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An Approach to Fly-by-Wire Handling Qualities Testing Linking Development Tools to Civil Certification Requirements

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16. Abstract

Traditional certification methods may not be suitable for aircraft in the powered-lift category. These novel aircraft feature alternative fuels (e.g. electric), distributed propulsion, over-actuated control surfaces, and advanced fly-by-wire technology. A larger research portfolio focuses on developing a variety of flight test techniques for this category. One area that requires consideration for certification is handling qualities.

In previous efforts, work conducted by Systems Technology, Inc. (STI), outlined an approach to using Handling Qualities Task Elements (HQTEs) for civilian certification. In addition, a catalogue of HQTEs was presented along with supporting flight test techniques. HQTEs are proposed for partial compliance demonstration.

This research report extends this work further, through the introduction of the ‘Flight Test Scorecard’ (FTSC) approach. This report provides a linkage between the proposed HQTEs and certification requirements to aid the applicants in their use during the certification process. In addition, this report provides an overview of the FTSC approach intended to support the FAA and applicant to display information relating to the completion of HQTEs and any supporting data that may be shared as part of the certification process. The scope also includes revisited HQTEs, including proposed boundaries and tolerances, which were refined during flight testing conducted in this work.

The objectives of this work were to review aircraft accident databases, to create the FTSC approach, to test this approach and define metrics suitable for applicants to collect as ‘Supporting Data’, and to further refine the HQTEs developed in previous work. The final demonstration of this research effort was a dedicated flight test campaign using a variable stability helicopter.

17. Key Words

Flight Test, Certification, Means of Compliance, Handling Qualities, Cooper-Harper Handling Qualities Ratings.

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Contents

Figures

Tables

Acronyms

Acronym	**Definition**
AAM	Advanced Air Mobility
ACAH	Attitude Command Attitude Hold
ACVH	Acceleration Command Velocity Hold
AFM	Aircraft Flight Manual
AQTE	Automation Qualities Task Element
ASTM	American Society for Testing and Materials
CG	Center of Gravity
CONOPS	Concept of Operations
DVE	Degraded Visual Environment
EASA	European Union Aviation Safety Agency
EUROCAE	European Organisation for Civil Aviation Equipment
eVTOL	electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
FBW	Fly By Wire
FCS	Flight Control System
FQ	Flying Qualities
FQA	Flying Qualities Assessment
FTE	Flight Test Engineer
FTG	Flight Test Guide
FTM	Flight Test Maneuver
FTSC	Flight Test Score Card
GPS	Global Positioning System
GVE	Good Visual Environment
HOGE	Hover Out of Ground Effect
HTH	Hover Turn and Hold
HQ	Handling Qualities
HQR	Handling Qualities Rating
HQTE	Handling Qualities Task Element
IGE	In Ground Effect
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
MCRUER	Means of Compliance Requirements for UAM Evaluations and Ratings

MDAS	MCRUER Data Acquisition System
MOC	Means Of Compliance
MTE	Mission Task Element
NASA	National Aeronautics and Space Administration
NFE	Normal Flight Envelope
NRC	National Research Council (Canada)
OGE	Out of Ground Effect
OFE	Operational Flight Envelope
PF	Pilot Flying
PIO	Pilot-Induced Oscillation
PIOR	Pilot-Induced Oscillation Rating
PNF	Pilot Not Flying
PUSS	Pitch-Up with Sideslip
RCHH	Rate Command Height Hold
RPM	Revolutions Per Minute
SQA	System Qualities Assessments
SVO	Simplified Vehicle Operations
TIA	Type Inspection Authorization
TFCPs	Trimmed-Flight Control Positions
TRC	Translational Rate Command
UAM	Urban Air Mobility
VFR	Visual Flight Rules
VFS	Vertical Flight Society
VNE	Never Exceed Speed
VNO	Maximum Structural Cruising Speed
VRS	Vortex Ring State
VMC	Visual Meteorological Conditions

Glossary

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

Indirect Flight Control	Aircraft response generated by pilot movement of the control inceptors through a flight control computer or other means that then drives the actuation of the control surfaces or propulsors.
Mission Task Element	Flight test maneuvers that provide a basis for an overall assessment of the aircraft's ability to safely perform its intended functions, as adapted from ADS-33E-PRF, March 2000.
Pilot-Induced Oscillation	Unintentional sustained or uncontrollable oscillations resulting from pilot efforts to control the aircraft where aircraft response that is being controlled by the pilot is approximately 180° out of phase with pilot inputs.
Response-Type	A characterization of the vehicle response to command inputs with respect to augmentation that include, but are not limited to, the following examples: Rate Command Attitude Hold (RCAH), Attitude Command Attitude Hold (ACAH), Translational Rate Command (TRC), and Acceleration Command Velocity Hold (ACVH).
System Qualities Assessments	Flight test methods that provide the data required to evaluate indirect flight control systems.

Executive summary

Novel aircraft featuring alternative fuels (e.g. electric), distributed propulsion, over-actuated control surfaces or effectors, and advanced fly-by-wire (FBW) technology are currently in development and certification testing. It is widely acknowledged that traditional certification methods may not be suitable for these types of aircraft. In the United States, some of these aircraft will be certified as a powered-lift category aircraft. One area that requires consideration for the certification of these aircraft is handling qualities. Both in Europe and the United States, closed-loop, short-look, highly constrained tasks are proposed as features of compliance for stability and controllability rules or airworthiness criteria. Through Federal Aviation Administration (FAA)-sponsored research, these have been termed Handling Qualities Task Elements (HQTEs). Much inspiration for these approaches is taken from the handling qualities guidance document, Aeronautical Design Standard 33 (U.S. Army Aviation and Missile Command, 2000), which has been used in various incarnations since Army's Aviation Systems Command (AVSCOM) adopted the 8501 Update effort as Aeronautical Design Standard-33 in 1987 to determine the suitability of military rotorcraft for a given mission and requirements. Using this approach, standardized tasks are proposed with similar performance requirements, which should be met to ensure acceptable handling qualities. In previous efforts, work conducted by Systems Technology, Inc. (STI), outlined an approach to using HQTEs for civilian certification and presented a catalogue of HQTEs with supporting flight test techniques.

This report provides a linkage between the proposed HQTEs and civil requirements formulated by STI, which can aid the applicants during the certification process. The focus of this work has been powered-lift aircraft, capable of vertical takeoff and landing (VTOL). STI has conducted further work through the development of the 'Flight Test Scorecard' (FTSC) approach. There is also an overview of the FTSC intended to support the FAA and applicant to display information relating to the completion of HQTEs and any supporting data that may be shared as part of the certification process. The scope revisited HQTEs, including proposed boundaries and tolerances, which were refined during flight testing conducted in this work.

The objectives of this work were to review aircraft accident databases, to develop and apply the FTSC approach, to test this approach and define metrics suitable for applicants to collect as 'Supporting Data', and to further refine the HQTEs developed in previous work. The final demonstration of this research effort was a dedicated flight test campaign using a variable stability helicopter.

The intention of this report is to outline the initial process for the FTSC, with the intention to support applicants in the handling qualities compliance demonstration. This is the initial

proposed format for the FTSC, linking HQTEs to certification requirements, and it is expected that this will continue to mature with use and feedback from industry. The report also further expands on the concept of HQTEs and ‘Supporting Data’, which may be used to abet certification. The use of subjective ratings and tailoring of HQTEs for specific aircraft and certification needs is also discussed. Though the results and processes contained in this report were developed with objectives geared towards VTOL, the work is applicable to conventional fly-by-wire aircraft in the future.

1 Introduction

1.1 Background

This project fits in within a larger portfolio sponsored by the FAA that includes research works from others including NASA Langley, NASA Ames, Adaptive Aerospace, Flight Level Engineering, Eagle Works, Auburn University, Georgia Tech, Florida Institute of Technology, and National Test Pilot School. That body of research and other research with Systems Technology was focused on developing a framework for flight test techniques that can be used for testing advanced flight controls on a variety of aircraft. The flight test techniques described here are meant to supplement traditional flight test techniques for a partial showing of compliance to stability and controllability, and can be applied to any aircraft with advanced flight controls, including fly by wire.

The goal for the framework is to focus simulator and on-aircraft testing to ensure that, at the limits of the operating envelope, handling qualities do not exhibit adverse or unanticipated behavior. Handling qualities are one small piece in overall certification and are assessed with task elements. Task elements (referred to in this paper as Handling Quality Task Elements or HQTEs) are isolated from other pilot workload tasks such as running checklists (normal, abnormal and emergency) navigation, and ATC communications. HQTEs are not pass/fail and do not have absolute prescriptive criteria to meet to be certified. The airworthiness authorities' decision as to whether the handling qualities are suitable for civil certification must only be made after other integrated evaluations are considered that take into account overall workload in an operationally relevant environment.

1.2 Purpose

Future powered lift Part 23 "Small Airplane" aircraft that feature advanced indirect flight controls offer drastically different characteristics and handling as contemporary aircraft, particularly those certified under Part 23 regulations (Federal Aviation Administration). In recent years, both in Europe (through European Organisation for Civil Aviation Equipment, or EUROCAE) and through FAA-funded research, a 'mission-oriented approach' has been proposed for means of compliance demonstration for acceptable handling qualities. Much inspiration for these approaches is taken from the handling qualities guidance document, Aeronautical Design Standard 33 (U.S. Army Aviation and Missile Command, 2000), which is the current standard to determine the suitability of military rotorcraft for a given mission and requirements.

The most recent edition of ADS-33 (U.S. Army Aviation and Missile Command, 2000) presents a mission-orientated approach centering around testing the aircraft using suitable short-look tasks that represent the level of aggressiveness and performance expected during operations. Using this approach, standardized tasks were proposed with similar performance requirements, which should be met to ensure acceptable handling qualities for certification. In previous research efforts performed by STI, an approach inspired by this was proposed for civil certification of powered-lift aircraft. Within the Flight Test Guide (Klyde, Mitchell, Shubert, & Jones, 2024), an outline of the process was provided, along with detailed descriptions of how to conduct testing, criteria to use, and proposed HQTEs.

The focus of the previous effort was on laying the foundations for this approach. Initial proposals were made for which aspects of certification these HQTEs would cover, but they are not extensive. This report provides a linkage between the proposed HQTEs and certification requirements to aid the applicants in their use during the certification process. In addition, this report provides an overview of a Flight Test Scorecard Approach (FTSA) intended to support the FAA and applicant to display information relating to HQTEs completion along with supporting data that may be shared as part of the certification process. The scope also includes revisited HQTEs, including proposed boundaries and tolerances, which were refined during flight testing conducted in this work. It is important to note that the flight test guide and HQTEs are meant to be a standardized framework for testing. Selection and tailoring of HQTEs will need to be negotiated between the applicant and the FAA as appropriate for a given configuration and design.

1.3 Mission

In previous supporting efforts, STI, with collaborators, delivered both an emerging catalogue of HQTEs for certification compliance demonstration, and a Flight Test Guide (FTG), which outlines best practices for demonstration of acceptable handling qualities in flight and simulation testing. To further build on these efforts, the STI team, including David Mitchell of Mitchell Aerospace Research, Martin Shubert of Tiltrotor Flight Test Consulting LLC, and Richard Newman are working to develop a method for both conducting and reporting of test activities.

The objectives of this effort included but were not limited to:

- Review aircraft incident/accident databases to better discern the impact of mode changes and/or transitions.
- Create a Flight Test Score Card (FTSC) that will track vehicle and systems testing from concept to flight test in conjunction with the emerging FTG.

- Identify and define the processes and supporting data that can be provided by the applicants to the certifying agency such that the number of required flight test HQTEs can be reduced.
- Using a representative vehicle model, demonstrate how to populate the FTSC and provide the supporting data in an appropriate manner.

1.4 Report structure

This report is structured in five sections. First, this section introduces the introduction, scope, terminology, and the initial concept of FTSC approach. Section 2 presents , results from a review of the accident database, specifically focusing on accidents resulting from mode changes. This includes fixed and rotary-wing events and categorizes these. Next, the concept of the FTSC is introduced, along with guidance and initial examples in Section 3. This includes an overview of initial proposed HQTEs and the software solution that has been developed for the FTSC. In Section 4, the Supporting Data is discussed in detail, including the intended use and calculations. Example uses and data are shown.

Following, in Section 5, the example use cases and flight tests are discussed in detail. Flight tests were conducted at National Research Council (NRC) Canada with a number of candidate HQTEs. These were used to populate the FTSC and test the feasibility of the approach to track test artifacts, including example data that would be stored. In addition, the concepts of tailoring were explored. Conclusions and recommendations drawn from this work are included in this section.

1.5 Terminology

In the FTG (Klyde, Mitchell, Shubert, & Jones, 2024), a novel approach for determining acceptable handling qualities for civil certification was proposed. In this document, both piloted flying tasks, used for the final evaluations, and supporting data, used for analysis before, during, or after these tests were introduced. During the current work, the scope of supporting data has shifted following feedback from industry and regulator.

An important step to initiating the FTSC methodology was to finalize definitions for the 'task element' approach. These definitions are critical to apply and understand the benefits of the methodology. The category definitions used in our analysis are shown below. Whether it is necessary or not to introduce new definitions to the certification discussion will be the decision of the FAA, but it is informative to describe how the HQTEs that are proposed will fit into the overall flight testing process, so these other tests need to be outlined.

1.5.1 System Qualities Assessments

System Qualities Assessments (SQAs) are used to determine stability margins and other predictive measures to give insight into the flying and handling qualities expected during piloted evaluations. SQAs may include both the data ascertained from flight or simulated tests and analysis on these data, including calculation of specific parameters and control system characteristics (e.g., stability margins). SQAs may also include system identification used for modeling and simulation development. The flight test techniques for SQAs are well documented within Klyde et al. (2024). Additional information regarding specific SQAs proposed for the FTSC is outlined in Section 3. of this report. Some proposed SQAs are equivalent to predictive handling quality (HQ) criteria contained in MIL-DTL-32742 (U.S. Department of Defense, 2023) (i.e., bandwidth phase delay). The regulator should consider requiring SQA data as part of the System Description Document. Note however, that meeting a specific standard for these data is not required. Confidence in data and results obtained from SQAs (e.g., vehicle model match, criteria results considered to be good), should give confidence that the vehicle characteristics and performance are well understood. Analysis of SQAs can also support selection and eventual tailoring (discussed later in this report) of handling/automation quality task elements.

1.5.2 Flying Qualities Assessments

Flying Qualities Assessments (FQAs) identify characteristics of the aircraft from both open-loop and controllability demonstrations. These assessment methods are proposed to be like (or the same) as present-day certification tests. Two types of FQAs have been identified. The first, open-loop demonstrations, are specific loosely constrained flying tasks which exercise the response of the aircraft. Examples of this may include tests to observe time-to-bank, to ascertain stall speed, or to test envelope limitations. Typically, there is no requirement for the pilot to perform 'recovery action' from these tests, hence the 'open-loop' nature of the tests. The second type of FQA, controllability demonstrations, include qualitative evaluation from the pilot regarding the ability to recover from conditions. These tests would include determinations on controllability following failures, control mode changes, stalls and low power margins as well as envelope protections being active. Typically, Cooper-Harper Handling Quality Ratings (HQRs) – a pilot rating system used to quantify aircraft handling qualities based on task performance and pilot workload (Cooper & Harper, 1969) – are not awarded during FQAs, due to the nature of the tasks and the absence of the quantitative task constraints required to award subjective ratings. During piloted evaluations, alternative means such as failure evaluation scale (Hindson, Schroeder, & Eshow, 1990) or workload ratings (Hicks, Durbin, Morris, & Davis, 2014) may be used to collect pilot subjective feedback.

As FQAs are predominantly synonymous with current certification test methods, they are not the specific focus of the effort detailed in this report. The use of FQAs in the FTSC process is discussed, but no specific FQAs were developed or tested as part of the current efforts.

1.5.3 Handling Qualities Task Elements

The general definition from the FTG remains the same. Through continued research and discussions with certification authorities, the authors of this report have refined the definition of HQTEs to include the following considerations:

1. HQTEs are pilot closed-loop tests to assess handling qualities for operationally relevant tasks and conditions. These tests can be tailored to the aircraft and utilize engineered maneuver constraints and tolerances that stress the pilot-integrated design.
2. HQTE testing will assign Handling Qualities (HQ) levels with associated pilot comments towards the goal of:
    a. Assuring safe operations within the operational envelope (both on-ground and in-flight).
    b. Identifying Pilot Induced Oscillations (PIO) susceptibility, HQ deficiencies, Human Machine Interface (HMI) deficiencies, or other hazardous flight control characteristics.
    c. Assuring the intended operations can be accomplished without requiring exceptional piloting skill, alertness, or strength.
3. While potentially linking acceptable HQ levels to the following conditions, the HQTE matrix should account for:
    a. Flight Conditions: flight envelope, environmental conditions, and configuration, including transition (across flight modes, response-types, reference frames, vehicle configurations).
    b. State: normal conditions and failure conditions not shown to be extremely improbable. Conditions include flight control failures that reduce capability or degrade handling qualities.
    c. Settings: Selectable Flight Controls Modes (e.g., normal, training, backup/reversionary, if they exist).

To support the objectives of Item 2 in the definition stated above, these requirements are interpreted to mean that HQTE should be used to stress the flight control design through these engineered maneuvers. These maneuvers also provide insight into whether the flight control design provides for acceptable handling qualities that meet a baseline or floor requirement. This baseline ensures the intended operations can be accomplished without requiring exceptional piloting skill, alertness, or strength. The use of two different levels of HQ performance, as embodied in the Cooper-Harper Ratings (CHR) scale (Cooper & Harper, 1969), described as "desired" and "adequate", lends itself toward meeting both of these objectives which will be discussed in further detail later.

HQTEs are closed-loop, tightly constrained flying tasks, analogous to Mission Task Elements (MTEs) as described in Klyde et al. (2024). The difference between HQTEs and MTEs is their application toward determining whether the aircraft is safe and airworthy for a broad range of civil operations and their use for certification compliance demonstration, rather than pure HQ evaluations. They employ the following attributes:

- Maneuvers are relatable to the operational elements of interest in the certification of the vehicle.
- Maneuvers potentially cover the areas of concern with advanced flight control concepts. Examples include automated transitions of control response types, new inceptor configurations, novel inceptor control mappings, and evaluation of potential non-linear behavior.
- Task Performance tolerances, in combination with other constraints, are used to press the pilot into the control-loop.
- Task performance is cued and measured in real time, with immediate feedback to the pilot, through ground courses for the low-speed environment, for instance.
- Maneuvers are designed efficiently in that they are short-look tasks that examine individual maneuver elements. This allows for easy practice of the maneuvers, toward the pilot identifying issues with the design and determining what amount of compensation is needed by the pilot with respect to those issues.
- Tasks are performed within the already established flight envelope with sufficient margins from performance and control boundaries.
- Maneuvers, when examined in combination, provide comprehensive coverage of the HQ elements in the selected environment. For example, in the Low-speed VTOL regime:

  - Small amplitude precision maneuvers
  - Moderate amplitude aggressive maneuvers
  - Axes examined individually and in combination
  - Two speed regimes, near hover and higher groundspeeds for VTOL
  - Calm winds and moderate winds

HQTEs are intended to be representative of the intended performance of the aircraft. Using standardized maneuvers and tolerances allows different applicants to demonstrate equivalent performance. In Klyde et al. (2024), an initial catalogue of 28 HQTEs were proposed for evaluations.

The development and refinement of HQTEs form a significant part of the work described in Section 5. The aspect of specific tailoring for certification is also discussed in this report.

Full demonstrations of relevant operational maneuvers are still expected to be performed in Type Inspection Authorization (TIA), in addition to HQTE, to fully assess the aircraft HMI in a mission representative manner and understand how the handling qualities of the aircraft supports the safe execution of such maneuvers.

1.5.4 Automation Qualities Task Elements

Automation Qualities Task Elements (AQTEs) are intended to be like HQTEs, however, they are chosen to assess autonomous features. This supports certification of aircraft designed to operate as optionally-piloted or autonomously, including supervision with and without a pilot/operator on board. AQTEs have been preliminarily considered; however, their treatment is not fully developed within the scope of this work.

Table 1 shows an overview of the categories introduced, the terms used in the FTSC, their purpose, example tests, existing example criteria, and some additional information.

Table 1: Description of Terms used in Scorecard Process

Term	**Purpose**	**Example Tests as envisioned for the FAA**	**Associated ADS-33 Criteria**	**EUROCAE WG112**	**Action**
SQA	Determine stability margins and other predictive measures of FQ and HQ. System Identification to support modeling and simulation.	Time domain and frequency domain control response tests: rap, steps, doublets, 2-1-1, 3-2-1-1, frequency sweeps, multi-sines, and dwells.	Predictive systems criteria such as Phase and Gain Margins for inner, outer broken loops. Predictive FQ and HQ such as Bandwidth and Phase Delay. Short-term-response. Character of response types.	N/A	FAA should require applicant to provide SQA data in system description document. Note this does not mandate meeting a standard like ADS-33 unless the FAA specifies a standard in its airworthiness criteria.
FQA: Open-Loop Demonstration	Quantitative evaluation of Flying Qualities (pass/fail)	SHSS, dynamic stability, trimmed-flight control positions (TFCP), time-to-bank, stall speed (+prevention), wind-up turn (stick force per g), maneuver stability, attitude quickness, etc.	Mid-term response criteria. Small, medium, and large amplitude criteria, Axis Stability, Axis Control power.	Specific Flight (SpFl): Accel to speed never exceed (VNE)/Deceleration to maximum structural speed (VNO), VNE Demonstration, Low-speed Controllability and TFCP, Forward flight TFCP Lateral Control: Roll Capability	Includes traditional FQ test maneuvers as well as additions from ADS-33 and elsewhere. Traceable to requirements, quantitative evaluation.
FQA: Closed-Loop Controllability Demonstrations	Qualitative evaluation of controllability, often to determine flight envelope.	Stall recovery, critical azimuth, envelope protection, low power margin, etc.	Rotorcraft limits, Equilibrium Characteristics		Traceable to requirements, qualitative evaluation.
HQTE	Formal qualitative evaluation using a minimum of 3 pilots, within flight envelope	Piloted closed-loop engineering tasks: Precision Hover, Hovering Turn and Hold, Vertical Reposition and Hold, Lateral reposition and Hold, Rejected Takeoff, urban air mobility (UAM) approach, etc.	MTEs	Flight Test Maneuver (FTM):VTOL Hover, Hovering Turn, Takeoff, Landing and Vertical Step up, Lateral Maneuver, etc.	Traceable to requirements, qualitative evaluation. While optional, it is also recommended to track quantitative measures of task performance to enhance understating of the qualitative evaluations.

Term	Purpose	Example Tests as envisioned for the FAA	Associated ADS-33 Criteria	EUROCAE WG112	Action
AQTE	(Likely) Quantitative assessment of autonomy in relevant task elements.	Automated HQTE	MTEs		Traceable to requirements, quantitative evaluation of task performance requirements and other relevant assessment metrics.

1.5.5 Terminology applied

The work outlined in this report focuses on the proposal of a new FTSC process to support the applicant and the FAA for the powered-lift category. Terminology is developing with processes, so in this work, the terms SQA and FQA are replaced with the overarching term ‘Supporting Data’.

AQTEs are outside the scope of the initial FTSC proposal. Therefore, FTSC certification requirements consider HQTEs and Supporting Data comprising frequency sweeps, frequency sweeps, flight test techniques, control inputs, analysis metrics (e.g., stability margins, bandwidth).

1.6 Civil Certification and Mission Oriented Approach

A key consideration in this effort was to evolve the military mission-oriented approach, as described by the U.S. Army Aviation and Missile Command (2000), as a foundational reference and adapt it into a process aligned with civil certification requirements. This had been explored to a limited extent in previous work, but not in detail. Military specifications for determining HQs are based on the ‘mission-oriented approach’. Examples include scout/attack and cargo/utility type operations. It is not expected that a cargo/utility helicopter, for example, will have the same level of agility as an attack helicopter. Furthermore, an attack helicopter must demonstrate additional capabilities, an example being rapid turn to target and fire. This requires agility, precision, and the necessary pilot control to perform. Aligning the handling qualities with the mission enables classification of specific rotorcraft, making the eventual requirements representative. For civilian powered-lift aircraft, a similar philosophy is proposed but based on the concept of operations (CONOPS). Each aircraft may have a different CONOPS based on the design and proposed business model.

For this approach to be successful, it is important that there is direct linkage between the certification requirements and the Supporting Data/HQTEs. Each ‘element’ considered should relate directly to a specific requirement, allowing results from any tests to be traceable for credit. In this work, several examples have been used to show the linkage, from certification paragraphs to the corresponding data and selected HQTEs.

2 Accident database review - mode change emphasis

2.1 Overview

This section presents a review of available databases relative to a selected group of fixed and rotary wing aircraft incident and accident reports, focused on flight control system mode changes or vehicle transitions. Specifically, the following mode changes and/or transitions will be considered in the review of accident databases:

Table 2: Descriptions of Different Types of Transition/Mode Changes

Type #	Description	Examples / Notes
1	Vectored thrust to support thrust-borne / wing-borne / thrust-borne flight	
2	Response type changes	Height rate to flight path rate or Translational Rate Control (TRC) to forward flight modes, also augmented to direct, autopilot disengagements, maintenance mode.
3	Envelope protections	Includes prioritization, warnings, and blending (in/out)
4	Ground mass to air mass	Frames of reference used by Flight Control System (FCS) (inertial vs. stability axes vs. body axes)
5	Radar Altitude vs. MSL.	
6	Wind and turbulence effects	Disturbances includes Vortex Ring State (VRS) and other rotor interactions
7	Weight-on-wheels (or skids) state changes	True or False
8	Dynamic Behavior at Limits/Insufficient Control Power	
9	System nonlinearities	Rate limits, position limits, hysteresis, command gain shaping
10	Ground effect transitions	In ground effect (IGE)/out of ground effect (OGE)
11	FCS software-related behaviors	Gain blending, logic trees, integrator wind-up

Three independent reviews were undertaken of available, public domain aircraft incident/accident databases and other sources to better understand the role of mode changes/transitions listed above as causal influences. The reviews were undertaken by program team members STI, Tiltrotor Flight Test Consulting (TFTC), and Crew Systems (CS). Details of each review are provided in the appendices, while the main text that follows summarizes the findings illustrating the significance of each element of the above list.

2.2 Database summaries

The summary tables provided in the following sections identify events by aircraft type and date. These are then easily traceable to the detailed descriptions found in the corresponding appendix. For each event, the tables identify primary, secondary, and tertiary transitions and/or mode changes (1 – 11) from Table 2 provided above as causal factors in the events. When appropriate, the summary tables identify those cases where primary or secondary factors may be due to other causes not associated with the list of transitions (e.g., a failure case). Summary charts were then created for each database to illustrate the number of occurrences of a given transition (1 – 11) as a primary, secondary, or tertiary factor.

2.2.1 Systems Technology, Inc. database

The STI incident/accident database represents a collection of commercial transport and powered lift events. There is some overlap with the commercial transport database compiled by Crew Systems in Section 2.3. Table 2 provides a summary of the principal causes related to the transitions and/or mode changes listed above in the Introduction for each of the occurrences reported in the STI database that is compiled in Appendix A. The database features 14 fixed wing and 6 powered lift configurations (i.e., tiltrotor and helicopter) for 20 total cases.

Table 3: Summary of Incident/Accident Transition/Mode Change Related Causes

Aircraft Type	**Date of the Event**	**Transition/Mode Changes Causes**		
		Primary	**Secondary**	**Tertiary**
Fixed Wing Examples				
A320-213	02/07/2001	6	11	3
A320-200	06/25/2005	11	---	---
B737-3Q8	09/23/2007	11	2	---
A330-223	05/21/2009	6	---	---
A330-203	06/01/2009	6	11	2
A330-300	06/23/2009	2	11	---
A340-313	03/13/2012	2	---	---
B737-236A	04/20/2012	Pilot Error	2	---
Sukhoi 100-95B	07/21/2013	7	---	---
A320-200	09/07/2013	2	---	---
A320-200	12/28/2014	Failure	2	---
B737-MAX8	03/10/2019	Failure	11	2
A310-325	09/24/1994	3	2	---

Aircraft Type	Date of the Event	Transition/Mode Changes Causes		
		Primary	**Secondary**	**Tertiary**
A330-303	10/07/2008	11	---	---
Powered Lift Examples (Tiltrotors and Helicopters)				
CV-22	06/13/2012	6	8	9
MV-22	04/11/2022	1	6	---
AW609	10/30/2015	8	11	---
Bell 525	07/06/2016	8	6	---
Sikorsky S-97A Raider	08/02/2017	7	2	---
CH148822 Cyclone	04/29/2020	11	2	8

The number of primary, secondary, and tertiary occurrences of a given transition and/or mode change (1 – 11) are identified in Figure 1 for the 20 events listed in Table 2 and detailed in Appendix A. For this mixed vehicle database, the following observations are made:

- Primary:
    - Transitions 1, 2, 3, 6, 7, 8, and 11 all appear as primary causal factors in the events.
    - Transition 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions) and 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) each have four occurrences (20% of cases).
    - Transition 2 (Response Type Changes) appears three times (15% of cases), while Transitions 7 (Weight-on-Wheels or Skids, True or False) and 8 (Dynamic Behavior at Limits/Insufficient Control Power) each appear twice (10% of cases).
    - Transitions 1 (Vectored thrust to support Thrust Borne/Wing Borne/Thrust Borne flight) and 3 (Envelope Protections including prioritization, warnings, and blending) each appear once (5% of cases).
- Secondary: Only four transitions appear as secondary causal effects.
    - Transition 2 (Response Type Changes) occurs 6 times (30% of cases), while Transition 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) occurs 5 times (25% of cases).

  - Transition 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions) appears twice (10% of cases)
  - Transition 8 (Dynamic Behavior at Limits/Insufficient Control Power) appears once (5% of cases).
- Tertiary: With respect to tertiary causal factors, like secondary factors, only four transitions were identified.
  - Transition 2 (Response Type Changes) appear twice (10% of cases).
  - Transitions 3 (Envelope Protections including prioritization, warnings, and blending), 8 (Dynamic Behavior at Limits/Insufficient Control Power) and 9 System nonlinearities including rate and position limits, hysteresis, command gain shaping, etc.) appear once (5% of cases).
- From the review of the STI database, Transitions 2 (Response Type Changes), 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions), and 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) are most prevalent.

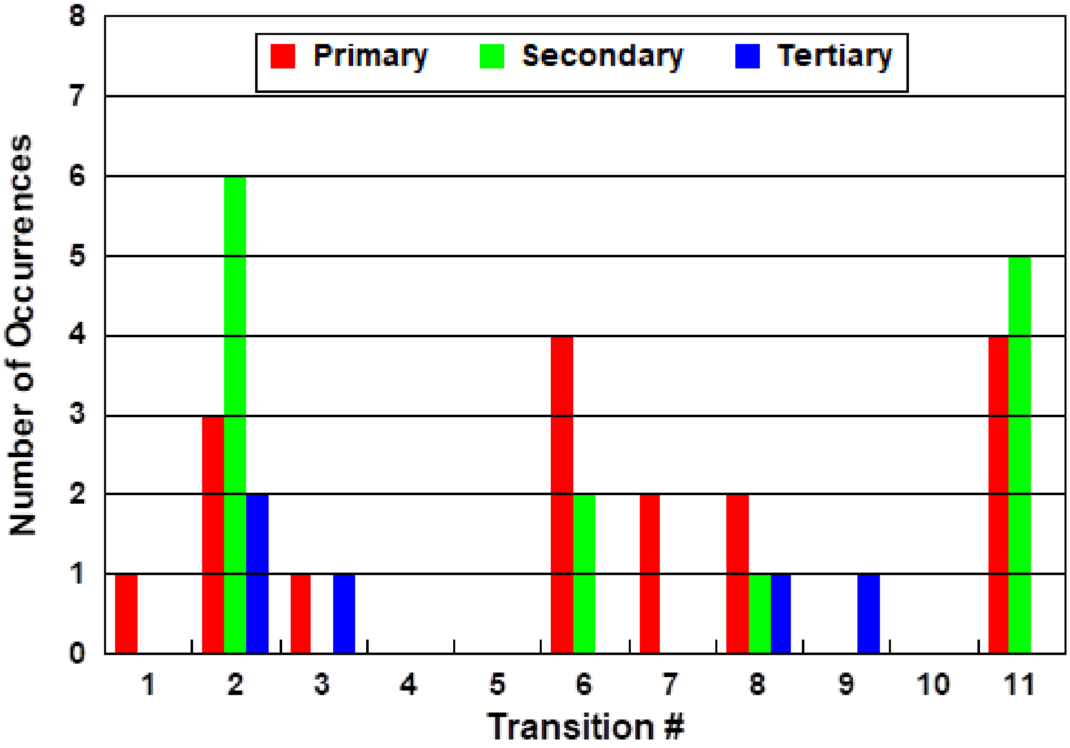


Figure 1: Key Transitions Identified from STI Event Database

2.2.2 Tiltrotor Flight Test Consulting database

The TFTC incident/accident database focuses specifically on examples generated by the XV-15, V-22, and AW609 family of tiltrotor aircraft as found in Table 3. With over two decades of experience as a test pilot flying tiltrotor aircraft, Marty Shubert of TFTC has specific and detailed comprehension into many of these incidents. Details with respect to the identified examples are provided in Appendix A, Section 3. Since many of these incidents involve military aircraft, the details provided are from public release sources only. There are a total of 17 events in the table.

Table 4: Summary of TFTC Database with Identified Transition/Mode Changes

		Transition/Mode Changes		
Aircraft	**Date of Event**	**Primary**	**Secondary**	**Tertiary**
XV-15	7/30/1979	1	---	---
MV-22	4/2012	8	1	Lack of 3
AW609	7/17/2014	8	11	---
AW609	10/30/2015	8	11	---
CV-22	6/13/2012	6	8	9

Aircraft	**Date of Event**	**Transition/Mode Changes**		
		Primary	**Secondary**	**Tertiary**
MV-22B	4/8/2000	6	Lack of 3	8,1
CV-22	4/10/2010	1	11	---
MV-22B	5/2015	Failure	11[1]	---
MV-22B	8/5/2017	10	6	---
MV-22B	3/18/2022	8	---	---
MV-22B	10/2014	HMI[2]	10	---
MV-22B	6/11/1991	11	HMI[2]	1
MV-22B	7/20/1992	Failure	1	---
XV-15	8/30/1992	Failure	1	---
MV-22B	12/2000	Failure	11	HMI[2]
MV-22B	3/27/2006	Failure	11	---
MV-22B	6/8/2022	Failure	11	---

The number of primary, secondary, and tertiary occurrences of a given transition and/or mode change (1 – 11) are identified in Figure 2. For this tiltrotor database, the following observations are made:

- Primary:
  - Five transitions are revealed as primary causal factors (1, 6, 8, 10, and 11) with Transition 8 (Dynamic Behavior at Limits/Insufficient Control Power) occurring four times (24% of cases).
  - Transitions 1 (Vectored thrust to support Thrust Borne/Wing Borne/Thrust Borne flight) and 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions) each occur twice (12% of cases).
  - Cases 10 (In Ground Effect/Out of Ground Effect) and 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) each occur once (6% of cases).
- Secondary: For the 17 tiltrotor events, five transitions populate the secondary causal factor.

---

[1] Inappropriate response type for the environment.

[2] HMI: Automation/augmentation confusion or design induced crew error.

    - These are dominated by seven occurrences of Transition 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) representing 65% of the cases.
    - There are three secondary occurrences of Transition 1 (Vectored thrust to support Thrust Borne/Wing Borne/Thrust Borne flight), 18% of cases.
    - Transitions 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions), 8 (Dynamic Behavior at Limits/Insufficient Control Power), and 10 (IGE/OGE) each had one occurrence representing 6% of cases.
- Tertiary: Three transitions highlight the tertiary causal factors.
    - Transition 1 (Vectored thrust to support Thrust Borne/Wing Borne/Thrust Borne flight) appears twice as a tertiary factor (12% of cases).
    - Transitions 8 (Dynamic Behavior at Limits/Insufficient Control Power) and 9 (System nonlinearities including rate and position limits, hysteresis, command gain shaping, etc.) each appear once, 6% of cases.
- From the review of the tiltrotor aircraft database, Transitions 1 (Vectored thrust to support Thrust Borne/Wing Borne/Thrust Borne flight), 8 (Dynamic Behavior at Limits/Insufficient Control Power) and, 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) are the most prevalent as causal factors.

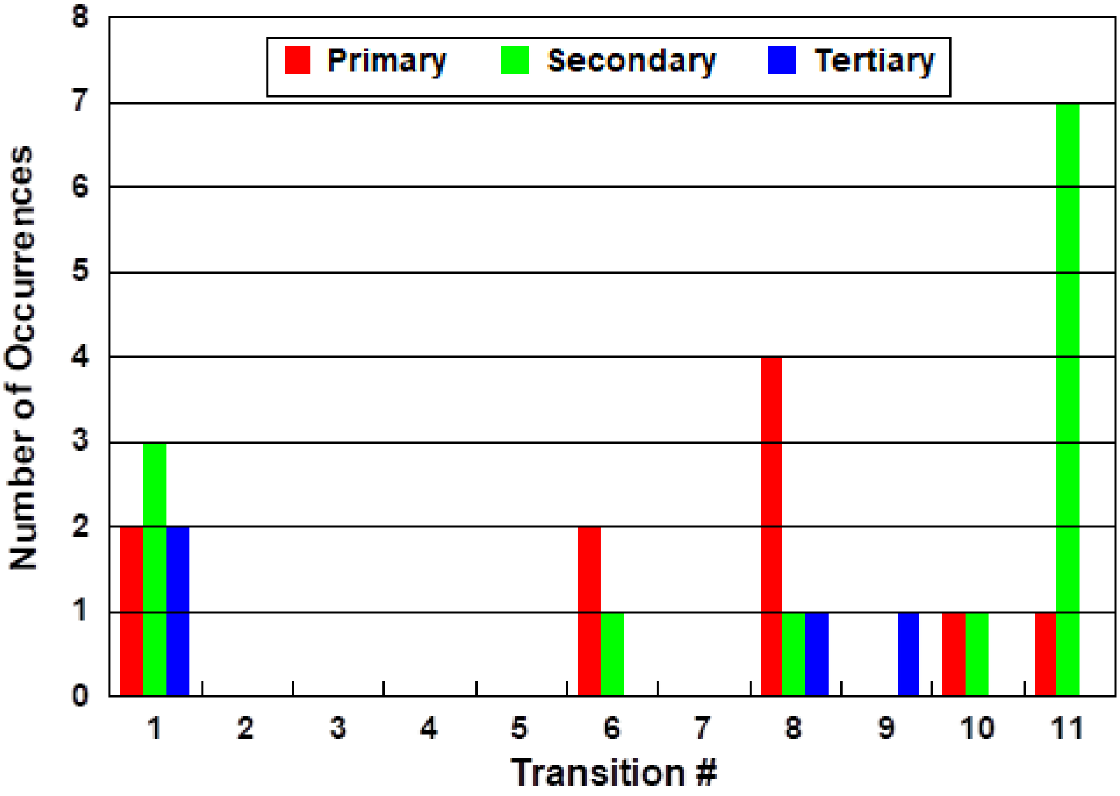


Figure 2: Key Transitions as Identified from TFTC Event Database

2.2.3 Crew Systems database

Table 4: Summary of Crew Systems (CS) database with Identified Transition/Mode Changes summarizes a subset of the events identified by CS, the complete set of which is provided in Appendix C. Not all examples from the database are included because they do not feature distinct transitions and/or mode changes. Several of these examples are common with the STI database discussed in Section 2.1 and Appendix A.

Table 5: Summary of CS Database with Identified Transition/Mode Changes

		Transition/Mode Changes		
Aircraft	**Date of Event**	**Primary**	**Secondary**	**Tertiary**
A330-200	6/1/2009	6	11	2
A330-200	6/23/2009	2	11	3
A330-600	2/3/2013	6	2	11
MD-11	7/13/1996	2	---	---
A330-300	3/13/2012	2	---	---

Aircraft	Date of Event	Transition/Mode Changes		
		Primary	Secondary	Tertiary
B777-200	8/1/2005	11	---	---
A320-200	4/8/1998	6 w/ icing	Failure	2
Swearengin-226	11/18/1988	3	---	---
B737-300	9/23/2007	11	2	---
A330-300	10/7/2008	11	---	---
A340	10/2/2000	2	3	---
A320-200	9/24/1998	6	3	---
A320-200	2/7/2001	6	11	3

The number of primary, secondary, and tertiary occurrences of a given transition and/or mode change (1 – 11) are identified in Figure 3. For this transport database of 13 events, the following observations are made:

- Primary:
  - The dominant primary causal transitions from this database are Transitions 2 (Response Type Changes) and 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions), with five occurrences (38% of cases) four occurrences for Transition 2 (31% of cases).
  - Transition 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) appears twice (15% of cases).
  - Transition 3 (Envelope Protections including prioritization, warnings, and blending) appears once (7.7% of cases).
- Secondary: With respect to secondary causal factors, Transitions 2, 3, and 11 are present.
  - Transition 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) appear three times (23% of cases)
  - Transition 2 (Response Type Changes) and Transition 3 (Envelope Protections including prioritization, warnings, and blending) each appear twice (15% of cases).
- Tertiary: For the tertiary causal factors, like the secondary factors, only Transitions 2, 3, and 11 are present.

  - Transition 2 (Response Type Changes) and Transition 3 (Envelope Protections including prioritization, warnings, and blending) each appear twice (15% of cases)
  - Transition 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) appears once (7.7% of cases).

- From the review of the CS database, Transitions 2, 3, 6, and 11 are the only transitions and/or mode changes that appear with Transition 2 (Response Type Changes) and Transition 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions) most prevalent as primary factors.

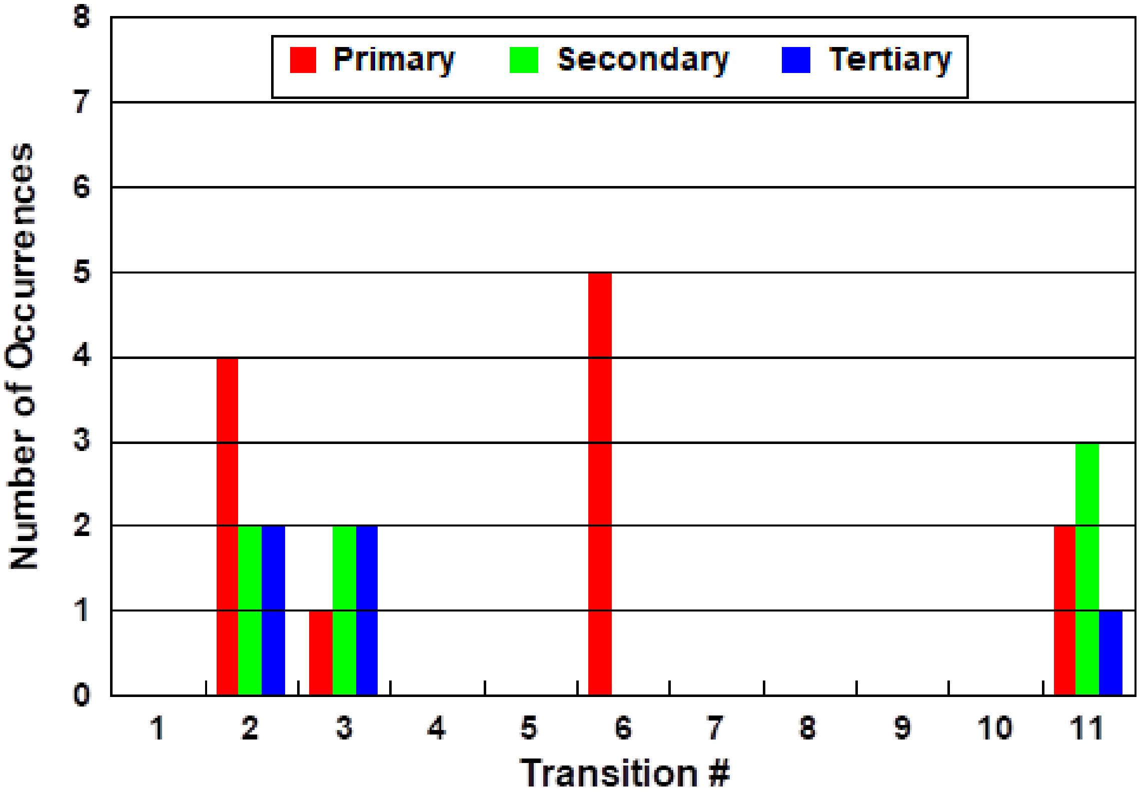


Figure 3: Key Transitions as Identified from CS Event Database

2.3 Summary

There were a total of 42 events in the combined databases when duplicates were removed,. The combined number of primary, secondary, and tertiary occurrences of a given transition and/or mode change are identified in Figure 4. The figure illustrates that Transitions 4 (Ground Mass to Air Mass including frames of reference used by FCS) and 5 (Radar Altitude vs MSL) were not found to be causal in any of the 42 events. For the remaining transitions and/or mode changes, the following observations are made:

- Primary:
    - Transition 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions) was found to be the most pervasive at 19% of cases.
    - Transitions 2 (Response Type Changes), 8 (Dynamic Behavior at Limits/Insufficient Control Power), and 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) next at 12% of cases.
    - Note that as a primary causal factor, Transition 8 only appears in the tiltrotor database, which points to the challenges associated with this configuration.
- Secondary:
    - Transition 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) at 26%.
    - Transition 2 (Response Type Changes) at 17% were found to be the dominant secondary causal factors.
- Tertiary: No transition has more than three appearances in the database though Transition 2 (Response Type Changes) and Transition 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) show here as well.
- When combining all factors, Transitions 2 (Response Type Changes), 6 (Wind and Turbulence Effects including Vortex Ring State and other rotor interactions), and 11 (FCS software challenges that include gain blending, logic trees, integrator wind-up, etc.) appear most and should be considered when assessing new aircraft fly-by-wire flight control designs.

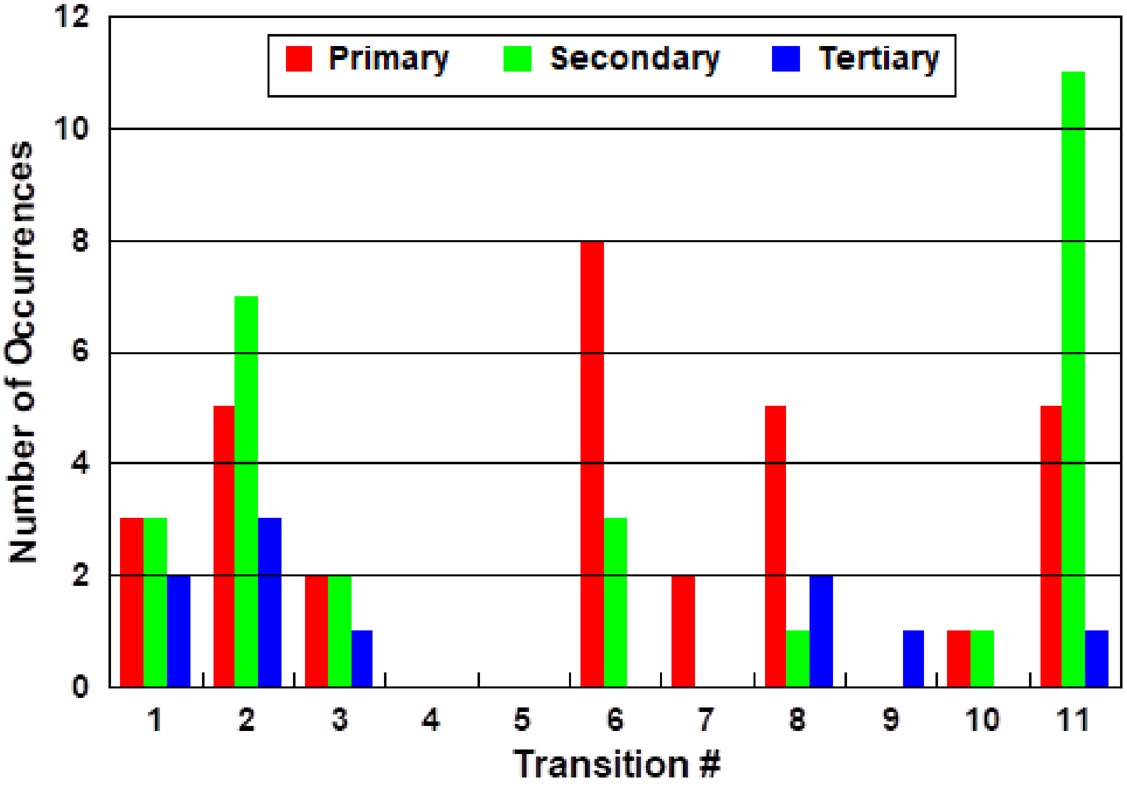


Figure 4:Key Transitions Identified from Combined Event Databases

2.3.1 Cumulative incident/accident analysis

It is interesting to note that the focus of the original investigation was on examining the contribution of flight control transitions to Fly By Wire (FBW) accident rates, which appeared in 42 accidents FBW accidents reviewed for tiltrotors, helicopters, and airplanes. While these areas warrant further examination through design oversight and flight test methods, it was informative to open the aperture of the investigation to the broader causal effects. As a result, the focus on FBW flight control transitions was diminished considerably.

The research found that the accident rates of mature designs of helicopters and fixed-wing aircraft do not necessarily reflect issues related to the evolution of FBW. Instead, they tend to reflect traditional issues representative of the vehicle types, and specifically, the layering of automation upon the aircraft that is not directly associated with indirect flight controls (FBW). In large transport aircraft, this is in general associated with the pilot interface with the Flight Guidance System (FGS), which makes sense in part since most flight time is done with the use of the FGS. Figure 5 illustrates the breakdown of all the FBW accidents from the accident reviews conducted, including tiltrotors, helicopters, and airplanes.

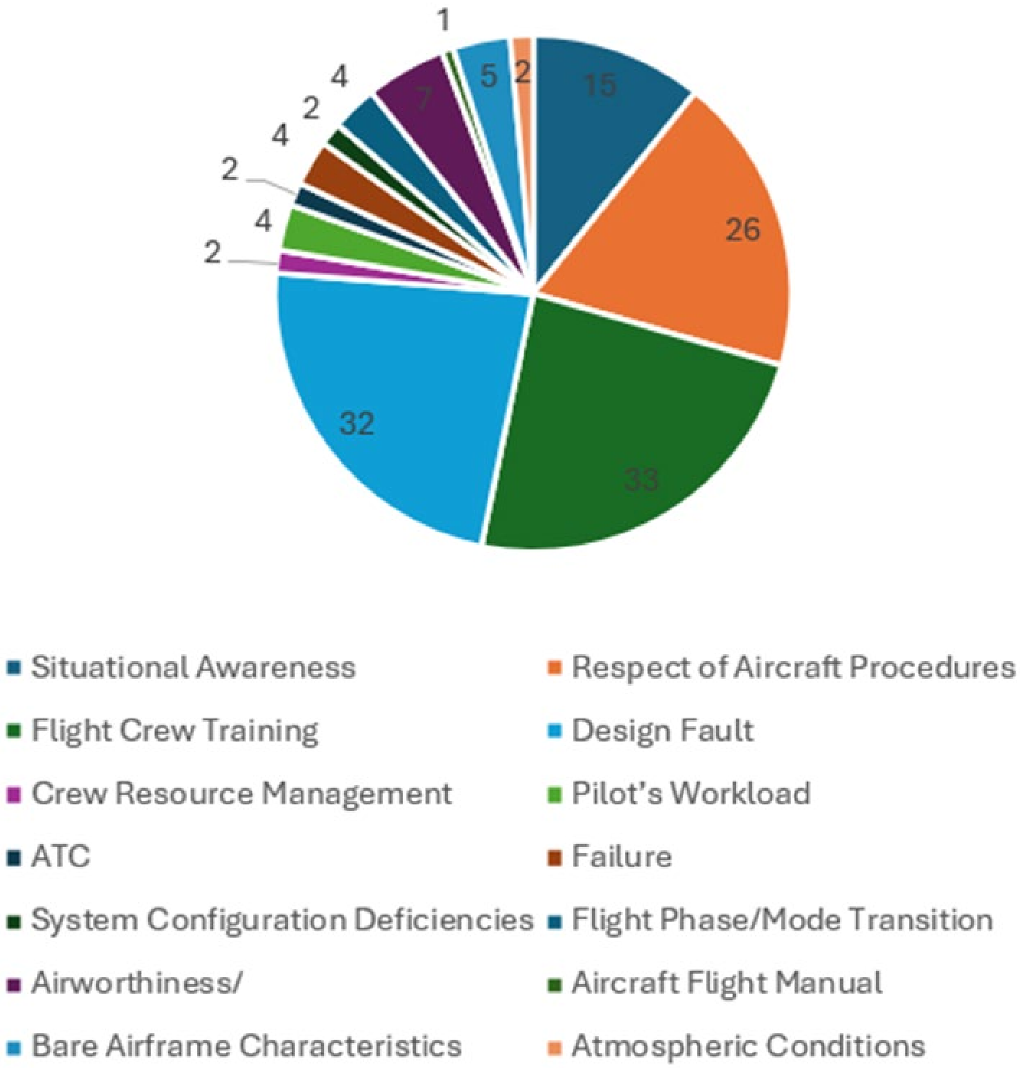


Figure 5. Cumulative Incidents/Accidents Critical Aspects

Critical factors common to most of the incidents/accidents were found to include mainly four categories. The top four shown in the legend of Figure 5:

1. Flight Crew Situational Awareness
2. Flight Crew Respect of Aircraft Procedures
3. Flight Crew Training
4. Design Fault

These four categories are more closely related to human decision-making, either in the cockpit or during the aircraft's design and development phases. The impact on flight safety related to flight crew understanding of the automation appears to be significant: the effect of most of the reported occurrences reviewed this report could have been mitigated by appropriate training and respect of the aircraft procedures by the flight crew. Mismanagement of the Automatic Flight Control System (AFCS) or FMS seems to derive from both the complexity of the systems and an inappropriate approach varying from that typical of conventional, un-augmented, and non-automated type of aircraft. Issues with situational awareness, respect for aircraft procedures, and flight crew training are the most recurring critical aspects related to human factor components.

The study of tiltrotor accidents, on the other hand, points to substantially different causes of mishaps as compared to the more mature traditional aircraft designs. From accident surveys discussed above, tiltrotors suffer from some immaturity of design in that the delicate balances of flight control design for the variable thrust vector. The requirement for an additional control of thrust vector in an axis-based control design burdens the pilot and requires substantial flight control guard-rails along with requiring extensive pilot training.

Additionally, some unique aerodynamic hazards associated with powered-lift designs were discovered early in development that had not been fully appreciated through modeling and simulation. Tiltrotor accident history argues that designers focus on making their vehicles robust against pilot error and look hard for unexpected material failures as the fleet ages. One can anticipate that new VTOL designs will encounter similar challenges, and as they mature, they will evolve toward accident rates akin to those of more mature fixed-wing aircraft, where many of the mishaps are related to the automation, as embodied in the FGS interface.

The data presented in this section indicates that new powered-lift aircraft suggests a potentially higher importance of HMI factors due to the various and novel inceptor architectures being developed and the flight crew's adaptation to them. Control allocation and related situational awareness can be considered a fundamental aspect of the system design phase, considering the redundant control surfaces and control effectors typical of powered-lift aircraft, along with the reliance on state-based flight control. Additionally, the issues described here must be addressed for the single-pilot powered-lift vehicle through rigorous stress testing of the design.

3 Flight Test Scorecard Concept

This section outlines the FTSC concept and approach. Specific examples are included to demonstrate the concept of application.

3.1 Overall concept

The FTSC is intended to support the efficient completion of both flight and ground testing, with a specific focus on verification of acceptable handling qualities. The following are key aspects of the Scorecard:

- Using the scorecard process allows the applicants to use data and results for both development and to share with the FAA, to focus on critical conditions to test.
- The scorecard is a test results artifact tracker. Using the scorecard allows the applicant to display the wealth of testing that has been performed to support certification.
- All results from the scorecard must be relatable to airworthiness requirements. This allows relationship traceability between the requirements and the subsequent proposed 'Supporting Data' and HQTEs, providing the necessary linkage.
- The airworthiness criteria should, if possible, be related to Means of Compliance (MOC) documents. Specific airworthiness requirements for powered lift aircraft are not available for this project; however, generic criteria may be used to demonstrate linkage.
- The scorecard can take inspiration from aspects of the 'Integrated Cockpit Evaluation' (ICE) plan developed by the FAA team and use this as a potential starting point for development.

The FTSC will demonstrate to the applicants the benefit of conducting HQTEs and show how performing/completing these will lead to gains in the certification process.

In addition, there are several assumptions regarding the use of the FTSC approach. The FTSCs:

- can be used to propose specific Supporting Data and HQTEs to be completed for specific airworthiness requirements.
- can be applied in the same way for both simulator and flight testing.
- can be used for nominal, and abnormal (failures, winds) conditions testing.
- will be used to display company testing conducted on a single page, with the ability to further inspect individual data, ratings, recorded comments, and recommendations.
- will not necessarily reduce flight testing but will provide guidance and support for selecting relevant tests to demonstrate compliance.

Based on these mission statements, requirements, and assumptions, the following concept is proposed for the scorecard:

- The top level of the FTSC will relate to the requirements, in particular the G2 Means of Compliance. This should include all requirements for certification. These would be “building blocks” of the FTSC, with additional blocks to be added with requirements.
- Within each of these blocks would be recommended HQTEs to be completed, along with supporting data that should be collected. These would be referred to as elements of the FTSC process.
- Within each block the applicant would be able to record specific testing and data as information that has been performed and conducted. These would be marked with key information. Both simulator and flight testing, at relevant airspeeds could be displayed. These would be elements selected.
- Behind each of the elements would be data stored as results. This data would show the primary results from the specific cases. For example, bandwidth testing would show bode plots, stability margins, or other pertinent data (to be defined in this project). HQTE analysis might show the aircraft position, control inputs, and desired/adequate performance tolerances/metrics.

In general, it is envisaged that the FTSC is an artifact tracker, which allows the applicant to display the testing that has been performed to support certification. In the ideal case, the FTSC could potentially support the applicant to complete certification testing more efficiently, through testing in a validated simulator, for example.

The FTSC could be valuable for certification testing if it offers benefits to the overall process and clearly links the Airworthiness regulations to the “mission task element” approach.

Top-level concepts for the FTSC include the following:

- It is likely, if not certain, that there will be multiple sets of FTSC templates. These templates will be for specific aspects to be tested, potentially separated by flight speed or vehicle condition. An illustrative example is a template based on flight speed: 1) Hover and low speed (lift provided entirely or significantly by thrust); 2) Conversion and transition (lift shared by thrust and aerodynamic surfaces, more or less equally); and 3) Forward flight (lift may be provided by thrust, such as helicopter main rotors, or may be provided entirely or significantly by aerodynamic surfaces).
- A useful FTSC should be multi-directional; it should allow the user to start at any point in the process and move in any direction – what is required for initial analysis, or what is required for final airworthiness testing.

- A user should be able to determine initial assessments from validated analytical models, from simulation, or from early flight testing, what will be required as a minimum level of documentation for FAA approval.
- The FTSC should be clear about the benefits of following the steps completely; or if the user chooses to skip some steps, what the consequences will be on the details and extent of the next level of testing.
- An applicant must be able to test for airworthiness compliance without using the Scorecard at all – but with the clear understanding that using the Scorecard will lead to a significant reduction in flight test hours (this is a long-term goal of the approach).
- In the initial application, the FTSC should increase efficiency in the certification process, convincing the certification authority that sufficient safety is demonstrated. Correlation between results from Supporting Data, HQTE in simulation, and HQTEs in-flight, should support this confidence.
- To the extent possible, the final product of the FTSC task elements should relate to specific requirements in airworthiness regulations. It is recognized that many may fall under the general umbrella of "controllability" or "stability" (for example, FAR 23.2135 and 23.2145 for general aviation airplanes), and this may be sufficient for future certification as well.
- A critical point: the Supporting Data and HQTE are intended to be a means of compliance, but not the only means, and there will be more testing required than that contained in the Scorecard of tests and tasks.

Figure 6 shows a diagram of the elements proposed for inclusion in the FTSC approach. Four categories are defined:

- Supporting Data – Simulation
- HQTEs – Simulation
- Supporting Data – Flight
- HQTEs – Flight

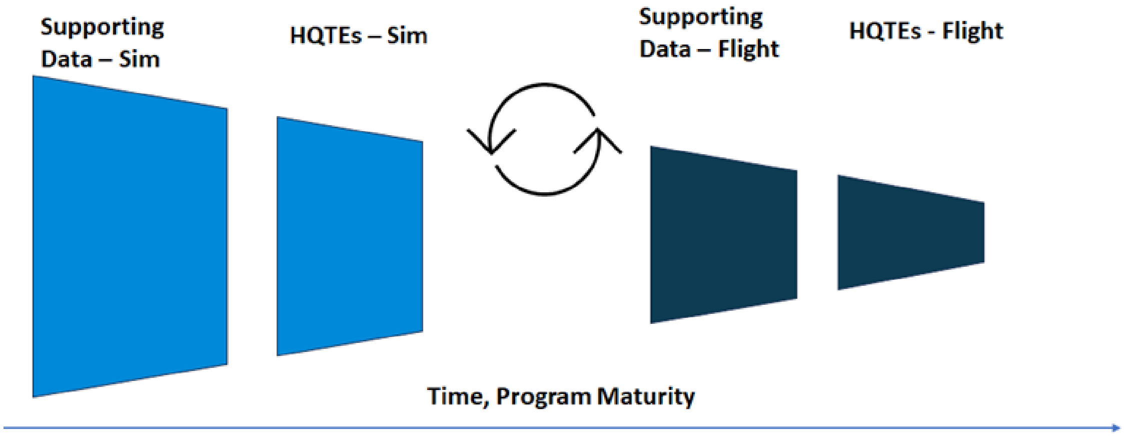


Figure 6: Flight Test Scorecard Approach

As also shown in the diagram, it is expected that the progression from simulation to flight, and from supporting data to HQTEs is a function of program maturity and time. Collecting supporting data from simulation tests is considered a precursor to piloted HQTEs. Additionally, it is also hypothesized that applicants will collect more data from the former than the latter, due to the ability to collect this data using simulations. This may also include batch mode processing and faster than real-time analysis. Blocks shown in the diagram are sized based on the amount of testing required. It is envisaged that dedicating time to simulation testing can reduce the required flight test points. Arrows represent continuous feedback between flight and simulation testing. Flight test results may be used to update simulation results, or findings in simulation may motivate specific tests in-flight test. If the FTSC proves to be successful in the goal of reducing dependency on flight testing, the expected supporting data and HQTE sets from flight will be further reduced from those in simulation. Reasons for a potential reduction in flight testing following the adoption of the FTSC may be due, but not limited to, the following considerations:

- Equivalency in results from simulation compared to flight data. An example would be high confidence in simulation model fidelity through check cases of Supporting Data, or equivalency in HQTE qualitative and quantitative metrics from simulation and flight testing.
- Conducting high risk points using simulation, using supporting data as additional justification. Examples would be failure testing or extreme operating conditions which may be replicated and tested in the simulator, with justification for equivalency and representative simulation fidelity.
- Modifications or 'tailoring' of HQTEs or supporting data based on operational limitations of flight testing. Agreement on changes to HQTEs in flight with respect to those used in

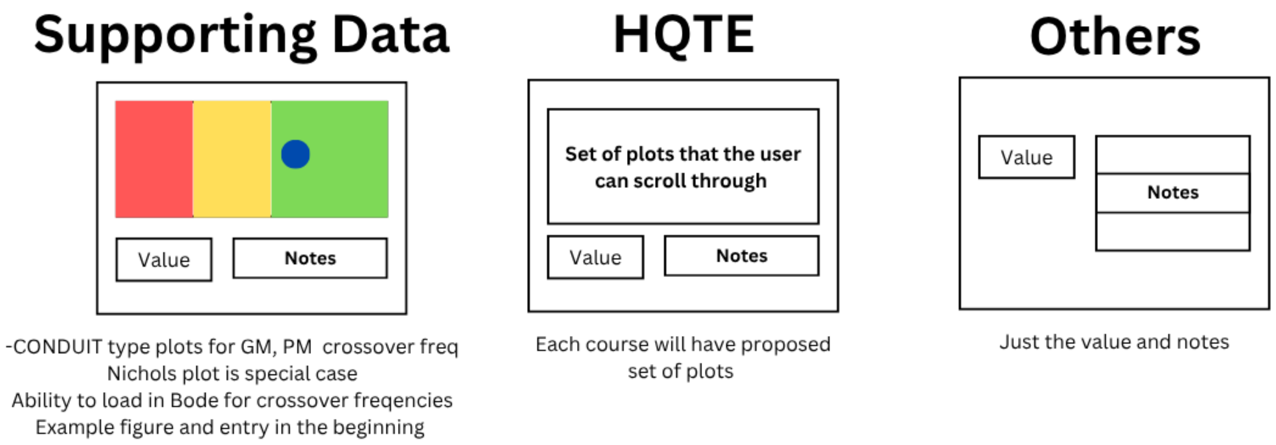
simulation, due to limitations agreed between the applicant and the FAA, and presented Supporting Data and HQTE data from simulation.

Other aspects may also be suitable to reduce the amount of flight testing to be performed when applying the FTSC process. One eventual goal of the FTSC is to aid the process of down-selecting or potentially reducing points intended for eventual flight testing.

During a certification program, the recommended approach is to work through the Scorecard process shown in the diagram first from left to right. The applicant should start by collecting supporting data from simulation. Next, where possible, HQTEs should be conducted in simulation. At this stage, both objective and subjective data have been collected. Following simulation testing, a subset of these tests should be performed in flight testing. Supporting data should be collected and compared with those from simulation. Discrepancies or unexpected results should be revisited through further simulations. Following confidence in supporting data from flight, a subset of the HQTEs recorded from simulation should be conducted. As with supporting data, discrepancies between HQTEs from flight test and the simulation should be explained.

If desirable, users of the FTSC may approach the testing differently, and perform more flight tests prior to simulation testing. Consequently, however, this may lead to a larger number of flight test points than when first using simulation.

It is proposed that the FTSC contains three types of information for the applicant/user to store: HQTEs, Supporting Data, and Others, as shown in Figure 7. The Supporting Data is intended to be shown with respect to the guidelines for parameters and data. These will be described in more detail in Section 4. This allows for an initial look at whether desired parameters are met. Supporting Data should be accompanied by notes, data, and configuration information. HQTE Data is intended to show whether these were completed to the desired standard, through a combination of notes (including pilot comments, etc..) and plots of completed performance. These should be simple to view and be accompanied by all necessary information to determine if the test points were successful. The FTSC should also include additional notes as required, to support the certification process.



Supporting Data

-CONDUIT type plots for GM, PM crossover freq
Nichols plot is special case
Ability to load in Bode for crossover freqencies
Example figure and entry in the beginning

HQTE

Each course will have proposed set of plots

Others

Just the value and notes

Figure 7: Examples of Data Included in FTSC

3.1.1 FTSC Inputs

The following are considerations for inputs to the FTSC:

3.1.1.1 Certification paragraph

The applicant/user should provide specific information on the certification paragraph for which they are testing.

