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# Handling Qualities Test Guide for Powered Lift VTOL Capable Aircraft with Indirect Flight Controls and Operating in Day Time Visual Flight Rules

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Final Report

U.S. Department of Transportation
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16. Abstract

Decades ago, the U.S. Army introduced an *Aeronautical Design Standard* that defined *Handling Qualities Requirements for Military Rotorcraft*, ADS-33E-PRF in its most recent incarnation and now superseded by MIL-DTL-32742(AR), which introduced a mission-oriented approach that featured a catalog of flight test maneuvers (FTMs) or mission task elements (MTEs). These flight test maneuvers, when executed by at least three test pilot evaluators, provide assigned levels of handling qualities using the well-established Cooper-Harper Handling Qualities Rating Scale. Later, a comprehensive flight test guide was created to layout the procedures and test methods needed to generate the required data to evaluate a given design against the quantitative requirements included in the design standard. Building upon this approach, selected FTMs/MTEs will be used along with other supporting data as means of compliance (MOC) towards civilian type certification of the powered lift configurations designed for the emerging advanced air mobility (AAM) market. This includes the many designs envisioned for personal air vehicles, urban air taxis, and regional transit operations. The scope of this document is to guide users through the execution of the FTMs/MTEs as applicable to piloted aircraft operating under daytime visual flight rules that will yield a successful evaluation of aircraft handling qualities. Further guidance is provided for the generation of test data that can ultimately be used to assess designs against industry standard criteria though the focus here remains on generating the data. Finally, the appendices include an example test plan template for conducting FTM/MTE flight tests and a catalog of FTMs/MTEs with the understanding that the catalog will undergo revisions and additions based upon ongoing and further research that will likely include flight test demonstrations.

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## Contents

## Figures

## Tables

## Acronyms

| **Acronym** | **Definition** |
|---|---|
| AAM | Advanced Air Mobility |
| ACAH | Attitude Command Attitude Hold |
| ACVH | Acceleration Command Velocity Hold |
| ADI | Attitude Direction Indicator |
| AFM | Airplane Flight Manual |
| AIR | FAA Aircraft Certification Service |
| ANSP | Aircraft Network Security Program |
| AQTE | Automation Qualities Task Element |
| ASTM | American Society for Testing and Materials |
| CLAWS | Control LAWS |
| CG | Center of Gravity |
| CONOPS | Concept of Operations |
| DAS | Data Acquisition System |
| DER | Designated Engineering Representatives |
| DVE | Degraded Visual Environment |
| eVTOL | electric Vertical Takeoff and Landing |
| FAA | Federal Aviation Administration |
| FC | Failure Condition |
| FCS | Flight Control System |
| FE | Flight Envelope |
| FQ | Flying Qualities |
| FQA | Flying Qualities Assessment |
| FTM | Flight Test Maneuver |
| GPS | Global Positioning System |
| GVE | Good Visual Environment |
| GW | Gross Weight |
| HMI | Human-Machine Interface |
| HOTL | Human-On-The-Loop |
| HOVTL | Human-Over-The-Loop |
| HQ | Handling Qualities |
| HQR | Handling Qualities Rating |

| | |
|---|---|
| HQTE | Handling Qualities Task Element |
| HWTL | Human-Within-The-Loop |
| IFR | Instrument Flight Rules |
| IMC | Instrument Meteorological Conditions |
| KIO | Knock-It-Off |
| MOC | Means Of Compliance |
| MTE | Mission Task Element |
| NASA | National Aeronautics and Space Administration |
| NATO | North Atlantic Treaty Organization |
| PAO | Pilot-Assisted Oscillation |
| PF | Pilot Flying |
| PIO | Pilot-Induced Oscillation |
| PIOR | Pilot-Induced Oscillation Rating |
| PNF | Pilot Not Flying |
| PTI | Programmed Test Inputs |
| RCAH | Rate Command Attitude Hold |
| RPM | Revolutions Per Minute |
| SAS | Stability Augmentation System |
| SWB | Symmetric Wing Beam |
| SWC | Symmetric Wing Chord |
| SNR | Signal to Noise Ratio |
| SQA | System Qualities Assessments |
| SVO | Simplified Vehicle Operations |
| TIA | Type Certification Authorization |
| TM | TeleMetry |
| TRC | Translational Rate Command |
| UAM | Urban Air Mobility |
| UML | UAM Maturity Level |
| VFR | Visual Flight Rules |
| VMC | Visual Meteorological Conditions |
| VTOL | Vertical Takeoff and Landing |

# Glossary

| **Term** | **Definition** |
|---|---|
| Adverse Aircraft-Pilot Coupling | A coupling of aircraft response to pilot input through either biomechanical feedback or pilot-induced oscillation, or a combination of the two that results in degraded handling qualities. |
| Aeroelastic | The interactions between the inertial, elastic, and aerodynamic forces occurring when an elastic structure is exposed to an aerodynamic flow. |
| Aeroservoelastic | The interaction between an aeroelastic phenomenon and the flight control system, which may include adverse aircraft-pilot coupling. |
| Augmented | A vehicle response that reflects changes from the bare airframe dynamics to improve stability, speed of response, mode of response, etc., typically achieved through an indirect control system. |
| Automated | A flight mode that controls an aspect of vehicle flightpath without pilot intervention such as hold modes (altitude, attitude, heading, speed), landing approach, altitude changes, heading changes, etc. This automation is typically accessed by the pilot through a flight management system. |
| Automation Qualities Task Elements | Autonomously flown maneuvers to evaluate the performance of automation via quantified assessment of task performance. |
| Direct Flight Control | Aircraft response generated by pilot movement of the control inceptors through a physical connection to the control surfaces. |
| Flying Qualities | The stability and control characteristics that have an important bearing on the safety of flight and on the pilots’ impressions of the ease of flying the aircraft in steady flight and in maneuvers. (Also referred to as “predicted handling qualities.”) |
| Flying Qualities Assessments | Open-loop and controllability demonstrations that are designed to characterize vehicle flying qualities. |
| Good Visual Environment | For ground-referenced operations, this is clear daylight with good out-the-window cueing and unaided vision. |
| Handling Qualities | 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 the air vehicle’s role. (Also referred to as “assigned handling qualities.”) |
| Handling Qualities Task Element | Closed-loop piloted tasks that are designed to evaluate handling qualities and uncover handling qualities cliffs if they exist. |
| Human-within-the-Loop (HWTL) | The pilot is always in direct control of the automation (systems). (Also referred to as “pilot-in-control”) |

| | |
|---|---|
| Human-on-the-Loop (HOTL) | The pilot has supervisory control of the automation (systems) and can take full control when required or if desired. (Also referred to as “pilot-on-controls”) |
| Human-over-the-Loop (HOVTL) | The pilot is “informed or engaged by the automation (systems) to take action.” Furthermore, the pilot passively monitors the systems and is “informed by the automation if and what action is required.” Finally, the pilot is “engaged by the automation either for exceptions that are not reconcilable or as part of rule set escalation. |
| Indirect Flight Control | Aircraft response generated by pilot movement of the control inceptors through a flight control computer or other means that then drives the actuation of the control surfaces. |
| Mission Task Element | As adapted from ADS-33E-PRF, March 2000, these are flight test maneuvers that provide a basis for an overall assessment of the aircraft’s ability to safely perform its intended functions. |
| Pilot-Induced Oscillation | Unintentional sustained or uncontrollable oscillations resulting from pilot efforts to control the aircraft where aircraft response that is being controlled by the pilot is approximately 180 degrees out of phase with pilot inputs. |
| Pilot-Assisted Oscillation | An adverse coupling of aircraft response to pilot input through biomechanical feedback. |
| Response-Type | A characterization of the vehicle response to command inputs with respect to augmentation that include, but are not limited to, the following examples: Rate Command Attitude Hold (RCAH), Attitude Command Attitude Hold (ACAH), Translational Rate Command (TRC), and Acceleration Command Velocity Hold (ACVH). |
| System Qualities Assessments | Flight test methods that provide the data required to evaluate indirect flight control systems. |

## Executive summary

This research project is part of a portfolio of research sponsored by AIR 714 of the FAA's Aircraft Certification Service. This report documents one of three specific projects developed to address gaps in means of compliance for fly-by-wire aircraft. The projects leveraged FAA civilian certification experience with fly-by-wire special conditions for Part 25 Airplanes as well as military experience with evaluating handling qualities of fly-by-wire helicopters (see ADS-33E-PRF, now MIL-DTL-32742(AR)). The guidelines for the three projects were to adapt ADS-33E-PRF style maneuvers ("Mission Task Elements or MTEs") to civilian aircraft and civilian missions. In addition, consider how best practices could be adapted from some military procurement specifications for design guidelines that yield suitable handling qualities.

The research teams were tasked with developing a catalog of maneuvers and a consistent process that can be used to systematically evaluate fly-by-wire airplanes and powered lift aircraft with integrated flight and propulsion control. The maneuvers should map to regulatory criteria of stability, controllability, maneuverability, and trim. The maneuvers should stress test the pilot's ability to smoothly transition between flight conditions and sources of lift without exceptional skill strength or alertness. These maneuvers do not need to be operationally representative and should reveal any latent design deficiencies and handling quality deficiencies.

Furthermore, the maneuvers should focus on transitions. For example, some transitions include response type changes (i.e. inceptor input to effector output discontinuities) and fly-by-wire sensor input switching (such as weight on/off skids or air data inputs vs inertial inputs.) Historically, fly-by-wire accidents have been caused by integrator wind-ups and other non-linear events where the pilot is surprised by the output of the flight control system. Another example of non-linear vehicle response is the result of wind inputs (magnitude or azimuth changes) during thrust-borne to wing-born transition where the flight control modes are switching and have hysteresis. The maneuvers and process tools are necessary to supplement classical flight test techniques that do not work as a means of compliance for new and novel designs. For example, the static stability of conventional airplanes with reversible (non-fly-by-wire) flight controls is demonstrated by longitudinal control force when the airplane is displaced from trim. This technique for measuring and demonstrating static stability for compliance with 14 CFR rules may not apply to fly-by-wire flight control systems. Consequently, a different approach must be used.

The three FAA sponsored projects were performed by Adaptive Aerospace Group (AAG), Systems Technology Incorporated (STI), and NASA. The AAG report is titled "Development

and Evaluation of Mission Task Elements for Certification of Aircraft with Non-Conventional Control Interfaces”. The NASA report is titled “Evaluation of Novel V/STOL Aircraft Pilot Interface Concepts”. All three projects had slightly different focus areas but were common in developing a toolset for consistent FAA evaluation of new and novel civilian fly-by-wire designs. This report documents one of the three FAA sponsored projects, and the project herein is different from a typical simulator evaluation. The deliverable is the development of an approach to conduct certification flight tests for novel vehicles. This includes developing maneuvers, test courses, and performance criteria for vehicles that have different degrees of automation integration ranging from none to a remote pilot. Consequently, the data products for the final report are not the detailed comments about the vehicle under test, but the proposed tools and certification process.

The advent of new and disparate vehicle concepts for personal air vehicles, urban air mobility, and regional air mobility resulted in the need to facilitate more comprehensive and more rapid assessment of these vehicles under Part 21-16, Special Conditions. These vehicles may employ unique power designs that are hybrid or all electrical; utilize unique propulsion and indirect control designs that are hybridized; and employ highly augmented and automated flight control designs to support improved handling qualities. These designs are expected to provide increased stabilization and precision for 24-hour operations while still affording necessary agility, evolving toward Simplified Vehicle Operations (SVO) that reduce pilot training requirements and facilitate transition toward remotely piloted operations. It is anticipated that there will be greater reliance on simulation for design, and that valid simulation models may be used for certification credit to a much greater extent than any current designs, allowing for a reduction in flight test time and considerable cost savings. For these reasons, traditional assessment approaches may be invalid or require modification to suit each of the individual designs.

This report is intended to be used as Test Guide that aids the Determination of Compliance with Part 21-16. It documents steps to be taken to apply flight test techniques and software tools to produce quantitative system identification data for validated metrics, and application of well-established assessments of handling qualities capabilities via the use of Handling Qualities Task Elements (HQTEs). The HQTEs are defined to facilitate use of the Cooper-Harper Handling Qualities rating scale as a means to generate pilot comments and associated ratings. A test plan template for application of the tests described in this document is included as an appendix in this report. A catalog of possible HQTEs is also included as an additional appendix. The catalog is separated by required level of precision and aggressiveness that supports a natural build-up approach for flight test. This test guide is currently limited in application to powered lift VTOL-capable aircraft with indirect flight controls while operating in day time Visual Flight Rules.

# 1 Introduction

## 1.1 Purpose

Decades ago, the U.S. Army introduced an Aeronautical Design Standard that defined Handling Qualities Requirements for Military Rotorcraft, ADS-33E-PRF in its most recent incarnation (US Army, 2000) and now superseded by MIL-DTL-32742(AR) (U.S. Department of Defense, 2023), which introduced a mission-oriented approach that featured a catalog of flight test maneuvers (FTMs) or mission task elements (MTEs) depending on desired nomenclature. These flight test maneuvers when executed by at least three test pilot evaluators provide assigned levels of handling qualities using the Cooper-Harper Handling Qualities Rating Scale (Cooper & Harper, Jr., 1969). Later, a comprehensive flight test guide (Blanken, Hoh, Mitchell, & Key, 2008) was created to layout the procedures and test methods needed to generate the required data to evaluate a given design against the requirements (US Army, 2000). Building upon this approach, selected FTMs/MTEs are suggested to be used along with other supporting data as means of compliance (MOC) towards civilian type certification of the powered lift configurations designed for the emerging advanced air mobility (AAM) marketplace. This includes the many designs envisioned for personal air vehicles, urban air taxis, and regional transit operations. The scope of this document is to guide users through the execution of the FTMs/MTEs as applicable to piloted aircraft operating under daytime visual flight rules that will yield a successful evaluation of aircraft handling qualities. These maneuvers are envisioned to be performed during development with simulators and prototype flight test vehicles as well as during showing of compliance to civilian airworthiness criteria.

## 1.2 Overview

With the advent of new and disparate vehicle concepts for personal air vehicles, urban air mobility, and regional air mobility, there is a need to facilitate more comprehensive and more rapid assessment of these vehicles:

1. These vehicles may employ unique power designs that are hybrid or all electrical. They may likely utilize unique propulsion and indirect control designs. These vehicles may also employ highly augmented and automated flight control designs to support improved handling qualities. These highly augmented and automated designs are expected to evolve toward providing increased stabilization and precision for 24-hour operations while still affording necessary agility. Additionally, they are expected to evolve toward Simplified Vehicle Operations (SVO) that provide for reduced pilot training requirements

and facilitate transition toward remotely piloted operations. For these reasons, some of the more traditional assessment approaches may be invalid or require modification to suit each of the individual designs. This argues for more universal assessments of handling qualities capabilities via the use of quantitative system identification-based methods along with Handling Qualities Task Elements (HQTEs), which will be described later.

2. These vehicles will likely have to do repetitive constrained flight operations within tightly defined corridors and busy heliports and vertiports. This argues for the possible use of task specified HQTEs as has been defined by this team and the FAA in other work.
3. We anticipate the eventual adoption of vehicle-configuration-agnostic, frequency domain metrics for handling qualities prediction similar to those promulgated in ADS-33E-PRF (US Army, 2000). While this is a military standard for rotorcraft, it has also been applied in civilian designs throughout the Vertical Takeoff and Landing (VTOL) industry as well. This argues for the quantitative assessment of vehicles with frequency response test techniques. It is recognized that the civilian airworthiness requirements are much different than military design specification requirements but the fundamental techniques in ADS-33E-PRF can be useful in focusing specific FAA testing.
4. We anticipate the higher reliance on simulation for design of these vehicles which will likely rely on quantitative system identification methods of validation which is supported through frequency response test techniques. Valid simulation models may also be used for certification to a much greater extent than any current designs, allowing for a possible reduction in flight test time and considerable cost savings, though what constitutes a “valid” simulation remains illusive as industry groups work to address the issue.
5. We anticipate the use of software tools that reduce quantitative system identification data and validated metrics to aid in optimization of vehicle designs for improved handling qualities.

## 1.3 Holistic approach (intent of this test guide)

### 1.3.1 Civil certification and the Flight Test Maneuver/Mission Task Element concept

Certification of civil aircraft in the United States is a joint effort between the FAA and the aircraft designer or a designated representative. Once an application for Type Certification is submitted, the designer or representative becomes the “applicant” and the responsible office for the FAA is the Aircraft Certification Service (AIR). The Type Certification process follows procedures in FAA Order 8110.4C (Federal Aviation Adminsitration, 2017), and policies stated in 14 CFR Part 21. Initially, the FAA will review and approve the applicant's Certification Plan.

With the increased use of fly-by-wire technology – common in the military world but seldom used in civil aircraft, especially in small airplanes and helicopters – the possibilities for novel control-response modes, enhanced augmentation and automation to reduce pilot workload, and eventually, fully autonomous flight, are almost infinite. A more formalized set of methods and means of compliance is required to deal with advanced aircraft. In reality, such a formalized set of certification standards will benefit the designer as well, as it will clarify the process to be followed to obtain type certification.

One process under consideration for civil certification is the use of FTMs/MTEs (Klyde, et al., 2020). These are common in military research, development, and evaluation, but are a relatively new concept in the civil world. The FTM/MTE concept was originally introduced in the Aeronautical Design Standard (US Army, 2000) and its predecessors for rotorcraft; here, an FTM/MTE is defined as "An element of a mission that can be treated as a handling qualities task." It is a tightly defined short-look task that includes clearly stated objectives, task description, and requirements for performance. The structure of the FTM/MTE assists the pilot flying to provide comments about controllability; required pilot workload and compensation; and ease and precision of task performance to assess overall handling qualities using rating scales such as the 10-point Cooper-Harper rating scale (Cooper & Harper, Jr., 1969). Not surprisingly, there is considerable discussion about the role of such a process in civil certification. The addition of fly-by-wire technology and advanced multi-axis lift/thrust/control mechanizations, with the promise of increased autonomy, makes it clear that a more systematic approach to testing for certification is needed.

While there are obvious advantages to using formal FTMs/MTEs for evaluating aircraft handling qualities, the primary goal of the FAA is airworthiness, and handling qualities are but a very small part of the overall certification process. Work is ongoing to define a more general certification structure that uses the intent of the FTM/MTE, but that expands on its application. Figure 1 illustrates[1] an evolving holistic approach for certification of these aircraft including system qualities assessments, flying qualities assessments, handling qualities task elements, and automation qualities task elements. This approach recognizes that flying qualities assessments are well-defined in current certification test methodologies but need to be augmented and better

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[1] Note that while only MTEs are called out in the Figure, it is understood that the FTM term also applies. TC = Type Certification and TIA = Type Inspection Authorization.

integrated within this new approach that utilizes design and simulation efforts throughout the process. Specifically, four sets of FTMs/MTEs (i.e., SQA, FQA, HQTE, and AQTE) are under development that may be applied beginning in analysis, through simulation, and into flight test. These are defined below starting in Section 1.3.1.1.

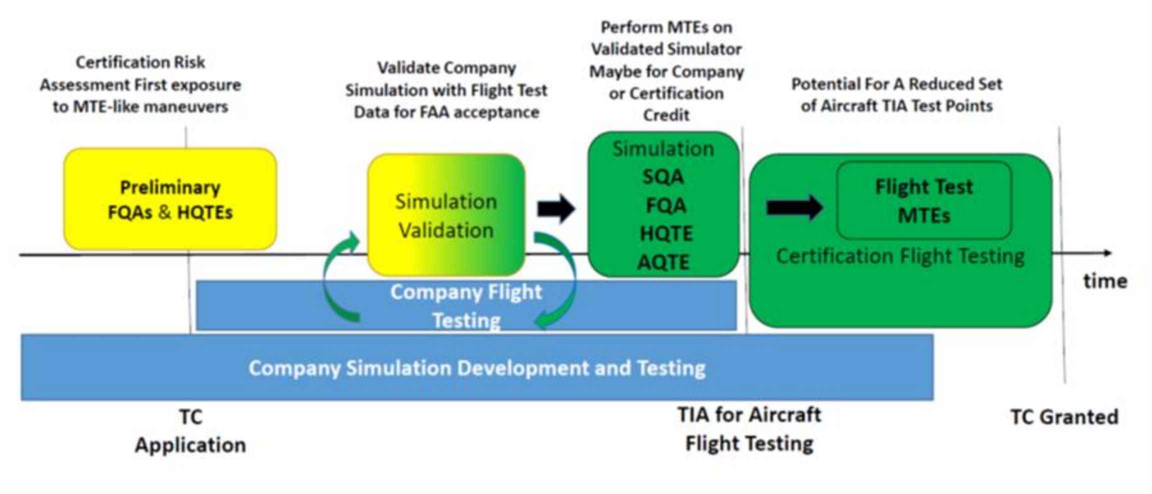


Figure 1. Notional FTM/MTE use throughout the certification process

Figure 2 shows a schematic of the progression in assessment methodology as certification efforts move from human within-the-loop (HWTL) systems to human-over-the-loop (HOVTL), see Glossary for term definitions. These are considered only as broad estimations of how the assessment will change. For HWTL systems, pilot feedback is considered key, usually collected through subjective opinion. Objective assessment of the performance is also considered to determine whether the vehicle handling qualities are suitable. Ride qualities are also important as poor characteristics can lead to perceived poor handling qualities. As automation increases, objective performance assessment is expected to become more important, while the pilot feedback plays less of a role. The trust in automation starts to become important as does the feedback from the operator or occupant. As vehicles become fully autonomous (HOVTL), performance assessment, ride qualities, automation trust, and operator feedback are important, and the feedback of the “pilot” is no longer required.

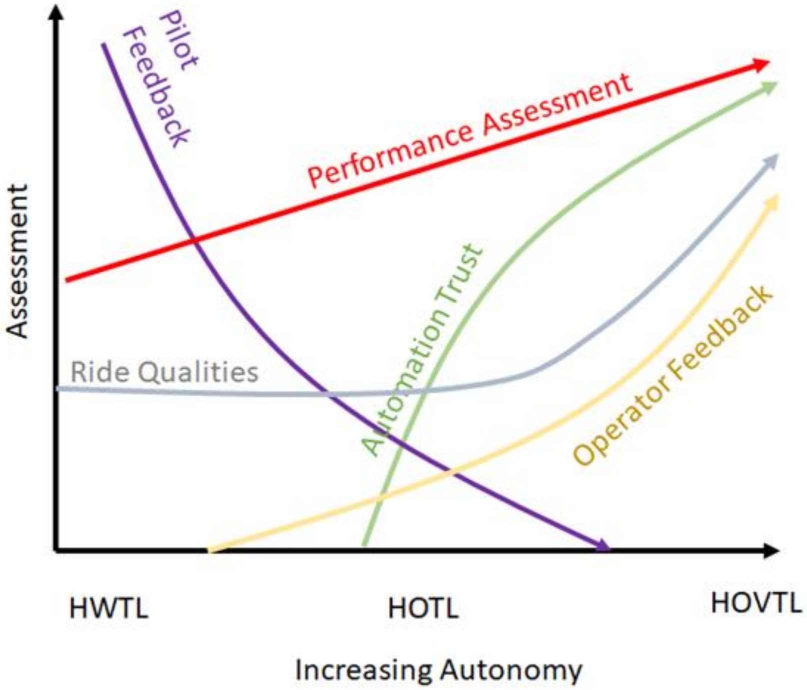


Figure 2. Schematic of expected trend in assessment methods with increasing autonomy

Figure 3 shows the progression of handling qualities demonstrations expected due to increasing autonomy. Currently, there is wide agreement in the community that the first electric Vertical Takeoff and Landing (eVTOL) vehicles to achieve certification and 'entry to service' will likely be piloted, with HWTL concepts, and this is therefore the focus of the guidance material included herein. In this situation, a combination of HQTEs, systems qualities assessments (SQAs), and flying qualities assessments (FQAs) is required. As autonomy increases, the proportion of HQTEs will reduce, as the human pilot is no longer required to "fly" the vehicle in certain conditions. The pilot may be required to "operate" the vehicle, however, and the handling qualities in these situations should be demonstrated using automation qualities task elements (AQTEs). In addition, as the use of autonomy increases, SQAs are expected to increase, due to increased systems and functions. As the technology progresses and the human is no longer controlling the flightpath of the vehicle, only AQTEs are required with the importance of SQAs further magnified.

The holistic approach will account for this progression in increasing autonomy. Simulation is expected to play a critical role in the certification process of AAM. The use of simulation is likely to be more prominent as compared to traditional aircraft certification. Using simulation is expected to in many cases offset some of the requirements for flight testing, either through the reduction in required test condition matrices or eliminating the need for specific testing. It is expected that validated simulators may be used to identify the critical non-high-risk conditions that will be verified in actual flight test. The following subsections define SQAs, FQAs, HQTEs, and AQTEs.

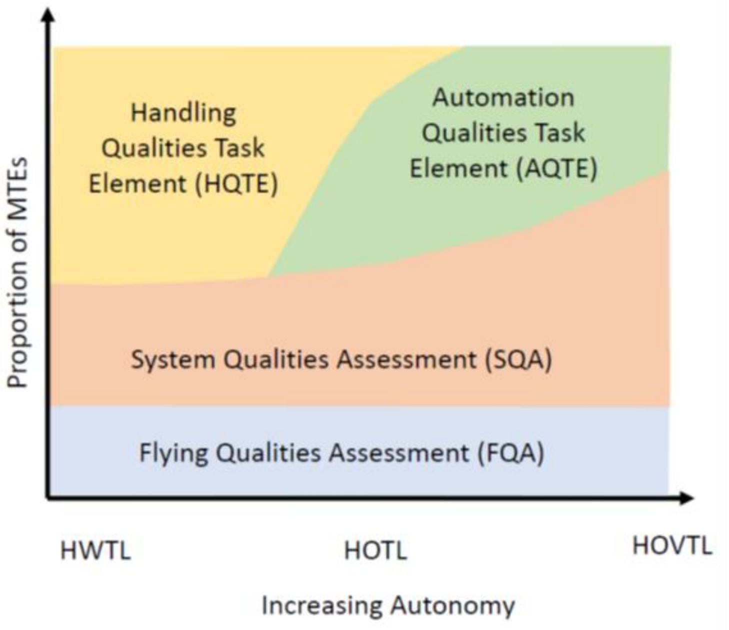


Figure 3. Progression of HQ assessments with respect to automation

### *1.3.1.1 System Qualities Assessments (SQAs)*

System Qualities Assessments (SQAs) are flight test methods that provide the data required to evaluate indirect flight control systems (FCS). SQAs are used to determine system stability, stability margins, and other measures of system performance, as well as predictive measures of flying qualities and handling qualities. Further, SQAs are used for system identification to support modeling and simulation. Examples include stick raps, steps, doublets, 2-1-1, 3-2-1-1, frequency sweeps, multi-sines, and dwells. SQAs are the subject of Section 2 of this Test Guide.

### *1.3.1.2 Flying Qualities Assessments (FQAs)*

FQAs identify characteristics of the aircraft from open-loop demonstrations and controllability demonstrations. These assessment methods will be similar to, and in some cases the same as, present-day certification tests. There are ongoing efforts to revise these methods, if needed, for indirect flight control designs for means of compliance testing. Examples of open-loop demonstrations include Steady Heading Sideslip, Dynamic Stability, Maneuver Stability, Time-to-Bank, Stall characteristics and speed, Wind-up Turn (stick force per g), and Attitude

Quickness. Examples of controllability demonstrations include Stall Recovery, Critical Azimuth, Envelope Protection, Control Margin, and Low Power Margin.

#### *1.3.1.3 Handling Qualities Task Elements (HQTEs)*

HQTEs are the subset of FTMs/MTEs as described above, involving the applications of closed-loop tasks and piloted evaluation using scales such as the Cooper-Harper rating scale. The applications of HQTEs in the certification means of compliance process is described further in Klyde et al. (2020). The HQTE is a critical feature of this test guide. Reflecting this importance, the definition provided here reflects the consensus definition developed by the eVTOL HQ MOC Advisory Committee of the Vertical Flight Society's eVTOL Flight Test Council.

HQTEs are pilot closed-loop tests intended to assess an aircraft's handling qualities. These tests may be tailored to the aircraft or operationally relevant tasks or conditions, using engineered maneuver constraints and tolerances that stress the pilot-vehicle integrated design.

HQTE testing will assign Handling Qualities (HQ) levels with associated pilot comments towards the goal of:

- Assuring safe operations within the aircraft flight envelope (FE), both on-ground and in-flight.
- Identifying handling qualities deficiencies, pilot-induced oscillations (PIO) susceptibility, Human Machine Interface (HMI) deficiencies, or other hazardous flight control characteristics.
- Assuring the intended operations can be accomplished without requiring exceptional piloting skill, alertness, or strength.

While potentially linking acceptable HQ levels to the following conditions, the HQTE matrix should account for:

- Flight conditions: flight envelope, environmental conditions, and configuration, including transition (across flight modes, response-types, reference frames, vehicle configurations).
- State: normal conditions and failure conditions not shown to be extremely improbable. Conditions include propulsive and non-propulsive flight control failures that reduce capability or degraded handling qualities.
- Settings: selectable flight controls modes (e.g., normal, training, backup/reversionary).

HQTEs involve the application of standardized closed-loop tasks and piloted evaluation using the Cooper-Harper Handling Qualities Rating Scale. The applications of HQTEs in the certification means of compliance process is described further in Klyde et al. (2020) and will be described in detail in section 5 of this test guide. HQTEs are expected to be executed within the controllability limits as described by the FE. In this context HQTEs are based on the premise that all missions anticipated for the aircraft are assumed to be capable of being accomplished within the FE. It is not uncommon to then further constrain the FE based on HQTE findings, for instance in the identification of PIO, handling qualities cliffs (i.e., those deficiencies that can lead to loss of pilot-vehicle system control), and/or significant non-linear behavior. A catalog of HQTEs is provided in Appendix B.

HQTEs are:

- Necessary, but not sufficient for demonstrating means of compliance.
- Related and sometimes directly derived from the MTEs found in military use such as ADS-33E-PRF or elsewhere, but they are adapted here for the civilian concept of operations.
- Intended in this Test Guide for VTOL aircraft that feature distributed propulsion.
- Focused on transitions (see list in Section 5) that may contribute to fly-by-wire mishaps or were shown to be causal in past accidents.

#### *1.3.1.4 Automation Qualities Task Elements (AQTEs)*

With unprecedented layers of automation, the urban air mobility (UAM) vehicles of the future will require special test methods beyond those used in a typical certification program today. The task descriptions will be equivalent to HQTEs, only an autonomous system will conduct the task (perhaps with a pilot observer) and outcomes will be quantitative, based on task performance, demands on the system, and, if appropriate, measures of ride qualities. AQTEs will cover at least the following:

1. Safe operation in a high-traffic-density environment;
2. Ability to detect and avoid traffic, and divert to an alternate landing site as necessary;
3. Communicate with other aircraft and air traffic control authorities;
4. Recover from, and adapt to handle, in-flight emergencies; and
5. Operate the aircraft in a predictable manner.

## 1.4 Extension of MTEs to civil certification testing

In attempting to extend the FTM/MTE concept to civil certification testing, there are important distinctions to be drawn from military applications. They include the following:

1. By the time a military aircraft is modeled in a ground-based simulator, it is likely a single acquisition from a supplier under contract to the government. The focus, then, is not on whether the aircraft will be commercially viable, but whether it is going to be suitable for its intended mission(s). In the civil world, it is possible that no money has changed hands prior to FAA certification, as the burden is on the developer to demonstrate a commercially viable and attractive product. The concern is thus not specifically on demonstrating desired handling qualities, but on commercial appeal.
2. Certification by the FAA of a new aircraft design is meant to confirm that it is airworthy and safe, not that it will meet the needs of its intended customers. Handling qualities testing of a military aircraft certainly includes safety and airworthiness, but more than that, it includes confirmation that pilot workload and required compensation are sufficiently low that the properly-trained pilot can operate the aircraft as intended. When a military design fails to meet the needs of its intended customers – or more commonly, as customer requirements change between initial contract award and operational deployment – it is not uncommon to find the missions of that aircraft modified to match its capabilities, rather than find a different aircraft to perform the desired mission tasks.
3. Failure to perform an FTM/MTE to a defined level in a military aircraft will not result in cancellation of the program, but rather a negotiation between the developer and the government buyer to determine whether the reduced performance is tolerable or if changes are required. On the other hand, failure to meet even a single FAA requirement means the aircraft will not be certified, and the designer must change something to generate the desired outcome, which is type certification.
4. The final arbiter for military aircraft is the government; the final arbiter for civil aircraft is the end user, which may include newer pilots with limited flight hours or experienced airline pilots. Even if the military aircraft has some shortcomings, it is, more often than not, still purchased in quantity, and workarounds or operational fixes are devised as needed. If the civil aircraft has shortcomings, sales will suffer. Thus, it is incumbent on the builder of the civil aircraft to make it safe and airworthy, and then to make it attractive to a commercial market.

## 1.5 Restrictions to scope

This guide provides a first step toward addressing the evolving requirements for HQ assessment of these new concept vehicles and is expected to be a foundation for expanded scope later. This initial step is estimated to support Urban Air Mobility Level 2 (UML-2) requirements as outlined in Goodrich & Theodore (2021).

*Note:* The UAM Maturity Level (UML) is used here as an example only for the Concept of Operations and would not be prescriptive in determining certification requirements. It is quite likely that aircraft automation and complexity of operations may evolve at different rates within the various applicant designs and therefore the impacts to HQTE selection would be adjusted accordingly.

The techniques for certification of UML-2 operations here will be supportive of the higher certification requirements of UML-3, albeit with different criteria or environmental constraints applied. The UML aircraft state is illustrated in Figure 4 (Goodrich & Theodore, 2021) and summarized below:

> The aircraft at UML2 will be piloted by a trained pilot in visual flight rules (VFR) conditions. The Service Provider, Aircraft Network Security Program (ANSP), and Supplemental Data Providers will coordinate and advise the pilot through communications/datalinks but not be integrated into aircraft automation. Pilot-controlled automation is contained within the aircraft. Given that the configurations considered herein are likely to be both unstable and over-actuated, at least in powered-lift flight, relatively sophisticated, high-authority flight control systems will likely be needed to assist pilots flying the aircraft in achieving the required levels of safety, performance, and robustness. Also, aircraft power and energy management systems will likely require relatively sophisticated automation. Beyond control and power management systems, it is not expected that higher levels of aircraft automation would be necessary for low density and low complexity VFR operations, and the vehicles may have relatively minimal automation beyond these basic control and management systems to limit initial certification costs, risks, and delays. The augmentation and automation in this regard is therefore considered “assistive.”

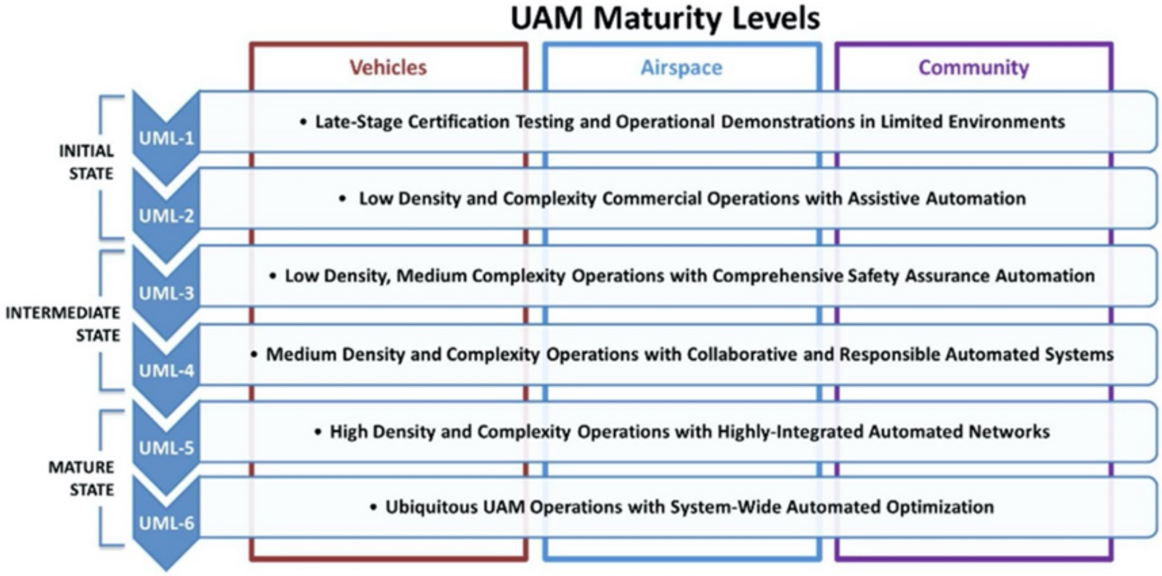


Figure 4. Definition of UAM maturity levels

Specific initial restrictions to scope for this test guide include:

1. VFR flight only
2. Planned operations to heliports under air carrier guidelines. In this context, vertiport guidelines have yet to be established. These vehicles, in operational context, are viewed as distributed air carriers in that many smaller vehicles are anticipated to replace larger traditional helicopter air carriers.
3. Initial operations will be constrained to existing air infrastructure but evaluated toward an evolving UAM corridor concept.
4. This guide will focus on adapting HQ flight test techniques, as embodied in documents supporting certification of these vehicles using general quantitative frequency response techniques as well as qualitative HQTE (US Army, 2000; Blanken, Hoh, Mitchell, & Key, 2008). The guide will not focus on the specific quantitative performance specification handling qualities requirements, but it assumes that use of these requirements for FAA certification as part of a means of compliance package will later evolve, and that the general techniques addressed here will be supportive of these specific evaluation requirements. Proposed HQTE tolerances will be based on the anticipated predictive metrics as embodied in the specific quantitative performance specifications of ADS-33E-PRF (2000) and resulting from on-going flight simulations and investigations

sponsored by the FAA as undertaken by the National Aeronautics and Space Administration (NASA) and industry.

5. Assessment techniques will focus on piloted handling qualities and not focus on automation assessment as seen in flight directors and autopilots.
6. Failure Condition (FC) requirements are not addressed in this test guide but it is expected that HQTE techniques proposed here will be applicable to assessment of such conditions, albeit with expanded tolerances or differing handling qualities levels of acceptance, based on permitted levels of HQ degradation.

## 1.6 Structure of the Test Guide

The Test Guide  has definitions of relevant terms as seen in the Glossary. Like other aspects of this document, the authors anticipate that this material will be refined and grow with future releases. Section 2 describes systems testing via the use of short and long duration flight test inputs. Ultimately, data obtained via system testing will be used to validate models, assess stability margins within the flight control laws, and evaluate the aircraft against industry standard handling qualities criteria (e.g., those found in ADS-33E-PRF, other military standards, and industry standards from SAE, ASTM, etc.). Section 3 describes the use of pilot rating scales, while Section 4 describes handling qualities testing including the factors that are important in the selection of HQTEs. Finally, the appendices include an example test plan template for conducting FTM/MTE flight tests and a catalog of FTMs/MTEs with the understanding that the catalog will undergo revisions and additions based upon ongoing and further research that will likely include flight test demonstrations.

