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Development and Evaluation of Mission Task Elements for Certification of Aircraft with Non-Conventional Control Interfaces

June, 2023

Final report

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16. Abstract

Electrification of aircraft is resulting in configurations that had not been possible. These configurations use fly-by-wire flight controls and introduce novel control concepts that do not map back to traditional mechanical flight controls. The control concepts also do not map to existing Federal Aviation Administration (FAA) certification requirements and therefore need alternate means of compliance. This report addresses that need by considering the use of Cooper-Harper Ratings, ADS-33, and developing a means of compliance for transportation missions. Additionally, a lift + cruise aircraft simulation was developed and implemented in the National Aeronautics and Space Administration (NASA) Langley Research Center's Cockpit Motion Facility to evaluate the means of compliance developed. The report presents a possible approach and discussion for using the Cooper-Harper rating scale. It also contains discussion about the use of ADS-33. A means of compliance for evaluating 14 CFR Part 23 rules for stability and controllability is presented. The means of compliance was evaluated in the simulation and results are discussed. The researchers did not conclude that use of CHR was helpful for certification.

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Contents

Figures

Tables

Acronyms

Acronym	**Definition**
AAG	Adaptive Aerospace Group
AC	Advisory Circular
ACS	Airman Certification Standards
AFM	Aircraft Flight Manual
AGASE	AAG Generic Aircraft Simulation Environment
AGL	Above Ground Level
AIM	Aeronautical Information Manual
AoA	Angle of Attack
ATC	Air Traffic Control
ATP	Airline Transport Pilot
CDI	Course Deviation Indicator
CFIT	Controlled Flight into Terrain
CFR	Code of Federal Regulations
CG	Center of Gravity
CHR	Cooper-Harper Rating
CMF	Cockpit Motion Facility
DoD	Department of Defense
eVTOL	Electric Vertical Takeoff and Landing
FAST	Future Aircraft Safety Team
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAR	Federal Aviation Regulation
fpm	Feet per Minute
FQTE	Flying Qualities Task Element
FTE	Flight Test Engineer
GA	General Aviation
GAMA	General Aviation Manufacturers’ Association
GPS	Global Positioning System
HQ	Handling Qualities
HQTE	Handling Qualities Task Element
HUD	Heads-up Display
IFR	Instrument Flight Rules

Acronym	**Definition**
ILS	Instrument Landing System
ISD D3S	Information Systems Delft DELPHINS Display Design System
KGS	Knots Groundspeed
KIAS	Knots Indicated Airspeed
LNAV	Lateral Navigation
LNAV+V	Lateral Navigation with Vertical Guidance
LOC	Loss of Control
LPV	Localized Performance with Vertical Guidance
MAP	Missed Approach Point
MDA	Minimum Descent Altitude
MOC	Means of Compliance
MTE	Mission Task Element
NASA	National Aeronautics and Space Administration
N_{zU}	Normal Acceleration and Speed Command
ND	Navigation Display
PFD	Primary Flight Display
PTS	Practical Test Standards
RFD	Research Flight Deck
SC	Special Condition
SFAR	Special FAR
SVO	Simplified Vehicle Operations
UAM	Urban Air Mobility
UGeVA	Unified Generic eVTOL Aircraft
VFR	Visual Flight Rules
VNAV	Vertical Navigation
VOR	Very High Frequency Omni-directional Range
VRS	Vortex Ring State
VTOL	Vertical Takeoff and Landing

Variables

Symbols	**Description**	**Units**
A_Y	Y-axis Linear Acceleration	ft/s^2
b	Wingspan	ft
C_D	Drag Coefficient	
C_{D_0}	Zero-lift Drag Coefficient	
$C_{D_{LG}}$	Landing Gear Drag Coefficient	
C_L	Lift Coefficient	
C_{l_p}	Rolling Moment Coefficient due to Roll Rate	s/deg
C_{l_r}	Rolling Moment Coefficient due to Yaw Rate	s/deg
C_{l_β}	Rolling Moment Coefficient due to Sideslip	1/deg
$C_{l_{\delta_{a_{max}}}}$	Rolling Moment Coefficient due to Max Aileron Deflection	
$C_{m_{POS}}$	Max Pitching Moment Coefficient due to Elevator Deflection	
$C_{m_{NEG}}$	Min Pitching Moment Coefficient due to Elevator Deflection	
C_{m_q}	Pitching Moment Coefficient due to Pitch Rate	s/deg
C_{n_p}	Yawing Moment Coefficient due to Roll Rate	s/deg
C_{n_r}	Yawing Moment Coefficient due to Yaw Rate	s/deg
$C_{n_{\delta_{r_{max}}}}$	Yawing Moment Coefficient due to Max Rudder Deflection	
C_{n_β}	Yawing Moment Coefficient due to Sideslip	1/deg
C_t	Coefficient of Thrust	
C_Y	Sideforce Coefficient	
D	Rotor Diameter	ft
F	A Factor that Defines the Approach Speed as a Function of Minimum Achievable Speed	
L/D	Lift-Drag ratio	
M_D	Design Mach Speed	M
M_{mo}	Maximum Operating Mach	M
MAC	Mean Aerodynamic Chord	ft
N_X	Body X-axis Linear Acceleration	g
N_Y	Body Y-axis Linear Acceleration	g
N_Z	Body Z-axis Linear Acceleration	g
p	Roll Rate	deg/s
pdot	Roll Acceleration	deg/s^2
q	Pitch Rate	deg/s

Symbols	**Description**	**Units**
qdot	Pitch Acceleration	deg/s^2
r	Yaw Rate	deg/s
R	Rotor Radius	ft
rdot	Yaw Acceleration	deg/s^2
S	Wing Area	ft^2
T_{max}	Max Thrust of a Rotor	lb
u	Body X-axis Airspeed	ft/s
V	Indicated Airspeed	ft/s
V_1	Takeoff Decision Speed	knot
V_D	Design Dive Speed	knot
V_{fc}	Maximum Speed for Stability Characteristics	knot
V_{mc}	Minimum Control Speed	knot
V_{mcg}	Minimum Control Ground Speed	knot
V_{mm}	Minimum Maneuvering Speed	knot
V_{mo}	Maximum Operating Limit Speed	knot
V_{ne}	Never Exceed Velocity	knot
V_r	Rotation Speed	knot
V_{ref}	Minimum Commandable Airspeed	knot
$V_{tip_{max}}$	Max Rotor Tip Speed	knot
V_{warn}	Low Speed Warning Speed	knot
V_x	Best Angle of Climb Speed	knot
V_y	Best rate of climb speed	knot
V_S	Stall Speed	knot
W	Vehicle Weight	lb
α	Angle or Attack	deg
α_0	Zero-lift Angle of Attack	deg
α_{min}	Minimum Achievable Speed AoA for Current Configuration and Flight Condition	deg
α_{mw}	Minimum Speed Warning AoA	deg
α_X	V_x AoA for the Current Configuration and Flight Condition	deg
γ	Flight Path Angle	deg
ρ	Air Density	slug/ft^3
ϕ	Bank Angle	deg
ϕ_{man}	Maneuver Margin Bank Angle	deg

Symbols	Description	Units
ω_{max}	Max Rotor Angular Rate	rad/s

Executive summary

Electrification of aircraft is resulting in configurations that had not been possible. These configurations use fly-by-wire flight controls and introduce novel control concepts that do not map back to traditional mechanical flight controls. The control concepts also do not map to existing Federal Aviation Administration (FAA) certification requirements and therefore need alternate means of compliance. This report addresses that need by considering the use of Cooper-Harper Ratings, ADS-33, and developing a means of compliance for transportation missions. Additionally, a lift + cruise aircraft simulation was developed and implemented in the National Aeronautics and Space Administration (NASA) Langley Research Center's Cockpit Motion Facility to evaluate the means of compliance developed. The report presents a possible approach and discussion for using the Cooper-Harper rating scale. It also contains discussion about the use of ADS-33. The researchers did not conclude that use of CHR or ADS-33 is useful for FAA certification. A means of compliance for evaluating 14 CFR Part 23 rules for stability and controllability is presented. The means of compliance was evaluated in the simulation and results are discussed.

1 Introduction

Recent advances in navigation, guidance, computation, automation, and electric servo technologies, have made it feasible to outfit General Aviation (GA) aircraft with full authority fly-by-wire (FBW) control systems having novel control interfaces and displays. The legacy and current aircraft certified under 14 Code of Federal Regulations (CFR) Part 23 (2020) Amendment 64 and Part 25 (2021) exhibit behavior, or a response-type, which is familiar to pilots but based on 100-year-old technology. This response type can now be replaced with easier-to-learn and safer-to-fly response-types designed to improve the human interface for moderate cost. Additionally, electrification (hybrid and all electric propulsion) is enabling a wide variety of new aircraft design types with multiple control effectors that could not be reasonably managed by a pilot without FBW. The electric vertical takeoff and landing (eVTOL) configurations are unstable in parts of their flight envelope and thus not manageable by a pilot in at least parts of their flight envelope without stability augmentation of FBW. The combination of propulsion electrification and FBW offer, improved flight safety, and reduction of loss of control accidents, reduced training and proficiency requirements; improved efficiency; and reduced emissions. Combined, they also provide potential new missions such as Urban Air Mobility (UAM) (Hill, et al., 2020) and many others. However, for Part 23 aircraft, standardized means of compliance the FAA can use to certify control systems with novel pilot control interfaces and displays do not currently exist. These are needed to ensure the aircraft can be developed and certified at a cost the market will bear.

Current unaugmented GA aircraft control systems are direct-to-control surface systems where the pilot “commands” the position of a control surface; the response of the aircraft is initially an angular acceleration about one or more axes, with the long-term response being a change in angle-of-attack (AoA) in the longitudinal axis or roll rate in the lateral axis. Most pilots are familiar with this response-type, which dates back more than a century. This conventional response-type requires tens of hours of training to master, particularly in the landing task. The pilot is required to develop unconscious mental compensation filters to be able to gently flare and touch down with an acceptable sink rate, to manage crosswinds and gusts, and even to enter and sustain a level turn. Unfortunately, each type of aircraft requires introductory and recurrent training to achieve and maintain proficiency of these skills.

Augmented FBW flight controls with novel pilot interface can provide direct control over three-dimensional flight trajectories and airspeed while also providing envelope protection. This provides aircraft responses that are intuitive, safe, and easy for new and experienced pilots to understand and master. Results of this work lay groundwork for development of means of compliance needed to certify direct flight path control for Part 23 aircraft, while promoting increased safety, heightened pilot situation awareness, and further “refuse to crash” goals. Together these provide a basis for pilot interface reference concepts leading to Simplified Vehicle Operations (SVO) and leveraging advanced flight path management systems.

FBW control systems have been used in modern commercial, business, and military aircraft for nearly four decades to provide simpler, more intuitive, and accurate flight path control responses, generally tailored to specific tasks. Noting that the commercial FBW systems were certified using special conditions, some business-jet aircraft are already certified with augmented FBW. However, commercial implementations to date have mimicked mechanical systems to make them more closely match the current regulations. Smaller aircraft have not been outfitted with full authority FBW control systems despite the revolution that microelectronics has established in their guidance, navigation, and flight information capability and dramatic improvements in electric motors that can drive control surfaces.

The research discussed herein is twofold. The focus was on development and evaluation of means of compliance for aircraft with FBW that have novel control approaches. In support of this purpose, a simulation model of an eVTOL aircraft with a full-authority FBW and novel control mapping was developed for use in ground-based piloted flight simulators. The main simulator was NASA Langley’s Cockpit Motion Facility (CMF), while Adaptive Aerospace Group’s (AAG) Engineering Simulator was used by AAG to develop and test the implementation before it was ported to NASA’s CMF.

This work built on previous NASA, industry, and DoD research to provide a certification path for significantly more intuitive control response-types for professional and non-professional pilots in Part 23 aircraft. Pilot inputs will directly command the path of the aircraft relative to the ground (e.g., runway) instead of the position of a control surface. The resulting system will also be compatible with envelope protection, providing stall/overspeed protection, load factor protection, bank angle limits; other possible projection provisions include terrain, traffic, obstacle and weather avoidance, and fuel exhaustion prevention. Envelope protections were implemented for this work. Complimentary displays were developed for the vehicle as well. These are also described in this report.

The FAA currently has many applicants for certification of FBW eVTOL aircraft with non-conventional FBW flight controls that are approaching them and many more in various stages of development. Some are well into their flight test programs. Most have advanced flight control methods that existing certification requirements do not address.

This paper presents work that was focused on developing a set of means of compliance (MOC) that could be used by the FAA and applicants for certification of novel FBW implementations. All references to 14 CFR Part 23 are related to Amendment 64 unless otherwise stated. The work is discussed in the following order:

1. The authors addressed the possible applicability of the Cooper-Harper Rating (CHR) Scale (Cooper & Harper Jr, 1969) for 14 CFR Part 23 certification and developed a set of Mission Task Elements (MTEs) similar to those discussed in *Aeronautical Design Standard Performance Specification Handling Qualities Requirements For Military Rotorcraft* (ADS-33E-PRF, 2000). A modified CHR scale for potential use in certification was developed and is discussed. The authors had differing views on its usefulness. The modified scale is presented and discussed in Section 2. However, the scale and approach were not evaluated.
2. A series of MTEs were developed as proposed partial means of compliance for certification. They include closed loop tasks, open loop tasks, system evaluation tasks, and some potential failure scenarios. The MTEs are presented together with a preamble that makes the write-up akin to an Advisory Circular (AC), e.g., AC 23-8c. Lessons learned from development and limited evaluation is discussed. The MTEs, how they should be used, and what the applicant and FAA should be looking for are described in this report. See Section 0.
3. A generic eVTOL configuration was developed for use in evaluating the MTEs. The simulation was implemented in NASA Langley's CMF. The eVTOL vehicle was a general representation of NASA's Revolutionary Vertical Lift Program's Lift + Cruise configuration (Advanced Rotorcraft Technology, Inc., 2019) but with a custom flight control implementation and other changes. The flight control system was a modified version of the Unified flight control system developed by the US and British Navies for the F-35B (Denham Jr & Paines, 2008). The simulation and flight control implementation and simulators are discussed at a high level in Section 4.
4. Evaluation of some of the developed MTEs was done by an FAA pilot and flight test engineer in the CMF. The time conducting the evaluations was far less than planned due to Covid-19 lockdowns in 2020 and early 2021. The MTEs that were evaluated are discussed with observations and lessons learned included. See Section 5.
5. Conclusions are recommendations are found in Section 6.

2 Use of Cooper-Harper ratings in certification

The use of Cooper-Harper Rating (CHR) and other rating scales in certification was assessed as part of this work. The Cooper-Harper Scale was considered for use with MTEs in nominal cases and separately for evaluation of hazards. The CHR scale is used while an aircraft is being developed to determine areas where handling qualities (HQ) need to be improved. They are also used regularly in military acceptance testing to assure the aircraft meets mission requirements. The use of a scale like Cooper Harper is important for military acceptance because it provides a standardized means for evaluation pilots to discuss the suitability of an aircraft for its intended mission and ease of handling of the aircraft while accomplishing the mission. The evaluation pilot represents the end customer in this environment and therefore has the responsibility to ensure that the government is getting a useful asset. Use of CHR has proven to be a very useful way for the evaluation pilot to perform this role. By contrast, FAA certification evaluation is intended to determine if a conforming aircraft design meets the FAA certification rules. The rules are written to ensure that if the aircraft meets the rules, it is safe. FAA certification has no role to play in determining the usefulness of an aircraft for any mission, or whether or not it is a good design – the market determines that. As such, it is a binary decision (complies with the rules or does not comply with the rules). The CHR scale has no binary acceptable/not-acceptable decision points nor is there any reference to acceptable criteria. One of the FAA rules is that the aircraft must be controllable without exceptional pilot skill. The authors worked hard to develop a way to use CHR to make the "exceptional pilot skill" finding. The approach developed is discussed in this section.

In the end, the authors did not agree on the potential usefulness of the approach developed. Some authors who have little FAA certification experience think the approach may be useful in helping define “without exceptional pilot skill or strength,” the FAA criterion in the rule. The only author with extensive FAA certification experience as an applicant thinks it unnecessarily delays and complicates certification and makes it more expensive while adding no value because in the end, a determination of whether the aircraft meets the rule must be made and a CHR evaluation does not make that determination. An author with extensive military experience but no FAA certification experience thinks CHRs should be used in certification akin to how they are used for military aircraft acceptance.

The original plan for this work was to develop the vehicle, MTEs, CHR use approach, and have three disconnected weeks in the simulator to evaluate them:

- Week 1 was for the FAA pilot and flight test engineer (FTE) to become familiar with the aircraft and MTEs and provide feedback. Tweaks would be made to both the simulation and the MTEs between week one and two.
- Week 2 was for additional familiarization and feedback. Tweaks would again be made between weeks two and three.
- Week 3 was to be evaluation of the MTEs using the CHR approach. The CHR approach would have been briefed to the pilot and FTE in detail and then applied throughout that week.

The Covid-19 pandemic denied access to the Langley Cockpit Motion Facility for over six months and access was limited for another three months, including preventing access for three weeks to an author who had been key to development of the aircraft model due to having Covid. That resulted in significantly delayed progress in getting the simulation ready. With continued limited access and travel limitations, the FAA test pilot and FTE only had one week of the planned three weeks in the simulator. That week was necessarily focused on becoming familiar with the aircraft, proposed MTE procedures, and some of the MTEs.

The CHR approach was discussed with the FAA test pilot and FTE before the week in the simulator, but it was not briefed in detail, and it was not used during the week. Given these limitations, evaluation of the proposed CHR approach was not done. Like the MTEs state, the aircraft should be flown to check ride proficiency before maneuvers are done to say it is certifiable or not, and the same should be done when using the Cooper-Harper scale.

After the week, and given schedule pressures and broader needs, the FAA test pilot and FTE determined that additional time for them was not the top priority. A second week of simulator time was used to introduce the Unified control system to FAA Flight Standards and Human Factors personnel.

The use of CHRs for certification is not new. There is a section in AC 25-7D (2018) that discusses it. The AC also warns that it should not be used unless a Special Condition calls for it.

2.1 Use of numeric handling qualities rating scales

Numerical HQ scales may be used to assist in forming a certifiable / not certifiable conclusion. However, numerical ratings and areas of deficiencies are not appropriate for inclusion in the certification report. The result of the evaluation is to be a binary determination of certifiability. When multiple evaluations are done using numerical scales (by the same pilot or different pilots) different numerical results are expected. When this occurs, comments made by the pilots and knowledge of the flight conditions should be discussed and a consensus conclusion should be drawn as is discussed in more detail in the next section. The original Cooper-Harper paper emphasizes the importance of pilot comments made as the pilots use the rating scale.

Variability of ratings is sometimes addressed with statistical analysis tools that are used to determine a final number. Potential ways of dealing with these different numerical results are to average the numerical ratings, take the median value, throw out outlier numerical ratings, and similar means of dealing with numerical test results. These statistical tools have the inherent danger of inadvertently over-ruling one evaluation pilot who finds a deficiency that the others may have missed. The HQ community generally frowns on the use of statistical analysis of numerical ratings, yet they are occasionally used.

Use of statistical tools to determine certifiability is not appropriate. The evaluation pilots need to come to a consensus as to the certifiability of the design, they are not to provide individual ratings or a combined rating for the design. The only conclusion for the certification report should be a consensus statement for each mission task element concerning its certifiability. This statement shall be clearly binary (certifiable or not certifiable). It shall not categorize the characteristics as adequate, desirable, or anything other than certifiable or not certifiable. If the statement concludes that the design is not certifiable, then comments concerning the characteristics that make it not certifiable are required. If the aircraft is not certifiable the comments will be provided to the applicant, but no report will be written.

2.2 Use of Cooper Harper or other numerical rating scales

One of the objectives of this project was to examine the CHR scale and propose a means by which it could be used to help determine aircraft certifiability. The CHR scale (Figure 1) has been used successfully for many years to help determine if military aircraft are acceptable for their intended mission. It provides a common language by which the “goodness” of a particular aircraft’s HQ while performing specified maneuvers may be described. Although any method may be used, to standardize the qualitative evaluation criteria, the CHR scale is suggested as a guide if the test pilot(s) determine that such a guide is needed. For the purpose of this document, the characteristics that describe a CHR 4 aircraft (moderate pilot compensation is required) are considered to meet the definition of not requiring exceptional piloting skill, alertness, or strength. The characteristics that describe a CHR 5 aircraft (considerable pilot compensation) or worse may or may not be considered to require exceptional piloting skill, alertness, or strength. In addition, the required performance level in the proposed handling qualities task elements (HQTEs) is considered equivalent to the desired performance level referenced in the Cooper Harper rating scale. The pilot is to evaluate the aircraft while meeting the required performance. Allowances are made for wind and turbulence just like in airmen testing. If the evaluation pilot cannot achieve the required performance level, (while making allowance for turbulence and wind) the aircraft is considered to require excessive pilot skill for that maneuver. In calm conditions, if the CHR is higher than four, but the required performance is met, then the pilots need to determine whether exceptional pilot skill is required. If the required performance cannot be achieved in calm conditions, then the aircraft is not certifiable. Note that the certification decision always goes back to the FAA rule – not a CHR.

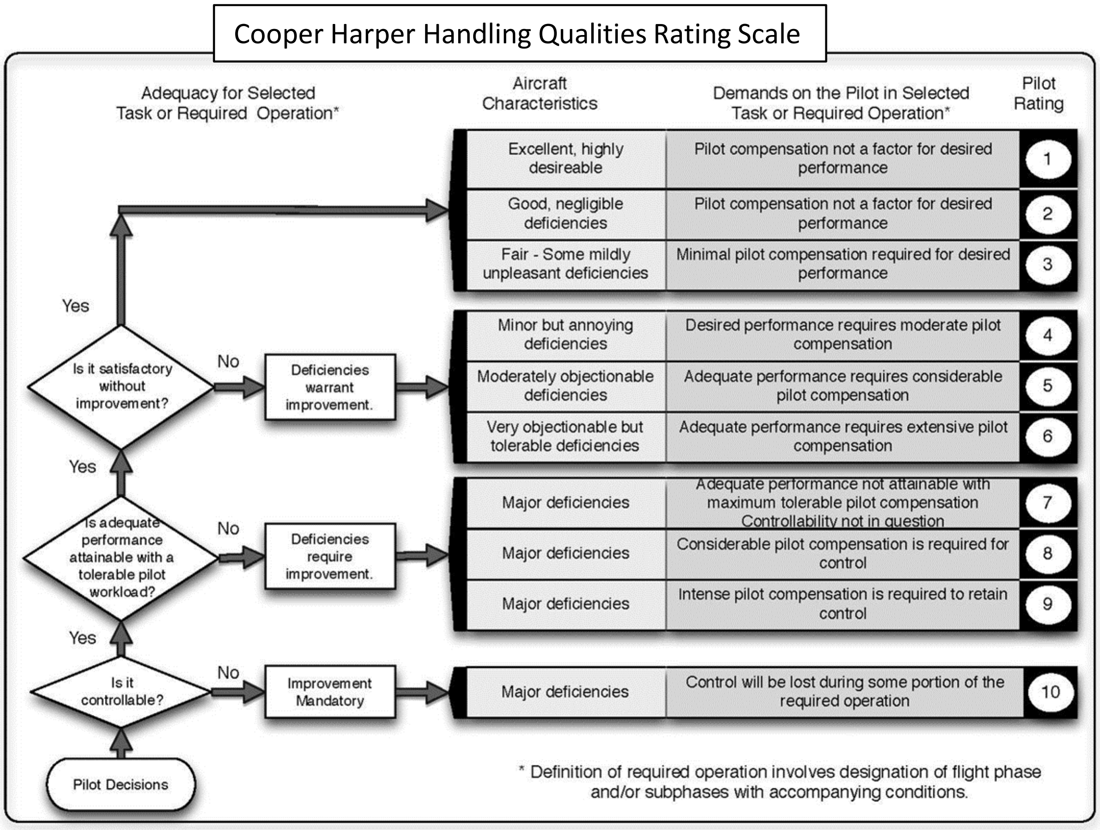


Figure 1: Cooper-Harper rating scale

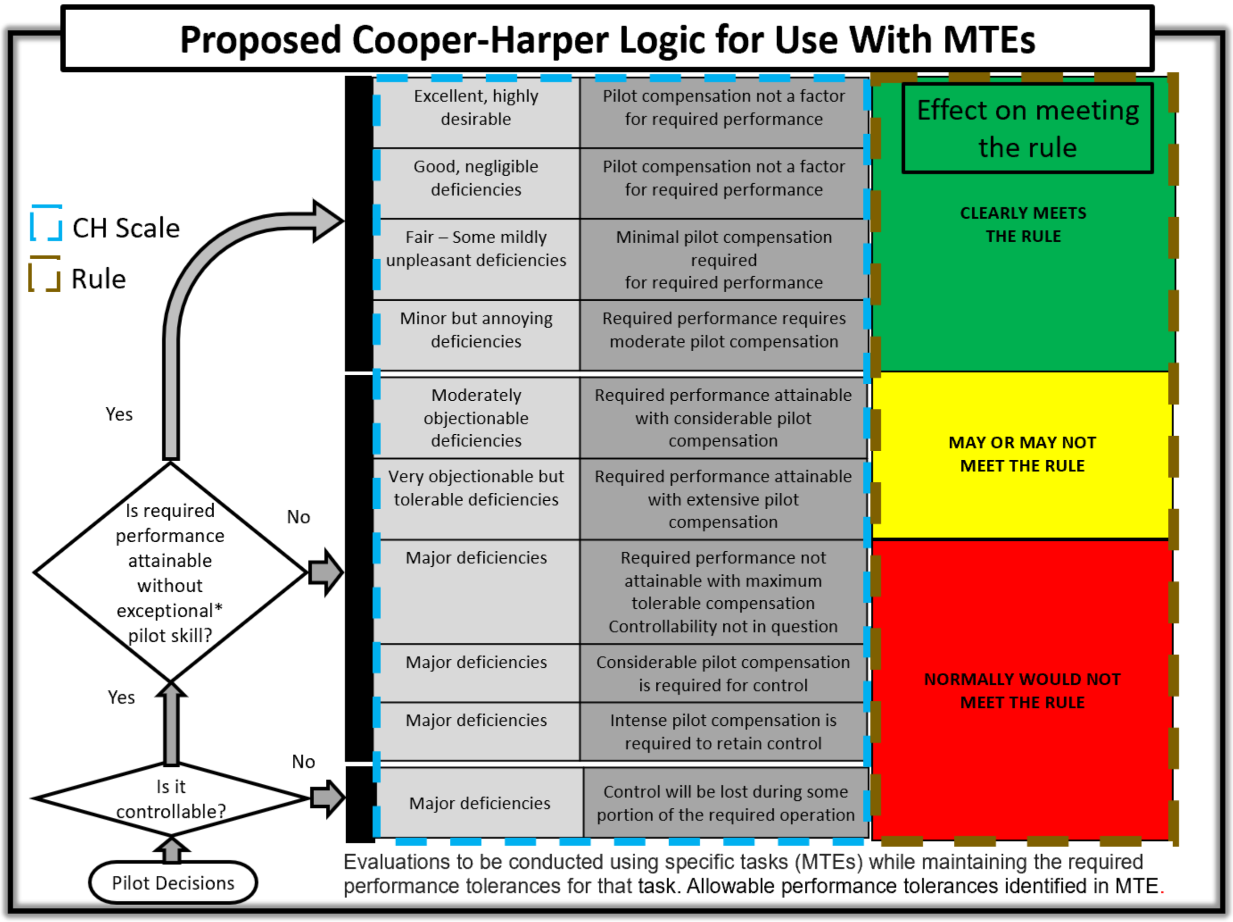
There have been other efforts to correlate CHR to certifiability. AC 25-7D appendix E is an example. It defines “minimum appropriate HQ requirements that take into account the features, characteristics, and limitations of an EFCS (electronic flight control system)" (FAA AC 25-7D, 2018, pp. E-1). The minimum HQ rating for Light atmospheric conditions and a Normal Flight Envelope is Satisfactory, which the AC equates to CHR 1 to 3. Note that in the CHR scale desired performance is achieved for CHRs 1 to 4.

As discussed in Section 3.4.3, the required performance level for all maneuvers is that required for a pilot to pass an FAA check ride. Reducing this requirement would allow an aircraft to be certified which cannot meet the requirements for pilot certification. This did not seem to be appropriate for FAA certifiable aircraft. Therefore, the only performance level is the required performance level, which generally comes from the airman certification requirements.

Exploring the scale, CHR of seven or worse indicate that neither desired nor adequate performance can be attained. Since this is an FAA certification, the performance level is that required of a pilot to obtain a license or rating. In this case, the required performance takes the place of adequate performance for the purpose of compliance to a rule. Since the required performance level is not attained with the maximum tolerable pilot compensation at level 7, and the required performance level is that required to obtain a license, the implication of a CHR of 7 or worse would mean that a pilot flying this aircraft could not meet the minimum standard required to obtain a pilot license. Therefore, it can be surmised that this level of HQ would normally not be certifiable.

Note that this reduces the CHR scale to three categories – four and better, which clearly meets the rule, five and six, which may or may not meet the rule, and seven or worse, which normally would not meet the rule. Figure 2 shows the CHR logic flow with some edits to align better with certification, there is only "required performance" for example. Note that the numbers were removed leaving three options for how the rule was met: "CLEARLY MEETS THE RULE" in the green box (top); "MAY OR MAY NOT MEET THE RULE" in the yellow box (middle); and "NORMALLY WOULD NOT MEET THE RULE" in the red box (bottom). The words in the CHR logic flow are effectively used to help determine whether "exceptional piloting skill, alertness, or strength" are needed per §23.2135. If the consensus of the evaluation pilots is that the aircraft is in the green box for a maneuver within the flight envelope, then they may consider it certifiable for that maneuver. If the modified CHR logic tree results in the yellow or red box for one or more pilots, the result should be discussed, and a determination made based on the rule – not a CHR. As mentioned above, numerical CHRs are not to be included as part of a certification report and the modified chart removes the numbers. Also, statistical analysis (average, mean, ignore outliers, etc.) of numerical ratings to determine the certifiable / not certifiable determination are not to be done. This document requires a consensus of the evaluation pilots concerning the binary determination of certifiability. If it is deemed not certifiable, then comments are required to explain why it is not certifiable. If it is deemed certifiable, then comments are not expected. The intent is not to prohibit the use of the full Cooper Harper scale or any other scale as a tool to arrive at a binary certifiable / not certifiable determination. However, the certification report should not contain the CHR; it should only contain the binary certification conclusion and comments to explain why it is not certifiable according to the rule if that is the case.

In practice, the only use for the modified CHR below is to try to equate the CHR phrases “moderate compensation”, “considerable compensation”, “extensive compensation”, “maximum tolerable compensation”, etc. with the FAA words “exceptional pilot skill”. It may be worth noting that none of these phrases is precisely defined.



		Effect on meeting the rule
Excellent, highly desirable	Pilot compensation not a factor for required performance	CLEARLY MEETS THE RULE
Good, negligible deficiencies	Pilot compensation not a factor for required performance	
Fair – Some mildly unpleasant deficiencies	Minimal pilot compensation required for required performance	
Minor but annoying deficiencies	Required performance requires moderate pilot compensation	
Moderately objectionable deficiencies	Required performance attainable with considerable pilot compensation	MAY OR MAY NOT MEET THE RULE
Very objectionable but tolerable deficiencies	Required performance attainable with extensive pilot compensation	
Major deficiencies	Required performance not attainable with maximum tolerable compensation Controllability not in question	NORMALLY WOULD NOT MEET THE RULE
Major deficiencies	Considerable pilot compensation is required for control	
Major deficiencies	Intense pilot compensation is required to retain control	
Major deficiencies	Control will be lost during some portion of the required operation	

Evaluations to be conducted using specific tasks (MTEs) while maintaining the required performance tolerances for that task. Allowable performance tolerances identified in MTE.

Figure 2: Cooper-Harper logic path with edits to align with certification.

To illustrate why the actual numerical values are not important, and why statistical methods should not be used to determine the conclusion and why it is important to comment when the criteria is not met, the following two scenarios are offered.

In this example, the Level Flight Maximum Acceleration in Autopilot Mode MTE can have the same evaluation results from each pilot in two scenarios, but different outcomes as seen in Table 1.

Table 1. Evaluation scenarios

Pilot #1	Pilot #2	Pilot #3	Pilot #4
Low pilot workload, ± 50 ft alt	Exceptional pilot skill not required performance requirements met	No pilot compensation required, ± 50 ft alt	No pilot compensation required. Aircraft suddenly dove 150 ft but recovered.

Scenario 1: The pilots convene and discuss the results. It is discovered that the fourth pilot flew in conditions that allowed for a slightly faster acceleration rate, which required more control deflection. The control saturated, momentarily causing the altitude deviation. The result is the aircraft is NOT certifiable.

Scenario 2: The pilots convene and discuss the results. It is determined that during the fourth pilot's flight, there was a large aircraft in the test area, and it was likely the deviation occurred due to flying through its wake. The result is the aircraft is certifiable.

Note that a vote was not taken; no average of numerical scores was done, nor was the outlier evaluation discounted. The result was the discovery of a design deficiency in the first case and turbulence that caused a deviation in the second. **The test results were the same, but the conclusion was different.**

A similar discussion should occur if the aircraft does not meet a performance requirement, but it is determined that this is because an intentional protection limited the performance and in doing so prevented the aircraft from entering a risky flight condition. In this case, the evaluators may conclude that the aircraft is certifiable despite the fact that it did not meet the required performance.

While they may help a pilot determine whether exceptional pilot skill was required, use of HQ rating scales do not determine certifiability – the FAA rule does. In the absence of an accepted Special Condition, Equivalent Level of Safety Finding or the like that specifically allows the rating scale to be used in lieu of the rule, any use of a rating scales would support the rule, not replace it.

It is stressed that for the purpose of certification, the evaluation pilot must determine if the aircraft meets the requirements of the rule (exceptional piloting skill, alertness, or strength within the operating envelope per §23.2135 or excessive concentration, skill, alertness, or fatigue per §23.2600), not whether or not a HQ level is met. However, as discussed, some authors of this report believe that using the CHR process may aid in the determination.

2.3 Use of CHR for evaluations with failures (§23.2510)

§23.2510 states:

Equipment, systems, and installations.
For any airplane system or equipment whose failure or abnormal operation has not been specifically addressed by another requirement in this part, the applicant must design and install each system and equipment, such that there is a logical and acceptable inverse relationship between the average probability and the severity of failure conditions to the extent that:
(a) Each catastrophic failure condition is extremely improbable;
(b) Each hazardous failure condition is extremely remote; and
(c) Each major failure condition is remote.

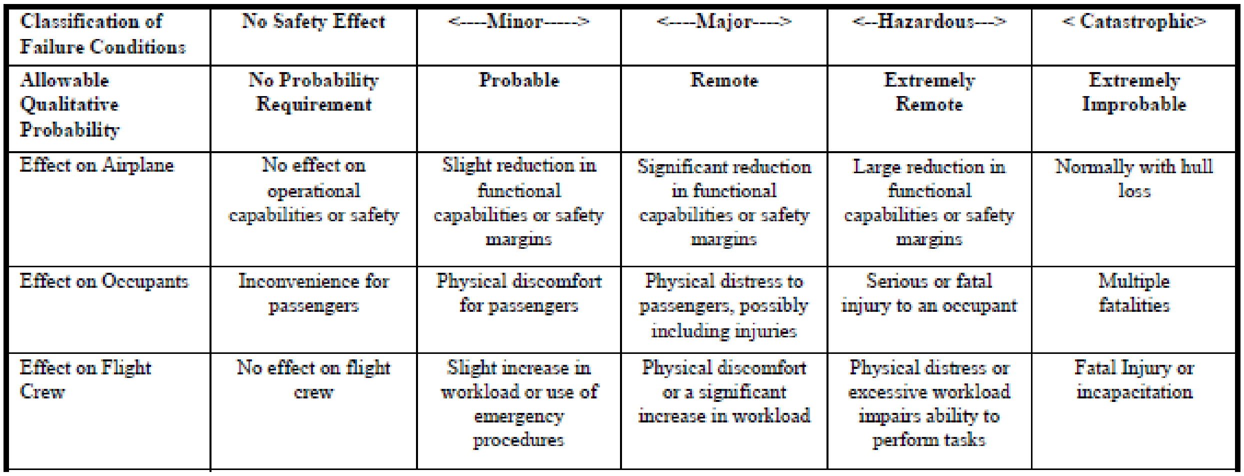
AC 23.1309 (2011) has been used as the guide to define safety as it relates to the certification and performance level of the airplane. This AC describes various hazard levels and assigns required design assurance levels to the various hazard levels for different aircraft certification levels. During the design of the aircraft, hazard levels are assigned to potential failures and these assignments are described in a Failure Modes and Effects Analysis report. Part of the determination of a hazard level is the effect on the flight crew and their workload. For some failures, flight tests are conducted to verify that the hazard level assigned by the Failure Modes and Effects report is appropriate.

The Failure Modes and Effects Analysis will determine which flight tests are required. Therefore, each failure, or combination of failures, has no effect, a HQ effect, a performance effect, or a combination of HQ and performance effects. The severity of the effect(s) determines the hazard classification of that failure or combination of failures. The hazard classification (Table 2), along with aircraft characteristics and intended operations, determines the required design assurance level for that failure or combination of failures.

Failures with a hazard classification of no effect do not need to be flight-tested. Failures with a hazard classification of minor may or may not be tested at the discretion of the evaluation pilots. Failures with a classification of catastrophic are not tested. Major and hazardous failures may be tested. If the test crew determines a test with a failure is too risky to perform, then that failure is considered catastrophic. In that case, an applicant must show compliance through design assurance instead of testing.

For operations with failures, a table in AC 23.1309E maps the effect of a failure on the crew, the occupants, and aircraft performance to the various hazard levels. A part of this table is provided in Table 2 below. Critical mission task maneuvers will be evaluated with simulated failures in the same way that they are evaluated for normal operations. Operations with failures are not expected to meet the performance level required for certification. Instead, the results of the evaluations will determine the appropriate hazard level.

Table 2. Failure classification table from AC 23.1309-1E



Classification of Failure Conditions	No Safety Effect	<----Minor----->	<----Major---->	<--Hazardous--->	< Catastrophic>
Allowable Qualitative Probability	No Probability Requirement	Probable	Remote	Extremely Remote	Extremely Improbable
Effect on Airplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants	Inconvenience for passengers	Physical discomfort for passengers	Physical distress to passengers, possibly including injuries	Serious or fatal injury to an occupant	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload or use of emergency procedures	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatal Injury or incapacitation

For the purpose of this document, the Table 3 maps the AC 23.1309E table effect to a CHR and description. However, the descriptions from AC23.1309E should be used for determining the hazard level – not the CHR. The Cooper Harper rating and description is included to illustrate a potential correlation between the two.

For the purpose of using Cooper Harper to determine an appropriate hazard level, desired performance as referenced by Cooper Harper is considered to be that specified in the evaluation as the required performance level (usually the performance level required for an Air Transport Pilot (ATP) check ride). Adequate performance as referenced by Cooper Harper is considered to be any lesser level of performance that is safe, and such that successful completion of the task and the flight is never in question.

Note that there is overlap of the CHR for hazard levels and the CHR for certification of normal operations. In fact, using the CHR ratings alone could lead to the conclusion that a failure condition that results in a hazard classification of Major could be certified as normal operations. This emphasizes the need to apply the wording of the §23.2135/§23.2600 and AC23.1309 as opposed to relying on CHR to make a determination. Also note that the required performance when using CHR as an aid for certification is different than the allowed performance when using CHR as an aid in determining a hazard level. For the purpose of normal operation, the required performance as specified in the MTEs is required. For failure evaluations, the required performance level is reduced to that which indicates safe operation, and the successful completion of the maneuver is not in doubt.

Table 3: AC 23.1309E table 2 mapping to CHR rating.

AC 23.1309E effect on flight crew or aircraft performance	**AC 23.1309E hazard level**	**Similar Cooper Harper rating**
No effect on the flight crew No effect on functional capabilities or safety margins	No safety Effect	4 - Minor but annoying deficiencies. Desired (Required) performance requires moderate pilot compensation.
Slight increase in workload or use of emergency procedures Slight reduction in functional capabilities or safety margins	Minor	5 – Moderately objectionable deficiencies. Adequate performance requires considerable pilot compensation.
Physical discomfort or significant increase in workload Significant reduction in functional capabilities or safety margins	Major	6 - Very objectionable but tolerable deficiencies. Adequate performance requires extensive pilot compensation.
Physical distress or extensive workload impairs ability to perform tasks Large reduction in functional capabilities or safety margins	Hazardous	8 - Major deficiencies. Considerable pilot compensation is required for control.

AC 23.1309E effect on flight crew or aircraft performance	**AC 23.1309E hazard level**	**Similar Cooper Harper rating**
Fatal Injury or incapacitation Normally with hull loss	Catastrophic	9 - Major deficiencies. Considerable pilot compensation is required for control.

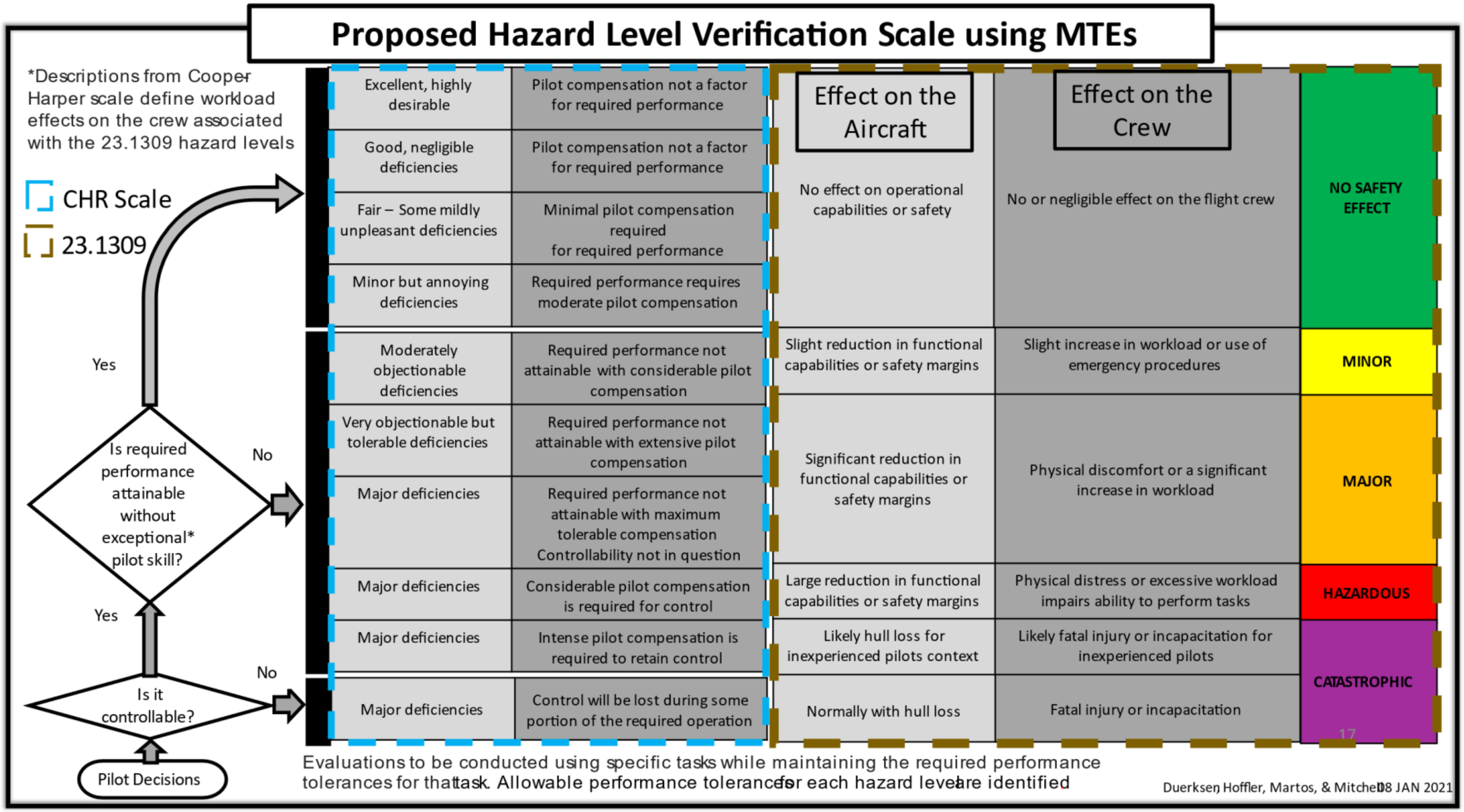
Note: The catastrophic category includes deficiencies for which inexperienced pilots may be expected to lose control – not just evaluation pilots. In addition, failures in the catastrophic category need not be flight-tested. If the evaluation pilot determines that a failure condition is too risky to flight test, then that failure condition is considered catastrophic, and the aircraft must meet the probability requirements of catastrophic through design assurance for that condition for the aircraft to be certified.

Figure 3 depicts the potential scale for hazard classification verification using the CHR scale logic and its approximate AC 23-1309 equivalent. Required performance for hazard classification is safe operation and that successful completion of the maneuver was not in doubt.

Note that the initial descision is based on the wording of the rule and long established guidance, not a Cooper Harper rating.

The Cooper Harper rating terminology as applied in this document (Figure 3) is intended to support the established guidance of AC 23-1309E – not replace it.

The MTE 2510 Failures section at the end of the MTEs (sub-sections of Section 3.4) describes the flight tests in more detail.



Proposed Hazard Level Verification Scale using MTEs

*Descriptions from Cooper-Harper scale define workload effects on the crew associated with the 23.1309 hazard levels

		Effect on the Aircraft	Effect on the Crew	
Excellent, highly desirable	Pilot compensation not a factor for required performance	No effect on operational capabilities or safety	No or negligible effect on the flight crew	NO SAFETY EFFECT
Good, negligible deficiencies	Pilot compensation not a factor for required performance			
Fair – Some mildly unpleasant deficiencies	Minimal pilot compensation required for required performance			
Minor but annoying deficiencies	Required performance requires moderate pilot compensation			
Moderately objectionable deficiencies	Required performance not attainable with considerable pilot compensation	Slight reduction in functional capabilities or safety margins	Slight increase in workload or use of emergency procedures	MINOR
Very objectionable but tolerable deficiencies	Required performance not attainable with extensive pilot compensation	Significant reduction in functional capabilities or safety margins	Physical discomfort or a significant increase in workload	MAJOR
Major deficiencies	Required performance not attainable with maximum tolerable compensation Controllability not in question			
Major deficiencies	Considerable pilot compensation is required for control	Large reduction in functional capabilities or safety margins	Physical distress or excessive workload impairs ability to perform tasks	HAZARDOUS
Major deficiencies	Intense pilot compensation is required to retain control	Likely hull loss for inexperienced pilots context	Likely fatal injury or incapacitation for inexperienced pilots	CATASTROPHIC
Major deficiencies	Control will be lost during some portion of the required operation	Normally with hull loss	Fatal injury or incapacitation	

Evaluations to be conducted using specific tasks while maintaining the required performance tolerances for that task. Allowable performance tolerances for each hazard level are identified

Duerksen, Hoffler, Martos, & Mitchell 08 JAN 2021

Figure 3: Cooper Harper Scale logic mapped to AC 23.1309E hazard categories

3 Recommended changes to selected Part 23 rules and means of compliance for FBW aircraft with unconventional controls including VTOL

This section is intended to stand on its own as a set of recommended changes to the rules for FBW Part 23 aircraft including aircraft with vertical takeoff and landing capability and non-traditional flight controls. It includes a proposed means of compliance to those Special Conditions and includes explanations concerning the rationale behind the Special Conditions. FAA discussion and approval is needed for their use.