3.1.1.2 Conditions

The applicant/user should provide information on the conditions for which they would like to receive credit for the given certification paragraph.

3.1.1.3 Flight modes

The applicant/user should provide information on the flight modes for which they would like to receive credit for the given certification paragraph. This includes information regarding the speed range, the configuration (e.g., powered-lift, thrust-borne), and the control responses to be used.

3.1.1.4 Configuration information

The applicant/user should provide information on any known configuration changes including transitions that may occur for the range of condition and flight modes for the given certification paragraph.

3.1.1.5 Proposed HQTEs

Applicants should propose any HQTEs they wish to use to demonstrate compliance

3.1.2 Output from FTSC

The following are considerations for outputs from the FTSC:

3.1.2.1 Recommended supporting data (Sim)

The FTSC will give an overall recommendation of supporting data to collect. This is a recommendation only and can be discussed between the applicant and the FAA. Recommendations Supporting Data is supported through a justification for its use.

3.1.2.2 Recommended HQTEs (Sim)

The FTSC will give an overall recommendation of HQTEs to conduct in simulation. This is an initial recommendation and can be discussed between the applicant and the FAA. HQTEs are supported through the justification for use for the specific paragraph.

3.1.2.3 Recommended supporting data (Flight)

The FTSC will give an overall recommendation of supporting data to collect in-flight based on the Inputs and Supporting Data. Recommendations Supporting Data is supported through a justification for its use. Reduction of Supporting Data from flight testing will be dependent on information regarding fidelity of simulation used to generate data. Currently, no standards of simulation model fidelity for certification have been agreed upon for powered-lift indirect flight control aircraft. As these standards emerge, additional input to the FTSC may include information regarding the range of validity of the simulation model, which can lead to an agreed upon process to down-select Supporting Data.

3.1.2.4 Recommended HQTEs (Flight)

The FTSC will give an overall recommendation of HQTEs to perform based on the Inputs and HQTEs performed in simulation. Proposed HQTEs are supported through a justification for use for specific paragraph.

3.1.2.5 Stored data

This set of data includes metrics, supporting data, HQTE data, and pilot subjective comments and ratings. The applicant/user will input information and data into the scorecard, which will be stored and can be accessed throughout the process, implementing the use of the FTSC as an ‘artifact tracker’ for all data, metrics, comments, and ratings collected as part of the certification process. It is intended that the information and data within the FTSC is stored and consistently updated as new tests and analysis are performed.

3.2 Proposed Handling Qualities Task Elements

A catalogue of HQTEs proposed for certification means of compliance demonstration are contained in Klyde et al. (2024), Section 1.1.3. These are categorized as ‘Precision’ and ‘Aggressive’ terms used to generally characterize HQTEs, akin to ADS-33 (U.S. Army Aviation and Missile Command, 2000). The concept and application of HQTEs are described in detail in Klyde et al. (2024).

HQTEs in Klyde et al. (2024) were initial proposals from dedicated testing and development, previous research, and experience. HQTEs are a blend of elements intended to replicate specific maneuvers expected during operation (e.g., landing tasks), to those related to stress-test the configuration or expose handling qualities cliffs (e.g., offset landing, pirouette).

Figure 8 shows a visual representation of the HQTEs with respect to Precision/Aggression level and flight speed. Selecting the correct range of applicability for the HQTE is critical for its use in the certification process. Each can only be used for the correct speed range/configuration for means of compliance demonstration.

Figure 8: Proposed HQTEs for Flight Test Scorecard Approach

Table 6. HQTE Abbreviations Shown in Figure 8

	Handling Qualities Task Element (HQTE)
Ac	Altitude Change
BaC	Bank Angle Capture

	Handling Qualities Task Element (HQTE)
DA	Depart Abort
FpC	Flightpath Capture
FR	Flightpath Regulation
Gt	Ground Taxi
HA	Heliport Approach
Hc	Heading Change
HT	Hover Turn
Lc	Landing CTOL
LR	Lateral Reposition
t	Landing VTOL
P	Pirouette
PaC	Pitch Attitude Capture and Hold
PCT	Precision ILS Capture and Track
Ph	Precision Hover
PoL	Precision Offset Landing
PP	Pull-up Push-over
RC	Altitude Rate Capture and Hold
RR	Roll Reversal
Sc	Speed Change
SL	Vertical Slope Landing
SoSp	Sum of Sines Tracking Pitch
SoSr	Sum of Sines Tracking Roll
TDc	Take off CTOL
TDv	Take off VTOL
Tr	Transition
VR	Vertical Reposition
WGo	Waveoff Go-around

As outlined in the FTSC process, piloted closed-loop tests are anticipated to follow analysis of Supporting Data, collected through simulation or flight-testing exercises. The new concept of

HQTE must first be understood as a subset of the various existing HQ demonstration maneuvers that are presently used in certification flight tests. Example demonstration maneuvers other than HQTEs that are still anticipated for certification involve the definition of flight envelope, where controllability or performance limits are anticipated to be reached. Examples of these requirements are described in Part 29-143 (2024) for transport category helicopters, but similar requirements will be used for the powered lift vehicles of interest in this guide. For these higher risk tests that explore controllability limits, such as low-speed all azimuth testing part 29-143 (b), (c), (d), the formal HQTE that requires multiple pilots in the evaluation process would not be prudent.

Other similar type HQ demonstration tests that evaluate controllability and maneuverability thresholds include VNE control margin demonstration (29-143f), engine failure demonstration (29-143e), as well as envelope protection verifications, or low power margin tests, where one can expect flight test techniques other than formalized HQTE. Such demonstration requirements are similarly called for in ADS-33E-PRF section 3.1.15 “Rotorcraft Limits”, and in sections 3.71, “failure of a flight control system” and 3.7.2 Engine failure, as tests separate from HQTE (Blanken, Hoh, Mitchell, & Key, 2008).

In summary, an HQTE is meant to supplement legacy flight test techniques, and may be needed where the traditional flight test specified for airplanes (i.e., AC23-8 and AC 25-7) are no longer appropriate, due to the specifics of the flight control system (e.g., stick force per velocity plot may not be relevant in an FBW design with a speed hold function.)

3.3 Software solution

This section details the flexible software solution that has been developed to demonstrate the application of the FTSC approach. This is shown with some examples of its use.

3.3.1 Flight Test Scorecard software application

The FTSC concept introduced in 3.1 has been developed into a software application to satisfy the requirement of displaying data on a single page. To store data and results, the software application can index appropriate results, pilot comments, and observations.

The FTSC application has been developed with Python and the PySide6 Python module which provides access to the Qt 6.0+ framework. Python is developed under an open-source license, known for its ability to visualize data and perform data analysis. Applications developed with Python are compatible with multiple platforms. The Qt framework is originally a C++ framework used for application development for graphical user interfaces. The PySide6 module gives access to the graphical user interface framework for a Python application. A Python and PySide6 application suit the FTSC mission as a simple, graphical user interface to store and display data. The FTSC will track vehicle testing from concept to flight test in conjunction with the emerging Flight Test Guide.

3.3.1.1 Data management

A significant feature of the FTSC application would be data management. Although this application is independent of MATLAB, compatibility with MATLAB data formats is still desired. To ensure that the Python application is robust enough to handle multiple data formats, three test applications were developed to write and read data from .mat, .csv and .json file formats. The application currently focuses on implementation using .json files as the main file format. Compatibility with the other file formats is possible and remains a future development goal.

3.3.2 Project architecture

3.3.2.1 Metrics

The application configures which metrics the FTSC will show by looping through a metrics folder in the application configuration folder. The metrics folder will include a .json file for each metric, the .json files created via an initialization file which the user can edit to either remove, alter, or add metrics. Each metric file includes information such as how the metric is displayed in the app, its name, description, etc. The application loops through this metrics folder and initializes as a list of metric objects from the metric class in the application to keep track of each metric. This class-based structure is a feature to allow for easier modification of metrics for both developers and users.

3.3.2.2 Template filters

The application allows for the user to update the “template” of the task card, modifying which metrics are required via filtering with certification paragraphs, speeds, and configurations. This feature of the FTSC will guide the users in completing specific metrics and tests for certain MOC paragraphs, speeds, and aircraft configurations. For the paragraphs, a .json file for each paragraph exists in the application configuration folder. The .json file includes a Boolean value for each of the metrics which will indicate whether a certain metric is applicable to the selected paragraph. Similarly, .json files with the corresponding information for which metrics are applicable for certain speeds and configurations exist. In the application, the user will have the ability to disable and enable certain filters. The UI will update accordingly, showing the user which metrics are applicable based on the activated filters.

3.3.2.3 Project folders

The files would be saved in a folder system on the same level as the application. A new project folder is created for each project the user creates. Upon creating a new project, a project directory is created with the following directory structure:

- Project Directory
    - Metric Data: Folder including subfolders for each metric. Users will upload the entries for the metrics into these subfolders.
    - metric_status.json: File that stores the current progress of each metric.
    - project_config.json: Stores which filters are activated, and which filter type is selected. For example, this file stores the paragraph that the current project is created for.

3.3.3 Application development

When opening the application, the user will see the project template preview screen with the project manager menu on the left (see Figure 9).

The template for the design includes a 'Project Manager Menu' and a "Template Preview". The former displays the selected paragraphs, flight conditions and configurations. The latter shows all supporting data and HQTEs recommended, those included in the application. The template shows both Supporting Data/HQTEs from simulation and from in-flight.

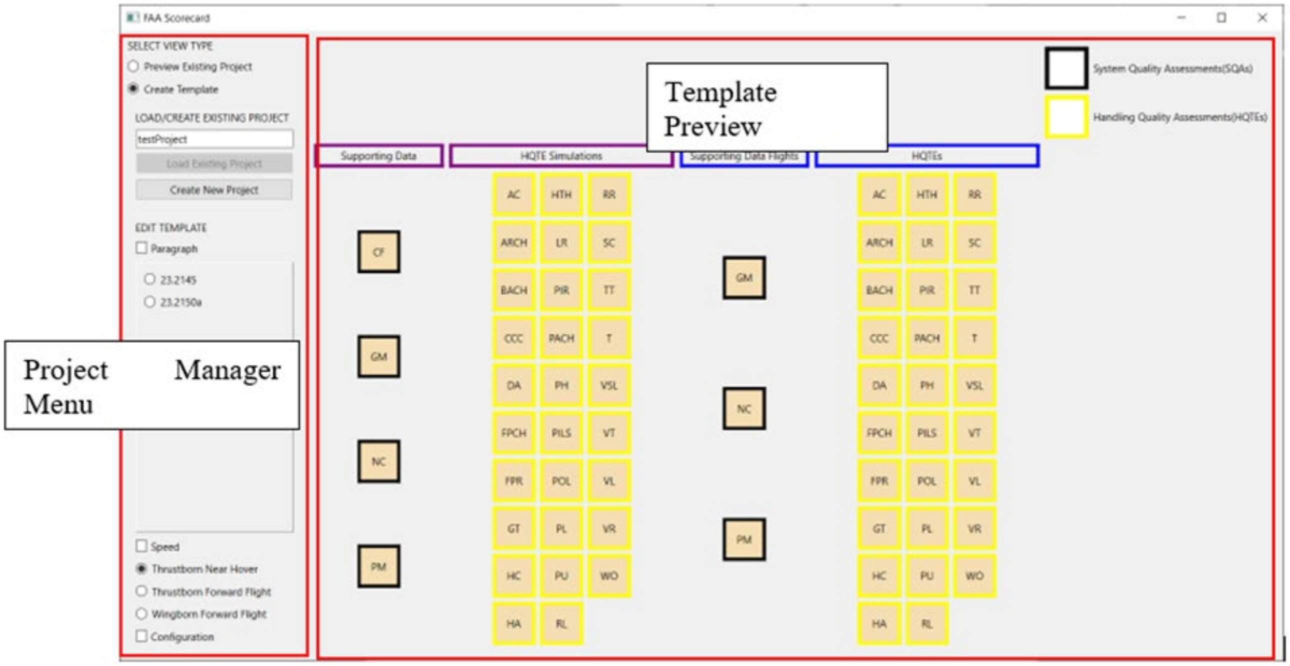


Figure 9: Project Creation and Preview Menu

Note that in the template view, there are multiple buttons that are labeled with truncations of the metric names. Each button represents a metric, and the full name of the metric can be viewed as a tooltip by hovering over the metric (see Figure 10).

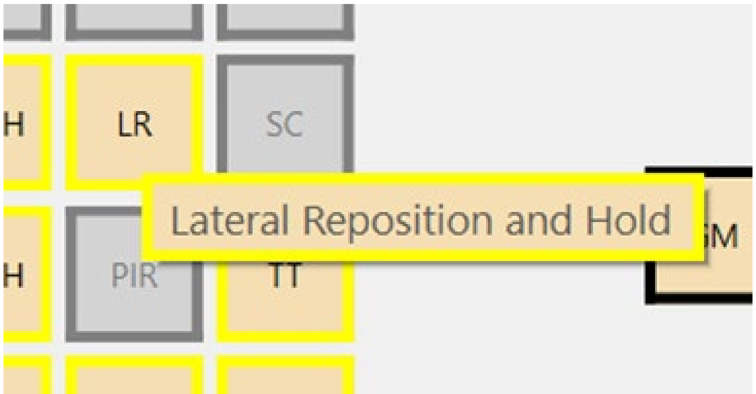


Figure 10: Metric Button Tooltip

During project creation, the user will have the view type selected as “Create Template”. To edit the template, the user can select which filters they would like to apply to the task card by using the checkboxes in the menu (Figure 11). For activated filters, the user will then choose which filter -for example, which MOC paragraph- is desired. The task card preview portion will update accordingly by greying out the proper metrics. Once the desired template is created, the user can press the ‘Create New Project’ button with a unique project file name in the input box. This will create a new project folder with the specified filter settings.

SELECT VIEW TYPE
○ Preview Existing Project
● Create Template

LOAD/CREATE EXISTING PROJECT
testProject

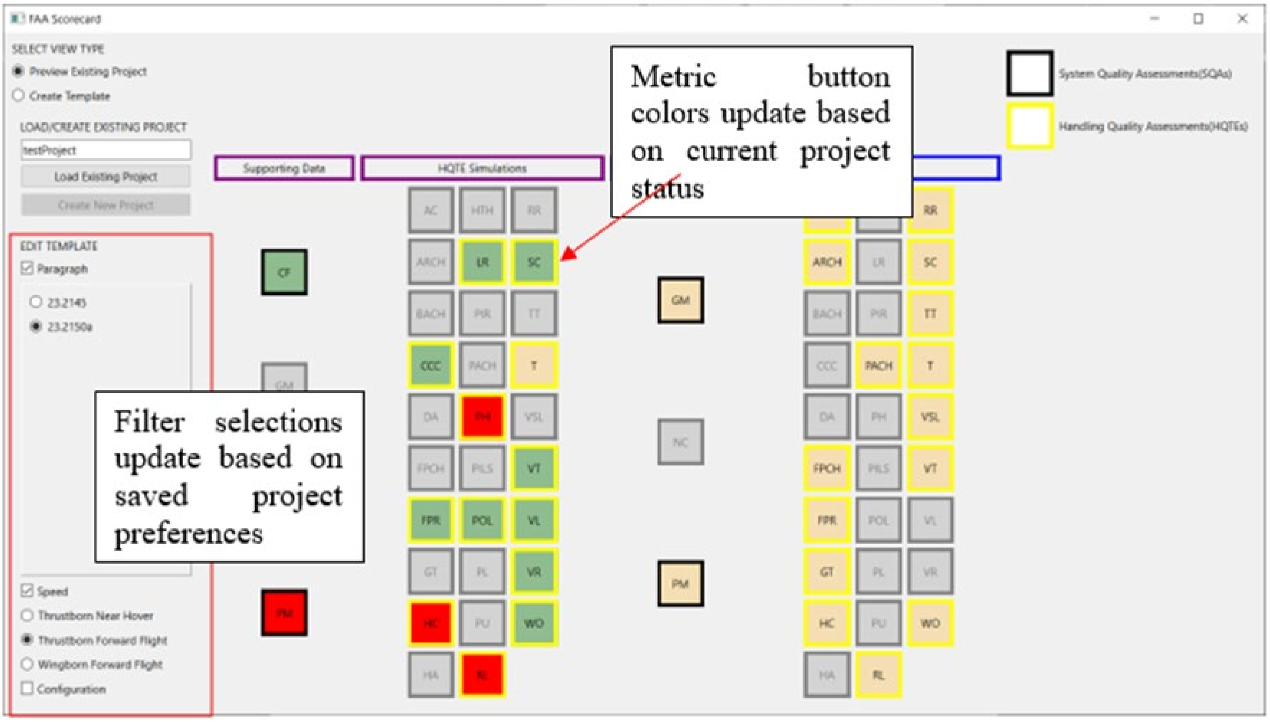
EDIT TEMPLATE
☑ Paragraph
● 23.2145
○ 23.2150a
☑ Speed
● Thrustborn Near Hover
○ Thrustborn Forward Flight
○ Wingborn Forward Flight
☐ Configuration

User selects and activates filters to update the task card template

Figure 11: Filter Selection and Template Preview

Selecting specific filters will activate filters to show the relevant Supporting Data/HQTEs to be demonstrated, including information whether they have been completed.

On this screen, as shown in Figure 12, the user can also preview an existing project folder by selecting the “Preview Existing Project” view type. If an existing project folder name is in the input box, the Scorecard preview populates with the status of the project as indicated by the color of the button (green for complete, red for failed, yellow for to do). The template options will also update based on the existing project’s selected templates.



FAA Scorecard

SELECT VIEW TYPE

● Preview Existing Project

○ Create Template

LOAD/CREATE EXISTING PROJECT

testProject

EDIT TEMPLATE

☑ Paragraph

○ 23.2145

● 23.2150a

☑ Speed

○ Thrustborn Near Hover

● Thrustborn Forward Flight

○ Wingborn Forward Flight

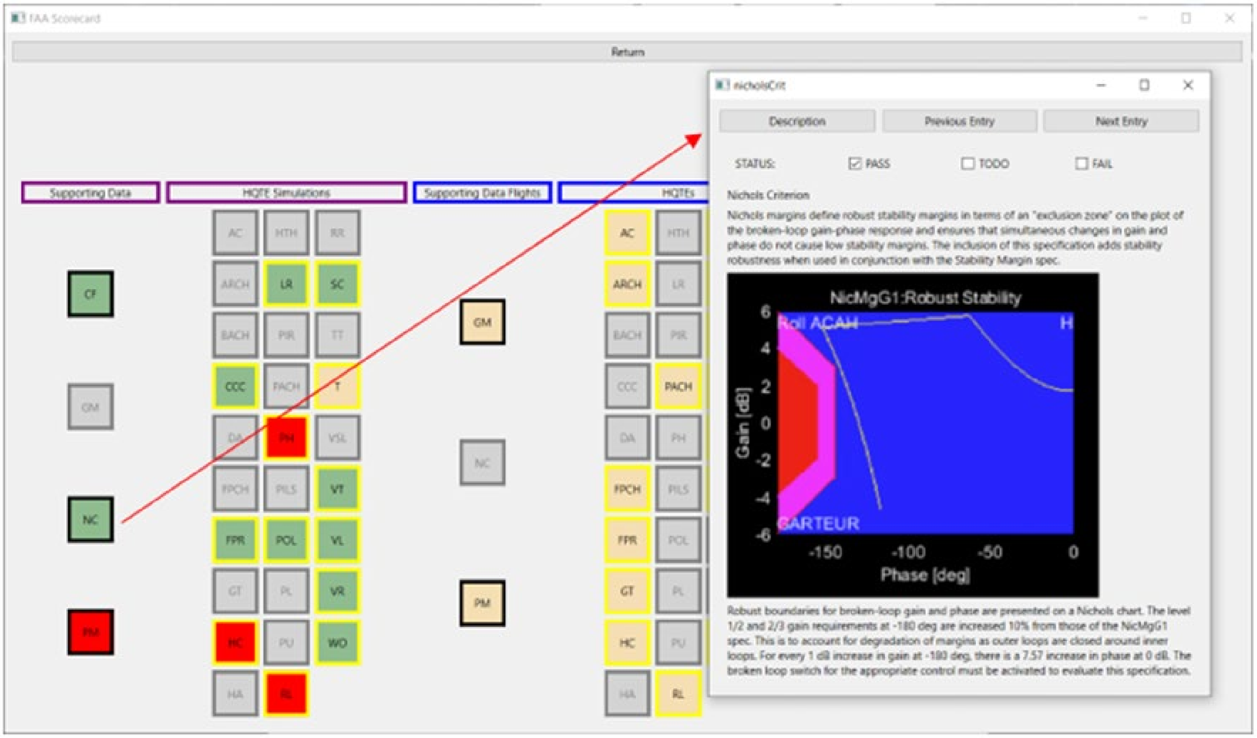
☐ Configuration

Metric button colors update based on current project status

Filter selections update based on saved project preferences

Figure 12: Existing Project Preview

Once the user is satisfied with the preview, pressing “Load Existing Project” or “Create New Project” will take the user to the main Scorecard view. Here, the users can click on the metric buttons to bring up a sub-window for the metric. As seen in Figure 13 the sub-window will initially show a description and example plot for the metric. Furthermore, the user can set the status of the metric here.



STATUS: ☑ PASS ☐ TODO ☐ FAIL

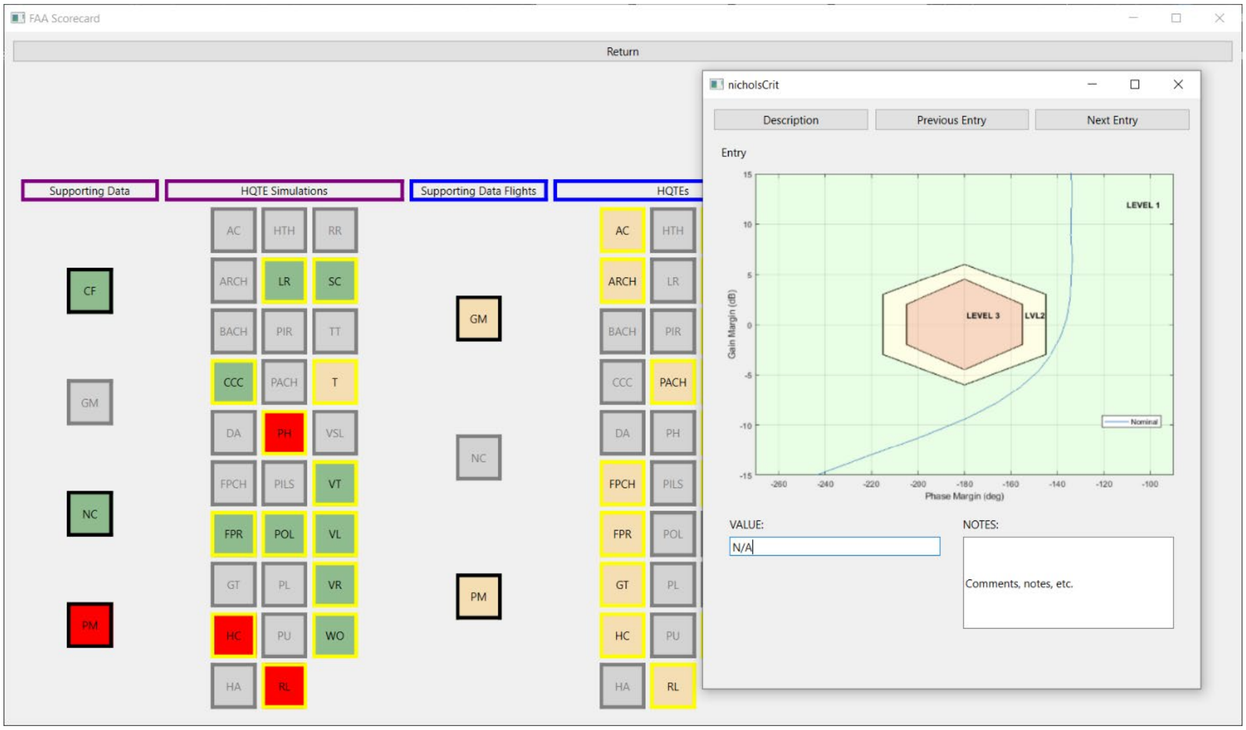
Nichols Criterion

Nichols margins define robust stability margins in terms of an "exclusion zone" on the plot of the broken-loop gain-phase response and ensures that simultaneous changes in gain and phase do not cause low stability margins. The inclusion of this specification adds stability robustness when used in conjunction with the Stability Margin spec.

Robust boundaries for broken-loop gain and phase are presented on a Nichols chart. The level 1/2 and 2/3 gain requirements at -180 deg are increased 10% from those of the NicMgG1 spec. This is to account for degradation of margins as outer loops are closed around inner loops. For every 1 dB increase in gain at -180 deg, there is a 7.57 increase in phase at 0 dB. The broken loop switch for the appropriate control must be activated to evaluate this specification.

Figure 13: Metric Sub-window Description Page

If entries exist for the metric, the user can then use the buttons at the top to navigate through the entries. The entry view consists of an area to preview the plot provided by the user for the entry, the value of the metric if applicable, and comments and notes on the entry (see Figure 14).



VALUE: N/A

NOTES: Comments, notes, etc.

Figure 14: Metric Sub-window Entry Page

Each selectable box can hold a large amount of data collected from flight and simulation. This data should be labelled with comments, with pass/fail information with respect to requirements stored for view.

3.4 Simple example approach paragraphs

The following section describes how the FTSC can be used in practice for specific certification aspects. Two examples of the approach are shown; the first is to select a specific performance aspect whereas the second is more generalized to a specific example certification paragraph.

3.4.1 Controllability and maneuverability

The example shown here is for Title 14 Code of Federal Regulations §27.143 (2024). A significant proportion of handling qualities testing is likely to be linked to controllability and maneuverability (§27.143) descriptions. For rotorcraft, this is currently given in §27.143. It is believed that many of these aspects are relevant for powered-lift aircraft.

The controllability and maneuverability paragraph requires demonstrations through the flight envelope with weight and rotor RPM selected by the applicant, critical center of gravity and calculated altitude. The controllability must be demonstrated in various flight conditions (including turning flight) and at wind velocities from zero to 17kts, from all azimuths. This is to demonstrate that the aircraft can be operated without loss of control on or near the ground (such as for takeoffs and rearward flights.

To illustrate the use of the FTSC and to simplify the application, it is useful to break down §27.143 into smaller sub-requirements. These can be divided in several ways, including flight speed, operating condition, vehicle configuration, and flight axis. An intuitive way to divide the paragraph is to isolate each control axis: pitch, roll, yaw, heave controllability. Each of the control axes must be considered across the flight envelope, for different control modes, flight conditions, and vehicle configurations. Examples include controllability in gusts/winds from all-azimuths, control mode switching and modes.

An illustrative example is for the yaw controllability in calm conditions, and in the low-speed envelope.

3.4.1.1 Supporting data

Requirements should be given and met for all supporting data provided. Users will utilize the Scorecard interface as described in Section 3.3.3 to provide linear stability margins (gain and phase margins, phase and gain crossover frequencies) for the yaw axis, trim control positions for yaw command (for tests in wind, this will be required for all-azimuths), and bandwidth for yaw axis. All should be provided for all selectable control modes. Additional selections can be made for open-loop response data from step and impulse control input, for varying magnitudes of input. Off-axis responses (pitch/roll/heave) for step/impulse control inputs. Criteria or requirements not met should be discussed, with explanations and justifications provided.

In addition, where applicable, users can provide block diagrams of the control systems, including identification of broken-loop and open-loop points for stability analysis. Information relating to configurations, assumed/simulated ambient wind speeds and directions, modes of operation should be included. The data may be obtained from a validated mathematical model of the aircraft (method for validation TBD).

List of supporting data for Yaw Controllability (Calm conditions) includes:

- Yaw axis stability margin (all control modes)
- Yaw bandwidth (all control modes)
- Trim control positions (low speed envelope, yaw control)
- Open-loop response – yaw step (varying magnitude, all control modes)
- Open-loop response – yaw impulse (varying magnitude, all control modes)

- Pitch off-axis response, from open-loop inputs
- Roll off-axis response, from open-loop yaw inputs

3.4.1.2 HQTE

HQTEs should be selected to exercise the yaw axis controllability, including the observation of any cross-axis responses from the primary axis. The HQTE should be completed using all applicable flight control modes where the applicant is seeking credit. Articles supporting demonstration of no unsafe HQ issues include pilot comments and subjective ratings, along with sufficient flight data to demonstrate performance requirements of HQTE were met (or not met) and the vehicle state information, ensuring margins of controllability etc. For tests to confirm acceptability in winds, HQTEs in varying conditions may be required. Discussions as to the performance tolerances, required handling qualities ratings, and general practices for this testing are still ongoing.

The Hover Turn and Pirouette HQTEs are recommended for yaw controllability. As with most HQTEs, these are multi-axis tasks, where the pilot is required to manage performance tolerances in all four primary control axes. Both HQTEs are recommended, as they exercise the yaw controllability in different ways. Further HQTEs are available where heading is held constant (e.g., lateral reposition, precision hover), which may be used to further demonstrate the controllability of the axis. However, for these HQTEs, no disturbance in this axis is required and therefore, these HQTEs are not considered as appropriate as the two selected.

The Hover Turn HQTE requires a turn-around, either about the pilot's center of gravity or aircraft's center of gravity (applicant choice), through a given heading. It is required to maintain the longitudinal/lateral position to a point on the ground (depending on the reference used) when performing the turn. Following the turn, the pilot is required to arrest the turn rate and stabilize within a given tolerance. This HQTE tests both the response to a moderately aggressive yaw control input and the ability to stabilize the yaw motion. It also confirms that the pilot can control any off-axis response induced by the input of the yaw command, in roll, pitch, and yaw.

The Pirouette HQTE requires following the circumference of a circular path, with a specific tolerance. During the completion of the HQTE, the pilot is required to point the aircraft nose towards the center of the circle. This HQTE tests the pilot control of the yaw with smaller corrections and tracking. The control inputs required are more sustained than for the Hover Turn HQTE.

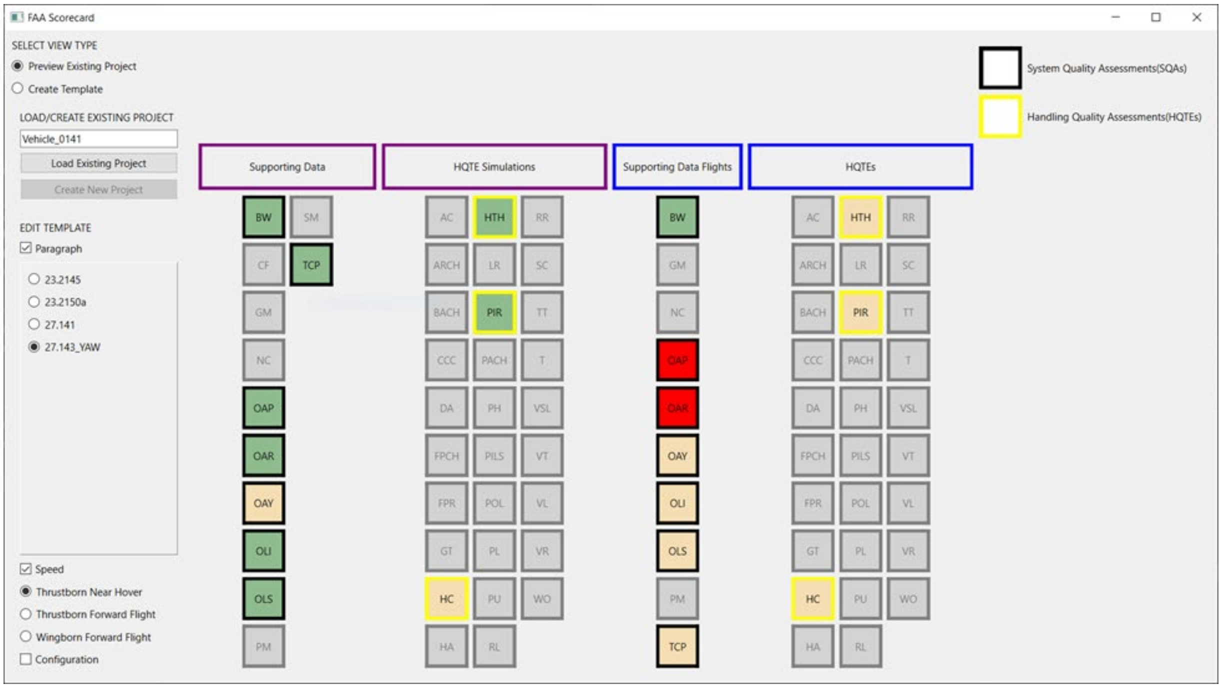
Completing these HQTEs in a validated simulation may allow for a reduced scope of testing in-flight and/or additional 'tailoring' of the performance tolerances (to be discussed later in this report). One example may be testing in turbulence or winds. If testing is conducted in a validated simulator, and supporting data is used to support this, demonstrations in all-azimuth winds may be limited to flight simulation, with spot checks conducted in-flight, given appropriate conditions. The same may be applicable for testing a different altitude, temperatures, or vehicle weight and CG.

List of HQTEs for Yaw Controllability (Calm conditions) includes:

- Hover Turn HQTE (all control modes)
- Pirouette HQTE (all control modes)
- Data displaying flight data against defined performance tolerances
- Data displaying pilot control activity and controllability margins

3.4.1.3 Scorecard view

Figure 15 shows the example FTSC for the §27.143 example outlined above. As per previous examples, Supporting Data and HQTEs are separated for simulation and flight test. The template shows all applicable Supporting Data and HQTEs for the aircraft. Greyed out boxes are not applicable to the specific paragraph, filtered by the search bars to the left side. Boxes highlighted in green signify example completed tests, which pass requirements. Boxes highlighted in yellow are to be completed, data not yet available. Boxes highlighted in red signify completed tests, which either do not meet requirements or are flagged for further investigation and discussion.


FAA Scorecard

SELECT VIEW TYPE
● Preview Existing Project
○ Create Template

LOAD/CREATE EXISTING PROJECT
Vehicle_0141

EDIT TEMPLATE
☑ Paragraph
○ 23.2145
○ 23.2150a
○ 27.141
● 27.143_YAW

☑ Speed
● Thrustborn Near Hover
○ Thrustborn Forward Flight
○ Wingborn Forward Flight
☐ Configuration

Figure 15: Example of FTSC view for §27.143

4 Supporting Data

This section expands in detail on which criteria and methods may be used in conjunction with the FTSC approach, including aspects for consideration of SQA, FQA (i.e., Supporting Data), HQTE, and AQTEs. Examples will give a full overview of available analysis techniques and methods of application.

Examples of Supporting Data include:

- Flight test methods that provide the data required to evaluate indirect flight control systems (FCS).
- Determine system stability, stability margins, and other measures of system performance, as well as predictive measures of flying qualities and handling qualities.
- Used for system identification to support modeling and simulation.
- Examples include stick raps, steps, doublets, 2-1-1, 3-2-1-1, frequency sweeps, multi-sines, and dwells.

The following sections give an overview of various supporting data that are proposed for use with the FTSC process.

4.1 Frequency sweeps

From the developed HQTE test guide by Klyde et al. (2024), frequency sweeps are defined as critical to both understanding the response of the vehicle and to validating simulation models, using techniques such as system identification. Frequency responses characterize the system, with results used to determine overall qualities of the vehicle, which may influence handling qualities. This includes phase information, delays, and system gain, for example. Frequency responses can also be used to generate linear models of aircraft through system identification techniques, including extraction of vehicle modes and aerodynamic derivatives. There are a range of frequency sweeps that can be conducted to support certification testing. For example, command path frequency sweeps can be used for model validation, bandwidth-phase delay, and system stability and loop closures.

4.1.1 Command path frequency sweeps

These are pilot or computer-generated sweep that allow for the generation of frequency domain Bode plots for the following:

- The complete closed-loop response across the command path
- Intermediate command path elements:
    - Feel System
    - Closed-loop controller
    - Actuator
    - Bare Airframe

Here, frequency sweeps are called out as they have been used traditionally for rotorcraft testing. Other valid signals for wide-band frequency identification include multi-sines (a well-defined multi-sines input can be used for simultaneous multi-axis identification). These will only be computer generated inputs.

For the purposes of the FTSC and Supporting Data, it may be beneficial to exemplify both types of frequency sweep input.

4.1.2 Injected frequency sweeps

- In flight testing, there is often a built-in test capability to inject frequency sweeps into the system loop structure

- Most typically, these computer-generated sweeps (or other test signals) are injected at the actuator.
- This allows for system identification of the actuator and bare airframe, important for model verification and validation, but it does not allow for predicted FQ, HQ, or system parameters to be directly measured.
- Injected sweeps may require additional corrections to ensure that attitudes do not exceed agreed values. This is particularly the case for rate-type commands, where low frequency inputs must be reduced amplitude, to ensure no excessive build-up of rates.
- For injected sweeps, it may be necessary to apply corrections to the off-axis responses. This can be achieved through a low frequency control system to apply corrections or through additional input from the pilot. For both cases, power must be low to ensure clean frequency sweep in on-axis.

4.1.3 Manual frequency sweeps

- Manual frequency sweeps do not require any specific software modifications to perform testing. As they are flown by a pilot, they may also provide information relating to the inceptor feel system, not necessarily exercised through injected sweeps.
- It may be easier for the human pilot to stabilize off-axis response, particularly at low frequencies, avoiding specific software modifications required to achieve this.
- Sweeps at high frequencies may be difficult for the pilot to achieve, due to the feel system and specific flight limitations.
- Unlike automated frequency sweeps, manual sweeps include characterization of the hardware from pilot control inceptors and any other elements in the system prior to software injection point for automated sweeps. This is necessary when determining overall bandwidth relating to pilot control with inceptors.
- It is important to ensure that power of control inputs in the off-axis remains small to obtain clean frequency sweeps. For manual sweeps, the pilot may be required to correct off-axis responses with small, low frequency control inputs.

4.1.4 Frequency sweeps and approximations

- Multi-sines should be provided as a computer-generated input.

- Orthogonal optimized multi-sines can be used to provide simultaneous multi-axis excitation, which can improve test efficiency.
- If it is not possible to generate frequency sweeps and/or computer-generated multi-sines are not possible, then 2-1-1, and 3-2-1-1 inputs can be used as approximations
- The transformation to the frequency domain will likely provide incomplete measures of all desired parameters, especially those measured at higher frequencies such as Phase Delay.
- These inputs can also be used as part of a time domain model verification and validation process.

4.2 Bandwidth/phase delay

The bandwidth criteria, used in U.S. Army Aviation and Missile Command (2000), is intended to characterize the small amplitude responses of the aircraft, using data collected from frequency sweeps. Both injected and manual sweeps can be used to generate data, but to capture the total system response to pilot input, manual sweeps at the inceptor should be used. The associated criteria for bandwidth and phase delay were determined through test and evaluation of rotorcraft and presented in ADS-33. These boundaries are generally widely accepted as appropriate; however several proposals and recommendations have been considered since introduction. As with most criteria in ADS-33, boundaries are presented based on aircraft type, flight speed, and axis. For some conditions, the criteria are not appropriate, and no boundaries are presented. Additionally, ADS-33 defines boundaries only for rate and attitude command response types. The consideration for outer-loop bandwidth is not included.

Measured parameters include:

- Neutral stability frequency
- Phase bandwidth frequency (rate or attitude response type)
- Gain bandwidth frequency (rate response type)
- Change in phase between neutral stability frequency and 2x that frequency

Bandwidth Frequency and Phase Delay are determined from the above measured parameters (Pitch, Roll, and Yaw attitude). Independent of control response type, the bandwidth is always calculated using the command to attitude response. This relates to the theory that the pilot primarily uses attitude information to control the aircraft, regardless of response type. For attitude response type systems, the phase bandwidth is always used for the calculation of bandwidth; this is the frequency where the phase between the input and attitude is -135°, a 45° margin to the point of instability. For rate command systems, the gain bandwidth should be used as bandwidth, if this is lower than the phase bandwidth. This is calculated as the point where the gain is 6dB greater than the gain at the point where phase reaches instability (-180°). This is shown in Figure 16 from Blanken et al. (2008).

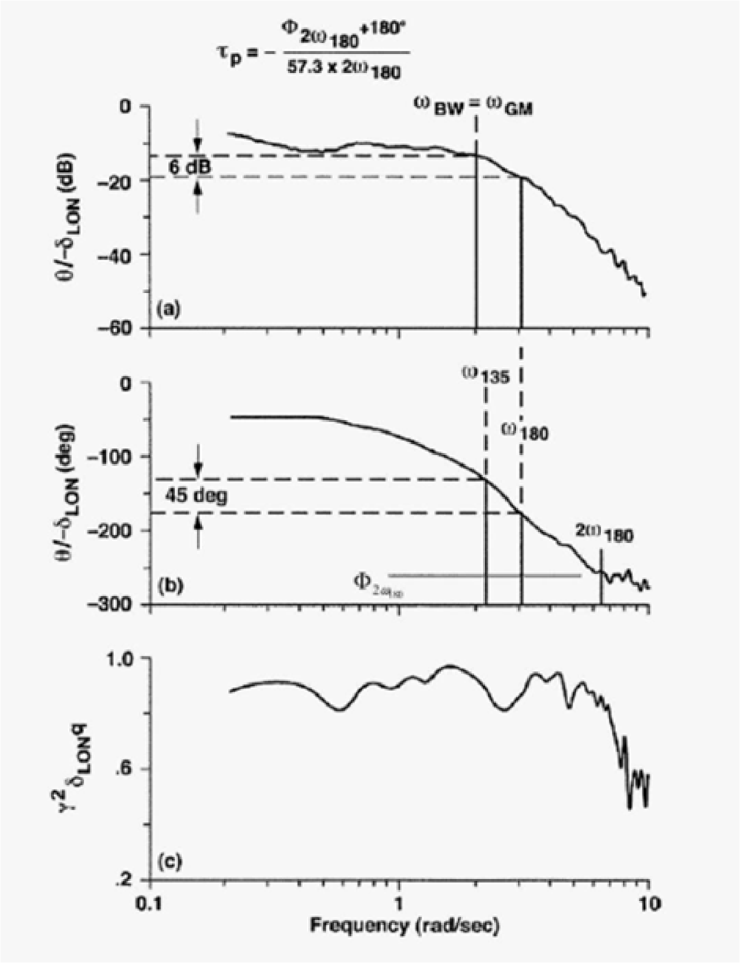


Figure 16: Calculation of Bandwidth-Phase Delay Metrics (Blanken, Hoh, Mitchell, & Key, 2008)

Although for attitude command systems, the phase bandwidth is always used; gain bandwidth should also be calculated to determine whether PIO tendencies may exist. It is noted that if gain bandwidth is less than phase bandwidth, the aircraft may be prone to PIO.

For systems with TRC or Acceleration Command Systems, Bandwidth and Phase Delay checks can be made on the attitude and/or rate inner loops, if the controller is structured in a suitable form. Ongoing work is currently being conducted to determine suitable boundaries for velocity and position loops, for bandwidth calculation. Encouraging results have been presented from studies with scaled unmanned systems (Ivler & Geyer, 2024).

4.3 Stability margins

Stability margins, specifically gain and phase margins, are key criteria to determine the overall control system stability. One benefit of stability margins is that they can be conducted at different points in the control loop, to determine stability through the system. Stability margins are used in current certification efforts, therefore suited for future Supporting Data for powered-lift. Stability margins are considered key criteria in flight control design. Usually, they are required for the safety of the system.

- For a given control system this piece of supporting data provides information on the stability of the design.
- The minimum gain and phase margin values should be identified from all crossings of the 0dB and -180° lines.
- Margins depend on the frequency of the first aeroelastic mode and on the airspeed.
- Stability margin boundaries must be specified for their specific frequency range.

  Given defined signals in the data along the command path (typically loop output to loop input error), broken loop frequency responses can be obtained from these "open-loop" responses, system stability can be characterized by direct measures of:

    - Crossover frequency
    - Neutral stability frequency
    - Gain Margin
    - Phase Margin
- Other useful parameters such as steady state gain can be measured.
- Given proper frequency resolution in the input forcing function, gain margins for low damped dynamic modes (e.g., rotor modes, structural modes, aeroelastic modes) can be measured.

Figure 17 shows calculation of gain margin (GM) and phase margin (PM) for a general case. This shows the points used to calculate these parameters. Figure 18 shows the same data displayed GM v. PM. Levels refer to acceptable criteria. The Level 1 region represents acceptable gain and phase margin.

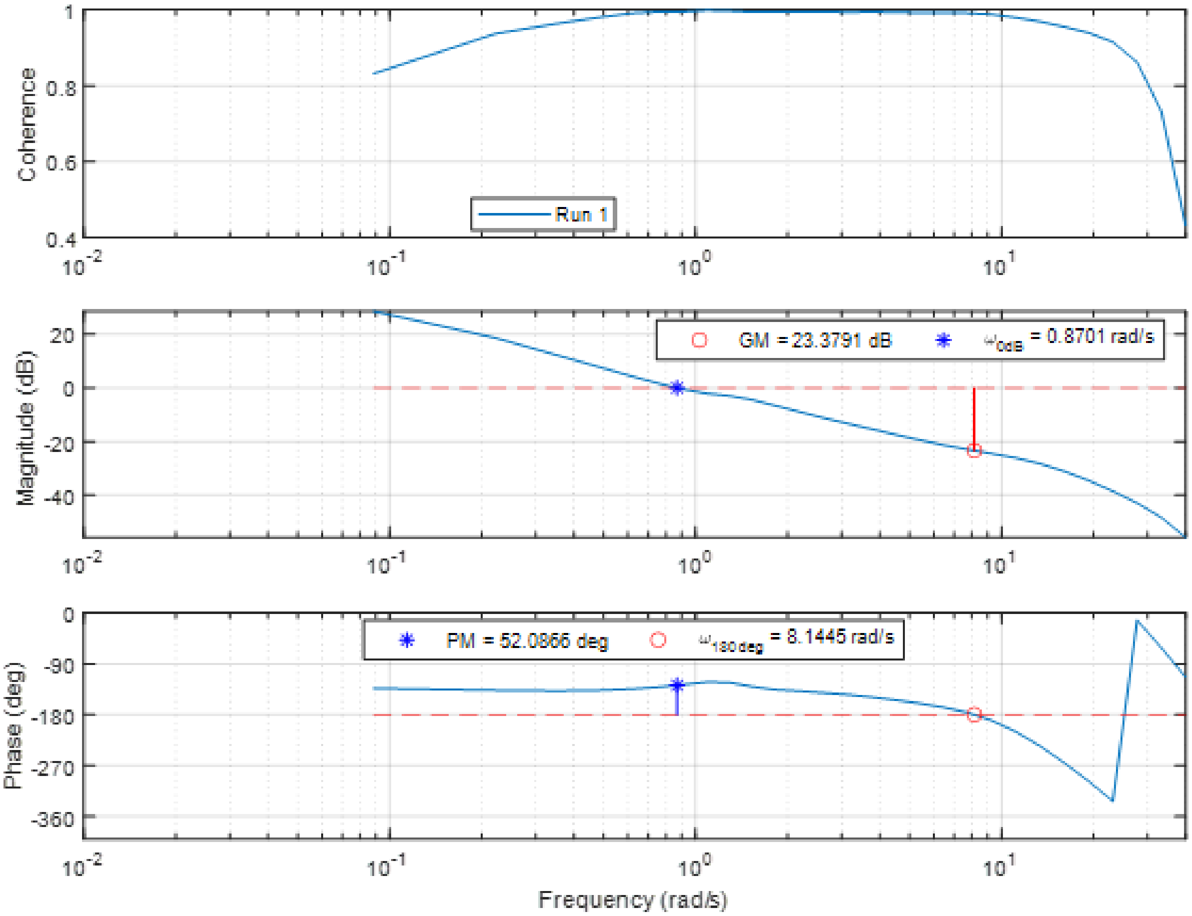


Figure 17: Example of Stability Margin, Gain and Phase Margin calculations

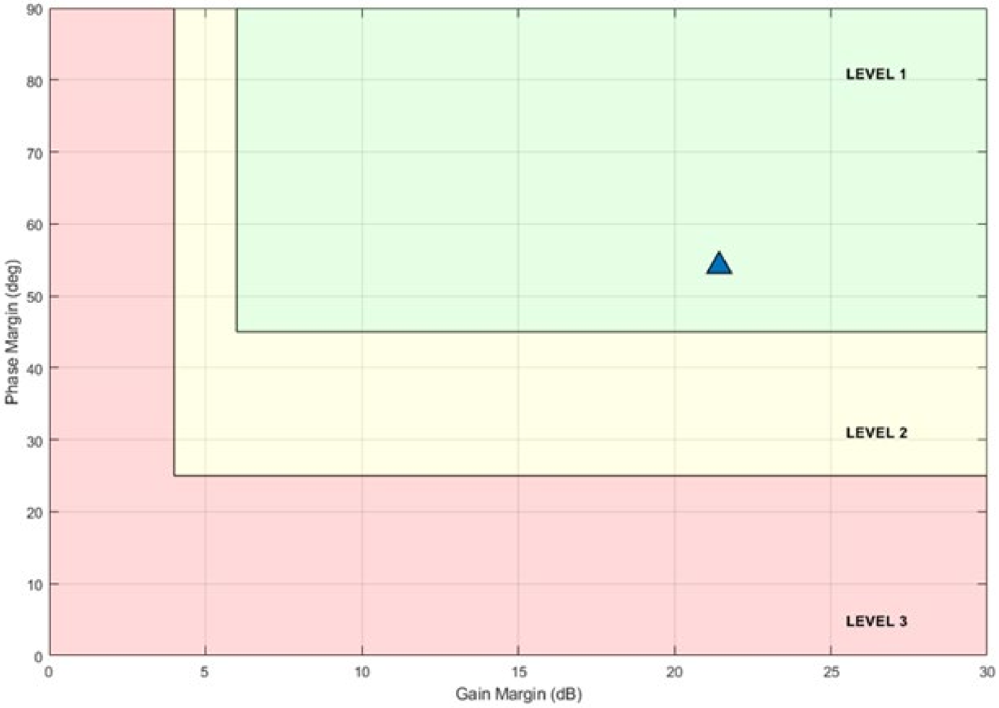


Figure 18: Gain and Phase Margin Criteria

4.4 Nichols margins

Nichols margins, or Nichols stability criteria, use the same data as used for stability margins but present a locus of points with respect to gain and phase. The Nichols chart features an exclusion zone. If the locus violates the boundary of the Nichols exclusion zone, this is not considered acceptable. Conveniently, the same frequency sweep data can be used to determine both the Nichols and stability margins, depending on overall quality. An example of the Nichols margin is shown in Figure 19.

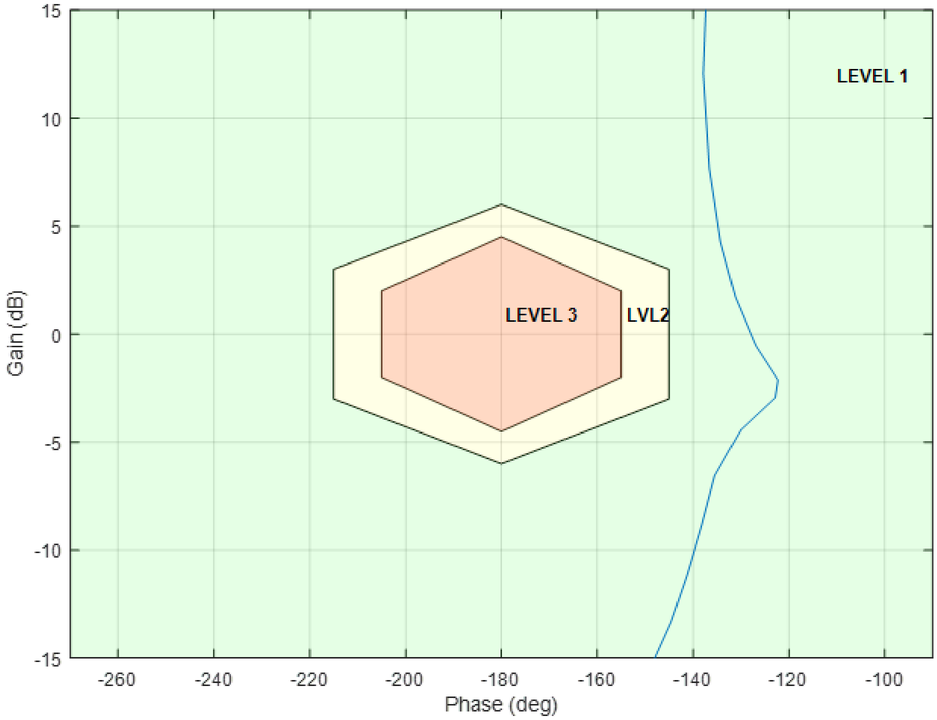


Figure 19: Nichols Margin and Exclusion zone, Corresponding Levels

4.5 Pulse responses and step responses

Detailed introduction and overview of pulse, step, and other response types are included within the FTG (Klyde, Mitchell, Shubert, & Jones, 2024). Here, some of these are reintroduced, as specific criteria are used to determine acceptance. These response characteristics reflect the low frequency, large amplitude motion of the aircraft, and the subsequent control. In ADS-33, minimum requirements are given depending on the class of the rotorcraft, axis, and flight speed (U.S. Army Aviation and Missile Command, 2000).

Step responses can give insight into the response of the vehicle to low frequency, high amplitude control inputs. This is through the control power and represents the agility of the aircraft. As with other criteria, ADS-33 for rotorcraft requires different control power for different classes of rotorcraft, flight speeds, and control response types (U.S. Army Aviation and Missile Command, 2000). Maximum control power is determined through maximum control input. Furthermore, the change in control power or general response over the control envelope can be observed through step inputs of different magnitudes, either using force or positional information.

Step responses can be used for all control response types, with the eventual response of the aircraft varying. Pulse inputs can also be used. The step and impulse control inputs are also used to calculate Attitude Quickness, for attitude and rate command systems respectively.

For translational rate command systems (TRC), A step inceptor force input is used to measure an equivalent rise time from the longitudinal and/or lateral translational rate response. This is used to determine the acceptability of TRC response. If the rise time is too small, the response may be oversensitive. If the rise time is too slow, the TRC may feel sluggish. A further criterion to consider for TRC systems is the force and displacement with respect to control deflection. An example of the TRC rise time response calculation is shown in Figure 20 and example boundaries are shown in ADS-33 (U.S. Army Aviation and Missile Command, 2000). This is to ensure that the correct sensitivity is used for these systems. The criteria, however, should be treated as guidance only, as the boundaries shown do not have substantial evidence to support. Additionally, current helicopters may not fall within this region. An example on Figure 21 shows the CH-47, which has a much higher rate with respect to control deflection than indicated by boundaries (Blanken, Hoh, Mitchell, & Key, 2008). Further research is required in this area to construct suitable boundaries for powered-lift aircraft.

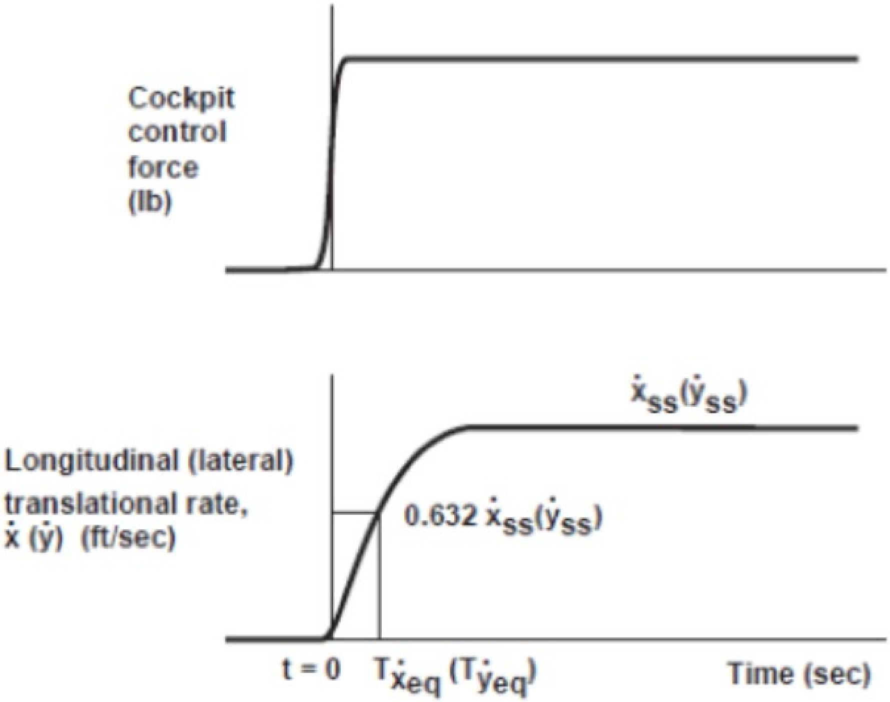


Figure 20: Translational Rate Command Step Response Example (U.S. Army Aviation and Missile Command, 2000)

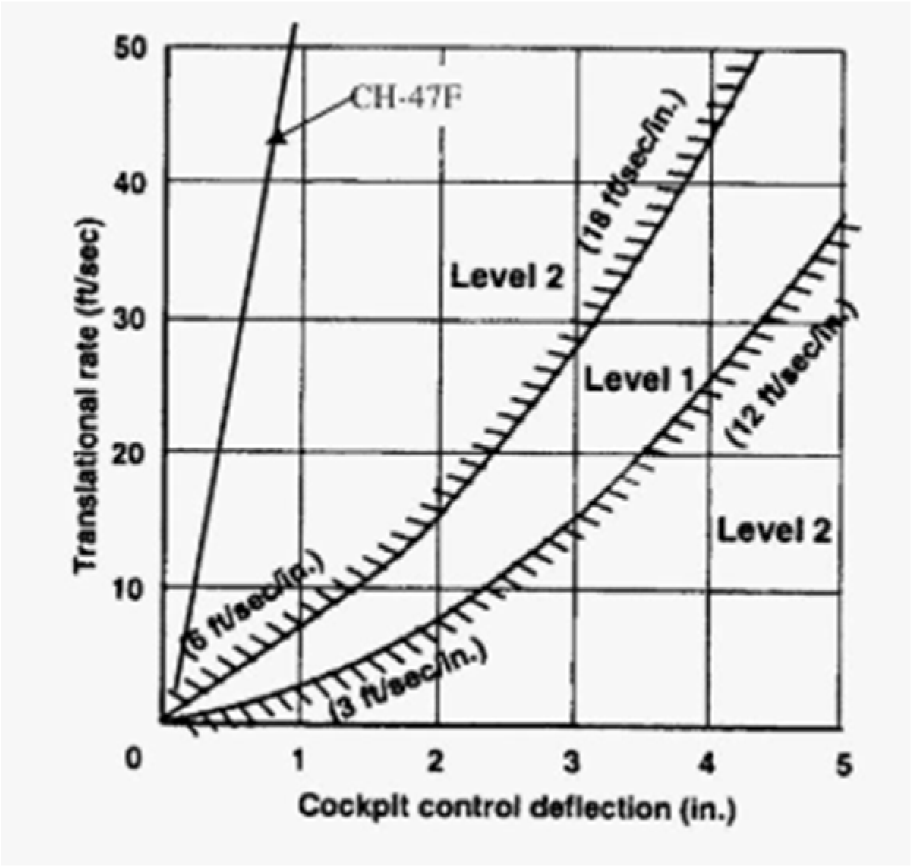


Figure 21: Control Deflection with Translational Rate (Blanken, Hoh, Mitchell, & Key, 2008)

4.5.1 Attitude quickness

Attitude Quickness is a U.S. Army aviation metric (U.S. Army Aviation and Missile Command, 2000) used for short-term response of the aircraft. It measures the ratio between peak rate over attitude with respect to overall attitude change. The quickness must be calculated for representative aggression/attitude changes. For rate control systems, for example, it is common for attitude quickness to reduce with magnitude of attitude change. It is common to conduct a range of attitude quickness tests to measure how the parameter changes. Input signals for the attitude quickness depend on the control system type. The purpose of the control input signal is to achieve a steady attitude. For rate command systems, the suggested inputs are spike shapes to produce high angular rates for attitude changes. For attitude command systems, step inputs are recommended, returning steady state attitudes.

4.6 Other relevant criteria

4.6.1 Oscillations

Criteria for lateral oscillations as determined by U.S. Army aviation (U.S. Army Aviation and Missile Command, 2000) should be considered.

4.6.2 Inter-axis coupling

It is important to consider the interactions between axes for any design. For rotary-winged aircraft, cross couplings are common due to methods of control and vehicle dynamics. General guidance should be used with respect to maximum off-axis motion as a fraction of the on-axis response. This is for aggressive maneuvering, with guidance established by U.S. Army aviation in ADS-33E-PRF (2000). There are also applicable limits on the ratio of peak off-axis attitude response from trip to the desired on-axis response from trim.

For the heave axis, specific criteria is established in ADS-33E-PRF (2000). For helicopters, yaw-heave coupling is caused by changes to rotational moment due to changes in thrust. The tail rotor is used as a counter-torque method and in most helicopters, the pilot is required to manually correct for changes in torque using the yaw control (pedals). Powered lift aircraft feature distributed propulsion, often with counter rotating effectors, which should limit any yaw-heave cross-couplings. Nonetheless, the metric can still be used to confirm that the response is satisfactory.

Applying both up and down heave inputs (or equivalent in powered lift configuration) is used to generate the time response parameters that measure yaw due to coupling. The yaw rate after both 1 sec and 3 sec are measured and used to calculate parameters. Figure 22 shows the calculation of parameters and applicable boundaries (Blanken, Hoh, Mitchell, & Key, 2008). Lower values of yaw rate with respect to rate of climb are preferred.

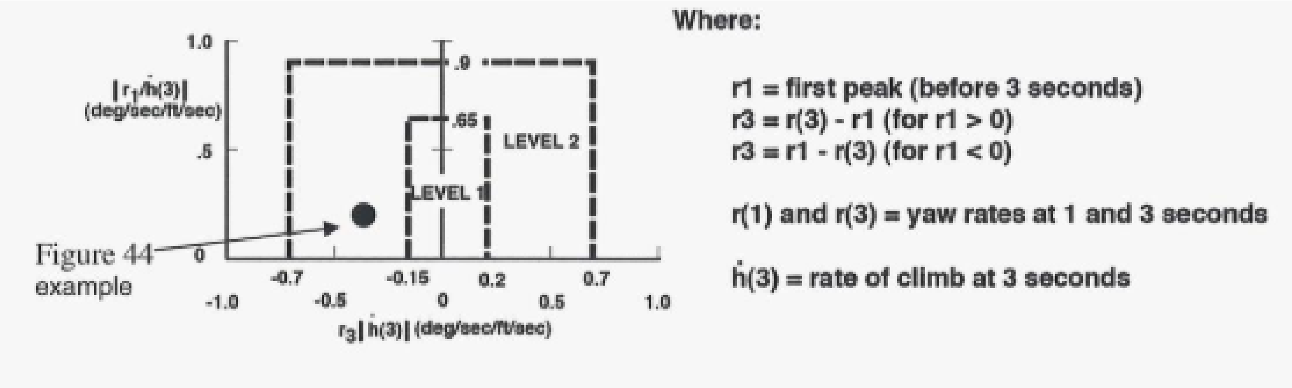


Figure 22: Yaw due to Collective Cross-coupling Analysis (Blanken, Hoh, Mitchell, & Key, 2008)

Coupling requirements and limits are also available for the pitch-to-roll and roll-to-pitch couplings. These can be calculated in both the time and frequency domains. Specific calculations are contained within ADS-33E-PRF (2000). For frequency domain calculation, bode plots of both on-axis and off-axis response are used to calculate ratios of roll/pitch responses. Applicable boundaries are shown in Figure 23 (U.S. Army Aviation and Missile Command, 2000).

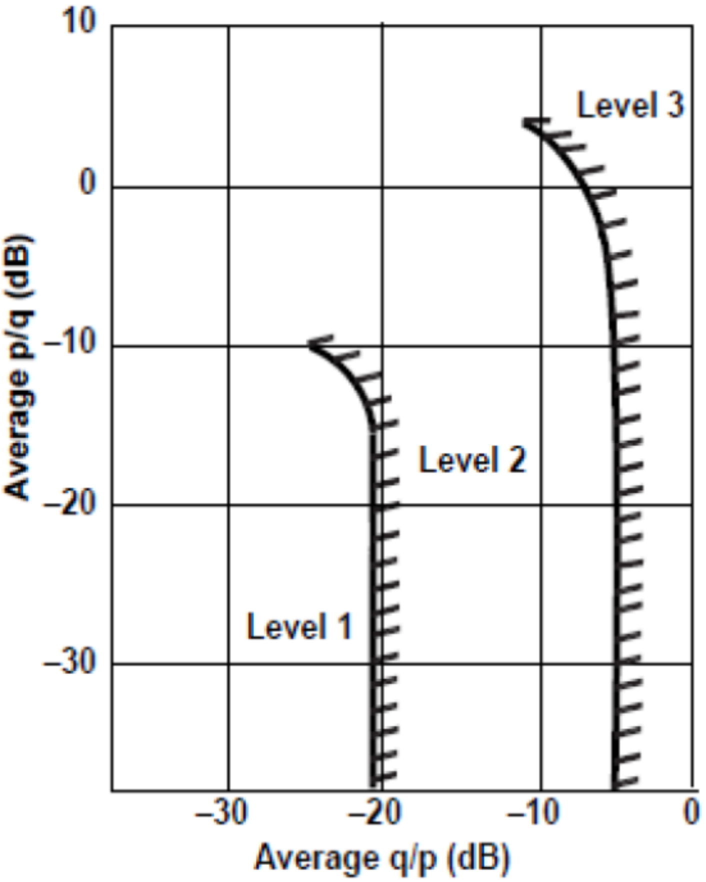


Figure 23: Roll(p)/Pitch(q) Coupling boundaries for Frequency Domain Analysis (U.S. Army Aviation and Missile Command, 2000)

5 Example HQTE demonstration flights

This section presents results from a flight test campaign, conducted to demonstrate the application of HQTEs for civil certification . A variable stability helicopter was used as a surrogate to evaluate the concepts discussed in this paper. The campaign was also used to show how the FTSC approach can be applied, including subsequent data analysis. Flight tests were limited, so only a subset of potential HQTEs were performed.

5.1 Test campaign overview

The test campaign was conducted together with National Research Council Canada (NRC), with the successful participation from FAA test pilots, an FAA flight test engineer, and the STI teams. The campaign investigated two elements relating to the scorecard process:

- ‘Tailoring’ of HQTEs for specific vehicle types, transitions, constraints, and preference.

- Effectiveness for HQTEs to successfully highlight deficiencies within the vehicle configurations for certification.

Within the tailoring selected, the team also included modifications to the HQTEs to reflect those considerations of EUROCAE efforts to define similar suitable maneuvers (EUROCAE, 2024). It is believed that this will help with harmonization of these HQTEs in the future.

