removing or reversing cyclic control inputs once the desired attitude is reached. Doing this requires sensory feedback (usually visual). Due to the limited visual FOV (especially in the vertical axis), ground references were difficult to see, making it very difficult for the pilot to stabilize. In fact, as seen in the hover performance results, after reaching the hover point the pilot was never able to stabilize and drifted out of the desired/adequate region. In addition, the accelerations seen in the groundspeed time history are significantly larger. For this evaluation, the 10-knot groundspeed was reached more rapidly than with the ACAH-1a configuration. In the hands of a trained pilot, a highly responsive RCAH system is great for rapidly and precisely reaching commanded attitudes. However, with limited visibility, stabilization can be an issue.



a) Hover Point Offsets

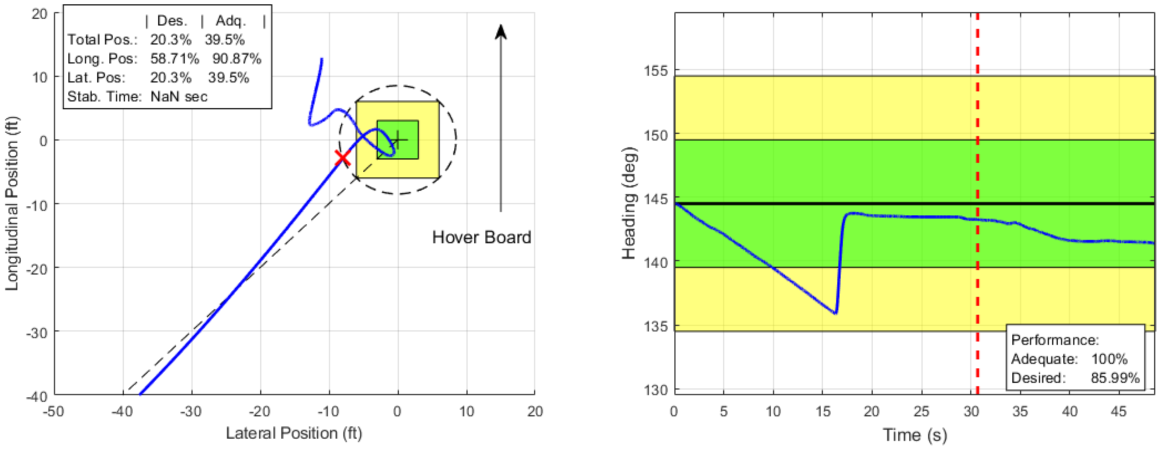
b) Heading vs. Time



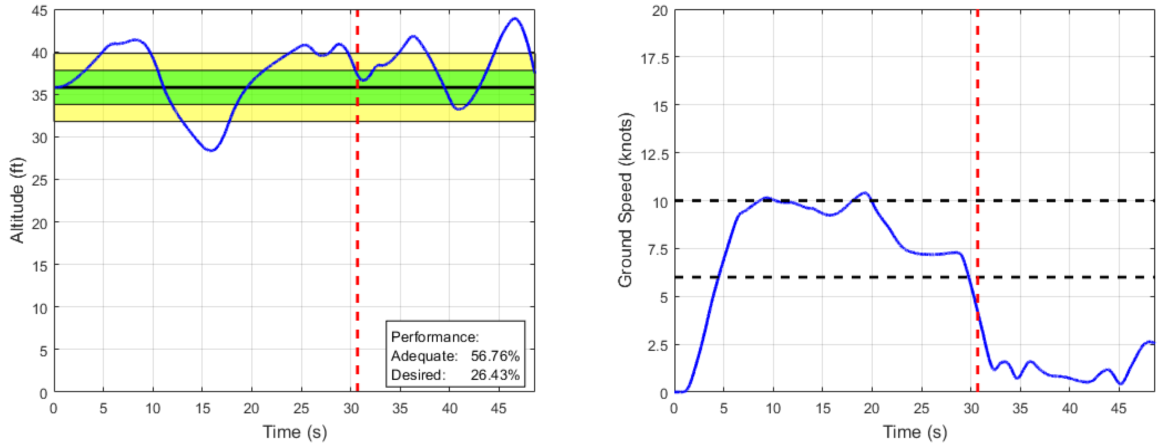
c) Altitude vs. Time

d) Groundspeed vs. Time

Figure 35. Precision Hover performance, configuration: ACAH-2b, Run ID: 104801



a) Hover Point Offsets b) Heading vs. Time



c) Altitude vs. Time d) Groundspeed vs. Time

Figure 36. Precision Hover performance, configuration: RCAH-1a, Run ID: 135400

In ADS-33E-PRF, from which this HQTE is derived, visual conditions are defined using the Usable Cue Environment (UCE) concept [3]. From this, ADS-33E-PRF defines UCE levels where increased UCE implies degraded visual cueing and a need for increased stabilization. With this, ADS-33E-PRF recommends the following response-types to achieve Level 1 handling qualities in Hover and Low Speed:

- UCE = 1, RCAH is required.
- UCE = 2, ACAH is required.
- UCE = 3, Translation Rate + Position Hold (TRC+PH) is required.

Since UCE = 1 would roughly correspond to real-world VFR conditions, without formally determining the UCE level, it can be assumed that the simulator used in the evaluation had a

UCE level greater than 1. As such, it is expected that an ACAH response-type would be required to achieve Level 1 performance. With a formally trained helicopter pilot, stabilization and improved performance within this simulation setup should still be achievable. However, with the limited time within the simulator, the engineer pilot evaluator was not able to develop an adequate compensation strategy to stabilize the aircraft.

B.4.2 Hovering Turn and Hold HQTE

The following metrics, based off the HQTE requirements described in Section 6 of the main text of this report, were used to assess the Hovering Turn and Hold HQTE task performance:

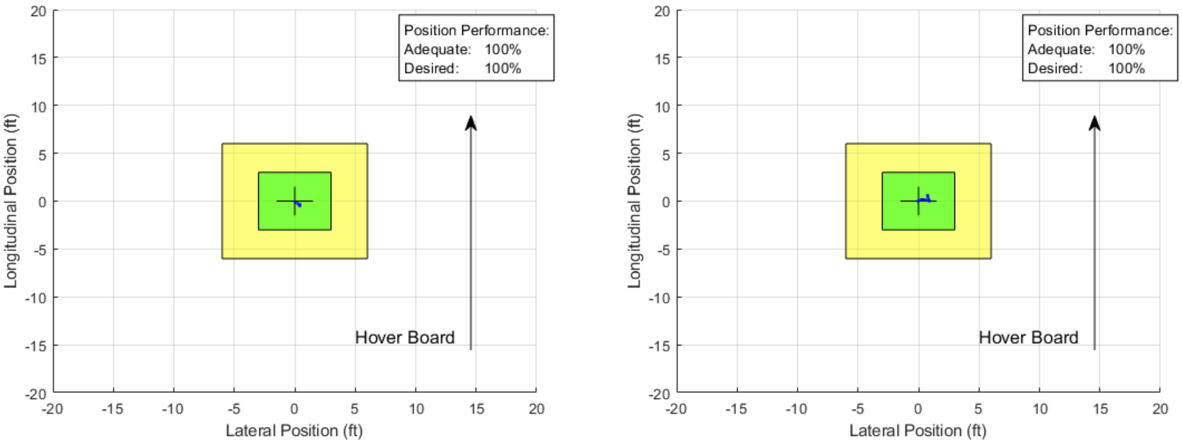
- Percentage of time within the desired and adequate longitudinal and lateral position.
- Observation of overshoots/undershoots of target headings.
- Percentage of time within desired and adequate altitude limits.
- Time to complete maneuver.

For reference, the Hovering Turn and Hold HQTE requirements are shown in Table 4.

Table 4. Hovering Turn and Hold HQTE Performance Requirements

Requirement	**Desired Performance**	**Adequate Performance**
Maintain the longitudinal and lateral position within ±X feet from the hover point.	3	6
Maintain altitude within ±X feet.	3	6
Stabilize the final rotorcraft heading at the 90-degree point and 270-degree point within ±5 degrees.	5	10
Complete turn (360-degree heading change) to a stabilized hover (within the desired position window) within 50 seconds from the initiation of the maneuver.	50	TBD
There shall be no undesirable motions in the yaw axis during the heading capture or hold.	N/A	N/A

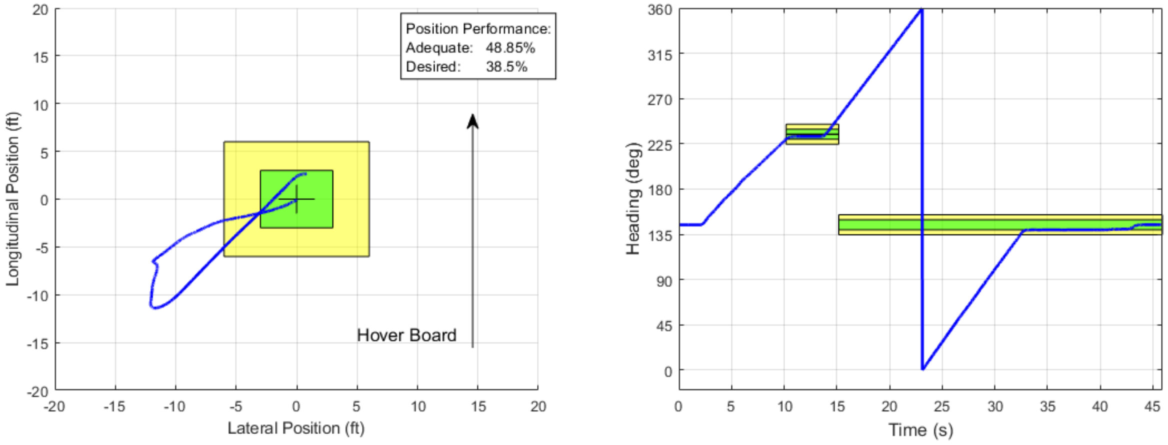
The myCopter model represents idealized responses of an augmented rotorcraft as a strictly non-physical process [5]. As such, cross-coupling between the pitch, roll, yaw, and heave axes, which is typically of even augmented rotorcraft systems, are not fully represented within the myCopter model. Evidence of this is shown in the two example Hovering Turn and Hold HQTE position performance plots shown in Figure 37, where the left plot is from an ACAH-1a evaluation and the right plot is from an ACAH-2b configuration. Performance for both configurations is identical and is essentially perfect. Since the maneuver was initiated trimmed over the hover point in the presence of no wind, without the pilot inadvertently inducing a drift, the myCopter model would remain perfectly trimmed over the hover point. This is certainly the case in the two examples presented in Figure 37. Additionally, for this simulation the eyepoint was placed at the C.G. of the aircraft model. Since the aircraft rotates about its C.G., an offset between the eyepoint and C.G. would naturally create position errors during a hovering turn that the pilot would have to correct. Since there was no offset for this evaluation these position errors were not generated during the turn, thus reducing the overall workload of the task.



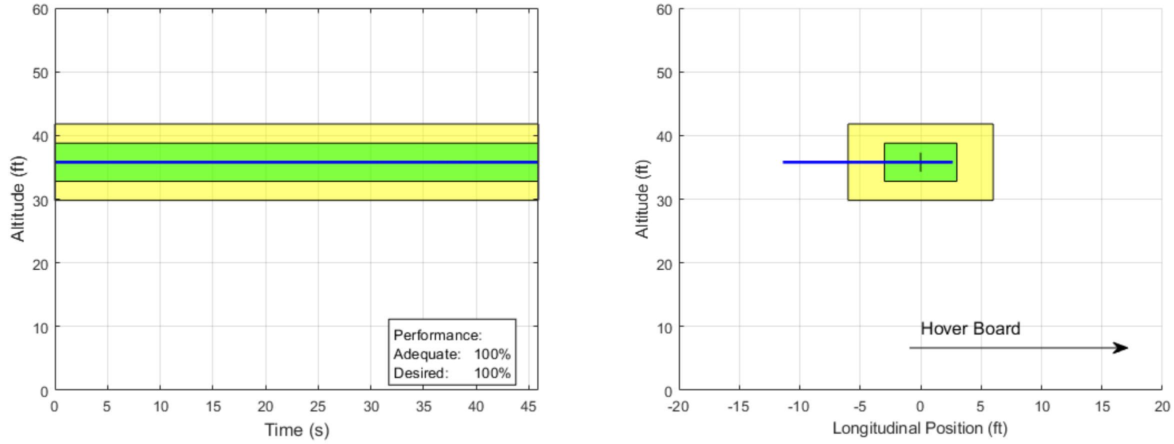
a) ACAH-1a Configuration Example b) ACAH-2b Configuration Example

Figure 37. Hover Turn and Hold HQTE example

In the next set of examples, with ACAH-1a configuration shown in Figure 38 and ACAH-2b configuration shown Figure 39, the pilot did induce a drift that had to be corrected to maintain performance. For both configurations, desired performance was achieved for the altitude and heading criteria. The pilot captured the prescribed headings and maintained within the desired bounds. As such, it is recommended to evaluate this task with further degraded yaw-axis configurations (for example RCAH-1c or RCAH-2c) to determine if the HQTE can adequately reveal degraded yaw-axis handling qualities and an inability to precisely capture and maintain heading angles.