# 2 Systems testing

Traditional systems testing incorporates input types often used for identifying flight dynamics (i.e., modes of motion for aircraft with little or no stability augmentation). Such input types are referred to as “short-duration” because they typically require only a few seconds of flight time to apply. The focus for such inputs is usually on measures of time delay, damping, and frequency characteristics of the aircraft response modes.

For modern aircraft with extensive augmentation and feedback control systems, or for aircraft for which such augmentation and feedback systems are planned, inputs must of necessity be of different form, and will take longer to apply. “Long-duration” inputs can be as long as several minutes, but they will provide much richer dynamic information that is crucial to building models of the aircraft or confirming that the aircraft dynamics match existing models.

This section describes the most common of both short-duration and long-duration inputs. The input form to be used will depend upon the desired outcome from flight testing, and for modern aircraft in early development testing, it is not unusual to apply short-duration inputs early – to confirm the aircraft is stable and exhibits no unusual response characteristics – followed by long-duration inputs – to provide data for building accurate dynamic models and for checking compliance with certification requirements. These inputs are the System Qualities Assessments (SQAs) defined in Section 1.3.1.1.

## 2.1 Expected products

Test planning for SQAs, and ultimately certification, must always begin by asking a simple question: what do you need to know? Test planning requires the definitions of data sources and formats, input types, and output variables to be applied, before testing starts. While the test methods described in this section fall into two broad groups based upon input types, there are many more steps involved in defining the detailed systems testing that will be applied. By determining these details before flight testing starts (i.e., through analysis, computer simulation, piloted simulation, hardware-in-the-loop testing, etc.), the tester can avoid having to take unpleasant, and perhaps expensive, retroactive steps to gather necessary flight data.

### 2.1.1 Outcomes from short-duration and long-duration tests

The short-duration tests documented here are well suited for initial checks of latency and static and dynamic stability. The pulse, or stick rap, will provide some measure of latency and secondarily damping and frequency of a dominant response mode. The doublet is more useful than the rap for measuring frequency and damping, and the more exotic 2-1-1 and 3-2-1-1 are simply improved inputs for these purposes.

Long-duration inputs, represented in this test guide by the frequency sweep, provide much richer data for multiple applications. The determination of a wide-band frequency response of output state to input effector results in data, which can be applied to SQAs that predict control system performance including automation and FQAs that predict handling qualities; estimation of vehicle dynamics for developing and verifying simulation models; generation of dynamics models for refinement of flight control systems designs; checks for the presence of nonlinearities in the closed-loop aircraft response; and much more.

### 2.1.2 Input sources

All of the inputs described in this section can be applied manually by the pilot or automatically from a command generator, and each method has its strengths and weaknesses.

Manual inputs are simplest, but not always best. Flying qualities requirements are written in terms of aircraft response (typically angular attitude or rate, or linear acceleration) to cockpit control movements (either deflection or force applied), so there is a direct connection to manually generated commands. No special actuators are needed, as long as control deflection and/or force data are collected.

Pilot-applied inputs carry with them the advantage of real-time adjustment. An experienced test pilot, possibly with extensive simulation practice, can apply an input (either short- or long-duration) at or near the intended amplitude and frequency. If the ground support team (monitoring telemetered data) or flight test engineer or co-pilot (onboard with the pilot) observes an input that is too small or too large, too fast or two slow, too long or too short, a quick discussion with the pilot is all that is needed to improve the quality of the input.

Manual inputs from the pilot's seat may not meet all requirements in a flight test program. For instance, if the objective is to observe how the aircraft responds to a gust input at the actuator, or to deflection of a single surface, it can be challenging to get the information from a pilot-applied input.

Automatically generated inputs are much more capable than manual pilot-applied inputs in several ways. The automated input can be shaped precisely (size, duration, frequency) as desired to obtain specific information. This can be especially critical if there is any concern about exceeding some physical aircraft limit: injecting an automatic input well below the limit and gradually increasing the input parameters allows for a careful approach to the limit. A pilot might not be able to apply so precise a command.

Automatic inputs can also be sent to one or more aircraft effectors, allowing for identification of control powers, for instance.

But automatic inputs, especially frequency sweeps, must be shaped to avoid large-amplitude, out-of-trim response at low frequencies and possible exceedance of aircraft limits at higher frequencies. In addition, there must be a clear 'knock-it-off' switch to allow for aborting any input that appears to be dangerous – an action a pilot is going to be able to provide more quickly in most cases. An additional problem with automatic inputs is that, if the intent is to generate data for aircraft response to cockpit control inputs, it must be possible to apply the forcing functions directly to the cockpit control, or at least closely downstream. Finally, a challenge with automatic command inputs is that the parameters of those commands must be defined early in the development cycle, not after the aircraft has been built.

## 2.2 Short-duration test inputs

Short-duration inputs are highly effective at providing initial observations about aircraft stability and time delays. Output data can be as simple as a hand-measurement of peak responses and times to the peaks, though data recording will enable much more precise analysis and will be required if the results are to be submitted for certification.

Five basic input forms have been found to be most effective. They are the control rap (pulse), doublet, 2-1-1, 3-2-1-1, and step, each described and illustrated herein. Generally, all input forms are intended to identify damping ratio and damped frequency of the dominant response mode in the axis of interest. Each has certain advantages and disadvantages that must be considered in their selection, planning, and execution.

In contrast to frequency sweep command inputs, these input types are considered “narrow spectrum.” Narrow spectrum means that the output content is limited to a narrow time (or in the frequency domain, a narrow frequency) range, depending on the input type. Long duration inputs such as frequency sweeps produce “broad spectrum” output data and are much more effective at generating frequency response plots that are used in control system analysis and design and in flying qualities assessment.

Short-duration inputs must be sufficiently sharp-edged to avoid contamination from exciting unintended dynamic responses, but very sharp-edged inputs run the risk of reaching actuator acceleration or rate limits and introducing contamination due to the change in effective aircraft dynamics that may result. It is possible to obtain frequency-domain data from short-duration inputs, but the character of the inputs means there is not wide-spectrum input power. Sketched below in Figure 5 are the power spectra for typical doublet, 2-1-1, and 3-2-1-1 inputs, plotted as input powers (in units of power and measured in decibels) as functions of output frequency in Hertz. The power spectrum for a rap, not shown, is typically similar to, but even narrower than, that shown for the doublet. As the sketch shows, the 2-1-1 and 3-2-1-1 provide a broader input frequency range, but at the expense of relative difficulty in manual application by a pilot. If the input is automated through an onboard system, the 3-2-1-1 will provide the most useful data. As with any such inputs, practice in a ground-based simulator will be valuable for the pilot and the test team.

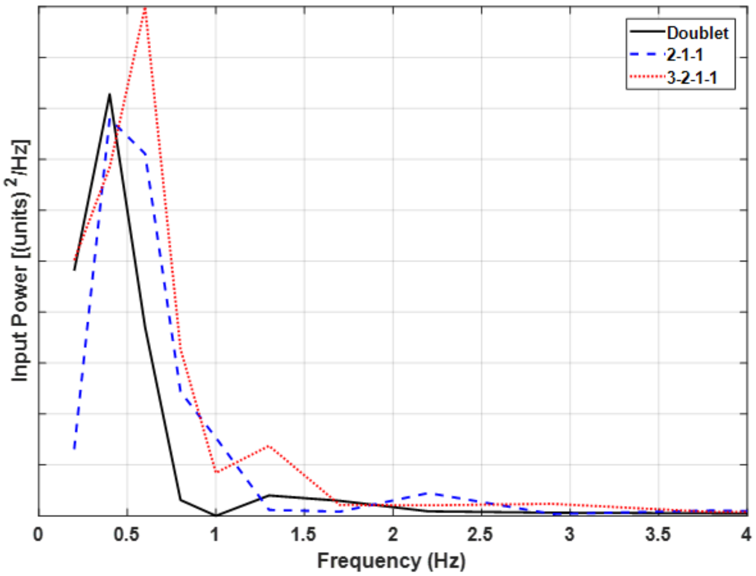


Figure 5. Power spectra from example short-duration inputs

A typical flight test sequence will include multiple repeats at a test condition. Direction of the initial inputs should be varied to check for differences in response. For example, if pitch doublets are to be performed, the first input might be aft control, the second forward, then repeat by starting with a forward input first. This also will provide data to check for consistency in input forms as well as responses to the inputs. Initial direction for the inputs may also be dictated by flight condition; for example, inputs near stall may of necessity be forward (higher speed) first, and aft first for inputs near maximum speed or never-exceed speed.

### 2.2.1 Control rap (pulse)

Pulse inputs – sometimes referred to as stick raps or control raps – are used to excite a physical system without generating a large transient from trim. They are meant to be very brief, generating data for the free response of the aircraft. We call this a pulse as opposed to an impulse, since impulse has a strict mathematical definition of an input size approaching infinity for a vanishingly small input time. While an impulse might be the ideal forcing function, it is neither achievable nor necessary for the purposes of flight test.

The ideal control rap will be as short a time duration as possible, in other words, a very sharp-edged single input. The pilot-applied pulse will typically resemble the flight test example shown in Figure 6.

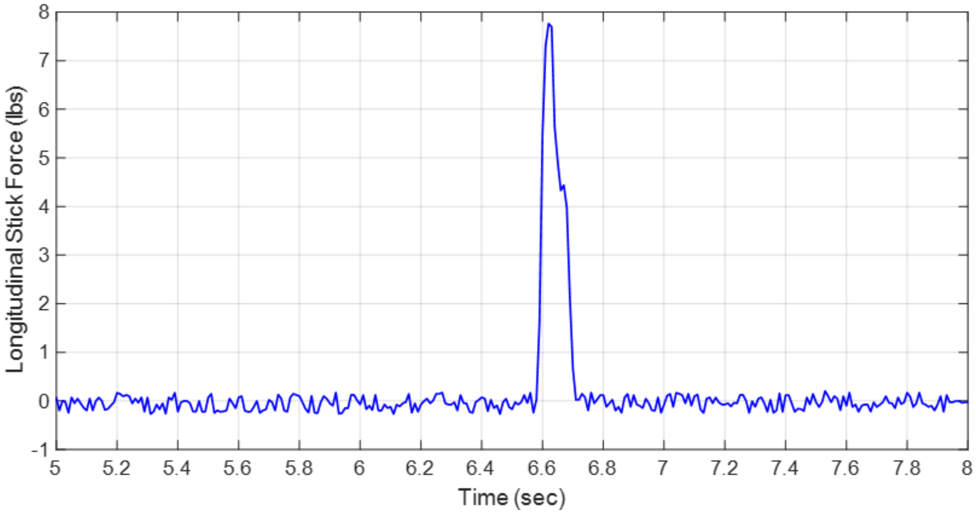


Figure 6. Example of pilot-applied control rap (pulse) input

It is difficult to move a cockpit control effector rapidly enough to get a sharp-edged pulse, unless one is willing to use a hand-held exciter such as a rubber mallet (as has been done, but is not recommended on a routine basis). Note that for the flight test pulse shown above, time t = 0 is just prior to 6.6 seconds.

Cockpit control raps tend to be easiest for the pilot to apply, but difficult to get the desired application rate and amplitude. A rap that is too small may not excite the response of interest, but a large-amplitude rap can drive the aircraft away from initial trim and possibly to an undesirable flight condition.

#### *2.2.1.1 Rap test techniques*

The following steps are used to generate a control rap (pulse) input:

- Trim the aircraft.
- If recording digital data, take a trim shot; otherwise, note trim airspeed, altitude, etc.
- Apply one sharp, quick rap to the control effector. Fixtures held by the copilot for traditional linked dual-control aircraft can be used for containing amplitudes.
- Do not apply any other control inputs until:
    - resulting oscillations have subsided,
    - aircraft is no longer near the initial trim conditions, or
    - safety of flight dictates pilot intervention.
- Typically, 15 seconds is a sufficient run time.

#### *2.2.1.2 Rap data required*

Follow these guidelines when conducting stick raps:

- Handheld measures can be sufficient for an initial check of damping ratio and natural frequency of a dominant mode. In this case, video is best so that reasonably accurate estimates can be made. Whether from video or by an observer in the cockpit, the following should be considered for using handheld measures.
    - Be very clear on the timing of the control rap. The pilot applying the rap should clearly count down, such as “Rap in 3…2…1…now.” If video is recorded, pilot audio should be captured as well.
    - The output state to be observed depends on the type of control system. For conventional airplanes with no more than simple stability augmentation systems (SAS) systems, angle of attack in pitch, bank angle in roll, and sideslip in yaw are the best states. With attitude command, attitude is the preferred state, and with rate command, angular rate is best.
    - Remember that commercial attitude director indicator (ADI) displays usually have filtering on the displayed variables, and the observed values of any state may not match actual values from onboard instrumentation.
- A data acquisition system (DAS) is required for best results, and to assure suitable data are available for FAA review and acceptance. If a DAS is used, consider the following.
    - Design in capability for short-duration testing. While the pilot can provide sufficiently good input power, the aircraft response will be the total response to pilot commands. It can be desirable to limit the input to a single surface or control (such as thrust on a single rotor), and this is best done by building the commands into the flight control system. Math model development and verification, confirmation of control effectiveness, and evaluation of failure effects are all much simpler when inputs can be sent to single effectors.
    - Be aware of typical data errors, such as differing sample rates, asynchronous sample times, prefilters, etc. As mentioned above, commercial attitude packages often incorporate filtering on the sensed signals, and the presence of such filters must be known.
    - Minimum data required are cockpit control deflections, control effector deflections, angular rates, and attitudes. Trim information such as airspeed,

altitude, outside air temperature, and trim control positions should also be noted or recorded.

#### 2.2.1.3 Rap test criteria

Provides estimates of dominant-mode frequency and damping, and approximate time delay, for further flight test planning. Recorded data can be applied to moderate-amplitude handling qualities requirements, particularly if length of the pulse is varied.

#### 2.2.1.4 Rap maneuver variations

Increasing duration and amplitude of the pulse can provide data for determining moderate-amplitude handling qualities (i.e., agility). The doublet overcomes trim concerns that result from a single-direction pulse. Doublets are usually preferred over pulses.

#### 2.2.1.5 Rap safety considerations/risk management

Consider the following when conducting stick raps:

- Start with small control inputs. The larger the input amplitude, the more likely one is to reach command limits, pilot comfort levels, or structural safety margins.
- Linear model data can be obtained with small input amplitudes that avoid system nonlinearities (e.g., actuator rate and position limits).
- If structural or loads limits are a concern, loads analyses should be completed before flight testing. A simulator can help confirm that reasonably sized control raps will not approach safety margins.
- Telemetry with real-time monitoring is encouraged, though onboard observers with access to safety data may suffice. Calls to increase or reduce control input amplitudes and sharpness of inputs can be made based on observed responses.

### 2.2.2 Doublet

Control doublets are perhaps the most effective short-duration inputs in flight test. They provide a means to perturb the aircraft to excite dynamic modes without perturbing it far from trim (as can happen with the control rap). If the interest is in identification of a response mode, and the approximate natural frequency of that mode is known, doublets are more effective at confirming the frequency and measuring damping than any other control inputs considered here. Broader inputs in the frequency domain, the 2-1-1 and 3-2-1-1, for example, are more effective at homing in on a mode and its frequency, but the doublet is easier and quicker to apply than those input forms.

Even if the interest is in identifying long-term, oscillatory modes, such as the phugoid or spiral modes in conventional airplanes, the doublet will provide the power necessary to excite those modes, again without driving the aircraft too far away from initial trim.

#### *2.2.2.1 Doublet test techniques*

The following steps are used to generate a doublet input:

- Trim the aircraft.
- If recording digital data, take a trim shot; otherwise, note trim airspeed, altitude, etc.
- Apply doublet targeting the aircraft's natural frequency in the axis of interest.
- Most of the input power should be slightly below the expected natural frequency.
- Pilot-applied doublets will not be perfectly symmetric or square. A typical pilot-applied doublet from flight test is shown in Figure 7.
- Automated doublets are more consistent in shape and frequency as shown in Figure 8. Be aware that a pure square-wave doublet, as sketched below, commands an instantaneous aircraft response. It is likely that limiters in the flight control system (whether intentional or as a result of acceleration limits on control actuators) will be reached.
- Do not apply any other control inputs until:
    - resulting oscillations have subsided,
    - aircraft is no longer near the initial trim conditions, or
    - safety of flight dictates pilot intervention.
- Typically, 15 seconds is a sufficient run time.

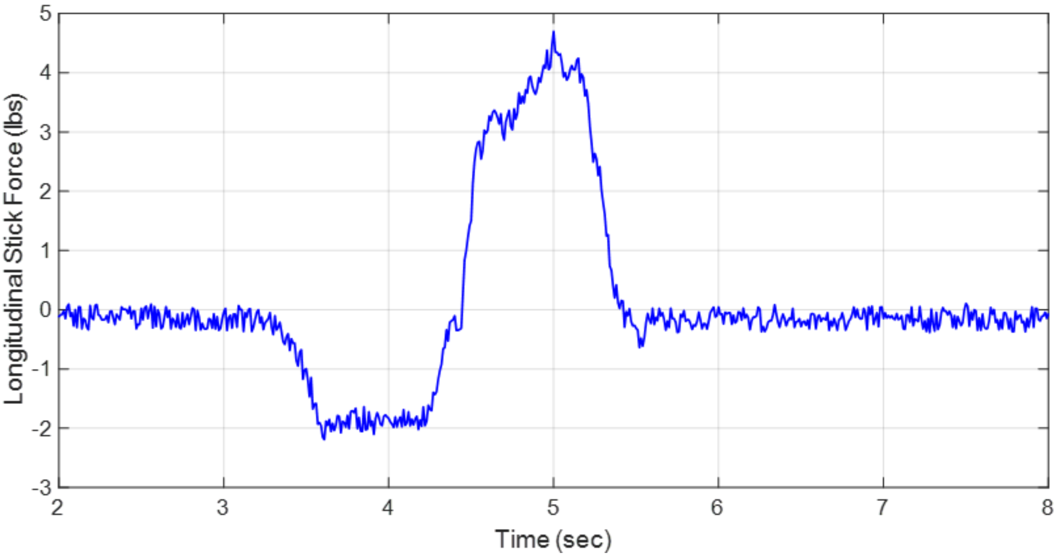
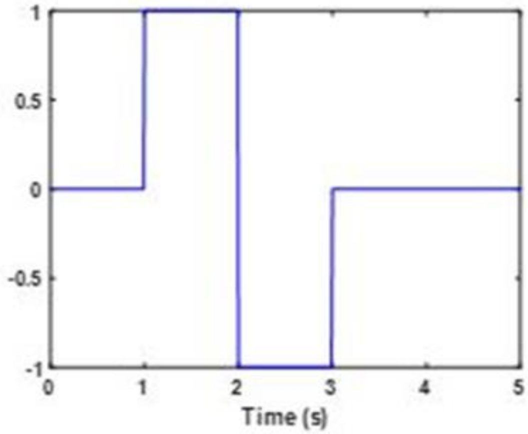
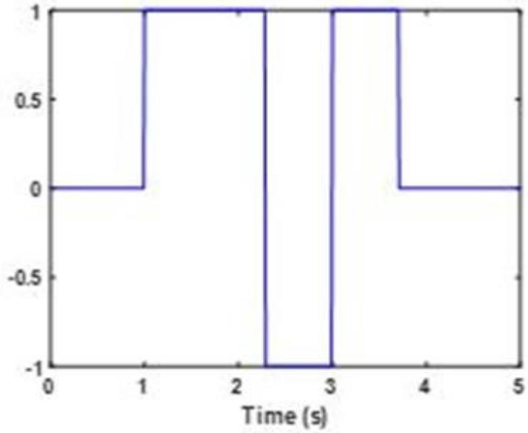


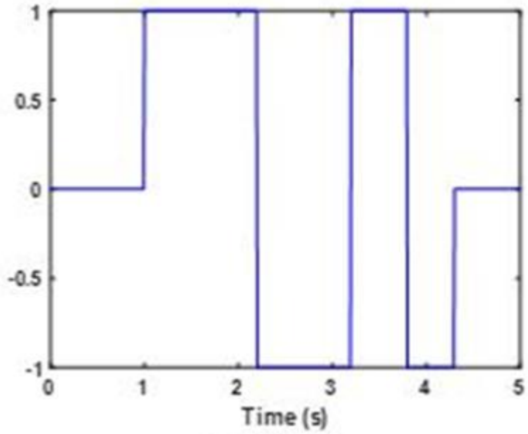
Figure 7. Example of pilot-applied doublet input



**a) Doublet**



**b) 2-1-1**



**c) 3-2-1-1**

Figure 8. Example computer-generated inputs

#### *2.2.2.2 Doublet data required*

Follow these guidelines when conducting doublets:

- Handheld measures can be sufficient for an initial check of damping ratio and natural frequency of a dominant mode. In this case, video is best so that reasonably accurate estimates can be made. Whether from video or by an observer in the cockpit, the following should be considered for using handheld measures:
    - Be very clear on the timing of the doublet. The pilot applying the input should clearly count down, such as "Doublet in 3…2…1… Mark." If video is recorded, pilot audio should be captured as well. The pilot can continue count for frequency estimation, such as 1,2, Mark (for control reversal) 1,2, Mark (for back to trim). Ground practice with telemetry feedback prior to flight can refine this timing.
    - The output state to be observed depends on the type of control system. For conventional airplanes with no more than simple SAS systems, angle of attack in pitch, bank angle in roll, and sideslip in yaw are the best states. With attitude command, attitude is the preferred state, and with rate command, angular rate is best.
    - Remember that commercial ADI displays usually have filtering on the displayed variables, and the observed values of any state may not match actual values from onboard instrumentation.
    - Observer notes number of overshoots and undershoots resulting after the doublet is complete, and if possible, uses a stopwatch to measure either the time between overshoots or time from the first over/undershoot to the next. This will probably require multiple runs to get the numbers recorded accurately.
- A data acquisition system is recommended for best results, and to assure suitable data are available for FAA review and acceptance. If a DAS is used, consider the following:
    - Design in capability for short-duration testing. While the pilot can provide sufficiently good input power, the aircraft response will be the total response to pilot commands. It can be desirable to limit the input to a single surface or control (such as thrust on a single rotor), and this is best done by building the commands into the flight control system. Math model development and verification, confirmation of control effectiveness, and evaluation of failure effects are all much simpler when inputs can be sent to single effectors.

  - Be aware of typical data errors, such as differing sample rates, asynchronous sample times, prefilters, etc. As mentioned above, commercial attitude packages often incorporate filtering on the sensed signals, and the presence of such filters must be known.
  - Minimum data required are cockpit control deflections, control effector deflections, angular rates, and attitudes. Trim information such as airspeed, altitude, outside air temperature, and trim control positions should also be noted or recorded.

#### *2.2.2.3 Doublet test criteria*

- Provides estimates of dominant-mode frequency and damping, and approximate time delay, for further flight test planning.
- With recorded data, provides measures of those parameters for analysis and test planning.

#### *2.2.2.4 Doublet maneuver variations*

Variations in input form have been used, though they are generally difficult for the pilot and might require automatic command signal generators. For instance, triangular doublets decrease the chance of hitting a rate or position limiter; sinusoidal doublets do the same and may provide more input power around the frequency of interest. Square wave doublets, as sketched above, tend to be easiest for a pilot to apply.

The doublet is typically the most common input type used in flight test. More sophisticated variations – such as the 2-1-1 or the 3-2-1-1 – will provide broader power but are more challenging for the pilot.

#### *2.2.2.5 Doublet safety considerations/risk management*

Consider the following when conducting doublets:

- Start with small control inputs. The larger the input amplitude, the more likely one is to reach command limits, pilot comfort levels, or structural safety margins. Fixtures held by the copilot for traditional linked dual-control aircraft can be used for containing amplitudes.
- Linear model data can be obtained with small inputs.
- If structural or loads limits are a concern, loads analyses should be completed before flight testing. A validated simulator can help confirm that reasonably sized control doublets will not approach safety margins.

- Telemetry with real-time monitoring is encouraged, though onboard observers with access to safety data may suffice. Calls to increase or reduce control input amplitudes and sharpness of inputs can be made based on observed responses.

### 2.2.3 Input 2-1-1

For initial identification of the natural frequency of a response mode, the 2-1-1 is more than adequate. A doublet is most effective when the frequency is known, and a 3-2-1-1 is more useful to find the modal frequency, but the 2-1-1 is a relatively easy-to-apply compromise.

#### *2.2.3.1 Test techniques for 2-1-1*

The following steps are used to generate a 2-1-1 input:

- Trim the aircraft.
- If recording digital data, take a trim shot; otherwise, note trim airspeed, altitude, etc.
- Apply the 2-1-1 with the initial input targeting slightly below, and the second and third inputs slightly above, the frequency of interest. A typical computer-generated 2-1-1 sequence is sketched in Figure 8 for reference.
- Pilot-applied inputs will not be perfectly symmetric or square. They will resemble the inputs for the pilot-applied doublet sketched in Figure 7.
- Do not apply any other control inputs until:
    - resulting oscillations have subsided,
    - aircraft is no longer near the initial trim conditions, or
    - safety of flight dictates pilot intervention.
- Typically, 15 seconds is sufficient run time.

#### *2.2.3.2 Data required for 2-1-1*

Follow these guidelines when conducting 2-1-1 inputs:

- Handheld measures can be sufficient for an initial check of damping ratio and natural frequency of a dominant mode, though the doublet is superior to the 2-1-1 for this purpose. In this case, video is best so that reasonably accurate estimates can be made.
- A data acquisition system is recommended for best results, and to assure suitable data are available for FAA review and acceptance. If a DAS is used, consider the following:

    - Design in capability for short-duration testing. While the pilot can provide sufficiently good input power, aircraft response will be the total response to pilot commands. It can be desirable to limit the input to a single surface or control (such as thrust on a single rotor), and this is best done by building the commands into the flight control system. Math model development and verification, confirmation of control effectiveness, and evaluation of failure effects are all much simpler when inputs can be sent to single effectors.

    - Be aware of typical data errors, such as differing sample rates, asynchronous sample times, prefilters, etc. As mentioned above, commercial attitude packages often incorporate filtering on the sensed signals, and the presence of such filters must be known.

    - Minimum data required are cockpit control deflections, control effector deflections, angular rates, and attitudes. Trim information such as airspeed, altitude, outside air temperature, and trim control positions should also be noted or recorded.

#### *2.2.3.3 Test criteria for 2-1-1*

- Excellent test to narrow the frequency range of interest for identification of the frequency and damping of an otherwise unknown oscillatory mode.

- Provides estimates of dominant-mode frequency and damping, and approximate time delay, for further flight test planning.

- With recorded data, provides measures of those parameters for analysis and test planning.

#### *2.2.3.4 Maneuver variations for 2-1-1*

The 2-1-1 is a good test input if the frequency of an oscillatory mode has not been clearly identified. Making the long, initial input well below, and the doublet that follows above, the suspected frequency of the mode, can help capture the mode of interest. Angular rate is particularly useful as a response state, as rate will typically reach a peak during the long input and not reach peak during the short ones, if the frequency of the mode is between the frequencies of the inputs.

If DAS is not available, consider using a doublet instead of a 2-1-1. A 2-1-1 will provide broader power but is much more challenging for the pilot and provides little additional information if only handheld measurements are taken.

The 3-2-1-1, discussed below, generates a broader spectrum and should be used if test time is limited, and especially if wide-frequency testing such as frequency sweeping is not planned.

#### *2.2.3.5 Safety considerations/risk management for 2-1-1*

Consider the following when conducting 2-1-1 inputs:

- Start with small control inputs. The larger the input amplitude, the more likely one is to reach command limits, pilot comfort levels, or structural safety margins. Fixtures held by the copilot for traditional linked dual-control aircraft can be used for containing amplitudes.
- The pilot can count for input estimation, such as Mark,1, 2, Mark (for control reversal) 1, Mark (for control reversal) 1, Mark (for back to trim). Ground practice with telemetry feedback prior to flight, can refine this timing.
- Linear model data can be obtained with small inputs.
- If structural or loads limits are a concern, loads analyses should be completed before flight testing. A validated simulator can help confirm that reasonably sized control inputs will not approach safety margins.
- Telemetry with real-time monitoring is encouraged, though onboard observers with access to safety data may suffice. Calls to increase or reduce control input amplitudes and sharpness of inputs can be made based on observed responses.

### 2.2.4 Input 3-2-1-1

The 3-2-1-1 is a special input form in flight test. It is usually applied to a new design where there is expectation of a dominant mode, but the frequency of that mode is not yet well-known. Proper design of the 3-2-1-1 will provide data to quickly identify the mode, and if the inputs are properly adjusted, allow for precise measurement of the frequency and damping of the mode. But it is a challenging set of inputs for the pilot, much better left to an onboard automatic command generator.

#### *2.2.4.1 Test techniques for 3-2-1-1*

The following steps are used to generate a 3-2-1-1 input:

- Trim the aircraft.
- If recording digital data, take a trim shot; otherwise, note trim airspeed, altitude, etc.

- Apply the 3-2-1-1 with the initial input targeting below, the second (reverse-direction) input near, and the third and fourth (doublet) inputs slightly above, the frequency of interest. A typical computer-generated 3-2-1-1 sequence is sketched in Figure 8 for reference.
- Pilot-applied inputs will not be perfectly symmetric or square. They will resemble the inputs for the pilot-applied doublet sketched in Figure 7.
- Do not apply any other control inputs until:
  - resulting oscillations have subsided,
  - aircraft is no longer near the initial trim conditions, or
  - safety of flight dictates pilot intervention.
- Typically, 15 seconds is a sufficient run time.

#### *2.2.4.2 Data required for 3-2-1-1*

Follow these guidelines when conducting 3-2-1-1 inputs:

- Handheld measures can be sufficient for an initial check of damping ratio and natural frequency of a dominant mode, though experience has shown that the doublet, which is simpler to apply, is superior to the 3-2-1-1 for this purpose.
- A data acquisition system is recommended for best results, and to assure suitable data are available for FAA review and acceptance. Consider the following if a DAS is used:
  - Design in capability for short-duration testing. While the pilot can provide sufficiently good input power, aircraft response will be the total response to pilot commands. It can be desirable to limit the input to a single surface or control (such as thrust on a single rotor), and this is best done by building the commands into the flight control system. Math model development and verification, confirmation of control effectiveness, and evaluation of failure effects are all much simpler when inputs can be sent to single effectors.
  - Be aware of typical data errors, such as differing sample rates, asynchronous sample times, prefilters, etc. As mentioned above, commercial attitude packages often incorporate filtering on the sensed signals, and the presence of such filters must be known.

    - Minimum data required are cockpit control deflections, control effector deflections, angular rates, and attitudes. Trim information such as airspeed, altitude, outside air temperature, and trim control positions should also be noted or recorded.

#### *2.2.4.3 Test criteria for 3-2-1-1*

- Provides estimates of dominant-mode frequency and damping, and approximate time delay, for further flight test planning.
- With recorded data, provides measures of those parameters for analysis and test planning.

#### *2.2.4.4 Maneuver variations for 3-2-1-1*

The 3-2-1-1 is a good test input if the frequency of an oscillatory mode has not been clearly identified and a broad input frequency range is desired. Making the initial input well below, the second input near, and the doublet above, the expected frequency of the mode, can help capture the mode of interest. Angular rate is particularly useful as a response state, as rate will typically reach a peak during the long input and not reach a peak during the short ones, if the frequency of the mode is between the frequencies of the inputs.

If DAS is not available, consider using a doublet instead of a 3-2-1-1. The 3-2-1-1 will provide broader power but is much more challenging for the pilot. It provides little additional information if only handheld measurements are taken.

#### *2.2.4.5 Safety considerations/risk management for 3-2-1-1*

Consider the following when conducting 3-2-1-1 inputs:

- Start with small control inputs. The larger the input amplitude, the more likely one is to reach command limits, pilot comfort levels, or structural safety margins. Fixtures held by the copilot for traditional linked dual-control aircraft can be used for containing amplitudes.
- The pilot can count for input estimation, such as Mark, 1, 2, 3, Mark (for control reversal) 1, 2, Mark (for control reversal) 1, Mark (for control reversal) 1, Mark (for back to trim). Ground practice with telemetry feedback prior to flight, can refine this timing.
- Linear model data can be obtained with small inputs.
- If structural or loads limits are concerns, loads analysis should be completed before flight testing. A validated simulator can help confirm that reasonably sized control inputs will not approach safety margins.

- Telemetry with real-time monitoring is encouraged, though onboard observers with access to safety data may suffice. Calls to increase or reduce control input amplitudes and sharpness of inputs can be made based on observed responses.

### 2.2.5 Step

A number of flying qualities criteria are based upon the response to a step input. Despite this, the step is a challenging input in flight test and is recommended only for those tests that require it (e.g., control power for an attitude command system). In any case, the step should be maintained for as short a time as necessary to obtain useful data.

#### *2.2.5.1 Step test techniques*

The following steps are used to generate a step input:

- Trim the aircraft.
- If recording digital data, take a trim shot; otherwise, note trim airspeed, altitude, etc.
- Apply the step with the initial input with a rapid displacement or force, then maintain the desired displacement or force.
- Pilot-applied inputs will not be perfect steps. There will be a natural tendency to overshoot and then drop back slightly from the initial input.
- Do not apply any other control inputs until:
    - required data have been obtained,
    - resulting oscillations have subsided,
    - aircraft is too far from the initial trim conditions, or
    - safety of flight dictates pilot intervention.
- Typically, 15 seconds is a sufficient run time.

#### *2.2.5.2 Step data required*

- Because of the intended usage for step-input data, handheld measurement alone is not recommended.
- A data acquisition system should be used to extract the desired results, and to assure suitable data are available for FAA review and acceptance. Consider the following with DAS:

  - Design in capability for short-duration testing. While the pilot can provide sufficiently good input power, aircraft response will be the total response to pilot commands. It can be desirable to limit the input to a single surface or control (such as thrust on a single rotor), and this is best done by building the commands into the flight control system. Math model development and verification, confirmation of control effectiveness, and evaluation of failure effects are all much simpler when inputs can be sent to single effectors.

  - Be aware of typical data errors, such as differing sample rates, asynchronous sample times, prefilters, etc. As mentioned above, commercial attitude packages often incorporate filtering on the sensed signals, and the presence of such filters must be known.

  - Minimum data required are cockpit control deflections, control effector deflections, angular rates, and attitudes. Trim information such as airspeed, altitude, outside air temperature, and trim control positions should also be noted or recorded.

#### *2.2.5.3 Step test criteria*

- Provides estimates of dominant-mode frequency and damping, approximate time delay, and control power.

- With recorded data, provides measures of those parameters for analysis and test planning.

#### *2.2.5.4 Step maneuver variations*

Because of challenges with proper application, the step is recommended only for those requirements and flying qualities criteria for which it is specified. If desired, a “boxcar” (step and release) input can be used instead. In this case, the dynamic response at control release is also of value.

#### *2.2.5.5 Step safety considerations/risk management*

- It can be difficult for the pilot to apply a pure step input: it is common to relax force or position on a cockpit control after the initial input, causing the input to droop with time.

- A step can command a rapid change in flight conditions. In a conventional airplane, for example, an aft step control input will command a nose-up pitch, a climb, and a decrease in airspeed. This could at least result in a rapid movement away from the initial trim condition, and at worst lead to a safety-of-flight issue. Unusual attitude recovery procedures should be preplanned and can be practiced in a simulator or in flight on smaller input amplitudes before they are actually needed on larger amplitude inputs.

- Steps are typically small in amplitude for most response types, and it must be determined in advance if the desired step is to be in force (if pilot-applied, a handheld force gauge will prove handy) or in position (with a displacement control/fixture). Use of copilot held fixtures for traditional linked dual control aircraft can be used for containing amplitudes. Clearing the fixture from the flight controls, in recovery of the aircraft, is critical and should be briefed and rehearsed.
- Start with small control inputs. The larger the input amplitude, the more likely one is to reach command limits, pilot comfort levels, or structural safety margins.
- Linear model data can be obtained with small inputs.
- If structural or loads limits are a concern, loads analysis should be completed before flight testing. A validated simulator can help confirm that reasonably sized control inputs will not approach safety margins.
- Telemetry with real-time monitoring is encouraged, though onboard observers with access to safety data may suffice. Calls to increase or reduce control input amplitudes and sharpness of inputs can be made based on observed responses.

## 2.3 Frequency sweep command inputs

Flight control excitations within the flying qualities frequencies (generally below about 3 Hz, or three cycles of control input per second) are used to determine the frequency response characteristics of the aircraft and flight control system. These inputs consist of frequency dwells (single sinewave), frequency sweeps (quasi-sinewaves of continuously increasing frequency), filtered and shaped pseudo-noise, or multisines, about a given trimmed flight condition. They provide valuable data for multiple applications in control system analysis and design, system identification to extract accurate dynamic models of an aircraft from the measured response to specific control inputs[2] , and assessment of predicted handling qualities.

Once a simulation model is validated, piloted simulation can possibly be used for some HQ assessments such that actual flight test on the vehicle spot checks the predicted HQ. These frequency-dependent inputs can be done manually, or through the use of Programmed Test

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[2] The SAE G-35 committee is exploring the applicability of modelling for qualification and certification using simulation for flight testing.

Inputs (PTI), depending on the data that are desired in combination with safety considerations. Generally, frequency sweeps are done manually to better handle attitude changes that may result at low frequencies and to shape/bias inputs to maintain symmetry of the maneuver about trim. Manual inputs also have the additional benefit of providing spectral richness in response as compared to a PTI sweep. Two methods for manual sweeps will be discussed as well as the most common method used for PTI. Narrower frequency sweeps may be used to facilitate identification of modal frequencies such as the dutch-roll mode, while dwells may be used for various investigations of modal response.

The requirements for planning the safe conduct of frequency domain tests while meeting data requirements should not be underestimated. The planning should include a detailed understanding of the system to be identified, measurement and instrumentation requirements, test input design, definition of constraints and limits, test team coordination and training, and other safety considerations.