3.1 Introduction

The original task for this document was to produce proposed MTEs or HQTEs that use the CHR scale as a MOC to Amendment 64 of Part 23 as modified by the proposed Special Conditions developed by the FAA Future Aircraft Safety Team (FAST). These MTEs were to follow the form and approach used in ADS-33E-PRF (ADS-33E-PRF, 2000).

While developing the MOCs it became clear that neither the Part 23 Amendment 64 rules nor the FAST proposed Special Conditions apply well to many of the functions and features being incorporated into the current eVTOL designs. Therefore, to develop a set of MOCs for Part 23 Amendment 64, a different set of Special Conditions was required. This chapter contains recommended changes for Part 23 aircraft with FBW controls that do not mimic mechanical control systems, including VTOL (vertical takeoff and landing) aircraft.

In developing the proposed recommended changes to part 23, it also became clear that for the proposed recommendations to be useful, proposed means of compliance to the proposed recommended changes was required. Therefore, this chapter also includes proposed means of compliance to the recommended changes.

This chapter is organized in the general order of the affected Part 23 rules. Each section identifies the affected rule(s), discusses the deficiencies in the rule(s) along with the proposed FAST Special Condition, and proposes a recommended change that embodies the intent of the Part 23 rule written in a general form that can be applied to a wide range of aircraft configurations, control strategies, and performance capabilities (including high altitude transonic and VTOL).

In some cases, related rules are grouped together such that the numerical order is not strictly followed. This allows for a smoother flow of the discussion sections when multiple rules are affected by the same concept. For example, the stall speed and stall characteristics rules are two separate rules that are not sequential but, in this document, a single recommended change is proposed to replace both rules.

To retain historical consistency, the proposed set of changes is in a form similar to the Special Conditions typically used for FBW Part 25 aircraft. This document also adds a discussion section for each proposed change to explain why it was proposed and then goes on to propose a MOC to that rule change in a form similar to AC 23-8C (2011). It also includes guidelines for flight test procedures for that MOC.

The original intent was to use ADS-33E-PRF (Handling Qualities Requirements for Military Rotorcraft) to create MTEs which would then be evaluated using the CHRs. Evaluations of aircraft using ADS-33 MTEs and CHR has a long and successful history for military helicopters. However, the mission for military helicopters is significantly different from the mission for air taxis intended for the public. While the MTEs from ADS-33 may represent realistic maneuvering requirements for military helicopters, many are not necessary for civilian air taxis. Some maneuvers, pirouettes for example, may not be possible because the eVTOL aircraft have insufficient cooling for sustained hover times, and sustained hover is not part of their missions. An approach to using CHRs to help a pilot determine whether “excessive pilot skill, strength, alertness, concentration, or fatigue” is required is provided in Section 2. The concept of ADS-33 has been retained and the use of CHR is discussed in this document. The maneuvers specified in ADS-33 and the implementation of CHR has been modified in an attempt to fit the Part 23 certification requirements. This is discussed in detail in the §23.2135 / §23.2600 section where these concepts are used.

The Part 23 amendment 64 rules that this document addresses are

▪	§23.2110, §23.2150	Stall Speed and Characteristics
▪	§23. 2115, §23.2120, §23.2125	Takeoff and Climb Performance
▪	§23.2130	Landing
▪	§23.2135, §23.2600, §23.2500	Controllability, Crew Interface and Reliability
▪	§23.2140	Trim
▪	§32.2145	Stability

The elements of this set of proposed changes along with their proposed MOC are inter-related and, in many cases, depend on each other for complete coverage of the safety intent embodied in

Part 23 rules. Therefore, they cannot be used piecemeal without careful consideration of the other elements in this set to ensure that all safety aspects are accounted for. For example, it does not make sense to apply the recommended change for stall characteristics in this document without also applying the recommended change for stability in this document because they are inter-related. (Unlike how Part 23 separates stall characteristics and stability.)

The MTEs were developed by breaking the transportation mission down to each phase: pre-flight, startup, taxi, takeoff, climb, cruise, descent, landing, shutdown, and postflight. Failure modes, emergency descents, and evasive maneuvers were also addressed, as they are necessary parts of transportation missions. The concept is that evaluating all the MTEs (breaking down the transportation mission) would result in satisfying the certification rules they address.

Note that the MTEs do not provide specific airspeeds, altitudes, climb/descent rates, etc. for each task element. It is important that the certification team know and understand the vehicle and assure the maneuvers are done in the most critical portion of the flight envelope and done at and around points where configuration and command mapping are changing. This is common practice in existing Part 25 FBW certification programs.

MTEs in this report include maneuvers that would be part of a transportation mission, including emergency maneuvers, and nothing else. However, one of the MTEs is open to other maneuvers the FAA may require or an applicant may want to do. The same procedures would be followed to assess additional maneuvers and meet the maneuver requirements. For example, an aircraft that will do missions beyond transportation, such as crop dusting, would require development and evaluation of additional maneuvers.

3.1.1 Application for VTOL aircraft

Although Part 23 does not cover aircraft with vertical flight capability, these recommended changes are intended to extend Part 23 to include VTOL capability. These recommended changes are intended to merge the safety intent of Part 23 and Part 27 into a single set of requirements in a performance-based form. These recommended changes are written to apply to aircraft that behave fully as an airplane, fully as a helicopter, or aircraft that can transition to either one. However, some VTOL designs may be only intended to use the VTOL capability as a transient condition for takeoff and landing, and are not intended to hover. Two potential examples of this are described below.

1. A battery-powered aircraft with rotors, wings, and wheels has very short endurance. Hovering requires much more power than wing borne flight and hovering time significantly reduces the aircraft's range. Because of this, for practical purposes, the aircraft only hovers for a few seconds as a transient condition for takeoff and landing.
2. An aircraft with rotors, wings, and wheels has an Aircraft Flight Manual (AFM) limitation on hovering time of a few seconds because there is inadequate cooling for extended hovering (high power combined with low airflow). The VTOL capability is used only for takeoff and landing transients.

Many of the requirements in these recommended changes that apply to aircraft with VTOL capability should not be imposed on aircraft that use vertical flight capability only as a transient condition. For these aircraft, testing these requirements may cause hovering times that exceed their AFM or practical limitations. This concept has significant implications for the controllability section (§23.2135) and the stability section (§23.2145) in that many of the hovering maneuvers listed in these sections need not be conducted because they are not representative of the aircraft's practical capabilities when operated within its limitations. However, aircraft that are intended to taxi by hovering and aircraft without limitations on hovering (either practical or stated in the AFM) should comply with all hovering requirements.

3.1.2 Definition of configuration

To avoid potential confusion, the term "configuration changes" as used in this document refers to any aircraft changes that affect its operation. This includes changes in aircraft shape (landing gear, flaps, nacelle tilt, wing tilt, etc.), functional changes (lift provided by wings, rotors, thrusters, rockets, compressed gas, boundary layer blowing, etc.), control system operation (control algorithm changes, sensor changes, actuator changes, control effector changes, control modes, etc.). In essence, any change of the aircraft that can cause a change in the aircraft's operational characteristics is considered a configuration change. Some examples of configuration changes are listed below.

- Landing gear retraction or extension
- Nacelle tilt
- Flap deployment or retraction
- Changing roll control from ailerons to rotors
- Control law changes
- Changing from an air mass referenced control system to an earth referenced control system
- Changing from a vertical speed command to a flight path angle command
- Changing from “normal mode” to terrain protection
- Transition from “manual flying” to “coupled” on an approach

Identifying configuration changes for a particular aircraft is important since configuration changes can cause changes in controllability and HQ.

The airplane community has typically limited the term “configuration” to mean landing gear and flap position. However, this document refers to the general use of the term “configuration” in the English language, which is much more general and includes the concept described above.

3.1.3 General flight test considerations

A full data acquisition system with plotting capability may be used if desired. However, all of the recommended changes and suggested flight test procedures were written such that they can be done using only standard aircraft instrumentation and hand recorded data.

For some of the tests the aircraft will need to be modified so that it can simulate failures or fly outside of the normal flight envelope. For tests that require the aircraft to fly outside of the normal operating envelope, the aircraft will not be in conformity and the FAA may accept the applicant’s data.

The applicant must provide the FAA with the most adverse combination of weight and center of gravity (CG) for each flight test. The tests will be conducted at the most critical combination of weight, CG, and at critical battery states that reduce power available but are within AFM constraints.

3.2 §23.2110 / §23.2150 stall speed, warning and characteristics

Part 23 as written:

§23.2110 Stall Speed

The applicant must determine the airplane stall speed or the minimum steady flight speed for each flight configuration used in normal operations, including takeoff, climb, cruise, descent, approach, and landing. The stall speed or minimum steady flight speed determination must account for the most adverse conditions for each flight configuration with power set at—

(a) Idle or zero thrust for propulsion systems that are used primarily for thrust; and

(b) A nominal thrust for propulsion systems that are used for thrust, flight control, and/or high-lift systems.

§23.2150 Stall characteristics, stall warning, and spins

(a) The airplane must have controllable stall characteristics in straight flight, turning flight, and accelerated turning flight with a clear and distinctive stall warning that provides sufficient margin to prevent inadvertent stalling.

(b) Single-engine airplanes, not certified for aerobatics, must not have a tendency to inadvertently depart controlled flight.

(c) Levels 1 and 2 multiengine airplanes, not certified for aerobatics, must not have a tendency to inadvertently depart controlled flight from thrust asymmetry after a critical loss of thrust.

(d) Airplanes certified for aerobatics that include spins must have controllable stall characteristics and the ability to recover within one and one-half additional turns after initiation of the first control action from any point in a spin, not exceeding six turns or any greater number of turns for which certification is requested, while remaining within the operating limitations of the airplane.

(e) Spin characteristics in airplanes certified for aerobatics that includes spins must recover without exceeding limitations and may not result in unrecoverable spins—.

1. With any typical use of the flight or engine power controls; or
2. Due to pilot disorientation or incapacitation.

The FAA FAST has proposed the following Special Conditions:

(From the FAAST GAMA document. Underlined text indicates FAST changes.)

SC.2110 Minimum safe speed.

The applicant must determine the airplane minimum safe speed for each flight configuration used in normal operations, including applicable modes and phases of flight. The minimum safe speed determination must account for the most adverse conditions for each flight configuration.

SC.2150 Minimum safe speed flight characteristics, minimum safe speed warning, and spins.

(a) The airplane must have controllable minimum safe speed flight characteristics in straight flight, turning flight, and accelerated turning flight with a clear and distinctive minimum safe speed warning that provides sufficient margin to prevent inadvertent stalling, if applicable.
(b) Single-engine airplanes, not certified for aerobatics, must not have a tendency to inadvertently depart controlled flight.
(c) Levels 1 and 2 multiengine airplanes, not certified for aerobatics, must not have a tendency to inadvertently depart controlled flight from thrust asymmetry after a critical loss of thrust.
(d) Airplanes certified for aerobatics that include spins must have controllable stall characteristics and the ability to recover within one and one-half additional turns after initiation of the first control action from any point in a spin, not exceeding six turns or any greater number of turns for which certification is requested, while remaining within the operating limitations of the airplane.
(e) Spin characteristics in airplanes certified for aerobatics that includes spins must recover without exceeding limitations and may not result in unrecoverable spins—
  (1) With any typical use of the flight or engine power controls; or Due to pilot disorientation or incapacitation.

3.2.1 Stall definition from §23.201 and §23.2110 along with minimum safe speed from FAST

§23.201(b) and AC 23-8C define stall as

1) Uncontrollable downward pitching motion;
2) Downward pitching motion resulting from the activation of a device (for example, stick pusher); or
3) The control reaches the stop.

There are no rules that prohibit an aircraft from flying below stall speed. But the definition of stall and the physics of flight make it impossible to fly below stall speed in normal flight.

§23.2150 replaced §23.201 in amendment 64 but kept the term stall (and with it the definition of a stall). With the amendment 64 rules, there is either a natural or artificial barrier to flying more than a few knots below stall speed (definition of a stall). When an artificial barrier is used, it is usually to prevent the aircraft from slowing to the natural stall speed – in essence, the stall speed is artificially increased to prevent flying at slower speeds by providing a barrier to flying slower. Stall characteristics are tested at stall speed (natural or artificial) but no slower. §23.2110 also refers to the minimum steady flight speed. This is really the same as the stall definition as the control reaching the stop. With either an aerodynamic stall or a control limited flight speed, as the pilot moves the stick aft there comes a point where the aircraft pitches down despite the stick position. In all cases, the result is that the aircraft experiences an uncontrollable downward pitching motion. The amendment 64 and prior rules do not prevent stalls. Stalls have been one of the leading causes of loss of control accidents.

The Special Conditions proposed by the FAST replaced the word "stall" with the words "minimum safe flight speed". Since the words "minimum safe flight speed" do not imply a barrier, this wording change removes the requirement for a barrier and replaces it with a requirement for the applicant to establish a minimum safe flight speed, provide a warning when that speed is approached, and show that the aircraft is controllable at this minimum safe flight speed. There is no requirement that the aircraft be controllable below this speed nor that the aircraft be prevented from flying below this speed (enforced by a natural or artificial barrier). There is nothing to prevent the pilot from flying below the "minimum safe flight speed", unlike the stall speed, which has a natural or artificial barrier to flying slower than stall speed.

In essence, the FAST proposal removes the requirement for a barrier and replaces it with an aircraft limitation for the pilot to observe. That limitation is a minimum safe flight speed. Since it is a limitation, the minimum safe flight speed is embodied as a marking on the airspeed indicator, a placard in the cockpit and a printed message in the Airplane Flight Manual not to fly slower than this speed. It does not provide a barrier to flight at speeds below the minimum safe flight speed. The regulations do not require any level of handling characteristics below the minimum safe flight speed. Thus, the aircraft may have dangerously unacceptable HQ at speeds below the minimum safe flight speed and there is no required barrier preventing the pilot from inadvertently flying below the minimum safe flight speed.

The concept of a "maximum safe flight speed" without a barrier exists on aircraft today, but in conjunction with the maximum safe flight speed (V_{ne}, V_{mo}, or M_{mo}), there are requirements to demonstrate stability at speeds above the maximum safe flight speed (e.g., V_{fc}), and then further demonstrate the ability to control the aircraft and recover at speeds even higher (e.g., V_d).

FAA policy and guidance define the physics of a stall as separated flow over the wing and define the stall using aircraft response as an uncommanded nose down pitch. The aircraft response definition requires that the aircraft motion becomes opposite of the pilot commanded aircraft motion. Fundamentally, from the pilot's perspective, a stall is a condition in which the aircraft moves opposite the commanded direction (up is commanded but the aircraft goes down). Many modern FBW do not allow the aircraft to stall. In addition, the concept of stall can get very confusing when there is a combination of wing lift and rotor lift. Many regulations are based on stall speed. Since stall speed is integral to so many other regulations, an alternate definition of a speed that can be used instead of stall speed is required. This recommended change addresses this for FBW aircraft including VTOL aircraft that prevent a stall. It also defines accompanying low speed protections, characteristics, and awareness/warning.

FBW aircraft are well suited for preventing stalls. Therefore, it is suggested that for FBW aircraft the following recommended changes be applied instead of §23.2110 and §23.2150.

3.2.2 Recommended changes to §23.2110 and §23.2150

The contractors recommend the following changes to §23.2110 and §23.2150.

The following is added to the Amendment 64 version of §23.2110.

(c) For FBW aircraft the following apply instead of (a) and (b)
  (1) A minimum achievable speed must be determined for each configuration. The minimum achievable speed is the minimum speed at which the aircraft can maintain level flight.
  (2) For configurations that rely on free stream velocity for all or part of their lift, V_{ref} will be 1.3 times the minimum achievable speed unless V_{ref} is greater than 100 kt., for these aircraft V_{ref} may be 1.23 times the minimum achievable speed.
  (3) For aircraft in which the pilot commands airspeed (does not have direct control of power or thrust), the minimum commandable airspeed when not less than 50' above ground level (AGL) during takeoff or landing is V_{ref} for that configuration.
  (4) For aircraft in which the pilot has direct control of power or thrust, (does not command airspeed), the minimum allowed speed when not less than 50' AGL during takeoff or landing is V_{ref} for that configuration.
  (5) The aircraft may fly slower than V_{ref} at climb power if V_x is slower than V_{ref}. However, aircraft configured to rely on free stream velocity for all or part of their lift may not be allowed to fly slower than V_x (speed for best angle of climb). V_x must consider maneuver margin and gusts. V_x for the purpose of this regulation may be faster than the aerodynamic V_x.

§23.2150 is replaced with the following:

§23.2150 Stall characteristics, stall warning, spins, and upsets

(a) The aircraft must not have reversals or discontinuities of aircraft vertical motion relative to the commanded vertical motion during normal operations.

(i) For FBW aircraft that mimic mechanical controls, pitch attitude can be considered to be the vertical motion command during landing flare.

(b) The aircraft must not experience control reversals or control discontinuities due to gusts of 10 kt. for less than 1 second from any direction. Transient response to the gust is expected.

(c) For severe turbulence induced upsets, the aircraft shall return to controlled flight within the normal flight envelope without pilot action within 5 seconds after the turbulence has subsided for a bank upset and 10 seconds for a pitch upset.

(d) Failure to maintain continued controlled flight after a failure in continuous turbulence of 20 kt. gusts from any direction is considered catastrophic.

(e) Aircraft capable of vertical flight must be designed to prevent settling with power such that maximum available power does not produce less than 0.2 G of upward acceleration in any flight condition other than climbing.

(f) There must be an indication to the pilot when the minimum commandable speed has been commanded. There must also be an indication to the pilot that the minimum commandable speed is being approached or has been crossed due to a vertical path command.

3.2.2.1 Definitions of low-speed terms

The recommended change identifies five speeds. Their definitions are as follows. See the discussion section for examples of how these speeds are applied to various configurations.

Minimum Achievable Speed

The minimum achievable speed is the slowest speed at which the aircraft can maintain steady straight and level flight. This speed is used like stall speed for regulations that reference stall speed. The aircraft cannot get to this speed in normal operations (unless this speed is zero).

Minimum Allowable Speed

The minimum allowable speed is the slowest speed that the flight control system will allow except during takeoff and landing transients. This is typically V_x (best angle of climb speed).

This speed can only be reached with maximum thrust (except during landing flare). Maneuver margins and resistance to departure from controlled flight due to turbulence must be demonstrated at this speed. For most existing Part 23 aircraft, the minimum allowable speed will be V_x (best angle of climb speed) except during ground operations, and takeoff and landing of VTOL capable vehicles.

For high altitude aircraft, the applicant may desire to set the minimum allowable speed to limit the speed to no lower than maximum L/D speed (V_y) at high altitude to ensure that the airplane does not get on the back side of the power curve during a zoom climb and become unable to maintain level flight.

Minimum Commandable Speed

The minimum commandable speed if the minimum speed that the pilot can command. The flight controls may allow the aircraft to slow to less than the minimum commandable speed during maximum power operations (climbs). The minimum commandable speed is normally V_{ref} (landing approach speed). The minimum commandable airspeed will be zero or backwards for configurations in which hovering is possible.

Below the minimum commandable speed, the control system will automatically provide thrust to prevent flying slower than this speed. The minimum commandable speed cannot be lower than the minimum allowable speed.

Minimum Flight Speed

The minimum flight speed is the minimum commandable or allowable speed as appropriate for the flight condition. (The minimum flight speed is the minimum allowable when at maximum climb thrust or more, and minimum commandable when not at maximum climb thrust or more.)

Low-Speed Warning Speed

The low speed warning speed is a speed 5 – 10 kt above the minimum achievable speed that triggers a warning that the minimum achievable speed is being approached. This speed cannot be obtained in normal flight. Activation of this warning indicates that a failure has occurred, and that the aircraft is getting dangerously slow. This speed is similar to stall warning speed for a conventional airplane.

The applicant must provide a minimum achievable airspeed for each configuration. At the option of the applicant, this speed may be higher than the actual minimum achievable airspeed. The minimum achievable airspeed will be zero for configurations in which hovering is possible in which case a low-speed warning is not required. The low-speed warning airspeed, minimum allowable airspeed, and minimum commandable airspeed will be determined from the minimum achievable airspeed.

3.2.3 Discussion for §23.2110 / §23.2150

These recommendations are not intended to be applied to aircraft certified for aerobatics.

Part 23 rules were intended to cover conventional mechanically controlled airplanes and FBW aircraft with controls that mimic mechanical control systems. As such, they allow the airplane to stall as long as there is adequate warning and the aircraft remains controllable through a stall – even if the airplane's response to the controls is opposite of the controls (e.g., command the airplane to climb but it descends instead) as long as there is a reliable recovery technique. This is normal operation for mechanically controlled airplanes. However, stalls are one of the main causes of loss of control accidents for these airplanes.

FBW aircraft have the capability to prevent a stall and preserve the concept that the aircraft motion will always match the pilot command. The pass criteria of this recommended change require this concept be preserved for all operations. It assumes that for configurations that use free stream velocity for a significant part of their lift, there is a minimum allowable speed for that configuration. It also assumes that this minimum allowable speed provides sufficient maneuver margin, such that normal maneuvering and turbulence will not cause the aircraft motion to depart from the commanded motion. (A stall typically causes an airplane motion to depart from the commanded motion – pull back on the stick, which normally commands the airplane to climb but the airplane stalls and descends instead).

§23.2150 considers low-speed handling characteristics including spins and failures of the propulsion system that are not considered catastrophic. This recommended change meets the intent of §23.2150 with its requirements related to upsets and failures.

If credit is taken for automated configuration changes, failures of the automated configuration system need to be considered. See the failure part of the §23.2135 / §23.2600 (controllability) section.

The stability recommended changes (§23.2145) combined with the controllability recommended changes (§23.2135) require tests over the entire speed range of a configuration including at the minimum commandable and minimum allowable speeds. Therefore, tests for these recommended changes may be combined with the recommended change for §23.2150 (stall characteristics, stall warning spins, and upsets). There is considerable overlap between these recommended changes.

The low-speed stability test conditions are duplicated here for completeness. Note that the flight characteristics requirements do not extend down to the minimum achievable speed since it is outside the normal operating envelope of the aircraft.

3.2.4 Means of compliance for recommended changes to §23.2110 / §23.2150

3.2.4.1 Verifying the minimum achievable airspeed

The applicant is expected to provide the minimum achievable airspeed for each configuration. This recommended change is intended to verify that the minimum achievable airspeed that is provided by the applicant is equal to or higher than the actual minimum achievable airspeed.

The minimum achievable airspeed is verified by modifying the aircraft for test purposes so that it can fly at speeds below the minimum commandable speed and below the minimum allowable speed while maintaining level flight. Because the aircraft must be modified to demonstrate the minimum achievable speed, and therefore is out of conformity for these tests, the FAA may elect to accept company data in lieu of conducting these tests.

For altitudes above the highest altitude for which takeoffs or landings are approved, the minimum achievable flight speed need not be determined or demonstrated, however the minimum commandable, minimum allowable and low speed warning speeds must be established. Maneuver margins and recovery characteristics apply at the minimum allowable and minimum commandable speeds, and the aircraft must be controllable and easily recoverable at the low-speed warning speed.

If an aircraft automatically changes configurations as it slows, and if the configuration changes are fast enough such that the aircraft can never fly at a speed where it is in danger of experiencing an aircraft motion / command decoupling due to aerodynamic flow separation in both normal and emergency operations, then the minimum achievable speed for configurations other than the configuration that supports the lowest speed need not be verified. However, for these aircraft, the minimum flight speed (minimum commandable speed and minimum allowable speed) tests must still be conducted for each configuration.

The hazard classification of a failure of the automatic configuration system combined with the probability of such a failure may require the minimum achievable tests and associated airspeed markings for a configuration during the failed condition even if the aircraft would not require them in normal operations.

3.2.4.2 Low speed warning

There must be an aural or tactile warning when the aircraft is slower than 5 to 10 knots above the minimum achievable speed. This warning must not occur during normal flight. It indicates a failure of the low-speed protection systems combined with a flight condition that may present dangerous handling characteristics. The aircraft must be controllable at this speed and must demonstrate that it can be recovered back to above the minimum allowable speed with minimal pilot skill (typically only reducing the commanded climb rate).

The low-speed warning need not be provided for configurations and flight conditions with a minimum achievable speed of less than 10 kt.

3.2.4.3 Low speed airspeed markings

FBW aircraft that use this recommended change and have a minimum achievable speed greater than zero in at least one configuration, and for which the pilot does not command speed directly shall have an airspeed indicator that shows airspeed trend (a moving needle or tape satisfies this requirement). The airspeed indicator shall have markings that clearly indicate the minimum commandable speed, minimum allowable speed and maneuver margin. See the example below of one implementation of airspeed markings that is considered acceptable.

For aircraft for which the pilot commands speed directly, there must be an indication when the aircraft is at or approaching the minimum commandable airspeed and the minimum allowable airspeed.

3.2.4.4 Required information and configuration

Before the test procedure, the applicant will define

3. weight and CG range for allowed operations
4. allowed aircraft configurations
5. the weight and CG location for each test condition that provides the fastest minimum achievable speed
6. the weight and CG location for each test condition that provides the least stability or controllability at the minimum achievable speed

3.2.4.5 Data collection

For the flight tests, record the configuration, flight condition and at least the

1. minimum airspeed.
2. speed at which the low-speed warning turns on and turns off.

3. flight characteristics and maneuver conducted along with the maximum bank angle, sideslip angle or lateral velocity, or altitude or speed variation as appropriate for the test.
4. any conditions where the aircraft motion did not follow the commanded aircraft motion.

3.2.4.6 Pass criteria

During the minimum achievable speed demonstration, the aircraft must maintain

1. level flight within +/- 50 ft.
2. bank angle within +/- 5 degrees.
3. heading within 5 degrees.
4. For configurations that cannot hover, a warning must start 5-10 kt faster than the minimum achievable speed and stop the warning 5-10 kt faster than the minimum achievable speed.
5. The low-speed warning must not occur during normal operations. (The low-speed warning may occur briefly during turbulence and upset recoveries.)

During the flight characteristics at minimum flight speed tests, the aircraft shall (note this is the same criteria as for the stability recommended changes)

1. provide initial motion in the direction of the command.
2. provide the initial response within 200 ms of the command.
3. not reverse direction until passing the command.
4. not exhibit delays between the command and the response such that it may induce pilot induced oscillations – particularly for novice pilots.
5. not exhibit oscillations that increase pilot workload. For pitch roll and yaw attitude, oscillations shall damp to less than 1/10th amplitude in less than three cycles. For vertical and longitudinal speed, oscillations shall not be divergent and shall have a period of more than 10 seconds
6. not exhibit any movement that is not negligible in the direction opposite of the command.
7. not exhibit residual oscillations that negatively affect pilot performance. Residual oscillations greater than 0.5 degrees or 0.05 Gs at the pilot station are considered excessive (ref ADS-33E-PRF para 3.1.17).

8. produce at least 0.2 G relative (1.2 G absolute) in the up direction during the maximum rate descent at the minimum commandable speed when a climb is commanded.

During the turbulence upset and recovery tests, the aircraft shall

1. Recover to within 45 degrees of bank within 5 seconds of releasing the controls and the roll control has moved past the neutral position and towards the direction of righting the aircraft.
2. Recover to within 15 degrees of level flight (either flight path or pitch attitude) within 10 seconds of releasing the controls and the vertical control has moved past the neutral position and towards the direction of righting the aircraft, or has established a G loading of at least 0.7 relative to level flight in the correct direction within one second of releasing the controls
3. Not depart controlled flight.

Compliance to the proposed recommended change§23.2150(d): Failure to maintain continued controlled flight after a failure in continued turbulence of 20 kt. gusts from any direction is considered catastrophic. Compliance to this requirement may be shown by analysis.

Compliance to the proposed recommended change§23.2150(e): The ability to prevent ground contact at descent rates allowed by the controls can be shown by analysis given the aircraft's measured allowable descent rate as a function of height and the measured available upward G level from the flight characteristics at minimum allowable speed tests. To allow for landings, the flight controls may allow ground contact when the test condition (or initial condition for analysis) is less than 5 ft above the ground. For these tests (or analyses), the aircraft may contact the ground at no more than the applicant's stated maximum normal landing descent rate (typically about 300 ft per min). Maximum descent rate during vertical or nearly vertical descent is limited by the vortex ring state for rotorcraft, which is typically 300 fpm (FAA-H-8083-21B, 2019).

3.2.4.7 Summary of V_{ref}, V_x, and V_{warn}

Generally, these speeds for most cases are as follows:

- V_{ref} = 1.3 times the minimum achievable speed. This is the minimum commandable speed.
- V_x is the best angle of climb speed. This is the minimum allowable speed (achievable only at climb power and above).

- V_{warn} = minimum achievable speed plus 5 to10 knots.

For aircraft that can hover, the minimum achievable speed is zero and these speeds are all zero. They need not be displayed nor used as warnings.

See the discussion of V_{ref}, V_x, and V_{warn} section for a detailed discussion of V_{ref}, V_x, and V_{warn} including examples of choosing V_{ref}, V_x, and V_{warn} for various aircraft types.

3.2.4.8 Suggested flight test procedures for recommended change §23.2110 / §23.2150

This section discusses special aircraft modifications.

For aircraft that have automatic configuration changes as a function of airspeed, the aircraft must be modified to prevent configuration changes as the speed slows below the automatic transition speeds for configurations where the minimum achievable speed demonstration is required.

Since the minimum commandable airspeed and the minimum allowable airspeed are higher than the minimum achievable airspeed, the aircraft must be modified to allow level flight at speeds below the minimum commandable airspeed and below the minimum allowable airspeed.

For the turbulence upset tests, the aircraft may need to be modified to allow the aircraft to get to the upset conditions. For example, envelope protections that prevent the pilot from commanding a steep bank may need to be modified to allow the test pilot to command a steep bank to demonstrate that the aircraft can recover form a steep bank when upset by an external force.

3.2.4.9 Suggested test conditions for recommended changes §23.2150 / §23.2110

Minimum achievable speed demonstration

The minimum speed protections are removed for these tests. Because the aircraft must be modified for these demonstrations it will not be in conformity, therefore at the FAA’s option, properly documented company tests may be accepted in leu of FAA participation in the minimum achievable speed demonstration.

a. Test conditions

- For each configuration, the tests shall be conducted at an altitude below 5,000 ft and at the maximum practical altitude for the configuration being tested.
- For aircraft which can hover out of ground effect at some flight conditions and not at others (e.g., density altitude), a test condition at the point where the transition occurs is required (this verifies the maximum weight, altitude, temperature limit for hover out of ground effect).

- For each configuration, the minimum achievable speed shall be verified at the weight and CG location that produces the highest minimum achievable speed.
- For each configuration, the handling characteristics at the minimum achievable speed shall be verified at the weight and CG location that produces the least stability or controllability at the minimum achievable speed. Note that the pass / fail criteria at the minimum achievable speed is different from the pass / fail criteria for the minimum flight speed (minimum allowable and minimum commandable) tests.

b. Test procedure

- Start in level flight at V_{ref} for the configuration and flight condition.
- While maintaining altitude, slow to the minimum achievable speed selected by the applicant at no more than one knot per second.
- Upon reaching the minimum achievable speed, maintain that speed for at least 5 seconds.
- Accelerate to V_{ref} at no more than one knot per second while maintaining altitude.
- The intent is to demonstrate that the aircraft is capable of maintaining one G flight at the minimum achievable airspeed and is controllable approaching that speed, at that speed, and accelerating away from that speed.
- Note the speed at which the low-speed warning turns on and turns off.

<u>Flight Characteristics at the Minimum Flight Speed</u>

For these tests, the aircraft shall be configured for normal operations (the speed protections removed for the minimum achievable flight speed demonstration are in place). Thus, the aircraft cannot slow to less than the minimum flight speed (minimum allowable or minimum commandable) for that configuration.

a. Test conditions
    i. Use the same altitude and configurations that were used for demonstrating the minimum achievable speed.
    ii. For configurations not capable of hovering
        1. For each configuration and altitude, the test shall be conducted at
            a. minimum allowable speed while at maximum climb rate.
            b. minimum commandable speed while in level flight.
            c. minimum commandable speed while at the maximum descent rate.
    iii. For configurations capable of hovering

        1. For each configuration and altitude, the test shall be conducted at
            a. zero speed while at maximum climb rate.
    b. zero speed while in level flight.
    c. zero speed while at the maximum descent rate.

b. Test procedure

Start in steady state climbing, level or descending flight as appropriate.

- i. Command maximum left and right turns. Use maximum command. Turns need not command bank angles of more than 35 degrees.
    1. From the maximum climb, command the maximum left and right turns.
    2. From level flight, command the maximum left and right turns.
    3. From a maximum descent, command the maximum left and right turns.
- ii. Command maximum sideslip or lateral velocity.
    1. From the maximum climb, command the maximum left and right sideslip or lateral velocity.
    2. From level flight, command the maximum left and right sideslip or lateral velocity.
    3. From a maximum descent, command the maximum left and right sideslip or lateral velocity.
- iii. Command maximum climb and descent transitions.
    1. From the maximum climb, rapidly command a maximum decent rate.
    2. From level flight, rapidly command a maximum climb rate.
    3. From level flight, rapidly command a maximum descent rate.
    4. From a maximum descent, rapidly command a maximum climb.

Turbulence induced upset recoveries (Note: These tests are intended to demonstrate the aircraft’s ability to recover from turbulence induced upsets. They are not intended to test the aircraft’s envelope protections nor it’s command limits. It is expected that the aircraft will need to be modified for test purposes so that the test pilot can achieve the attitudes specified.)

a. Test conditions
    - i. These tests shall be conducted below 5,000 ft MSL.
    - ii. Conduct the test at cruise speed and configuration and also at approach speed and configuration.
    - iii. These tests are intended to simulate recovery from a wake turbulence encounter or strong gust.

b. Test procedure
    - i. For the cruise configuration stabilize the aircraft in level flight at a normal cruise speed.

    1. Bank the aircraft to at least 75 degrees left and release the controls.
    2. Bank the aircraft to at least 75 degrees right and release the controls.
    3. Pitch the aircraft up to at least 25 degrees and release the controls.
    4. Pitch the aircraft down to at least 25 degrees and release the controls.

ii. For the approach configuration stabilize the aircraft at approach speed with a decent rate representative of a 3-degree approach path.

    5. Bank the aircraft to at least 75 degrees left and release the controls.
    6. Bank the aircraft to at least 75 degrees right and release the controls.
    7. Pitch the aircraft up to at least 25 degrees and release the controls.
    8. Pitch the aircraft down to at least 25 degrees and release the controls.

3.2.4.10 Discussion of V_{ref}, V_x, and V_{warn}

The minimum achievable speed is equivalent to the stall speed for mechanically controlled aircraft (or FBW aircraft that mimic mechanical controls). For mechanically controlled aircraft, there is nothing to prevent the pilot from slowing to stall speed and stalling the airplane. In fact, inadvertent stalls are one of the leading causes of accidents. In normal operations other than takeoff and landing transients there is no reason to fly at a speed slower than V_{ref} (about 1.3 times stall speed) other than for maximum performance climbs and below V_x (maximum climb angle speed) when climbing. Therefore, for safety purposes, this recommended change limits the minimum commandable speed to V_{ref} and the minimum allowable speed to V_x except for takeoff and landing transients. Thus, unless there is a failure, the aircraft cannot slow to the minimum achievable speed. The effects of failures that allow the aircraft to fly below the minimum flight speed (V_{ref} or V_x as appropriate) along with the probability of those failures are considered in the failure effects and probability analysis.

Because the aircraft cannot fly at the minimum achievable speed, there is no need to demonstrate the equivalent of stall characteristics as defined by amendment 64 at the minimum achievable speed. Instead, the normal stability and control requirements are applied to the minimum flight speeds that can be obtained in normal operations (minimum commandable speed at less than climb power and minimum allowable speed at climb power and above).

V_{ref}

Part 23 airplanes typically have a landing approach speed (V_{ref}) of 1.3 times stall speed. History shows that this speed generally produces adequate maneuver margins and gust margins while allowing slow landing speeds. See Section 3.2.4.11 V_{ref} discussion related to VTOL aircraft.

For aircraft that use this recommended change, the minimum achievable speed (V_{min}) is treated the same as stall speed for the purpose of determining V_{ref}.

Except for maximum power climbs, descents at maximum available power (failure condition) and landing flare, there is never a need to fly slower than V_{ref}. For airplanes where the pilot commands airspeed, the commandable speed is limited to no less than V_{ref}. For other aircraft including those for which the pilot commands acceleration, thrust or power, preventing the airplane from flying slower than V_{ref} can be accomplished by automatically engaging a throttle-based envelope protection system to advance thrust to prevent flying slower than V_{ref} when not in a landing flare.

An adequate maneuver margin and gust margin must also be provided. An adequate maneuver margin may be considered the ability to generate 0.2 G in addition to the commanded G level. In level flight, this equates to the ability to bank to 35 degrees and hold altitude. Mathematically, it is also approximately a 10% increase in calibrated airspeed above stall or minimum achievable speed. Adding at least 5 to10 kt. to stall speed has generally been shown to provide adequate gust margin (this is where stall warning speed is typically set for conventional airplanes). Thus, for configurations with very a low V_{min}, V_{ref} should be the greater of 1.3 times V_{min} or V_{min} plus 10 kt. (Note, the crossover point is $V_{min} = 33$ kt.)

Many Part 25 and high-end Part 23 airplanes with approach speeds of more than 100 knots set V_{ref} at 1.23 times stall speed. This has been shown through experience to also be satisfactory. Although the reasoning for using 1.23 instead of 1.3 as the stall speed multiplier is not due to the higher speeds, in practice, it has worked out that way and therefore the 1.23 factor is allowed for configurations with high minimum achievable speeds. Therefore, for configurations where V_{ref} is greater than 100 kt. when using 1.3 and less than 100 kt. when using 1.23, V_{ref} of 100 kt. is appropriate and where V_{min} is greater than 81 kt., V_{ref} may be 1.23 times V_{min}.

V_x

Below the minimum commandable speed, the flight controls will be commanding maximum thrust. With maximum thrust below V_{ref} the aircraft will be climbing. While climbing, there is never a need to fly slower than the speed for the maximum angle of climb. V_x is therefore the minimum allowable speed and may be lower than V_{ref}.

The gust and maneuver margin requirements must be satisfied at the minimum allowable speed. The aircraft can be considered to meet these requirements if the aircraft is holding maximum bank allowed at the minimum allowable speed and a 20 kt longitudinal or lateral gust lasting 2 seconds is experienced, or a 10 kt vertical gust lasting 2 seconds is experienced, and the aircraft does not show a tendency to depart controlled flight.

For simplicity, the gust levels specified can be flight tested by overriding the flight control protections and pulling a G level that produces the AoA equivalent to the AoA produced by the gust for 2 seconds and demonstrating that the aircraft will recover immediately.

For aircraft that transition from one type of lift to another, the more conservative speed can be used for the entire transition, or the transition can be broken up into segments and the more conservative speed for each segment used for that segment.

These minimum speeds can be fixed values (as long as they are conservative) or determined in real time for each flight condition as described below.

V_{ref} and / or V_x (minimum commandable speed and minimum allowable speed respectively) may be set to be conservative at the option of the applicant for some configurations / flight conditions to simplify operations and / or certification.

3.2.4.11 VTOL minimum allowable speed

For aircraft in flight conditions where they can hover out of ground effect, the minimum achievable speed is zero, the maximum climb angle occurs at zero airspeed, and warning that the aircraft is approaching zero is only a nuisance since it is a normal operation. Although there may be a recommended approach speed for aircraft that can hover, this is not a safety related speed and therefore V_{ref} is not established for the purpose of this recommended change. Thus, for these aircraft there is no minimum flight speed.

For aircraft that can hover but are in a flight condition where they cannot hover out of ground effect (e.g., high density altitude, high weight, partial power failure, intentional power limiting, etc.), and when at a flight condition where they cannot hover out of ground effect, the aircraft has a minimum achievable speed, a minimum allowable speed, minimum commandable speed and a low-speed warning speed.

The practical effect of this is that an aircraft that can hover normally does not have any low-speed airspeed markings. As it climbs to an altitude where it can no longer maintain zero airspeed out of ground effect the low-speed airspeed markings are displayed.

An example of this is a configuration with only rotors or lift fans that climbs to an altitude where it can fly with the help of translational lift but cannot maintain altitude in a hover. When this aircraft reaches the altitude and weight combination where hovering out of ground effect is not possible, then the flight controls enforce the minimum flight speed. This condition is communicated to the pilot by the posting of the airspeed markings that show minimum commandable and minimum allowable speeds (see markings below). Since the only way to get to this condition (other than a power failure) is by climbing, the aircraft will be at high power and above or near V_x (the exception to this is a partial power failure or transition to an intentional power limiting mode). Therefore, transients in airspeed and flight path due to transition from no minimum flight speed to a minimum flight speed enforced by the flight controls should be minimal. However, to ensure this, the applicant should consider the effects of power failures, power management mode transitions, and climbing when developing control law transitions from no enforced minimum flight speed to an enforced minimum flight speed. It is recommended that in transitioning from no minimum speed to a minimum speed that they do so in a manner so as not to lose altitude. The main purpose for transitioning to an enforced minimum flight speed for these types of aircraft is to prevent a pilot from climbing to an altitude where the aircraft cannot maintain altitude at low speed and then slowing such that altitude cannot be maintained and the aircraft cannot accelerate without descending. An acceptable way to handle this transition when the applicant chooses to use an artificially high minimum achievable speed at high altitude is to allow speeds lower than the minimum flight speeds until the aircraft accelerates above the minimum flight speed and then subsequently enforce the minimum flight speeds.

A means for the pilot to override the minimum flight speed may be provided for emergency conditions for aircraft that are capable of doing an unpowered or semi-powered autorotation to a vertical or “run on” landing with an approach speed less than V_{ref}, . This applies as long as it can be shown that this maneuver can be done consistently and safely without exceptional pilot skill. This override is for emergency conditions only because a go around may not be possible.

Low speed warning (V_{warn})

For conventional airplanes, there is a stall warning 5 to 10 knots above stall speed. Aircraft that use this recommended change will never get to stall nor the minimum achievable flight speed. Therefore, the concept of a warning to alert the pilot that they are approaching a stall is not the same. However, if there is a failure such that the pilot can slow to a speed below the minimum allowable speed, then such a warning is appropriate. Therefore, an aural or tactile low speed warning shall be incorporated that indicates the aircraft is below the low-speed warning speed. The low-speed warning speed sensor should be independent of the airspeed sensor and may be an angle of attack sensor. The low-speed warning should not activate in normal operations (flying at the minimum commandable speed – V_{ref}, or the minimum allowable speed – V_x). V_{warn} should be about 5 to 10 kt faster than the minimum achievable speed.

Examples of how the speed definitions are applied to various configurations:

- Configurations that can hover out of ground effect (helicopter, multi-copter, tilt rotor / tilt wing in hover configuration, lift plus cruise aircraft in hover configuration, etc.)
  - Minimum Achievable Speed: Zero since they can hover
  - Minimum Allowable Speed: Zero since they can hover (may be negative)
  - Minimum Commandable Speed: Zero since they can hover (may be negative)
  - Minimum Flight Speed: Zero since they can hover (may be negative)
  - Low-Speed Warning Speed: None; there is no need to warn of approaching zero speed.

- Configurations with VTOL capability but are operating at a flight condition (weight, altitude, temperature) where they cannot hover out of ground effect but can maintain level flight at some speed greater than zero (helicopter, multi-copter, tilt rotor / tilt wing in hover configuration, lift plus cruise aircraft in hover configuration, etc.):
  - Assume for the sake of this example that the maximum angle of climb speed is 50 kt. and the minimum speed that the aircraft can maintain level flight in this condition is 30 kt. but the applicant elects to declare the minimum achievable speed for this configuration when unable to hover out of ground effect to be 40 kt.
  - Minimum Achievable Speed: 40 kt.
  - Minimum Allowable Speed: 50 kt. (V_x)
  - Minimum Commandable Speed: 40 kt. * 1.3 = 52 kt. (V_{ref})
  - Minimum Flight Speed: 50 kt. when at maximum climb power and 52 kt. otherwise
  - Low Speed Warning Speed: 40 kt. + 7 kt. = 47 kt.

- Conventional airplanes and aircraft with VTOL capability but are operating in a configuration where the wing provides all or much of the lift (conventional airplanes, tilt rotor with rotors not vertical, lift plus cruise aircraft with lift fans off or at reduced power, etc.):
  - Assume for the sake of this example that the maximum angle of climb speed is 60 kt. and the minimum speed at that the aircraft can maintain level flight (stall speed) in this condition is 50 kt.
  - Minimum Achievable Speed: 50 kt.
  - Minimum Allowable Speed: 60 kt. (V_x)
  - Minimum Commandable Speed: 50 kt. * 1.3 = 65 kt. (V_{ref})
  - Minimum Flight Speed: 60 kt. when at maximum climb power and 65 kt. otherwise
  - Low Speed Warning Speed: 50 kt. + 7 kt. = 57 kt.

3.2.4.12 Airspeed markings

Experience from Part 25 and high end Part 23 aircraft that have glass cockpits has shown that the following markings provide good airspeed awareness. Note that all of these speeds are actually AoA driven and change as the airplane's weight, G loading and configuration change. While the following example is not the only way to satisfy the requirement for airspeed markings, it is considered to meet the requirement.

A low-speed warning speed, V_{warn}, is established at 5 to 10 kt. above the minimum achievable flight speed. This is the speed at which the low-speed warning alert sounds. There is a red band on the airspeed tape at the minimum speed warning speed. The position of the top of the red band is calculated as follows.

$$V_{warn}=V\sqrt{\frac{\propto-\propto_0}{\propto_{mw}-\propto_0}}$$

V_{warn} = minimum speed warning (top of red band)
V = current indicated airspeed
$\propto$ = current AoA
$\propto_0$ = zero lift or high-speed cruise AoA
$\propto_{mw}$ = minimum speed warning AoA for the current configuration and flight condition

The top of the red band moves in response to the varying G loading on the airplane (due to turbulence or maneuvering).

There is an amber band from the top of the red band to the maneuver margin speed. The maneuver margin speed is the speed at which the airplane can bank to 35 degrees and hold altitude without triggering the low-speed warning (the red band rises due to G loading such that the current airspeed would be inside the red band at bank angles above 35 degrees at this speed). Note that a 35-degree bank in level flight produces 1.22 Gs, which also raises the minimum speed warning speed by about 10%. The position of the top of the amber band is calculated as follows.

$$V_{mm}=\frac{V_{warn}}{\sqrt{\frac{1}{\cos(\phi)}}}\sqrt{\frac{1}{\cos(\phi_{man})}}$$

Where:

V_{mm} = minimum maneuvering speed (the top of the amber band)
V_{warn} = low speed warning speed as calculated above
ϕ_{man} = maneuver margin bank angle
ϕ = current bank angle

The top of the amber band does not move in response to the varying G loading due to bank angle but does move in response to level pulls and turbulence. The amber band gets smaller as the bank angle increases and disappears at bank angles above 35 degrees.

If 35 degrees is used for the maneuvering margin bank angle, at zero current bank angle the radicals combine to be 1.1, which then makes V_{mm} 10% higher than V_{warn} in wings level flight.

There is a green bar or circle at V_{ref}. This is also the minimum commandable airspeed. The position of the V_{ref} marking is calculated as follows.

$$V_{ref}=F*V\sqrt{\frac{\propto - \propto_0}{\propto_{min} - \propto_0}}$$

Where
V_{ref} = position of the green circle or green bar on the airspeed tape
F = a factor that defines the approach speed as a function of minimum achievable speed
V = the current indicated airspeed
$\propto$ = current AoA
$\propto_0$ = zero lift or high-speed cruise AoA
$\propto_{min}$ = minimum achievable speed AoA for the current configuration and flight condition

F is typically 1.3 or 1.23 depending on V_{ref} for the configuration – configurations with V_{ref} over 100 kt typically use 1.23 and slower configurations typically use 1.3 since using the same multiple adds excessive conservatism at higher speeds.