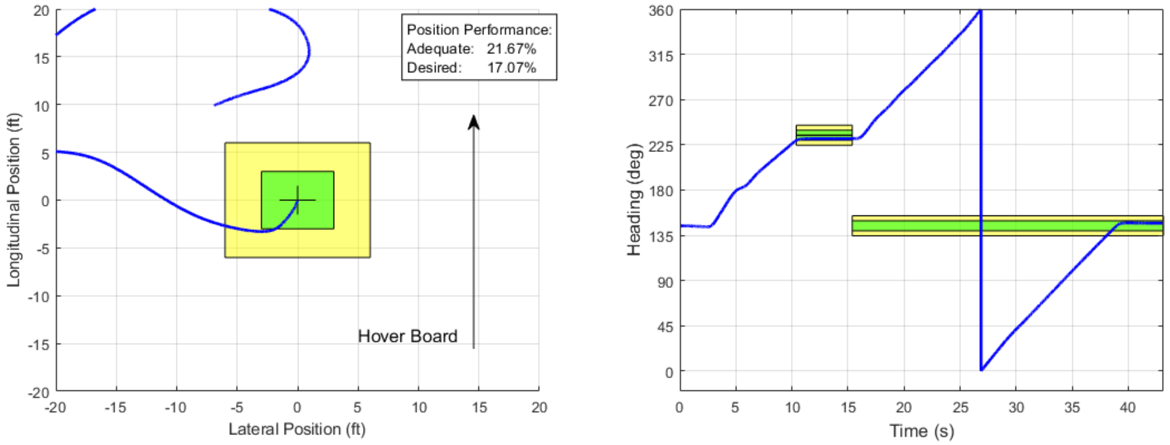


a) Hover Point Offsets b) Heading vs. Time

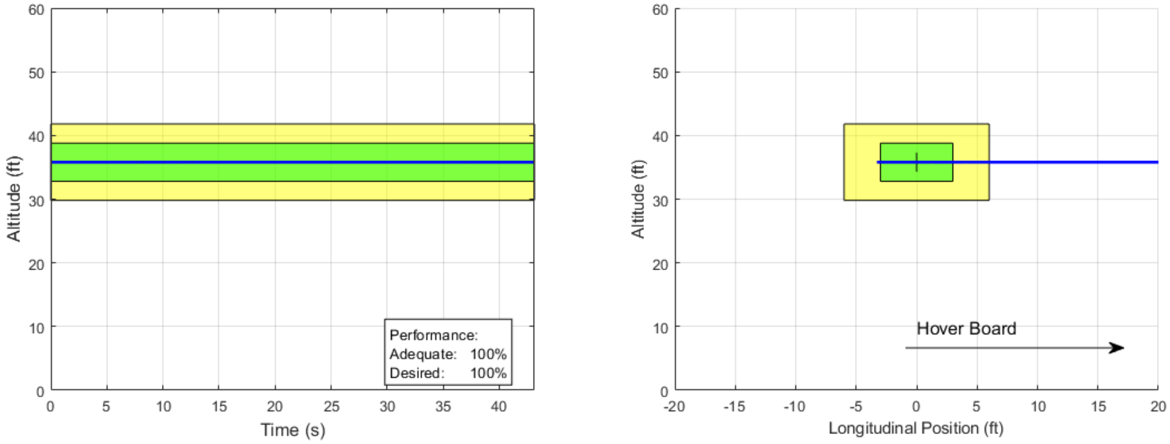


c) Altitude vs. Time d) Altitude vs. Longitudinal Offset

Figure 38. Hovering Turn and Hold Performance configuration: ACAH-1a, Run ID 110001



a) Hover Point Offsets b) Heading vs. Time



c) Altitude vs. Time d) Altitude vs. Longitudinal Offset

Figure 39. Hovering Turn and Hold Performance configuration: ACAH-1a, Run ID 110001

Between the two configurations, there is a clear change in position performance. For both configurations, when performing the yawing turn, the pilot drifted outside the adequate position region. With the ACAH-1a configuration, the pilot was able to correct back into the desired position region. With the ACAH-2b configuration, the drift was much larger and the pilot was not able to correct back into the desired position region. For both configurations, the commanded yaw rates were typically between 11– 14 deg/s. At this rate, the desired maneuver time of 50 seconds was achieved for both configurations. Based on this first check, the desired maneuver time criteria of 50 seconds appears to be appropriate. A recommended adequate maneuver time, not specified in the description, could be ~60 seconds.

As mentioned earlier, for these evaluations there was no pilot station offset from the C.G. The eyepoint for these evaluations was placed directly at the C.G. location. Pilot station offset from the C.G. of the vehicle can have a dramatic impact on yaw axis handling qualities. With large pilot offsets, on the order of 30 ft or more, yaw axis maneuvering can confer large, sudden, lateral accelerations, or side-forces, at the pilot station, which can severely interfere with the ability of the pilot to capture a precise heading [6]. Given that these evaluations were conducted with no offset and that the simulator is fixed-based, these evaluations do not consider the impact of pilot station offset on yaw-axis maneuvering and handling qualities. Although a 30-ft offset is more typical of large rotorcraft, larger than those expected for eVTOL Urban Air Mobility vehicles, the effect of pilot station offset should still be considered. It is recommended that future evaluations include a pilot station offset.

B.4.3 Vertical Reposition and Hold HQTE

The following metrics, based off the HQTE requirements described in Section 6 of the main text of this report, were used to assess the Vertical Reposition and Hold HQTE task performance:

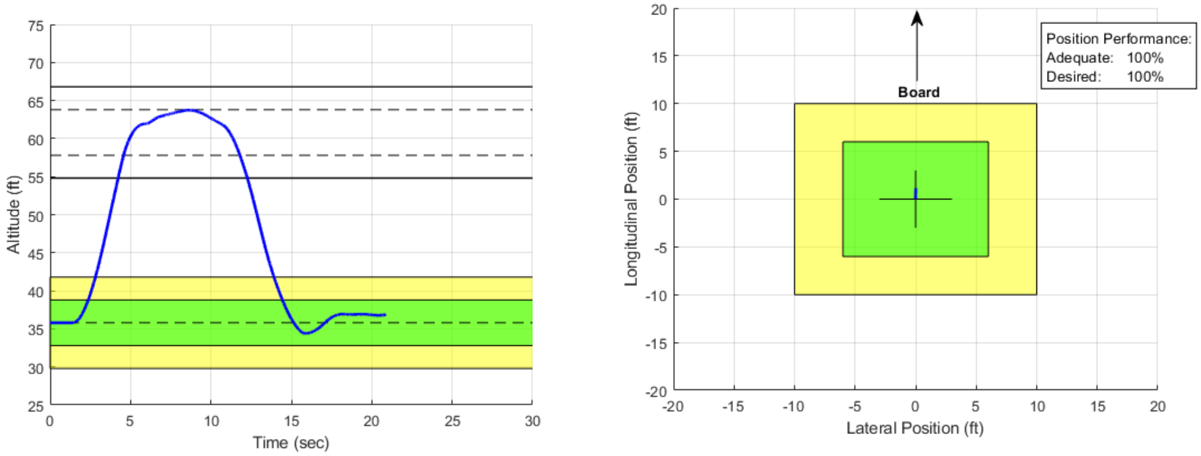
- Percentage of time within the desired and adequate longitudinal and lateral position.
- Observation of exceedances of upper/final altitude limits.
- Percentage of time within desired and adequate heading limits.

For reference, the Vertical Reposition and Hold HQTE requirements are shown in Table 5.

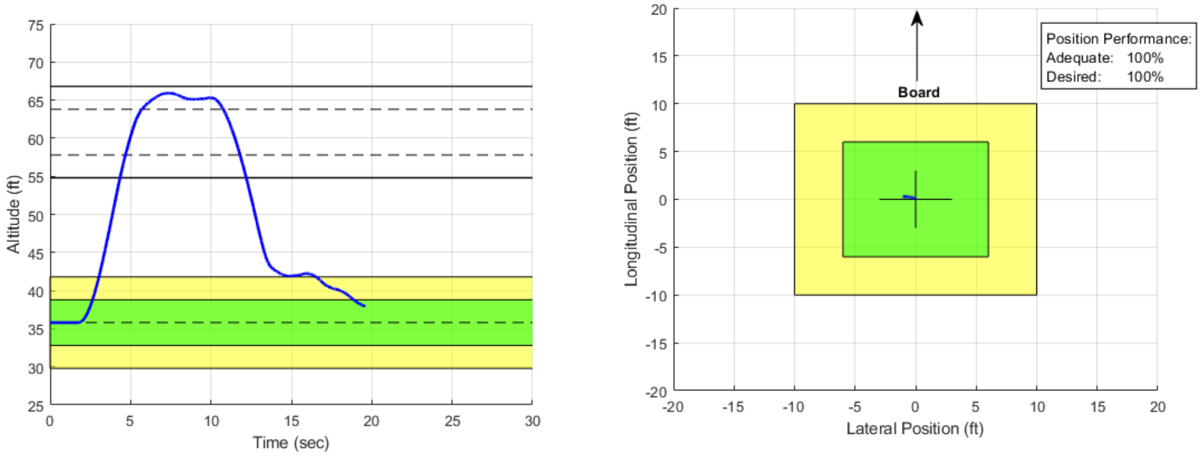
Table 5. Vertical Position and Hold HQTE Performance Requirements

Requirement	Desired Performance	Adequate Performance
Maintain the longitudinal and lateral position within ±X feet from the hover point.	3	6
Maintain upper/final altitude within ±X feet.	3	6
Maintain heading within ±X degrees.	5	10
There shall be no undesirable motions in the vertical axis during the altitude capture or hold.	N/A	N/A

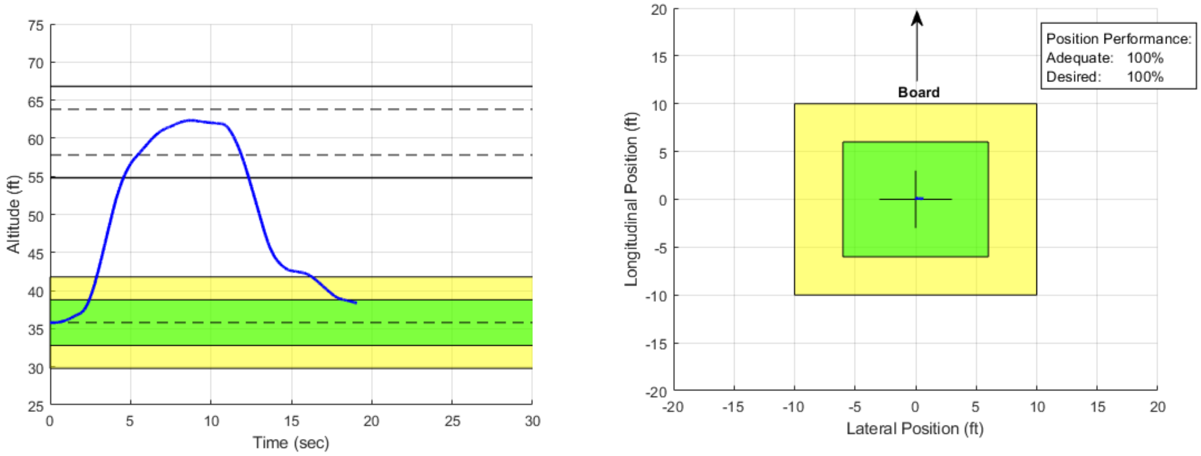
Example Vertical Reposition and Hold HQTE results for each configuration are shown in Figure 40. During post-processing of the data from these evaluations, it was revealed that the vertical-axis configurations were not changing as expected. When switching between the ACAH-la and ACAH-2b lateral/longitudinal axis configurations, it was intended that the vertical axis change with it. With the ACAH-la configuration, the 1a vertical axis configuration is selected. Then, when switching to the ACAH-2b configuration, the vertical axis configuration should change from 1a to 1b. However, a switching logic error caused the vertical axis to remain fixed with the 1a configuration. Thus, only a single vertical axis configuration was evaluated, but the cyclic axes (lateral and longitudinal) were varied. Except for the higher altitude capture of the ACAH-1b configuration, the performance for each configuration was very similar. Due to the simple nature of the Vertical Reposition and Hold HQTE, the lack of other disturbances (i.e. wind), the use of an idealized (not fully coupled) model, and the use of a single vertical axis configuration, no discernable differences in performance were detected. In the presence of winds, this single-axis task becomes a multi-axis task with significantly increased workload. In such an environment, a degraded configuration would be much more easily revealed. Particularly, the addition of wind would reveal clear differences in position maintenance performance.



a) ACAH-1a Configuration (Run ID: 111417)



b) ACAH-1b Configuration (Run ID: 112047)



c) ACAH-1c Configuration (Run ID: 112708)

Figure 40. Example Vertical Reposition and Hold HQTE results

B.4.4 Lateral Reposition and Hold HQTE

The following metrics, based off the HQTE requirements described in Section 6 of the main text of this report, were used to assess the Lateral Reposition and Hold HQTE task performance:

- Percentage of time within the desired and adequate longitudinal and lateral ground track.
- Percentage of time within desired and adequate altitude limits.
- Percentage of time within desired and adequate heading limits.