### 2.3.1 Test planning and prerequisite testing

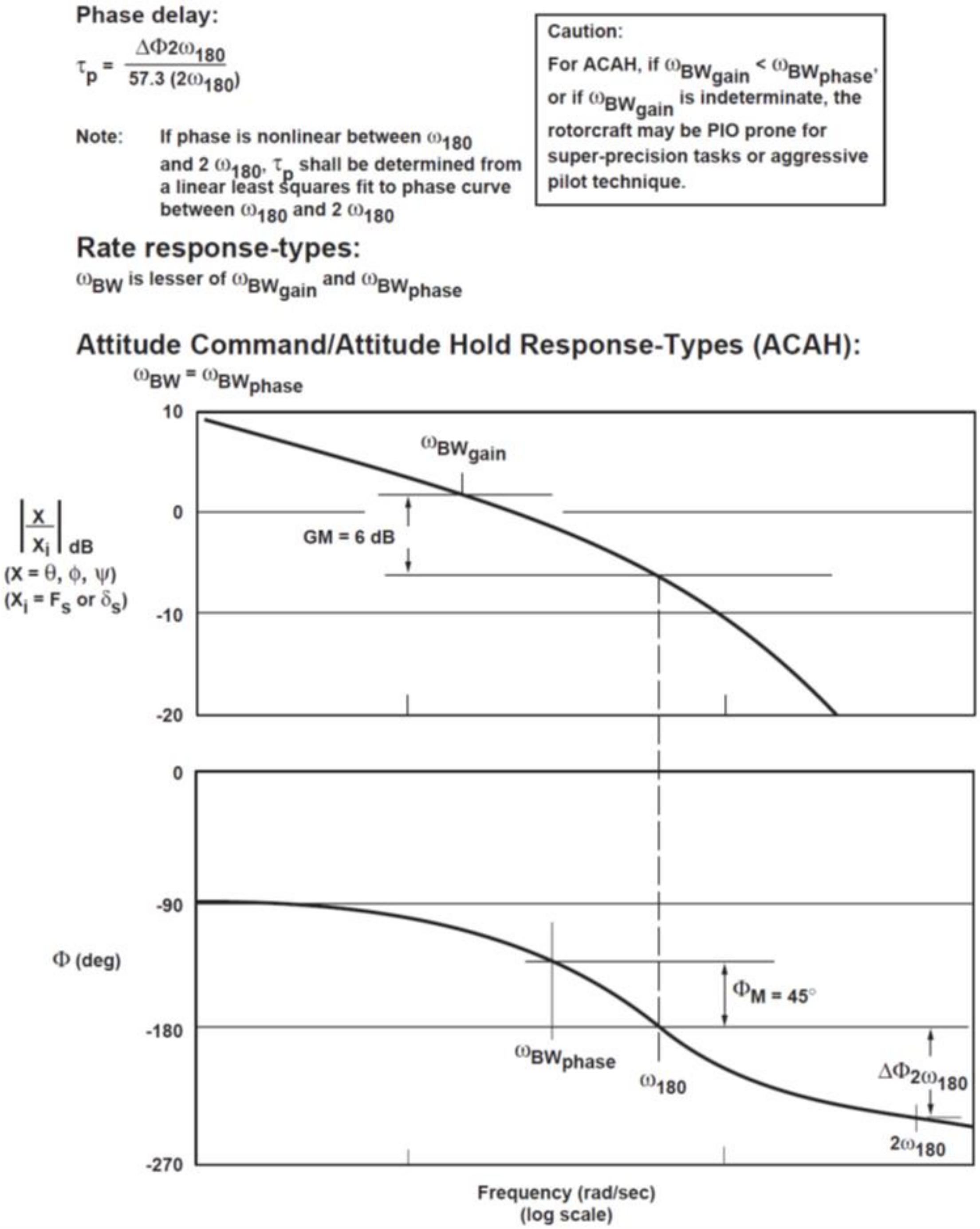
The first step in the planning process is to thoroughly research the flight control system or control system element to be identified and to determine the applicability of the test technique to meet the data requirements. While frequency response techniques can be used for a host of dynamic system analyses, the focus here will be on:

1. The flight dynamics simulation model validation for pilot evaluation.
2. The assessment of predicted handling qualities, similar to that described in ADS-33E-PRF (2000) and elsewhere.

In this context, characterization of the frequency domain, through piloted flight testing from approximately 0.3 rad/sec to 12 rad/sec (0.05 Hz – 2 Hz), should generally be sufficient to achieve both goals.

Pretest analysis should focus first on system definition with a threefold purpose: to identify potential risks to be managed and mitigated, to determine aircraft configuration requirements, and to identify the data requirements to meet the test objectives.

Other analysis includes determination of instrumentation requirements as well as preliminary determination of expected Aircraft Attitude Bandwidth and Phase Delay, to inform proper build-up in data collection. Definitions of these parameters from ADS-33E-PRF (2000) is provided in Figure 9. There are required thresholds in ADS-33E-PRF for these parameters, but they are not requirements in civil certification.



**Phase delay:**

$$\tau_p = \frac{\Delta\Phi 2\omega_{180}}{57.3\,(2\omega_{180})}$$

Note: If phase is nonlinear between $\omega_{180}$ and $2\,\omega_{180}$, $\tau_p$ shall be determined from a linear least squares fit to phase curve between $\omega_{180}$ and $2\,\omega_{180}$

Caution:

For ACAH, if $\omega_{BW_{gain}} < \omega_{BW_{phase}}$, or if $\omega_{BW_{gain}}$ is indeterminate, the rotorcraft may be PIO prone for super-precision tasks or aggressive pilot technique.

**Rate response-types:**

$\omega_{BW}$ is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$

**Attitude Command/Attitude Hold Response-Types (ACAH):**

$\omega_{BW} = \omega_{BW_{phase}}$

Figure 9. Aircraft Attitude Bandwidth and Phase Delay definitions

#### *2.3.1.1 System definition*

For handling qualities investigations, it is necessary to have detailed definition of the flight control system, including an understanding of stability and control augmentation, trim systems, flight control system modes, control mixing or coupling, degraded or backup systems, and envelope protection algorithms. Known or predicted aircraft dynamic modes should be identified for not only rigid-body aerodynamic modes, but also rotor/propulsor dynamics as well as structural and drive-train modes, with a particular interest in the lower frequency lightly damped modes. Additionally, susceptibility to aircraft pilot coupling should be examined, as well as subsystem performance limitations that may introduce non-linear response.

#### *2.3.1.2 Flight control system considerations*

Examination of the flight control design should be undertaken to determine the effect of frequency of input on the design and to set appropriate limits on amplitude and frequency based on expected changes in response, as well as to determine flight test build-up procedures. Some factors to consider include, but are not limited to:

- partial authority versus full authority designs
- flight control system saturation effects
- response types used
- trim and control margin management
- transition points for response change according to response type and control mixing
- compensation applied for expected inter-axis coupling
- control gain schedules based on configuration and environmental parameters and understanding of critical design points based on these parameters
- envelope protection and limiting interactions

#### *2.3.1.3 Rigid-Body Aeromechanic Modes and Dynamic Coupling*

Analysis and modeling should sufficiently identify modes of interest such as the phugoid, short period, and Dutch roll modes in wing-borne lift aircraft and the long period and short period longitudinal and lateral-directional modes of VTOL aircraft. Highly augmented aircraft do not exhibit traditional flight dynamics modes, but there are always dominant modes in the region of piloted control that will be of concern for modeling. The focus here should be to anticipate the interaction of these modes and expect and plan for higher response at their natural frequencies. Planning should also attempt to identify inter-axis coupling and not necessarily attempt to eliminate these off-axis inputs in frequency sweeps but plan for managing them through off-axis control applications to maintain symmetry about trim for the excited axis. Many advanced flight-control designs apply compensation to eliminate such inter-axis coupling, and in early design this may not have been optimized; for example, control mixing on the main rotor hub of a single-main-rotor helicopter can take many hours of dedicated flight testing.

#### *2.3.1.4 Structural and drive-train modes*

Torsional modes in interconnected drivetrains should be examined. For instance, the rotor-to-rotor torque mode of the tandem rotor and the asymmetric drive-train mode of the tiltrotor have manifested themselves in frequency response tests. Tail-rotor drive-train torsional modes and "soft" tail-boom modes have manifested themselves in helicopter tests. Other structural modes that may be encountered are those associated with wing and nacelle/pylon interactions such as the Symmetric Wing Beam (SWB) or Symmetric Wing Chord (SWC) modes of a tiltrotor. Also, airframe appendages and instrumentation airspeed boom modes should be considered. Many advanced flight control designs utilize notch filters that mitigate the effect of excitation of structural modes at certain frequencies. Preliminary analysis of these modes may not be sufficiently accurate in frequency and especially in damping and the breadth and depth of such filtering may be insufficient. Prerequisite flight testing of those structural and drive-train modes close to the frequency range for piloted control, utilizing PTI, is recommended prior to conducting frequency sweeps.

#### *2.3.1.5 Rotor/propulsor modes*

For traditional helicopters, rotor/propulsor system dynamics of interest include the flapping and lead-lag modes. In most cases, the system rotor/propulsor modes will be at a damped natural frequency well above the frequency range of interest and sufficiently damped. In the conduct of flight test frequency sweeps up to 2 Hz there will be some spillover of higher frequency excitation to effectively identify modes closest to the frequency range of interest (3-4 Hz) for the rotary-wing flap and lead-lag modes. For a constant revolutions per minute (RPM) rotary-wing aircraft, consideration should be given to examining how these modes may be excited with off-nominal RPM, and appropriate limits applied for flight test.

#### *2.3.1.6 Subsystem limitations*

Subsystem performance limitations such as actuator rate limits, hydraulic pump rates, gearbox limits, etc., should be well understood. Flight test limits and monitoring of these subsystems should be planned.

#### *2.3.1.7 Aircraft pilot coupling (pilot-assisted oscillation PAO)*

The record of aircraft testing is replete with instances where flight control interactions with aerodynamics and structural modes have resulted in what is known as an aeroservoelastic response. Part of the flight control aspect of this interaction can be that of the pilot coupling biodynamically with the motions and feeding the response. These interactions should be anticipated, and robust knock-it-off (KIO) criteria put in place that not only stop the frequency test but are oriented toward breaking the chain of response through adjusting pilot control gain, and control grip, along with adjusting flight regime. Ground vibration tests in the 1-7 Hz frequency range, that yield data from pilot control coupling with vibration, can inform flight test and more importantly be fed into aircraft software or mechanical design to avoid these interactions.

### 2.3.2 Data requirements/construct of the Flight Test Frequency Sweep

#### *2.3.2.1 Trim condition/test conditions*

Test configurations should emphasize low-speed regimes where VTOL aircraft demand greater augmentation and stabilization, and where dynamic models are less predictable with traditional flight test techniques. Additionally, for variable-configuration aircraft, where control mixing occurs in transition, selected mixed configurations should be examined. For wing-borne lift aircraft, low-speed flight, where inherent bare-airframe dynamics may be nonlinear, and where augmented flight control may be needed to maintain stability, should be the focus. Testing at high speeds, especially in pitch or vertical axes, must proceed carefully, as aircraft loads can build rapidly with dynamic pressure.

Early flight testing should be performed at low gross weights, mid- Center of Gravity (CG), at low altitudes (but out of ground effect for VTOL aircraft). As testing proceeds, and as the team gains confidence in the dynamics of the identified model, testing should include those conditions most critical from the standpoint of stability, control margins, or maneuverability. An obvious example for a VTOL is high, hot, and heavy, but most aft CG may be more critical than max gross weight.

For flight testing of VTOL aircraft in hover, winds should be 5 kts or less. For forward-flight testing of thrust-borne lift aircraft or wing-borne lift aircraft, no higher than light turbulence is recommended for testing. Any significant atmospheric disturbance will result in a lower signal to noise ratio (SNR) and likely manifest itself in lower coherence of the data (i.e., there will be a reduction in the linear correlation between input and output responses as measured in the frequency domain).

Altitudes for VTOL aircraft in the hover should be biased upward to allow for gradual descents that will occur with constant-power lateral, longitudinal, and directional sweeps. Heave axis sweeps can result in even greater descents, and therefore should be flown at high hover altitudes that still allow for good visual reference of trim but provide for safe ground clearances. Some of this can be mitigated by starting the heave axis sinusoidal sweep in the upward direction.

If an open-loop response is desired, the test may have to be conducted with some or all of the augmentation disabled, depending on the measurements available and the coupling that the augmentation suppresses If there is significant coupling between responses, such as altitude deviations during pitch maneuvers, it may be necessary to turn off some feedback loops to generate meaningful data. If the out-of-axis loops are also under investigation, however, it might be prudent to leave those loops closed and assess the overall response.

As a general rule, analytical predictions, followed by simulation, should be relied upon to help reduce the number of test conditions to those that are most critical.

#### 2.3.2.2 Frequency range

While 3 Hz represents near the maximum of pilot capability in control sweeps and dwells, the target frequency band for test is actually predicated on the expected bandwidth of the system under test. Any significantly higher frequencies pose an uneven trade of flight risk for data value, especially in manual sweeps. For these reasons, frequency sweep testing for predicted handling qualities is typically constrained to 2 Hz and below as described in Blanken et al. (2008). Per Tischler & Rempel (2006), handling qualities frequency sweeps should span a range of frequencies that starts below the estimated Aircraft Attitude Bandwidth frequency and covers the estimated neutral-stability frequency in angular attitude:

$$0.5\omega_{\text{BW}} \leq \omega \leq 2.5w_{180} \qquad 1$$

where $w_{\text{BW}}$ is determined as described in ADS-33E-PRF (2000) and illustrated in Figure 9. Here, $\omega_{180}$ represents the frequency at which the aircraft/system response is neutrally stable at -180 degrees out of phase with input, for the output-to-input signals of greatest interest (for example, pitch attitude output to pitch controller input). Initial estimates of these values can be obtained through analytic models as well as time domain inputs and can support initial frequency sweeps of lesser range based on the assessed modeling fidelity in combination with associated risks of excitation of modes.

For sweeps with most or all augmentation systems switched off, the bandwidth frequency may be difficult to estimate in advance. Good results are usually assured if the initial frequency is around one cycle in 12 seconds – about 0.5 rad/sec.

#### 2.3.2.3 Low frequency input

Frequency sweeps are done from low frequency to high frequency. The minimum frequency is generally low enough to identify aeromechanical modes, and as discussed above can be estimated based on the expected bandwidth of the aircraft system. The start of the sweep will be asymmetric and non-sinusoidal, therefore a second long period input at the start frequency is done prior to increasing frequency of input.

#### 2.3.2.4 Record length

One of the drawbacks of frequency sweeps is record length. Sweep duration should be sufficiently long to capture the dynamics under investigation. Per Tischler & Rempel (2006), as a general rule individual sweep record length ideally should be 4-5 times longer than maximum dynamic periods of interest, such as the short-period mode or any similar short-term dominant response mode. Another way to determine this is to determine the period ($T_{MAX}$) for the lowest frequency at the start of the sweep based on bandwidth (US Army, 2000), and then use a multiple of that period for record length determination $T_{REC} \geq (4 \text{ to } 5)T_{MAX}$. For most aircraft, this record length would be somewhere between 60 to 80 seconds typically. Shorter records could be used if targeting higher frequency dynamic modes.

#### 2.3.2.5 Amplitude

Amplitudes are selected to capture a range of operational attitudes of the aircraft and sufficiently high enough to be differentiated from noise that may arise in instrumentation, or due to atmospheric effects and other test aspects. Amplitudes may vary based on test objectives and the control response type under test. For instance, greater amplitude may be used for an attitude command as compared to a rate command system. Incremental build-up in both frequency range and amplitude can be expected. For instance, while higher amplitude excitations may present increased risk in flight test, they can be of significant value in identifying non-linear behavior that may contribute to PIO susceptibility and may be warranted given the design under test. For high-speed flight in any aircraft, amplitudes should be constrained to avoid high structural loads.

Existing flying and handling qualities metrics in ADS-33E-PRF (2000) make use of frequency sweep data, but are explicitly defined for small-amplitude inputs, attitude changes under about ±10 deg for example. As noted above, however, it has been found in practice that there is valuable information to be gained by running sweeps at higher input and output amplitudes. Starting frequencies will need to be increased as amplitude is increased to prevent excessive trim changes.

It is difficult for a pilot to apply constant input amplitude throughout the duration of the sweep. While a constant amplitude is not essential in most cases, it is useful whenever there is concern about nonlinearities in the aircraft response. Tracking degradation in flying qualities parameters as sweep amplitude increases has been found to be of great value in determining propensity for PIO, for example.

For multi-crew aircraft, it has been found advantageous to use a device to help the pilot performing the sweeps judge and limit input size. A specifically designed handheld control fixture with a rubber band around one end, held by the pilot not flying, has proven effective; if the pilot needs to knock off the sweep, the worst outcome is the fixture is knocked out of the other person's hand.

#### *2.3.2.6 Sweep repetitions*

For a given trim test condition, three sweeps are recommended, after the pilot achieves some proficiency in application of the test technique. These will be later linked (concatenated) for data reduction to provide maximum coherence. They should be accompanied by two doublets (see Section 2.3.2.7) before proceeding to the next axis or trim condition.

#### *2.3.2.7 Adding a doublet*

A time domain maneuver at trim is best done in conjunction with the frequency sweep tests as a means of model verification. It has a two-fold purpose in first checking that the time domain response predictions of the model are correct and then that the model will be robust enough to be applicable for prediction of other input forms. The goal of the doublet is to achieve peak angular rate before reversal. Because it is symmetric, a series of doublets of varying durations will generally approximate the frequency range of the dynamic model characteristics derived from the frequency sweeps.

#### *2.3.2.8 Real-time monitoring/telemetry*

Real-time monitoring of the frequency sweep via telemetry (TM) is highly recommended, both for safety reasons and for meeting data requirements. Parameters to be monitored include, as a minimum, the pilot control input and the key output responses (i.e., accelerations, rates, and attitudes). For flying qualities evaluations, all controls and aircraft rates and attitudes, as well as overall health parameters such as RPM or torque, should be monitored to ensure a satisfactory input and that the response remains within predetermined bounds for the excitation axis as well as for off-axis. The various pre-determined safety limits for parameters that define structural or rotor/propulsor mode excitation should also be included. If structural/flight loads parameters are available then key health parameters in this context should be monitored.

For manual sweeps, some coaching from TM with respect to amplitude and KIO frequency can be expected.

Since safety is a priority, it is best to display both input and output on one time history, real-time. An experienced flight test engineer can identify if the input signal becomes too large or too small, and the 180-frequency (see Figure 9) will be obvious. Signals should be scaled and their displayed signs set so that the 180-frequency shows up as the time when output is exactly out of phase with input; a quick estimate of frequency can be made from adjacent peaks of either the input signal or the output signal. There are professional flight test data acquisition packages that will generate a simple frequency-response plot near real-time, allowing the engineer to see the 180 frequency and when a frequency twice that is reached, providing a good KIO point.

#### *2.3.2.9 Build-up*

A build-up in frequency sweep amplitude may be undertaken to assess the impact of system nonlinearities on handling qualities.

### 2.3.3 Test execution

#### *2.3.3.1 General technique considerations for manual frequency sweeps*

- Perhaps the most imperative part of the sweep procedure is to start from stabilized trim (at least 3 seconds) and end the sweep near that same stabilized trim condition (at least 3 seconds). This is required for the analysis to differentiate the excitation from the trim condition effectively.

- Lowest frequency input should be repeated since the initial low frequency cycle is not likely to be sinusoidal. A focus on near-sinusoidal timing of input while concentrating on control of the output response within defined test limits is sufficient in the low frequency band.

- Exact sinusoidal input is not required, and in fact is not desirable. The pilot, in attempting to follow sinusoidal timing cueing while simultaneously maintaining symmetry about trim, will provide sufficient input power with sufficient modulation/irregularity in the sweep which ensures broader excitation of the various frequencies. Variability between sweeps is not a bad thing. When repeated sweeps are linked together (concatenated) for data analysis then a broader bandwidth of excitation can be achieved which will provide for high coherence.

- Exact frequency progression is not mandatory, so elaborate devices for shaping inputs are not necessary. Pilot timing of control reversals and maintaining symmetry of maneuver is sufficient to capture the data required.
- As discussed previously, constant amplitude of the frequency sweep does not have to be maintained, especially for low frequency inputs where excessive attitude change from trim may occur. Coaching from team members either in the aircraft or the control room is considered for safety of build-up and avoidance of various aircraft limits. For multi-crewed aircraft, target amplitude can be cued or contained through the use of hand-held control fixtures but it is not necessary for data purposes. Target amplitude can be cued or contained through the use of control fixtures but it is not necessary for data purposes. The use of the fixture or coaching from team members either in the aircraft or the control room, is considered for safety of build-up and avoidance of various aircraft limits. If a fixture is used, the Pilot Not Flying (PNF) holds the control fixture with posts set on either side of the stick at a pre-determined point to achieve correct amplitude. The Pilot Flying (PF) should attempt to lightly touch the posts, which can be learned quickly. The PNF then adjusts the position of the fixture as the sweep proceeds to stay symmetric about trim point. There will be some tendency to push through the fixture at higher frequencies. The PNF should not constrain the input rigidly with the fixture but instead cue the pilot verbally to reduce amplitude. The test team should be aware of, and plan for the tendency for less response at higher frequencies which will commonly drive pilots to over-amplification of input amplitude, which increases risk of interacting with structural and drive-train modes.
- For the axis of excitation, focus on controlling output to a near sinusoidal response at low frequencies and then transition to a focus on constant amplitude sinusoidal input at higher frequencies (see Figure 10).
- For the axis of excitation, a drift off-of-trim should be corrected. For low frequency inputs, a shaping of the input will generally be sufficient to contain the response within established limits and maintain symmetry about trim. At other frequencies, a low frequency correction through shift of the cycle midpoint can be used to bias back toward trim to maintain symmetry. If TM coaching is used, the monitoring engineer should understand that higher amplitudes in one direction may be necessary for maintaining response symmetry and therefore factor this into their coaching, such as not calling the amplitude unless it is persistently high over several cycles.

- Get agreement ahead of time as to how to deal with off-axis responses. There is a pilot tendency to couple an off-axis control with the desired input frequency sweep. That tendency can be caused either by inertial properties of the pilot and controller, or by the tendency for the pilot to suppress coupled responses. The pilot should try to focus on excitation of the axis in question and disregard/not interact with any oscillatory off-axis response. Slowly diverging off-axis response from trim should be corrected through an agreed upon procedure. Use of a technique, that is not correlated to the inputs in the axis of excitation, should be emphasized. Off-axis inputs that are faster than those applied in the axis of excitation will generally meet this requirement. Pulse inputs toward trim in the off-axis applied from the non-flying pilot have been shown to be effective.
- A knock-it-off (KIO) call for the highest frequency should be established, whether crew initiated, TM initiated, or cued through the use of a metronome. Redundant methods are recommended. Aircraft communications, such as coaching, should be short and succinct, and be avoided in the higher frequencies as the KIO frequency is approached.

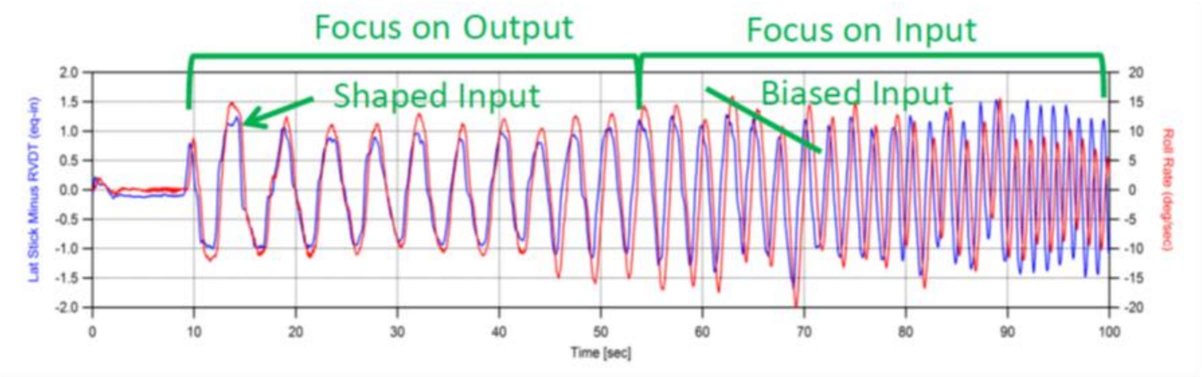


Figure 10. Focus of pilot-generated frequency sweep

### 2.3.3.2 Manual self-paced sweeps

These sweeps are timed by the pilot or assisted by an onboard non-flying pilot or flight engineer. Some sort of count is needed in the low frequency regime to approximate the period of initial inputs. Some flight test institutions use apps on tablets or smart phones to aid in this process. With practice, pilots can provide surprisingly good continuous increases in frequency by just feel of the aircraft response. Some practice may be required to slow this increase in frequency to spread it over the required record time. Two examples of self-paced sweep timing are provided here.

- The pilot, knowing the period of the initial long period input (for example 20 seconds), breaks the timing down into quarter-period intervals, with control reversal at 5 seconds, pass-through-trim at 10 seconds and control reversal at 15 seconds, etc. Then, as the frequency increases and period decreases, the pilot adjusts the quarter-period intervals, until only half-period timing can be achieved with control reversals at the half-periods. After that it is generally pilot feel of the frequency increase. Copilot coaching can help in the low frequency timing.

- A similar concept that does not depend on a full count but still cues the quarter-period is the use of a clock method as described in Tischler & Rempel (2006) where the copilot or even TM, based on period timing, will call out 3, 6, 9, 12, for control reversal, and pass-through-trim, alternatively.

#### *2.3.3.3 Metronome paced sweeps*

To facilitate collection of sufficient frequency content in the sweeps the crew may use a Modified “Chirp” metronome to cue the timing. A normal Chirp signal utilizes a uniformly increasing frequency within the range of interest. For the purposes of predicted handling qualities assessment, the initial low frequency cycle is repeated twice and then transitions to the uniformly-increasing frequency Chirp. The metronome can be a small tablet/mini pad that uses a visual indication of stick motion as well as differentiable audible beeps at the opposite points of stick reversal. This device helps avoid some of the common problems that pilots have in executing these manual sweeps such as not dwelling long enough in the mid-frequency band, going to too high a frequency which might risk structural mode interactions, and “locking” on to areas where natural mode excitation may occur. This device also helps avoid a lot of practice sweeps that may be required to sweep all frequencies within the assigned record length. The sweep shown in Figure 10 illustrates the efficacy of using a metronome. Considerations for its use are as follows:

- Place the device high enough in the pilot’s scan such that he/she can focus outside on aircraft response while still peripherally seeing cue movement for the low frequency timing.

- Wire audio such that the tones are easily differentiable but do not interfere with TM and intercom communications.

- If the metronome is used for dwells, it should be programmed to allow at least 2 cycles for pilot flying to achieve synchronization with the metronome. Desired dwell timing starts then.

- Sweep frequencies will be programmed into the metronome and marked for the appropriate axis since start and end frequencies vary according to the axis being excited (do not mistakenly use a longitudinal sweep command to conduct a yaw axis sweep, for example).
- At low frequency the pilot references the visual cue on the metronome to achieve timing with aircraft response. With medium and high frequency inputs the pilot uses audio cueing from the metronome to cue stick reversals for the sweep while concentrating on smooth sinusoidal inputs.
- If the pilot gets out of phase with the metronome at some point, it is advisable to simply focus on getting back in phase with the audio tone that is nearest to the input reversal and cue on it for the remainder of the sweep, even if the visual metronome is completely 180 out of phase.
- KIO will be called by TM upon reaching target highest frequency, but the PF should already be stopping since the metronome will time out.

#### *2.3.3.4 Programmed test inputs (PTI) sweeps*

Sweeps generated with programmed test inputs (PTI) can be an effective, and efficient, method for obtaining the desired data. There are a number of issues with automated sweeps, however, and the user must be able to account for and minimize these issues.

A key concern is defining the input size of the automated sweep. At the low-frequency end, sweep amplitude must be low to prevent driving the aircraft far from initial trim. Subsequent cycles will be at higher frequencies, so that the aircraft might never return to near initial trim, and the flight condition at the end may be far from (perhaps even dangerously so) the initial trim condition.

Pilots can bias inputs to correct for long-term divergence from intended trim. Pilots can also reduce amplitude if there is any sign that the aircraft response is higher than predicted, or stop entirely if safety is a concern.

### 2.3.4 Safety considerations

Various limits can be applied for KIO call based on the axis of test, and the aircraft system definition. Examples of some common KIO criteria are described below for a manual longitudinal hover sweep:

- Less than 10% remaining pilot control margin (i.e., effector-based) in any axis.
- Bank or pitch attitudes in excess of ±15 degrees.
- Altitude below half of initial altitude or average descent rates in excess of 200 fpm (hover).
- Input greater than 0.5 in. from target amplitude over several cycles or greater than 1 in. from target for a single cycle (center stick controllers).
- Frequency greater than the test condition target final frequency.
- Any substantial excitation of an unexpected modal frequency.

KIO actions should be robust and consider excitation of drivetrain, rotor/propulsor and aeroservoelastic modes, pilot-assisted oscillation (PAO), and PIO. An example for actions following a manual sweep KIO is described below:

- Abandon the task and go low gain on control toward re-establishing trim condition.
- Relax grip on the designated flight control to the extent possible.
- Set nominal RPM (may be aircraft and test condition specific).
- If response continues, consider a trim change toward a known safe condition -typically level flight at a lower airspeed for high-speed points.

## 2.4 Data reduction methods

### 2.4.1 Data quality assessments

To achieve the best estimated system in the time or frequency domain, careful attention should be paid to the factors that can influence and expose the quality of the results. This section briefly discusses several of these key factors as described in Klyde & Schulze (2020).

#### *2.4.1.1 Signal quality review*

Before processing a selected input and output data set, the signals should be evaluated for the following items:

- A consistent sample time or signal update rate (see Figure 11);
- Time shifts, especially when signals are obtained from different sources and have not been time-synched;

- Data drop outs (see Figure 12);
- Data buffering (see Figure 13); and
- Nonlinear behavior (see Figure 14), the triangle-like stabilizer position indicates control surface actuator rate limiting.

Issues with any of the above items can significantly degrade the quality of the identification results.

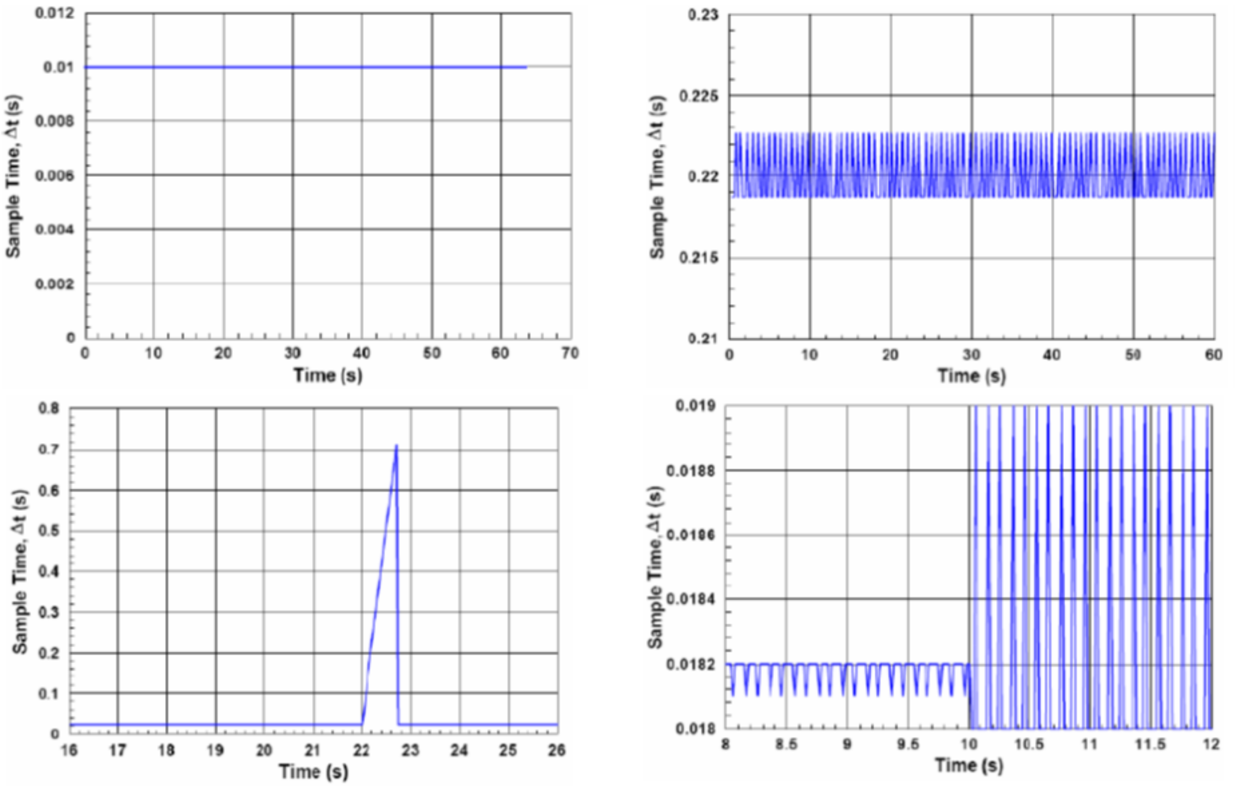


Figure 11. Sample times from example flight test data sets

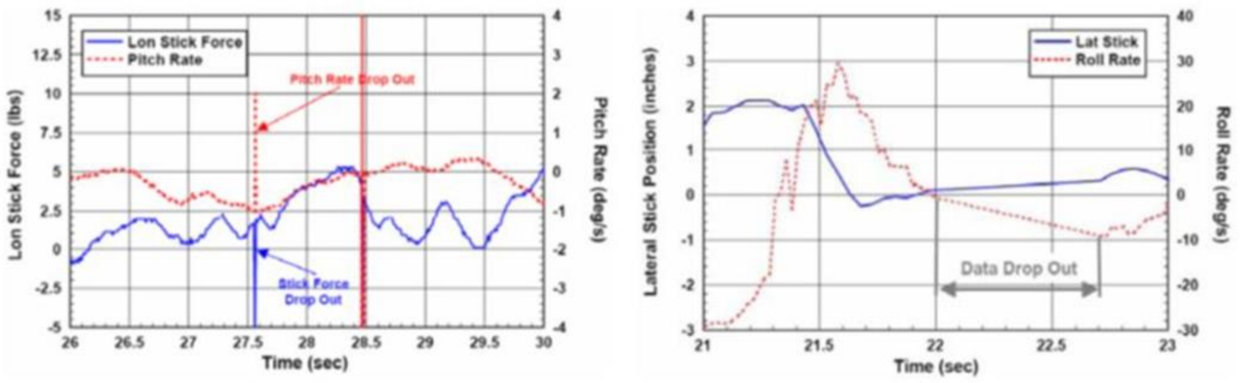


Figure 12. Example flight test data drop outs

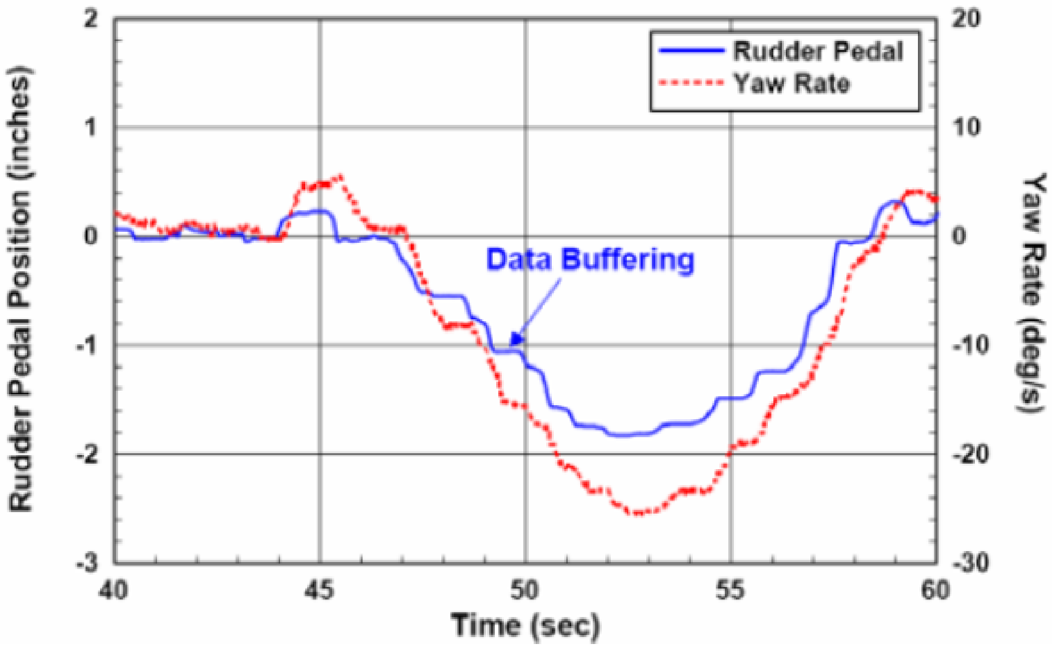


Figure 13. Example flight test data buffering

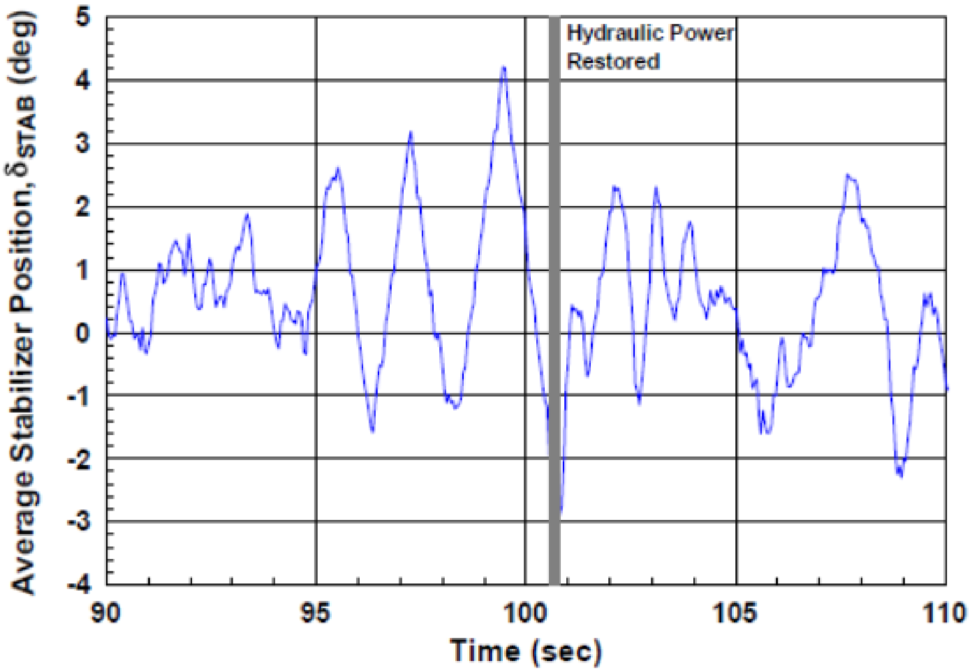


Figure 14. Example flight test nonlinearity (control surface rate limiting)

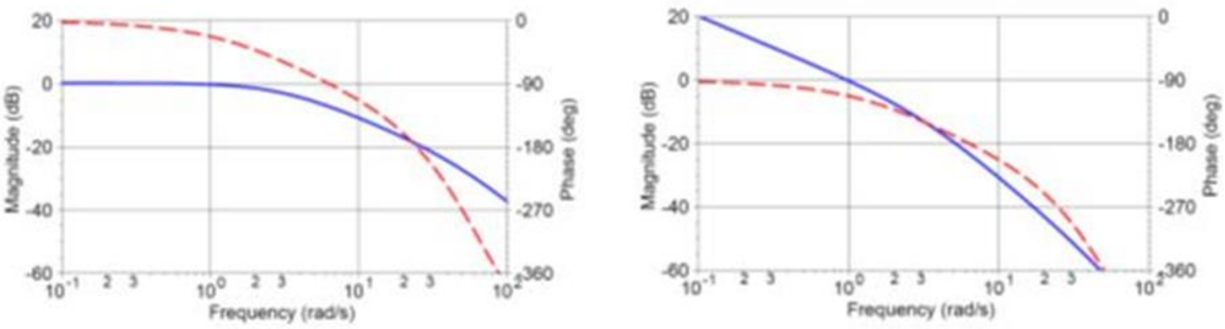
#### *2.4.1.2 Summary*

When conducting analysis on time series signals:

- Inspect the time series signals for possible anomalies as described above.
- Consider running checks on kinematic consistency. If body-axis rates (P, Q, R) and earth-axis angles (Φ, Θ, Ψ) are available, calculate earth-axis rates and confirm that they correctly give the corresponding body-axis rates (e.g., body-axis roll rate P should be equal to $-\sin\Theta\dot{\Psi}+\dot{\Phi}$). Small differences indicate possible synchronization issues, but large differences suggest measurement errors. Equations for converting between earth axes and body axes can be found in any good flight mechanics textbook, for example Yechout et al. (2014).
- To minimize bias, reduced power at higher frequencies, and low signal to noise issues, use attitude rate (pitch rate, roll rate, or yaw rate) as the primary output signal when conducting frequency responses analysis. Since angular attitude is used as a primary handling qualities state, body-referenced pseudo-attitude can be created by postprocessing the frequency response by 1/jω (on a Bode plot, change slope of the magnitude curve negatively by -20 dB per factor of 10 in frequency, and subtract 90 degrees from phase). Example rate and integrated rate (i.e., pseudo attitude) frequency

responses are shown in Figure 15 where the magnitude response is the solid blue line and the phase response is the dashed red line.