V_{ref} is based on the minimum achievable speed AoA, not minimum speed warning AoA like the red and amber bands.

When the aircraft is climbing, V_x is indicated on the airspeed tape. V_x is the minimum allowable speed with climb power and may not be slower than the maneuver margin speed in level flight. The only way to fly at this speed is to command a flight path angle or rate that the aircraft cannot sustain at V_{ref} or higher speeds. This will only occur with climb power since the aircraft will add thrust to keep the airplane above V_{ref} until maximum thrust is achieved. This speed may be determined by climb performance, stability, controllability, gust margins or any other characteristic chosen by the applicant – it need not be determined by climb performance although V_x may not be slower than the speed at which the aircraft achieves the maximum climb gradient in the current configuration. The position of the V_x marking is calculated as follows.

$$V_X=V\sqrt{\frac{\propto - \propto_0}{\propto_X - \propto_0}}$$

Where:

V_X = maximum angle of climb speed or the minimum allowable speed
V = the current indicated airspeed
$\propto$ = current AoA
$\propto_0$ = zero lift or high-speed cruise AoA
$\propto_X$ = V_x AoA for the current configuration and flight condition

These airspeed marking requirements and protection functions do not apply to aircraft that have the ability to slow from cruise speed to zero airspeed and back without configuration changes, or to aircraft for which automatic (not pilot controlled) configuration changes prevent stalls or any other source of aircraft motion-to-command decoupling during rapid speed changes.

In addition to the above markings, all aircraft are expected to have

1. A bug that indicates the commanded airspeed.
2. An airspeed trend vector. The airspeed trend vector is a magenta line extending from the current airspeed to the airspeed that the aircraft will achieve 5 to 6 seconds from the current time. It is based on the current acceleration rate.

Figure 4 provides an example of acceptable airspeed markings. In this particular example:

- The minimum achievable speed is 55 kt.
- V_{warn} – low speed warning is 60 kt. (minimum achievable + 5 kt.).
- V_{mm} – maneuver margin speed is 66 kt. (V_{warn} * 1.1).
- V_{ref} – minimum commandable speed is 71.5 kt (minimum achievable speed * 1.3).
- V_x is 67 kt. (determined by climb performance).
- The current commanded speed is 80 kt.

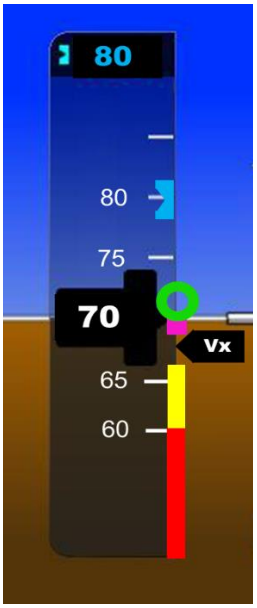


Figure 4: An example of acceptable low speed airspeed markings

From the airspeed tape and knowledge of the control system, the following information is available:

- The aircraft is flying at 70 kt.
- The aircraft is currently in a configuration and/or flight condition where it cannot hover out of ground effect (the V_{ref} and V_x markings are visible).
- The aircraft is climbing at maximum thrust (it is flying slower than V_{ref}).
- The aircraft is decelerating at about 2 kt. per second (the airspeed trend vector is displayed below the current airspeed).
- The aircraft will not decelerate below 67 kt. (the V_x marker).
- When the airspeed reaches the V_x marker the aircraft will be climbing at the maximum climb angle.
- At the current speed, and when the aircraft slows to V_x, there is adequate speed margin to maneuver the aircraft.
- When a shallower climb angle is commanded, the aircraft will accelerate to 80 kt.

3.3 §23.2115 / §23.2120 takeoff and initial climb performance

The following table lists the proposed changes for §23.2115/§23.2120.

Table 4. Proposed changes for §23.2115/§23.2120

FAR 23 amendment 64 as written	The FAA FAST replacement proposal
§**23.2115 Takeoff Performance** (a) The applicant must determine airplane takeoff performance accounting for— (1) Stall speed safety margins; (2) Minimum control speeds; and (3) Climb gradients. (b) For single engine airplanes and levels 1, 2, and 3 low-speed multiengine airplanes, takeoff performance includes the determination of ground roll and initial climb distance to 50 feet (15 meters) above the takeoff surface. (c) For levels 1, 2, and 3 high-speed multiengine airplanes, and level 4 multiengine airplanes, takeoff performance includes a determination the following distances after a sudden critical loss of thrust— (1) An aborted takeoff at critical speed; (2) Ground roll and initial climb to 35 feet (11 meters) above the takeoff surface; and (3) Net takeoff flight path. (p. 179)	**SC.2115 Takeoff performance.** The applicant must determine takeoff performance accounting for flight envelope and obstacle safety margins. Airplanes designed for continued flight after a loss of thrust not shown to be extremely improbable must determine takeoff performance and account for performance after the loss of thrust.
§**23.2120 Climb Requirements** (2022) The design must comply with the following minimum climb performance out of ground effect: (a) With all engines operating and in the initial climb configuration— (1) For levels 1 and 2 low-speed airplanes, a climb gradient of 8.3 percent for landplanes and 6.7 percent for seaplanes and amphibians; and (2) For levels 1 and 2 high-speed airplanes, all level 3 airplanes, and level 4 single-engines a climb gradient after takeoff of 4 percent.	**SC.2120 Climb requirements**. The applicant must demonstrate minimum climb performance at each weight, altitude, ambient temperature, and critical battery state within the operating limitations using the procedures published in the flight manual. Airplanes designed for continued flight after a loss of thrust not shown to be extremely improbable must determine climb performance and account for performance after the loss of thrust.

FAR 23 amendment 64 as written	The FAA FAST replacement proposal
(b) After a critical loss of thrust on multiengine airplanes— (1) For levels 1 and 2 low-speed airplanes that do not meet single-engine crashworthiness requirements, a climb gradient of 1.5 percent at a pressure altitude of 5,000 feet (1,524 meters) in the cruise configuration(s); (2) For levels 1 and 2 high-speed airplanes, and level 3 low-speed airplanes, a 1 percent climb gradient at 400 feet (122 meters) above the takeoff surface with the landing gear retracted and flaps in the takeoff configuration(s); and (3) For level 3 high-speed airplanes and all level 4 airplanes, a 2 percent climb gradient at 400 feet (122 meters) above the takeoff surface with the landing gear retracted and flaps in the approach configuration(s). (c) For a balked landing, a climb gradient of 3 percent without creating undue pilot workload with the landing gear extended and flaps in the landing configuration(s). (p. 180)	

3.3.1 Takeoff and climb requirements as they apply to VTOL and unconventional aircraft

Part 23 amendment 64 does not apply to VTOL or unconventional aircraft well. It is believed that the FAST recognized this. Unfortunately, the proposed replacement regulations are vague and do not actually specify any performance requirements. The authors believe it is the FAA's intent that means of compliance material provide the actual requirements as appropriate for these aircraft. This recommended change and its MOC is intended to take the original Part 23 requirements and modify them considering Part 27 to develop appropriate specific requirements for these VTOL and unconventional aircraft.

3.3.2 Definitions of conventional aircraft and catastrophic probability

For the purpose of this recommended change, the following definitions apply.

3.3.2.1 Conventional airplane

A conventional airplane is defined as having one, two, three, or four engines used for thrust substantially along the longitudinal axis of the aircraft, and a control system that only uses aerodynamic surfaces for control, and does not rely on adding energy to the airstream for control.

3.3.2.2 Conventional helicopter

A conventional helicopter is defined as having one or two rotors used for lift substantially along the vertical axis of the aircraft and a control system that uses a combination of cyclic and collective mechanisms on at least one rotor for aircraft control.

All aircraft that do not meet the definition of conventional airplane or conventional helicopter above are considered unconventional aircraft for the purpose of this recommended change.

3.3.2.3 Catastrophic probability

Catastrophic probability is the required maximum probability of a failure or combination of failures that maps to a catastrophic event for the particular aircraft. The actual probability number will vary with aircraft. For instance, a level 2 aircraft may allow a failure that results in a catastrophic event with a probability of no more than 10E-7 while a level 4 aircraft may allow a failure that results in a catastrophic event with a probability of no more than 10E-9. In these examples, the catastrophic probability is 10E-7 and 10E-9 respectively.

3.3.2.4 Critical reliability envelope

If there is a portion of the flight envelope in which a failure with a probability greater than catastrophic probability will likely cause a catastrophic event, then that portion of the flight envelope is the critical reliability envelope. This concept is similar to the height velocity envelope of a helicopter except where the height velocity envelope only addresses an engine or drive train failure, the critical reliability envelope addresses all failures.

3.3.3 Recommended changes for §23.2115 and §23.2120

3.3.3.1 §23.2115 takeoff

The following modifications are suggested for §23.2115.

(a) applies as written except for the reference to stall speed and minimum control speed.

> (1) Stall speed safety margins; is replaced with
>
> (1) Minimum flight speed margins for aircraft that use free stream velocity for all or part of their lift:
>
> (2) Minimum control speeds; is replaced with
>
> (2) Component or system failures during takeoff;

(b) applies as written but other requirements (such as reliability requirements) may affect the application of this requirement. The definition of takeoff as implied by this rule (up to 50 ft) is retained.

(c) applies as written except that "critical loss of thrust" is replaced with "critical failure".

A new requirement is added.

(d) If there is a critical reliability envelope where continued safe flight cannot be maintained after failure with a probability greater than the catastrophic probability, it must be determined.

3.3.3.2 §23.2115 takeoff discussion

The following are recommended changes to §23.2115.

(a)(1) Stall speed

Minimum achievable flight speed replaces stall speed since stall speed does not exist for airplanes with smooth AoA protection as would be expected for many FBW aircraft. For airplanes with a stall speed (identified by an uncontrollable nose down pitching) the stall speed may be used.

The "free stream" clause is added to avoid an unnecessary burden for VTOL only aircraft.

(a)(2) Minimum control speed

V_{mc} in Part 23 aircraft has a specific meaning and is related to failure of an engine in multi-engine airplanes. It is a fixed speed, which is marked on the airspeed indicator (with a blue radial). The other requirements of this document (including the concept of a critical reliability envelope) make the V_{mc} requirement on its own redundant.

For aircraft where a component failure will result in longer takeoff distances, the effect of this must be determined. The effect of all failures need not be considered - only the effect of the most critical one needs to be determined.

(b):

The failure of an engine in these airplanes may cause a catastrophic event due to insufficient performance. Thus, performance after an engine failure combined with powerplant reliability must be considered.

(c):

There is nothing special about an engine from a reliability perspective except that the old rule treated them differently than other failures. The effect of the failure, whether it is an engine or something else, needs to be considered for takeoff performance.

(d):

14 CFR §27.87 requires that if there is any combination of height and forward speed (including hover) under which a safe landing cannot be made after a power failure, a limiting height-speed envelope must be established. This new airworthiness criterion brings this concept to Part 23 VTOL aircraft in the form of a critical reliability envelope.

3.3.3.3 Category A §23.2115 Takeoff Performance

For category A certification (aircraft intended for commercial use over urban areas), the following is added to §23.2115:

- (e) If a critical reliability envelope exists as established in §23.2115 (d), then the aircraft will not allow flight within that envelope.

3.3.3.4 Category A Takeoff Discussion

Category A operations are commercial operations over urban areas. This concept comes from the Category A requirements of Part 27 (which references 14 CFR §29.59 Takeoff Path: Category A and §29.85: Balked Landing Category A). The concept is to prevent the aircraft from entering a flight envelope in which if a system failure occurs, the aircraft cannot make a safe landing.

Note: Helicopters used for commercial purposes over urban areas in Europe are required to meet category A requirements. This may become a requirement for UAM in the US as well.

3.3.3.5 §23.2120 Climb requirements

The following are recommended changes to §23.2120.

(a) applies as written except for aircraft capable of vertical takeoff. The following is added to the rule.

(a)(3) For all aircraft (including VTOL), the minimum steady state rate of climb is 500 ft/min for land planes and 400 ft/min for amphibians and sea planes. The takeoff profile must provide the specified climb rate and gradient.

(b) is replaced by

An event or combination of events that causes the climb performance to fall below that specified by (b)(1), (b)(2) or (b)(3) as appropriate for the aircraft is considered a catastrophic event.

(b)(1) applies as written, except for aircraft capable of vertical takeoff. The following is added to the rule.

For aircraft capable of vertical takeoff, compliance with this recommended change may be demonstrated by a 1.5 percent climb gradient at 60 kt or greater, or a minimum climb rate of 100 ft/min at any lower speed at 5,000 ft. density altitude. For all aircraft, at 5,000 ft density altitude, the aircraft must be able to climb at 100 ft/minute or a climb gradient of 1.5 percent, whichever provides a higher climb rate. Note: A 1.5% climb gradient at 60 kt is about 100 fpm.

(b)(2) & (b)(3) apply as written except for aircraft capable of low takeoff speeds. The following is added to the rule.

For aircraft capable of very low (or zero) takeoff speed, compliance with this rule may be demonstrated by the climb gradient specified in the recommended change at 100 knots indicated airspeed (KIAS) or greater, or a minimum average climb rate of 200 ft/min at any lower speed from 50 ft to 400 ft AGL.

(c) applies as written, with the following additions.

> (1) If the aircraft automatically reconfigures after a go around, then the go around configuration may be used if the required climb gradient is achieved in less than 6 seconds and is maintained.
>
> (2) In addition to the minimum climb gradient, the minimum balked landing climb rate is 200 feet per minute, which is about equivalent to 3% at 60 kt.

3.3.3.6 Climb performance discussion

The following is a discussion about the recommended changes to §23.2120.

(a):

A climb gradient requirement makes no sense for an aircraft going straight up (the gradient is infinite). However, there does need to be a minimum climb requirement for these aircraft. For aircraft that take off conventionally, a 60 kt climb speed with a climb gradient of 8.3 percent results in about 500 fpm climb rate, and 6.7 percent results in about 400 ft/min. This is a reasonable minimum climb rate for VTOL operations. The words "higher of the climb rate and gradient" are included to ensure that an aircraft (such as an electric VTOL aircraft) that needs to reduce power after takeoff can still achieve an acceptable climb gradient and rate with the reduced power.

(b):

The amendment 64 rule was written specifically for aircraft with two independent engines (but covers three or more) and does not consider engine reliability (it just assumes a failure will occur) or potential propulsion system integration issues. The wording was changed to reflect the potential for many different propulsion configurations and bring propulsion system reliability in line with other critical system reliability.

(b)(1):

The intent of this rule is to require airplanes to have at least a minimum climb capability up to 5,000 ft so as to be able to continue level flight at a reasonable altitude. The rule specifies this in the form of a 1.5 percent climb gradient. At 60 kt, a 1.5 percent climb gradient is about 100 ft/min. Thus, a 100 ft/min minimum climb rate at low speeds accomplishes the intent.

(b)(2) & (b)(3):

The intent of this rule is to ensure that after loss of an engine, that the aircraft has the ability to clear reasonable obstacles along the takeoff flight path. For aircraft with vertical takeoff capability, a gradient requirement does not make sense. However, it is still desired to require a reasonable climb capability after loss of an engine on takeoff. Requiring a maximum of two minutes to reach 400 ft at very low speeds demonstrates this capability.

(c):

If an aircraft automatically configures for go around, then credit should be allowed for this. Part 25 field performance allows the applicant to skip first segment climb gradient calculations if the landing gear retraction time is less than 6 seconds. (The first segment climb is the takeoff segment between leaving the ground and the landing gear being fully retracted.) Therefore, a 6 second transition time for go around seems reasonable here since go around is less critical than takeoff.

The 200 ft/minute requirement is to account for aircraft that can fly at very low or zero forward speed. This requirement ensures a reasonable climb rate after a go around.

3.3.3.7 Category A §23.2120 Climb requirements

For category A certification the following is added to §23.2120.

(d) Failure to meet the climb requirements of §23.2120 (b) is considered a catastrophic event for system reliability purposes.

(e) From the takeoff point to 1000’ above the takeoff point, the climb gradient shall always be positive or level.

(f) Failure to meet the climb requirements of §23.2120 (c) is considered a catastrophic event for system reliability purposes.

3.3.3.8 Category A climb discussion

The Category A requirements as indicated in AC 23.1309 specifically defines low climb gradients after a failure as a Catastrophic event so for the purpose of including failures that cause low climb gradients to be considered as Catastrophic for system reliability purposes.

The requirement for the takeoff gradient to always be positive or level is to prevent the applicant from developing a maneuverer where the aircraft climbs along a gradient and then uses altitude to accelerate to a higher speed before climbing again.

Note: Helicopters used for commercial purposes over urban areas in Europe are required to meet category A requirements. This may become a requirement for UAM in the US as well.

3.3.3.9 Combined Takeoff and Climb Performance Discussion

The takeoff and initial climb requirements are both included in this recommended change because they are very closely related, and they are both needed to predict the ability of an aircraft to clear obstacles along the takeoff flight path or provide a climb margin for safety and traffic flow.

The intent of this recommended change is to provide guidance for FBW aircraft that are not conventional airplanes nor conventional helicopters. The intent is to require these aircraft to provide at least one takeoff procedure that substantially meets the requirements of Part 23 regarding initial climb requirements. There is also the requirement for publication of this performance without limiting VTOL capable aircraft from accomplishing the unique missions that they are capable of, even when they do not meet the Part 23 reliability or initial climb requirements.

3.3.3.10 Applicability

Note that for the purpose of this recommended change, the definitions should be applied to each proposed takeoff configuration – not the aircraft as a whole.

For instance:

- a single aircraft with two tilting rotors that has a procedure to takeoff with the rotors tilted forward
- another procedure for taking off with the rotors tilted upwards
- a third procedure with the rotors tilted at 45 degrees might qualify as a conventional airplane with the rotors tilted forward, a conventional helicopter with the rotors tilted upwards and neither with the rotors tilted at 45 degrees.

Note that an aircraft may change from one definition to another during the takeoff maneuver. For an aircraft to qualify as a conventional airplane or conventional helicopter, it must comply with the definition for the entire takeoff procedure.

For conventional airplane configurations, use the procedures of AC 23-8C (Flight Test Guide for Certification of Part 23 Airplanes pages 23 through 45) or other appropriate guidance as a means of compliance. If the aircraft has a minimum achievable speed instead of a stall speed (see recommended change §23.2110 / §23.2150 Stall Speed Warning and Characteristics), use the minimum achievable speed in place of the stall speed.

For conventional helicopters, use the procedures of AC 27-1B (Certification of Normal Category Rotorcraft Pages B-9 through B-45) or other appropriate guidance as a means of compliance. Note that Part 27 does not require any level of takeoff performance nor publication of takeoff performance for helicopters. However, it does require publication of the maximum weight altitude and temperature combinations that allow hover in ground effect. For helicopters, it is assumed that if the helicopter can hover in ground effect, the helicopter can accelerate in ground effect to a speed where it can take advantage of effective translational lift and climb. This technique also typically keeps the helicopter out of the height velocity envelope.

For other configurations, use this recommended change. Use the methods of AC 23-8C and 27-1B as much as practical. When not practical or when the number of powerplants and/or the control scheme does not fit either, then modify the procedure as required using this recommended change as guidance.

The intent is to determine and then publish takeoff and initial climb performance data for configurations that do not meet the definition of conventional airplane or conventional helicopter as defined by this recommended change. Takeoff performance includes ground roll (which may be zero), obstacle clearance distance, initial climb rate, and initial climb gradient up to 400 ft for the combination of weight, altitude, and temperature approved. (Initial climb rate and gradient are the rate or gradient after climbing 50 ft. above the surface. Below 50 ft. above the surface is considered part of the takeoff.) A particular configuration may have more than one procedure along with associated performance data. For example, a vehicle that has multiple tilting rotors, a wing, and a pusher propeller may have a procedure for a vertical takeoff with zero ground roll and no forward speed. The same vehicle in the same configuration may have another procedure where its pusher propeller provides forward thrust at the beginning of the takeoff while the upward tilted rotors provide lift and benefit from effective translational lift. The first procedure may allow a takeoff with zero takeoff distance and the later may allow a takeoff with a higher payload.

A procedure for each type of approved takeoff must be developed by the applicant. At least one normal procedure must provide the required climb capability without putting the aircraft in a condition where a failure with a catastrophic probability would result in a catastrophic event. Takeoff procedures that do not comply with the reliability requirement and / or climb requirement may be included as long as they are clearly identified as not meeting the reliability requirements or climb requirements as appropriate.

If the design is such that there is no single failure, or combination of failures that have a probability of failure of more than that associated with a catastrophic event, then a critical reliability envelope (similar to a height velocity envelope but including more than just engine failures) need not be identified. This applies even if a successful power off landing (autorotation or glide) is unlikely from within this envelope.

The performance must be determined for the range of weight, altitude, and temperature that is approved for that procedure.

Each approved procedure along with its corresponding performance over the approved range of flight conditions must be published in the Aircraft Flight Manual in a manner that makes it possible to calculate the obstacle clearance along the takeoff flight path up to 400 ft. Each approved procedure must include the conditions (weight, altitude, temperature, etc.) that produce at least a 50 ft/min steady state initial climb rate outside of ground effect when the climb requirement is not met (typically vertical takeoffs).

Note that the only failures addressed by AC 23-8C and AC 27-1B are engine failures. This recommended change treats all failures that can affect takeoff performance and control the same by creating the concept of a critical reliability envelope. This concept replaces the V_{mc} concept in Part 23 and the height velocity envelope concept in Part 27 while adding control system failures.

3.3.3.11 An example showing the relationship between reliability and performance requirements

The following is an example using a VTOL vehicle with multiple rotors that use collective pitch for control and a single powerplant driving all of the rotors. Note that this is just an example intended to illustrate the concept. The concept should be applied to all takeoff operations whether the aircraft is capable of vertical flight or not.

The vehicle has a single powerplant with reliability that does not meet probability of failure numbers required for a catastrophic event. Because this vehicle uses collective pitch on its lift rotors, it can autorotate and has a height velocity envelope. The height velocity envelope partially defines the critical reliability envelope for this aircraft (there may also be control system failures that further define the critical reliability envelope). If a powerplant failure occurs on takeoff while the aircraft is inside the height velocity envelope, a catastrophic event is likely. Thus, a takeoff procedure that satisfies the reliability requirement would be to accelerate at a low height until sufficient forward speed is obtained to ensure a successful autorotation can be entered at any point along the takeoff path. For this machine, a vertical takeoff to a height that puts it in the height velocity envelope would not meet the reliability requirement.

Assume that this same vehicle cannot climb vertically at the minimum climb rate required, but it can meet the climb requirement if it accelerates to a speed that allows it to take advantage of effective translational lift.

The requirement is that the applicant provides at least one takeoff procedure that meets the reliability requirements and meets the climb requirement. The procedure that allows the aircraft to accelerate at low height meets both requirements and therefore satisfies the requirement for at least one procedure that satisfies both the reliability and climb requirements. This does not prevent the applicant from providing other takeoff procedures. An example procedure could be a vertical takeoff for this machine. A vertical takeoff would allow the aircraft to takeoff out of confined places that prevent obtaining forward speed before getting to a height where a successful autorotation is possible. This takeoff procedure would violate the reliability requirements because it requires flight in the height velocity envelope. This takeoff procedure would also violate the climb requirement. It is acceptable for the applicant to provide this vertical takeoff procedure as long as this procedure is identified as not meeting the reliability requirement and the initial climb requirement.

3.3.4 Means of Compliance for §23.2115 / §23.2120

3.3.4.1 Data Collection

A full data acquisition system with plotting capability may be used if desired. However, less sophisticated instrumentation may be used as long as it is shown to be conservative (show the same or lower performance level than the aircraft actually accomplishes). The intent is to allow simple measurement systems for applicants who choose (typically when conservative performance prediction can be tolerated), but also allow sophisticated systems (typically when the best possible published performance data is desired).

The minimum instrumentation is as follows.

1. Appropriate cockpit instrumentation to ensure the appropriate procedure is followed.
2. A means of determining height above the ground other than pressure altitude using an aircraft mounted static source when determining ground distance to clear an obstacle. (Aircraft mounted static sources are often not accurate during transition from ground to air.)
3. A means to determine climb rate and gradient. (This may be an altimeter with an aircraft mounted static source.)
4. A means of measuring distance
    a. from the start of takeoff to leaving the ground.
    b. to a height of 50’ above ground.
5. A means of determining wind speed and direction.
    a. Applicant supplied wind measurement device (must be at least 5’ above the ground).
    b. Real time readings from a control tower (not from a recorded or automated broadcast).
6. A means of determining pressure altitude of the test site, temperature, and humidity (if humidity has a measurable effect on performance).

   a. Applicant supplied pressure altitude measurement device (or altimeter set to 29.92 in-hg), temperature and humidity measurement device (must be at least 5’ above the ground).

   b. Real time readings of altimeter setting, temperature, and dew point from a control tower (not from a recorded or automated broadcast). The altimeter setting will be converted to pressure altitude.

7. Airspeed indicator as required to conduct the procedure properly.

8. Power measurement instrumentation as required to conduct the procedure properly and additional instrumentation as required to verify that the actual power generated during the test is not more than the minimum expected for the power system during the life of the system under expected operating conditions.

3.3.4.2 Required Information and Configuration

Before the procedure, the applicant will define

1. Weight and CG range for allowed operations
2. The CG location for each test condition that provides the most conservative performance
3. A definition of each procedure for which approval is requested, including aircraft configuration(s) for each procedure
4. Altitude range for each procedure

The applicant must determine the lowest level of power expected during the life of the system for the test condition. The tests must be done at no more than this power level. This power level should account for previous system use, component aging, wear, and performance degradation as the system wears. If the system performance can degrade due to inactivity, then this should be accounted for as well.

3.3.4.3 Flight Test Procedure

Use the test conditions, procedure, and data analysis techniques described in AC 23-8C or AC 27-1B as appropriate for the takeoff configuration.

3.4 §23.2135 Controllability §23.2600 Crew Interface §23.2510

3.4.1 §23.2135 Controllability

The following table lists suggested changes for §23.2135.

Table 5. Suggested changes for §23.2135

FAR 23 amendment 64 as written	The FAA FAST has proposed the following Special Condition
§23.2135 Controllability (2022) (a) The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope— (1) At all loading conditions for which certification is requested; (2) During all phases of flight; (3) With likely reversible flight control or propulsion system failure; and (4) During configuration changes. (b) The airplane must be able to complete a landing without causing substantial damage or serious injury using the steepest approved approach gradient procedures and providing a reasonable margin below V_{ref} or above approach angle of attack. (c) V_{mc} is the calibrated airspeed at which, following the sudden critical loss of thrust, it is possible to maintain control of the airplane. For multiengine airplanes, the applicant must determine V_{mc}, if applicable, for the most critical configurations used in takeoff and landing operations. (d) If the applicant requests certification of an airplane for aerobatics, the applicant must demonstrate those aerobatic maneuvers for	SC.2135 Controllability. (From the FAAST GAMA document <u>underlined</u> text indicates FAST changes) (a) The airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope— (1) At all loading conditions for which certification is requested; (2) During all phases <u>and modes</u> of <u>operation</u>; (3) With likely flight control or propulsion system failure; and (4) During configuration changes; (5) In all degraded flight control system operating modes not shown to be extremely improbable; and (6) In vertical operation and must be able to land safely in wind velocities from zero to a wind limit appropriate for the airplane from any azimuth angle. (b) The applicant must determine if there are any critical control parameters, such as V_{mc} or limited control power margins, and if applicable, account for those parameters where appropriate. (c) It must be possible to make a smooth transition from one flight condition to another without danger of exceeding the approved flight envelope.

FAR 23 amendment 64 as written	The FAA FAST has proposed the following Special Condition
which certification is requested and determine entry speeds. (p. 180)	

1.1.1.1 Recommended changes to §23.2135

(a)(3) is replaced with

With flight control or propulsion system failures that are more probable than allowed for a catastrophic event and

(c) is replaced with

For aircraft with multiple thrust, lift or power sources, the flight condition(s) and configuration envelope inside of which a critical power, lift or thrust failure would result in loss of control must be determined, and if the probability of such a failure is greater than allowed for a catastrophic event, the control system must be designed to prevent flight in this envelope.

(e) is added

For aircraft with hover taxi capability, the aircraft must be controllable and maneuverable during hover taxi, without requiring exceptional piloting skill, alertness, or strength, with wind velocity of zero to 17 knots from all azimuths.

1.1.1.2 Discussion of recommended change for §23.2135

(a)(3) refers to reversible controls. The aircraft covered by this airworthiness criteria may not have reversible controls. However, there is a potential analogous failure for FBW. The rewritten (a)(3) covers this.

The words “likely failure” are used in both the original regulation and the FAST proposal, but these words are not defined. The recommended change defines the failure rate applicable to this rule. The FAST proposal adds item (5) which duplicates item (3) but uses the words “extremely improbable”. This is also not defined. In the FAST proposal, (3) and (5) basically say the same thing but use different words to identify the failure rate. This provides for a potential conflict within the FAST proposal depending on how the two different terms used to identify the failure rate are interpreted.

(c) was written in amendment 64 with conventional twin-engine aircraft that have mechanical controls in mind. New aircraft configurations or FBW may have flight envelopes in which a failure could result in loss of control (like loss of an engine below V_{mc} in a conventional twin can result in loss of control). This regulation proposal is expanded to include these potential new designs. It also specifies that the control system should prevent operations within this envelope if the probability of a failure that could result in loss of control is greater than that allowed for a catastrophic event. This is because it is assumed that loss of control is catastrophic.

The FAST proposal eliminates the amendment 64 item §23.2135 (b) and replaces (c) with their item (b) which basically says that the applicant must determine critical parameters and limited control power situations and account for them but does not mention how this accounting should affect control (if at all).

(e) is a concept from §27.143(c) and (d). Part 27 requires controllability and maneuverability with winds up to 17 knots. Part 23 has no wind requirements but does require publishing a maximum demonstrated crosswind speed (not a limitation). VTOL aircraft often hover taxi, so a wind from all azimuths is appropriate. The 17-knot requirement comes directly from Part 27. The hover taxi provision specifically allows for VTOL aircraft that do not have the ability to hover laterally or backward at 17 kt and are therefore limited to landing with a crosswind or tailwind less than 17 kt but have the ability to taxi without hovering (for example, VTOL aircraft with wheels).

The FAST proposal addresses this by adding item (6) to §23.2135(c). However, Part 27 experience has determined that 17 knots is an appropriate minimum based on expected atmospheric conditions. While it is generally good not to include specific design requirements in a rule, the identification of 17-knots recognizes normal atmospheric conditions and requires the aircraft be designed to operate in normal atmospheric conditions. It is not a requirement to design the aircraft in any specific way to operate in normal atmospheric conditions and therefore should be included. It is a lower limit. A designer is free to design the aircraft to operate in higher winds.

3.4.2 §23.2600 Flight crew interface

The following table lists suggested changes for §23.2600.

Table 6. Suggested changes for §23.2600

§23.2600 as written	Recommended changes to §23.2600
(a) The pilot compartment, its equipment, and its arrangement to include pilot view, must allow each pilot to perform his or her duties, including taxi, takeoff, climb, cruise, descent, approach, landing, and perform any maneuvers within the operating envelope of the airplane, without excessive concentration, skill, alertness, or fatigue. (b) The applicant must install flight, navigation, surveillance, and powerplant controls and displays so qualified flight crew can monitor and perform defined tasks associated with the intended functions of systems and equipment. The system and equipment design must minimize flight crew errors, which could result in additional hazards. (c) For level 4 airplanes, the flight crew interface design must allow for continued safe flight and landing after the loss of vision through any one of the windshield panels.	(b) is changed to Flight, powerplant and systems instrumentation and controls must be installed as required by the system design to allow the crew to detect failures and take appropriate action if the failure is not detected automatically and appropriate action is not taken automatically. (d) is added: (d) Exhaust gases may not impair pilot vision at night due to glare.

3.4.2.1 Discussion of recommended changes for §23.2600

The following is a discussion of the recommended changes to §23.2600.

(b):

New design aircraft may not need to have the controls and displays required by the Part 23 rule for safe operation. If this is the case, then these controls and displays should not be required. This is especially true if the system monitoring is automatic and corrective action is taken by the automation in the event of abnormal operations. It is envisioned that for many vehicles, when a failure occurs, the aircraft notifies the operator that maintenance is required on landing and no further action is required by the pilot.

(d):

Some configurations of VTOL aircraft may emit exhaust gasses that cause heat mirages that can impair operation or glare at night. §27.1121 (e) addresses this.

Although not directly related to control, this regulation is an overall requirement. As such, if a design meets the individual controllability requirements, but the overall handling characteristics require excessive concentration, skill, alertness, or causes fatigue, then §23.2600 (a) would apply to the general HQ of the aircraft. An aircraft may meet the controllability requirements, but in doing so, excessive concentration, alertness is required, or it is fatiguing. These characteristics are not addressed in the controllability rule but directly affect the HQ of the aircraft.

3.4.3 §23.2510 Equipment, systems, and installations.

Part 23 as written

For any airplane system or equipment whose failure or abnormal operation has not been specifically addressed by another requirement in this part, the applicant must design and install each system and equipment, such that there is a logical and acceptable inverse relationship between the average probability and the severity of failure conditions to the extent that:

(a) Each catastrophic failure condition is extremely improbable;

(b) Each hazardous failure condition is extremely remote; and

(c) Each major failure condition is remote.

3.4.3.1 Recommended changes to §23.2510

The following text replaces §23.2510.

This section applies generally to installed equipment and systems unless a section of this part imposes requirements for a specific piece of equipment, system, or systems.

§23.2510 (a) The equipment and systems required for an aircraft to operate safely in the kinds of operations for which certification is requested (Day VFR, Night VFR, IFR) must be designed and installed to—

> (1) Meet the level of safety applicable to the certification and performance level of the aircraft; and
>
> (2) Perform their intended function throughout the operating and environmental limits for which the aircraft is certificated.

§23.2510 (b) The systems and equipment not covered by paragraph (a), considered separately and in relation to other systems, must be designed and installed so their operation does not have an adverse effect on the aircraft or its occupants.

§23.2510 (c) For all FBW control systems, the probability of a failure of the flight control system that causes a catastrophic event shall be no more than the following.

- Level 1 used primarily for pleasure or recreation: $< 10^{-6}$
- Level 1 not used primarily for pleasure or recreation: $< 10^{-7}$
- Level 2: $< 10^{-7}$
- Level 3: $< 10^{-8}$
- Level 4: $< 10^{-9}$

1. The maximum probability for a hazardous event may be 10 times that of a catastrophic event.
2. The maximum probability for a major event may be 100 times that of a catastrophic event.
3. The maximum probability for a minor event may be 1000 times that of a catastrophic event.
4. There is no probability requirement for events that provide no safety hazard.

If the propulsion system is used to control the aircraft, provide lift, augment lift (thrust vectoring, blown flaps, etc.), or affects control of the aircraft, the propulsion system is considered part of the control system for the purposes of this part.

For the purpose of this part, a pilot is considered to be part of the flight control system and represents a probability of failure equal to 0.7 failures per 100,000 flight hours. The pilot failure is considered to exhibit two failure modes, 1) inaction by the pilot and 2) erroneous action by the pilot. When considering pilot failures, the worst case of these two failure modes is to be considered.

No single event involving any system or component (including systems and components not associated with the control system) may cause a catastrophic event. Some examples of single events may be:

- An undetected manufacturing flaw such that the same flaw affects multiple sensors
- An undetected process flaw that affects multiple rotors
- A single software bug
- An incapacitated pilot
- A pilot action
- For an aircraft certified in icing, an event that overwhelms all pitot probes
- Jamming or loss of GPS

Structural fatigue and fatigue due to damage in normal operations and manufacturing flaws must be considered when calculating failure effects and probability of failures.

3.4.3.2 Discussion of recommended changes for §23.2510

To avoid confusion and ambiguity, actual probability numbers are specified for the various aircraft levels and operations in this recommended change.

To provide a safety level at least as good as today's general aviation accident rate, the following maximum probabilities of a failure causing a catastrophic result are proposed. The following assumes that all loss of control (LOC) and controlled flight into terrain (CFIT) accidents are eliminated but about 1/10th the number of LOC/CFIT accidents occur as a result of flight control system failures. Thus, the overall system safety is improved by about a factor of 10.

For reference, §23.2005 defines aircraft levels as follows.

- Level 1 – for aircraft with a maximum seating configuration of 0 to 1 passenger.
- Level 2 – for aircraft with a maximum seating configuration of 2 to 6 passengers.
- Level 3 – for aircraft with a maximum seating configuration of 7 to 9 passengers.
- Level 4 – for aircraft with a maximum seating configuration of 10 to 19 passengers.

Note that these probability levels are also the allowable failure probabilities specified in AC §23.1309 for class 1, 2, 3 and 4 respectively.

Note that flight instruction, business travel, or operations for compensation are not considered pleasure or recreation. Therefore, a 2-place aircraft that is used for flight instruction must be certified like a 2 to 6 passenger aircraft for reliability purposes.

This recommended change assumes there is no mechanical backup that can be used to land the aircraft safely. Therefore, the FBW control system is considered to be flight critical.

The maneuvers in the failure section also aim at verifying a hazard classification. Advisory Circular (AC) 23.1309 maps the effect a failure has on the crew to a hazard classification. The hazard classification then determines the reliability level and software design assurance level required for that system in that level of aircraft. In summary, this recommended change is intended to verify, through testing, the failures (and combinations of failures) tested are classified correctly for the purposes of the vehicle system safety analysis. The evaluations contained in this recommended change also apply for §23.2600.

3.4.4 Means of Compliance for recommended change §23.2135, §23.2600 and §23.2510

3.4.4.1 Introduction

This recommended change is intended to cover all of the Part 23 regulations that require qualitative pilot evaluation.

The only Part 23 amendment 64 regulations that specifically require qualitative evaluation are

- §23.2135 – Controllability, which requires that the airplane must be controllable and maneuverable, without requiring exceptional piloting skill, alertness, or strength, within the operating envelope.

- §23.2600 – Crew Interface, which requires … and perform any maneuvers within the operating envelope of the airplane, without excessive concentration, skill, alertness, or fatigue.
- §23.2510 – Hazard Level Determination, which uses crew workload as part of the determination of the appropriate hazard level for a failure.

The Part 23 rules do not define an acceptable level of concentration, alertness, skill, strength, or fatigue. This document is intended to provide guidance for determining an acceptable level of concentration, alertness, skill, strength, or fatigue as appropriate for each maneuver that is part of the normal operating envelope and part of a normal transportation mission. It is also intended to define standardized methods of evaluation relative to these definitions. As such, it is intended to be used as a MOC for §23.2135 and §23.2600, but it is not the only means.

This recommended change also includes criteria for validating the appropriate hazard level of a failure as determined by its effect on the pilot or aircraft performance.

It is not the FAA's role to determine an aircraft's suitability for any particular mission. However, some kind of maneuver set must be developed to evaluate an aircraft as it flies within its normal operating envelope as specified by the rule. A normal transportation mission is a common aircraft mission and contains maneuvers that are part of the aircraft's normal operating envelope. Therefore, a transportation mission is proposed as a framework to identify and develop maneuvers and tasks that make up the normal operating envelope. This mission is broken up into its task elements (MTEs – Mission Task Elements). One or more representative maneuvers are provided to evaluate each MTE.

This recommended change contains a collection of 26 MTEs. It is intended that this set is comprehensive for all of the certification tests that require qualitative (subjective) evaluation as opposed to only quantitative (objective) evaluation.

In addition to MTEs that typically occur on every transportation mission, MTEs are included that typically do not occur in every transportation flight but which none the less, may occasionally be a part of a transportation mission (for example a sudden maneuver to avoid traffic).

The recommended change also recognizes the fact that some aircraft may have specific characteristics or missions that require MTEs that are not listed here. To accommodate that, the last listed MTE is "any other test required by the administrator". This is not intended to be a "blank check" for the FAA. It is intended to cover unique handling characteristics or mission elements not covered in the list of transportation mission task elements.

Each of these MTEs contains a set of one or more representative maneuvers. Each maneuver description also contains required performance criteria for that maneuver. The set of maneuvers are designed to cover the entire flight envelope of the aircraft.

3.4.4.2 Background and applicability

This recommended change is intended to apply to general aviation aircraft (including VTOL aircraft) designed as transportation vehicles and which possess advanced FBW control systems that may not mimic the operation of mechanical control systems, and therefore, may not meet the requirements of Part 23 amendment 64. As such, it tests the vehicle's HQ based on the requirements of a typical transportation mission and the HQ expected by the target pilot group.

Although Part 23 allows for FBW control systems, it assumes that these control systems will mimic the handling characteristics of mechanical control systems. FBW technology allows the development of controls that are much different from mechanical controls, and which may be significantly easier for pilots to learn to fly and maintain currency. The requirements of the stability, trim and stall sections of this recommended change are designed to apply to FBW systems that do not mimic mechanical control systems. The MTEs of this section also reflect this.

In summary, the above referenced recommended change for FBW aircraft that replace the existing Part 23 requirements for stability, trim and stalls that are based on mechanical controls with the following.

1. Each axis must be statically stable about its commanded reference independently of any other axis. (Stability)
2. Each axis must be dynamically stable such that it does not increase the pilot's workload during normal operations or endanger the aircraft or occupants. (Stability)
3. For long term steady state operations, a means must be provided to achieve zero force at the pilot inceptor. Short term operations like changing direction (laterally or vertically) and moving while hovering may require a force. (Trim)
4. Any control input must always result in aircraft motion in the same direction as the control input. (Stall)

3.4.4.3 Practical application

This section of the recommended change is designed to demonstrate that the design is capable of performing all of the maneuvers required for a typical transportation mission and is controllable through these maneuvers without requiring exceptional piloting skill, alertness, or strength as required by §23.2135 and §23.2600.

3.4.4.4 Applicability for VTOL aircraft

Even though an aircraft may have vertical flight capability, not all of the hovering maneuvers may be appropriate if the aircraft has either AFM or practical limitations on hovering time. For such aircraft, hovering may be limited to a transient condition for takeoff and landing only. For these aircraft, maneuvers that require extensive hovering time need not be evaluated. See the introduction section concerning the application of this recommended change to VTOL aircraft for more discussion.

3.4.4.5 Applicability to control modes

This document applies to all control modes, including automatic control modes. Some new configurations have control systems that automate some flight functions (for example, heading hold, altitude hold, doing the last part of an approach to landing, or doing a takeoff to a given height). These functions may work like an autopilot function or may be part of the basic flight control system for a FBW aircraft. These new aircraft can cause a blurring of the traditional boundary between manual flight and automated flight. This document applies to all control modes (manual, automatic, or any combination of manual and automatic) and applies the same criteria to all of them. Thus, there is no distinction between flight control modes as far as controllability requirements are concerned. The exception is flight control modes that result from a failure. These are discussed separately in the failures section.

3.4.4.6 General Means of Compliance description

A typical transportation mission is broken down into its MTEs. The procedure is to fly the aircraft through a series of HQTEs that represent the MTEs, which in turn represent maneuvers that the aircraft is expected to perform during a normal mission. Regulations §23.2135 (controllability) and §23.2600 (crew interface) specify that the aircraft shall not require exceptional piloting skill, alertness, or strength for normal operations. For all HQTEs, a qualitative evaluation of the specified task is conducted. This evaluation is intended to determine whether or not exceptional piloting skill, alertness, or strength is required to perform any normal task element of a normal transportation mission to acceptable performance criteria.

Special attention should be paid to configuration changes, control mode changes, and control or aerodynamic discontinuities (such as envelope protections).

3.4.4.7 Evaluation criteria

In all cases, the aircraft shall respond quickly to the control input, move in the direction of the control input, and be heavily damped to avoid man machine coupling (pilot induced oscillations).

During the flight tests, the aircraft shall

1. Provide initial motion in the direction of the command.
2. Provide the initial response within 200 ms of the command.
3. Not reverse direction until passing the command (small overshoots with correction are allowed).
4. Not exhibit delays between the command and the response such that it may induce pilot induced oscillations.
5. Not exhibit oscillations that increase pilot workload. For pitch attitude, oscillations shall damp to less than 1/10th amplitude in less than three cycles. For vertical and longitudinal speed, oscillations shall not be divergent and shall have a period of more than 10 seconds
6. Not exhibit any movement that is not negligible in the direction opposite of the command.
7. Not exhibit residual oscillations that negatively affect pilot performance. Residual oscillations greater than 0.5 degrees or 0.05 Gs at the pilot station are considered excessive (ref ADS-33E-PRF para 3.1.17).

Minor momentary deviations from the command are acceptable during configuration changes.

There are usually two parts to the evaluation criteria – performance criteria (quantitative) and a qualitative HQ evaluation. Some tests do not include specific performance criteria, but all tests include a qualitative HQ evaluation. When there are performance criteria, these criteria are usually the same performance criteria used for an ATP check ride, and the HQ evaluation is to be conducted while accomplishing the performance criteria. The test pilot must demonstrate that the aircraft can meet the performance requirements during normal operations for the aircraft to be certifiable. The evaluation pilot will determine whether exceptional pilot skill, alertness or strength as referenced in §23.2135 and §23.2600 is required to achieve the required performance level while executing the maneuver. If the required performance criteria are not met, then the aircraft is typically not certifiable – independent of the HQ evaluation.

The performance criteria generally assume smooth air or a constant wind. As with the airman check ride performance criteria, momentary deviations from the performance criteria are allowed, and allowances can be made for turbulence.

3.4.4.8 Performance standard

The performance standard for all task elements is the same as is in the airplane ATP Airman Certification Standards (ACS) or helicopter ATP Practical Test Standards (PTS) as appropriate unless the task element specifically requires a different standard. However, in all cases the performance shall meet or exceed the respective ATP performance standard. This is consistent with the FAA transportation mission. The reason for this standard is that §23.2600(a) requires that maneuvers be conducted without excessive concentration. It is expected that test pilots doing the evaluations will have skills at or above the ATP level. It is assumed that if highly experienced test pilots can fly an aircraft to ATP standards, then less experienced pilots can fly to normal standards without excessive concentration. In addition, it is expected that pilots skilled at the ATP level will be able to use the aircraft in question for an ATP check ride. Therefore, it is appropriate that the aircraft is capable of performing to the ATP standards with a skilled pilot.

The task elements are to be done using all control modes. This includes automation modes. During a flight check it is expected that some of the flight will be conducted using the available automation. Therefore, the automation should fly to ATP standards for it to be usable during ATP flight checks.

For all performance, allowance may be given for turbulence and gusts – just as it is for pilot certification tests.

3.4.4.9 Evaluating for the target pilot group

The evaluation pilot should be very careful when evaluating aircraft intended for reduced pilot training (SVO – simplified vehicle operations - aircraft). These aircraft may have characteristics that are designed with operating characteristics intuitive to people without pilot experience and therefore may be counterintuitive to pilots with significant experience flying conventional aircraft. The evaluations should be made from the perspective of the target pilot's perspective – not the evaluation pilot's expected response model.

This may mean that the evaluation pilot provides a "certifiable" determination despite the fact that it was difficult for the evaluation pilot to meet the performance criteria due to having to concentrate to fight muscle memory developed from experience flying conventional aircraft.