For reference, the Lateral Reposition and Hold HQTE requirements are shown in Table 6.

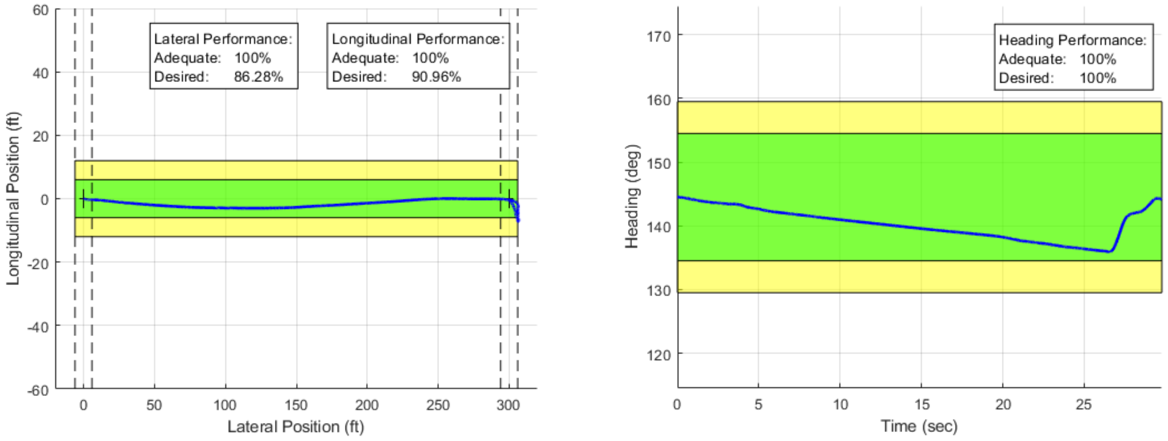
Table 6. Lateral Position and Hold HQTE Performance Requirements

Requirement	Desired Performance	Adequate Performance
Maintain the longitudinal position track within ±X feet from reference line	6	12
Maintain altitude within ±X feet.	5	10
Maintain heading within ±X degrees.	10	15
There shall be no undesirable motions in the lateral axis during the capture or hold.	N/A	N/A

In the Lateral Position and Hold HQTE description, the pilot is required the repeat the lateral reposition back in the other direction after capturing and maintaining a stabilized hover for 5 seconds at the end point. Due to limitations in the simulator, having three monitors displaying only the right-side view of the aircraft, the Lateral Position and Hold HQTE was only performed in one direction.

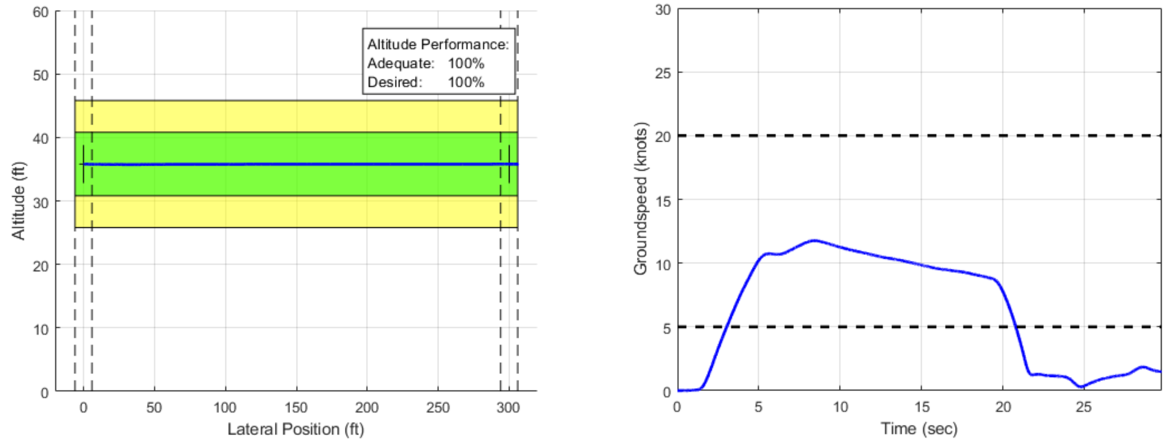
Example Lateral Position and Hold HQTE analysis plots for the ACAH-1a and ACAH-2b configurations are shown in Figure 41 and Figure 42, respectively. Each set of analysis plots includes a longitudinal and lateral ground track position plot, an altitude vs. lateral position plot, and time history plots of heading and groundspeed with the desired and adequate performance limit bounds indicated in green and yellow, respectively. For the longitudinal and lateral ground track plots, the desired and adequate performance indicates the percentage of time the aircraft was within the desired and adequate ground track bounds of the Lateral Reposition and Hold Course. A longitudinal exceedance occurred if the aircraft drifted fore or aft, outside the indicated bounds. A lateral exceedance occurred if the aircraft overshot the target hover end point and drifted outside the Lateral Reposition and Hold Course.

In ACAH-1a configuration (Figure 41), the pilot was able to achieve desired performance, remaining within the desired heading, altitude, and position tolerances for the duration of the evaluation. The largest positional drifts were seen during the end point hover capture. During the final position capture there was a slight aft drift to the desired/adequate boundary. The aircraft remained within the desired tolerances and the pilot was able to arrest the drift and maneuver back to the target hover point. While maneuvering down the course, it appears that the pilot unintentionally held a small yaw-rate command of around 0.3 deg/s. Just as was observed in the Precision Hover HQTE, this indicates an overly sensitivity pedal control and the need to add some form of breakout. In viewing the groundspeed time history, the pilot was able to smoothly accelerate up to 10 knots and then smoothly decelerate during position capture.



a) Hover Point Offsets

b) Heading vs. Time

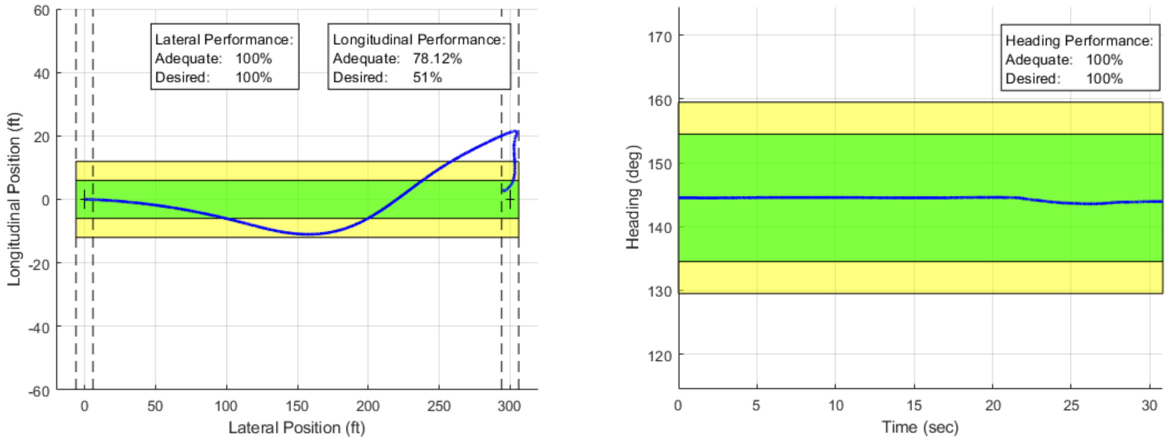


c) Altitude vs. Lateral Position

d) Groundspeed vs. Time

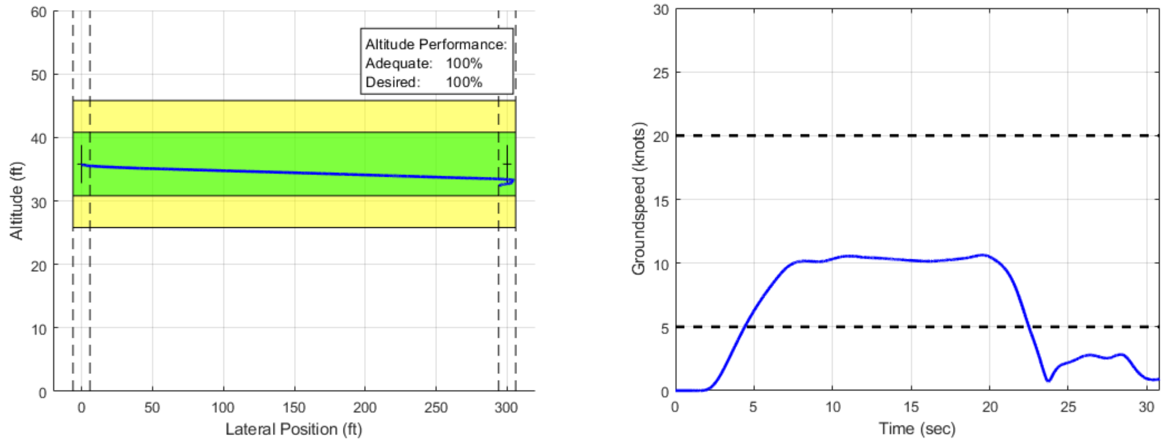
Figure 41. Lateral Reposition and Hold performance, config.: ACAH-1a, Run ID: 113631

In the ACAH-2b results, shown in Figure 42, borderline adequate performance was achieved. For this evaluation, the aircraft drifted fore, outside the adequate position region, during the final position capture. The pilot was able to arrest this drift and slowly correct back to the target hover point. Degradation in position maintenance performance was the primary difference in performance between the two configurations. As presented, the Lateral Reposition and Hold HQTE is able to show distinct differences in performance between configurations with different level of predicted handling qualities. For this evaluation, the pilot was again able to smoothly accelerate and capture a 10-knot groundspeed during the translation and smoothly decelerate during the hover capture. In the description for this HQTE, a target groundspeed is not specified. However, based on the results from this analysis, it appears that a 10-knot groundspeed provided an appropriate level of precision and aggressiveness.



a) Hover Point Offsets

b) Heading vs. Time

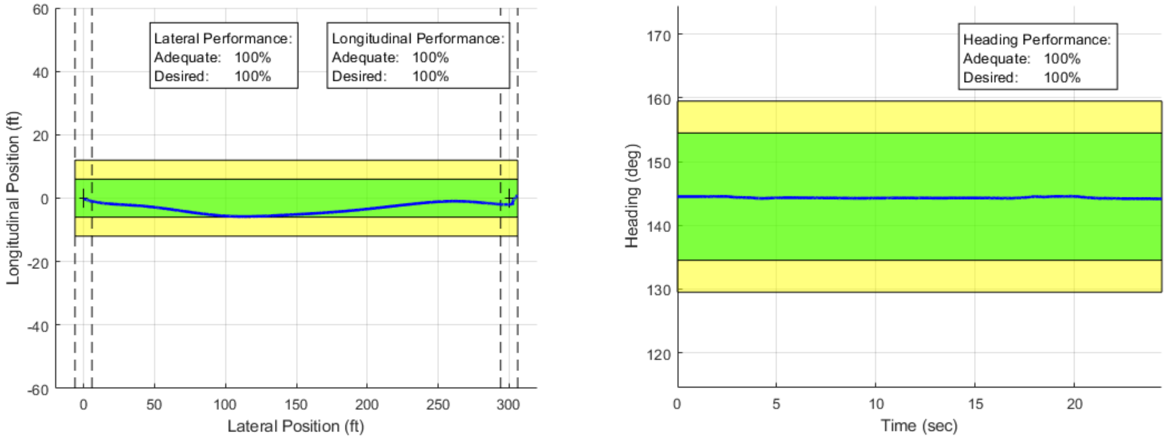


c) Altitude vs. Lateral Position

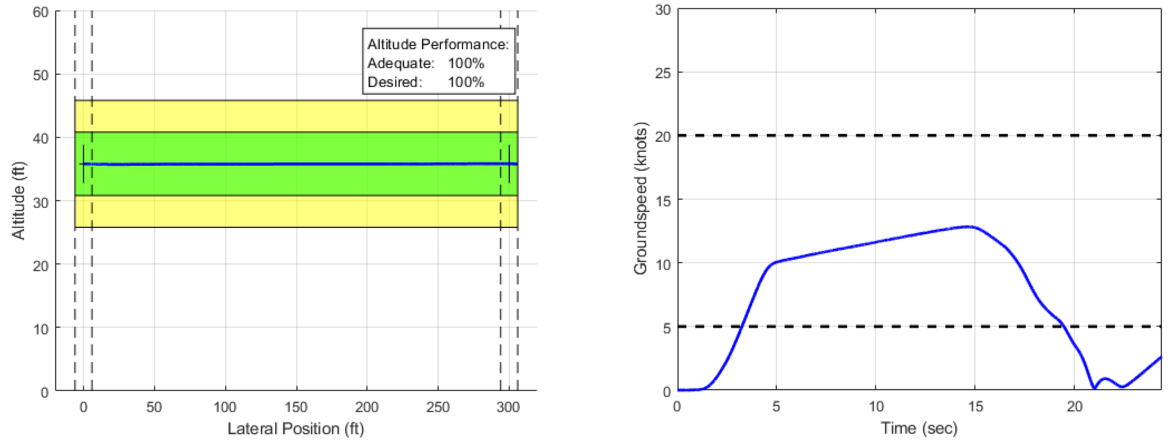
d) Groundspeed vs. Time

Figure 42. Lateral Reposition and Hold performance, config.: ACAH-2b, Run ID: 105728