- To obtain a complete controlled element response including the feel system, flight control system, and vehicle, use inceptor force as the input. This will include the complete command path for any inceptor configuration or control mode response type.
- To obtain a controlled element response including the flight control system and vehicle, use inceptor position as the input.
- To obtain a controlled element response of the vehicle, use inceptor position as the input; use control surface position as the input to obtain bare airframe response.



**a) Pitch rate** **b) Integrated pitch rate**

Figure 15. Example rate and integrated rate frequency response

## 2.4.2 Short duration inputs

### *2.4.2.1 Stick rap (pulse)*

- If a DAS is available, follow recommendations above for confirming data quality.
- Handheld data can be used to get a reasonable estimation of dynamic response if a DAS is not available. An observer notes number of overshoots and undershoots resulting from the rap, and if possible, uses a stopwatch to measure either the time between overshoots or time from the first over/undershoot to the next. This will probably require multiple runs to get the numbers recorded accurately.
    - If there is a single, dominant mode, rough approximations for damping ratio and undamped natural frequency can be obtained from the hand-recorded data. Do not count the initial response following the rap, but the response after the initial (the

sketch below may be useful for this discussion). Count the number of undershoots and overshoots.

    - If the number is seven or greater, damping ratio is less than 0.1.
    - If the number is between one and six, see Mitchell & Klyde (2008), $\zeta \approx \left[7 - \text{ number of over/undershoots}\right]/10$.
    - If there is no noticeable undershoot, damping ratio is 0.7 or greater.
  - Time between peaks for the first undershoot and the first overshoot can be used to estimate undamped natural frequency. Defining that time as $T$, $\omega_n \approx \pi / (T\sqrt{1-\zeta^2})$

- For the sketch below in Figure 16, there is one undershoot and one overshoot (peaks labeled 1 and 2, respectively). Time between them is $T = 1.7$ sec. From the above, $\zeta = 0.5$ and $\omega_n = 2.0$ rad/s. The simple system used for this example is a fourth-order transfer function with a dominant root at $\zeta = 0.5$ and $\omega_n = 2.0$ rad/sec and a high-frequency second-order pair that adds a slight amount of lag.

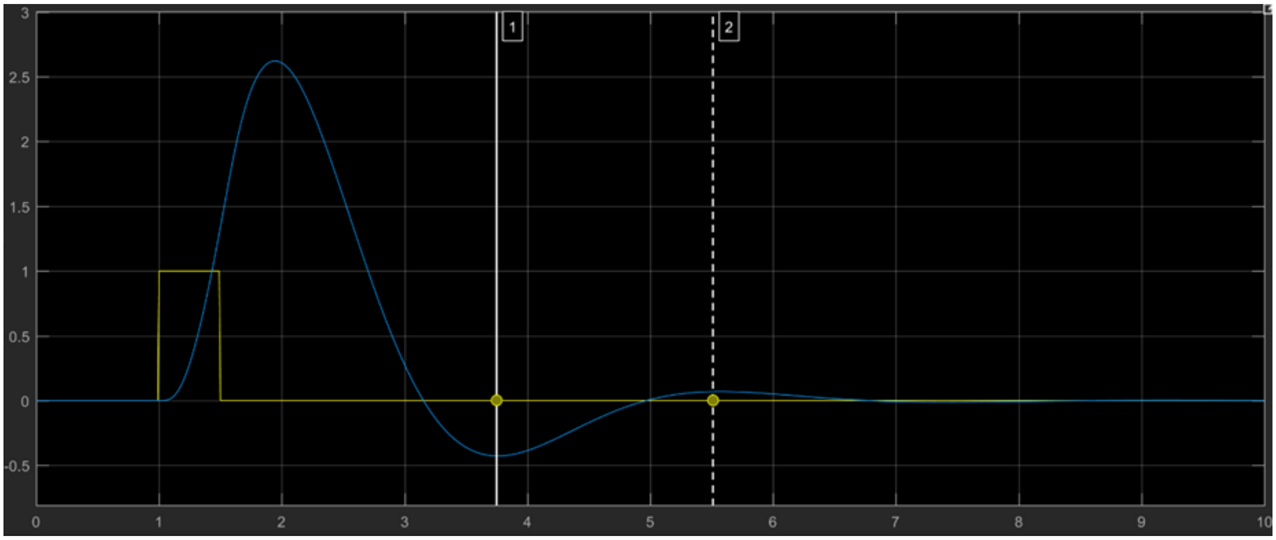


Figure 16. Example time response measures for a second-order system

# 3 Use of pilot rating scales

## 3.1 Cooper-Harper handling qualities rating scale

### 3.1.1 Application and usage of the Cooper-Harper scale

The desired and adequate performance thresholds of the emerging FTM/HQTE catalog were developed specifically for use with the Cooper-Harper Handling Qualities Rating Scale shown in Figure 17 (Cooper & Harper, Jr., 1969). While the use of this scale will generate a numeric rating, it is the commentary accompanying the ratings that is most important to the handling qualities evaluation. The use of Cooper-Harper Ratings requires the definition of numerical values for desired and adequate performance. The performance thresholds are set primarily to drive the level of aggressiveness and precision to which the maneuver is to be performed. Adherence to 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 pilots, however, should not be expected to base their ratings solely on performance, especially rigid "pass/fail" requirements. For example, if desired performance requires tracking an attitude within 2 degrees for 50% of the task time and the actual performance was 49.5% of the task time, did the pilot really fail to meet this requirement? In cases where the performance does not meet the specified limits, it is encouraged for the evaluation pilot to make as many repeated runs as necessary to ensure 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 maneuvers that are by design very short in duration, at least a total of three runs should be encouraged.

For some maneuvers the pilot may find it difficult to perceive actual performance. For example, in the offset landing task a limited field-of-view will restrict the pilot's ability to see the touchdown zone. In such instances, the pilot will frequently comment that better performance is 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 Precision Hover, hover boards and cones are located so that they are easily visible to the pilot to indicate the correct reference for achieving desired performance. In any case, 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, especially for those excursions that may have little to no impact on the assessment of handling qualities in the task. In this case the pilot should be asked to add comments on the effects of the visual field – as opposed to just 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. Occasional exceedances may be due to lack of perception of the requirements, not lack of intensity or precision on the part of the evaluation pilot.

For use in the evaluation of military aircraft, the ratings are grouped into handling qualities levels where Level 1 corresponds to ratings of 1 – 3, Level 2 corresponds to ratings of 4 – 6, and Level 3 corresponds to ratings of 7 – 9. While not part of the civilian certification process, these levels are related to the criteria that are used within the military specifications (e.g., ADS-33E-PRF) to predict handling qualities.

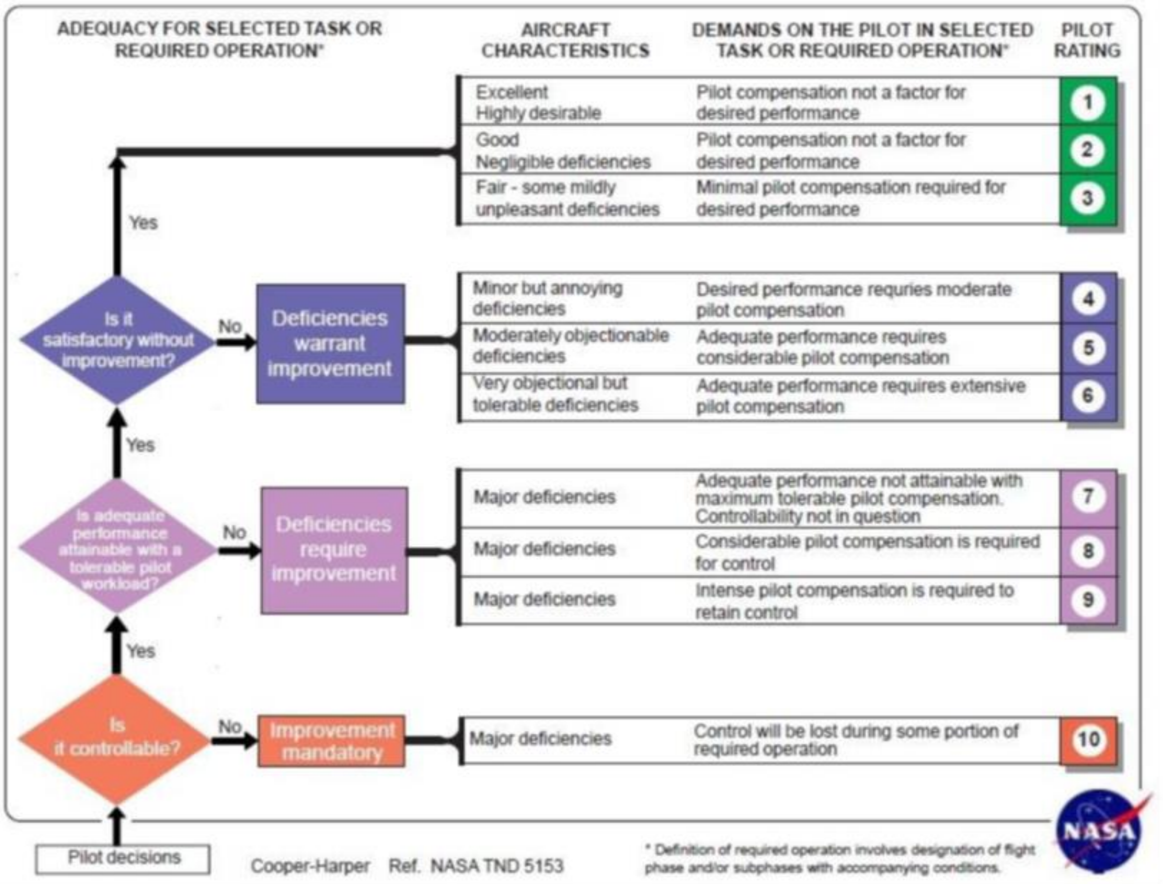


Figure 17. Cooper-Harper handling qualities rating scale

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 compensation required. It is important to remember that desired performance can still result in a Level 2 rating if achieved with moderate compensation. Conversely, a configuration should not be down rated by an occasional small 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.

### 3.1.2 Considerations when using the Cooper-Harper scale

The Cooper-Harper scale is often misinterpreted. It is not uncommon for those unfamiliar with the scale to focus on the ten-point ordinal values on the right side of the chart. In its correct application, however, the scale is used in HQTE development and application to formalize methods for handling qualities testing; to clearly delineate expectations for task performance; and most importantly, after the HQTE is flown, to assist the test pilot in focusing subjective opinions about a particular aircraft and task. In engineering, there is always a drive to quantify everything, even the purely qualitative, so HQRs as numbers become valued commodities. But it is the comments that have the most value.

For a single HQTE, the scale is to be applied to a single aircraft configuration, loading, operational state, and flight condition, though transitions (e.g., in response type/flight control system modes) are anticipated. It is considered a necessary, but not sufficient, method to provide a comprehensive evaluation. If multiple pilots consider the aircraft to be satisfactory without improvement, it has exhibited satisfactory handling qualities for the particular HQTE and aircraft state, not for the aircraft throughout its flight envelope. This means that it is not possible to verify the level of handling qualities of an aircraft everywhere in the envelope; the HQTEs are instead spot-checking individual points. It is entirely possible that the selection of HQTEs may miss some important element of the aircraft's intended use, or that the catalog of HQTEs may not adequately address all elements. Thus, the HQTEs alone are a necessary, but not sufficient method to demonstrate compliance.

## 3.2 Pilot-induced oscillation tendency rating scale

### 3.2.1 Defining pilot-induced oscillations

Pilot-induced oscillations (PIO) continue to persist at least partly because the signature or nature of PIO often goes unrecognized (Mitchell & Klyde, 2008), whether in the design process, flight test, or normal operations. That is, it goes unrecognized until a catastrophic or near catastrophic event occurs. To lay the groundwork for a road forward, a definition of PIO was introduced.

PIO is defined as a sustained or uncontrollable unintentional oscillation in which the airplane attitude, angular rate, normal acceleration, or other quantity derived from these states, is approximately 180 degrees out of phase with the pilot's control inputs.

There must also be recognition that there are different types of PIO of varying intensity. Not all PIOs are severe enough to ground an aircraft, however, all PIOs do require comprehension, so that the likelihood of a catastrophic event is diminished. To this end, the following elements that encompass the PIO signature should be considered throughout the life of the aircraft, even late in its operational life as missions are expanded and new loading configurations added:

- Closed-loop pilot-vehicle system: Comprehension of the interacting elements of PIO is paramount to recognizing the PIO signature. PIO shows itself in those closed-loop scenarios that can result in reduced pilot-vehicle system stability margins. Due to the nature of those evaluation tasks that require higher precision and aggression, the pilot may respond with higher pilot-vehicle system bandwidth inputs in such scenarios (Mitchell & Klyde, 2020), environmental conditions, or an unpredictable aircraft response, such as that associated with actuator rate limiting.

- Oscillations: PIO is, by definition, an oscillatory response. However, the presence of oscillations alone does not indicate PIO. It is important that oscillatory behavior in which the airplane is responding as intended to pilot inputs not be identified as a PIO. Look for the complete PIO signature before making such judgments.
- Control inputs: For a given task, control inputs are generally significantly higher in amplitude in a PIO when compared to a non-PIO case.
- Body axis rates: For a given task, body axis rates are generally significantly higher in amplitude in a PIO when compared to a non-PIO case.
- Input/output phase: In a PIO, a key aircraft response will be at least 180 degrees out of phase with the pilot, typically attitude or acceleration. If this out of phase character is not present, then it is not a PIO, even if other elements of the PIO signature are present.
- Large increase in input/output power: There is a dramatic increase in input and output power when a PIO is encountered (Mitchell & Klyde, 2008). Peaks in input/output power are centered at PIO frequency.

### 3.2.2 Rating tendency for pilot-induced oscillations

Additional ratings may be collected to provide further insights into a given evaluation. The most significant of these is the Pilot-Induced Oscillation Rating (PIOR) Scale shown in Figure 18.

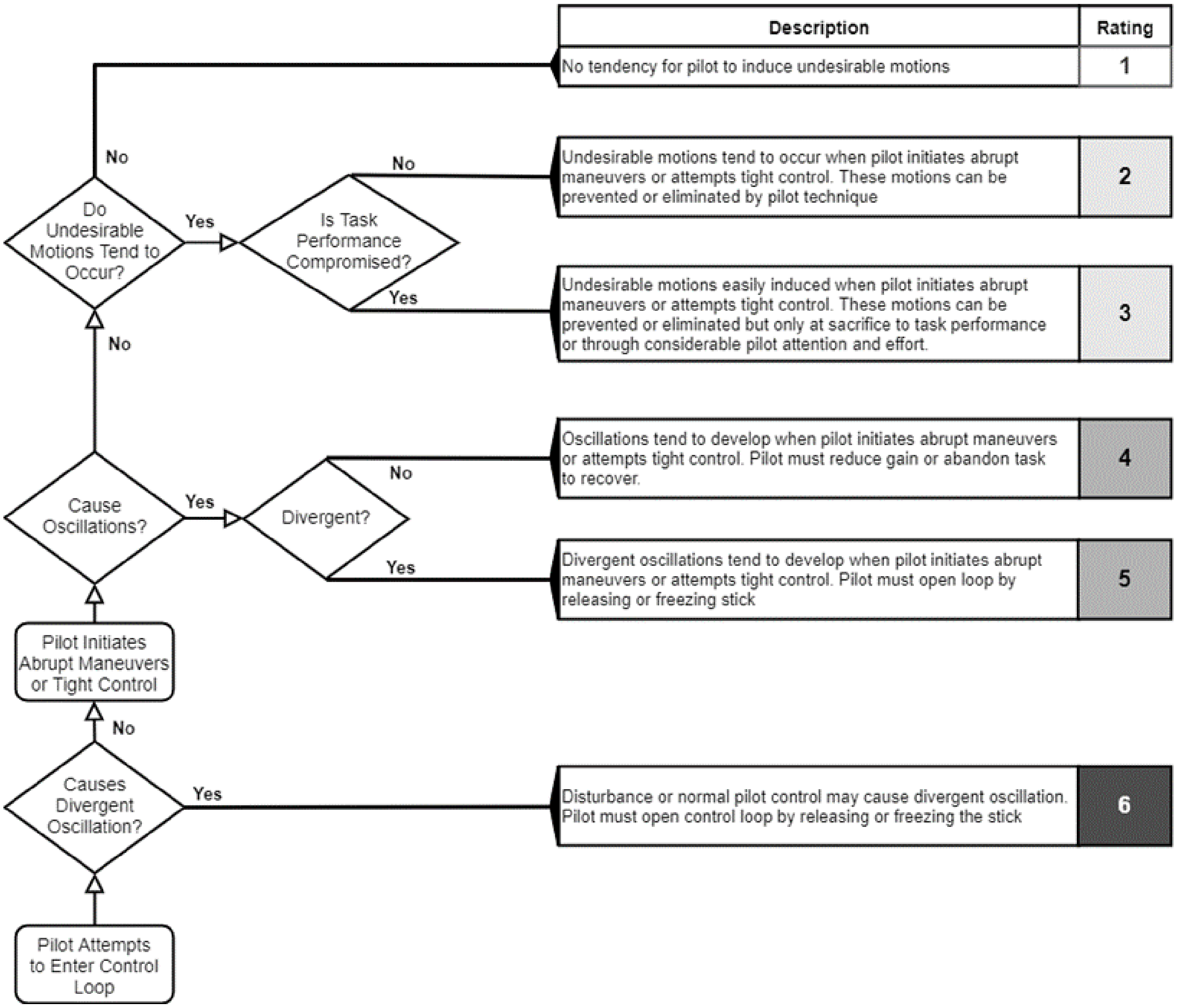


Figure 18. Pilot-induced oscillation tendency rating scale

Although not specifically designed to expose PIO tendencies, many of the precision FTEs/HQTEs (e.g., precision hover, attitude captures, and attitude tracking maneuvers) often reveal the handling qualities “cliffs” that can lead to PIO. A hybrid of two scales is shown in Figure 18, one is a decision tree scale (Weingarten & Chalk, 1981) and the other is the original “word” scale (DiFranco, 1967) that have been combined into an entity. The decision tree should be applied by the pilot in a manner similar to that discussed for the Cooper-Harper HQR scale. To aid in distinguishing between “oscillations” and “undesirable motions,” the evaluator can add “out-of-phase” to the “causes oscillations” question in the decision tree. That is, as described above, the oscillation will be approximately 180 degrees out of phase with the pilot command input. The additional dialog in the word scale, however, should also be considered prior to assigning a rating. This will help the pilot evaluator to further distinguish between undesirable motions such as “pitch bobble” and oscillations. Configurations are often rated too harshly when the decision tree scale alone is used to assign ratings.

# 4 Handling qualities testing

## 4.1 Operational relevance

MTEs in ADS-33E-PRF are not, and never were intended to be, precise replications of operational mission tasks. Rather, they are stylized, formalized task elements that are meant to require pilot effort, attention, and workload that is representative of the more challenging tasks that might be encountered in operational use such that handling qualities cliffs may be identified, if they exist. They are, by design, more difficult than the usual operational task. With respect to the powered lift aircraft testing described herein, consider, for example, the Precision Hover HQTE. In this maneuver, there is a translation portion, a flare portion, and a station-keeping portion. These pieces might roughly correspond to hover taxi, quick stop, and hover in a typical flight, except that the task constraints (the maneuver itself) and the performance limits (measures of performance execution) are generally much more stringent than would be required in a “typical” operational flight. The Hover HQTE is therefore intended to represent not the “typical” hover taxi, etc., but a more demanding composite task, to expose potential handling qualities issues that might not show up in normal operation. Most developmental flight testing, and even early operational testing, is performed in good weather, with low winds and high visibility. Tight task constraints in HQTEs are meant to compensate, to some degree, for the absence of outside influences.

## 4.2 Piloted simulation evaluations in a validated simulator

### 4.2.1 What is a validated simulator?

This topic is beyond the scope of this test guide but remains an important issue to be resolved. Standards for addressing this topic are in process on the civilian side. On the military side, a recent compendium of knowledge was published by the North Atlantic Treaty Organization (NATO) (2021). In short, a validated simulator will feature vehicle models that have been validated against flight data for the flight conditions used in the evaluation, high fidelity cockpit inceptors that are representative of the flight vehicle, and visual displays that offer the field-of-view necessary for the selected evaluation task. Motion may or may not be required for a given evaluation scenario.

### 4.2.2 Testing in a validated simulator

In addition to acting as a predictive data collection tool, a validated flight simulator may allow the applicant to take credit for testing that would otherwise be required to be demonstrated in flight. This very concept is being explored in current industry consensus body committees such as SAE and ASTM. Flight simulation can further be utilized in other ways to provide possible relief for actual flight test requirements. These can include:

- As a flight test rehearsal tool to practice SQA and FQA maneuvers and HQTEs to proficiency, hone TM procedures, and generally improve test efficiency.
- Establishing HQTE course familiarity and exposing the pilot to potential control law and/or handling qualities issues early in the design process.

## 4.3 Understanding HQTE

### 4.3.1 What are HQTEs?

Given the complete definition in Section 1, in short, HQTEs are pilot closed-loop tests intended to assess the handling qualities of the aircraft through piloted simulation and flight test. The HQTEs are “standard” tasks or conditions, using engineered maneuver constraints and tolerances that stress the pilot-vehicle integrated design.

### 4.3.2 What is the intent of HQTE testing?

HQTE testing will assign handling qualities levels through the use of Cooper Harper Handling Qualities Ratings and associated pilot comments towards the goal of:

- Assuring safe operations within the operational envelope (both on-ground and in-flight).
- Identifying Pilot Induced Oscillations susceptibility, handling qualities deficiencies, Human Machine Interface deficiencies, or other hazardous flight control characteristics.
- Assuring the intended operations can be accomplished without requiring exceptional piloting skill, alertness, or strength.

### 4.3.3 How are HQTEs applied?

While potentially linking acceptable HQ levels to the following conditions, the HQTE matrix should account for:

- Flight conditions: flight envelope, environmental conditions, and configuration, including transition (across flight modes, response-types, reference frames, vehicle configurations).
- State: normal conditions and failure conditions not shown to be extremely improbable. Conditions include propulsive and non-propulsive flight control failures that reduce capability or degrade handling qualities.

- Settings: selectable flight controls modes (e.g., normal, training, backup/reversionary).

### 4.3.4 HQTE philosophy

HQTEs as “elements” of operational maneuvers, reflect an evolution in handling qualities evaluations where more quantitative short-look evaluations are focused on certain aspects of the design in a highly constrained task. A series of these element tests has been shown in military flight test programs to evaluate an indirect flight control system (FCS) design in a more comprehensive and efficient way than traditional HQ demonstration flight tests. Their application for certification testing is a direct benefit of the experience gained in the military community, where issues with advanced flight control systems have been exposed, verified, or in some cases, directly refuted, by the application of HQTEs. As indirect FCS become more prevalent in civilian aircraft, as they have become in military rotorcraft, more elaborate means are required to test for possible HQ issues related to the operation of the FCS, as distinct from aircraft performance or stability limitations. The HQTE philosophy as adapted from the Aeronautical Design Standard (US Army, 2000) is as follows:

- HQTEs are designed to be used with the Cooper-Harper Handling Qualities Rating Scale (Cooper & Harper, Jr., 1969), shown in Figure 17.
- Formal HQTE evaluations (i.e., those for certification to stability, controllability, and trim airworthiness requirements) are to be flown by at least 3 pilots.
- HQTEs are intended to be flown in those conditions that are considered most critical in terms of handling qualities, controllability, and maneuverability. This is an example of the direct benefit of detailed analysis and piloted simulation, as the potentially most critical conditions can be defined in advance of flight test.
- Several aspects are employed in the HQ evaluation to increase validity and therefore reduce variability in assigned handling qualities between pilots when using the Cooper-Harper Handling Qualities Rating Scale:
    - Task performance is explicitly controlled and related to aircraft quantitative predictive flying qualities metrics (e.g., those found in ADS-33E-PRF) for the given aircraft operational case.
    - Performance tolerances, in combination with other constraints, are used to press the pilot into the control-loop. They are also meant to be surrogates for conditions that add to pilot stress or urgency but cannot be specified in a formal manner.

  Fatigue, distractions from other duties, and environmental factors are examples of these stressors that force high pilot precision.

  - Tasks are performed within the already established flight envelope with sufficient margins from performance and control boundaries to differentiate HQ deficiencies and avoid dispersion in pilot ratings that might result from encountering aircraft limits.
  - Task performance is cued and measured real-time with immediate feedback to the pilot prior to formal evaluations that receive ratings. To facilitate this feedback, various measures are used, to include easily configured ground-courses.
  - The pilots are afforded practice in the maneuver toward achieving proficiency and better understanding of the required pilot compensation. Then, the pilot repeats the task “for record” toward evaluating repeatability of compensation. “Record” runs are rated by the pilot based on perceived task performance. Past experience has shown that pilots may over-emphasize task performance at the expense of considerations toward pilot compensation required and observed aircraft characteristics when direct feedback of task performance is given as part of the rating/commentary process.
  - Pilot assessment of compensation and workload remains subjective, but is refined through detailed process guidelines, as described in Section 4.

## 4.4 HQTE test considerations

To better understand the integration of the HQTE concept into flight test certification, it is important to describe, through example, an analysis of how HQTEs might be determined and utilized in the overall design and certification process. This will be based on some of the concepts found in ADS-33E-PRF (2000), as adapted to the civil certification.

### 4.4.1 UAM Maturity Level (UML) as an example for aircraft CONOPS to support HQTE integration

The vehicle Concept of Operations (CONOPS) will figure heavily into HQTE analysis, and in this regard the UAM Maturity Level (UML) as proposed by NASA (Goodrich & Theodore, 2021) is offered here as one example of UAM aircraft CONOPS. The UML concept was introduced in Section 1.5 and will be applied in the following discussions.

#### *4.4.1.1 UAM Maturity Level (UML) scale*

The UAM Maturity Level (UML) was proposed by NASA to categorize significant phases expected during the evolution of a UAM transportation system from the current state of the art to a highly developed, future state where UAM is a ubiquitous capability, like automobiles today. The UML are differentiated by a combination of 3 primary attributes: traffic density, operational complexity, and reliance on automation. These are then matrixed against the areas of evolution that include the vehicle design, airspace design, and community, see Figure 4. The vehicle design evolution, as described under UML is largely a function of automation level that can then be mapped to the means of compliance for certification guidelines. A notional example is offered in Figure 4 in Section 1. The restricted scope of this test guide is such that it is representative of the UML-2 level, where the focus is on piloted handling qualities.

#### *4.4.1.2 Example UML-2 Concept of Operations*

UML-2 is used here as an example CONOPS in that there is sufficient requirement for driving safety and redundancy into the aircraft design to achieve type certification and allow for operations under a Part 135 air carrier certificate while piloted by a certified and rated Pilot in Command. This UML will support initial commercial use of the air vehicle at usage levels slightly higher than current helicopter operations and will allow for the early development of the infrastructure that is critical for later large-scale UAM operations. Here, the aircraft will largely be flown through augmented flight controls, and therefore HQTE usage figures heavily into certification.

The aircraft at UML-2 will be piloted by a single trained pilot in VFR conditions. The Service Provider, ANSP, and Supplemental Data Providers will coordinate and advise the Pilot through communications/datalinks but not be integrated into aircraft automation. Pilot-controlled automation is contained within the aircraft. Given that powered lift UAM configurations are likely to be both unstable and over-actuated, at least in powered-lift flight, relatively sophisticated, high-authority flight control systems will likely be needed to assist pilots flying the aircraft in achieving the required levels of safety, performance, and robustness. Also, aircraft power and energy management systems will likely require relatively sophisticated automation. Beyond control and power management systems, it is not expected that higher levels of aircraft automation would be necessary for low density and low complexity VFR operations, and the vehicles may have relatively minimal automation beyond these basic control and management systems to limit initial certification costs, risks, and delays. The augmentation and automation in this regard is therefore considered "assistive." Flight operations under this example are planned to heliports under air carrier guidelines. Vertiport guidelines, as of this writing, are still being formulated. The example vehicles, in operational context, are viewed as "distributed air carriers" in that many smaller vehicles are anticipated to replace larger traditional helicopter air carriers, so a various mix of normal and transport guidelines is expected in certification of these new vehicles. Initial operations in this example will be constrained to existing air infrastructure but evaluated toward an evolving UAM corridor concept.

### 4.4.2 Selection of HQTE for the evaluation of the Aircraft Flight Control design

To further illustrate the HQTE verification process, an example UAM aircraft is proposed that employs a generic hybrid-lift design. It is assumed that the aircraft will have VTOL hover capability through thrust-borne lift at low-speed and wing-borne lift at high-speed and that it may employ any combination of propulsors to achieve these means. It is assumed that indirect flight controls are used throughout the flight envelope. The example vehicle employs wheeled landing gear.

#### *4.4.2.1 Examination of flight control response types and mappings*

Augmentation and automation design can be directly related to CONOPS details. It is this very concept that is embraced in the ADS-33E-PRF (2000). This standard takes a two-pronged approach in the analysis of the aircraft design and testing as they relate to CONOPS. This can be described through two means: 1) “Operational Environment” and 2) “Operational Mission” requirements in context with the concept of operations. This melds well with the performance-based approach for certification means of compliance testing.

#### *4.4.2.2 Operational environment*

While ADS-33E-PRF  (2000) prescribes required flight control response types based on the operational environment, it is not the intent of this test guide to do so. It is, however, anticipated that consideration of the various aspects of the operational environment provides valuable insight into the assessment of the overall handling qualities of the aircraft, and helps in focusing on flight control design integration. By flight phase, the CONOPS details can be translated into these “Operational Environment” considerations that include the following:

- low-speed ground-referenced visual environment,
- cruise flight air-referenced visual environment,
- divided attention requirements,
- slope landing requirements,
- winds and turbulence, and
- flight displays.

Table 1 below reflects the expected operational environment considerations for UML-2. It is broken into flight phases as well as both air-referenced and ground-referenced operations in that control response-types and their associated sensors may vary accordingly. This delineation of the many environmental factors can then aid in the understanding of stability and augmentation designs for the piloted aircraft.

Table 1. Operational environment representative of UML-2

| Flight Phase | Ground Referenced | Air Referenced |
|---|---|---|
| On-Heliport Operations | GVE[1] | |
| Climb-out | GVE[1], Divided Attention[3] | VMC[2], Divided Attention[3] |
| Cruise | | VMC[2], Divided Attention[3] |
| Approach | GVE[1], Divided Attention[3] | VMC[2], Divided Attention[3] |
| Landing | GVE[1] | VMC[2] |
| Off-Heliport Precautionary Landing | GVE[1]<br>Slope Operations to "x" degrees. | |

[1]Good Visual Environment (GVE) based on expected minimal vertiport visibility requirements and the provision of sufficient detail to allow for aggressive and precise maneuvering.

[2]Visual Meteorological Conditions (VMC)

[3]Divided attention where the single pilot flying is required to perform non-control-related side tasks for a moderate period of time. Otherwise, fully attended operations are assumed.

### Visual environment

For this example, the term Good Visual Environment (GVE) is used to describe and better differentiate ground-referenced visibility such that it does not limit aggressive and precise maneuvering near the ground. Visual Meteorological Conditions (VMC) is used in its traditional definition for air-referenced flight.

### Divided attention

Divided attention, here, is defined where the single pilot flying is required to perform non-control-related side tasks for a moderate period-of-time. This would require the aid of various hold features of flight control augmentation or autopilot like automation. In this example, there is some expectation that a single-piloted aircraft in the UAM environment may have diverse pilot duties that may require the pilot to remove his hands from the flight controls momentarily or divert his attention to operating systems other than flight controls. Otherwise, fully attended operations are assumed for on heliport operations.

### Slope landing

As an environmental factor, slope landing gets little attention in ADS-33E-PRF (2000) or other certification guidance. However, lessons learned in fly-by-wire designs would suggest that land-air transitions can become critical design areas for initializing higher augmentation modes and changing sensitivities of controls that may be desensitized on the ground to avoid adverse ground reactions. With weight-on-wheels sensor selection, sustained operations with one landing gear in contact with the ground may be found useful for investigation. In this example, some amount of slope operations is anticipated due to landing on an unimproved surface in the case of a precautionary off-vertiport landing.

### Winds and turbulence

The UAM mission, where urban environments are likely to represent inconsistent, variable wind and turbulence conditions, must be considered in the flight control design. The disturbance rejection capabilities of advanced flight control designs are expected to address these conditions but may do so at the cost of performance and control margin awareness. Additionally, as learned in tiltrotor development, there are unique considerations that impact flight control design associated with flying an airplane-like fuselage and empennage at various wind azimuths in VTOL flight.

### *4.4.2.3 Flight displays as part of operational environment*

Higher augmentation strategies that provide improved stability and precision can come in conflict with agility requirements. This conflict, observed in military aircraft, has driven various approaches, to include mission-task-tailorable selectable flight control modes, or hybrid flight control responses that utilize regime recognition for automatic transition to less agile more stable modes as the aircraft approaches the hover regime. A third approach is to attempt to provide cueing and symbology to allow for sufficient awareness of attitude and drift in a degraded visual environment (DVE) to utilize a lesser augmentation flight control design that preserves agility. These methods all have various issues that have been historically difficult to achieve due to either sensor requirements, failure rates, abuse cases for improper mode interactions, or poor mode awareness. To achieve the balance of agility requirements and stability and precision, modern military platforms have all tended toward a mixed use of all three of these methods.

One can anticipate that in UAM operations, high fidelity flight displays that provide for attitude and drift cueing as well as predictive capabilities (i.e., deceleration point for the Translational Rate Command response-type or TRC) will likely be employed to provide for improved handling qualities. The combined use of displays with higher flight control augmentation, and especially automation, will likely figure heavily into the evolution of these air vehicles toward remotely piloted operations. Improved techniques for evaluating their use and incorporating them into the overall handling qualities assessment of the aircraft should be examined in certification. Experience in FAA sponsored research has shown that handling qualities are often tied up inextricably with the flight control system, the inceptor design, and the displays used by the pilot.

#### *4.4.2.4 Operational mission as a driver for HQTE selection*

The operational mission requirements that are anticipated within the CONOPS will be the chief driver for selecting HQTEs and will additionally inform flight control design. In our example, the elements of Table 1 are further subdivided in Table 2 into anticipated "Operational Mission" tasks based on CONOPS for the UAM mission. This HQTE list is not comprehensive and not all of those listed have been fully vetted. They are listed here to exemplify the selection process.

Table 2. UAM HQTE List for UML-2 Example

| **Example: UML-2** | **Ground-Referenced** | **Air-Referenced** | **Precision, Aggression**[2] | **Representative HQTEs** | **Augmentation Considerations**[3] |
|---|---|---|---|---|---|
| On-Heliport Operations | GVE1 | | Nominal Ops | | |
| | | | P, NA | Ground Taxi** | Fully Attended |
| | | | P, NA | Precision Hover* | |
| | | | P, NA | Hovering Turn & Hold | |
| | | | P, NA | Vertical Landing | |
| | | | P, NA | Vertical Reposition & Hold | |
| | | | P, NA | Rolling Takeoff** | |
| | GVE1 | | Boundary Avoid4 | | |
| | | | NP, A | Lateral Reposition & Hold* | Fully Attended |
| | | | NP, A | Depart-Abort* | |
| Climb-out | GVE1 | VMC | P, NA | (VTOL) Takeoff | Divided Attention |
| | | | P, NA | Waveoff/Go-Around | |
| | | | P, NA | Transition | |
| Cruise | | VMC | Nominal Ops | | |
| | | | P, NA | Speed Control | Divided Attention |
| | | | P, NA | Pitch Attitude/FPA Capture and Hold | |
| | | | P, NA | Bank Angle Capture and Hold | |
| | | | Collision Avoidance5 | | |
| | | | NP, A | Pull-up & push-over | Fully Attended |

| **Example: UML-2** | **Ground-Referenced** | **Air-Referenced** | **Precision, Aggression[2]** | **Representative HQTEs** | **Augmentation Considerations[3]** |
|---|---|---|---|---|---|
| | | | NP, A | Roll Reversal | |
| Approach | GVE1 | VMC | P, NA | Transition | Divided Attention |
| | | | P, NA | Heliport Approach* | |
| | | | P, NA | Rolling Landing** | Fully Attended |
| Off-Heliport Precautionary Landing | GVE1, Slope Operations | VMC | P, NA | Decelerating Approach<br>Slope Landing | Fully Attended |

[1] Good Visual Environment -Based on expected vertiport visibility requirements.

[2] Precision and Aggression metrics of "P" for Precision, "NP" for non-precision, "A" for Aggressive, and "NA" for non-aggressive.

[3] Divided attention: the single pilot flying is required to perform non-control-related sidetasks for a moderate period of time. Otherwise fully attended operations.

[4] "Boundary Avoid": anticipated corrective maneuver to avoid low speed flight near another aircraft or across a no-transgression type boundary.

[5] The "Collision Avoidance" is an anticipated corrective action at high speed to avoid potential midair collision with structure or other aircraft.

* Abuse cases for VTOL operations where multiple selectable modes may be available, and for approach profiles that may be stress-tested by steeper than normal angles.