For example, an aircraft's control system may be designed such that it requires constant inceptor force or displacement to command a turn. This is the same control concept that is used for nearly all surface vehicles (cars, motorcycles, boats, etc.) and therefore may be very intuitive for pilots without previous aircraft experience. In conventional aircraft, an inceptor force or displacement commands bank rate, and when the desired bank angle is achieved, the pilot holds neutral force and displacement. Thus, the experienced pilot may find the surface vehicle control concept in an aircraft to be very counter-intuitive. The experienced evaluation pilot may find that the surface vehicle concept adds to their workload. However, this control concept may be exactly what the target pilot group needs for reduced training, reduced workload, and ease of operations because it is consistent with all of their previous experience operating vehicles.

Another example of this may be the evaluation of a VTOL aircraft by an evaluation pilot with significant helicopter experience. The evaluation aircraft may have a control system very similar to a hobby drone. This is very different from a helicopter and as such may significantly increase the workload for the evaluation pilot. However, someone from the target pilot group may find this type of control system extremely easy to fly.

An FAA evaluation pilot may need additional time in the applicant's simulator to overcome muscle memory or experience bias for flying vehicles with novel control mapping.

The amount of strength required should also be evaluated to be appropriate for the target pilot group and inceptor characteristics. This includes both short term and long-term fatigue aspects.

Another interesting aspect of evaluations for a target pilot group is the concept of the vehicle potentially being evaluated by people specifically not in the target group. An analogy of this may be an airplane pilot with no helicopter experience being asked to evaluate a helicopter. Undoubtedly, the airplane pilot with no helicopter training would give the helicopter a very different rating than an experienced helicopter pilot. The question then becomes, is the rating given by the airplane pilot valid? The same could be true for an FAA test pilot evaluating a machine with a control system and stability characteristics that have not existed before. Just as an airplane pilot can be trained to become a proficient helicopter pilot, the FAA pilot can undoubtedly be trained to become a proficient pilot of the new design. The question is then how much training is required? Current FAA training requirements for transitioning from airplane to rotorcraft or rotorcraft to airplane may be consulted as a guide. In addition, HQ that are unique to a type or model do not need to be disqualifying and may be delt with through training. Examples of this are the Special Federal Aviation Regulation (SFAR) 73 for the Robinson R22 and R44 models as well as SFAR 108 for the Mitsubishi MU-2.

In addition, HQ discontinuities may not be disqualifying. The training associated with the aircraft can be taken into account when making this determination. For example, in a conventional airplane, a stall is a discontinuity that can be fatal, but through training, the FAA allows airplanes with this behavior and regulates the aircraft behavior after the discontinuity occurs. Likewise, for helicopters with teetering rotors catastrophic mast bumping is possible in normal operations but this is mitigated through training. These highlight the link between aircraft certification and training for new aircraft types.

A very important concept for evaluation pilots is that the evaluation pilot must have an equivalent amount of training and experience in the aircraft being evaluated as would be expected of a pilot licensed to fly that aircraft. This means that if a new category of license or new type rating or special training is required for this aircraft, the evaluation pilot must have substantially met the training / licensing requirements for this aircraft before doing the evaluation.

3.4.4.10 Required information and configuration for flight test

Before the procedure, the applicant will define

1. Weight and CG range for allowed operations including lateral CG
2. The most critical weight and CG location(s) for each test condition
3. Allowed aircraft configurations
4. Speed range for each allowed configuration
5. Altitude range for each configuration
6. Configuration (note definition of configuration described in Section 3.1.2) transition points and the conditions that cause the transition if not pilot controlled
7. Flight conditions where the aircraft prevents configuration transitions even if commanded by the pilot (if any).

3.4.4.11 Flight test procedure

The tests will be conducted at the most adverse weight and CG location (both longitudinal and lateral) for the configuration and flight condition tested.

The tests will be conducted at the minimum power available. This shall include environmental conditions (altitude, temperature) and system states (level of charge, temperature of batteries or motors, discharge capability with age, engine wear, manufacturing tolerances, etc.).

If there are conditions where control power is limited or nearly limited, then the test aircraft shall be adjusted to provide the minimum control power. This may be through mechanical rigging, limiting control input during the test, special test software, or other methods.

For many aircraft, the pilot is part of a “control loop” that includes sensors and displays as well as control inceptors and effectors. Therefore, HQ evaluations must include these components. Part 23 specifically deals with this in the pilot interface section with §23.2600 (a) by stating the following.

(a) The pilot compartment, its equipment, and its arrangement to include pilot view, must allow each pilot to perform his or her duties, including taxi, takeoff, climb, cruise, descent, approach, landing, and perform any maneuvers within the operating envelope of the airplane, without excessive concentration, skill, alertness, or fatigue.

It is expected that in the course of a normal certification program that most of these test conditions will be evaluated without doing specific tests. This document is intended to be a checklist to ensure that no mission task element evaluations fall through the cracks. For instance, in the course of a certification program many VFR landings will be made. It is appropriate for the test crew to indicate that the VFR landing item is satisfactory without indicating a specific test on a specific flight. VFR landings will obviously be evaluated many times (informally if not formally) during the course of a certification program. Other items in the list may not be. All items that are part of a normal transportation mission are included in the list of MTEs for completeness.

Particular attention should be devoted to areas that may contain stability, control, or HQ discontinuities. Although the tests in the Appendix are intended to be comprehensive, it is impossible to create a generic document such as this, which covers all possible design concepts and their potential deficiencies. The evaluator must know the aircraft, its control system, and its characteristics so they can examine areas where HQ deficiencies may exist. Of particular interest should be flight conditions where control laws change, methods of control change, aerodynamic configuration changes, method of propulsion changes, method and source of lift changes, and other areas where changes might affect handling characteristics.

3.4.4.12 Familiarity with the evaluation aircraft

Before conducting these evaluations, the evaluation pilot should be familiar with the aircraft in a manner that a pilot who has just finished a complete checkout in the aircraft would be. Since the pilot is expected to be very familiar with the aircraft, it is acceptable to use aircraft specific procedures during these evaluations. The use of these kinds of procedures is illustrated by the following two examples. For a Beech Bonanza, in level flight, lowering the landing gear produces about a 3-degree descent path with no change in power, speed or trim, thus, flying an ILS approach with the gear up until intercepting the glide slope and then extending the gear reduces pilot workload. In a Mooney Ovation with a G1000 autopilot, holding the electric trim switch in the up direction as flaps are lowered produces very low trim forces through the configuration change. Thus, when lowering flaps the pilot can proactively run electric trim to reduce workload. These aircraft procedures can reduce pilot workload. They should be used by pilots who fly these airplanes.

3.4.4.13 Data collection

Hand recorded data or electronically collected data is acceptable.

For the flight tests, record at least the

1. initial conditions of each test
2. description of the maneuver
3. deviation from the target (distance from landing spot, maximum glideslope and localizer deviation, altitude excursion, etc.)
4. wind speed and direction

3.4.4.14 Results format

Any format that shows that the aircraft meets the intent of §23.2135 is acceptable.

Because many of the maneuvers in this section will be informally evaluated during the course of a normal certification program (such as VFR landing), a suggested way to document completion of the MTEs is to create a spreadsheet with each test condition listed. The test condition can be addressed by listing a flight number and test condition number for a formal evaluation, or by noting it was informally evaluated on multiple flights, or any other appropriate indication that the condition was considered. The point is not to formally evaluate each condition; it is to make sure each of the conditions is considered.

3.4.5 Required Mission Task Elements for transportation aircraft

This section contains a comprehensive set of maneuvers that represent the complete set of MTEs that make up an FAA transportation mission. A task element may contain multiple test conditions and may require multiple flights to complete. Many of the task elements are informally evaluated during the normal course of a flight test campaign and therefore need not be formally evaluated.

Note that all of the listed MTEs are representative of a transportation mission. There are no maneuvers listed that are not a part of a normal transportation flight. Many HQ evaluations tests – especially those done for military aircraft – include maneuvers such as pitch pointing, pirouettes, rapid periodic direction changes, and diagonal hovering. These kinds of maneuvers may be very helpful in evaluating the ability to point the aircraft for specific purposes but are not required for the transportation mission. These kinds of maneuvers may be included in an evaluation to assist the applicant in creating a list of maneuvers that are not approved if appropriate. For example, an evaluation pilot may determine that pirouettes require excessive pilot skill, in which case the applicant may prohibit pirouettes thereby eliminating them from the flight envelope referenced by the rule. In another example, a bobbing up and down maneuver in hover may uncover an unacceptable anomaly. In this case, the applicant may prohibit bobbing up and down maneuvers in hover, thereby eliminating this maneuver from the flight envelope referenced by the rule. Because aircraft are designed to the regulations, unnecessary maneuvers should not be included in the regulations. An example of this could be a designer that wants to build a machine that can hover but can only hover forward relative to the ground for safety and ease of training (like an airplane can only taxi forward relative to the ground) this forces the aircraft to only go in the direction of good visibility. If a pirouette or diagonal hover maneuver is listed as a required maneuver, then the aircraft with this safety feature could not be certified. The applicant would need to negotiate the removal of this maneuver, which provides extra certification risk or abandon the safety concept. This then becomes a disincentive to provide innovative safety features.

3.4.5.1 MTE 2135-1 Aircraft start

Preflight checks

All of the preflight checks required by the Flight Manual shall be evaluated. If the aircraft does not require a crewmember other than a single pilot, all of the preflight checks in the Flight Manual must be designed such that a single person can accomplish these checks without use of tools that are not a required part of the aircraft and have a specific place to be stowed on the aircraft. For instance, a receptacle for taking a fuel sample is allowed if there is a place on the aircraft designated for storage of that receptacle and such a receptacle is required for flight. A ladder to get up to an oil reservoir sight glass or dip stick is not allowed for this evaluation unless a ladder is part of the required equipment and there is a place to store the ladder on the aircraft.

Preflight checks shall be designed such that people with characteristics typical of the expected operators can easily accomplish these tasks. Characteristics to consider are height, strength, reach, balance, dexterity, flexibility, and other physical limitations. People representing height and weight characteristics from the 5th percentile to the 95th percentile of the adult population should be considered except that people who exceed the approved weight per seat need not be accommodated for this task element.

For the purpose of this requirement, preflight checks include fueling the aircraft, charging or exchanging its batteries, or replenishing its energy source. If exchanging its energy source requires special tools that are not part of the aircraft, then these are allowed if they are always available as part of the replenishing process.

Hand-held flashlights shall not be required to examine items during daylight.

Starting

If the Flight Manual does not require a crewmember other than a single pilot, then the entire staring operation shall be conducted from the pilot station. The starting procedure shall be such that a pilot's attention is not required in more than one place at a time and if there are any limitation exceedances or abnormal occurrences during the start process, that this fact is clearly and prominently displayed to the pilot and latched at least until the pilot acknowledges it. If the exceedance normally requires a maintenance action (including an inspection), the display shall be shown until the maintenance action is accomplished (a master maintenance reset that cannot be reached from inside the aircraft is acceptable). Examples of such exceedances may be a turbine engine that temporarily exceeds the starting temperature limit, a piston engine that is connected to a transmission through a clutch and over speeds during startup before the clutch is engaged, a power distribution circuit breaker that trips and then resets itself. Some examples of abnormal occurrences are a higher than expected current during a rotor runup check, lower oil pressure than expected, etc.

Energy management planning for the intended flight and contingencies

The aircraft shall provide a means to predict the energy available compared to the energy required to complete the proposed mission if it requires more than simple mental math. The proposed mission includes provision for a go around flight to an alternate and appropriate reserve. Different aircraft types using different energy technologies may have very different ways to calculate this.

For example, a very simple gas-powered airplane without vertical capability may indicate in the Flight Manual that it burns 4 gallons per hour and cruises at 120 kt. If the pilot knows that the destination is 60 miles away, and there is an alternate 10 miles from the destination, then he/she can readily estimate that 6 gallons is more than enough. If the fuel gauge indicates that there is

10 gallons in the tank, then she/he has the required energy. This only requires simple mental math and therefore an on-board energy reserve calculation device is not required.

For a different example, a battery powered VTOL aircraft may have a power pack for which energy available cannot be determined by voltage level alone – it may require a history of current supplied by the battery since its last charge. The proposed flight profile may also have a significant effect on the amount of energy required for a given distance. In this example, the destination may require a near vertical descent from a considerable height above the touchdown zone. This may require much more energy than a shallow descent and therefore the type of approach may have a significant effect on the energy required to complete the mission – this is especially true if a go around is required in which the go around is a vertical accent. The choice of an alternate may also depend on the type of approach and landing available (high energy vertical decent and touchdown or low energy with run on landing). All of these factors make an accurate estimation of required vs available energy well above the level of simple mental math. Therefore, in this example an onboard computing device would be required to calculate required vs. available energy.

3.4.5.2 MTE 2135-2 Taxi to a location from which a takeoff is performed

This evaluation shall be conducted using wheels or hovering or both depending on the aircraft's approved method(s) of taxiing.

Although the mission task element is to taxi from an initial location to a location from which a takeoff can be performed, this task need not actually end at a takeoff location. The intent is to demonstrate that the aircraft can in fact taxi with good handling characteristics.

The task is to taxi to the line and track along the line including corners. Turns in both directions should be included, and the aircraft should be exposed to wind of at least 17 kt from all directions. The aircraft is to stop within 10 ft of, but not past, a designated spot along the line (simulating a runway hold short line) and configure such that the pilot does not need to direct attention to holding that spot (set the brakes for wheels, set down and reduce lift power for skids, etc.).

Taxi ground speed should be between 6 and 10 knots. The ground line for taxi should consist of straight segments of at least 100 ft in length. Deceleration from taxi to hover (or stopping if in wheeled taxi) should be performed in one smooth maneuver.

Required performance:

- Track the line within 2 feet.
- Maintain a hover height ± ½ of the recommended hovering height when the recommended height is less than 10 ft and ± 5 ft when it is above 10 ft.
- Maintain between 6 and 10 kt after initial acceleration and before final deceleration.
- Stop within 10 ft of a designated spot without passing that spot.

Momentary deviations may be acceptable, and allowance should be made for gusts. The test should also be conducted near solid obstacles that reflect the aircraft's downwash, such as taxiing between a row of hangars or other structures.

3.4.5.3 MTE 2135-3 Execute a takeoff

This MTE includes the following maneuvers

- Transition to initial climb
- Failures that are not considered catastrophic
- Aborted takeoff
- Configuration changes that may occur automatically during a takeoff
- Configuration changes that are done as part of a takeoff (e.g. gear retraction)
- Transition to maximum angle climb
- Transition to maximum rate climb
- Transition to normal or cruise climb

For the purpose of this task element, a takeoff starts from a stop in position to takeoff with power at idle or equivalent and ends as the aircraft passes through 400 ft AGL.

The takeoffs preformed for this task element shall demonstrate that distances in the flight manual are conservative for both ground roll and total distance.

At least one takeoff in each approved configuration shall be evaluated. If a configuration change occurs automatically during the takeoff, or if a configuration change is part of the normal procedure, then the effect of the configuration change should be noted. Some examples of configuration changes would be retraction of landing gear or flaps, changing the tilt of rotors, starting, stopping, or changing the power used for aerodynamic blowing, transitioning from rotor lift to wing lift, etc.

Failures of control systems and propulsion systems that are not considered catastrophic shall be simulated at the most critical time to verify that the aircraft is controllable though the failure and that the required workload is consistent with the hazard classification of that failure.

Aborted takeoffs shall be evaluated up to V_1 or V_r as appropriate for aircraft that have wheels and V_x for configurations that do not have wheels. For aircraft approved for a skidding takeoff, aborted takeoffs shall be evaluated up to V_y.

For configurations with vertical takeoff capability, a rejected takeoff shall be conducted with the aircraft accelerating at low altitude until reaching V_y and then decelerating to a hover as quickly as practical.

For aircraft with vertical takeoff capability, a vertical takeoff to just out of ground effect and then an immediate landing back in the same spot shall be conducted. This shall also be done on a sloped surface with the aircraft just leaving the ground and then sets back down.

For all approved configurations, rejected takeoffs shall be evaluated with the rejection occurring just after the aircraft leaves the ground.

For each approved configuration, a takeoff shall be evaluated with transition to maximum angle of climb as quickly as possible consistent with the published procedure, to maximum rate of climb consistent with the published procedure and to a normal climb as prescribed by the published procedure.

During all takeoffs the aircraft shall remain within 5 ft of the centerline of the runway until liftoff and then within 5 degrees of heading or track after liftoff.

Except for aborted takeoffs, the aircraft shall not descend until 400 ft AGL. It may level off to accelerate.

At least one rejected takeoff in each approved configuration shall be evaluated with wind of at least 17 kt from the most critical direction.

Of particular interest are handling characteristics for aircraft that transition from airmass referenced commands to ground referenced commands.

The manufacturer’s procedure for an aborted takeoff will be used.

For aircraft with wheels, if there is no published procedure, the pilot shall initiate the takeoff using maximum practical acceleration and when the appropriate speed is reached, apply maximum deceleration (brakes and / or drag devices).

For hovering takeoffs, if there is no published procedure, the pilot shall lift to a hover at the appropriate height for that aircraft and apply maximum practical acceleration. At the appropriate speed, initiate an aborted takeoff. Maintain less than 75 ft altitude. If there is no published aborted takeoff distance for a hovering takeoff, the aircraft shall accelerate to 50 kt and then decelerate to hover within 800 ft. For aircraft that use pitch attitude to control longitudinal accelerations, pitch attitudes of more than 20 degrees shall not be used (unless specified by the manufacturer).

Required performance:

- During a rolling takeoff, track the centerline within 5 ft during normal operations.
- During a rolling takeoff, track the centerline within 30 ft during failures that are not classified as catastrophic (from AC 25-7D V_{mcg} tests).
- For hovering takeoffs track the centerline within 30 ft (normal and aborted).
- Maintain heading within ± 5 degrees.
- Maintain published target climb speed within + 5 -0 kt when not accelerating.
- Takeoff distance less than the published distance for the current conditions.
- Rejected takeoff less than the published distance for the current conditions.

Momentary deviations may be acceptable, and allowance should be made for gusts.

3.4.5.4 MTE 2135-4 Transition to a constant altitude from a climb

Transition to a constant altitude from each of the following climb conditions:

- From maximum angle climb
- From maximum rate climb
- From normal climb

The transition should be evaluated starting from each approved configuration for climb.

Required performance:

- Maintain the desired heading within ± 5 degrees.
- Level off at and maintain the desired altitude within ± 50 ft
- Maintain speed within + 5 knots

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.5 MTE 2135-5 Transition to an emergency descent from a climb

From a stabilized climb in each of the above conditions, transition to a stabilized emergency descent as quickly as practical while respecting the G limits of the aircraft.

- From maximum angle climb
- From maximum rate climb
- From normal climb

The transition should be evaluated starting from each approved configuration for a climb.

For the purpose of the task element, configuration changes required to get to the emergency descent configuration shall be made at the most critical time. For manually selected configuration changes, common pilot errors (especially timing errors) should be considered.

These maneuvers shall be conducted with a sense of urgency consistent with a real emergency that would cause a pilot to initiate an emergency descent such as a fire in the cockpit.

Required performance:

- Establish and maintain the desired speed within ± 5 kt but not to exceed any published limitations.
- Maintain the desired heading within ± 5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.6 MTE 2135-6 Level flight acceleration

Start with the aircraft at the slowest practical speed for level flight and accelerate at constant altitude to the fastest practical speed for level flight.

Conduct this test at an acceleration rate of about 1 kt per second.

Conduct this test at the fastest acceleration rate the aircraft can achieve and still meet the required performance.

The tests should be done at the maximum power to weight ratio and at the minimum power to weight ratio. Note that for electric aircraft the power available will likely depend on the condition of the batteries. They should also be done at the most critical CG if CG has an effect on handling characteristics during accelerations.

The test is intended to cause the aircraft to go through configuration changes rapidly and slowly. Particular attention should be directed to transients that may cause handing qualities changes.

The aircraft should not be capable of accelerating faster than its configuration changes can keep up, such that it exceeds a configuration’s maximum speed without pilot intervention to slow the rate of acceleration. As an example: The vehicle should not accelerate beyond V_{fe} before the flaps have time to retract.

This test shall be conducted using all approved control modes.

Required performance:

- Maintain the desired heading within ± 5 degrees.
- Maintain the desired altitude within ± 100 ft while accelerating.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.7 MTE 2135-7 Extended level flight at constant speed

This evaluation should be done at high-speed cruise, maximum range cruise and loiter speeds. It need not be done for each configuration – only the configuration chosen by the applicant for each of the above speeds. The intent is to verify that flying the aircraft in the above conditions over an extended period does not result in fatigue.

The evaluation should be conducted in actual instrument meteorological conditions if the aircraft is approved for instrument flight rules (IFR).

The time required for the evaluation is that represented by the longest reasonable mission for the aircraft.

The task should be conducted while navigating along a preplanned route using navigational guidance. Altitude changes due to Air Traffic Control (ATC) requirements while doing the test are allowed.

Because of the time component of this evaluation, the evaluation should focus on the amount of attention required to maintain flight within the specified parameters. Periodically during the flight, the pilot should be required to perform other flight related tasks such as re-planning the flight to avoid unexpected weather.

Any flight control mode that is required to be operational for dispatch may be used for any or all parts of the evaluation. If the flight control modes required to be available for dispatch allow the level flight part of the flight to be conducted without active pilot input, or with only occasional input, then this evaluation need not be conducted. However, failure of flight modes that reduce pilot workload must be considered as part of the system safety analysis.

Required performance:

- Maintain the desired heading within ± 5 degrees.
- Maintain the desired altitude within ± 100 ft.
- Maintain the desired speed ± 10 kt.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.8 MTE 2135-8 Level flight deceleration

Start with the aircraft at the fastest practical speed for level flight and decelerate at constant altitude to the slowest practical speed for level flight.

Conduct this test at a deceleration rate of about 1 kt per second.

Conduct this test at the fastest deceleration rate that the aircraft can achieve. Deploy drag devices so as to decelerate as rapidly as possible.

The tests should be done at the maximum weight and at the minimum practical weight. They should also be done at the most critical CG if CG has an effect on handling characteristics during decelerations.

The test is intended to cause the aircraft to go through configuration changes rapidly and slowly. Particular attention should be directed to transients that may cause handing qualities changes.

The aircraft should not be capable of decelerating faster than its configuration changes can keep up, such that pilot needs to intervene to arrest the deceleration rate to avoid a stall or other control discontinuity.

This test shall be conducted using all approved control modes.

Required performance:

- Maintain the desired heading within ± 5 degrees.
- Maintain the desired altitude within ± 100 ft while decelerating.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.9 MTE 2135-9 Transition to an emergency descent from level flight

- From level flight at each of the above conditions, transition to a stabilized emergency descent as quickly as practical while respecting the G limits of the aircraft.From slow speed
- From maximum cruise speed

The transition should be evaluated starting from each approved configuration for level flight.

For the purpose of the task element, configuration changes required to get to the emergency descent configuration shall be made at the most critical time. For manually selected configuration changes, common pilot errors (especially timing errors) should be considered.

These maneuvers shall be conducted with a sense of urgency consistent with a real emergency that would cause a pilot to initiate an emergency descent such as a fire in the cockpit.

Required performance:

a. Establish and maintain the desired speed within ± 5 kt but not to exceed any published limitations.
b. Maintain the desired heading within ± 5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.10 MTE 2135-10 Transition to a normal descent from level flight

Transition to a stabilized normal descent from level flight for each of the following conditions. This will usually result in an acceleration for aircraft that cannot cruise at their speed limit.

- From slow speed
- From high speed

The transition should be evaluated starting from each approved configuration for level flight.

The desired descent rate is the normal descent rate specified by the manufacturer. If the published procedure is a power / speed condition instead of a target vertical speed, the aircraft shall be stabilized on the condition and the resulting vertical speed shall be noted and maintained for at least 1,000 ft. or 2 minutes whichever is longer.

Required performance:

- Establish and maintain the desired speed within ± 5 kt but not to exceed any published limitations.
- Maintain the desired heading within ± 5 degrees.
- Maintain the desired descent rate ± 100 ft/min or ± 10% of the desired descent rate.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.11 MTE 2135-11 Transition to level flight from a descent

- From either a normal or an emergency descent, level off and maintain speed if practical. If not practical maintain speed as fast as practical.

The transition should be evaluated starting from each approved configuration for descent. The descent should be stabilized before the level off is started.

Required performance:

a. Maintain the desired heading within ± 5 degrees.
b. Maintain the desired altitude within ± 100 ft while decelerating.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.12 MTE 2135-12 Typical VFR traffic patterns

For the purpose of this section, the following illustration from the FAA Aeronautical Information Manual (AIM) Section 4-3-1 identifies the parts of a typical VFR traffic pattern (Figure 5).

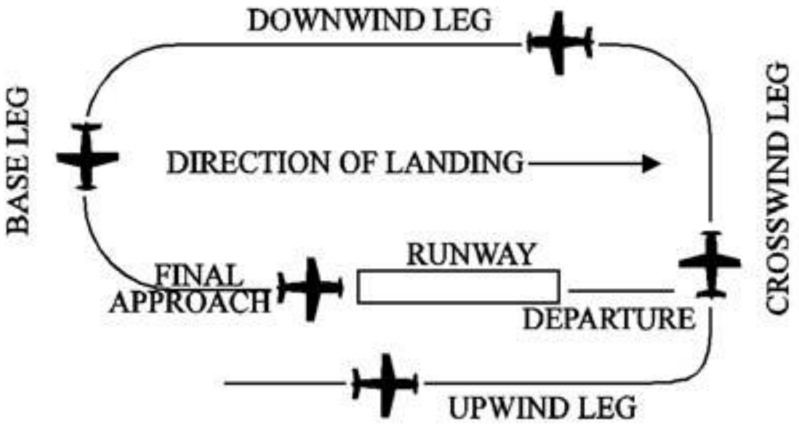


Figure 5: Parts of the VFR pattern from the AIM

<u>Overhead entry</u>

Starting from 1,000 ft AGL on a track approximately 90 degrees to the direction of landing, cross over the intended landing spot at low cruise speed in the cruise configuration but no more than 200 KIAS. Execute a normal visual flight rules (VFR) pattern consisting of downwind, base, and final segments. Configuration changes should be initiated at the beginning of turns if configuration changes are pilot controlled. The aircraft should be at V_{ref} for the short final configuration before reaching a point about 1000 ft from the touchdown spot. If there is a maximum speed for drag devices (flaps, gear, etc.) then the initial speed need not be greater than the maximum speed for the first drag device. Conduct the test using both left and right turns.

<u>Downwind entry</u>

Start from abeam the intended touchdown spot on a track parallel to the direction of landing at 800 ft AGL in the cruise configuration at low cruise speed but no more than 200 KIAS. Start a deceleration abeam the touchdown point and change configurations as needed. The aircraft should be at V_{ref} for the short final configuration before reaching a point about 1000 ft from the touchdown spot. If there is a maximum speed for drag devices (flaps, gear, etc.) then the initial speed need not be greater than the maximum speed for the drag device with the highest deploy speed. Conduct the test using both left and right turns.

Short approach to enter on base

Conduct a visual approach to enter a 3-mile base (a 2 to 2.5-mile final leg) from about a 45-degree angle at about ½ to 1 mile from the centerline of the final approach path. Start from a speed and configuration appropriate for the aircraft. At least one configuration change is expected through this maneuver. The aircraft should be at V_{ref} for the short final configuration before reaching a point about 1000 ft from the touchdown spot. The vertical approach path may include level segments to decelerate. Conduct the test using both left and right turns.

Expedited approach from 5 miles to enter on base

Start this test with an initial position about 5 miles from the landing spot, about 1500 ft AGL, at cruise speed or 250 kt whichever is less and on an initial track perpendicular to the direction of landing. Execute an approach to landing from this initial condition so as to get to the landing spot in the minimum practical amount of time. The test is complete at 1000 ft from the touchdown spot with the aircraft at V_{ref} for the short final configuration before reaching a point about 1000 ft from the touchdown spot. Conduct the test using both left and right turns. Executing the approach in the absolute minimum possible time is not the objective. The objective is for the aircraft to transition from high speed through the required configuration and speed changes as rapidly as would be expected to be reasonable during normal operations.

Entering on short final

Establish the aircraft in the final approach configuration and V_{ref} for the short final configuration at 2 miles out along the final approach path. Maintain the minimum commandable speed or V_{ref} minus 10 kt to a point 1000 ft from the touchdown point. The vertical path should be smooth but may include an increase in descent angle when near the touchdown point.

VTOL entering on short final

When a VFR approach to a vertical landing is conducted, the final approach speed shall be the minimum IFR speed if the configuration has one, or 50 kts if it does not (note: many IFR certified helicopters have a minimum IFR speed of 50 to 60 kt and copter approach design requirements assume a maximum speed of 70 kt at the missed approach point).

This set of maneuvers is expected for each final approach configuration. For the purpose of this test, the final approach configuration is the intended configuration of the aircraft at 1000 ft from the touchdown point.

Required performance:

a. Maintain the desired speed within ± 5 kt.
b. Maintain the desired altitude within ± 100 ft.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.13 MTE 2135-13 Steep approach

Start from level flight at cruise speed but no more than 200 kt and 1500 ft AGL and 5 miles from the landing zone.

- For aircraft with the steepest approach angle of less than 10 degrees, slow to approach speed and transition to the steepest approach angle approved for the aircraft. The aircraft shall intercept a glide path from which a normal landing can be made before reaching 500 ft AGL.
- For aircraft that can descend at an angle steeper than 10 degrees, slow to approach speed and descend at an angle no steeper than 15 degrees to a point from which a normal landing can be made. (Note: Vertical approaches to a landing are a part of the landing task element.)

The same aircraft may have multiple configurations approved for landing – some of which may support vertical landings and others that may require a roll-on landing. For these aircraft, the test needs to be conducted for each approved landing configuration.

Special attention should be paid to the handling characteristics as the aircraft slows, changes configuration and transitions to the descent.

Part of the intent of this task element is to demonstrate the aircraft’s characteristics when the aircraft is high and fast and needs to slow down and descend rapidly to a landing.

Required performance:

a. Maintain the desired speed within ± 5 kt.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.14 MTE 2135-14 Instrument approaches

This MTE is required for aircraft approved for instrument flight. It is optional for aircraft not approved for instrument flight. The following nomenclature is standard terminology for IFR flights, and each can be found in the Acronyms list.

- Tracking from FAF to MAP for ILS, LPV, LNAV/VNAV, LNAV+V
- Tracking for LOC, LNAV, VOR with altitude step downs
- Circling approach transition from short final to the runway

An approach using each type of guidance approved for the aircraft shall be conducted.

For at least one of the approaches that has a long straight in segment (for example, an ILS) a transition to the approach shall be done from level-flight cruise speed but not more than 200 kt at a 90-degree intercept angle at a point about 8 miles from the runway (3 miles outside the FAF). This intercept should be done from both directions and include at least one intercept with a tailwind of 20 kt or more (the tailwind is relative to the aircraft track before the intercept turn starts).

The approaches with step down fixes shall include at least one approach with a descent gradient as specified below (this is the maximum angle allowed when generating a civilian approach procedure per FAA order 8260.3D). If more than one configuration is approved for instrument approaches, then each configuration must be flown with the appropriate descent angle. The maximum descent angle should cover at least 800 ft. of altitude change. Note that to achieve these angles and range, the test crew may need to substitute test altitudes for published altitudes.

At least three types of circling approaches shall be conducted.

1. A sidestep approach with an offset of at least 500 ft. starting at the minimum visibility limit. Note that this may require doing a visual approach to simulate the sidestep if an airport with parallel runways is not available. For instance, an aircraft configured for a category A approach may conduct a visual approach to a point 400 ft AGL and 500 ft offset and 1 mile from the runway and then execute the sidestep from that point.
2. A straight in, downwind approach and then sidestep to a downwind leg to then land into the wind.
3. An overhead approach where the aircraft flies over the touchdown point on a track nearly 90 degrees to the direction of the final approach and executes a turning maneuver to land on a runway 90 degrees to the wind with a17 kt wind.

Circling approaches can transition from any type of approach. It is assumed for the purpose of this task element that the circling MDA is the circling altitude below and the visibility minima is the circling distance in the table below. All circling approaches shall be flown at the circling MDA and within the circling distance of the runway or touchdown point. Maneuvering for the circling approach cannot start until within the circling distance of the runway or touchdown point.

Table 7. Performance criteria for instrument approaches

Approach Speed ~ kt	Approach Category	Maximum Descent Angle ~ ft / NM	Maximum Descent Angle ~ Degrees	Circling Altitude	Circling Distance ~ SM
	Copter	800	7.5	400	½
80	A	682	6.4	400	1
90	A	606	5.7	400	1
120	B	446	4.2	500	1
140	C	400	3.77	500	1 ½
165	D	372	3.5	600	2
200	E	329	3.1	600	2

Performance criteria for the instrument approaches are the same as of that required in the appropriate ACS or PTS for an ATP license.

Approaches shall be conducted in all approved control modes. This means that fully automated modes must perform at the level of an ATP.

Control mode transitions from more automated control modes to less automated modes should also be evaluated if approved. Of particular interest is transition from one control mode for the approach to another for landing (e.g., a coupled ILS approach and then a transition to manual control at the decision height for landing).

Required performance:

a. For all approach segments
    (i) Maintain the desired speed within ± 10 kt.
    (ii) Maintain the desired altitude within ± 100 ft.
    (iii) Maintain the desired heading or track ± 5 degrees.
    (iv) Intercept the course with no more than ½ scale CDI (Course Deviation Indicator) overshoot.

b. For a circling approach at the MDA
    (i) Maintain the desired speed within ± 5 kt.
    (ii) Maintain the MDA within + 100 - 0 ft.
    (iii) Maintain the desired heading or track ± 5 degrees.
c. For the final approach segment
    (i) Maintain the desired speed within ± 5 kt.
    (ii) Maintain the MDA within + 50 - 0 ft.
    (iii) Maintain the desired heading or track ± 5 degrees.
    (iv) Maintain no more than ¼ CDI deflection laterally and vertically.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.15 MTE 2135-15 Landing

This section covers landing from the following conditions:

- From a VFR pattern
- From 1000 ft prior to the touchdown point, at V_{ref} and on a 3-degree path in visual conditions execute a normal landing.
- From an instrument approach with vertical guidance
- From the lowest expected minimums transition from instrument guidance to visual conditions at V_{ref} and on a 3-degree path to execute a normal landing.
- From an instrument approach without vertical guidance
- From 400 ft AGL and the lowest expected visibility minimums for a non-precision approach transition from instrument guidance to visual conditions at V_{ref} and execute a normal straight in landing.
- From a circling approach
- From 500 ft AGL and the lowest expected visibility minimums for a circling approach transition from instrument guidance to visual conditions at the recommended circling speed over the touch down point and on a track perpendicular to the runway, cross over the runway to execute a circling approach to a normal landing.
- From the steepest approved approach angle:

If the steepest approved approach angle for the configuration is less than 10 degrees, then start the landing maneuver from 1000 ft AGL at V_{ref} and execute a normal landing.

If the steepest approved approach angle for the configuration is steeper than 10 degrees, then approach the landing area in level flight at 500 ft AGL and transition to the steepest angle before 100 ft AGL and execute a normal landing (for some configurations the final 100 ft will be a vertical decent).

To a designated spot for configurations capable of hovering:

Aircraft that can maintain flight in ground effect at less than 17 kt airspeed shall demonstrate the ability to conduct a normal approach from 500 ft AGL on a smooth continuous descent and land with negligible movement after initial ground contact. The aircraft shall make initial ground contact within the specified distance of the designated spot and stop within the specified distance of the designated spot. The touchdown shall occur within 10 seconds of descending through 10 ft AGL.

On the steepest practical slope for aircraft capable of hovering:

For aircraft that can land at zero groundspeed, handing characteristics should be evaluated on sloped landing zones that have the steepest slope appropriate for that aircraft. The evaluations should be conducted with the aircraft oriented relative the slope in all directions appropriate for that aircraft. In addition, there shall be a method of determining that the slope is too steep for a landing. This method shall also be evaluated by selecting slopes that are too steep and testing the method and aborting the landing.

For all conditions, the test shall be conducted with winds at the maximum approved from the most critical direction. Lateral deviations relative to the runway centerline and deviations from the designated landing spot due to gusts are permissible.

Of particular interest are handling characteristics for aircraft that transition from airmass referenced commands to ground referenced commands.

For aircraft that transition from an air mode to a ground mode, lower the aircraft just to the point where the ground mode is triggered, and then hold it there without settling to the ground for at least 5 seconds. This is to examine the characteristics of an air to ground transition on a sloped landing area.

For aircraft that can land and takeoff vertically, the aircraft should be evaluated while landing on a pinnacle such as a small helipad on the top of a building. Particular attention should be paid to visibility as it relates to landing on a pinnacle with limited visual ques other than the actual landing surface.

Required performance:

a. For at least one precision rolling (or run-on) landing
   (i) Touchdown within 5 ft of the centerline
   (ii) Touchdown at the aim point +100 / - 0 ft.
   (iii) Touchdown at the recommended speed considering gust factors ± 5 kt.
   (iv) Remain within 5 ft of the centerline until stopped.
   (v) Come to a complete stop within less than the published landing distance for the prevailing conditions (including both total distance and ground roll distance).
b. For all other normal landings other than the spot landing for configurations capable of zero airspeed flight
   (i) Touchdown within 10 ft of the centerline
   (ii) Touchdown at the aim point +500 / -250 ft.
   (iii) Touchdown at the recommended speed considering gust factors ± 5 kt.
   (iv) Remain within 10 ft of the centerline until stopped or exiting the runway.
c. For the spot landing for configurations capable of zero airspeed flight
   (i) Initial ground contact within 2 ft of the designated spot.
   (ii) Stop within 2 ft of the designated spot.
   (iii) Maintain heading ±5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.16 MTE 2135-16 Go Around

This section covers go-arounds from the following conditions:

- Normal approach
- Steep approach
- V_{ref} -10 kt

In each configuration approved for landing, just before touchdown execute a go around from a 3-degree approach and an approach as steep as practical but no more than 10 degrees.

Repeat the above two go arounds from an approach that is as slow as practical but not less than 10 kt below V_{ref}.

For VTOL configurations, vertical approaches are covered in the vertical approach to hover evaluations and vertical takeoff evaluations.

Required performance:

- Maintain target altitudes within ± 100 ft.
- Maintain target speed within ± 5 kt.
- Maintain heading within ±5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.17 MTE 2135-17 Hovering maneuvers

For the purpose of this document, the terms hover taxi and air taxi are defined as described in FAA publication FAA-H-8083-21B Helicopter Flying Handbook 2019 edition. A Hover taxi is used when operating below 25 ft above ground level. An air taxi is preferred when movements require greater distances within an airport or heliport boundary. It is expected the helicopter will remain below 100 ft AGL.

Transition from approach to hover:

- From a normal 3-degree approach, transition to a hover above a designated spot on the runway.
- From a normal steep approach (about 10 degrees or the maximum practical) transition to hover above a designated spot.
- From a vertical descent (if approved), transition to a hover above a designated spot.

These maneuvers should be a smooth descent to a stop above the landing spot.

Transition from approach to a hover taxi:

- From a normal 3-degree approach, transition to a hover taxi at an appropriate taxi speed and height.
- From a normal steep approach (about 10 degrees or the maximum practical) transition to a hover taxi at an appropriate taxi speed and height.
- From a vertical descent (if approved), transition to a hover taxi at an appropriate taxi speed and height.

These maneuvers should be a smooth descent and smooth continuous transition to a hover taxi.

Transition from hover-to-hover taxi:

- From a steady state hover, transition to a hover taxi.

Transition from hover taxi to hover

- From a hover taxi transition to hover

Transition from air taxi to hover:

- From an air taxi transition to hover:
    - Land on a designated spot not into the wind from hover taxi
- From a hover taxi, slow and land in a smooth continuous motion on a designated spot. This maneuver should be done with at least 17 kt wind from the most adverse angle.
    - Rotate 360 degrees during a steady hover
    - Starting from a stabilized hover above a designated spot, rotate through 360 degrees while remaining above the designated spot. This maneuver should be demonstrated with wind at least 17 kt.

Required performance:

- Fly directly without stopping to a steady hover within:
    - 2 ft of the designated spot
    - 5 degrees of the desired heading
    - 2 ft of height of the designated hover height
    - Maintain the final hover position for at least 30 seconds

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.18 MTE 2135-18 Shutdown and securing

If the Flight Manual does not require a crewmember other than a single pilot, then the entire shutdown procedure shall be conducted from the pilot station. The shutdown procedure shall be such that a pilot’s attention is not required in more than one place at a time.

If abnormal conditions were detected during the flight and not corrected, then these must be prominently displayed during the shutdown process.

If the aircraft does not require a crewmember other than a single pilot, then all of the shutdown and securing procedures must be designed such that a single person can accomplish these checks without use of tools that are not a required part of the aircraft and have a specific place to be stowed (see preflight task element).

Securing procedures shall be designed such that people with characteristics typical of the expected operators can easily accomplish these tasks. Characteristics to consider are height, strength, reach, balance, dexterity, flexibility, and other physical limitations (see preflight task element).

For the purpose of this requirement, securing includes tying down the aircraft if appropriate and locking all compartments.

3.4.5.19 MTE 2135-19 Evasive maneuvers

For all configurations, the aircraft shall have the ability to change direction rapidly and sustain a maximum rate turn.

The aircraft meets the change of direction requirement by demonstrating that it can roll from coordinated flight of 30 degrees bank in one direction to 30 degrees in the other direction within 4 seconds for aircraft less than 6,000 lb and [(W + 2800) / 2200] seconds for aircraft more than 6,000 lb but not to exceed 7 seconds for any aircraft. Note that in the formula a weight of 12,600 lb would require 7 seconds. The demonstration shall be conducted at the most adverse speed but not less than V_{ref} for configurations that cannot hover.

For configurations that can hover, the aircraft shall be able reverse a turn rate of 15 degrees per second in one direction to 15 degrees per second in the other direction in less than 4 seconds.

The performance requirement for this task element is based on 14 CFR 23.157 Amendment 50 through Amendment 63 during approach for configurations that cannot hover.

For aircraft that can hover, the following rationale is used for the requirement.

A stall speed of about 35 kt is near a practical low speed limit for manned airplanes using only free stream velocity for lift. This corresponds to a V_{ref} of 43 kt. At 43 kt a bank angle of 30 degrees produces a turn rate of about 15 degrees per second. Thus, the bank requirement and the turn requirement are substantially the same at 43 kt. It requires less bank change to accomplish the turn rate change as the speed goes down. Note: A turn rate of 15 degrees per second requires 6 seconds to make a 90-degree heading change in hover.

The aircraft shall demonstrate a turn of 360 degrees in both directions using the maximum practical bank angle at both minimum and maximum speed for each configuration. The bank angle need not exceed 45 degrees and the turn rate need not exceed 30 degrees per second.

Required performance:

- Maintain altitude ± 100 ft.
- Maintain airspeed ± 10 kt.
- Maintain the target bank angle ± 5 degrees for non-hovering maneuvers.
- Stop the turn at the desired heading ± 5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.20 MTE 2135-20 Configuration changes

- While maneuvering: All possible configuration changes should be evaluated while:
    - at maximum airspeed for the configuration change
    - at minimum airspeed for the configuration change
    - transitioning from straight flight to a turn in both directions
    - transitioning from level flight to a maximum climb (as appropriate)
    - transitioning from level flight to a maximum descent (as appropriate)
    - transitioning from a climb to level flight (as appropriate)
    - transitioning from a descent to level flight (as appropriate)
- During maximum rate turns, all possible configuration changes should be evaluated while in steady state maximum rate turns:
    - at maximum airspeed
    - at minimum airspeed
    - while accelerating from the minimum speed to the maximum speed
    - while decelerating from maximum speed to minimum speed
    - at the minimum airspeed that allows the maximum bank angle for aircraft with a maximum allowable bank angle
- During envelope protections: Configuration changes that are likely to occur during envelope protections shall be evaluated. These include automatic configuration changes as well as pilot commanded changes. Configuration changes shall not materially reduce the effectiveness of the protection.

Required performance for the above maneuvers are as follows:

- Maintain altitude ± 100 ft. for configuration changes that are to be performed at, or to be completed in, level flight.
- Maintain climb or descent rate within 100 ft/min, or 0.1 deg flight path angle, whichever is greater, for configuration changes that are performed while climbing or descending.
- Maintain airspeed ± 10 kt. for configuration changes at constant speed.
- Attain and maintain final airspeed within 5 kt for configuration changes after accelerating or decelerating.
- Maintain heading ± 5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.21 MTE 2135-21 Envelope protections

This section covers the following items:

- Pilot commanded configuration change outside approved envelope
- Entry characteristics
- Pilot commands while being protected
- Exit characteristics

This task element only applies to aircraft that have the applicable envelope protections.

Envelope protections such as bank limits, overspeed limits, AOA limits, ground protection limits etc. shall be evaluated.

Each protection should be evaluated at various speeds and configurations. Determining the actual test conditions requires in depth knowledge of the aircraft and the protection systems. Particular care should be used to evaluate the protections when they may provide large control inputs and the aircraft is near its control power limits.

To avoid control mode confusion, when the envelope protection system is activated, it shall not latch into a new control mode – it shall always return to the previous mode when the aircraft is within the limit. For instance, if while accelerating in a descent the aircraft changes its control mode to pitch up and reduce the flight path angle as the aircraft exceeds the airspeed limit, the control system shall not remain in the new control mode after the speed is reduced to within the limit. However, in this example, if the pilot continues to command a descent angle that results in exceeding the airspeed limit, then the protection system shall continue to provide protection as long as the command would result in exceeding the limit. In this case, the pilot may command a maximum speed descent by continuously commanding a descent that would result in an overspeed condition, but the protection would limit the aircraft to the maximum speed until the pilot reduces the commanded descent.

When a pilot commands a configuration change that would put the aircraft outside of the protected envelope (e.g., lower flaps while faster than V_{fe}), the aircraft shall either prohibit that change and post an alert as long as the envelope and the commanded configuration are not compatible, or bring the aircraft within the protected envelope quickly before making the configuration change.

For example, if the aircraft has a flap limit of 150 kt and an overspeed envelope protection system that includes flap protection and the pilot selects flaps at 160 kt then the aircraft may prevent the flap deployment while the aircraft is going faster than 150 kt. An alert will indicate to the pilot that the selected configuration and the flight condition are not compatible. This alert shall persist as long as the selected configuration and the flight condition are not compatible. Alternatively, when the pilot selects flaps, the aircraft can quickly and automatically slow down to 150 kt. and deploy the flaps, which will stop any associated alert.

The engagement and disengagement characteristics of an envelope protection system shall be evaluated considering that when the protection is activated, the pilot may be in a stressful condition and may be task saturated. In these situations, reflexes often override thought processes. Flight controls that do not respond as they do for normal operations may be interpreted as a malfunction. Although not prohibited, systems that provide discontinuities are discouraged. An example of a protection system with discontinuities is a stick pusher.

Protection systems should be designed such that if the pilot commands an input in the direction to bring the aircraft back within the protected envelope faster than the protection system would, the system shall follow the pilot command.

Evasive maneuvering should not be completely inhibited by envelope protection systems. While it is not required to meet the evasive maneuver requirements while envelope protection systems are active, reasonable turning maneuvers must be allowed.

Required performance:

- Maintain altitude ± 100 ft.
- Maintain airspeed ± 10 kt.

- Maintain heading ± 5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.22 MTE 2135-22 Sideslips

For each configuration, maximum sideslips in both directions shall be evaluated across the speed and power range for that configuration. Sideslips at low speed shall be evaluated up to at least a 17 kt lateral wind component.

There shall be no control discontinuities or reversals in any axis due to sideslip.

Required performance:

- Maintain altitude ± 100 ft.
- Maintain airspeed ± 10 kt.
- Maintain heading ± 5 degrees.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.23 MTE 2135-23 Turbulence and upsets

Aircraft HQ in moderate turbulence and its response to momentary severe turbulence that causes an upset must be considered.