The test campaign was conducted between 19 – 23 August 2023, at NRC Canada. Four HQTEs were evaluated by both pilots. Each of the HQTEs featured modifications to either the course layout or to the performance tolerances. Pilots assessed handling qualities using the Cooper-Harper scale. This was to award subjective handling qualities ratings. Three flight control modes were tested during the investigation: Attitude Command Velocity Hold (ACVH), nominal and degraded, and a Translational Rate Command (TRC).

The four HQTEs tested were HQTE Hover, HQTE Pirouette, HQTE Lateral Reposition, and HQTE Hover Turn and Hold. These were all taken from the test guide, and course setup and performance tolerances modified accordingly. During the test campaign, it was possible to complete all HQTEs using the various control mode configurations. Both pilots awarded subjective ratings.

For several test points, the tablet display Means of Compliance Requirements for UAM Evaluations and Ratings (MCRUER) system was used to aid the pilot when completing HQTEs. MCRUER is an on-board, real-time virtual display of HQTE courses, to support the handling qualities evaluations (Vo, Schulze, & Jones, 2025). Displays can be used both by the pilot and flight test engineer. MCRUER enables HQTEs to be conducted on test sites where limited external cueing is available. For this study, the system was used to verify that the modified performance tolerances of the physical courses matched the tolerances of the visual courses as cued by the application. Additionally, the system is used as additional cueing to the external environment to inform pilots of modified tolerances not presented in the static physical courses. For all cases, the MCRUER system was used to record data for in-flight feedback on performance to the pilot, and post-flight debriefing and analysis. The aircraft, the Bell-412 Advanced Systems Research Aircraft (ASRA), and test team are shown in Figure 24.

Figure 24: NRC Canada Test Team and Aircraft, Bell-412 ASRA

5.2 Scorecard/certification paragraphs of interest

One aim of the investigation was to determine the suitability of HQTEs for certification, including using these in the FTSC process outlined in this report. To demonstrate the application, generic FAA requirement paragraphs have been selected, to show how these relate to HQTEs. These are intended to be examples of how HQTEs can be applied to partially demonstrate compliance. This is not to say that HQTEs selected for the paragraphs shown will be the only ones which are recommended for testing, nor that additional tests should not be conducted (e.g., traditional certification test methods). Subsections of 'Controllability and Maneuverability' were selected to demonstrate the concept of application of HQTEs.

5.2.1 Controllability and maneuverability (§27.143)

For §27.143 compliance, safe and controllable flight must be demonstrated. This includes take-off, climb, level flight, turning flight, autorotation, landing, etc. For the purposes of this test trial, aspects relating to §27.143 were limited to low-speed flight, for level and turning flight, along with behavior in winds. HQTEs were selected to determine the controllability in this low-speed envelope. Concerning winds, as citing 14 CFR §27.143 (c), the following is required:

> Wind velocities from zero to at least 17 knots (kts), from all azimuths, must be established in which the rotorcraft can be operated without loss of control on or near the ground in any maneuver appropriate to the type (such as crosswind takeoffs, sideward flight, and rearward flight). (14 CFR §27.143 (c), (2024))

This was also partially tested through the HQTEs selected as described in Table 6. Other aspects of §27.143, including failure testing and configuration changes, were beyond the scope of the limited flight testing. Table 6 shows section (a) and (c) of §27.143. These were partially tested, with Supporting Data and selected HQTEs. The low-speed flight regime was tested. For (a), supporting data recommended is stability margins, Nichols margins, bandwidth, and other control response criteria. HQTEs recommended to demonstrate controllability at low speed are Precision Hover, Pirouette, Hover Turn and Hold, and Lateral Reposition and Hold. Completing all HQTEs should ensure that the aircraft is controllable in the low-speed regime. Similar selections are made for (c), however HQTEs should be conducted in the wind. In addition, dedicated critical azimuth testing should be conducted and provided as additional 'Supporting Data'.

Table 7: Linkage Between Certification Paragraph, Supporting Data, and Selected HQTEs

Certification Paragraph §27.143	**Flight Regime Tested**	**Supporting Data**	**HQTE**
(a) The rotorcraft must be safely controllable and maneuverable— (1) During steady flight; and (2) During any maneuver appropriate to the type	Low speed (0-40 kts)	Stability margins Nichols margin Bandwidth Other Control response criteria	Precision Hover Pirouette Hover Turn and Hold Lateral Reposition and Hold
(c) Wind velocities from zero to at least 17 knots, from all azimuths, must be established in which the rotorcraft can be operated without loss of control on or near the ground in any maneuver appropriate to the type (such as crosswind takeoffs, sideward flight, and rearward flight)—	Low speed (0-40 kts)	Stability margins Nichols margin Bandwidth Other control response criteria Trimmed Flight Control Positions Critical Azimuth Tests to determine low-speed envelope	Precision Hover (in wind, tbc) Pirouette (in wind, tbc) Hover Turn and Hold (in wind, tbc) Lateral Reposition and Hold (in wind, tbc)

The HQTEs were selected due to the characteristics, exercising multi-axis response of the aircraft in closed-loop flight. However, without necessary testing, there is a lack of evidence to show that these HQTEs can adequately give sufficient evidence to show full controllability for the selected flight regime. This was one of the motivations of the flight test campaign, to collect feedback from experienced FAA pilots and flight test engineers.

5.3 Considerations

There were important pretest considerations discussed with FAA evaluation pilots. An important aspect of the flight campaign was the collection of feedback and considerations for the suitability of the proposed HQTE evaluation process and test maneuvers for civil certification.

5.3.1 Suitability of HQTEs for civil certification

A key aspect of the flight test campaign was to determine whether HQTEs are suitable for civil certification. These are highly constrained engineering maneuvers, abstract from the operational requirements of the vehicle. The approach is also a departure from traditional civil certification maneuvers and tests. In this regard, the team reviewed the detailed objectives of HQTE in support of civil certification as already presented in Section 1.5.3.

It is important that maneuvers potentially cover the areas of concern with advanced flight control concepts, automated transitions in these concepts, new inceptors configurations and control mappings, that have been proposed by applicants. In addition, they should be designed efficiently. A third dimension to consider is the requirement to achieve proficiency in the task. A complex high workload task, with various segments, will drive significant practice maneuvers to achieve proficiency and assess compensation. This can represent a heavy cost for those developing electrically-powered VTOL aircraft with minimal hover endurance. A mitigation is to use validated simulators for most hover work and only spot check very limited cases on the actual aircraft.

A small subset of the proposed 'HQTE catalogue' was flown during the campaign. However, it was important to consider whether selected HQTEs adequately exposed potential deficiencies for the highlighted certification paragraphs.

5.3.2 Course layout and cueing

Participants were asked to consider the cueing elements used to display task performance requirements. When using physical courses, an important consideration is the safety of the external references. This is particularly true when flying with vehicles of novel type and design, as there may be significant opportunity for over-control, pilot induced oscillations, and even temporary loss of control that drives task abandonment. For this reason, the original course set-up proposed in the FTG should be considered and the need for potential cluttered obstacles in the environment should be justified with the potential associated risk (Klyde, Mitchell, Shubert, & Jones, 2024).

The cost in the setup of these maneuver courses in materials, manpower, and time should also be considered. This can be especially complicated by the requirement to setup courses for different wind azimuths. Every effort should be made to achieve the goals of each of the HQTE with a minimum expenditure of resources, while preserving adjustability for wind conditions that may be mandated. In this context combining courses, in setup and tolerances, should be emphasized. Differences between simulation and flight may exist for course cueing, due to either safety concerns highlighted above or due to cueing deficiencies within the test environment. For example, a fixed-based simulation facility may lack necessary cueing for pilots to perceive drift, requiring additional elements in the simulated world. This is common in simulation facilities. In addition, during flight tests, it may not be possible to achieve the required level of precision due to lack of cueing elements.

A further aspect that was considered concerning the course layout was the flexibility. The concept of 'tailoring' is discussed in this report. To achieve this, it's important to understand how the course tolerances and requirements can be easily modified. Depending on the rules for tailoring, there may be a need to modify the course for different flight control or vehicle modes, or due to specific aircraft limitations including configuration, aeromechanics, etc.

5.3.3 Performance tolerances

The appropriateness of tolerances was important to consider. The HQTE catalogue has been developed from the combination of several research efforts, combining aspects from fixed and rotary-wing guidance documentation, from piloted simulation experiments and from flight testing. However, no data from full-scale eVTOL flight testing has been used to determine boundaries or thresholds. Generally, adequate tolerances are based on certification thresholds derived from various operational standards, while desired tolerances were considered tighter to stress the design. However, variations for each HQTE exist, and it should not be assumed that desired and adequate performance requirements replicate certification requirements exactly. During the campaign, feedback relating to the suitability of tolerances was solicited.

As part of the process in assessing the HQTE, previously proposed metrics and performance requirements were revisited from ADS-33E-PRF (2000), the Flight Test Guide (Klyde, Mitchell, Shubert, & Jones, 2024), EUROCAE ED-295 (EUROCAE, 2024), and any recent simulation studies or ongoing work.

The focus of the campaign was not to ‘pass’ or ‘fail’ the specific aircraft, but to investigate whether deficiencies were present and if process shows promise for use in civil certification, and to collect comments, feedback, and data. Currently, there are ongoing discussions regarding the use of CHR. This subject is not considered here in detail.

5.3.4 Handling qualities assessment utilizing the Cooper-Harper Rating scale

The following guidance was offered to better standardize the assignment of ratings and to promote discussion as to the nuances of using HQRS from the Cooper-Harper Rating scale for certification of civil aircraft.

It is beneficial to review the following definitions in support of the Cooper-Harper scale usage (Cooper & Harper, 1969).

- Performance: The precision of control with respect to aircraft movement that a pilot can achieve in performing a task.
- Compensation: The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics. Cueing should be sufficiently good so that the pilot does not have to compensate for any cueing deficiencies.
- Workload: The integrated physical and mental effort required to perform a specified piloting task.

It should be possible for the pilot to determine immediately if desired or adequate performance has been achieved using the cueing that is available on the test course or within the aircraft. Performance in this context is normally considered as the precision of aircraft control. It is acceptable to inform the pilot if he or she achieved desired or adequate performance to calibrate the pilot perception in practices, but repeated questions about this are good reasons to consider modifying cueing or tolerances. The purpose of attaining HQRs through the Cooper-Harper Ratings scale is not to determine cockpit visibility limitations, but to assess the HQs, given that the visual cues are not a factor in the evaluations. If they are, the task or cueing should be modified to provide for sufficient controllability.

While cued performance tolerances may be readily evident, some efficiency can be achieved by the pilot, or FTE that is briefing the pilot, by shortly reviewing other task constraints that are not self-evident, such as time constraints, off-axis response, or the requirement to perform a maneuver in a smooth fashion.

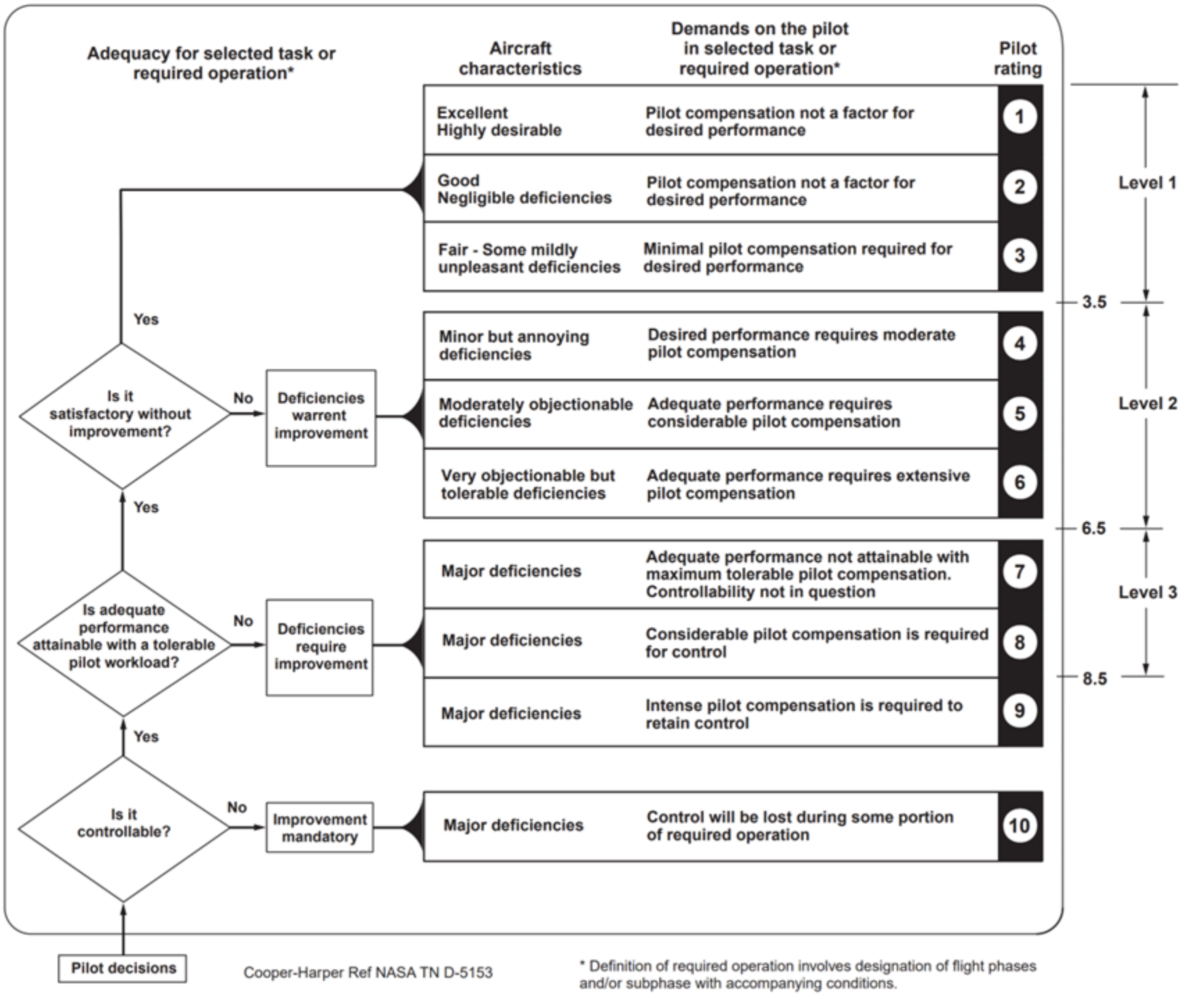
The use of displays in cueing should be quantified and any divided attention between outside visual reference and inside cockpit displays should be highlighted. For maneuvers that require a hover capture for example, call ‘stable’ or ‘mark’ when you have mentally transitioned from the act of hover-capture to maintaining desired or adequate hover performance tolerances.

After completing the maneuvers ‘for record’, the pilot should begin by self-assessing their performance against tolerances and then detailing compensation used in attempting the task. When using the Cooper-Harper Ratings scale (see Figure 25) to award HQRs, the pilot should always start at the lower-left and work up the decision tree, answering the questions first before assigning numbers (Cooper & Harper, 1969). Experience has shown that dispersions between pilots can be minimized by always enforcing adherence to this somewhat tedious, but very important, decision process.

When using the Cooper-Harper Ratings scale, emphasize workload and pilot compensation over performance. If there is an evident disconnect between the three, there may be reason to examine the tolerances against the operational task that informs the HQTE.

The major decisions on the Cooper-Harper Ratings scale do not allow for half ratings. That is, ratings of 3.5, 6.5, and 9.5 cannot be assigned. Generally, it is advised not to award half-ratings (e.g., 2.5), however it may be permissible in certain circumstances.

PIO ratings were generally not collected during the campaign. However, the rating scale was made available to the pilot in case they experienced undesirable and unintentional oscillations. PIO ratings are often confusing in that various overcontrol may be attributed to PIO tendency. Terms relating to oscillations were included in desired/adequate performance requirements for most of the task flow. Several works have highlighted difficulties employing the PIO scale for evaluations (Jones & Barnett, 2020), and further efforts are required to develop alternative rating schemes for PIO due to limitations in current rating scales (Jones M. , 2015). PIO considerations are discussed below.



Cooper-Harper Ref NASA TN D-5153

* Definition of required operation involves designation of flight phases and/or subphase with accompanying conditions.

Figure 25: Cooper-Harper Handling Qualities Rating Scale (Cooper & Harper, 1969)

5.3.5 Test execution

Planned Flight Examination of the maneuvers combined the different considerations in the test matrix. Winds were not in the test plan matrix but were light and varying throughout testing. Therefore, some variability in results can be expected from the various wind conditions throughout the tests.

Only limited flight hours were available during the flight test campaign. Therefore, a specific process was flown to maximize the output of the campaign relating to the areas of interest. The following process was followed when performing HQTEs:

1. Fly the baseline version of the FTG maneuver, or similar.

2. Fly all maneuvers in a nominal Attitude Command Velocity Hold (ACVH) with Level 1 HQs predicted using a subset of Supporting Data, based on guidance in ADS-33.
3. Fly selected maneuvers in a degraded ACVH with borderline Level 1/2 HQ predicted by ADS-33 metrics. This was implemented through a command path lag.
4. Fly selected maneuvers in TRC with Level 1 HQ predicted by ADS-33 metrics.
5. Fly variations of maneuvers based on analysis of references, briefed to the pilots along with general questions that the authors felt provide insight into the suitability question. From this study, variations to performance tolerances were flown. Tailoring of the HQTE were also examined in this regard.

5.3.6 Account modification for PIO

The performance constraint on oscillations in the FTG for some of the HQTEs investigated in the flight tests were found to conflict with both ADS-33 and EUROCAE guidance. Additionally, the term oscillation can be misunderstood or confused, especially since it is used in the PIO scale. Based on discussions prior to the test campaign, an alternate version of this was proposed for flight test which better aligns with the PIO rating scale that is proposed for use in supporting HQRs. Under the current guidelines in Klyde et al. (2024), a PIO rating of 4 would be considered acceptable for adequate tolerances. To aid in this distinction it is perhaps good to provide a definition of PIO that can be used by evaluation pilots.

PIO is a sustained or uncontrollable unintentional oscillation in which the airplane attitude, angular rate, normal acceleration, or other quantity derived from these states, is approximately 180 degrees out of phase with the pilot's control inputs (Klyde, Mitchell, Shubert, & Jones, 2024). This definition of PIO is defined using the following relevant terminology:

- Oscillations: PIO is an oscillatory response; however, the presence of oscillations alone does not indicate PIO. It is important that oscillatory behavior in which the airplane is responding as intended to pilot inputs not be identified as a PIO. Look for the complete PIO signature before making such judgments.
- Control inputs: For a given task, control inputs are generally significantly higher in amplitude in a PIO when compared to a non-PIO case.
- Body axis rates: For a given task, body axis rates are generally significantly higher in amplitude in a PIO when compared to a non-PIO case.

- Input/output phase: In a PIO, a key aircraft response will be at least 180° out of phase with the pilot, typically attitude or acceleration. If this out of phase character is not present, then it is not a PIO, even if other elements of the PIO signature are present.

The decision tree of the PIO rating scale should be applied by the pilot in a manner like that discussed for the Cooper-Harper HQR scale. To aid in distinguishing between 'oscillations' and 'undesirable motions,' the evaluator can add 'out-of-phase' to the 'causes oscillations' question in the decision tree. The additional dialog in the word scale, however, should also be considered prior to assigning a rating. This will help the pilot evaluator to further distinguish between undesirable motions such as 'pitch bobble' and oscillations. For example, to support this argument, the tolerances were adjusted to reflect better agreement with the PIO rating scale for the Precision Hover task as follows:

- Desired: Residual motions from transition to hover or disturbances from stabilized hover are easily damped with no oscillatory tendencies.
- Adequate: Residual motions can be damped but impact performance; any oscillatory behavior is not objectionable.

5.3.7 Winds and conditions

All maneuvers are expected to be performed in Calm winds. The FAA position is that HQTE testing in moderate winds is subject to ongoing discussions. Furthermore, there is still significant discussion regarding definitions of turbulence levels and methods to test. Some of these discussions have been held within the Vertical Flight Society (VFS) eVTOL Flight Test Handling Qualities Advisory Committee. Some of the considerations from this group are summarized below.

1. There is good reason to accomplish HQTE tests in wind and turbulence.
    a. Quantitative evaluation of flight control disturbance rejection capabilities.
    b. Quantification of HQ degradations to support simulations, that may support certification.
    c. Evaluate various control mappings and response transitions that may be groundspeed-based.
2. Recommend the use of wind requirements for low-speed ground-referenced HQTE: Recommend a wind-band of 10-15 kts steady component. Flight in Calm winds will be in winds from 0-5 kts steady component.
    a. The 10-15 kt wind band would have sufficient turbulence associated with it so turbulence or gust spread would not have to be specified.
    b. This 10-15 kt wind band would not unreasonably constrain limited flight tests.

3. Avoid overspecification of wind direction as much as possible. HQTE testing in natural winds using HQTE courses is problematic and expensive. Flight at critical azimuths should not be mandated for HQTE tests since it would be near aircraft flight manual (AFM) boundaries and considered outside the normal flight envelope (NFE) per EASA. This data will otherwise be gathered under current all azimuth testing techniques for envelope definition and the SPCL test maneuver per EUROCAE ED295.
4. Use a limited number of selected HQTE for formal evaluation in winds. Aggressive Maneuvers may be done in calm winds only. Azimuth constraints, if stated on selected HQTE, should be liberal (+/-30 deg for example). Example HQTE: Crosswind for UAM approach OR Depart Abort/Rejected Takeoff.

5.3.8 Task tailoring

In ADS-33, the concept of modifying performance requirements is handled through establishing vehicle classification; scout/attack, cargo utility, and sling-load (U.S. Army Aviation and Missile Command, 2000). In addition, task tolerances and performance standards are dependent on whether the conditions are good-visual-environment (GVE) or degraded-visual-environment (DVE). These approaches are not preferred for civil certification.

In Europe, EUROCAE has released proposed standards for HQ demonstrations (EUROCAE, 2024). This standard proposes to account for different classes of aircraft using the physical size of the vehicle. This approach is also used to scale vertiports in proposed guidance documents. Furthermore, several research outputs have shown the applicability of Froude scaling methods to size tasks for smaller vehicles (namely small UAS). Although innovative, the approach to scale tasks based on vehicle size can be confusing and presents challenges when looking at equivalency for different vehicles.

The concept of tailoring is proposed to modify task performance requirements given specific vehicle constraints and performance requirements. Tailoring should be considered for certain requirements and constraints only and may not be applicable to those which can be linked directly to a certification standard. Tailoring may be conducted due to the intended performance of the vehicle (which should relate to the general CONOPS) or due to operational constraints, particularly during flight testing. Although the details of task tailoring are being discussed, typical examples may include course lengths, heights and dimensions. It is important to understand how changes to task performance standards impact on the overall task thresholds when tailoring. The concept of modifying military variants of HQTEs (i.e., MTEs) is not new. Since their initial introduction, tasks contained in ADS-33 have been modified with justification for specific rotorcraft. This includes changes to course sizes, layouts, and removal of certain performance requirements. Some of these changes have been incorporated in the latest release of these MTEs (U.S. Department of Defense, 2023).

In summary, the following should be considered:

- The use of tailoring should have distinct limitations in place that do not allow for dilution of the HQTE criteria to a point where it does not meet the goals of HQTE. Required precision and aggression levels of HQ performance should remain consistent.
- HQTE tailoring should be considered to capture HQ-related flight control issues such as inceptor mappings, non-linear behavior, response type changes, and sensor input changes.
- Examples of acceptable tailoring investigated in this effort include ground course adjustment to provide sufficient cueing based on aircraft design, adjustment of reposition distances based on target velocity and changes to target capture speed based on given response types.

5.4 HQTEs

The following sections outline the selected HQTEs for the flight test. For each, a description of the purpose is first given. Then, modifications from previous versions proposed in the FTG are presented, along with a comparison against EUROCAE ED-295 tolerances and procedures. A description of proposed cueing is given and then a discussion of tailoring elements explored during the flight test.

5.4.1 Hover HQTE

5.4.1.1 Description and purpose

The Hover HQTE is a transition and maintenance task which checks the ability to transition from translating flight to a stabilized hover with precision. The maneuver also has the objective of checking for inceptor control harmony across axes and identification of pilot-induced oscillations.

The pilot initiates the maneuver from a hover, accelerating to a target groundspeed. Translation at an approximate 45° toward the hover location is performed until a smooth deceleration is initiated to capture the hover point. The pilot should then attain a stabilized hover at the hover point while maintaining position, heading, and altitude tolerances as specified below.

5.4.1.2 Modifications from Flight Test Guide and ADS-33

The criteria for the Hover HQTE compared to the criteria for the ADS-33 Precision Hover is seen in Table 7. These requirements were found to be very similar, with the HQTE developed directly from ADS-33. In previous iterations, there has been discussion of relaxing the capture time for the HQTE, given intended powered-lift mission. The drawback of relaxed capture time is that handling qualities deficiencies, or ‘cliffs’, may not be unmasked. The hover maintenance time is also subject to discussions and was investigated during the campaign. A difference is shown with the comparison in the following section.

Table 8: Hover-Comparison between HQTE and ADS-33

Requirement	**HQTE**		**ADS-33 (Cargo/Utility)**	
	Desired	**Adequate**	**Desired**	**Adequate**
Capture time (s)	5	8	5	8
Hover position (ft)	3	6	3	6
Altitude (ft)	2	4	2	4
Heading (deg)	5°	10°	5°	10°
Hover maintenance time (s)	30	30	30	30
Run-In Speed (kts)	6-10		6-10	

5.4.1.3 Comparison to EUROCAE ED-295

A notable difference between the FTG and ED-295 is the hover maintenance time. Whereas the FTG and ADS-33 call for 30 seconds of maintenance, ED-295 only calls for 10 seconds. In the applications of eVTOL, efficiency in these test campaigns is significant due to limited battery life. Minimizing flight time for each run is further explored as a part of the tailoring elements of the maneuver.

Within the EUROCAE tolerances, the concept of scaling using the size of the aircraft (i.e., D-factor) is introduced for a number of HQTEs (so-called FTEs). The scaling is based on the diameter of a circle drawn around the two furthest points of the aircraft from above (e.g., the complete structure should be contained within an imaginary circle). Using this technique, distances are scaled based on the overall size. This is the same method that has been used to scale vertiport designs. As shown in Table 8, a scale factor of 0.1D represents the desired performance. On initial inspection, this may seem very different to the HQTE requirement. However, replacing D = 10m gives and approximate desired tolerance of 3ft, the same as the HQTE.

Table 9: Hover-Comparison between HQTE and ED295

Requirement	**HQTE**		**ED-295**	
	Desired	**Adequate**	**Desired**	**Adequate**
Capture time (s)	5	8	5	8
Hover position (ft)	3	6	0.10 D (m)	0.20 D (m)
Altitude (ft)	2	4	2	4
Heading (deg)	5°	10°	5°	10°
Hover maintenance time (s)	30	30	10	10
Run-In Speed (kts)	6-10		6-10	

5.4.1.4 Cueing elements

The test course at NRC Canada utilizes a hover board on the ground, with a target pole before it. While being much safer and more efficient than a vertical hover board, the disadvantage was that it confounded the longitudinal and vertical axis control. For instance, with the pilot relying on Rate Command Height Hold (RCHH) to maintain height, the corrective action for being out of the vertical constraint on the hover board, was to move longitudinally. Had the pilot had to control vertical, there is some expectation that this task would have been iterative between the axes. The FTG does allow for movement of hover boards farther away from the aircraft depending on circumstances, if it cues the same performance constraints. Further investigation should be undertaken to recommend a minimum angle that can be tolerated for each of the maneuvers.

An enhanced feature seen on the NRC course was the use of bright blue cones. These provided for very defined lineups. One could easily see the line and whether a single cone was not aligned, indicating a strong reference. Consideration should be given to investigating this further.

5.4.1.5 Tailoring elements

For the Hover maneuver, three aspects of tailoring were investigated. Firstly, the task starting position was investigated. In U.S. Army Aviation and Missile Command (2000), no requirement is given for the start position, with the stipulation that the target run-in speed should be reached prior to deceleration. Secondly, the run in speed was investigated, to show the implication of running the HQTE with a 6kt and 10kt run-in speed. Thirdly, the stable hover time was investigated. The current HQTE requires a 30 second stabilization time, however it is proposed that lower hover times may be acceptable.

5.4.2 Lateral reposition HQTE

5.4.2.1 Description and purpose

The Lateral Reposition HQTE is designed to check the roll and heave axis HQs through a lateral maneuver. It is a moderately aggressive low speed translation with a capture and position maintenance goal at the end. The HQTE seeks to check for undesirable cross axis coupling and pilot-inducted oscillation tendencies.

The FTG prescribes the maneuver as follows: starting at a stabilized hover, the pilot induces a lateral acceleration toward the final hover position 400 ft away. A ground speed of 15 kts is achieved, maintained, before decelerating onto the end point, terminating the task in a stable hover. The stabilized hover is maintained for 5 seconds. This task should be repeated in both directions.

5.4.2.2 Modifications from Flight Test Guide and ADS-33

There is significant conflict within the FTG description in that it categorizes this maneuver as a precision non-aggressive maneuver but in further description it implies that a moderately aggressive maneuver is the objective (see Table 10). Para B17.3 of the FTG (2024) states that the maneuver is precision/non-aggressive while the objectives reflect moderately aggressive maneuvering. In agreement with the stated objective, the first part of the maneuver should concentrate on precision while the later capture should be timed to drive aggression, akin to a boundary avoid maneuver. In this way it supports evaluation of moderate amplitude inputs that may examine non-linear flight control response and PIO tendencies. It will also be useful in examining transitions such as those used for a low speed TRC boundary where for instance an acceleration command may transition to TRC in the deceleration to capture hover.

Table 10: Lateral Reposition HQTE comparison to ADS-33

Requirement	**HQTE**		**ADS-33 (Cargo/Utility)**	
	Desired	**Adequate**	**Desired**	**Adequate**
Longitudinal track	5 (ft)	10 (ft)	10 (ft)	20 (ft)
Ground speed	2	4	N/A	N/A
Altitude (ft)	5	10	10	15
Heading (deg)	10°	15°	10°	15°
Time to Complete Maneuver (s)	N/A	N/A	18	22
Hover Position	5 (ft)	10 (ft)	N/A	10 (ft)

5.4.2.3 Comparison to EUROCAE ED-295

ED295 suggests that the lateral distance is set through the D-value, set as 12.5D. for D = 10m, this is approximately 400ft, the same as ADS-33 and the proposed HQTE. The ADS-33 maneuver uses a 35 kt target speed (since removed from MIL-DTL due to level of aggression), while the FTG stated 15 kts and the ED-295 had variable sideward flight speed predicted by 100% NFE or 80% operational flight envelope (OFE). ADS-33 looks for 35 kts but provides no maintenance of the speed before deceleration. Furthermore, the ADS-33 task provides time criteria to complete the task while neither the FTG nor ED-295 do (see Table 11).

Table 11: Lateral Reposition HQTE and ED-295

Requirement	**HQTE**		**ED-295**	
	Desired	**Adequate**	**Desired**	**Adequate**
Longitudinal track	5 (ft)	10 (ft)	0.30 D (m)	0.60 D (m)
Ground speed	2	4	N/A	N/A
Altitude (ft)	5	10	10	15
Heading (deg)	10°	15°	10°	15°
Time to Capture (s)	N/A	N/A	8	12
Hover Position	5 (ft)	10 (ft)	0.30 D (m)	0.60 D (m)

5.4.2.4 Tailoring elements

The under-specification of time for the FTG maneuver and the slow sideward flight speed for the 400 ft reposition makes for an extremely mild maneuver with many different techniques that may be employed in execution. The team felt that there was an opportunity to capture both precision attributes within the early part of the maneuver and aggressive attributes in the later part by providing greater specification of the maneuver. The ADS-33 maneuver is obviously representative of a military type of aggressiveness. This maneuver also suffers from under-specification in that the pilots can make acceleration much more aggressive than deceleration, and therefore allows for variability in the deceleration. The EUROCAE maneuver does link the sideward flight course length to the various sideward flight speeds that could be encountered. For these reasons the team re-examined the design of the maneuver toward assessing sideward flight precision assessment as well as looking at an aggressive capture of final tolerances to approximate a boundary avoidance type maneuver that would require moderate amplitude control inputs. The course was flown with 10kts and 15kts, with a shorter course length.

5.4.3 Pirouette HQTE

5.4.3.1 Description and purpose

The Pirouette HQTE is a multi-axis, low speed, precision maneuver meant to identify undesirable coupling between the roll, pitch, yaw, and heave axis controllers (see Table 11). From a stabilized hover, the aircraft starts the maneuver along the circumference of a 100 ft radius circle while keeping the nose of the aircraft pointed toward the center of the circle. The lateral translation around the circle is completed when the pilot terminates the maneuver with a stabilized hover on the starting point. Altitude is meant to be maintained during the whole task and should be performed in both directions.

5.4.3.2 Modifications from Flight Test Guide and ADS-33

The Pirouette performance requirements are similar for both the HQTE and ADS-33, except for the time to complete the full circumference of the circle (see Table 12). This of course impacts the overall speed of the translation. All other requirements for this HQTE are unchanged from ADS-33.

Table 12: Pirouette HQTE comparison to ADS-33

Requirement	**HQTE**		**ADS-33**	
	Desired	**Adequate**	**Desired**	**Adequate**
Radial Position	10(ft)	15(ft)	10(ft)	15(ft)
Altitude (ft)	3	5	3	10
Heading (deg)	10	15	10	15
Completion time (s)	60	80	45	60
Capture Time	5	10	5	10
Hover Capture Position	10°	15	10	15
Maintain Hover (s)	5	5	5	5

5.4.3.3 Comparison to EUROCAE ED-295

All three versions of the maneuver showed a full 360° turn around a point with a circle radius of about 100 ft. The FTG and EUROCAE versions share the same time tolerances around the circle for desired and adequate tolerances while the ADS-33 maneuver uses a significantly shorter time. All three versions differ in the capture requirements (see Table 13).

Table 13: Pirouette HQTE comparison to ED-295

Requirement	HQTE		ED-295	
	Desired	**Adequate**	**Desired**	**Adequate**
Radial Position	10(ft)	15(ft)	0.30 D (m)	0.45 D (m)
Altitude (ft)	3	5	3	10
Heading (deg)	10	15	10	15
Completion time (s)	60	80	60	80
Capture Time	5	10	N/A	N/A
Hover Capture Position	10	15	0.30 D (m)	0.45 D (m)
Maintain Hover (s)	5	5	5	5

5.4.3.4 *Tailoring elements*

To address eVTOL concerns regarding battery limitations, shortening the course to 180° was considered in the campaign to see if performing half the course will fulfill the same purpose as the full 360°. The time of this shortened HQTE was also investigated for suitability.

5.4.4 Hover turn HQTE

5.4.4.1 *Description and purpose*

The Hover Turn HQTE has the purpose of checking for undesirable HQs during low aggression, hovering turns. It checks the ability for an aircraft to stabilize after hover turn rates with precision. The maneuver also reveals undesirable inter-axis coupling and pilot-induced oscillation tendencies.

As defined in the FTG, the aircraft starts at a stabilized hover before turning 90° while maintaining the position of the hover. Stabilizing at 90°, the pilot holds that position before performing a 270° turn in the same direction to return to its initial starting position and heading.

5.4.4.2 *Modifications from Flight Test Guide and ADS-33*

The FTG maneuver differs from the other two maneuvers in that it has a turn to 90° from the start position with a capture and then continues the turn 270° further and all the way back to the start heading and position. This would seem to combine the Hover turn and Heading Capture of the ADS-33 (see Table 13). It is assumed here that the turn is about the CG or mast in the helicopter.

Table 14: Hover Turn HQTE and ADS-33

Requirement	HQTE		ADS-33	
	Desired	**Adequate**	**Desired**	**Adequate**
Lat/Lon	3 (ft)	6 (ft)	3 (ft)	6 (ft)
Altitude (ft)	3	6	3	6
Heading (deg)	5	10	5	10
Time to complete (s)	50	60	15	20

5.4.4.3 Comparison to EUROCAE ED-295

The Hovering Turn MTE in ADS-33 consists of 180° done at moderately aggressive level. It should be stated that the ADS-33 also has a Hover Capture MTE which turns 45°, stops and then reverses turn direction 45° back to the start heading (see Table 14). This is also done at a moderately aggressive level. It is assumed that the turn in ADS-33 is about the CG of the aircraft instead of the pilot station although not explicitly stated. The maneuver is to be done in 15 sec (>12° /sec) for desired tolerances and 20 sec (9°/sec) for adequate tolerances.

In EUROCAE ED-295 The turn is performed at 100% NFE or 80% OFE, both assumed to be relatively aggressive. A timing requirement is also presented, which is believed to over constrain the maneuver.

Table 15: Hover Turn HQTE and ED-295

Requirement	HQTE		ED-295	
	Desired	**Adequate**	**Desired**	**Adequate**
Lat/Lon	3 (ft)	6 (ft)	0.10 D (m)	0.20 D (m)
Altitude (ft)	3	6	2	4
Heading (deg)	5	10	5	10
Time to complete (s)	50	60	15	20

5.4.4.4 Tailoring Elements

During the campaign, the timing of the Hover Turn was investigated for tailoring. In addition, the requirement to arrest the yaw rate at 90° in addition to the 180° point was also considered.

5.5 MCRUER system

The MCRUER system was used during this test campaign for data acquisition, course verification, and run logging. Developed by STI and Bolder Flight Systems as part of NASA sponsored research, the MCRUER system is a tablet-based cockpit display and sensor system that provides an FTE interface for test campaign logging, and a virtual 'HQTE' course cueing for the pilot (see Figure 26). The original purpose of this system was to minimize the need for standard physical courses to streamline the testing and certification process. As the system provides an organized data recording process along with its adaptable HQTE courses, the team found it beneficial to install and use the system to drive the test campaign.

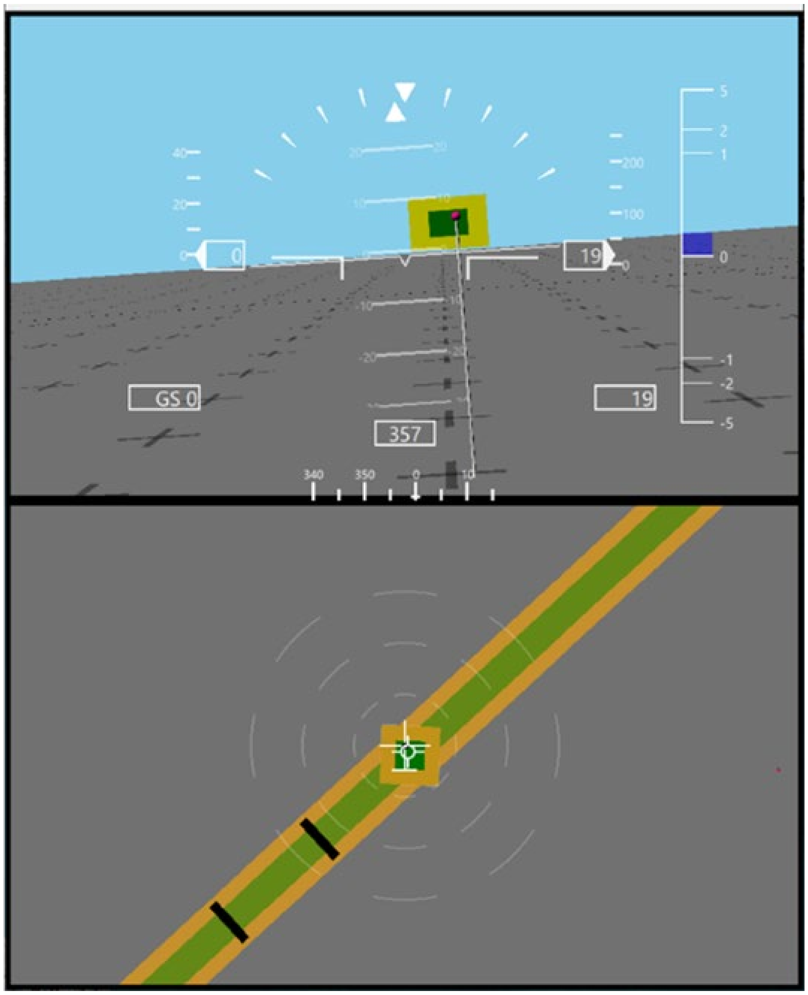


Figure 26: MCRUER Application Pilot MTE Cueing

The system is composed of two key elements for onboard usage: the tablet-based displays and the MCRUER Data Acquisition System (MDAS). The tablet-based displays provide the interface for pilot cueing and data collection for the FTE. The MDAS is a system that collects live-time research quality inertial data and GPS position. The MDAS drives the displays, directly feeding data to both pilot and FTE applications.

The tablet-based display provided to the pilot is mounted on the dash, practically becoming a heads-down display that gives pilots general aircraft state information when no test points are being collected. The pilot tablet is controlled by the FTE tablet which resides with an onboard FTE. On the first checkout day, the virtual HQTE courses being displayed to the pilot are used to verify the boundaries of the physical courses. As seen in Figure 26, the desired and adequate boundaries are displayed with the MCRUER system. The checkout pilot was able to fly the physical courses against the virtual display to confirm proper course setup. For the rest of the test campaign, MCRUER was used for its testing process. Figure 27 highlights the key elements of the system.

Figure 27: MCRUER System Overview

When ready to start the evaluations, the flight test engineer (FTE) selects the first HQTE from the available list. This action opens the task card review display in Stage 1 on the FTE's tablet. The pilot will see a summary of the HQTE along with the relevant performance criteria. The FTE will view similar information, along with a preview of the task display. Once the pilot is prepared, the FTE confirms the HQTE to be assessed and proceeds to Stage 2. In this stage, the pilot views the task display, while the FTE sees a smaller version alongside time history performance figures. Once the pilot is in the HQTE's starting position, the FTE initiates the task, triggering a brief countdown on both displays. The pilot then executes the HQTE as the FTE observes and makes notes, using time history charts and live performance calculations to track the pilot's performance and comments. After the task is completed, the FTE transitions the display to Stage 3, where both the FTE and the pilot can view and record scores for the relevant rating scales, such as the Cooper-Harper HQR and Pilot-Induced Oscillation Tendency rating. Cabin audio including the pilot's commentary is recorded throughout the evaluation for each run. The data, audio files, performance calculations are all individually saved for each run, diminishing the need to do post process data splitting. After a flight, all the data collected during the tests is made available as a tool to support pilot debrief and discussion. This live playback, ratings, pilot comments, cabin audio, and plots.

5.6 Results

The following section presents results from the flight test campaign. Tables of the results obtained are contained in Appendix B. Tables B-2 to B-5 displays below show the recorded runs from the test campaign, separated with respect to HQTE. Notes from the tests, HQR, PIOR, and configuration information are also shown.

5.6.1 Precision hover

All three versions of the maneuver involved a run-in speed of 6-10 kts on a 45° azimuth from the nose to capture a target. All three control response configurations were tested for both 6kt and 10kts.

5.6.1.1 Run-in speed

The team agreed that it may be beneficial to have a groundspeed stabilization requirement/recommendation prior to executing the hover capture to elicit comments on this capability. Per the general discussion above, this will not affect the HQ rating assessed. There was no intended limitation on run-in distance. Allowing for stabilization on a run-in speed, with repeatability allows the pilot to quickly discern a deceleration point for repeat events and shortens the adaptation time to proficiency in the maneuver. There should be some recognition that some response such as TRC may be integrated automatically based on groundspeed. The consensus here was that if the TRC automated transition occurs within the 6-10 kt speed band then the capture should be demonstrated on either side of the speed that the transition occurs. If multiple selectable modes are available such as TRC and a baseline mode, then the maneuver should be performed with the baseline response type such as ACVH, and then in TRC. Additionally, the team felt that the different run-in speeds did not require that the capture times be adjusted. In fact, in some cases, such as TRC, the requirement to modulate the capture changed such that the 10 kt run-in showed lower workload than the 6 kt run-in.

5.6.1.2 Capture performance

Both FAA pilots agreed that the constraints on position capture and the timing requirements were appropriate for civil certification. Both FAA pilots and NRC safety pilots also agreed that the stabilization criteria that were briefed were worthy of documentation to reduce variability in ratings. For the degraded mode of ACVH the pilots quickly learned that high gain inputs resulted in overcontrol, but that the underlying aircraft disturbance rejection and hold capability could be counted on. Therefore, there was compensation applied to make a low frequency deceleration capture and then endeavor to get out of the loop as quickly as possible to rely upon the velocity hold or TRC to maintain position.

5.6.1.3 Stabilized hover

The current requirements in EUROCAE ED-295 call for a 10 second stabilized hover only, while ADS-33 and the FTG call for 30 seconds. To examine this difference, pilots were given a mark call at 10 seconds and then one at 30 seconds and asked if they felt that there was sufficient activity to warrant keeping the 30 second difference. In the cases examined using degraded ACVH, both pilots found it preferable to allow the aircraft to stabilize the hover, even if on a boundary near the desired tolerance. Residual motions tended to occur if the pilots attempted to sweeten the solution on the targets. Ultimately, both pilots felt it a good practice to leave the 30 second stabilization time in place, to examine such degraded conditions and to provide a temporal requirement for the task.

5.6.1.4 Tailoring performance criteria

Hover height, as discussed above, would likely be tailored to some degree and bears further discussion outside the results of this testing. As for the other performance tolerances, the traditional criteria is maintained.

5.6.1.5 Questions

The questions proposed for the evaluation were answered as follows:

- Is the precision versus aggression objective met along with small amplitude control inputs? - Yes
- Is the 45° azimuth for control harmony examination appropriate? - Yes

- Definition of undesirable motions should agree with PIOR? - Yes
- Do we constrain tolerances for run-in velocity? - Potentially, yes but don’t use for CHR.
- Should we avoid overly constraining winds? Yes- any wind in band from any direction is acceptable.

5.6.1.6 Course layout and cueing

The team felt that having two vertical hover-boards on two sides of the aircraft was not appropriate from a safety perspective and instead opted for a cone-field on either side, which appeared to provide sufficient longitudinal cueing. As mentioned in the general comments, the placement of the hover board on the ground to the front of the aircraft confounded the vertical cueing with longitudinal drift.

5.6.1.7 Performance

For the different run in times, pilots indicated differences in aggressiveness, yet did not find the need to adjust the capture time. Although pilots did not indicate differences in workload, Pilot 2 performed with higher precision during the 6 kt run compared to the 10 kt runs in both attitude command and translational rate command modes. Ultimately, the 6-10 kt range was appropriate, and requires no adjustment. Figure 28, Figure 29, and Figure 30 show results from the completion of the Hover HQTE. All results shown compare runs conducted at 6 kts and 10 kts. As shown in the results and stated by the pilots, no large differences in performance were found for the specific cases flown during these tests. However, it is acknowledged that the translation speed and therefore the required deceleration is significantly different for the tests. It was found that, for the 10 kt case however, pilots were not able to hold this speed. For these cases, they reached or barely reached the target and then immediately started the deceleration. For the 6 kt cases, the speed could be sustained, which may lead to cleaner test results.

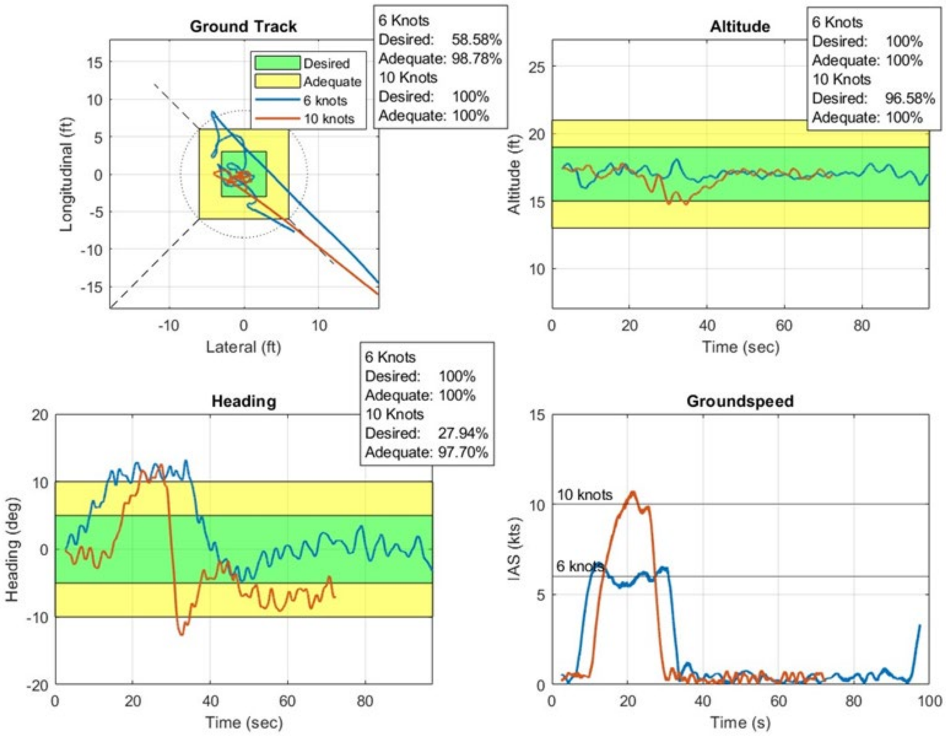


Figure 28: Precision Hover TRC Pilot 1

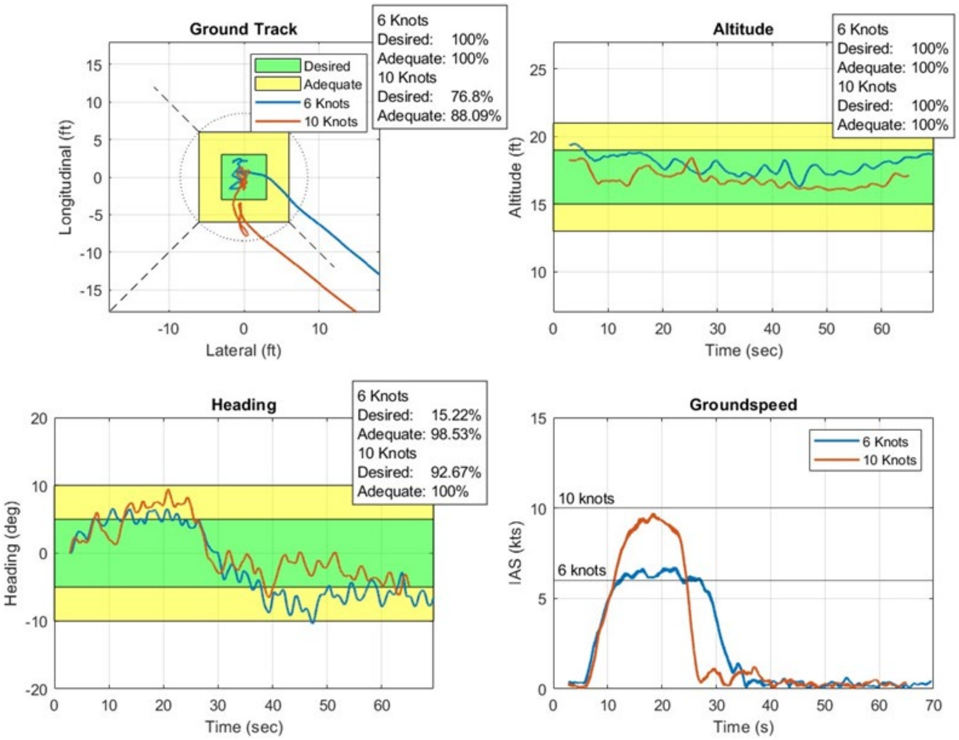


Figure 29: Precision Hover TRC Pilot 2

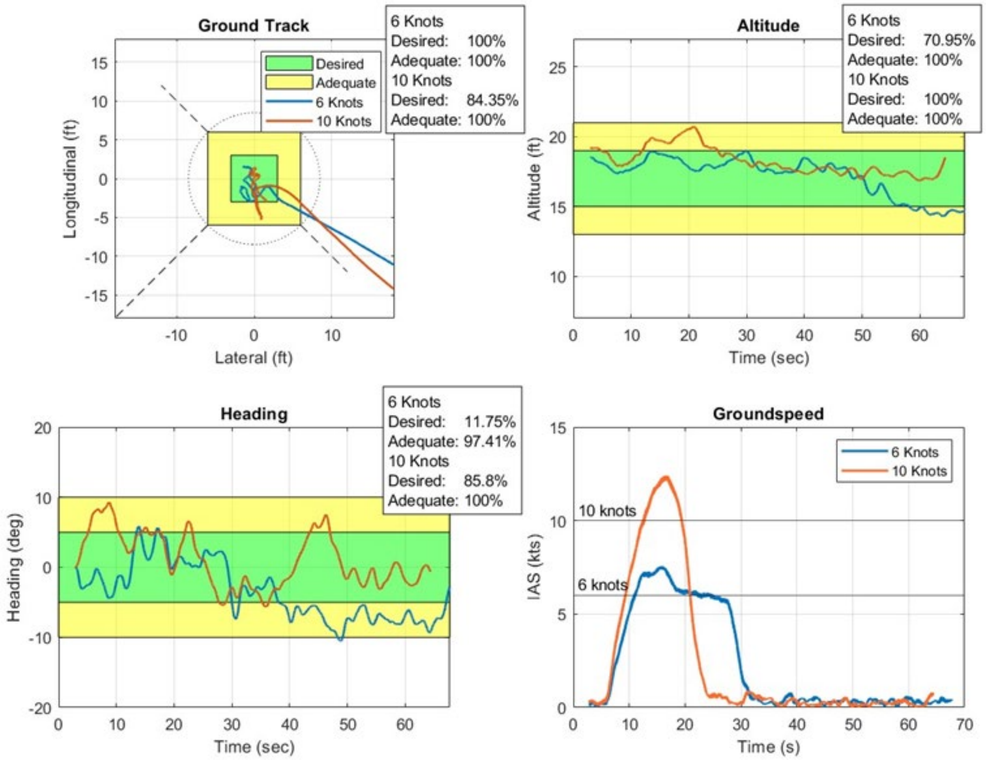


Figure 30: Precision Hover AC

To investigate the difference in required stable hover time with ED-295, pilots were asked to also call a 10 second mark during runs before continuing to maintain the hover for the total 30 seconds. Both pilots favored the 30-second hover time as it allowed them to further examine activity during hover maintenance, especially for the degraded mode. The positional error results, however, show negligible differences throughout the whole hover maintenance portion.

5.6.2 Pirouette

5.6.2.1 Time constraint for entire maneuver

The time constraint for the entire maneuver was deemed suitable in that it drove a sideward flight velocity of around 6-7 kts around the course. Both the nominal ACVH and TRC showed good performance in this regard. During degraded ACVH tests the pilots mentioned that they chose to make corrections slower and in a sequential fashion but were still able to perform the maneuver well enough to achieve desired tolerances.

5.6.2.2 Final capture constraints

The ADS-33 Pirouette has no specific position or timing constraints on the final hover. The team felt that position capture tolerances like that proposed by EUROCAE were appropriate for the precision/aggressive maneuver but that a time constraint on capture would further define capture aggressiveness. This is important as it informs us how harmonious the lateral-directional cross-control is and how easily it can be washed out by the pilot. The capture times that are like the precision hover were questioned as possibly being too tight, but the greater position tolerances balanced this concern.

5.6.2.3 Height

Both ED-295 and ADS-33 indicate a tolerance of +/-10 ft for the adequate tolerances, while the FTG indicates +/- 5 ft for adequate. The tolerance of 10 ft makes more sense than 5 ft and that a constraint such as 10 ft or +/- half of the hover height, might be better suited to safe operations and can be adjusted based on later IGE/OGE discussions.

5.6.2.4 Tailoring

There were suggestions that tailoring was preferred by applicants to preserve hover endurance in eVTOL so 180° turns were accomplished. The full 360° turn made less demands on course with only one cone-field required, pressed a temporal stress on the pilot, and captured various wind effects better. It was also noted that in 180° of turn there could be little time in maintenance of the cross-control since the pilot had to accelerate and decelerate in the shorter arc of 180°. If, for instance, a control response type has a transition band in the range of 6-7 kts, such as TRC to acceleration command, some negotiation should be expected to adjust total time for the maneuver based on faster or slower speeds, but the capture constraints should remain the same.

5.6.2.5 Winds

The team felt that the requirement to fly in winds was warranted and drives the cross-control maneuver and helps illustrate the benefits of advanced flight control designs that utilize groundspeed. The team agreed that the use of the 360° maneuver addresses this requirement nicely and that for the sake of efficiency it is not necessary to start the maneuver at a critical azimuth or off the nose but rather except winds from any azimuth, as long as they are in band.

5.6.2.6 Questions

The following questions proposed for the evaluation were answered by the FAA pilots as follows:

- Is the examination of cross-axis harmony appropriate? - Yes
- Do we constrain position tolerances for final hover? - Yes
- To avoid overly constraining wind direction, does making turns in both directions suffice? - Yes

- Is shortening of the Course to 180° appropriate? - No

5.6.2.7 Course layout and cueing

The NRC course utilizes a series of four cones every 45°around the circle and normally has a pole with a ball at the center to cue altitude. Since this same course was being used for the hover turn the pole was not installed. However, the RCHH control kept the aircraft within tolerances vertically without pilot intervention.

The lateral and longitudinal cueing could be improved somewhat with cones between the 45° cones or with a circle indicated on the ground. One pilot felt the circle concept might be too powerful and not support a better cross-check between heading and track. Both pilots commented on weak heading cueing and that that was likely the tolerance that could be exceeded easily with late notice of error. The aircraft had a test boom on it that provided some help in this regard.

The start position used a cone-field for lateral tolerances which was again used for the final capture. This worked well and was considered beneficial as opposed to the two cone-fields required of the 180° variance. If the Pirouette course is used also for the Hover Turn this will require this cone-field to have two different sets of position tolerances indicated.

Figure 31 and Figure 32 show results from the completion of the Pirouette HQTE, both for the 180° and 360° tailored versions. As shown, the 360° version was completed within the time available, with results suggesting that this time could be shortened. However, the reader is reminded that the tests were conducted with a helicopter, and not a powered-lift aircraft. Halving the course length led to a reduction in time required by approximately 25%. This shows that the relationship between time required and course length is not linearly correlated and requires calculation to ensure similar levels of aggression, if the course will be reduced. One observation was that both pilots were able to hold ground speed for both tailored versions of the maneuver.

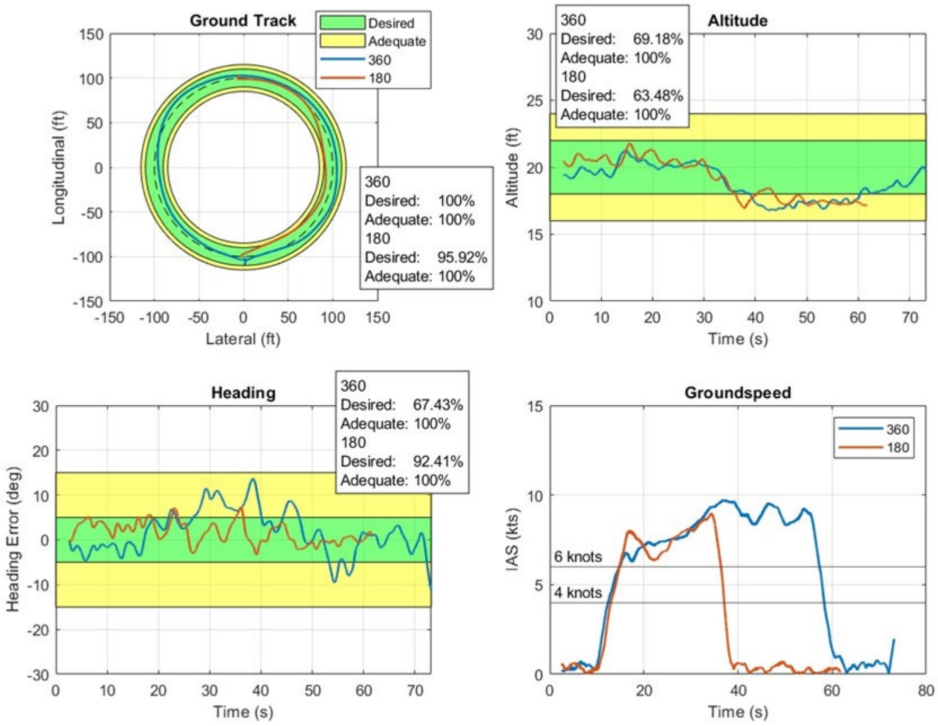


Figure 31: Pirouette AC Pilot 1

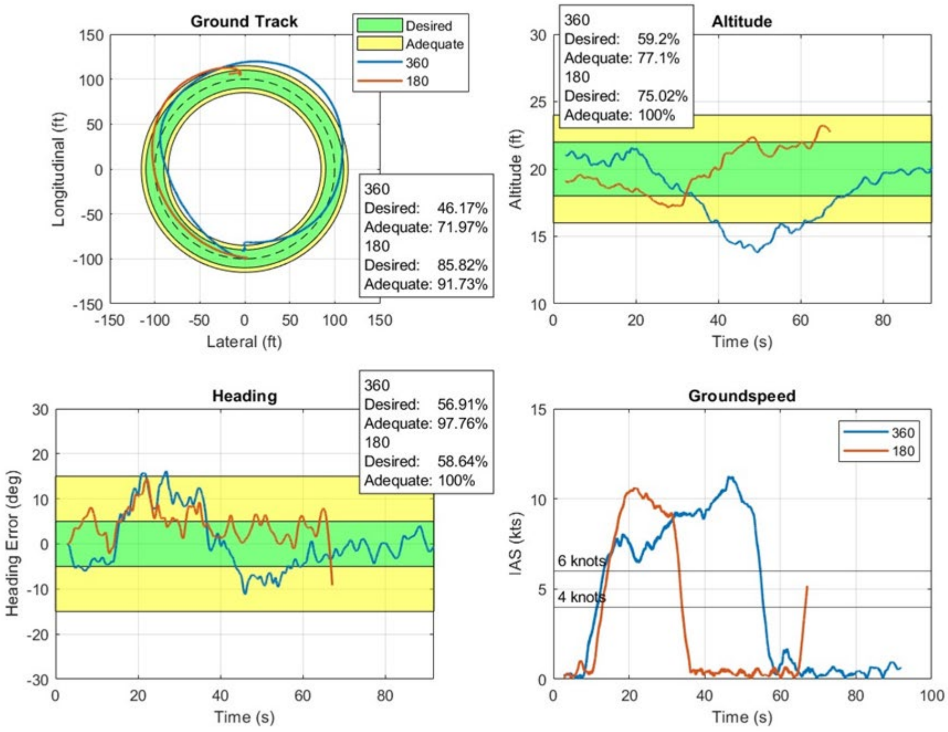


Figure 32: Pirouette AC Pilot 2

The team felt that the full 360° turn made less demands on course with only one cone-field required, pressed a temporal stress on the pilot, and captured various wind effects better. Pilots indicated that it was harder to connect larger inputs in the shorter arc as they were given less time to stabilize their controls before having to enter the deceleration state.

5.6.3 Lateral reposition

5.6.3.1 Run-in velocity

The 15 kt velocity, as described in FTG maneuver, could provide for very relaxed acceleration and decelerations if all the pilot had to do was reverse his acceleration upon reaching 15 kts. Recall that the ADS-33 maneuver does this same thing within 400 ft for 35 kts. The team felt it would be preferable to use this time on the 400 ft course to assess how well a groundspeed could be achieved and held for a time. For the 400 ft distance, a requirement to hold speed at 15 kts for 4 seconds allowed for a reasonable acceleration to capture this speed and at the same time allowed for a deceleration that approximated the adequate time that was to be imposed on the final deceleration for capture of the hover with some margin. As in the precision hover, the requirement to capture and hold speed was not used as a driver for the assignment of CHRs but rather to solicit comments on the efficacy of the response types. There was not a clear answer to the top sideward flight speed that makes sense. With the capture constraint in place, one could change the distance according to the higher speed used if there was a desire to capture NFE boundaries. For now, the 15 kt sideward flight speed would be equivalent to the top of the proposed moderate wind band for demonstration in winds, which seems argument enough for that speed.

5.6.3.2 Hover capture

Since the maneuver was deemed to be an aggressive maneuver the team felt that a time constraint placed on the deceleration and capture, like that used in Precision Hover, would ensure an aggressiveness level that would stress the design appropriately. Additionally, the position tolerances used by both ADS-33 and EUROCAE seemed more appropriate for final capture of an aggressive capture than the tight tolerances of the FTG. This was borne out in the flight tests where desired position tolerances in the secondary longitudinal axis were sometimes violated during the deceleration and capture of the hover using the Level 1 FQ designs.

5.6.3.3 Distance

The team recognized that different sideward flight speeds that may be examined should utilize different distances for the reposition to elicit similar responses. In this vein, 10 kt points were done at shorter distances. However, insufficient time was available to fully examine various speed and distance combinations toward a formula that we could recommend for tailoring. For lack of this formula, we can still provide guidance as to how we were constructing the maneuvers. The distance should allow for: a moderate acceleration + capture of the target speed + 4 seconds on speed + margin of about 2 seconds + a smooth deceleration to achieve the final hover position within "adequate" time tolerances. If targeting desired time tolerances, this should allow for even greater margin after the run-in speed is established and before the deceleration is started.

The shorter course with the same target ground speed warranted a smaller speed maintenance time, but the pilot indicated a controllable deceleration and did not notice much difference. The pilot indicated for 10 kt case with a 300 ft track that it was a very leisurely maneuver. The speed was maintained for about 10 seconds, longer than the nominal and 15 kt variation.

Since the 300 ft run at 15 kts was comparable to the nominal run, tailoring may be applicable to adjust the length of the course given that the other criteria remain in place.

5.6.3.4 Winds

The FTG dictates that the maneuver be performed in moderate winds. A late draft of the guide also constrained this to having the winds off of the nose. The ADS-33 and EUROCAE ED-295 do not require that the maneuver be done in anything but calm winds. Because of the proposed change in the maneuver aggressiveness, the team felt that this maneuver need not be done in winds. These courses are not easily adjusted and requiring them to be done into the wind would be considered unreasonable.