** Example configuration unique HQTE for a wheeled aircraft. All other HQTEs are assumed to be core HQTEs required of all UAM aircraft.

### Core HQTEs

In recognition of common UAM mission requirements, there will be core tasks expected for demonstration for all UAM vehicles that will consist of cruise, approach, and on-heliport/vertiport operations. These core HQTEs will be specified in the emerging HQTE catalog, the initial version of which is included in Appendix B.

### HQTEs and transitions

Mode changes are historically where most augmented aircraft incidents have occurred. Here also, the rate of change in/out of transition matters. Therefore, a factor in HQTE selection will be the need to capture the impact of any such mode changes present in the design. The following mode changes and/or transitions should be considered in the selection process:

1. Vectored thrust to support Thrust Borne/Wing Borne/Thrust Borne flight.
2. Response type changes (e.g., height rate to flight path rate or TRC-Translational Rate Control to forward flight modes, also augmented to direct, autopilot disengagements, maintenance mode, etc.).
3. Envelope protections including prioritization, warnings, and blending (in/out).
4. Ground mass to air mass including frames of reference used by FCS (inertial vs stability axes vs body axes).
5. Radar altitude vs MSL.

6. Wind and turbulence effects including Vortex Ring State (VRS) and other rotor interactions.
7. Weight-on-wheels (or Skids), True or False.
8. Dynamic behavior at limits/insufficient control power.
9. System nonlinearities including rate and position limits, hysteresis, command gain shaping, etc.
10. In Ground Effect (IGE)/Out of Ground Effect (OGE).
11. FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.

### Addressing unique configurations

It is understood that there will be unique powered lift VTOL aircraft designs that incorporate indirect flight controls. There is therefore an expectation that HQTEs may be targeted for the given design, some of which may include:

- Unique flight control designs that may employ, for example, integral envelope protections.
- Mission deltas from core HQTEs due to unique aircraft configurations. In this context, a simple example is used in the verification matrices that follow, where three unique HQTEs are proposed for the wheeled configuration; the ground taxi, rolling takeoff, and rolling landing. These example HQTEs are included here to exemplify the process but have yet to be fully vetted.
- Unique configurations and maneuvers for failure modes. For safety considerations, it is anticipated that many of the failure mode configurations will be evaluated via piloted simulation.

### Precision and aggression

HQTEs are designed according to anticipated operational controllability and agility requirements for UAM vehicles. These often-misinterpreted terms are synthesized down to more easily understood terms of “aggression” and “precision” which are better related to task tolerances and constraints. For civilian VTOL aircraft, nominal operations are then expected to focus on precision and low aggression. However, there is recognition that some gross maneuver capability is required for safe operations, such as collision avoidance that is portrayed as aggressive maneuvering. In these HQTE there is allowance for loosening of precision requirements to afford such aggression.

**Abuse cases**

Abuse cases, where HQTEs may be required to be repeated with some variation to better stress the design, are anticipated. These may include such things as multiple options for selectable control responses as well as approach profiles that may be stress-tested by steeper than normal angles. Abuse cases are strongly configuration dependent and will be identified by considering more stringent adjustments to the nominal HQTE requirements.

### 4.4.3 Use of HQTEs throughout the design and certification process

#### *4.4.3.1 HQTE as part of a holistic process*

After HQTEs have been selected, the HQTEs in their various forms can be anticipated to be used throughout the design, development, and certification process as shown in Figure 1. The following focuses on providing guidance as to the use of HQTEs in the design and certification process. The concept of HQTEs should be understood as a tool in means of compliance, and a procedure toward making a subjective pilot evaluation of handling qualities more quantitative. The following is offered for better understanding of their most formalized use.

- Formalized HQTEs are designed with specific cueing provided through ground-course or other means for the pilots to achieve proficiency, discern compensation, and self-assess task performance to attain specific pilot comments and associated Cooper-Harper Handling Qualities Ratings (Cooper & Harper, Jr., 1969).
- The HQTEs must be sufficiently structured through tolerances, constraints, and cueing to provide for comparable pilot ratings for equivalent test conditions and pilot proficiency. The HQTE tolerances should be correlated to respective operations of the aircraft as well as the appropriate levels of predicted handling qualities derived from quantitative predictive criteria.
- Through repeated execution of the HQTE, the pilot achieves a level of proficiency to adequately understand and describe compensation. Then, through walking through the Cooper-Harper Scale, with comments defending the subjective opinion with detailed descriptions of compensation, the pilot is able to provide a more quantitative assessment. The use of additional rating scales (PIO tendency ratings in this context) aid in the understanding of compensation and strengthen the dataset. This quantitative method utilizes at least 3 test pilots.
- Disparate ratings between pilots are normally a consequence of failing one, or a combination, of the following three things: 1) pilot/test team training and rigor in the assessment of HQR, 2) pilot proficiency in the HQTE, and 3) sufficiency of HQTE

description. Occasionally, an outlier rating may be the consequence of non-linear behavior, or encountering a handling qualities "cliff," and should be investigated further, not ruled out.

- Annotation of overall pilot experience levels, especially in the design under evaluation, is common for data purposes and to judge the acceptability of the design for these levels. Time to achieve proficiency is worthy of note also in this regard. Recording other factors such as background in the use of these test techniques can be useful in better understanding nuances in observation. For data purposes, pilot anonymity is maintained, and pilots are generally sequestered from one another in the evaluation of the HQTE if possible.

It is understood that such rigor in test comes at a price with respect to dedicated flight test time. Therefore, the use of the formal HQTE process should be expected to be constrained to certain conditions and maneuver subsets for means of compliance.

#### *4.4.3.2 Differing applications of HQTE*

**Formal HQTE flight tests**

The formal HQTE process requiring a minimum of three pilots will be established through applicant coordination with the FAA. A set of formalized demonstration HQTEs will be selected based on the following:

- operational use (e.g., UAM)
- aircraft configuration (e.g., lift + cruise)

Factors further affecting the types of formal HQTE demonstrations and the size of the HQTE test matrix that is to be negotiated between the Applicant and the FAA are:

- unique cockpit inceptor design and mapping along with use of flight displays,
- flight control response-types featured in the flight control system,
- envelope protections integrated in the flight control system,
- sufficiency of quantitative predictive testing done; Flying Qualities Assessments (FQAs) using quantitative predictive metrics that predict, for example, Level 1 HQ, which are clearly acceptable, may mitigate requirements for some formal HQTEs to be demonstrated in flight.

- sufficiency of validated piloted simulation flown; Extensive use of simulation is anticipated in the design and certification process. Validated piloted simulation testing is intended to reduce actual flight certification HQTE requirements.

**Demonstration HQTEs**

Demonstration HQTEs will be used for those flight tests that do not require three pilots but will be backed up by proper recording of performance and workload. These may include use of HQTE procedures to include ground courses. Examples are:

- Matrixed conditions for center of gravity, winds and turbulence, or combinations of weight, altitude, and temperature, where limited single point demonstrations may be sufficient to identify trends and provide for envelope definition while the formal HQTE may be done at a single mission representative gross weight (GW), density altitude, critical CG, and prescribed winds.
- Applicant flight test data collection in support of design.
- Applicant simulator validation data collection.
- Selected failure conditions demonstration tests.
- Final certification flight test data negotiated between the applicant and FAA under the Type Inspection Authorization that shows sufficiency of flying qualities quantitative predictive metrics that show Level 1 HQ, which are clearly acceptable.
- Final certification flight test data negotiated between the applicant and FAA under the Type Inspection Authorization that shows sufficiency of validated simulation flown.
- For demonstration maneuvers where a single pilot is evaluating the design, a methodology such as the following is offered as an example of how to vet identified HQ issues:
    - For test conditions that require assignment of an HQR: If the test condition receives a rating of HQR 5 to 7, a second pilot shall evaluate the test condition.
    - If the HQRs assigned by the two pilots vary by more than one, the condition shall be repeated as required to further investigate the disparity. A third pilot may also be used in this case.
    - Test conditions that are assigned a HQR of 8 or higher will not be repeated within the same flight and require a team review for understanding the related

deficiencies and appropriate risk mitigations applied before any repeats are considered.

#### *4.4.3.3 Discussion of pilot requirements for HQTE evaluation*

There is a need to formalize the "qualified HQTE evaluation pilot" for proper certification. Firstly, the pilot must be conversant on the use of FTMs/MTEs, and use of the Cooper-Harper Rating scale. Inclusion of a school-trained experimental test pilot helps achieve this but does not guarantee it. What guarantees it, instead, is a rigorous test team process of trial and feedback on performance, along with a well-designed test maneuver. Secondly, the pilot needs to demonstrate proficiency in the maneuver to adequately understand and describe compensation. Trained experimental test pilots may have the upper hand in achieving this proficiency quickly based on their broad aircraft experience base, especially with higher augmentation control response-types. This will pay in evaluation efficiency. Other pilots may take longer but do not necessarily become disqualified from the evaluation process. HQTEs, as described in this Flight Test Guide, are intended to be quantitative in nature and necessarily diagnostic tools that require the use of Cooper-Harper Ratings. This drives the requirement for pilot evaluators that are trained and practiced in the application of Cooper-Harper ratings:

- for both formal and demonstration HQTEs as described above,
- including the applicant's test pilots, per Part 21.37, as delineated in the Applicant's Certification Plan,
- including Designated Engineering Representatives (DER) pilots as delineated in the Applicant's Certification Plan, and
- including FAA pilot participation in this process as expected from Air Certification Service with test pilot representatives.

Requiring the applicants to use diverse pilot staff backgrounds in HQTE evaluations (related to rotary wing, powered lift, or fixed wing) is considered an undue burden at this time, especially with highly trained test pilots being utilized in the HQTE process. This may be addressed through the FAA pilot participation of the various directorates. Other piloted evaluations such as Flight Standards evaluations or Human Factors investigations, separate from the HQTE process, will likely address other than HQ concerns and be part of the Certification Plan. These additional evaluations may be conducted to validate failure conditions and the need to consider overall workload including checklist usage.

It should be emphasized that the pilot is only the "tip of the spear" and a test team conversant in the concepts discussed here can contribute to the successful application of these methods. Additionally, the detailed prescription of the HQTE process can help avoid the variability and subjectivity of individual pilot ratings and mitigate differing levels of training among participating pilots. In this regard, it can be assumed that some formal training may be proposed by the FAA and other authorities for evaluation pilots and other test team members. The procedures for application of pilot ratings can be found in Section 4.

#### *4.4.3.4 HQTE verification matrix*

The use of the term "verification" is purposeful as it reflects the confirmation of previously collected quantitative predictive metrics of handling qualities (e.g., those defined in ADS-33E-PRF (2000), against the demonstrated handling qualities of the HQTE).

With the various handling qualities flight test methods in mind, Table 3 offers a view of how the various HQTEs can be integrated into a development and certification plan. With the catalog of HQTEs still emerging, those listed in the table are used to illustrate the process and may not reflect a final maneuver set. The "HQTE Verification" column illustrates the process of continuous assessment of handling qualities during aircraft development. Here, it is broken into a "Preliminary" design phase (Prel Sim), later "Validated" simulation work (Val Sim), and then "Certification Flight" tests (Cert Flt). The participation of FAA pilots in the Cert Flt process, as outlined in a Type Inspection Authorization, would be agreed upon by the applicant and FAA and is not delineated in detail here. In each of these columns, the use of qualitative demonstration (D) of the HQTE is shown as compared to more formal Full Demonstration (FD) of HQTE with 3 pilots.

The designation of qualitative demonstration maneuvers in this context is not intended as comprehensive, in that here it is expected that the maneuvers designated as (D) may utilize HQTE methods to include courses and performance metrics from the HQTE catalog but will be less stringent with respect to the use of three pilots, as described earlier. It is expected that unique maneuvers, not contained within the HQTE catalog, may be designed by applicants to examine flight control transitions, envelope-protection algorithm interactions, and various other non-linear behavior that may be anticipated. These maneuvers will likely be considered demonstration maneuvers and therefore may only require single pilot evaluations.

**Flight conditions**

The flight conditions shown at the top of Table 3 are largely a function of anticipated flight environmental factors that affect handling qualities and drive flight control designs. These include atmospheric turbulence to include winds, visual conditions in which the vehicle will be operated, and the flight envelope of the vehicle.

### HQTE and the flight envelope (FE)

HQTE demonstrations are constrained to within the FE of the aircraft. In this regard operations are based on normal CONOPS, in that all missions anticipated for the aircraft are assumed to be accomplished within the FE. The FE is generally described in terms of combinations of center-of-gravity, airspeed, altitude, load factor, rate-of-climb, sideward velocity, and other parameters that may be related to performance, structural loading margins, and/or handling qualities. Warnings or indication of limiting or dangerous flight conditions will generally occur outside of the FE. The FE will generally be established by the applicant through various flight tests that typically includes HQ demonstration maneuvers, and then HQTEs demonstrated within the FE. It is not uncommon to then further adjust the FE based on HQTE findings, for instance in the identification of PIO, handling qualities cliffs, and/or significant non-linear behavior.

### HQTE and the visual environment

For the example UML-2 case, GVE is considered for near ground operations and VFR for flight. However, there are still several considerations to be addressed. First, the requirement to provide sufficient cueing in ground courses to ensure that proficiency in the maneuver can be achieved with minimal practice and that immediate feedback on test tolerances is available to the pilot on task performance during task/vehicle familiarization. The courses suggested in the catalog will go a long way toward ensuring this is done, but additional cueing may have to be added to facilitate execution, especially in the piloted simulator where the usable cue environment (US Army, 2000) is typically reduced when compared to the flight environment. It should be possible for the pilot to determine if desired or adequate performance has been achieved using the cueing that is available on the test course. While learning/practicing an HQTE, it is acceptable to inform the pilot if he or she achieved desired or adequate performance, but repeated questions about this are good reason to consider modifying the course. The purpose of the tests is not to determine cockpit field-of-view limitations, but to assess the handling qualities given that the visual cues are not a factor in the evaluations.

Task performance should be documented as a confirmation and backup to pilot commentary and ratings. The level of sophistication of such quantitative data will be at the judgment of the testing organization but should provide for some certification confidence. Techniques that have been employed include:

- use of ground observers,
- strategically mounted cameras with time-stamped video, and
- ground tracker instrumentation or differential Global Positioning System (GPS).

Table 3. HQTE Verification Matrix for UML-2 Example

| Flight Condition | Flight Envelope<br>Good Visual Environment (Near Ground) and VMC (Flight) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Calm Wind No Turbulence | | | Moderate Wind Light Turbulence | | | Calm wind No Turbulence | | | Moderate Wind Light Turbulence | | |
| State[1] | Normal and $(P_f)<10^{-5}$ Flight Hours | | | | | | Failure Conditions with $10^{-5}>(P_f)>10^{-7}$ Flight Hours | | | | | |
| Settings** | Normal Flight Control | | | | | | Selectable Backup Mode or Reversionary Control Mode | | | | | |
| Loadings | Range of Loadings to include Critical WAT and CG for Mission Configurations | | | | | | | | | | | |
| HQTE Verification | Prel Sim | Val Sim | Cert Flt | Prel Sim | Val Sim | Cert Flt | Prel Sim | Val Sim | Cert Flt | Prel Sim | Val Sim | Cert Flt |
| Ground Taxi | | | FD | | | FD | | | | | D | |
| Precision Hover | D | FD | FD* | D | FD | FD | | | | D | FD | |
| Hovering Turn and Hold | D | FD | FD | D | FD | D | | | | D | FD | |
| Vertical Reposition & Hold | D | FD | FD | D | FD | D | | | | D | FD | |
| Vertical Landing | D | D | FD | D | D | D | | | | | D | |
| Lateral Reposition & Hold | D | FD | FD* | | | | | | | | D | |
| Rolling Takeoff | | | FD | D | FD | FD | | | | | FD | |
| Depart Abort | D | FD | FD* | | | FD | | | | | D | |
| (VTOL) Takeoff | D | FD | FD | | D | D | | | | | D | |
| Go-Around | D | FD | FD | | | | | | | D | FD | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transition | D | FD | FD | | | FD | | | | D | FD | |
| Speed Control | D | FD | FD | | | FD | | | | D | FD | |
| Pitch/FPA Capture and Hold | D | FD | FD | D | FD | FD | | | | | D | |
| Bank Angle Capture and Hold | D | FD | FD | D | FD | FD | | | | | D | |
| Pull-up and Push-over | D | | FD | | FD | | | | | | D | |
| Roll Reversal | D | | FD | | FD | | | | | | D | |
| Decelerating Approach | D | FD | FD* | D | FD | FD | | | | D | FD | |
| Rolling Landing | | | FD | | | FD | | | | | FD | |
| (VTOL) Slope Landing | | D | FD | | D | D | | | | D | FD | |

[1] Failure conditions as defined in AC 29.1309-2.
(D)- Qualitative Demonstration; (FD)- Full Demonstration HQTE with 3 pilots.
*Repeat as abuse case for selectable augmented modes as well as approach angle with (D).
**The representation of a Primary and Secondary Flight control mode, for those systems that share this complexity, represents pilot select ability of flight control stabilization, such as AFCS or a backup mode with less outer loop functionality.

Air-referenced flight in VMC is expected to utilize a combination of instrument cross-check and outside visual reference. The use of external aids to achieve tolerances, for instance a glidepath lighting system in a visual approach, is permissible, but any navaid that may be utilized in an approach needs to be examined for availability and failure rates. For many high-speed maneuvers, instrument reference will be sufficient to meet the maneuver requirements and would in essence be applicable to later Instrument Meteorological Conditions (IMC) certification.

As mentioned earlier, flight displays can have a significant impact on handling qualities and therefore some attempt to quantify their use in the cueing environment should be undertaken. If flight displays do materially affect the test maneuver execution and assigned HQR, consideration should be given to assessing the ability to conduct the maneuver in the absence of the displays with separate HQRs assigned for the purely visual maneuver.

**Winds and turbulence**

The requirement for testing in moderate winds in ground-referenced maneuvers and light turbulence in air-referenced maneuvers is considered as necessary for the UAM mission where urban environments are likely to represent inconsistent, variable wind and turbulence conditions that must be contended with. The military rotorcraft handling qualities standard (US Army, 2000) recognizes that winds and turbulence generally have a degrading effect on handling qualities, and while stressing flight test in winds, the standard does not describe the extent of permissible degradation. Instead, it provides that the "Government will decide on the extent of HQR degradation due to moderate winds is acceptable." This same concept is resident in the FAA certification process in that the demonstrated HQ in winds should be achievable without requiring exceptional piloting skill, alertness, or strength. Additionally, demonstration of good handling qualities in the presence of wind will generally be accepted as sufficient demonstration for calm wind conditions. Individual maneuvers will specify wind azimuth if required. If winds are specified as a variation of an HQTE and no specific azimuth is given, then a zero degree (headwind) initial azimuth is assumed. Recommended wind magnitudes are as prescribed below in Table 4.

Table 4. Definitions of wind level

| | |
|---|---|
| **Calm** | Steady component of less than 5 knots. |
| **Light** | Steady component of greater than 5 and less than 10 knots. |
| **Moderate** | Steady component of 10-15 knots. |

Low speed testing in winds is expected to be accompanied by some level of gusts and light turbulence. At this time no specification of gust variance or turbulence level is associated with the wind specification. Wind magnitude, described in Table 4 is defined as the steady component of wind, not including gusts for test purposes. In piloted simulations, one can expect that test conditions will target moderate winds, at 17 kts of wind per Part 27 guidelines.

Testing in turbulence is assumed to be for air-referenced maneuvers, not low speed/hover. Metrics for determination of turbulence levels are adapted from AC 25-7D Appendix E (2018) and are expressed in Table 5. It should be noted that AC 25-7D combines winds and turbulence in their scales. Here only the turbulence definition is used since winds have been defined differently in Table 5. A key point is that winds should be appropriately evaluated with FCS design transitions (i.e., ground speed to air mass transition) and hysteresis in blend regions (i.e., thrust-borne to wing-borne).

Table 5. Definitions of turbulence level (adapted from AC 25-7D Appendix E)

| | |
|---|---|
| **Light** | Turbulence that momentarily causes slight, erratic changes in altitude and/ or attitude (pitch, roll, yaw). |
| **Moderate** | Turbulence that is similar to light turbulence, but of greater intensity. Changes in altitude and/or attitude occur. Usually causes variations in indicated airspeed. |
| **Severe** | Turbulence that causes large, abrupt deviations in altitude and/or attitude. Usually causes large variations in indicated airspeeds. |

**State (HQTE use in support of failure condition testing)**

The “State” column in Table 3 takes into account the use of HQTEs in the evaluation of normal states and failure conditions. For this example, the Probability of Failure (Pf) for failure conditions are defined in Advisory Circular 29-2C (2014), 29.1309-2. It is beyond the scope of this discussion to go into the details of the various considerations in this regard, but it is offered here as a consideration in development of the HQTE verification matrix, and where HQTE use may be of benefit in evaluating assumptions of failure conditions. It is important to note, in the context shown here, that failure modes are demonstrated in the lowest selectable augmentation mode as well as the moderate wind condition, not requiring HQTE demonstration in more benign conditions. The use of HQTE for actual in-flight failure condition demonstrations is anticipated as minimal for the various failure states of VTOL indirect flight control aircraft but is instead expected to utilize validated simulation.

**Settings (HQTE use in support of evaluating selectable flight control response)**

The “Settings” row in Table 3 accounts for any selectable flight control configuration that may be used. The selection of flight control mode by the pilot that affects the overall operation of the aircraft, such as a backup mode with less outer-loop functionality is captured in this row. The term “Normal” represents the commonly used flight control architecture/response as used in ASTM WK 61549A for Indirect Control Systems. Normal mode is not to be confused with a baseline capability, that may be used in a partial authority design. In this context, normal mode would include augmented modes on top of the baseline control response, e.g., Translational Rate Command. An augmented mode deselection would be considered a mode change to the backup or reversionary mode. Full authority designs may not allow for pilot-controlled selection of a backup capability that utilizes different sensors or fewer outer loops. In this case, for Settings, the Normal Mode will be considered for both normal and failure conditions. Any automated default to a backup mode or functionality based on sensed failures, would be considered a failure condition, and treated appropriately according to its probability of occurrence. Lastly, any selectable training mode incorporating changes to power levels or handling characteristics should be considered for applicable matrixed conditions related to normal and failure condition states.

**Recommended HQ threshold**

It stands to reason that delineating expectations of acceptable criteria for certification will aid the applicant in the design and later certification process. Additionally, while the anticipated HQTE catalog is meant to be comprehensive, it is conceivable that it will not cover unique aspects of every design. What is intended here, by placing assigned thresholds in the verification matrix, is to highlight the differential in handling qualities levels that can be expected based on the matrix requirements.

It must be emphasized upfront that the assignment of HQRs, and their ranking against recommended thresholds, is only part of the certification process. HQTEs are intended to be a check of the overall handling qualities. As such, they do not address all issues that lead to good handling qualities. Latitude in interpretation of the results by the FAA, especially based on pilot comments regarding deficiencies, should be understood by the applicant.

The best reporting of pilot opinion is done first through the pilot comments and then through reporting of all ratings, not median ratings. Outliers of greater than two HQRs should have detailed analysis to support possible identification of deficiencies. It is not uncommon to exhibit good handling qualities in many of the HQTEs, while failing to meet criteria for a single or a few HQTEs. Latitude is anticipated in the certification effort in this regard, based on an understanding of the various underlying issues.

The recommended thresholds are based on the following interpretations:

- The use of desired performance tolerances and workload tolerances generally represents the maximal aircraft HQ performance expected in normal operations. Here, tight performance metrics for precision or time are prescribed to stress the design and better find handling qualities cliffs, PIO tendencies, and HMI issues. This would argue against strictly requiring the design to meet only Level 1 (ratings of 1 to 3) according to the prescribed HQTE and not, for example, the wider “desired performance” indicated by ratings of 1 to 4.
- The use of the adequate performance tolerances of the HQTE be equivalent to certification performance thresholds for the given operational task.
- The level of pilot workload acceptable for certification, as described in the rating, should be representative of that allowed under current certification guidelines based on a matrix

of conditions, state, and settings (e.g., Table 6). It should be emphasized that these are general guidelines and not prescriptive.

- The critical design point for normal state and normal flight control settings would then be based on operations in moderate winds and turbulence, where workload thresholds would be equivalent to various guidelines in Parts 29 and 23 subparts B for ability to operate the aircraft "without requiring exceptional piloting skill, alertness, or strength." In this way, HQR 5 is defined as the threshold for acceptable normal operations. In this context, the term "extensive" as used in the HQR 6 is equated to "exceptional" from the CFR. Operations in calm winds for these states and conditions would then be expected to have a lower HQR threshold.
- For given failure conditions, a critical design point would be predicated on using a selectable backup mode or reversionary mode in winds and turbulence. Here the aircraft should meet the guidelines of Part 29-143(a) where "the aircraft must be safely controllable and maneuverable." In this way a rating of 7 is defined as the threshold for controllability, with the understanding that the pilot may have to abort operational tasks and accept less than adequate performance as a means of balancing workload. No individual rating of 8 or higher will be considered acceptable. For failure conditions in calm winds the recommended threshold is adjusted lower.

Table 6. Recommended maximum HQR thresholds for certification

| Conditions | Calm Wind No Turbulence | Moderate Wind Light Turbulence | Calm Wind No Turbulence | Moderate Wind Light Turbulence |
|---|---|---|---|---|
| Setting | Normal Flight Control | | Selectable Backup Mode or Reversionary Control Mode | |
| Recommended maximum CHR | ≤ 3 with considerations for ≤ 4 in some cases* | ≤ 5 | ≤ 6 | ≤ 7 |
| Equivalent CFR requirement** | Parts 29 and 23 subparts B; "aircraft must be controllable and maneuverable without requiring exceptional piloting skill, alertness, or strength." | | 29.143(b) "aircraft must be safely controllable and maneuverable" | |

[1] Failure conditions as defined in AC 29.1309-2.

(D)- Qualitative Demonstration; (FD)- Full Demonstration HQTE with 3 pilots.

*Repeat as abuse case for selectable augmented modes as well as approach angle with (D).

**The representation of a Primary and Secondary Flight control mode, for those systems that share this complexity, represents pilot select ability of flight control stabilization, such as AFCS or a backup mode with less outer loop functionality.

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# A Test plan guidelines

This appendix provides guidelines that can be followed to generate a test plan for handling qualities flight test evaluations using HQTEs. The plan is easily adapted for piloted simulation evaluations.

## A.1 Introduction

The introduction provides a brief overview of the planned test campaign. Here it is common to identify the test article, test site, and proposed dates for testing. The overview may also succinctly state the overall test objective and any other unique elements of the campaign (e.g., special test configurations, required environmental conditions, etc.).

## A.2 Purpose

This section provides a clear and concise listing of the technical objectives. For added clarity, these may be enumerated or listed in bullet form. From this list, a reader should easily discern the intent and expected outcomes of the campaign.

## A.3 Aircraft and equipment requirements

### A.3.1 Aircraft description

This section will provide a description of the test article including appropriate figures. It is important to fully identify and describe those features of the test article that are significant to the test campaign and objectives.

[For piloted simulation evaluations, in addition to a description of the vehicle model, a description of the simulator facility is included that identifies key characteristics including fixed base/motion, display type (e.g., dome with projectors), field-of-view, etc. An indication of the fidelity of the cockpit inceptors (e.g., flight representative, game-type, etc.) and displays (e.g., flight representative, generic primary flight display, projected head-up display, etc.) is also appropriate.]

### A.3.2 Modifications

Describe any modifications that must be made to the aircraft in support of the test objectives.

### A.3.3 Test instrumentation

List and describe all instrumentation that is needed to acquire the required data at each test point. Define required update rates for the data acquisition system. For typical handling qualities evaluations, data rates of at least 50 Hz are desired with 100 Hz preferred. In some cases, data rates of 20 Hz may be acceptable for time domain analysis, but these rates may impact analysis in the frequency domain.

### A.3.4 Test items

List and describe any items that are required onboard the aircraft to execute this test plan. This may, for example, include a flight test interface panel that can be used to inject command signals directly to the flight controls.

## A.4 Scope of test

### A.4.1 Limitations to scope

Describe all factors that impact the scope of the test program. These factors may include budget constraints, aircraft availability, pilot availability, restrictions based on risk or test hazard analysis, etc.

### A.4.2 Test envelope

#### A.4.2.1 Aircraft limits

Define the test envelope for the aircraft including any required limits on operations such as low speed/hover only, for example. Test conditions discussed next are defined with respect to these limits.

#### A.4.2.2 Test conditions

The test conditions for each test point will be identified. Test points can be collected into groups that share a common flight condition. Key flight condition elements include speed, altitude, winds (steady and turbulence level), etc.

### A.4.3 Flight restrictions

Identify any flight restrictions that may be a result of aircraft modifications, equipment, etc.

### A.4.4 Aircraft configurations

The test article configuration for each test point will be defined. Test points can be collected into groups that share a common configuration. Key configuration elements to be identified include flight mode (e.g., powered lift, transition, forward flight, etc.), weight, center of gravity balance (e.g., forward, mod, aft), control law response type (if a condition of the test), etc.

### A.4.5 Defined visual condition

In this section, the visual condition requirements for the test campaign will be identified – Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). For some evaluations, especially simulator test campaigns, where quantitative characterizations of the visual environment are required, the Usable Cue Environment (UCE) approach from ADS-33E-PRF can be applied.

### A.4.6 Test criteria

Test criteria are the items that will determine if the objectives and scope of test have been met. These can be provided as a bullet or enumerated list.

## A.5 Method of test

### A.5.1 Test method and procedures

#### A.5.1.1 Flight preparation and ground checks

To the extent possible, describe how piloted simulation will be used to practice the HQTEs at the designated test conditions prior to flight test. Describe the required steps and ground checks that will be used to demonstrate flight test readiness.

#### A.5.1.2 Operational procedures

Operational procedures will define Go/NO-GO decisions, use of build-up and/or familiarization runs, specific test techniques that may be required, and KIO (knock-it-off) procedures.

#### A.5.1.3 Test maneuver descriptions

For the handling qualities evaluations that are a focus of this Test Guide, the test criteria will be the specific HQTEs that are the focus of the test. As documented in the Appendix B HQTE catalog, each test maneuver features objectives, a detailed description, course requirements, and performance requirements.

#### A.5.1.4 Measurands

Tabulate Analysis Critical (AC) and Safety of Test (SOT) measurands. Tables will include name, symbol, units, and description of each signal. There may be overlap amongst the two signal sets.

### A.5.2 Support requirements

Identify support requirements including HQTE ground course infrastructure (e.g., hover boards, cones, etc.). Further support requirements may include a chase aircraft, videography (onboard and ground based), telemetered data, radar tracking, etc.

### A.5.3 Personnel requirements

Identify the personnel requirements for the test including aircraft crew, ground crew, and control room. Examples include evaluation test pilot, safety pilot, chase aircraft pilot, on-board flight test engineer, etc.

## A.6 Risk management

### A.6.1 Safety checklist

Create a safety checklist that addresses all aspects of the test campaign from ground checks to completion of each sortie.

### A.6.2 Test hazard analysis

Identify all potential hazards. Perform and document the Test Hazard Analysis (THA) for each identified hazard. An example THA for Foreign Object Damage is shown below to exemplify the process (Table A- 1).

Table A- 1. Test hazard analysis

| **Hazard** | **Cause** | **Effect** | **Probability**[1] | **Severity**[2] | **Risk**[3] | **Mitigation** | **Emergency Procedure**[4] |
|---|---|---|---|---|---|---|---|
| Foreign Object Damage | Aircraft downwash picking up and throwing debris | Equipment damage or injury to personnel | Occasional | Major | Medium | Maintain a safe separation distance between equipment and aircraft as per preflight brief.<br>Ground personnel | KIO: abort maneuver with climb away from course.<br>Assess damage and provide |

| **Hazard** | **Cause** | **Effect** | **Probability[1]** | **Severity[2]** | **Risk[3]** | **Mitigation** | **Emergency Procedure[4]** |
|---|---|---|---|---|---|---|---|
| | | | | | | must have a radio and have two-way communications with the test aircraft.<br>PPE is required of ground personnel<br>Aircraft crew and airfield crew will brief emergency procedures jointly prior to the flight.<br>Perform FOD walk of ground-course after setup | first aid as necessary |

1. Likelihood that the risk will occur—Improbable, Remote, Occasional, Probable, or Frequent.
2. Consequence if the hazard occurred—No Safety Effect, Minor, Major, Hazardous, or Catastrophic.
3. Combination of Probability and Severity—Low, Medium, High, Avoid.
4. This column is your plan of action if the event still occurs.

### A.6.3 Risk assessment

Conduct a risk assessment using FAA Order 4040.26B that addresses flight test risk management. As stated in the FAA Order, perform the subjective risk assessment by:

- Estimating the probability of each hazard occurring; defined as improbable, remote, occasional, probable, or frequent.
- Estimating the severity of each hazard, if it occurs; defined as no safety effect, minor, major, hazardous, or catastrophic.
- Defining the risk of each hazard as a combination of the probability and severity; defined as low, medium, high, or avoid.

Use the following chart from FAA Order 4040.26B to document the risk of each hazard (Figure A- 1).

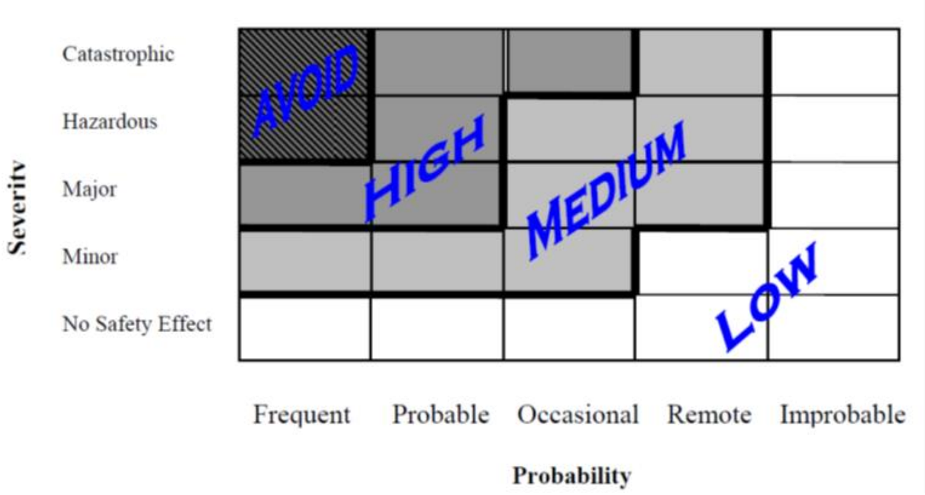

Figure A- 1. Risk assessment chart

### A.6.4 Real-time data monitoring

Safety of flight procedures include the need for real-time data monitoring of the SOT measurands. This may be accomplished on-board from flight test engineer station(s) and/or via ground control stations using telemetered SOT data.

### A.6.5 Additional special precautions

Identify any additional special precautions not covered elsewhere in the test plan that are important to flight test safety.

## A.7 Additional general test considerations

If applicable, identify and describe any additional test considerations that have yet to be covered within the content of the test plan.

## A.8 References

1. Anon., *Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft*, US Army Aviation and Missile Command, ADS-33E-PRF, March 2000.
2. Anon., *Aircraft Certification Service Flight Test Risk Management Program*, Order 4040.26B, U.S. Department of Transportation, Federal Aviation Administration, National Policy, 31 Jan. 2012.

# B HQTE Catalog

The HQTE catalog presented herein is a living document and as such revisions and additions are expected as its use expands. A complete listing of the maneuver set is given in Table B- 1 below. Levels of precision and aggressiveness are used to categorize the maneuvers. The first column identifies the MTE number that is used in the maneuver catalog, while the second column provides the MTE name. The final three columns indicate the status of the maneuver at the completion of this program. Check marks are given to those maneuvers that were evaluated either in flight or in a ground-based simulator, or to those maneuvers that require further refinement. The following statements originally drafted for the release of the "original 6" HQTEs[3] are repeated here with some updates to facilitate use of the catalog.

- HQTEs are intended to be used throughout the design process, not just as part of the means of compliance process. They can be used to inform designs as well as focus testing efforts. They are designed to reveal potential handling qualities deficiencies via analytical methods (computer simulation), piloted simulation, and flight test. Demonstration of system performance and flying qualities early in the design phase may reduce the number of required handling qualities test points needed for certification.
- HQTE evaluations are intended for use by trained test pilots wherein the primary objective is to identify handling qualities cliffs and give reasonable assurance that adequate testing was performed.
- HQTEs are intended to be part of a holistic approach to handling qualities assessments that feature a combination of two related methods of assessment, Predicted Levels via quantitative objective criteria and Assigned Levels via flight test with HQTEs. Note that these levels are not tied directly to minimum thresholds for certification. Rather, they are used to gather observations to give the FAA reasonable assurance that there are no objectionable handling qualities, and that the pilot can predictably perform maneuvers within the scope of the applicant's stated mission.
- HQTEs are designed with specific cueing provided through ground-course or other means for the pilots to achieve proficiency, discern compensation, and assess task performance to attain ratings via the Cooper-Harper scale and pilot comments. The performance measures such as those found in ADS-33E-PRF are linked to the HQTE through application of appropriate maneuver tolerances. Furthermore, some maneuver tolerances are based on FAA Airman Certification Standards and Practical Test

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[3] Klyde, D., D. Sizoo, M. Feary, D. Webber, Ross Schaller, "Descriptions of Six Low Speed/Hover HQTEs," 16 September 2021

Standards. This process aids in consensus of pilot ratings and provides for a coherent assessment of overall handling qualities.

- HQTEs are selected based on a combination of aircraft mission assessment as well as anticipated environment of operation. This initial HQTE set is defined for Day VFR operations. The combination of precision and aggressiveness performance metrics were selected based on demonstrated performance in piloted simulation studies that featured using high fidelity simulators and flight test.
- The HQTEs and task performance requirements are intentionally designed as abstractions of operationally relevant maneuvers, but are designed to stress the pilot-vehicle system beyond what is typically considered for normal operations. Some maneuver tolerances may differ from real world heliport dimensions to expose handling qualities deficiencies.
- Low speed VTOL test requirements in winds are recommended for certain precision maneuvers. The intent here is to determine the degradation in handling qualities due to these environmental effects.