The evaluations were repeated using RCAH configurations. Example Lateral Position and Hold HQTE analysis plots for the RCAH-1a and RCAH-2b configurations are shown in Figure 43 and Figure 44, respectively. For the RCAH-1a configuration, the pilot was able to achieve desired performance. In comparison to the ACAH-1a configuration, the accelerations for this configuration were a bit more aggressive, and a constant groundspeed was not maintained but desired performance was still achieved. Given adequate cueing, this configuration is predicted to have Level 1 handling qualities and desired performance should be attainable.



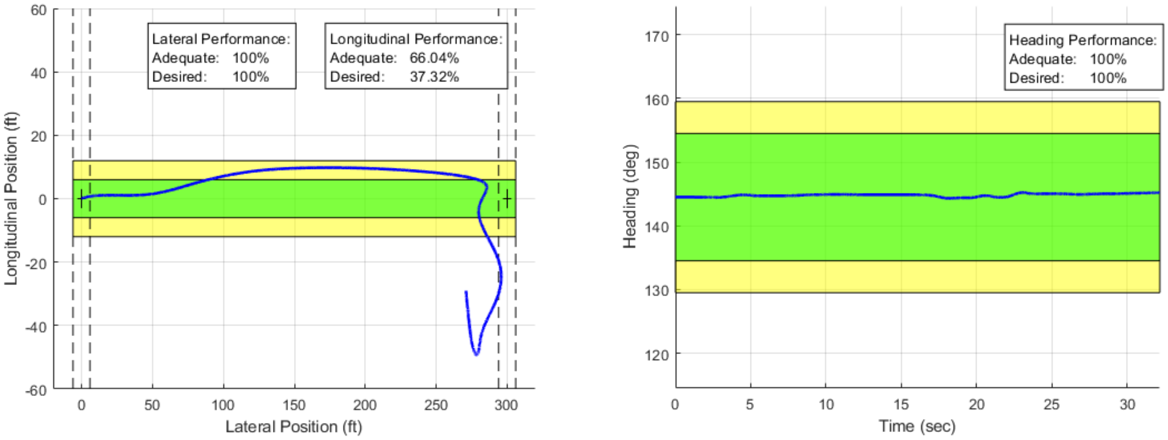
a) Hover Point Offsets b) Heading vs. Time



c) Altitude vs. Lateral Position d) Groundspeed vs. Time

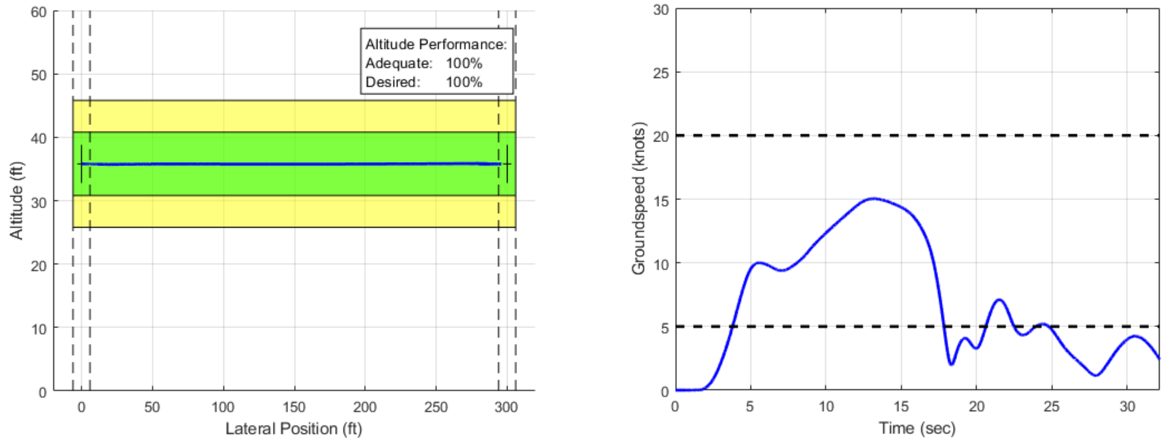
Figure 43. Lateral Reposition and Hold performance, config.: RCAH-1a, Run ID: 113631

For the RCAH-1b configuration, there was a large degradation in performance. The pilot was not able to stabilize at the target hover point. During the capture, the pilot induced an aft drift from which he was not able to recover. Additionally, the groundspeed time history highlights the pilot’s inability to smoothly accelerate and decelerate the aircraft. For this configuration, the degraded handling qualities characteristics of the RCAH-1b configuration were too much for the pilot to overcome and still be able to stabilize the RCAH response-type system. This, of course, is all stated with the caveat that an engineer pilot was performing the evaluation and performance should be improved with a formally trained helicopter pilot.



a) Hover Point Offsets

b) Heading vs. Time



c) Altitude vs. Lateral Position

d) Groundspeed vs. Time

Figure 44. Lateral Reposition and Hold performance, config.: RCAH-1b, Run ID: 113631

B.4.5 Pirouette HQTE

The following metrics, based off the HQTE requirements described in Section 6 of the main report, were used to assess the Pirouette HQTE task performance:

- Percentage of time within desired and adequate ground track.
- Percentage of time within desired and adequate altitude limits.

- Percentage of time within desired and adequate heading (or bearing angle) limits.

For reference, the Lateral Reposition and Hold HQTE requirements are shown in Table 7.

Table 7. Lateral Position and Hold HQTE Performance Requirements

Requirement	**Desired Performance**	**Adequate Performance**
Maintain a selected reference point on the rotorcraft within ±X ft of the circumference of the circle.	10	15
Maintain altitude within ±X ft.	5	10
Maintain heading so that the nose of the rotorcraft points at the center of the circle within ±X deg	10	15
Complete the circle and arrive back over the starting point within X sec.	45	60
Achieve a stabilized hover, at the original starting position, within X seconds after returning to the starting point.	5	10

Example Pirouette HQTE analysis plots for the ACAH-1a configuration are shown in Figure 45. The Pirouette HQTE was only evaluated with the ACAH-la configuration. The engineer pilot evaluator had difficulty learning and completing this task, especially with the limited FOV within the simulator. Since the pilot was barely able to complete the task with the baseline ACAH-1a configuration, it was deemed unnecessary to repeat the task with the degraded ACAH-2b configuration. Conclusions regarding the appropriateness of the performance standards cannot be drawn from this limited evaluation. However, the presented analysis provides an example as to how performance can be determined. For this MTE, the following analysis plots are presented:

- Ground track performance along the pirouette course
- Bearing angle error during the maneuver (difference between current bearing angle and bearing angle when the nose of the aircraft points at the center of the circle)
- Altitude maintenance throughout the maneuver
- Groundspeed during the maneuver

The evaluation shown in Figure 45 was the only attempt in which the engineer pilot evaluator was able to reasonably complete the task. Overall, adequate performance was not achieved, save the altitude criteria where desired performance was obtained. The pilot had large position deviations outside the course and was not able to capture the desired endpoint of the course, stabilizing outside of the adequate boundary. The pilot also took about 85 seconds to complete the maneuver, well over the 60-second adequate requirement. Stabilization times for capturing the final position were not recorded. Further evaluations will be required to determine the appropriateness of the performance criteria (i.e., course boundaries, completion time, stabilization time, etc.).

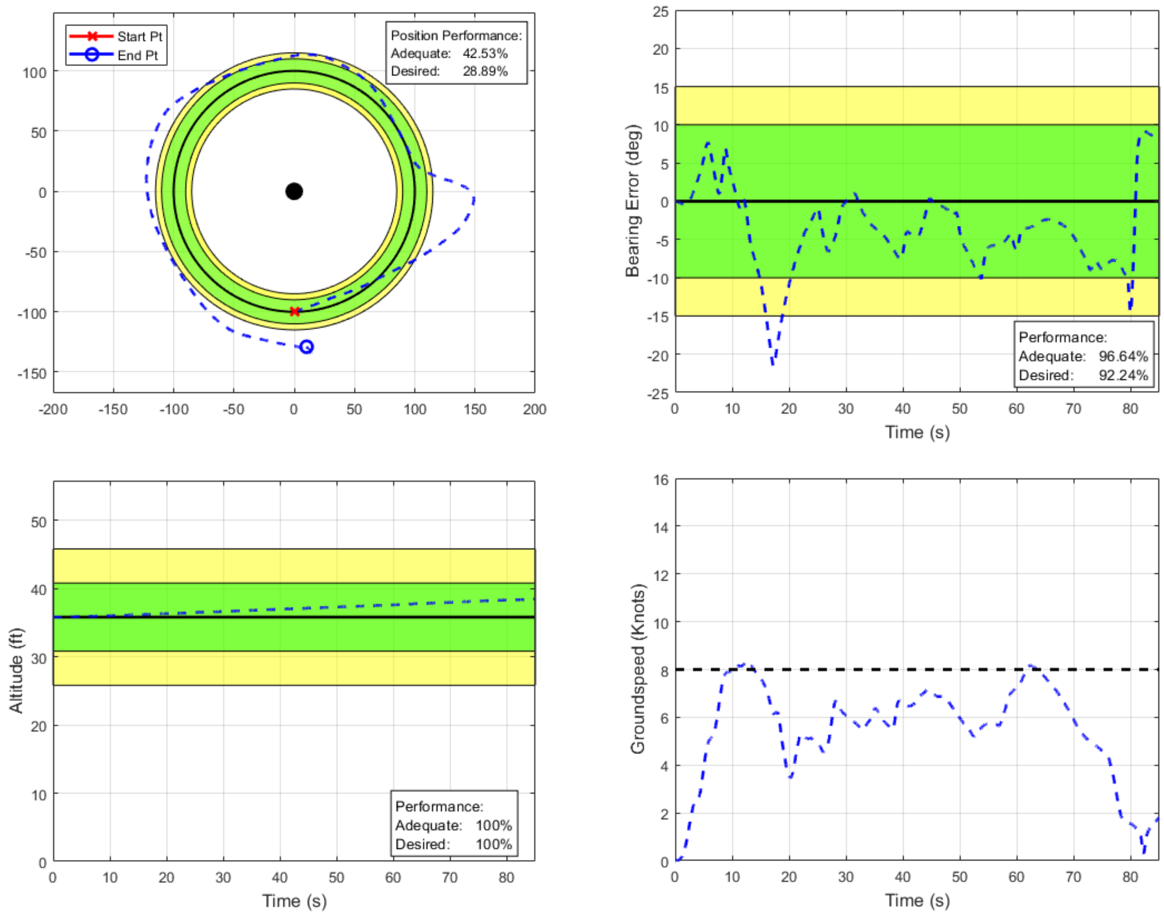


Figure 45. Pirouette Performance, configuration: ACAH-1a, Run ID: 132327

B.5 Discussion and recommendations

B.5.1 Precision Hover HQTE

- The Precision Hover HQTE was able to display distinct differences in performance across configurations with varied levels of predicted handling qualities.
  - With the ACAH-1a configuration, borderline desired performance was achieved.
  - With the ACAH-2b configuration, adequate performance was not achieved. However, it should likely have been achieved by a formally trained helicopter pilot and/or improved simulator visuals and improved pedal/collective inceptors.