5.6.3.5 Questions

The following questions proposed for the evaluation were answered by the FAA pilots as follows:

- Capture and Maintenance of a sideward flight speed? - Yes
- Aggressive deceleration akin to boundary avoidance maneuver? -Yes
- Targeting Moderate amplitude control inputs? - Yes
- Should distance be tailorable for airspeed envelope? -Yes
- Winds- off the nose or no wind requirement? -No moderate winds
- Guidance for Top speed? - 15 kts good, but tailoring may be allowed here with distance

5.6.3.6 Course layout and cueing

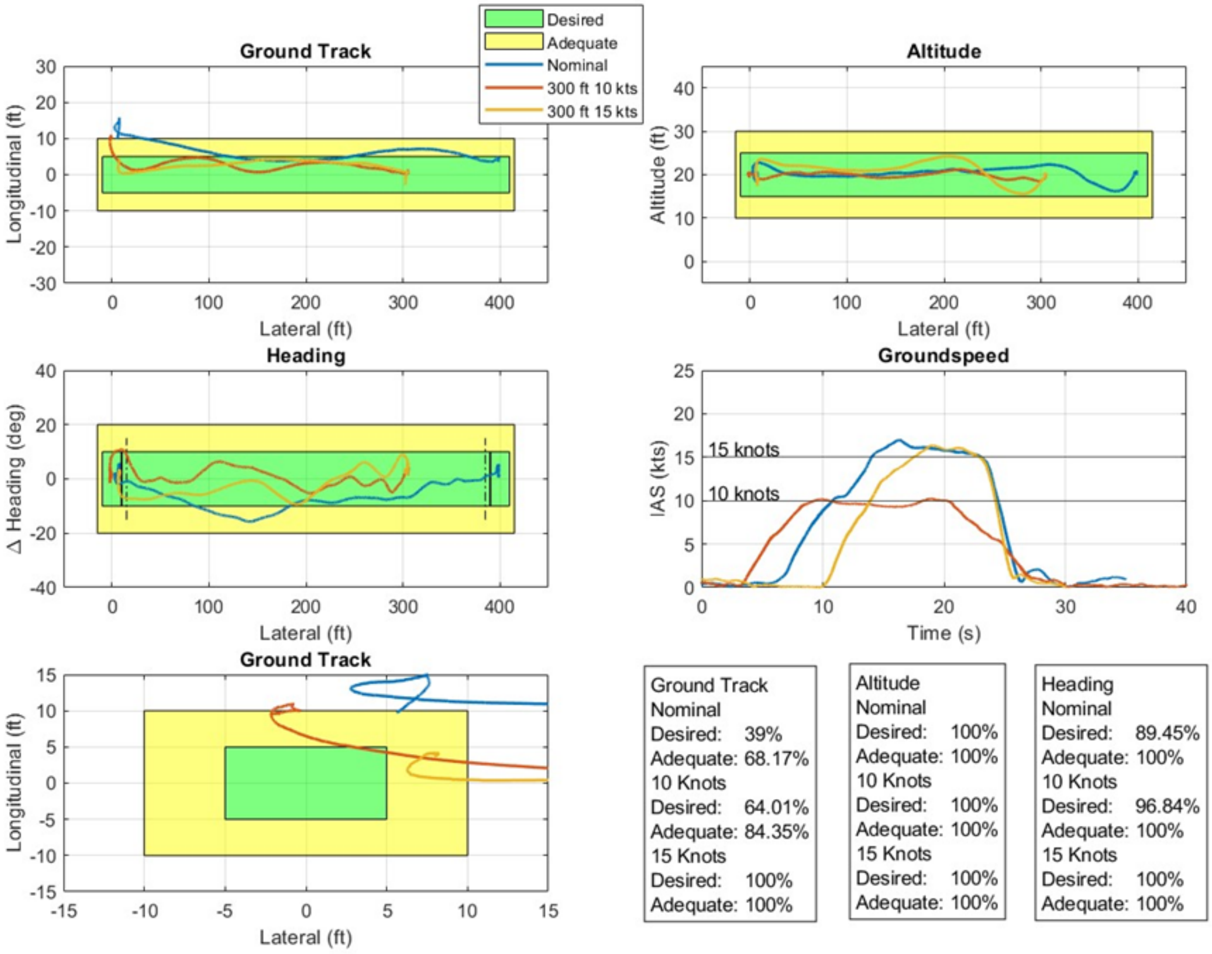
The ADS-33 Lateral Reposition course at NRC was changed to include hover boards at the start and stop positions. These boards were placed on the ground in a fashion like the Precision hover.

They indicated the 5 ft and 10 ft position tolerances of the original FTG maneuver with lines of cones outside them, which helped cue the modified tolerances of 10 ft and 20 ft. In recognition of the large hover board size for the increased tolerances, allowances were made to use the cone-fields for adequate position tolerances in combination with a board that represented desired tolerances.

To view the hover boards completely from 20 ft height when at the aggressive bank angles for deceleration, the center of the lateral course was shifted back 20 ft and position tolerances indicated with lines of cones down the course as described in the FTG. Additional cone-fields were set outside the course on either side for better longitudinal cueing.

As in many versions of this course, height cuing for the actual course was weak when transiting between the target boards. The RCHH control response that was flown aided in meeting the height tolerances throughout the maneuver.

Figure 33 shows three versions of the Lateral Reposition completed by Pilot 1. These were flown with different aspects of tailoring. This includes changes to the course length, and the speed. Performance for all of the attempts was consistent throughout. It was found that the 4 second stable translation did force the aggression in the maneuver and appears a good requirement to drive the length of the course. For the 10 kt case, the pilot was able to maintain a stable 10 kt translation for over 10 seconds. This indicates that the course could be shortened for this case.



Ground Track
Nominal
Desired: 39%
Adequate: 68.17%
10 Knots
Desired: 64.01%
Adequate: 84.35%
15 Knots
Desired: 100%
Adequate: 100%

Altitude
Nominal
Desired: 100%
Adequate: 100%
10 Knots
Desired: 100%
Adequate: 100%
15 Knots
Desired: 100%
Adequate: 100%

Heading
Nominal
Desired: 89.45%
Adequate: 100%
10 Knots
Desired: 96.84%
Adequate: 100%
15 Knots
Desired: 100%
Adequate: 100%

Figure 33: Lateral Reposition Pilot 1

5.6.4 Hover turn and hold

5.6.4.1 Position Tolerances

All three versions of the maneuver use 3 ft and 6 ft for desired and adequate position tolerances respectively. Because the hover turn has been notoriously weak in cueing this based on ADS-33 experience, the position tolerances may need to be rethought, especially if turns are done in winds and at greater than 180° of heading change. One should remember that the turn is around the CG and not the pilot and pilot estimation of this will be affected by his distance away from the CG.

5.6.4.2 Arc of turn

Multiple versions of the maneuver were flown with first the FTG version, then a 90° with stop and continued 90° turn to the 180° position, and a 180° turn as described in both the EUROCAE and ADS-33. Surprisingly, the FAA pilots both preferred the current FTG maneuver of turning to 90°, and then continuing a 270° turn back to the start. Various reasons were offered. The full 360° turn, like the pirouette, pressed a temporal stress on the pilot, and captured various wind effects better. It was also noted that in the180° of turn there could be little time in maintenance of the turn rate since the pilot had to accelerate and decelerate in the shorter arc of 180°, especially if it were broken up into two 90° segments. The team also felt that the full 360° turn made less demands on course setup with only one two cone-fields or hover-boards required.

5.6.4.3 Timing of maneuver

This HQTE as described in the FTG emphasizes precision maneuvering and a reduced level of aggressiveness as will be expected for civilian applications when maneuvering within a heliport. In this vein, the time limits showed a desired rate below 9°/sec and focused on a precision capture of heading 90° away from the start position. These timings were deemed suitable by the FAA pilots.

5.6.4.4 Winds

Wind effects were perhaps the strongest reason for preferring a full 360° hover turn over the 180° turn. This specially made sense if the winds for the start position were not prescribed. In this way maximum efficiency could be gained by not requiring course orientation into the wind. The 90° hover capture also made sense for the wind case, ensuring that the hover capture would be at a substantially different wind azimuth than the start point, for instance, headwind to crosswind.

The team felt that it may be important to demonstrate this HQTE in the wind since it would highlight differences in attitude-based, groundspeed-based or position-based control response types. It would also highlight inter-axis coupling if present.

5.6.4.5 Questions

The following questions proposed for the evaluation were answered by the FAA pilots as follows:

- Inter-axis coupling or cross-axis contamination is assessed? - YES
- Do we need a 90° stop? - YES
- Can we avoid overly constraining winds by making 360° turns in both directions? - YES

5.6.4.6 Course layout and cueing

As stated before, cueing for CG position is notoriously weak and hard to integrate into the pilot cross-check for the hovering turn. ADS-33 does recommend using the pirouette course in this regard. In the NRC case the few cones every 45° of arc did not present sufficient cueing for CG position. From past ADS-33 experience, a continuous circle at 100 ft is more helpful but still pilots tend to misinterpret the delta between the nose position and the circle, when altitude changes or the pitch attitude changes. Some discussion was offered as to placing a circle with radius of that approximating the pilot eye position from the center of the pirouette course. This would minimize the issues just mentioned with the 100 ft circle. Due to time constraints this was not examined as a cueing option.

Another issue was in placing the aircraft CG over the center of the pirouette course in the first place. Having two hover boards at the 0° point and 90° point, as depicted in the FTG did not align the pilot view to the side with the center of the board to the side. Instead, one had to adjust their eyepoint to establish this eye-point delta. This becomes problematic in the dynamic maneuver if this is used to aid in position maintenance. Having hover boards also made little sense from a safety perspective in that during the maneuver the aircraft would be tail to the boards. In the end, cone-fields were used at the 0° and 90° positions.

Figure 34 shows the results from three of the Hover Turn HQTEs. As shown, ground track maintenance was a significant issue during the completion of the HQTE, as the course cueing was not adequate for the pilot to correctly maintain his position. There were no apparent changes in performance with various course lengths and timings were generally found to be acceptable.

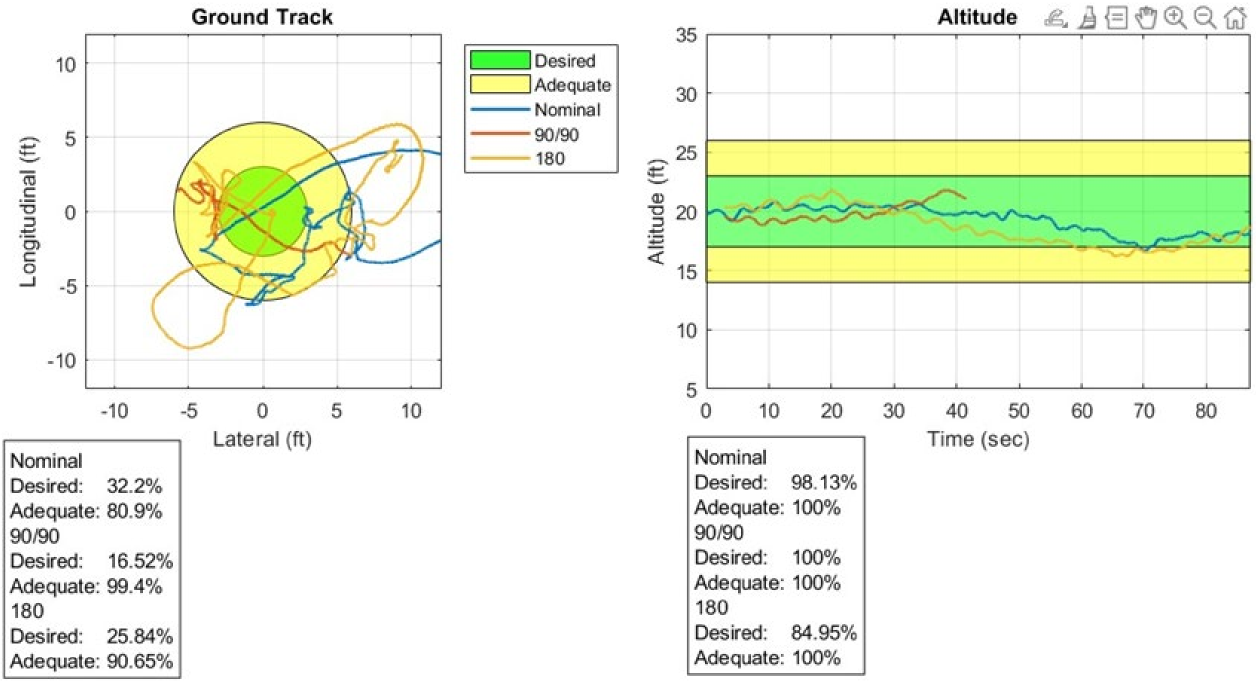


Figure 34: HTH Pilot 2

5.7 Discussion

In this section, the overall results are discussed, along with considerations for HQ testing to be conducted for civil certification.

5.7.1 Cooper-Harper Scale Handling Qualities Ratings

It is not intended, in the current HQ approach, to use HQRs as strict pass/fail criteria. Subjective ratings alone are not seen as sufficient to ensure that the vehicle is safe for operation. Moreover, HQRs are intended as guidance only, to determine potential HQ issues which may occur. For this reason, no thresholds are placed on minimum HQRs obtained. Acceptance must be discussed on a case-by-case basis. In addition, it is not intended to average HQRs to obtain a single rating. Individual ratings are important to ascertain deficiencies and pilot intra-variability.

5.7.2 Cueing

Adequate cueing is critical to obtain representative feedback regarding HQs from pilots. It is important to ensure that all cues to judge both desired and adequate performance are available during completion of the HQTEs. These should be evaluated in a dedicated test prior to evaluations. Cueing in-flight and simulator may be different given the visual cueing field of view. Commonly, in simulation, additional cues are made available, particularly to judge height cueing. If external visuals cannot give the pilot all information to make judgement on desired/adequate performance, it may be acceptable to use display-based cueing and/or feedback from flight test engineers. This was demonstrated during the flight tests conducted in this study, with the use of the MCRUER tablet display system.

5.7.3 Task tailoring

Given the nature of certification testing and the range of vehicle types and concepts of operations to be certified in the powered-lift category, it is believed that some degree of task tailoring will be required. Examples include performance-based limitations of the aircraft and transition speeds/envelopes. It is important however to consider that HQTE performance tolerances where the requirements correspond to rules cannot be tailored and must be standard. In this work, task tailoring was considered for several HQTEs. Generally, tailoring such as shortening HQTEs etc. was not advised. Further work is required to conclude on suitable tailoring aspects for all HQTEs. For the four tested in the flight test, proposed tailoring aspects are included alongside the updated performance tolerances. This should act as guidance for any applicant intending to tailor specific HQTEs.

Handling qualities are one piece in overall certification and are assessed with task elements. Task elements (referred to in this report as HQTEs) are isolated from other pilot workload tasks such as running checklists (normal, abnormal and emergency) navigation, and ATC communications. HQTEs are not pass/fail and do not have absolute prescriptive criteria to meet to be certified. The airworthiness authorities' decision as to whether the handling qualities are suitable for civil certification must only be made after other integrated evaluations are considered that take into account overall workload in an operationally relevant environment.

Furthermore, the success criteria for an element (HQTE) are the absence of handling qualities cliffs. The final determination for vehicle suitability to operate safely in the NAS can only be made combining findings following additional evaluations relating to pilot workload. For example, integrated evaluations of workload are performed by flying operationally relevant scenarios. This is done during human factors evaluations to assess other workload stressors beyond handling qualities. Some of these other tasks include navigation, communications with ATC, traffic avoidance, and checklist usage. Examples of these evaluations are already performed in FHA validations.

After handling qualities are assessed via multiple elements (HQTEs) and supporting data are reviewed, the authorities can assimilate other findings on pilot workload (from integrated evaluations using a sample mission) decide if the handling qualities are sufficient to allow an average pilot to perform the mission without exceptional skill, strength, or alertness. The integrated evaluations are accomplished anyway in the course of applicant showing of human factors compliance. This does not constitute an additional burden on an applicant.

5.7.4 Desired/adequate performance tolerances

Desired and adequate performance tolerances have been investigated in this work. These were tested in-flight, with feedback solicited from three qualified test pilots. The philosophy of the use of HQTEs and setting desired/adequate performance tolerances is to ensure that ‘no unsafe condition’ is found, relating to the context of operational relevance. HQTEs are flown both in-flight and in-simulation to demonstrate this. After performing HQTEs to verify there are no handling qualities cliffs, the authority should review all supporting data to decide if there is an operationally relevant safety impact.

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A Accident/incident analysis

1. Background

The incident and accident reports contained in this appendix were sourced from the official documentation prepared by the flight safety agencies conducting the corresponding investigation, when available. Other sources, like flight safety websites and aviation specialized magazines, were used when official documents were not available. Pilot-error accidents were addressed in the context of design-induced error because of the flight control system design.

Indirect flight controls or Fly-by-Wire (FBW) control system designs have been used in military airplanes and civilian transport category airplanes for decades, they have been employed in a small number of military rotorcraft since the 1980's and they are a recent evolution in commercial civilian rotorcraft. Many of the lessons identified from incidents and accidents occurred in aircraft equipped with FBW control systems are applicable to advanced flight controls and Flight Guidance Systems, whether indirect or direct.

Electric Vertical Take Off and Landing (eVTOL) aircraft using indirect flight control systems may employ unique power designs that are hybrid or all electrical; they can utilize unique propulsion and indirect control designs that are hybridized and employ Advanced Flight Controls (AdFCS) to achieve satisfactory handling qualities. These designs are expected to provide increased stabilization and precision for 24-hour operations while affording necessary agility, evolving toward Simplified Vehicle Operations (SVO) that reduce pilot training requirements and it can facilitate transition towards remotely piloted operations.

Below are definitions of Advanced Flight Controls (AdFCS) and Flight Guidance Systems (FGS), derived from Federal Aviation Administration (FAA) guidance material:

- **Advanced Flight Controls** [3]
  From FAA Policy Statement, Rotorcraft Advanced Flight Controls (AdFC) Handbook- The term "Advanced Flight Controls" (AdFC) describes systems that differ from conventional flight control systems with respect to the applied signal processing and signal transmission technology. Conventional flight control systems typically use mechanical elements (rods, bell cranks) for transmitting command inputs from the pilot's controls to the rotor blades for primary control. Conventional systems may include superimposing electronic stability augmentation systems and autopilots with some level of control on a mechanical primary

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[3]. Anon., *Guidance on Analyzing an Advanced Flight Controls (AdFC) System*, AC 29-C; AC-MG 17 Federal Aviation Administration, June 13, 2014.

flight control system. AdFC systems, on the other hand, typically feature electronic signal processing and signal transmission using electrical wires, such as fly-by-wire, optical fibers (fly-by-light), or potentially even non- mechanical media (radio frequency control). Novel forms of these types of flight controls systems include unique hardware like inceptors (e.g., side stick controllers). Since AdFC systems typically employ a high level of integration and increased functionality relative to conventional systems, a greater possibility exists for development errors that are not as obvious or testable as those for conventional flight control systems.

- **Flight Guidance Systems** [4]
  The FGS is primarily intended to assist the flight crew in the basic control and tactical guidance of the airplane. The system may also provide workload relief to the pilots and provide a means to fly a flight path more accurately to support specific operational requirements, such as Reduced Vertical Separation Minimum (RVSM) or required navigation performance (RNP). The term "FGS" includes all the equipment necessary to accomplish the FGS function, including the sensors, computers, power supplies, servo-motors/actuators, and associated wiring. It includes any indications and controllers necessary for the pilot to manage and supervise the system. Excluded from definition. Any equipment or component that remains mechanically connected to the primary flight controls or propulsion controls when the FGS is not in use is regarded as a part of the primary flight controls and propulsion system, and the provisions for such systems are applicable.

The implemented AdFCs are expected to depend on significant automation and augmentation, leading to a degree of disconnect between the flight crew and the direct control of the aircraft effectors. In the attempt to move towards Simplified Vehicle Operations (SVO), response types are expected to evolve from attitude control-based types towards flight path controls, which tend to increase the pilot's disconnection from direct control over the individual effectors.

As stated in page 6 of Lotterio (2022)[5], reported here verbatim, "The underlying concept of SVO is to use automation to support and eventually partially replace the pilot in his different functional skills."

The General Aviation Manufacturers Association (GAMA) identified the following nine pilot's skill categories:

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[4]. Anon., *Approval of Flight Guidance Systems, Including Change 1*, AC 25.1329-1C, Federal Aviation Administration; October 27, 2014.

[5]. Lotterio, M., *Develop a Method of Compliance to Support Certification of Advanced Flight Controls in General Aviation and Hybrid Vehicles*, DOT/FAA/TC-21/6, Federal Aviation Administration; February 2022.

- Planning and decision making
- Systems management
- Basic airmanship
- Takeoff and landings
- Terminal procedures
- Navigation
- Communication
- Detect and avoid
- Emergency procedures

Research published by GAMA [6] states that "over half of the functional skill categories that are part of traditional pilot training curriculum can be more reliably performed by automated systems than by the average pilot." The intended effect of FBW system integration in Part 23 E-VTOL/UAMV aircraft is to reduce the demand on the pilot to fly the vehicle to eventually reduce his/her training time and cost."

The implementation of an irreversible flight control system implies the use of an artificial feel system, producing control forces that do not correspond to those that would be produced by the control effectors in a reversible control system. The impact on safety of flight is to affect pilot's recovery procedures in case of failure conditions.

The transition from a reversible control system to a highly augmented FBW control system corresponds to transitioning from a control surface demand to a maneuver demand aircraft, in which the demand is a function of the inceptor travel or of the pilot's force exerted on it. This entails a different pilot approach to the execution of the maneuvers and to the compensation technique. More extensive information on the effect of irreversible control systems and high-level augmentation on pilot's situational awareness is available in Lotterio (2022)[5] and Lotterio et al. (2016)[7].

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[6]. Anon., "A Rational Construct for Simplified Vehicle Operations (SVO)," GAMA EPIC SVO Subcommittee Whitepaper, Version 1.0, May 20, 2019.

[7]. Lotterio, M., R. McMahon, P. Schifferle, D. Alvarez, D. Klyde, and P. C. Schulze, *FAA Fly-By-Wire Research Program — Year 2 Follow-On*, DOT/FAA/TC-15/13, Federal Aviation Administration, March 2016.

A specific characteristic of the emerging class of eVTOL aircraft is the redundancy of control effectors in the axes of aircraft control. This can involve automatic control blending/tasking and prioritization, further increasing pilot's "detachment" from the feeling of direct control of the aircraft. The differentiation between primary flight controls and flight guidance systems, as described in the FAA advisory circular AC 25.1329-1C [4], is increasingly blurred with new evolving designs.

An SVO approach to the design and development of AdFCSs inherently leads to an increased level of cockpit automation. Management and understanding of automation can be traced to many of the accidents summarized in the next section. Flexibility in flight control system designs in the form of selectable automation optimizes performance, based on given operations. At the same time, it induces the risk of increased complexity, which can compound control system mode abuse and mode awareness issues. This drives a significant amount of training required to safely operate highly automated aircraft.

While fixed wing aircraft hazard avoidance focuses on prevention of stall or of exceedance of structural loads limits in the high airspeed regime, rotorcraft avoid regions are rotor loadings, structural loads limits, low-speed entry into vortex ring state, and controllability issues related to low-speed wind azimuth. Hazards related to aeroservoelastic (ASE) phenomena are common to both aircraft categories. The hybrid aircraft configurations with mixed rotor and wing borne lift generation that are becoming more prevalent for Urban Air Mobility (UAM) operations must deal with varying combinations of the hazards reported above. The incidents and accidents reported in this document are relative to fixed, rotary and tilt rotor aircraft, with the objective of illustrating the different types of hazards, not necessarily related to the same safety related occurrence.

Table A- 1 contains the occurrence reports, the specific events surveyed by STI, and the main information identifying the event. The aspects considered to be critical are summarized in the table. Table A-2 and Table A-3 contain summaries of the incidents and accidents critical aspects respectively occurring with higher and lower frequency, relative to the selected database. Identifiers to specific events are not included in these tables so that the focus can be on the causal factors.

2. Observations and results

As a general trend, a preponderance of accidents in transport category aircraft can be categorized as Controlled Flight into Terrain (CFIT) or Loss of Control (LOC) which are mostly related to Flight Guidance System crew errors. The large number of FGS errors is because the flight is conducted largely with the use of the FGS instead of baseline primary flight controls in the IFR environment. Many of the LOC are related to inadvertent entry into stall. This is broadly confirmed by the high number of FGS mismanagement and flight crew training related aspects listed in Table A-2.

Referring to the occurrences of incidents and accidents reported herein, the following characteristics can be identified:

1. Over-dependence on automation: failure to self-identify approaching hazardous flight conditions and envelope exceedance such as stall, in one case.
2. Delay of the flight crew to disable erroneous FGS operation and revert to more basic control in the B757-223 occurrence.
3. Incorrect design of hard envelope protection logics, in the A320-213 occurrence.
4. Sensor failures and fault reaction - air data, AOA:
    - Unidentified stall condition in four cases.
    - Reversion to alternate law successful in regaining flight control in two cases, unsuccessful in one case.
    - Active envelope protections not supported by sufficiently redundant sensors, for the B 737 Max.
    - Insufficient annunciation of sensor failure/disagree, for the B 737-max.
    - Data spikes in AOA sensor are not dispositioned properly causing un-commanded pitch down, in one case.
5. Configuration and response type/automation mismatch, in two cases
    - Misunderstanding side-effects of partial automation engagement. Example: AP off but auto-throttles still on, in one case.
    - Using wrong configuration for a given automation function, in one case.
6. Pilot resisting normal autopilot automation to point of extreme aircraft response, in MD-11 and CH-148 occurrences.
7. Pilot's awareness of control laws mode:
    - Assumed automation control when not fully in place, in A320-231 case.

    - Not aware of actual automation mode in use, in A320-111 and A300-622-R cases.
    - Intentional or unintentional abuse of automation mode, in MD-11 case.
    - Failure to use appropriate mode such as go-around.

8. Improper application of non-published emergency procedures for troubleshooting, in one case.
9. Inadvertent actuation of FGS mode: ergonomics of control allowed for inadvertent arm of go-around mode (GO), in A300-622R case.
10. Inappropriately high control forces integrated into the flight controls did not allow for sustained manual override of automation in a failure and did not allow for crew spare capacity, in B 737-Max case.
11. Crew operator training and limitations to be monitored were shown to be inadequate for addressing hazard to be avoided in multiple cases.
12. Multiple controls for a given axis afford conflict of control and loss of control power, in A310 and MV-22 cases.
13. Improper or inadequate blending/prioritization/tasking of multiple control effectors in hybrid-lift aircraft, in CV-22, AW609 and MV-22 cases.
14. Out-of-Phase Oscillatory response: off-axis feed-forward compensation not optimized, in AW 609 case.Aeroservoelastic Interaction: low RPM induced aeroservoelastic interaction, in Bell 525 case. Weight-off-wheels transition in control laws, in S-97 case.

The categories of the critical aspects leading to the incidents and accidents reported herein can be grouped into two main classes: human factors and system related aspects. Below are the lists of the categories forming each of the two classes.

1. Human factor related aspects:
    - Situational awareness
    - Respect for aircraft procedures
    - Flight crew training
    - Crew resource management
    - Pilot’s workload

- Air Traffic Control

2. System-related aspects*:*

- Design fault
- Failure
- System configuration deficiencies
- Flight phase/mode transition
- Airworthiness
- Aircraft flight manual
- Bare airframe characteristics
- Atmospheric conditions

Figure A-1 and Figure A-2 are the graphical representations of the incidence of human factor and system related aspects, respectively, on the occurrence of the incidents and accidents reported above. The prevalence of the four main categories reported above is visible and it is a potential indication of a trend, even if they derive from the current selective, non-comprehensive group of occurrences.

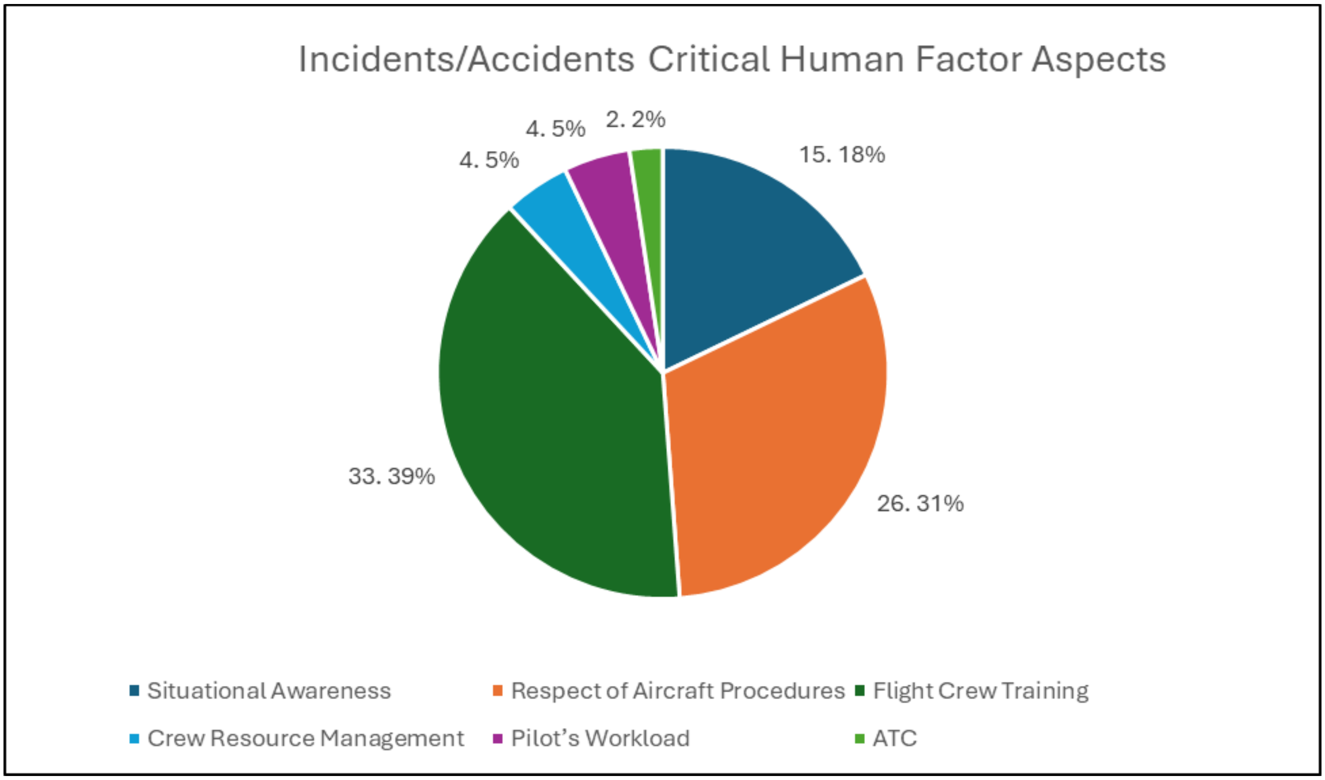

Figure A-1: Incidents/Accidents Critical Human Factor Aspects

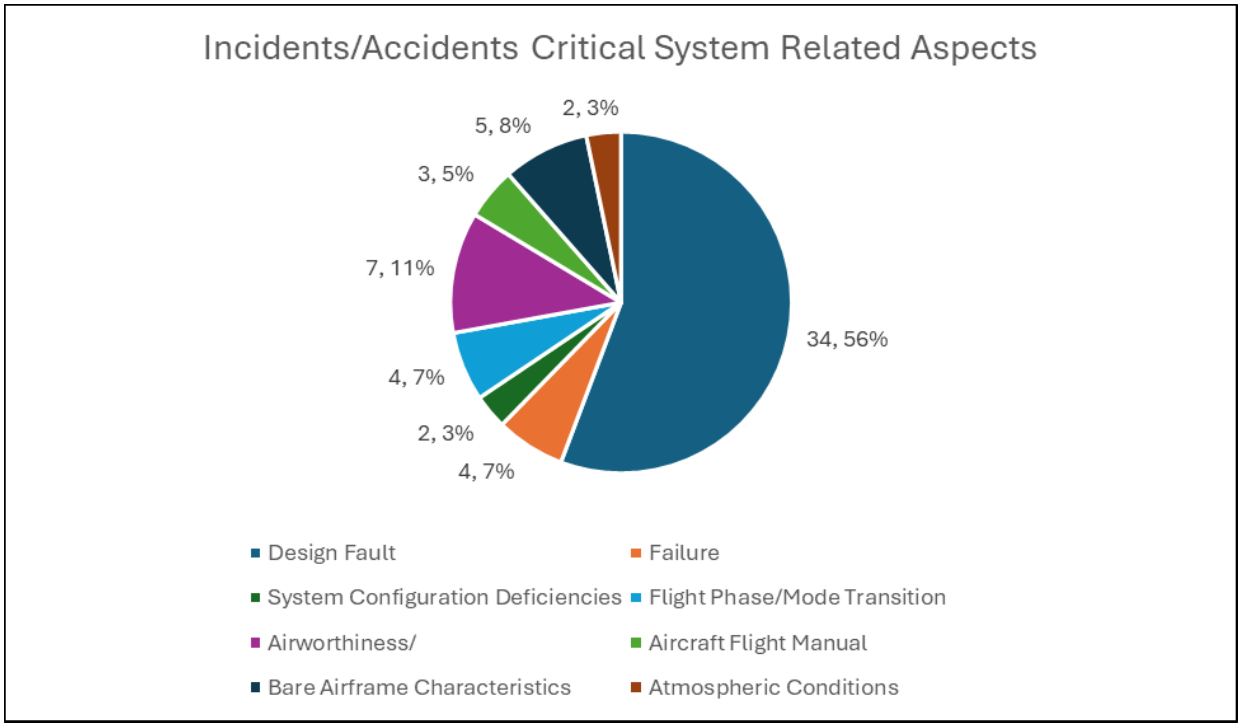

Figure A-2: Incidents/Accidents Critical System Related Aspects

Figure A-3 is the graphical representation of the cumulative incidence of the different critical factors on the occurrence of the incidents and accidents reported above. Flight crew training and design fault are the more frequent categories, with a comparable total number; respect for aircraft procedures and situational awareness correspond to a slightly lower frequency, still higher than the number of all the other categories. Potential connections between critical aspects of different categories can be addressed in a dedicated part of the research.

It is important to consider that data are extracted from a relatively small number of occurrences, focused on mode transition of FBW aircraft. The significantly higher frequency of the aspects from the four main categories reported above suggests that the trend can be considered qualitatively valid also for datasets of a larger number of occurrences.

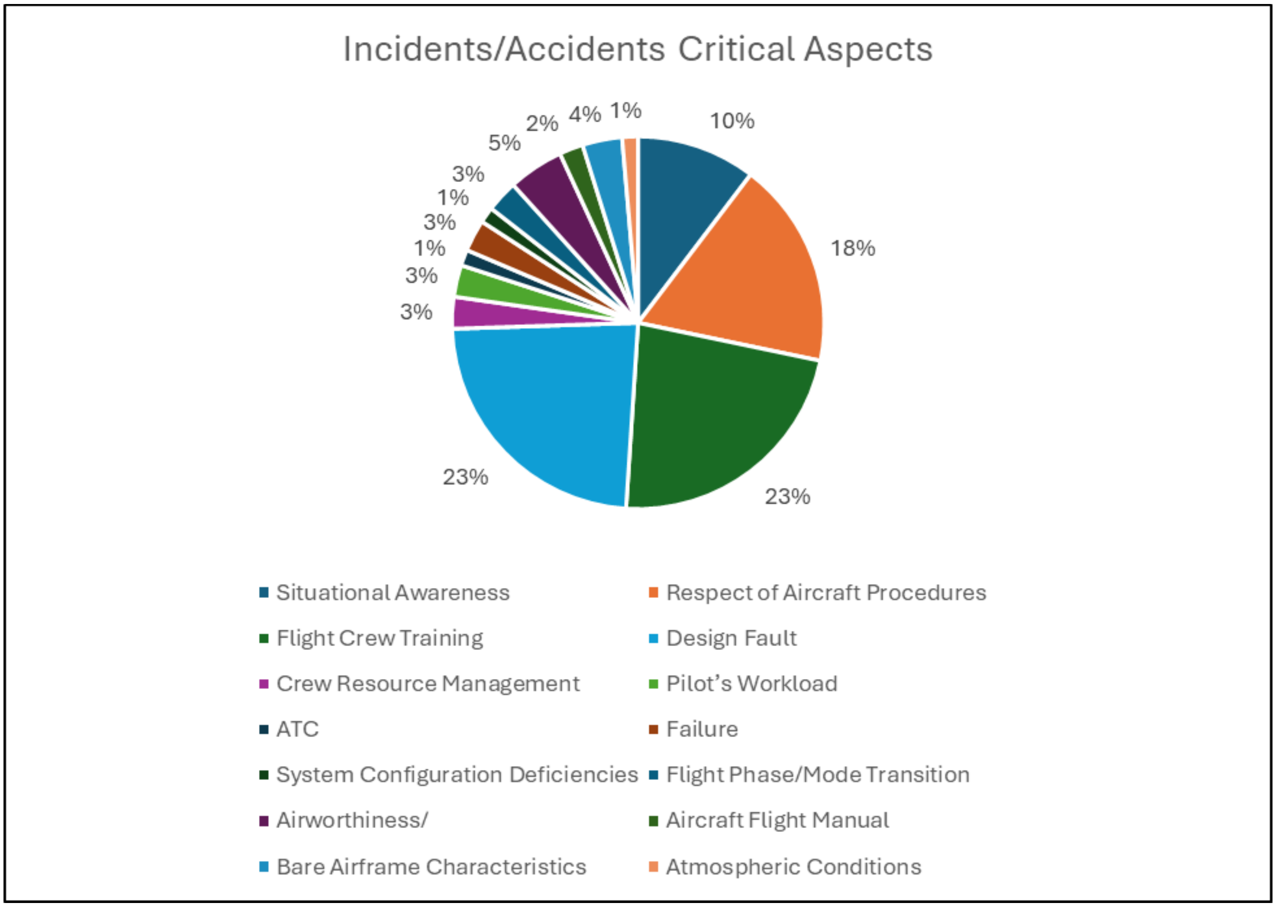

Figure A-3: Cumulative Incidents/Accidents Critical Aspects

The percentages of the different types of critical aspects of incidents/accidents calculated for the selected database broadly match those reported in Belcastro et al. (2017)[8], which were calculated for a larger database and included a wider range of incident/accident types. Figure A- 4 displays the percentages calculated from the database collected in Belcastro et al. (2017)[8]. The categories of the two databases do not coincide exactly. It is possible to identify that the incidence of Respect of Aircraft Procedures is respectively 15% for the current database and 18% for that in Belcastro et al. (2017)[8], Situational Awareness is 10% for both databases, Flight Crew Training, comparable to the sum of Loss of Altitude and Ineffective Recovery, is respectively 23% and 26%. For the system related aspects, the sum of Design Fault and Failures, comparable to the sum of System Failures, Component Failures and Sensor Failures, is respectively 26% and 22%.

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[8] .Belcastro, C. M., J. V. Foster, G. H. Shah, I. M. Gregory, D. E. Cox, D. A. Crider, L. Groff, R. L. Newman, and D. H. Klyde, "Aircraft Loss of Control Problem Analysis and Research Toward a Holistic Solution," *J. of Guidance, Control, and Dynamics*, April 2017.

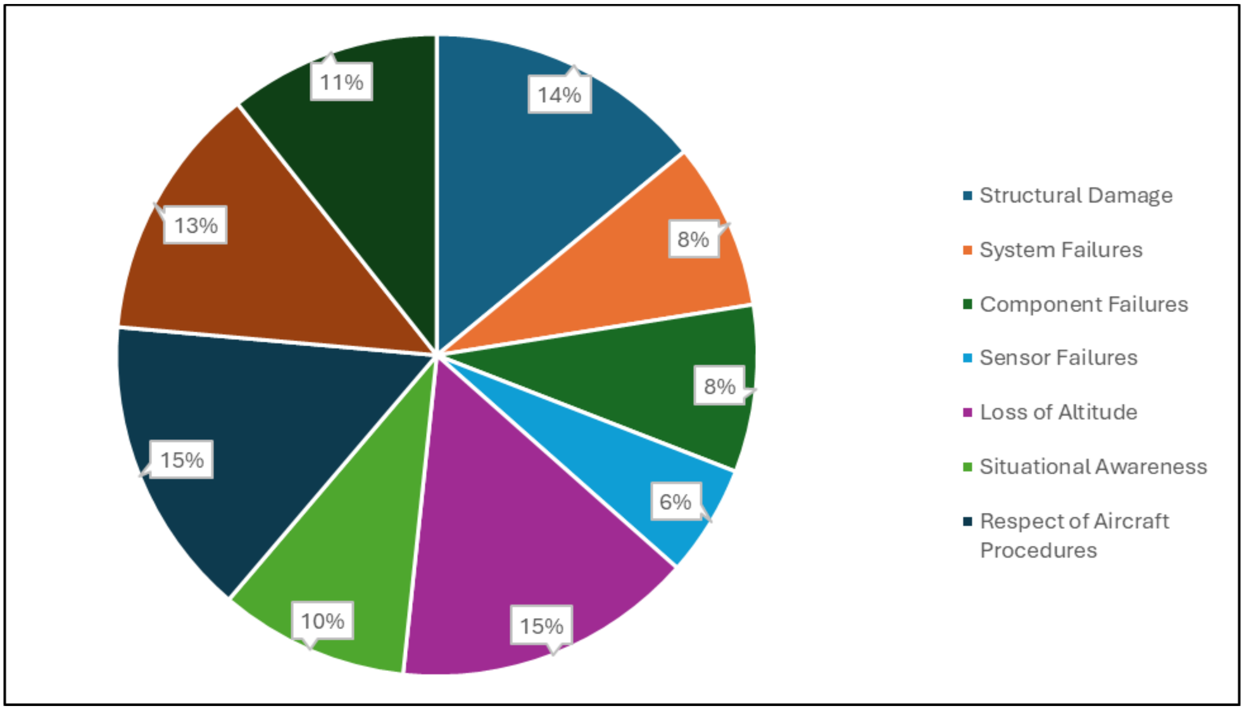
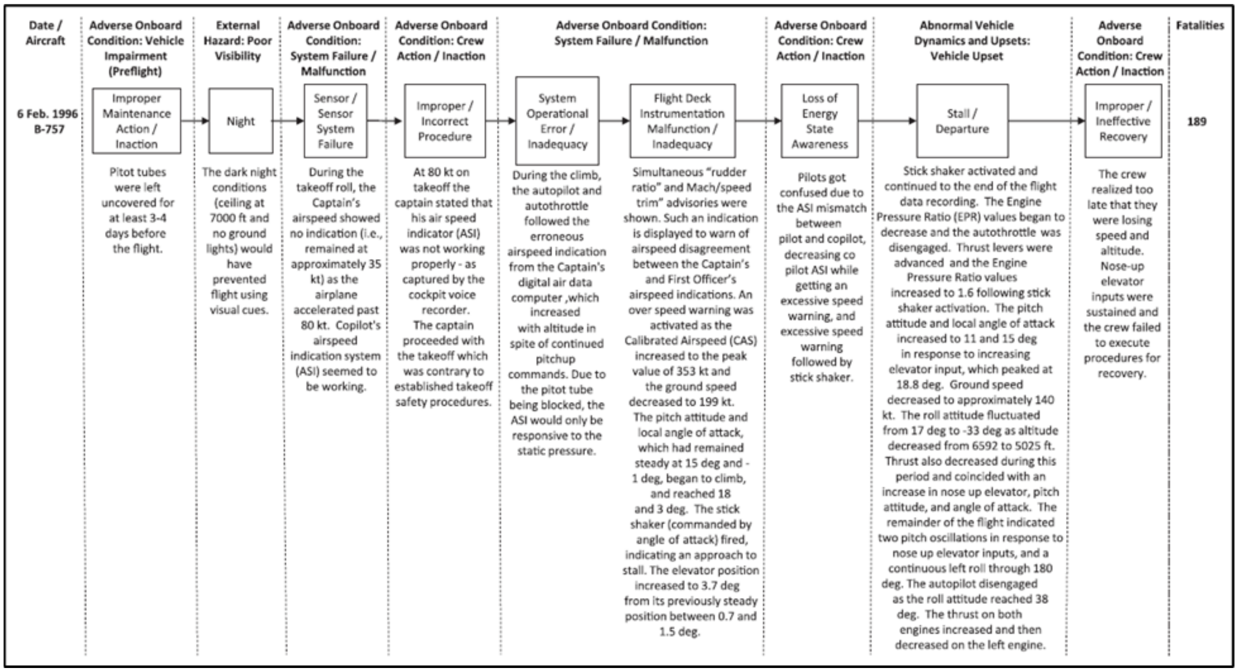


Figure A- 4: Cumulative Incidents/Accidents Critical Aspects

The relatively good match of the incidences of the main critical aspects categories between the two databases is an indication that underlying incidents/accidents causes tend to be stable. This can be considered facilitating a targeted resolution, at the same time it is an indication of the difficulties of an effective application of risk mitigating approaches and procedures.

This trend is suggested also by the relatively close coincidence of the series of events which characterized a sample accident reported in Belcastro et al. (2017)[8], and reproduced in Figure A-5, with a number of incidents and accidents occurrences reported in Table A- 1. This is particularly valid for the accident that occurred on 26 April 1994 at Nagoya Airport and the incident that occurred on 24 September 1994 at Paris-Orly Airport. In the three cases mentioned above, pilots' recovery action from upset conditions demonstrated to be not completely adequate, which is a critical factor independent from the aircraft automation. At the same time, automation contributed to the upset conditions themselves, due to the mismanagement of the automatic system or due to sensor failure. Sensors functional state is a determining factor in initiating the sequence of events producing a part of the reported incidents or accidents.

Analysis of the different occurrences suggests that the effect of automation on the overall capability of the pilot(s) to perform the specific mission phase as required is not univocally enhancing and that automation can affect the execution of multiple tasks within a given flight phase. Understanding of the automatic system functionalities, of the sequence of functions performed autonomously by the aircraft, and of the related procedures is critical. For this reason, as it results from the listed incident and accident reports, a hard separation between “pilot error” and design fault is not always possible. Information about the aircraft manufacturer’s actions following a given occurrence can provide valuable information about its underlying causes.



Pitot tubes were left uncovered for at least 3-4 days before the flight.

The dark night conditions (ceiling at 7000 ft and no ground lights) would have prevented flight using visual cues.

During the takeoff roll, the Captain’s airspeed showed no indication (i.e., remained at approximately 35 kt) as the airplane accelerated past 80 kt. Copilot's airspeed indication system (ASI) seemed to be working.

At 80 kt on takeoff the captain stated that his air speed indicator (ASI) was not working properly - as captured by the cockpit voice recorder. The captain proceeded with the takeoff which was contrary to established takeoff safety procedures.

During the climb, the autopilot and autothrottle followed the erroneous airspeed indication from the Captain's digital air data computer ,which increased with altitude in spite of continued pitchup commands. Due to the pitot tube being blocked, the ASI would only be responsive to the static pressure.

Simultaneous “rudder ratio” and Mach/speed trim” advisories were shown. Such an indication is displayed to warn of airspeed disagreement between the Captain’s and First Officer’s airspeed indications. An over speed warning was activated as the Calibrated Airspeed (CAS) increased to the peak value of 353 kt and the ground speed decreased to 199 kt. The pitch attitude and local angle of attack, which had remained steady at 15 deg and -1 deg, began to climb, and reached 18 and 3 deg. The stick shaker (commanded by angle of attack) fired, indicating an approach to stall. The elevator position increased to 3.7 deg from its previously steady position between 0.7 and 1.5 deg.

Pilots got confused due to the ASI mismatch between pilot and copilot, decreasing co pilot ASI while getting an excessive speed warning, and excessive speed warning followed by stick shaker.

Stick shaker activated and continued to the end of the flight data recording. The Engine Pressure Ratio (EPR) values began to decrease and the autothrottle was disengaged. Thrust levers were advanced and the Engine Pressure Ratio values increased to 1.6 following stick shaker activation. The pitch attitude and local angle of attack increased to 11 and 15 deg in response to increasing elevator input, which peaked at 18.8 deg. Ground speed decreased to approximately 140 kt. The roll attitude fluctuated from 17 deg to -33 deg as altitude decreased from 6592 to 5025 ft. Thrust also decreased during this period and coincided with an increase in nose up elevator, pitch attitude, and angle of attack. The remainder of the flight indicated two pitch oscillations in response to nose up elevator inputs, and a continuous left roll through 180 deg. The autopilot disengaged as the roll attitude reached 38 deg. The thrust on both engines increased and then decreased on the left engine.

The crew realized too late that they were losing speed and altitude. Nose-up elevator inputs were sustained and the crew failed to execute procedures for recovery.

Figure A-5: LOC Accident Sequence for Sample Accident Case (Belcastro, et al., 2017)

The categorized summary in Table A-2 and Table A-3 of the safety related critical aspects extracted from the incident/accident reports allows to derive approximate tendencies of the principal causes of occurrences in Fly by Wire (FBW) aircraft.

Critical factors common to most of the incidents/accidents are mainly of four categories:

1. Flight Crew Situational Awareness
2. Flight Crew Respect of Aircraft Procedures
3. Flight Crew Training
4. Design Fault

The four categories are more closely related to human decisions and/or decisional processes in the cockpit or in the aircraft design and development phases.

The impact on flight safety of flight crew understanding of the automation appears to be significant: the effect of most of the reported occurrences could have been mitigated by appropriate training and respect of the aircraft procedures by the flight crew. Mismanagement of the Automatic Flight Control System (AFCS) seems to derive both from the complexity of the systems and from an approach resulting from that typical of conventional, unaugmented and non-automated type of aircraft. Issues with situational awareness, respect for aircraft procedures and flight crew training are the most recurring critical aspects related to human factor components. A tendency can be identified, of pilots' excessive reliance on automation or Air Traffic Control (ATC), combined with corresponding relatively low proficiency in the critical phases of flight.

The report of the accident occurred on 14 February 1990 during landing at Bangalore airport contains critical aspects from the three of the main categories reported above:

1. Low pilot's situational awareness of aircraft flight path and energy status.
2. Pilots' uncertainty of the engaged control system mode.
3. Failure of the pilots to realize the gravity of the situation and respond immediately towards proper action of moving the throttles.

Other incidents and accidents that occurred in the terminal phases of flight highlight similar flight crew approach to management of aircraft automation and of cockpit resources. A relevant example is the incident that occurred on 24 September 1994 during approach to Paris Orly airport. In this occurrence, flight crew initial mismanagement of the automation led to flight conditions in which the envelope protection could not avoid the aircraft entering upset attitudes and flight conditions. This was aggravated by the pilot's incorrect stall recovery inputs, as indicated in the report: "Just before the stall, the Captain pulled the control column fully back.". Recovery from upset and stall without fatal consequences was mostly due to conditions outside the control of the flight crew, with the aircraft reaching a minimum indicated airspeed of 35 kts at 4,100 ft and a minimum altitude above ground level (AGL) of 800 feet. In this case, the inherent static and dynamic stability of the bare airframe can be considered fundamental factors for the recovery of the aircraft from upset conditions. Part of the automation mismanagement was reported to be due to inadequate Crew Resource Management (CRM) and to confusion between functions of sidestick buttons across different aircraft types that the Captain had previously flown. This incident includes components related to system design and its consequent exposure to system mismanagement, and related to system partial functioning due to the quality of the air data system sensors signals. Relatively to these aspects, the incident report indicates that "Envelope Alpha-floor protection could not play its role as, when angle of attack of 14.5° was reached, the throttle levers were already on maximum thrust." and that "The stall warning did not sound and the stick shaker did not operate in the flight phase prior to the stall, because of the disturbance of the angle of attack sensors due to the dynamics of the aircraft's movements, with the speed having dropped below 60 kt before the angle of attack reached 17.5°."

Impact of sensor malfunctioning leads to considering the incident occurred on 07 October 2008 enroute to Perth, Australia, and the accident occurred on 10 March 2019 after takeoff from Addis Ababa-Bole Airport, Ethiopia. In both events, the AFCS commanded inconsistent pitch inputs due to potential weakness in sensor hardware, sensor failure and system design limitations which did not address the possible occurrence of the failure. The incident report of the first event cites: "Combination of a design limitation in the flight control primary computer (FCPC) software of the [aircraft] [-], and a failure mode affecting one of the aircraft's three air data inertial reference units (ADIRUs).". From the accident report of the second event:" System design process not considering potential for uncommanded activation of MCAS [system] and it did not evaluate all the potential alerts and indications that could accompany a failure leading to an uncommanded MCAS [system].". A significant component of the second event was also the lack of documented procedures regarding the automatic system, as stated in the report: "Failure by the manufacturer to provide procedures regarding MCAS operation to the crew during training or in the Flight Crew Operating Manual (FCOM).".

Design aspects regarding control allocation, and partially airframe, can be identified from the report of the accident occurred on 30 October 2015 during flight testing of a tilt rotor aircraft over Tronzano Vercellese, Italy. The accident report notes that: "The flying pilot's attempt to counteract the oscillations with a roll-tracking maneuver to level the wings was ineffective, partly because the FCS was designed to 'couple' on more axes than the command inputs given on the single axis by the pilot."

Criticality of mode transition and its handling by the pilot is illustrated in the accident that occurred on 11 April 2022 of a tilt rotor aircraft, in which premature rotation of the engine nacelles led to an excessive forward shift of the center of gravity and simultaneous saturation of the longitudinal control, aggravated by tailwind. The accident report states: "The pilot tilted the nacelles and rotors down from 90° and brought them to an angle significantly less than 75° – a position that violated flight manual limits on nacelle angles at low forward airspeed."; "Nacelle's tilt shifted the aircraft center of gravity too far forward, causing the nose to plunge downward."; "Tailwind pushing the bottom of the horizontal stabilizer as the tail of the aircraft angled upward."; "Operating Limitations section of the NATOPS manual WARNING: 'When transitioning to forward flight from a hover, limit nacelles to greater than 75 degrees until 40 KCAS (Knots Calibrated Air Speed) is reached.'".

Aircraft airworthiness conditions, maintenance processes and bare airframe characteristics result being important contributing factors to the occurrences reported in Table A- 1. Overall, appropriate flight crew training on the specific aircraft type, accurate execution of aircraft procedures and CRM appropriate for highly automated aircraft can be considered the principal factors to address when aiming at reducing the occurrence of incidents and accidents in automated aircraft. The design of the system is strictly connected to these factors on the human machine interface (HMI) side. The fault analysis is a system design phase in which margins of improvement can be identified, based on the reported contributing factors to the safety related events listed above.

Extrapolation of the information above to Advanced Air Mobility (AAM) type aircraft suggests a potentially higher importance of HMI factors, due to the various and novel inceptor architectures being developed and correspondingly due to the adaptation to them of the flight crew. Control allocation and related situational awareness can be considered a fundamental aspect of the system design phase, considering the redundant control surfaces and control effectors typical of AAM aircraft.

A critical aspect, initially to be explored through flight test, is the difference between the flight phases of conventional fixed and rotary wing aircraft and those of AAM vehicles. As an example, the relatively limited power available to this type of vehicles makes duration of the maneuver and atmospheric conditions critical factors for safe operation. The impact on the vehicle dynamics of failures and of the reversion to simpler/less augmented modes will be specific of each aircraft model/configuration. The combination of these aspects must be investigated in tests, under the functional and operational standpoints.

It is important to rely on the lessons identified from incidents and accidents of conventional configuration aircraft, to determine trends of safety related occurrences that are less dependent, or independent from aircraft type and configuration, and that can be applied to AAM vehicles.

Table A- 1: Accident reports summary

Accident Reports Summary									
Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
14 February 1990	A-320-231	Scheduled Passenger Flight	Landing	D - V	Flight Crew Error/CFIT 92 Fatalities of 146 Occupants	Narrative: Indian Airlines Flight 605 took off from Mumbai, India, at 11:58 for a domestic flight to Bangalore. At 12:25 Bangalore approach was contacted and prevailing weather was passed on to the crew (wind variable 5 knots, visibility 10 km, clouds 2 octa 2000 feet, temperature 27 degrees C, QNH 1018). At 12:44 the aircraft was cleared to descend to FL110. Reaching FL110, vectors were given for a visual runway 09 approach. On final approach, the aircraft descended well below the normal approach profile and kept descending until it struck the boundaries of the Karnataka Golf Club (2300 feet short of the runway and 200 feet right of the extended centerline. The aircraft rolled for 80 feet and lifted off again for about 230 feet and came down again on the 17th green of the golf course. The landing gear wheels dug into the ground and the aircraft impacted a 12 feet high embankment, causing the gears and engines to be sheared off. The aircraft continued over the embankment and came to rest in a grassy, marshy and rocky area. Probable Cause: "Failure of the pilots to realize the gravity of the situation and respond immediately towards proper action of moving the throttles, even after the radio altitude call-outs of "Four hundred", "Three hundred" and "Two hundred" feet, in spite of knowing that the plane was in idle/open descent mode. However, identification of the cause for the engagement of idle/open descent mode in short final approach during the crucial period of the flight is not possible."	https://aviation-safety.net/database/record.php?id=19900214-2	Critical aspects: • Low pilot's situational awareness of aircraft flight path and energy status. • Pilots' uncertainty of the engaged control system mode. • "Failure of the pilots to realize the gravity of the situation and respond immediately towards proper action of moving the throttles.". • Insufficient discussion as to whether there was mode confusion such as mistaken auto-throttle use.	

20 January 1992	A-320-111	Scheduled Passenger Flight	Approach	N - I	Flight Crew Error/FCS Mode Confusion CFIT	Narrative (partial): While trying to program the angle of descent, "-3.3", into the Flight Control Unit (FCU) the crew did not notice that it was in HDG/V/S (heading/vertical speed) mode. In vertical speed mode "-3.3" means a descent rate of 3300 feet/min. In TRK/FPA (track/flight path angle) mode this would have meant a (correct) -3.3deg descent angle. A -3.3deg descent angle corresponds with an 800 feet/min rate of descent. Probable Cause: 1 - The crew was late in modifying its approach strategy due to ambiguities in communication with air traffic control. They then let the controller guide them and relaxed their attention, particularly concerning their aircraft position awareness, and did not sufficiently anticipated preparing the aircraft configuration for landing. 2 - In this situation, and because the controller's radar guidance did not place the aircraft in a position which allowed the pilot flying to align it before ANDLO, the crew was faced with a sudden workload peak in making necessary lateral corrections, preparing the aircraft configuration and initiating the descent. 3 - The key event in the accident sequence was the start of aircraft descent at the distance required by the procedure but at an abnormally high vertical speed (3300 feet/min) instead of approx. 800 feet/min, and the crew failure to correct this abnormally high rate of descent. 4 - The investigation did not determined, with certainty, the reason for this excessively high rate of descent . Of all the possible explanations it examined, the commission selected the following as seen most worthy of wider investigation and further preventative actions: 4.1 - The rather probably assumptions of confusions in vertical modes (due either to the crew forgetting to change the trajectory reference or to incorrect execution of the change action) or of incorrect selection of the required value (for example, numerical value stipulated during briefing selected unintentionally) . 4.2 - The highly unlikely possibility of a FCU failure (failure of the mode selection button or corruption of the target value the pilot selected on the FCU ahead of its use by the auto-pilot computer). 5 - Regardless of which of these possibilities short-listed by the commission is considered, the accident was made possible by the crew's lack of noticing that the resulting vertical trajectory was incorrect, this being indicated, in particular, by a vertical speed approximately four times higher than the correct value, an abnormal nose-down attitude and an increase in speed along the trajectory . 6 - The commission attributes this lack of perception by the crew to the following factors, mentioned in an order which in no way indicates priority: 6.1 - Below-average crew performance characterized by a significant lack of cross-checks and checks on the outputs of actions delegated to automated systems. This lack is particularly obvious by the failure to make a number of the announcements required by the operating manual and a lack of the height/range check called for as part of a VOR DME approach. 6.2 - An ambiance in which there was only minimum communication between crew members;	https://aviation-safety.net/database/record.php?id=19920120-0	Critical aspects: • Pilots' excessive reliance on ATC support. • Pilots' inadequate workload management. • Crew Resource Management: minimum communication between crew members. • Pilots' proficiency in the specific flight phase, low crew performance. • Absence of a GPWS as an aggravating factor. • The accident report indicates "that the ergonomic design of the auto-pilot vertical modes controls could have contributed to the creation of the accident situation", leading to Mode confusion between two vertical control modes. • Pilots' check of the actual aircraft descent rate, more than four times higher than the usual descent rate with -3.3 deg descent angle would have mitigated the impact of the error in selecting the control system mode.	

Accident Reports Summary									
Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						6.3 - The ergonomics of the vertical trajectory monitoring parameters display, adequate for normal situations but providing insufficient warning to a crew trapped in an erroneous mental representation; 6.4 - A late change to the approach strategy caused by ambiguity in crew-ATC communication; 6.5 - A relaxation of the crew's attention during radar guidance followed by an instantaneous peak workload which led them to concentrate on the horizontal position and the preparation of the aircraft configuration, delegating the vertical control entirely to the aircraft automatic systems; 6.6 - During the approach alignment phase, the focusing of both crew members attention on the horizontal navigation and their lack of monitoring of the auto-pilot controlled vertical trajectory; 6.7 - The absence of a GPWS and an appropriate doctrine for its use, which deprived the crew of a last chance of being warned of the gravity of the situation. 7 - Moreover, notwithstanding the possibility of a FCU failure, the commission considers that the ergonomic design of the auto-pilot vertical modes controls could have contributed to the creation of the accident situation. It believes the design tends to increase the probability of certain errors in use, particularly during a heavy workload			

26 April 1994	A300-622R	Scheduled Passenger Flight	Approach	N - U	Flight Crew Error/FCS Mode Confusion Uncontrolled Descent due to Loss of Control-Stall	While the aircraft was making an ILS approach to Runway 34 of Nagoya Airport, under manual control by the F/O, the F/O inadvertently activated the GO lever, which changed the FD (Flight Director) to GO AROUND mode and caused a thrust increase. This made the aircraft deviate above its normal glide path. The Auto Pilots (AP)s were subsequently engaged, with GO AROUND mode still engaged. Under these conditions the F/O continued pushing the control wheel in accordance with the CAP'S instructions. As a result of this, the THS (Horizontal Stabilizer) moved to its full nose-up position and caused an abnormal out-of-trim situation. The crew continued approach, unaware of the abnormal situation. The AOA increased. The Alpha Floor function was activated and the pitch angle increased. It is considered that, at this time, the CAP (who had now taken the controls), judged that landing would be difficult and opted for go-around. The aircraft began to climb steeply with a high pitch angle attitude. The CAP and the F/O did not carry out an effective recovery operation, and the aircraft stalled and crashed. The AAIC determined that the following factors, as a chain or a combination thereof, caused the accident: 1. The F/O inadvertently triggered the GO lever. It is considered that the design of the GO lever contributed to it: normal operation of the thrust lever allows the possibility of an inadvertent triggering of the GO lever. 2. The crew engaged the APs while GO AROUND mode was still engaged, and continued approach. 3. The F/O continued pushing the control wheel in accordance with the CAP'S instructions, despite its strong resistive force, in order to continue the approach. 4. The movement of the THS conflicted with that of the elevators, causing an abnormal out-of-trim situation. 5. There was no warning and recognition function to alert the crew directly and actively to the onset of the abnormal out-of-trim condition. 6. The CAP and F/O did not sufficiently understand the FD mode change and the AP override function. It is considered that unclear descriptions of the AFS (Automatic Flight System) in the FCOM (Flight Crew Operating Manual) prepared by the aircraft manufacturer contributed to this. 7. The CAP'S judgment of the flight situation while continuing approach was inadequate, control take-over was delayed, and appropriate actions were not taken. 8. The Alpha-Floor function was activated; this was incompatible with the abnormal out-of-trim situation, and generated a large pitch-up moment. This narrowed the range of selection for recovery operations and reduced the time allowance for such operations. 9. The CAP'S and F/O's awareness of the flight conditions, after the PIC took over the controls and during their recovery operation, was inadequate respectively. 10. Crew coordination between the CAP and the F/O was inadequate. 11. The modification prescribed in Service Bulletin SB A300-22-6021 had not been incorporated into the aircraft. 12. The aircraft manufacturer did not categorise the SB A300-22-602 1 as "Mandatory", which would have given it the highest priority.	https://www.baaa-acro.com/crash/crash-airbus-a300-622r-nagoya-264-killed	Critical aspects: • Pilot's neglect of flight manual procedures. • Inadequate Crew Resource Management: lack of communication between Captain and First Officer. • Design of the GO lever contributing to triggering GO AROUND mode. • Pilot inappropriately resisted control automation which drove out-of-trim condition. • No warning and recognition function to alert the crew directly and actively to the onset of the abnormal out-of-trim condition. • Clarity of AFM. • Pilots' limited knowledge of AFCS modes. • Issue with aircraft airworthiness: modifications prescribed in Service Bulletins not being incorporated into the aircraft. • Manufacturer not categorizing Service Bulletin as mandatory. • The airworthiness authority of the nation of design and manufacture did not issue promptly an airworthiness directive pertaining to implementation of relevant SB.	

Accident Reports Summary									
Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						13. The airworthiness authority of the nation of design and manufacture did not issue promptly an airworthiness directive pertaining to implementation of the above SB.			

20 December 1995	B-757-223	Scheduled Passenger Flight	Approach	N - U	Flight Crew Error/ CFIT	Narrative: At about 18:34 EST, American Airlines Flight 965 took off from Miami for a flight to Cali. At 21:34, while descending to FL200, the crew contacted Cali Approach. The aircraft was 63nm out of Cali VOR (which is 8nm South of the airport)) at the time. Cali cleared the flight for a direct Cali VOR approach and report at Tulua VOR. Followed one minute later by a clearance for a straight in VOR DME approach to runway 19 (the Rozo 1 arrival). The crew then tried to select the Rozo NDB (Non Directional Beacon) on the Flight Management Computer (FMC). Because their Jeppesen approach plates showed 'R' as the code for Rozo, the crew selected this option. But 'R' in the FMC database meant Romeo. Romeo is a navaid 150nm from Rozo, but has the same frequency. The aircraft had just passed Tulua VOR when it started a turn to the left (towards Romeo). This turn caused some confusion in the cockpit since Rozo 1 was to be a straight in approach. 87 Seconds after commencing the turn, the crew activated Heading Select (HDG SEL), which disengaged LNAV and started a right turn. The left turn brought the B757 over mountainous terrain, so a Ground Proximity (GPWS) warning sounded. With increased engine power and nose-up the crew tried to climb. The spoilers were still activated however. The stick shaker then activated and the aircraft crashed into a mountain at about 8900 feet (Cali field elevation being 3153 feet). Probable Cause: "Aeronautica Civil" [of Colombia] determines that the probable causes of this accident were: 1. The flight crew's failure to adequately plan and execute the approach to runway 19 at SKCL and their inadequate use of automation; 2. Failure of the flight crew to discontinue the approach into Cali, despite numerous cues alerting them of the inadvisability of continuing the approach; 3. The lack of situational awareness of the flight crew regarding vertical navigation, proximity to terrain, and the relative location of critical radio aids; 4. Failure of the flight crew to revert to basic radio navigation at the time when the FMS-assisted navigation became confusing and demanded an excessive workload in a critical phase of the flight. Contributing to the cause of the accident were: 1. The flight crew's ongoing efforts to expedite their approach and landing in order to avoid potential delays; 2. The flight crew's execution of the GPWS escape manoeuvre while the speed brakes remained deployed; 3. FMS logic that dropped all intermediate fixes from the display(s) in the event of execution of a direct routing; 4. FMS-generated navigational information that used a different naming convention from that published in navigational charts."	https://aviation-safety.net/database/record.php?id=19951220-1	Critical aspects: • Flight crew's failure to adequately plan and execute the approach. • Inadequate use of automation. • Delay of the flight crew to discontinue the approach and move to basic HDG control. • Failure of the flight crew to revert to basic radio navigation. • Flight crew's execution of the GPWS escape manoeuvre, performed with speed brakes deployed. • FMS-generated navigational information that used a different naming convention from that published in navigational charts.	