Table B- 1. HQTE performance requirement list

| **No.** | **Handling Qualities Task Element (HQTE)** | **HQTE Status** | | |
|---|---|---|---|---|
| | | **Evaluated (Flight)** | **Evaluated (Simulator)** | **Needs Refinement** |
| **Non-Precision, Non-Aggressive HQTEs** | | | | |
| 1 | Ground Taxi | | | ✓ |
| 2 | (CTOL) Rolling Takeoff and Departure Climb | ✓ | ✓ | |
| 3 | (VTOL) Vertical Takeoff | | | ✓ |
| 4 | Heading Change | ✓ | ✓ | |
| 5 | Altitude Change | ✓ | ✓ | |
| 6 | Speed Change | | | ✓ |
| 7 | Waveoff/Go-Around | | ✓ | |
| 8 | (CTOL) Rolling Landing | ✓ | ✓ | |
| 9 | (VTOL) Vertical Landing | ✓ | ✓ | |
| **Non-Precision, Aggressive HQTEs** | | | | |
| 10 | Depart Abort/Rejected Takeoff | ✓ | ✓ | ✓ |
| 11 | Pull-up/Push-over | ✓ | ✓ | ✓ |
| 12 | Roll Reversal | ✓ | ✓ | ✓ |
| 13 | (VTOL) Vertical Slope Landing | ✓ | ✓ | |

| **No.** | **Handling Qualities Task Element (HQTE)** | **HQTE Status** | | |
|---|---|---|---|---|
| | | **Evaluated (Flight)** | **Evaluated (Simulator)** | **Needs Refinement** |
| | **Precision, Non-Aggressive HQTEs** | | | |
| 14 | (VTOL) Precision Hover | ✓ | ✓ | |
| 15 | (VTOL) Hovering Turn and Hold | ✓ | ✓ | ✓ |
| 16 | (VTOL) Vertical Reposition and Hold | ✓ | ✓ | ✓ |
| 17 | (VTOL) Lateral Reposition and Hold | ✓ | ✓ | ✓ |
| 18 | Transition (VTOL to Airplane Mode) | | ✓ | ✓ |
| 19 | Altitude Rate Capture and Hold | ✓ | ✓ | |
| 20 | Flightpath Capture and Hold | | ✓ | ✓ |
| 21 | Pitch Attitude Capture and Hold | ✓ | ✓ | |
| 22 | Bank Angle Capture and Hold | ✓ | ✓ | |
| 23 | (VTOL) Heliport Approach | ✓ | ✓ | ✓ |
| 24 | (CTOL) Precision ILS Capture and Track | ✓ | ✓ | |
| 25 | (CTOL) Precision Offset Landing | ✓ | ✓ | |
| | **Precision, Aggressive HQTEs** | | | |
| 26 | Pitch and Roll Sum of Sines Tracking | ✓ | ✓ | |
| 27 | Flightpath Regulation | | ✓ | ✓ |
| 28 | Pirouette | ✓ | ✓ | |

Definitions and rationale for selection and tailoring of maneuvers including desired/adequate performance measures were derived from the following sources:

- FAA regulatory requirements, Airman Certification Standards (ACS), Practical Test Standards (PTS), Operational Rules, and Aircraft Certification Rules
- ADS-33E-PRF (now a tri-service specification, MIL-DTL-32742(AR))
- STI-Paper-1310-1 (a public release version of fixed wing handling qualities demonstration maneuvers developed for the United States Air Force)
- NASA-FAA National Campaign Flight Test Results
- Air Force Agility Prime Simulator and Flight Test Results
- Preliminary flight tests at NRC Canada of a novel tablet-based cockpit display and sensor system (the MCRUER system developed by Systems Technology, Inc.), that provides the

test pilot evaluator virtual MTE courses to evaluate handling qualities in support of certification testing

- Research Simulator Testing Results and Engineering Judgement

The course descriptions provided in this catalog illustrate the “furniture” (i.e., hover boards, cones, tarmac markings, etc.) that are required for successful simulator evaluations. In a fixed base simulator, it can be especially challenging for pilots to recognize fore/aft position in a low speed/hover HQTE. Thus, additional features in the form of cones and tarmac markings may be needed to enhance cueing. Because of natural visual acuity in a flight test environment and the motion cueing available to the pilot, less “furniture” is typically required to achieve desired outcomes.

Actual physical courses may then vary from those described in this appendix based on safety considerations, cost, aircraft field-of-view, and efficiency in setup due to wind requirements. These variations should be backed up with sufficient flight test data showing that the tolerances specified in this appendix were appropriately cued, whether they were achieved or not in testing. Some examples of these variations include:

- Use of cone-fields in lieu of hover-boards for obstacle avoidance, cost savings, and setup efficiency.
- Use of low hover boards (below aircraft hover height) for obstacle avoidance.
- Use of more distant hover boards (sizing increased to still drive same tolerances) to avoid rotor wake interactions with the course or for obstacle clearance.
- Dual use of certain courses, which may afford cost efficiencies, with some adjustments that may be necessary to facilitate this dual use. For example, the Vertical Reposition and Hold task and Precision Hover task may use the same course or the Hover Turn and Hold task may use the Pirouette task course.

Testing in Winds and Turbulence will be in accordance with the Section 5.4.3.4 descriptions in the main text. For course setups it is understood that winds will be variable and can cause considerable expenditure of time in course setup, therefore some latitude should be afforded as may be necessary. In this regard actual wind directions for data purposes should be allowed within +/-30 degrees of that specified.

# B.1 Ground taxi

## B.1.1 Mission phase

- On airport operations

## B.1.2 FAR Part 23 Requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls
- §23.2155, 27.235 Water handling characteristics

## B.1.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.1.4 Objectives

- Assess vehicle controllability and stability during the ground aircraft task of taxiing.
- Check directional control characteristics using available effectors (nose wheel steering, differential braking, differential power or a combination as applicable).

## B.1.5 Description

1. Centerline capture
    a. Stabilize the aircraft 10 ft offset the centerline (left and right) at 10 knots ground speed.
    b. Capture the centerline within 4 seconds.

2. Centerline maintenance
    a. Stabilize the aircraft on the centerline at 10 knots ground speed.
    b. Maintain the centerline for 30 seconds with no more than occasional braking (no more than 1 brief and light application every 10 seconds).
3. Heading reversal
    a. Stabilize the aircraft at 5 knots ground speed.
    b. Apply maximum permissible control inputs (left and right) to minimize turn radius.
    c. Reverse the heading (180 degrees change).
    d. Maintain maximum permissible control inputs until the heading capture is initiated.
    e. Capture the opposite heading within 3 seconds from the heading capture initial control application.

### B.1.6 Course description

The test course shall make use of the reference lines or markers on the ground indicating the desired track. The taxiway must be wide enough to safely execute the heading reversal with adequate margins.

### B.1.7 Performance requirements

Table B- 2. Ground taxi performance requirements

| | **Desired** | **Adequate** |
|---|---|---|
| Centerline Capture: | | |
| Capture centerline within: | ± 1 ft | ± 2 ft |
| Capture centerline with: | 1 or less overshoots | 2 or less overshoots |
| Maintain ground speed within: | ± 2 kts | ± 4 kts |
| Centerline Maintenance: | | |
| Maintain centerline within: | ± 1 ft for at least 80% of the time | ± 2 ft for at least 80% of the time |
| Maintain ground speed within: | ± 2 kts | ± 4 kts |

| | **Desired** | **Adequate** |
|---|---|---|
| Heading Reversal: | | |
| Capture heading within: | ± 2 degrees | ± 5 degrees |
| Capture heading with: | 1 or less overshoots | 2 or less overshoots |
| Maintain ground speed within: | ± 1 kt | ± 2 kt |

## B.1.8 Variations

- The Ground Taxi HQTE can be conducted on various runway surface conditions (e.g., dry, wet, icy) and various wind conditions up to a 17 kt crosswind.

## B.1.9 Rationale

- This HQTE is designed to evaluate the ability of the aircraft to maneuver on an airport taxiway at taxi speeds.

## B.1.10 Applicable documents

1. Lotterio, M., *Develop a Method of Compliance to Support Certification of Advanced Flight Controls in General Aviation and Hybrid Vehicles*, DOT/FAA/TC-21/6, Feb. 2022.

# B.2 Rolling takeoff and departure climb (CTOL)

## B.2.1 Mission phase

- On airport operations from a traditional runway

## B.2.2 FAR Part 23 Requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.2.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.2.4 Objectives

- Evaluate ability to perform takeoff ground roll in gusty conditions.
- Evaluate handling qualities in rotation.
- Evaluate ability to attain reference attitude and airspeed following takeoff.
- Evaluate ability to achieve smooth, continuous pitch rate to climb attitude.

## B.2.5 Description

From hold position on runway centerline, smoothly apply takeoff power and perform normal takeoff. At rotation speed, rapidly attain reference takeoff attitude. Adjust power to maintain climb airspeed and continue to climb through an altitude of at least 500 ft AGL or until the airplane is reconfigured for climb, whichever occurs last. There shall be no objectionable oscillations in any axis during the takeoff roll or climb.

## B.2.6 Performance requirements

Table B- 3. Rolling takeoff and departure climb (CTOL) performance requirements

| | **Desired** | **Adequate** |
|---|---|---|
| ±X ft deviation of aircraft centerline from runway centerline throughout takeoff roll | ±10 ft | ±27 ft |
| ±X deviation from reference climb attitude (or flightpath angle if appropriate) or ±Y kts deviation from climb airspeed | ±2°/±5 knots | ±4°/±10 knots |
| Maximum bank angle of ±X° | ±5° | ±10° |
| Deviation from runway heading of ±X° | ±5° | ±7° |

## B.2.7 Variations

- The takeoff and departure climb should also be performed in wet and icy conditions. The specific definition of "wet or icy" is still to be determined since conditions can vary greatly. In any case, the ability to retain alignment with the runway centerline will be degraded if the runway is slippery, or if the pilot's visibility is reduced due to associated fog, rain, snow, etc. In such conditions it is only reasonable that some relaxation in performance be permitted. The performance requirements for runway centerline deviation have therefore been relaxed to ± 27 ft for desired and ± 50 ft for adequate.

- Demonstrate control of heading down the runway for sideslip maintenance as proof that the aircraft could be oriented to the landing direction in the event of land-back due to failures. As opposed to Part 25 aircraft, where the aircraft is expected to continue takeoff with failures, land-back may be considered as an option.

## B.2.8 Rationale

- This HQTE is designed to be representative of a conventional aircraft rolling takeoff and departure climb.

## B.2.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.
2. Anon, *Flight Test Guide for Certification of Part 23 Airplanes*, AC23-8C, Department of Transportation, Federal Aviation Administration, Nov. 16, 2011.
3. Anon., Flight Test Guide for Certification of Transport Category Airplanes, AC25-7D, Department of Transportation, Federal Aviation Administration, May 4, 2018.

# B.3 Vertical takeoff (VTOL)

## B.3.1 Mission phase

- Heliport/vertiport operations

## B.3.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.3.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.3.4 Objectives

- Check ability to precisely control the aircraft position during the initial takeoff and vertical climb.
- Check for transients or undesirable motions in the ground-to-air transition.

## B.3.5 Description

Starting from a parked position, perform a smooth vertical takeoff into a low hover within 10 seconds of initiating the takeoff. The maneuver is complete when the aircraft is established in a hover position approximately 10 feet above ground level.

This task may be performed using the Precision Hover course (see HQTE 14) with the final position provided by hover reference cues.

## B.3.6 Performance requirements

Table B- 4. Vertical takeoff (VTOL) performance requirements

| | **Desired** | **Adequate** |
|---|---|---|
| Accomplish a vertical takeoff into a low hover with | No objectionable oscillations or control inputs | Minor objectionable oscillations or control inputs |
| Attain a hover position within ±X ft longitudinally and laterally of the designated reference point. | 5 ft | 10 ft |
| Attain a heading at the hover position that is aligned with the heading at takeoff within ±X deg. | 5° | 10° |

## B.3.7 Variations

- Take off with wind from the most critical direction, and during the takeoff, perform a pedal turn to align with wind, if the most critical direction is not from the nose of the aircraft. In this case, the position reference cues should be aligned with the final hover heading.
- Assess ground-to-air-to-ground transitions by reducing power and landing immediately after lifting off. Assess task performance by using the performance requirements for the vertical landing MTE.

## B.3.8 Rationale

- This HQTE is designed to provide an assessment of takeoff handling qualities for powered lift aircraft. While this is a newly defined task, variations have been considered but not yet adopted for use in the Army's aeronautical design standard for rotorcraft handling qualities.

## B.3.9 Applicable documents

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. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.4 Heading change

## B.4.1 Mission phase

- Cruise

## B.4.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.4.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.4.4 Objectives

- Evaluate ability to accurately change heading.

## B.4.5 Description

Initiate the maneuver in steady level flight. Perform a 10° heading change to the right with a bank angle of 30° and maintain this new heading within the specified tolerances for 10 seconds or until stable. Repeat the maneuver back to the original heading, to the left 10°, and back again to the original heading.

## B.4.6 Performance requirements

Table B- 5.Heading change performance requirements

| | **Desired** | **Adequate** |
|---|---|---|
| ±X deviation from target heading. | ±2° | ±3° |
| No more than one heading overshoot. | Magnitude of overshoot remains within the desired region. | Magnitude of overshoot remains within the adequate region. |

## B.4.7 Variations

- Attempt the 10° heading change at various bank angles, for example 45° and 60°. The larger bank angles may transition this from a non-aggressive HQTE to an aggressive HQTE. If Larger and smaller heading changes may also be attempted. In addition, the pilot may vary level of aggressiveness from smooth to abrupt inputs.

- The task should be attempted with and without manual or automated turn coordination active as applicable.

## B.4.8 Rationale

- Although variations of the maneuver described here have been used in flight tests for years, the Heading Change is considered "new" in that the specific performance requirements have been defined to aid the pilot in evaluating the handling qualities identified in the Objectives.

- After initial development this maneuver was refined using a simulator that features commercial transport and various fighter configuration models. In-flight evaluations were then conducted with a general aviation aircraft.

## B.4.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.

# B.5 Altitude change

## B.5.1 Mission phase

- Cruise

## B.5.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.5.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.5.4 Objectives

- Evaluate ability to accurately change altitude.
- Identify potential flightpath and airspeed coupling.

## B.5.5 Description

Initiate the maneuver in steady level flight. Smoothly pitch up to a steady climb rate of at least 1,000 fpm and maintain this rate until within 100 ft of the target altitude. Level off at an altitude 500 ft above the initial altitude and maintain steady conditions for a minimum of 15 seconds. Then push over to return to the initial altitude at a steady descent rate of at least 1,000 fpm and maintain this rate until within 100 ft of the initial altitude. Level off at the initial altitude and maintain steady conditions for a minimum of 15 seconds. Maintain bank angle, heading, and power throughout the maneuver. To evaluate potential low frequency problems, maintain steady conditions for at least 30 seconds to start and end the maneuver and at the acquired altitude.

## B.5.6 Performance requirements

Table B- 6. Altitude change performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| ±X of target altitude. | ±50 ft | ±100 ft |
| ±X bank angle deviation from wings level. | ±2° | ±5° |
| ±X deviation in heading. | ±2° | ±5° |

## B.5.7 Variations

- To modify the level of aggressiveness of the pilot, vary climb rates and target altitude changes.
- When initiating the maneuver near minimum speed, begin with the descent first prior to the climb.

## B.5.8 Rationale

- Although variations of the maneuver described here have been used in flight tests for years, the Altitude Change is considered "new" in that the specific performance requirements have been defined to aid the pilot in evaluating the handling qualities identified in the Objectives.
- This maneuver was originally developed for the evaluation of the handling qualities of high-speed aircraft as part of a research effort undertaken for NASA DFRC (now Armstrong Flight Research Center). The maneuver description and performance objectives provided here have been modified for subsonic flight.
- After initial development this maneuver was refined using a simulator that features commercial transport and various fighter configuration models. In-flight evaluations were then conducted with a general aviation aircraft.

## B.5.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.

# B.6 Speed change

## B.6.1 Mission phase

- VTOL (low speed), Cruise, Transition

## B.6.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.6.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.6.4 Objectives

- Check for undesirable coupling between the longitudinal, lateral-directional, and unconventional (e.g., tilt rotor/wing, if applicable) axes.
- Ensure that handling qualities do not degrade during transitional flight regimes (e.g., powered lift to wing- borne flight), if applicable.
- Check for harmony between the heave axis, pitch axis controllers, and unconventional/auxiliary control axes/inceptors, if applicable.
- Check pitch and heave axes handling qualities for mildly aggressive maneuvering throughout the speed range envelope.

## B.6.5 Description

From trimmed level flight at a selected speed and regime (i.e., low speed powered lift, transition, and wing-borne flight) decelerate by 20 knots and retrim for hands-off flight. Then accelerate to the original trim speed and retrim for hands off flight. Finally, accelerate by 20 knots and retrim.

## B.6.6 Performance requirements

Table B- 7. Speed change performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| • Maintain altitude within ±X: | 100 ft | 200 ft |
| • Trim hands-off at target airspeed within ±X: | 3 knots | 5 knots |
| • Change from one trim airspeed to another within X: | 1 minute | 2 minutes |
| • Maintain heading within ±X: | 5° | 10° |

## B.6.7 Variations

- As stated in the description, the maneuver is intended to be explored in multiple flight regimes. Depending on the configuration being evaluated in a selected flight regime, the magnitude of the speed change can be adjusted to assess speed change sensitivity.

## B.6.8 Rationale

- This HQTE is designed to evaluate the ability to change speed as originally defined in the military rotorcraft handling qualities design standard.

## B.6.9 Applicable documents

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. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.7 Waveoff/Go-around

## B.7.1 Mission phase

- Power approach and landing

## B.7.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.7.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.7.4 Objectives

- Evaluate ability to rotate flight path at low airspeeds.
- Identify potential adverse responses to large control inputs at low airspeeds.

## B.7.5 Description

From nominal stabilized approach, initiate sudden go-around at gear height above runway of 50ft or less. Rapidly pitch up, attain climb attitude and apply appropriate power. Attain reference climb attitude within 10 seconds after start of go-around. End maneuver when positive rate of climb is attained. If contact with runway is unavoidable due to power limitations, such contact is acceptable provided the aircraft is safely controllable and there is no danger of tail strike.

## B.7.6 Performance requirements

Table B- 8. Waveoff/go-around performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| ± X deviation from reference climb attitude once attained. | ± 2° | ± 4° |

## B.7.7 Variations

- This HQTE was defined primarily for CTOL operations. Therefore, variations can be defined for STOL and VTOL modes.

## B.7.8 Rationale

- A waveoff/go-around from a field landing may be relatively benign or extremely demanding, depending on the altitude at which the maneuver is initiated. The intent of this maneuver is to evaluate the ability to rotate the airplane’s flight path at low speeds, not to look for any specific “cliffs” in the response (more aggressive maneuvers are used for that purpose). Hence, this go-around maneuver is not meant to be overly demanding.

- In the past, research experiments that focused on approach handling qualities used the go-around as a way to end the evaluation, but the task itself was not included as a part of the evaluation. Recently, it has become clear that “approach” should always include the final landing, since it is often in the final few feet of the flare that handling qualities problems surface. Performance requirements in the go-around were carefully worded to avoid such factors as altitude loss, because this is fundamentally a function of pitch performance, not handling qualities. The desired and adequate performance requirements listed below intentionally avoid such airframe-specific inferences.

- Some aircraft may have difficulty performing this maneuver as described. The difficulty is due to the control power demands of both rotating the airplane and compensating for adverse coupling effects. Since this maneuver is not intended to test pitch control power, it may be necessary to either limit the maximum throttle required or initiate the go-around at a higher altitude (for example, 70 or 100 ft).

## B.7.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.

# B.8 Rolling landing (CTOL)

## B.8.1 Mission phase

- Power approach and landing

## B.8.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.8.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.8.4 Objectives

- Evaluate ability to control horizontal and vertical flightpath and airspeed for landing.
- Evaluate ability to control sink rate and attitude in the flare.
- Evaluate control sensitivity and harmony in landing.

## B.8.5 Description

Initiate the maneuver approximately one mile out on final, on the nominal approach conditions (glideslope and localizer or visual landing indicator) in landing configuration, Vref* per (Airplane Flight Manual) AFM held down to 50 ft. The approach angle (glideslope) shall be as appropriate for the aircraft being tested (roughly 3˚ for conventional approach). Touch down within the prescribed touchdown zone with the aircraft centerline within the width of the zone and the main gear within the length of the zone. The task may be performed in any wind or turbulence conditions as allowed by the operational limits of the aircraft. Testing in extreme wind conditions (crosswinds and shears) is recommended. Additional constraints that are necessary for safety may be implemented as appropriate. For example, restrictions may be placed on bank angles attained by large aircraft at low altitude.

*Vref for hybrid-lift aircraft employing thrust tilt may be a combination of nacelle/pylon angle and speed per AFM to provide for appropriate landing attitudes.

## B.8.6 Performance requirements

Table B- 9. Rolling landing (CTOL) performance requirements

| | **Desired** | **Adequate** |
|---|---|---|
| Touch down within ±X of landing airspeed. | ±5 kts | ±10 kts |
| Touch down in a box that is X wide by Y long. | 20 ft wide by 1,000 ft long* | 40 ft wide by 1,500 ft long** |
| Touchdown sink rate less than X: | 4 fps (or no bounce and no hard landing if touchdown sink rate is difficult to measure) | Less than 6 fps or 80% of the gear limit (or no more than one bounce and no hard landing if touchdown sink rate is difficult to measure) |

* This is for an approach groundspeed of 132 kts. If approach groundspeed differs from this speed by more than 10 kts, adjust the box length by 7.576×(VG/S – 132), where VG/S is the approximate groundspeed in the approach (in kts).

** This is for an approach groundspeed of 132 kts. If approach groundspeed differs from this speed by more than 10 kts, adjust the box length by 11.36×(VG/S – 132), where VG/S is the approximate groundspeed in the approach (in kts).

## B.8.7 Variations

- Reduce the length of the landing box to that specified for the Precision Offset Landing HQTE.

## B.8.8 Rationale

- While every CTOL aircraft is expected to be able to perform a straight-in rolling landing, on glideslope, as a handling-qualities evaluation maneuver it should not be expected to expose potentially serious deficiencies. This maneuver is included here for completeness, with the expectation that the more demanding precision offset landing will instead be used as a primary evaluator of handling qualities during landing. Before the more demanding offset landing is attempted, however, straight-in landings will be required.

This maneuver is therefore a natural build-up task. The performance requirements for the straight-in landing maneuver are relaxed only slightly from those for the precision offset landing. Because of the uncertainty of this task, there are no counterparts for STOL aircraft.

- Experience has shown that aircraft approach speed and ambient winds can combine to introduce great variability to the landing task. An airplane that has a very low approach airspeed, or an airplane with a high approach speed in a strong headwind, will have a much easier task than a high-speed airplane in no winds or in a tailwind. The landing box lengths are nominally 1,000 and 1,500 ft for desired and adequate performance, respectively, for an airplane with an approach speed of 132 kts and no wind. This is roughly the approach speed of the USAF TIFS and NT-33A that were operated by Calspan Corporation from which the bulk of experience with this maneuver comes. It is assumed that KIAS is approximately equal to groundspeed for flight experiments with these aircraft.
- Including a performance parameter that is based on a variable such as wind can make the determination of the size of the landing box difficult at best. It is not intended that the box size change from run to run, but rather that it be adjusted whenever there is a sufficiently large wind to justify such a change. A good rule of thumb is that any difference in approach speed from 132 kts should be accounted for when it will result in a change in box length of 100 ft or more.
- Although it is not specified in the maneuver, a clearly defined aimpoint for the landing can greatly improve performance. Such an aimpoint may be a large white box (5 ft by 5 ft or larger) or a line, typically placed ¼ of the way down the desired landing zone. Lack of such a target sometimes results in apparent landing scatter simply because different pilots will use different target points on the runway.
- After initial development, this maneuver was refined using a simulator that features commercial transport and various fighter configuration models. In-flight evaluations were then conducted with a general aviation aircraft.

## B.8.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.

# B.9 Vertical landing (VTOL)

## B.9.1 Mission phase

- Heliport/Vertiport Operations

## B.9.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.9.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.9.4 Objectives

- Check ability to precisely control rotorcraft position during final descent to precision landing point.
- Check pilot-vehicle dynamics if pilot is forced into tight compensatory tracking behavior.

## B.9.5 Description

Starting from altitude greater than 10ft, maintain steady descent to prescribed landing point. It is acceptable to arrest sink rate momentarily to make last-minute corrections before touchdown. Final position shall be the position that existed at touchdown. It is not acceptable to adjust rotorcraft position and heading after all elements of landing gear have made contact with the pad.

## B.9.6 Course description

Task may be performed using Precision Hover course (HQTE 14) with designated landing point being directly under the reference point on rotorcraft when pilot's eye is at the hover point.

## B.9.7 Performance requirements

Table B- 10. Vertical landing (VTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Once altitude is below 10 ft, complete the landing within X seconds. | 10 s | 15 s |
| Touch down within ±X longitudinally of the designated reference point. | ±3 ft | ±6 ft |
| Touch down within ±X laterally of the designated reference point. | ±2 ft | ±4 ft |
| Attain a rotorcraft heading at touchdown that is aligned with the reference heading within ±X. | ±5° | ±10° |
| Descent and landing characteristics: | Accomplish a gentle landing with a smooth continuous decent and with no objectionable oscillations. | Accomplish a landing with no sustained oscillations. |

## B.9.8 Variations

- Landing may be performed in calm/moderate wind conditions including critical azimuth.

## B.9.9 Rationale

- There is a need for maneuvering capability that demonstrates a vertical landing.
- This HQTE is designed to evaluate the ability to conduct a vertical landing as originally defined in the military rotorcraft handling qualities design standard.

## B.9.10 Applicable documents

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. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.10 Depart abort/rejected takeoff

## B.10.1 Mission phase

- Heliport/Vertiport Operations

## B.10.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.10.3 Precision and aggressiveness level

- Non-precision/ aggressive

## B.10.4 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.

### B.10.5 Description

From a stabilized hover at 35 ft and 800 ft from the intended endpoint, initiate a longitudinal acceleration to perform a normal departure. Abort the departure and decelerate to a hover such that at the termination of the maneuver, the cockpit shall be within 25 ft of the intended endpoint, overshooting the target hover region is not permitted. 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 25 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.

### B.10.6 Course description

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 B- 1.

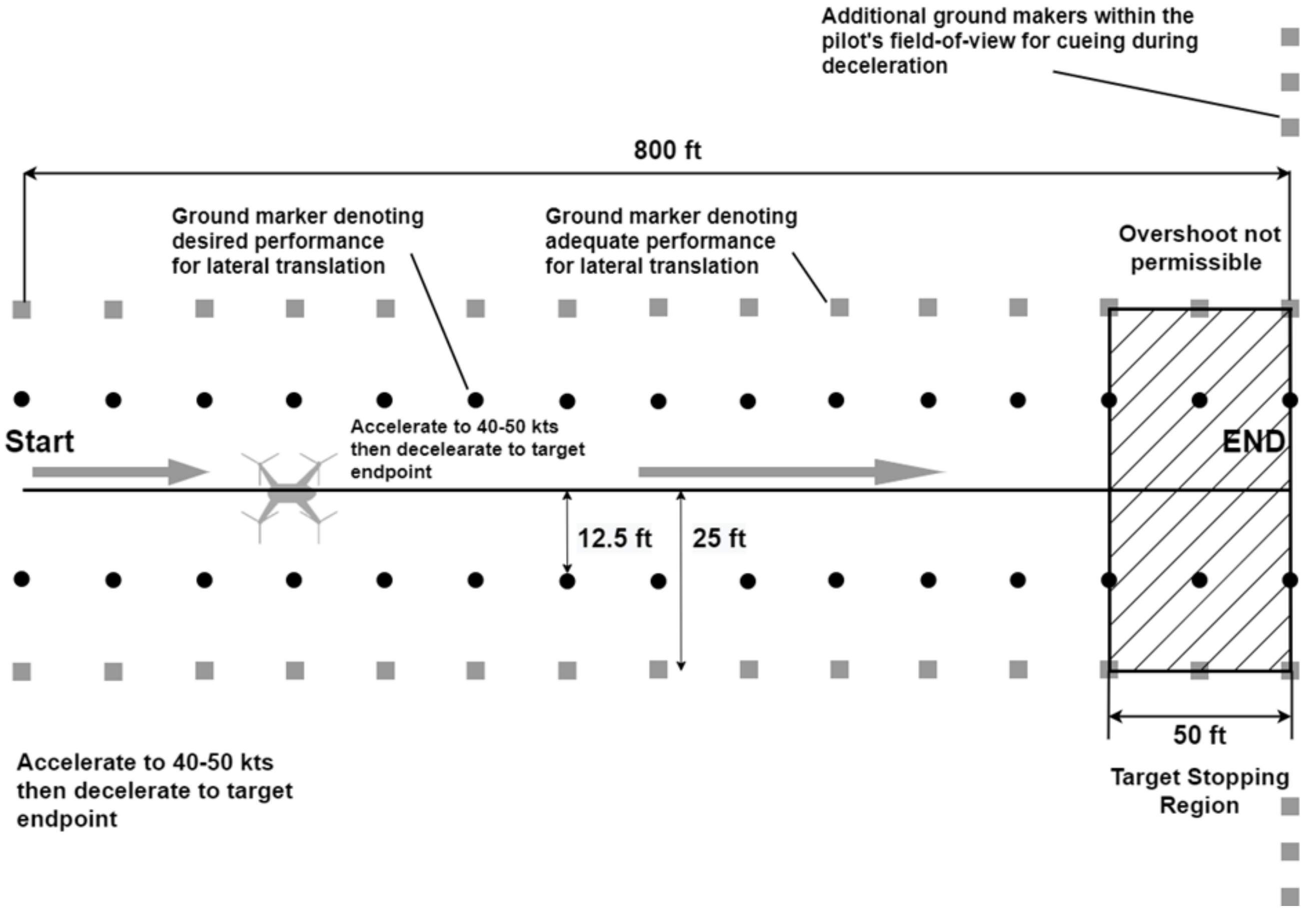


Figure B- 1. Suggested course for Depart/Abort HQTE

## B.10.7 Performance requirements

Table B- 11. Depart abort/rejected takeoff performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Maintain the lateral position track within ±X from reference line. | ±12.5 ft | ±25 ft |
| Maintain altitude below ±X. | ±50 ft | ±75 ft |
| Maintain heading within ±X. | ±10° | ±15° |
| Complete maneuver within X. | 25 seconds | 30 seconds |
| There shall be: | No undesirable motions that impact task performance during the capture and hold at the termination of the maneuver. | No divergent oscillations during the capture and hold at the termination of the maneuver. |

## B.10.8 Variations

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

## B.10.9 Rationale

- There is a need for maneuvering capability that demonstrates an aborted takeoff. The restriction on overshooting the end zone stopping region is to simulate an obstacle avoidance, hence a hard stop requirement.
- This maneuver, adapted from the U.S. Army's rotorcraft specification ADS-33E-PRF, is intended to simulate a push/pull, as might be needed to evade another aircraft.
- This maneuver as written has not been flown and, therefore, may need further refinement.

## B.10.10 Applicable documents

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. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.11 Pull-up/Push-over

## B.11.1 Mission phase

- Cruise (Obstacle Avoidance)

## B.11.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.11.3 Precision and aggressiveness level

- Non-precision/ Aggressive

## B.11.4 Objectives

- Check handling qualities at elevated and reduced load factors and during transition between elevated and reduced load factors.
- Check for undesirable coupling between pitch, roll, and yaw for aggressive maneuvering in forward flight.
- Check for ability to avoid obstacles.

## B.11.5 Description

From level unaccelerated flight at the lesser of VH or 120 knots, attain a sustained positive load factor in a symmetrical pullup. Transition, via a symmetrical pushover, to a sustained negative load factor. Recover to level flight as rapidly as possible.

## B.11.6 Performance requirements

Table B- 12. Pull-up/Push-over performance requirements

| | **Desired** | **Adequate** |
|---|---|---|
| Attain a normal load factor of at least the positive limit of the FE ($n_L(+)$) within X seconds from the initial control input. | 1 sec | 2 sec |
| Maintain at least $n_L(+)$ for at least X seconds: | 2 sec | 1 sec |
| Accomplish transition from $n_L(+)$ pullup to a pushover of not greater than the negative normal load factor limit of the FE ($n_L(-)$) within X seconds. | 2 sec | 4 sec |
| Maintain a load factor of not greater than $n_L(-)$ for at least X seconds. | 2 sec | 1 sec |
| Maintain angular deviations in roll and yaw within ±X degrees from the initial unaccelerated level flight condition to completion of the maneuver. | 10° | 15° |

## B.11.7 Variations

- No variations are proposed for this HQTE.

## B.11.8 Rationale

- There is a need for maneuvering capability at elevated load factor for obstacle avoidance and other aggressive maneuvering scenarios. This maneuver, adapted from the U.S. Army's rotorcraft specification ADS-33E-PRF, is intended to simulate a push/pull, as might be needed to evade another aircraft.

- This maneuver as written has not been flown and, therefore, may need further refinement.

## B.11.9 Applicable documents

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. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.12 Roll reversal

## B.12.1 Mission phase

- Cruise (Obstacle Avoidance)

## B.12.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.12.3 Precision and aggressiveness level

- Non-precision/ Non-aggressive

## B.12.4 Objectives

- Evaluate handling qualities while maneuvering at elevated load factors.
- Evaluate roll damping and roll authority at elevated load factors.

## B.12.5 Description

Starting from a wings-level dive, pull up to achieve the selected load factor. The target load factor should occur as the aircraft passes through level attitude. At this point execute a rapid aggressive roll to a bank angle of 45° and back to zero while maintaining the target load factor. Repeat the maneuver to the left and to the right.

## B.12.6 Performance requirements

Table B- 13. Roll reversal performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| ±X deviation from target bank angles. | ±5° | ±7° |
| Maintain the target load factor within ±X. | ±0.30g | ±0.50g |

## B.12.7 Variations

- Increase load factor from 2g to within 0.50g of the positive [nL(+)] boundary of the Flight Envelope. To perform an offensive variation of this maneuver roll to acquire and track a target aircraft (performance requirements will need refinement).

## B.12.8 Rationale

- There is a need for maneuvering capability at elevated load factor for obstacle avoidance and other aggressive maneuvering scenarios. This maneuver, adapted from the U.S. Army's rotorcraft specification ADS-33E-PRF, is intended to simulate a defensive turn, as might be needed to evade another aircraft.
- This maneuver as written has been flown almost solely for military applications, therefore, refinement.

## B.12.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.
2. Anon., *Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft*, US Army Aviation and Missile Command, ADS-33E-PRF, Mar. 2000.
3. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.13 Vertical slope landing (VTOL)

## B.13.1 Mission phase

- Heliport/Vertiport Operations

## B.13.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2130 Landing
- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.13.3 Precision and aggressiveness level

- Non-precision/Aggressive

## B.13.4 Objectives

- Check adequacy of any stability and control augmentation system changes that respond to partial or full landings.
- Check ability to precisely coordinate control of the heave axis and lateral axis with either the left or right part of the landing gear in contact with the ground.
- Check ability to precisely coordinate control of the heave axis and longitudinal axis with either the aft or forward part of the landing gear on the ground.

## B.13.5 Description

Perform a vertical landing to a sloped surface with the rotorcraft longitudinal axis oriented perpendicular to the fall line. Also perform vertical landings to a sloped surface with the rotorcraft longitudinal axis oriented parallel to the fall line. The landings shall be made with the nose pointed uphill and downhill, and with the up-slope to the left and right. For all of the slope landings, follow the following procedure. Once the upslope landing gear is in contact with the ground, maintain a level rotorcraft attitude for a short period of time, and then gently lower the downslope landing gear to the ground. Raise the downslope landing gear, keeping the upslope landing gear in contact with the ground, and maintain a level rotorcraft attitude for a short time before liftoff. Any load limits encountered shall remain within the flight envelope. There shall be no perceptible horizontal drift at touchdown or liftoff.

### B.13.6 Course description

The test area shall consist of sloped terrain that is at least 75% of the rotorcraft slope landing performance limits. The landing area shall be clearly marked on the ground.

### B.13.7 Performance requirements

Table B- 14. Vertical slope landing (VTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Touch down and maintain a final position within an area that is X ft longer than the rotorcraft landing gear | 6 ft | 12 ft |
| Touch down and maintain a final position within an area that is X ft wider than the rotorcraft landing gear | 4 ft | 8 ft |
| Maintain heading within ±X deg: | 5° | 10° |
| Maintain a level rotorcraft attitude with one part of the landing gear in contact with the ground and the rest in the air for at least X seconds before lowering and raising the downhill part of the landing gear | 5 sec | 5 sec |

### B.13.8 Variations

- No variations are proposed for this HQTE.

### B.13.9 Rationale

- This HQTE is designed to evaluate the ability to conduct a slope landing as originally defined in the military rotorcraft handling qualities design standard.

### B.13.10 Applicable documents

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. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.14 Precision hover (VTOL)

## B.14.1 Mission phase

- Heliport/Vertiport Operations

## B.14.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2130 Landing
- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.14.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.14.4 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.
- Identify pilot workload for translation to a stabilized hover and ability to maintain precision hover.

## B.14.5 Description

Initiate the maneuver from a hover and accelerate to 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 aircraft. The target hover point must be a repeatable, ground-referenced point from which aircraft deviations can be measured. The ground track should be such that the aircraft will arrive over the target hover point after performing a 45-degree translation toward to hover point (see illustration in Figure 20a) while maintaining the aircraft offset from the track axis. 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 while attempting to maintain the specified desired position tolerances.

## B.14.6 Course description

A suggested course for the Precision Hover HQTE is presented in Figure B- 2. The course includes several visual references that allow the pilot to perform the task and provide performance cues to the pilot. These minimum visual references include:

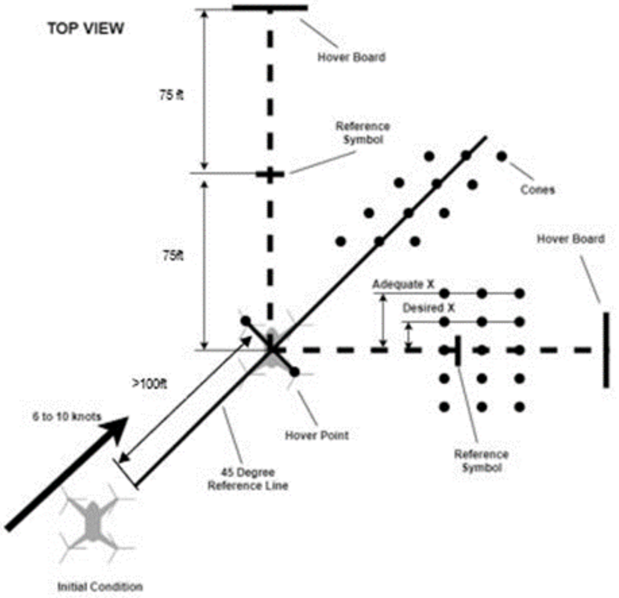
- 45 Degree Reference Line (e.g., painted lines and/or cones).
- A physical ground marker indicating the target hover point (e.g., painted “X” and/or cones).
- Two “Hover Boards” and “Reference Symbols.” One set of these is positioned in front of the hover point and the other set is positioned 90 degrees 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.

