DOT/FAA/TC-22/49

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

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

January 2023

Final report

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-22/49		
4. Title and Subtitle Developing Methods of Compliance for eVTOL Vehicles: Phase II Final Report		5. Report Date January 2023 6. Performing Organization Code
7. Author(s) D. H. Klyde, Ph.D., M. G. Jones, Ph.D., A. Kotikalpudi, Ph.D., and M. Lotterio		8. Performing Organization Report No.
9. Performing Organization Name and Address Systems Technology, Inc. 13766 Hawthorne Blvd. Hawthorne, CA, 90250		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 692M15-18-C-00010
12. Sponsoring Agency Name and Address Small Airplane Standards Branch FAA Central Regional Office 901 Locust St Kansas City, MO 64106 FAA Sponsors: David Sizoo and Ross Schaller.		13. Type of Report and Period Covered Phase 2 14. Sponsoring Agency Code

15. Supplementary Notes "This project is part of a portfolio of AIR 714 sponsored projects. The portfolio of collaborative projects involves SMEs from industry, the FAA, NASA, and US Air Force AFWERX Agility Prime. The goal is to advance FAA policy and to develop methods to consistently test Advanced Air Mobility Vehicles with integrated flight and propulsion control. The methods investigated are proposed by AIR 714 and are being incorporated into industry consensus standards."

16. Abstract

Development of new air vehicles types (e.g., personal air vehicles, urban taxis, etc.) have led to a proliferation of Vertical Takeoff and Landing (VTOL) vehicle concepts including electric vehicles, many of which are well funded and are in various stages of prototype development and testing. These vehicles almost exclusively feature fly-by-wire (FBW) flight control systems with advanced flight control system response-types. The processes and requirements needed to certify these disparate vehicles for operation within the National Airspace System are still emerging. To aid in the requirements and certification process, a mission-oriented approach is being applied to define Mission Task Elements (MTEs), often referred to as Flight Test Maneuvers (FTMs), that will serve as a means of compliance with Part 21.17(b) of certification regulations. This report summarizes the Phase II effort of this program wherein an industry representative lift plus cruise electric Vertical Takeoff and Landing (eVTOL) configuration was used to develop and exercise via analysis and fixed-base simulation candidate Handling Qualities Task Elements (HQTEs), a subset of MTEs/FTMs, that address control law transitions, envelope protections, and automation. MTEs/FTMs are repeatable tests based on the vehicle Concept of Operations (CONOPS) and tailored to evaluate aircraft characteristics that assure safe operations within the flight envelope and the ability to perform the intended mission(s) with acceptable pilot workload/compensation. Based on the research conducted herein, elements of a holistic approach to means of compliance testing were successfully demonstrated using HQTEs. The HQTEs were found to provide an effective assessment process across vehicle response-types, with and without envelope protection. Structured HQTE-like testing can also be used to assess increasing automation via Automation Qualities Task Elements (AQTE). To demonstrate, automated transitions were evaluated from hover to forward flight and vice versa with and without envelope protections active.

17. Key Words	18. Distribution Statement
Certification – Means of Compliance Flight Control – Law Transitions, Flight Control – Envelope Protection Flight Control – Handling Qualities	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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Symbols and Acronyms

Symbol	Definition
h	Altitude
$\dot{h}$	Altitude rate (climb rate, descent rate)
p	Roll rate
q	Pitch rate
r	Yaw rate
V_x	Longitudinal velocity
V_y	Lateral velocity
α	Angle of attack
α_{lb}	Angle of attack envelope protection lower bound
α_{ub}	Angle of attack envelope protection upper bound
δ_{ail}	Aileron control surface position
δ_{elv}	Elevator control surface position
ϕ	Roll attitude (bank angle)
θ	Pitch attitude
$\dot{\theta}$	Euler angle pitch rate
τ_{cmd}	Torque command
ψ	Heading angle
Acronym	**Definition**
AAM	Advanced Air Mobility
ACAH	Attitude Command/Attitude Hold response-type
AFRC	Armstrong Flight Research Center
AGL	Above ground level
AoA	Angle of attack
AQTE	Automation Qualities Task Element
BACH	Bank Angle Capture and Hold
CONOPS	Concept of Operations
eVTOL	Electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FBW	Fly-by-wire
FCS	Flight control system
FQA	Flying Qualities Assessments

FTM	Flight Test Maneuver
HOVTL	Human-Over-The-Loop
HQTE	Handling Qualities Task Element
HWTL	Human-Within-The-Loop
I-TRAC	Integrated-Translational Rate & Acceleration-trim Command
KCAS	Knots Calibrated Air Speed
KGS	Knots Ground Speed
KTAS	Knots True Air Speed
LHI	Left-hand Inceptor
LACVH	Linear Acceleration Command/Velocity Hold
MOC	Means of compliance
MTE	Mission Task Element
NASA	National Aeronautics and Space Administration
PACH	Pitch Attitude Capture and Hold
PH	Position Hold
PI	Proportional-integral
PIO	Pilot-induced Oscillation
RCAH	Rate Command Attitude Hold
RCDH	Rate Command Direction Hold
RCHH	Rate Command Height Hold
RHI	Right-hand Inceptor
SQA	System Qualities Assessments
STI	Systems Technology, Inc.
SVO	Simplified vehicle operations
TRC	Translational Rate Command
USAF	United States Air Force
VTOL	Vertical Takeoff and Landing

Executive summary

Development of new air vehicle types (e.g., personal air vehicles, urban taxis, etc.) have led to a proliferation of Vertical Takeoff and Landing (VTOL) vehicle concepts including electric vehicles, many of which are well funded and are in various stages of prototype development and testing. These vehicles almost exclusively feature fly-by-wire (FBW) flight control systems with advanced flight control system response-types. The processes and requirements needed to certify these disparate vehicles for operation within the National Airspace System are still emerging. To aid in the airworthiness requirements and certification process, a mission-oriented approach is being applied to define Mission Task Elements (MTEs), often referred to as Flight Test Maneuvers (FTMs) that will serve as a means of compliance with Part 21.17(b) of certification regulations.

This report summarizes the Phase II effort of this research wherein an industry representative lift plus cruise electric vertical takeoff and landing (eVTOL) configuration was used to develop and exercise via analysis and fixed-base simulation candidate Handling Qualities Task Elements (HQTEs), a subset of MTEs/FTMs, that address control law transitions, envelope protections, and automation. MTEs/FTMs are standardized handling qualities tests based on the vehicle Concept of Operations (CONOPS) and tailored to evaluate aircraft characteristics that assure safe operations within the flight envelope and the ability to perform the intended mission(s) with acceptable pilot workload/compensation.

The industry representative lift plus cruise eVTOL model used in this study was of sufficient fidelity and level of detail to successfully carry out the developments and piloted simulation evaluations shown herein. Key results from this study are summarized as follows:

- FBW offers the Advanced Air Mobility (AAM) marketplace many unique flight-control system response-types or flight control modes that can not only augment basic stability, but also provide increasing automation such that simplified vehicle operations (SVO) with a single pilot can be made safe in dense urban environments.
- Using the industry representative vehicle model, envelope protection methods were reviewed for use in cruise and hover/low speed flight regimes. Selected simplified envelope protection schemes were then designed and integrated with the lift plus cruise model.
    - Piloted simulation was used to demonstrate the effectiveness of HQTEs to assess the impact of envelope protection on handling qualities of the vehicle. To maximize the utility of this process, the envelope limits were set lower

than would likely be expected in actual operations. Given this assessment environment, the HQTEs were found to effectively stress the envelope protection systems while exposing handling qualities challenges, typically in the form of undesirable motions or oscillations when encountering protection limits.

    - Descending and ascending turns were used to demonstrate issues that may arise if conflicts between envelope protections develop. In the piloted simulation evaluations, the maneuvers were flown as flying qualities assessments, as specific desired and adequate performance requirements have not yet been defined. While the level of detail in the model used in this study may not have been sufficient to fully expose potential deficiencies, the assessment process was found to be valid.

- Using the industry representative lift plus cruise vehicle model, an autonomous transition feature was designed and integrated such that the vehicle could maneuver from hover to forward flight and vice versa without pilot interaction.
    - Piloted simulation evaluations were conducted using manual transitions to provide a reference point for the automation design.
    - Automated transitions were evaluated via computer simulation with and without envelope protections active.

Based on the research conducted herein, elements of a holistic approach to means of compliance testing were successfully demonstrated using HQTEs. The HQTEs were found to provide an effective assessment process across vehicle response-types, with and without envelope protection. Structured HQTE-like testing can also be used to assess increasing automation via Automation Qualities Task Elements (AQTE). To demonstrate, automated transitions were evaluated from hover to forward flight and vice versa with and without envelope protections active.

1 Introduction

Development of new air vehicle types have led to a proliferation of Vertical Takeoff and Landing (VTOL) vehicle concepts including electric vehicles. These vehicles will almost exclusively feature fly-by-wire (FBW) flight control systems (FCS) that may feature advanced response-types. The processes and requirements needed to certify these disparate vehicles for operation within the National Airspace System are still emerging. To aid in the requirements and certification process, Systems Technology, Inc. (STI) has defined and assessed means of compliance (MOC) through analysis and piloted simulation in the form of Mission Task Elements (MTEs)/Flight Test Maneuvers (FTMs), repeatable tests based on the vehicle Concept of Operations (CONOPS) and tailored to evaluate aircraft characteristics that assure:

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

MTEs/FTMs consist of the following:

- System Qualities Assessments (SQAs) are methods to evaluate indirect flight control systems, (e.g., (Anon., 2007)). SQAs consist of system stability and robustness measures identified from frequency sweeps or similar inputs, applied during analysis, in hardware/software-in-the-loop simulators, and flight tests, including:
    - phase and gain margins
    - disturbance rejection
    - time delays
- Flying Qualities Assessments (FQAs) identify characteristics of the aircraft from open-loop control inputs (e.g., steps, doublets, 3-2-1-1, frequency sweeps, etc.), see ADS-33E-PRF (Anon., 2000). 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 for indirect flight control designs for means of compliance testing.
- Handling Qualities Task Elements (HQTEs) are the subset of FTMs/MTEs as described above, involving the application of closed-loop tasks and piloted evaluation using the Cooper-Harper rating scale. The applications of HQTEs in the certification means of compliance process is described further in DOT/FAA/TC-21/19 (Klyde, Pitoniak, Schulze, Manriquez, & Gray, 2021). 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 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 operational envelope (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 propulsory and non-propulsory 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. HQTEs are expected to be executed within the controllability limits as described by the aircraft flight envelope (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 and/or significant non-linear behavior.

- These HQTEs are intended to address the evaluation needs of new VTOL intended to operate as personal transport or urban commuter transport vehicles. The work described herein expands upon the Phase I work reported in DOT/FAA/TC-21/19 (Klyde, Pitoniak, Schulze, Manriquez, & Gray, 2021) to address transitions from hover to forward flight and vice versa, envelope protection, and automated modes.

The technical objectives for this Phase II research effort were as follows:

- Develop HQTEs to explore the aircraft handling qualities of FBW FCS with different integrated envelope protection systems and different envelope protection prioritization schemes.
- Develop HQTEs to explore control law transitions between thrust borne lift and wing borne lift modes of flight for VTOL. These would look at normal and emergency operations.
- Investigate how the changes in automation affect the HQTEs that have been developed and determine if new HQTEs are needed to effectively evaluate the aircraft's handling qualities.

2 Background

Modern powered lift aircraft typically feature FBW flight control systems with control modes or response-types that can be tailored to the CONOPS. This section provides a brief introduction to common response-types that have been implemented on powered lift vehicles. The objective of these advanced response-types for the AAM marketplace is to not only provide increased augmentation, but also response tailoring such that a single pilot can safely and proficiently operate the vehicle in a dense urban environment without exceptional skills or strength. This builds upon the simplified vehicle operations (SVO) construct (Anon., 2019) introduced by the General Aviation Manufacturers Association (GAMA).

2.1 Rate Command (RC)/Rate Command Attitude Hold (RCAH)

Most rotorcraft, without augmentation, are RC response systems in all axes. With a RC system, angular rates are a function of the corresponding control inputs. As such, to stabilize at a desired pitch or roll attitude, the pilot must close the attitude loop by removing or reversing the cyclic control input once the desired attitude is reached. Doing this typically requires the pilot to rely on visual (out-the-window) cueing, so the task of stabilizing becomes more difficult (and dangerous) as the visual cueing degrades.

A typical RCAH system can include the following features:

- longitudinal and lateral stick command proportional attitude rates,
- stick in detent holds attitude, and
- potential to use trim beeps to change attitudes.

2.2 Attitude Command Attitude Hold (ACAH) response-type

An ACAH system has increased augmentation over an RCAH system. With an ACAH system, control inputs to the cyclic produce corresponding aircraft attitudes. Larger control input deflections command larger attitudes, holding an input holds the corresponding attitude, and returning to center detent returns the aircraft back to zero attitude or a trimmed attitude. A step longitudinal/lateral input into the cyclic with an ACAH system would produce a step response in pitch/roll attitude. The implementation of ACAH can vary and considerations for repositioning of detent and release of stick forces can be made. For example, the design of the CH-47F DAFCS (Colosi, Einthoven, Kocher, Parsons, & Carrothers, 2015; Irwin, Einthoven, Miller, & Blanken, 2007) included a backdrive capability in the pitch axis. A longitudinal backdrive servo allowed for repositioning of the longitudinal detent. Additionally, the backdrive capability allowed the pilots to trim out stick forces when using the ACAH response-type in the pitch axis, resulting in lower pilot workload during relatively long duration accelerated flight maneuvers.

A typical ACAH system can include the following features:

- longitudinal and lateral stick command proportional aircraft attitudes
- stick in detent returns to zero attitude (or potentially a trimmed attitude), and
- potential to use trim beeps to change attitudes.

2.3 Translation Rate Command (TRC) response-type

A TRC system has further increased augmentation over an ACAH system. With a TRC system, control inputs to the cyclic command proportional translational rate. Larger cyclic stick deflections command faster translations and returning to detent commands zero translational rate. It is common to include a Position Hold (PH) mode in a TRC system. The PH is typically implemented to automatically engage below a set groundspeed threshold (for example, groundspeed < 1 knot), at which point a GPS reference point in selected and held. A typical TRC system can include the following features:

- longitudinal and lateral stick command proportional translational rates,
- stick in center detent decelerates aircraft back to zero groundspeed and holds zero groundspeed, and
- potential to use trim beeps to command translational rates.

2.4 Linear Acceleration Command Velocity Hold (LACVH)

The LACVH response-type is a highly augmented response-type that has been tested (in both simulation and flight). Two examples are the CH-147F (Irwin, Einthoven, Miller, & Blanken, 2007) and MH-47G (Bender, Irwin III, Spano, & Schwerke, 2011), both of which were flight tested with LACVH modes. With the LACVH system, stick deflections command lateral and longitudinal aircraft accelerations. Larger stick deflections command larger accelerations and when the stick is returned to detent, the system maintains the achieved groundspeed. The LACVH is a lower speed mode and in its implementations, it is typically active below a set groundspeed threshold. LACVH modes are also typically blended with less augmented higher speed modes and low speed TRC modes when near hover. An example of this can be seen in MH-47G DAFCS response diagram shown in Figure 1 (Bender, Irwin III, Spano, & Schwerke, 2011). Below 40 kts groundspeed the aircraft transitions from an attitude command (AC) in the pitch and roll axes to a LACVH. Then, below 5 kts groundspeed, the aircraft transitions to a TRC mode.

In summary, a typical LACVH system can include the following features:

- longitudinal and lateral stick command proportional translational accelerations,
- stick in detent holds velocity,
- potential to use trim beeps to command velocity changes, and
- commonly blended with higher speed and lower speed modes.

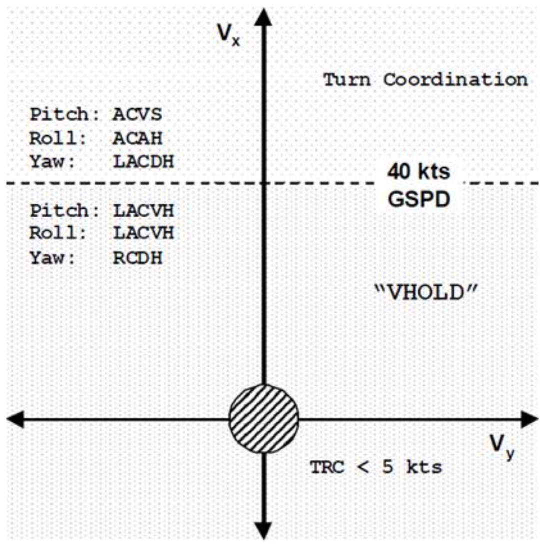


Figure 1. MH-47G DAFCS response

2.5 Position Hold (PH)

PH is commonly included in TRC modes as a pilot selectable mode that activates below a set groundspeed threshold. However, there is the potential to include PH with other response-types. The Background Information and User's Guide for Handling Qualities Requirements for Military Rotorcraft (BIUG) (Hoh, Mitchell, Aponso, Key, & Blanken, 1989) cites a National Research Council (NRC) variable stability helicopter flight test study (Hoh R. , 1986) where RC+PH and ACAH+PH response-type were evaluated. When implemented, PH typically engages when the stick is returned to detent and the aircraft is below a set groundspeed threshold. When active, the system will grab a reference position that is then held and maintained by the control laws. The addition of a PH also allows for the potential to utilize stick trim beep pushes to command incremental changes in position.

In summary, a typical PH system can include the following features:

- stick in detent position is held,
- PH engaged below a set groundspeed threshold, and
- potential to use trim beeps to command position changes.

2.6 Rate Command Height Hold (RCHH)

Typically, rotorcraft have a rate command system in the vertical axis where displacements of the inceptor (typically a collective, in the case of the V-22 in hover mode it uses a Thrust Control Lever (TCL)) command proportional vertical rates. It is common to also include a Height Hold (HH) in the vertical axis, thus creating a RCHH system. With a RCHH system, the control inceptor inputs command vertical rates and when the inceptor is returned to detent, the system holds altitude. The selected height that is held is typically dependent on the inceptor returning to detent and a vertical rate threshold.

In summary, a typical RCHH system can include the following features:

- inceptor displacements command vertical rates,
- returning the inceptor to detent holds height above ground level (AGL), and
- potential to use inceptor trim beeps to command incremental altitude changes.

2.7 Rate Command Direction Hold (RCDH)

In the yaw axis, rotorcraft typically have a rate command system where pedal inputs command a proportional yaw rate. It is common for rotorcraft to include a Direction Hold (DH), thus creating a RCDH system. With a RCDH system, pedal inputs command proportional yaw rate and when the pedals are returned to detent, the system holds the captured yaw angle.

In summary, a typical RCDH system can include the following features:

- pedal displacements command yaw rates,
- returning the pedal to detent holds yaw angle, and
- beep features are not typically included.

2.8 Unified Control Concept: Integrated-Translational Rate and Acceleration-trim Command (I-TRAC)

Integrated-Translational Rate and Acceleration-trim Command (I-TRAC) is a low speed/hover mode concept that was developed as part of the Joint Strike Fighter Unified Control Concept for the F-35B (Denham & Paines, 2008). The concept, illustrated in Figure 2 (Denham & Paines, 2008), includes different control modes, that transition based off ground/airspeed thresholds, for the left- and right-hand inceptors.

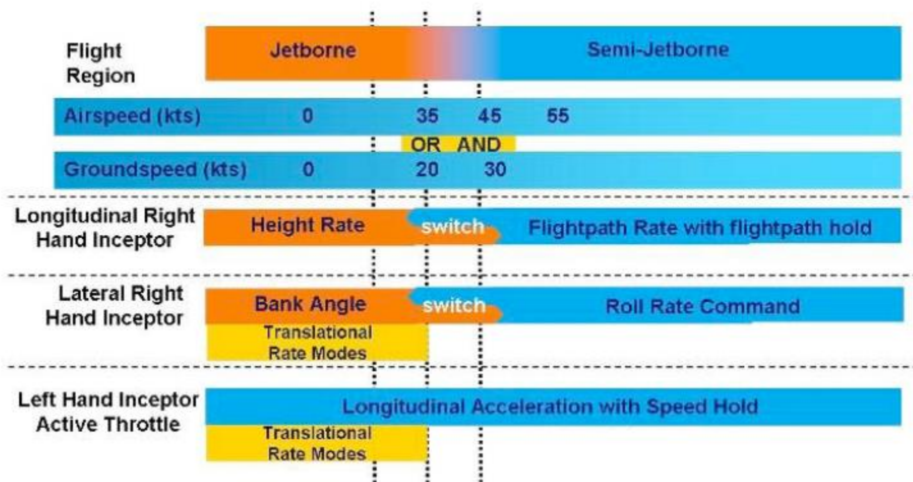


Figure 2. Unified Control Concept I-TRAC

The control strategy includes two inceptors, a Right-hand Inceptor (RHI) active sidestick and a Left-hand Inceptor (LHI) active throttle lever. At low-speed flight, powered lift for example, Knots Ground Speed (KGS) less than 20 and/or Knots Calibrated Air Speed (KCAS) less than 35, fore/aft inputs on the RHI sidestick commands height rate and left/right inputs into the sidestick command left/right translational rates. Fore/aft inputs into the LHI throttle lever command forward/aft translational rates during low-speed flight, making this concept quite unique. Longitudinal and lateral translational rate commands are controlled via two different inceptors and the single inceptor commands (RHI sidestick) both translation and vertical rates.