- The limited simulator FOV, low fidelity collective and pedal inceptors, and the use of an engineer pilot impacted performance. As such, predicted levels of HQ were difficult to achieve.
- Utilizing the less augmented RCAH response-type for the pitch and roll axes dramatically reduced HQTE performance and demonstrated the impact of limited simulator cueing (High UCE).
- There may be justifications for reducing the upper specified approached groundspeed of 10 knots. Reducing this max groundspeed would reduce the aggressiveness level of the task to levels more appropriate for urban/civilian transport applications.
- The existing requirements for the Precision Hover HQTE provide reasonable performance tolerances. The selected metrics also provide suitable means of assessing task performance.
- These performance levels serve as a good starting point for this HQTE, and they will be carried forward to the formal evaluations later in the program. Based on these observations, the Precision Hover HQTE was determined to be a suitable HQTE candidate for assessing handling qualities during translating flight to a stabilized hover.

B.5.2 Hovering Turn and Hold HQTE

- The use of an idealized model, the lack of a pilot station offset, and no wind conditions can make the evaluation results unremarkable.
- Degradation in yaw-axis handling performance was not seen in these evaluations. In both configurations, the pilot was able to precisely capture and maintain new heading angles. It is recommended to perform this evaluation with more degraded yaw axis configurations (RCAH-lc or RCAH-2c) and include the effects of pilot station offset.
- In evaluation cases where the pilot was correcting drifts, the degraded configuration showed notable degradation to position maintenance performance. However, this reflects the degradation in the lateral and longitudinal axes, not the directional-axis that was the primary objective of the HQTE.
- It is recommended to include disturbances (i.e., winds) when performing this maneuver, especially with the use of an idealized model.
- The specified 50-second maneuver completion time appears approximate.
- A 60-second maneuver time is recommended for adequate performance.

B.5.3 Vertical Reposition and Hold HQTE

- Clear differences in performance across the evaluated configurations were not revealed with the Vertical Reposition and Hold HQTE.
- The use of an idealized model, the lack of disturbances (i.e., winds), the simple nature of the task, and the use of a single vertical axis configuration were the primary causes of the lack of distinguishable performance levels across the various configurations.
- Work will be done to verify that the vertical axis configuration change functionality is working as expected and that the desired vertical axis degradations are achieved.
- The presence of winds, or other external disturbances, would dramatically increase task workload and would reveal clear differences in position maintenance performance.

B.5.4 Lateral Reposition and Hold HQTE

- The Lateral Reposition and Hold HQTE displayed distinct differences in performance across configurations of varied levels of predicted handling qualities. The primary differences in performance were observed in hover capture and position maintenance.
    - With the ACAH-1a configuration, the pilot was able to achieve desired performance.
    - With the ACAH-2b configuration, the pilot was able to achieve adequate performance.
- The specified requirements for the Lateral Reposition and Hold HQTE provided appropriate performance tolerances.
- The 10 knots groundspeed that the pilot typically captured during the transition appeared to provide an appropriate level of precision and aggressiveness for the task. It is recommended that a groundspeed of ~10 knots be specified for this maneuver.
- With the RCAH-1a configuration, the pilot was again able to achieve desired performance.
- There was a severe degradation in hover capture performance with the RCAH-1b configuration. The pilot was not able to stabilize with this configuration. The engineer pilot evaluator clearly benefited from the higher level of augmentation provided by the ACAH response-type.

B.5.5 Pirouette HQTE

- The engineer pilot evaluator was not able to adequately complete the task and achieve consistent levels of performance.
- Attempts at completing the HQTE were only made with the ACAH-1a configuration.

- Conclusions regarding the appropriateness of the performance standards cannot be drawn from this limited evaluation; further evaluations with formally trained rotorcraft pilots will be required.

B.6 References

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C myCopter PAV model

C.1 Introduction

With an increasing stream of Personal Air Vehicles (PAV) being developed, including Vertical Take-Off and Landing (VTOL), there is a need for a system to be in place to allow entities and private parties to operate these vehicles within controlled airspace. As envisioned by the myCopter consortium, a Personal Air Transportation System (PATS) is foreseen to provide a point-to-point connection between any working place and any living area [1]. The scope of the myCopter project was to determine the necessary systems that would enable the implementation of PAVs. An important aspect of the PATS is the flight control system imagined for PAVs and the operator's successful interaction with this system.

This Appendix describes the top-level functionality of the myCopter model, primarily focusing on the controls and dynamics of the "reference" vehicle. A brief description of the Concept of Operations and review of the model dynamics are provided. This is followed by a survey of the myCopter configuration predicted handling qualities, where the Aircraft Bandwidth/Phase Delay criteria of ADS-33E-PRF [2] are applied to the various myCopter configurations.

The model was provided to Systems Technology, Inc. for use on this project by the University of Liverpool.

C.2 Concept of Operations for myCopter

As mentioned previously, the desired purpose for the PAVs is to be a point-to-point transportation method for commuters. Figure 46 below shows a simple overview of the scenario-based Concept of Operations (CONOPS). The operations envision that the PAV would be used for commuting from a sparsely populated area (Site B) to a densely populated area (Site A) and vice-versa. Scenarios were created to imagine these types of commutes. One example is a user walking from Origin Site A to their PAV that is stationed at a lot near the site, then preparing their flight plan to autonomously travel to Destination Site B [3]. The user could also decide to manually pilot the PAV, in which case they would remain in the Highway-in-the-Sky (HITS), Figure 47, as described below.

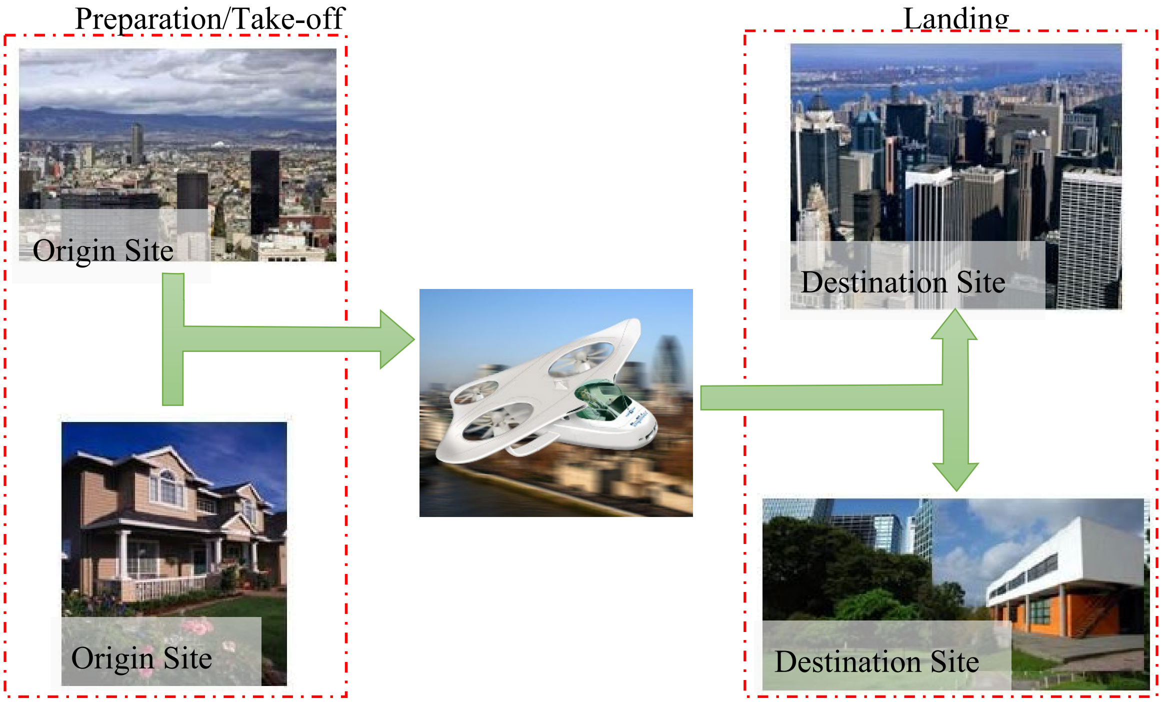

Figure 46. Scenario-based CONOPS

For ground-based commuters, drivers simply follow the network of roads with displayed driving rules. This, however, would not be available to PAV users as there are no established indicators on how the user would manually pilot his or her vehicle. A 3D representation of the path, the HITS, which the PAV user would need to follow was created, as shown in Figure 47. This concept was proposed some decades ago and has not yet been applied on a large scale [1].

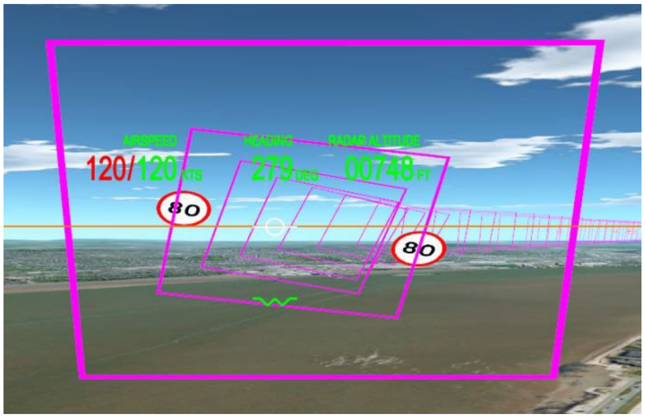

Figure 47. Highway-in-the-Sky concept for PAV navigation

The HITS concept as envisioned by the EU team provides insight into their CONOPS for PAVs, but may not be viable for VTOL integration the National Airspace System in the US.

C.3 Reference vehicle specifications

The “design” reference PAV is the scenario-driven, conceptual vehicle that was used for the myCopter project. The following “design” specifications for the reference PAV are intended to keep PAV designers mindful of desirable transportation characteristics to compete with the experience of driving a ground vehicle for commuters. This was a constraint for the EU project, but as applied to the more general VTOL problem in this project, a full range of pilot control options will be considered from standard rotorcraft controls to JSF-like unified controls.

Table 8 shows the basic physical specifications of the reference PAV [1]. The intention for PAVs is to be able to compliment preexisting transportation infrastructure. This means that PAVs would need to be sized in a way that allows them to be stored in small hangars or garages like today’s cars. The maximum take-off weight (MTOW) was selected to remain unregulated as per the Basic Regulation in Annex II by the European Aviation Safety Agency (EASA). Although it was not the scope of the myCopter project to fully define the PAV, the desire of the reference vehicle was to be an electric Vertical Take-off and Landing (eVTOL) variant or to feature low emission propulsion. Statistical European traffic trends showed that the occupancy rate for commuting were about 1.1 to 1.2 passengers per vehicle. Similarly, the number of commuters per automobile in the US was 1.22 in 2014 [4]. The seating for PAVs would ideally have one seat for the pilot and one seat for either an additional passenger or more cargo.

Table 8. Reference PAV Physical Specifications

	Units (SI)	**Units (English)**
Dimensions	Comparable to that of a mid/large-sized car, “garageable”	
Maximum take-off weight	450 kg	~992 lbs.
Propulsion	Electric, preferably	
Seating	1 + 1	

The reference PAV performance specifications are provided in Table 9 [1]. The cruise speed shown was selected so PAVs would be superior to ground based transportation and would not limit conceptual designs too early. The maximum range was selected to represent typical commute distances. As EU PAVs are intended not to interfere with preexisting air traffic, the required cruise altitude would have to be 500 m above ground level (AGL).

Table 9. Reference PAV Performance Specifications

	Units (SI)	**Units (English)**
Cruise Speed	100-200 km/h	~54-108 kts
Average cruise altitude, AGL	500 m	~1640 ft
Maximum range	100 km	~62 miles

C.4 Model dynamics

The model represents generic responses of an augmented rotorcraft as a strictly non-physical process [5]. It is broken down into three main components: rotational dynamics, translational dynamics, and response augmentations. The rotational dynamics is broken down into two response types: Rate Command Attitude Hold (RCAH) and Attitude Command Attitude Hold (ACAH). A transport time delay, τ , is applied to the commanded rate or attitude to incorporate simulation delays and lags. The delay can be set to 0s or to account for the processing time for real-time pilot simulation.