## B.14.7 Performance requirements

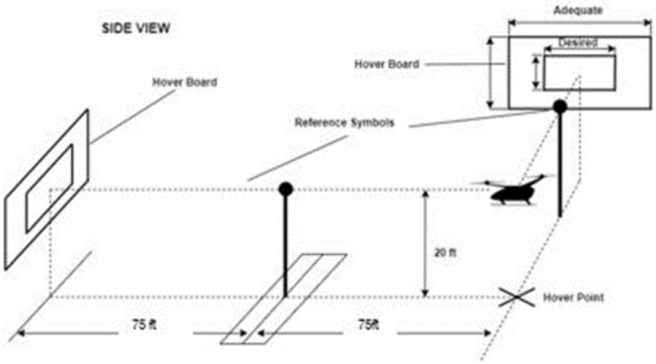
Table B- 15. Precision hover (VTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Attain a stabilized hover position from start of deceleration within: | 5 sec | 8 secs |
| Maintain lateral-longitudinal position within | ± 3 ft | ± 6 ft |

| | **Desired** | **Adequate** |
|---|---|---|
| Maintain altitude within: | ± 2 ft | ± 4 ft |
| Maintain heading within: | ± 5 deg | ± 10 deg |
| Maintain a stabilized hover for at least X seconds. | 30 secs | 30 secs |
| Oscillations: | No objectionable oscillations in any axis either during the transition to hover or the stabilized hover. | No divergent oscillations in any axis either during the transition to hover or the stabilized hover. |



a) Top View



b) Side View without cones

Figure B- 2. Suggested minimum course for precision hover HQTE

## B.14.8 Variations

- In addition to calm winds, the maneuver should be performed in moderate wind conditions off the nose of the test aircraft.
- The described HQTE test course visual cueing may need adjustment due to aircraft configuration (e.g., downwash, vortices) adversely affecting the visual cueing.
- The altitudes may also need to be adjusted to stay out of H-V avoid areas. If the altitude is modified, the hover board and reference marker locations will also need adjustment.

## B.14.9 Rationale

- This HQTE, including graphic elements in the maneuver description, are based on the MTE maneuver described in ADS-33E-PRF.
- The described maneuver does not provide for variations in technique, but these variations could be considered in future versions if needed.
- The maneuver may be flown at various stabilized altitudes to assess in- and out-of-ground effect performance.

## B.14.10 Applicable documents

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. Anon., *Commercial Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-16B, Feb. 2013.
3. Anon., *Private Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-15A, Feb. 2013.
4. Anon., *Certification of Normal Category Rotorcraft, AC27-1B*, Department of Transportation, Federal Aviation Administration, June 29, 2018.

# B.15 Hovering turn and hold (VTOL)

## B.15.1 Mission phase

- Heliport/Vertiport Operations

## B.15.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2130 Landing
- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.15.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.15.4 Objectives

- Check for any undesirable handling qualities during short and long duration low aggression hovering turns.
- Check ability of aircraft to establish and stabilize recovery from low aggression hover turn rates with precision.
- Check for any undesirable inter-axis coupling.
- Identify if pilot-induced oscillation tendencies are present.

## B.15.5 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 in 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.

### B.15.6 Course description

In a simulator, the test course should include Hover Board and ground markings that provide visual cues that clearly define desired and adequate performance. It is suggested to use the test course described with the Precision Hover HQTE shown again in Figure B- 3. Additional hover boards can be included as feasible to provide enhanced visual cueing during the turns. The recommended course cueing assumes that the maneuver will be executed about the center of gravity of the aircraft and not the pilot position. The pilot should expect that the reference symbol to the side of the aircraft will not be aligned with the center of the hover-board and start position longitudinal cueing may therefore need to be adjusted accordingly. For flight test setups, a more simplified course can be used. For example, the pilot may establish position at the center of the Pirouette course, see Figure B- 17 and maneuver about this point using the circular course markings for position reference. The forward and 90-degree hover boards in this case would be replaced by cone-fields that provide for adequate and desired tolerance cueing.

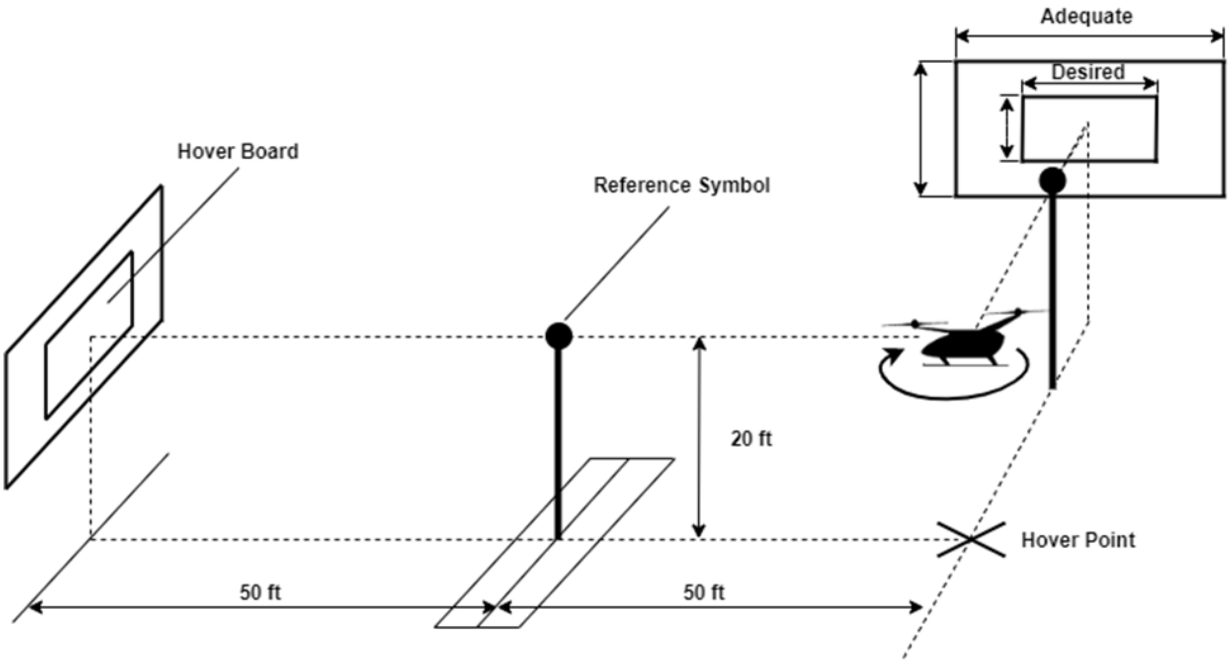


Figure B- 3. Suggested course for Hovering Turn and Hold HQTE

## B.15.7 Performance requirements

Table B- 16. Hovering turn and hold (VTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Maintain longitudinal and lateral position within ±X from the hover point. | ±3 ft | ±6 ft |
| Maintain altitude within ±X. | ±3 ft | ±6 ft |
| Stabilize the final rotorcraft heading at the 90-degree point and 270-degree point within ±X. | ±5 deg | ±10 deg |
| Complete maneuver within X. | ≤ 50 s | ≤ 60 s |
| PIO tendencies in the capture and hold. | No undesirable motions that impact task performance | No divergent PIO (out-of-phase oscillations) |

## B.15.8 Variations

- In addition to calm winds, the maneuver should be performed in moderate wind conditions.

## B.15.9 Rationale

- This HQTE, including graphic elements in the maneuver description, are derived from the Hovering Turn MTE described in ADS-33E-PRF. The dimensions of the test course and graphic elements have been modified, based on expected civilian applications.
- This HQTE emphasizes precision maneuvering and a reduced level of aggressiveness as will be expected for civilian applications when maneuvering within a heliport.
- Definitions for conditions, (e.g., aggression, precision, wind and turbulence limits) are defined in the main text of this Test Guide.

## B.15.10 Applicable documents

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. Anon., *Commercial Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-16B, Feb. 2013.

3. Anon., *Private Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-15A, Feb. 2013.

# B.16 Vertical reposition and hold (VTOL)

## B.16.1 Mission phase

- Heliport/Vertiport Operations

## B.16.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2130 Landing
- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.16.3 Precision and aggressiveness level

- Precision/non-aggressive

## B.16.4 Objectives

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

## B.16.5 Description

From stabilized hover at 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.

## B.16.6 Course description

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 with an additional Hover Board and Reference Symbol set to align with the upper altitude reference. A suggested course is shown in Figure B- 4.

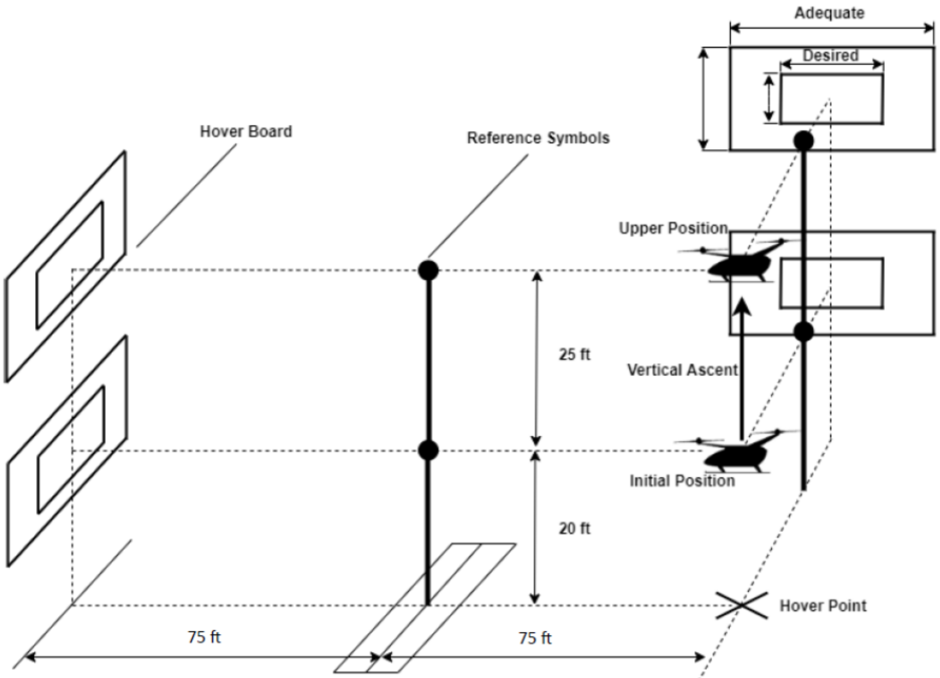


Figure B- 4. Suggested minimum course for Vertical Reposition and Hold HQTE

## B.16.7 Performance requirements

Table B- 17. Vertical reposition and hold (VTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Maintain longitudinal and lateral position within ±X from the hover point. | ±3 ft | ±6 ft |
| Maintain start/finish altitude within ±X. | ±3 ft | ±6 ft |
| Maintain heading within ±X. | ±5 deg | ±10 deg |
| Complete maneuver within X. | 25 s | 30 s |
| PIO tendencies in the capture and hold. | No undesirable motions that impact task performance | No divergent PIO (out-of-phase oscillations) |

## B.16.8 Variations

- In addition to calm winds, the maneuver should be performed in moderate wind conditions with aircraft nose into the wind.
- Light Turbulence
- The maneuver may be flown at various stabilized altitudes to assess in- and out-of-ground effect performance.
- The altitudes may also need to be adjusted to stay out of H-V avoid areas.
- If altitude is modified, hover board and reference marker locations also need adjustment.

## B.16.9 Rationale

- This HQTE, including graphic elements in the maneuver description, is derived from the Vertical Maneuver MTE described in ADS-33E-PRF. The maneuver described here emphasizes precision maneuvering over level of aggressiveness as will be expected when maneuvering within a heliport.
- The performance criteria have been adjusted based on an assumption of increased precision and reduced aggressiveness requirements for civilian applications as compared to ADS-33E.
- The hover altitudes may require adjustment for specific aircraft configurations to prevent flight in known H-V avoid areas.

## B.16.10 Applicable documents

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. Anon., *Commercial Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane),* US Department of Transportation Federal Aviation Administration, FAA-S-8081-16B, Feb. 2013.
3. Anon., *Private Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane),* US Department of Transportation Federal Aviation Administration, FAA-S-8081-15A, Feb. 2013.

# B.17 Lateral reposition and hold (VTOL)

## B.17.1 Mission phase

- Heliport/Vertiport Operations

## B.17.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2130 Landing
- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.17.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.17.4 Objectives

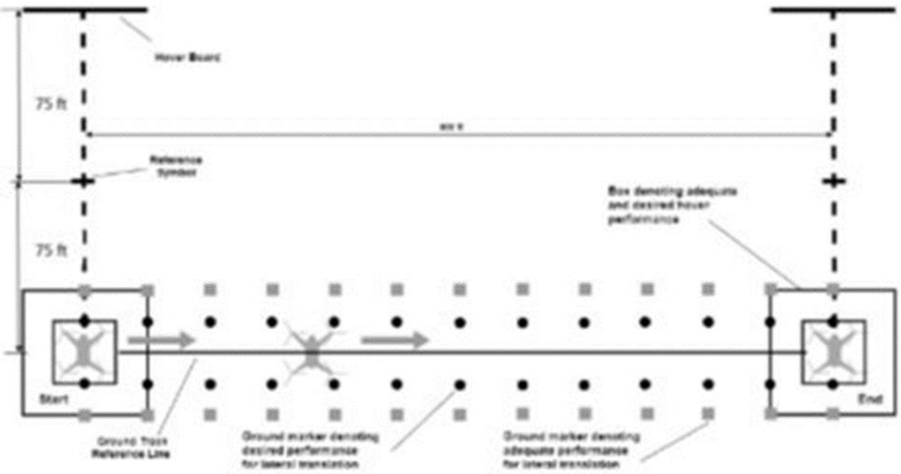
- Check roll axis and heave axis handling qualities during moderately aggressive low speed lateral maneuvering.
- Evaluate the ability to capture and maintain position and hover height.
- Check for any undesirable coupling between the roll controller and other axes.
- Check ability to recover from moderate lateral translation rate with reasonable precision.
- Identify pilot-induced oscillation tendencies if present.

## B.17.5 Description

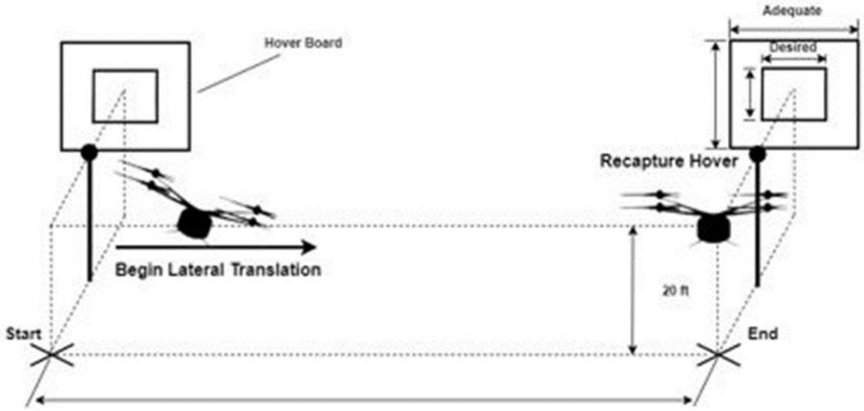
Start in a stabilized OGE hover at 20 ft altitude with the longitudinal axis of the aircraft oriented 90 degrees to a ground track reference line marked on the ground. Initiate a lateral acceleration up to a groundspeed of 15 kts followed by a deceleration to laterally reposition the aircraft in a stabilized 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 ±5 ft of the endpoint during the deceleration, terminating in a stable hover within this band for desired performance. A stabilized hover shall be maintained for 5 seconds. The maneuver will be repeated back in the other direction towards to original starting point. The maneuver is complete when a stabilized hover is achieved at either hover point.

## B.17.6 Course description

The test course shall consist of a reference line and markers indicating ground 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, while the ground track provides fore/aft cueing. A course layout for the Lateral Reposition and Hold HQTE is shown in Figure B- 5.



a) Top View



b) Side View

Figure B- 5. Course for Lateral Reposition and Hold HQTE

## B.17.7 Performance requirements

Table B- 18. Lateral reposition and hold (VTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Maintain ground track within ±X from the reference line. | ±5 ft | ±10 ft |
| Attain target ground speed within ±X. | ±2 knots | ±4 knots |
| Maintain altitude within ±X. | ±5 ft | ±10 ft |
| Maintain heading within ±X. | ±10 deg | ±15 deg |
| At capture, maintain ±X lat/lon position | ±5 ft | ±10 |
| PIO tendencies in the capture and hold. | No undesirable motions that impact task performance | No divergent PIO (out-of-phase oscillations) |

## B.17.8 Variations

- In addition to calm winds, the Lateral Reposition and Hold HQTE may be performed in moderate wind conditions with aircraft nose into the wind.
- The maneuver may be performed at multiple target ground speeds, from 5 knots and up to 20 knots. The lateral ground track distance should be adjusted with airspeed, (e.g., smaller for slower airspeeds) to approximate the same level of aggression as the baseline maneuver.
- The maneuver may be flown at various stabilized altitudes to assess in- and out-of-ground effect performance. This will require adjustment to the hover board and reference marker heights.

## B.17.9 Rationale

- This HQTE is designed to be representative of low-speed/hover maneuvering within the vicinity of a heliport/vertiport where precision, moderate aggressive maneuvering is required to avoid other aircraft obstacles, or non-transgression zones.
- This task is primarily a single-axis task that is designed to expose handling qualities deficiencies in the lateral axis, if they exist.
- Wind azimuth is prescribed off the nose to avoid interactions with sideward flight envelope limits.

## B.17.10 Applicable documents

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. Anon., Commercial Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane), US Department of Transportation Federal Aviation Administration, FAA-S-8081-16B, Feb. 2013.
3. Anon., Private Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane), US Department of Transportation Federal Aviation Administration, FAA-S-8081-15A, Feb. 2013.

# B.18 Transition

## B.18.1 Mission phase

- Transition from VTOL to Airplane Mode

## B.18.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.18.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.18.4 Objectives

- Check pitch and heave axes handling qualities for aggressive maneuvering throughout the speed range envelope.
- Check for undesirable coupling between the longitudinal, lateral-directional, and unconventional (e.g., tilt rotor/wing, if applicable) axes.
- Ensure that handling qualities do not degrade during transitional flight regimes (e.g., rotor-borne to wing- borne flight), if applicable.
- Check for harmony between the heave axis, pitch axis controllers, and unconventional/auxiliary control axes/inceptors, if applicable.

## B.18.5 Description

From 50 knots forward flight at altitude, initiate a maximum-performance acceleration to capture VH -10 knots within altitude limits. The second portion of the maneuver is to initiate a maximum-performance deceleration from VH -10 knots while holding altitude constant until 50 kts is captured. Each phase will be rated separately.

## B.18.6 Performance requirements

Prior to the maneuver for score, the Minimum Acceleration ($T_{minimum\_accel}$) and Deceleration Times ($T_{minimum\_decel}$), maximum performance, must be determined. This can be done analytically (via offline simulation, performance charts, or other means) or empirically (via real-time piloted simulation or in flight). When determining the minimum time, the other task tolerances should be used as a guide but do not have to be adhered to strictly. The airspeed of 50 ±5 kts is to be captured in deceleration. While the tolerances are used as guides, altitude and heading should not be exchanged for performance. Each phase can have a different Minimum Time.

Table B- 19. Transition performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Acceleration Phase:<br>Complete acceleration within time $T < \Delta T + T_{minimum\_accel}$ | $\Delta T = 8.0$ s | $\Delta T = 15.0$ s |
| Deceleration Phase:<br>Complete deceleration within time $T < \Delta T + T_{minimum\_decel}$ | $\Delta T = 10.0$ s | $\Delta T = 20.0$ s |
| Both Phases:<br>Final airspeed to be captured within: | ± 2 kts | ± 3 kts |
| Maintain heading within X degrees of initial heading: | ± 5° | ± 10° |
| Maintain bank angle (from trim) within: | ± 5° | ± 10° |
| Maintain initial altitude within: | ±100 ft | ±200 ft |
| Any oscillations or inter- axis coupling shall not be: | Undesirable | Objectionable |
| Control harmony between axes shall not be: | Undesirable | Objectionable |

## B.18.7 Variations

- Variations of this maneuver can be expected to include assessment of the ability to modulate the transition rate and reverse it, as well as assessment of maneuverability for collision avoidance while in transition.
- Longitudinal axis integration is the primary challenge here where multiple effectors such as elevator, propulsor tilt and cyclic tilt of rotors has to be integrated in a fashion with one or two inceptors to allow for ease of operation while still providing for the ability to modulate speed and provide for evasive maneuvering.

## B.18.8 Rationale

- Transition corridors may be anticipated to have various automations associated with envelope protection. With tiltrotor as a basis, the upper boundary of the corridor, predicated on speed and configuration, will likely be based on structural load considerations on propulsors and other aircraft components, while the lower bounds of the transition corridor will likely be based on wing stall avoidance.
- How envelope limits are integrated will dictate certain aspects of HQTE application. For instance, in the tiltrotors, envelope limiting such as the upper conversion corridor protection is safe to interact with, but not considered to be safe to ride-on for an extended time, with corridor limits typically displayed on the nacelle indicator on the primary flight display.
- Conversion corridor interaction would be considered an abuse case. The HQTE deceleration maneuver, if not properly described and constrained, would then result in various dispersed CHR in the event that some encountered limiting and some did not. In this case the pilots are advised to observe the conversion protection boundaries in the HQTE, and the CHR will then converge, albeit with higher pilot workload associated with observance of margins in the maneuver.
- In the case of the lower conversion corridor boundary, limiting of maximum downward nacelle rate is used to avoid easily lowering the nacelles into a stall configuration before the aircraft has had a chance to accelerate. The pilot display of nacelle position can be integrated into the acceleration task, increasing workload to avoid the modulation effects of the lower boundary and possible stall.

- For many new concepts, the corridor boundary will be completely avoided through automation, and it is therefore incumbent upon the applicants to ensure that such envelope limiting for stall prevention is suitable for all gross weight and load factors associated with the design, while still providing acceptable handling qualities with interaction of the limiting.

## B.18.9 Applicable documents

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. Brewer, R., F. Conway, R. Mulato, H. Xin, C. E. Fegely, W. C. Fell, Klyde, J. Horn, P. Ruckel, J. Rigsby, D. H. Klyde, S. P. Pitoniak, P. C. Schulze, J. Horn, C. R. Ott, and C. L. Blanken, “Further Development and Evaluation of a New Acceleration / Deceleration ADS-33 Mission Task Element,” presented at the *AHS International 74th Annual Forum*, Phoenix, AZ, May 14–17, 2018.

# B.19 Altitude rate capture and hold

## B.19.1 Mission phase

- Cruise

## B.19.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.19.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.19.4 Objectives

- Evaluate precision climb rate characteristics in isolation.
- Evaluate phugoid stability.

## B.19.5 Description

From steady level flight rapidly capture and maintain a climb rate of 1,000 fpm for an altitude change of 500 ft. Then immediately capture and hold a sink rate of 1,000 fpm and return to the initial altitude. Then immediately return to level flight. Power should be held constant throughout the maneuver. To evaluate potential low frequency problems maintain steady conditions for at least 30 seconds to start and end the maneuver and at the acquired climb and sink rates.

## B.19.6 Performance requirements

Table B- 20. Altitude rate capture and hold performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| ±X deviation in climb or sink rate: | ±100 fpm | ±300 fpm |
| No more than one climb or sink rate overshoot. | Magnitude of overshoot remains within the desired region. | Magnitude of overshoot remains within the adequate region. |

## B.19.7 Variations

- Additional target climb rates may be used to vary the level of aggressiveness.

## B.19.8 Rationale

- This particular maneuver was originally developed for the evaluation of the handling qualities of high-speed aircraft as part of a research effort undertaken for NASA DFRC (now Armstrong Flight Research Center).
- This maneuver is designed to track altitude rate. Without a direct readout of rate, however, the evaluation pilot will need to determine the appropriate pitch attitudes that correspond to the desired climb and descent rates.

## B.19.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.

# B.20 Flightpath capture and hold

## B.20.1 Mission phase

- Cruise

## B.20.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.20.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.20.4 Objectives

- Evaluate ability to maintain airspeed during initiation of climbs and descents.
- Evaluate coupling between airspeed and flightpath.

## B.20.5 Description

From steady level flight, rapidly pitch over and reduce power to attain a steady dive angle of -5˚ within the specified tolerances. After an altitude loss of 500 ft, rapidly pitch up and increase power to attain a steady climb angle of 5°within the specified tolerances. Smoothly level off at the initial altitude. Repeat the maneuver by first climbing and then diving.

## B.20.6 Performance requirements

Table B- 21.Flightpath capture and hold performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| ±X deviation in flightpath angle. | ± 1° | ± 2° |
| Attain target descent and climb angles with no more than one overshoot. | Magnitude of overshoot remains within the desired region. | Magnitude of overshoot remains within the adequate region. |
| ±X deviation in airspeed. | ± 10 kts | ± 20 kts |

## B.20.7 Variations

- The climb and descent angles may be varied and the pilot may adjust the level of aggressiveness from smooth to abrupt inputs.

## B.20.8 Rationale

- Precise control of flightpath, while maintaining airspeed, is critical for many operational elements. This maneuver is aimed specifically at evaluating path/speed coupling that might degrade the ability to perform aerial recovery or rendezvous tasks.

## B.20.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.

# B.21 Pitch attitude capture and hold

## B.21.1 Mission phase

- Cruise

## B.21.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.21.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.21.4 Objectives

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

## B.21.5 Description

This task is driven by an automated command signal selected by the flight test engineer (see Figure B- 6). 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 HQTE 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.

## B.21.6 Cockpit display descriptions

Several cockpit display variations can be used to support the pilot evaluations. These designs were all inspired by the evaluation pilot displays that have been used by Calspan Corporation in their Learjet In-Flight Simulators[4]. Two essentially equivalent display variations (see Figure B-7) are typically used, the bowtie and the whiskers. 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. Similarly, with the whisker display, the objective is for each commanded attitude to maintain the orange dot capture and hold within the green circles for pitch.

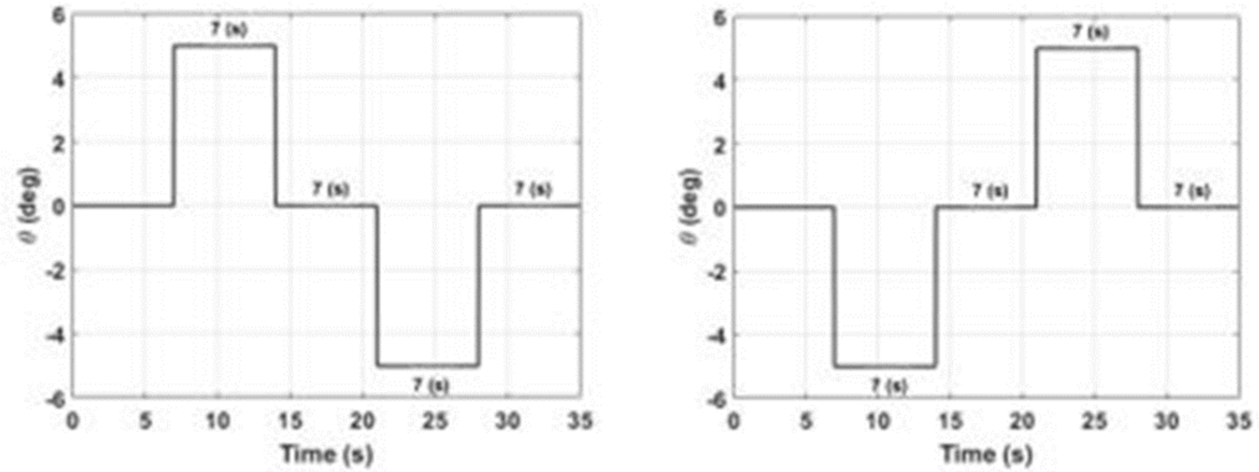


Figure B- 6. Example pitch attitude capture and hold command signals

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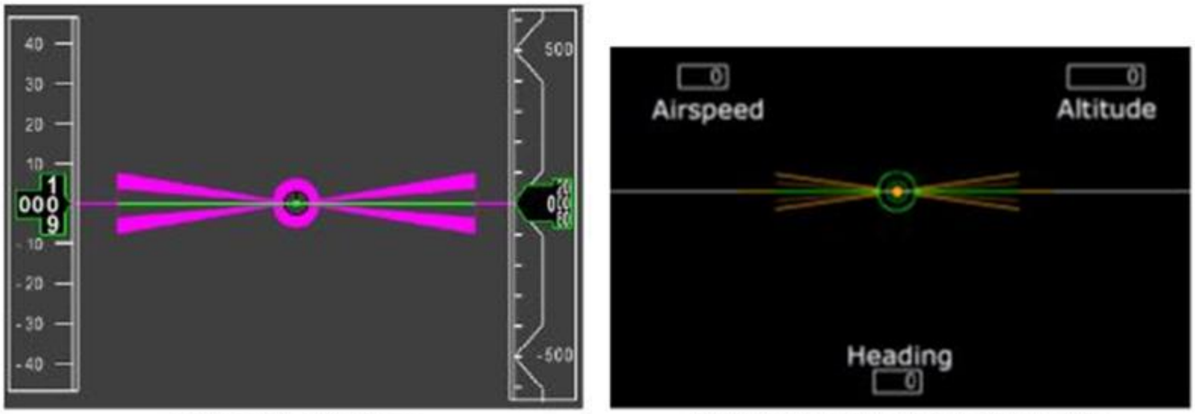
[4] Weingarten, N. C., “History of In-Flight Simulation & Flying Qualities Research at Calspan,” *J. of Aircraft*, Vol. 42, No. 2, March-April 2005



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

Figure B- 7. Example cockpit displays for pitch attitude capture and hold

## B.21.7 Performance requirements

Table B- 22. Pitch attitude capture and hold performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Pitch angle error (from command) tolerance: | ±1° | ±2° |
| Airspeed deviation tolerance: | ±5 kts | ±10 kts |
| No more than one pitch attitude overshoot on the initial capture of each attitude. Magnitude of overshoot is less than: | 1° | 2° |
| PIO considerations: | No PIO tendencies | No divergent PIO tendencies |
| Inter-axis coupling shall not be | Undesirable | Objectionable |

## B.21.7 Variations

- Variations of this MTE 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 B- 6, 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 MTE.

## B.21.8 Rationale

- Although variations of the maneuver described here have been used in flight tests for years, the Pitch Attitude Capture and Hold was considered “new” when introduced as part of the USAF Demonstration Maneuvers program in that the HQTE and specific performance requirements were defined to aid the pilot in evaluating the handling qualities identified in the Objectives. This particular maneuver was originally developed for the evaluation of the handling qualities of high-speed aircraft as part of a research effort undertaken by Systems Technology, Inc. for NASA AFRC.
- After initial development, the fixed wing maneuver was refined via in-flight evaluations conducted with a general aviation aircraft.
- Variations of this HQTE have also been flown extensively in the Calpsan Learjet with test pilot evaluators as part of programs conducted by Systems Technology, Inc. for NASA AFRC and the USAF.
- The HQTE defined herein, derives directly from an MTE developed under the “Rotorcraft Handling Qualities Requirements for Future Configurations and Missions” project sponsored by the Vertical Lift Consrtium and the US Army. This program investigated and developed a comprehensive update to the mission task elements (MTEs) required for evaluating different rotorcraft configurations with respect to the US Army Future Vertical Lift requirements.

## B.21.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog,* STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.
2. Klyde, D. H., S. P. Pitoniak, P. C. Schulze, P. Ruckel, J. Rigsby, H. Xin, C. E. Fegely, W. C. Fell, R. Brewer, F. Conway, R. Mulato, J. Horn, C. R. Ott, and C. L. Blanken, “Piloted Simulation Evaluation of Attitude Capture and Hold MTEs for the Assessment of High-Speed Handling Qualities,” presented at the *AHS International 74th Annual Forum,* Phoenix, AZ, May 14–17, 2018.
3. Klyde, D. H., and D. G. Mitchell, “Development of Supersonic Demonstration Maneuvers with the NASA SR-71 Aircraft and Simulator,” AIAA 98-0493 presented at *36th Aerospace Sciences Meeting & Exhibit,* Reno, NV, January 12 – 15, 1998.

# B.22 Bank angle capture and hold

## B.22.1 Mission phase

- Cruise

## B.22.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.22.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.22.4 Objectives

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

## B.22.5 Description

This task is driven by an automated command signal selected by the flight test engineer (see Figure B- 8). 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.

## B.22.6 Cockpit display descriptions

Several cockpit display variations can be used to support the pilot evaluations. These designs were all inspired by the evaluation pilot displays that have been used by Calspan Corporation in their Learjet In-Flight Simulators[5]. Two essentially equivalent display variations (see Figure B-9) are typically used, the bowtie and the whiskers. For the roll evaluations with the bowtie 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 capture and hold the green line within the diagonal whisker bounds.

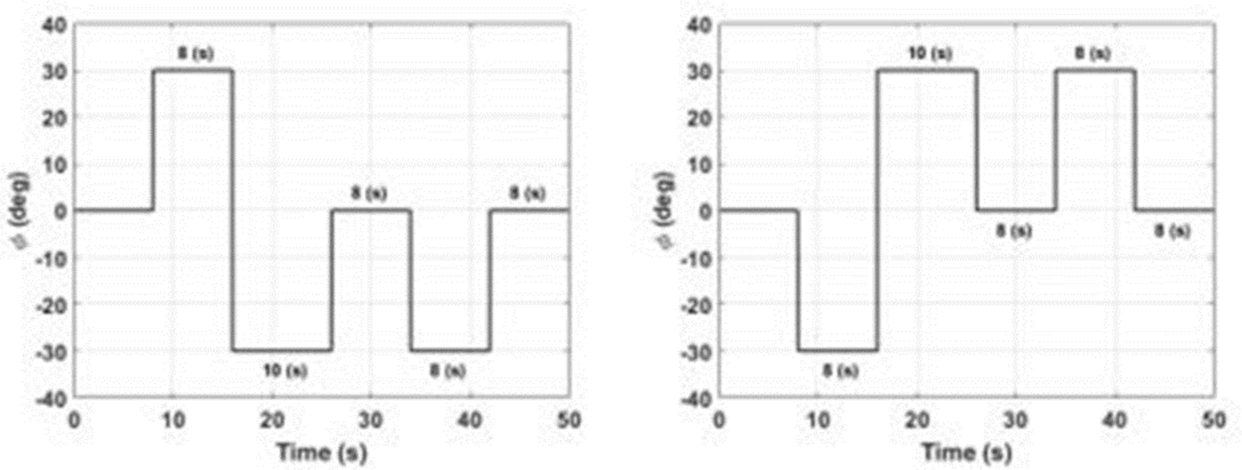


Figure B- 8. Example bank angle capture and hold command signals

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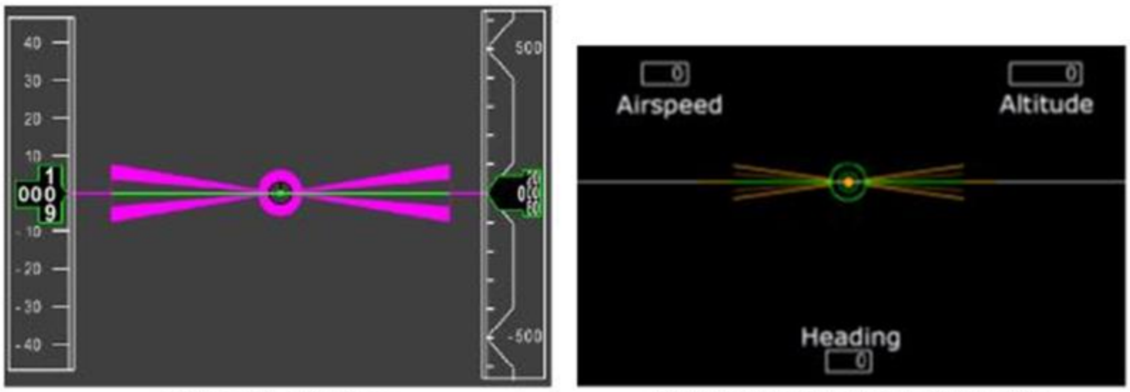
[5] Weingarten, N. C., “History of In-Flight Simulation & Flying Qualities Research at Calspan,” *J. of Aircraft*, Vol. 42, No. 2, March-April 2005



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

Figure B- 9. Example cockpit displays for bank angle capture and hold

## B.22.7 Performance requirements

Table B- 23. Bank angle capture and hold performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Bank angle error (from command) tolerance: | ±5° | ±10° |
| Airspeed deviation tolerance: | ±5 kts | ±10 kts |
| No more than one bank angle overshoot on the initial capture of each attitude. Magnitude of overshoot is less than: | 5° | 10° |
| PIO considerations: | No PIO tendencies | No divergent PIO tendencies |
| Inter-axis coupling shall not be | Undesirable | Objectionable |

## B.22.8 Variations

- 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 B- 8, 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.

## B.22.9 Rationale

- Although variations of the maneuver described here have been used in flight tests for years, the Bank Angle Capture and Hold was considered “new” when introduced as part of the USAF Demonstration Maneuvers program in that the HQTE and specific performance requirements were defined to aid the pilot in evaluating the handling qualities identified in the Objectives. This particular maneuver was originally developed for the evaluation of the handling qualities of high-speed aircraft as part of a research effort undertaken by Systems Technology, Inc. for NASA AFRC.
- After initial development, the fixed wing maneuver was refined via in-flight evaluations conducted with a general aviation aircraft.
- Variations of this HQTE have also been flown extensively in the Calspan Learjet with test pilot evaluators as part of programs conducted by Systems Technology, Inc. for NASA AFRC and the USAF.
- The HQTE defined herein, derives directly from an MTE developed under the “Rotorcraft Handling Qualities Requirements for Future Configurations and Missions” project sponsored by the Vertical Lift Consortium and the US Army. This program investigated and developed a comprehensive update to the mission task elements (MTEs) required for evaluating different rotorcraft configurations with respect to the US Army Future Vertical Lift requirements.

## B.22.10 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog,* STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.
2. Klyde, D. H., S. P. Pitoniak, P. C. Schulze, P. Ruckel, J. Rigsby, H. Xin, C. E. Fegely, W. C. Fell, R. Brewer, F. Conway, R. Mulato, J. Horn, C. R. Ott, and C. L. Blanken, “Piloted Simulation Evaluation of Attitude Capture and Hold MTEs for the Assessment of High-Speed Handling Qualities,” presented at the *AHS International 74th Annual Forum*, Phoenix, AZ, May 14–17, 2018.
3. Klyde, D. H., and D. G. Mitchell, “Development of Supersonic Demonstration Maneuvers with the NASA SR-71 Aircraft and Simulator,” AIAA 98-0493 presented at *36th Aerospace Sciences Meeting & Exhibit*, Reno, NV, January 12 – 15, 1998.

# B.23 Heliport approach (VTOL)

## B.23.1 Mission phase

- Power approach

## B.23.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.23.3 Precision and aggressiveness level

- Precision/Non-aggressive

## B.23.4 Objectives

- Check ability to accomplish precision control of the aircraft simultaneously in the pitch, roll, yaw, and heave axes.
- Check for any undesirable behavior introduced by transitions across for example:
    - Lift-Modes
    - Command modes/functions
    - Response types
    - Reference frames
    - Configuration changes
- Check for ability to maintain steady approach to landing.
- Identify pilot-induced oscillation tendencies, if present.