In the transition regime, between 35 < KGS < 45 and/or 20 < KCAS < 30, the flight control modes transition to higher speed modes. Here, fore/aft inputs on the RHI sidestick command flightpath rate changes with flightpath hold and left/right inputs on the RHI sidestick command roll rates. For the LHI throttle, the response transitions to a longitudinal acceleration command with speed hold. In the implementation of this mode, softstops were placed on the inceptors when a limit for a particular mode was reached. If a pilot were in the “Jetborne” flight region and wanted to command longitudinal translational rates or bank angles beyond what the I-TRAC mode provided, the pilot would simply have to push through the softstop on the throttle and sidestick, and the system would transition to an acceleration command in the longitudinal axis and an attitude command in the lateral axis. The Unified Control Concept is summarized in Table 1.

Table 1: Unified Control Concept summary

Inceptor	**Input**	**Powered Lift**	**Transition**
Right-hand Inceptor (RHI, active sidestick)	Forward/Aft	+/- Height Rate	Flightpath rate with flightpath hold
	Left/Right	Left/Right TRC	Roll rate command
Left-hand Inceptor (LHI, active throttle lever)	Forward/Aft	Forward/Aft TRC	Longitudinal acceleration with speed hold

3 Representative eVTOL model

For the Phase II program, an industry representative lift plus cruise electric vertical takeoff and landing (eVTOL) configuration was used to develop the simplified envelop protection schemes and automated modes that were used to develop the HQTEs described herein. Most of the model related work was done under a companion National Aeronautics and Space Administration (NASA) Phase II Enhanced program with the Armstrong Flight Research Center. This lift plus cruise configuration featured a pusher propeller for forward flight and four wing boom mounted rotors for low speed/hover. The baseline simulation model was created primarily in the MATLAB/Simulink environment and features nonlinear airframe dynamics, linear actuator and propulsion motor models, table-lookup based propeller models and aerodynamic models, and a basic attitude command response-type. A description of the model is provided in Appendix A. The NASA Revolutionary Vertical Lift Technology program has also been developing a generic lift plus cruise model (Silva, Johnson, Solis, Patterson, & Antcliff, 2018) that has been used for extensive piloted simulation testing at NASA Ames Research Center including the development of HQTEs.

4 Envelope protection

4.1 Envelope protection methods

The primary role of an envelope protection system is to ensure that the air vehicle remains within the target flight envelope. Specifically, the system ensures that all states of the vehicle remain within preset bounds that always keep the vehicle safe and airworthy. Important protections include those for angle of attack (AoA) and angle of sideslip (AoS), vehicle attitude, airspeed, and load factor. Depending on the vehicle configuration and mission, some or all these protections and more may be implemented. As such, it is of great importance and interest to study the impact of these protections on vehicle handling qualities.

There are multiple ways to develop and implement envelope protection schemes, see (Falkena W. , Borst, Chu, & Mulder, 2011; Sahani N. , 2005). They can be divided into three categories as defined below.

1. Command-limiting

   Command-limiting methods involve putting bounds on pilot commands that get transmitted across the command path and filters through the vehicle dynamics to produce the desired limits on the aircraft response. To achieve this, a reverse-mapping from the aircraft states to pilot commands is carried out analytically and via simulation. Since the command path is involved, the mapping is usually a function of the flight control system that changes with flight modes. This may be considered a disadvantage for the transitions required and relative blending between mappings, and for the requirement of multiple mappings in the design phase. It is not a disadvantage in terms of envelope protection effectiveness in the given mode.

2. Effector-limiting

   Under the effector-limiting approach, bounds are placed on control effectors that receive commands from the pilot/FCS. The bounds result in limiting of the aircraft response and when done correctly, produce the desired envelope protection. Since effector outputs are also downstream to the control laws forward path, the mapping from vehicle states to effector outputs is independent of the control law mode and is therefore likely to remain the same across all control law modes.

3. State-limiting

The state-limiting approach involves feeding back measured states and other important auxiliary variables and enforcing the desired bounds on them via feedback control. It can be achieved by designing the envelope protection within the control laws from the outset.

All three methods have been employed for different vehicles, and for protecting from envelope exceedance of different states (Wilson & Peters, 2011; Falkena W. , Borst, Chu, & Mulder, 2011). However, keeping in mind the nature of the vehicle used in this work (i.e., an eVTOL with attitude command), as well as the challenges of multiple flight modes that greatly expand the envelope (hover to cruise), a state-limiting approach was identified as the most appropriate. Angle of attack (AoA) and attitude protection designs and associated results for cruise conditions were considered first, followed by design and preliminary results in hover mode.

4.2 Envelope protections in cruise

4.2.1 Angle of attack protection scheme

In cruise flight mode, STI has developed AoA and attitude protection schemes. Using the state-limiting approach, a separate set of feedback gains are incorporated within the cruise branch of the FCS within the model, that measure the excess AoA or attitude (pitch/bank) beyond stipulated limits and generate an appropriate command for relevant control surfaces (elevator/aileron). Unlike a regular feedback control law for AoA regulation/tracking, the envelope protection system is expected to be a quick response system that aggressively counter-acts AoA exceedance, bringing the vehicle back within stipulated limits. It may be useful for the system to provide certain margins of safety when it brings the aircraft back within the limits. Specifically, the elevator command correction should not reduce to zero as soon as AoA returns to the boundary values of the stipulated interval. The system developed that uses an enabled subsystem is shown below in Figure 3.

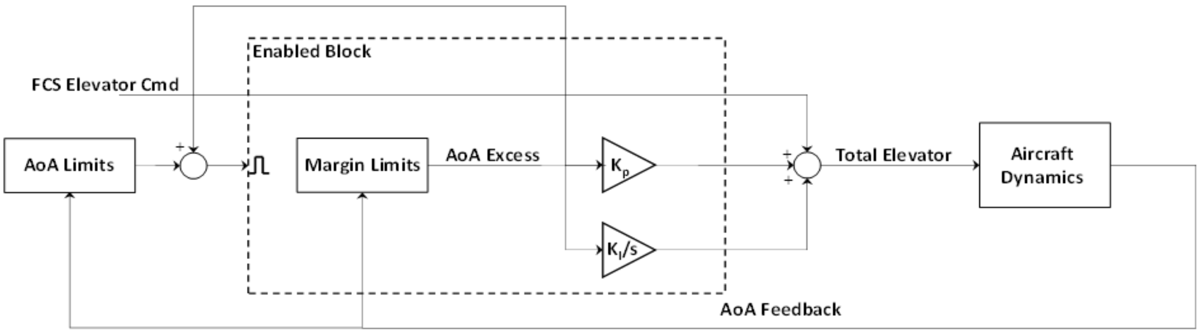


Figure 3. Angle of attack protection system with safe return margins

Figure 3 shows a AoA protection design where the feedback gains are housed within an enabled subsystem that conditionally executes the block based on output from the *AoA Limits* as well as *Margin Limits* blocks. The *Margin Limits* block contains the desired AoA limits that the system has to be restored to, with some safety margin built-in. Usually, margins are set with respect to the target envelope to account for the aircraft dynamic response, transients, sensors accuracy, model accuracy, etc. For the example herein, AoA limits are set to -5° and 15° and margin limits are set to {-2°, 12°}. The protection system is therefore tasked to restore the vehicle to within these limits before disengaging. The design ensures that the conservative *Margin Limits* are just the restoring limits; the system is triggered only when AoA exceeds the larger AoA limits set by the user. In practice, the published AoA design limits for the vehicle will be different from those used here. The logic within *AoA Limits* block produces the signal *AoA Excess*, computed as seen in Equation 1.

$$\Delta\alpha = \min(\alpha - \alpha_{lb}, 0) + \max(\alpha - \alpha_{ub}, 0) \qquad 1$$

In this equation, $\Delta\alpha$ is the AoA excess variable, and $\{\alpha_{lb}, \alpha_{ub}\}$ are the lower bound and upper bound specified for AoA. The computation ensures that AoA excess is zero when the AoA measured and fed back is within the stipulated limits, negative when it is below the lower bound, and positive when above the upper bound. The AoA excess signal is then input to a proportional integral controller, to produce the command to the elevator actuator – positive gains ensure that a negative $\Delta\alpha$ produces a negative elevator command, thus providing a pitch up moment, and likewise for a positive $\Delta\alpha$.

4.2.2 Angle of attack protection HQTE

Task objectives

- Evaluate ability of the envelope protection system to limit angle of attack exceedances.
- Assess the ability to hold flightpath while encountering an angle of attack limit.

- Identify departures from controlled flight when encountering an angle of attack limit.

Precision and aggressiveness level

- non-precision
- moderate agility

Task description

- Starting in straight and level cruise, proceed into a shallow dive.
- Subsequently, push the nose up.
- For conventional arrangement inceptors, the maneuver involves reducing power (retarding the throttle) and pulling the longitudinal stick aft.
- Maintain the maneuver until the angle of attack limits are reached and held for a minimum of 5 seconds.
- The angle of attack must remain at or below the specified limit, thus there are no desired or adequate task requirements for AoA.

Performance requirements

The performance requirements are shown in Table 2.

Table 2: Angle of attack protection performance requirements

	Desired	**Adequate**
Maintain peak AoA:	±1°	±2°
Maintain Bank Angle:	±5°	±10°
Maintain Heading:	±10°	±20°
Flightpath maintenance (oscillations):	No sustained flightpath oscillations	No divergent flightpath oscillations
Flightpath maintenance (departures):	No departures from desired flightpath	No departures from controlled flight
Inter-axis coupling shall not be	Undesirable	Objectionable

Task variations

- Variations of this MTE can be made to alter the entry into the angle of attack limit.

- Hold target AoA in the presence of disturbances.

Rationale

- Developing HQTEs that specifically addresses angle of attack envelope protection is a recent innovation. Thus, further vetting of the task description and performance requirements is needed using more sophisticated vehicle models and protection schemes.

4.2.3 Angle of attack protection demonstration

The AoA protection scheme was tested using the STI flight simulator (described in Appendix B), the above HQTE, and the industry representative lift plus cruise configuration. To better demonstrate the utility of the HQTE, AoA limits were set lower than what would typically be expected to stress the process. The outcomes with and without envelope protection are shown in Figure 4. The stick input with both protection on and off cases is shown with the maximum stick input observed between 20 and 50 seconds. For the protection case, both the elevator deflection and the resulting angle of attack are limited by the protection scheme. Here, the angle of attack is successfully limited to the maximum set limit of 12°.

4.2.3.1 Attitude protection schemes

The attitude protection systems employed for cruise and hover are similar in design, albeit with different effectors that produce the corrective moments. In cruise, the attitude protection system works on the control surfaces, while, in hover, it works on the high-lift motor differential torques. For both pitch and roll attitude protections, it is also important to account for the corresponding rates to prevent any oscillations triggered due to rapid (over) corrections.

Figure 5 below shows the schematic for attitude protection using rate feedback in addition to attitude angle feedback.

For pitch angle protection, it is recommended to use the Euler angle rate $\dot{\theta}$ rather than the body angular rate q, which can get triggered during sustained turns (Wilson & Peters, 2011). Note that the rate feedback is not passed through an integral gain, which is typical for rate feedback design. Also, given the generally lower sensitivity of attitude angles to stability, safe return margins are deemed not to be required.

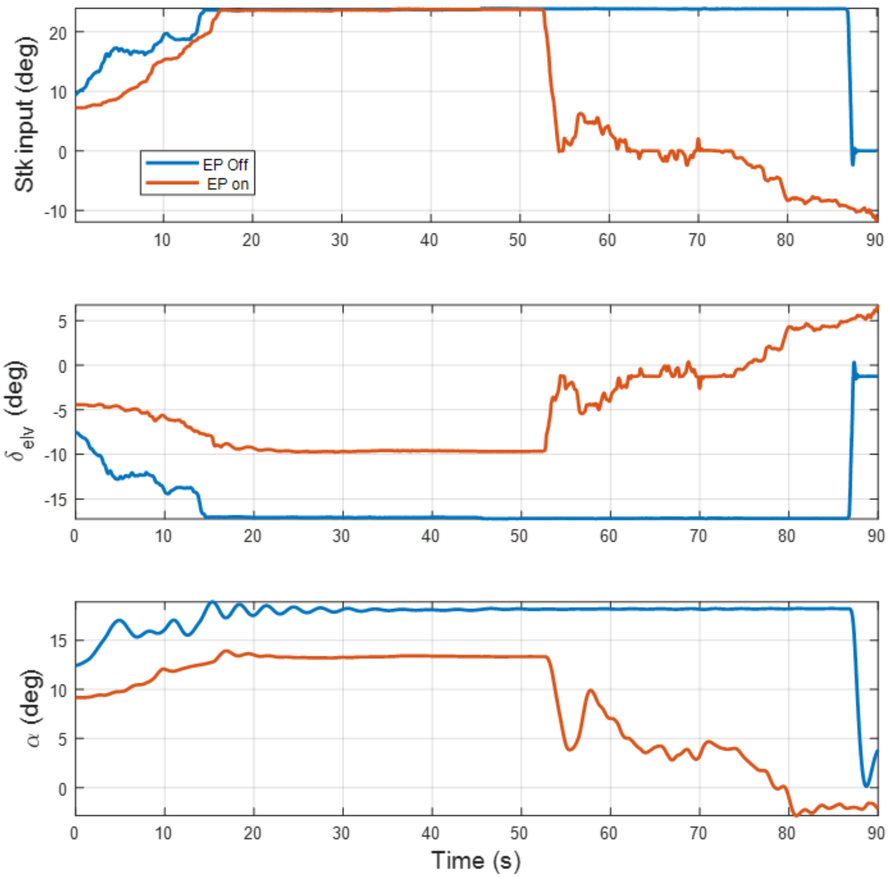


Figure 4. Angle of attack envelope protection simulation test data

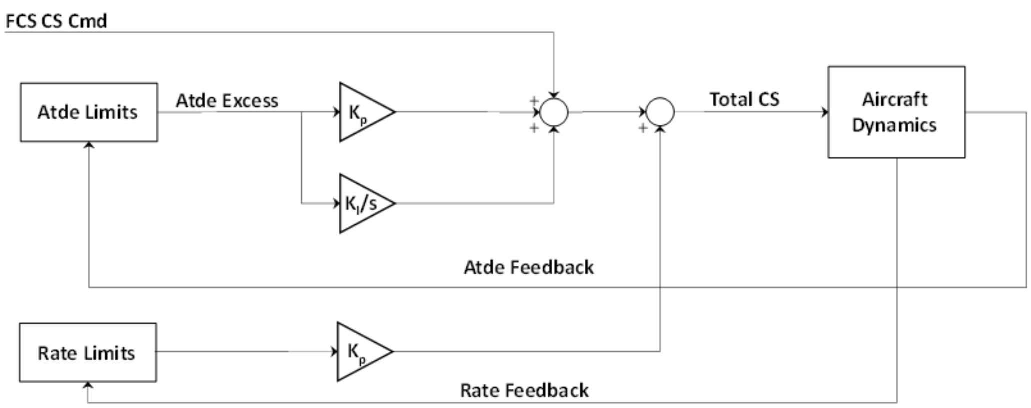


Figure 5. Attitude protection design using rate feedback

4.2.4 Bank Angle Capture and Hold (BACH) HQTE

Task objectives

- Evaluate ability to roll and capture a desired bank angle.
- Identify maneuverability limitations and Pilot-induced Oscillation (PIO) tendencies.
- If applicable, determine the effectiveness of bank angle envelope protection.

Precision and aggressiveness level

- precision
- limited agility

Task description

This task is driven by an automated command signal selected by the flight test engineer (see Figure 6). The magnitude of the command signal can be varied to evaluate the effectiveness of an envelope protection system.

- 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 requirement 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 MTE that features approximately 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.

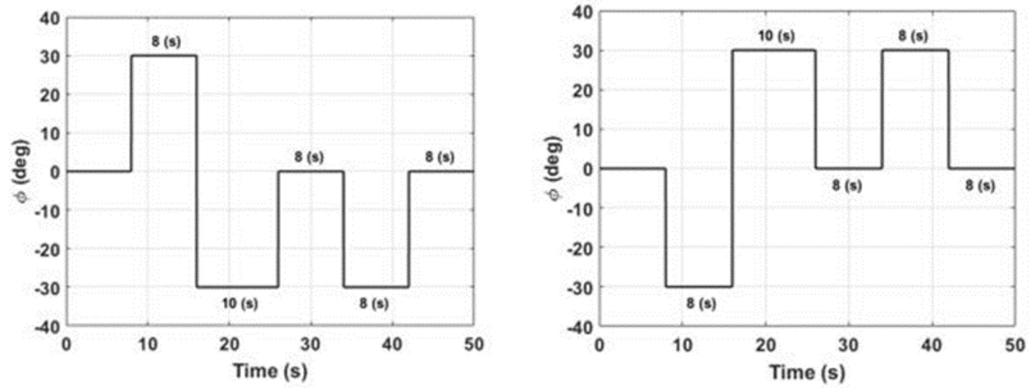
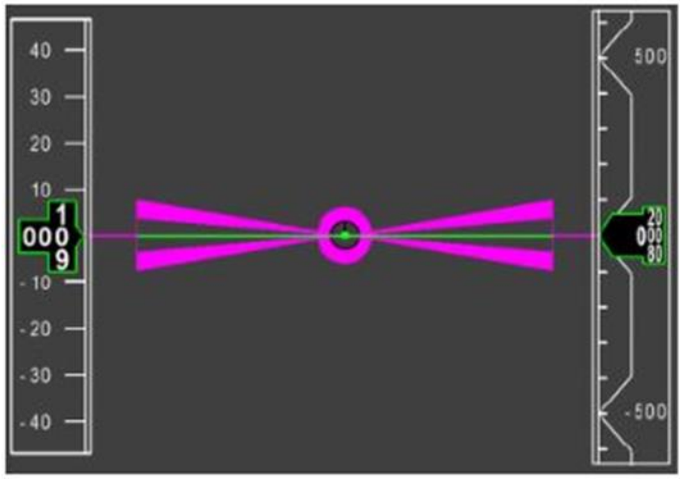


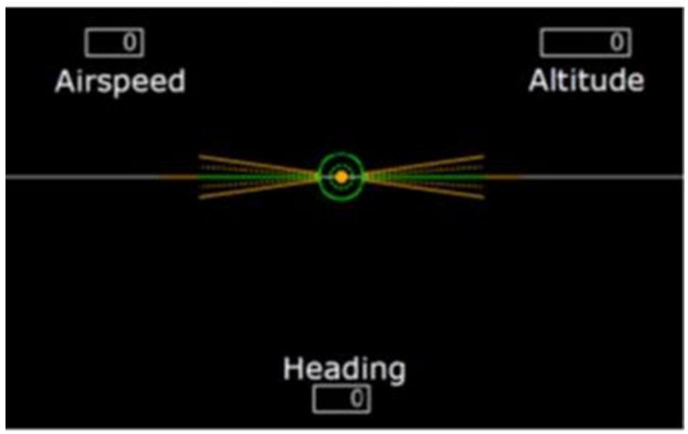
Figure 6. Example Bank Angle Capture and Hold (BACH) command signals

Cockpit display description

Several cockpit display variations were created in this program to support the pilot evaluations. The designs were all inspired by the evaluation pilot displays that have been used by Calspan Corporation in their Learjet In-Flight Simulators (Weingarten, 2005). Two essentially equivalent display variations (see Figure 7) were ultimately 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. For the roll evaluations with the same 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 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. The *bowtie* and *whisker* variations of the tracking display, in either a head-down or head-up format, have been well-vetted via piloted simulations (Klyde, et al., 2018; Berger, 2019).



a) Bowtie Display



b) Whisker Display (with labels)

Figure 7. Cockpit displays

Performance requirements

The performance requirements are shown in Table 3.

Table 3: Bank Angle Capture and Hold (BACH) performance requirements

	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

Task variations

- Variations of this MTE can be made to increase the level of aggressiveness. For example, the capture angles can be increased to ±45° with one 90° change. Such increases in command amplitude can be used to evaluate attitude protection systems.
- Alternatively, given the same commanded attitudes as shown in Figure 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.

Rationale

- Although variations of the maneuver described here have been used in flight tests for years, the (BACH) was considered *new* when introduced as part of the United States Air Force (USAF) Demonstration Maneuvers program in that the MTE 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 STI for NASA Armstrong Flight Research Center (AFRC).
- After initial development, the fixed wing maneuver was refined via in-flight evaluations conducted with a general aviation aircraft (Klyde, Aponso, & Mitchell, 1997).
- Variations of this MTE have also been flown extensively in the Calspan Learjet with test pilot evaluators as part of programs conducted by STI 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 (Klyde, et al., 2018). This program investigated and developed a comprehensive update to the MTEs required for evaluating different rotorcraft configurations with respect to the US Army Future Vertical Lift requirements.