C.4.1 Rate Command Attitude Hold

A first-order transfer function is used to generate the roll, pitch, and yaw responses. Using the lateral axis as an example, the RCAH transfer function can be seen in Equation 1.

$$\frac{p_{cmd}}{\delta_{lat}} = \frac{K_{lat}}{T_{lat}s+1} \tag{1}$$

where,

p_{cmd}	is the commanded roll rate
δ_{lat}	is the lateral control input
K_{lat}	is the lateral stick to roll rate gearing
T_{lat}	is the roll response time constant

C.4.2 Attitude Command Attitude Hold

A second-order transfer function is used to generate the roll and pitch responses for ACAH. The yaw response, however, remains a first-order rate command transfer function as described above. Using the lateral axis as an example, the ACAH transfer function can be seen in Equation 2.

$$\frac{\phi_{cmd}}{\delta_{lat}} = \frac{K_{lat}}{\frac{1}{\omega_{lat}{}^2}s^2 + \frac{2\zeta_{lat}}{\omega_{lat}}s + 1} \tag{2}$$

where,

ϕ_{cmd}	is the commanded bank angle
δ_{lat}	is the lateral control input
K_{lat}	is the lateral stick to roll attitude gearing
ω_{lat}	is the natural frequency
ζ_{lat}	is the damping ratio

C.4.3 Translational dynamics

The translational response of the vehicle is determined for both RCAH and ACAH by integration of the body axes accelerations that are shown in Equations 3-5. The velocities are then transformed to the earth axis system and then integrated once more to provide the vehicle's position in space.

$$\dot{u} = vr - wq - g\sin\theta + X_u u \tag*{3}$$

$$\dot{v} = wp - ur - g\cos\theta\sin\phi + Y_v v \tag*{4}$$

$$\dot{w} = uq - vp - g\cos\theta\cos\phi + Z_{\delta_{col}}\delta_{col} + Z_w w \tag*{5}$$

where,

δ_{col}	is the collective control input
$Z_{\delta_{col}}$	is the heave control derivative
Z_w	is the heave damping derivative
X_u	is the surge damping derivative
Y_v	is the sway damping derivative
g	is the acceleration due to gravity
u, v, w	are the longitudinal, lateral, and vertical velocities, respectively

C.4.4 Response augmentation

The target PAV users might not be commercial pilots; therefore, it is preferable to reduce the workload for certain command tasks. Additionally, it is important from the energy management perspective to achieve this, as more energy will be spent without the response augmentation. This section addresses some of these command tasks and provides the necessary equations to accomplish them.

C.4.4.1 Translational Rate Command

A velocity feedback loop was created to replace the direct inputs of the pilot to the ACAH system to provide direct command to the translational velocity of the vehicle. The Translational Rate Command (TRC) is defined by the vehicle roll attitude generated from Equation 6 and the translational velocity command, Equation 7, from the low-pass filtered version of the pilot's control inputs.

$$\phi_{TRC} = v_{horiz_{cmd}} - \left(K_{v_{TRC}} \times \, v_{horiz} \right) \tag{6}$$

$$\frac{v_{horiz_{cmd}}}{\delta_{lat}} = \frac{K_{TRC_{lat}}}{T_{TRC_{lat}} \times \left(s+1 \right)} \tag{7}$$

where,

ϕ_{TRC}	is the bank angle command generated by the TRC outer loop
$K_{v_{TRC}}$	is the lateral velocity feedback gain
v_{horiz}	is the vehicle lateral velocity (in plane parallel to Earth's surface)
$v_{horiz_{cmd}}$	is the pilot's commanded lateral velocity
$K_{TRC_{lat}}$	is the lateral velocity command prefilter gain
$T_{TRC_{lat}}$	is the lateral velocity command prefilter time constant

Similarly, the TRC for the longitudinal loop is nearly identical to that of the lateral loop. Equation 8 defines the pitch attitude command.

$$\theta_{TRC} = u_{horiz_{cmd}} + \left(K_{u_{TRC}} \times u_{horiz} \right) \tag{8}$$

C.4.4.2 Sideslip command and turn coordination

A feature of traditional helicopters is the constant yaw alignment with the direction of flight while in forward flight, known as "weathercock" stability. For PAVs, however, a sideslip angle feedback loop is implemented to minimize the sideslip angle, β, unless the pilot makes a pedal input. The sideslip control is only active in the control loop while the vehicle is in a 15 kts forward flight. The yaw rate needed for the sideslip control is generated by Equation 9, as seen below.

$$r_{\beta} = K_{beta} \left(\delta_{ped} + \beta \right) \tag{9}$$

A turn coordination system is employed to implement weathercock stability characteristics. This system calculates the required pitch, roll, and yaw rates, Equations 10-12, to keep the vehicle in a zero sideslip flight. It should be noted that only the turn coordinated yaw rate is required with the ACAH system as the attitude hold for pitch and roll is already implemented.

$$q_{tc} = \tfrac{g}{u}\cos\theta\tan\phi\sin\phi \tag{10}$$

$$p_{tc} = -\tfrac{g}{u}\sin\theta\tan\phi \tag{11}$$

$$r_{tc} = \tfrac{g}{u}\cos\theta\sin\phi \tag{12}$$

C.4.4.3 Heave augmentation

A simple PI (Proportional + Integral) controller is used to correct the error between the respective vertical rate and flight path angle of the model and the pilot's commanded rate. This controller is seen in Equation 13.

$$\delta_{col_{cmd}} = K_{p_{\dot{h}}}\left(\delta_{col} \times K_{\dot{h}} - \dot{h}\right) + K_{i_{\dot{h}}}\int\left(\delta_{col} \times K_{\dot{h}} - \dot{h}\right)dt \tag{13}$$

where,

$\delta_{col_{cmd}}$	output of the vertical rate command system; replaces δ_{col} in Eq. 5
$\dot{h}$	is the vehicle vertical rate
$K_{\dot{h}}$	is the gearing of pilot control deflection to resultant vertical rate
$K_{p_{\dot{h}}}$	is the proportional gain for vertical rate feedback control
$K_{i_{\dot{h}}}$	is the integral gain for vertical rate feedback control

C.4.4.4 Turn rate and turn radius command

By modifying the lateral control input, a turn rate response is implemented by defining the required bank angle to provide the desired turn rate. The required bank angle is calculated by Equation 14. Similarly, a turn radius response is defined by the required bank angle calculated by Equation 15.

$$\phi_{req} = \tan^{-1}\left(\frac{u_{horiz}\Omega_{cmd}}{g}\right) \tag{14}$$

$$\phi_{req} = \tan^{-1}\left(\frac{u^{2}_{horiz}}{R_{cmd}\,g}\right) \tag{15}$$

where,

ϕ_{req}	is the required bank angle
u_{horiz}	is the vehicle airspeed
Ω_{cmd}	is the commanded turn rate
g	is the acceleration due to gravity
R_{cmd}	is the commanded turn radius

The commanded turn rate and commanded turn radius both have a linear relationship with the predetermined maximum turn rate, $\Omega_{\max}$, and minimum turn radius, $R_{\min}$ with the pilot commanded lateral control deflection. These relationships are shown in Equations 16 and 17.

$$\Omega_{cmd} = \Omega_{max}\delta_{lat} \tag{16}$$

$$R_{cmd} = \frac{R_{\min}}{\delta_{lat}} \tag{17}$$

The required bank angle is then used to calculate the equivalent lateral control input, Equation 18, which would be used with Equation 2.

$$\delta_{lat_{eq}} = \frac{\phi_{req}}{K_{lat}} \tag{18}$$

C.4.4.5 Autopilot

A typical autopilot that offers flight assist modes is implemented into the model. The autopilot features selectable modes such as automatic acquire/holds of speed, altitude, and heading. Waypoint navigation can be accomplished by using these modes to automatically determine the necessary speed, altitude, and headings to follow the route. The autopilot model requires the use of speed tracking elements; thus, the "hybrid" configuration is needed. The autopilot works by utilizing a basic proportional feedback controller.

C.4.5 Turbulence model

The turbulence model currently employed is one that resembles turbulence that a rotorcraft would experience during hover and low speed flight. The Control Equivalent Turbulence Input (CETI) method does not necessarily demonstrate aerodynamic details of the turbulence, but rather the equivalent control inputs of the vehicle to mimic the effect of turbulence. The gust control input is generated by a white noise signal passing through a low-pass filter, which can be seen in the equation below. The gust input is then added to the pilot's command input.

$$\frac{\delta_{lon_{gust}}}{W_{noise}} = \frac{A_{lon}}{\left(s + \frac{U_0}{L_W}\right)} \tag{19}$$

where,

$\delta_{lon_{gust}}$	is the longitudinal control contribution from the gust model
W_{noise}	is the white noise signal
A_{lon}	is the longitudinal turbulence filter amplitude
U_0	is the mean wind speed
L_W	is the turbulence scale length

C.5 Predicted handling qualities

An outline of the handling qualities and system responses of the different myCopter configurations that were used to evaluate the HQTEs under consideration is provided in this section. For each configuration, the Aircraft Bandwidth/Phase Delay criteria (requirements for small-amplitude attitude changes) from ADS-33E-PRF [2] was applied. The configurations are split into two command modes: Rate Command Attitude Hold (RCAH) and Attitude Command Attitude Hold (ACAH). Each mode has multiple configurations with a diverse range of handling qualities. Each configuration has matching handling qualities across the lateral (roll), longitudinal (pitch), and heading (yaw) axes.

C.5.1 RCAH – Rate Command Attitude Hold

Figure 48, Figure 50, and Figure 52 show the bode plots for roll, pitch, and heading, respectively, for the RCAH mode. The drop-offs seen in the magnitude subplot reflect the reduction in bandwidth frequencies. Additionally, the lower frequency phase roll-offs in the phase subplot are indicative of the increasing phase delay in the configurations. Figure 49, Figure 51, and Figure 53 show the requirements for small-amplitude changes in roll, pitch, and heading, respectively. These figures are generated from ADS-33E-PRF [2], Handling Qualities Requirements for Military Rotorcraft, as a template. It is predicted that configuration 1a would perform the best due to the high bandwidth and low phase delay, thus signifying a configuration representative of a highly responsive vehicle. Conversely, configuration 2c represents a configuration for a vehicle with a “sluggish” response due to the low bandwidth and high phase delay. Table 10 shows the RCAH configuration parameters.