The FAA Aeronautical Information Manual (AIM) Section 7-1-23 characterizes turbulence levels as light, moderate, and severe. These are defined as follows.

Light turbulence momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw). Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encountered in walking

Moderate turbulence causes changes in altitude and/or attitude to occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed. Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult.

Severe turbulence causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control. Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about. Food service and walking are impossible. The aircraft's handling characteristics in moderate turbulence must be evaluated while flying the MTEs that are most likely to cause fatigue or a high workload during moderate turbulence.

At least the following MTEs shall be evaluated in continuous moderate turbulence.

- Takeoff transition to initial climb
- Transition to maximum angle climb
- Level flight acceleration
- Extended level flight constant speed
- Level flight deceleration
- VFR pattern with a short approach to enter on base
- VFR expedited approach from 5 miles to enter base
- Steep approach
- Precision IFR approach
- IFR approach with step down fixes
- Circling approach
- Landing from a precision approach
- Landing from the steepest approved approach angle
- Landing on a designated spot for configurations capable of hovering
- Transition from approach to hover
- Land on a designated spot not into the wind from a hover taxi
- Rotate 360 degrees during a steady hover

In addition, each configuration change shall be evaluated in steady state flight except that for configuration changes controlled by a change in flight conditions, the flight condition that causes the change shall be varied slowly.

The required performance for the turbulence HQTEs is the same as for the base HQTE except that continuous deviations from the desired reference consistent with the level of turbulence are acceptable. The purpose is not to achieve the required performance level in turbulence; the purpose is to evaluate the skill, workload, and fatigue associated with controlling the aircraft to a reasonable performance standard while in moderate turbulence.

The following example demonstrates an acceptable level of performance in turbulence. In level flight, the altitude performance standard is ±100 ft. In smooth air it is expected that the pilot can achieve this level of precision. However, in turbulence, the pilot would be expected to maintain within the ±100 ft tolerance except when experiencing a gust that moves the aircraft outside of that tolerance, but then fly back into the tolerance band promptly. The mean altitude should be within the tolerance.

For all tolerances (altitude, heading, airspeed, etc.), the tolerance should not be expanded by more than a factor of 2 for moderate turbulence.

It is not appropriate to intentionally fly an aircraft in severe turbulence (turbulence that may cause the aircraft to momentarily be out of control). These HQTEs are intended to evaluate the skill and workload required to regain control after an upset. As such, they may be conducted in smooth air. The procedure is for the pilot to intentionally put the aircraft into flight conditions consistent with a turbulence induced upset and then recover the aircraft back to straight and level flight. For aircraft with envelope protections, the aircraft may need to be modified so that the upset flight condition can be obtained.

For powered lift flight, the following initial upset conditions should be evaluated. Note: these attitudes are relative to the initial condition – not absolute values.

For zero airspeed:

- bank to 25 degrees each direction
- pitch to 25 degrees up and down

For 40 kt airspeed:

- bank to 35 degrees each direction
- pitch to 25 degrees up and down (note that G limits shall not be exceeded)

For 80 kt airspeed:

- bank to 75 degrees each direction
- pitch to 25 degrees up and down (note that G limits shall not be exceeded)

For the maximum speed for the configuration

- bank to 75 degrees each direction
- pitch to 25 degrees up and down (note that G limits shall not be exceeded)

When the maximum speed for a configuration is less than 80 kt, interpolate between the appropriate speeds to obtain the target upset values.

For flight that primarily relies on free stream lift the following conditions should be evaluated.

For the minimum and maximum speed for the configuration

- bank to 75 degrees each direction
- pitch to 25 degrees up and down (note that G limits shall not be exceeded)

For flight where the aircraft is transitioning between powered lift and primarily free stream lift, at least one set of upsets (pitch and roll) should be evaluated near the mid-point of the transition. The upset initial condition need not be greater than the upset condition for the powered lift configuration at that speed.

The evaluation may be started by the pilot maneuvering the aircraft to the upset condition or by a programmed maneuver that puts the aircraft in the upset condition. For either case, the controls are released immediately when the upset condition is reached. If pilot action is required to affect a recovery back to steady level flight, then a delay of 3 seconds before initiation of pilot recovery shall be observed.

Note that Section 3.2 on §23.2110 and §23.2150 Stall speed Warning and Characteristics also deals with upsets at low speed. These conditions are intended to be in addition to the ones specified in §23.2110 and §23.2150. However, there is considerable overlap so the two sets of tests should be considered together.

To meet the required performance, the aircraft must be back within the normal flight envelope within 5 seconds for bank upsets and within 10 seconds for pitch upsets (except that G limits shall not be exceeded). The normal flight envelope is considered half of the upset values for powered lift configurations and transitions, and 30 degrees of bank and 10 degrees of pitch for free stream configurations.

3.4.5.24 MTE 2135-24 Tests unique to the aircraft or its mission

During previous testing (company development, company certification, or FAA certification), if there are maneuvers that would be executed as part of a normal mission for this aircraft that are not covered in the preceding list, MTE(s) should be developed by the test crew to demonstrate and evaluate the HQ during these maneuvers. The evaluation maneuvers should be representative of realistic maneuvers.

The required performance should reflect the performance required by the ATP ACS for airplanes, or if the maneuver is not covered by the ACS, then by the ATP PTS for helicopters. If neither provides a performance requirement, for most maneuvers the following may be used.

Required performance:

- Maintain altitude ± 100 ft.
- Maintain airspeed ± 10 kt.
- Maintain heading ± 5 degrees.

However, these are just guidelines and appropriate performance levels should be developed when these are not appropriate for the particular maneuver.

Momentary deviations may be acceptable, and allowance should be made for turbulence.

3.4.5.25 MTE 2135-25 Any other tests deemed necessary by the administrator

Some aircraft have unique operating characteristics that are not covered in the tests above and are within the normal operating envelope of the aircraft. This section is provided as a place to identify and describe tests required for a particular aircraft or configuration. It is expected that since the applicant knows the aircraft the best, that the applicant will propose any tests that show unique handling characteristics of the design. The applicant should not expect that FAA to discover these characteristics, since this almost always results in a delay of the certification process.

3.4.5.26 MTE 2510-26 Failures

In addition to the failures specifically mentioned in the takeoff task element, all failures that can adversely affect the performance or control of the aircraft must be considered.

Representative MTEs that are determined to be the most critical during a particular failure shall be conducted with the simulated failure. Configuration changes are of particular interest. It is acceptable to prohibit a configuration change when a failure is present. However, that prohibition may adversely affect aircraft performance, which may change its hazard classification.

The stability, controllability, and trim requirements need not be met after a failure. However, the extent to which the failure adversely affects performance or control will determine the hazard classification for that failure.

Tests that are likely to cause damage to the aircraft need not be conducted to the point where damage may occur. This specifically applies to failures that may cause a hard landing in which the aircraft may be damaged. For these tests, the aircraft shall be flown to a point where it is clear that the landing can be made, but the maneuver may be abandoned before touchdown.

For failures that require immediate pilot action, a delay from the first indication of the failure to the first pilot action shall be no less than one second for situations where the pilot is precisely controlling the aircraft (such as during takeoff, landing, and instrument approaches where the pilot is expected to be monitoring closely). It shall be no less than three seconds otherwise. These pilot reaction times are consistent with AC 25 1329-1C (2014, p. 78).

For failures that result in vibrations, the vibration guidance is based on §23.2160. Vibration and buffeting, for operations up to $V_D/M_{D,}$ must not interfere with the control of the aircraft or cause excessive fatigue to the flight crew.

A flight using emergency procedures shall also be evaluated to verify the correct hazard classification and to verify that exceptional pilot skill or strength are not required to accomplish the procedure. Of particular interest are failures, which require the pilot to enter an autorotation or a glide.

For failures where a pilot action more complicated than simply activating a switch is required for continued safe flight and landing, it should be possible to simulate the failure for training purposes (unless the applicant provides a simulator or other acceptable means to practice the procedure). The recovery procedure for failure training should also be evaluated in flight. For example, for an aircraft that can autorotate after an engine failure, the procedure for exiting an autorotation before touchdown should be evaluated.

Failures during configuration changes and failures of the configuration change (e.g., two or more components out-of-sync or the change hangs up partially through the sequence, etc.) should be evaluated.

For some control modes, the pilot is part of the control feedback loop. For these modes, a display then becomes an integral part of the control system. For these control modes, display failures need to be considered.

For failures that prevent maintaining altitude, the aircraft shall be controllable to a touchdown (or enter a flare or hover) within 100 ft of the target touchdown point. If this criterion is not met, the failure is considered catastrophic unless the aircraft can demonstrate a descent rate that prevents injury when obstacles are present (for example, it has a ballistic parachute).

Minor deviations may be acceptable, and allowance should be made for turbulence.

Abnormal or emergency conditions are conditions that result from a failure. These evaluations are not intended to evaluate the effectiveness of the procedure associated with a failure – that is a separate activity. The purpose of this evaluation is to examine the handling characteristics and verify the assigned hazard level using the established procedure associated with that failure. Some evaluation schemes use the term “degraded operations”. For the purpose of FAA certification, approved operations are all considered normal operations. Normal operations are not considered degraded. Therefore, the only non-normal operations for certification purposes are operations with failures.

See the Evaluations with Failures (§23.2500) section above for a detailed discussion of hazard levels and evaluation criteria for the various levels.

3.5 §23.2140 Trim requirements for FBW aircraft.

Part 23 as written:

§23.2140 Trim

(a) The airplane must maintain lateral and directional trim without further force upon, or movement of, the primary flight controls or corresponding trim controls by the pilot, or the flight control system, under the following conditions:

(1) For levels 1, 2, and 3 airplanes in cruise.
(2) For level 4 airplanes in normal operations.

(b) The airplane must maintain longitudinal trim without further force upon, or movement of, the primary flight controls or corresponding trim controls by the pilot, or the flight control system, under the following conditions:

    (1) Climb.
    (2) Level flight.
    (3) Descent.
    (4) Approach.

(c) Residual control forces must not fatigue or distract the pilot during normal operations of the airplane and likely abnormal or emergency operations, including a critical loss of thrust on multiengine airplanes.

SC.2140 Trim

The FAA FAST has proposed the following Special Condition

(From the FAAST GAMA document underlined text indicates FAST changes)

(a) The airplane must maintain lateral and directional trim without further force upon, or movement of, the primary flight controls or corresponding trim controls by the pilot, or the flight control system, under normal phases and modes of flight:

    (1) For levels 1, 2, and 3 airplanes in cruise.
    (2) For level 4 airplanes in normal operations.

(b) The airplane must maintain longitudinal trim without further force upon, or movement of, the primary flight controls or corresponding trim controls by the pilot, or the flight control system, under the following conditions:

    (1) Climb.
    (2) Level flight.
    (3) Descent.
    (4) Approach.

(c) Residual control forces must not fatigue or distract the pilot during normal operations of the airplane and likely abnormal or emergency operations, including of thrust not shown to be extremely improbable on multiengine airplanes.

3.5.1 Recommended changes for §23.2140

Recommended replacements of §23.2140:

(a) During non-hovering flight, the aircraft must require no pilot force to maintain a straight path at constant speed.
(b) During hovering flight, the aircraft must require no pilot force to maintain heading and zero speed.
(c) At speeds near hover, a constant force may be allowed to command slow constant lateral or longitudinal speed.
(d) During abnormal operations, pilot control forces must not fatigue or distract the pilot, including a critical loss of thrust on aircraft with multiple power sources, thrust or lift devices.
(e) The airplane cannot be trimmed for a speed less than the minimum speed for the current configuration or the maximum speed for the current configuration.
(f) If the aircraft automatically changes configuration without pilot input, it must remain substantially in trim throughout the configuration change.

(a)(1) is eliminated, (a)(2) and (b) are covered by the new (a), (b) and (c). The new (d) covers the intent of the original (c).

3.5.2 Discussion of trim requirements changes for FBW aircraft and VTOL aircraft

FBW aircraft provide force independent of aerodynamic or mechanical forces from the control system.

Part 23 also requires that the aircraft be trimmable (produce zero force at the pilot inceptor) for any normal operation. The implication is that they may require force for normal long-term operations if the pilot does not trim the force out. Some of the new FBW control systems are always in trim (require zero force) for long term operations without pilot action. Some of these new FBW control systems also intentionally require a force for short term steady state normal operations. Examples of these are holding a force while changing the direction of flight (both laterally and vertically) and holding a force in the desired direction to move during hover. These characteristics are more like vehicles that novice pilots are familiar with (such as cars and drones), as opposed to airplanes.

§23.2140 (a)(1) is a concession for small mechanically controlled airplanes that typically don't have trim in all axes. With FBW, there is no need for this concession.

VTOL aircraft may takeoff, land, and taxi in a hovering mode. Neither the Part 23 regulation nor the FAST proposed Special Condition address hover. §27.161 requires that the trim system "Must trim any steady longitudinal, lateral, and collective control forces to zero in level flight at any appropriate speed;". Appendix B of Part 27 (Airworthiness Criteria for Helicopter Instrument Flight) states "It must be possible to trim the cyclic, collective, and directional control forces to zero at all approved IFR airspeeds, power settings, and configurations appropriate to the type."

The intent of this recommended change is to provide a zero-force reference for the stability requirement (§23.2145). Constant pilot force is specifically allowed during a turn since a turn is a temporary condition of short duration. The zero-force requirement may be met by a position hold function of the controls such as a climb rate stick position lock for aircraft that command a climb rate or flight path angle and have a stick that is spring loaded to the zero vertical speed position (such as Unified in the hover and low speed condition).

The minimum and maximum trim speed requirements are intended to prevent a situation where the pilot is required to provide a force to keep the aircraft inside the normal envelope.

With an attitude command system for which configuration changes are all pilot initiated, large trim transient trim changes are acceptable pending HQ evaluations described in the section for §23.2135.

3.5.2.1 Trim during automatic configuration changes

If the control system design includes automatic configuration changes, then the airplane characteristics across the configuration change must be consistent with constant configuration flight. For example, if an aircraft has a control system where the stick position commands G level and the stick being centered commands a constant rate of climb or descent, a configuration change not controlled by the pilot shall produce only small transient deviations (if any) from the command while transitioning and then return to substantially the same climb or descent after the transition.

The requirement to maintain a command through a configuration change is important when the pilot has set up a trajectory and an automatic (uncommanded by the pilot) configuration change occurs. Since the pilot is not tightly in the loop to control the trajectory after setting it up to follow a trajectory, it is important that the trajectory be maintained through configuration changes that the pilot does not command directly. If the pilot commands the configuration change, then it is acceptable for the pilot to re-setup the trajectory, since it was a pilot action that upset it. This is much like a pilot commanded flap change in a conventional airplane, which can change the trim and the pilot is expected to retrim if needed. However, if the flap change occurs automatically as the airplane changes speed, the change may occur at a time when the pilot is busy doing some other task and he/she may not notice the trajectory change. Thus, it is required that the aircraft remain substantially in trim during configuration changes that are not directly commanded by the pilot.

Trim and stability are related. See the discussion in the stability recommended change section (§23.2145) for more information.

3.5.2.2 Practical application

This MOC for §23.2140 tests the range of aerodynamic configurations, control system modes and configurations, phases of flight, and flight conditions that an aircraft will normally experience in service. This includes changes to the aircraft's external shape, control system changes (including computer, sensor, actuator, data path and software algorithm changes), takeoff, climb, cruise, descent, landing and maneuvering throughout the entire approved flight envelope.

3.5.3 Means of Compliance for Recommended Change §23.2145

3.5.3.1 Steady state flight

The procedure is to fly the aircraft through its speed, altitude, and configuration range while stabilizing on specific flight conditions. A way to do this is to set a configuration and altitude then start at one end of the speed range and accelerate or decelerate to the other end of the speed range while periodically stabilizing the aircraft in a steady state condition.

3.5.3.2 Required information and configuration

Before the procedure, the applicant will define:

1. Weight and CG range for allowed operations
2. The most adverse weight and CG location
3. Allowed aircraft configurations
4. Speed range for each allowed configuration
5. Altitude range for each configuration
6. Configuration transition points and the conditions that cause the transition if not pilot controlled

3.5.3.3 Flight test procedure

The tests will be conducted at both the forward and aft CG location, at the most adverse lateral CG limit along with the most adverse weight for the configuration and flight condition tested.

The test conditions listed are intended to convey the granularity expected when conducting flight tests. The vehicle characteristics and capabilities should determine the actual test conditions.

In addition to the regularly spaced test conditions, particular attention should be given to conducting tests at the edges of configuration boundaries.

1. Steady state test conditions
    a. For each configuration the following range shall be tested
        i. Airspeed from the minimum practical speed for the configuration to the maximum practical speed with stabilized points at a minimum of 4 speeds between the minimum and maximum, but fewer speeds are allowed if the resulting test conditions are less than 20 knots apart.
        ii. At each airspeed and altitude
            1. In level flight
            2. At the maximum achievable steady state climb rate
            3. At a climb rate approximately half of the maximum climb rate
            4. At the maximum achievable steady state descent rate
            5. At a descent rate approximately half of the maximum descent rate
        iii. Altitude from 5,000 ft or lower to the maximum practical altitude for the configuration at no more than 10,000 ft intervals.

        iv. If the aircraft is capable of hovering, the zero-airspeed test must also be conducted in ground effect at the lowest practical height above ground.
        v. Tests must be conducted in all configurations that can be flown as a steady state configuration.

2. Steady state test procedure
    a. At each test condition, stabilize the aircraft at the specified speed and vertical rate, then reduce the control force to zero and release the control.
    b. Observe the aircraft motion relative to the trimmed condition.
    c. If trim is settable by the pilot, set the trim to the maximum travel in each direction for each axis individually then fly the aircraft to the flight condition closest to that which produces zero force and release the control. Verify that the aircraft does not depart from the normal flight envelope.

3. Automatic configuration change test conditions
    a. For each configuration change that occurs without direct pilot control
        i. Conduct the test starting from one configuration and then transitioning to the other by flying the aircraft so as to trigger the automatic configuration change.
        ii. If there is more than one set of logic to cause the transition, then each set must be addressed (either by test, analysis, or similarity).
        iii. The transition must be addressed in both directions.
        iv. For each transition, the most adverse combination of weight, CG and flight condition must be tested.

4. Automatic configuration change test procedures
    a. For each configuration change identified in the test conditions section
        i. Stabilize and trim the aircraft in the initial configuration.
        ii. Command the aircraft to execute the maneuver that triggers the configuration change (accelerate, descend, turn, etc.) using zero force to control the other flight parameters that are normally held constant during this maneuver when a configuration change does not occur (for example, accelerating at a constant altitude and constant heading with zero stick force required to hold zero vertical speed and straight flight).
        iii. Observe the change in the commanded parameters as the aircraft changes configuration while holding zero force on the controls. (In the example above observe the resulting vertical speed change and turn rate if any.) Note that minor transient behavior is allowed but the aircraft should return to the original command immediately after the configuration change is complete.

3.5.3.4 Pass criteria

During each of the flight tests, the aircraft shall demonstrate that

1. it holds the stabilized flight path with zero pilot control force in all axes
2. when trim is set to its limits that no pilot force is required to keep the aircraft inside the normal flight envelope.
3. when an automatic configuration change occurs, no pilot force is required to maintain the trajectory established before the configuration change.

3.6 §23.2145 Stability requirements for FBW aircraft.

Part 23 as written:

§23.2145 Stability

(a) Airplanes not certified for aerobatics must—
    (1) Have static longitudinal, lateral, and directional stability in normal operations;
    (2) Have dynamic short period and Dutch roll stability in normal operations; and
    (3) Provide stable control force feedback throughout the operating envelope.
(b) No airplane may exhibit any divergent longitudinal stability characteristic so unstable as to increase the pilot's workload or otherwise endanger the airplane and its occupants.

The FAA FAST did not propose any changes to this rule.

Required rule changes for FBW aircraft:

In both the original amendment 64 language and the FAST Special Condition (a)(1) inadvertently requires that FBW aircraft mimic mechanical flight controls. This was not the FAA's intent. A recommended change is proposed that recognizes the classical definition of stability and also recognizes the reality that FBW can actually make aircraft stable in all axes. See discussion below concerning the intent of the regulation and rationale for the new recommended change.

3.6.1 Recommended change for §23.2145

Recommended replacements of §23.2145:

SC- §23.2145 Stability

(a) The aircraft must have static and dynamic stability about the following states for all operations.

(i) Vertical flight path or vertical speed, or vertical acceleration
(ii) Altitude when zero vertical speed is commanded (altitude stability replaces vertical path or speed stability)
(iii) Forward speed
(iv) Bank angle or turn rate
(v) Lateral speed during hover (lateral speed stability replaces bank stability)
(vi) Heading or track when zero bank is commanded (heading or track stability replaces bank stability)

Static stability is defined as

(i) the tendency to return to a commanded state when a disturbance causes the aircraft to deviate from the commanded state and
(ii) The pilot may exert a force on an inceptor which results in a displacement of the inceptor and a resulting deviation of the aircraft from the initial commanded state. The inceptor displacement is proportional to the aircraft deviation from the initial commanded state.

(c) The aircraft must be dynamically stable about the commanded state with heavy damping - heavy damping is defined as less than 1/10th amplitude in 3 cycles. However, Dutch roll may be damped to 1/10th amplitude in no less than 7 cycles.

(d) Dynamic preprogrammed maneuvers such as takeoff, landing, and go around may provide stability about some other state than is listed in (a). However, they must provide stability about a defined state such as pitch attitude, normal acceleration, longitudinal acceleration, etc. This defined state may change as the maneuver progresses.

3.6.2 Stability discussion

The terms “static longitudinal stability” and “static lateral stability” have specific FAA definitions (see AC 23-8C and the discussion below) that describe how longitudinal and lateral stability is provided in mechanically controlled airplanes.

Since the 1960s the terms static longitudinal stability and static lateral stability have been defined in Parts 23, 25, 27 and 29 as well as various Advisory Circulars and other FAA materials. Amendment 64 of Part 23 drops the definition but does not redefine it – it just does not duplicate the definition that is still in the other rules and FAA material. This proposed means of compliance defines longitudinal and lateral stability in a more appropriate manner for FBW aircraft and rewords the rule such that the new definition can be used.

The regulations were written assuming airplanes that have mechanical controls or have FBW controls that mimic mechanical controls. As such they describe a very specific type of stability that airplanes with mechanical controls exhibit.

The recommended change is required to allow FBW aircraft to deviate from the design requirements imposed by these definitions.

3.6.2.1 Static longitudinal stability

According to the FAA definition, static longitudinal stability is shown by the need to push on the control stick to maintain a speed faster than the trim speed and to pull to maintain a speed slower than the trim speed.

A mechanically controlled airplane with static longitudinal stability has strong stability with respect to angle of attack. This is provided by the horizontal stabilizer. For a given weight, a given angle of attack provides a given airspeed. Changing the elevator position changes the angle of attack and therefore changes the steady state airspeed. The elevator is designed to weathervane, so it takes a force to move the elevator from its trimmed position. Thus, the angle of attack stability and the weathervane tendency of the elevator combine to produce stick force-based speed stability. The FAA refers to this as static longitudinal stability in §25.173.

3.6.2.2 Static lateral stability

According to the FAA definition in §25.177, static lateral stability is shown by pushing on the right rudder pedal and observing the aircraft rolls to the right and vice versa.

In the lateral axis, mechanically controlled airplanes are not stable, but the speed at which they diverge is slowed through roll yaw coupling combined with yaw stability.

It is desired that an airplane has stability with respect to bank angle. Such stability would return an airplane to its original bank angle after it is disturbed When an airplane banks it starts to “slide sideways downhill” creating sideslip. Dihedral causes a rolling motion as a function of sideslip. Therefore, we can reduce the banking by providing dihedral. Since the rolling is produced by sideslip, we can test this tendency by using the rudder to produce sideslip and observing the resulting bank angle. The FAA defines this tendency to raise a wing by using the rudder to create sideslip as static lateral stability. The vertical fin provides yaw stability by keeping the amount of sideslip small. The sideslip caused by the bank angle also causes a yaw rate. This roll / yaw coupling is known as Dutch roll and is often lightly damped. It also does not create the bank stability that is desired. However, it does reduce the speed at which the bank angle increases (reduces the natural instability). This stability mode is called the spiral mode because if left alone the airplane spirals down with increasing bank angle and airspeed. Enough dihedral can be provided to make the spiral mode stable, but this reduces Dutch roll damping. Passenger carrying airplanes must have acceptable Dutch roll damping and therefore sacrifice spiral stability.

3.6.2.3 Mechanical six degree of freedom stability

Pitch axis rotation

The short period pitch mode of Part 23 size airplanes has a high enough frequency that if it is not heavily damped (statically stable and dynamically stable such that oscillations decay to nearly nothing in about one cycle or less), the airplane is prone to pilot / aircraft coupled oscillations. The pilot inputs become out of phase with the aircraft motion and the system is driven unstable by pilot inputs. Therefore, all general aviation airplanes have a horizontal tail large enough and an aft CG limit far enough forward to provide strong angle of attack stability with heavy damping. Thus, rotation about the pitch axis is stable.

Longitudinal motion

The mechanical design that creates static longitudinal stability provides speed stability as described above. The longitudinal motion (airspeed) is stable in the short term. In the long term, the airplane may have a phugoid mode, which occurs at constant angle of attack but changes airspeed and G loading. The phugoid stability mode may be dynamically unstable but has a long enough period that it is un-noticed by the pilot since the pilot makes many elevator inputs (angle of attack changes which result in G changes) to hold the desired flight path in the time it takes for the phugoid to change airspeed a noticeable amount.

Vertical motion

The engine (without auto throttle) provides constant power. The climb rate is determined by the amount of power supplied by the engine minus the amount of power required to overcome drag in level flight. Therefore, for a given speed and weight (which defines the power required for level flight) a constant power setting will produce a constant vertical speed. The vertical motion is stable.

Roll axis rotation

Nearly all general aviation airplanes have a spiral divergence stability mode. This means that if the airplane is banked and there is no pilot input, it will slowly continue to bank further. Thus, there is no roll stability. However, static lateral stability couples the roll and yaw axes and uses the yaw axis stability to reduce the roll instability by reducing the time it takes to double the bank angle. The roll axis is usually not stable. Adding dihedral increases roll stability and with enough, the airplane becomes stable in roll. However, this comes at the cost of an uncomfortable roll / yaw dynamic coupling that is lightly damped (Dutch roll mode). The amount of dihedral required to make an airplane stable in roll usually results in unacceptable motions for passengers.

Yaw axis rotation

The vertical fin creates strong directional stability. The yaw axis is stable.

Lateral motion

The airplane has vertical surface area (the side of the fuselage and the vertical fin). This vertical area serves to resist the aircraft from flying sideways. The lateral motion is stable.

3.6.2.4 Mechanical controls and longitudinal stability

As seen in the discussion above, a mechanically controlled airplane designed to have static longitudinal stability and an engine with a conventional throttle provides stability about the three longitudinal states.

Static longitudinal stability is the best method available to provide acceptable handling characteristics for airplanes that have mechanical controls. However, FBW technology provides many possible methods of providing the stability required for acceptable HQ. The existing regulation is a design-based regulation as opposed to a performance-based regulation.

3.6.2.5 Mechanical controls and lateral stability

As seen in the discussion above, a mechanically controlled airplane designed to have static lateral stability, directional stability, and lateral speed stability provides stability about the directional axis and lateral motion, but does not provide roll stability. The roll yaw coupling combined with directional stability reduces the roll instability. The pilot is required to provide roll stability. This is not desired but is the best that can done realistically with mechanical controls without unacceptable performance or passenger comfort impact.

3.6.2.6 VTOL mechanical stability

Aircraft in hover (as exemplified by an aircraft that uses propellers/rotors for lift) do not exhibit aerodynamic pitch stability longitudinal stability, roll stability, yaw stability, or lateral motion stability. The vertical motion is highly affected by ground effect, rate of descent and velocity changes (both longitudinal and lateral). In some flight conditions, the vertical motion is mildly stable (hover in ground effect) and in others, it is very unstable (settling with power). In addition, longitudinal and lateral motion couple with pitch and roll during velocity changes. An aircraft that hovers using rotors or lift fans is not stable aerodynamically and cannot meet the stability regulation without augmentation.

Applying static longitudinal stability combined with static lateral stability to VTOL aircraft would significantly degrade handling characteristics. For instance, in hover it is desired to make a pivoting turn. If static lateral stability is imposed, then pushing on the right pedal to turn would also result in a right bank, which in turn would result in a lateral acceleration to the right which the pilot would have to counter. Therefore, for a VTOL aircraft in hover, it is undesirable to couple roll and sideslip.

3.6.2.7 Mechanical controls and six degrees of freedom stability

The intent of the regulations was not to specify a particular design method of providing stability, but given the limitations of mechanical control systems, that was the result. While these rules did not actually result in stability about all six degrees of freedom, they did provide for predictable handing qualities that pilots could learn to manage. At the time the regulation was written, the design method prescribed was the only realistic method of providing acceptable aircraft performance and passenger comfort with acceptable handling characteristics.

3.6.2.8 Stability for FBW

FBW has the capability of providing the desired stability for an individual axis without coupling to another axis as is required for a mechanically controlled airplane. Thus, it can produce an aircraft that is much easier to fly. Using the reworded performance-based regulation as opposed to the original design-based regulation allows designers to be innovative and produce designs that are safer and easier to fly than traditional mechanically controlled airplanes.

The classic definition of static stability is the tendency of a system to return to its original state when disturbed. Dynamic stability is the tendency of motions to damp out or stop. A system can be statically stable and dynamically unstable. This is the case when a system keeps coming back to its original state, but the motion overshoots and each overshoot is larger than the last.

The intent of the recommended change is to ensure that the aircraft has stability about all six degrees of freedom – not to specify a particular design method of providing that stability.

3.6.3 Applicability

This recommended change is intended to apply to all aircraft that use FBW as the primary means of control about the pitch axis of the aircraft but do not have static longitudinal stability or static lateral stability as described in AC 23.8C (speed stability is provided through force feedback about a pilot determined trim airspeed and the tendency to raise a wing using rudder). For aircraft with static longitudinal stability and static lateral stability, use AC 23-8C as a means of compliance.

3.6.3.1 Practical Application

This recommended change tests the range of aerodynamic configurations, means of providing lift, control system modes and configurations, phases of flight, and flight conditions that an aircraft will normally experience in service. This includes changes to the aircraft's external shape, control system changes (including computer, sensor, actuator, data path and software algorithm changes), takeoff, climb, cruise, descent, landing and maneuvering throughout the entire approved flight envelope. Stability is examined through use of sharp-edged control inputs.

3.6.3.2 Applicability to Control Modes

This document applies to all control modes, including automatic control modes. The overriding concept for this document is that the aircraft must move in the direction the pilot commands it to move at all times. Some new configurations have control systems that automate some flight functions (for example, heading hold, altitude hold, doing the last part of an approach to landing, or doing a takeoff to a given height). These functions may work like autopilot functions in legacy aircraft but may be part of the basic flight control system for a FBW aircraft. These new aircraft can cause a blurring of the traditional boundary between manual flight and automated flight. This document pulls in any and all control modes (manual, automatic, or any combination of manual and automatic) and applies the same criteria to all of them. Thus, there is no distinction between flight control modes as far as stability requirements are concerned. The exception is flight control modes that result from a failure. These are discussed separately.

Identifying configuration changes and examining stability during configuration changes is important since configuration changes often cause changes in stability. Note that configuration changes occur due to changes in control laws (software), aerodynamic shape (deployment of flaps, etc.), and the manner in which lift is produced, etc.

3.6.3.3 Applicability related to zero rate

The recommended change requires that when a control is commanding zero rate, then the control system shall hold position. This makes flying much easier since commanding zero rate results in holding the position instead of just holding zero rate. The difference between the two is that holding zero rate results in the aircraft moving as a result of a disturbance and then holding the new position until a new disturbance occurs, while holding position results in the aircraft moving back to the original position after the disturbance. For example, if while holding zero vertical speed the aircraft experiences a gust that forces it 50 ft higher, then the zero-rate control system will keep the aircraft 50 ft higher. If while holding altitude the aircraft experiences a gust that forces it 50 ft higher, the aircraft will go back to the original altitude.

3.6.3.4 Applicability to preprogrammed maneuvers

Paragraph (d) was added to the recommended change specifically to apply to maneuvers that are primarily conducted automatically. For instance, an automated vertical takeoff may start with a commanded vertical acceleration but zero horizontal speed until a height of 5 feet is reached, then a forward acceleration is commanded. As the vertical speed reaches 1000 fpm a constant climb rate is commanded while the aircraft accelerates to 50 kt. airspeed and holds 50 KIAS. The defined states for this maneuver are vertical acceleration and ground position, followed by vertical acceleration and airspeed acceleration, followed by climb rate and airspeed. For this automated maneuver, it must be shown that when the aircraft is disturbed, it quickly returns to its programmed trajectory without excessive oscillations.

3.6.4 Means of compliance for recommended change §23.2145

3.6.4.1 Suggested flight tests

The procedure is to fly the aircraft through its speed, altitude and configuration range while disturbing it and observing the response. The general procedure is to set a configuration and altitude then start at one end of the speed range and accelerate or decelerate to the other end of the speed range while periodically entering sharp edged command inputs to upset the aircraft. The control inputs are intended to upset the aircraft's flight condition relative to each degree of freedom.

All parameters that are being actively controlled must respond quickly to the control input and be heavily damped to avoid man machine coupling (pilot induced oscillations).

3.6.4.2 Required information and configuration

Before the procedure, the applicant will define

1. Weight and CG range for allowed operations
2. The weight and CG location for each test condition that provides the least stability
3. Allowed aircraft configurations
4. Speed range for each allowed configuration
5. Altitude range for each configuration
6. Configuration transition points and the conditions that cause the transition if not pilot controlled
7. Flight conditions including weight and CG that may provide questionable stability characteristics as defined by the aircraft deviating from the pilot's command or not immediately returning to the initial condition when disturbed.

Note it is acknowledged that the applicant will have much more flight experience with their design than the FAA. As such, the applicant is obligated to disclose all flight conditions that may result in unsatisfactory results per this recommended change. The purpose of certification is for the applicant to show the FAA that the design meets all requirements in all approved flight conditions – particularly in-flight conditions with reduced stability. The purpose of certification is not to "allow" the FAA to discover areas where the requirements may not be met. This includes rapid maneuvering up to the aircraft's limits. The applicant is required to explore the entire flight envelope and proactively address areas of weakness before applying for certification.

3.6.4.3 Pass criteria

During the flight tests, the aircraft shall

1. Provide initial motion in the direction of the command.
2. Provide the initial response within 200 ms of the command.
3. Not reverse direction until passing the command.
4. Not exhibit delays between the command and the response such that it may induce pilot induced oscillations – particularly for novice pilots.

5. Not exhibit oscillations that increase pilot workload. For pitch, roll and yaw attitude, oscillations shall damp to less than 1/10th amplitude in less than three cycles. For vertical and longitudinal speed, oscillations shall not be divergent and shall have a period of more than 10 seconds
6. Not exhibit any movement that is not negligible in the direction opposite of the command.
7. Not exhibit residual oscillations that negatively affect pilot performance. Residual oscillations greater than 0.5 degrees or 0.05 Gs at the pilot station are considered excessive (ref ADS-33E-PRF para 3.1.17).
8. Not provide uncommanded motion that requires pilot input to counter.
9. Not exit the normal flight envelope.
10. Return to the original initial condition without pilot input.

Temporary, uncommanded deviations from a command through a configuration change are acceptable as long as the aircraft returns to the commanded state promptly without pilot action. For example, a commanded acceleration may trigger a configuration change that temporarily increases drag such that the aircraft slows slightly during the configuration change and then accelerates to the commanded speed. This is acceptable. Temporary altitude deviations up to 150 ft. are acceptable when not less than 500 ft from terrain or obstacles.

Uncommanded coupling between axes is acceptable as long as the coupling is transient and no pilot action is required to return the aircraft to the original uncommanded state. For example, a commanded climb rate change during a configuration change may result in a temporary, uncommanded heading change. This is acceptable as long as the original heading is restored without pilot action.

For a well-designed FBW aircraft, it is expected there will be no question regarding meeting the requirements without qualitative data. However, if there is a question, the requirements of MIL-F-8785C (Military Specification Flying Qualities of Piloted Airplanes) or MIL-HDBK-1797 (Department of Defense handbook Flying Qualities of Piloted Aircraft) or ADS-33E-PRF (Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft) may be used as guidance. These documents are designed for military aircraft executing military missions and as such should not be applied verbatim. Complying with the requirements of these documents requires extensive data analysis. It is not intended that these requirements be imposed on FAA certified aircraft, nor that extensive data analysis be required, but the requirements of these documents can be used as a guide when subjective judgement does not provide a clear pass / fail result.

3.6.4.4 Data collection

Hand recorded data or electronically collected data is acceptable.

For the flight tests, record at least the

1. initial conditions of each test
2. command change (command that was changed, pulse, step, approximate value, duration, etc.)
3. aircraft transients (time to reach the commanded value, overshoot, frequency, and cycle to damp for oscillations, etc. for each state that was disturbed by more than a negligible amount
4. time to the maximum if an overshoot
5. any cross coupling between axis that was not commanded and that is more than negligible

3.6.4.5 Flight test procedure

The tests will be conducted at the most adverse weight and CG location for the configuration and flight condition tested. This includes lateral center of gravity.

The test conditions listed are intended to convey the granularity expected when conducting these tests. The vehicle characteristics and capabilities should determine the actual test conditions.

In addition to the regularly spaced test conditions, particular attention should be given to conducting tests that cross configuration boundaries or produce rapid changes in configuration. A longitudinal example of this may be an aircraft that automatically protects against overspeed or underspeed with a configuration change based on being outside or inside of the allowable speed envelope (or approaching a boundary) for a configuration. A configuration change includes changing flap position, starting or stopping lift fans, unfolding rotors, changing a control algorithm, transitioning from tracking a pilot command to tracking an airspeed or angle of attack limit, or changing from control surfaces to thrusters. A lateral example of this may be an aircraft that automatically protects against overbank by configuration changes based on being outside or inside of the allowable bank envelope (or approaching a boundary) for a configuration. This includes changing a control algorithm, adding more control power than normal, etc. For these aircraft, test conditions that cause the changes, and which demonstrate stability while the changes are occurring, would be expected.

The regularly spaced test conditions may be conducted from a stabilized condition or in a progression from one condition to the next. For example, at a given altitude control upsets may be conducted as the aircraft is accelerating from a previous test condition through the current test condition and on to the next as opposed to stabilizing at each condition before the test. However, the acceleration should not be so fast as to mask or cause any stability effects. Note: the effects of acceleration and rapid altitude changes are considered in the recommended change for §23.2135 Controllability.

1. Test conditions
    a. For each configuration the following range shall be tested
        i. Airspeed from the minimum practical speed for the configuration to the maximum practical speed with upsets at a minimum of 4 speeds between the minimum and maximum, but fewer speeds are allowed if the resulting test conditions are less than 20 knots apart. However, at least one intermediate speed shall be tested.
        ii. For the minimum practical speed test, in addition to the level flight test condition, a test condition at maximum climb rate and a test condition at maximum decent rate shall be included.
        iii. For the maximum practical speed test, in addition to the level flight test condition, a test condition at maximum climb rate and a test condition at maximum decent rate shall be included.
        iv. If the aircraft is capable of hovering, a test at zero and approximately 10 knots airspeed (forward and rearward) is required. A test at the maximum practical rearward velocity (at least 17 kt.) is also required.
        v. If the aircraft is capable of hovering and can be commanded to move laterally, a test at approximately 10 knots lateral airspeed (left and right) is required at 10 kt forward and 10 kt backward as well as the maximum practical lateral velocity (at least 17 kt) at zero forward speed.
        vi. Altitude from 5,000 ft or lower to the maximum practical altitude for the configuration at no more than 10,000 ft intervals.
        vii. Tests must be conducted during configuration changes in both directions and in any configuration that can be flown as a steady state configuration.
        viii. If different size control inputs produce different characteristics (rise time, damping, etc.) then an input that demonstrates each characteristic response type shall be tested. Note that systems with rate limiters often produce different response characteristics depending on whether or not the command was large enough to cause the rate limiter to be exercised.

2. Test procedure
    a. Start each test or test sequence in level flight out of ground effect at a constant altitude and airspeed.
        i. For aircraft capable of hovering, the zero, 10 kt. forward, 10 kt. rearward, maximum rearward and lateral speed tests must also be conducted in ground effect as low as practical.
    b. At each test condition, create a sharp-edged control input (step input, or pulse) that disturbs the aircraft sufficiently to observe its stability characteristics relative to longitudinal speed, vertical speed, pitch attitude, bank angle, heading, and sideslip or lateral speed. Note that a single command may disturb more than one state. This is acceptable. Commands shall include those that produce a change in:
        i. longitudinal speed or acceleration
        ii. vertical speed or acceleration
        iii. pitch attitude
        iv. bank angle
        v. heading
        vi. sideslip or lateral speed
    c. Special test software may be used that provides repeatable and defined inputs designed to produce the desired control inputs. However, if such software is used, manual inputs shall also be used to verify that the electronic inputs produce responses similar to responses to inputs that are not preprogrammed.
    d. For configuration changes, the aircraft need not be modified to stop a configuration change midway to show stability. However, if the configuration change is controlled manually such that it can be stopped between defined configurations, then enough increments between the defined configurations must be tested to show that all intermediate configurations meet the stability criteria. Configuration changes that move between defined configurations fast enough that instabilities do not affect pilot workload, and the configuration change cannot be stopped at an intermediate configuration in normal operations need not be tested in intermediate configurations. However, if the configuration change can be reversed before it is complete, then the effect of reversing a configuration change part way through must be tested.
    e. Force gradients
        i. It shall be shown that the force required to command a change in an aircraft state is proportional to the amount of change being commanded, and that the slope of the force vs. command curve does not reverse.
            1. Inputs that command more than one parameter shall show a proportional and non-reversing slope for each parameter individually. For example, an N_{zU} control law which commands a

combination of normal acceleration and speed change from a trim speed shall show that the force per G and the force per knot are both proportional and non-reversing when the other parameter is constant. Likewise, a control law which commands a combination of roll rate and sideslip angle from a single inceptor input shall show that the force for roll rate and the force for sideslip are both proportional and non-reversing when the other parameter is constant.

3.6.4.6 Transient stability requirements for FBW aircraft.

It is recognized that aircraft designs that were not envisioned at the time this recommended change was written may have stability characteristics in certain flight conditions that may present HQ issues that are not addressed in the above sections. This section is intended to address those designs and/or flight conditions that exhibit these characteristics.

The tests in this section are intended to be conducted as a result of observations made during the tests conducted for the stability, controllability, and low speed flight tests above. They are intended to show compliance when control inputs to one axis affect motion about another axis, transient conditions exist or otherwise do not fit the criteria of the stability, controllability, and low speed characteristics recommended change requirements. As such this section is a place to capture and document unique handing qualities characteristics not documented in other sections.

The results of previous tests along with engineering judgment will determine the test conditions required by this section. The intent is to capture and document HQ phenomena that is noted by the applicant or test pilots as warranting further examination and providing a place for this when other test conditions do not provide for adequate examination of the phenomena.

Of particular note are flight conditions where control inputs on one axis produce motion on a different axis, and conditions where uncommanded motion occurs. Particular attention should be directed to flight conditions where configuration changes are being made. A partial list of the conditions that should be specifically considered are:

- the effects of accelerating rotors,
- control scheme transitions (e.g., ailerons to differential thrust),
- aerodynamic surfaces transitioning from attached to separated flow,
- gyroscopic effects,
- control algorithm changes (e.g., stall protection, overspeed, etc.),

- rotor wake interaction with other rotors or aerodynamic surfaces.

The procedure is to fly the aircraft to the conditions of interest and disturb it using control inputs that may cause motion different from normally expected motion in steady flight and observe the response. This control input may involve multiple axes simultaneously or may occur at critical times during a configuration change.

Because the potential conditions of interest can vary greatly between aircraft, specific test conditions are not described here. If through the evaluations done in the process of executing the other tests, no potentially unusual HQ are identified, then there are no tests required for this section.

When tests are required for this section, all parameters that are being actively controlled must respond quickly to a control input and be heavily damped to avoid man machine coupling (pilot induced oscillations).

The results of other tests, along the applicant's knowledge of the flight characteristics will determine the test conditions for this section. These test conditions (if any) will be agreed to between the applicant and the FAA.

Because of the nature of some of the proposed aircraft designs, there exists a likelihood that there may be interactions between axes and transient deviations from commanded states during configuration changes. The intent of this section is to recognize that some designs may temporarily not exhibit stability during all combinations of control inputs or configuration changes and therefore the intent is to provide guidance concerning these interactions and transients.

The purpose of these tests is not to demonstrate static or dynamic stability in the classical sense for all flight conditions, control input combinations and transient conditions. Tests should show that the aircraft demonstrates safe characteristics for all flight conditions, control input combinations and transient conditions that the aircraft demonstrates safe characteristics. Test should also show that temporary instabilities are restricted to small amplitudes and short durations that do not adversely affect control of the aircraft before the aircraft again exhibits static and dynamic stability as shown by the stability tests above.

It is acknowledged that the applicant will have much more flight experience with their design than the FAA. As such, the applicant is obligated to disclose all flight conditions that may result in unsatisfactory results per this section. This includes rapid maneuvering up to the aircraft's limits. The applicant is required to explore the entire flight envelope before applying for certification and proactively address areas of weakness before applying for certification.

The intent and spirit of certification is not to "allow" the FAA to discover areas where the requirements may not be met. The intent and spirit of certification is for the applicant to show the FAA and document that the design meets all requirements in all approved flight conditions – particularly during flight conditions with reduced stability. It is the applicant's obligation to disclose any questionable areas and demonstrate that the flight characteristics in these areas are satisfactory.

The tests will be conducted at the most adverse weight and CG location for the configuration and flight condition tested.

The effects of acceleration and rapid altitude changes are also considered in recommended change 2135 Controllability.

1. Test conditions

   The results of the controllability, longitudinal and lateral stability tests, along with aircraft characteristics and the applicant's knowledge of the flight characteristics will determine the test conditions for this section. Test conditions for this section (if any) will be agreed to between the applicant and the FAA.

2. In general, the test procedure is as follows
   a. The test will start with the aircraft stabilized at or near the flight condition to be tested.
   b. A maneuver will be performed to get the aircraft to the flight condition to be tested if the condition involves configuration changes or maneuvering.
   c. When on condition, the control inputs required to disturb the aircraft will be applied.

This section is intended to examine motion that would normally be unexpected by the pilot that is the result of non-linear aerodynamics, aerodynamic coupling, gyroscopic coupling or other effects.

Some (but not all) of the issues that this section is designed to expose are

(a) gyroscopic coupling
(b) high angle of attack departures
(c) high angle of attack departures due to sideslip
(d) unexpected motion due to high sideslip angles
(e) aerodynamic blanking (e.g., stabilizer stall due to fin blocking at high sideslip angles)

(f) unexpected motion during configuration changes
(g) unexpected motion during configuration changes due to high angle of attack
(h) unexpected motion during configuration changes due to sideslip
(i) unfavorable rotor / rotor wake interaction (including settling with power)
(j) unfavorable rotor wake / aerodynamic surface interaction including control surfaces
(k) unfavorable multiple rotor wake interactions
(l) tendency to lose control in turbulence

4 Aircraft, simulation, and simulator

The focus of this work was on developing MTEs that can be used as a means of compliance for aircraft with full-authority FBW systems that do not mimic mechanical systems. The ability of the MTEs to evaluate the simulated aircraft flight controls was being tested, not the aircraft. Thus, the developed simulation intentionally had HQ issues in all the time and optional for the MTEs to uncover. There was a version that flew well for most maneuvers and there were versions with various and more significant HQ problems. Sections 4.1 through 4.6 describe the nominal vehicle simulated and control law implementation. Section 4.7 describes the HQ problems in the nominal configuration and ones that could be switched on and off. Note that some of the HQ problems were not really problems with the implementation. Some are how the vehicle modeled should operate, but fixed and rotary wing pilots were surprised by certain behaviors and had to adapt their reactions to them.