13 July 1996	MD-11	Scheduled Passenger Flight	Descent	D - V	Flight Crew Error/ autopilot override Cabin injuries	Narrative: On July 13, 1996, about 2040 eastern daylight time, an McDonnell Douglas MD-11, N1768D, operated by American Airlines as flight 107, experienced an abrupt maneuver during a descent, while operating near Westerly, Rhode Island. The airplane was not damaged. There were 180 occupants onboard the airplane, of which, one passenger received serious injuries, and one passenger and two flight attendants received minor injuries. Visual meteorological conditions prevailed, and flight 107 which had departed London, England, at 1354, was operated on an Instrument Flight Rules (IFR) under 14 CFR Part 121. Flight 107 was inbound to John F. Kennedy Airport, Jamaica, New York. In a telephone interview the Captain reported that the flight had crossed Boston at FL350 (35,000 feet), and was then instructed by ATC to cross 20 miles northeast of PARCH intersection at FL 240 (24,000 feet). At that time the flight was 45 miles from PARCH. The flight was operating in visual meteorological conditions (VMC), and the air was smooth. The first officer was performing the duties of the operating pilot. The descent was initiated with the auto-pilot engaged in the vertical profile (PROF) mode. The speed brakes had been extended full, and as the airplane neared FL 250 (25,000 feet), he became concerned that the airplane would not level off at FL 240. He instructed the first officer to slow the rate of descent. The first officer complied by using the pitch thumbwheel on the auto-pilot control panel, but no effect was observed. The Captain then took control of the airplane, retracted the speed brakes, and a few seconds later, disconnected the auto-pilot. This was followed by an immediate pitch up, which the captain described as similar to flying through a jet wake. The captain then applied forward pressure to the yoke, and the airplane leveled off at FL237 (23,700 feet), after which it was hand flown back to FL 240. One passenger in the aft lavatory received a fractured ankle (serious injury). One passenger received minor injuries and refused treatment. Two flight attendants on duty in the aft portion of the airplane received minor injuries. Following the incident, the flight continued into John F. Kennedy Airport where an uneventful landing was made. The Digital Flight Data Recorder (DFDR) was forwarded to the NTSB laboratory in Washington, DC for readout. According to the recorder, the maximum vertical "G" loading was +2.28 Gs, at an indicated airspeed of 354 knots, and at a pressure altitude of 23,781 feet. Additionally, on the descent between 25,900 feet and 23,900 feet, there were 7 excursion of the pitch thumbwheel. As the airplane descended between 25,700 feet and 25,300 feet, there was a momentary increase of g loading on the vertical axis. As the airplane passed through 24,200 feet, there was an increase in the elevators to the airplane nose up position. As the airplane passed through 23,800 feet, there was a momentary further increase of the elevator displacement which corresponded to the peak g load of +2.28 gs observed on the DFDR. Following this the elevators immediately went to a negative position and then returned to their pre-incident position through a series of oscillations. According to the American Airlines MD-11 Operating Manual, Auto-Flight section, when the auto flight system is engaged in the vertical profile (PROF) mode, rotation of the pitch thumbwheel will disengage the PROF mode. When the thumbwheel is released, the system reverts to the PROF mode. According to MDC personnel, the auto-pilot was programmed to initiate a level off at a maximum g loading of	https://www.fss.aero/accident-reports/dvdfiles/US/1996-07-13-US.pdf	Critical aspects: • Pilots' partial understanding of the autopilot functioning. • Pilot's incorrect application of correcting input, with autopilot engaged. • Pilot resisting control automation.	

Accident Reports Summary

Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						0.2 gs. Use of the pitch thumbwheel would interrupt the automatic level off process, and once released, the system would wait for two seconds prior to initiating the level off process again. Each time the pitch thumbwheel was released, the pre-programmed level-off routine would re-initiate after a 2 second pause. The continued use of the pitch thumbwheel allowed the airplane to continue its descent to an altitude whereby a level off at FL240 would exceed the maximum g load of 0.2 gs that the system was designed to handle. Auto-pilot 2 was engaged and was driving the right inboard elevator. The other three sections of the elevator were being driven by the right inboard elevator through mechanical linkage. When the auto-pilot was overpowered by force to the control yoke, the three elevator sections not connected directly to the auto-pilot responded. The amount of force required for the deviation exceeded the control force necessary to move the elevators with the auto-pilot dis-connected. Additionally, when the auto-pilot was disconnected while control force was applied, two actions took place simultaneously. The auto-pilot driven section moved to match the position of the other three control surfaces and the control yoke, and the force that was restricting control movement before was removed. According to MDC personnel, it would be extremely difficult for a person applying control force and releasing the auto-pilot to avoid having a further excursion of the elevator in the direction of control force applied due to the reduction in control force when the auto-pilot was dis-connected. Examination of the MD-11 Flight Crew Operating Manual found the following under the title of "SEVERE TURBULENCE AND/OR HEAVY RAIN INGESTION" : "...Do not attempt to overpower the auto-pilot with control forces. This can cause the auto-pilot to disengage with too much control input, which could result in over control during recovery. Every attempt should be made not to over control. Longitudinal control forces at high altitude will be lighter than those which the pilot experiences at low altitude due to altitude effect as aft CG...."			

07 February 2001	A320-213	Scheduled Passenger Flight	Landing	N - V	Flight Controls/ 1 serious injury	On 7th February 2001, an Iberia A320 was about to make a night touch down at Bilbao in light winds when it experienced unexpected windshear. The attempt to counter the effect of this by initiation of a go around failed because the automatic activation of AOA protection in accordance with design criteria which opposed the crew pitch input. The aircraft then hit the runway so hard that a go around was no longer possible. Severe airframe structural damage and evacuation injuries to some of the occupants followed. A mandatory modification to the software involved was subsequently introduced. Description On 7th February 2001, an Airbus A320-200 being operated by Iberia on a scheduled domestic passenger flight from Barcelona to Bilbao with pilot early-stage line training in progress and a safety pilot present was about to make a night touch down in VMC and light surface winds when it experienced unexpected windshear and a very hard landing followed. The aircraft did not leave the paved surface but severe airframe structural damage was sustained and there were injuries to 25 of the 143 occupants, one serious, during the subsequent evacuation. Investigation An Investigation was carried out by the Spanish Investigation Agency, the Comisión de Investigación de Accidentes e Incidentes de Aviación Civil (CIAIAC). Using DFDR and CVR data, the Investigation found that below 100 feet agl, both the trainee First Officer as PF and the aircraft commander has simultaneously made sidestick inputs in an attempt to arrest a descent caused by a sharp downdraft but their combined sudden input had triggered the threshold for AOA protection which had negated their control input. It was noted that the actual AOA was not abnormal and that the protection activation was attributable to a predictive algorithm in the software involved. An attempt by the aircraft commander to begin a go around had not had the intended effect before the aircraft hit the runway in a slightly nose down attitude at 4.35g. The nose landing gear had collapsed and the aircraft had come to a stop after an 1100 metre ground run. As the aircraft approached its final resting place, directional control had been lost but the aircraft had remained on the runway. Airframe damage was so extensive that the aircraft was declared a hull loss. It was considered that: if the windshear had appeared higher, the TOGA setting would probably have been triggered by the alpha floor protection. if the configuration of the aircraft had been FLAP 3, the alpha prot value would have been higher and maybe would not have triggered the AOA protection.	..\..\References\2001-02-07-A320-213_accident-incident_report.pdf	Critical aspects: • Incorrect design of the hard envelope protection logics, under a particular combination of vertical gusts and windshear and simultaneous sidestick inputs from both pilots. • Potentially inadequate pilot's flap settings. • Initiation of the go around maneuver occurred at too low altitude. • Insufficient crew alerting from ATC. • Early stage line training with the trainee as PF, absence of adequate operator guidance in this respect.	Corrective Actions: AFM revision followed by subsequent software modification.

if both pilots had not pulled both sidesticks at the same time, the system would probably not have predicted or anticipated a high angle of attack that was actually never very high.
if the go-around had been initiated earlier, it could have been possible to recover level flight before the hard contact with the runway.
It was noted that during the earlier part of the approach, there had been some signs of conditions conducive to low level windshear but that Iberia SOPs for Bilbao did not suggest such a hazard given the light surface wind velocity. The location of the airport in relation to surrounding terrain alignment was considered to be conducive to mountain wave generation in the conditions which had prevailed at the time of the accident and it was noted that there was an opportunity to improve crew alerting in this respect subject to review by meteorological experts.

The wisdom of conducting early stage line training with the trainee as PF was also question and it was concluded that there had been an absence of adequate operator guidance in this respect

Once the root cause of the accident had been identified as the way the protection software had activated AOA protection in accordance with the design criteria, the following Preliminary Safety Recommendation was issued on 12 March 2001 in conjunction with the French Bureau d'Enquêtes et d'Analyses (BEA):

that the Certification Authority of this type of aircraft, the French DGAC should define with the manufacturer and immediately issue, safety measures to prevent the repetition of this kind of events in aircraft of the A-320 family and in other aircraft equipped with similar flight control systems.
Pending this action, on 23 March, Airbus released a temporary revision to AFM operating procedures which was issued as a telegraphic Airworthiness Directive by the French DGAC and applicable to all A320 and A319 aircraft fitted with the same standard of Elevator and Aileron Computer (ELAC) as the accident aircraft. It was noted that these modifications had been retrofitted Fleet-wide by the end of 2002.

The subsequent software modification was certified by mid 2001 and the corresponding Mandatory Service Bulletin was published in September 2001.
The Cause of the accident was formally stated as:

“the activation of the angle of attack protection system which, under a particular combination of vertical gusts and windshear and the simultaneous actions of both crew members on the sidesticks, not considered in the design, prevented the aeroplane from pitching up and flaring during the landing”.

Four further Safety Recommendations were issued at the conclusion of the Investigation as follows:

Accident Reports Summary									
Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						that the INM (National Meteorological Institute) conduct thorough research on meteorological phenomena within the area of Bilbao, aimed at improving our knowledge of the development of turbulence, gusts and windshear in the vicinity of the airport, and to use this information to improve operations during the approach phase. [REC 20/06] that Iberia improve the instruction of their A320 crews in order to avoid the simultaneous activation of the sidestick by both pilots without pushing the override button, regardless of the type and composition of the flight crew. [REC 21/06] that Iberia establish adequate restrictions in its Operation Manual in respect of crew members undertaking line flying under supervision to taking into account the different phases of flight and the characteristics of the airports of operation. [REC 22/06] that the Spanish Aeronautical Authority (DGAC) consider, as a valid criteria for the approval of commercial air transport operators, the inclusion in their Operation Manuals of adequate restrictions applicable to crew members line flying under supervision.			

Accident Reports Summary

Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
14 May 2004	MU-2B	Nonscheduled Cargo Flight	VFR pattern	D - V	Stall/ Loss of Control Uncontrolled Descent	The pilot was finishing his third round-trip, Part 135 cargo flight. He was operating flight EPS101. The first round trip began the previous evening, about 2150, and the approach back to the origination airport resulted in a landing on runway 15R at 2305. The second approach back to the origination airport resulted in a landing on runway 28 at 0230. Prior to the third approach back to the airport, the pilot was cleared for, and acknowledged a visual approach to runway 33R twice, at 0720, and at 0721. However, instead of proceeding to the runway, the airplane flew north of it, on a westerly track consistent with a modified downwind to runway 15L. During the westerly track, the airplane descended to 700 feet. Just prior to an abeam position for runway 15L, the airplane made a "sharp" left turn back toward the southeast, and descended into the ground. Witnesses reported the airplane's movements as "swaying motions as if it were going to bank left, then right, and back left again," and "the nose...pointing up more than anything...but doing a corkscrew motion." Other witnesses reported the "wings straight up and down," and "wings vertical." Tower controllers also noted the airplane to be "low and tight," and "in an unusually nose high attitude close to the ground. It then "banked left and appeared to stall and then crashed." A post-flight examination of the wreckage revealed no evidence of mechanical malfunction. The pilot, who reported 6,800 hours of flight time, had also flown multiple round trips the previous two evenings. He had checked into a hotel at 0745, the morning prior to the accident flight, checked out at 1956, the same day, and reported for work about 1 hour before the first flight began. Probable Cause: The pilot's failure to maintain airspeed during a sharp turn, which resulted in an inadvertent stall and subsequent impact with terrain. Factors included the pilot's failure to fly to the intended point of landing, and his abrupt course reversal back towards it.	https://aviation-safety.net/wikibase/44862	Critical Aspects: • Pilots' low situational awareness of the aircraft flight conditions and energy state. • Pilot's failure to maintain airspeed during a sharp turn. • Potential for high pilot's fatigue.	

Accident Reports Summary

Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
25 June 2005	A320-200	Scheduled Passenger Flight	Approach	D - U	Bad Input to FCS/ Flight Controls Mode Change	The aircraft had departed on a scheduled passenger flight from Milan to London Heathrow Airport, with an unserviceable No 3 Air Data Inertial Reference Unit (ADIRU). On final approach to Runway 09L at London Heathrow, in Instrument Meteorological Conditions (IMC), the Inertial Reference (IR) part of the No 1 ADIRU failed, depriving the commander (the pilot flying) of much of the information on his Primary Flight and Navigation Displays. ATC required the aircraft to go-around from a height of 200 ft on short final approach due to another aircraft still occupying the runway. The co-pilot, who had been handed control, performed the go-around and the aircraft was radar vectored for a second approach. The crew then turned off the No 1 ADIRU whilst attempting to diagnose the problem, contrary to prescribed procedures. As a result, additional data was lost from the commander's electronic instrument displays, the nosewheel steering became inoperative and it became necessary to lower the landing gear by gravity extension. The aircraft landed safely.	..\..\References\2005-06-25-A320-200_accident-incident_report.pdf	Critical aspects: • Aircraft flown with failed ADIRU, still within MEL requirements. • Incorrect application of prescribed procedures when a second ADIRU failure occurred, causing loss of navigational data and of noseweheel steering operation. • Low ATC situational awareness of the runway status and slowness in requiring go-around maneuver.	

23 September 2007	B-737-3Q8	Scheduled Passenger Flight	Final approach	N - I	Flight Crew error/Lack of FCS Mode Awareness Uncommanded Pitch	The Air Accidents Investigation Branch was notified by the operator on the 5 October 2007 of an unstable approach and stall during a go-around by a Boeing 737-300 aircraft, G-THOF, at Bournemouth Airport. The event had occurred 12 days previously on the 23 September 2007. The following Inspectors participated in the investigation: Mr K Conradi Investigator-in-charge Mr A Blackie Operations Ms A Evans Engineering Mr P Wivell Flight Data Recorders The Boeing 737-300 was on approach to Bournemouth Airport following a routine passenger flight from Faro, Portugal. Early in the ILS approach the auto-throttle disengaged with the thrust levers in the idle thrust position. The disengagement was neither commanded nor recognised by the crew and the thrust levers remained at idle throughout the approach. Because the aircraft was fully configured for landing, the air speed decayed rapidly to a value below that appropriate for the approach. The commander took control and initiated a go-around. During the go-around the aircraft pitched up excessively; flight crew attempts to reduce the aircraft's pitch were largely ineffective. The aircraft reached a maximum pitch of 44º nose-up and the indicated airspeed reduced to 82 kt. The flight crew, however, were able to recover control of the aircraft and complete a subsequent approach and landing at Bournemouth without further incident. Although the commander reported the event to the operator the following morning, his initial Air Safety Report (ASR) contained limited information and the seriousness of the event was not appreciated until the Quick Access Recorder (QAR) data was inspected on 4 October 2007. G-THOF was not subjected to an engineering examination to ensure its continued airworthiness and remained in service throughout this period. The investigation identified the following causal factors: 1. The aircraft decelerated during an instrument approach, to an airspeed significantly below the commanded speed, with the engines at idle thrust. Despite the application of full thrust, the aircraft stalled, after which the appropriate recovery actions were not followed. 2. The trimmed position of the stabiliser, combined with the selection of maximum thrust, overwhelmed the available elevator authority. The investigation identified the following contributory factors: 1. The autothrottle warning system on the Boeing 737-300, although working as designed, did not alert the crew to the disengagement of the autothrottle system. 2. The flight crew did not recognise the disengagement of the autothrottle system and allowed the airspeed to decrease 20 kt below Vref before recovery was initiated. Three Safety Recommendations have been made. **Safety Recommendation 2009-043** It is recommended that Boeing, in conjunction with the Federal Aviation Administration, conduct a study of the efficacy of the Boeing 737-300/400/500 autothrottle warning and if necessary take steps to improve crew alerting. **Safety Recommendation 2009-044** It is recommended that The European Aviation Safety Agency review the requirements of Certification Standard 25 to ensure that the disengagement of autoflight controls including autothrottle is suitably alerted to flightcrews. **Safety Recommendation 2009-045** It is recommended that Boeing clarify the wording of the approach to stall recovery Quick Reference Handbook Non-normal Manoeuvres to ensure that pilots are aware that trimming forward may be required to enhance pitch control authority.	..\..\References\2007-09-23-B737-3Q8_accident-incident_report.pdf ..\..\References\Summary - AAR_3-2009_Boeing_737-3Q8__G-THOF_06-09.pdf	Critical aspects: • Disengagement of the autothrottle was neither commanded nor recognized by the crew and the thrust levers remained at idle throughout the approach. • The aircraft decelerated to an airspeed significantly below the commanded speed, 20 kt below Vref, with the engines at idle thrust. • The autothrottle warning system on the Boeing 737-300, although working as designed, did not alert the crew to the disengagement of the autothrottle system.	

Accident Reports Summary									
Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
21 May 2009	A-330-223	Scheduled Passenger Flight	Enroute	N - I	Instruments, Sensors/ Landing no further incident	Description: On May 21, 2009, at 2147 EDT, an Airbus A330-200, Brazilian registration PT-MVB, operated by TAM Airlines as flight 8091 from Miami International Airport, Florida, to Sao Paulo Guarulhos International Airport, Brazil, experienced a loss of primary speed and altitude information while in cruise flight at FL370. Initial reports indicated that the flight crew noted an abrupt drop in outside air temperature and observed St. Elmo's Fire, followed by the loss of the Air Data Reference System, disconnections of autopilot and autothrust, and loss of primary airspeed and altitude. The flight crew continued using backup instruments, and after approximately 5 minutes, primary data was restored. The airplane remained in alternate flight law and displayed a rudder travel limit flag. The crew determined they could not restore normal law and continued the flight under the appropriate procedures. The flight landed at Sao Paulo with no further incident and there were no injuries or damage.		Critical aspects: • Loss of primary airspeed and (pressure) altitude information. • Known tendency of the aircraft air data system to fail due to large temperature variations.	

Accident Reports Summary

Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
01 June 2009	A-330-203	Scheduled Passenger Flight	Enroute	N - I	Instruments, Sensors/ Loss of control stall Uncontrolled Descent	On 31 May 2009, the Airbus A330 flight AF 447 took off from Rio de Janeiro Galeão airport bound for Paris Charles de Gaulle. The aeroplane was in contact with the Brazilian ATLANTICO control centre on the INTOL – SALPU – ORARO - TASIL route at FL350. At around 2 h 02, the Captain left the cockpit. At around 2 h 08, the crew made a course change of 12 degrees to the left, probably to avoid returns detected by the weather radar. At 2 h 10 min 05, likely following the obstruction of the Pitot probes by ice crystals, the speed indications were incorrect and some automatic systems disconnected. The aeroplane's flight path was not controlled by the two copilots. They were rejoined 1 minute 30 later by the Captain, while the aeroplane was in a stall situation that lasted until the impact with the sea at 2 h 14 min 28. The accident resulted from the following succession of events: • Temporary inconsistency between the measured airspeeds, likely following the obstruction of the Pitot probes by ice crystals that led in particular to autopilot disconnection and a reconfiguration to alternate law, • Inappropriate control inputs that destabilized the flight path, • The crew not making the connection between the loss of indicated airspeeds and the appropriate procedure, • The PNF's late identification of the deviation in the flight path and insufficient correction by the PF, • The crew not identifying the approach to stall, the lack of an immediate reaction on its part and exit from the flight envelope, • The crew's failure to diagnose the stall situation and, consequently, the lack of any actions that would have made recovery possible. The BEA has addressed 41 Safety Recommendations to the DGAC, EASA, the FAA, ICAO and to the Brazilian and Senegalese authorities related to flight recorders, certification, training and recurrent training of pilots, relief of the Captain, SAR and ATC, flight simulators, cockpit ergonomics, operational feedback and oversight of operators by the national oversight authority.	..\..\References\2009-06-01-A330-203_accident-incident_report.pdf ..\..\References\2009-06-01-A330-203_CVR_transcript.pdf	Critical aspects: • Temporary inconsistency between the measured airspeeds, that led in particular to autopilot disconnection and a reconfiguration to alternate law. • Insufficient crew situational awareness, not connecting the loss of indicated airspeed and the appropriate procedure. • Inappropriate crew control inputs. • Crew not identifying the approach to stall, consequently no reaction, enter of unidentified stall conditions with no recovery inputs until impact with the sea.	

23 June 2009	A330-300	Scheduled Passenger Flight	Enroute	D - I	Instruments, Sensors/Automatic engagement of alternate law Landed Without Further Incident	On July 7th the NTSB reported, that the airplane was enroute at FL390 about 50nm southwest of Kagoshima (Japan) in normal cruise and in visual conditions with thin cirrus clouds, while the weather radar displayed some convective weather 25nm north of the flight track. After entering the cirrus, moderate precipitation and moderate turbulence the crew observed - and the flight data recorder (FDR) confirmed - the autopilot and autothrust disengage and the fly by wire change to alternate law. Master caution and master warning activated. The crew followed manual flight procedures and within one minute the autopilot could be reengaged and fly by wire returned to normal law. The event quickly repeated itself now lasting for about 2 minutes. The autopilot and autothrust returned to function, the fly by wire however remained in alternate law for the remainder of the flight. The crew observed and the FDR confirmed large airspeed fluctuations, small altitude fluctuations and an overspeed alert. The Japanese Transportation Safety Board (JTSB) delegated the investigation into the incident to the NTSB. The JTSB assigned an accredited representative to the investigation. The NTSB have released their final report concluding the probable cause of the incident was: Brief and temporary blockage of the pitot probes in cruise flight, most likely due to ice crystals aloft, leading to erroneous airspeed indications and airplane automation degradation as designed. Contributing to the incidents were design features of the Thales AA probes which left them more susceptible to high altitude ice crystal icing than other approved pitot probe designs. The NTSB reported that the flight data recorder and quick access recorders showed there was a speed fluctuation on the captain's air speed indicator from 245 to 110 KIAS (0.81 mach to 0.35 mach), within one second autopilot and autothrust disconnected and a brief stall warning occurred. The fly by wire changed to alternate law twice in the first 35 seconds of the event but returned to normal law after 35 seconds. About 105 seconds after the initial event another speed fluctuation occurred again between 245 and 110 KIAS on both captain's air data reference unit as well as the stand by unit (first officer's unit was not recorded). The captain's ADR showed fluctuations for the next 3 minutes, while the stand by instrument fluctuated for about 30 seconds. After the stand by indications returned to normal the crew was able to engage the autoflight systems again, the flight law remained alternate for the remainder of the flight. The NTSB stated that this type of airspeed anomaly is not normally reportable.	http://avherald.com/h?article=41bb9740	Critical aspects: • After entering the cirrus, moderate precipitation and moderate turbulence, the autopilot and autothrust disengaged and the fly by wire system changed to alternate law. • Brief and temporary blockage of the pitot probes in cruise flight, most likely due to ice crystals aloft, leading to erroneous airspeed indications and airplane automation degradation as designed. • Design features of the Thales AA probes left them more susceptible to high altitude ice crystal icing than other approved pitot probe designs.	

Accident Reports Summary									
Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
04 November 2010	A-380-842	Scheduled Passenger Flight	Climb	D - V	Propulsion System/ Return-to-Base	On November 04, 2010, Qantas Flight 32, an Airbus 380 operated by Qantas Airways Ltd, departed Changi Airport, Singapore on a scheduled passenger flight to Sydney, Australia. The flight carried 469 passengers and crew. About four minutes after take-off, while the aircraft was climbing through about 7,000 feet over Batam Island Indonesia, the flight crew heard two "bangs." The noises were the result of an uncontained failure of the No. 2 engine, a Rolls-Royce Trent 900 series turbofan. Debris from the engine impacted the aircraft, causing significant damage to the structure and airplane systems and resulted in fuel leakage from the left-wing fuel tank. The airplane entered a holding pattern and, after 50 minutes of completing procedures and performing progressive aircraft controllability checks, the flight crew landed the aircraft safely at Changi Airport. Following landing, the No. 1 engine could not be shut down. With the No. 1 engine still running, and with flight crew concerns about leaking fuel and potential passenger injuries, passenger offloading was delayed for approximately an hour. Offloading was completed approximately one hour after offloading began (two hours after landing), using a single cabin exit. The No. 1 engine was successfully shut down three hours after landing by spraying firefighting agent into the engine inlet. The accident investigation determined that the probable cause of the engine failure was a manufacturing error involving an internal oil feed stub pipe. The oil feed pipe was manufactured with a reduced wall thicknesses that eventually cracked and caused oil spray leakage and fire in the High Pressure/Intermediate Pressure (HP/IP) bearing support hub assembly. The fire weakened the intermediate turbine drive arm, which subsequently fractured, allowing the IP turbine disk to overspeed and break apart. High speed engine debris penetrated many areas of the airplane, including damage to buildings beneath the flight path. There were no reported injuries to the passengers, crew, or persons on the ground.	https://www.faa.gov/lessons_learned/transport_airplane/accidents/VH-OQA	Critical aspects: • The probable cause of the engine failure was a manufacturing error involving an internal oil feed stub pipe.	

13 March 2012	A-340-313	Scheduled Passenger Flight	Final approach	D - I	Navigation System/FCS Mode Abuse Upset	Narrative: The crew took off from Bamako, Mali, on 12 March 2012 at 23 h 59 heading for Paris Charles de Gaulle (CDG) Airport. On arrival, the ATIS indicated that the low visibility procedure (LVP) was in force. The crew prepared themselves for a CAT III precision approach. The aeroplane was stable at FL90 at about 30 NM from the threshold of runway 08R. Autopilot 1 was engaged in HDG and ALT mode. The autothrottle (ATHR) was engaged in SPEED mode. The speed was stable at 250 kt in accordance with the controller's request. The crew was in contact with CDG approach. They were cleared to intercept localizer 08R. At 04:40, the controller cleared the crew to descend to FL80 and five seconds later the aeroplane, stable at FL90, passed above the 3° glide path. The crew was then cleared to descend to FL60. They selected an altitude of 6000 ft on the FCU and the autopilot mode changed to OP DES. The autopilot captured the localizer 08R signal (LOC) and then the LOC mode engaged. When the aeroplane descended to 7220 ft, and was 17.5 NM from the threshold, or about 1275 ft above the glide path, the controller requested that a speed of more than 200 kt be maintained. The aeroplane's speed was about 250 kt. The crew read back and requested to continue the descent. The controller apologised for his omission then cleared the crew to descend to 3000 ft to intercept the 08R ILS. The crew selected 220 kt and 3000 ft. The OP DES mode remained active. The aeroplane speed and rate of descent decreased which resulted in increasing the deviation from the glide path. The crew extended the airbrakes. When the aeroplane speed reached the target speed of 220 kt, the rate of descent increased again to a value of -1840 ft/min. At 10 NM from the runway threshold and at an altitude of 5500 ft, the approach controller requested that the crew maintain a speed of more than 160 kt and that they contact the tower. He did not inform the tower controller that the aeroplane was above the glide path. The crew selected a speed of 210 kt then 183 kt and wing slats/flaps configuration 1. Again, the rate of descent decreased and the aeroplane deviated from the 3° glide path. The crew contacted the tower and indicated that they were 9 NM out. The aeroplane was at an altitude of 4950 ft (1750 ft above the glide path). The controller initially cleared the crew to continue the approach. The latter read back "Cleared to land 08 right...". The controller indicated that he then checked that the CAT III ground services were clear then confirmed clearance to land. The crew selected slats/flaps configuration 2 and retracted the airbrakes. About one minute later, they re-extended the airbrakes, set the G/S mode using the APPR switch and engaged autopilot 2. The glide deviation displayed on the PFD indicated to the crew that they were approaching the glide path from above. The aeroplane was 4 NM from the runway threshold, at about 3700 ft (that is 2100 ft above the glide path at 3°) and was located in an ILS signal sidelobe.	..\..\References\2012-03-12-A340-313_accident-incident_report.pdf	Critical aspects: • Inadequate monitoring of the airplane's flight path by the controller and by the crew. • Reliance of the crew on the autopilot to perform the go around maneuver. • Crew's decision to continue the approach after the Final Approach Point when the airplane was above the glide path. • Abuse case of high descent with Autothrottle engaged.	

Accident Reports Summary

Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						About 30 seconds later, the crew extended the landing gear. The glide path capture mode (G/S) was activated when the aeroplane was 2 NM from the runway threshold at 2850 ft (that is about 1600 ft above the glide path at 3°). The ATHR changed to SPEED mode. The pitch attitude increased from 1° to 26° in 12 seconds. The PNF stated that he had called out the difference in the pitch attitude when the chevrons appeared. When the aeroplane pitched up, the speed dropped from 163 kt to 130 kt, the vertical speed changed from – 1600 ft/min to + 3300 ft/min. When the pitch attitude reached 26°, the crew disconnected both autopilots and the PF made a pitch down input almost down to the stop. The pitch attitude and vertical speed decreased. The crew retracted the airbrakes. The throttle levers were in the IDLE position. The speed was 143 kt and the ATHR disengaged. About 30 seconds later, autopilot 1 was engaged, the levers were repositioned on the CL setting and the ATHR was activated. The PF explained that he engaged autopilot 1 to perform a go-around on automatic. The LOC and G/S modes were active and the ATHR was in SPEED mode. The speed was 147 kt. The aeroplane was directly above the runway threshold at an altitude of about 2700 ft. The pitch attitude then decreased from 2° to -5° and the aeroplane descended. The PF stated that he realised that the modes displayed on the FMA were not appropriate. He then disengaged the AP 8 seconds after having activated it and then displayed a pitch attitude of about 6° and placed the throttle levers in the TOGA setting at an altitude of about 2000 ft. The crew made a second approach and landed without further difficulties. Conclusion: This serious incident was due to: - Inadequate monitoring of the aeroplane's flight path by the controller and by the crew during the CAT III precision approach under radar vectoring; - The crew's decision to continue the approach after the FAP when the aeroplane was above the glide path. The following factors contributed to it: - The absence of visual reference points on the controllers' radar screen for glide path interception at altitudes lower than 5,000 ft. - The crew's use of an unsuitable method to intercept the glide path from above. - The autopilot's capture of an ILS signal from a sidelobe, which generated an excessive increase in pitch attitude. Flight crew and controller fatigue may have contributed to the occurrence of this serious incident.			

20 April 2012	B-737-236A	Scheduled Passenger Flight	Approach	D - I	Wind Shear, Atm Convection/ Collision with Terrain	Narrative: A Boeing 737-236 passenger plane, operated by Bhoja Airlines, was destroyed in an accident near Islamabad, Pakistan. All 121 passengers and six crew members were killed. Bhoja Airlines flight 213 departed Karachi (KHI) at 17:05 on a domestic flight to Islamabad (ISB). This was the inaugural evening flight for the airline on this route. The flight climbed to a cruising altitude of FL310 and continued towards Islamabad. Weather at the destination was poor due to a passing thunderstorm. At 18:19 the captain at a distance observed the squall line. Moments later the flight was cleared to descend to FL200. During the descent the captain and first officer discussed the weather. They were worried about the severity of the thunderstorm ahead. At 18:26 the first officer contacted Islamabad Approach and received clearance for the One Foxtrot arrival for an ILS approach to runway 30. After receiving further descent clearance the first officer discussed opportunities to approach the airfield through a gap in the squall line. The Approach controller gave radar vectors and descent instructions to fly through the gap in the storm. At 18:35, Islamabad Approach gave a weather update and said "Bhoja 213 surface wind at Islamabad ah is varying between 180° to 270°, 10 kts and ah sometimes gusting to 20 kts and runway condition is wet, light drizzle is ah uhm going on, braking action not known". Two minutes later the airplane entered the squall line. Although the Bhoja Air Operational Manual prohibited flight in these conditions, the captain decided to continue. The airplane was configured for the approach with flaps and slats selected and the undercarriage was down. The first officer then reported the speed to be 220 knots, which was 30 knots higher than the recommended speed. The captain reacted surprised as he did not expect this because he was flying with the auto-throttle engaged. Likely the increase in speed was a result of windshear. The aircraft then entered the active weather cell with precipitation continuing in varying intensity. At 18:39 the airplane captured the ILS and descended on the glide slope. At this point the aircraft should have been in landing configuration with flaps at 30°. However, only flaps 5 were selected. The aircraft then encountered an increasing downdraft. The pitch attitude increased and computed airspeed decreased as the autopilot attempted to maintain the glide slope. The GPWS consequently sounded with the aural alarm: "Wind shear - Wind shear - Wind shear". Although the first officer anxiously called for a go around, no action was taken. The downdraft dissipated and the pitch attitude decreased but the aircraft deviated left of the extended runway centerline, and was brought back by the captain. At that moment the autopilot disconnected due to the aircraft deviation beyond the autopilot maximum authority limits. The auto throttle remained engaged in IAS speed mode. Following autopilot disconnect, there was no control wheel activity recorded for approximately 6 seconds and no control column activity for approximately 8 seconds. The crew were likely confused. During this period of control inactivity, the aircraft deviated below the glide slope.	..\..\References\2012-04-12-B-737-236A_accident-incident_report.pdf	Critical aspects: • Poor weather conditions, thunderstorm, windshear. • Ineffective automated flight deck management in extreme adverse weather conditions by cockpit crew. • Incorrect selection of cockpit crew on account of their inadequate flying experience, training and competence. • Absence of formal simulator training in respect of FO for handling an automated flight deck. • Non-existence of cockpit crew professional competence/skill level monitoring system at operator level (Bhoja Air). • Autopilot disconnection due to the aircraft deviation beyond the autopilot maximum authority limits, following pilot's input. • Incomplete execution of manufacturer stall and recovery procedures. • Inappropriate execution of go around procedures. • Partial autopilot disengagement. • Stall recovery and go-around procedures required and not executed properly.	

Accident Reports Summary									
Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
						Then the Terrain Awareness Warning System (TAWS) alarm sounded: "Whoop, Whoop, Whoop". No action was taken by either crew member. A few seconds later the aircraft entered another downdraft and the rate of descent increased rapidly. The TAWS alarm sounded again, directing the crew to "pull up". The captain responded with a nose-up column input. However, pressure altitude and thrust continued to decrease. The downdraft dissipated rapidly, resulting in a rapid increase in angle of attack of the aircraft, which activated the stick shaker for almost 2 seconds. It appeared that captain lowered the nose down to get out of stick shaker regime however, proper and complete Boeing recommended stall and recovery procedures were not carried out. This resulted in a 12° nose down pitch. Then another windshear alarm sounded, followed by another stick shaker activation. The first officer shouted to "get out" and "go around" but the attempts by the captain failed as he did not apply the proper procedures to execute a go around. Shortly after initial ground contact, the aircraft struck a steeply sloped terrace about 5 meters high which resulted in significant structural breakup of the aircraft structure. Probable Cause: The ineffective automated flight deck management in extreme adverse weather conditions by cockpit crew caused the accident. The ineffective automated flight deck management was due to various factors including; incorrect selection of cockpit crew on account of their inadequate flying experience, training and competence level for Boeing 737-236A (advanced version of Boeing 737-200 series), absence of formal simulator training in respect of FO for handling an automated flight deck, non-existence of cockpit crew professional competence/skill level monitoring system at operator level (Bhoja Air). The cockpit crew incorrect decision to continue the flight for destination and non-adherence to Boeing recommended QRH and FCOM remedial actions /procedures due to non-availability of customized aircraft documents (at Bhoja Air) for Boeing 737-236A (advanced version of Boeing 737-200 series) contributed towards the causation of accident. The inability of CAA Pakistan to ensure automated flight deck variance type training and monitoring requirements primarily due to incorrect information provided by the Bhoja Air Management was also a contributory factor in causation of the accident.			

21 July 2013	Sukhoi 100-95B	Test & Evaluation	Unknown	D - I	Flight Crew Error/ Runway Overrun	Narrative: A Sukhoi Superjet 100-95 was involved in a flight test accident during a go-around at Keflavík International Airport (KEF), Iceland. The five persons on board suffered minor injuries. At 04:03 hours local time the Sukhoi Superjet took off from runway 20 at Keflavík Airport for flight testing with a crew of five on board. The airplane had been undergoing certification flight tests for almost one month at Keflavík Airport. This was the crew's fourth test flight since their work shift started at 18:00 the day before. The pilot flying was sitting in the right cockpit pilot seat. Seven approaches and go-arounds were performed with possible landing gear touchdown to runway 20, followed by two to runway 11. During the final approach to runway 11 at 05:22, the landing gear was selected down. The approach was normal. At 05:23 the flight crew initiated the 9th test of the flight. The purpose of the test was to simulate a CAT IIIA automatic approach, close to the airplane's maximum landing weight limit, while in crosswind exceeding 10 m/s (19.5 knots), with a critical engine failure occurring at radio altitude of 25 feet, resulting in a low pass/missed approach. When the aircraft was at radio altitude of about 10 ft the flight certification expert sitting in the jump seat in the cockpit shut down the right engine using the ENG MASTER SWITCH. After the right engine was shut off, the right autothrottle disconnected and the right throttle lever stopped moving to idle, while the left autothrottle continued moving the left throttle lever back to idle. At a radio altitude of about 4 feet the pilot flying disengaged the autopilot. This caused disengagement of all autopilot/flight director control modes and the left autothrottle reverted to SPEED mode. When the left autothrottle reverted to SPEED mode, the left throttle lever had already reached IDLE. At that time the airplane speed had reduced down below the "limit selectable speed", so the left autothrottle started moving the left throttle lever forward. The pilot flying pressed the TOGA (Take Off/Go Around) button on the right throttle lever to initiate a goaround. Almost simultaneously the main landing gear touched the runway. The left engine autothrottle and flight director then disengaged automatically. The pilot flying then noticed at the primary flight display that the go-around mode had not engaged when he selected the TOGA switch. The pilot flying also noticed that the flight director was not available and that the autothrottle was switched off. The pilot flying then started to perform a go around in manual mode, setting the right (inoperative) engine throttle lever to TO/GA, pitched-up the aircraft and ordered landing gear retraction. During the go-around procedure, after the landing gear was retracted, the airplane started to lose speed. The airplane stopped climbing having reached a maximum radio altitude of 27 feet at and then started to descend. The speed decreased further, below 120 knots. The pilot flying then set the right throttle lever to MAX. The speed continued to decrease and the pilot flying, now aware of both the speed loss and the loss of altitude, reduced the nose pitch to try to counteract stalling.	..\..\References\2013-07-21-sukhoi-100-95B_accident-incident_IMR_investigation.pdf	Critical aspects: • Flight crew fatigue. • Test pilot controlling the inoperative engine while performing an automatic approach with a critical engine failure. • The left engine autothrottle and flight director disengaged automatically when the landing gear touched the runway. • Go-around mode had not engaged when the pilot flying selected the TOGA switch. • Landing gear was in retracted position when the aircraft hit the runway.	

Accident Reports Summary

Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						The airplane's aural warning "LANDING GEAR NOT DOWN" triggered at that time. The pilot flying realized that engine was not in takeoff mode and checked engine power settings. He found out that operating left engine was in N1=50% mode and realized that he had been controlling the inoperative engine. The pilot flying set the left engine throttle lever to MAX. The airplane was still descending and while the left engine was spooling up, the airplane hit the runway. As the landing gear was in the up position, it was the fuselage aft lower belly that hit the runway first. This was on the left side of the runway center line, as due to the loss of airspeed and the crosswind the airplane had drifted to the left. This was followed by the engines' cowlings touching the runway. As the airplane nose had been turned into the wind when it hit the runway, it initially veered to the right, as it skidded down the runway, across the runway centerline. The pilot flying counteracted this movement with a left rudder input and steered the airplane back towards the runway centerline. The pilot flying set both throttle lever's to IDLE position at and then to deploy the thrust reversers. The airplane skidded off the end of runway 11 and came to rest after having passed 163 meters beyond the threshold of runway 29. After the airplane had come to a stop, the pilot in command, who was also the pilot flying, ordered an emergency evacuation. The forward left door was opened by the cockpit crew, but the emergency escape slide did not deploy. The crew member operating the test equipment in the cabin opened the rear left door and its slide deployed. The cockpit crew then opened the forward right door. The slide deployed, but due to the crosswind it blew underneath the belly of the airplane and was unusable. The whole crew evacuated the airplane via the rear left door. Probable Cause: The Icelandic Transportation Investigation Board determined that the most probably cause of the accident to be flight crew fatigue, which resulted in the flight crew advancing the incorrect throttle lever to TO/GA position. This occurred after the airplane touched the runway, which had resulted in the automatic flight control system shutting off.			

Accident Reports Summary

Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
07 September 2013	A320	Scheduled Passenger Flight	Approach	D - U	Flight Controls/Lack of FCS Mode Awareness Altitude Deviation	On 7 September 2013, an Airbus A320, registered VH-VFJ, was on descent into Auckland, New Zealand via a Required Navigation Performance (RNP) approach to runway 23L. During the later stages of their descent, the crew managed the aircraft speed to meet an Air Traffic Control request and according to applicable company speed restrictions. The auto-flight system sequenced to final approach mode passing about 4,200 ft, but exited final approach mode when the crew subsequently levelled the aircraft approaching 3,000 ft. The crew levelled the aircraft to reduce speed to comply with a company speed restriction of 210 kt maximum below 3,000 ft. Having slowed sufficiently, subsequent manipulation of the auto-flight system resulted in the inadvertent engagement of open climb mode, which resulted in an increase in engine thrust and aircraft acceleration. Attempting to avoid exceeding the limiting speed applicable to the existing aircraft configuration, the captain retarded the thrust levers to the idle stop, inadvertently disconnecting the auto-thrust system. The crew resumed the approach, unaware that the auto-thrust system was disconnected, and therefore no longer controlling aircraft speed. As the aircraft continued to decelerate, soon after the final stage of flap was selected for landing, the Flight Management Guidance System generated a low energy warning. As the crew was responding to the low-energy warning, alpha-floor auto-thrust mode engaged. The crew accelerated the aircraft to approach speed using manual thrust control, and was able to continue the approach for an uneventful landing. The operator’s investigation into the incident found that, among other things, there may be some commonly held misunderstandings with respect to some aspects of instrument approach procedures, particularly their application to RNP approaches. The operator planned to communicate relevant procedural information to flight crew, with appropriate explanatory information, and communicate with flight crew regarding procedural requirements associated with auto-flight system mode awareness and speed monitoring. The operator also planned to include more guidance in appropriate documentation dealing with transfer of aircraft control between flight crew. This incident highlights the need for robust and clear instrument approach and auto-flight system management procedures. It also highlights the need for consistent attention to aircraft auto-flight modes and energy state.	..\..\References\2013-09-07-A320_accident-incident_report.pdf	Critical aspects: • Inadvertent engagement of open climb mode. • Inadvertent disconnection of the auto-thrust system. • Low crew general situational awareness: unawareness of disconnected auto-thrust during approach and of low energy state. • General misunderstanding of aspects of approach procedures.	

28 December 2014	A320-200	Scheduled Passenger Flight	Enroute	U - I	Flight Controls/ Loss of control-Stall Uncontrolled Descent	Narrative: An Indonesia AirAsia Airbus A320-216, performing flight 8501, was destroyed when it impacted the water of the Java Sea between Surabaya and Singapore. All 156 passengers and six crew members on board were killed. The flight took off from runway 10 at Surabaya-Juanda Airport (SUB) at 05:35 hours local time (22:35 UTC). The airplane turned left, tracking 329° over the Java Sea. The planned cruising altitude of FL320 was reached about 05:49. At 06:00 the Electronic Centralized Aircraft Monitoring (ECAM) amber advisory AUTO FLT RUD TRV LIM 1 appeared. One minute later a failure on both Rudder Travel Limiter Units triggered a chime and master caution light. The ECAM message showed "AUTO FLT RUD TRV LIM SYS" (Auto Flight Rudder Travel Limiter System). The pilot in command read and performed the ECAM action to set the Flight Augmentation Computer (FAC) 1 and 2 push-buttons on the overhead panel to OFF then to ON one by one. Both Rudder Travel Limiter Units returned to function normally. Upon entering the Jakarta Flight Information Region (FIR) over the TAVIP waypoint at 06:11 the flight contacted Jakarta ACC. The flight stated that they were deviating to the left of their planned route along airway M635 to avoid clouds and requested a climb to FL380. The requested climb was not possible due to other traffic but the flight was cleared to climb to FL340. At 06:13, a single chime sounded and the amber ECAM message "AUTO FLT RUD TRV LIM SYS" was again displayed. This was the third failure on both Rudder Travel Limiter Units on this flight. The pilots performed the ECAM actions and the system returned to function normally. At 06:15, the fourth failure on both Rudder Travel Limiter Units occurred and triggered ECAM message "AUTO FLT RUD TRV LIM SYS", chime and master caution light. At 06:16 the flight was cleared by Jakarta Radar to climb to FL340 but there was no reply. The Jakarta Radar controller then called the pilot for several times but received no reply. Meanwhile on the flight deck, the pilot in command decided not to follow the same ECAM actions as before to rectify the failure. He had recently observed a ground engineer resetting the FAC Circuit Breakers (CB) to rectify the rudder travel limiter failure and assumed he could use the same method in flight. This action however was not allowed in flight. The consequences of resetting FAC CBs in flight are not described in Airbus documents. It requires good understanding of the aircraft system to be aware of the consequences. Following a reset of the circuit breakers, several master cautions were triggered in relation to FAC's 1 and 2. After electrical interruption the autopilot and the auto-thrust then disengaged. Flight control law reverted from Normal Law to Alternate Law. The aircraft started to roll to the left up to 54° angle of bank. Nine seconds after the autopilot disengaged, the right side-stick activated. The delayed response of the pilot flying was likely due to his attention not being directed to the PFD as many events occurred at this time. He may have been startled when he realized the unusual attitude of the aircraft.	..\..\References\2014-12-28-A320-200_accident-incident_report.pdf	Critical aspects: • Repetitive faults unresolved by maintenance. • In-flight electrical system failure. • Incorrect flight crew action in response to Rudder Travel Limiter Units caution: the incorrect reset of Flight Automation Computers without any recovery procedures for inflight reset. The action is compatible with manual resetting of the circuit braker. • Autopilot disengage and transition from Normal to Alternate control laws. • Inability of the flight crew to control the aircraft when flown in Alternate law, leading to stall and departure from controlled flight until impact with the sea.	

						After the right side-stick activated, the aircraft roll angle reduced to 9° left. This rapid right rolling movement might cause an excessive roll sensation to the right. The pilot flying may have experienced spatial disorientation and over-corrected by shifting the side stick to the left which caused the aircraft rolled back to the left up to 50° The input on his side-stick was mostly pitch up and the aircraft climbed up to approximately 38,000 feet with a climb rate of up to 11,000 feet per minute. The aircraft pitch reached 24° up. The pilot in command then stated: "pull down...pull down" however the input on the pilot flying's side stick was backward and increased resulting in the AOA increasing up to a maximum of 48° up. At 06:17:17 the stall warning activated and continued until the end of the CVR recording. In a response the pilot in command applied nose down commands with his side stick while the pilot flying's side stick input was mostly at maximum pitch up until the end of the recording At 06:17:41 the aircraft reached the highest altitude of 38,500 feet and the largest roll angle of 104° to the left. The aircraft then lost altitude with a descent rate of up to 20,000 feet per minute. At approximately 29,000 feet the aircraft attitude was wings level with pitch and roll angles of approximately zero with the airspeed varied between 100 and 160 knots. The Angle of Attack (AOA) was almost constant at approximately 40° up. The aircraft then lost altitude with an average rate of 12,000 feet per minute until the aircraft impacted the sea. On December 30 pieces of debris and bodies were recovered from the sea. On January 12 and 13, 2015 the Flight Data Recorder (FDR) and Cockpit Voice Recorder (CVR) were retrieved. On January 14 the main fuselage was located by a Singapore Navy ship. Probable Cause, Contributing factors: - The cracking of a solder joint of both channel A and B resulted in loss of electrical continuity and led to RTLU failure. - The existing maintenance data analysis led to unresolved repetitive faults occurring with shorter intervals. The same fault occurred 4 times during the flight. - The flight crew action to the first 3 faults in accordance with the ECAM messages. Following the fourth fault, the FDR recorded different signatures that were similar to the FAC CB's being reset resulting in electrical interruption to the FAC's. - The electrical interruption to the FAC caused the autopilot to disengage and the flight control logic to change from Normal Law to Alternate Law, the rudder deflecting 2° to the left resulting the aircraft rolling up to 54° angle of bank. - Subsequent flight crew action leading to inability to control the aircraft in the Alternate Law resulted in the aircraft departing from the normal flight envelope and entering prolonged stall condition that was beyond the capability of the flight crew to recover.			

10 March 2019	B-737-MAX8	Scheduled Passenger Flight	Climb	D - V	Instruments, Sensors/ Uncontrolled Descent	Narrative: Ethiopian Airlines flight ET302, a Boeing 737 MAX 8, crashed shortly after takeoff from Addis Ababa-Bole Airport, Ethiopia. There were no survivors among the 157 occupants. Takeoff roll began from runway 07R at 08:38 hours local time, with a flap setting of 5 degrees and a stabilizer setting of 5.6 units. At 08:38:44, ten seconds after rotation, the left and right recorded Angle of Attack (AOA) values deviated. The left AOA decreased to 11.1° then increased to 35.7° while value of right AOA indicated 14.94°. This resulted in the onset of the stick shaker followed by a master caution light. At the same time the captain's primary flight display (PFD) showed a drop in indicated airspeed (IAS) from 170Kt to 156Kt. The captain initially responded by reducing the pitch as a reaction to the stick shaker. This did not stop the stick shaker and the captain to stopped applying further nose down column input at a pitch angle of 7-8° above horizon Approaching 400 ft, the captain attempted to engage the autopilot (AP) but it was not successful. A second attempt failed as well. Passing 1000 ft radio altitude, at the third attempt, the autopilot was successfully engaged. The captain asked the first officer to advise ATC of the inability to follow the planned departure due to a flight control problem and to request runway heading and climb 14,000ft. The left stall management yaw damper computer which was affected by inputs from a failed left AOA sensor calculated the left hand minimum operational airspeed erroneously above 340kt (VMO). This resulted in an overspeed warning. At the same time, the auto throttle operation was affected by the erroneous left AOA sensor value and remained in the Arm mode and failed to transition to N1 mode, which would have reduced the take-off thrust to climb thrust automatically. The auto throttle did not give a warning or a failure flag for the flight crew when its operation was affected by the failed AOA sensor value. The first activation of the Maneuvering Characteristics Augmentation System (MCAS) system occurred within a second where the auto throttle was supposed to reduce from take-off thrust to climb trust. And in less than another second the GPWS aural alert "DON'T SINK" sounded twice. The activation of MCAS followed by GPWS aural alert with already ongoing stick shaker coupled with no failure flag or warning from the auto throttle in an extremely high workload environment must have caused the auto throttle remaining in the ARM mode with take-off thrust set to remain unnoticed by the crew. At 08:39:45, captain requested flaps up and the first officer moved the flap handle to position 0. The autopilot then disengaged and the flaps reached the up position.	..\..\References\2019-03-10-B-737-MAX8_accident-incident_report.pdf ..\..\References\2019-03-10-B-737-MAX8_accident-incident_report_NTSB.pdf	Critical aspects: • Left and right recorded Angle of Attack (AOA) values deviated. • AoA values deviation resulting in an overspeed warning and in erroneous operation of the auto throttle, which did not transition from Arm mode to N1 mode. • Repetitive and uncommanded airplane-nose-down inputs from the MCAS due to erroneous AOA input. • Intermittent flight control system abnormalities began well before the accident flight. • Several pilot write ups involving temporary fluctuations of vertical speed and altitude prior to accident. • The airplane suffered intermittent electrical/electronic anomalies in addition to the flight control system malfunctions. • The possibility of intermittent electrical/electronic system defects were an underlying issue: the AOA sensor malfunction on the accident flight most likely occurred as the result of a power quality problem that resulted in the loss of power to the left AOA Sensor Heater. The loss of power was likely due to a production related intermittent electrical/electronic failure involving the airplane's Electrical Wiring Interconnection System (EWIS) and the AOA Sensor part. • System design process not considering potential for uncommanded activation of	

						At 08:40:00, because of the erroneous left AOA value, the MCAS activated the first automatic nose down trim for 9 seconds. At the end of the first MCAS activation the stabilizer position was 2.1 units with the captain pulling to pitch up the airplane, with a force of around 90 lbs (41 kg). At different times when the pilot applied electrical trim for short duration or longer duration the trim stopped at about 2.3 for unknown reasons. At 08:40:20 the second MCAS activation, lasting 7 seconds, was interrupted by the captain's electric trim up inputs. The captain applied a nine second electric trim-up input which fully counteracted the second MCAS input and stopped the GPWS warning but it did not bring the aircraft to a neutral trim condition. When MCAS activated for the third time an automatic nose-down trim was commanded there was no corresponding motion of the stabilizer, which is consistent with the stabilizer trim cutout switches being in the "cutout" position. The captain repeatedly requested the first officer to pull up with him on the control column with pitch values oscillating between 7° nose up and -2° nose down. Pitch increased when both pilots applied forces, pitch decreased when a single pilot applied force (force oscillated between 80 lbs and 110 lbs (36-50 kg)). The vertical speed variations followed the variations of the pitch angle, with vertical speed was oscillating between -2,500 ft/min and 4,400 ft/min. The captain requested the first officer to try the manual trim wheel, and after seconds of intense efforts, the first officer told the captain that it was not working. This was due to the amount of force required to turn the trim wheel. At this moment the stabilizer trim was at 2.3 units with the IAS at 340 Kts. At 08:42:10 the captain asked and the first-officer to request radar control a vector to return. ATC instructed ET302 to turn right heading 260 degrees. During the radio communications with the ATC, the first officer's action on the control column was released which increased forces on the captain's control column. The captain then requested the first officer to check the Master Caution. Then, they both announced "left alpha vane". At this time the airplane was almost reaching the minimum safe altitude. After about 10 seconds the captain then told the first officer that they should pitch up together. The captain then told the first officer "pitch is not enough" and "put them up". A sound similar to stab trim cut-out switches being returned to normal was recorded on the CVR, thus the stab trim cut out switches were most likely turned back on at that moment. After a failed attempt to trim using the manual trim wheel as per the runaway stabilizer non-normal checklist and significant and unbearable amount of force on the control column, the flight crew were trying to find other means to relieve the force. The airplane was at 13800 ft; IAS was 367kt, pitch just below 1°, stabilizer at 2.3 units of trim, bank angle 21° right. The crew was busy pulling on the controls with high muscular force trying to maintain airplane flight path control and reach 14000 ft, a target on which they remained focused. Trying to maintain flight path control was a very demanding task and represented here a high workload, physically and mentally, to the detriment of every other task.		MCAS and it did not evaluate all the potential alerts and indications that could accompany a failure leading to an uncommanded MCAS. • MCAS system relying on single AOA sensor. • Absence of AOA DISAGREE warning flag on the flight display panels (PFD). • The B737 MAX Crew difference CBT training did not cover the MCAS system. • Failure by the manufacturer to provide procedures regarding MCAS operation to the crew during training or in the FCOM. • Failure by the manufacturer to address the safety critical questions raised by the airline which would have cleared out crew confusion and task prioritization. • Active flight Envelope protection predicated on sensor paths with inadequate sensor redundancy. • Irreversible flight controls that utilized excessive control force architecture, not allowing for successful manual override of automation.	

						An overspeed warning added another disruption and disturbance on board. The cockpit noise environment was unsettling and further impacted the flight crew’s concentration. Immediately after the stab trim cut-out switches were put back in normal position, the crew attempted another unsuccessful autopilot engagement as the plane was approaching 14000 ft. At the same time, the captain applied two brief electric trim up inputs of 1 second each while pulling on the control with an average force of 100 lbs (45 kg). The force on the controls remained between 75 and 100 lbs. At 08:43:20, five seconds after the trim-up inputs, the fourth MCAS triggered. The plane started to descend. During the 9-second MCAS activation, the stabilizer decreased from 2.3 units to 1 unit of trim. The captain repeatedly shouted to the first officer to pitch up. The forces were physically unmanageable by both flight crews. The aircraft began pitching nose down. The airplane hit the ground eighteen seconds after the end of the 4th MCAS. The investigation noted that intermittent flight control system abnormalities began well before the accident flight. Maintenance actions of relevance started occurring in December 2018 when the airplane was one month old and included several pilot write ups involving temporary fluctuations of vertical speed and altitude. There were also three reports of the airplane rolling during autopilot operation. Altitude and vertical speed indications on the PFD showed erratic and exaggerated indications. From the maintenance log book report the airplane also suffered intermittent electrical/electronic anomalies in addition to the flight control system malfunctions. For example, three days before the crash the Auxiliary Power Unit (APU) Fault Light illuminated, and the APU had a protective shutdown. The onboard maintenance function computer message also indicated the Start Converter Unit (SCU) showed the APU’s start system was inoperative. The SCU is located in the electrical and electronics (E/E) compartment. The captain’s personal computer power outlet also had no power. The possibility of intermittent electrical/electronic system defects were an underlying issue. The AOA sensor malfunction on the accident flight most likely occurred as the result of a power quality problem that resulted in the loss of power to the left AOA Sensor Heater. Evidence indicates the loss of power was likely due to a production related intermittent electrical/electronic failure involving the airplane’s Electrical Wiring Interconnection System (EWIS) and the AOA Sensor part. Probable Cause: Repetitive and uncommanded airplane-nose-down inputs from the MCAS due to erroneous AOA input, and its unrecoverable activation system which made the airplane dive with the rate of -33,000 ft/min close to the ground was the most probable cause of the accident. Contributing Factors			

Accident Reports Summary									
Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
						1. The MCAS design relied on a single AOA sensor, making it vulnerable to erroneous input from the sensor; 2. During the design process, Boeing failed to consider the potential for uncommanded activation of MCAS, but assumed that pilots would recognize and address it through normal use of the control column, manual electric trim, and the existing Runaway Stabilizer NNC. The OMB and Emergency AD issued after the Lion Air accident included additional guidance but did not have the intended effect of preventing another MCAS-related accident; 3. While Boeing considered the possibility of uncommanded MCAS activation as part of its FHA, it did not evaluate all the potential alerts and indications that could accompany a failure leading to an uncommanded MCAS; 4. The MCAS contribution to cumulative AOA effects was not assessed; 5. The combined effect of alerts and indications that impacted pilot's recognition and procedure prioritization were not evaluated by the Manufacturer; 6. Absence of AOA DISAGREE warning flag on the flight display panels (PFD); 7. The B737 MAX Crew difference CBT training prepared by Boeing and delivered to Pilots did not cover the MCAS system; 8. Failure by the manufacturer to design simulator training for pilots with regards to safety critical systems like MCAS with catastrophic consequences during undesired activation. 9. The manufacturer failed to provide procedures regarding MCAS operation to the crew during training or in the FCOM; 10. Failure by the manufacturer to address the safety critical questions raised by the airline which would have cleared out crew confusion and task prioritization.			

24 September 1994	A310	Scheduled Passenger Flight	Approach	N/A	Incorrect approach procedure-misunderstanding of mode reversion/ Unusual attitudes	No injuries	Narrative: Tarom flight 381 was making an approach to Paris-Orly runway 26 and the captain was at the controls. He decided to perform an automatic approach and landing. The flight crew started to put the aircraft into the approach configuration, with slats and flaps at 15/0 at 10:42:05, then at 15/15 at 10:42:53. The landing gear was extended at 10:42:57. Approaching the OYE beacon at indicated speed 250 kt and heading 325, before lining up with the runway, the Captain noted that the aircraft was not capturing the ILS glide slope automatically. He disconnected the AP and continued the approach on manual control, keeping the Autothrottle in operation. As the aircraft descended through 1,700 feet, at 10:43:22, with a speed of about 195 knots, the Captain asked for flap extension to 20°. The VFE, the speed limit authorized for this new configuration, is 195 knots. When the flap control was set to 20°, the thrust levers advanced and engine thrust increased. The flight crew countered the nose-up effect resulting from the increase in thrust by using the pitch controls, with the auto-throttle (ATHR) remaining in automatic mode. The throttle levers were then quickly brought back to the idle position. At the same time, the trimmable horizontal stabilizer started to move in a nose-up direction. The nose up effect that resulted was countered by the flight crew through gradual nose-down action on the elevators. When the trimmable horizontal stabilizer reached its maximum nose-up value and the elevators also reached their maximum nose down value, the throttle levers, according to the FDR readout, moved rapidly to their stops. In a few seconds, the flight path started to rise and the pitch attitude went to 60°. Witnesses saw the aircraft climb. It banked sharply to the left and the right and stalled before adopting a strongly negative pitch attitude (-33 degrees) towards the ground. The maximum altitude reached was 4,100 feet, while a minimum indicated speed of 35 knots was recorded. The stall and ground proximity warnings sounded during the descent. The flight crew managed to regain control of the aircraft, with the lowest point being around a height of 800 feet, that is 240 meters from the ground. The flight crew then performed a visual circuit, followed from the tower by the controller. The second approach was made with a configuration with slats and flaps at 20/20. Landing took place at 10:52:25. Probable Cause: "The direct causes of the unusual attitudes and the stall to which the aircraft was subjected were a movement of the THS towards the full pitch-up position and a rapid increase in thrust, both of which maneuvers were the due to the Captain, following an AFS mode reversion which was not understood. The pitch-up force caused a sudden change in attitude that the flight crew was unable to contain with the elevators. The following elements contributed to the incident: - Too rapid an approach, due to a late start in the descent, followed by a reduction of the standard procedure. - Inadequate crew resource management. - Premature selection of the go around altitude and precipitous setting of the configuration with slats and flaps at 20-20, which led to activation of the speed protection.	..\..\References\1994-09-24-A310_accident-incident_report.pdf	Critical aspects: • Captain asking for 20 deg flap deflection at 195 kts airspeed, with V_{FE} = 195 kts . Decision leading to the main cause of the incident: engagement of speed protection. • Captain misunderstanding of the automatic flight system mode. • Trimmable Horizontal Stabilizer (THS) deflected trailing edge up, for pitch up trim, “unintentional[ly] and unconscious[ly] by one of the pilots”. • Pitching up moment due to full throttle counteracted by pilot’s manual maneuver commanding trailing edge down (pitch down) elevator deflection. • Pilot’s confusing control functions between different aircraft types. • Saturation of the longitudinal elevator control due to maximum trailing edge up deflection of THS, leading to uncontrolled pitch up when Captain moved the throttles to the stops. • Just before the stall, the Captain pulled the control column fully back. • No actions which could be called “return to basics” on the part of the flight crew. • The flight crew did not notice the several AFS mode changes. • The flight crew did not carry out an in flight de-briefing of the event and a briefing for the new approach. • It is the positioning of the flaps selector and not extension thereof which introduces the new V_{FE}. As	

Accident Reports Summary

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						- Difficulty in understanding the action of the auto-throttle increasing thrust in its overspeed protection function."		a result, V_{MAX} instantaneously switches from 210 to 195 kt on selection of flaps from 15° to 20°. • Envelope Alpha-floor protection could not play its role as, when angle of attack of 14.5° was reached, the throttle levers were already on maximum thrust. • The stall warning did not sound and the stick shaker did not operate in the flight phase prior to the stall, because of the disturbance of the angle of attack sensors due to the dynamics of the aircraft's movements, with the speed having dropped below 60 kt before the angle of attack reached 17.5°. • The inherent static and dynamic stability of the bare airframe were fundamental factors for the recovery of the aircraft from the upset conditions.	

07 October 2008	A330-303	Scheduled Passenger Flight	Enroute	N/A	Issue with control laws algorithm/abrupt, uncommanded pitch down maneuver 110 passengers injured, with 12 seriously injured, 9 crew members injured	Narrative: At 09:32 local time (01:32 UTC) on 7 October 2008, an Airbus A330-303 aircraft, registered VH-QPA, departed Singapore (SIN) on a scheduled passenger transport service to Perth (PER), Australia. On board flight QF72 were 303 passengers, nine cabin crew and three flight crew. At 12:40:28, while the aircraft was cruising at 37,000 ft, the autopilot disconnected. That was accompanied by various aircraft system failure indications. At 12:42:27, while the crew was evaluating the situation, the aircraft abruptly pitched nose-down. The aircraft reached a maximum pitch angle of about 8.4 degrees nose-down, and descended 650 ft during the event. After returning the aircraft to 37,000 ft, the crew commenced actions to deal with multiple failure messages. At 12:45:08, the aircraft commenced a second uncommanded pitch-down event. The aircraft reached a maximum pitch angle of about 3.5 degrees nose-down, and descended about 400 ft during this second event. At 12:49, the crew made a PAN emergency broadcast to air traffic control, and requested a clearance to divert to and track direct to Learmonth. At 12:54, after receiving advice from the cabin crew of several serious injuries, the crew declared a MAYDAY. The aircraft subsequently landed at Learmonth Airport, WA (LEA) at 13:50. At least 110 of the 303 passengers and nine of the 12 crew members were injured; 12 of the occupants were seriously injured and another 39 received hospital medical treatment. Most of the injuries involved passengers who were seated without their seatbelts fastened. Probable Cause: Contributing Safety Factors: - There was a limitation in the algorithm used by the A330/A340 flight control primary computers for processing angle of attack (AOA) data. This limitation meant that, in a very specific situation, multiple AOA spikes from only one of the three air data inertial reference units could result in a nose-down elevator command. [Significant safety issue] - When developing the A330/A340 flight control primary computer software in the early 1990s, the aircraft manufacturer's system safety assessment and other development processes did not fully consider the potential effects of frequent spikes in the data from an air data inertial reference unit. [Minor safety issue] - One of the aircraft's three air data inertial reference units (ADIRU 1) exhibited a data-spike failure mode, during which it transmitted a significant amount of incorrect data on air data parameters to other aircraft systems, without flagging that this data was invalid. The invalid data included frequent spikes in angle of attack data. Including the 7 October 2008 occurrence, there have been three occurrences of the same failure mode on LTN-101 ADIRUs, all on A330 aircraft. [Minor safety issue]	..\..\References\2008-10-07-A330_accident-incident_report.pdf	Critical aspects: • Event: sequence of two uncommanded pitch downs. • Combination of a design limitation in the flight control primary computer (FCPC) software of the Airbus A330/A340, and a failure mode affecting one of the aircraft's three air data inertial reference units (ADIRUs). • ADIRU serial number 4167 subject to previous instances of the data spike failure mode, potential marginal weakness in its hardware. • Design not considering effects of ADIRU data spike failure mode. • ADIRU failure mode occurred three times previously, all on A330 aircraft. • ADIRU manufacturer did not identify the data spike failure mode.	