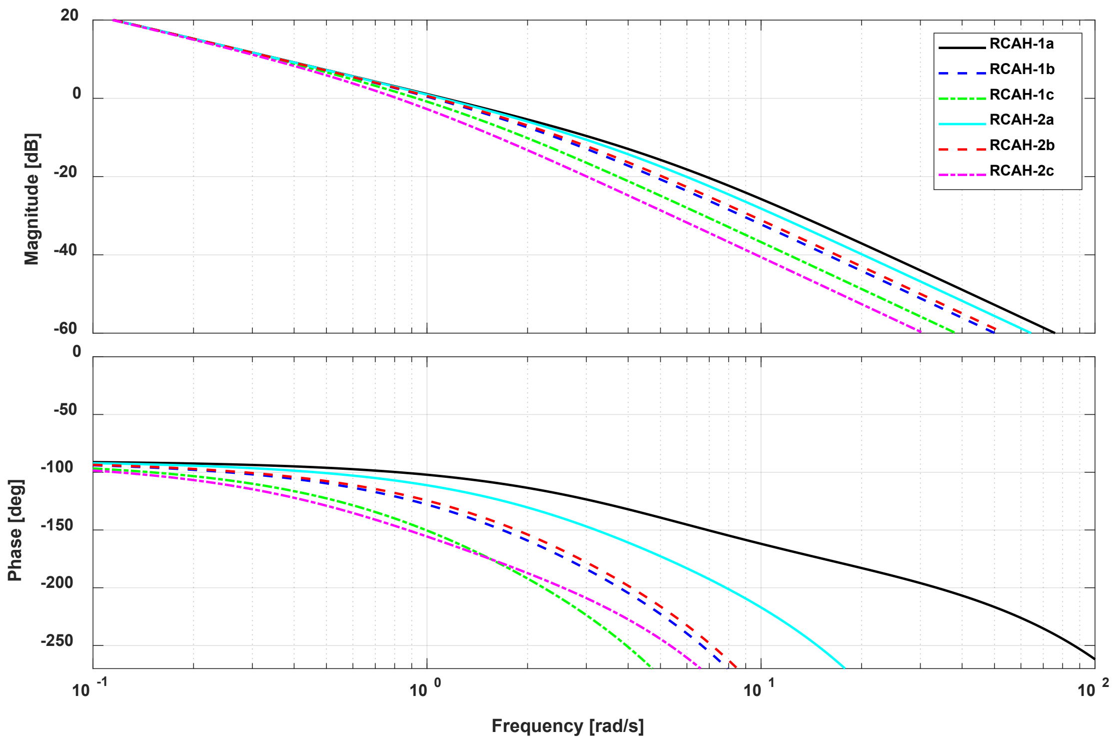

Figure 48. Roll axis frequency response Bode plot – RCAH

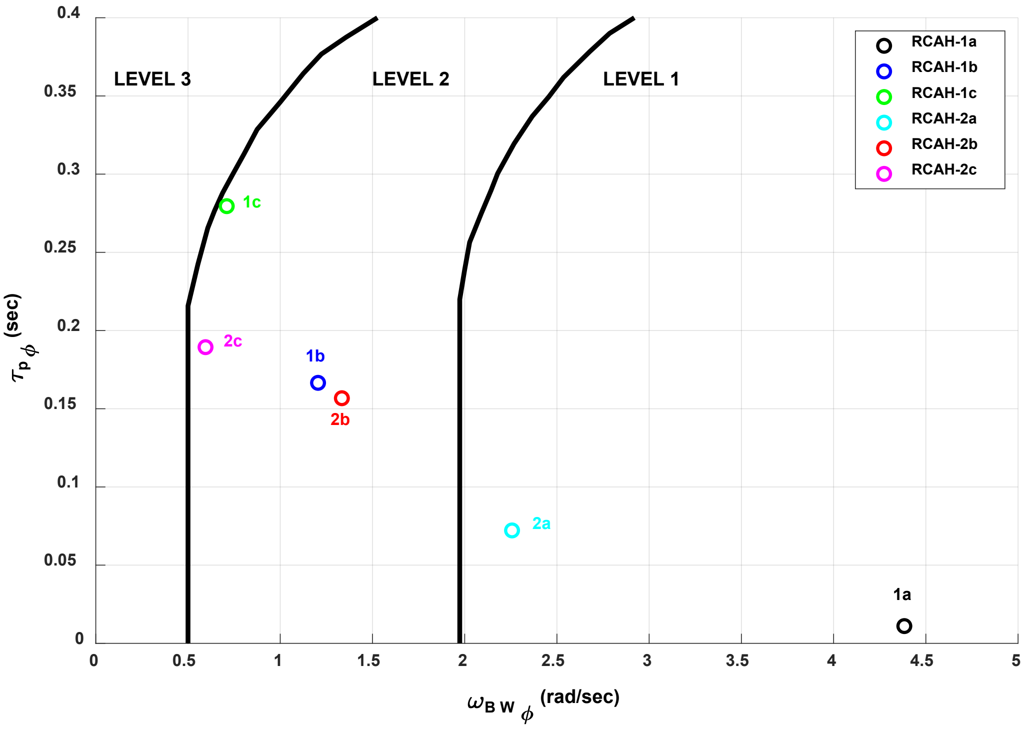

Figure 49. Requirements for small-amplitude roll attitude changes – RCAH

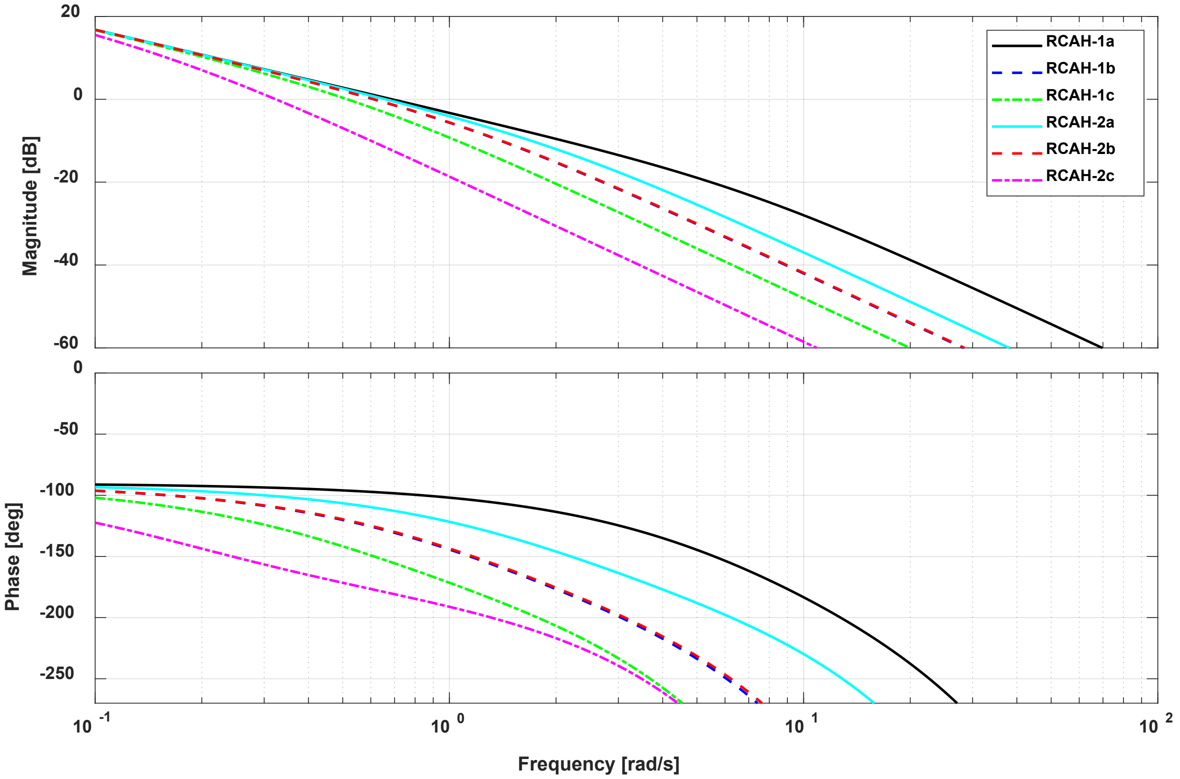

Figure 50. Pitch axis frequency response Bode plot – RCAH

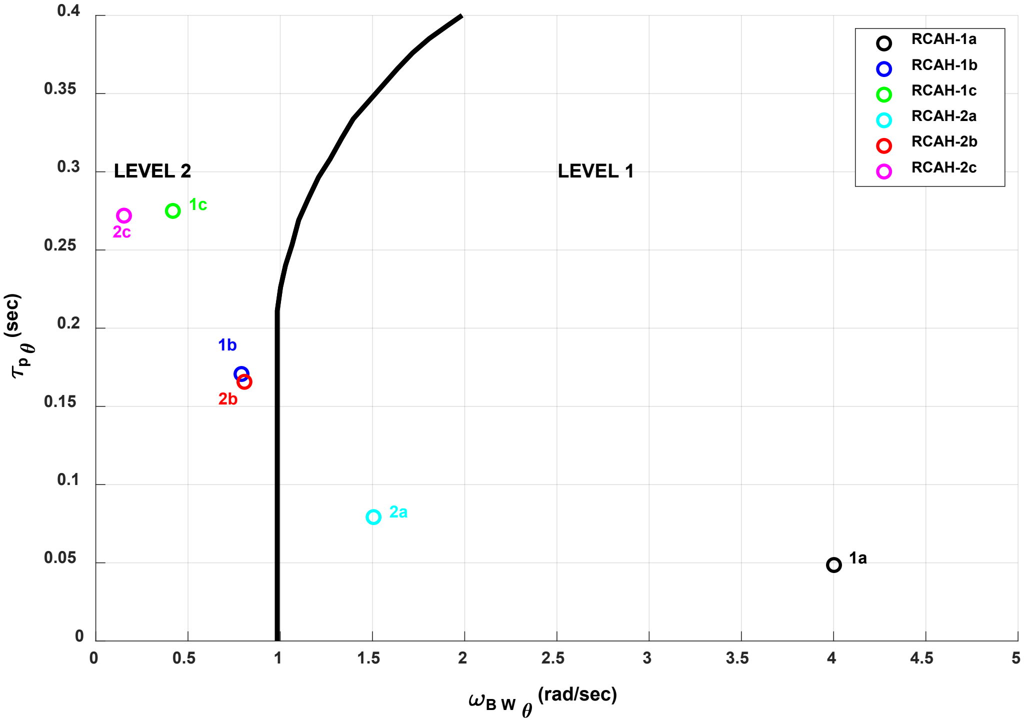

Figure 51. Requirements for small-amplitude pitch attitude changes – RCAH

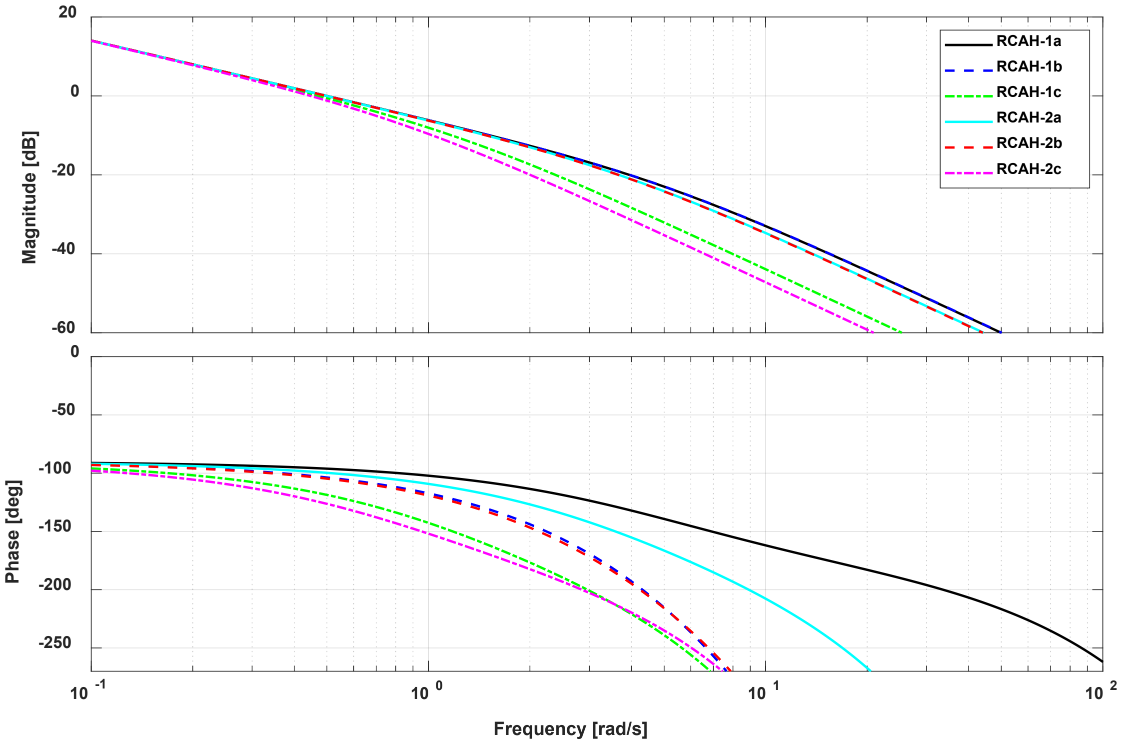

Figure 52. Directional axis frequency response Bode plot – RCAH

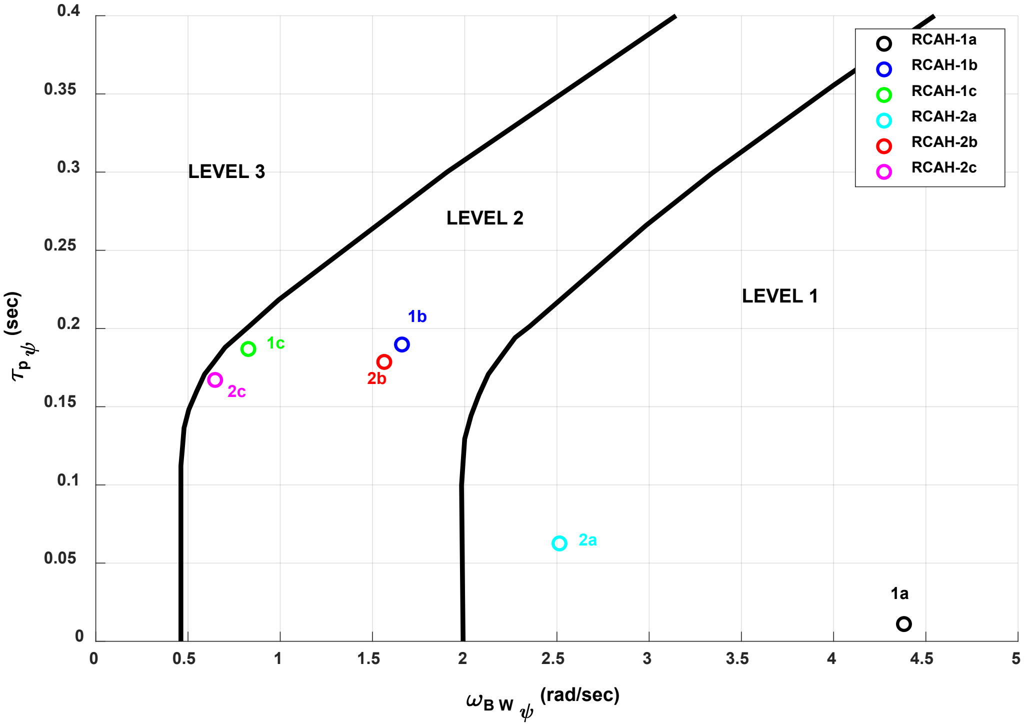

Figure 53. Requirements for small-amplitude heading changes – RCAH

Table 10. RCAH Configuration Parameters

Configuration	**Axis**	**Bandwidth (rad/sec)**	**Phase Delay (sec)**
1a	roll	4.383	0.011
1a	pitch	4.002	0.049
1a	yaw	4.381	0.011
1b	roll	1.205	0.167
1b	pitch	0.790	0.171
1b	yaw	1.660	0.190
1c	roll	0.710	0.280
1c	pitch	0.418	0.275
1c	yaw	0.827	0.187
2a	roll	2.257	0.072
2a	pitch	1.506	0.079
2a	yaw	2.514	0.063
2b	roll	1.334	0.157
2b	pitch	0.806	0.166
2b	yaw	1.564	0.179
2c	roll	0.595	0.189
2c	pitch	0.153	0.272
2c	yaw	0.647	0.167

C.5.2 ACAH – Attitude Command Attitude Hold

Figure 54 and Figure 56 show the bode plots for roll, and pitch, respectively, for ACAH mode. The drop-offs seen in the magnitude subplot reflect the change in bandwidth frequencies. Additionally, the lower frequency phase roll-offs in the phase subplot are indicative of increasing phase delay. Figure 55 and Figure 57 show the requirements for small-amplitude changes in roll and pitch, respectively, for ACAH mode. The ACAH configuration handling qualities follow the same scheme as those from the RCAH mode. Configuration 1a represents the best configuration, as it is highly responsive, whereas 2c indicates the worst. Table 11 shows the ACAH configuration parameters.