4.2.4.1 Roll attitude protection results

Extensive analysis and piloted simulation testing were carried out to study the impact of envelope protection systems on the handling qualities of the vehicle. Here, the purpose of these evaluations was to perform a checkout of cruise (airplane mode) envelope protection schemes via the BACH HQTE. The limits on both roll and pitch attitude were artificially set lower than typical, to study their impact on angle capture HQTEs flown by the pilot. The amplitude of roll and pitch angles captured under the HQTEs were also varied to demonstrate that protection systems only engage when the set limits are breached.

Figure 8 to Figure 11 show the results for roll angle protection. In Figure 8, a 20° bank angle capture and hold maneuver is demonstrated with the protection turned off. This sets the baseline for comparisons in further tests. A 20° roll angle capture maneuver is demonstrated with the protection turned on in Figure 9 with attitude limits set to ±25°. This demonstrates the lack of impact of the protection system on the attainment of task requirements as long as the capture angles are smaller than the protection limits. In Figure 10, the roll angle capture amplitude is increased to 30°, as defined for the BACH HQTE defined above, and the captures are successfully attained with protection off. Finally, in Figure 11, the roll angle capture angle of 30° is set higher than the protection limit of ±25° and the aircraft is prevented from breaching the limit, even though the pilot stick input does not reduce in amplitude when compared to the stick amplitudes of Figure 10, the no protection case. Thus, the envelope protection functions as intended even though the selected bank angle command cannot be matched.

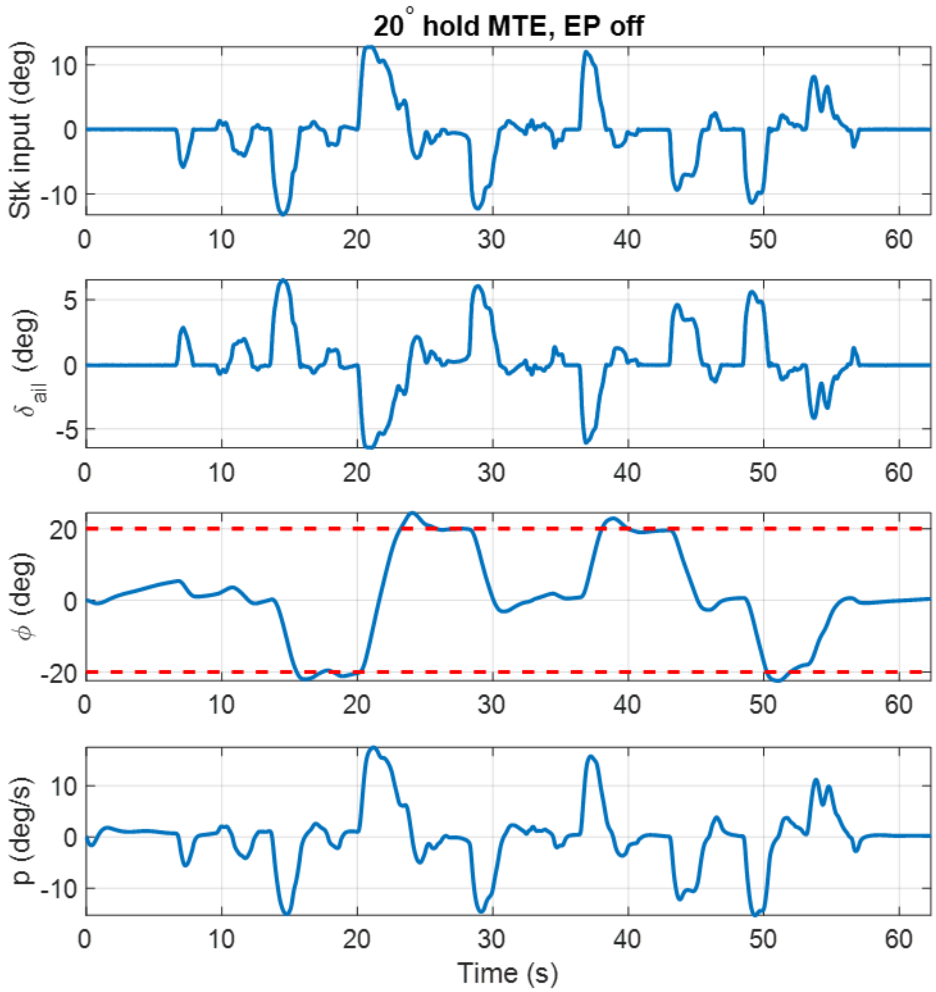


Figure 8. Roll attitude capture of 20° with envelope protection off

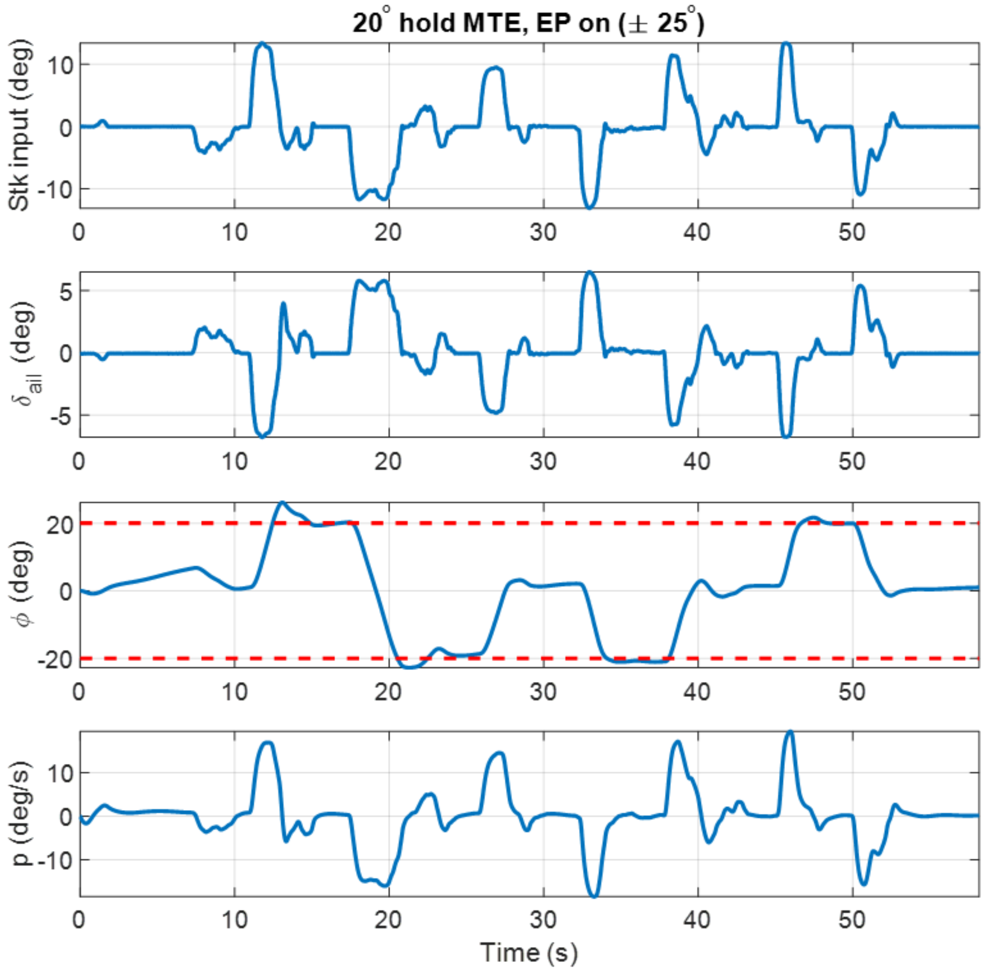


Figure 9. Roll attitude capture of 20° with envelope protection set to ±25°

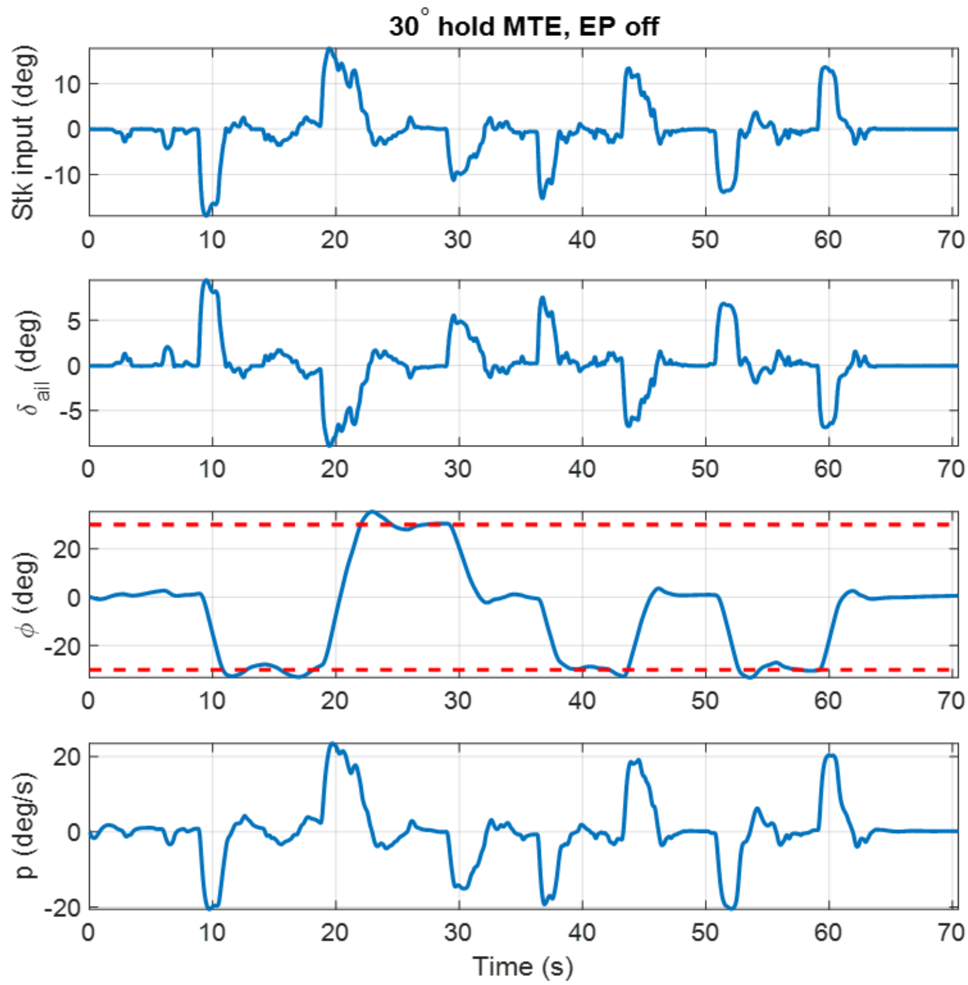


Figure 10. Roll attitude capture of 30° with envelope protection off

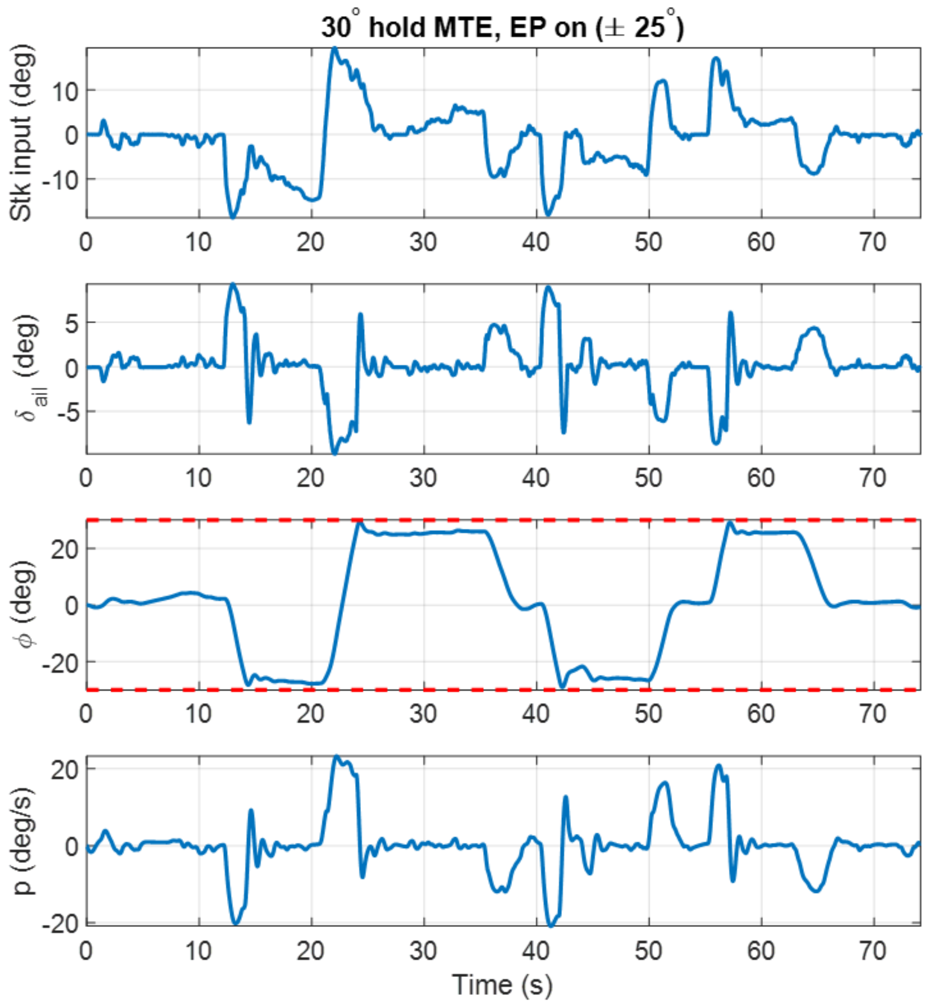


Figure 11. Roll attitude capture of 30° with envelope protection set to ±25°

4.2.5 Pitch Attitude Capture and Hold (PACH) HQTE

Task objectives

- Evaluate ability to pitch and capture a desired attitude angle.
- Identify maneuverability limitations and PIO tendencies.
- If applicable, determine the effectiveness of bank angle envelope protection.

Precision and aggressiveness level

- precision

- limited agility

Task description

This task is driven by an automated command signal selected by the flight test engineer (see Figure 12). The magnitude of the command signal can be varied to evaluate the effectiveness of an envelope protection system.

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

This task represents a precision, non-aggressive MTE that features approximately 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 in Figure 12. Alternating the initial pitch attitude command is intended to minimize pilot shaping from anticipated commands.

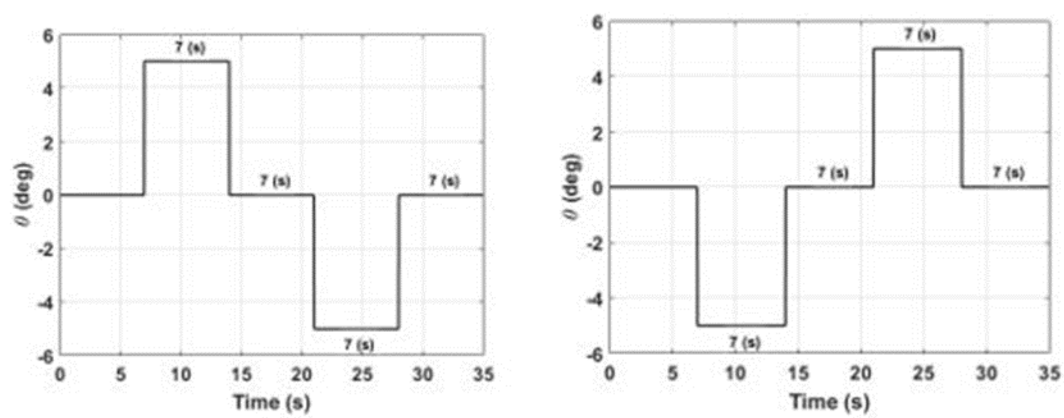


Figure 12. Example Pitch Attitude Capture and Hold (PACH) command signals

Cockpit display description

The cockpit displays are as previously introduced in Figure 7.

Performance requirements

The performance requirements are shown in Table 4.

Table 4: Pitch Attitude Capture and Hold (PACH) performance requirements

	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

Task 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. Such increases in command amplitude can be used to evaluate attitude protection systems.
- Alternatively, given the same commanded attitudes as shown in Figure 12, 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.

Rationale

- Although variations of the maneuver described here have been used in flight tests for years, the Pitch Attitude Capture and Hold (PACH) was considered *new* when introduced as part of the USAF Demonstration Maneuvers program in that the MTE 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 STI for NASA AFRC.
- After initial development, the fixed wing maneuver was refined via in-flight evaluations conducted with a general aviation aircraft (Klyde, Aponso, & Mitchell, 1997).
- Variations of this MTE have also been flown extensively in the Calpsan Learjet with test pilot evaluators as part of programs conducted by STI 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 (Klyde, et al., 2018; Berger, 2019). 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.

4.2.6 Pitch attitude protection results

Figure 13 to Figure 16 show the results for pitch attitude protection. Here, the purpose of these evaluations is to perform an informal checkout of cruise (airplane mode) envelope protection schemes via the PACH HQTE.

Figure 13 shows results for a 10° pitch capture task performed with pitch protection turned on and limits set to ±15° where the HQTE is performed with relative ease. In Figure 14, the capture angle amplitude is raised to 20° with the protection activated. Despite extensive effort by the pilot as indicated in the stick input, the protection system prevents capture of the desired pitch attitude. A pitch rate oscillation develops as the protection *fights* the pilot command. In Figure 15 a 15° pitch capture is performed with protection activated with the attitude limit set to the same value. The protection system seems to have minimal impact on the attainment of task requirements. This can be concluded by reviewing Figure 16 where the same HQTE is repeated with the protection system turned off. The control surface oscillations created by the protection system as indicated by elevator response (e.g., around 40s), may lead to ride quality issues for the pilot as well as onboard passengers.