4.1 Aircraft overview

The Unified Generic eVTOL Aircraft (UGeVA) developed by Adaptive Aerospace Group is a loose representation of NASA’s Lift + Cruise eVTOL aircraft that is representative of proposed UAM vehicles. The vehicle is full FBW with no reversion modes. It incorporates control inceptor mapping akin to the flight controls implemented in the F-35B known as “Unified.” Noting that Unified is a concept, not a precise implementation, some changes from the Unified references were made because the performance and intended use of UGeVA are very different from the F-35B.

The aircraft has a wing and tail with a pusher propeller akin to conventional aircraft. It has four pods under the wings with two lift rotors mounted on each pod. Each propeller/rotor is driven by an electric motor that can act independently. The conventional airplane carrying the lift rotors has ailerons, an elevator, and a rudder. This totals 13 control effectors. The aircraft can hover using the lift rotors and cruise on the wing for efficient forward flight. This resulted in the development of three operational modes: Hover, Transition, and Cruise. The flight control system makes use of control effectors and changes in flight modes transparent to the pilot. Transitions are fully automatic, and the pilot has no ability to override the mode selection. Images of the vehicle are shown in Figure 6, and some parameters in Table 8.

Table 8: Vehicle model mass properties and dimensions.

Number of Passengers	6
Weight (lb)	5800
Ixx (slugs-ft^2)	6893
Iyy (slugs-ft^2)	4500
Izz (slugs-ft^2)	9611
Main Wing Area (ft^2)	190
Wing Loading (lb/ft^2)	30.53
Main Wing Span (ft)	47.72
MAC (ft)	3.81
Lifting Rotor Disk Area (ft^2)	78.54
Disk Loading (lb/ft^2)	9.23

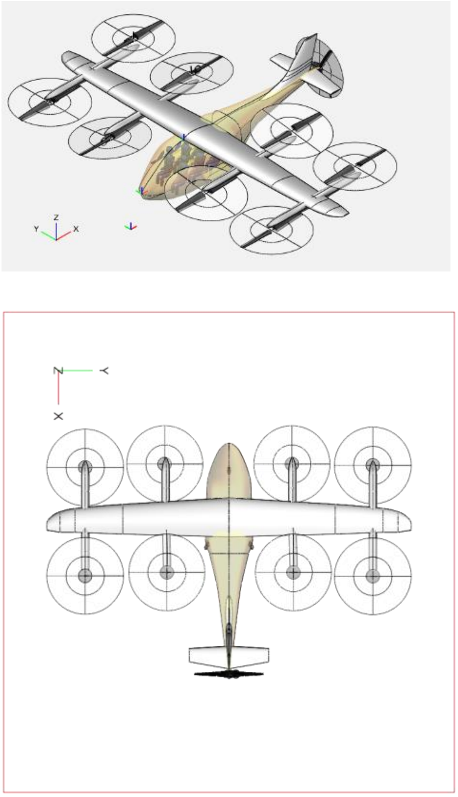


Figure 6: UGeVA perspective and top view

4.2 Unified implementation

UGeVA has three flight modes: Hover; Transition; and Cruise. The flight modes can be thought about in two ways. One is how lift in generated, i.e.: 1) when the rotors alone are generating the lift; 2) when the rotors and wing are/can be generating lift; and 3) when the wing alone is generating the lift. However, all mode changes are automatic, and the pilot does not have to be aware of them. Therefore, when the three modes are discussed herein and by the pilots operating the aircraft, they will use the three modes to refer to control inceptor mapping, i.e., how the aircraft reacts to pilot input.

It is important to note that the points where inceptor mapping changes do not match the points where lift generation changes. In other words, the pilot may be flying with cruise inceptor mapping while the aircraft is generating all of its lift via the lift fans.

The aircraft has three pilot inceptors.

- A side stick at the pilot's right hand that can move fore and aft and left and right.
    - Fore and aft motion = Longitudinal Stick
    - Left and right motion = Lateral stick
- Foot pedals
- A linear inceptor at the pilot's left hand. This inceptor position always commands a speed but mechanically it has two regions that act differently (Figure 7):
    - The aft 1/3rd of travel commands speeds between -10 and 10 knots ground speed. It has force feedback that will drive it to the center of this section. Thus, if the pilot releases the lever when in this region it will move to command zero groundspeed (hover).
    - The forward 2/3rd of the travel has no force feedback, only friction. When the pilot moves the inceptor to a position it equates to a commanded airspeed. It is essentially an autothrottle with speed command mode only.
    - Between the aft third and rest of the travel, there is a detent that is noticeable to the pilot providing haptic feedback and an aural "click" when moving between them.

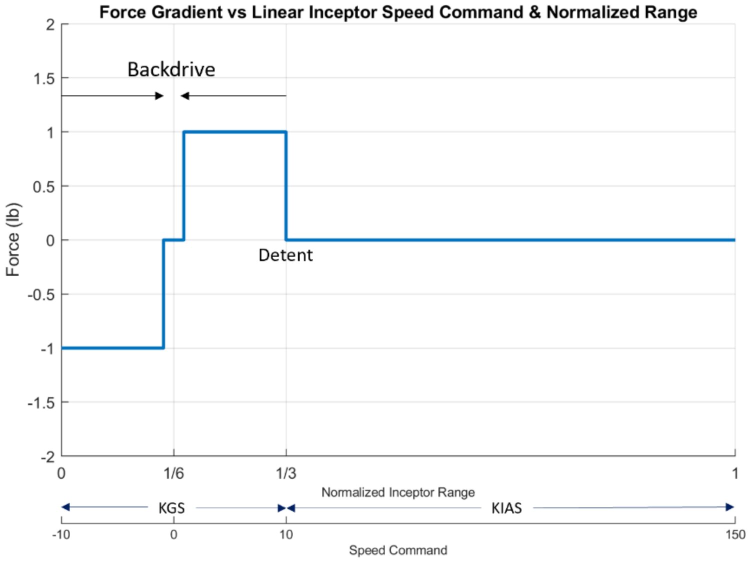


Figure 7: Linear inceptor force gradient

When controlling the aircraft, the pilot should think of Hover, Transition, and Cruise mode which align pilot input with aircraft reaction. Changes between the three flight modes are completely automatic. The three modes are described below and depicted in Figure 8:

- Hover
  - Mode in effect between -10 and 10 knots ground speed.
  - Longitudinal stick commands altitude rate. Neutral is altitude hold.
  - Lateral stick commands lateral translation rate, ground speed. Neutral is lateral position hold.
  - Linear inceptor commands longitudinal translation rate, ground speed. Force feel is active requiring the pilot to hold the inceptor for non-zero speeds. Neutral is longitudinal position hold.
  - Pedals command heading rate. Neutral is heading hold.
  - Hands and feet off results in hover at constant altitude, heading, and position.
- Transition
  - Mode in effect between 10 and 35 KIAS, generally.
  - Inceptors smoothly convert from Hover to Cruise mapping with a mix of the two.
- Cruise
  - Mode in effect 35 KIAS to V_{ne} (160 KIAS). (Note: Flight control mode, the rotors are still generating the lift.)
  - Longitudinal inceptor commands flightpath angle rate. Neutral is flightpath angle hold.
  - Linear inceptor commands air speed, max command = 150 KIAS.
  - Lateral stick commands bank angle rate. Neutral is bank angle hold.
  - If bank angle is less than 2.5 degrees and the lateral stick is neutral, the controls assume the pilot wants wings level and washes out the bank.

- Pedals command steady track side slip.

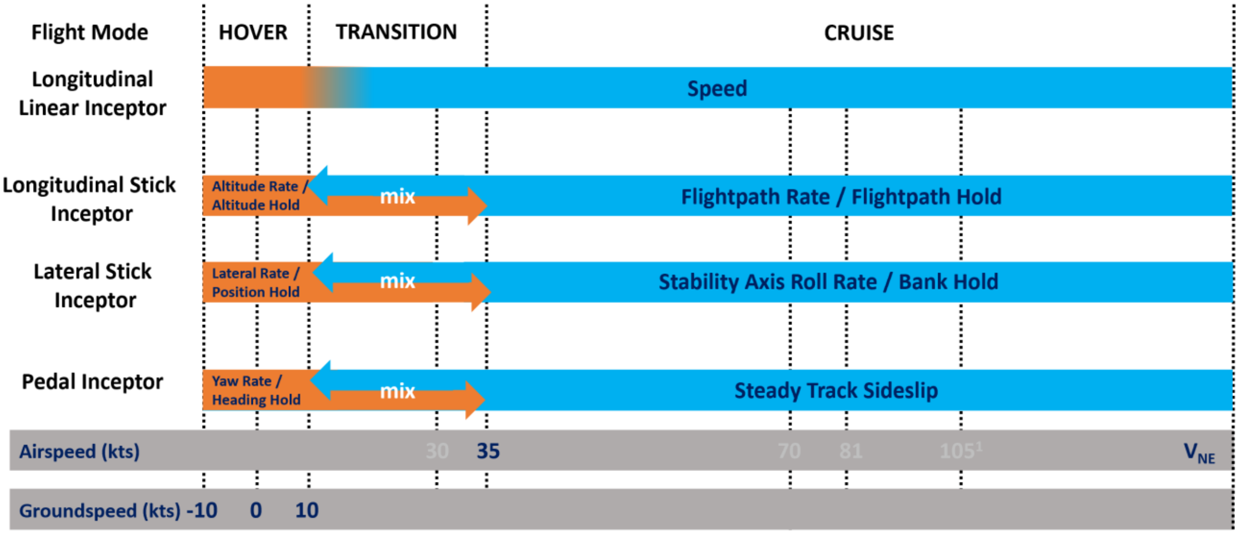


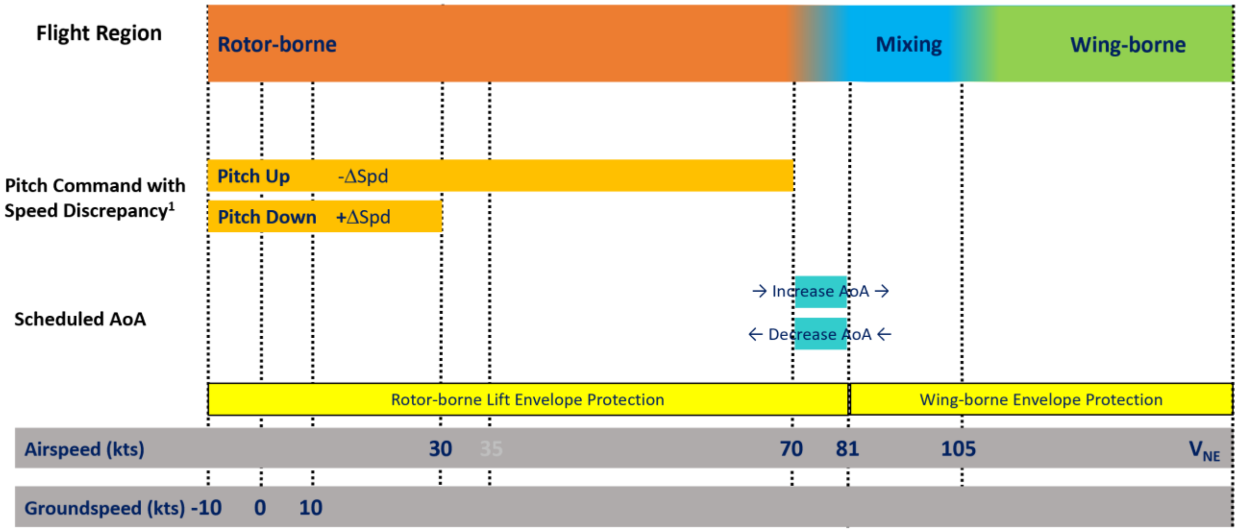
Figure 8: Flight control mapping

If the speed command is kept at or above 105 KIAS the lift rotors are locked out. If a climb angle is commanded that causes the aircraft to lose speed, the control system will reduce the climb angle to prevent wing stall at ~81 KIAS, effectively limiting AoA. If the pilot moves the speed command below 105 KIAS the lift rotors will come on and the wing stall prevention logic is disabled. However, a stall will not occur since the rotors provide the lift required.

Landing gear is modeled and uses a gear handle in the CMF to extend and retract it. Aerodynamically the landing gear model only effects drag. The model allows wheel and hover landings as well as taxiing and it has brakes.

Note that changes between modes occur only when both commanded and actual speed move from one mode to the next. There are functions of this vehicle model that are not directly commanded by the pilot but that vary depending on the stage of the flight. The rotors are phased out automatically by the flight control system when the wing of the vehicle is generating enough lift. To turn off the rotors as early as possible and limit power consumption, the vehicle automatically pitches up to approximately L/D_{max} angle of attack at V_s (Figure 9).

There is no direct acceleration command. However, the bigger the difference between commanded and actual speed the more acceleration the aircraft will attempt to achieve. When accelerating at speeds <30 KIAS or decelerating at speeds <70 KIAS the vehicle will pitch nose-down or nose-up to accelerate or decelerate rapidly if a large acceleration is commanded (Figure 9). The amount of nose-down/up commanded is a function of the difference between the current and commanded speed (Figure 10). Without this feature, it is difficult to stop the aircraft at a precise spot for hover because of limited acceleration capability. With this feature, it can be difficult to manage precise vertical maneuvering, like flying the 9-degree glide slope implemented for this study while slowing to a hover, because the pitch seems uncommanded and pitch ups can obstruct view of the landing spot. Therefore, when rapid acceleration is not needed the pilot should command accelerations gradually by moving the speed command lever slowly keeping the commanded speed and current speed close. This technique allows for slow speed changes in cruise and approach when precise vertical control is needed, and allows rapid speed changes for takeoff and urgent stops.



[1] To achieve helicopter-like acceleration the vehicle will pitch down when the speed command is above current airspeed when below 30 KIAS and will pitch up when the speed command is below current airspeed when below 70 KIAS

Figure 9: Indirect pilot commands

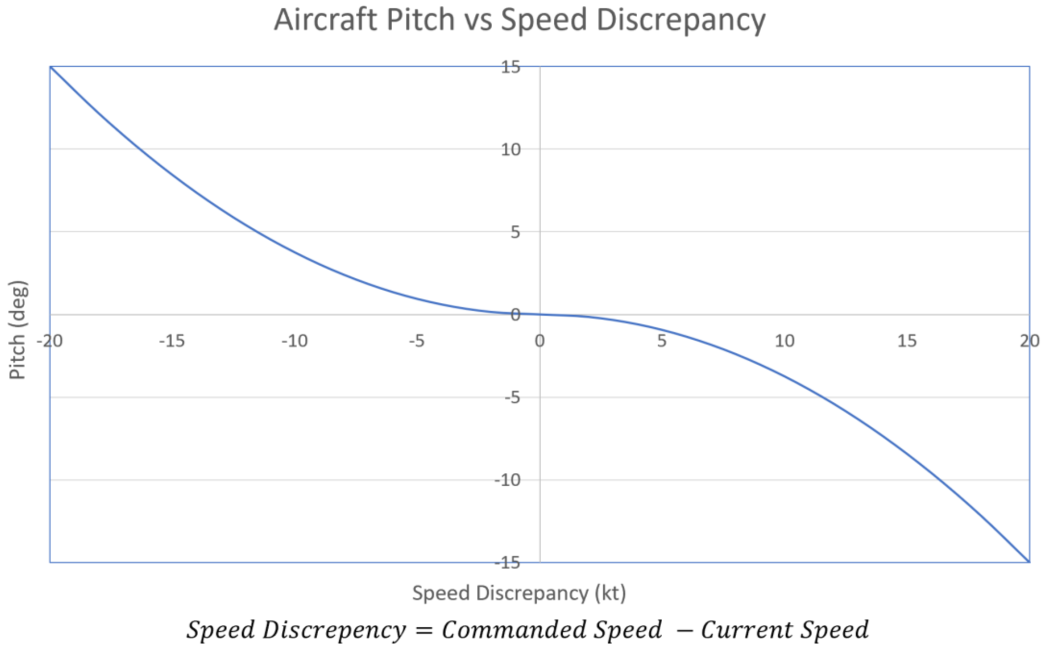


Figure 10: Aircraft pitch due to speed discrepancy

4.3 Envelope protection

The flight control system of UGeVA includes envelope protections that vary with flight mode and airspeed. The protections are described in detail below and collected in Table 9. The pilot cannot override the envelope protections.

Overspeed protection: If the aircraft has a negative gamma or is in a sufficient updraft and is approaching V_{ne} with the pusher prop at idle, the flight controls will increase the flight path angle to prevent overspeed. The aircraft will continue to increase flight angle until the max commanded speed of 160 KIAS is reacquired.

Stall/under-speed protection: If the pilot keeps the speed command above 105 knots and the airspeed of the vehicle falls below 105 knots, the lift rotors will not come on until the pilot also commands below 105 knots. This was done to assure the pilot has control over when to use the lift rotors as they consume a lot of power. In this state, if gamma is high enough that the airspeed bleeds down to 81 knots (V_s) the flight controls will reduce the gamma to hold the speed and prevent an aerodynamic stall. If the aircraft has a bank angle larger than 5 degrees, as the gamma is reduced to keep speed at 81 knots, the bank angle will also be reduced at a 3 deg bank-to-1 deg pitch ratio until bank angle is 5 degrees. It does not reduce bank angle to zero so the pilot will still have some turn rate available in the desired direction.

Flight path angle protection: The flight angle is limited to ±20 degrees by the flight control system whenever the hover mode vertical rate is less than the vertical rate associated with the flight path angle. That allows vertical climb/descent in and approaching hover mode while preventing steep angles in airplane mode.

Bank angle protection: The bank angle limit is reduced with airspeed. The limit is 45 degrees at and above 105 knots, the phase in flight where the lifting rotors are always turned off. The bank angle limit is reduced to 10 degrees at 20 knots, well into the transition flight mode.

Vertical speed protection: Below 20 KIAS descending vertical speed is limited to 500 fpm (Feet per Minute) to protect against vortex ring state (VRS). This is smoothly engaged between 20 and 30 KIAS to prevent apparent discontinuities.

Table 9: Envelope protection parameters.

Hover			Transition			Cruise		
	lower	upper		lower	upper		lower	upper
Speed Cmd (KGS)	-10	10	Speed cmd (KIAS)	10	35	Speed Cmd (KIAS)	35	150
Bank angle (deg)	[-10 -5]	[5 10]	Bank angle (deg)	[-15 -10]	[10 15]	V_{s0}/V_{ne} (KIAS)	81	160
Translation (KGS)	-10	10	Roll rate (deg/s)	-20	20	Bank angle (deg)	[-45 -15]	[15 45]
Vertical rate (fpm)	-500	1200				Sideslip (deg)	-5	5
						Service ceiling (ft)	-	8000
						Gamma (deg)	-20	20
						Gamma rate (deg/s)	-5	5
						Roll rate (deg/s)	-40	40

4.4 Displays

The displays described in this section were implemented in NASA Langley's Cockpit Motion Facility and AAG's simulator, which are described in Section 4.5 and 4.6 respectively. Both sims utilize two heads-down displays, a primary flight display (PFD) and a navigation display (ND). The CMF also has a heads-up display (HUD) that can be used or folded up.

DELPHINS (E. Theunissen, 2005) was the display software used to generate the PFD and the ND. The DELPHINS simulation software is used for testing and evaluation of prototype

Avionics Displays. It relies on the Information Systems Delft DELPHINS Display Design System (ISD D3S) rapid prototyping environment for design, implementation, and integration of new display formats and/or changes to existing ones. It has been used in flight-testing and simulation-based evaluations for over 20 years. The DELHINS system allowed easy modifications to accommodate the aircraft and control system implemented.

The PFD has features typical of modern PFDs including synthetic vision and a highway in the sky. The ND has two modes, a moving map display that shows waypoints and a look down video display that is from a simulated gimbal-stabilized camera on the bottom of the aircraft. These modes can be toggled between by the pilot using the trigger on the side stick. The look down display has a predictive line and circle indicating where the aircraft will be in two seconds (Figure 15) based on the current trajectory.

There is also the option to have a HUD in the CMF per the pilot’s preference. The HUD essentially replicates the PFD graphics but has a slightly smaller field of view. A highway-in-the-sky was available for navigation on the PFD and HUD. The HUD could be configured with or without the highway in the sky.

The HUD and PFD have a pointer on the airspeed tape that indicates the commanded airspeed coming from the linear inceptor. There is also a reference speed marker that can be programmed and is currently set up to indicate desired speed when flying routes, including approaches.

Images of the PFD from the CMF are show in Figure 11 through Figure 13. They show the vehicle taking off from a rooftop helipad, climbing up to the highway-in-the-sky, and coming in for a final approach to a helipad on a pier. Various display elements discussed above are depicted and labeled.

Below 15 KIAS the PFD will display a vertical rate diamond to provide the pilot a more centralized indicator during vertical takeoff and landing. The diamond’s location on the pitch ladder indicates the vertical rate in 100s of feet per minute and the rate is also shown in the box below the diamond.

Figure 14 shows the HUD from the same flight condition in Figure 13 of the PFD. The display layout is identical to that of the PFD except the highway-in-the-sky was turned off in the HUD.

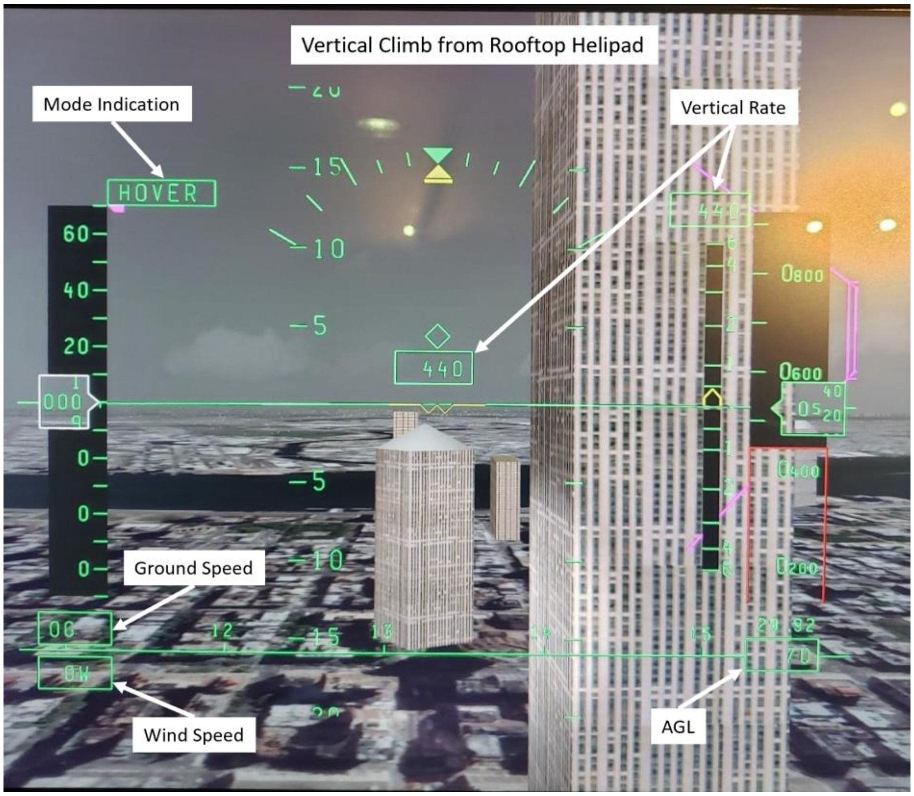


Figure 11: PFD image in the CMF

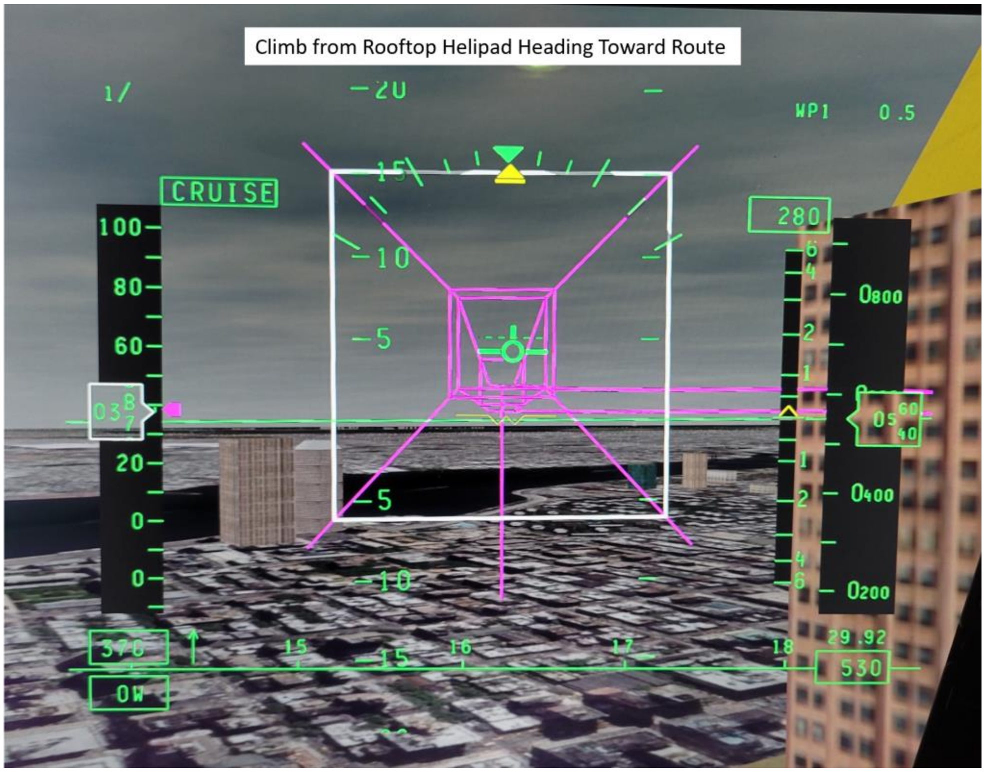


Figure 12: PFD image showing the highway-in-the-sky

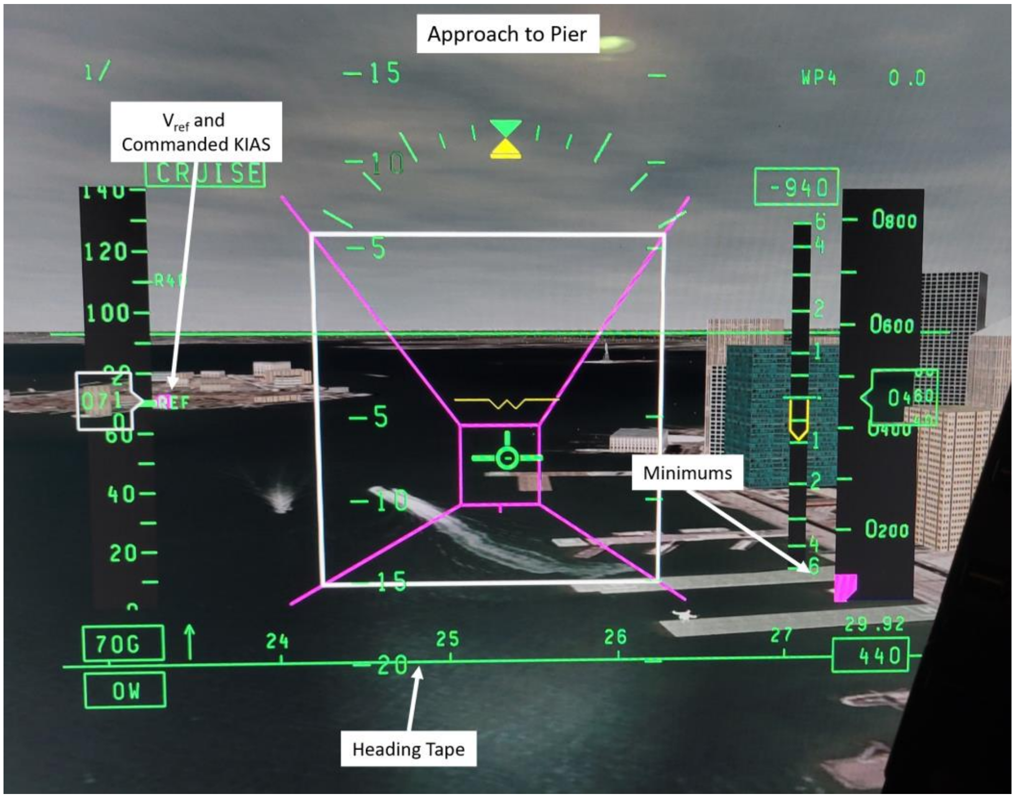


Figure 13: PFD image during final approach

Figure 14: HUD image from CMF

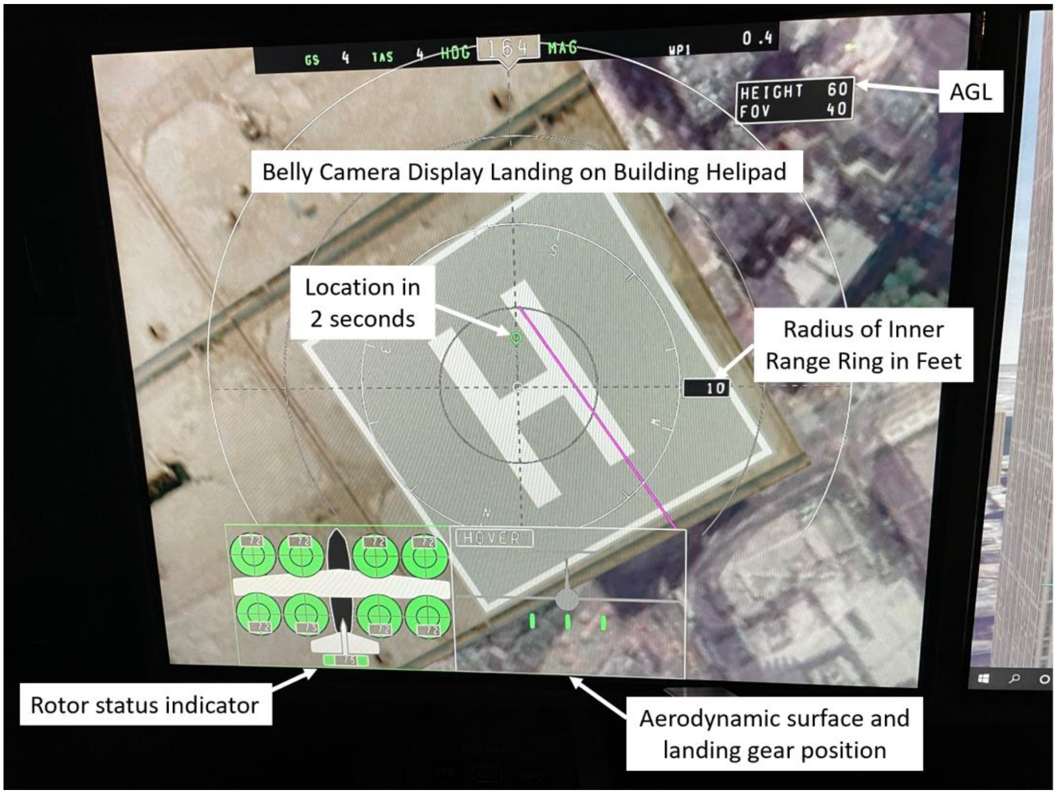


Figure 15: Look-down camera from ND

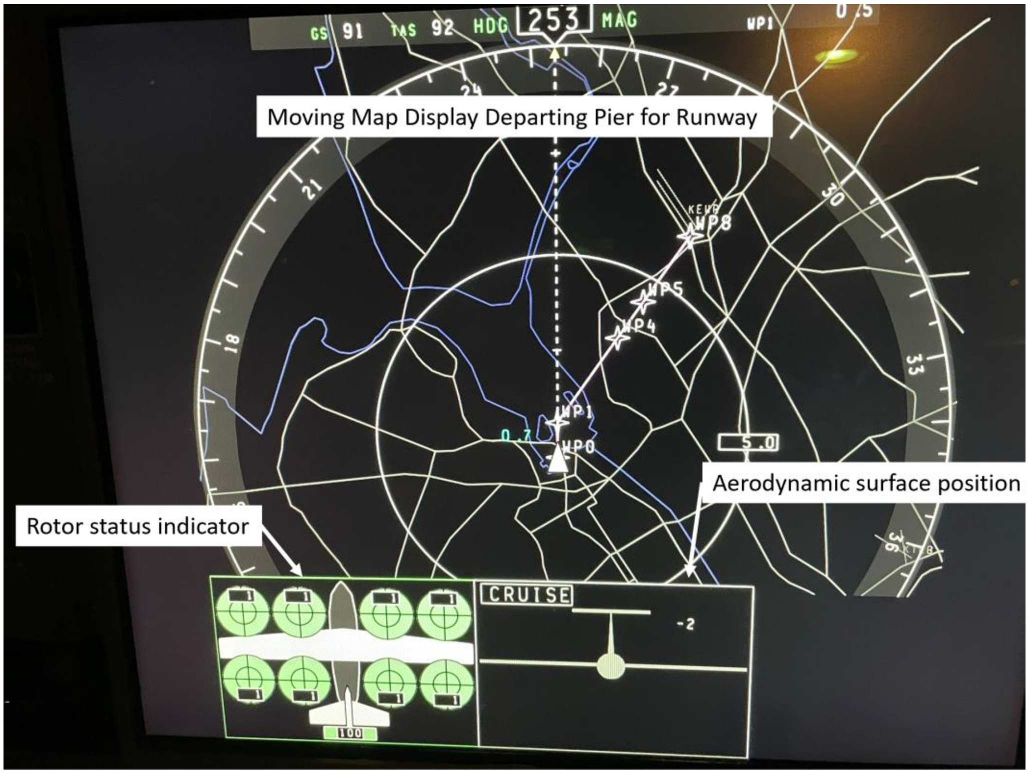


Figure 16: ND in moving map mode

4.5 Cockpit Motion Facility

NASA Langley Research Center's CMF (National Aeronautics and Space Administration, 2021) is made up of one motion system site and four fixed-base sites. The CMF (Figure 17) is a multifaceted motion and fixed-base flight simulation research laboratory. It is designed to support aeronautics and space flight vehicle research studies in which motion cues are critical to the realism of the experiments being conducted. The motion system site contains a six-degree-of-freedom state-of-the-art synergistic motion base with 76-inch extension actuators. The four fixed-base sites provide homes for the simulator cockpits when they are not resident on the motion system. The cockpits are fully operational when located in the fixed-base sites and run independently of each other and the motion system site. When a research study requires use of the motion system, the appropriate cockpit is moved from its fixed-base site to the motion system by use of an overhead facility crane system and lifting rig. Each fixed-base site and the motion system site are equipped with quick disconnect features for power, air conditioning, hydraulics, video, audio, data communication and fire detection to allow for rapid changeover. The four cockpits are the Research Flight Deck Simulator, the Integration Flight Deck Simulator, the Generic Flight Deck Simulator, and a future, undefined simulator.

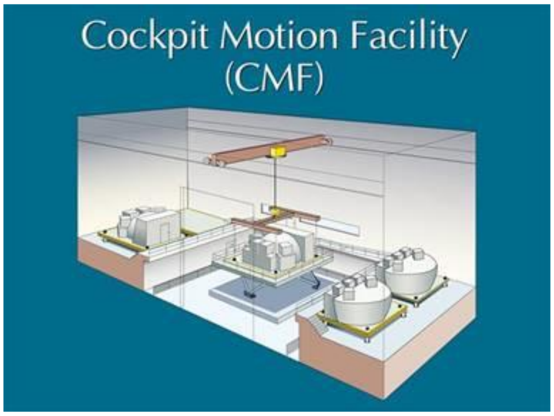


Figure 17: Cockpit Motion Facility

The Research Flight Deck (RFD) Simulator is an advanced all-glass jet transport simulator (Figure 18). The simulator can utilize mathematical models of any aircraft. The cockpit main instrument panel is completely glass with all instrumentation generated by computer graphics. All displays can be changed to meet researchers' requirements. There is a heads-up display mounted in front of each pilot, and there is a center aisle stand mounted between the two pilots. There are two control display units located in the center aisle stand mounted between the pilots. Each pilot has a two-axis side stick control loader system for pitch/roll control and a set of

Figure 18: Research Flight Deck

hydraulic control loaded rudder pedals. The pilot’s side stick controller is mounted on the left side, and the copilot’s side stick controller is mounted on the right side. RFD is also equipped with electronics flight bags and unobtrusive eye trackers. The cockpit’s visual system is a collimated panorama system, which provides 200 degrees horizontal field-of-view and 40 degrees vertical field-of-view. The visual system is driven by a state-of-the-art computer-generated image system. Numerous very highly detailed terminal areas and surrounding area visual databases are available to the researcher. The RFD is considered equivalent to an FAA certified Level D simulator for the 737.

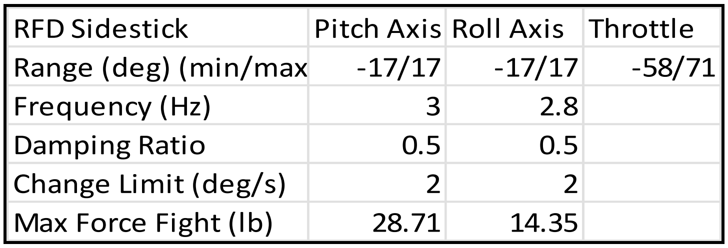
The RFD has a two-panel display setup at the pilot and copilot station that were used for this work: the inboard panel displayed the PFD and the outboard displayed the ND (see Section 4.4). The pilot flew from the right seat for this study.

The side stick (Figure 19) can be programmed with various stick force gradients and dynamics. The RFD throttle (Figure 20) had a motor that was used to drive the grip back to the 0 KGS commanded position. To account for the detent, a spring-loaded mass was attached to the grip that traveled along a track installed adjacent to the throttle with a detent at the 10 KGS commanded position. The RFD inceptor parameters are given in Table 10.

Figure 19: RFD sidestick

Figure 20: RFD throttle with mechanical detent

Table 10: CMF Inceptors.



RFD Sidestick	Pitch Axis	Roll Axis	Throttle
Range (deg) (min/max	-17/17	-17/17	-58/71
Frequency (Hz)	3	2.8	
Damping Ratio	0.5	0.5	
Change Limit (deg/s)	2	2	
Max Force Fight (lb)	28.71	14.35	

4.6 AAG simulator

AAG's flight simulator (Figure 21) runs on a Windows 10 desktop computer and is compatible with most PC-based flight simulator software packages such as FlightGear or X-Plane. The MATLAB® and Simulink® airplane and control system models are interfaced to the simulator and FlightGear provides the graphics. The simulator hardware components include a desk mounted Saitek® yoke with throttle quadrant as well as floor mounted Saitek rudder pedals. Dual display monitors are installed and are used to render a single wide-view cockpit or customizable separate views of the aircraft and cockpit. The control inceptors have very light loading generated by centering springs.

Figure 21: AAG simulator

To achieve the functionality necessary for the speed command concept, two additional inceptors were purchased and mounted adjacent to the simulator. These included a sidestick (Brunner Elektronik AG CLS-P Joystick) and a longitudinal linear inceptor (Brunner Elektronik AG CLS-P Linear Motion) from Brunner Elektronik AG. Both inceptors were fully programmable allowing us to easily create and adjust the detent and throttle driving for the linear inceptor as well as the force feedback on the sidestick. The characteristics of both inceptors were set up to replicate the ones used the CMF as described in Section 4.5.

The MATLAB® and Simulink® airplane and control system models were interfaced directly with FlightGear, used for generating the simulation environment. The PFD and ND were both put on the heads-down touchscreen display while the HUD window was overlaid on top of FlightGear in the middle display.

The software simulation environment used in the simulators is based on the AAG Generic Aircraft Simulation Environment (AGASE). AGASE is an aircraft simulation tool set that includes an atmospheric model; 6-degree of freedom equations of motion; a turbulence model, multiple axis transformation blocks, and other components that would be used by any aircraft simulation.

4.7 Intentional handling qualities issues

Handling qualities problems were programmed in the simulation model intentionally to test the robustness of the MTEs and their ability to discover known or possibly unknown issues. Some of the problems were in the nominal model and some were optional, could be switched on or off. There were also necessary functions in the control system that were as they should be given the physics of the lift + cruise configuration that are not what fixed or rotary wing pilots are familiar with. These functions resulted in surprises and initial incorrect reactions. Pilot reactions and interactions with the MTEs are discussed in Section 5. The following is a list of some of the problems and features that were in the nominal model:

1. One known problem occurred during transition between the wing lift and rotor lift at 60 KIAS while in a steep descent. A nose down pitch departure occurs during descents steeper than a 12-degree flight path angle.

2. The pitch up or pitch down for acceleration and deceleration was an important component of the control system and the vehicle performance. However, it was initially perceived by pilots as uncommanded pitch changes.

3. When going from 70 to 81 knots, the vehicle pitched up to go from rotor lift to wing lift. When slowing down it pitched down to go from wing lift to rotor lift. This was initially interpreted as an uncommanded vehicle response by the pilots.

4. The stall/under-speed protection detailed in Section 4.3 is another control system function that the pilot may view as uncommanded. This vehicle prevents any type of wing stall. It will not turn the rotors on to compensate for any post-stall conditions if the speed command remains above 105 KIAS. Instead, the envelope protection decreased AoA and reduced bank angle if necessary.

5. The vehicle’s overspeed protection can appear as an uncommanded pitch up.

6. In transition flight mode, the vehicle transitions between turn rate being commanded by the pedals in hover flight mode to turn rate being indirectly commanded by the lateral stick in cruise mode. The transition results in the pilot having to transition from using

pedals to using stick and using both in the middle of the transition speed range. This was confusing to pilots initially.

Optional handling qualities problems were developed that could be toggled between simulation runs. Three degraded configurations are listed below:

1. A switching logic problem could be toggled on or off. If on, switching from transition to hover flight modes required both actual airspeed and commanded speed to be less than 10 knots to be satisfied. This would result in the system not switching to hover mode when the pilot commanded zero ground speed if winds were 10 knots or higher. It would transition to hover if the pilot commanded a negative groundspeed sufficient to get airspeed less than 10 knots. In the nominal configuration, a signal that fades from groundspeed to airspeed was used to prevent the logic problem. This is an interesting problem in the testing environment because it only appears when winds are above 10 kt.
2. The lifting rotor actuator time constant and therefore rate of response to commands was reduced to cause slow response to commands, which caused handling qualities problems, especially in hover taxi. This may be a prominent problem for vehicles with fixed pitch rotors, due to the time it takes to accelerate the rotor to cause a change in lift. This was assessed in (Malpica & Withrow-Maser, 2020).
3. In the nominal configuration the maximum pitch up and down was 15 degrees for maximum acceleration/deceleration commands. For this configuration, the max change in pitch was reduced from 15 degrees to 4 degrees. This made acceleration/deceleration relatively sluggish and stopping at precise points difficult.

5 Observations/lessons learned/discussion

5.1 Evaluation process

The plan for this work was for an FAA test pilot and flight test engineer (FTE) to visit the NASA Langley CMF on three occasions to evaluate the aircraft simulation, MTEs, and proposed use of CHRs. The first visit would have been primarily focused on the aircraft and the next two on MTEs with opportunities to iterate on both the simulation and MTEs between visits. The last visit would have been to evaluate the MTEs using the proposed CHR logic approach. However, as previously discussed, the Covid-19 pandemic of 2020/2021 and a change in priorities by the FAA reduced the FAA exposure to the simulation and MTEs to one visit. Thus, pilot and FTE were becoming familiar with the aircraft and MTEs at the same time, which is far less than ideal. As a result, the entire set of MTEs was not evaluated (see Section 0) and the proposed CHR approach was not evaluated (see Section 2). Time was focused on the controllability MTEs (§23.2135, MTEs requiring the pilot to close the loop on something) with limited assessments of the stability ones (§23.2145, open loop inputs). Since the aircraft had stall protection, the stall speed and characteristics MTEs were not evaluated. Likewise, trim MTEs (§23.2140) were not evaluated given the aircraft essentially always auto trims. The pilot did a broad set of controllability MTEs including rolling takeoffs to particular climb speeds, hover taxi, takeoffs followed by emergency descents, climbs to a level off altitude, level accelerations and decelerations, instrument approaches, etc. The target speeds and angles were tailored to the aircraft and its flight control system. A few stability MTEs were flown, doublets at a few flight conditions. The tailored maneuvers were things like starting an emergency descent at 80 KIAS, which is where the control system switches from rotor lift to wing lift (See Section 5.2.2). The order of pilot input in that specific case can change the maneuver outcome. MTEs evaluated did reveal all the known/intentional and in some cases switchable handling qualities issues with the aircraft (see Section 4.7) to the FAA test pilot and FTE.

The two FAA personnel that flew the simulator and evaluated MTEs were an FAA test pilot and flight test engineer that are tasked with developing MOC for aircraft that fly in ways that do not align with the current certification rules. The FAA test pilot has experience as a US Air Force pilot and test pilot. After leaving the Air Force, he has both fixed wing and rotary wing experience flying many types of Part 23 and 27 aircraft, including certification flight evaluations. The FAA FTE has decades of experience evaluating Part 23 aircraft for certification.

Other visitors flew the simulation and experienced some of the MTEs. They included FAA personnel whose focus is on pilot training or human factors. There were fixed and rotary wing focused/experienced people in this group. Additionally, personnel from the US Air Force Detachment 62, AFWERX Agility Prime (associated with the Air Education and Training Command), flew the simulation. They similarly had a mix of fixed and rotary wing experience. These two groups only flew the nominal configuration with some of the nominal issues discussed in Section 4.7 addressed. These groups flew brief familiarization flights. Thus, no MTE related comments from them are in the results/discussion. However, observations of these groups contributed and strengthened some comments about the vehicle.

The simulation had several HQ deficiencies that were known before the FAA's evaluation (see Section 4.7). Some were intentional and some were initial implementation errors that were left in for the evaluation. Some of the problems were "always" on and others optionally switched on or off. The evaluation procedures were all written before the deficiencies were known so they were not "targeted" at known deficiencies. The set of potential test conditions to be conducted was far too large to be conducted in the time available. Since the purpose of the evaluations was to evaluate the test condition's ability to detect handing qualities problems, test conditions were intentionally chosen to include (but not focus on) the known deficiencies.

The first day was spent mostly getting the FAA test pilot and FTE familiar with the simulator, simulation, and the aircraft that it represented. This is appropriate since the controllability HQTE requires that the evaluator be familiar with the aircraft being evaluated. Normally, there would not be an instructor role for these tests, but in this case, the evaluation pilots only had a couple of hours of aircraft familiarization time and were not familiar with the details of the simulator, aircraft, or HQTEs. Given the very limited time available, one of the authors sat in the jump seat and acted as a flight instructor walking the FAA evaluators through the training and MTEs. A key purpose of this was to develop the MTEs, but also inform the FAA on how to use them. Note that the MTEs in Section 0 do not contain information on where in the flight envelope the maneuvers should be flown, but rather point to the applicant knowing the vehicle and the location of the critical points. The authors developed the aircraft and knew the most critical parts of the flight envelope for the vehicle, thus as the MTEs were flown the FAA pilot and FTE were directed to key parts of the flight envelope for maneuvers. Generally, those parts were at and around configuration changes: physical changes like rotor lift vs. wing lift for example, and command changes like lateral rate vs. bank-angle rate for example. Over the course of the week, the FAA personnel became aware of how to focus on areas of interest based on the description of the aircraft and its control system. As the MTEs state, it is critical to not just evaluate the aircraft's characteristics at the change point, but it is critical to evaluate around that point and possibly approaching it from different directions and possibly with different rates of change and/or sequence of pilot inputs.