- Check for overly complex power management requirements.
- Check ability to perform precision vertical and lateral tracking to very low decision height and groundspeed with a reasonable pilot workload

## B.23.5 Description

The Heliport Approach consists of four segments: capture, glidepath tracking, deceleration, and transition for landing. Begin the maneuver in straight and level flight at the specified approach speed (see Table B- 24), at an altitude of >500 ft above and > 1 nmi downrange of the target landing area. Capture and maintain the specified target approach glide path angle. At the Hdecel altitude, begin a smooth deceleration while maintaining the approach glidepath angle to cross the landing area (e.g., FATO) threshold at the Helipad Crossing Height (HCH) of 20ft Height Above Threshold (HAT) and 5 kts groundspeed (VAT) with the aircraft configured for landing.

The approach profile and suggested test course is shown in Figure B- 10. The minimum visual cues for the test course shall 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 Visual Glide Path Indicators and the cockpit PFD as illustrated in Figure B- 11 and Figure B- 12.

Maneuver Test Conditions:

- Any operational weight, most adverse CG location

Table B- 24. Suggested approach glide path angles and speeds

| Glideslope | 3° | 6° | 9° | 11°<br>(calm winds only) |
|---|---|---|---|---|
| $H_{FAF}$ | (500’ AGL/1 nm above/from TLOF elevation) | | | |
| $H_{decel}$ (RA) | 150 ft or below | 200 ft or below | 200 ft or below | 150 ft or below |
| $V_{AT}$ Speed Target | 5 kts groundspeed | | | |
| HCH | 20 ft HAT | | | |

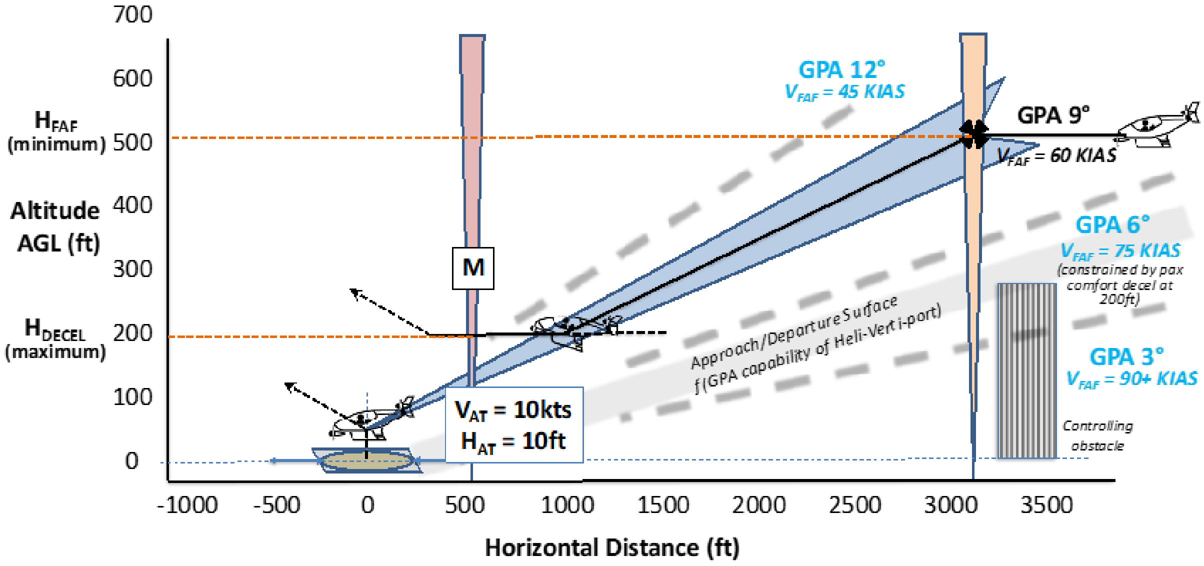


Figure B- 10. Suggested approach profile and test course for the UAM heliport approach

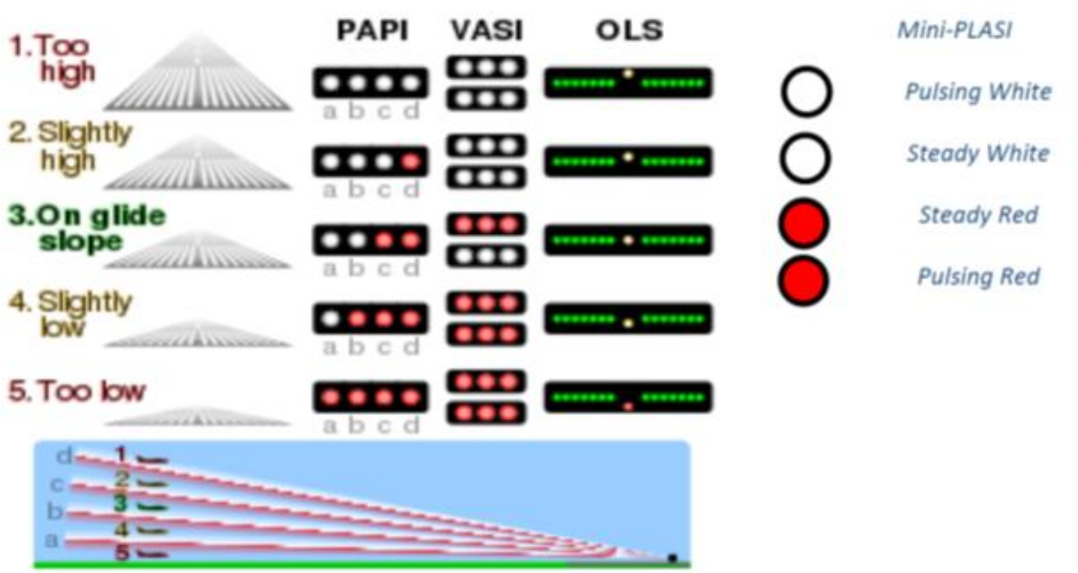


Figure B- 11. Visual glide path/slope indicators

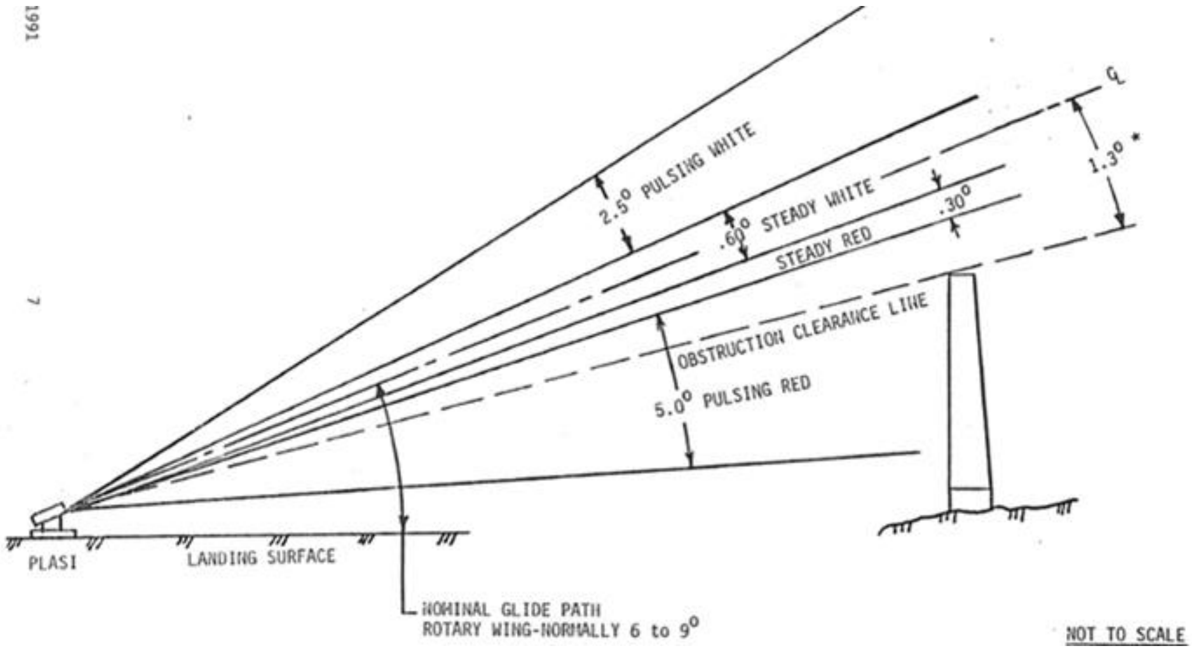


Figure B- 12. PLASI glide path indications

## B.23.6 Performance requirements

Table B- 25. Heliport approach (VTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Maintain a vertical glidepath from HFAF to 200 ft within: | ±0.7° | ±2.1° |
| Maintain a lateral approach course from HFAF to 200 ft AGL within: | ±0.7° | ±2.1° |
| Altitude at FATO boundary within: | ±10 ft | ±20 ft |
| Lateral deviation from center of FATO within: | ±20 ft | ±60 ft |
| Maintain VAT at HCH within: | ±2 kts | ±5 kts |

## B.23.7 Variations

The UAM Heliport Approach HQTE shall be performed in:

- VMC conditions/Good Visual Environment
- Calm winds

- Moderate (10-15) knot crosswinds
- Light Turbulence
- At different Glide Path Angles (GPA)
- GPA +2˚ (calm wind) abuse case

## B.23.8 Rationale

- This maneuver, including graphic elements in the maneuver description, are based on the nominal UAM Heliport approach profile developed by Webber (2022).
- The approach maneuver is intended to terminate such that multiple landing maneuver variations can be initiated from the approach maneuver, either before or after the deceleration segment.
- Symmetric Touchdown and Liftoff (TLOF), Final Approach and Takeoff (FATO) and Safety Area designed in accordance with FAA Advisory Circular AC 150 5390-2C on Heliport Design.
- The lateral and vertical glidepath performance metrics were designed to meet the criteria defined in FAA Advisory Circular AC 150 5390-2C for VFR General Aviation heliport approaches, adjusted for a nominal 6-degree glidepath. The performance criteria were defined by ATP approach performance standards for desired performance and instrument rating approach performance standards for adequate performance.
- Approach speed targets are limits based on expectations about Rate of Descent, passenger comfort. The 3-degree approach speed limit reference is based on ICAO Category H operational speed limits.
- The maneuver accommodates vehicles that will make a constant decelerating approach on a fixed glidepath to a hover point directly over the touchdown point.
- The approach is constructed to comply with assumed aircraft performance constraints (e.g. maintain adequate energy/control margin, avoid Vortex Ring State or autorotation regimes).
- The approach speeds for Glide Path Angles (GPA) above 9° may be adjusted to agree with the Vs speed for the aircraft.

- Glidepath Angles may vary for different aircraft configurations.
- The crosswinds are needed to expose deficiencies associated with transitions to low speed maneuvering (e.g., reference frame transitions).

## B.23.9 Applicable documents

1. Webber, D., *NASA Advance Air Mobility (AAM) National Campaign (NC) UAM Helicopter Flight Testing Presentation*, Federal Aviation Administration, November 2020.
2. https://www.faa.gov/training_testing/testing/test_standards/, site accessed August 25, 2019.
3. Anon., *Commercial Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-16B, Feb. 2013.
4. Anon., *Private Pilot Practical Test Standards for Rotorcraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-15A, Feb. 2013.
5. Anon., *Airline Transport Pilot and Aircraft Type Rating Practical Test Standards for Helicopter*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-20, Aug. 1998.
6. Anon., *Commercial Pilot – Airplane Airman Certification Standards*, US Department of Transportation Federal Aviation Administration, FAA-S-ACS-7A, June 2018.
7. Anon., *Private Pilot – Airplane Airman Certification Standards*, US Department of Transportation Federal Aviation Administration, FAA-S-ACS-6B, June 2018.
8. Anon., *Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft*, US Army Aviation and Missile Command, ADS-33E-PRF, Mar. 2000.
9. Anon., *Certification of Normal Category Rotorcraft*, AC27-1B, Department of Transportation, Federal Aviation Administration, June 29, 2018.
10. Anon., *Flight Test Guide for Certification of Transport Category Airplanes*, AC25-7D, Department of Transportation, Federal Aviation Administration, May 4, 2018.
11. Anon., *Flight Test Guide for Certification of Part 23 Airplanes*, AC23-8C, Department of Transportation, Federal Aviation Administration, Nov., 16, 2011.
12. Anon., *Heliport Design*, AC150/5390-2C, Department of Transportation, Federal Aviation Administration, May 24, 2012.
13. Anon., *United States Standard for Terminal Instrument Procedures (TERPS)*, ORDER8260.3D, Department of Transportation, Federal Aviation Administration, Feb., 16, 2018.

# B.24 Precision ILS capture and track (CTOL)

## B.24.1 Mission phase

- Power approach

## B.24.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.24.3 Precision and aggressiveness level

- Non-precision/non-aggressive

## B.24.4 Objectives

- Evaluate ability to acquire and track an approach signal in IMC.
- Evaluate speed stability (control force per knot).
- Identify path/speed coupling in IMC.

## B.24.5 Description

With the aircraft configured for final approach and from an approach course that is offset at least 1½ dots laterally and vertically, rapidly maneuver to reacquire centerline of the ILS beam. Start correction when the aircraft is 5 nm from the runway threshold, or as it crosses the outer marker. The most critical combination of offsets (high, low, left, right) should be emphasized. Track the ILS beam until the missed approach point or an altitude of 400 ft AGL, whichever is higher.

## B.24.6 Performance requirements

Table B- 26. Precision ILS capture and track (CTOL) performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Attain trimmed flight on the ILS: | at a range from the runway of 2 nm or greater | before crossing the middle marker (~0.5 nm from the runway) |
| Maintain trimmed approach speed within ±X kts: | ±5 kts | ±10 kts |
| Maintain glideslope and localizer within ±X dot: | ±½ dot | ±1 dot |

## B.24.7 Variations

- No variations are defined for this task.

## B.24.8 Rationale

- The ability to capture and precisely track an ILS (Instrument Landing System) signal depends upon good airspeed stability and control as well as favorable path/speed coupling.

- This maneuver is written specifically in terms of an ILS command signal, but it is not meant to be used only when an ILS is to be used. It may be applied for other ground-based, or even aircraft-based (such as GPS), landing signals intended for operations in IMC.

- The requirements for precision, written here in terms of conventional "dots," will need to be converted to comparable requirements for other types of displays.

## B.24.9 Applicable documents

1. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.

# B.25 Precision offset landing

## B.25.1 Mission phase

- Power approach and landing

## B.25.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.25.3 Precision and aggressiveness level

- Precision/non-aggressive

## B.25.4 Objectives

- Evaluate ability to precisely control horizontal and vertical flightpath and airspeed.
- Evaluate ability to precisely control sink rate and attitude in the flare.
- Evaluate tendency for nose bobble or PIO.
- Evaluate control sensitivity and harmony in landing.

## B.25.5 Description

Initiate the maneuver approximately one mile out on final approach with a lateral offset of 200 ft from the runway centerline and on glideslope. The approach angle (glideslope) shall be as appropriate for the aircraft being tested (roughly 3° for conventional approach). At 200 ft AGL aggressively correct the lateral offset to land on the runway centerline with wings level. This is for an approach groundspeed of 132 kts. If approach groundspeed differs from this speed by more than 10 kts, adjust the offset correction altitude by $1.515\bigcirc(V_{G/S} - 132)$, where VG/S is the approximate groundspeed in the approach (in kts). Touch down within the prescribed touchdown zone with the aircraft centerline within the width of the zone and the main gear within the length of the zone. The task may be performed in any wind or turbulence conditions as allowed by the operational limits of the aircraft. Testing in extreme wind conditions (crosswinds and shears) is recommended. Additional constraints that are necessary for safety may be implemented as appropriate. For example, restrictions may be placed on bank angles attained by large aircraft at low altitude.

## B.25.6 Performance requirements

Table B- 27. Precision offset landing performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Touch down within ±X kts of landing airspeed: | ±5 kts | ±10 kts |
| Touch down in a box that is X ft wide by Y ft long: | 20 ft wide by 400 ft long* | 40 ft wide by 1,000 ft long** |
| Touchdown sink rate less than X fps: | 4 fps<br>(or no bounce and no hard landing if touchdown sink rate is difficult to measure) | 6 fps<br>(or no more than one bounce and no hard landing if touchdown sink rate is difficult to measure) |

* This is for an approach groundspeed of 132 kts. If approach groundspeed differs from this speed by more than 10 kts, adjust the box length by 3.03□(VG/S – 132), where VG/S is the approximate groundspeed in the approach (in kts).

** This is for an approach groundspeed of 132 kts. If approach groundspeed differs from this speed by more than 10 kts, adjust the box length by 7.576□(VG/S – 132), where VG/S is the approximate groundspeed in the approach (in kts)

## 25.7 Variations

- Initiate the maneuver with vertical as well as lateral offsets. Vary the vertical offsets to as much as 200 ft above glideslope.

## 25.8 Rationale

- The offset landing has become a common task for evaluation of handling qualities in landing formation. Previously, it was not unusual for “landing” handling-qualities evaluations tasks to end with a low approach, but it has since become clear that the final few feet before main-gear touchdown are critically important in exposing any dangerous deficiencies.

- The landing task has evolved to include lateral offsets from the runway centerline, both to investigate lateral handling qualities and to force the pilot to maneuver aggressively just prior to touchdown.

## 25.9 Applicable documents

1. *Notice of Change to MIL-STD-1797A, Notice 1*, Department of Defense Interface Standard, 28 June 1995.
2. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.
3. Anon., *Flight Test Guide for Certification of Transport Category Airplanes*, AC25-7D, Department of Transportation, Federal Aviation Administration, May 4, 2018.

# B.26 Pitch and roll sum-of-sines tracking

## B.26.1 Mission phase

- Cruise

## B.26.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.779 Motion and effect of cockpit controls

## B.26.3 Precision and aggressiveness level

- Precision/aggressive

## B.26.4 Objectives

- Evaluate handling qualities in a tight, closed-loop tracking task.
- Evaluate feel system and control sensitivity characteristics.
- Identify bobble or Pilot-Induced Oscillation (PIO) tendencies.

## B.26.5 Description

This task is driven by an automated command signal selected by the flight test engineer. From steady, wings level flight aggressively track the displayed signal and attempt to keep errors within the specified tolerances.

This maneuver does not require a test course. The maneuver does require a display with the desired and adequate performance criteria displayed to the pilot as described earlier. Examples of pitch and roll angle command signals are shown in Figure B- 13. The length for scoring time is recommended to be 60 seconds.

The recommended command signals as flown in the formal piloted simulation evaluations are defined in Table B- 28.

Table B- 28. Precision, Aggressive MTE

| Parameter | $i$ = 1 | $i$ = 2 | $i$ = 3 | $i$ = 4 | $i$ = 5 | $i$ = 6 | $i$ = 7 |
|---|---|---|---|---|---|---|---|
| $\omega$ (rad/s) | 0.314 | 0.523 | 0.837 | 1.361 | 2.199 | 3.560 | 5.760 |
| Pitch Amp (deg) | 2.493 | 1.793 | 1.216 | 0.776 | 0.487 | 0.303 | 0.188 |
| Roll Amp (deg) | 11.814 | 7.854 | 5.104 | 3.190 | 2.002 | 1.232 | 0.770 |

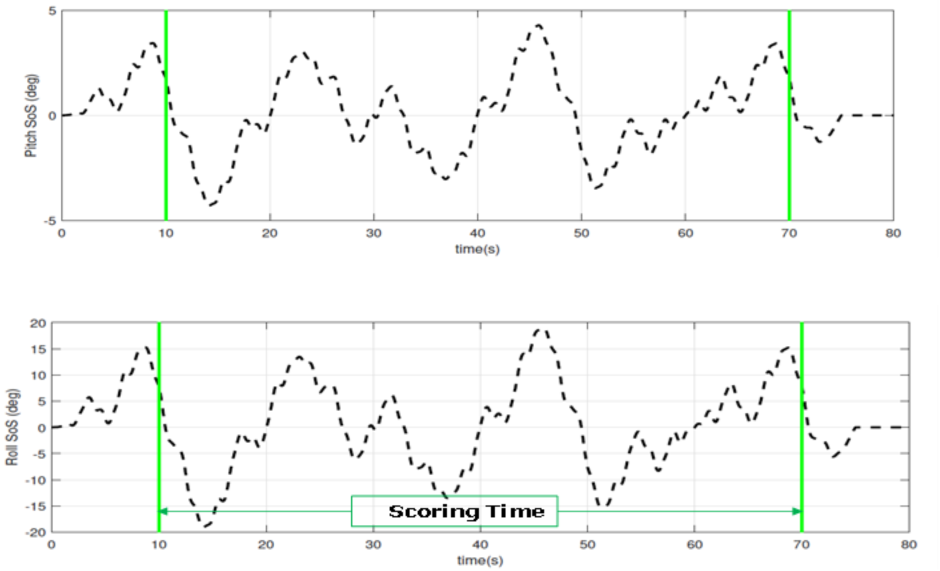


Figure B- 13. Example pitch and roll sum-of-sines command signals

## B.26.6 Display description

Figure B- 14 illustrates a pitch attitude compensatory display. In the figure, the green bar with inner and outer reticles is the aircraft attitude indicator, while the orange bar with center dot is the command. The difference between the command and attitude is the error that the pilot attempts to minimize within the defined desired and adequate performance constraints as represented by the inner and outer reticles, respectively. The pilot therefore compensates for the displayed error, hence a compensatory display.

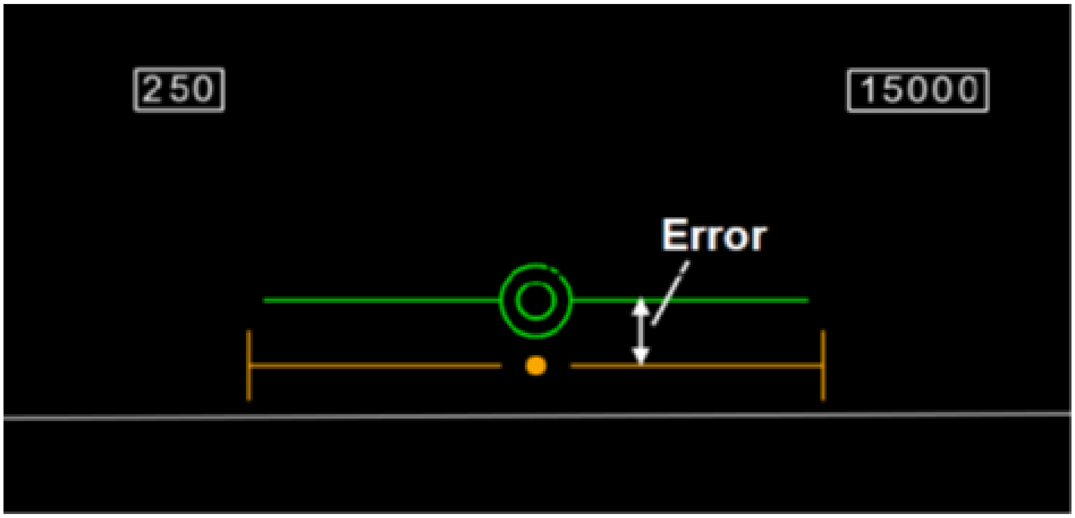
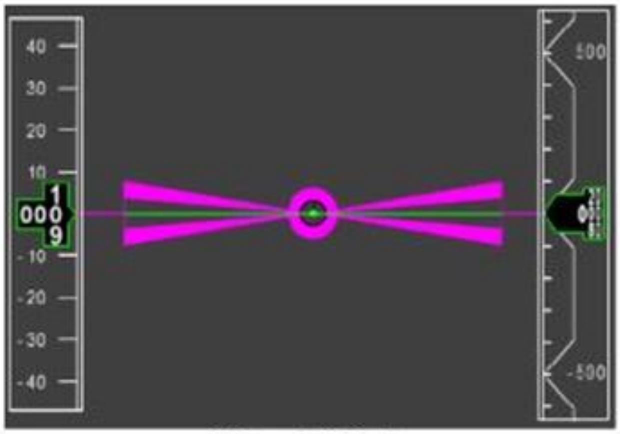
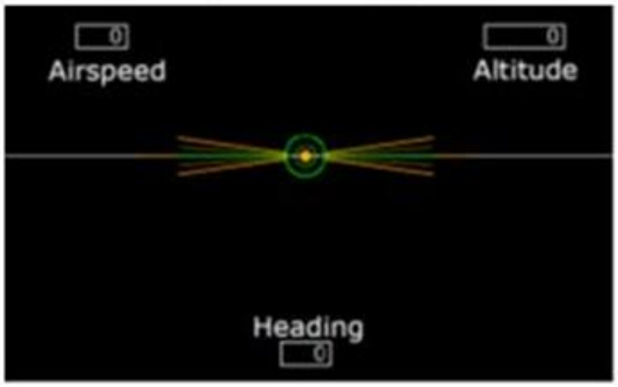


Figure B- 14. Example compensatory tracking display

Two essentially equivalent display variations are shown in Figure B- 15, the bowtie and the whiskers. 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 capture and hold within the green circles for pitch and to capture and hold the green line within the diagonal whisker bounds for roll.



a) Bowtie Display



b) Whiskers Display (with Labels)

Figure B- 15. Example cockpit displays

## B.26.7 Performance requirements

Table B- 29. Pitch and roll sum-of-sines tracking performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Pitch: at least X% of the scoring time within pitch attitude error tolerance: | 50%<br>±1° | 75%<br>±2° |
| Roll: at least X% of the scoring time within roll attitude error tolerance: | 50%<br>±5° | 75%<br>±10° |
| PIO Considerations: | No PIO tendencies | No divergent PIO tendencies |
| Inter-axis coupling shall not be | Undesirable | Objectionable |

## B.26.8 Variations

- This task can be performed at a variety of cruise airspeeds. Evaluations should start in the center of the flight envelope before moving to edge of the envelope cases.

## B.26.9 Rationale

- This HQTE is designed as a handling qualities stress test wherein the pilot must continuously track a command based on the displayed error between the reference and actual attitude. The primary objective is to mitigate displayed errors within the task performance bounds, a compensatory tracking task, since the pilot must "compensate" for the errors.

- Tracking a computer-generated command signal produces a highly repeatable, precise task from which measures of pilot performance can be obtained. While such measures should never be interpreted as a direct indicator of handling qualities, they are one sure way to monitor pilot workload and confirm that workload is as desired. Use of similar tracking tasks has for decades provided a source of information on pilot/vehicle closed-loop dynamics. The maneuver proposed here is based on this experience, but with some of the nuances of past applications removed for simplicity.

## B.26.10 Applicable documents

1. Klyde, D. H., S. P. Pitoniak, P. C. Schulze, P. Ruckel, J. Rigsby, C. E. Fegely, H. Xin, W. C. Fell, R. Brewer, F. Conway, R. Mulato, J. Horn, C. R. Ott, and C. L. Blanken, "Piloted Simulation Evaluation of Tracking MTEs for the Assessment of High-Speed Handling Qualities," *J. of the Vertical Flight Society*, Volume 65, Number 3, July 2020, pp. 1-23(23).
2. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft: Maneuver Catalog*, STI-Paper-1310-1, Systems Technology, Inc., 2 June 2023.
3. Anon., *Flight Test Guide for Certification of Transport Category Airplanes*, AC25-7D, Department of Transportation, Federal Aviation Administration, May 4, 2018.

# B.27 Flightpath regulation

## B.27.1 Mission phase

- Cruise and approach

## B.27.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.779 Motion and effect of cockpit controls

## B.27.3 Precision and aggressiveness level

- Precision/aggressive

## B.27.4 Objectives

- Evaluate handling qualities in a tight, closed-loop disturbance regulation task.
- Evaluate feel system and control sensitivity characteristics.
- Identify bobble or Pilot-Induced Oscillation (PIO) tendencies.

## B.27.5 Description

Aggressively minimize the displayed flightpath error (□e) signal and attempt to keep the error within the specified tolerances. A sum-of-sines (SOS) disturbance input forcing function is used to “mimic” random atmospheric turbulence with a known input as part of a pilot regulation tracking task. That is, the disturbance continually displaces the vehicle from its path (e.g., the approach glide slope), while the pilot attempts to minimize the displayed path error within desired performance constraints. Such a task is exemplified in Figure B- 16. Here, the pilot will regulate against the flightpath disturbance. If the pilot is on glideslope as indicated here, then there is no command input, only the disturbance. For flightpath command response types, this task can also be used for cruise flight conditions where the flightpath command is the trim condition attitude. Thus, the pilot will regulate against the disturbance to maintain the trim flightpath.

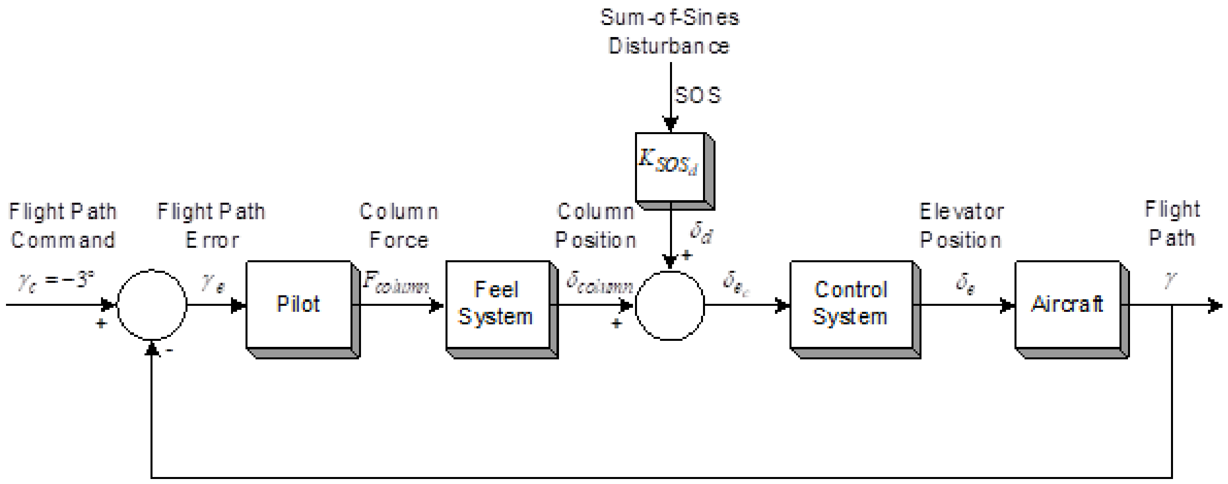


Figure B- 16. Glide slope regulation task with pitch rate command system

Table B- 30 presents the parameters for an example Fibonacci series-based SOS input. Here, the input is defined for a 60 second scoring time run length. Thus, each sine wave frequency is defined by fn (Hz) = Nn (cycles/run)/60 (s/run). The amplitude of the disturbance can be adjusted using the gain shown in Figure B- 16.

Table B- 30. SOS disturbance input

| Parameter | *i* = 1 | *i* = 2 | *i* = 3 | *i* = 4 | *i* = 5 | *i* = 6 | *i* = 7 |
|---|---|---|---|---|---|---|---|
| $\omega$ (rad/s) | 0.314 | 0.523 | 0.837 | 1.361 | 2.199 | 3.560 | 5.760 |
| Disturbance Amp (deg) | +1.000 | -0.6000 | +0.3750 | -0.2308 | +0.1429 | -0.0882 | +0.0545 |

## B.27.6 Performance requirements

Table B- 31. Flightpath regulation performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Flightpath: at least X% of the scoring time within pitch attitude error tolerance: | 50%<br>±1° | 75%<br>±2° |
| PIO Considerations: | No PIO tendencies | No divergent PIO tendencies |
| Inter-axis coupling shall not be | Undesirable | Objectionable |

## B.27.7 Variations

- This task can be performed at a variety of cruise and approach airspeeds. Evaluations should start in the center of the flight envelope before moving to edge of the envelope cases.

## B.27.8 Rationale

- The regulation task features the benefits of the sum-of-sines tracking, but with a scenario that may appear more operationally relevant to the evaluation pilots.

## 27.9 Applicable documents

1. Lotterio, M., R. McMahon, P. Schifferle, D. Alvarez, D. Klyde, P. C. Schulze, "FAA Fly-by-Wire Research Program — Year 2 Follow-On, DOT/FAA/TC-15/13, March 2016.

# B.28 Pirouette

## B.28.1 Mission phase

- Heliport/vertiport operations

## B.28.2 FAR Part 23 requirement(s)

Handling qualities requirements apply to:

- §23.2130 Landing
- §23.2135 Controllability
- §23.2145 Stability
- §23.2300 Flight control systems
- §23.2500 Airplane level systems requirements
- §23.2600 Flight crew interface
- §23.2615 Flight, navigation and powerplant instruments
- §23.779 Motion and effect of cockpit controls

## B.28.3 Precision and aggressiveness level

- Precision/aggressive

## B.28.4 Objectives

- Demonstrated ability to accomplish precision control at low speed 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.

## B.28.5 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 aircraft pointed at a reference point at the center of the circle, and at a hover altitude of approximately 10 ft. The pilot position should be aligned with the centerline of the tolerances (data collection with regard to aircraft center should be adjusted accordingly to this position). Accomplish a lateral translation around the circle, keeping the nose of aircraft pointed at the center of the circle, and the centerline circumference of the circle under the pilot position. Establish and maintain essentially constant lateral groundspeed to accomplish the maneuver within the target time tolerance. Terminate the maneuver with a stabilized hover over the starting point. Perform the maneuver in both directions.

## B.28.6 Course description

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 B- 17 is considered adequate for the evaluation. Typically ground markers included 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

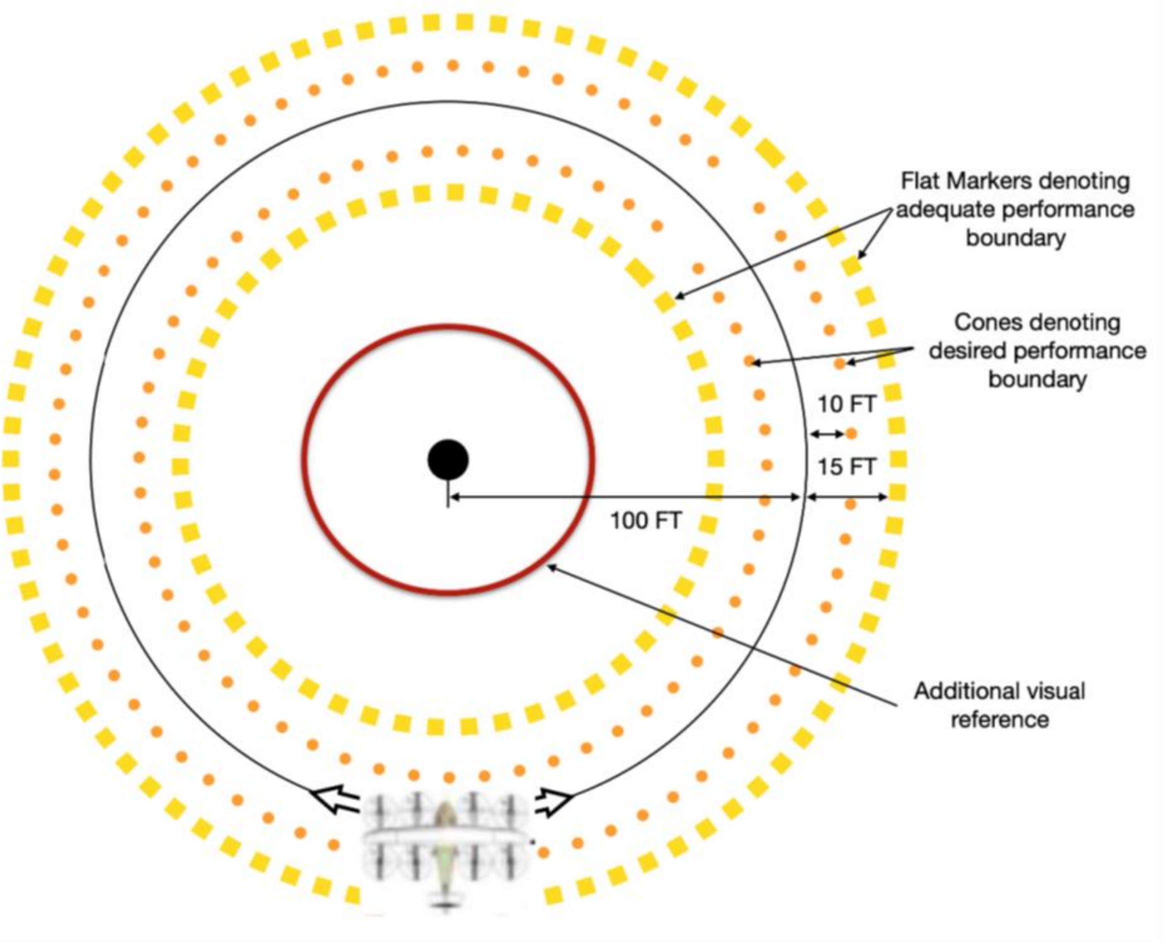


Figure B- 17. Suggested minimum course for pirouette HQTE

## B.28.7 Performance requirements

Table B- 32. Pirouette performance requirements chart

| | **Desired** | **Adequate** |
|---|---|---|
| Maintain a selected reference point on the aircraft within ±X ft of the circumference of the circle. | ± 10 ft | ± 15 ft |
| Maintain altitude within ±X ft: | ±3 ft | ± 5 ft |
| Maintain heading so that the nose of the aircraft points at the center of the circle within ±X deg: | ± 10 deg | ± 15 deg |
| Complete the path within: | ≤ 60 secs<br>(6 kts) | ≤ 80 secs<br>(4-5 kts) |
| Achieve a stabilized hover (within desired hover reference point) within X seconds after returning to the starting point. | 5 secs | 10 secs |
| Maintain the stabilized hover for an additional X sec: | 5 secs | 5 secs |

## B.28.8 Variations

- In addition to calm winds, the maneuver should be performed in moderate wind conditions with the start of the maneuver with aircraft nose into the wind.

## B.28.9 Rationale

- This HQTE, including graphic elements in the maneuver description, are based on the MTE maneuver described in ADS-33E-PRF.
- This multi-axis engineering maneuver is considered especially valuable in evaluation of novel unique inceptor mappings and control response types. The test course size was designed for heliport operations.
- A change in lateral translation rate groundspeed at 180 degrees was proposed early on to expose any handling deficiencies associated with recovering from disturbances. This was determined to be unnecessary since these disturbances would be manifested with execution of the maneuver in winds.

## B.28.10 Applicable documents

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. Anon., *Commercial Pilot Practical Test Standards for Aircraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-16B, Feb. 2013.
3. Anon., *Private Pilot Practical Test Standards for Aircraft (Helicopter and Gyroplane)*, US Department of Transportation Federal Aviation Administration, FAA-S-8081-15A, Feb. 2013.