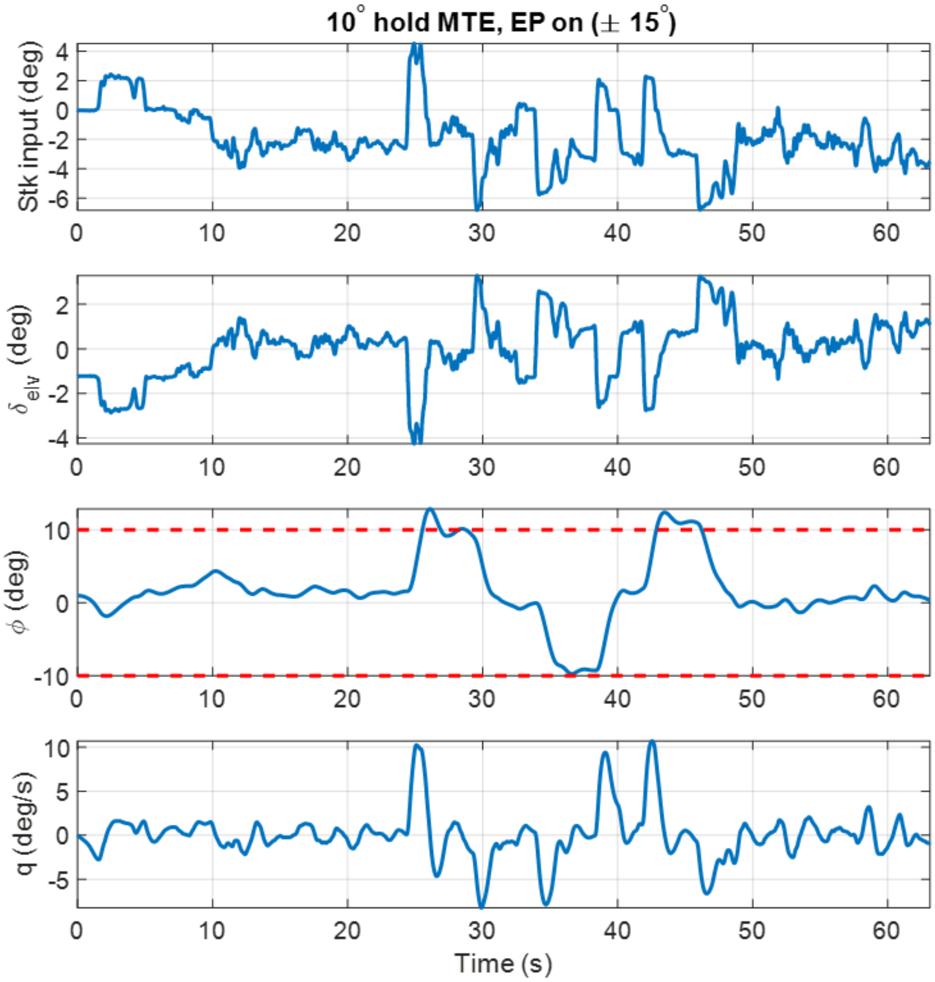


Figure 13. Pitch attitude capture of 10° with envelope protection set to ±15°

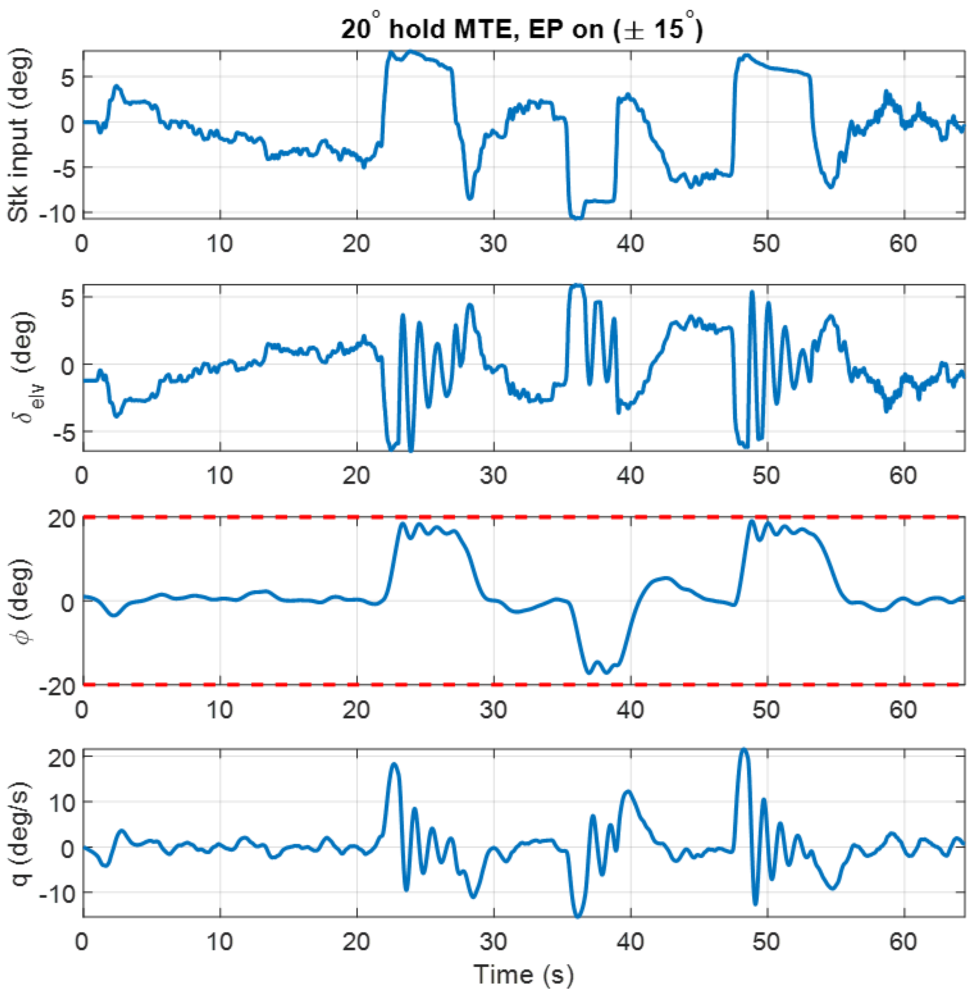


Figure 14. Pitch attitude capture of 20° with envelope protection set ±15°

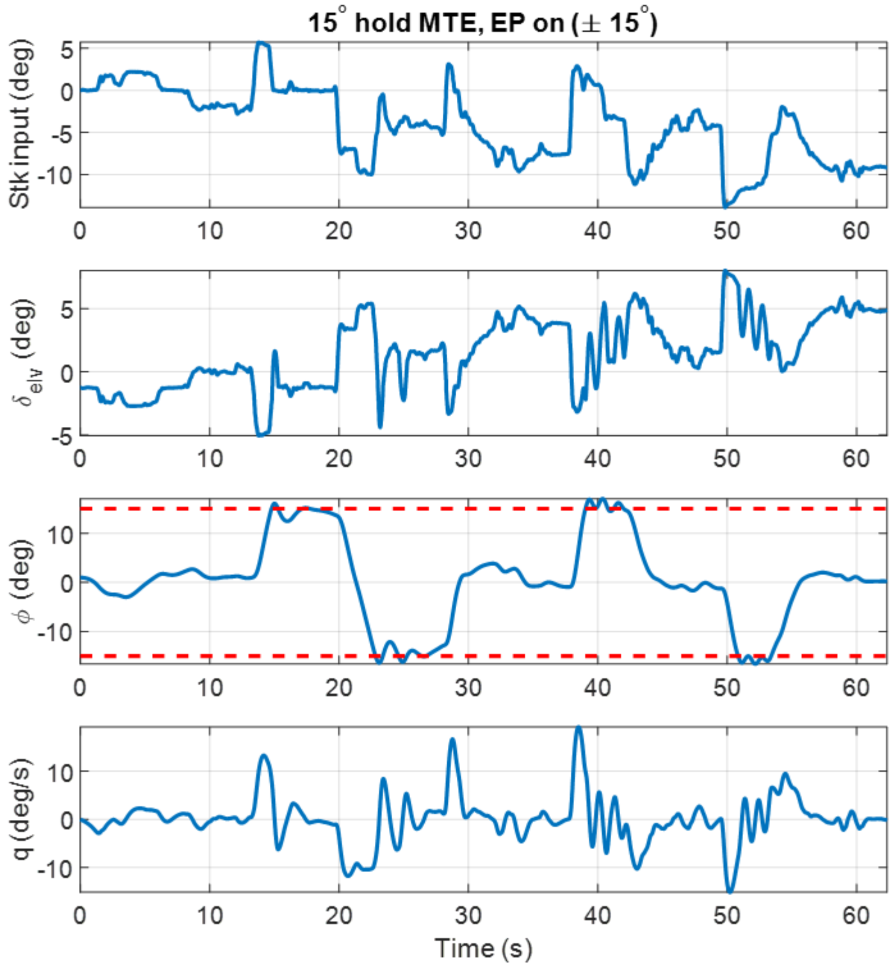


Figure 15. Pitch attitude capture of 15° with envelope protection set to ±15

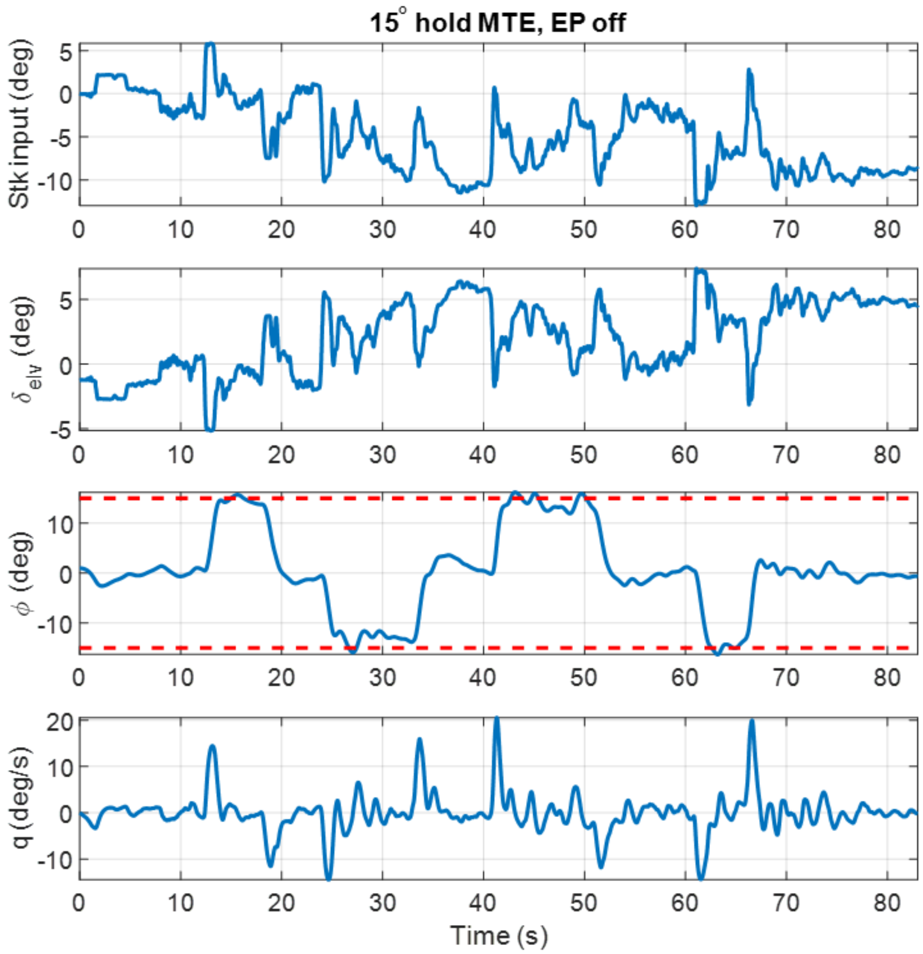


Figure 16. Pitch attitude capture of 15° with envelope protection off

4.3 Envelope protections in hover

Attitude protections (roll and pitch) were designed and implemented in hover mode for the representative eVTOL vehicle. Similar to cruise, relevant states are fed back to determine the onset of a protection system as well as the response, which is proportional to the exceedance with respect to pre-defined limits. However, a key difference between the two modes is the presence of an attitude command system coupled with a motor command mixer in hover, that perceives stick inputs to be attitude commands. Since the selected approach does not directly limit pilot inputs, the envelope protection system is essentially in direct conflict with the attitude command system once the limits are breached. Conceptually, this is shown in Figure 17 (complete details of the loop closures are not included).

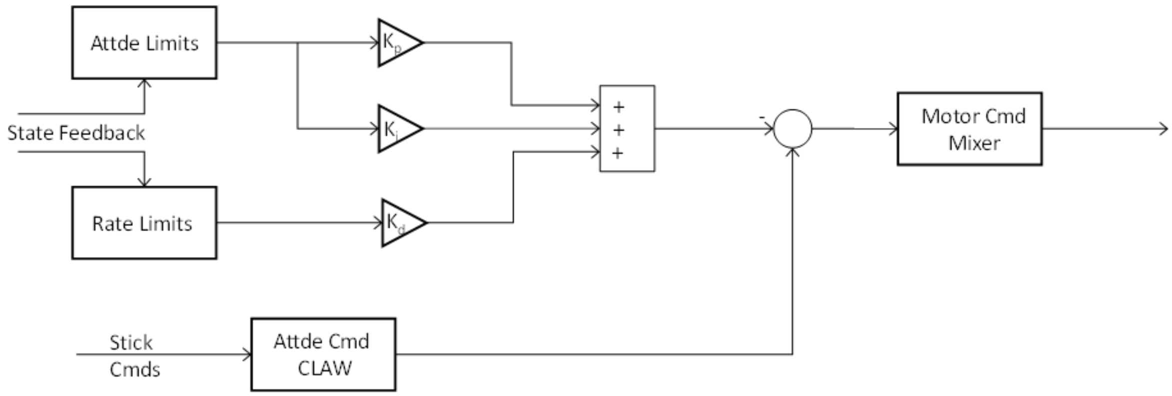


Figure 17. Attitude protection schematic in hover mode

The protection scheme illustrated in Figure 17 was implemented with the STI fixed base piloted simulation and preliminary tests were conducted to gauge its effectiveness, beginning with roll attitude limiting. The results for roll protection are shown in Figure 18 and Figure 19.

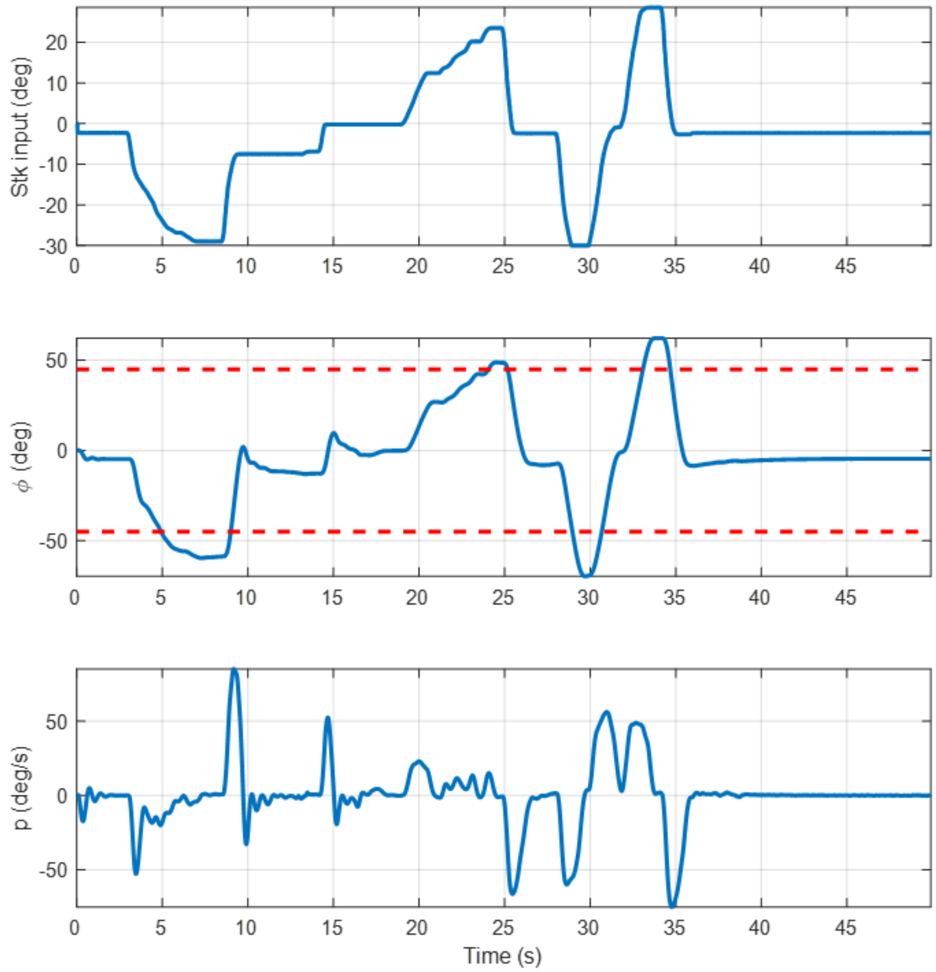


Figure 18. Roll due to maximum stick input with envelope protection off

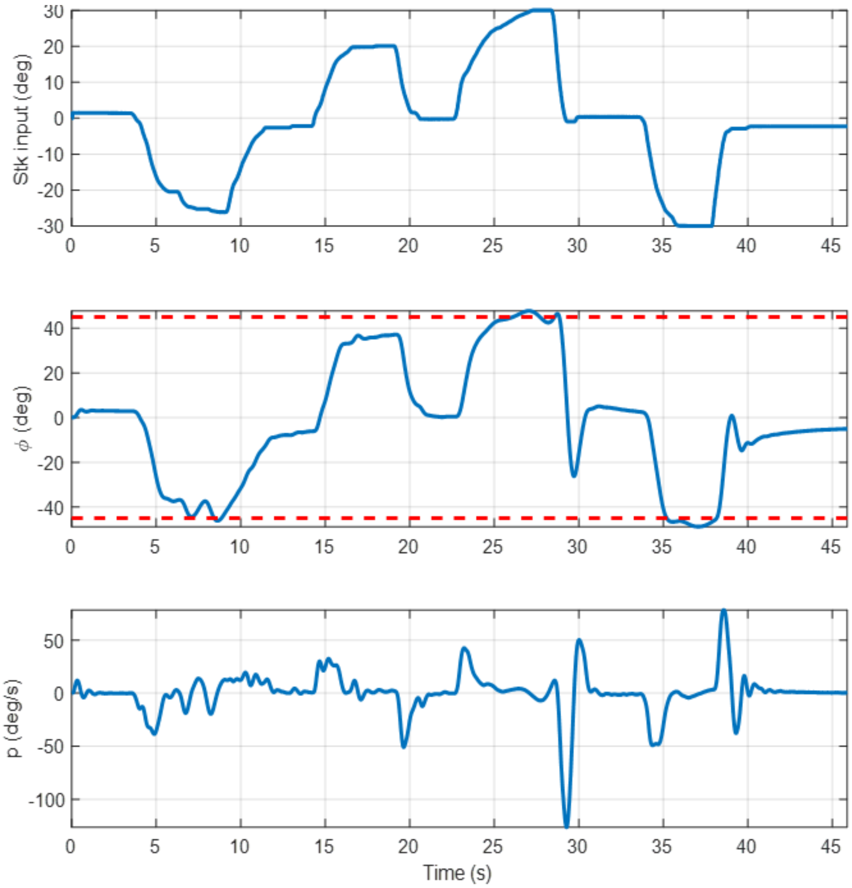


Figure 19. Roll due to maximum stick input with protection system on

The tests were intended to stress the roll attitude protection system by generating stick inputs of increasing amplitudes to push the vehicle beyond the set limits. In Figure 18, the maximum roll angles achieved at the corresponding maximum stick inputs goes up to ±60°. However, with protection system enabled (limit ±45°), Figure 19 shows that the roll angles are successfully limited even at maximum stick deflections.

4.4 Envelope protections in transition

The most complex flight mode for a lift plus cruise and other similar eVTOL vehicles is the transition mode from hover to cruise and vice-versa. The protection systems for transitions are therefore expected to be just as complex and can be a function of several independent variables like motor torque and angle of attack. Protection systems here have the primary goal to prevent (catastrophic) loss of lift, either due to wing stall (low airspeed) or low vertical thrust from high-lift motors. Therefore, as the transition progresses and generation of lift moves from one source to another, the protection system must constantly revise its allowable limits on the state and auxiliary variables of interest. For instance, Figure 20 shows the schematic of what an *allowed* set of vertical throttle inputs (mapped to corresponding motor torques) would be as a function of airspeed, forming what may be called a transition corridor within the parameter space.

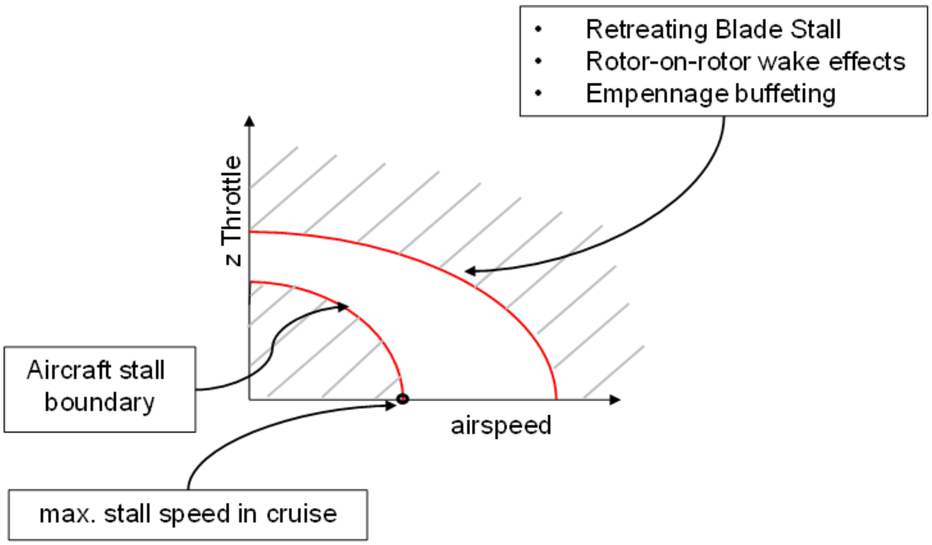


Figure 20. Example transition corridor

Figure 20 essentially establishes a lower and upper limit on lift motor torques as a function of airspeed, thereby preventing any loss of lift due to a simultaneous lack of dynamic pressure as well as vertical propulsive force. The curves shown thematically in Figure 20 can be quantifiably obtained via either an analytical approach, or by bootstrap-sampling the simulation results across the parameter space of interest. A critical part of putting the protection in place is automating the mode itself, to schedule parameters like altitude (AGL) and airspeed reliably. The approach to automating transition mode is described later in this report, within which the stall protection system has also been described along with preliminary results.

4.5 Additional piloted simulation results with envelope protection

Given that a design may feature multi-axis envelope protection schemes that are all active, conflicts may arise wherein a protection in one axis impacts the effectiveness of a protection in another axis. Thus, issues of protection priority may arise. These issues were examined on a limited basis using the industry representative lift plus cruise model, the envelope protection mechanisms described herein, and the STI fixed-base piloted simulation. Limitations in flight control system complexity and sophistication of the protection mechanisms provided a *first-look* at potential issues in this arena.

4.5.1 Turning Climb/Descent – AoA Protection versus Roll Attitude Protection

Climbing and descending turns were conducted to explore the impact of AoA protection as well as roll attitude protection on a handling qualities task. The AoA protection is enabled individually as well as in concert with roll protection for the said tasks. In Figure 21, a climbing turn is attempted with no envelope protection, in cruise/airplane mode. The low thrust provided by the pusher propeller at full throttle typically results in a low climb rate. The bank angle is held at around 30°, and airspeed is held at around 50 m/s (97.2 knots).