Key observations and lessons learned are discussed in the sub-sections below.

5.2 Small changes in maneuver entry can be consequential

Small changes in how a maneuver is entered can make a big difference in the outcome of the maneuver if there are changes in the control laws, aerodynamics, or aircraft flight characteristics near the maneuver initiation point.

5.2.1 Lesson learned

The controllability evaluations (§23.2135) should be conducted in a free form manner to encourage the evaluator(s) to vary the maneuver inputs (timing of inputs relative to each other, magnitude of the inputs, speed at which the inputs are made, etc.) especially near potential control law, aerodynamics, or flight dynamics changes.

5.2.2 Discussion

The aircraft simulation had a stability issue near 60 kt at descent angles steeper than 12 degrees. The simulation had UAM approaches to rooftops and piers that included nine-degree descent angles. They could be flown without any trouble. However, one of the MTEs in the Controllability section is to enter an emergency descent from a maximum angle climb with rotors off. This test condition put the aircraft in a situation where the issue would manifest itself depending on the sequence of pilot inputs.

The climb was established at about 80 KIAS. (Note that in level flight the vehicle transitions from rotor lift to wing lift between 60 and 81 KIAS, this varies some with flight condition.) The stick was moved full forward to command a rapid descent followed about a second later by a rapid command to reduce speed to zero. The aircraft smoothly pitched over to the -20 γ limit to follow the change in flight path command and accelerated toward V_{ne}. The lift rotors stayed off. If the descent was maintained, upon approaching V_{ne} the envelope protection would reduce the descent angle. The maneuver was uneventful.

However, upon establishing the same climb, if the speed command was rapidly moved zero speed followed about a second later by the descent command (the order of the speed and flight path commands was reversed) a very different result was seen. In this case, the aircraft decelerated rapidly, and the lift rotors came on before starting to pitch over. In this configuration, the vehicle could then slow to a hover. However, with the -20 γ as the aircraft slowed through 60 KIAS a rapid uncommanded nose down pitch and acceleration motion occurred which was clearly unacceptable. This caused the evaluation pilot to hit the simulation motion emergency stop button to prevent the jolt that would have been associated with an eminent crash. The uncommanded and uncontrollable pitch down only occurred slowing through 60 KIAS with a descent angle steeper than 12 degrees. While the commanded values were stable, the physical transition from rotors to wing in this case was not. (This was a known problem that was fixed before the other FAA and the Agility Prime personnel flew the simulator.)

In the first case, the aircraft sped up and remained on the wing with the rotors off. In the second case, the aircraft slowed down, and the rotors came on and stayed on. It was in “cruise” command mode in both cases, but the aircraft behavior was different because it transitioned to using the lift rotors and could continue to slow down. The problem occurred as the physical change switched from lift rotors and wing lift to just rotor lift. Interestingly, if the problem did not exist, both input sequences would be problem free, but they would result in a very different aircraft response. The pitch first would result in a rapid descent at V_{ne}, and speed first would result in a rapid descent while decelerating to zero airspeed. Starting from a speed slightly higher or lower would not have the dual potential response.

This illustrated that both command and physical changes the vehicle is going through can have problems that need to be sought. The set of MTEs revealed the problem, but it required a change in input sequence and starting from a particular airspeed to find it. The vehicle can descend from the stated condition on the wing or on the rotors. Making sure both were evaluated was the key. In both cases, control inputs were the same and the second control input was initiated between one and two seconds after the first. The difference was in the order in which they were initiated. The root cause of this was the control law of the vehicle in that the transition from wing to rotor flight with a descent angle steeper than 12 degrees was not handled correctly. The problem caused a strong uncommanded nose down pitch when passing through 60 KIAS. Speeds 10 KIAS above or below 60 KIAS did not have a problem with the steep descent angle.

If highly scripted test procedures are followed, then the results can be expected to be consistent and repeatable. Consequently, it is likely that unacceptable behaviors will not be found. An expectation of scripted tests also provides an opportunity for an unscrupulous applicant or an applicant that has not tested the design exhaustively to only show good conditions when unacceptable conditions also exist. This also highlights the point made in Section 0 that the applicant needs to test the vehicle extensively and not expect the FAA evaluations to uncover all issues.

The applicant is expected to know the aircraft’s characteristics in all parts of the flight envelope and present any questionable areas to the FAA evaluators. The FAA evaluators need a sufficient understanding of the vehicle and its flight controls to understand where to look for problems and then do variations around those points. The FAA should be briefed on all configuration transitions, command and physical ones, and focus testing in those areas.

5.3 Strong familiarity with the aircraft is required

These aircraft exhibit characteristics and responses that will surprise pilots that only have experience in aircraft with conventional controls. Thus, evaluation pilots need time and experience with the new characteristics to become familiar enough to not revert to their ingrained habits and responses. This aircraft had two significant characteristics that were different from either fixed wing or rotary wing familiar to pilots. A third characteristic that occurred when transitioning from hover to cruise command mode also required learning and experience to properly manage. These three characteristics are discussed below. There were other more subtle differences that required pilots to adjust their expectations when commanding maneuvers.

These were not HQ issues planted in the simulation, they were the result of the physics of how this configuration best accelerates, decelerates, and transitions from rotor to wing lift and back. They were not finely tuned to pilot or passenger opinion. They may have been overly aggressive, especially the pitch up to go from rotor lift to wing lift. Aggressively driving sideslip to zero was also likely done at airspeeds lower than would be required by this configuration.

5.3.1 Difference 1: Control system forces beta to zero above 10 KIAS:

Unlike a conventional airplane, this aircraft is capable of slowing to a hover. For this aircraft, the sideslip angle is limited in airplane mode; therefore, the aircraft cannot slip enough to keep the nose pointed down the runway as it slows to less than conventional wheel landing speeds for airplanes when there is a strong crosswind. (An airplane has limited sideslip capability too, but once the wheels are on the ground during a landing, the sideslip angle limit no longer applies.) The effect of this sideslip limit along with the very low flight speed capability results in the nose increasingly pointing to the upwind side of the runway as the aircraft slows. Conversely, as the aircraft accelerates from a hover through 10 KIAS the nose will rapidly point into the wind even though the flight path remains steady. With a 17 knot cross wind this can result in the nose turning 45 degrees to point into the wind soon after passing 10 KIAS. The pilot cannot significantly affect this unless the speed is below 10 KIAS.

This is very un-natural for pilots used to an airplane that will not slow to the point where this occurs. It is also un-natural to a helicopter pilot; helicopters do not have a sideslip limit (other than the lateral velocity that they can generate) and accordingly allow the pilot to point the aircraft down the runway at slow speed with large crosswinds. The first time the evaluation pilot tried to decelerate and hover land in a 17 kt crosswind, he declared the aircraft uncontrollable. With some instruction and practice, the task became manageable.

It is interesting to note that the evaluation pilot thought that the characteristic that forced the large crab angle as the aircraft slowed was the result of a control law change (it was different than both an airplane and a helicopter – both of which the pilot had experience flying). In fact, it was the preservation of the airplane control law to very low speeds so as to avoid a control law change that caused the unexpected characteristic. A way to make this more like what the evaluation pilot was used to would be to limit lateral velocity instead of sideslip angle up to some to be determined and likely configuration dependent speed.

It takes many practice landings to master crosswind landings in airplanes and several hours of practice to hover a helicopter. If an aircraft has characteristics like this that are not common in current aircraft, proper training is required before licensing the pilot to fly it. The evaluation pilot should obtain the required training and practice before evaluating the aircraft.

It would be commonly accepted that for someone who has never flown an airplane before, it takes exceptional pilot skill to land an airplane successfully without training or practice. It also takes exceptional pilot skill to hover a helicopter without training or practice. Consistent with this, it would be expected that a pilot with airplane and/or helicopter experience, but without training or practice in an aircraft that has very different control characteristics than an airplane or helicopter, would require exceptional pilot skill to control. However, given the appropriate training and practice, the pilot could master each task in the new aircraft. In this case, while the pilot could manage the aircraft after some training, it was still difficult. This problem should be addressed.

5.3.2 Difference 2: The pilot controls flight path angle and the aircraft controls pitch attitude.

In a conventional aircraft when the pilot wants to go faster, a throttle and stick command are required to accelerate and maintain level flight. The stick command changes continue throughout as the aircraft speed changes.

A helicopter accelerates very differently than an airplane and the pilot inputs are different. When a helicopter accelerates from a hover, the pilot uses the cyclic to pitch nose down using the rotors to accelerate. At the same time, the pilot pulls up on the collective to maintain altitude and uses the pedals to counter the torque change. The three inputs are coupled, requiring constant adjustment.

The FBW aircraft modeled here has direct speed and flight path command through the inceptors. Thus, from a hover, the pilot simply moves the speed command forward and the flight controls manage the rest. If the pilot commands 100 KIAS from a hover the aircraft initially pitches nose down to accelerate like a helicopter. It pitches back to level going through 30 KIAS. Then at 60 KIAS, it starts to pitch nose up for the wing to generate lift as the rotors shut off going through about 90 KIAS. With no input from the pilot the altitude and ground track barely change through this process. A fixed wing or helicopter pilot with little or no experience with the aircraft sees these pitch changes as uncommanded. They tend to react trying to counter the changes, which yields an undesirable result.

Even after being briefed on this behavior, helicopter pilots and fixed wing pilots that flew this aircraft initially reacted to the pitch changes that seemed uncommanded. Their reaction differed depending on their experience. Fixed wing pilots tended to pull up in response to the nose down pitch rate causing the aircraft to climb. Helicopter pilots are familiar with the pitch over, but feel they are not in control because they did not command it. In both cases, they adjusted to this quickly.

The pitch up to generate wing lift that occurs from 60 to 80 KIAS continued to make most pilots uncomfortable, especially if the aircraft was in a climb when this occurred. Then it was unsettling to both fixed and rotary wing pilots, and even to passengers. From an aerodynamic efficiency perspective, the aircraft did this right. However, from a human factors perspective, the pitch change to start generating wing lift maybe should occur over a broader speed range, occur slower. Since human factors was not a focus of this study, the speed range over which the angle-of-attack change occurred was not modified.

Reactions of the FAA test pilot, FTE, and other pilots to the pitch changes reinforce that an evaluation pilot must become very familiar with an aircraft’s flight characteristics before conducting the official evaluation. The pitch changes as implemented are necessary given the physics of this aircraft, though the exact implementation could be tweaked. An evaluation pilot not familiar with the flight characteristics may initially consider them uncomfortable and unacceptable. However, after gaining experience and understanding, they are necessary and make the aircraft far easier to fly than a conventional fixed wing airplane or a helicopter. Note that both helicopter and fixed wing pilots bring negative learning in relation to this aircraft behavior.

5.3.3 Difference 3: Lateral flight path control during transition

In hover mode, speeds less than 10 KIAS, the pedals are used to turn the nose and lateral flight path. In cruise mode, above 35 KIAS the lateral stick commands roll rate with bank angle hold resulting in a sustained turn rate with the stick neutral. Both modes are intuitive to pilots. However, in transition mode the commands are fading from one to the other. This initially caused confusion to both fixed and rotary wing pilots. For example, they would hover taxi at 10 KIAS getting used to turning with the pedals. If they then accelerated to 30 KIAS the pedals could command very little turn rate, and lateral stick was more effective. This had to be explained to the pilots and they had to practice it. It became easy, but it forced the pilots to pay attention to speed to know what to expect control mapping to be.

5.3.4 Summary observation

These three differences from conventional fixed wing and rotary wing vehicles show that when evaluating whether an aircraft requires exceptional pilot skill, the expected training and practice required to be considered proficient to fly that particular aircraft type must be provided to the evaluation pilot before the evaluation is conducted. Many potential control schemes for the new eVTOL aircraft are under development. This means that the determination of exceptional pilot skill as part of the aircraft certification may need to occur after (or simultaneously with) the determination of whether the pilot of the aircraft needs an airplane rating, rotorcraft rating, powered lift rating, type rating, special endorsement, separate license, or something else. This has the potential that flight standards may need to interface with aircraft certification earlier in the process than it has so historically.

5.4 Pilot comments/safety may override performance spec

5.4.1 Lesson learned

The MTE should be used to generate the test results needed to determine certifiability. The standard is exceptional pilot skill and achieving the required performance. If the MTE fails that does not necessarily mean the aircraft is not certifiable. If a test fails, the reason it failed should be determined and then a certifiability determination made using engineering judgment.

5.4.2 Discussion

The simulated aircraft has bank angle protection. The bank angle allowed is a function of airspeed with a lower bank angle limit at lower speeds. An MTE test condition was identified to test the aircraft’s maneuverability by banking from 30 degrees one way to 30 degrees the other way in a minimum amount of time. The required time to accomplish this bank change per the MTE was the same as is required by AC 23-8. When conducting this test, the aircraft started the roll with the expected acceleration but then slowed noticeably as it passed 20 degrees in the other direction. This slowing of the roll rate caused the airplane to fail the required performance and therefore fail the MTE. After some evaluation, it was determined that the bank angle protection was slowing the aircraft's roll rate as it approached 30 degrees so that it could prevent the aircraft from banking more than 30 degrees. (The envelope protection system limited the bank angle to 30 degrees at this speed to prevent departing controlled flight, but the 30-degree bank provided plenty of turn rate.)

At higher speeds the aircraft passed the MTE because the bank angle limit did not interfere by limiting the bank angle to less than or equal to that required by the MTE.

In this case, despite the fact that the aircraft failed the performance requirement of the MTE, it should be certifiable because the design provides the intent of the rule but also provides a safety feature that interferes with the performance requirement. The certification report should note the failure and then explain why it is still certifiable.

5.5 CHR, ADS-33, and certification

The MTEs all had performance requirements consistent with the ATP pilot check ride. It became clear as the tests were conducted that the presence of these precision flying standards really helped in determining the pilot skill level required for the various tasks. The MTEs developed and presented in this document are based on maneuvers that would be done in a transport mission using an eVTOL aircraft. ADS-33 maneuvers were intentionally excluded from the MTEs. An approach to using CHRs for certification was developed but it was not possible to evaluate the approach given time constraints. This section discusses some of the authors' views on the use of ADS-33 maneuvers and CHRs in certification. The authors views did not converge, thus there are conflicting views given in this section.

5.5.1 Training prior to evaluation

The MTE approach described in Section 0, ADS-33, and the Cooper-Harper approach all require that pilots become familiar with the aircraft before an evaluation is done for credit. If the aircraft is of a different type or has a different control scheme, then it becomes more critically important that the evaluation use an instruction curriculum with a minimum amount of experience in that aircraft. Pilots will then run through that curriculum, before evaluating the aircraft based on tasks with performance criteria. This is very similar to knowledge and experience requirements in CFR 14 Part 61 for pilots of both airplanes and helicopters. For example: A fixed wing pilot must have training with an authorized instructor, be found competent by that instructor, and pass a practical test to receive a helicopter endorsement. While not specified it generally takes about 20 hours to achieve this.

This requirement is validated by the experience of many airplane pilots who learn to fly helicopters. In hover, a helicopter is not stable, has coupling between all of the controls and axes, and has control-to-motion delay that is inconsistent between controls. In pitch and roll, the delay is in the frequency band that contributes to pilot-induced-oscillation. It could reasonably be expected that even after several hours of instruction an evaluation pilot with an airplane rating, but no previous helicopter experience would rate the helicopter to have poor characteristics. However, an evaluation pilot with a helicopter rating and many hours of operational experience flying helicopters may rate the same helicopter to have very good characteristics. The difference in the evaluators is the familiarity with the aircraft type (or more specifically the control and response type and training / experience). Some of the authors have experienced this transition.

Similarly, if an aircraft is very different from ones a pilot has flown before, they need to have sufficient training to know the aircraft and its characteristics before flying it. A simple thing like turbine spool-up time can cause a piston engine pilot problems when trying to land a jet transport Some of the authors have experienced this in a simulator and figured it out, but it took a few tries and a lot of focus. A good flying jet transport would get poor landing task ratings from a piston engine pilot until they have sufficient experience.

The aircraft modeled for this work had characteristics different from an airplane or a helicopter. Airplane pilots were initially surprised by an acceleration from a hover; the aircraft initially pitches down significantly to accelerate (like a helicopter). This characteristic caused most airplane pilots to initially pull back on the stick to stop the pitching when in fact pulling back on the stick caused a climb but had negligible effect on the pitch. Conversely, helicopter pilots tended to pull back on the stick to slow down on approach to landing. This caused the aircraft to climb instead of continuing the descent to landing and had no effect on speed. Some pilots took significant training / practice to overcome the reflexes that had developed from their previous experience. This highlights the need for evaluation pilots to be very familiar with a new aircraft before attempting to evaluate it.

FBW frees the designer to map control inputs in ways that differ from traditional mechanical controls. For example, pilots can directly control flight path as opposed to controlling the elevator to indirectly control flight path. The eVTOL aircraft being brought to market, like the simulation developed for this work, indeed have very different response characteristics than aircraft flown by either airplane or helicopter pilots. Both airplane and helicopter pilots bring negative learning to these aircraft and will initially be surprised by their responses to pilot inputs. It will take hours to become familiar with their flight characteristics both for an FAA pilot to evaluate them and for pilots to be proficient operators. Ab initio pilots may learn the manual skills to fly these more quickly, but will have to learn airspace, procedures, energy management, communications, weather, and other things aviators need to understand. They will not have to learn stall prevention or recovery for example because of envelope protection.

Given the negative experience transfer that was observed, it became clear that pilots flying an aircraft akin to the one represented by the simulator would require a different license or at least special training and an endorsement. This is only one of several proposed control types. The question of what type of training and pilot certification is required for these new aircraft types is very important.

The authors all agree that specific aircraft training is critical before an evaluation for certification can be done. How much training is needed is not currently evident. A suggestion is that the applicant should have a proposed transition-training regimen and the FAA evaluator should go through that training before rating the aircraft.

5.5.2 Use of ADS-33 maneuvers

The MTEs proposed in Section 0 as a MOC for certification break down maneuvers required for a transportation mission from pre-flight inspection to post-flight shutdown. There is also an option in the list for other maneuvers the FAA may require, or an applicant may desire so the aircraft can do other missions with crop dusting given as an example.

ADS-33 has additional maneuvers that would not be part of a transportation mission. These maneuvers are intended to test the control system in stressing conditions. Some of them are listed and discussed in Section 3.4.5. The pirouettes, which is not required for transportation missions is discussed below. They do stress the controls. Are they necessary for certification is the question?

A pirouette is an ADS-33 maneuver that requires the aircraft to point the nose at a spot while circling that spot. While it is not a maneuver used for transportation, is often used for helicopter hovering training. An interesting observation was made when observing an FAA pilot with lots of airplane time but no helicopter time. This pilot was asked to execute a hovering pirouette and declared that while hovering around with Unified controls was easy, doing a pirouette required exceptional pilot skill.

In a helicopter, there is no centering on the pedals and therefore little if any force is on the pedals as the helicopter goes around the circle. There is also very little if any force on the cyclic to maintain a lateral motion to cause the helicopter to go around the circle. Thus, in a helicopter there is very little if any force required on any control to do this maneuver. The UGEVA aircraft with Unified flight controls translating laterally in hover requires the pilot to apply and maintain lateral force on the stick. In addition, to keep from turning in the direction of the lateral force on the stick, the pilot must apply and hold opposite force to the pedals. Thus, even though the Unified system was designed to make vertical flight easier for airplane pilots, the characteristics that make it easy also make it more difficult to do a pirouette. This is because the pirouette required significant cross control (lateral stick force in one direction and pedal force in the opposite direction) at low speed. Cross controls at low speed in an airplane typically causes a stall and spin, thus pilots are trained to avoid this condition. To do a pirouette in an aircraft with a Unified control system the pilot must manage a strongly cross-controlled aircraft while ignoring previous training to avoid this condition.

After a little practice, the maneuver is easy to manage but physically hard because of the constant forces required. Again, the aircraft is easy to maneuver to check ride standards for transportation maneuvers. The pirouette also requires sustained hover, which many eVTOL cannot do because the batteries, motors, and/or wiring may overheat, and continuous hover uses a lot of power draining the batteries. An applicant can simply make a statement in the POH that pirouettes are prohibited or not recommended making the maneuver not required. Maybe it makes sense not to require the maneuver in the first place.

The diagonal maneuver requires hovering forward and sideways at the same time. This can be done with the configuration implemented. However, an applicant may choose to only allow the pilot to hover taxi in the direction the aircraft is pointing for safety. The pilot would only be able to go in the direction of best visibility. Requiring a diagonal maneuver would mean this safety feature would not be certifiable or would require a waiver.

While the controllability MTEs of Section 0 were used to evaluate the aircraft, the stability tests would also find the issues. The stability tests are designed to systematically go through the flight envelope to find issues while the controllability tests concentrate on actual maneuvers and therefore leave gaps in the flight envelope untested. This was verified in a few cases by repeating stability tests when the controllability tests found an issue. That does not mean that the controllability MTEs have no value, but stability tests are better at finding HQ issues than the controllability tests. This implies that a very good set of stability requirements and test conditions be developed.

The Unified control system, which the simulator had, was designed to make vertical flight easier for airplane pilots. The designers of Unified intended that it would be used primarily as a transient condition for takeoff and landing. It was not intended for extended hovering or agility while hovering. The transportation mission will be carried out this way as well. Hovering takes a lot of energy and will be minimized.

In addition to many pilots, some non-pilots flew the simulator. Some of the pilots had airplane experience but not helicopter experience. Some had helicopter experience but no airplane experience, and some had experience in both. At cruise speed airplanes, helicopters, and the Unified system are similar, and all pilots flew the simulation at speed with ease. In hover, the Unified system coupled to a lift + cruise aircraft is easier than either a helicopter or an airplane. The few non-pilots that flew the simulator seemed to learn to fly the Unified system in hover much faster than pilots (helicopter, airplane, or both). They had no negative learning to get past.

The precise maneuvering required by the MTEs in Section 0 was very important to finding the problems with the aircraft simulated. It was also critical to know where to look and make the maneuvers emphasize those flight conditions. Rather than listing the conditions here, it is more important to know how to look for them in any aircraft. All of the problems were in areas where transitions occurred. The physical transition from flying on the rotors to flying on the wing occurred over a speed range. Focus was on the ends of the transition and to a lesser extent the middle. It was also important to cross the transition slowly and rapidly and in various climbs and descents to discover the problems. Control transitions that may or may not align with physical transitions also need to be focused on. For the aircraft modeled here, the control and physical transitions were separate. The MTEs found all of the problems using nominal and emergency maneuvers that would be associated with transport missions without any “special” ADS-33 maneuvers required. That implies the ADS-33 maneuvers are not necessary. However, this single evaluation is not sufficient to definitively conclude that some ADS-33 maneuvers might uncover problems the transportation mission maneuvers would not. The set of maneuvers in ADS-33 are not sufficient for certification without maneuvers representative of the full mission like those in Section 0.

The author with significant certification experience believes requiring the ADS-33 maneuvers would raise the cost of certification and offer no benefit. The author with the most military aircraft experience believes the ADS-33 maneuvers control system stressing can offer insight on control system weaknesses. This study was not conclusive on which position is correct other than to say for the aircraft modeled, the ADS-33 maneuvers were not required to reveal problems with the control system, especially problems that would show up in a transportation mission.

5.5.3 Use of numerical rating scales

The authors developed an approach for using Cooper-Harper ratings for certification (Section 2). Unfortunately, the approach was not evaluated. ADS-33 indicates the use of CHRs so this section also addresses ADS-33.

During the MTE evaluations with the FAA test pilot and FTE, they immediately made certification judgement comments without referring to CHRs. These were informal comments as the test pilot and FTE had insufficient training on the aircraft to make formal comments about certification. This indicates that for evaluators familiar with certification rules the use of CHRs is not necessary. A means similar to the Cooper-Harper rating scale could be useful for certification, but it should be developed for supporting FAA certification. The proposed approach presented in Section 2 modifies the CHR scale to provide ratings that fall into three categories useful for certification. CHR logic descriptors can help a pilot determine whether “exceptional pilot skill or strength” is needed to perform the MTE. This approach was not properly evaluated. Future development and evaluation of the proposed scale or other approaches may be appropriate if the FAA determines it helpful.

The CHR approach described herein includes a modified version of the CH Scale to evaluate Hazard levels from AC 23.1309E. The authors developed the approach unaware of the Hindson Scale (Hindson, Eshow, & Schroeder, 1990) but became aware of it before writing this report. The Hindson Scale was also derived from the pattern of the CH Scale, but has more significant modifications. The Hindson Scale has been used in certification and modifications to it have been proposed and evaluated as seen in reference Taylor, et al. (2022). It is not possible to draw conclusions on whether the approach proposed has any benefit over the Hinson Scale, as it was not evaluated.

The authors' opinions vary on the use of CHRs in certification, with or without the proposed method. The author with significant certification experience believes its use would add to the cost of certification and offer no benefit. The author with a deep history of using the CH Scale but no certification believes it would bring benefits to certification through a well-defined approach to evaluating handling qualities. The other authors with no aircraft certification experience believe the proposed approach may offer a benefit by helping evaluation pilots think through their decision of whether exceptional piloting skill, alertness, or strength was required more consistently. Unless this approach is formally evaluated, there can be no definitive decision about the usefulness.

The work done for this report indicates the proposed MTE evaluations result in certifiability decisions without use of CHRs, indicating their use would be an unnecessary expense.

6 Conclusions and recommendations

The MTEs developed revealed all of the nominal and optional HQ problems in the evaluation aircraft simulation. Unfortunately, the evaluation time was limited compared to what had been planned before Covid-19. However, the MTEs are very detailed and cover all maneuvers required for a transportation mission, including failures and emergency procedures, and worked very well in the evaluation. There are many manufacturers/applicants coming to the FAA with aircraft akin to the one modeled. Currently each applicant has to develop a means of compliance and get it approved, which is a daunting task for the applicant and the FAA. The FAA should consider adapting Section 0 into an advisory circular for applicants to use as a partial means of compliance for aircraft with unconventional FBW flight controls.

Most of the MTEs developed intentionally do not have or recommend specific flight conditions. The specific flight conditions depend on the vehicle being evaluated. It is critical that the applicant and the FAA know where physical and command functions change and test in detail around those points and approaching those points from both directions.

The MTEs contain explanations for why they are recommended and how they should be used. Combined with observations and lessons learned discussed in this document they are instructive and may be helpful to both manufacturers and the FAA in evaluating an aircraft. Both can use it to know where to focus efforts in seeking handling qualities, stability and control, and performance issues that need to be addressed prior to certification. That applicant should explore the full aircraft envelope in detail of course. The FAA only needs to evaluate areas that may be of concern or certifiability may be questionable.

The CHR use in certification described in Section 2 was not meaningfully evaluated due to Covid-19 related time constraints. However, the limited evaluations conducted with the proposed MTEs indicate the use of CHRs is not required for certification and would therefore add cost with limited benefit.

Likewise, while the approach to evaluation proposed in ADS-33 and the Cooper-Harper process is represented in the MTE section of this report, the ADS-33 maneuvers are not included. Whether ADS-33 maneuvers would add value to the certification process was not evaluated but discussion in the report suggest that explicitly requiring them could be problematic for some vehicles. The requirement could unnecessarily limit design options, including safety related design options.

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The authors thank the NASA Revolutionary Vertical Flight Program and NASA Ames for providing the basis of the Lift + Cruise aircraft modeled herein. For clarity, the model herein was significantly modified from the NASA model and the control system is completely different. The NASA Configuration and associated data was a valuable starting point. The physical configuration is modeled but many specifics were altered.

The authors thank the team that operates NASA Langley's Cockpit Motion Facility. They provided excellent support including efficient hardware and software modifications to meet the needs of this project.

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A Aircraft model details

A.1 Aero model

Figures A-1 through A-5 show the aerodynamic coefficients of the UGeVA model used for this task. The force and moment coefficients used were based on a Cessna 172 due to the availability of the data and the similar dimensions of the aerodynamic surfaces of the Lift+Cruise model. The lift and drag coefficients as a function of angle of attack and side force coefficient as a function of sideslip were extended to include a full 360° envelope based on NASA datasets developed for spin and tumble simulations.

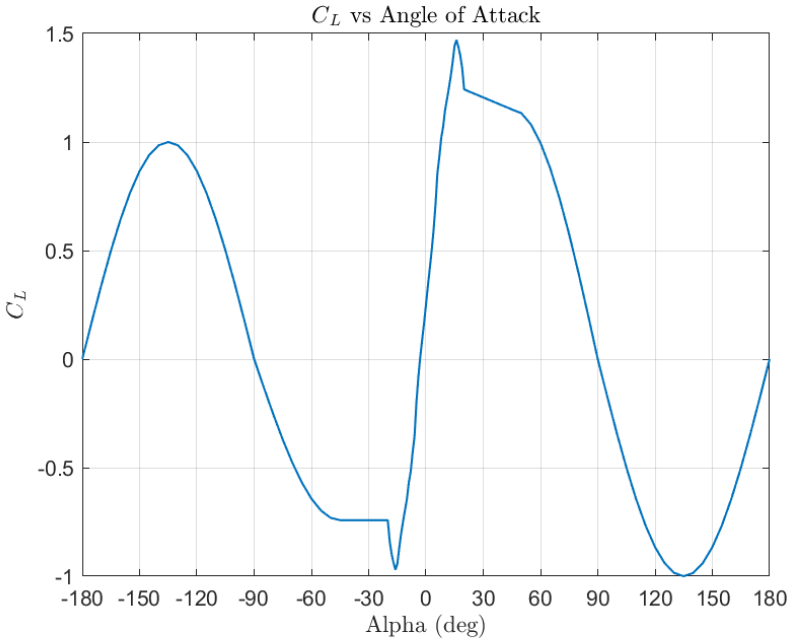


Figure A- 1. C_L versus angle of attack

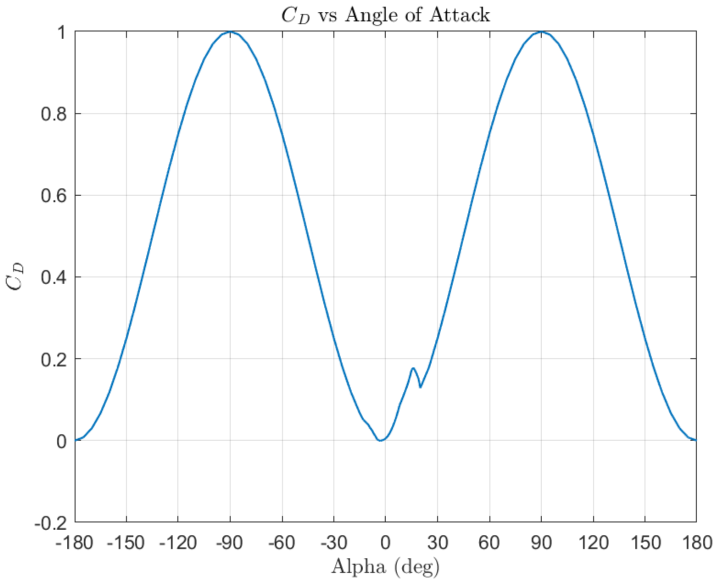


Figure A- 2. C_D versus angle of attack

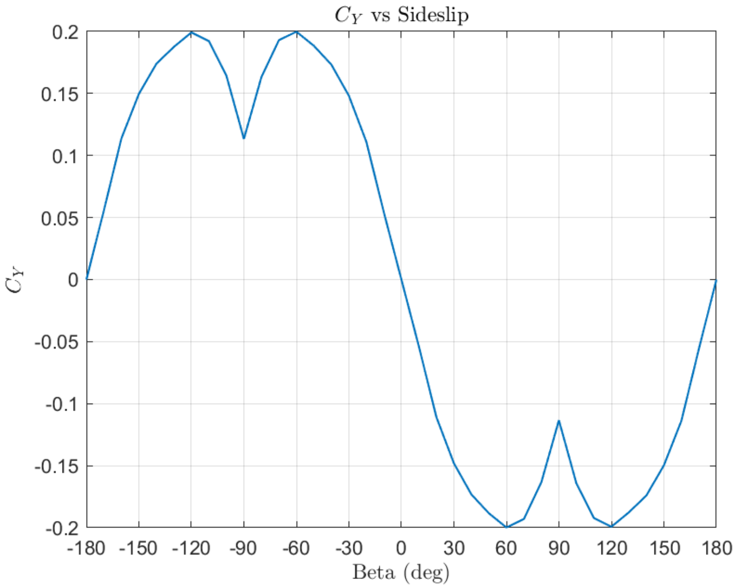


Figure A- 3. C_Y versus sideslip

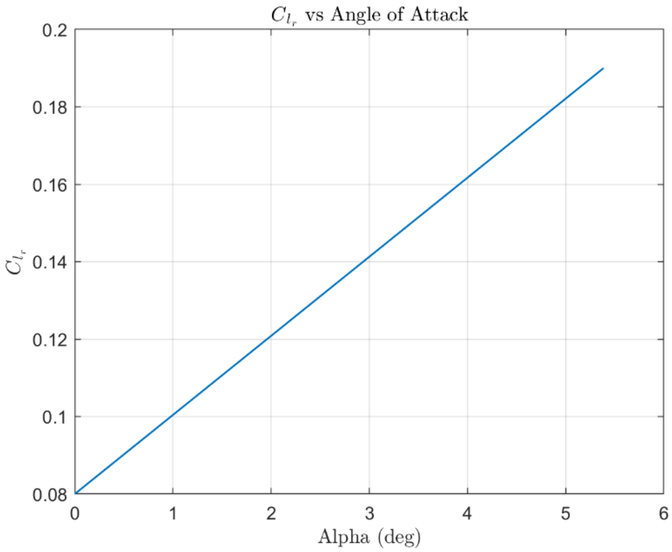


Figure A- 4. C_{l_r} versus angle of attack

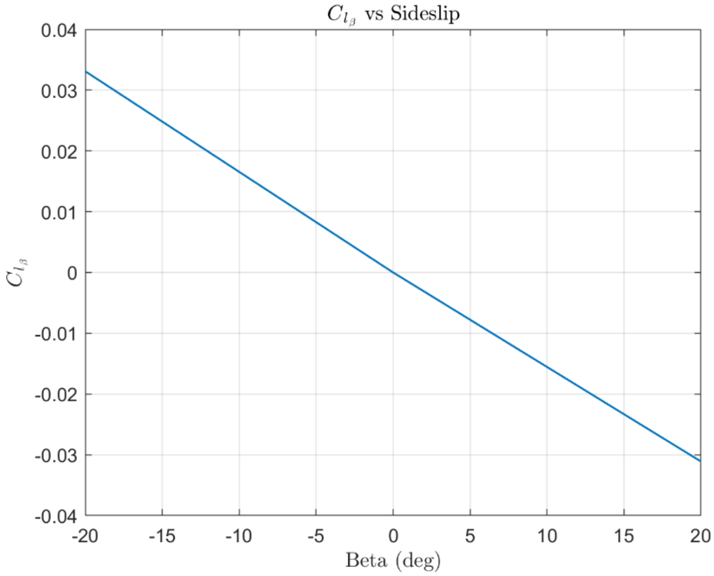


Figure A- 5. C_{l_β} versus sideslip

Figures A-6 and A-7 show the max positive and negative pitching moments due to angle of attack. These are essentially pitching moment coefficient multiplied by max and min elevator deflection summed with coefficient of pitching moment due to change in angle of attack.

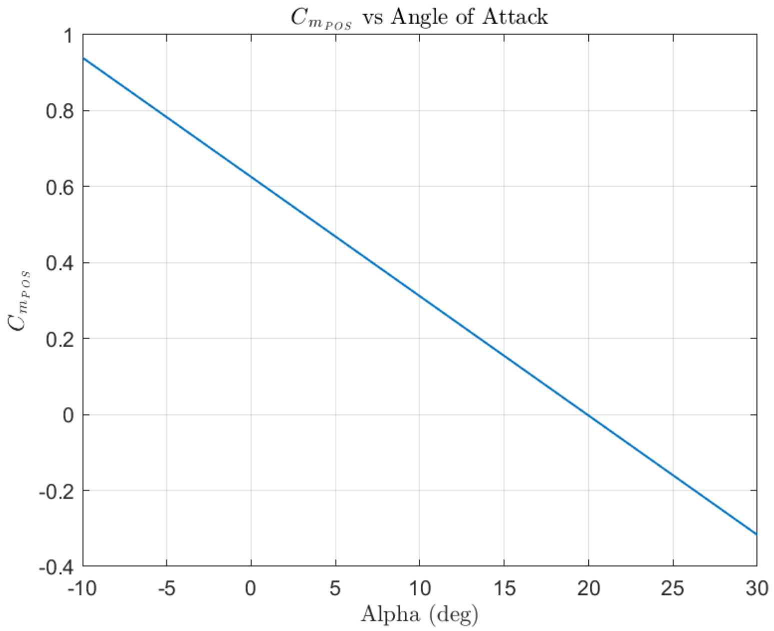


Figure A- 6. $C_{m_{POS}}$versus angle of attack

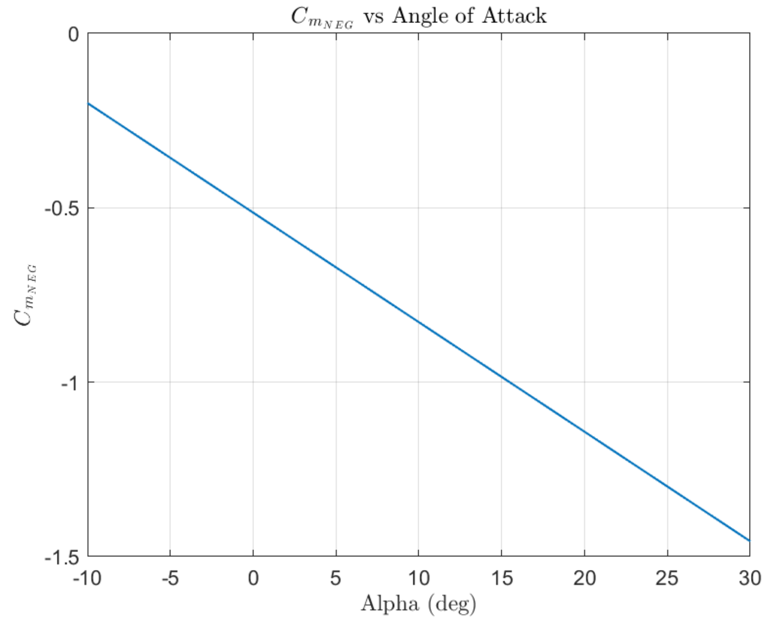


Figure A- 7. $C_{m_{NEG}}$ versus angle of attack

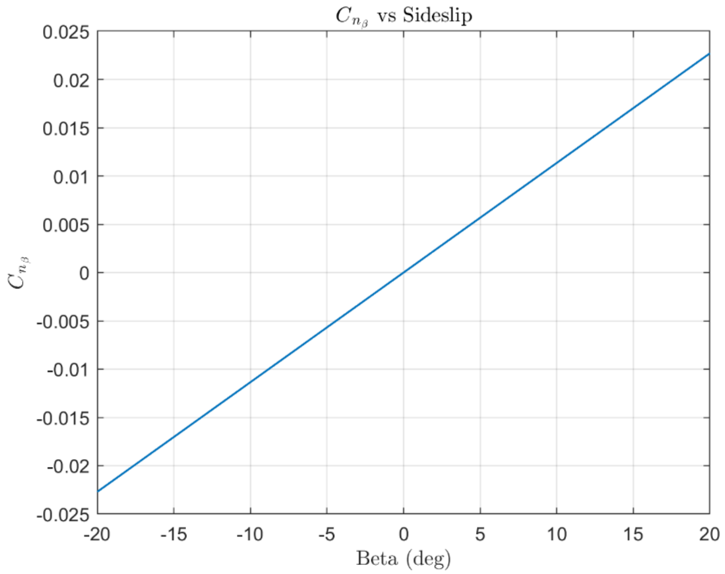


Figure A- 8. C_{n_β} versus sideslip

Table A-1 shows the constant aerodynamic coefficients used in the control power limit calculations. Note that rolling moment due to change in aileron and yawing moment due to change in rudder are already multiplied by the max deflection of their respective control surface since we are only calculating the limits of the given moment due to the generic nature of the model and are therefore dimensionless.

Table A- 1. Constant aerodynamic coefficients

Constant Coefficients		
C_{D_0}	0.026	1/deg
$C_{D_{LG}}$	0.034	-
$C_{l_{\delta_{a max}}}$	0.07025	-
C_{l_p}	-0.0082	s/deg
C_{m_q}	-0.2164	s/deg
$C_{n_{\delta_{r max}}}$	0.012	-
C_{n_p}	-0.0005236	s/deg
C_{n_r}	-0.0017	s/deg

B Lift and pusher models

Figure B shows the max allowable total lift from all eight rotors as a function of airspeed at sea level. The full model does incorporate density and speed of sound as a function of altitude. The equation used to calculate max thrust per rotor follows..

$$T_{max} = \rho D^4 C_t \omega_{max}^2$$

$$\omega_{max} = \frac{V_{tip_{max}} - |u|}{R}$$

Where ρ is density at sea-level, D is rotor diameter, C_t is thrust coefficient which is a function of dynamic pressure, $V_{tip_{max}}$ is max rotor tip speed, u is forward airspeed of the vehicle, and R is rotor radius.

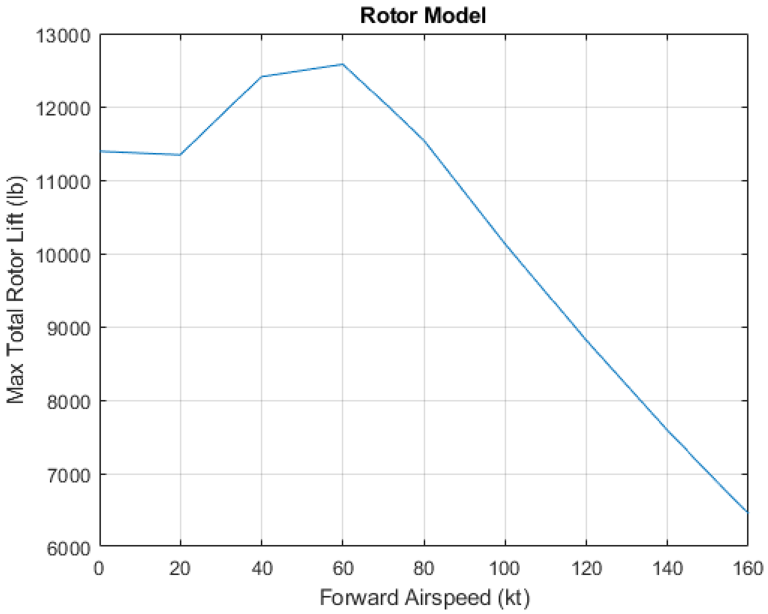


Figure B- 1. Total rotor lift versus forward airspeed

Figure B-2 shows the max thrust from the pusher as a function of forward airspeed of the vehicle.

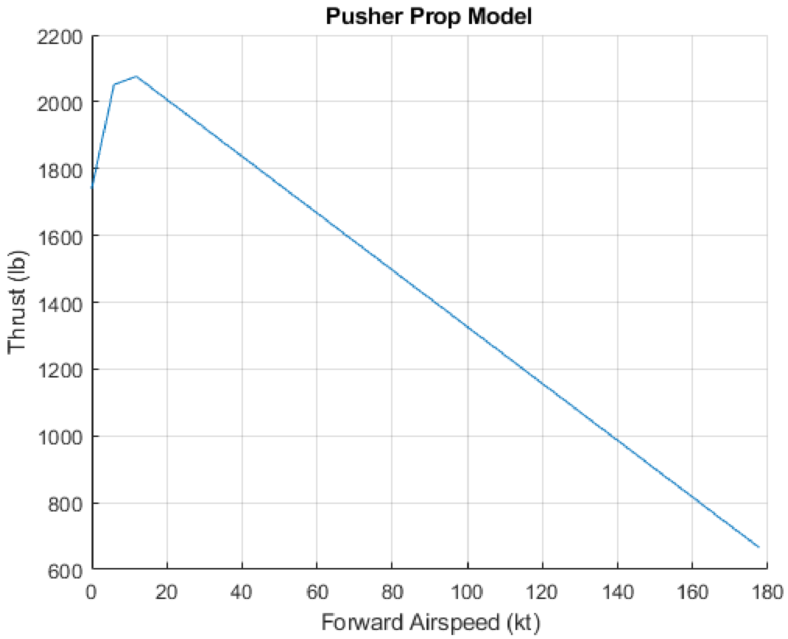
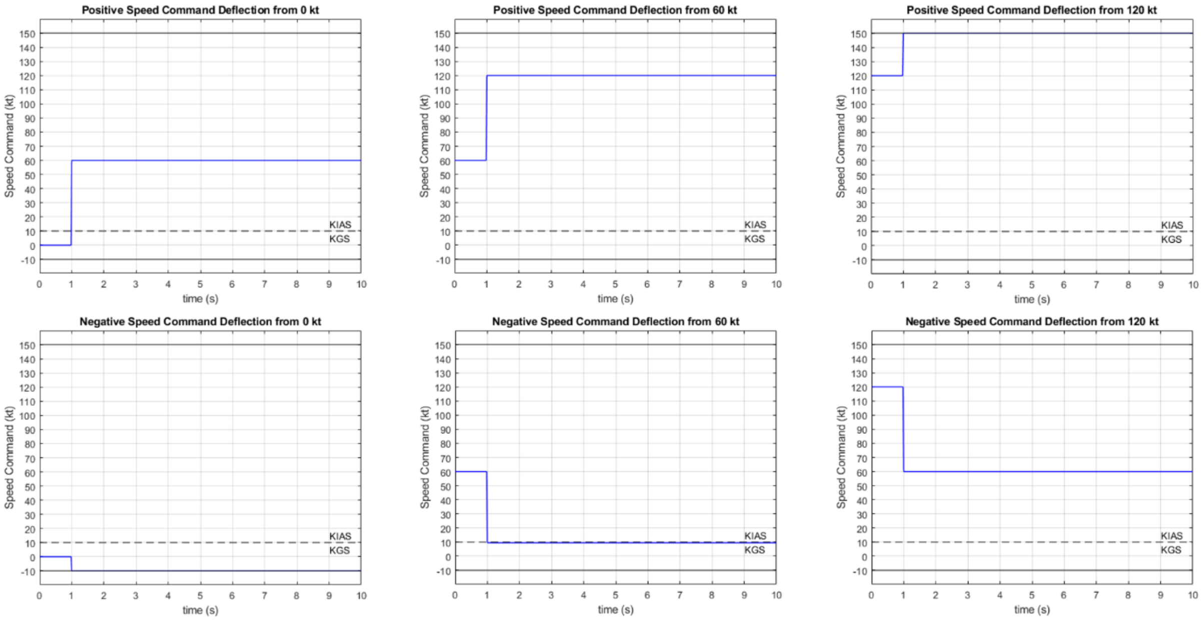


Figure B- 2. Pusher propeller thrust versus forward airspeed

C Time histories

The following time histories are 10 second runs trimmed at 0, 60, and 120 knots airspeed to portray the varying response types depending on flight mode. The pilot inputs are max step input and one-half deflection step input at 1 second. The list of commands includes positive longitudinal stick, negative longitudinal stick, right lateral stick, and right pedals. The lateral, longitudinal, and pedal commands are all normalized -1 to 1.