Accident Reports Summary									
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						- The LTN-101 air data inertial reference unit involved in the occurrence (serial number 4167) also had a previous instance of the data-spike failure mode, indicating that it probably contained a marginal weakness in its hardware, which reduced the resilience of the unit to some form of triggering event. - For the data-spike failure mode, the built-in test equipment of the LTN-101 air data inertial reference unit was not effective, for air data parameters, in detecting the problem, communicating appropriate fault information, and flagging affected data as invalid. [Minor safety issue] - The air data inertial reference unit manufacturer's failure mode effects analysis and other development processes for the LTN-101 ADIRU did not identify the data-spike failure mode.			

13 June 2012	CV-22	Training mission	Two-ship tactical formation	N/A	Wake Turbulence/ Uncommanded Ground Impact	The mishap sortie (MS) was a training mission flown as part of a two-ship tactical formation training line. The mishap flight (MF) consisted of the MA and the mishap lead aircraft (MLA), also a CV-22. At 2339:38Z, the MLA began a left 180-degree turn at 30 degrees of bank to bring the MF around to the southeast for the initial firing pass on A-78. During this turn, the MLA descended slightly from 366 to 336 feet mean sea level (MSL). Simultaneously, the Mishap Co-Pilot (MCP) (who was flying the MA throughout the MS) began a brief level right turn at 354 feet MSL, followed immediately by a 30-degree bank, level left turn to maintain separation from the MLA. Although this maneuver never took the MA directly behind the MLA, the MA did cross the MLA's turning flight path and the MLA's wake. As the MA crossed the MLA's flight path, the combination of the MLA's bank angle and the MA's bank angle caused the MA's left proprotor to enter the MLA's wake. Once the MA's left proprotor entered the MLA's wake, the MA immediately began an uncommanded roll to the left. The Mishap Pilot (MP) placed his hands on the flight controls and both he and the MCP attempted to recover the MA. They were able to stabilize the MA in a wings level flight condition but were unable to arrest the descent rate before the MA entered the 80- to 100- foot trees on the range and impacted the ground. The MP and the MCP believed that they maintained adequate lateral and vertical separation from the MLA's flight path and therefore that the MA would remain clear of the MLA's wake. However, data from the MA and MLA flight data recorders revealed that was not the case. The MP's and the MCP's misperception was most likely caused by a combination of the MF's turning flight path and minor changes in the MLA's altitude. The Accident Investigation Board President found by clear and convincing evidence that the cause of the mishap was the MP's and the MCP's failure to keep the MA clear of the MLA's wake. When the MA's left proprotor entered the MLA's wake, the MA's left proprotor lost lift, resulting in an uncommanded roll to the left, rapid loss of altitude and impact with the terrain. This error was due to a misperception by both the MP and the MCP of the MA's location in relation to the MLA's wake. This misperception caused the MCP, who was at the controls of the MA, to inadvertently fly the MA into the MLA's wake. This same misperception caused the MP, who was the aircraft commander, to fail to identify the hazardous situation and take appropriate corrective action either by directing the MCP to alter his position or by taking control of the MA and correcting its position to avoid the MLA's wake.	Ref: " Air Force Cites Pilot Error in Jun CV-22 Osprey Crash" , AOL defense, 9/11/2012 Ref: Silva, M, Et Al, " The Role of Modeling & Simulation in the Mitigation of V-22 Tiltrotor Formation Flight Wake-Induced Roll-off" , Presented at the AHS 72nd Annual Forum, West Palm Beach, Florida, USA, May 17-19, 2016. ..\..\References\2012-06-13-CV-22_accident-incident_report.pdf	Critical aspects: • Mishap Pilot's and Mishap CoPilot's failure to keep the Mishap Aircraft clear of the Mishap Leading Aircraft's wake. Later investigation revealed that in the V-22 design, blending of lateral controls with transition from thrust-borne lift to wing-borne lift effectively created a notch in the roll control effectiveness at 60 knots, where the primary effector, Differential Collective Pitch (DCP) of the proprotors was restricted by Structural Load Limiting. When the wake of another V-22 aircraft was encountered at low altitude, the roll upset of the trail aircraft could not be arrested and the aircraft impacted the ground inverted. Examination of the roll axis HQ showed borderline Level 2/3 HQ per Mil-F-83300, in the roll axis at this speed. The roll axis control was redesigned which allowed for greater use of other controls at this speed which included flaperons and lateral swashplate gearing. Additionally, with large lateral stick application, an asymmetric application of DCP was permitted to work with the Structural Load Limiting.	Para AC 29.143A, AC 29-2C Certification of Transport Category Aircraft, 7/02/2018. Para 3.4.6.3 Large-amplitude roll attitude changes, ADS-33E, Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military rotorcraft, 10 May 1996. Para 3.3.9, Roll Control Effectiveness, MIL-F-83300, Military Specification Flying Qualities of Piloted V/STOL Aircraft, 26 September 1991.

11 April 2022	MV-22	Troops deployment	Vertical Landing	D - V	Flight crew error/ Uncontrolled ground impact	An April 11 MV-22B Osprey crash in Morocco occurred because the pilot committed a fundamental flying error which investigators have found was rendered irreversible by a tailwind neither he nor a second pilot in the cockpit noticed. The Defense Department announced June 29 that the Marine Corps had ruled out any “mechanical or material failure” in the accident, in which two Marines were killed and the two pilots were injured. “This wasn’t a tiltrotor accident; it was bad flying,” said a government source with detailed knowledge of the findings, which are still being reviewed by Marine Corps leaders. Two military officers familiar with the findings separately confirmed that the pilot of the mishap aircraft started the sequence of events that culminated in the crash by violating an explicit instruction in the Osprey’s flight manual. “No-kiddin’ human error is involved here,” one military officer said. Another said of the pilots: “Unfortunately they put the aircraft in a position beyond the (flight manual) limits that are advertised and that are trained to, and they made an error.” The MV-22B that crashed in Morocco was attached to Marine Medium Tiltrotor Squadron 261 (VMM-261), based at Marine Corps Air Station New River, N.C. VMM-261 was participating in a joint military exercise with Moroccan armed forces when the accident occurred. Just prior to the accident, with the less experienced but fully trained copilot at the controls, the Osprey had set down helicopter-style to drop off at least the second load of troops its crew had delivered that day to the same austere landing zone. As the pilots took off to return to a temporary on-shore base, the following events unfolded in quick succession: From BREAKING DEFENSE Under a clear, daylight sky and with no dust interfering with the crew’s view, the pilot at the controls lifted the Osprey into a hover 20 or 30 feet above the ground with the plane’s nose pointing into the wind, as it had been when the aircraft landed a few minutes earlier. The pilot flying then used his foot pedals to turn the Osprey in a half-circle to the right, rotating in mid-air to head in the direction from which they’d arrived. As the aircraft turned, it climbed to about 50 feet. As the Osprey turned, the pilot pitched the aircraft’s nose down about 10 degrees by pushing the control stick forward with his right hand. At the same time, using his left hand, he turned a small thumbwheel on the	Ref: Whittle, Richard. “ Marines peg “ Bad Flying” as cause of April V-22 Crash in Morocco” , AOL Defense, 9 Jul 2012	Critical aspects: • The pilot tilted the nacelles and rotors down from 90 degrees and brought them to an angle significantly less than 75 degrees – a position that violated flight manual limits on nacelle angles at low forward airspeed. • Nacelle’s tilt shifted the aircraft center of gravity too far forward, causing the nose to plunge downward. • Tailwind pushing the bottom of the horizontal stabilizer as the tail of the aircraft angled upward. • “Below 40 knots calibrated air speed, there is insufficient wind moving across the conventional airplane control surfaces to add roll, pitch or yaw control authority. The aircraft relies on the controls of a helicopter.” • MV-22B NATOPS manual “severe pitch down and altitude loss can occur if nacelles are rotated too far forward too quickly at takeoff.” • Operating Limitations section of the NATOPS manual WARNING: “When transitioning to forward flight from a hover, limit nacelles to greater than 75 degrees until 40 KCAS (Knots Calibrated Air Speed) is reached.” • The operating limits were later determined to be an inadequate approach to this hazardous condition (ref: MIL-STD-882E). At low-speed in thrust-borne flight in the V-22, longitudinal control is accomplished by the use of	Paragraph 3.4. Control Authority Awareness., FAA Policy Statement, PS-ASW-27-J29-09, Rotorcraft Advanced Flight Controls (AdFC) Handbook, 27 March 2015. Paragraph 3.4.2 Pitch Control Power, *ADS-33E, Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military rotorcraft, 10 May 1996.*

						Osprey’s throttle, or Thrust Control Lever, to tilt the nacelles and rotors down from 90 degrees and brought them to an angle significantly less than 75 degrees – a position that violated flight manual limits on nacelle angles at low forward airspeed. The effect was to shift the Osprey’s center of gravity too far forward, causing the nose to plunge downward. As the nose went down, the pilot was unable to hold it where he wanted by pulling back on the control stick because the horizontal stabilizer at the aircraft’s tail was being pushed up and forward by a 20-knot tailwind. The tailwind’s speed and direction were depicted on a digital map inside the cockpit, but vegetation in the area was too sparse to alert the pilots to the wind as they looked outside the aircraft during takeoff. The tailwind pressure on the horizontal stabilizer reduced the stick’s “aft control authority” while adding downward leverage on the nose. “By the time the pilot realized he was out of back stick authority, it was too late,” one source observed. The aircraft plunged nearly straight down into the ground, hitting nose first. The cockpit was crushed, but the two pilots – whose identities haven’t been released – were strapped into their seats and survived, though with severe injuries. The two enlisted crew chiefs, Cpl. Robby A. Reyes, 25, of Los Angeles and Cpl. Derek A. Kerns, 21, of Fort Dix, N.J., were killed. MV-22B crew chiefs, like those on Marine Corps helicopters, ride in the back cabin and often stand during flights, secured only by a long strap attached to the aircraft to keep them from falling out if the back ramp is open. Despite being loaded with more than half the fuel an MV-22B can carry, the Osprey didn’t catch fire after crashing, and its Crash Survivable Memory Unit, or “black box,” was recovered. The CSMU, which records aircraft operating data, showed conclusively that there were no mechanical problems with the aircraft. By JUSTIN KATZ “Flight data information indicates that the aircraft performed as expected and described in the MV-22 Naval Air Training and Operating Procedures Standardization (NATOPS) Flight Manual,” the Defense Department’s June 29 news release said. “The U.S. Marine Corps has determined the aircraft did not suffer from a mechanical or material failure and there were no problems with the safety of the aircraft.” Additional analysis determined that the combination of the pilot violating the NATOPS limit on forward nacelle angle at low airspeed, the resulting excessive forward center of gravity and severe downward pitch of the aircraft’s nose, and the tailwind pushing the bottom of the horizontal stabilizer as the tail of the aircraft angled upward all contributed to the crash.		continuous nacelle control, through a nacelle thumbwheel, and longitudinal cyclic control of the proprotors through pilot stick. In one accident the aircrew, while in a hover, turned into a tail-wind condition which reduced longitudinal stick margin, and then applied rapid forward nacelle through the thumbwheel control. The forward nacelle created a downward pitch moment that was not able to be arrested with full aft pilot stick, and the aircraft nose-dived into the ground. The longitudinal axis control was redesigned to not permit rapid movement of forward nacelle when aft stick margins are reduced, along with automatic application of aft nacelle to restore stick margin when stick is on the aft stick stop.	

“The combination of those factors made the aircraft unrecoverable at low altitude,” one source said. “Below 40 knots calibrated air speed, there is insufficient wind moving across the conventional airplane control surfaces to add roll, pitch or yaw control authority. The aircraft relies on the controls of a helicopter.”

A helicopter’s controls change the craft’s position by changing the angle at which its rotor blades hit the air they’re moving into, known as the “relative wind.” An airplane’s controls change the angles at which control surfaces such as elevators and ailerons hit the relative wind. The helicopter-airplane hybrid Osprey’s computerized flight controls work like a helicopter’s at slow speeds and like an airplane’s once a V-22 gains enough forward air speed for its wing to produce more lift than its rotors — usually 110 knots or more with the wing horizontal. At nacelle angles between 75 and 30 degrees, the Osprey’s flight control computer blends helicopter and airplane controls.

Despite those characteristics, veteran Osprey pilots said the root aerodynamic cause of the Morocco accident wasn’t peculiar to a tiltrotor.

“As with any aircraft, there are center-of-gravity limitations,” said a pilot who agreed to discuss the crash on condition of anonymity because the results of the investigation have yet to be released. “Too much forward center of gravity in any aircraft, the aircraft will not have enough pitch authority to counter the nose-down pitching moment. Too much aft center of gravity and the aircraft will not have enough pitch authority to counter a nose-up pitching moment.”

Contrary to at least one report, the crash in Morocco had nothing to do with a well-known Osprey peculiarity known as Pitch Up With Side Slip. Aerodynamically, what happened in Morocco was the direct opposite.

In Pitch Up With Side Slip, the downwash from the rotors of an Osprey flying at a slight angle into relative wind of 20 to 30 knots, or hovering with a front quartering wind of 20 to 30 knots, can push down on the horizontal stabilizer at the tail, pitching the aircraft’s nose up. Osprey pilots are trained to compensate for Pitch Up With Side Slip by pushing the control stick forward a bit or turning the aircraft’s nose directly into the wind. The Osprey’s computerized flight controls also automatically compensate for Pitch Up With Side Slip by tilting the nacelles forward a touch when necessary.

The Flight Characteristics chapter of the MV-22B NATOPS manual contains several sections relevant to the crash in Morocco, including one “Warning” — a designation used to highlight risks that can lead to injury or death.

Accident Reports Summary									
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						The Warning cautions pilots that “severe pitch down and altitude loss can occur if nacelles are rotated too far forward too quickly at takeoff.” A separate note advises that when accelerating by tilting the nacelles forward, an Osprey pilot should apply “aft stick movement to maintain pitch attitude due to thrust and cg (center of gravity) effects.” The Operating Limitations section of the NATOPS manual explicitly instructs: “When transitioning to forward flight from a hover, limit nacelles to greater than 75 degrees until 40 KCAS (Knots Calibrated Air Speed) is reached.”			

30 October 2015	AW609	Developmental Tes & Evaluation	High Speed Descent	D - V	Impact of proprotor with aircraft wing\in flight break up	The ANSV said that a combination of ground debris mapping and telemetry data led it to "hypothesize with reasonable certainty" that the aircraft broke up in flight as a result of multiple prop-rotor strikes from excessive blade flapping on the wings as a consequence of excessive yaw angles reached during the fatal dive. This damaged the hydraulic and fuel lines that are positioned along the wing leading edges, precipitating the in-flight fire. The aircraft was equipped with flapping stops, but they were not designed to "contain the effects of the extreme aerodynamic forces generated during the event." Because of the aerodynamic characteristics of the aircraft and the specific conditions created by the dive, the flying pilot's attempt to counteract the oscillations with a roll-tracking maneuver to level the wings was ineffective, partly because the FCS was designed to "couple" on more axes than the command inputs given on the single axis by the pilot. Specifically, "Total lateral control resulting from the summation of pilot input and automatic FCS input has an effect on the yaw axis through aerodynamic coupling and feedforward and feedback turn coordination automatically provided by the FCS. Consequently, giving a command in counterphase on the roll axis to damp the relative oscillations creates an effect on the yaw axis that can be in phase with the yaw oscillations. This occurred during the accident: the correction of the roll oscillation induced by the control laws of the FCS, a maneuver in phase with the oscillations of the yaw axis, generating a divergence of the oscillations." The ANSV said that the "low frequency and low amplitude nature of the oscillations" made them difficult for the pilots or ground crew to perceive until the roll and yaw "reached excessive levels only a few seconds before loss of control." The pilot flying also made rudder-pedal inputs. As explained above, the inputs exacerbated the situation, taking sideslip to maximum values. The tiltrotor entered a dive at the 293-knot design dive speed. AC2 was fitted with a new tapered rear fuselage and redesigned vertical fin with less surface area. During the dive, the aircraft reached 306 knots. Investigators attempted to recreate the accident flight in the AW609 SIMRX in Philadelphia using the same software and flight conditions, but could not; they came close by inserting algorithms that changed the aerodynamic configuration of the aircraft, but even then the lateral-directional oscillations developed were in a different phase. They did, however, use the exercise to verify the "great difficulty" of recovery to controlled flight under the conditions. The ANSV found the inability to replicate the accident flight in the simulator unremarkable, given "the lack of experimental data obtained previously in the wind tunnel and in-flight evaluations with those speed conditions and relating to the recent modified geometry of the tail fin; this last change was considered conservatively by entering a reduction in the tail fin area into the database and then implementing the computational fluid dynamics."	Ref: Final Report, Accident; AgustaWestland AW609 aircraft registration marks N609AG, Tronzano Vercellese (VC), 30th of October, 2015. Agenzia Nazionale Per La Sicurezza Del Volo. ..\..\References\2015-10-30-AW609_accident-incident_report_english.pdf	Critical aspects: • The aircraft broke up in flight as a result of multiple prop-rotor strikes from excessive blade flapping on the wings as a consequence of excessive yaw angles reached during the fatal dive. • Multiple control allocation. • The flying pilot's attempt to counteract the oscillations with a roll-tracking maneuver to level the wings was ineffective, partly because the FCS was designed to "couple" on more axes than the command inputs given on the single axis by the pilot. • Giving a command in counterphase on the roll axis to damp the relative oscillations creates an effect on the yaw axis that can be in phase with the yaw oscillations. • Highly divergent yaw oscillations. • New tapered rear fuselage and redesigned vertical fin with less surface area. • Lack of experimental data obtained previously in the wind tunnel and in-flight evaluations with those speed conditions and relating to the recent modified geometry of the tail fin. In wing-borne flight the use of Differential Collective Pitch for yaw control and for torque balance between the proprotors that are connected by an interconnect driveshaft, came into conflict and yaw started to diverge. Additionally,	Existing Related Guidance: paragraph 3.1.4.2.3 Cat III PIO Highly Nonlinear Aircraft-Pilot Interactions. FAA Policy Statement, PS-ASW-27-J29-09 Rotorcraft Advanced Flight Controls (AdFC) Handbook, 27 March 2015,

Accident Reports Summary									
Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
						The ANSV made several safety recommendations after the accident: more high-speed and complex-flight-condition modeling, verification and wind tunnel testing as part of the AW609 certification process; and verification of the flight control laws in extreme flight conditions, in particular reviewing their effectiveness with regard to pilot inputs and uncommanded coupling effects.		roll control application to counter roll oscillation could produce out of phase response in the yaw axis through turn coordination and roll-rate to DCP control paths. In recovering the aircraft, through reducing collective pitch on the proprotors, the proprotor flapped into the wing and the aircraft experienced an inflight breakup. The aircraft design does not use the traditional rudder control for yaw but instead relies on DCP for yaw control. Refined flight Control laws have since been employed. The aircraft only uses longitudinal cyclic control of proprotor flapping and does not employ lateral cyclic control of proprotor flapping. This requires a delicate balance between torque balance and yaw control, while stringently controlling yaw rates that may produce dangerous flapping angles.	

06 July 2016	Bell 525	Developmental Tes & Evaluation	Demonstration of recovery from single engine failure	D - V	Diverging biodynamic coupling\in flight break up Two Fatal Injuries	The twin engine helicopter was demonstrating the ability to recover from a single engine failure at a high airspeed, high power flight condition. Upon initiating the single engine simulation, the main rotor rotational speed (RPM) decelerated as expected. The crew initiated a recovery of the rotor RPM but the rotor RPM decay was arrested but not restored. While remaining at this low RPM, high airspeed condition, an unexpected vibration emerged. The cabin vibration was amplified in a biomechanical feedback loop involving involuntary oscillations of the pilot collective control. Sensors utilized to stabilize the helicopter in gusts and maneuvers also participated in the feedback. The vibration grew rapidly as the aircraft continued to operate in a in this configuration, with large control inputs coinciding with the main rotor blades departing from their normal plane of motion, and the tailboom was severed. An inflight breakup of the aircraft ensued. Several fixes were applied. In particular, the biomechanical and sensor feedback was filtered by the control system so that these undesirable control inputs were not passed to the main rotor swashplate actuators, thereby preventing amplification of the vibrations present in this flight condition. Narrative: The first Bell 525 Relentless helicopter prototype (Flight Test Vehicle 1 - FTV1) was destroyed when it impacted terrain in Ellis County, Texas near the towns of Bell Branch and Italy. Both pilots were killed. There was a post crash fire. Bell said in a statement its helicopter was "conducting developmental flight test operations on the Bell 525 at our Xworx facility in Arlington, Texas, that resulted in a helicopter accident." A Bell spokesperson said there was one "chase" helicopter present as well, which is standard in test flight scenarios. According to an NTSB spokesman, the main rotors "departed their normal plane of rotation", and struck the tail and nose of the aircraft as a result. Flightradar24 records show the helicopter departing Arlington at 10:39 LT (15:39 UTC). It proceeded to the south were it flew pattern at altitudes between 2000 and 3000 feet. Last data point is at 1975 feet, at a groundpeed of 199 kts at 11:47 hours. At the time, it was tracking south to north with a 20-knot tailwind, equating to an approximate airspeed of 179 knots. Bell's projected high-speed cruise for the 525 is 162 knots. FTV1 first flew on 1 July 2015. Probable Cause: "The NTSB determined that the probable cause of the accident was a severe vibration of the helicopter that led to the crew's inability to maintain sufficient rotor rotation speed (Nr), leading to excessive	Bell 525 Flight Test Accident, Bell 525 Serial Number 62001, N525TA: Italy, Texas: 6 July 2016, Bell Helicopter Party Submission DCA 16FA199 to NTSB. https://aviation-safety.net/wikibase/188544	Critical aspects: • Pilot/vehicle biodynamic coupling, with unintentional oscillations of the pilot collective control. • Oscillations amplified by system to stabilize the helicopter in gusts and maneuver. • Highly divergent oscillations. • NTSB: the main rotors "departed their normal plane of rotation", and struck the tail and nose of the aircraft as a result.". • Lack of protections in the flight control laws against the sustainment and growth of adverse feedback loops. • Lack of an automated safeguard in the modified one-engine-inoperative (OEI) software used during flight testing. • Lack of distinct and unambiguous cues for low Nr.	Para 3.7.2.3 Command Signal Integrity, FAA Policy Statement PS-ASW-27-J29-09 Rotorcraft Advanced Flight Controls (AdFC) Handbook, 27 March 2015.

Accident Reports Summary									
Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						main rotor blade flapping, subsequent main rotor blade contact with the tail boom, and the resultant in-flight breakup. Contributing to the severity and sustainment of the vibration, which was not predicted during development, were (1) the collective biomechanical feedback and (2) the attitude and heading reference system response, both of which occurred due to the lack of protections in the flight control laws against the sustainment and growth of adverse feedback loops when the 6-hertz (Hz) airframe vibration initiated. Contributing to the crew's inability to maintain sufficient Nr in the severe vibration environment were (1) the lack of an automated safeguard in the modified one-engine-inoperative (OEI) software used during flight testing to exit at a critical Nr threshold and (2) the lack of distinct and unambiguous cues for low Nr.			

2 August 2017	Sikorsky S-97A Raider	Developmental Tes & Evaluation	Ground taxi to the takeoff	D - V	FCS mode transition, biodyn. Coupling\Ground impact Minor Injuries	This mishap occurred during a ground taxi to the takeoff location in which the pilot was simply applying collective and forward cyclic to taxi. The flight control system detected a transition to “flight mode” due to the combination of high collective position and reduced weight on wheels. As the pilot applied collective and became airborne, the helicopter rolled quickly left and then right, continuing with 2-3 roll reversals of increasing roll attitudes, eventually exceeding an estimated 60° angle of bank. The pilot applied counter roll control inputs, but roll rates experienced were excessive. After a large right angle of bank roll, as the helicopter reversed its roll, the pilot lowered the collective to full down to execute a landing. Investigation of the mishap determined that a larger than-expected roll response to the pilot's cyclic stick input was the unintended result of a flight control system design change that resulted in an increase in cyclic stick sensitivity in the roll axis during the transition from ground control mode to flight mode. The aircraft experienced significant damage and did not fly again. NTSB Releases Factual Report From 2017 S-97 Raider Accident Aircraft Experienced A Hard Landing While Hovering At The William P Gwinn Airport (06FA) In Jupiter, FL The NTSB has released a factual report from a hard landing which occurred August 2, 2017, at about 0720 EDT involving an experimental Sikorsky S-97A, N971SK, that was hovering at the William P Gwinn Airport (06FA) in Jupiter, FL. The aircraft sustained substantial damage during the test flight, however both airline transport-rated pilots sustained only minor injuries. According to the report, the helicopter taxied to the runway hold short line for runway 9/27 at taxiway A (alpha), lifted into a low hover, and immediately experienced excessive roll oscillations which lead to intermeshing of the counter-rotating coaxial rotor system, and a hard landing. The flight crew shut down the helicopter, allowed the rotors to coast to a stop, and egressed the helicopter normally. Damage to the helicopter included collapsed landing gear, structural cabin damage, and dynamic component damage, including rotor blade tip separation of all 8 rotor blades. The pilot-in-command told the NTSB he was in the right seat and manipulating the controls at the time of the accident. He stated that he applied collective to get the aircraft light on the wheels and then applied forward cyclic to initiate a roll forward (forward taxi). He ground taxied the aircraft to the runway just as he had done on other flights. He intended to hold short of the runway and wait to be notified that the SAR (search and rescue) aircraft was on station.	Ref: Aviation Accident Final Report, Accident Number ERA17LA263,” National Transportation Safety Board, Aug. 2017	Critical aspects: • Due to the light weight on wheels during the taxi, the flight control mode transitioned from ground mode to flight mode. • The larger than expected roll response to the pilot roll stick input was the effect of a flight control system design error that resulted in unintended changes in the pilot input sensitivity in the roll axis during the transition from ground control mode to flight mode.	

Accident Reports Summary									
Date	Aircraft Type	Mission	Flight Phase	Visual Cond.	Primary Cause/	Description from Results of Investigation	References	Comments	Regulations and Guidance
						As the aircraft approached the runway, a slight left roll developed. The pilot decided to lift the helicopter into a 5-foot hover and stabilize. As he applied collective and got airborne the helicopter rolled quickly left and then right, continuing with 2-3 roll reversals of increasing roll attitudes eventually exceeding estimated 60 degrees angle of bank. The pilot applied counter roll control inputs, but roll rates experienced were excessive. After 2-3 roll reversals and after a large right angle of bank roll, as the helicopter reversed its roll, the pilot lowered the collective to full down to execute a landing. After the landing, he shut the engine down, and completed the emergency shutdown procedure. He and the copilot egressed the helicopter normally. The event occurred while taxiing on the runway with light weight on wheels, high collective pitch, and a slight forward cyclic pitch stick. Due to the light weight on wheels during the taxi, the flight control mode transitioned from ground mode to flight mode. The slight forward pitch stick in combination with flight mode initiated a nose down pitch rate. The pilot took corrective action inputting aft cyclic stick to correct the nose down rate. The initial pitch axis correction led to a small initial left roll rate due to aircraft coupling. The pilot countered the small left roll rate with an appropriate magnitude right stick input. In conjunction with the right stick input, the pilot raised the collective to increase the altitude. The aircraft right roll response to the right stick input was larger than expected and the pilot countered with a large left stick input. The aircraft left roll response was also larger than expected. The larger than expected roll response to the pilot roll stick input was the effect of a flight control system design error that resulted in unintended changes in the pilot input sensitivity in the roll axis during the transition from ground control mode to flight mode. Sikorsky reported that the increased control sensitivity was never encountered in the initial piloted simulation evaluation, nor in the 15 subsequent aircraft flights after the flight control software revision was made. However, once the incident timeline was precisely determined, the increased sensitivity to pilot control input could be consistently replicated in the simulator.			

29 April 2020	CH148822 Cyclone	Surface surveillance	Shipboard Landing	D- V	FBW FCS Design error Six fatal injuries	Official RCAF report: On 29 April 2020, the crew was tasked as part of Operation REASSURANCE to conduct a routine surface surveillance mission in the Ionian Sea followed by flight deck evolutions for aircrew proficiency upon recovery to Her Majesty's Canadian Ship (HMCS) Fredericton. There were four members of the crew and two passengers on board the aircraft. During the return for recovery, the aircraft made a pass on the port side of the ship, from stern to bow. The aircraft then executed a left hand turn to establish a downwind leg in preparation for approach to the ship. Astern and inside the control zone of the ship, the aircraft commenced a final left turn to set-up for the approach. During this final complex manoeuvring turn to close with the ship, the aircraft did not respond as the crew would have anticipated. This event occurred at a low altitude and became unrecoverable. The aircraft entered a high energy descent and impacted the water astern the ship. The aircraft was destroyed and all six occupants were fatally injured. The investigation determined that the aircraft electronic flight control system was designed and certified in accordance with applicable specifications but contained a fly-by-wire flight control law that created a Command Model Attitude Bias Phenomenon - an aircraft objectionable behaviour characteristic - that resulted in the pilots' inability to effect a restorative pitch correction, while overriding the engaged airspeed/pitch axis flight director mode at low attitude. The aircraft fly-by-wire control laws, when coupled to the indicated airspeed pitch axis mode of the flight director in a multi-axes manual flight manoeuvre with excessive manual input to the pedals, induced a negative pitch attitude bias resulting in insufficient aft cyclic controller command response to recover the aircraft without deselection of the flight director mode. The primary flight controls were manipulated to override the engaged airspeed/pitch flight director modes during the final manoeuvre without verbalization to the crew nor was it challenged by the crew, as a result of ineffective crew resource management. The absence of standardized crew resource management was also observed during other phases of the mission. The original equipment manufacturer, Airworthiness Authorities and aircraft operators were unaware of the Command Model Attitude Bias Phenomenon prior to the accident.	Ref: CBC News, " Pilot in Deadly Canadian Military Helicopter Crash unaware of flight-control software conflict" , says report. June 28, 2021, Murray Brewster CBC News.	Critical aspects: • The fly-by-wire flight control law created a Command Model Attitude Bias Phenomenon that resulted in the pilots' inability to effect a restorative pitch correction, while overriding the engaged airspeed/pitch axis flight director mode at low attitude. • Ineffective crew resource management: the primary flight controls were manipulated to override the engaged airspeed/pitch flight director modes during the final manoeuvre without verbalization to the crew nor was it challenged by the crew. • Absence of standardized crew resource management, observed also during other phases of the mission. • Original equipment manufacturer, Airworthiness Authorities and aircraft operators unaware of the Command Model Attitude Bias Phenomenon prior to the accident. • CH148 publications contained information that may have been confusing or misleading to operators. • Numerous incomplete sections of publications on automation considerations, lacked manoeuvre descriptions that would have been required for operational use.	

Accident Reports Summary									
Date	**Aircraft Type**	**Mission**	**Flight Phase**	**Visual Cond.**	**Primary Cause/**	**Description from Results of Investigation**	**References**	**Comments**	**Regulations and Guidance**
						The investigation concluded that CH148 publications contained information that may have been confusing or misleading to operators, contained numerous sections on automation considerations that were incomplete, and lacked manoeuvre descriptions that would have been required for operational use. The investigation recommends amendments to CH148 publications regarding automation operating intent, automation philosophies, and automation employment strategies. The investigation also recommends modification to software embedded within the electronic flight control laws and to enhance flight mode annunciation and awareness to the crew. The investigation recommends that a working group be established to review the Maritime Helicopter Project Statement of Operating Intent, and to determine the operational requirement of the return-to-target, and similar manoeuvres, in the CH148. Unofficial narrative: Canadian CH-148 Cyclone, a militarized Sikorsky S-92 using FBW. Apr 30 2020 Pilot attempted to conduct a return-to-target maneuver which consisted of a high speed decelerating pull-up followed by a steep turn using roll and yaw to return on an opposite course by the ship. He was using a RALT hold and IAS Hold at the time and overrode the autopilot which resulted in a Command Model Attitude bias that drove a pitch down in the recovery and a dive into the ocean. The autopilot functions did not disengage, even with significant manual override. Override of autopilot features had been accepted as routine, however, the unique conditions of this override, setup a serious bias. The Flight director autopilot had not been tested for such an abuse case. A contributing factor was mode awareness of autopilot engagement.			

Table A-2: Summary of Incidents/Accidents Higher Frequency Critical Aspects

Design Fault	Flight Crew Training	Respect of Aircraft Procedures	Situational Awareness
The accident report indicates “that the ergonomic design of the auto-pilot vertical modes controls could have contributed to the creation of the accident situation”.	Pilots’ low proficiency in the specific flight phase, low crew performance.	Pilots’ excessive reliance on ATC support.	Low pilot’s situational awareness of aircraft flight path and energy status.
Design of the GO lever contributing to triggering GO AROUND mode.	Pilots’ limited knowledge of AFCS modes.	Pilot’s neglect of flight manual procedures.	Pilots’ uncertainty of the engaged control system mode.
No warning and recognition function to alert the crew directly and actively to the onset of the abnormal out-of-trim condition.	Inadequate use of automation.	Flight crew's failure to adequately plan and execute the approach.	"Failure of the pilots to realize the gravity of the situation and respond immediately towards proper action of moving the throttles.
Incorrect design of the hard envelope protection logics, under a particular combination of vertical gusts and windshear and simultaneous sidestick inputs from both pilots.	Failure of the flight crew to revert to basic radio navigation.	Failure of the flight crew to discontinue the approach.	Pilots’ check of the actual aircraft descent rate, more than four times higher than the usual descent rate with -3.3 deg descent angle would have mitigated the impact of the error in selecting the control system mode.
The autothrottle warning system on the Boeing 737-300, although working as designed, did not alert the crew to the disengagement of the autothrottle system.	Pilots’ partial understanding of the autopilot functioning.	Pilot’s incorrect application of correcting input, with autopilot engaged.	Pilots’ low situational awareness of the aircraft flight conditions and energy state.
Known tendency of the aircraft air data system to fail due to large temperature variations.	Pilot’s incorrect application of correcting input, with autopilot engaged.	Potentially inadequate pilot’s flap settings.	Disengagement of the autothrottle was neither commanded nor recognized by the crew and the thrust levers remained at idle throughout the approach.
Design features of the Thales AA probes left them more susceptible to high altitude ice crystal icing than other approved pitot probe designs.	Initiation of the go around maneuver occurred at too low altitude. Early stage line training with the trainee as PF, absence of adequate operator guidance in this respect.	Initiation of the go around maneuver occurred at too low altitude. Incorrect application of prescribed procedures when a second ADIRU failure occurred, causing loss of navigational data and of nosewheel steering operation.	The aircraft decelerated to an airspeed significantly below the commanded speed, 20 kt below Vref, with the engines at idle thrust.
AOA values deviation resulting in an overspeed warning and in erroneous operation of the auto throttle, which did not transition from Arm mode to N1 mode.	Pilot's failure to maintain airspeed during a sharp turn.	Disengagement of the autothrottle was neither commanded nor recognized by the crew and the thrust levers remained at idle throughout the approach.	Insufficient crew situational awareness, not connecting the loss of indicated airspeed and the appropriate procedure.
Repetitive and uncommanded airplane-nose-down inputs from the MCAS due to erroneous AOA input.	The aircraft decelerated to an airspeed significantly below the commanded speed, 20 kt below Vref, with the engines at idle thrust.	The aircraft decelerated to an airspeed significantly below the commanded speed, 20 kt below Vref, with the engines at idle thrust.	Crew not identifying the approach to stall, consequently no reaction, enter of unidentified stall conditions with no recovery inputs until impact with the sea.

Design Fault	Flight Crew Training	Respect of Aircraft Procedures	Situational Awareness
The possibility of intermittent electrical/electronic system defects were an underlying issue: the AOA sensor malfunction on the accident flight most likely occurred as the result of a power quality problem that resulted in the loss of power to the left AOA Sensor Heater. The loss of power was likely due to a production related intermittent electrical/electronic failure involving the airplane's Electrical Wiring Interconnection System (EWIS) and the AOA Sensor part.	Inappropriate crew control inputs.	Reliance of the crew on the autopilot to perform the go around maneuver.	Inadequate monitoring of the airplane's flight path by the controller and by the crew.
System design process not considering potential for uncommanded activation of MCAS and it did not evaluate all the potential alerts and indications that could accompany a failure leading to an uncommanded MCAS.	Crew not identifying the approach to stall, consequently no reaction, enter of unidentified stall conditions with no recovery inputs until impact with the sea.	Crew's decision to continue the approach after the Final Approach Point when the airplane was above the glide path.	Inadvertent engagement of open climb mode.
MCAS system relying on single AOA sensor.	Inadequate monitoring of the airplane's flight path by the controller and by the crew.	Autopilot disconnection due to the aircraft deviation beyond the autopilot maximum authority limits, following pilot's input.	Inadvertent disconnection of the auto-thrust system.
Absence of AOA DISAGREE warning flag on the flight display panels (PFD).	Reliance of the crew on the autopilot to perform the go around maneuver.	Incomplete execution of manufacturer stall and recovery procedures.	Low crew general situational awareness: unawareness of disconnected auto-thrust during approach and of low energy state.
Failure by the manufacturer to address the safety critical questions raised by the airline which would have cleared out crew confusion and task prioritization.	Ineffective automated flight deck management in extreme adverse weather conditions by cockpit crew.	Inappropriate execution of go around procedures.	Pilot's confusing control functions between different aircraft types.
It is the positioning of the flaps selector and not extension thereof which introduces the new V_{FE}. As a result, V_{MAX} instantaneously switches from 210 to 195 kt on selection of flaps from 15° to 20°.	Incorrect selection of cockpit crew on account of their inadequate flying experience, training and competence.	Test pilot controlling the inoperative engine while performing an automatic approach with a critical engine failure.	The flight crew did not notice the several AFS mode changes.
Envelope Alpha-floor protection could not play its role as, when angle of attack of 14.5° was reached, the throttle levers were already on maximum thrust.	Absence of formal simulator training in respect of FO for handling an automated flight deck.	Inadvertent engagement of open climb mode.	
The stall warning did not sound and the stick shaker did not operate in the flight phase prior to the stall, because of the disturbance of the angle of attack sensors due to the dynamics of the aircraft's movements, with the speed having dropped below 60 kt before the angle of attack reached 17.5°.	Non-existence of cockpit crew professional competence/skill level monitoring system at operator level (Bhoja Air).	Inadvertent disconnection of the auto-thrust system.	
Combination of a design limitation in the flight control primary computer (FCPC) software of the Airbus A330/A340, and a failure mode affecting one of the aircraft's three air data inertial reference units (ADIRUs).	Inappropriate execution of go around procedures.	Incorrect flight crew action in response to Rudder Travel Limiter Units caution: the incorrect action is compatible with the circuit braker reset.	

Design Fault	Flight Crew Training	Respect of Aircraft Procedures	Situational Awareness
ADIRU serial number 4167 subject to previous instances of the data spike failure mode, potential marginal weakness in its hardware.	General misunderstanding of aspects of approach procedures.	Captain asking for 20 deg flap deflection at 195 kts airspeed, with V_{FE} = 195 kts . Decision leading to the main cause of the incident: engagement of speed protection.	
Design not considering effects of ADIRU data spike failure mode.	Incorrect flight crew action in response to Rudder Travel Limiter Units caution: the incorrect action is compatible with the circuit braker reset.	Captain misunderstanding of the automatic flight system mode.	
ADIRU failure mode occurred three times previously, all on A330 aircraft.	Inability of the flight crew to control the aircraft when flown in Alternate law, leading to stall and departure from controlled flight until impact with the sea.	Trimmable Horizontal Stabilizer (THS) deflected trailing edge up, for pitch up trim, “unintentional[ly] and unconscious[ly] by one of the pilots”.	
ADIRU manufacturer did not identify the data spike failure mode.	The B737 MAX Crew difference CBT training did not cover the MCAS system.	Just before the stall, the Captain pulled the control column fully back.	
Multiple control allocation.	Failure by the manufacturer to provide procedures regarding MCAS operation to the crew during training or in the FCOM.	No actions which could be called “return to basics” on the part of the flight crew.	
The flying pilot's attempt to counteract the oscillations with a roll-tracking maneuver to level the wings was ineffective, partly because the FCS was designed to “couple” on more axes than the command inputs given on the single axis by the pilot.	Captain asking for 20 deg flap deflection at 195 kts airspeed, with V_{FE} = 195 kts . Decision leading to the main cause of the incident: engagement of speed protection.	The pilot tilted the nacelles and rotors down from 90° and brought them to an angle significantly less than 75° – a position that violated flight manual limits on nacelle angles at low forward airspeed.	
Giving a command in counterphase on the roll axis to damp the relative oscillations creates an effect on the yaw axis that can be in phase with the yaw oscillations.	Captain misunderstanding of the automatic flight system mode.	MV-22B NATOPS manual “severe pitch down and altitude loss can occur if nacelles are rotated too far forward too quickly at takeoff.”	
New tapered rear fuselage and redesigned vertical fin with less surface area.	Trimmable Horizontal Stabilizer (THS) deflected trailing edge up, for pitch up trim, “unintentional[ly] and unconscious[ly] by one of the pilots”.	Operating Limitations section of the NATOPS manual WARNING: “When transitioning to forward flight from a hover, limit nacelles to greater than 75°until 40 KCAS (Knots Calibrated Air Speed) is reached.”	

Design Fault	Flight Crew Training	Respect of Aircraft Procedures	Situational Awareness
Lack of experimental data obtained previously in the wind tunnel and in-flight evaluations with those speed conditions and relating to the recent modified geometry of the tail fin.	Pilot’s confusing control functions between different aircraft types.		
Oscillations amplified by system to stabilize the helicopter in gusts and maneuver.	Saturation of the longitudinal elevator control due to maximum trailing edge up deflection of THS, leading to uncontrolled pitch up when Captain moved the throttles to the stops.		
Lack of protections in the flight control laws against the sustainment and growth of adverse feedback loops.	Just before the stall, the Captain pulled the control column fully back.		
Lack of an automated safeguard in the modified one-engine-inoperative (OEI) software used during flight testing.	No actions which could be called “return to basics” on the part of the flight crew.		
Lack of distinct and unambiguous cues for low Nr.	The flight crew did not carry out an in flight de-briefing of the event and a briefing for the new approach.		
The larger than expected roll response to the pilot roll stick input was the effect of a flight control system design error that resulted in unintended changes in the pilot input sensitivity in the roll axis during the transition from ground control mode to flight mode.	Mishap Pilot’s and Mishap CoPilot’s failure to keep the Mishap Aircraft clear of the Mishap Leading Aircraft’s wake.		
The fly-by-wire flight control law created a Command Model Attitude Bias Phenomenon that resulted in the pilots’ inability to effect a restorative pitch correction, while overriding the engaged airspeed/pitch axis flight director mode at low attitude.	The pilot tilted the nacelles and rotors down from 90° and brought them to an angle significantly less than 75° – a position that violated flight manual limits on nacelle angles at low forward airspeed.		
Original equipment manufacturer, Airworthiness Authorities and aircraft operators unaware of the Command Model Attitude Bias Phenomenon prior to the accident.			

Table A-3: Summary of Incidents/Accidents Lower Frequency Critical Aspects

Failure	System Configuration Deficiencies	Flight Phase/Mode Transition	Airworthiness/ Maintenance	Aircraft Flight Manual	Bare Airframe Characteristics	Crew Resource Management	Pilot's Workload	ATC	Atmospheric Conditions
In-flight electrical system failure.	Absence of a GPWS as an aggravating factor.	The left engine autothrottle and flight director disengaged automatically when the landing gear touched the runway.	Issue with aircraft airworthiness: modifications prescribed in Service Bulletins not being incorporated into the aircraft.	Lack of Clarity of AFM.	The inherent static and dynamic stability of the bare airframe were fundamental factors for the recovery of the aircraft from the upset conditions.	Crew Resource Management: minimum communication between crew members.	Pilots' inadequate workload management.	Insufficient crew alerting from ATC.	Poor weather conditions, thunderstorm, windshear.
Intermittent flight control system abnormalities began well before the accident flight.	FMS-generated navigational information that used a different naming convention from that published in navigational charts.	Go-around mode had not engaged when the pilot flying selected the TOGA switch.	Manufacturer not categorizing Service Bulletin as mandatory.	CH148 publications contained information that may have been confusing or misleading to operators.	Nacelle's tilt shifted the aircraft center of gravity too far forward, causing the nose to plunge downward.	Inadequate Crew Resource Management: lack of communication between Captain and First Officer.	Potential for high pilot's fatigue.	Low ATC situational awareness of the runway status and slowness in requiring go-around maneuver.	Tailwind pushing the bottom of the horizontal stabilizer as the tail of the aircraft angled upward.
The airplane suffered intermittent electrical/electronic anomalies in addition to the flight control system malfunctions.		Autopilot disengage and transition from Normal to Alternate control laws.	The airworthiness authority of the nation of design and manufacture did not issue promptly an airworthiness directive pertaining to implementation of relevant SB.	Numerous incomplete sections of publications on automation considerations, lacked manoeuvre descriptions that would have been required for operational use.	"Below 40 knots calibrated air speed, there is insufficient wind moving across the conventional airplane control surfaces to add roll, pitch or yaw control authority. The aircraft relies on the controls of a helicopter."	Ineffective crew resource management: the primary flight controls were manipulated to override the engaged airspeed/pitch flight director modes during the final manoeuvre without verbalization to the crew nor was it challenged by the crew.	Flight crew fatigue.		

Failure	System Configuration Deficiencies	Flight Phase/Mode Transition	Airworthiness/ Maintenance	Aircraft Flight Manual	Bare Airframe Characteristics	Crew Resource Management	Pilot's Workload	ATC	Atmospheric Conditions
ADIRU serial number 4167 subject to previous instances of the data spike failure mode, potential marginal weakness in its hardware.		Due to the light weight on wheels during the taxi, the flight control mode transitioned from ground mode to flight mode.	Aircraft flown with failed ADIRU, still within MEL requirements.		Pilot/vehicle biodynamic coupling, with unintentional oscillations of the pilot collective control.	Absence of standardized crew resource management, observed also during other phases of the mission.	Landing gear was in retracted position when the aircraft hit the runway.		
			Repetitive faults unresolved by maintenance.		Highly divergent oscillations.				
			Intermittent flight control system abnormalities began well before the accident flight.						
			Several pilot write ups involving temporary fluctuations of vertical speed and altitude prior to accident.						

3. Literature Review by Tiltrotor Flight Test Consulting

3.1 Introduction

These accident descriptions seek to identify trends in powered-lift aircraft that employ advanced indirect flight controls designs. This will be used toward understanding key factors that will be considered in certification of the advanced flight controls and envelope protection systems that are being integrated into the now ubiquitous powered lift designs, including eVTOL. The descriptions will focus on tiltrotor designs and describe the accident in general, the unique aspect of the accident as it relates to advanced indirect flight control designs, and what fixes were applied. Pilot-error accidents will only be addressed in the context of design-induced error as a consequence of the flight control design. For more detailed understanding, accident-reporting references will be provided, along with existing related guidance on the particular design area. The following list of accidents is provided for reference. This is not comprehensive in that many other minor V-22 accidents are a consequence of combat operations and the austere environment which the aircraft was operated. Additionally, since these were military aircraft, the accident investigations are not necessarily in the public domain. Recent eVTOL accidents are not included here in that no significant details have yet been released. The following is a list of the events recorded in the Tiltrotor Flight Test Consulting database:

1. 1979, 30 July - Bell XV-15, Arlington Texas
2. 1991, June – MV-22 New Castle, DE.
3. 1992, 20 July – MV-22, Quantico VA.
4. 1992, 30 August - XV-15, Arlington, TX.
5. 2000, 8 April -MV-22B Marana, AZ.
6. 2000, 11 December - MV-22B, New River, NC
7. 2006, 27 March - MV-22B, New River, NC
8. 2010, 9 April - CV-22B, , Afghanistan
9. 2012, 11 April - MV-22B, Agadir, Morocco
10. 2012, 13 June - CV-22, Hurlburt Field, FL
11. 2014, 17 July - AW609, Venegono, Italy
12. 2014, October – MV-22B, USS Makin Island

13. 2015, 17 May - MV-22B, Bellows Field, HI
14. 2015, 30 October – AW609, Tronzano Vercelles, Italy.
15. 2017, 5 August - MV-22B, USS Green Bay
16. 2022, 18 March – MV-22B, Beiarn, Norway
17. 2022, 8 June - MV-22B, Glamis, CA

3.2 Transition in Power-Lift

Powered-lift vehicles represent a combination of wing-borne vehicle and thrust-borne vehicle, where sources of lift may need to be described to better understand the constraints of the vehicle and how this might figure into examining and certifying powered-lift designs. To first understand these transition issues, it is important to lay the groundwork for discussion by establishing a few definitions as they relate to sources of lift. The traditional view of "configuration" as a fixed set of attributes, does not necessarily apply. As an example, in the tiltrotor for a given speed there may be a range of nacelle settings not only for landing, but also for transition/conversion. Similarly, for a given nacelle position, there may be a range of speeds available which will also have a range of flap settings since the tiltrotors use autoflaps that are scheduled on speed. Even more confusing is that in evolving designs, an Autonacelle may be used for automatic configuration of nacelles based on a commanded speed. This in fact may employ different nacelle positions for the same speed based on whether the aircraft is accelerating or decelerating. And then these various "ranges of configurations" may be used for different flight phases. It is this variability that drives the need to define what I have determined here to be stages of configuration as it changes through the powered-lift thrust vector reconfiguration.

Phases of Flight can be defined in terms of ground operations, takeoff, climb, cruise, descent, approach, hover, and landing. *Flight Stages* are related to sources of lift as described below:

- **VTOL Stage**
  This represents the range of combinations of thrust-borne controls that can afford a vertical takeoff and landing with a resulting vertical thrust vector. In the AW609 tiltrotor this would consider a range of nacelle angles, (e.g., 95-85 nacelle) that when combined with cyclic pitch in the proprotors can provide for vertical takeoff and landing with a range of aircraft pitch angles. In other powered-lift vehicles this same balance may be achieved through a combination of differential thrust from rotors and/or rotor flapping angles to still affect a variation of acceptable aircraft attitudes for landing with the

resulting vertical thrust vector. The VTOL stage would also include consideration of all azimuth low-speed flight, within the range of VTOL configurations.

- **Wing-borne Stage**
  This represents where lift is entirely produced by fixed airfoil surfaces while thrust is oriented horizontally and dedicated to generating speed to produce lift.

- **Transition/Conversion Stage**
  This captures the range of forward flight configurations achieved through thrust vectoring that lies between VTOL Stage and Wing-borne Stage. Here the terms conversion and transition will be used to differentiate between the acts of reconfiguration of thrust vector in deceleration and acceleration respectively. The aircraft then transitions toward wing-borne flight and converts toward thrust-borne flight. In the Tiltrotor this is accomplished and represented through a range of nacelle angles. For other aircraft it may be wing tilt, or lift-sharing metrics between rotor systems, such as differential thrust.

3.3 Accident review and discussion

There are only a few powered-lift designs in service that can be examined to specifically look at the unique requirements related to transition of powered-lift aircraft from thrust-borne to wing-borne flight, but these few tiltrotor accidents all provide valuable insight. The chart below in Figure A-6 summarizes these accidents in showing where in the flight envelope they occurred and how they related to the transition/conversion corridor of the aircraft. The general takeaways from this analysis can easily be extrapolated to other powered-lift vehicles that control transition through thrust vectoring. Related accidents will be summarized and then discussion will focus on the broader implications for powered-lift. Generally, the accident analysis points to four different Major aspects, which are subdivided below.

1. Balancing flight control in powered-lift designs:
    a. Balancing sources of lift in transition
    b. Balancing multiple controls of the same axis
    c. Balancing multiple tasks/functions on the same single control effector
    d. Blending of control effectors to achieve appropriate control power throughout the transition/conversion
    e. Pilot adaptation to flight characteristics changes with transition/conversion reconfiguration

2. Handling aerodynamic risks unique to the powered-lift design:
    a. The conversion corridor, Vmin and Vcon
    b. Wake Turbulence
    c. Own-ship turbulence in vortex ring state (VRS)
    d. Own-ship turbulence and rotor outflows
    e. Low-speed Flight in VTOL Stage
3. Pilot Error
4. Material Failure

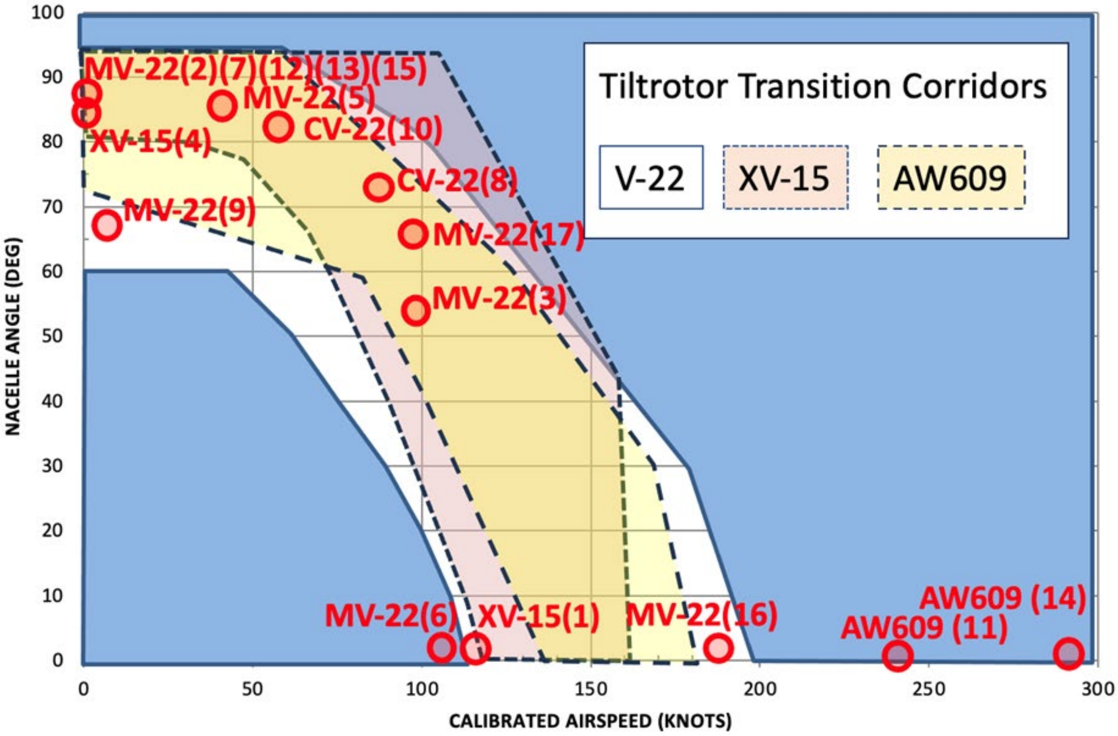

Figure A-6: Tiltrotor Accidents

3.3.1 Balancing Flight Control in Powered-Lift Designs

Powered-lift aircraft will use multiple control effectors in the aircraft, often blending helicopter like controls with fixed-wing type controls, and in the newer VTOL aircraft, by employing Distributed Electrical Propulsion (DEP). In many ways these aircraft can be considered over-actuated with necessarily complex designs driving prioritization issues for flight control and performance. The following examples illustrate some of the difficulties in striking this balance.

Bell XV-15, CFIT, July 30, 1979, at Arlington Texas, Mishap (1) [9]

The first example here addresses the requirement to balance sources of lift in transition to achieve a safe transition for the transition/conversion stage of flight. Here, there is the need to allow for sufficient airspeed to build-up in acceleration when the thrust vector is tilted forward to achieve a balance of wing-borne lift and thrust-borne lift.

Even though the XV-15 used a conventional flight control system with a Stability and Control Augmentation System (SCAS), its extensive legacy of research provides valuable insights into powered-lift flight control issues today. One of these issues involved the transition to wing-borne flight in a demonstration flight where a maximum rate transition was to be done down the runway at Arlington, Texas. As the nacelles came down toward the wing-borne stage, the aircraft had not developed enough speed to affect a safe climb at the end of the runway. The pilot faced a dilemma as he was forced to apply just enough pitch attitude to avoid wing stall but not enough to clear the trees at the end of the runway. The aircraft struck the trees at the end of the runway with its proprotors but was able to return to the airport and land safely. This highlighted the risks of operating at low energy states toward the bottom of the transition/conversion corridor. Subsequent designs, as embodied in the V-22 and AW609 utilize an envelope protection in the form of modulation boundaries on the corridor limits which will be discussed in greater detail later.

MV-22 Loss of Longitudinal Control, April 2012, Agadir, Morocco, Mishap (9) [10]

This second example speaks to how to balance multiple controls of the same axis used in transition. At low-speed in the VTOL stage of flight in the V-22, longitudinal control is accomplished by the use of continuous nacelle control, through a nacelle thumbwheel, and longitudinal cyclic control of the proprotors through pilot stick. In one accident the aircrew, while in a hover, turned into a tail-wind condition which reduced aft longitudinal stick margin, and then applied rapid forward nacelle through the thumbwheel control. The forward nacelle, set beyond prescribed operator manual limits for that speed, created a downward pitch moment that was not able to be arrested with full aft pilot stick, and the aircraft nose-dived into the ground. The longitudinal axis control was later redesigned to not permit rapid movement of forward nacelle when aft stick margins are reduced, along with automatic application of aft nacelle to restore stick margin when stick is on the aft stick stop. This envelope protection will be addressed in further detail later.

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[9]. Maisel, M. Giulianetti, D, Dugan, D., *"The History of the XV-15 Tilt Rotor Research Aircraft, From Concept to Flight"*. Monographs in Aerospace History, NASA, 2000.

[10]. Whittle, R. "*Marines peg "Bad Flying" as cause of April V-22 Crash in Morocco*," Defense Daily, July 9, 2012.

Multiple Functions on a Single Effector

Two related examples involve balancing multiple tasks/functions on the same single control effector are described next.

AW609. High-speed proprotor over-flap. 17 July 2014, Venegono, Italy, Mishap (11) [11]

During a test flight, while in a wind-up turn, simultaneous high values of AOA, AOB, Mach Number, rate of descent and normal acceleration "g" caused an accelerated stall of the aircraft right wing; a significant sideslip developed with lateral acceleration. This situation was not fully compensated for by the FCS and caused an excessive flapping on the right proprotor that resulted in light contacts of the proprotor with the leading edge of the right wing. Both the proprotor and leading edge of the wing were slightly damaged. The crew was able to maintain control of the aircraft and the test flight was terminated and ended with an emergency landing on the airport of Venegono, Italy. The AW609 did not have a traditional rudder for yaw control and instead depended on Differential Collective Pitch (DCP) on the proprotors for yaw control. However, in wing-borne flight the use of DCP had a dual use: for yaw control and for torque balance between the proprotors that are connected by an interconnect driveshaft. This second requirement for Structural Load Limiting (SLL) is referred to as QBAL in the accident report, which forwarded the following:

- The accelerated stall of the RH wing during the wind-up turn caused an increased aircraft asymmetry in the lateral directional plane; and
- The integral torque balance term QBAL of the total DCP command persisted, even though the aerodynamics associated with the maneuver rapidly changed. This reduced the capability of the directional DCP term to promptly compensate for the yaw excursion, which drove high proprotor flapping.

AW609, Yaw divergence. 30 October 2015, Tronzano Vercelles, Italy. Mishap (14) [12]

In a high-speed dive near 300 KCAS, a lateral-directional oscillation developed. The pilot initially countered with roll command which, through a feedforward control law to the yaw axis, came into phase with the yaw excursion and caused it to diverge. The pilot attempted to recover the aircraft through countering with pedal and reducing collective pitch on the proprotors. The proprotors flapped into the wing and the aircraft experienced an inflight breakup. The SLL torque balance term, QBAL, and the Yaw control, that are both employed through DCP

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[11]. Johnson, O. "AW609 Crash: Final Report Points to Oscillations and Flight Control Laws," *Vertical Magazine*, 15 May 2017.

[12]. Anon., *Final Report, Accident; AgustaWestland AW609 Aircraft Registration Marks N609AG*, Agenzia Nazionale Per La Sicurezza Del Volo, Tronzano Vercellese (VC), October 30, 2015.

command, came into conflict as yaw started to diverge. As a result, the pilot's pedal authority became ineffective, allowing yaw to diverge to more than twice that of the yaw limit for that airspeed. The combination of high yaw rate and reduced collective pitch through thrust reduction then allowed the proprotors to flap into the wing. A possible contributing factor was a reduction in tail volume due to a reduced size of the vertical stabilizer as compared to previous versions of the aircraft. There was no mention in the accident investigation as to whether control laws had been improved after the 2014 incident. Additionally, it should be noted that the aircraft only uses longitudinal cyclic control of proprotor flapping and does not employ lateral cyclic control of proprotor flapping as in the V-22. This then requires a delicate balance between torque balance and yaw control, while stringently controlling yaw rates that may produce dangerous flapping angles. Refined flight Control laws have since been employed. Other geometry fixes to the aircraft proprotor planes have also been applied since then.

CV-22 Roll-off. 13 June 2012. Eglin AFB, FL. Mishap (10)) [13, 14]

The fourth example represents the requirement to blend control effectors to achieve appropriate control power throughout the transition/conversion. The lesson to be learned here is that control power must be validated and ensured throughout the transition/conversion stage and that effector blending, when combined with envelope protections, can result in non-linear impacts to this control power. Large amplitude inputs should be examined in this context.

When the wake of another V-22 aircraft was encountered at low altitude, the roll upset of the trail aircraft could not be arrested and the aircraft impacted the ground inverted. In the V-22 design, blending of lateral controls in the transition from thrust-borne lift to wing-borne lift effectively created a notch in the roll control effectiveness at 60 kts, where the primary effector, Differential Collective Pitch (DCP) of the proprotors was restricted by Structural Load Limiting to avoid gearbox over-torque. Examination of the roll axis handling qualities (HQ) showed borderline Level 3 HQ in the roll axis at this speed, per Mil-F-83300. It is interesting to note that for small amplitude inputs the V-22 showed Level 1 HQ, but due to SLL interaction, large amplitude inputs showed diminishing effectiveness in a non-linear command of roll-acceleration. The roll axis control was redesigned in software changes known as Increased Lateral Control Power (ILCP) which allowed for greater use of other effectors at this speed which included flaperons and lateral swashplate gearing. Additionally, with sustained large lateral stick

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[13]. Staff Writer, "Air Force Cites Pilot Error in June CV-22 Osprey Crash," *Defense Daily*, September 11, 2012.

[14]. Silva, M, et al., "The Role of Modeling & Simulation in the Mitigation of V-22 Tiltrotor Formation Flight Wake-Induced Roll-off," presented at the *AHS 72nd Annual Forum*, West Palm Beach, Florida, May 17-19, 2016.

application, an asymmetric application of DCP was permitted to work with the Structural Load Limiting. This is illustrated in Figure A- 7, below.

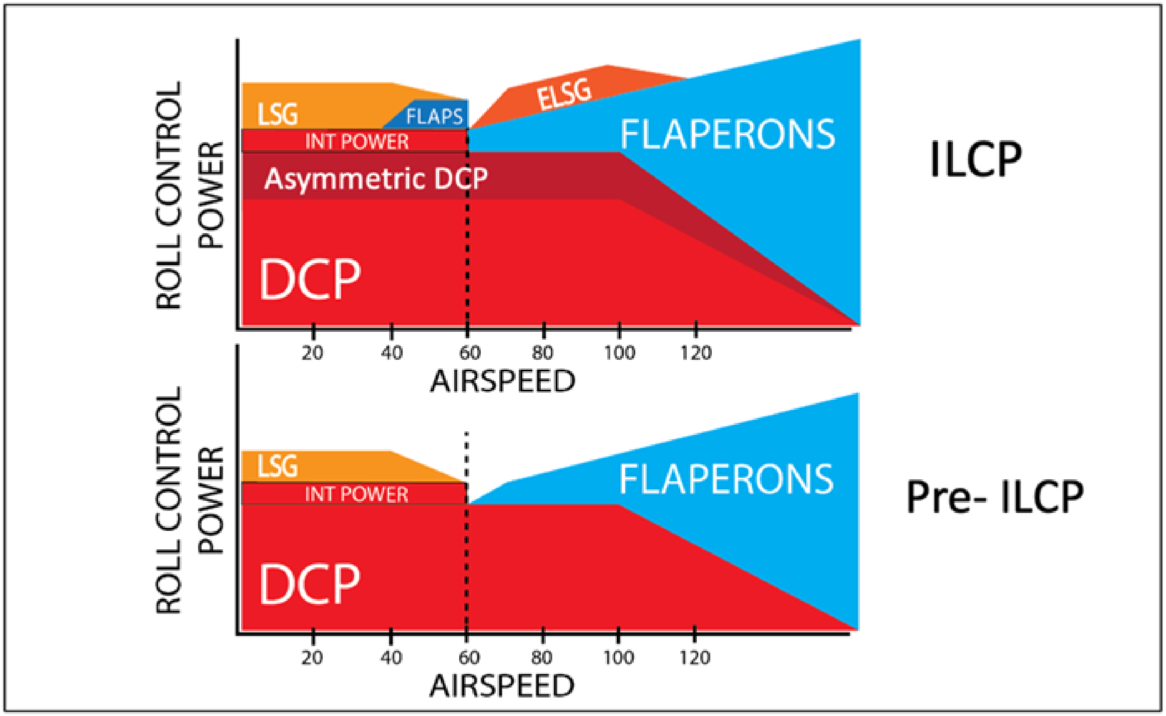

Figure A- 7: Roll Control Power Improvements for V-22

Pilot Adaption in Transition Region

A final consideration for transition regards pilot adaptation to flight characteristics changes with transition/conversion reconfiguration. Two V-22 incidents reflect a common theme in the conversion from wing-borne flight toward VTOL flight. The tiltrotor decelerates very rapidly with initial conversion which pilots have come to expect but is difficult to accurately account for, especially in very rapid conversion. A secondary effect that may delay conversion is interaction with the envelope protections associated with the upper conversion corridor boundary which will be discussed in detail later. In both incidents below, the conversion was done late in the approach profile and necessarily done very rapidly, where higher workload appeared to result from adaptation to the changing flight characteristics of the aircraft as nacelles were brought off of the down-stops. Another factor common to these two mishaps in this flight stage were the fact that both mishaps occurred at night. A final factor in these accidents is that in this stage of the transition, with the attitude-based controls of the V-22, the pilot must adapt his control strategy from that of a fixed-wing aircraft to that of a helicopter. The result is a high workload task in a less than intuitive aircraft response design. These mishaps argue for a stress-testing of new VTOL designs during transition and conversion to identify non-intuitive strategy changes in the aircraft where high workload may coalesce with Corridor interactions and create potentially hazardous conditions.

MV-22B, 8 April 2000. Marana, Arizona. Mishap (5)[15]

The accident aircraft was involved in an operational testing exercise involving night formation flight. In this mishap, the lead aircraft pilot was preparing to land his two-aircraft formation at a specified landing spot on the Marana airfield, but the combination of tailwind, late execution of his enroute decelerative letdown, and the night-time environment all contributed to his setting up a higher-than-normal rate of descent. Meanwhile, the wingman was having difficulty maintaining position during the decelerating transition. He was 11 seconds behind the leader in initiating his nacelle conversion, the leader having begun his conversion without signal, and having used maximum 8° per second nacelle rotation rate. As the lead aircraft slowed to VTOL stage, the wingman found himself ballooning to an 800 feet per minute (fpm) climb followed directly by a 3900 fpm descent, presumably to try to maintain position on the lead aircraft who had established an already high descent rate. As the two aircraft approached 40 kts, the trail aircraft was too far forward (3 o'clock high, according to the lead aircraft crew chief). He was moving back to his proper 45° azimuth position when he apparently lost control and rolled inverted and crashed. Notably, the lead aircraft incurred a hard landing. A "Blue Ribbon Panel" was appointed to investigate the V-22 program and specifically this accident. They concluded the following as related to the decelerative letdown: "Night formation flight approaches require inter-aircraft coordination, especially during early nacelle conversions."