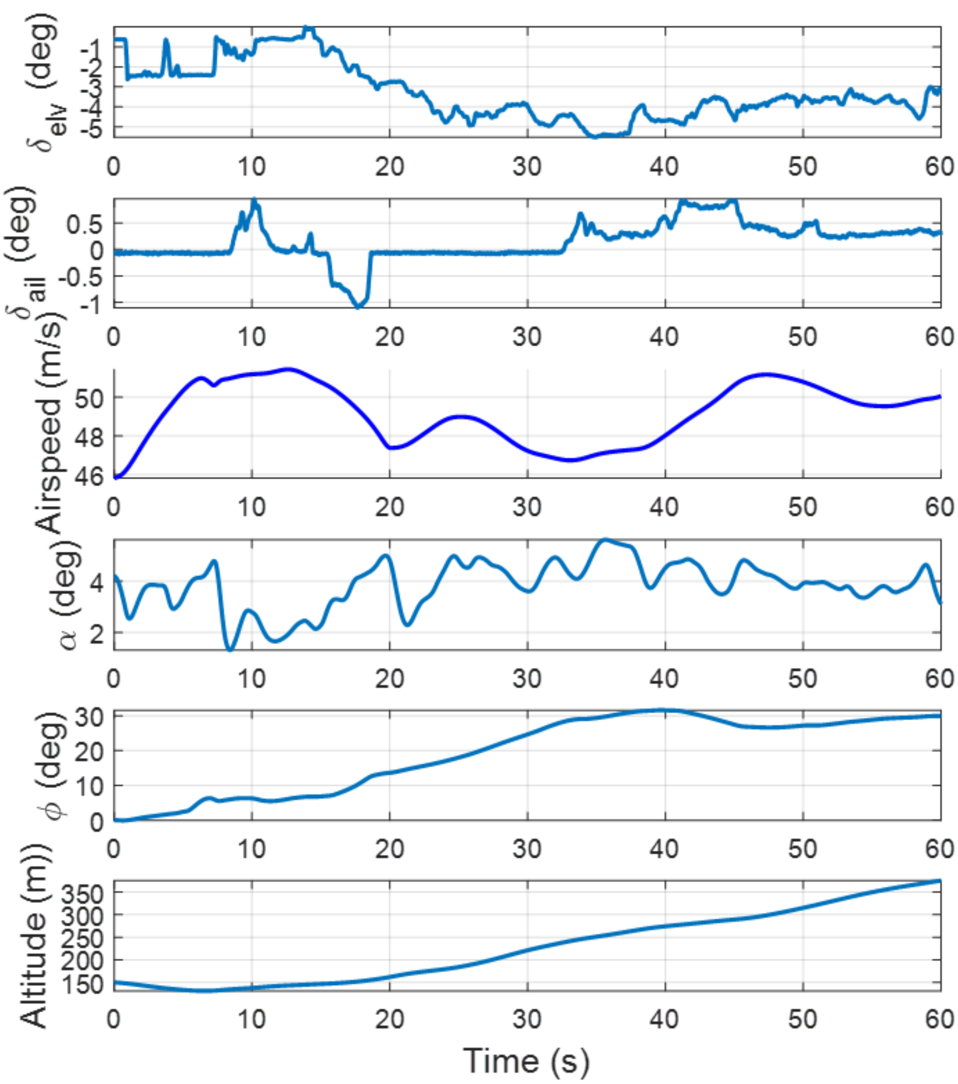


Figure 21. Climbing turn example with no envelope protection engaged

In Figure 22, the climbing turn maneuver is attempted with AoA protection engaged at a lower than typical limit, in this case a 7° limit. To ensure that this limit is encountered, a slightly higher roll angle hold of 35° is attempted for the maneuver. At around 30 seconds, the AoA limit is reached. However, the climb rate seems to be unaffected by the protection on AoA. For this run, the pilot commented that "the AoA limiter 'bounces' a little aggressively, should have a smoother limiting action." This behavior is clearly seen in the elevon and AoA time traces.

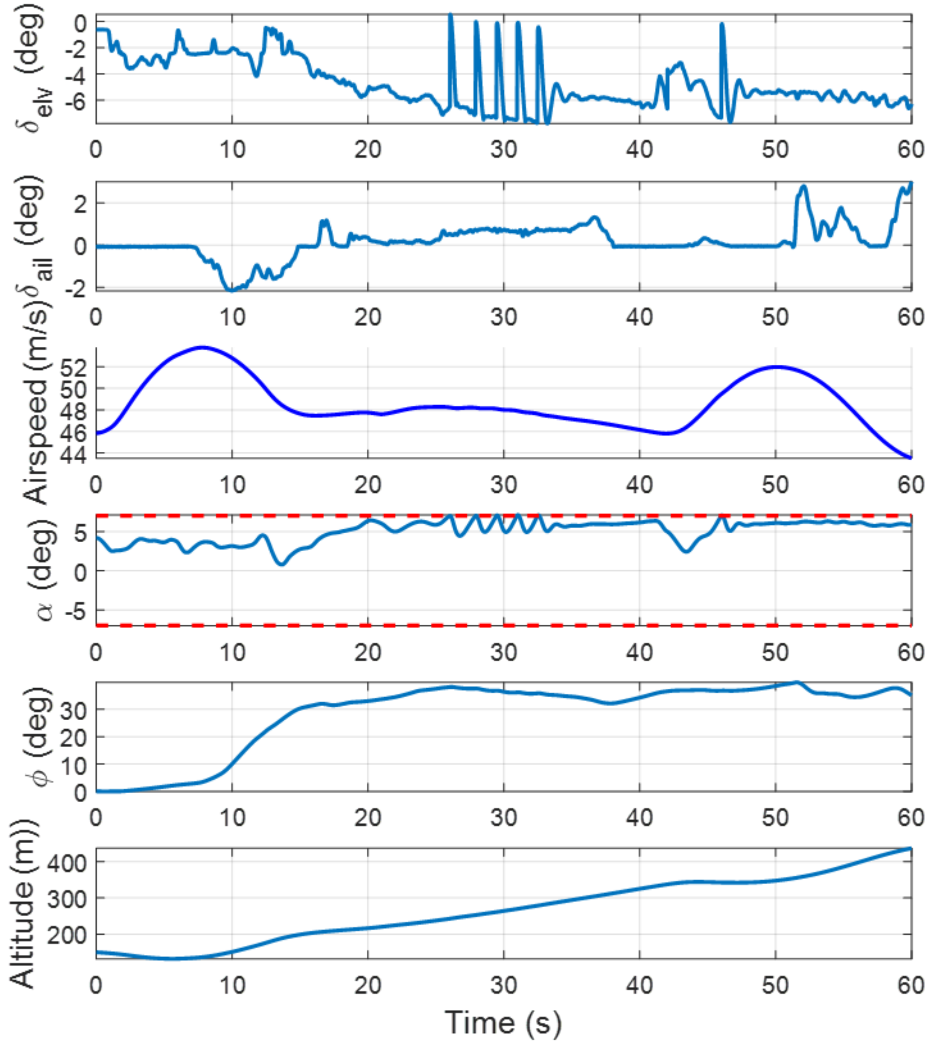


Figure 22. Climbing turn with AoA envelope protection engaged at 7°

In Figure 23, the climbing turn maneuver is attempted with both AoA and roll attitude protection engaged. For this example, the roll attitude protection is set at 20°, and is engaged right away. The limit on bank angle significantly affects climb rate, as seen in the altitude response, where the aircraft climbs at a significantly slower rate when compared to previous the previous two cases. Note that in this case, encountering the roll attitude limit first resulted in an AoA that never reached the 7° limit.

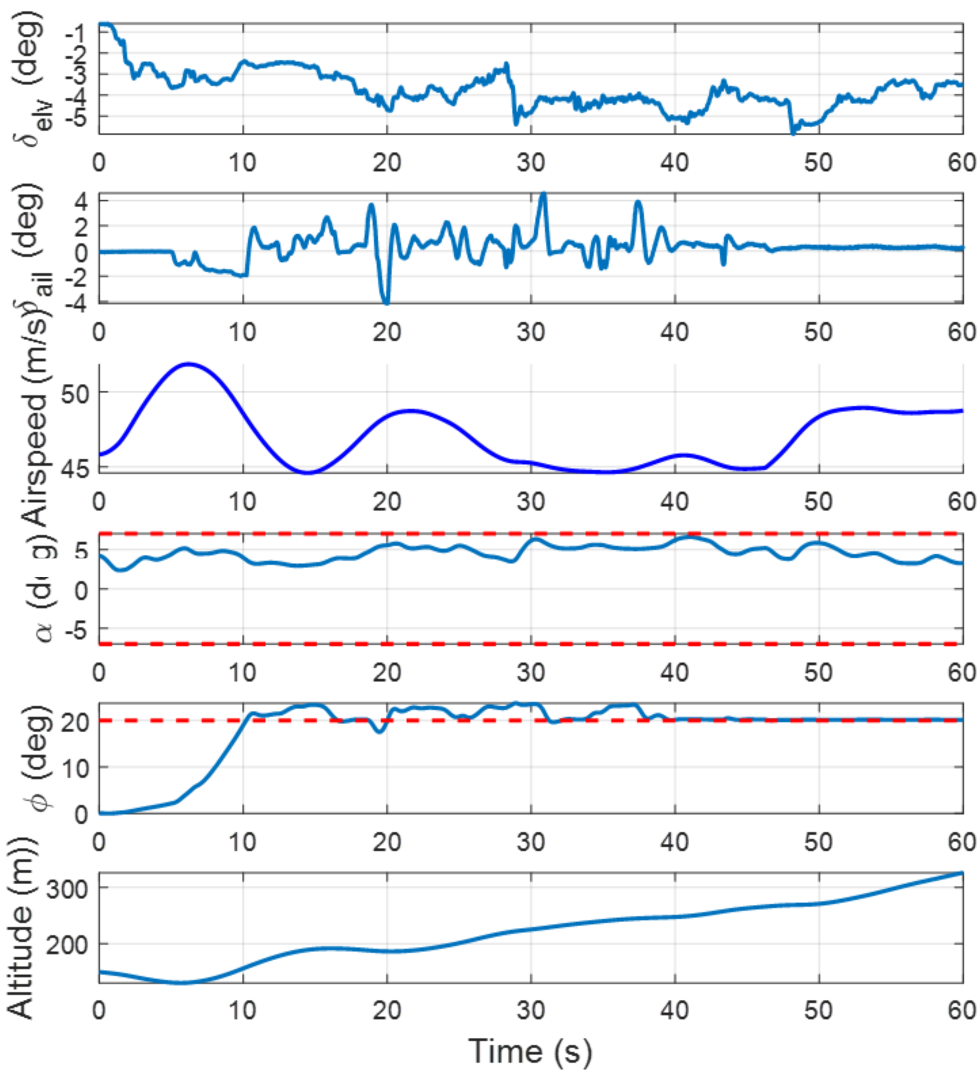


Figure 23. Climbing turn with AoA and roll attitude envelope protection engaged

Next, a descending turn maneuver was attempted with both AoA and roll attitude protections engaged. As shown in Figure 24, the descent rate is slow, and eventually leads to a stalled airplane beyond 100 seconds (not shown in the figure). The pilot generally found it difficult to lose altitude, even when significantly throttling back power and pulling the stick back. In the time region shown here, only the roll attitude limit is encountered as is expected in a descent.

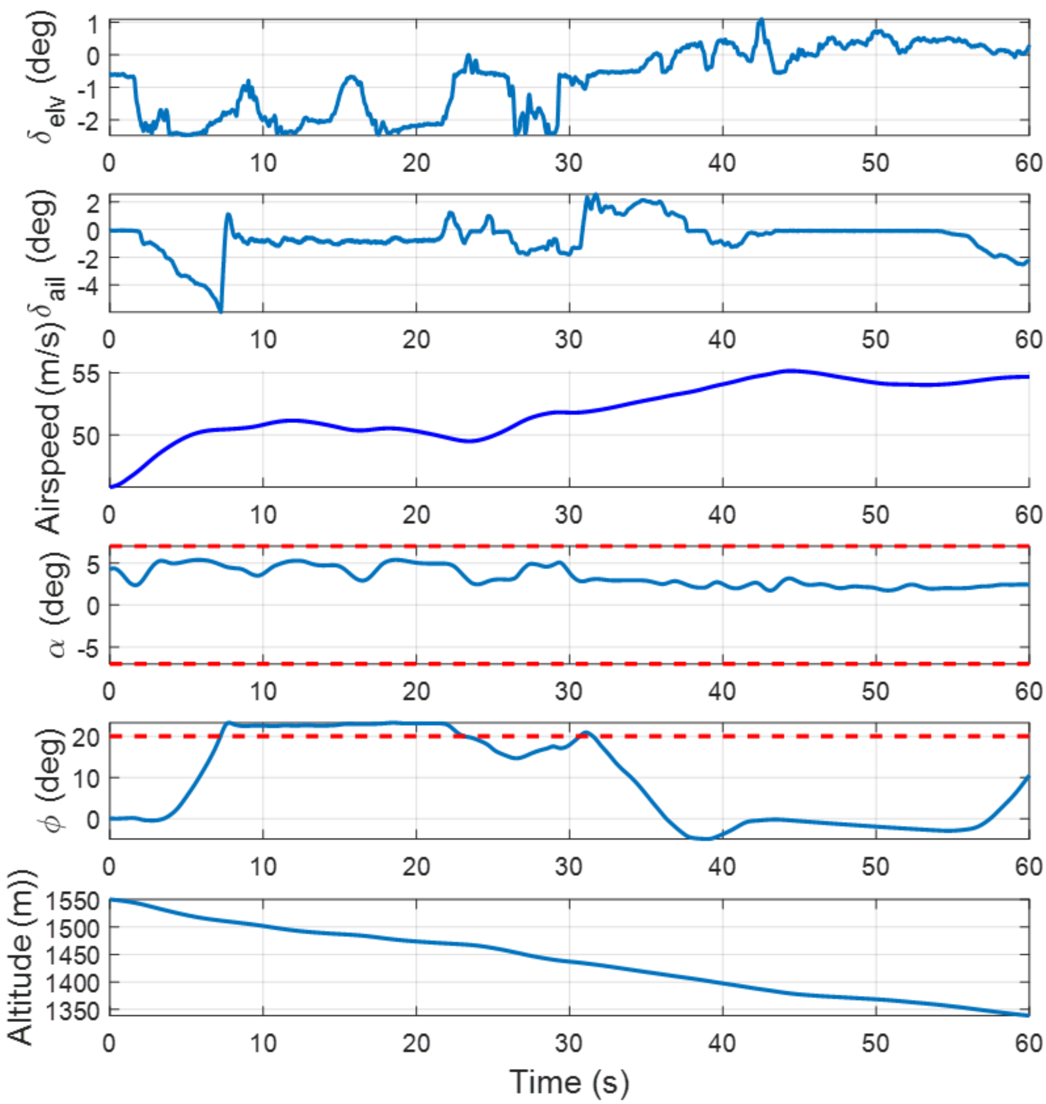


Figure 24. Descending turn with AoA and roll attitude envelope protection engaged

Figure 25 shows a descending turn maneuver with no protections engaged. The descent performance seems similar, with pilot resorting to straight and level flight occasionally and pointing the nose down to descend faster. The absence of protection in AoA and roll attitude results in roll attitudes that exceed the previous 20° limit early in the maneuver.

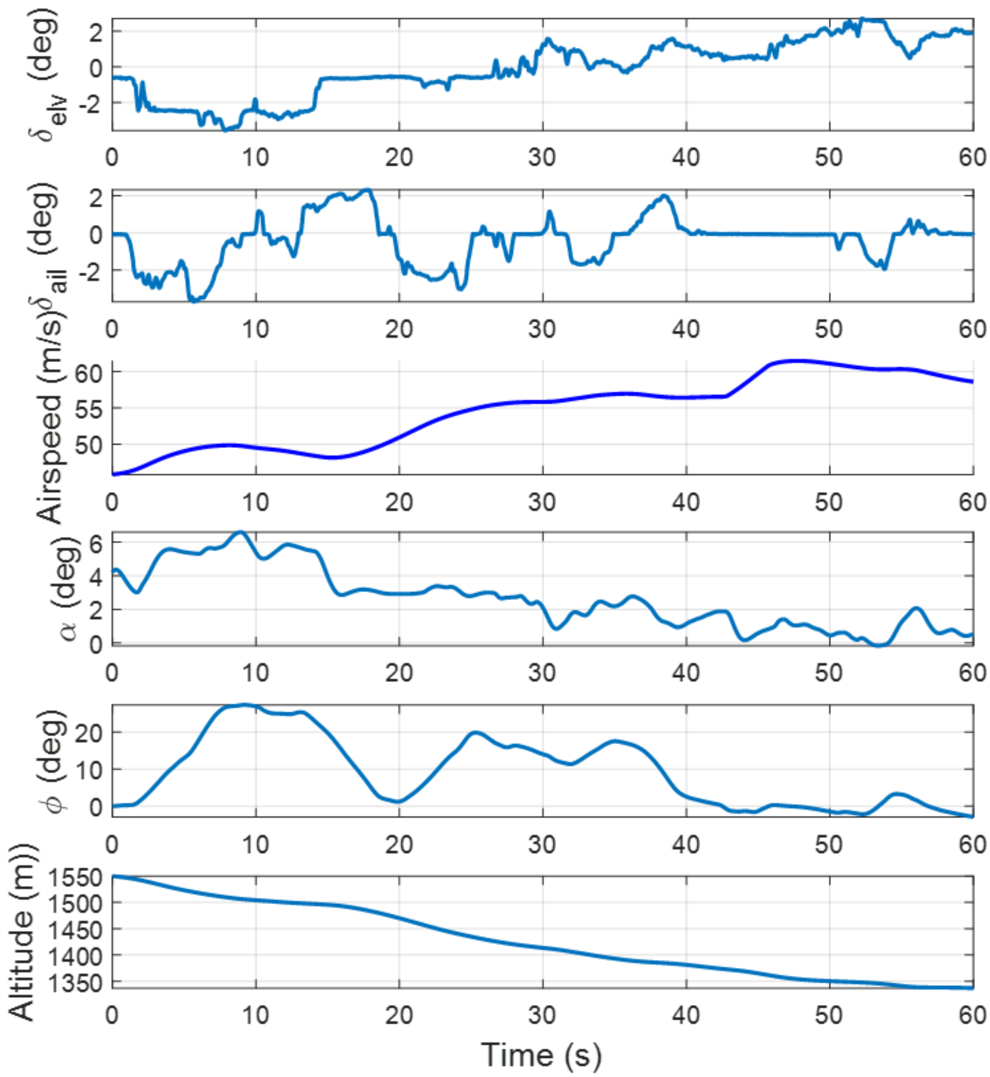


Figure 25. Descending turn with no envelope protection

5 Increasing autonomy and transitions

5.1 Evaluating increasing autonomy

Figure 26 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). 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, whereas the pilot feedback plays less of a role. The automation trust 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.

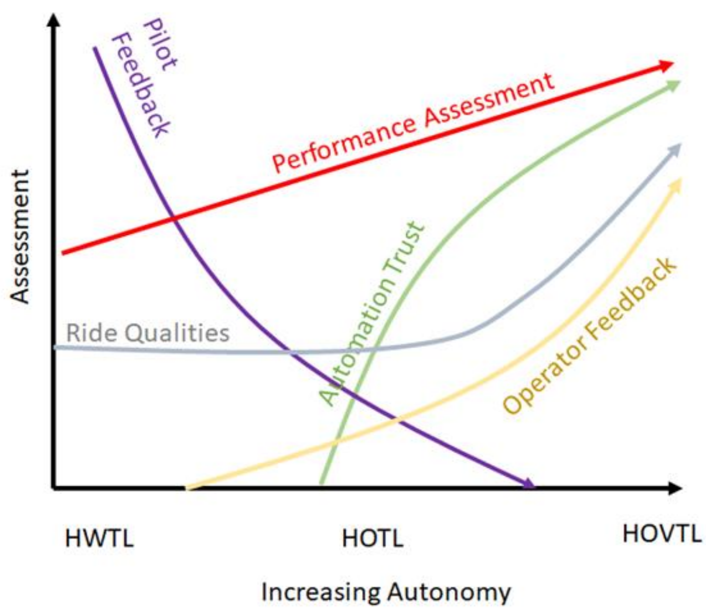


Figure 26. Schematic of expected trend in assessment methods with increasing autonomy

Figure 27 shows the progression of handling qualities demonstrations expected due to increasing autonomy. Currently, there is wide agreement in the community that the first eVTOL vehicles to achieve certification and 'entry to service' must be piloted, with HWTL concepts and this is therefore the focus of the guidance material included herein. In this situation, a combination of

HQTEs, SQAs, and 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 however may be required to *operate* the vehicle, and the handling qualities in these situations should be demonstrated using 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 will 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. The following subsections define SQAs, FQAs, HQTEs, and AQTEs.