Note: The ACAH 1b and 1c lateral configurations do not have matching longitudinal configurations. Longitudinal configurations 2a and 2b correspond, instead, to lateral configurations 1b and 1c, respectively. Additionally, ACAH does not have any heading configurations, as the heading configurations remain rate-based.

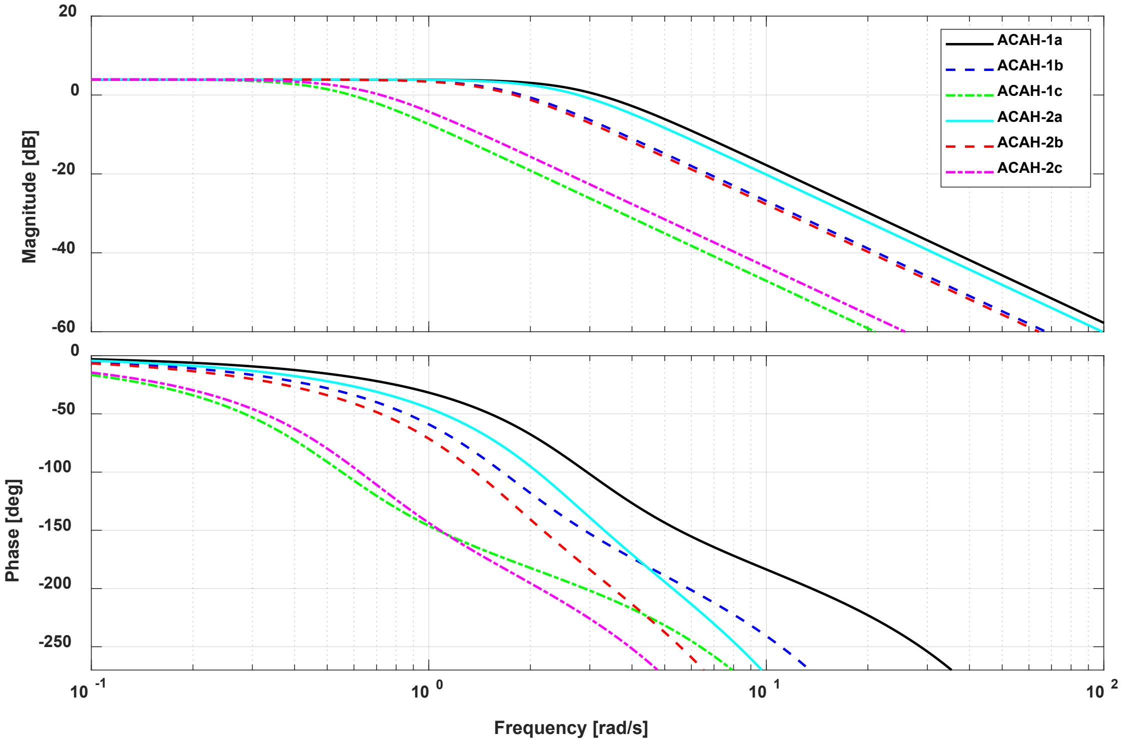

Figure 54. Roll axis frequency response Bode plot – ACAH

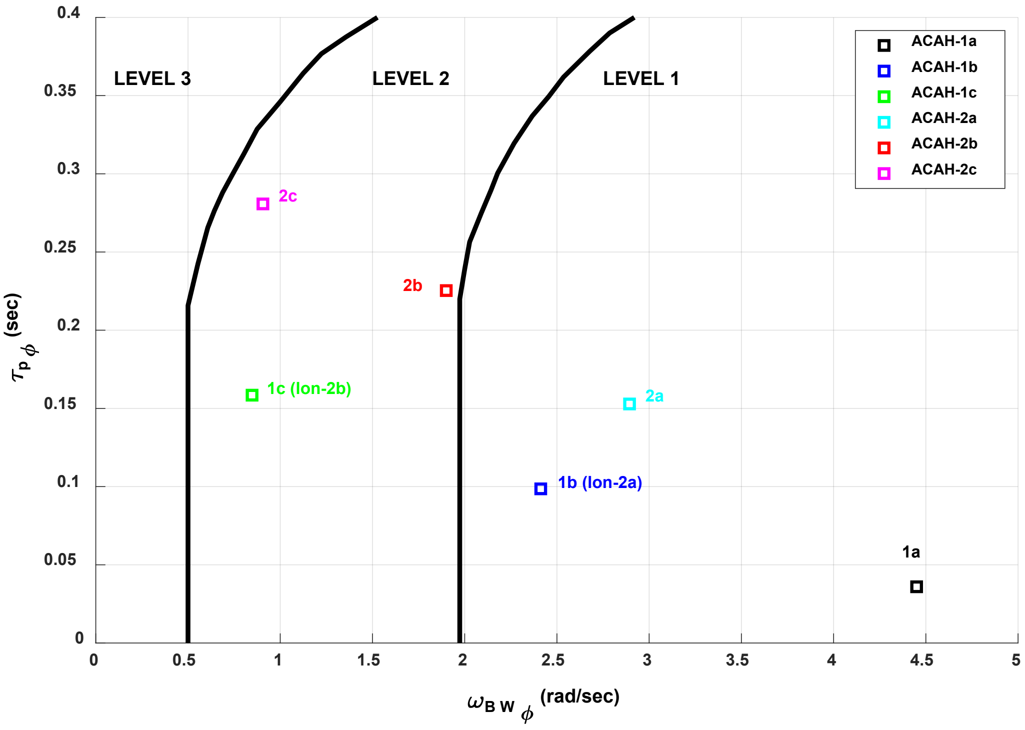

Figure 55. Requirements for small-amplitude roll attitude changes – ACAH

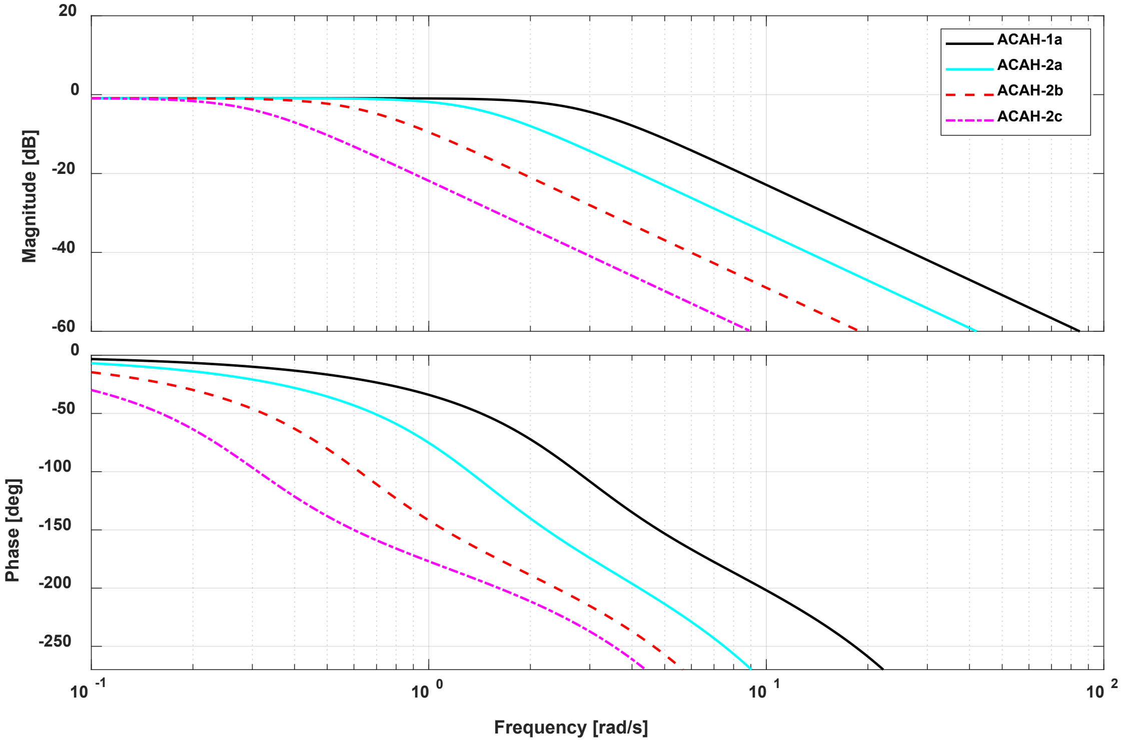

Figure 56. Pitch axis frequency response Bode plot – ACAH

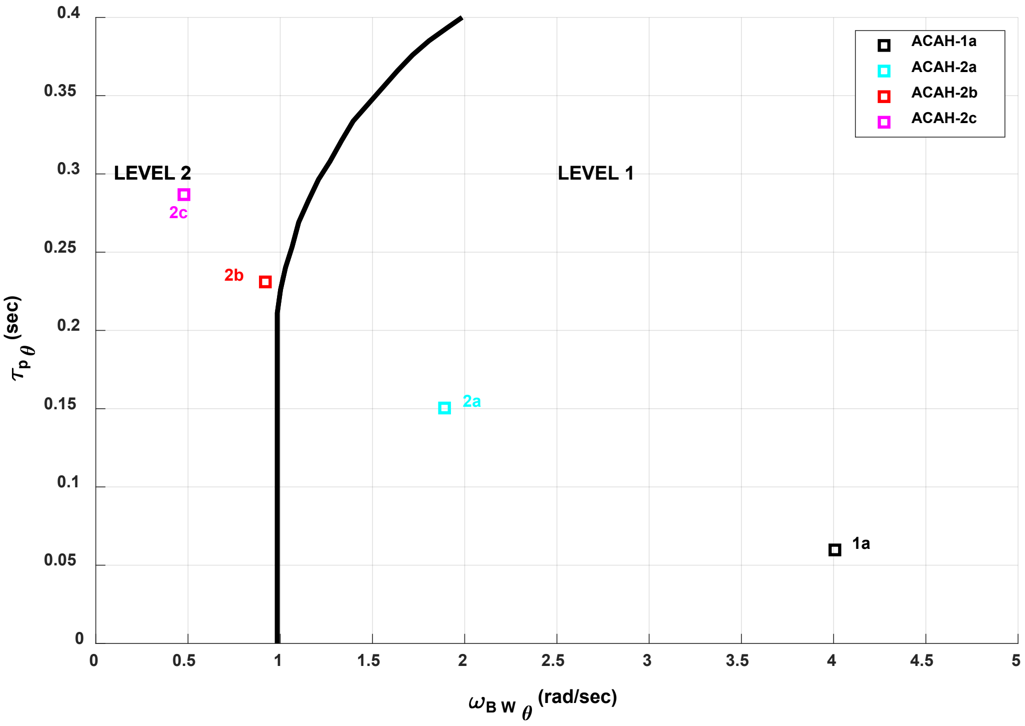

Figure 57. Requirements for small-amplitude pitch attitude changes – ACAH

Table 11. ACAH Configuration Parameters

Configuration	Axis	Bandwidth (rad/sec)	Phase Delay (sec)
1a	roll	4.450	0.036
1a	pitch	4.007	0.060
1b	roll	2.412	0.099
1c	roll	0.847	0.158
2a	roll	2.894	0.153
2a	pitch	1.891	0.150
2b	roll	1.900	0.225
2b	pitch	0.919	0.231
2c	roll	0.906	0.281
2c	pitch	0.478	0.287

C.6 References

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