CV-22 CFIT, 10 April 2010, Afghanistan, Mishap (8) [16,17,18]

A CV-22 flying a night special operations mission impacted the ground ¼ mile short of the intended landing zone at about 80 kts. They rolled 300 ft with gear down until impacting a ditch and flipping the aircraft, tearing the wings, proprotors and empennage off of the aircraft. 14 of the 16 crew and passengers survived. Two different accounts of the cause of this accident have been forwarded by the Safety Investigation Board (SIB) and the Accident Investigation Board (AIB). Both versions agree that the aircraft was too fast for the approach and that conversion was delayed for a profile to land at the intended landing zone. From there analysis diverges.

The prevailing account from the SIB is that it was essentially Controlled Flight into Terrain (CFIT) in that the mishap crew flew too fast due to multiple distractions and fixation and that the

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[15]. Anon., *Report of the Panel to Review the V-22 Program for the Secretary of Defense*, April 30, 2001.

[16]. Harvel, D., "Rotors in the Sand," ISBN# 978-1-09830-332-7, March 17, 2020.

[17]. Anon, "CV-22 Accident Investigation Board Results Released," *US Air Force News*, Dec. 17, 2010.

[18]. Axe, D., "Air Force Shoots Down Investigation into Deadly Crash," *Wired Magazine*, Oct. 17, 2011.

pilot failed to recognize an insidious descent due to time compression, channelized attention, task saturation and a visual illusion with respect to the landing zone. The other cause, posited by the AIB, is that, late in the approach a mechanical failure, such as dual engine failure, occurred during conversion and the crew was forced to land in the transition/conversion configuration. While a dual engine failure seems extraordinarily improbable, later revelations related to Proprotor Gearbox (PRGB) Hard Clutch Engagements (HCE) seem more plausible but were not known at that time. HCE events will be discussed later. One area that was examined in both the SIB and AIB was the fact that the aircraft had new flight control software where the scaling of the Thrust Control Lever (TCL) throw was redone to accommodate an increased thrust capability in wing-borne flight. Initial flight tests of this software showed that there was a tendency to not slow down as quickly with conversions since the pilot had "muscle memory" of the deceleration position of the old TCL throw. In this accident the crew had limited flight experience with the new software before flying the night mission. Regardless of the final investigation resolution, the review of the accident data clearly shows that the crew was fully occupied in handling the rapid deceleration of the aircraft and could easily miss a descent into rising terrain, or not effectively react to an emergency situation.

3.3.2 Handling Aerodynamic Risks Unique to the Powered-lift Design

The transition from VTOL stage to wing-borne stage is represented by many constraints in the powered-lift vehicle from controllability issues on the low-speed side of the corridor to flight loads on the high-speed side. Additionally, many of the aerodynamic issues in powered-lift aircraft, as embodied in the tiltrotors, are a consequence of using multiple highly disc-loaded rotors in combination with a fixed wing and empennage. These seem to occur disproportionally in low- speed flight, as represented in Figure A-6.

Transition/Conversion Corridor and Vmin and Vcon

- **Transition/Conversion Corridor**

  This corridor generally describes a range of acceptable speeds for a given conversion/transition configuration, which in the tiltrotors is represented through nacelle angle. In this description the corridor limits can further be refined and differentiated by the constraints involved in the reconfiguration of thrust vector. For the purpose of illustration, I will use the V-22 example which I am familiar. In the V-22, the upper speed boundary is largely a consequence of flight loads as shown in Figure A- 8. The lower left-hand boundary is representative of insufficient speed to provide for proper lift-sharing, stated in Figure A-6 as "Wing Stall". This is the concern illustrated by the XV-15 mishap (1). In the V-22 the upper left region is additionally constrained by insufficient stick margins for control if thrust vector is tilted too far forward at low speed. This is illustrated by the V-22 mishap (9). This chart, while based on the experience of the V-22, is quite representative of the similar constraints that are encountered by the AW609. One can expect that the corridor boundaries will be of similar concern for other powered-lift designs in that the upper bounds are generally dictated by flight loads while the lower bounds represent controllability limits.

- **Minimum Safe Speed (Vmin)**

  The lower conversion corridor talks to the larger issue of defining Minimum Safe Speed (Vmin) which is currently under review in ASTM working group WK 78955. It gets down to a philosophy of why we prescribe Minimum Safe Speed. In wing-borne flight it is an obvious relation to stall, in that for a given configuration you can't go any slower than that speed, which infers the act of decelerating without configuration change. The safe remedy then would be to accelerate in that configuration toward better lift while decreasing AOA of the wing. In the transition/conversion case it can still be prescribed as a minimum airspeed for three reasons:

  1. In that the transition of thrust vector cannot proceed toward lift-sharing with the wing until a sufficient speed is achieved. This infers dynamic thrust vector reconfiguration toward wing-borne flight. However, the remedy for overzealous thrust vector tilt, when below this speed, is two-fold, either accelerate, such as in descent, or to reconfigure backward toward greater thrust-borne capability.
  2. Another way to encounter Minimum Safe Speed is through deceleration for a fixed configuration of thrust vector, if applicable. In the V-22 this can result in definitive wing stall at nacelle angles up to 30°. Depending on flight loads this condition can be remedied by either accelerating such as in descent or reconfiguring backward toward greater thrust-borne capability.
  3. A third consideration, as described in the V-22 Mishap (9), is that rapid movement of nacelle below a given forward nacelle position at very low speeds, where elevator is not effective, can result in pitching moments on the aircraft that cannot be overcome by aft stick (longitudinal cyclic control of flapping) since only limited proprotor flapping is able to counter pitch-down moments from the nacelle movement.

  In this way Minimum Safe Speed in the transition/conversion corridor affords aircraft controllability in two ways, overall performance in maintaining flight condition for the phase of flight and maintaining control power for the controls that affect transition.

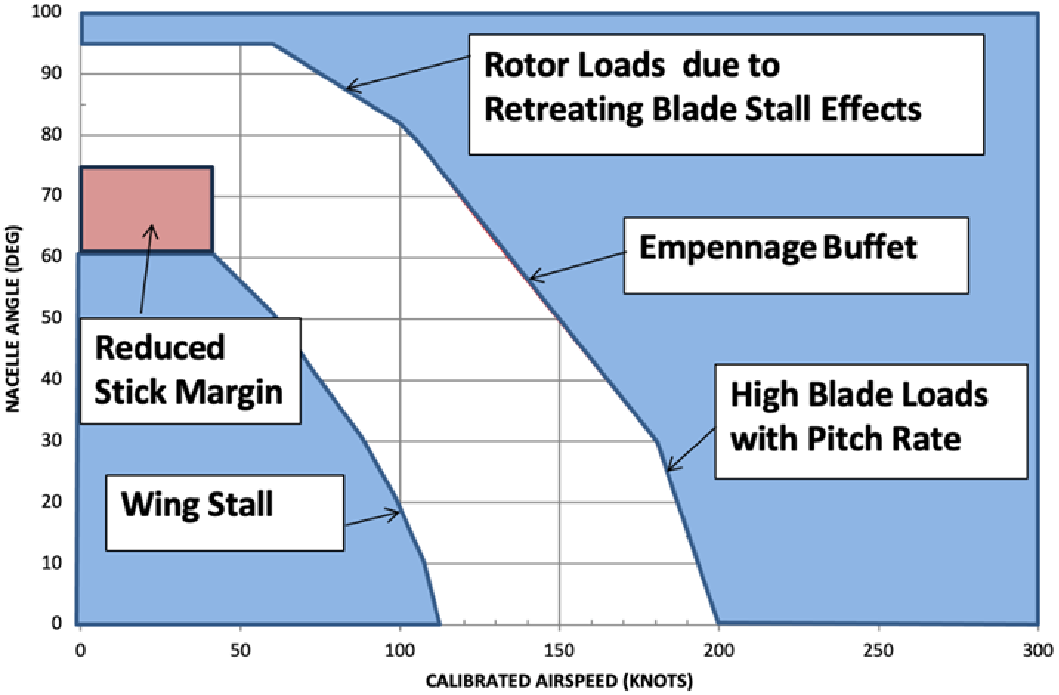

Figure A- 8: Constraints on Conversion Corridor

In wing-borne flight Minimum Safe Speed can be demonstrated through determination of stall speed as described in the Stall Speed section of Specification F3179/F3179M. In this specification envelope protections are considered as part of the Minimum Safe Speed demonstration. Similarly, envelope protections as used in powered-lift transition, should be included in Minimum Safe Speed demonstrations. The Vmin protections used in current tiltrotor designs are forwarded as examples.

Both the V-22 and AW609 utilize an envelope protection in the form of modulation boundaries on the lower corridor limits. In the AW609 If the pilot is moving the nacelles forward to reconfigure thrust vector towards the wing-borne stage but fails to accelerate sufficiently, the aircraft will be flying at or near the boundary designated as Vmin. When the airspeed gets to the modulation boundary (within three kts of Vmin), the nacelles will slow their forward movement to one degree per second from three degrees per second. If the airspeed slows to Vmin or below, in addition to visual and audio cues, the nacelles will stop moving. Once the pilot gets back into the conversion corridor, i.e., accelerates sufficiently, then the nacelles will start moving forward again without pilot action. The V-22 uses a similar modulation boundary but earlier in transition since the V-22 can use rates as high as 8 deg/sec for nacelle movement. Additionally in the V-22, the longitudinal axis control is designed to not permit rapid movement of forward nacelle at low speeds when aft stick margins are reduced, along with automatic application of aft nacelle to restore stick margin when stick is on the aft stick stop.

- **Maximum Conversion Speed (Vcon)**

  In tiltrotors the upper conversion corridor boundary represents restrictions based on flight loads on the aircraft and proprotor system as opposed to the risks of controllability as seen on the lower corridor boundary already described. For the AW609 in conversion, if the pilot fails to slow sufficiently through a combination of thrust reduction and pitch attitude change, the nacelles will slow their upward movement when the airspeed is within three kts of Vcon and stop it if the airspeed is at Vcon or above. Interaction with this boundary can in essence slow a deceleration if the deceleration is inappropriately attempted with just nacelle as opposed to pitch attitude and thrust reduction. Additionally, as implemented in the V-22, the nacelles may even reverse in order to preserve loads boundaries so if the pilot is attempting to rapidly decelerate, this boundary may interfere with good handling qualities in that a pitch ratcheting may occur when on the boundary and distract the pilot. This is likely to contribute to what has already been discussed as pilot adaptation to flight characteristics changes with transition/conversion reconfiguration. Altitude effects can exacerbate this issue in that at higher altitudes the Vcon occurs at lower nacelle settings for a given speed so interaction with envelope protections is more likely to occur which is even worsened for approaches by the fact that groundspeeds can be appreciably higher for a given airspeed at higher altitudes. The effect of altitude is reflected in Figure A- 9, showing how the corridor must be restricted further due to loads related to retreating blade stall. This boundary is conservatively predicated on pressure altitude as opposed to density altitude in order to avoid use of temperature as a parameter for control.

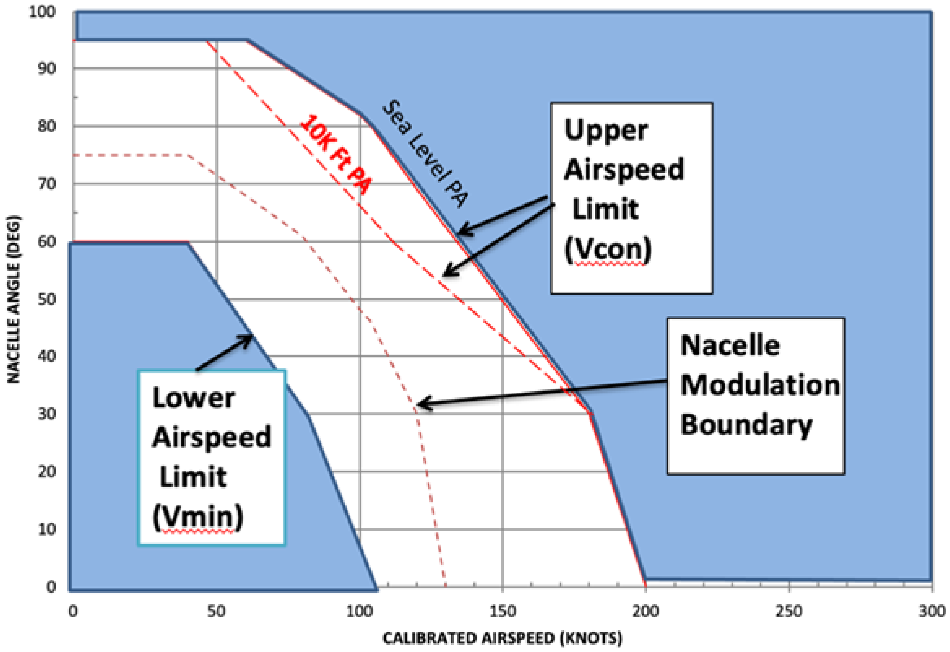

Figure A- 9: V-22 Envelope Protection for Transition/Conversion

Wake Turbulence

A disturbing finding from several events in the MV-22 are illustrated in the accident previously described as the *CV-22 Roll-off. 13 June 2012. Eglin AFB, FL. Mishap (10)* when the wake of another V-22 aircraft was encountered at low altitude. In Mishap (10))[14] The trail aircraft flying with nacelles set near 85° and flying at a speed near 60 KCAS passed through the strong super-vortex of the lead aircraft which was flying in a similar configuration. The resulting large roll upset of the trail aircraft could not be arrested and the aircraft impacted the ground inverted. Follow-on simulation and analysis revealed that the V-22 in that configuration produces a strong rotor-based super-vortex that is the result of the roll-up of individual blade vortices, acting much like that of a fixed-wing wingtip vortex (Figure A- 10). Flight simulations, wind tunnel tests and later actual flight tests, reinforced the idea that the super-vortex, when overlaid on the VTOL stage configuration of the tiltrotor, can result in reversed flows on the two rotors which can induce a significant roll-off, shown in flight tests to exceed 45° AOB. Extrapolating this to new powered-lift designs is not hard to imagine.

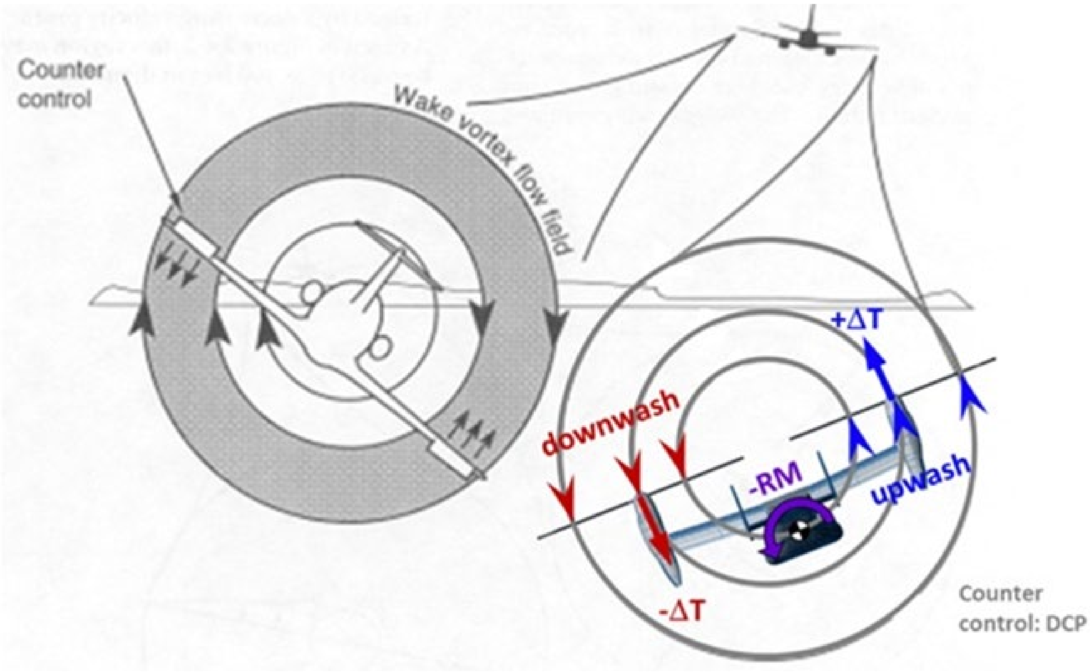

Figure A- 10: Wake Vortex Effects on Tiltrotor Configuration

Own-ship Turbulence and Vortex Ring State (VRS)

The unique side-by- side configuration of the tiltrotor makes encounters with Vortex Ring State, where the aircraft descends into its own turbulent wake, very hazardous, since individual rotors may enter VRS separately, and the flight control application to counter the upset will exacerbate the VRS. Mishap (9) bears repeating in this instance, albeit with greater detail.

MV-22B, 8 April 2000. Marana, Arizona. Mishap (5)[15, 19, 20]

The accident aircraft was involved in an operational testing exercise involving night formation flight. A large descent rate, into its own rotor wake, resulted in entry into Vortex Ring State on one proprotor which drove a roll-off due to the side-by-side proprotor configuration. In this mishap, the trail aircraft overshot the lead aircraft in a decelerative letdown. The lead aircraft was also in a higher-than-normal descent rate at this time. The trail aircraft crew then found themselves ballooning to an 800 feet per minute (fpm) climb which they reversed to a 3900 fpm descent, presumably to try to maintain position on the lead aircraft. As the two aircraft approached 40 kts, the trail aircraft was too far forward (3 o'clock high, according to the lead aircraft crew chief). He was moving back to his proper 45° azimuth position when he apparently entered vortex ring state on one proprotor, lost control, and crashed. The lead aircraft incurred a

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[19]. Brown, R. "Are eVTOL Aircraft Inherently More Susceptible to the Vortex Ring State than Conventional Helicopters," presented at the *48th European Rotorcraft Forum*, Winterthur, Switzerland, 6-8 Sept. 2022.

[20]. Brown, R., "VRS in eVTOL," Recorded Presentation to *VFS eVTOL Flight Test Committee*, Feb. 1, 2023.

hard landing in descent recovery. A ”Blue Ribbon Panel” was appointed to investigate the V-22 program and specifically this accident. They concluded the following as related to the Vortex Ring State:

1. Although the current 800-foot-per-minute sink rate at 80° nacelle angle or less flight limitation may offer adequate safety margin, the envelope, warning signs, and flight characteristics of V-22 vortex ring state are still not well defined.
2. If future operating limitations include a 40-kt indicated airspeed (or less) limit, then the V-22 airspeed indication system may not be adequate, as it is unreliable below 40 kts.

After extensive testing, this hazard was mapped and a Sink Rate warning system was designed that used airspeed and rate of descent references to drive visual and aural warnings to pilots to avoid the hazard. Since then, no known accidents have occurred due to this hazard.

This accident and its attendant investigation reignited interest in this known rotorcraft hazard and has since resulted in significant study and investigation. Worthy of note is the work done by R. Brown toward understanding how these lessons translate to new eVTOL concepts. A summary of some of the insights from Brown’s works include:

1. An ellipsoid shaped model, plotting non-dimensional ROD versus non-dimensional airspeed, of the VRS region can be approximated based on disc loading of the rotorcraft, which has shown good agreement to the tiltrotor investigations done to date. When this is shown in dimensional terms, comparison of a range of eVTOL designs can be done in relation to existing rotorcraft to gain some insight into evolving design risk (Figure A-11.)
2. While the higher disc loadings of eVTOL may provide greater descent rate margins from VRS in the low speed, the increased depth (descent rate band) and increased breadth (airspeed band) of the VRS region potentially increases susceptibility of VRS encounter.
3. The approach trajectories for eVTOL may necessarily have to be shallower and less aggressive than for conventional helicopters. Aggressive, steep final approaches, as depicted in draft EASA vertiport guidance, should be scrutinized in this context.
4. In practice, the non-dimensional model, has provided a powerful engineering-level tool that can be used very rapidly to assess the dangers posed by the onset of the VRS to a given rotorcraft under specified operational conditions. It can be especially good in providing insight into trajectory analysis for approaches.

5. Thrust vectoring, through pylon tilt, in the approach directly affects the rotor's incidence to trajectory and can potentially exacerbate VRS onset if application is misapplied for the approach.

6. Aerodynamic Interactions from multiple rotors, as well as interactions between rotors and wings will potentially change the ellipsoid shape of the non-dimensional model, but at this time a parametric analysis of these effects is not available.

7. Unique design characteristics for rotor twist, and blade-tip design will potentially change the ellipsoid shape of the non-dimensional model, but at this time a parametric analysis of these effects is not available.

8. Gusts can have varying effects on VRS. Vertical gusts will effectively change the resulting descent rate for low-speed and can impact VRS margins. At the same time, horizontal gusts can impact speed-based margins.

9. It is notable that Brown used collective controlled rotors in his analysis as opposed to RPM controlled rotors to avoid the time-lags that are introduced into the system by the rotor inertia, when using rotor speed control.

The following conclusions can be drawn from these observations:

1. Vortex Ring State should be considered a major driver of designs of the eVTOL aircraft which should examine disc-loading tradeoffs, minimum RPM levels, and the effects of aerodynamic interactions between the various rotors of UAM. Rotor design parameters such as twist, and tip shape may have pronounced effects on VRS susceptibility.

2. A warning system is recommended for a most rotorcraft, and should be mandatory for multi-propulsor rotorcraft, in that VRS onset can promote significant controllability issues.

3. Currently, there are no active Envelope Protections employed for VRS recovery. Such designs are anticipated but can be complicated in robust sensing of the phenomena and proper application of control. One can expect that flight directors utilized for approach would not allow for descent into a "known hazardous flight condition" and will employ VRS avoidance strategies with significant margins applied. This is the case in V-22 automated approach designs currently.

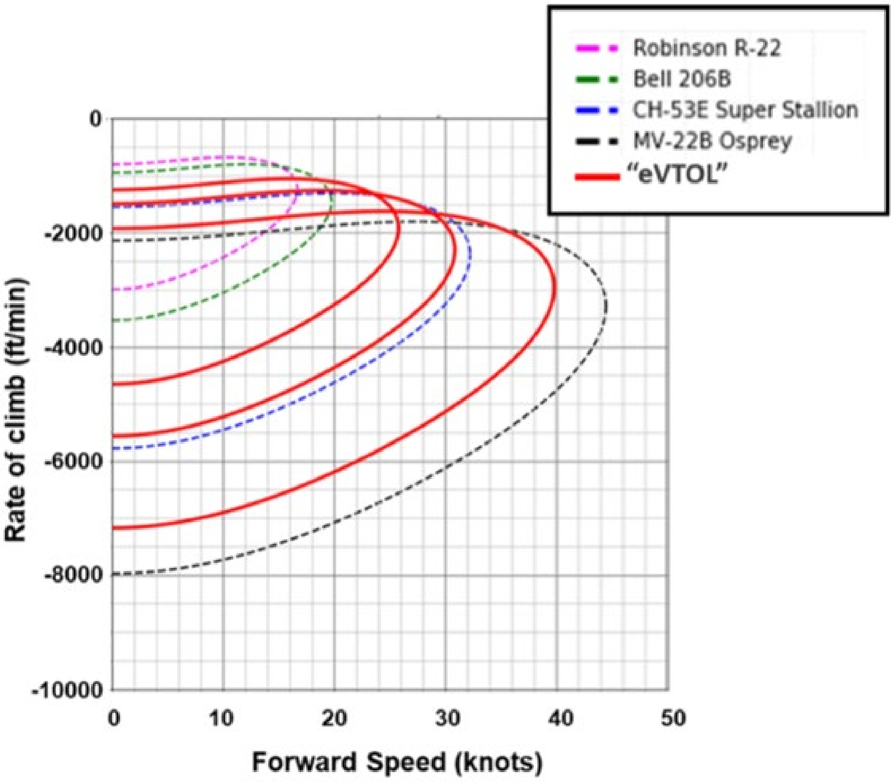

Figure A- 11: Dimensional Comparison of eVTOL VRS Regions to Helicopter and Tiltrotor

Own-Ship Turbulence and Rotor-Wake Outflows

The interference between the two counter-rotating rotors of the tiltrotor tends to direct rotor-wash forward of the aircraft in a phenomenon known as fountain flow (Figure A- 12), which entails unique risks. Firstly, As compared to traditional rotorcraft, it increases the risk of degraded visual conditions in austere landings which has resulted in numerous mishaps in the V-22. When this cloud immersion was combined with the baseline V-22 flight control design, the high risk for overcontrol of the aircraft and extended landing times posed significant risks to the aircraft and drove training requirements that routinely placed crew in uncomfortably hazardous conditions. This was illustrated in the first mishap described below. A second issue related to fountain flow is that in slow flight near obstacles, such as shipboard landing the forward projected wake can get re-entrained into the rotor. This re-circulation effect can rob the aircraft of performance as described in the second accident below. Such wake interference may be extrapolated to use of the many aircraft utilizing Distributed Electrical Propulsion (DEP) in the urban environment where landing to raised vertiports is expected, or in emergency off-nominal landing situation where austere landings could occur. While the expected Conops of the UAM do not involve austere landings, the limited energy reserves of these aircraft can reasonably be expected to drive occasional precautionary landings that may occur in austere landing conditions. The question should be asked as to whether they can handle such situations.

MV-22B, May 2015, Waimanalo, Oahu, HI. Mishap (13) [21, 22]

One of three Osprey aircraft participating in a training exercise at Bellows Air Station (Waimanalo, Oahu, Hawaii) suffered from a right engine failure due to glassification of sand ingested into the engine turbine, and then sustained a hard landing with fuselage damage, wing sheared off and a post-crash fire. The significant rotor-wash created by the Osprey poses a high risk of brown-out during landings. The baseline control response type of the aircraft required significant training in these conditions. In this accident the crew in training came to a hover in the cloud and could not achieve acceptable stability for landing and therefore elected to wave-off the approach. In the climb, with high power demand, the right engine compressor stalled, the engine failed, and the aircraft descended at a high rate vertically into the ground. The accident led to the deaths of two U.S. Marines, and injuries to 20 others. The accident caused the Marine Corps to recommend improved air filters, mandate reduced hover time in dust from 60 to 30 seconds, and also drove improvements in flight controls and flight director functions.

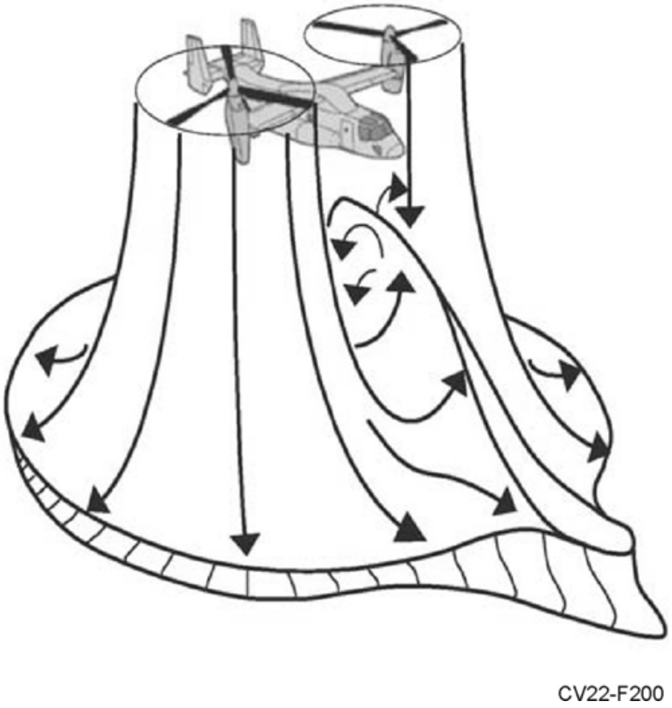

Figure A- 12: Fountain Flow Effect

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[21]. Anon., “Fatal MV-22 Crash in Hawaii Linked to Excessive Debris Ingestion,” *Flight Global*, Nov. 25, 2015.

[22]. Whittle, R., “Fatal Crash Prompts Marines to Change Osprey Flight rules,” *Breaking Defense*, July 16, 2015.

MV-22B, Power Deficit with Proprotor Recirculation, 5 August 2017 Mishap (15) [23, 24]

The MV-22 while attempting a landing to the deck of the USS Green Bay struck, settled on short final and struck the stern of the ship and then crashed in off the east coast of Australia. 23 personnel were rescued, with three confirmed dead. The aircraft was conducting a controlled low angle approach at low speed in nearly calm winds, when just prior to the ship edge the aircraft started to settle and yaw to the right. Analysis of this incident would eventually show that recirculation of the aircraft's rotor-wake due to its impact with the ship structure, could dramatically increase the power-required for hover. From this effort recommendations for power margins to 15% above zero-wind HOGE were determined for a zero-wind landing to a ship-deck. Higher wind-over-deck however can require much less power for landing and therefore heavy gross-weight landing capability is highly correlated to wind reporting. Similar effects can be anticipated in landing to raised vertiports, with some insights provided by Navy research studies documented by Silva and Tritschler.

Low-Speed flight in VTOL Stage

Various consequences have been encountered in low-speed flight due to unique characteristics associated with flying a fixed-wing type fuselage and empennage in various wind azimuths. These hazards as they are depicted below in Figure A- 13 for the V-22 can have unique consequences that have been encountered multiple times and in different ways in operations. The resultant "critical azimuths" of concern are illustrated in Figure A- 13.

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[23]. Silva, M. Tritschler, J. et al., "Full-Scale Investigation of Rotor/Obstacle Interactions using an Elevated Fixed Platform," presented at the *VFS 78th Annual Forum*, Ft. Worth, TX, May 10-12, 2022.

[24]. Lindsey, J., "V-22 Shipboard Recirculation Testing," *SETP 65th Annual Symposium*, videocast, Sept. 27-30, 2021.

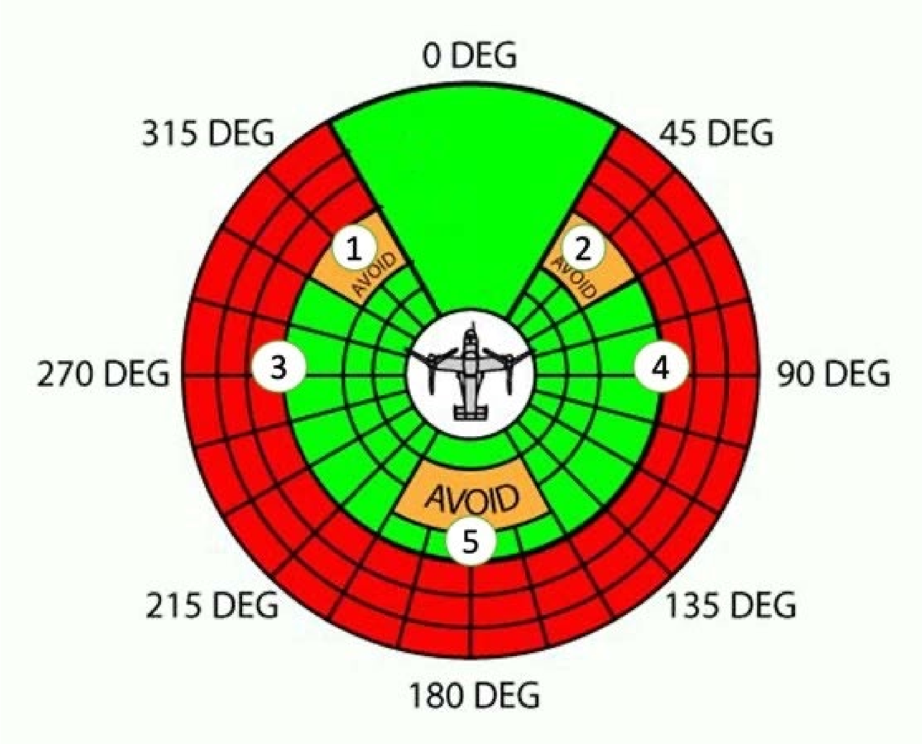

Figure A- 13: V-22 Wind Azimuth Chart, OGE Hover

The red prohibited areas represent controllability issues while the yellow avoid regions are related to handling qualities issues. The regions are summarized below.

1. Areas 1 and 2 at azimuths around 45° from the nose of the aircraft are where Pitch-Up with Sideslip (PUSS) can occur: the wake of the rotor impinges upon the horizontal tail in low-speed flight. At extreme aft CG, where the pilot may be required to apply significant forward stick, this pitch-up can be large enough to require full stick authority. Also of interest is dynamic entry into this region through yaw which can make the pitch-up more pronounced. This phenomenon was serious enough that envelope protection algorithms are in place at low speed that move nacelles downward in order to regain stick margin when it is on the forward stop. Some example incidents related to this avoid region include numerous encounters in the shipboard environment when the aircraft is transitioning over the deck-edge with a yaw to align to the ship's heading, early de-crabs in crosswinds that dynamically placed the aircraft in the PUSS region, and controllability issues when landing in crosswinds with rolling landings where the pilot interacted with the envelope protection logics.
2. Areas 3 and 4 around the 270° and 90° azimuths represent areas where, in sideward flight or crosswinds, the rotor wake on the wing and on the downwind rotor can create

diminished roll control power, which has resulted in prolonged loss of stick margin in recovering from sideward flight speeds above 40 kts. A secondary concern in this area is that of increased power required. As an example, during a crosswind approach to hover in 30 kts wind, the application of yaw to move from a crab angle to a sideslip where heading is aligned with approach path, can represent as much as a 20% increase in power required to maintain altitude. One incident combined both effects with a crew inadvertently flying in excessive crosswind while performing a lateral quick-stop. The non-linear roll response in the recovery flare drove the crew to hold lateral stick on the stop for several seconds while also descending with maximum power applied. The aircraft struck the ground with the nacelle before being recovered to a hover.

3. Area 5 represents an area of nuisance lateral-directional instability with a pronounced increase in pilot workload for precision hover as compared to other azimuths. This area, particularly in landing, can present the risk of side-loading the nose landing gear if aft nacelle is used to preserve stick margins and maintain position.

Critical azimuth testing is standard practice for conventional helicopters. Helicopters with single main rotors and anti-torque tail rotors will typically exhibit certain low-speed characteristics in wind azimuths related to fuselage and empennage weathervane or tail-rotor effectiveness that equate to concerns in the yaw axis. From these V-22 examples one can see that the handling qualities issues with powered-lift designs are not constrained to the yaw axis but more broadly to all axes, which can be exacerbated through dynamic interaction by the yaw axis.

3.3.3 Pilot Error

One must recognize that in military aircraft, some design shortfalls are often addressed through pilot training and operator manual limitations. Some of these compromises are made in-effect to retain agility and performance for combat operations by allowing for flexibility in maneuver. This flexibility however, comes at a cost of complexity of limitations and constraints on the pilot that only training and experience can address, and sometimes this even fails. Many of the accidents presented here have some aspect of pilot error described in this regard. However, it is informative that later actions to fix the design, as documented in many of these accidents, indicated the need for a design more robust to human error. In some cases, disregard for limitations imposed can have disastrous consequences. Some accidents stand-out as largely the consequence of pilot error in deliberate contravening of limitations such as the following. Still, there is some recognition that powered-lift vehicles may not have flight characteristics that are similar to other aircraft and the hazards associated with given limitations may be different than those expected based on experience in other aircraft.

MV-22B,18 March 2022, Gratadalen Valley, Norway. Mishap (16) [25]

Analysis of this fatal accident showed that the MV-22B was maneuvering at speeds up to 260 KCAS at low altitude in mountainous terrain in VMC. In maneuvering in the Gratadelan valley, in Norway, the aircrew applied a left bank angle of 68°. The steepness of the turn required an even harder turn as the wall of the valley came up on the other side. This follow-on turn resulted in loss of airspeed and altitude when the pilot over- corrected with a right bank of 89° for terrain avoidance. The aircrew could not recover the aircraft after the excessive bank angle (30 deg beyond operator manual limits). Airspeed had decreased to 200 KCAS and the descent rate had increased to 4000 fpm before the aircraft impacted the ground. An interesting conclusion from the accident investigation was that "the flight characteristics and normal operating envelope of the MV-22B create unique challenges when attempting to define and mitigate the risk of low altitude flight." From this observation came a recommendation for the Marine Corps to convene a working group to address the issue.

A stand-out mishap that was warned against by flight testers as potentially causing design induced error, eventually resulted in loss of a crew member.

MV-22B, October 2014, USS Makin Island, Mishap (12) [26]

Although power calculations showed that the aircraft had adequate hover power capability, the aircraft could not maintain altitude as it transitioned from the ship-deck to Out-of-ground effect hover after takeoff from the USS Makin Island. The aircraft fell into the Arabian Sea and was briefly partially submerged four feet. During the time in the water the crew in the back of the aircraft egressed. One of the marines drowned after his life preserver failed to inflate when he bailed out of the aircraft. After fuel dump the pilots were able to fly away and land back on deck. The accident was attributed to the aircraft being accidentally started in maintenance mode, which reduced engine power by a fifth due to activation of the nacelle exhaust deflectors which is normally used for ground operations only. This aspect was part of a recent software change to the aircraft, which was later reversed after this accident.

3.3.4 Material Failure

A significant number of mishaps in the V-22 have been the result of material failure. This is an outsized percentage of mishap totals as compared to more traditional mature aircraft designs. This must be understood as a consequence of the unique and revolutionary design of the aircraft in combination with the tough military environment that these aircraft are to operate in. Still, this

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[25]. *Command Investigation into the MV-22B Aviation Mishap that occurred on 18 March 2022 During Exercise Cold Response*, Jun 29, 2022, United States Marine Corps., 2ndMAW.marines.mil, 15 August 2022.

[26]. Kovach, G., "Deadly Osprey Crash Spurs Safety Changes," *San Diego Union Tribune*, June 30, 2015.

may be informative in that the new VTOL aircraft coming to civil certification represent as significant a leap from the tiltrotor as the tiltrotor was to the more traditional fixed-wing and rotary-wing aircraft. Additionally, the last mishap described below, with respect to Hard Clutch engagement (HCE) represents a unique material failure, not related to initial introduction of the aircraft but later in service where fatigue issues may be discovered. Examples are provided below:

MV-22B, Mis-wired Flight Control Sensors, 11 June 1991, New Castle, DE. Mishap (2) [27]
Two mis-wired roll rate sensors in the flight control system led to over-control in the roll axis in the 15 ft hover. The aircraft touched down and then became airborne again, finally rolling far enough to strike the left proprotor and nacelle on the ground, destroying the aircraft. Both pilots egressed the detached cockpit. The pilot, Grady Wilson, suspected that he may have accidentally set the poorly designed Thrust Command Lever (TCL) known affectionately as the “Blottle” the opposite direction to that intended, exacerbating the crash if not causing it. The program was paused for some time after this and the TCL integration redesigned, along with other fixes.

MV-22B, Engine failure and ICDS failure, 20 July 1992, Quantico, VA. Mishap (3) [27, 28]
The aircraft was completing a cross-country flight from Eglin AFB, Florida to Quantico, Virginia, when it began a conversion from wing-borne stage toward VTOL stage. In the conversion, the engine exploded, and the nacelle caught on fire. Soon afterward the aircraft rolled right and nosed down, with left yaw into the Potomac River at a high rate of descent, destroying the aircraft and killing all crew members. The engine failure was determined to be the result of pooling of a flammable fluid in the nacelle, which entered the engine when the conversion was underway. The subsequent fire was not contained to the engine and melted the composite short-shaft between the Tilt-axis gearbox and the Proprotor Gearbox (PRGB) that transmits power from an Interconnect Drive System (ICDS). The ICDS runs through the wings to synchronize the proprotors and transfer power between the proprotor systems and all accessory equipment. If one engine fails, the ICDS transmits power to the PRGB on the side of the failed engine. The ICDS is the only means of providing power to both PRGBs in the event of single engine failure, providing power from the single operating engine to both PRGBs. The failure of an engine and the ICDS connection through the short-shaft creates an asymmetric power condition that is considered unrecoverable below 170 KCAS.

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[27]. Whittle, R., The Dream Machine, Simon and Schuster Paperbacks, 2010.
[28]. Norton, B., Bell Boeing V-22 Osprey, Aerofax, Midland Printing, 2004.

XV-15, Loss of Control in Hover, 30 August 1992, Arlington, TX. Mishap (4) [29]

During a demonstration flight with a guest pilot the aircraft finished the flight with a hover. As the pilot initiated a descent to land the aircraft rolled right and crashed inverted. The wing fractured at the root, proprotor blades impacted the ground and shattered and the right nacelle broke off of the wingtip. Both crewmembers egressed the aircraft with only minor injuries. Subsequent investigation revealed that the proprotor collective angle linkage had disconnected from the hydraulic actuator when a critical nut backed off because it had not been secured properly with a cotter pin. The elaborate and ingenious mechanical controls of the XV-15 were necessarily complicated and stood as a good argument for later fly-by wire integration.

MV-22B, Hydraulic Failure- Flight Control Software Error, 11 December 2001, Jacksonville, NC. Mishap (6) [15]

The details of this mishap investigation came from the "Blue Ribbon Panel" investigating the V-22 program after two fatal crashes in 2000. The panel received a briefing by the Senior Member of the Mishap Board on preliminary results, and late in its study was able to review the recently released Accident investigation report. The factors involved in the mishap included both a hydraulic line failure and a flight-control-system software anomaly that was introduced when the pilot repeatedly reset the Primary Flight Control System (PFCS). Neither one of these two failures by itself would necessarily result in a mishap, but the combination produced an unforeseen loss of control due to airspeed decay in airplane mode. With each Flight control reset, the proprotor governor drove a thrust transient, but with one side of the aircraft in single hydraulic boost due to the hydraulic failure, the aircraft experienced a yaw. The multiple resets drove yaw and deceleration, eventually driving the aircraft into stall and loss of control. The panel conclusions with respect to the accident included:

1. The V-22 flight control hydraulic components are experiencing failures at higher rates than predicted. Flight safety is, therefore, highly dependent on the redundancy features in the system.
2. Inaccurate predictions of component reliability affect spares planning, squadron staffing, and flight safety.
3. Current Naval Air Systems Command policy requires that special attention (material, tolerances, quality inspections, tracking, etc.) be applied to all single-point failure modes

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[29]. Maisel, M. Giulianetti, D., Dugan, D., *"The History of the XV-15 Tilt Rotor Research Aircraft, From Concept to Flight,"* Monographs in Aerospace History, NASA, 2000.

in the flight control system, but it does not require any special attention be given to other exceptions to the redundancy design criterion.

4. The North Carolina mishap identified limitations in the V-22 Program's flight control software development and testing. The complexity of the V-22 flight control system demands a thorough risk analysis capability, including a highly integrated software/hardware/pilot-in-the-loop test capability.

5. A separate finding was that the PFCS reset was used for not only fly-by-wire faults but also hydraulic faults. Subsequent studies of degraded modes in the aircraft differentiated emergency procedures between the two systems.

MV-22B, 27 March 2006, New River, NC. Mishap (7) [30, 31]

The aircraft experienced an un-commanded engine acceleration while turning on the ground at Marine Corps Air Station New River, NC. Since the aircraft regulates power turbine speed with blade pitch, the reaction caused the aircraft to go airborne with the Thrust Control Lever (TCL) at minimum. The aircraft rose 6 to 7 feet (1.8 to 2.1 m) into the air (initial estimates suggested 20 to 30 feet) and then fell to the ground, causing damage to its right wing. The damage was later determined to be significant enough to declare the aircraft a complete loss. It was later found that a mis-wired cannon plug to one of the engine's two Full Authority Digital Engine Controls (FADEC) was the cause. The FADEC software was also modified to decrease the time needed for switching between the redundant FADECs to eliminate the possibility of a similar mishap occurring in the future.

MV-22B, Hard Clutch Engagement, 8 June 2022, Glamis, CA. Mishap (17) [32, 33, 34]

The Osprey was one of two flying near Glamis, California, for a live-fire tail gun training mission from Camp Pendleton. After the third pass, the V-22 crew reported via radio it had "hot boxes," meaning the aircraft's gearboxes were running at a high temperature. The crew then planned to climb to a higher altitude to cool the gearboxes. The aircraft crashed shortly after that in a near vertical descent destroying the aircraft and killing the crew of 5. It had evidently had a dual Hard Clutch Engagement (HCE) in its proprotor gearboxes, creating a single engine and

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[30]. Aviation Safety Network, ASN Wikibase Occurrence # 62458, 27 Mach 2006.

[31]. Helis.com, MV-22 B Osprey C/N D0056, SN 166389.

[32]. Anon., *Command investigation into the Class A Aviation Mishap that Occurred on 8 June 2022 in the R2512 Range Complex*, Commanding General I Marine Expeditionary Force, April 5, 2023.

[33]. Everstine, B., "Known V-22 Gearbox Problem Causes 2022 Crash," Aviationweek.com, July 21, 2023.

[34]. Rosenberg, Z., "US Marine Corps MV-22 Crash Traced to Hard Clutch Engagement," *Janes Magazine*, July 25, 2023.

interconnect drive system failure. This caused a “catastrophic loss of thrust” on the right proprotor, creating an unrecoverable departure from controlled flight.

A HCE is a V-22 aircraft emergency that results in a momentary input quill clutch slippage (between the engine and PRGB). When the clutch reengages, the HCE occurs at a higher-than-normal engine speed. A HCE can result in severe damage to drive system components including engine over-torque, PRGB over-torque, shaft driven compressor failure, nacelle blower failure, and damage to the engine Torquemeter (TM) shaft that transmits power to the gearbox. Indications of TM shaft damage may include poor rotor governor management with associated Nr (proprotor revolutions per minute expressed as a percentage) decay at high power demand. A further complicating factor of a HCE is that a HCE on one side can ultimately initiate a HCE on the opposing side.

In this case, while on climb-out to the overhead pattern at 95 KCAS, the mishap aircraft experienced a dual HCE that sent destructive impulses throughout the drivetrain. The dual HCE caused the RH TM shaft to shear and the LH TM shaft to yield, resulting in a RH Engine over-speed and a LH Engine power limited condition. In response to the RH engine over-speed the RH FADEC executed a controlled engine shutdown causing a rapid engagement of the ICDS to allow the LH engine to power the RH proprotor. The rapid transfer of torque sent destructive impulses through the drivetrain causing the ICDS to fail and led to a complete loss of RH proprotor thrust. The sudden loss of thrust from the RH proprotor triggered an extreme thrust asymmetry and departure from controlled flight.

3.3.5 Conclusions

This has been an attempt to provide a comprehensive review of tiltrotor accidents as they may relate to new and novel hybrid-lift designs and to outline the potential impacts related to design of the indirect flight controls that will necessarily be incorporated in them. Examples here have focused for the most part on larger hull-loss accidents for the powered-lift designs. The majority of these accidents have been seen in the V-22 tiltrotor in that it has operated extensively for the last several years. It is interesting to note that the Class A accident rate for the V-22, of 3.1 accidents per 100,000 hour of flight is still similar to the overall Navy aircraft accident rate, as summarized in the Mishap (17) accident investigation report. This however, is small consolation in that this is a transport aircraft and has resulted in a number of fatalities. A number of smaller accidents and incidents have occurred in the V-22 also, many of which were associated with combat or unique military operations, and therefore were not included here due to a lack of relevance.

Generally, the accident analysis points to four different Major aspects, which are subdivided below. These do not occur separately but are often combined.

1. Balancing flight control in powered-lift designs,
    a. Balancing sources of lift in transition
    b. Balancing multiple controls of the same axis
    c. Balancing multiple tasks/functions on the same single control effector.
    d. Blending of control effectors to achieve appropriate control power throughout the transition/conversion
    e. Pilot adaptation to flight characteristics changes with transition/conversion reconfiguration
2. Handling Aerodynamic risks unique to the powered-lift design,
    a. The conversion corridor, Vmin and Vcon
    b. Wake Turbulence
    c. Own-ship turbulence in VRS
    d. Own-ship turbulence and rotor outflows
    e. Low-speed Flight in VTOL Stage
3. Pilot Error
4. Material Failure

Pilot error deserves mentioning again in that many of the initial references for V-22 accidents include pilot error as the cause. One must recognize that in military aircraft, some design shortfalls are mitigated through pilot training and operator manuals provide guidance that informs safe operation. Some of these compromises are made in-effect to retain agility and performance for combat operations by allowing for flexibility in maneuver, or to facilitate fielding of the aircraft as quickly as possible albeit with certain identified shortcomings. This flexibility however, comes at a cost of complexity of limitations and constraints on the pilot that only training and experience can address, and sometimes these even fail. Many of the accidents presented here have some aspect of pilot error described in this regard. However, it is informative that later actions to fix the design, as documented in many of these accidents, indicated the need for a design more robust to human error. It should be noted that this was done for a dual-piloted aircraft where one would think the redundancy of two pilots would mitigate such errors. In this context, it is especially important to note that many of the new eVTOL designs are single-piloted, arguing for even greater robustness in designs with regard to pilot error. Flexibility and performance may then suffer as a compromise for more simplified deterministic operations.

The accident rates of mature designs of helicopters and fixed-wing aircraft do not necessarily reflect issues related to the evolution toward indirect flight controls. Instead, they tend to reflect traditional issues representative of the vehicle types, and specifically the layering of automation upon the aircraft, not specifically associated with indirect flight controls. In large transport aircraft this is largely associated with the pilot interface with the Flight Guidance System, which makes sense in some respect since the majority of flight time is done with use of the FGS. The Evaluation of the tiltrotor accidents, on the other hand, points to substantially different causes of mishaps as compared to the more mature air transport aircraft. One can see that the tiltrotor accidents suffer from some immaturity of design in that the delicate balances of flight control design for the variable thrust vector is not completely understood or is inappropriately administered. Additionally, there is some discovery of the unique hazards associated with the hybrid- lift design that were not anticipated and may not have been modeled effectively. Lastly, the novel tiltrotor designs represent unique challenges with respect to designs that may not yet be robust to pilot error, and may experience material failures at a higher rate than reflected in more mature aircraft designs. One can anticipate that new novel VTOL designs will face similar challenges, and then as they mature evolve toward risks similar to the more mature fixed-wing air transport aircraft where many of the mishaps are related to Flight Guidance System interface.

4. Literature Review by Crew Systems

4.1 Introduction

The goal of this appendix is to identify aircraft mishaps that show issues with mode change and mode confusion with modern electronic displays in aircraft. We reviewed various databases in the public domain for such mishaps. We searched for both fixed-wing and helicopter mishaps. This search was not intended to be a definitive list of all such mishaps – indeed, since we do not have a definition at this point in time. Any such list generated would only show exemplars.

The search encompassed existing mishap national databases, such as Australia, Canada, France, UK, and USA. Aviation Safety Network (aviation-safety.net) was also used. A starting point for transport airplanes mishaps was Newman and Lambregts (2010) [35]. We also consulted the FAA's Lessons Learned listings[36], which was not very helpful.

As it turned out, we found no electronic display mode change helicopter mishaps. Civil helicopter mishaps are more likely to involve mechanical, aerodynamic, or operation in confined spaces. The National Transportation Safety Board (NTSB) did a comparison of light airplanes equipped with either "glass cockpits" or with conventional instruments[37]. We shall discuss this NTSB Report in the next section.

4.2 Review of NTSB safety study on "Glass Cockpits"

The NTSB compared the accident rates for thirteen models of light single-engine aviation airplanes, manufactured between 2002 and 2006 **Error! Bookmark not defined.**. Of these aircraft models, the distribution of instrument configuration was:

✈ Glass Cockpit	5,516 built
✈ Round Dials	2,848 built
✈ Total	8,364 built

The NTSB compared the accident data from this cohort from 2002 through 2008. To quote the report: "The study aircraft fleet included aircraft manufactured between 2002 and 2006; therefore, the distribution of glass cockpit aircraft in the study aircraft fleet remained constant from 2006 through 2008 [38]." Table A- 4 shows the total and fatal accident rates for the two instrument configurations. Figure A-14 from the NTSB report shows this data graphically.

The NTSB also reported that glass cockpit airplanes were involved in higher percentages of loss-of-control in flight and collision-with-terrain events, and that round-dial airplanes were involved in more loss-of-control on ground and more takeoff and landing accidents. This is consistent with the use of the airplanes with glass cockpit airplanes being used in more personal and business transportation and round dial airplanes being used for training and local flights. A summary of the accident types is shown in Figure A-15 from the NTSB study. The totals do not round to 100 percent because of rounding.

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[35]. Newman, R. L., and A. A. Lambregts, "A Review of Fly-By-Wire Accidents," *ISASA Forum*, April-June 2010, pp. 18-22.

[36] www.faa.gov/lessons_learned

[37]. *Introduction of Glass Cockpit Avionics into Light Aircraft*, NTSB-SS-01-10, March 2010.

[38] This is a direct quote from the NTSB report.**Error! Bookmark not defined.**

The NTSB concluded that higher percentage for collisions-with-terrain compared with all other events for the glass cockpit cohort was the only statistically significant difference between the two cohorts in the accident events: χ^2 (1, N=255) = 3.980. p = 0.046.

There had been anecdotal reports of pilots using the red terrain color in their moving map displays to allow them to fly closer to mountainous terrain at night than they would have otherwise. These anecdotal reports provide a possible explanation for the NTSB conclusion.

Table A- 4: Accident Rates by Cockpit Configuration

Year	**Accident Rate Per 100,000 Flight Hours**			
	Total Accidents		**Fatal Accidents**	
	Round Dials	**Glass Cockpit**	**Round Dials**	**Glass Cockpit**
2006	3.70	4.10	0.51	1.37
2007	3.71	3,46	0.36	0.72
Combined	3.71	3.77	0.43	1.03
Standard Error	15.3%	12.7%	44.2%	19.2%

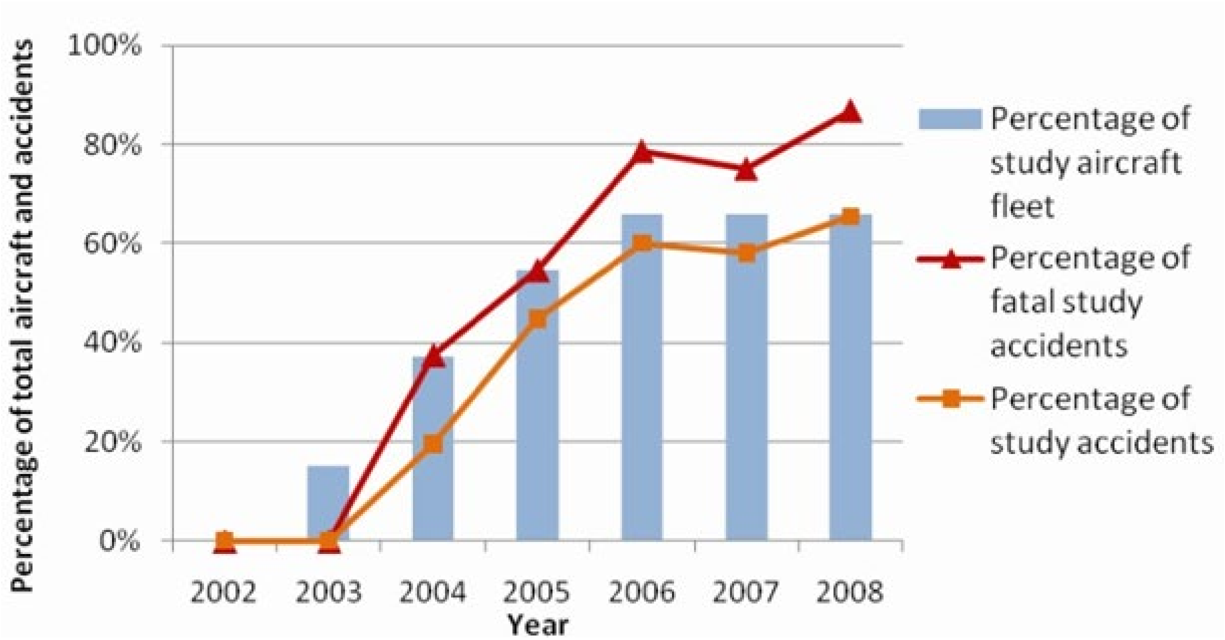

Figure A-14: Distribution of Glass Cockpit Cohort Aircraft and Accidents per Year

The NTSB concluded that these advanced displays did not show a significant improvement in safety for glass cockpit general aviation airplanes. They also raised concerns about a lack of knowledge and training requirements for glass cockpit displays. This is significant in view of the overwhelming success of TAWS in transport airplanes.

In our opinion, this supports the absolute need to consider pilot behavior during certification and to ensure adequate training and operational procedures for new technology equipment.

This is troubling. The lack of required operational training for pilots in the GA fleet has led to an increased occurrence of CFIT accidents compared with transport operations. Newman and Kolb analyzed the results for transport aircraft and showed a 99.2% reduction in CFIT accidents for the US air carrier fleet? Why, then, do we see an increase in GA airplanes? We have heard anecdotal stories of pilots who used the terrain display in the mountains at night to navigate through passes by descending to make the terrain display just turn red. In any event, introducing new technology without proper training and procedures is fraught with issues.

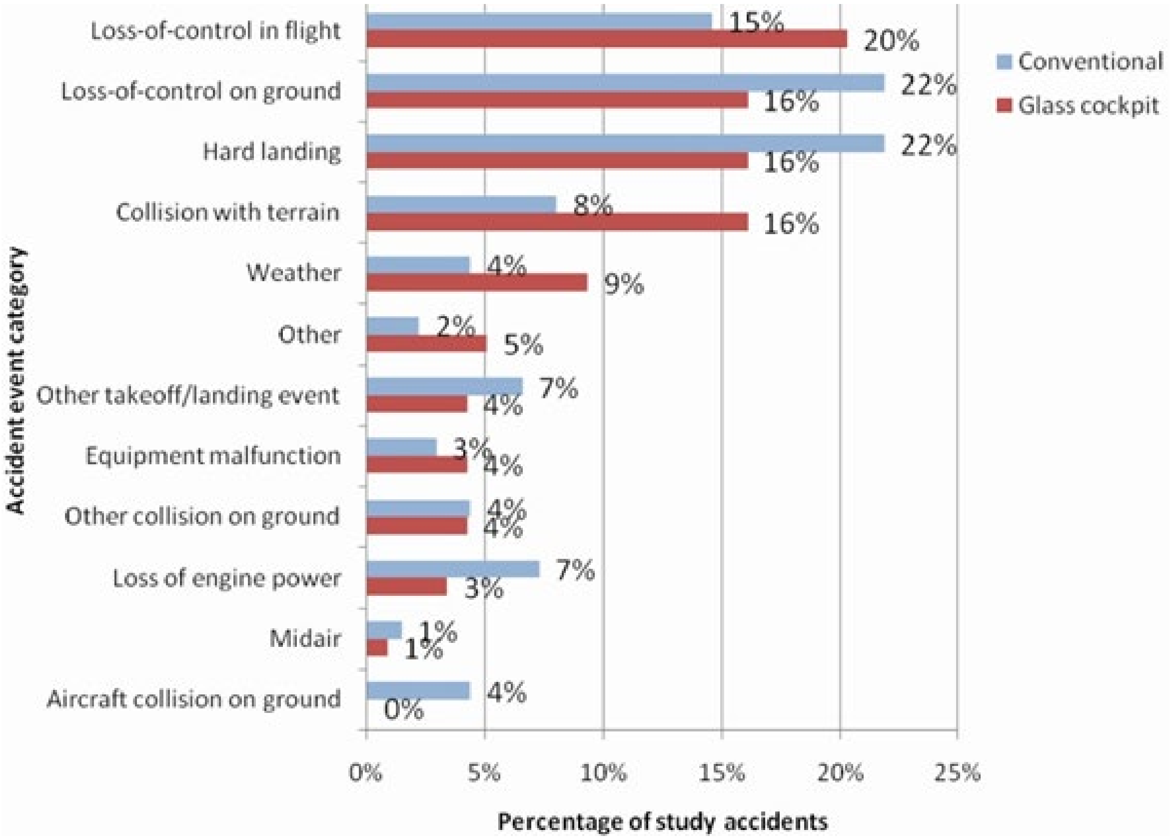

Figure A-15: Comparison of Accident Event Type by Instrument Configuration

(NTSB Aviation Accident Data 2002-2008, N=255)

4.3 Mode Confusion Mishaps

4.3.1 Airspeed Failure Leads to Alternate Control Law

The first mishap in this section was widely reported as a significant issue with fly-by-wire controls. The loss of airspeed data did cause a reversion to alternate control laws. Unfortunately, in this case the least experienced of the three pilots was the pilot flying and the other pilot was not permitted to handle the controls from the left seat. The pilot flying was very likely hand-flying the airplane at high altitude for the first time. The remaining two incidents show that reversion to alternate law does not always lead to a catastrophe.

1-June-2009; A330-200; F-GZCP
An Air France Airbus A330-200 was destroyed when it crashed into the sea while on transatlantic flight from Rio de Janeiro-Galeao International Airport to Paris-Charles de Gaulle Airport. At the time of the accident, the airplane was out of radar coverage. The Captain was taking a rest break and the second officer was the pilot flying (PF) and was in the right seat.

The airplane was flying at FL350 and at Mach 0.82 and the pitch attitude was about 2.5°. Autopilot 2 and auto-thrust were engaged. From 02:10:05, the autopilot then auto-thrust disengaged and the PF said "I have the controls". The stall warning sounded twice in a row. The recorded parameters show a sharp fall from about 275 kts to 60 kts in the speed displayed on the left primary flight display (PFD), then a few moments later in the speed displayed on the integrated standby instrument system (ISIS). At 02:10:16, the PNF said “so, we’ve lost the speeds” then “alternate law.”

The airplane’s altitude reached its maximum of about 38,000 ft, its pitch attitude and angle of attack being 16°. It then at about -10,000 ft/min until it struck the surface of the sea.

23-June-2009; A330-300; N-805NW
An Airbus A330-323, registration N-805NW, serial number 552, operated by Northwest Airlines as flight 08 between Hong Kong and Tokyo experienced a loss of primary speed and altitude information while in cruise flight at FL390 about 50 miles southwest of Kagoshime Airport, Japan. The crew reported airspeed fluctuations on the Captain’s, First Officer’s (FO), and the standby airspeed indicators. They reported receiving a stall warning, noted the flight law switched to Alternate Law, and saw messages indicating NAV ADR DISAGREE and NAV IAS DISCREPANCY. They reported the airspeed fluctuations and warnings lasted about one minute, and they controlled the airplane by pitch and power reference. The airspeed fluctuations and messages repeated for a duration of about two minutes. The airspeed indicators returned to normal and the crew re-engaged autopilot and completed the flight in alternate law.

3-Feb-2013; A330-600; A6-EHF

While cruising at FL350, just leaving the Colombo FIR and entering the Melbourne FIR, the Aircraft encountered moderate to heavy turbulence, and experienced significant airspeed oscillations on both the captain's and the standby airspeed indicators. The autopilot, autothrust, and flight directors disconnected automatically. The flight control law changed from "Normal" to "Alternate" Law, leading to the loss of some flight mode and flight envelope protections. Changes from Normal to Alternate Law occurred twice; thereafter the Aircraft remained in Alternate Law until the end of the flight. The autothrust system and the flight directors were successfully re-engaged, however, neither autopilot (autopilots 1 or 2) could be re-engaged, thus the Aircraft was flown manually until landing.

4.3.2 Confusing Digital Display Designs

20-Jan-1992; A320-100; F-GGED

In this Air Inter accident at Strasbourg, the procedure called for a -5.5% descent gradient (-3.3 deg flight path angle). Since the displays were in HDG/VS mode, -3.3 ° shows a descent rate of -3300 ft/min more than four times the desired rate [39].

4.3.3 Impromptu, Unauthorized Procedures

These mishaps result from a lack of training or organizational procedures. There were several in the early days of fly-by-wire (FBW) transports. There is some indication that general aviation operators may be using such procedures as well. The certification authorities must consider that proper training and procedures are in place for modern aircraft systems.

14-Feb-1990; A320-200; VT-EPN

The pilot tried to go-around by pulling back on the stick expecting the system would add thrust. The pilots didn't realize that the airplane was in a mode called open descent in which the adding power did not automatically add thrust. The Captain in the left seat was in Initial Operating Experience (IOE) and being checked by the pilot in the right seat [40].

13-Jul-1996; MD-11; N-1768D

The first officer (F/O) was making a descent from FL350 to FL240 in smooth air in VMC conditions with the autopilot (A/P) engaged. As the flight neared FL250, the captain became concerned that the airplane would not level off at FL240. He instructed the F/O to slow the rate of descent. The F/O attempted this by using the pitch thumbwheel on the A/P control panel. The

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[39]. *Rapport de la commission d'enquête sur l'accident survenu le 20 janvier 1992 près du Mont Sainte-Odile (Bas Rhin) à l'Airbus A 320 immatriculé F-GGED exploité par la compagnie Air Inter*, BEA F-ED920120.

[40]. ICAO Circular 263-AN/157.

captain then took control, attempted to overpower the A/P, and pulled back on the control yoke. With back pressure on the control yoke, he disengaged the A/P. With the reduced control column resistance after the A/P was disengaged, there was further excursion of the elevators to the up position. According to the flight data recorder, the airplane was subjected to a +2.28 G-load. A passenger in the aft lavatory suffered a fractured ankle. A 2nd passenger and 2 flight attendants received minor injuries [41].

The MD-11 Flight Crew Operating Manual (FCOM) advised against attempting to overpower the A/P; however, this was contained under the title, SEVERE TURBULENCE AND/OR HEAVY RAIN INGESTION. The manufacturer has subsequently issued FCOM changes to warn pilots about the hazards of applying force to the control wheel or column while the A/P is engaged and adjusting the pitch thumbwheel during a level off.

10-Nov-2004; PA-32R; N-803ZG
The airplane collided with upsloping high mountainous terrain during level, controlled cruise flight on a night cross-country. Prior to takeoff, the pilot informed the air traffic controller (ATC) that he had received the airport's weather. A broken sky condition existed with layers about 5,500 and 7,000 feet mean sea level (MSL). When the pilot subsequently climbed from 4,900 to 5,200 feet and requested information from ATC about the elevation of the clouds, he acknowledged that he "seems to be in a little bit of clouds...sort of in and out." The pilot continued climbing into clearer conditions. The flight continued and the airplane tracked near the centerline of Victor Airway 183, which had a published course of 195°. The pilot was familiar with the roundtrip route between his Santa Barbara home-base airport and Bakersfield, and he had previously flown over the route. During the last few minutes of the radar-recorded flight, the pilot was generally cruising about 6,500 feet, as indicated by the mode C altitude reporting transponder. The pilot was receiving radar flight following service from a controller at the Los Angeles Air Route Traffic Control Center. The controller observed the airplane and was aware that the minimum enroute altitude (MEA) for airplanes on instrument clearances along the airway was 9,000 feet. The controller and the pilot had sectional aeronautical charts available for use that depicted a 6,840-foot MSL mountain peak along the flight route. The pilot's course did not vary as he approached and impacted the mountain during the dark nighttime flight. The bearing between the initial point of impact (IPI) and the Santa Barbara Municipal Airport was 197°. Also, the bearing and distance between the IPI and the main wreckage was 198° and 0.25

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[41]. *Uncommanded Pitch-up, McDonnell Douglas MD-11, July 13, 1996*, NTSB-FILE-NYC96LA148.

miles. The controller did not issue a terrain-related safety alert, as required by a Federal Aviation Administration order [42].