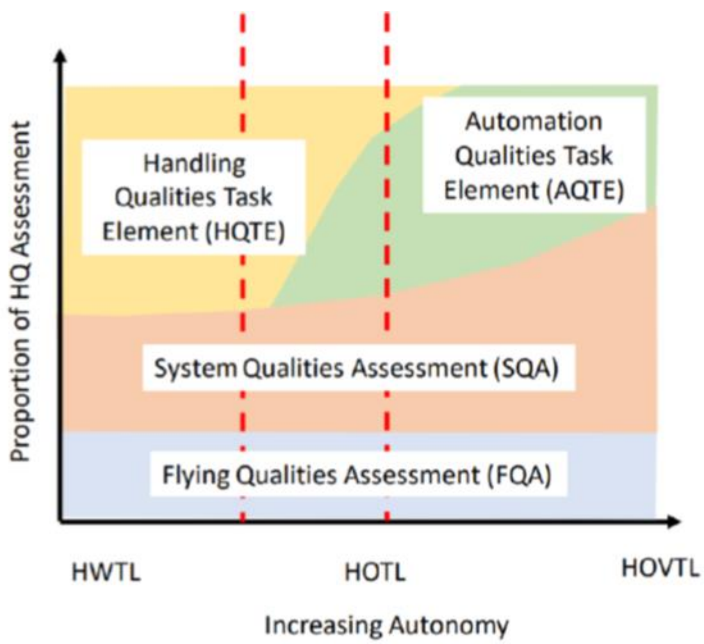


Figure 27. Progression of HQ assessments with respect to automation

5.2 Flight mode transitions

5.2.1 Manual transitions

Flight mode transition comprises of going from powered lift to wing-borne flight and vice-versa. Figure 28 and Figure 29 show the manual transition from hover to cruise and cruise to hover, respectively, as carried out by an engineer pilot in the STI fixed base simulator.

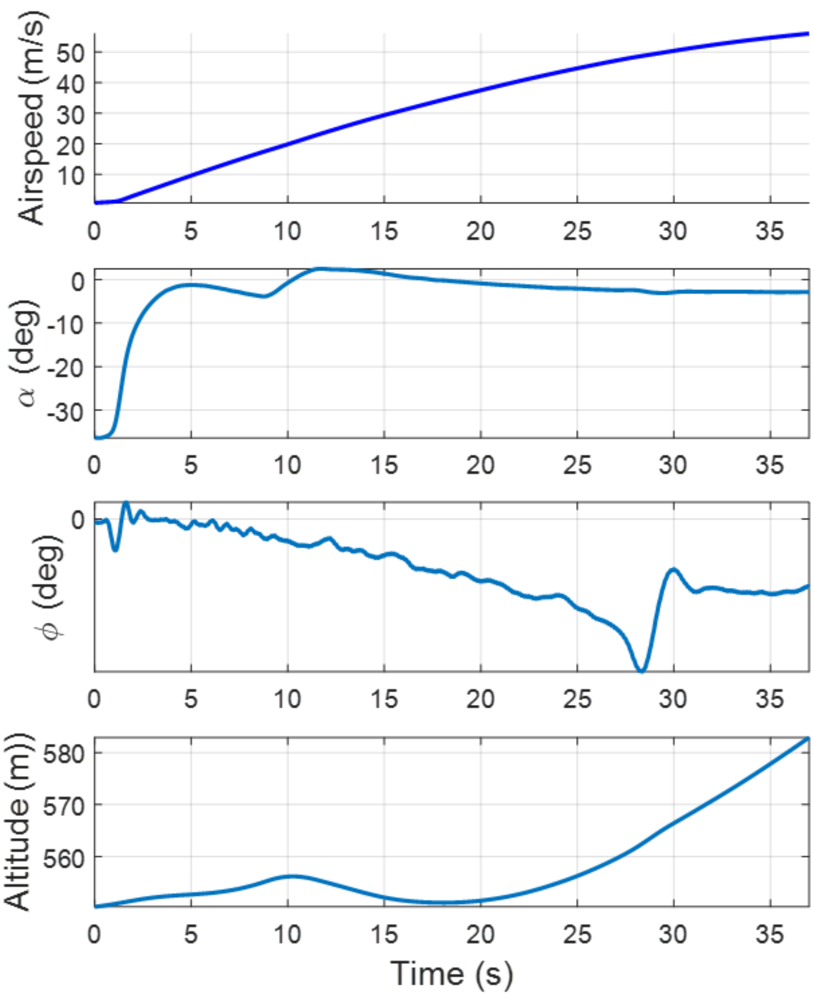


Figure 28. Manual transition from hover to cruise (rotor-borne to lift-borne)

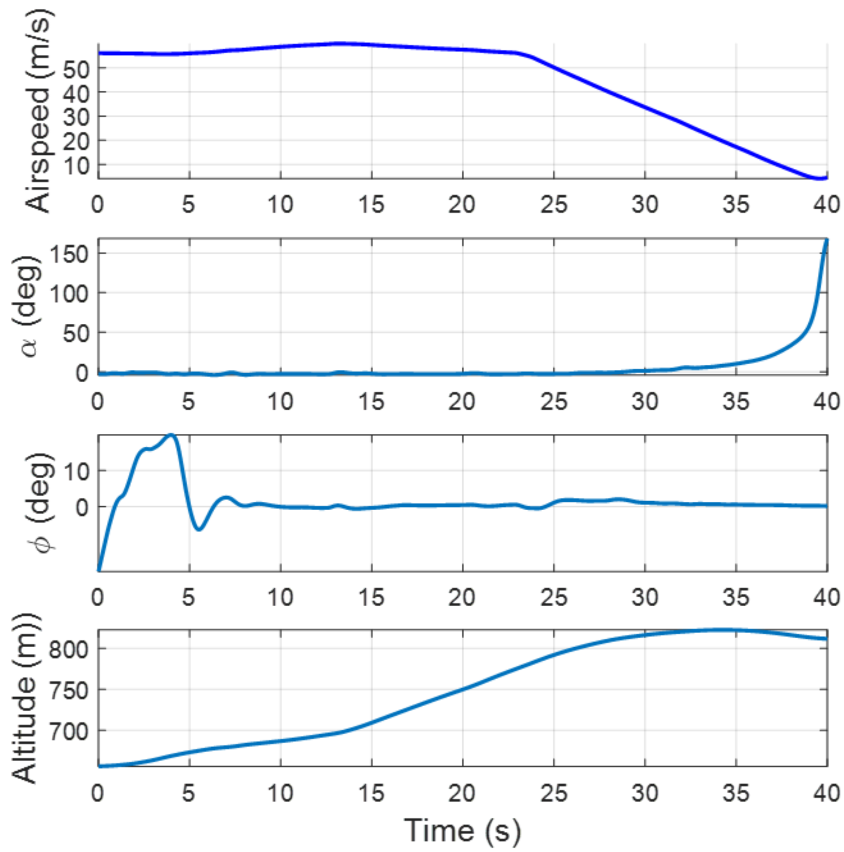


Figure 29. Manual transition from cruise to hover mode

5.2.2 Control architecture for autonomous transitions

In this section, the industry representative lift plus cruise model was used to explore automated transitions between powered lift to forward flight and vice versa. The transitions were intended to be between hover and cruise flight modes, with minimal or no pilot inputs required. The automation control laws for this task were developed by STI, except for the ACAH hover mode control laws that were provided with the lift plus cruise model. Although a transition is expected to be initiated by the pilot, the maneuver to bring the vehicle from a fixed set of states to another pre-determined, destination state is carried out via a combination of the different control modes described below.

1. Hover: Attitude Command Attitude Hold (ACAH)

   The ACAH control laws were provided with the lift plus cruise model as the primary flight control system for the vehicle in hover. The pilot stick commands are scaled and centered suitably to match the reference commands as required by the ACAH system.

The representative block diagram for an ACAH control mode such as that used herein is given in Figure 30.

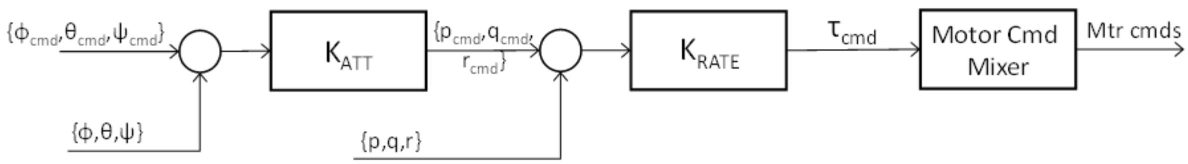


Figure 30. Representative schematic for ACAH control laws

The blocks K_{ATT} and K_{RATE} represent proportional-integral (PI) controllers for attitude and angular rate tracking respectively. The cascaded control architecture first computes the desired angular rates based on error between desired and measured Euler angles. The rate-tracking controller then computes the necessary vehicle torques needed to achieve the desired angular rates. Finally, a motor command mixer is used to translate vehicle torque commands to individual lift-motor commands. The ACAH control mode is used both during piloted maneuvers (where the desired attitudes are derived from inceptor signals) as well as autonomous transitions.

2. Hover: Autonomous Altitude Hold

The altitude-hold control law was designed to enable autonomous altitude tracking in hover. The objective is to help the vehicle achieve a desired altitude in a smooth, gradual manner while rejecting disturbances and pilot inputs. Figure 31 shows the schematic for this control mode. The altitude tracking control law is designed in a cascading architecture, with the error in measured and desired altitude providing the required climb/desired rate. A differential component has been added to the control law, as seen in Figure 31, to address some undesirable motions that were observed in the simulator. The altitude hold mode plays a key role in both hover to cruise and cruise to hover transitions.

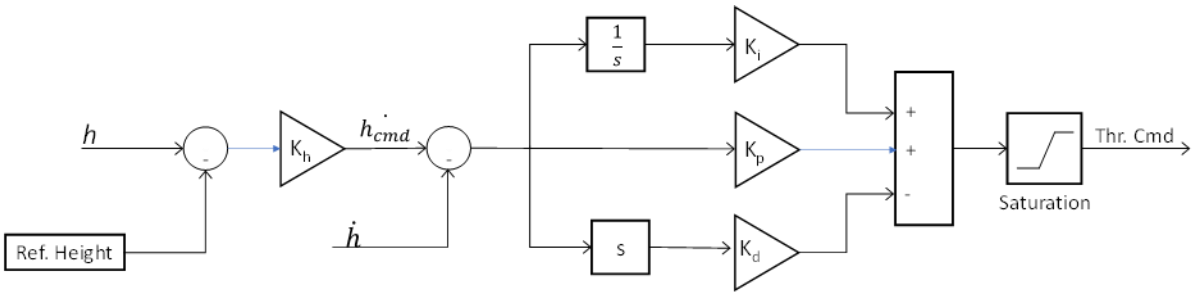


Figure 31. Schematic for autonomous altitude hold in hover mode

3. Cruise speed control with elevator and throttle

   Autonomous cruise speed tracking control was developed using both elevator and pusher motor throttle as primary inputs. The elevator-based control law is described in the schematic shown in Figure 32. This control law is designed for tracking airspeed as Knots True Air Speed (KTAS) at sufficiently high cruise speeds (~30 m/s, 58.3 KTAS, or more) where the elevator has good pitch authority. Elevator-based control provides higher bandwidth as well as more precise tracking. It forms a key part of both hover to cruise transition and vice versa.

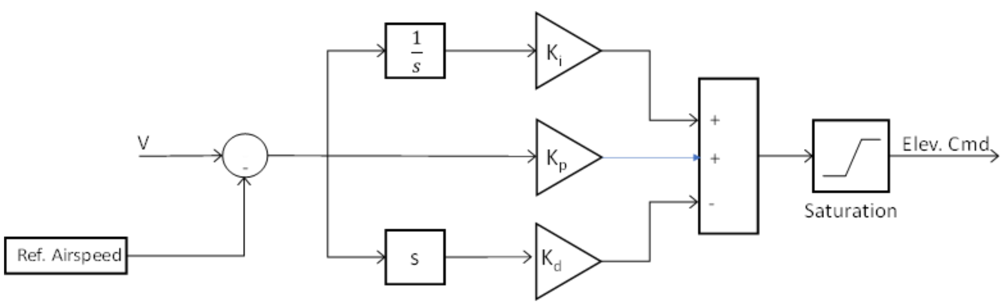


Figure 32. Schematic for speed control in cruise mode via elevator

A pusher motor throttle-based speed control law that tracks airspeed in cruise has also been developed. The schematic for the design is shown in Figure 33. This control law is meant for use in flight conditions where the elevator is ineffective, mainly due to low dynamic pressure. In transition flight mode, this control law is used to generate forward velocity starting from hover, which otherwise would require a pitch down in hover mode. The design itself is a standard PI design. However, it should be noted that since there is no reverse-thrust available, the control law essentially relies on drag to slow down in the event that the reference airspeed is lower than the measured entity. The natural dynamics of the vehicle also render the thrust-based speed control to have a lower bandwidth.

Therefore, it is not the preferred mode for speed control; rather it is only used when elevator-based control is not feasible.

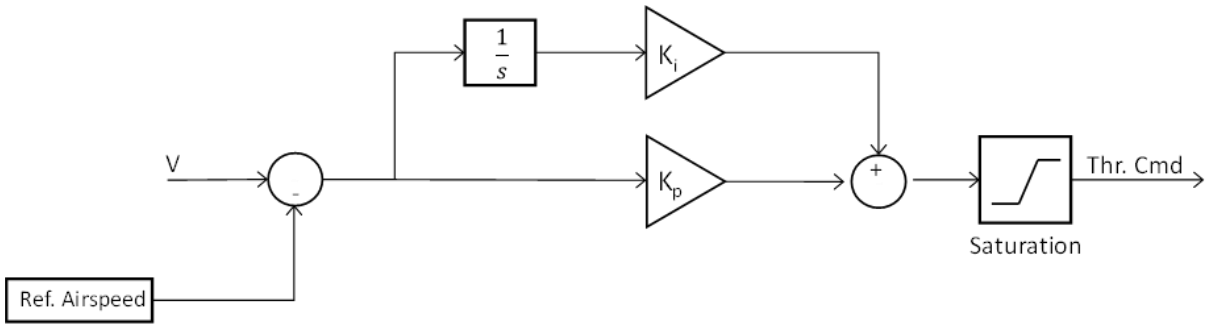


Figure 33. Schematic for speed control in cruise using pusher motor throttle

4. Pitch tracking with elevator

Pitch-tracking in cruise has been developed specifically for hover-to-cruise transitions, and plays the equivalent role of the ACAH mode, albeit in cruise flight mode. The schematic is shown in Figure 34. In addition to a PI control law on the pitch attitude feedback error signal, a proportional gain to the pitch rate feedback is also applied. The pitch rate feedback loop acts as the damping in the longitudinal axis, thereby making the tracking smoother. Just as in the case of elevator-based speed control, this control mode is most effective at sufficient cruise speeds where elevator has good control authority.

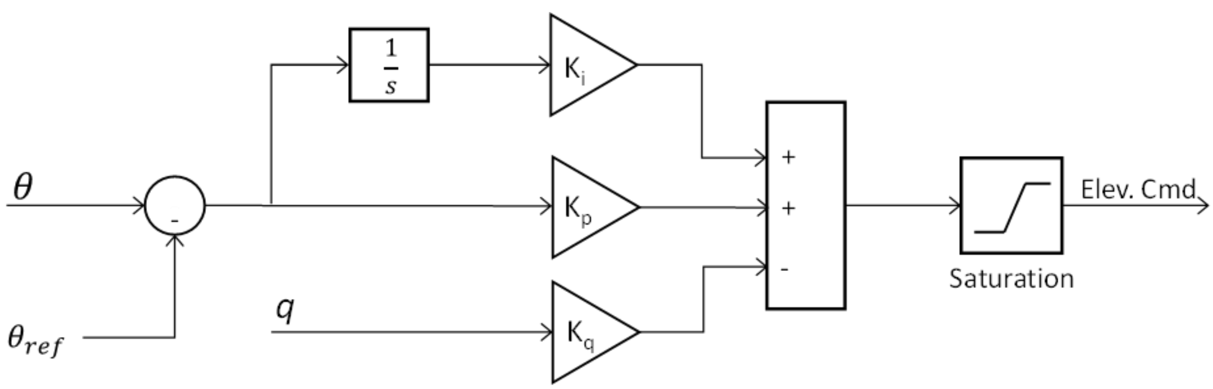


Figure 34. Schematic for pitch tracking in cruise via elevator

5. Cruise roll regulator

The roll regulator control mode is used to keep wings level autonomously in cruise flight mode. The schematic is provided in Figure 35. The main purpose of this control law is to maintain wings level during transitions where dynamic cross-coupling as well as asymmetric lift from the lift motors can cause significant drift in the lateral axis. Within the model, this control mode is turned on automatically with cruise speed control (both elevator and thrust-based) to ensure that the trajectory stays on the intended heading. The design is similar to the pitch-tracking control, except that the roll angle is directly fed back rather than an error with respect to a reference angle.

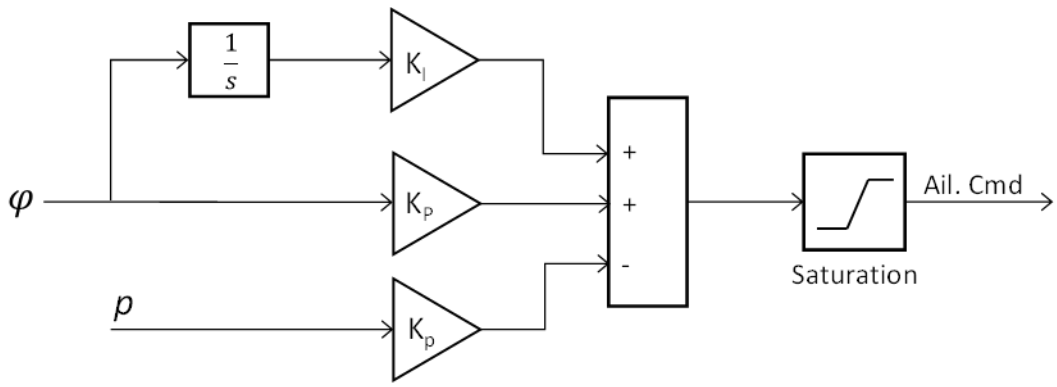


Figure 35. Roll angle regulator in cruise mode via ailerons

5.2.3 Autonomous transition using control modes

The autonomous transitions between hover and cruise flight modes are carried out using multiple control modes described above in tandem. The three main guiding principles for designing a transition trajectory are:

- All altitude/attitude changes should be highly damped to avoid undesirable oscillations.
- All transitions must occur in the local vertical x-z plane (i.e., heading and roll angles should remain unchanged).
- The transitions must occur within 60 seconds.

With these rules in mind, the transitions are achieved as described in the following sections.

5.2.3.1 Hover to cruise

To go from hover condition to cruise, a combination of ACAH, altitude hold, and cruise speed control modes are used. The specific steps are:

- Starting in trim hover conditions, the altitude hold mode is used to achieve the set altitude (150m above trim) via vertical ascent.
- Keeping the altitude hold on, ACAH mode is used to fix a pitch attitude of 3.5°, which is the intended trim AoA at cruise speed.
- Simultaneously, the thrust-based cruise speed control is turned on with the target airspeed of 35 m/s (68 KTAS), which is the trim cruise speed.
- Once 85% of the intended cruise speed is achieved, speed control is switched to the elevator-based mode, which zeroes in on the reference cruise speed. Simultaneously, the ACAH is turned off.

It should be noted that at the end of the last step mentioned above, the altitude hold mode automatically brings the lift motors' RPM down to around 15% of the trim hover RPMs. This amounts to an estimated 5% lift generated via rotors, the rest coming from the wing in cruise. It has been found that shutting of the rotors abruptly causes computational instabilities in the simulation, which necessitates a small, non-zero RPM on the motors all the time. Figure 36 and Figure 37 show the important model states, auxiliary parameters, inputs, and the overall transition trajectory. As noted earlier, the cruise speed control modes simultaneously deploy roll regulator mode that ensures wings are level throughout the transition.