Two speed command step inputs are performed at each trim speed. The commands are from 0 KGS to +60 KGS, 0 KGS to -10 KGS, 60 KIAS to 120 KIAS, 60 KIAS to 10 KIAS, 120 KIAS to 60 KIAS, and 120 KIAS to 150 KIAS. Each set of commands are trimmed at 0, 60 and 120 KIAS to depict the varying response types for the different flight modes as well as the vehicle pitch command due to change in speed command (Figure C-1).


Positive Speed Command Deflection from 0 kt

Positive Speed Command Deflection from 60 kt

Positive Speed Command Deflection from 120 kt

Negative Speed Command Deflection from 0 kt

Negative Speed Command Deflection from 60 kt

Negative Speed Command Deflection from 120 kt

Figure C- 1. Speed command deflections

The time histories shown below also include the control power limits for the rotors on the N_Z plot, rotors and aerodynamic surfaces on the angular accelerations, and the pusher propeller for N_X. This was done to show how control power used in the primary axis could limit the available control power for a secondary axis. This is most evident in the Figures below that show pilot commands from 0 knots or hover. From the max positive longitudinal step (Figure C-2) input it can be observed that as the rotors increase their RPM to achieve the commanded vertical rate, the remaining control power available in the secondary axes decrease.

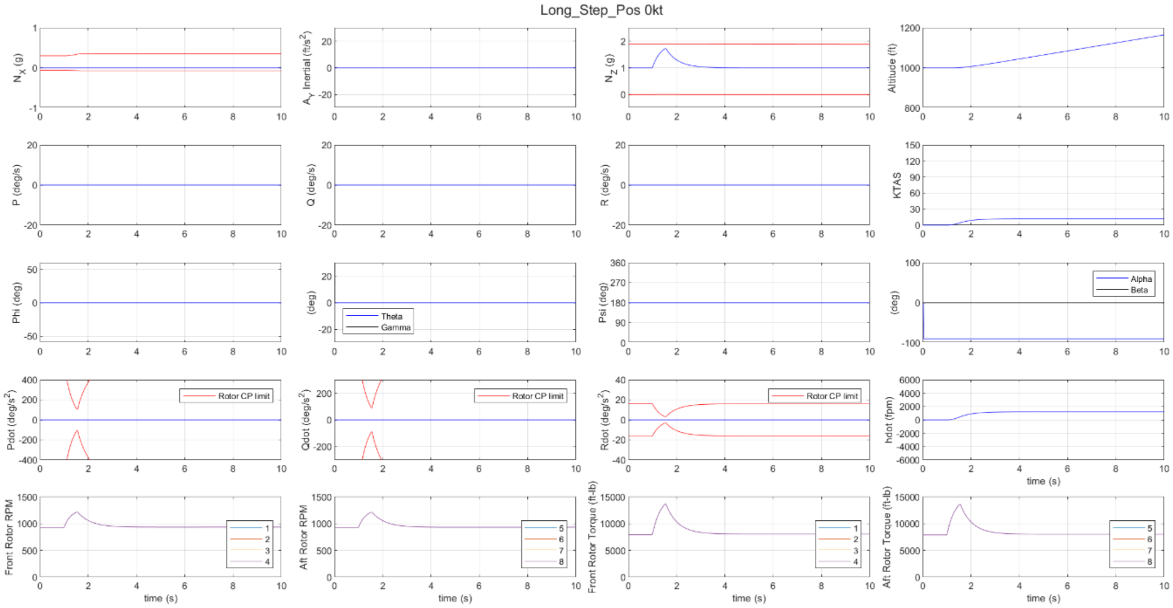


Figure C- 2. Max positive longitudinal step at 0 knots

Max positive step was not typically used during the simulation, so half-positive step was also investigated (Figure C-3).

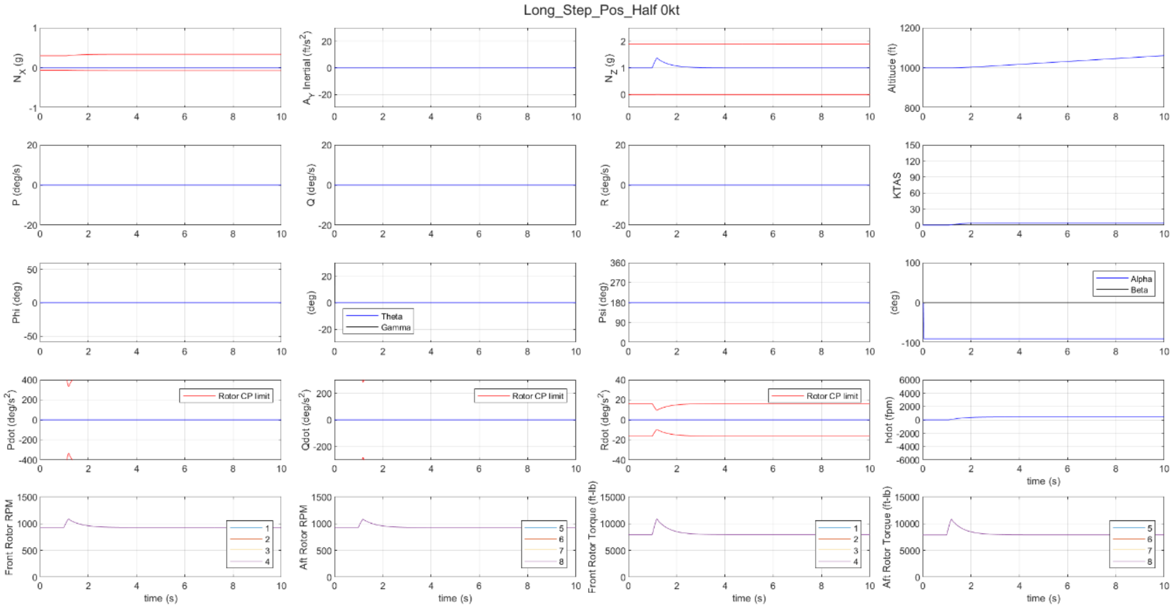


Figure C- 3. Half positive longitudinal step at 0 knots

It can be observed that the negative vertical rate for Figure C-4 is being limited by the VRS envelope protection.

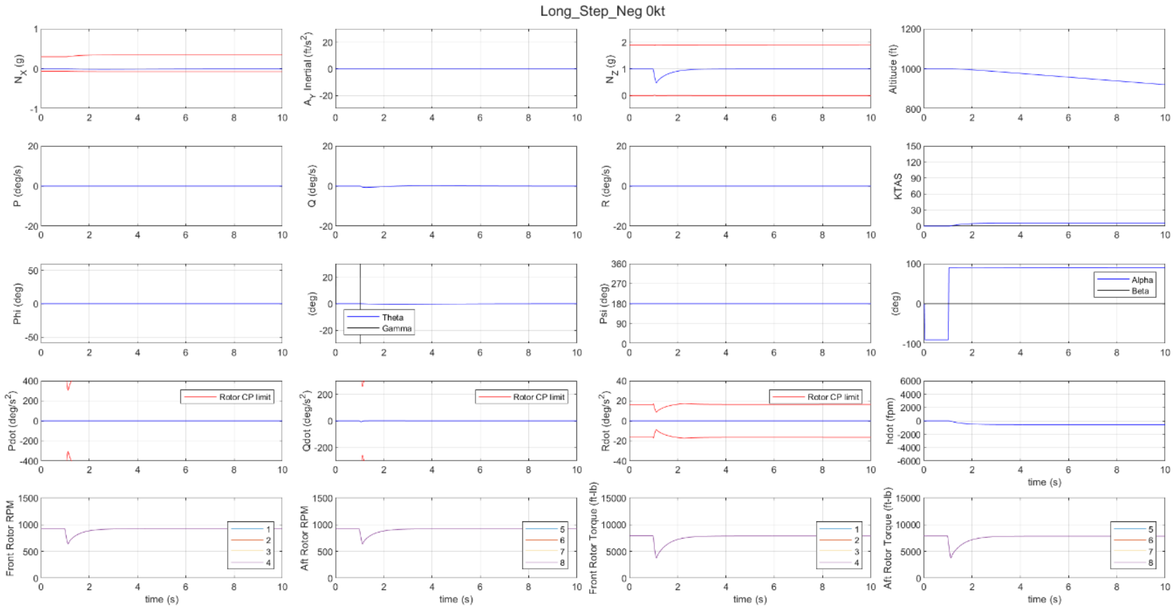


Figure C- 4. Max negative longitudinal step at 0 knots

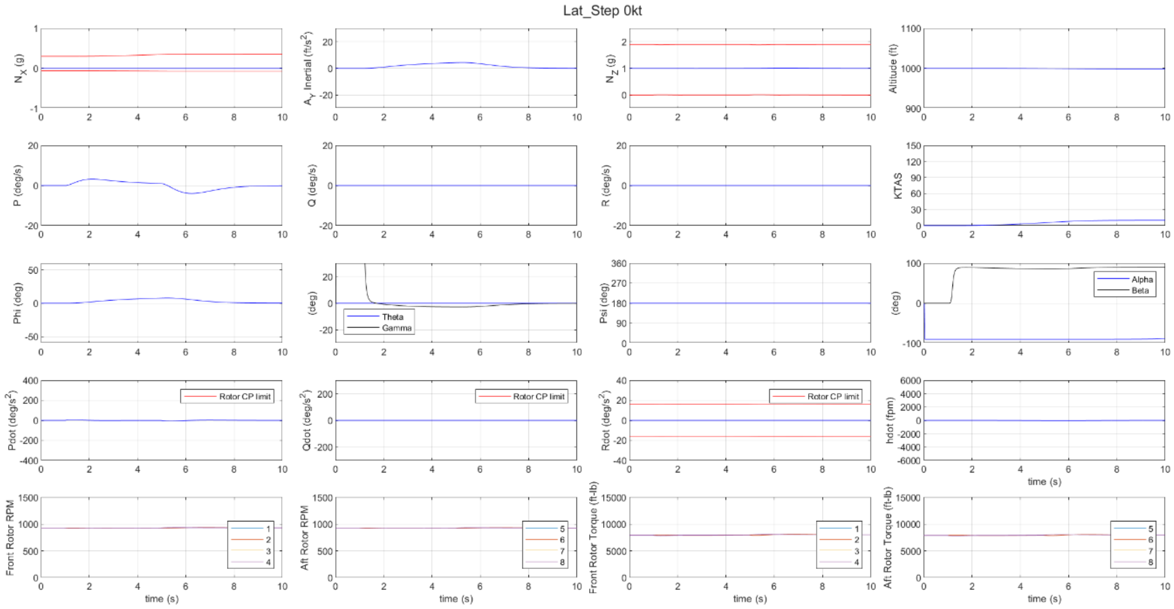


Figure C- 5. Max lateral step at 0 knots

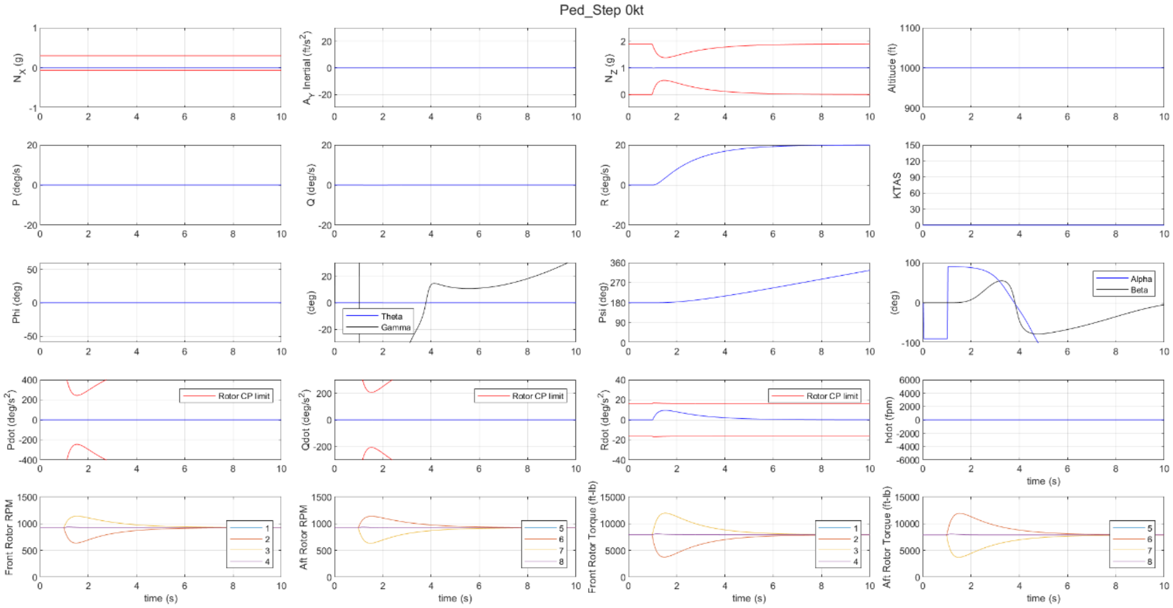


Figure C- 6. Max pedal step at 0 knots

Figure C-7 shows the control system pitching the vehicle down during a rapid forward acceleration commanded by the pilot. As the vehicle accelerates to 60 knots, the control system pitches the vehicle down to -15 degrees pitch.

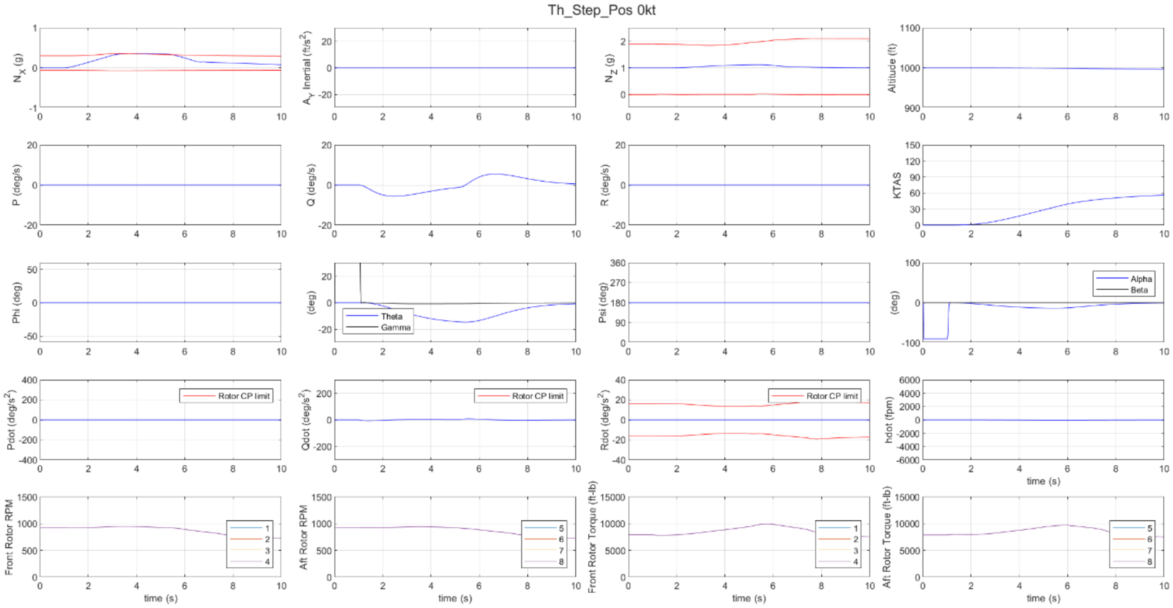


Figure C- 7. Positive speed command step at 0 knots

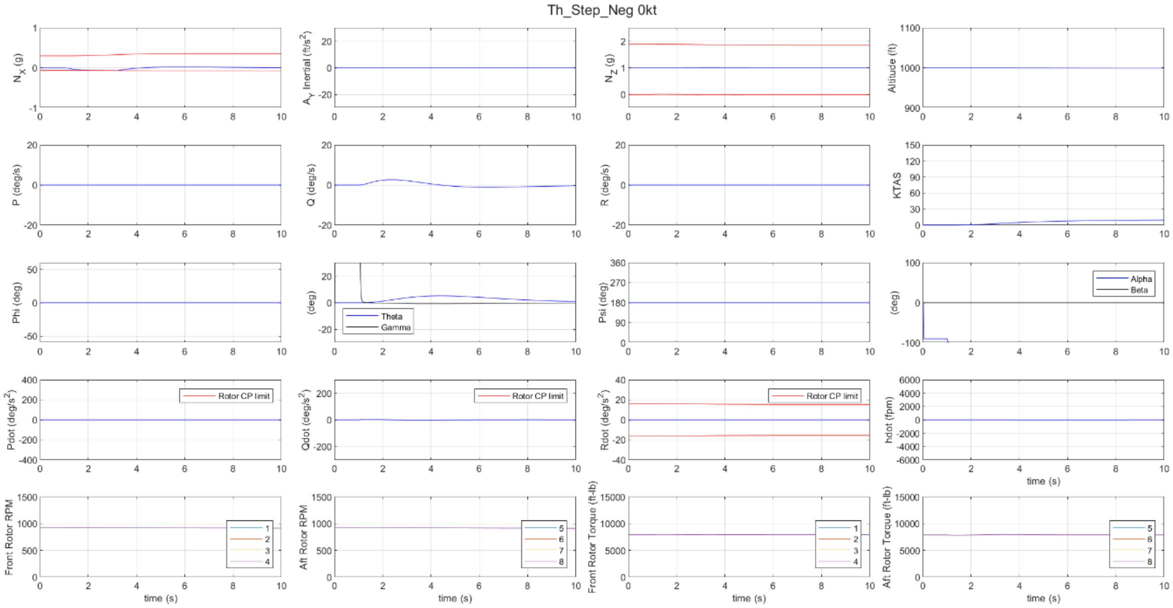


Figure C- 8. Negative speed command step at 0 knots

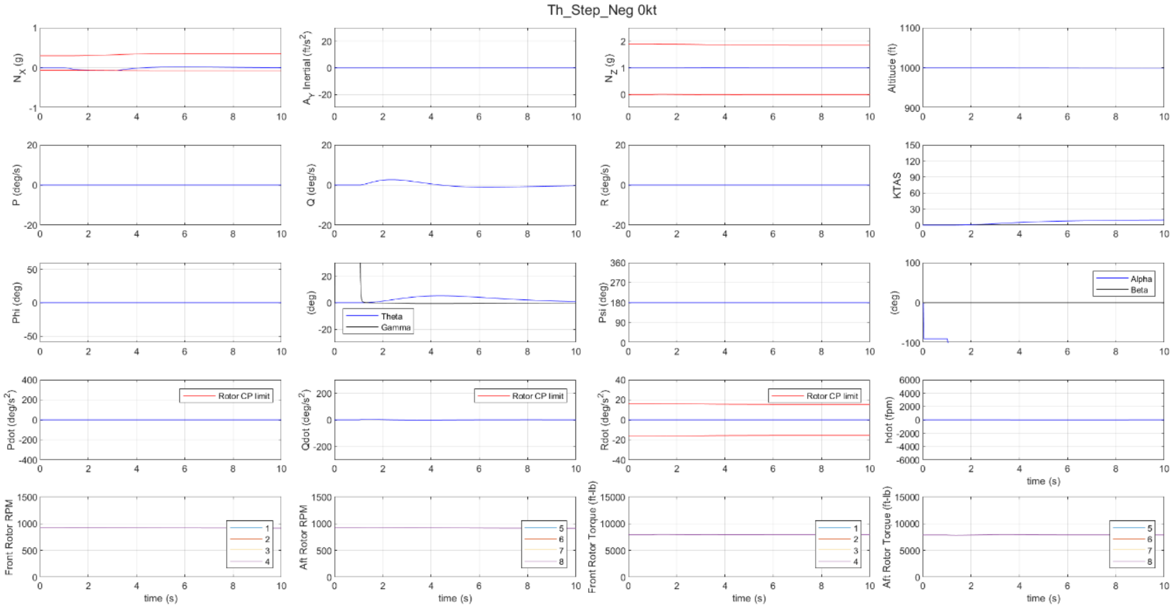


Figure C- 9. Negative speed command step at 0 knots

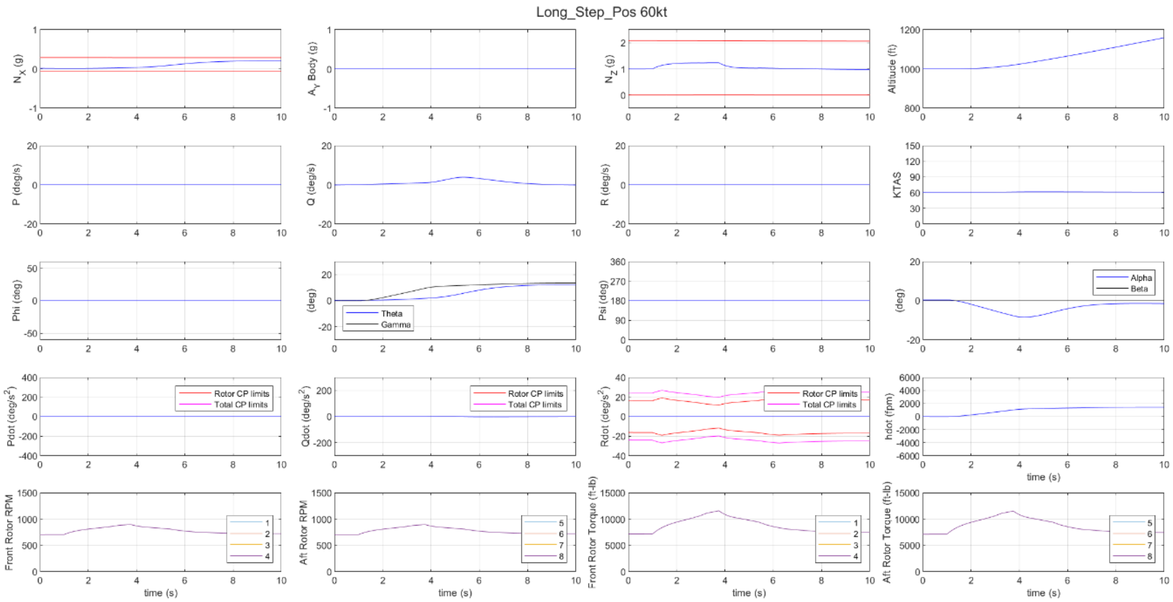


Figure C- 10. Max positive longitudinal step at 60 knots

Figure C-11 shows the 60 kt pitch departure caused by a rapid commanded descent. It is evident in the plots that control power was not the cause of the departure.

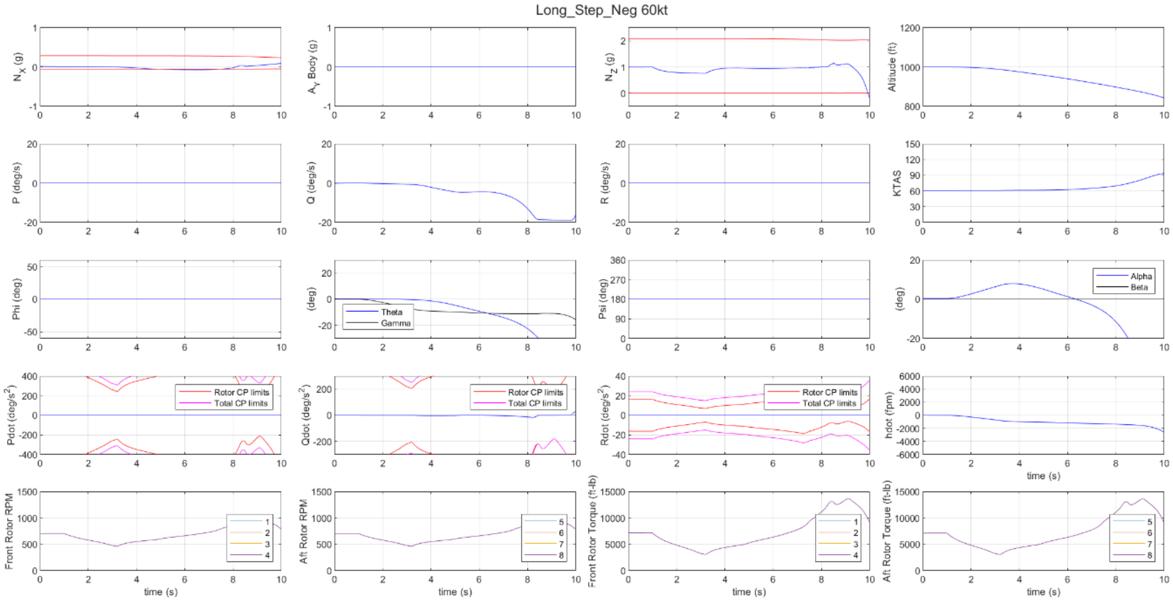


Figure C- 11. Max negative longitudinal step at 60 knots

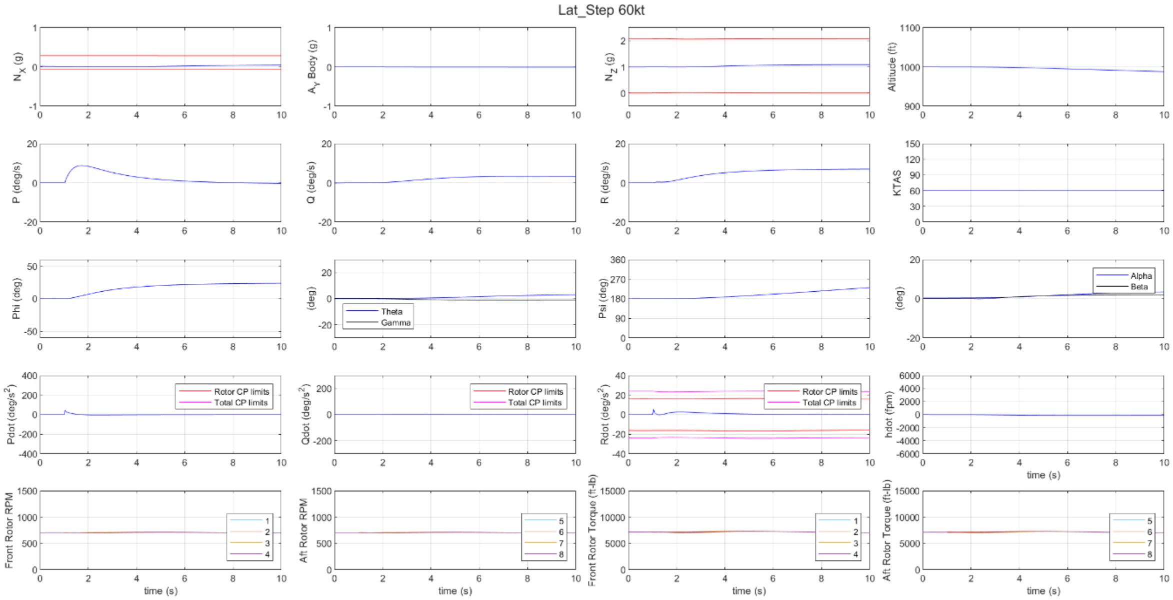


Figure C- 12. Max lateral step at 60 knots

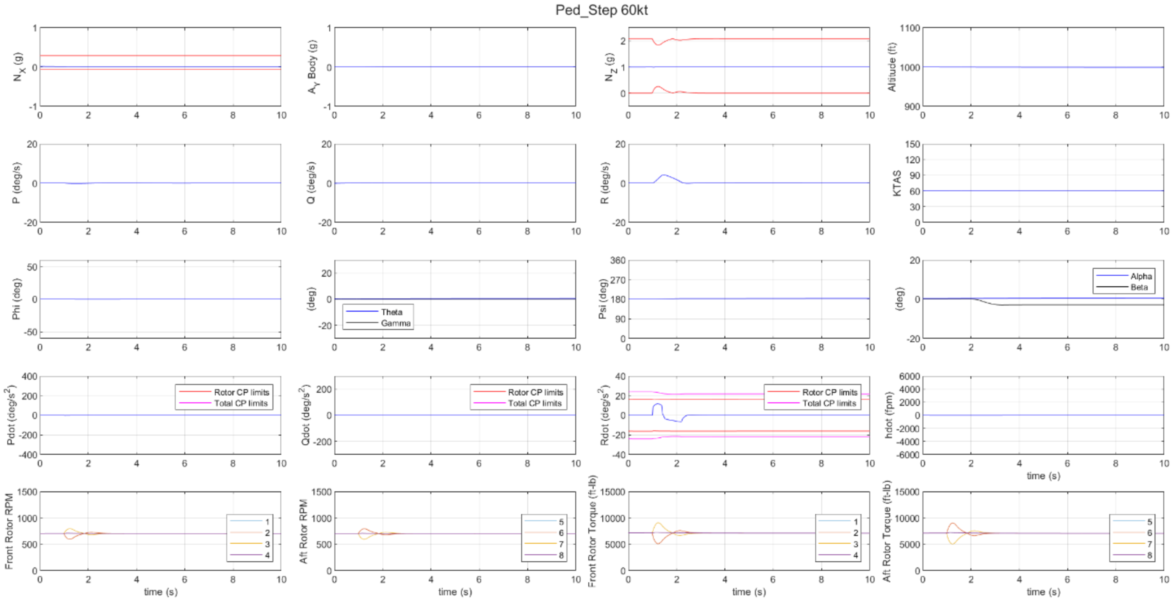


Figure C- 13. Max pedal step at 60 knots

Figure C-14 shows the vehicle accelerating from 60 knots to wing-borne lift. The control system slowly starts pitching up to L/D$_{max}$ angle of attack.

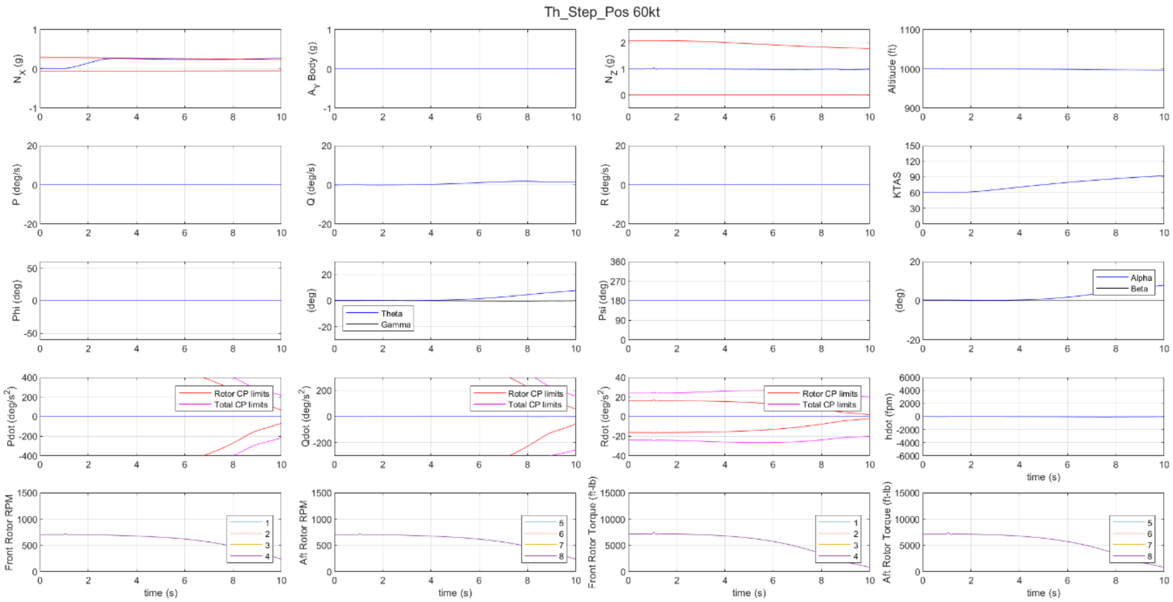


Figure C- 14. Positive speed command step at 60 knots

Figure C-15 shows the vehicle pitching up to +15 degrees in order to aid in deceleration of the vehicle.

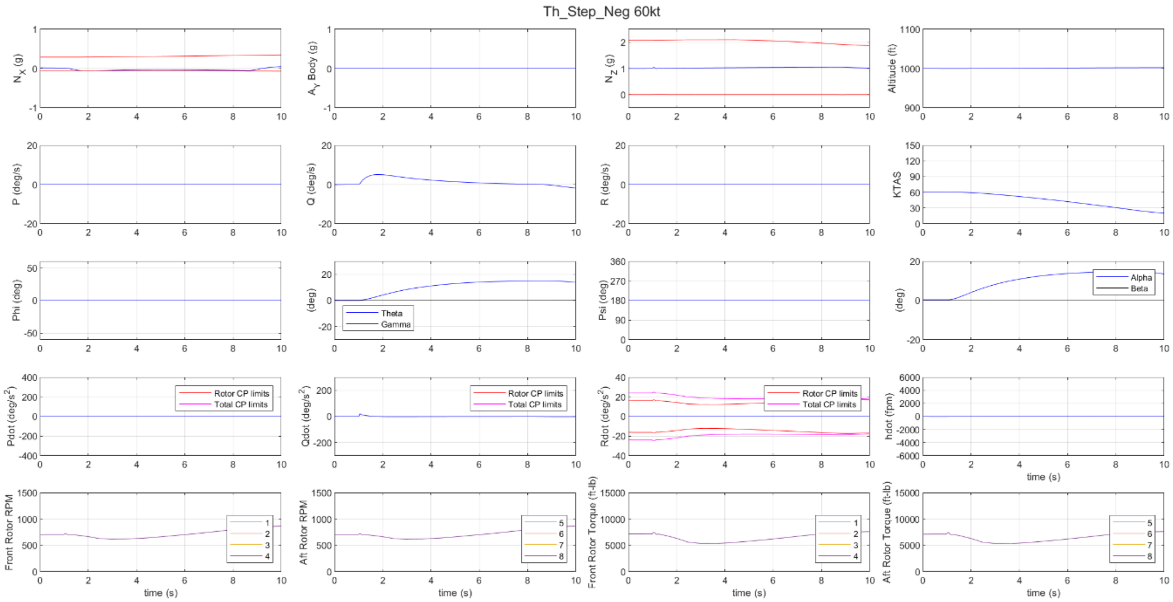


Figure C- 15. Negative speed command step at 60 knots

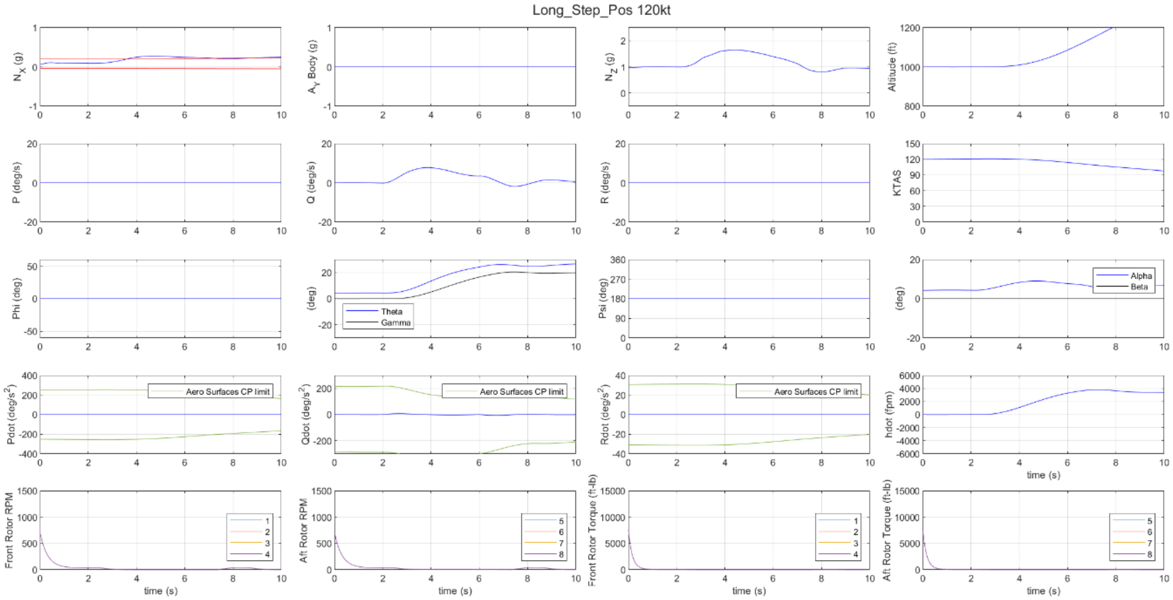


Figure C- 16. Max psositive longitudinal Step at 120 knots

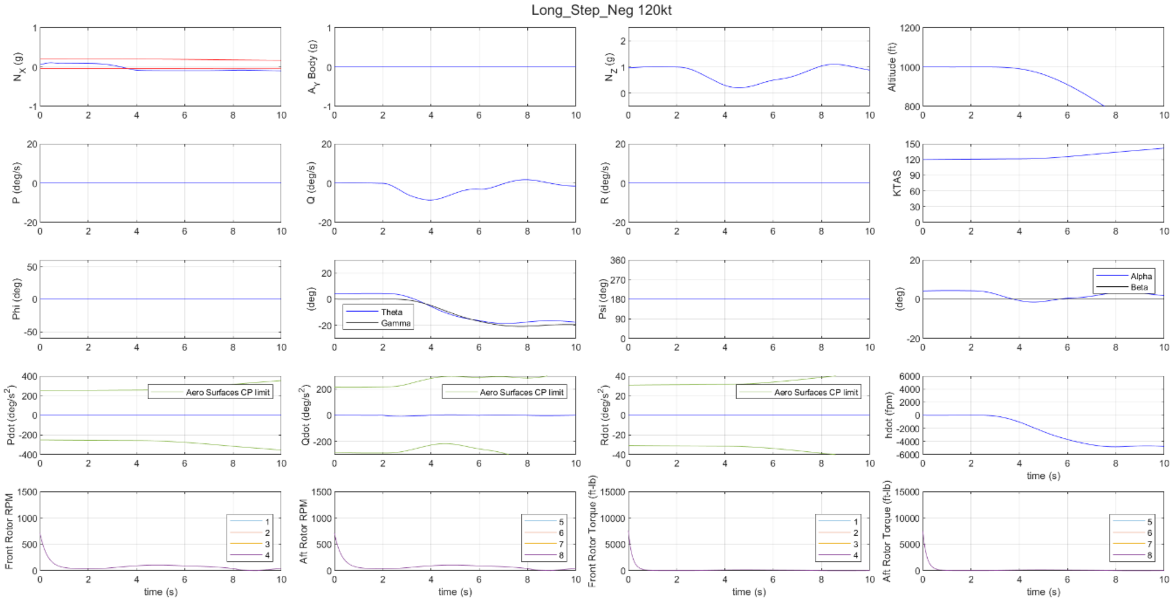


Figure C- 17. Max negative longitudinal step at 120 knots

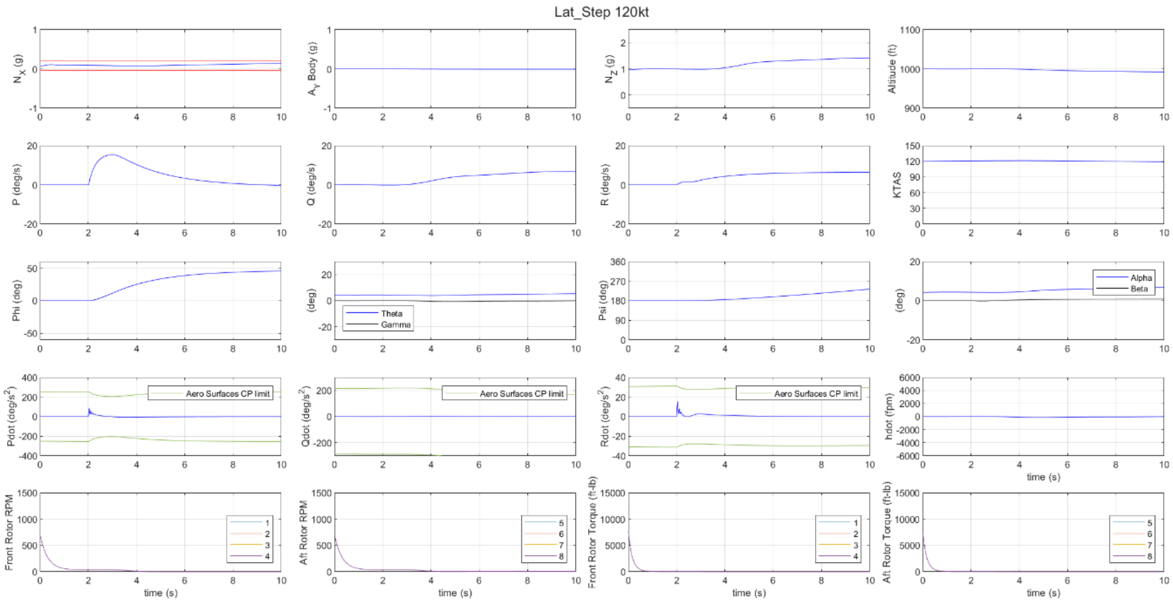


Figure C- 18. Max lateral step at 120 knots

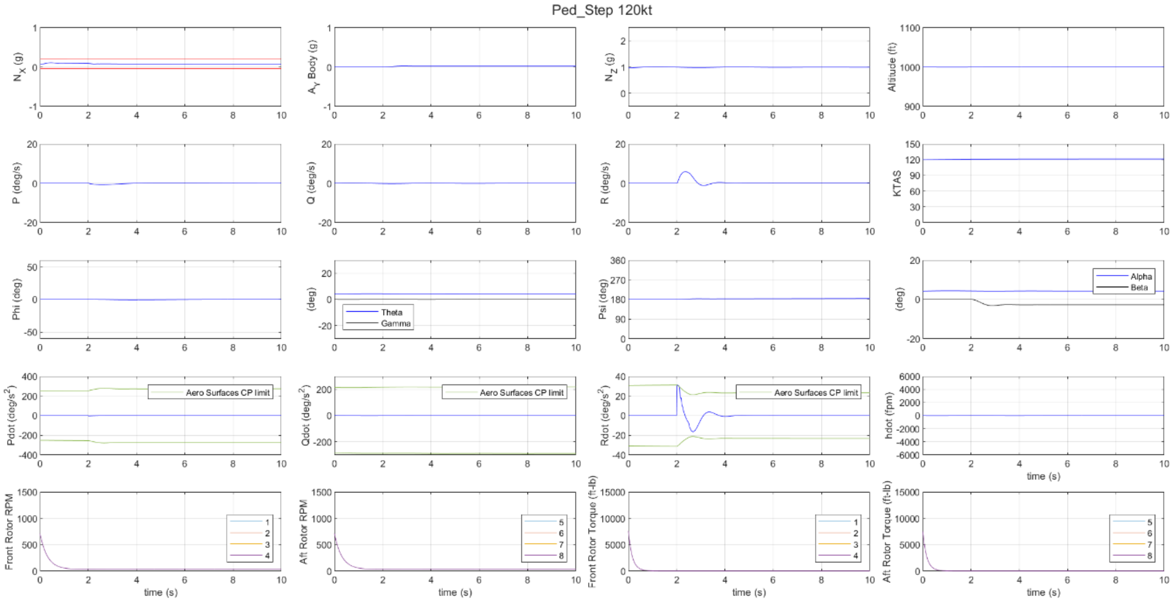


Figure C- 19. Max pedal step at 120 knots

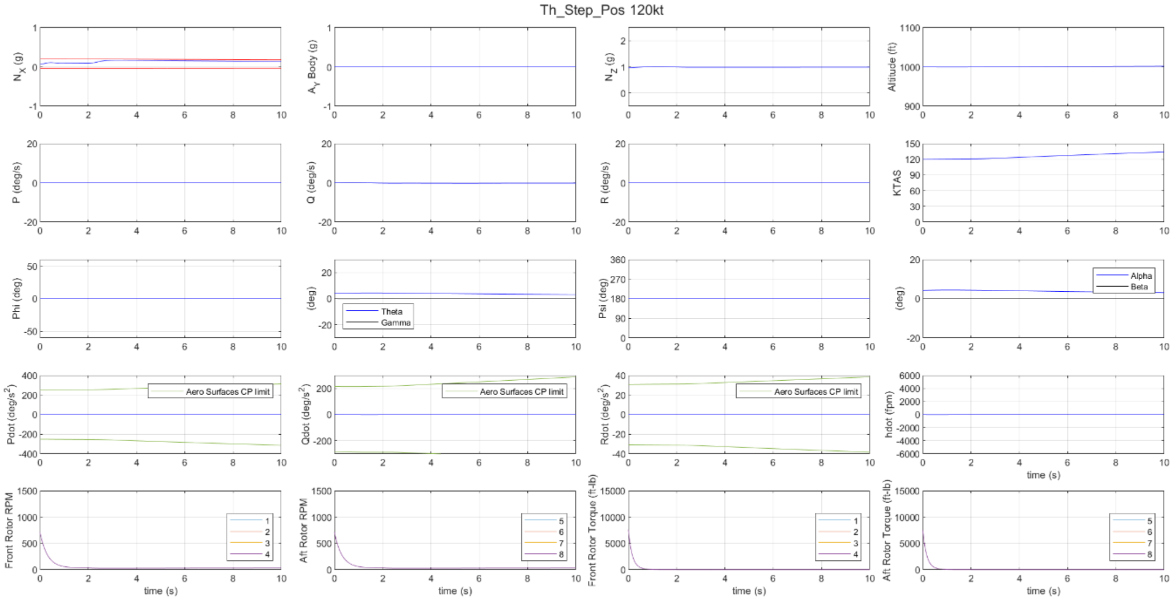


Figure C- 20. Positive speed command step at 120 knots

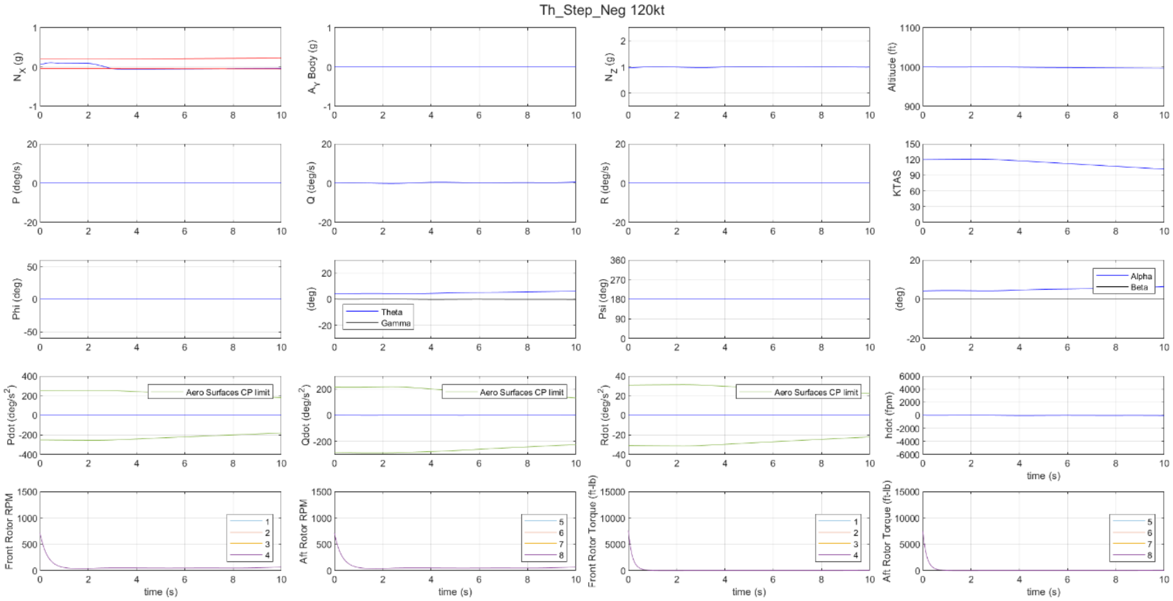


Figure C- 21. Negative speed command step at 120 knots