This flight was consistent with using the electronic terrain map to fly near the altitude where the color shifts between yellow and red. The have been anecdotal reports of general aviation pilots using their navigation displays in this manner.

4.3.4 Mode Confusion

31-Jul-1973; DC-9-30; N-975NE
Delta Flight 723 was descending, the approach clearance was given by the controller after a delay, because the controller was preoccupied with a potential conflict between two other aircraft. This caused the flight to be poorly positioned for approach. The aircraft passed the Outer Marker at a speed of 385 km/h (80 km/h too fast) and was 60 m above the glide slope.

The flight director was inadvertently used in the 'go-around-mode,' which led to abnormal instrument indications. This caused some confusion. The first officer, who was flying the approach became preoccupied with the problem. The DC-9 continued to descend and struck a seawall 3000 feet short of and 150 feet to the right of runway 04R, crashed and caught fire. RVR at the time was 500 m with 60 m overcast [43].

The ex-Northeast Airlines crew was originally trained on a Collins F/D, now flying Sperry F/D following the merger with Delta.

13-Mar-2012; A330-300, F-GLZU
The crew contacted the tower and indicated that they were 9 NM out. The airplane was at an altitude of 4950 ft (1750 ft above the glide path). The controller initially cleared the crew to continue the approach. The latter read back "Cleared to land 08 right..." The controller indicated that he then checked that the CAT III ground services were clear then confirmed clearance to land.

The crew selected slats/flaps configuration 2 and retracted the airbrakes. About one minute later, they re-extended the airbrakes, set the G/S mode using the APPR switch and engaged autopilot 2. The glide path capture mode (G/S) was activated when the airplane was 2 NM from the runway threshold at 2850 ft (that is about 1600 ft above the glide path at 3°). The autopilot's capture of an ILS signal from an upper sidelobe, which generated an excessive increase in pitch

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[42]. Aviation Investigation Final Report, NTSB-File-LAX05FA032.
[43]. *Delta Air Lines, Inc., DC-9-31, N975NE, Boston, Massachusetts, July 31, 1973*, NTSB-AAR-74-03.

attitude. Flight crew and controller fatigue may have contributed to the occurrence of this serious incident.

4.3.5 Inappropriate and Unpublished System Protection Schemes

27-Jan-1993; L-382-HTTB; N-130X
In an engineering test bed evaluating a FBW rudder. The system had been designed to prevent overstressing the rudder actuator. If the rudder position differed from the commanded, the hydraulic power to the actuator would be removed. During the first VMCA test point, the system removed power to the rudder actuator. The crew were surprised but were able to recover control. A second test produced the identical result. Subsequently, maintenance reported that the system met all specifications. The next day, the tests were repeated with the same results [44].

3-Feb-1993; L-382-HTTB; N-130X
The following week, the project pilot was not available, but ground VMCG tests were planned with a different crew who were not briefed on the results of the previous week's tests. In addition, the pilots had no training on conducting VMC tests. On the first test point, the pilot lost control, attempted to fly away, but crashed killing all on board. Sadly, four observers were on board and were killed [45]. In this accident, it appears that the system sacrificed the airplane in order to protect the actuator.

30-Jun-1994; A330; F-WWKH
This was a test of an A-330 autopilot. During the second test point, the airplane was to takeoff and climb out. The target altitude was left unchanged from the previous test and set at 2000 ft. When engaged, the flight path algorithm went immediately to Altitude Capture, not to Climb. In this mode, the pitch attitude is inactive. This caused the pitch attitude to reach 32° and the speed decreased to 100 kts. Roll control was lost, and the airplane crashed killing all on board. Again, there were four observers on board [46].

4.3.6 Incorrect Electronic Database – Database Differs from Navigation Charts

20-Dec-1995; B757-200; N-651AA
The crew was flying a long down right downwind to runway 01 to Cali. The crew was then recleared for a straight-in approach to runway 19 (the Rozo 1 arrival). The crew then selected the Rozo NDB (Non Directional Beacon) on the Flight Management Computer (FMC). Because

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[44] Personal recollection of the author of this appendix.

[45]. *Lockheed L382E, N-130X, Dobbins AFB, Marietta, GA, 3 February 1993*, NTSB File ATL93MA055.

[46]. *Commission D'Enquete Sur L'Accident Survenu Le 30 Juin 1994 A Toulouse-Blagnac (31) A L'Airbus A330 No 42 D'Airbus Industrie Immatricule FWWKH*, BEA Report.

their Jeppesen approach plates showed 'R' as the code for Rozo, the crew selected this option. But 'R' in the FMC database meant Romeo. Romeo is a navaid 150nm north from Rozo, but with the same frequency. The aircraft had just passed Tulua VOR when it started a turn to the left (towards Romeo). This turn caused some confusion in the cockpit since Rozo 1 was to be a straight in approach. 87 seconds after commencing the turn, the crew activated Heading Select (HDG SEL), which disengaged LNAV and started a right turn. The left turn brought the B757 over mountainous terrain, so a Ground Proximity (GPWS) warning sounded. With increased engine power and nose-up the crew tried to climb. The spoilers were still activated, however. The stick shaker then activated, and the aircraft crashed into a mountain at about 8900 feet (Cali field elevation being 3153 feet) [47].

Typically, using FMC's for in-flight changes does not allow easy preview of the effect of the changes. At the very least, there should be means to quickly undo the last change.

4.3.7 Incorrect Electronic Database – Terrain Database does not Match Real World

14-Mar-2017; S-92A; EI-ICR
A Sikorsky S-92A helicopter, registration EI-ICR (call sign Rescue 116), was being operated on behalf of the Irish Coast Guard, was enroute to Blacksod, County Mayo, on Ireland's west coast. The flight crew's intention was to refuel at Blacksod before proceeding, to provide Top Cover for another helicopter, which had been tasked to airlift a casualty from a fishing vessel, situated approximately 140 nautical miles off the west coast of Ireland. At 00.46 hrs, on 14 March 2017, while positioning for an approach to Blacksod from the west, the helicopter, which was flying at 200 feet above the sea, collided with terrain at the western end of Black Rock, departed from controlled flight, and impacted with the sea.

The helicopter was equipped with a Honeywell Mk XXII EGPWS system. Black Rock was not in the terrain database supplied by the system manufacturer. The EGPWS manufacturer informed the accident investigation team that the terrain data had been obtained from multiple Russian Military Topographic maps and delivered in Digital Elevation Model (DEM) format. The helicopter operator had received a pilot report concerning the absence of the Black Rock on the database, but that report had not been followed up.

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[47]. *Aircraft Accident Report controlled flight into terrain American Airlines Flight 965 Boeing 757-223, N651AA near Cali, Colombia December 20, 1995*, Aeronautica Civil-Columbia.

4.3.8 Latent Failures

6-Feb-1975; M-20F; N-6371Q

A Mooney M-20F, N6371Q, lost all attitude and directional instruments shortly after departing the Syracuse, New York Airport on the evening of February 6, 1975. The incident occurred in instrument meteorological conditions (IMC) during the hours of darkness. The airplane entered a spiral dive and regained visual conditions in time for recovery. There were no injuries or property damage. The shear failure of the vacuum pump driver shaft. Contributing to the seriousness of the malfunction was a previous, undetected failure of the turn rate gyro's electric drive. This electrical failure was masked by the backup vacuum drive of the turn rate gyro. In addition, the vacuum failure warning light did not show. The flight returned safely to Syracuse[48].

1-Aug-2005; B777-200; 9M-MRG

On August 2, 2005, at 1757 local time, a Boeing 777-200, registered in Malaysia as 9M-MRG, operated by Malaysian Airline System, experienced a pitch up about one-half hour after takeoff from Perth, Australia. This event occurred as the flight was climbing through 36,000 feet and while the aircraft was on autopilot. During the pitch up the aircraft climbed to 41,000 feet and the indicated airspeed dropped from 270 kts to 158 kts. The stick shaker and the stall warning indicator activated during the event. An anomaly existed in the component software hierarchy that allowed inputs from a known faulty accelerometer to be processed by the air data inertial reference unit (ADIRU) and use by the primary flight computer, autopilot and other aircraft systems. The software anomaly was not detected in the original testing and certification of the ADIRU. The flight landed uneventfully back at Perth [49].

4.3.9 Loss of Multiple Displays

22-Oct-2005; A319; G-EUOB

As the aircraft climbed to Flight Level (FL) 200 in night Visual Meteorological Conditions (VMC) with autopilot and autothrust engaged, there was a major electrical failure. This resulted in the loss or degradation of a number of important aircraft systems. The crew reported that both the commander’s and co-pilot’s Primary Flight Displays (PFD) and Navigation Displays (ND) went blank, as did the upper ECAM display. The autopilot and autothrust systems disconnected, the VHF radio and intercom were inoperative and most of the cockpit lighting went off. There were several other more minor concurrent failures.

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[48]. *Incident Report. Mooney M20-F, N6371Q, Syracuse, New York, February 6, 1975*, Pilot Report to NTSB.

[49]. *Pitchup Caused by Faulty Accelerometers (Dispatch with Inop) Zoomed From FL380 To FL410*, ATSB-AO-2005-3722.

The commander maintained control of the aircraft, flying by reference to the visible night horizon and the standby instruments, which were difficult to see in the poor light. The co-pilot carried out the abnormal checklist actions which appeared on the lower ECAM display; the only available electronic flight display. Most of the affected systems were restored after approximately 90 seconds, when the co-pilot selected the AC Essential Feed switch to Alternate. There were no injuries to any of the 76 passengers or 6 crew. After the event, and following discussions between the crew and the operator's Maintenance Control, the aircraft continued to Budapest [50].

15-Sep-2006; A319-100, G-EZAC

The serious incident occurred to an Airbus A319-111 aircraft operating a scheduled passenger flight between Alicante, Spain and Bristol, UK. The aircraft had experienced a fault affecting the No 1 (left) electrical generator on the previous flight and was dispatched on the incident flight with this generator selected off and the Auxiliary Power Unit generator supplying power to the left electrical network.

Attempts by the flight crew to reconfigure the electrical system proved ineffective and the aircraft systems remained in a significantly degraded condition for the remainder of the flight, making operation of the aircraft considerably more difficult. The flight crew were unable to contact air traffic control for the rest of the flight. The aircraft landed uneventfully at Bristol, with the radios and several other systems still inoperative [51,52].

25-Jan-2008; A320-200, N-462UA

A United Airbus A320, registration N462UA, experienced multiple avionics and electrical failures, including loss of all communications, shortly after rotation while departing Newark Liberty International Airport, Newark (EWR), New Jersey. The flight returned for landing at EWR and electrical power was restored to the cockpit after landing when the flight crew selected the AC Essential Bus button. There were no injuries to the 107 passengers and crew aboard the airplane and no damage to the airplane. The airplane was operating under the provisions of 14 Code of Federal Regulations Part 121 and was a regularly scheduled passenger flight to Denver International Airport, Denver, Colorado [53].

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[50]. *Report on the serious incident to Airbus A319-131, G-EUOB during the climb after departure from London Heathrow Airport on 22 October 2005*, AAIB-AAR-2/2008.

[51] *Lost PFD-1, ND-1, Upper ECAM, MCDU, Plus Other Systems*, AAIB S9/2006.

[52]. Lacagnina, M, "Partial-Panel Puzzle: The A319 Pilots Were Powerless To Rectify An Electrical System Gone Haywire," *AeroSafetyWorld*, September 2009, Pp. 16-21.

[53]. Aviation Incident Final Report, NTSB File DCA-08IA033, Published March 2020.

4.3.10 Multiple Airspeed Failures

5-Apr-1998; A320-200

Aircraft not identified: On a scheduled flight from Lyon to Frankfurt in a holding pattern the airspeed indications in both primary flight displays (PFD) and for a short time in the standby indication system failed. In conjunction with this failure, the automatic flight control systems switched off and the electronic centralized aircraft monitor showed several warning and error messages. The pilot-in-command immediately took over the controls from the candidate captain who up to the moment of the occurrence was the pilot flying. When he had stabilized the aeroplane manually at an altitude of 10000 ft on the basis of pitch angle and powerplant output (PITCH and POWER), the airspeed indications reappeared on all three instruments. As a precaution, the PIC manually switched the pitot tube heating on (PROBE/WINDOW HEAT on the overhead panel from AUTO to ON). At the moment of the incident, IMC with severe icing, rain showers and turbulence were prevailing. For the landing, the autopilot and autothrottle were available again [54].

4.3.11 Runaway Pitch Trim

18-Nov-1988; Swearingen-226; F-GCPG

It was still dark outside when Air Littoral flight 440 received clearance to taxi to runway 35 for its early morning flight to Paris. The first officer was pilot flying on this leg. Six minutes later, at 06:31, the throttles were advanced and the Metro II started the takeoff roll. Shortly after lifting off the runway, the nose pitched down. The Metro II descended and contacted the ground again 600m past the runway end and continued through bushes, eventually catching fire. It appears that the Stall Avoidance System (SAS) had activated, resulting in the stick pusher activation at a critical altitude. The Metro's SAS system, as well as the SAS system on this particular aircraft, had a history of problems. Reports are no longer available from either BEA or NTSB [55].

4.3.12 Uncommanded Pitch

23-Sep-2007; B-737-300; G-THOF

The Boeing 737-300 was on approach to Bournemouth Airport following a routine passenger flight from Faro, Portugal. Early in the ILS approach the auto-throttle disengaged with the thrust levers in the idle thrust position. The disengagement was neither commanded nor recognized by the crew and the thrust levers remained at idle throughout the approach. Because the aircraft was

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[54]. *Loss Of Airspeed Displays, Serious Incident, 05.04.1998, Near Frankfurt/Main Airport, To An Airbus A320-200.*, BFU 5X002-0/98.

[55]. *Rapport final sur l'accident survenu le 18 november 1988 près de l'aerodrome de Montlucon-Guéret (23) au Swearingen Metro II immatriculé F-GCPG de la compagnie Air Littoral.*

fully configured for landing, the air speed decayed rapidly to a value below that appropriate for the approach. The commander took control and initiated a go-around. During the go-around the aircraft pitched up excessively; flight crew attempts to reduce the aircraft's pitch were largely ineffective. The aircraft reached a maximum pitch of 44º nose-up and the indicated airspeed reduced to 82 kts. The flight crew, however, were able to recover control of the aircraft and complete a subsequent approach and landing at Bournemouth without further incident [56, 57] .

4.3.13 Undesired Sensor Failure Effect

7-Oct-2008; A330-300; QF-QPA

The Airbus A330-303 aircraft, registered VH-QPA, departed Singapore (SIN) on a scheduled passenger transport service to Perth (PER), Australia. On board were 303 passengers, nine cabin crew and three flight crew. While the aircraft was cruising at 37,000 ft, the autopilot disconnected. That was accompanied by various aircraft system failure indications. As the crew was evaluating the situation, the aircraft abruptly pitched nose-down. The aircraft reached a maximum pitch angle of about 8.4° nose-down and descended 650 ft during the event. After returning the aircraft to 37,000 ft, the crew commenced actions to deal with multiple failure messages. About 3:00 minutes later the aircraft commenced a second un-commanded pitch-down event. The aircraft reached a maximum pitch angle of about 3.5° nose-down and descended about 400 ft during this second event. About two minutes later, the crew made a PAN emergency broadcast to air traffic control and requested a clearance to divert to and track direct to Learmonth. At 12:54, after receiving advice from the cabin crew of several serious injuries, the crew declared a MAYDAY. The aircraft subsequently landed at Learmonth Airport, WA (LEA). At least 110 of the 303 passengers and nine of the 12 crew members were injured; 12 of the occupants were seriously injured and another 39 received hospital medical treatment. Most of the injuries involved passengers who were seated without their seatbelts fastened.

29-Oct-2018; B-737-MAX; PK-LQP

After the flaps were retracted, the FDR recorded automatic aircraft nose down (AND) trim for 10 seconds followed by flight crew commanded aircraft nose up (ANU) trim. Automatic AND trim briefly stopped when the flaps were temporarily extended to 5. In their communications with air traffic control, the flight crew asked the controller to confirm the altitude of the aircraft and later also asked the speed as shown on the controller radar display. The copilot reported experiencing

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[56]. *Report on the serious incident to Boeing 737-3Q8, registration G-THOF, on approach to Runway 26, Bournemouth Airport, Hampshire on 23 September 2007*, AAIB-AAR 3/2009.

[57]. *Study on Aeroplane State Awareness During Go-Around*, BEA Report, August 2013.

a "flight control problem" and that they were flying the aircraft manually. The aircraft impacted the sea some 15 km north off Tanjung Bungin. All 189 persons on board died in the accident [58].

10-Mar-2019; B-737-MAX; EX-AVJ
Ethiopian Airlines flight ET302, a Boeing 737 MAX 8, crashed shortly after takeoff from Addis Ababa-Bole Airport, Ethiopia. There were no survivors among the 157 occupants. Takeoff roll began from runway 07R at 08:38 hours local time, with a flap setting of 5° and a stabilizer setting of 5.6 units. Shortly after takeoff, the left and right AOA values deviated with the left AOA decreased to 11.1° then increased to 35.7° while the right AOA indicated 14.94°. At 08:38:44, ten seconds after rotation, the left and right recorded Angle of Attack (AOA) values deviated. The left AOA decreased to 11.1° then increased to 35.7° while value of right AOA indicated 14.94°. Several confusing and contradicting annunciations followed. The airplane ultimately collided with the ground [59].

4.3.14 Untimely Flight Envelope Protection Activation

6-Jul-1969; BE-99; N-844NS
Air South Flight 168 departed Atlanta at 21:07. At 21:13 the flight reported level at its assigned cruising altitude of 7,000 feet. The Beech had been cruising for eleven minutes when it attained a gradual nose down attitude due to a change in the longitudinal trim. The pilots noticed the change after about six seconds and initiated a recovery action. The horizontal stabilizer continued to move to a full nose down position. Excessive pulling force on the control column was necessary to recover from the high speed dive. The necessary stick forces for such an out-of-trim condition can exceed the capability of one pilot, and in some cases two pilots, to control. The Beech continued to descend until both wings failed at high speed, just before the airplane crashed into the ground in a near vertical attitude [60].

21-Jun-1994; B-757-200; Aircraft not identified
After takeoff, at 2,200 ft, the altitude capture mode cut power back while the flight director bars appeared to command a pitch up, and then disappeared. Airspeed dropped toward V2 and the crew pitched down to 10°. CAA says “problem considered to be well known and adequately trained” [61].

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[58]. *Aircraft Accident Investigation Report PT.Lion Mentari Airlines Boeing 737-8(MAX); PK-LQP. Tanjung Karawang, West Java, Republic of Indonesia. 29 October 2018*, KNKT 18.10.35.04 Final Report.

[59]. *Interim Investigation Report on Accident to the B737-MAX8 Reg. ET-AVJ operated by Ethiopian Airlines 10 March 2019*, Published December 23, 2022, Investigation Report AI-01/19.

[60]. *Aircraft Accident Report. Air South, Inc. Beechcraft B-99, N844AS Near Monroe, Georgia July 6, 1969*, NTSB-AAR-70-18.

[61]. Dornheim, MA, “Dramatic Incidents Highlight Mode Problems in Cockpits,” *Aviation Week*, January 30, 1995, Pp. 57-59.

4.3.15 Untimely Stall Protection Activation

2-Oct-2000; A340; TC-JDN

The A340 was en-route from Istanbul to New York and an A330 was en-route from London to Ottawa. The aircraft were in clear air as the A330 was slowly overtaking the A340 below it. The A330 commander stated that his aircraft was slightly to the right of the A340 and almost abeam it when he saw the A340's wings start to flex, followed by a TCAS warning. The A340 had entered Alpha-protection law, caused by an AOA projected to reach alpha protection (~ 4.2°). This forced the longitudinal flight control system into AOA protection law.

In this law, the AOA is commanded directly by the sidestick with zero stick input commanding alpha port at zero sidestick input and alpha max at full forward sidestick. Since the angle of attack was actually at normal cruise AOA (~2°). This would have resulted in a significant increase in AOA, resulting in a zoom climb [62].

It would appear that the AOA protection control laws assumed that all protection strategies would develop during an undesired increase in AOA during a landing, not in a calculated entry based a predicted future trend.

24-Sep-1998; A320-200; C-FKCO

The Airbus A320, C-FKCO, operating as Air Canada flight 639, was a scheduled flight from Toronto, Ontario, to St. John’s, Newfoundland. During the night localizer approach to runway 29, which had a relocated threshold, strong gusty winds were encountered. The aircraft touched down approximately 250 feet short of the relocated threshold, striking sawhorse-type construction barriers. The aircraft sustained damage to two brake lines and one brake temperature sensor. There were no injuries to any of the occupants. The aircraft touched down at 0053 Newfoundland daylight time.

During the encounter, the aircraft flight control system entered alpha-protection mode which prevented the flight crew from arresting the descent [63].

7-Feb-2001; A320-200; EC-HKJ

Following a nighttime flight from Barcelona to Bilbao, the crew positioned the plane for a runway 30 approach and landing. During their final ILS approach, the aircraft encountered heavy turbulence at about 200 feet AGL. with gusts up to 65 mph. The aircraft encountered windshear with 1.25G updraft, downdraft and a tailwind gust at just 70 feet AGL. When the Ground

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[62]. *Turbulence Encouter, Airspeed Excursion, Alpha Protection with Subsequent Altitude Excursion*, AAIB BULL 6/2001.

[63]. *Landing Short: Air Canada A320-211, C-FKCO, St John's, Newfoundland, 24 September 1999*, TSB-A99A0131.

Proximity Warning System (GPWS) sounded, the captain called for a go-around while pulling on the sidestick, reportedly without pressing his priority control button. The combination of dynamic winds and the crew actions created a situation that triggered the airplane's alpha protection system. As the crew applied TOGA power for a go-around, with both pilots pulling back on their sidesticks, the alpha protection law reduced the elevator nose-up command. Instead of a go- around, the aircraft struck the runway with a vertical speed of approx. 1,200 fpm. The nosegear collapsed and the aircraft skidded 3,280 feet (about 1000m) down the runway before coming to a stop [64].

25-Jun-2005; A320-200; I-BIKE
The flight departed from Milan Airport at 0547 hrs on a scheduled flight to London Heathrow Airport (LHR) with the commander as the Pilot Flying (PF). The previous day, the No 3 ADIRU was found to be unserviceable and had been turned off; the Minimum Equipment List (MEL) allowed the aircraft to depart in this condition, as both the Nos 1 and 2 ADIRUs were serviceable. During the flight, as a precautionary measure, the commander and co-pilot reviewed the Flight Manual Abnormal Procedures for the actions to be taken in the event of a second ADIRU becoming unserviceable. It seems strange that invoking a stall prevention strategy would actually increase the AOA [65].

It would appear that the AOA protection control laws assumed that all protection strategies would develop during an undesired increase in AOA during a landing, not in a calculated entry based a predicted future trend.

4.3.16 All-Engine Flameout

There was a flight test incident in the late 2000's with a business jet program in which an aircraft was being flown by the FAA demonstrating high altitude performance. I do not remember if this was a certification flight or a familiarization flight. I believe that was being flown by FAA test pilots from the Atlanta ACO. Because of the uncertainty about the circumstances and the date, this occurrence was not included in the database to date.

Around 2008; Business Jet
The experimental aircraft was being flown on an evaluation flight and was climbing through FL520. Both engines flamed out. The pilot was able to descend to the relight envelope around FL250, relight the engines and return to base. I remember discussions within the FAA concerning this event. As I remember, this was a business jet being flown by an FAA pilot. I

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[64]. *Accident Of Aircraft Airbus A-320-213, Registration EC-HKJ, And Bilbao Airport On 7 February 2001*, CIAIAC-TR-A-006/2001.
[65]. *Loss Of Two ADIRUS, Airbus A320-200, I-BIKE*, AAIB6/2006.

remember the pilot relating that "The airplane [altitude] started down and the cabin [altitude] started up. They met at about 40,000 ft – still well above the relight envelope[66]."

I remember some discussion about the FADEC data reaching the end of its altitude data. This event should be researched within the FAA flight test community.

4.3.17 Observations

The most obvious observation is the overwhelming benefit of proper crew training and clear and consistent operating procedures. This is most clearly demonstrated in the difference between air carrier and general aviation CFIT accidents. After TAWS was mandated, CFIT fatalities in US jet transport airplanes was reduced from 897 fatalities per ten years to 2 per ten years [67]. At the same time, the rate of CFIT actually increased if TAWS was installed **Error! Bookmark not defined.**.

It is essential that careful evaluation of crew responses to system failures be performed. There should be valid and objective test criteria. The use of subjective criteria should be avoided. The objective criteria must be based on performance measurements. The final tests should be mission scenarios and situation awareness tests. All testing prior to that are for risk reduction or proof-of-concept.

Test pilots or operational pilots? The ultimate tester is the user. The objective criteria mentioned above must be achieved by operational pilots – the users. A range of experience levels should be used for the evaluation pilots. Appropriate experience levels would range from 100 to 1000 hours for small single-engine airplanes to 200 to 2000 hours for a corporate jet [68].

These evaluation pilots should receive training on the system similar to initial training to be given to pilots during their checkout in the airplane in service.

As a final point, many failures have been masked by built-in redundancy. It is imperative that failed components be indicated and replaced promptly to retain the designed-in safety. We have seen two such instances where failed components were not replaced and led to further failure. Fortunately, the two examples did not lead to casualties.

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[66] This occurrence is not contained within our mishap database at this time.

[67]. Newman, R. L. and Kolb, M., *Development of Aircraft Certification Requirements*, Seattle: Crew Systems, 2022, ISBN 978-66786-791-5, p. 145.

[68]. Newman, R. L., *Display Evaluation Protocol*, University of Iowa, Operator Performance Laboratory, May 2003.

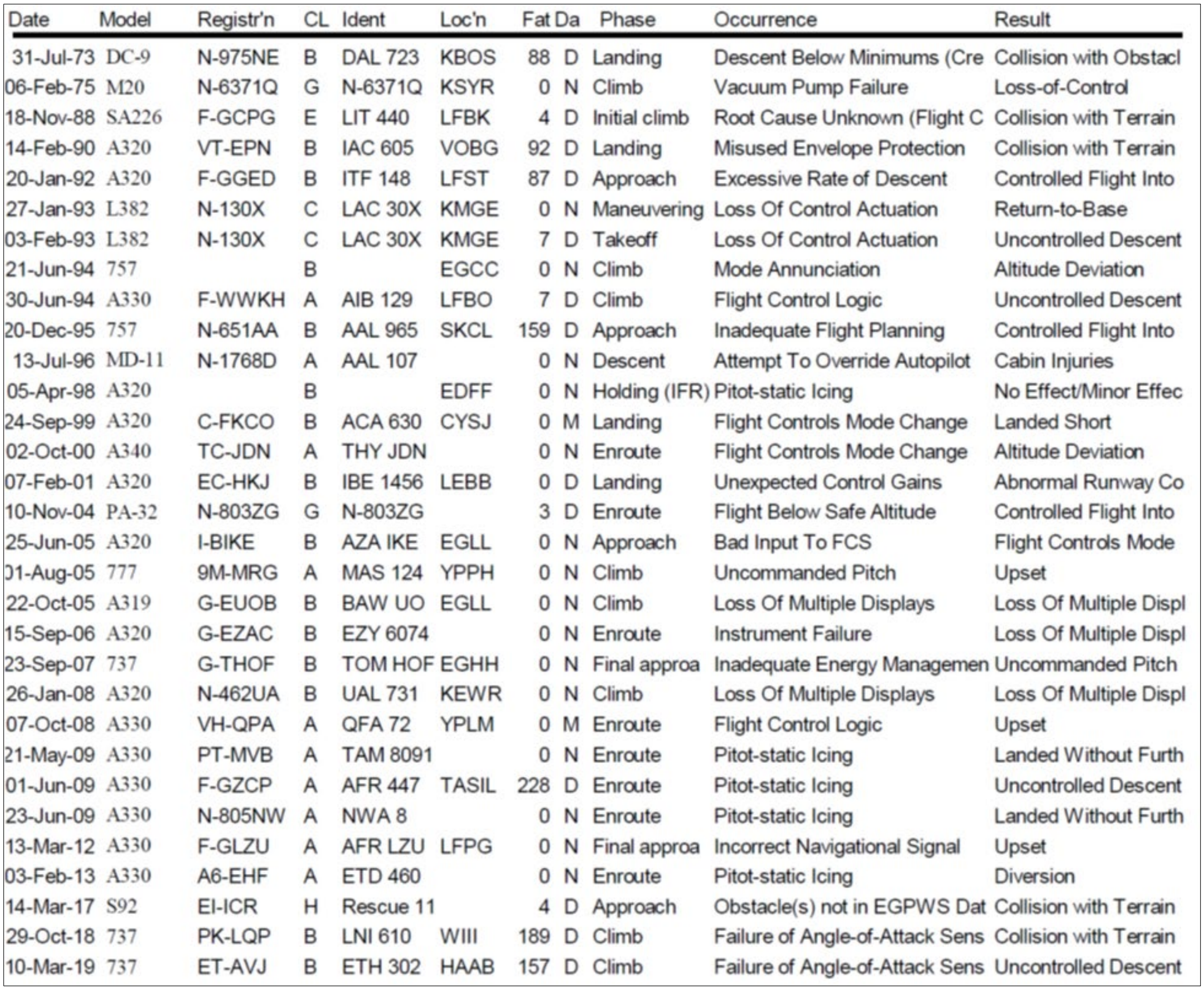
5. Abbreviations and Acronyms

A/P	Autopilot
ADIRU	Air Data Inertial Reference Unit
AGL	Above Ground Level
AND	Aircraft Nose Down
ANU	Aircraft Nose Up
AOA	Angle-of-Attack
ATC	Air Traffic Control
BEA	Bureau d'Enquêtes et d'Analyses
CAA	Civil Aviation Authority (UK)
CAT III	Category 3
DEM	Digital Elevation Model
ECAM	Electronic Centralized Aircraft Monitor
EGPWS	Enhanced Ground Proximity Warning System
F/O	First Officer
FBW	Fly by Wire
FCOM	Flightcrew Operating Manual
FIR	Flight Information Region
FMC	Flight Management Computer
G/S	Glideslope
GPWS	Ground Proximity Warning System
HDG	Heading
IMC	Instrument Meteorological Conditions
IOE	Initial Operating Experience
IPI	Initial Point of Impact
ISIS	Integrated Standby Instrument System
LNAV	Lateral Navigation
MEA	Minimum Enroute Altitude
MEL	Minimum Equipment List
ND	Navigation Display
NDB	Non-Directional Beacon
NTSB	National Transportation Safety Board
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot Not Flying
SAS	Stall Avoidance System
TCAS	Traffic [Alert and] Collision Avoidance System
TOGA	Takeoff and Go Around [Power/Thrust]
V/S	Vertical Speed
VHF	Very High Frequency (30 to 300 megahertz)

VMC	Visual Meteorological Conditions
V_{MC}	Minimum Control Speed
V_{MCA}	Minimum Control Speed (air)
V_{MCG}	Minimum Control Speed (ground)
VNAV	Vertical Navigation

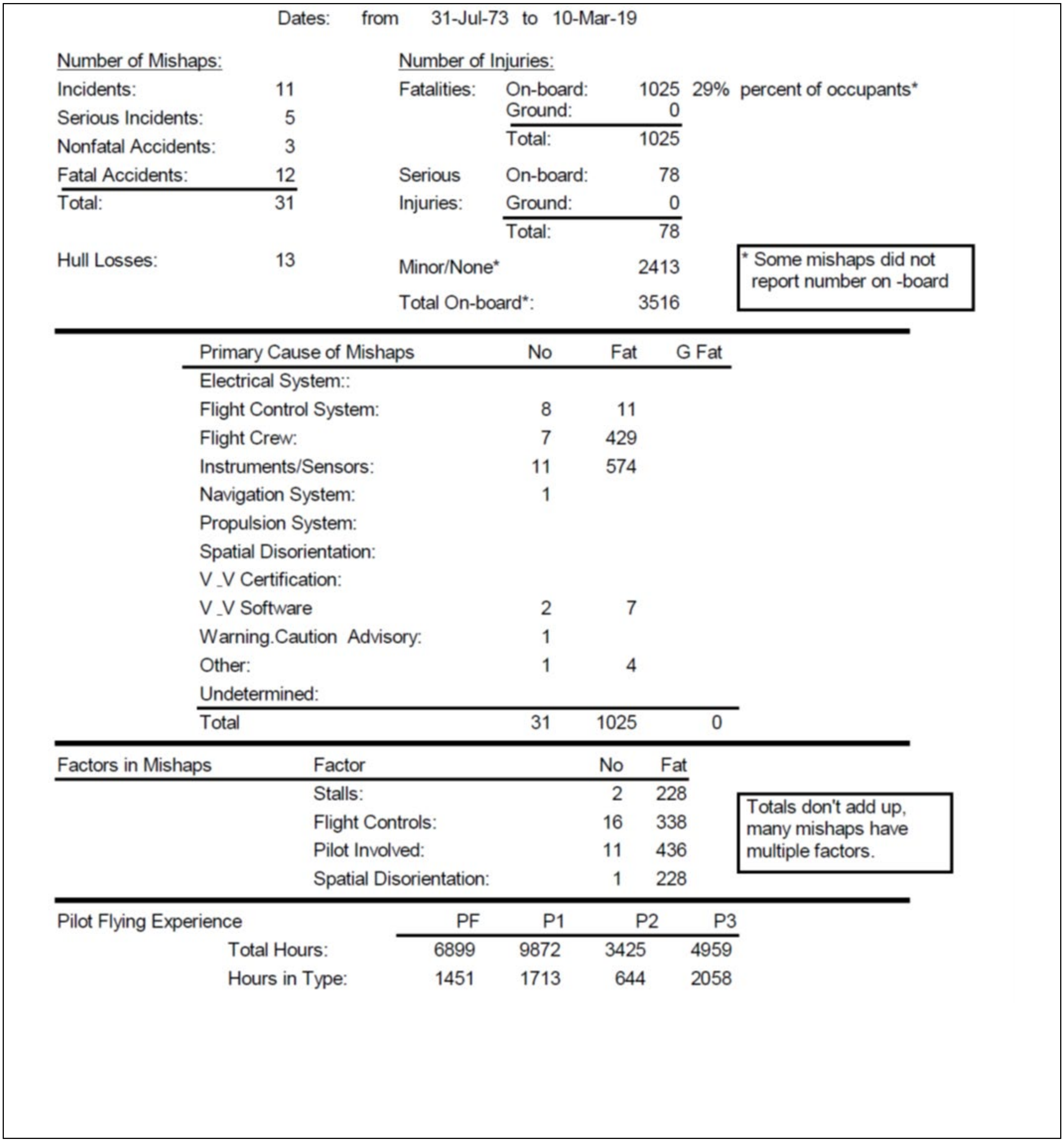
6. Summary Tables

6.1 Mode Change Mishap Chronological Listing



Date	Model	Registr'n	CL	Ident	Loc'n	Fat	Da	Phase	Occurrence	Result
31-Jul-73	DC-9	N-975NE	B	DAL 723	KBOS	88	D	Landing	Descent Below Minimums (Cre	Collision with Obstacl
06-Feb-75	M20	N-6371Q	G	N-6371Q	KSYR	0	N	Climb	Vacuum Pump Failure	Loss-of-Control
18-Nov-88	SA226	F-GCPG	E	LIT 440	LFBK	4	D	Initial climb	Root Cause Unknown (Flight C	Collision with Terrain
14-Feb-90	A320	VT-EPN	B	IAC 605	VOBG	92	D	Landing	Misused Envelope Protection	Collision with Terrain
20-Jan-92	A320	F-GGED	B	ITF 148	LFST	87	D	Approach	Excessive Rate of Descent	Controlled Flight Into
27-Jan-93	L382	N-130X	C	LAC 30X	KMGE	0	N	Maneuvering	Loss Of Control Actuation	Return-to-Base
03-Feb-93	L382	N-130X	C	LAC 30X	KMGE	7	D	Takeoff	Loss Of Control Actuation	Uncontrolled Descent
21-Jun-94	757		B		EGCC	0	N	Climb	Mode Annunciation	Altitude Deviation
30-Jun-94	A330	F-WWKH	A	AIB 129	LFBO	7	D	Climb	Flight Control Logic	Uncontrolled Descent
20-Dec-95	757	N-651AA	B	AAL 965	SKCL	159	D	Approach	Inadequate Flight Planning	Controlled Flight Into
13-Jul-96	MD-11	N-1768D	A	AAL 107		0	N	Descent	Attempt To Override Autopilot	Cabin Injuries
05-Apr-98	A320		B		EDFF	0	N	Holding (IFR)	Pitot-static Icing	No Effect/Minor Effec
24-Sep-99	A320	C-FKCO	B	ACA 630	CYSJ	0	M	Landing	Flight Controls Mode Change	Landed Short
02-Oct-00	A340	TC-JDN	A	THY JDN		0	N	Enroute	Flight Controls Mode Change	Altitude Deviation
07-Feb-01	A320	EC-HKJ	B	IBE 1456	LEBB	0	D	Landing	Unexpected Control Gains	Abnormal Runway Co
10-Nov-04	PA-32	N-803ZG	G	N-803ZG		3	D	Enroute	Flight Below Safe Altitude	Controlled Flight Into
25-Jun-05	A320	I-BIKE	B	AZA IKE	EGLL	0	N	Approach	Bad Input To FCS	Flight Controls Mode
1-Aug-05	777	9M-MRG	A	MAS 124	YPPH	0	N	Climb	Uncommanded Pitch	Upset
22-Oct-05	A319	G-EUOB	B	BAW UO	EGLL	0	N	Climb	Loss Of Multiple Displays	Loss Of Multiple Displ
15-Sep-06	A320	G-EZAC	B	EZY 6074		0	N	Enroute	Instrument Failure	Loss Of Multiple Displ
23-Sep-07	737	G-THOF	B	TOM HOF	EGHH	0	N	Final approa	Inadequate Energy Managemen	Uncommanded Pitch
26-Jan-08	A320	N-462UA	B	UAL 731	KEWR	0	N	Climb	Loss Of Multiple Displays	Loss Of Multiple Displ
07-Oct-08	A330	VH-QPA	A	QFA 72	YPLM	0	M	Enroute	Flight Control Logic	Upset
21-May-09	A330	PT-MVB	A	TAM 8091		0	N	Enroute	Pitot-static Icing	Landed Without Furth
01-Jun-09	A330	F-GZCP	A	AFR 447	TASIL	228	D	Enroute	Pitot-static Icing	Uncontrolled Descent
23-Jun-09	A330	N-805NW	A	NWA 8		0	N	Enroute	Pitot-static Icing	Landed Without Furth
13-Mar-12	A330	F-GLZU	A	AFR LZU	LFPG	0	N	Final approa	Incorrect Navigational Signal	Upset
03-Feb-13	A330	A6-EHF	A	ETD 460		0	N	Enroute	Pitot-static Icing	Diversion
14-Mar-17	S92	EI-ICR	H	Rescue 11		4	D	Approach	Obstacle(s) not in EGPWS Dat	Collision with Terrain
29-Oct-18	737	PK-LQP	B	LNI 610	WIII	189	D	Climb	Failure of Angle-of-Attack Sens	Collision with Terrain
10-Mar-19	737	ET-AVJ	B	ETH 302	HAAB	157	D	Climb	Failure of Angle-of-Attack Sens	Uncontrolled Descent

6.2 Mode Change Mishap Data Summary



Dates: from 31-Jul-73 to 10-Mar-19

Number of Mishaps:	
Incidents:	11
Serious Incidents:	5
Nonfatal Accidents:	3
Fatal Accidents:	12
Total:	31
Hull Losses:	13

Number of Injuries:				
Fatalities:	On-board:	1025	29%	percent of occupants*
	Ground:	0		
	Total:	1025		
Serious Injuries:	On-board:	78		
	Ground:	0		
	Total:	78		
Minor/None*		2413		
Total On-board*:		3516		

* Some mishaps did not report number on -board

Primary Cause of Mishaps	No	Fat	G Fat
Electrical System::			
Flight Control System:	8	11	
Flight Crew:	7	429	
Instruments/Sensors:	11	574	
Navigation System:	1		
Propulsion System:			
Spatial Disorientation:			
V_V Certification:			
V_V Software	2	7	
Warning.Caution Advisory:	1		
Other:	1	4	
Undetermined:			
Total	31	1025	0

Factors in Mishaps	Factor	No	Fat
	Stalls:	2	228
	Flight Controls:	16	338
	Pilot Involved:	11	436
	Spatial Disorientation:	1	228

Totals don't add up, many mishaps have multiple factors.

Pilot Flying Experience	PF	P1	P2	P3
Total Hours:	6899	9872	3425	4959
Hours in Type:	1451	1713	644	2058

B HQTE Tailoring -Variable Stability Helicopter Flight Test

NRC Flight Tests, August 2024

Table B- 1: NRC Flight Tests Data Legend

Abbreviation	Description
ACVH	Attitude Command Velocity Hold
TRC	Translational Rate command
N	Nominal
D	Degraded

Table B- 2: NRC Flight Tests, August 2024, Precision Hover

Tailoring (kts)	Pilot	Config.	Date	Type	HQR	Notes
6	2	TRC	21-Aug	Practice		
6	2	TRC	21-Aug	Practice		Hard time seeing final target with A-Frame
6	2	TRC	21-Aug	Practice		
6	2	TRC	21-Aug	Practice		
6	2	TRC	21-Aug	Score	3	Perturbations in cyclic
10	2	TRC	21-Aug	Practice		15 second capture, little aft enter forward
10	2	TRC	21-Aug	Practice		
10	2	TRC	21-Aug	Score	2	Lower score might be due to familiarization and learning curve.
6	2	ACVH N	21-Aug	Practice		
6	2	ACVH N	21-Aug	Score	4	6 second capture, felt more predictable than TRC
10	2	ACVH N	21-Aug	Practice		
10	2	ACVH N	21-Aug	Score	4	4 second table, yaw and longitudinal during run in, collective better due to learning curve
6	1	ACVH N	21-Aug	Practice		
6	1	ACVH N	21-Aug	Practice		9 second capture, went into adequate

Tailoring (kts)	**Pilot**	**Config.**	**Date**	**Type**	**HQR**	**Notes**
6	1	ACVH N	21-Aug	Score	2	6 second cap, desired performance with minor excursions
10	1	ACVH N	21-Aug	Practice		200 ft run in seems long, 7 second capture
10	1	ACVH N	21-Aug	Score	2	6.5 second capture
6	1	TRC	21-Aug	Score	2	half of cyclic input required, look down angle
10	1	TRC	21-Aug	Score	4	1 Hz cyclic, always flying the aircraft
6	2	ACVH D	22-Aug	Practice		8 second stable
6	2	ACVH D	22-Aug	Score	5	feels less predictable, harder to stabilize, does not feel higher gain
10	2	ACVH D	22-Aug	Practice		Adequate tolerances
10	2	ACVH D	22-Aug	Score	5	Rated as 3, but a 5 due to adequate performance
6	1	ACVH D	22-Aug	Practice		
6	1	ACVH D	22-Aug	Score	3	Not a big issue
10	1	ACVH D	22-Aug	Practice		8 second capture, hit about 12 kts
10	1	ACVH D	22-Aug	Score	3	5 second stable

Table B- 3: NRC Flight Tests, August 2024, Pirouette

Tailoring (deg)	**Pilot**	**Config.**	**Date**	**Type**	**HQR**	**Notes**
360	2	TRC	21-Aug	Practice		10 knots wind on nose
360	2	TRC	21-Aug	Score	3	Last 270° felt double workload on yaw
360	2	ACVH N	21-Aug	Practice		
360	2	ACVH N	21-Aug	Score	4	8 second capture 50 seconds around, deviated around 90°
180	2	ACVH N	21-Aug	Practice		32 seconds 6 second capture
180	2	ACVH N	21-Aug	Score	4	28 seconds 7 second capture, hard to connect larger inputs. Hard to control all axes at once, lat. long. yaw-> drifted aft, misses the

Tailoring (deg)	Pilot	Config.	Date	Type	HQR	Notes
						effect of the other 180°. purposeful headwind
360	1	ACVH N	21-Aug	Practice		
360	1	ACVH N	21-Aug	Practice		45 seconds with 7 second capture
360	1	ACVH N	21-Aug	Score	4	50 second 5 second capture, course is hard to judge, needs to keep spot checking
360	1	ACVH N	21-Aug	Score	3	Visibility to right is hard, 40 seconds with 4 second capture, acceptable performance
180	1	ACVH N	21-Aug	Score	3	28 seconds 3 second capture
180	1	ACVH N	21-Aug	Score	2	Not the same as the 360°
360	1	TRC	21-Aug	Score	2	
360	1	TRC	21-Aug	Score	2	No real issues observed
360	2	ACVH D	22-Aug	Practice		75 seconds to the left
360	2	ACVH D	22-Aug	Practice		Heading adequate, 60 seconds
360	2	ACVH D	22-Aug	Score	3	To the left, minimal spiral up
360	2	ACVH D	22-Aug	Practice		Good fore aft cueing given
360	1	ACVH D	22-Aug	Practice		
360	1	ACVH D	22-Aug	Score	3	To the left, 53 seconds complete, more pedal than anticipated
360	1	ACVH D	22-Aug	Score	3	To the right, 45 seconds complete
360	1	ACVH D	22-Aug	Practice		Aborted, lost control of position
360	1	ACVH D	22-Aug	Score	5	adequate performance, found as a perception issue. Pilot afraid to trust the inside view. Found fore aft cueing good
360	1	ACVH D+	22-Aug	Score	5	Extra degraded mode
360	1	ACVH D+	22-Aug	Score	5	Unsatisfactory controls, adequate performance

Table B- 4: NRC Flight Tests, August 2024, Hover Turn and Hold

Tailoring (deg)	**Pilot**	**Config.**	**Date**	**Type**	**HQR**	**Notes**
nom	2	ACVH N	22-Aug	Practice		90° left, torque exceedance
nom	2	ACVH N	22-Aug	Practice		90° right, 22 seconds position off
nom	2	ACVH N	22-Aug	Practice		90° right, 40 seconds
nom	2	ACVH N	22-Aug	Practice		90° right, adequate 180°
nom	2	ACVH N	22-Aug	Score	5	90° right, adequate performance, struggling with cueing that lead to adequate performance. Tolerance may be too tight. 36 seconds.
9090	2	ACVH N	22-Aug	Practice		Adequate performance, 26 sec
9090	2	ACVH N	22-Aug	Practice		Adequate performance, 25 sec
9090	2	ACVH N	22-Aug	Score	5	25 seconds, cueing is better for the 180. +/- 3 feet is hard to maintain. Same aggression, timing is different.
180	2	ACVH N	22-Aug	Practice		To the left 16 seconds
180	2	ACVH N	22-Aug	Score	4	To the right 20 seconds
nom	1	ACVH N	22-Aug	Practice		Took 22 seconds
nom	1	ACVH N	22-Aug	Score	3	Slowing down lets you focus on physical position more than angular position
9090	1	ACVH N	22-Aug	Score	3	Didn’t look out as much to verify position; benefits are that wind effects could be predicted. Would have to do with and without winds, allow HQR to change based on winds. Position still in desired range.
nom	1	TRC	22-Aug	Practice		Dip into adequate
nom	1	TRC	22-Aug	Score	2	Outside of adequate once due to challenging winds, but most in desired. 55 seconds

Table B- 5: NRC Flight Tests, August 2024, Lateral Reposition

Tailoring (deg)	**Pilot**	**Config.**	**Date**	**Type**	**HQR**	**Notes**
nom	2	ACVH N	22-Aug	Practice		Easier to go to the right
nom	2	ACVH N	22-Aug	Score	3	Drifted aft, 6 second capture
nom	2	ACVH N	22-Aug	Practice		Good positional cueing, speed is hard to gauge
nom	2	ACVH N	22-Aug	Practice		tripped in roll attitude
nom	2	ACVH N	22-Aug	Practice		False start
nom	2	ACVH N	22-Aug	Practice		False start
nom	2	ACVH N	22-Aug	Score	5 or 6	Hard to gauge ending, right to left capture is better than left tor right.
nom	1	ACVH N	22-Aug	Score	3	right to left
nom	1	ACVH N	22-Aug	Score	4	Left to right, excursions were scooting forward, had a lot of right pedal in at one point. Got desired but required moderate pilot comp.
300 ft 15 kts	1	ACVH N	22-Aug	Score	3	Aggressive to get to the speed, deceleration is controllable. Not really any difference with shorter course
300 ft 10 kts	1	ACVH N	22-Aug	Score	2	Very leisurely, easy to get to speed and to decelerate

C Updates to HQTEs for Variable Stability Helicopter Flight Test

Precision Hover HQTE

Objectives

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

Task Description

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

Description of Test Course

The test course for the maneuver is shown in Figure C- 1. The hover altitude is set by the position of the hover board. It should be confirmed that the height and the relative position of the board (for pilot visual cueing) are acceptable prior to completion of the HQTE. Cones are used to judge lateral and longitudinal deviation and it is also recommended that a start-point is set, for consistency in task completion. Both desired and adequate performance should be cued through the boards and cones.

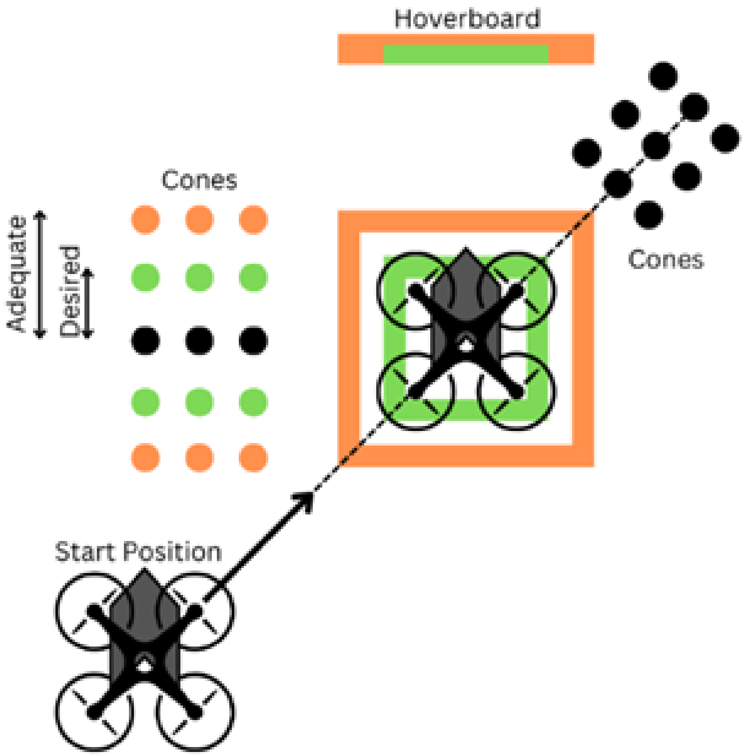


Figure C- 1: Recommended Course for Precision Hover HQTE

Performance Standards

The following performance standards are to be used for desired and adequate performance.

	Standard Powered-Lift Tolerances	
Performance Requirement	**Desired**	**Adequate**
Attain a stabilized hover within X seconds of initiation of deceleration:	5 sec	8 sec
Maintain a stabilized hover for at least X seconds:	30 sec	30 sec
Maintain the longitudinal and lateral position within ±X ft of a point on the ground:	3 ft	6 ft
Maintain heading within ±X°:	5°	10°
Maintain altitude within ±X ft:	2 ft	4 ft
Residual motions from transition to hover or disturbances from stabilized hover	Are easily damped with no oscillatory tendencies	Can be damped but are impacting performance

Acceptable Task Tailoring

- For the stabilized hover portion of the HQTE, 30 seconds is stated as the required time. This is to ensure that the aircraft can remain in a precise position following the transition to hover. The stabilization time may uncover oscillations or difficulty in control over this period of time. Therefore, the 30 second hover is strongly encouraged. Operational constraints may limit the hover time in flight test. In this case, a shortened hover time may be acceptable if the pilot is hands-off from the controls and the vehicle maintains position and desired performance tolerances for at least 10 seconds, consecutively.
- Certain flight control modes may transition in the 6-10 kts speed range. A typical example may be a TRC command. In this case, the HQTE may be tested at the upper or lower end of the speed range to accommodate. However, all pilot selectable flight control modes that operate in the 6-10 kts speed range should be tested separately.

Pirouette HQTE

Objectives

- Check ability to accomplish precision control of the aircraft simultaneously in the pitch, roll, yaw, and heave axes.
- Check ability to control the aircraft precisely in a moderate wind that is continuously varying in the direction relative to the aircraft heading
- Check for any undesirable coupling between roll, pitch, yaw, and heave axis controllers. Identify pilot-induced oscillation tendencies, if present.

Task Description

Initiate the maneuver from a stabilized hover over a point on the circumference of a 100 ft radius circle with the nose of the aircraft pointed at a reference point at the center of the circle, and at a hover altitude of approximately 15 ft. The pilot position should be aligned with the centerline of the tolerances (data collection with regard to aircraft center should be adjusted accordingly to this position). Accomplish a lateral translation around the circle, keeping the nose of aircraft pointed at the center of the circle, and the centerline circumference of the circle under the pilot position. Establish and maintain essentially constant lateral groundspeed to accomplish the maneuver within the target time tolerance. Terminate the maneuver with a stabilized hover over the starting point. Perform the maneuver in both directions.

Description of Test Course

The test course shall consist of markings on the ground that clearly denote the circular pathways that define desired and adequate performance and markings that denote a radial start/stop line. The suggested course shown in Figure C- 2 is considered adequate for the evaluation. It may also be useful to add objects to assist the pilot with vertical cueing, such as a post at the center of the circle.

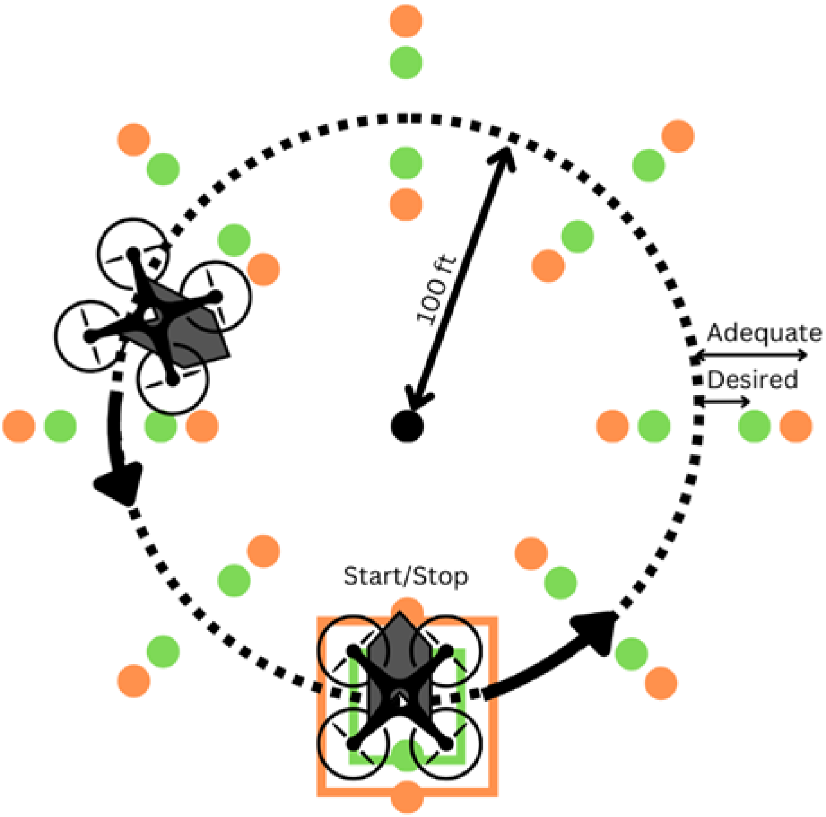


Figure C- 2: Recommended Course for Pirouette HQTE

Performance Standards

The following performance standards are to be used for desired and adequate performance.

	Standard Powered-Lift Tolerances	
Performance Requirement	**Desired**	**Adequate**
Maintain a selected reference point on the aircraft within ±X ft of the circumference of the circle:	10 ft	15 ft
Maintain heading so that the nose of the aircraft points at the center of the circle within ±X°:	10°	15°
Complete the circle and arrive back over the starting point within:	60 sec	80 sec
Achieve a stabilized hover (within desired hover reference point) within X seconds after returning to the starting point:	5 sec	10 sec
Maintain altitude within ±X ft:	3 ft	10 ft
Maintain stabilized hover for X seconds:	5 sec	5 sec

Acceptable Task Tailoring

In the performance requirements above, the Pirouette HQTE is to be completed with a full 360° translation around the circumference of a circle. This is designed to demonstrate that precise control can be maintained throughout, also accounting for any changes in wind condition. Operational constraints may limit the ability to perform the full Pirouette in flight test. In this case, a shortened Pirouette may be acceptable. This must be completed in both directions. The task performance requirements remain unchanged for a 180° Pirouette, apart from completion time. This is shorted to 40 sec for desired performance and 55 sec for adequate performance. In simulation, a full 360° Pirouette only should be demonstrated.

Lateral Reposition HQTE

Objectives

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

Task Description

Start in a stabilized hover at recommended 20 ft wheel height with the longitudinal axis of the rotorcraft oriented 90° to a reference line marked on the ground. The target lateral transition speed may be varied in the task, with 15 kts recommended. Initiate a lateral acceleration followed by a deceleration to laterally reposition the rotorcraft in a stabilized hover at a predesignated point laterally offset from the initial position. The acceleration and deceleration phases shall be accomplished as single smooth maneuvers. The aircraft must be brought to within ±10 ft of the endpoint during the deceleration, terminating in a stable hover within this band. Overshooting is permitted during the deceleration, but will show up as a time penalty when the pilot moves back within ±10 ft of the endpoint. A stabilized hover should be maintained for 5 seconds. Perform the maneuver both to the right and to the left.

Description of Test Course

The test course shall consist of any reference lines or markers on the ground indicating the desired track and tolerances for the acceleration and deceleration, and markers to denote the starting and endpoint of the maneuver. These should be clearly visible to the pilot during the complete HQTE. If the pilot is unable to see the end point at anytime during the maneuver, additional cueing should be considered to support the evaluation. The course should also include reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate longitudinal tracking performance, such as the example shown in Figure C- 3. The recommended maximum course length for the HQTE is 400 ft, however this may be shortened if desired performance can be demonstrated.

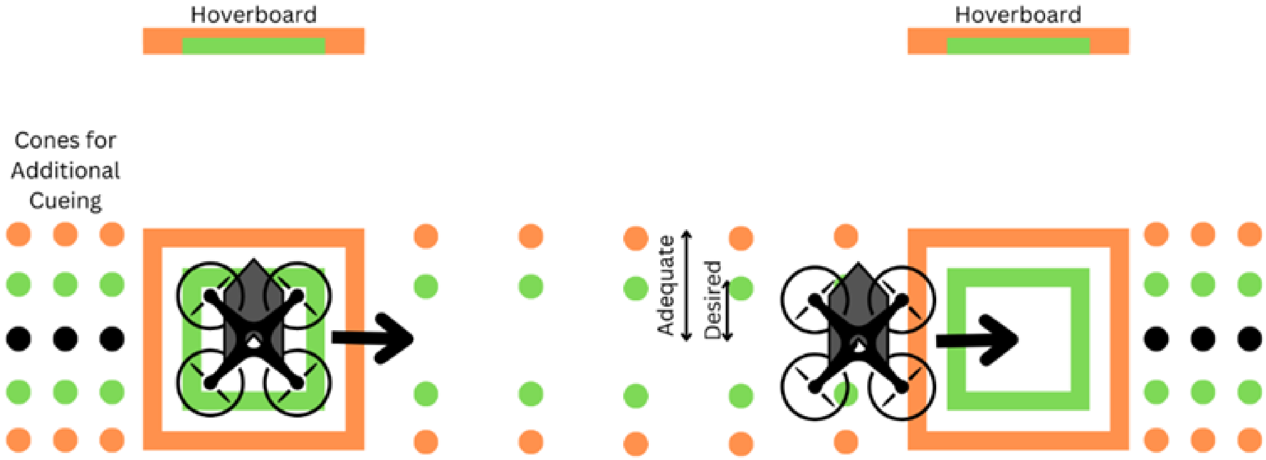


Figure C- 3: Recommended course for Lateral Reposition HQTE

Performance Standards

The following performance standards are to be used for desired and adequate performance.

	Standard Powered-Lift Tolerances	
Performance Requirement	**Desired**	**Adequate**
Maintain longitudinal track within ±X ft	10 ft	20 ft
Maintain altitude within ±X ft:	10 ft	10 ft
Maintain heading within ±X°:	10°	15°
Maintain lateral translational above or at target speed for greater than X sec:	4 sec	4 sec
Attain a stabilized hover within X seconds of initiation of deceleration	8 sec	12 sec
The aircraft must be brought to a controlled hover within ±X ft of the pre-defined end hover point:	10 ft	20 ft
Maintain stabilized hover for X seconds:	5 sec	5 sec

Acceptable Task Tailoring

A target speed of 15 kts is recommended for the task. However, it may be conducted at multiple speeds. It is acceptable for applicants to select a suitable course length which is appropriate to complete the task to desired performance standards. Importantly, the target translation speed must be held for at least 4 seconds during completion. Experience during flight tests has shown that, for this speed, approximately 300 ft is required. For 10 kt and 20 kt target speeds, distances of 200 ft and 400 ft respectively are recommended.

Hover Turn HQTE

Objectives

- Check for undesirable handling qualities in a moderately aggressive hovering turn.
- Check ability to recover from a moderate rate hovering turn with reasonable precision.
- Check for undesirable inter-axis coupling.
- Identify pilot-induced oscillation tendencies, if present.

Task Description

From a stabilized hover at an altitude of 20 ft, complete a 90° turn and stabilize for 5 seconds. This should be followed by a further 90° turn in the same direction. Perform the maneuver in both directions. The maneuver shall be accomplished in calm winds and in light winds from the most critical direction. The maneuver should be tested in both directions. During the HQTE, the pilot is required to maintain position with desired accuracy. When performing the HQTE, this position can either be the rotational center of the aircraft or the pilot position. When using the pilot position as reference, the pilot must adjust both longitudinal and lateral position simultaneously when completing the turn. When using the rotational center, the pilot must correct for any drift created by the turn. For this, additional cueing may be required.

Description of Test Course

The test course should consist of reference lines or markers on the ground indicating the desired position and tolerances. It is recommended that the Pirouette course is used to complete the HQTE. When performing the HQTE using the vehicle rotation point as the ‘point on the ground’, additional cueing is required to show the pilot station position reference. This will materialize as a smaller circle within the Pirouette course, where the pilot can judge his/her position during translation (Figure C- 4).

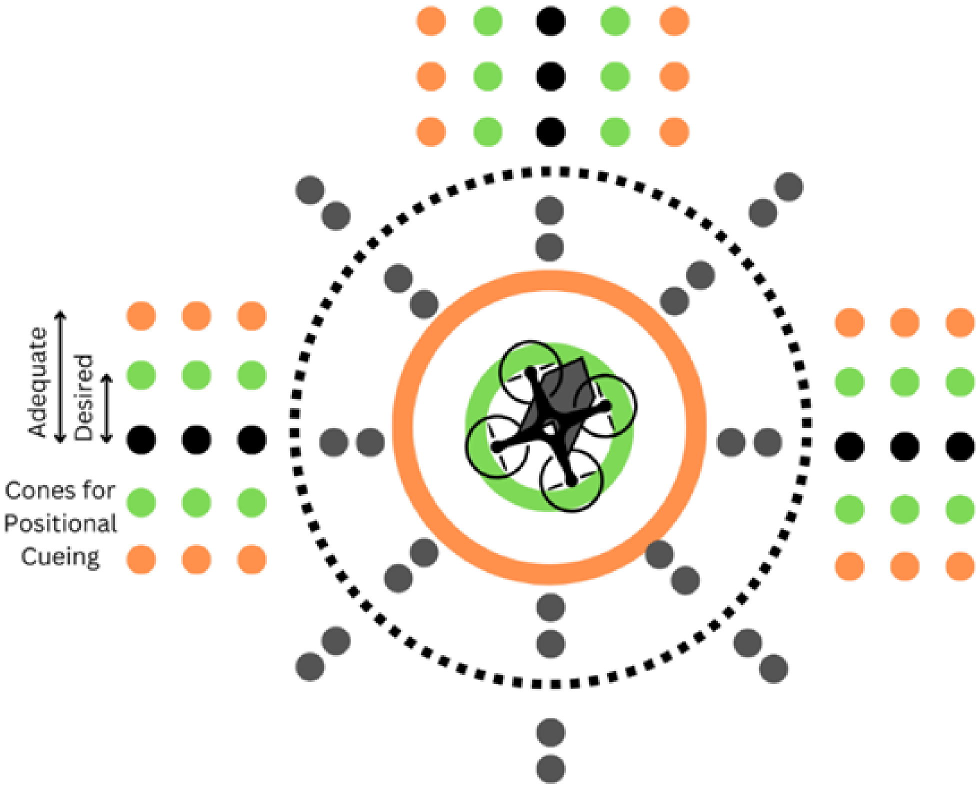


Figure C- 4: Recommended Course for Hover Turn HQTE

Performance Standards

The following performance standards are to be used for desired and adequate performance.

	Standard Powered-Lift Tolerances	
Performance Requirement	**Desired**	**Adequate**
Maintain the longitudinal and lateral position within ±X ft of a point on the ground.	3 ft	6 ft
Maintain altitude within ±X ft:	3 ft	6 ft
Stabilize aircraft heading at 90° and 180° from initial heading within ±X°:	5°	10°
Complete turn to a stabilized hover within X seconds from initiation of maneuver	30 sec	35 sec

Acceptable Task Tailoring

- It may be required/applicable to test the Hover Turn HQTE at various turn rates. These may be teste based on company/certification requirements. Here, it is proposed to use a calculation to determine the desired turn rate. The following is suggested based on tests conducted:

$$Desired\ Time\ to\ Complete\ (s) = 2 * \frac{90\ (deg)}{Turn\ Rate\ \left(\frac{deg}{s}\right)} + 15\ seconds \qquad \text{C-1}$$

$$Adequate\ Time\ to\ Complete\ (s) = 1.3 * (2 * \frac{90\ (deg)}{Turn\ Rate\ \left(\frac{deg}{s}\right)}) + 15\ seconds \qquad \text{C-2}$$

- The equation calculates the time it takes to complete a standard 90° turn based on a specified, target turn rate. Since the maneuver calls for two 90° turns, that value is doubled. The 15 additional seconds accounts for the 5 second stabilization. For the adequate calculations, adequate time to complete gives 30% more time to complete the turning portions.