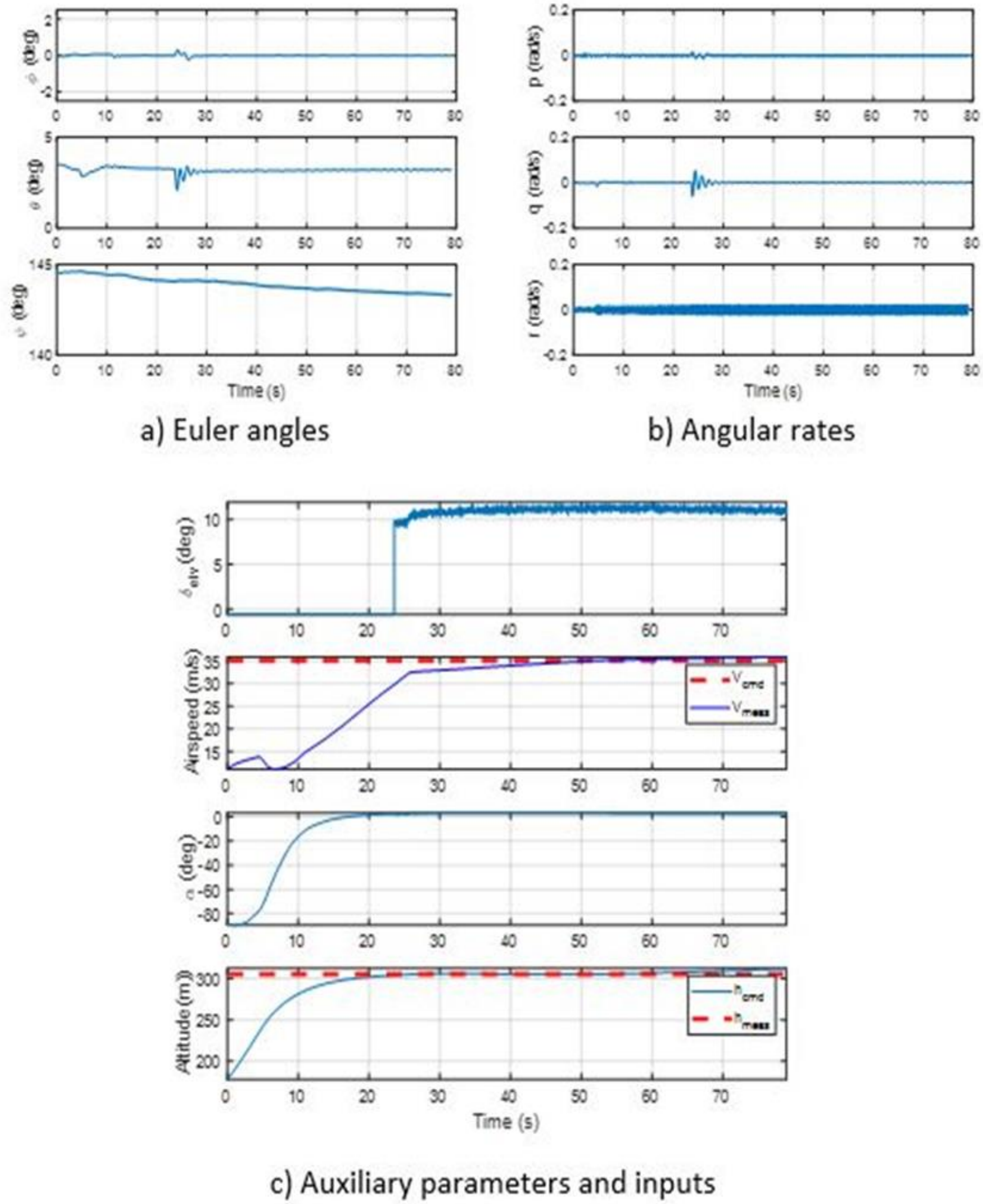


Figure 36. Hover to cruise transition

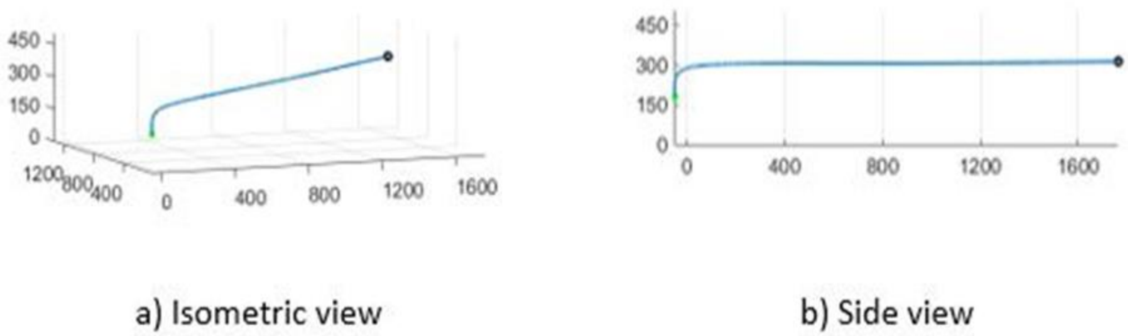


Figure 37. Trajectory for hover to cruise transition

As observed in Figure 36a, the wings remain level, and pitch angle remains mostly consistent. At around t = 25 seconds, the control mode for speed control switches from thrust-based to elevator-based, causing a small transient in pitch angle and rate, Figure 36a and Figure 36b. Empirically, 85% of targeted cruise speed was selected as the scheduling point to switch control modes, which causes minimal transient dynamics. Finally, the aircraft achieves the required airspeed, altitude, and AoA in Figure 36c, while Figure 37 shows that the transition is fairly smooth and in the longitudinal plane of the vehicle.

5.2.3.2 Cruise to hover

Cruise to hover transition has proven to be a little more challenging, given that the pitch attitude hold transition from cruise using elevator to ACAH system has to be smooth. The transition is achieved as follows:

- Starting from a cruise condition with an airspeed of 45 m/s (87.5 kts), the cruise pitch tracker is first engaged at t = 5 seconds to increase the pitch to 15°. Simultaneously, the thrust-based speed control is used to set target speed to zero.
- At t = 10 seconds, the ACAH mode is turned on, thereby engaging the lift motor control. The ACAH is tasked with bringing the vehicle gradually to 2.5° pitch hold.
- At t = 20 seconds, the altitude hold mode in hover is turned on to bring the aircraft to 50m altitude.
- Once the airspeed falls below 5 m/s, the ACAH pitch hold is set to 1°, gradually slowing the aircraft to a hover.

In the first step, the thrust-based speed control effectively shuts down the pusher motor, which remains shut for the rest of the transition. Therefore, for 5 seconds, the aircraft is in glide mode.

The ACAH is not turned on immediately since it was found that engaging the lift motors right away resulted in larger pitch transients. Therefore, bringing the vehicle to a high pitch attitude using elevator initially helps in gradually engaging the ACAH to bring it back to 2.5° without significant oscillations. Finally, the last step allows the vehicle to reduce speed mostly via drag, with an extremely small component of lift-thrust aiding it. This step can be anticipated as needed to bring the vehicle to a complete stop – hover. However, to achieve precision, it is preferable to have a TRC hover mode to regulate airspeed via lift motors, which has not yet been developed for this vehicle model.

The important states, auxiliary parameters, and inputs for the transition are shown in Figure 38. The time responses reveal that the transition is achieved relatively smoothly with no major oscillatory transients. Specifically, the control mode-switching between cruise and hover attitude control is achieved while ensuring that the pitch attitude changes smoothly and slowly throughout the transition. Altitude changes are also quite gradual, while managing to bring the vehicle down to 50 m and airspeed less than 2 m/s, < 4 kts, within 60 seconds. It should be noted that as the aircraft steadily transitions to hover mode, the AoA becomes a meaningless parameter. The trajectory for the cruise to hover automated transition is shown in Figure 39.

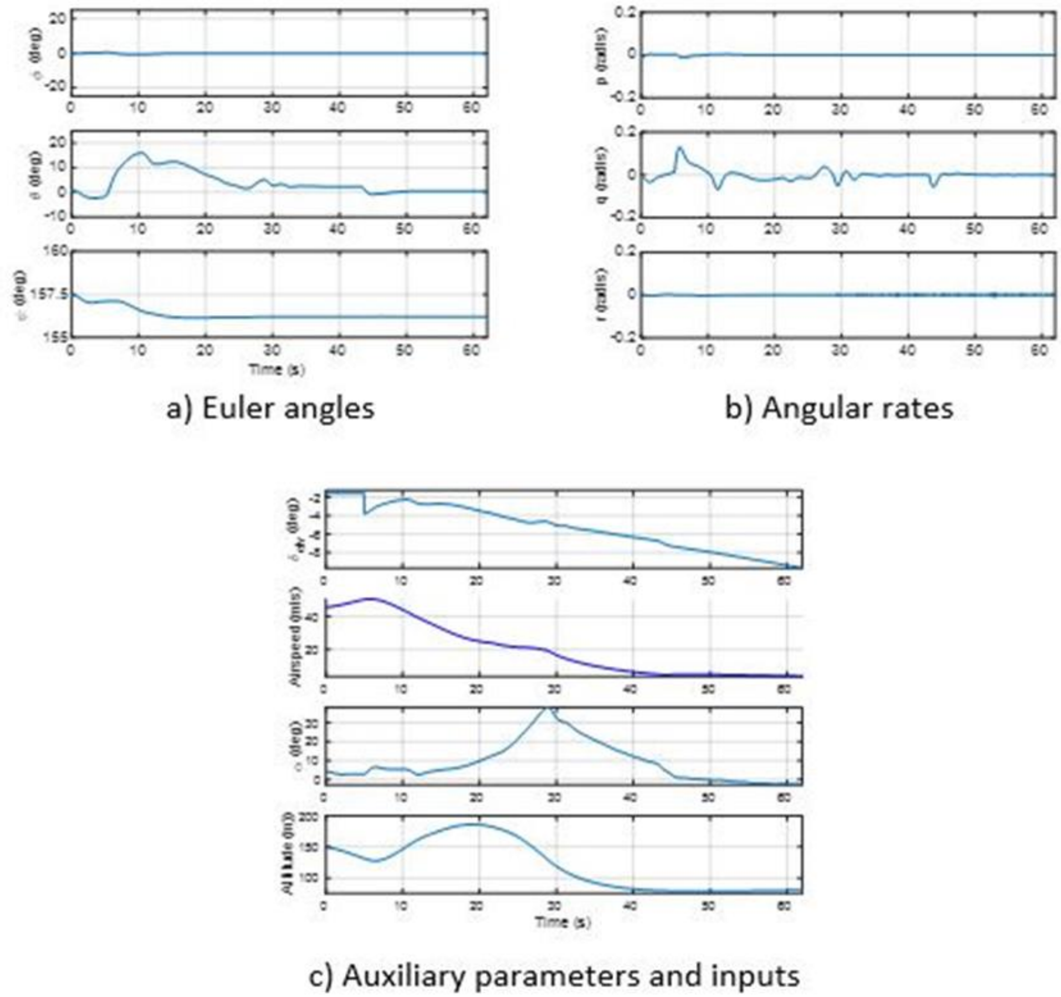


Figure 38. Cruise to hover transition

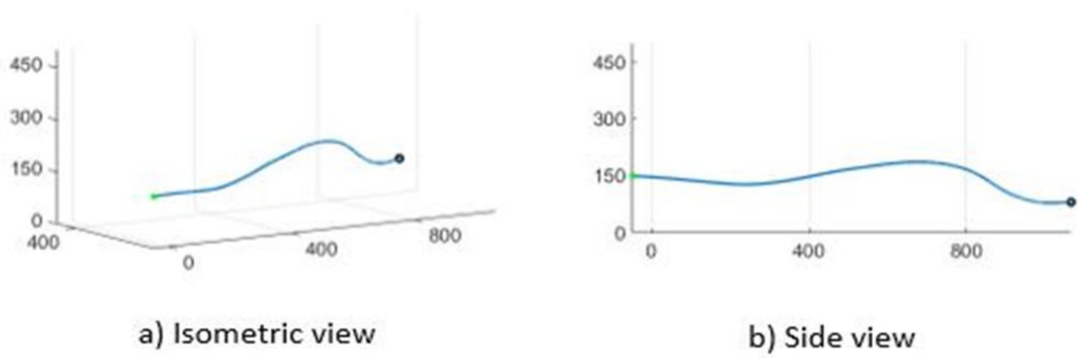


Figure 39. Trajectory for cruise to hover transition

5.2.3.3 Envelope protection in the automated transition

Automated transitions in the presence of different envelope protection schemes were also investigated. Specifically, the cruise to hover transition in presence of AoA protection (via elevator), pitch attitude protection (via lift motors), and stall protection during transition (discussed later), also via lift motors were examined. The cruise to hover transition is discussed here, since it is more complex dynamically and results in significant changes in pitch attitude and AoA.

A significant departure from the nominal cruise to hover transition described previously is that the target altitude is increased from 80 m to 175 m, which helps avoid the steep AoA increase seen in Figure 38. This was necessary since the sudden increases in AoA during a controlled vertical/near vertical descent affected the envelope protection significantly and resulted in de-stabilizing responses. The impact of AoA protection on the modified cruise to hover transitions is shown in Figure 40. Comparing the runs with and without AoA protection, it is seen that there are no significant changes in the variation of states through the transition, with AoA protection on, set to a limit of 10°, with safe return margins set to 8°. We see the impact of the protection in Figure 40c. Here, the AoA does not rise beyond the set limit and causes minimal transitions. It also impacts the rate at which the airspeed is reduced, as it takes the vehicle a few seconds more to slow down to below 5 m/s, < 10 kts.

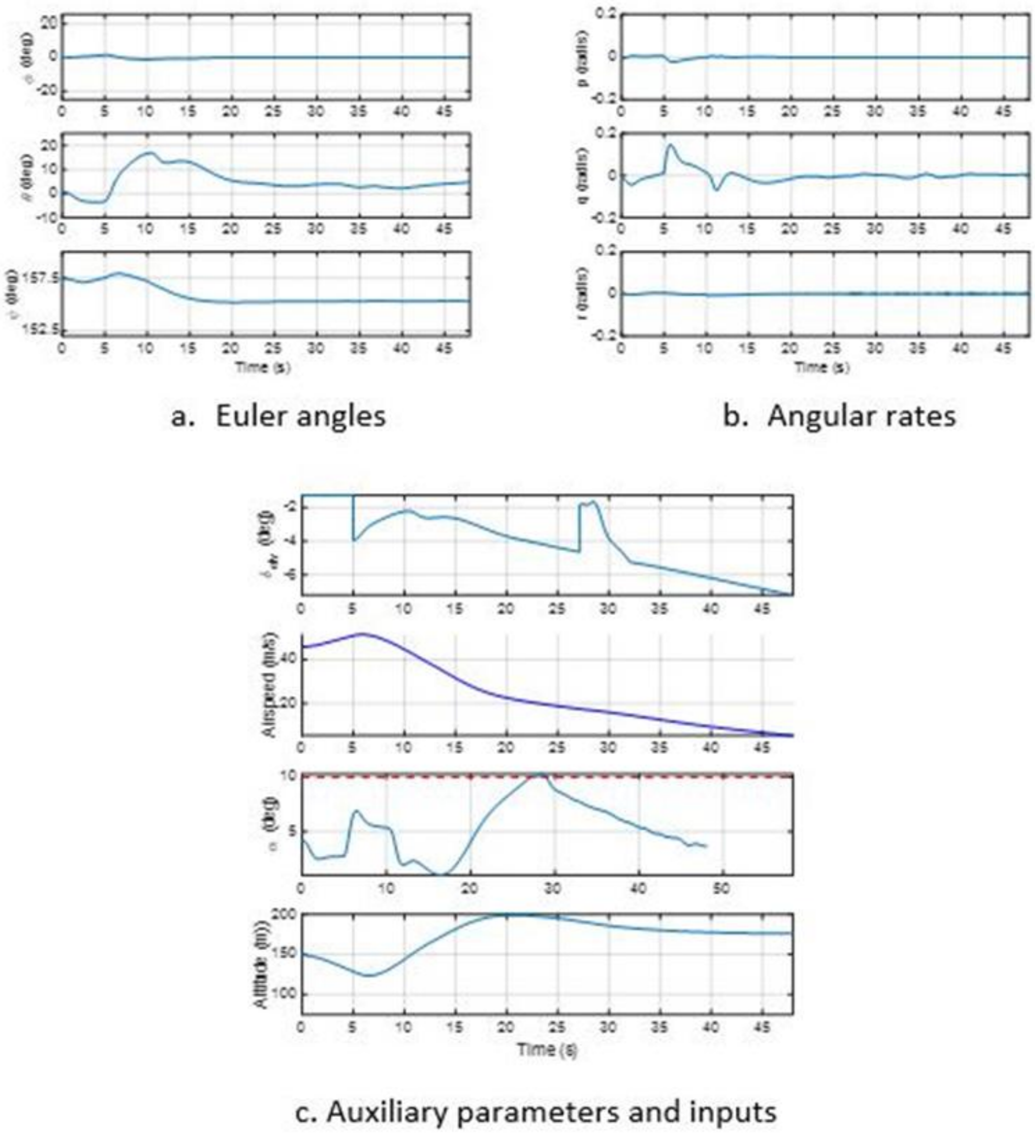


Figure 40. Cruise to hover transition with AoA protection engaged

Next, the impact of pitch attitude protection on the transition is investigated. Figure 41 shows the states, auxiliary parameters, and inputs from the simulation. Here, the impact of the pitch attitude protection system can be clearly seen in Figure 41a at around 10 seconds. The protection limit is set to 15°. There is an aggressive response from the system to keep it below that limit. However, the transients quickly die out, which is a positive sign for the system working in tandem with the automation.

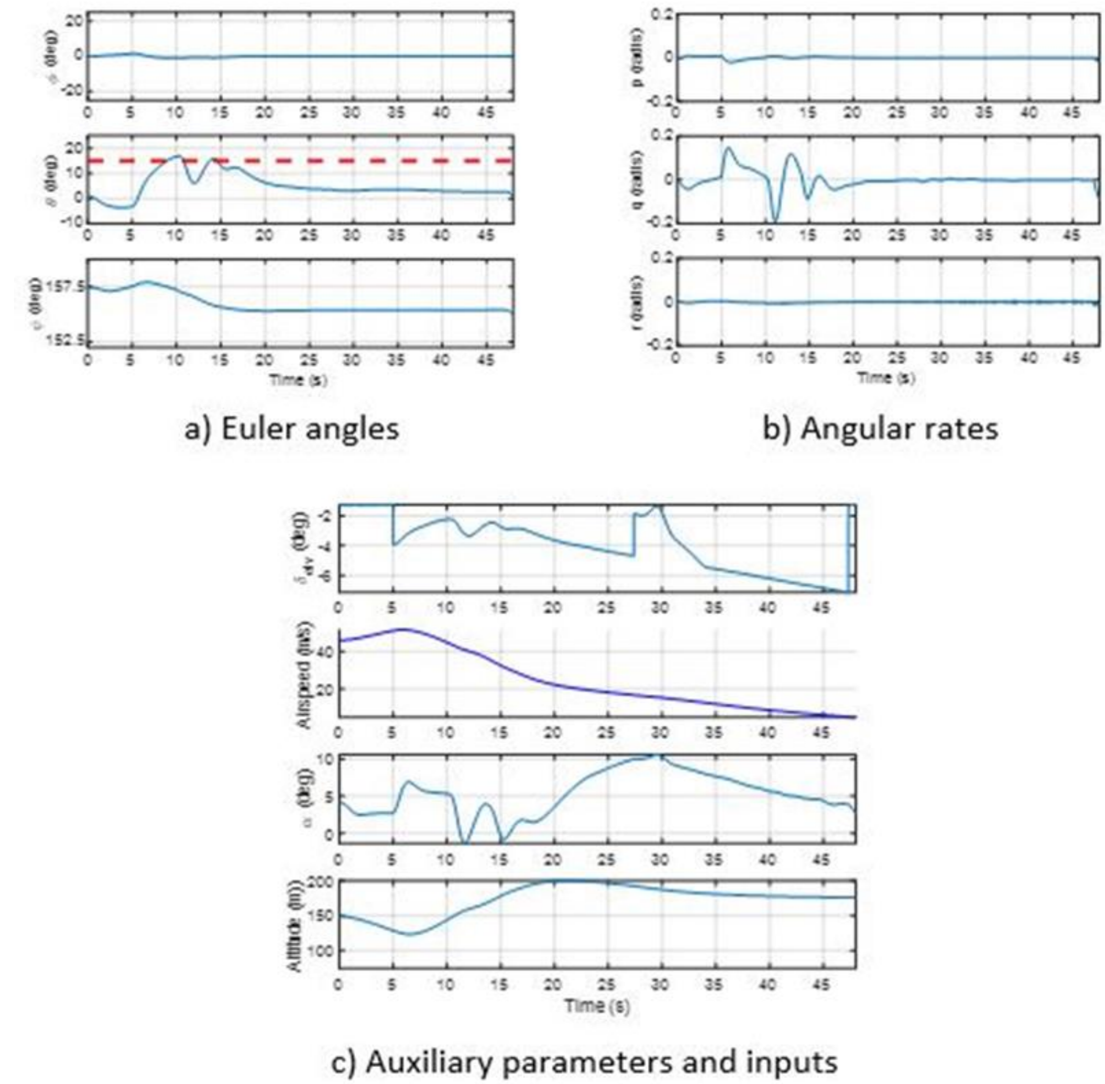


Figure 41. Cruise to hover transition with pitch attitude protection engaged

Finally, the impact of stall protection via lift motors on the automated transition is examined. Stall protection is essentially based on the transition corridor principles outlined in Figure 20. The protection design is based on the lower limits on lift throttle as a function of airspeed. The idea is that for low airspeeds, a minimum limit on lift throttle is applied to ensure there is no sudden loss of lift. Airspeed is selected as the primary scheduling parameter since AoA can be rendered meaningless quickly in hover, causing protection systems to go amiss. After some trial and error in the simulation at different airspeeds and throttle settings, the lower limit on lift throttle as a function of airspeed was set as shown in Figure 42. This variation is based on datapoints collected at 0, 5, 25, 40, 50, and 60 m/s forward velocities, and varying lift throttle until a small sink rate is observed. A 10% gain was incorporated into the corresponding throttle values to produce the function shown in Figure 42. Of course, a more complex, analytical approach should be used to produce similar functions for an actual vehicle design.

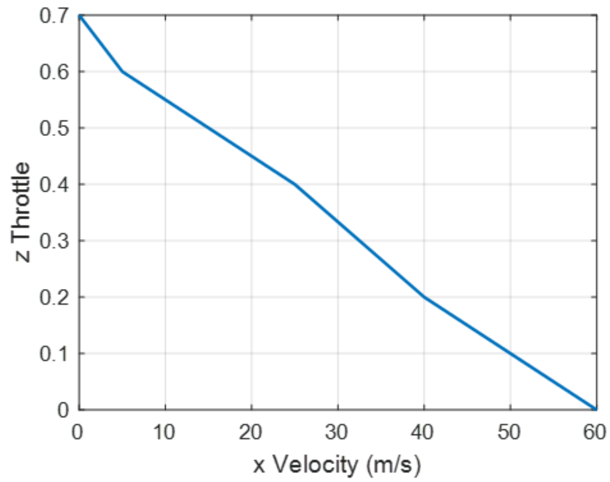


Figure 42. Lower limit on lift throttle as a function of surge airspeed

The impact of the stall envelope protection on the automated transition is examined next.

Figure 43 shows the relevant states and auxiliary variables for the transition. These do not look significantly different from the nominal transition discussed previously. An important difference, however, is that the altitude does not settle at the 175 m reference set by the controller. This is a consequence of the protection system not allowing the throttle to drop below a certain amount necessary for descent at low speed. This is confirmed by looking at the actual throttle response with and without the protection, shown in Figure 44. Here, the response beyond 20 seconds departs from the nominal, protection off condition. The higher lift throttle setting ensures that the aircraft stays in hover, despite a command from altitude hold control to go into a descent. This demonstrates that the protection worked as intended. It also shows the limitations it puts on the envelope, requiring some relaxation so that the aircraft may descend when the pilot and/or automation intends to descend.

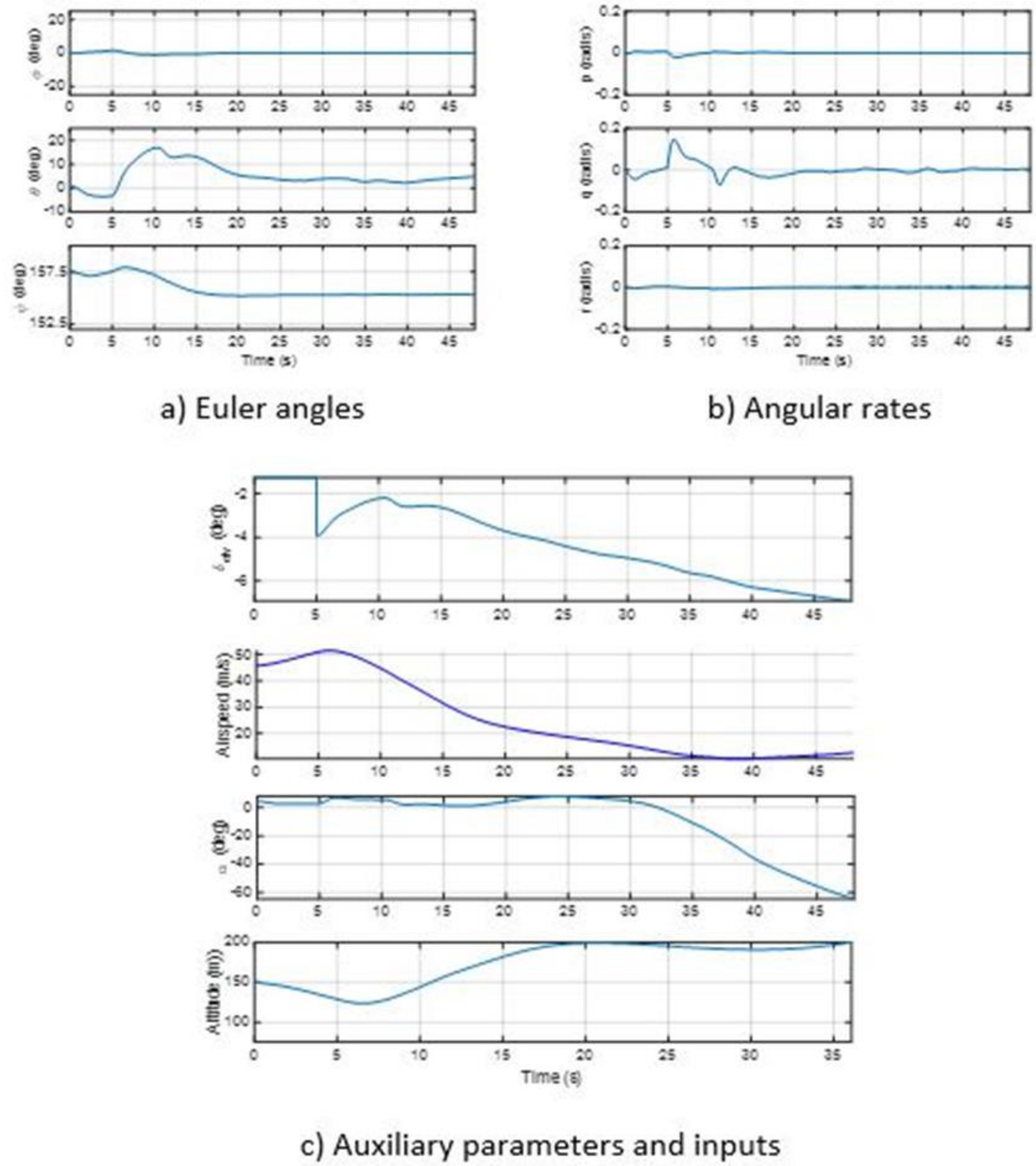


Figure 43. Cruise to hover transition with lift throttle protection engaged

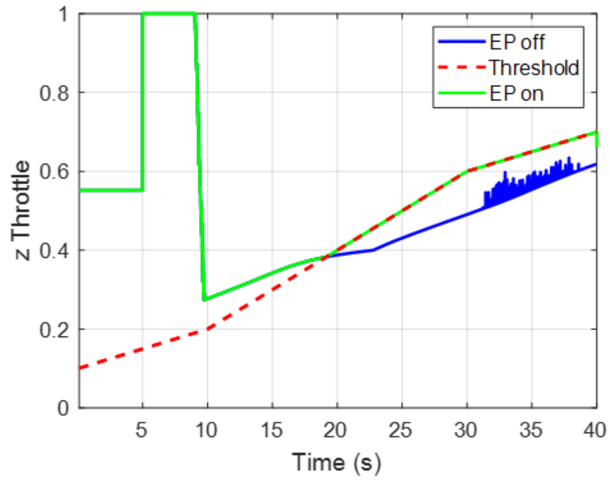


Figure 44. Throttle response for cruise to hover transition with and without envelope protection engaged

5.2.4 Candidate HQTEs for flight control mode transitions

While not examined via piloted simulation in this program, the following HQTEs have been used and vetted elsewhere and can be applied to evaluate flight control mode transitions as well as for transitions between powered lift and forward flight. These HQTEs include:

- Depart/Abort (Anon., 2000): This is a non-precision, aggressive HQTE that is akin to an aborted takeoff, or a runway obstacle avoidance. This task element was designed for military rotorcraft with a more aggressive intent than what would be expected for civilian CONOPS.

- Rejected Takeoff: This is a variation of the Depart/Abort that was defined by NASA Ames Research Center under Federal Aviation Administration (FAA) sponsorship featuring more relaxed task performance requirements when compared to the military rotorcraft version. When evaluated with a lift plus cruise configuration similar to that used herein, three flight control mode changes occurred when this task was conducted in the Ames Vertical Motion Simulator.

- Acceleration/Deceleration (Brewer , et al., 2018): This is a new task element that has been well vetted through piloted simulation evaluations that were conducted at multiple locations with a pool of test pilots and unique, advanced FBW military helicopter configurations. This task element takes the configuration completely through the transition from powered lift to forward flight.

6 Next Steps

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 (Anon., 2000), that 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 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 in (Anon., 2000). Building upon this approach, specific FTMs/MTEs will be used along with other supporting data as means of compliance towards 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 vehicle, urban air taxi, and regional transit operations. The scope of the emerging Test Guide is to direct 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.

7 Conclusions

Key results from this study are summarized as follows:

- Fly-by-wire (FBW) offers the Advanced Air Mobility (AAM) marketplace many unique flight control system response-types or flight control modes that can not only augment basic stability, but also provide increasing automation such that simplified vehicle operations (SVO) with a single pilot can be made safe in dense urban environments.
- The industry representative lift plus cruise electric vertical takeoff and landing (eVTOL) model used in this study was of sufficient fidelity and level of detail to successfully carry out the developments and piloted simulation evaluations shown herein.
- Using the industry representative vehicle model, envelope protection methods were reviewed for use in cruise and hover/low speed flight regimes. Selected simplified envelope protection schemes were then designed and integrated with the lift plus cruise model.
    - Piloted simulation was used to demonstrate the effectiveness of HQTEs to assess the impact of envelope protection on handling qualities of the vehicle. To maximize the utility of this process, the envelope limits were set lower

than would likely be expected in actual operations. Given this assessment environment, the HQTEs were found to effectively stress the envelope protection systems while exposing handling qualities challenges, typically in the form of undesirable motions or oscillations when encountering protection limits.

    - Descending and ascending turns were used to demonstrate handling qualities issues that may arise if conflicts between envelope protections develop. In the piloted simulation evaluations, the maneuvers were flown as flying qualities assessments, as specific desired and adequate performance requirements have not yet been defined. While the level of detail in the model used in this study may not have been sufficient to fully expose handling qualities deficiencies, the assessment process was found to be valid.

- Using the industry representative lift plus cruise vehicle model, an autonomous transition feature was designed and integrated such that the vehicle could maneuver from hover to forward flight and vice versa without pilot interaction.
    - Piloted simulation evaluations were conducted using manual transitions to provide a reference point for the automation design.
    - Automated transitions were evaluated via computer simulation with and without envelope protections active.

Based on the research conducted herein, elements of a holistic approach to means of compliance testing were effectively demonstrating using Handling Qualities Task Elements (HQTEs). The HQTEs were found to provide an effective assessment process across vehicle response-types, with and without envelope protection. Structured HQTE-like testing can also be used to assess increasing automation via Automation Qualities Task Elements (AQTE). To demonstrate, automated transitions were evaluated from hover to forward flight and vice versa with and without envelope protections active.

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A Representative eVTOL model description

A.1 Nonlinear model

The simulation is comprised of three main subsystems that model the physical systems, onboard software, and hardware-software interfacing. Each subsystem has its own initialization script that sets model parameter values, initializes data busses, and where applicable, runs initialization scripts of nested subsystems. The three top-level subsystems are discussed briefly below.

Real-World Software (RWSW)

The RWSW block contains the dynamic models for all physical systems – airframe rigid body dynamics, actuators and motors, propellers, aerodynamics, ground model, environment model, and sensor models. Several of these models have multiple implementation methods that are provided via variant blocks.

System

The system block handles the hardware-software interfacing, including rate-transitions, delays, and pilot inputs. The following labels are the names of the subsystem blocks within the model and brief descriptions of their primary functions are included with each.

a. SYSACT: Convert actuator and motor commands generated by onboard software (flight control software) to discrete, 8-bit signals that are accepted by the corresponding hardware.

b. SYSFCS: Convert pilot/autopilot commands into ‘system’ commands accepted by onboard software at specified sample rate and bit sizes.

c. SYSPLT: Accept user-defined signals and convert into pilot commands.

d. SYSSENS: Convert sensor data into relevant state data accepted by the flight control system.

Onboard Software (OBSW)

The OBSW block comprises mainly of the flight control system (FCS) model that provides roll, pitch, and yaw command in both hover and cruise conditions. The commands provided to the control system are fed to both hover and cruise control blocks. While the cruise control block computes the corresponding control surface deflections (aileron, elevator, and rudder, respectively), the hover control block estimates the torque commands to each of the four high lift motors. There is no airspeed command, and the forward speed is controlled directly via forward thrust input that is fed to the pusher motor as well as elevator command.

The purpose of the FCS is to generate appropriate control surface/motor torque commands, given the roll, pitch, yaw rate, and vertical and forward thrust commands from the pilot/autopilot. In hover, the arrangement assumes that a zero-degree attitude command along any axis corresponds to a normalized stick position of 0.5 (50%), while zero thrust corresponds to zero throttle stick deflection. The commands are then de-scaled to the limits imposed on the maximum and minimum attitude commands (i.e., ±30° for roll and pitch angle commands, and ±120° for yaw rate). A cascaded proportional-integral (PI) control law based on feedback of Euler angles and angular rates generates the required vehicle torque commands. These commands are fed into the command-mixing block to determine the distribution of motor torque commands across the four high-lift motors, by prioritizing pitch, roll, altitude (throttle-up command), and finally, yaw commands. The prioritization reflects the hardware limit of maximum available torque outputs (±1300N-m) for all motors. The allocation itself is based on mapping from the thrust on each motor to moments about the center of gravity along each axis.

For this program, the simulation was re-structured to ensure that the zero-attitude stick deflection is reset to the trim attitude commands obtained from the trim scripts. This modification re-purposes the attitude command controls to act as a regulator about the trim condition when there is zero pilot/autopilot input.

Trimming function

Scripts for trimming the nonlinear model at desired equilibrium positions were developed for the modified nonlinear simulation. The scripts trim the model in hover and cruise at a given altitude or airspeed, respectively. The scripts account for the attitude command FCS software in the loop and provide trim initial states as well as inputs for the closed loop system.

The trimming is carried out in two steps to ensure flexibility and retain numerical accuracy for a discrete-time based FCS model. In the first step, trim solutions for the continuous bare airframe model are generated, thereby obtaining the trim initial states (positions, velocities and attitudes, and motor angular rates) as well as required trim motor torque commands. In the second step, the FCS software block is trimmed to obtain the desired motor torque outputs as obtained from step 1, and the corresponding trim roll, pitch, and yaw rate commands as well as throttle commands. It should be noted that a simplified nonlinear model for the bare airframe, devoid of ground, environment and sensor models is used for trimming purposes.

The intention of the trimming function is to provide suitable initial conditions that the vehicle continues to hold in steady state in absence of pilot inputs. The pilot inputs are treated as a delta command from trim. The trim solutions are found using a sequential quadratic programming-based functionality provided by MATLAB for Simulink models. The simulation is modified to accept either static or dynamic trim conditions as generated by the scripts, as initial conditions. All states, including controller states are set to the initial trim values while initial pilot/autopilot/FCS inputs for attitude commands are set to zero. In hover, the vertical throttle command is set to the appropriate initial value and the pilot command is modeled additive to it.

Real-time implementation

To test FQAs and HQTEs as well as automated transition modes, a real-time version of the simulation was developed. The simulation was modified for real-time by including the Sim Pace Simulink block in the model. This block halts the simulation step for the difference in time between the step size and computation time creating a pace that attempts to match real-time. Additionally, an inceptor block was added that outputs command inputs from either a desktop joystick, or through STI's McFadden Control Loader Force Feel System described in Appendix B. The simulation outputs are sent to two visual displays. The first visual output is to the out-of-the-window graphics, which are currently driven using FlightGear. Within the scene are custom graphics models of Handling Qualities Task Element (HQTE) course elements (e.g., hover-boards, cones, runway markings, etc.). Additionally, a basic head-down primary flight display was provided that contains display elements for attitude, altitude, airspeed, heading, etc.

STI has successfully incorporated the model into its own simulation environment after some modifications (e.g., standard flat-Earth coordinate system) and additions that include altitude rate command control laws, and general debugging to ensure correct computations of sensed variables such as angle of attack. To improve the handling qualities, several modifications were made to the flight control design including feedback gains, altitude rate command development, and the state variable definitions.

B Piloted simulation

B.1 Overview

Piloted simulations have been conducted at STI to evaluate the impact of envelope protection system on handling/flying qualities of a typical electric vertical takeoff and landing (eVTOL) vehicle. Evaluations for AoA protection in cruise as well as attitude protection in all flight modes are conducted by flying specific tasks with and without the protection systems. The tasks are designed to be both within and beyond the set envelope, thereby allowing for a complete analysis of the protection system's impact on flying qualities across the envelope and beyond. In this section, description of the simulator used for evaluations is described, followed by the piloting tasks conducted for the evaluations. Finally, results from simulations are provided.

B.2 Simulator description

Hardware

The STI flight simulator has been developed as a research tool to strengthen the capabilities of STI in the field of real-time, pilot-in-the-loop flight simulation and pilot-vehicle system identification. The key elements of the simulator, including the pilot, are identified in Figure B-1. The STI simulator is comprised of a center stick, pedals, collective, head-down display, and an out-the-cockpit view, all of which can be seen in Figure B-2. The simulator can be set up to use a projected display or a 3-view monitor configuration with forward, right 45-degree, and 90-degree cockpit views. The 3-view monitor configuration was used for these evaluations. Due to the monitor configuration, the HQTEs were only evaluated in one direction, to the right. For example, the Lateral Position and Hold and Pirouette HQTEs were only flown translating to the right and the Hovering Turn and Hold HQTE was flown turning to the right. The full flight simulator and operator station can be seen in Figure B-3.

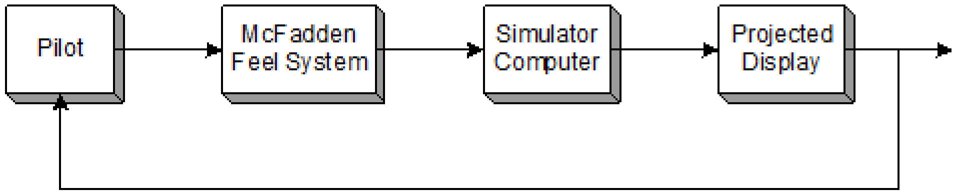
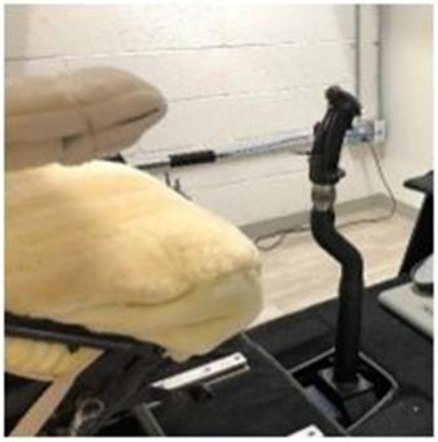


Figure B-1. Pilot-in-the-loop simulator elements

STI's McFadden feel system is comprised of a McFadden Series 292A 2-axis (pitch and roll) fighter stick and McFadden Control Loader shown in Figure B-4a and **Error! Reference source not found.**b, respectively. The system provides a wide range of control-stick force characteristics that are typical of traditional aircraft, including: linear and nonlinear spring gradients, damping, breakout, deadband, Coulomb friction, and travel limits. These characteristics may be used in any combination and changed *on the fly* via the McFadden Control Loader. The roll and pitch axes are independent of each other and therefore can be tuned to different performance characteristics.


Figure B-2. Simulator setup and control inceptors

Figure B-3. Flight simulator operator station and control loader



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

b) McFadden electronic control unit

Figure B-4. McFadden inceptor and control loader

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

Software

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

Simulation Setup

The simulation settings used for the informal HQTE testing were:

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

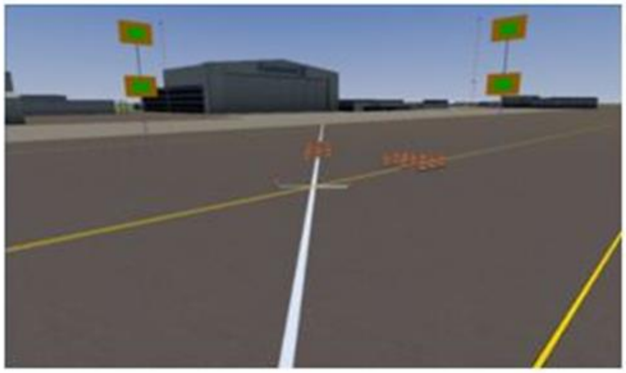
B.3 HQTE Courses

Hover Course

The *Hover Course* (Figure B-5) is the HQTE course used for the Precision Hover, Vertical Reposition and Hold, and Hovering Turn HQTEs. The Hover Course is based off the recommended course description in [**Error! Bookmark not defined.**]. The course includes the f ollowing cueing elements:

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

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



a) Hover board

b) Hover board within 3-view monitor setup at hover location

Figure B-5. Hover course