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Aviation Safety Research on Developing Mission Task Elements, Means of Compliance/Methods of Compliance, for Certification of General Aviation, VTOL, VSTOL, or Hybrid Aircraft

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16. Abstract

Aircraft manufacturers are currently advancing the implementation of Automatic Flight Control Systems (AFCS) in General Aviation (GA) aircraft, certifiable under 14 Code of Federal Regulations (CFR) Part 23 regulations. Additionally, several startup companies, often backed up by larger manufacturers, are developing an entirely new technology with the ultimate vision of deploying Urban Air Mobility (UAM) to a large scale; electric Vertical Takeoff and Landing (eVTOL) aircraft will be certified under 14 CFR 21.17(b) as powered lift aircraft. Other companies are trying to efficiently fill the gap between short distance ground transportation and long-range air transportation, designing economically viable Regional Air Mobility (RAM) vehicles. Different manufacturers are following different approaches, ranging from retro-fitting existing conventional flight control designs with AFCSs to exploit the capabilities of Fly-By-Wire (FBW) systems and integrated avionics, to developing completely new configurations capable of quiet, emission-free, vertical and forward flight. Common traits of most of these projects are FBW technology and electric propulsion.

Certification of FBW GA aircraft requires the development of dedicated regulations and processes. The previous National Test Pilot School (NTPS) research conducted for the Federal Aviation Administration (FAA) was aimed at providing guidance and best practices for the whole certification process of GA FBW aircraft. The currently proposed research addresses the verification and validation/qualification phases of the same certification process recommended in the previous research.

17. Key Words

Fly-by-wire, flight control systems, mission task element, urban air mobility vehicles, hybrid vehicles, flying qualities, handling qualities, certification, general aviation, flight clearance, flight test.

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Acronyms

Acronym	**Definition**
ADS	Aeronautical Design Standard
AFCS	Automatic Flight Control System
AoA	Angle of Attack
AoS	Angle of Sideslip
CAP	Control Anticipation Parameter
CAS	Command Augmentation System
CCC	Continuous Compensatory Control
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CHRS	Cooper Harper Rating Scale
ConOps	Concept of Operations
CTOL	Conventional Take Off and Landing
dB	Decibels
DGPS	Differential Global Positioning System
DoF	Degrees of Freedom
eVTOL	Electric Vertical Take Off and Landing
FAA	Federal Aviation Administration
FCS	Flight Control System
FFT	Fast Fourier Transform
FQTE	Flying Qualities Task Element
FTE	Flight Test Engineer
FTI	Flight Test Instrumentation
FTT	Flight Test Technique
FW	Fixed Wing
GA	General Aviation
GM	Gain Margin
GPS	Global Positioning System
HDD	Head Down Display
HQR	Handling Qualities Rating
HQTE	Handling Qualities Task Element
HUD	Head Up Display
Hz	Hertz

Acronym	**Definition**
KIO	Knock It Off
KSAS	Knots Calibrated Airspeed
MLE	Maximum Likelihood Estimation
MOC	Methods of Compliance
MTE	Mission Task Element
NTPS	National Test Pilot School
n_z	Normal load factor
P/D	Pitch Doublet
PIO	Pilot Induced Oscillations
PM	Phase Margin
PSD	Power Spectral Density
PTI	Programmed Test Inputs
R/D	Roll Doublet
RW	Rotary Wing
SAS	Stability Augmentation System
SETP	Society of Experimental Test Pilots
SFTE	Society of Flight Test Engineers
SM	Static Margin
SNR	Signal to Noise Ratio
STI	Systems Technology Inc.
TPR	Transient Peak Ratio
TPS	Test Pilot School
UAM	Urban Air Mobility
UCE	Usable Cue Environment
VFS	Vertical Flight Society
VTOL	Vertical Take Off and Landing
Y/D	Yaw Doublet

Symbol	**Definition**
α	Angle of Attack
β	Angle of Sideslip
δ_e	Elevator Deflection
θ	Pitch Attitude

Symbol	**Definition**
σ	Standard Deviation
$\omega_{BW_{act}}$	Actuator Bandwidth
ω_{GC}	Gain Crossover Frequency
ω_{PCL}	Lower Phase Crossover Frequency
ω_{PCU}	Upper Phase Crossover Frequency

Executive summary

Aircraft manufacturers are currently advancing the implementation of Automatic Flight Control Systems (AFCS) in General Aviation (GA), certifiable under 14 Code of Federal Regulations (CFR) Part 23 regulations. Additionally, several startup companies, often backed up by larger manufacturers, are developing an entirely new technology with the ultimate vision of deploying Urban Air Mobility (UAM) to a large scale; electric Vertical Takeoff and Landing (eVTOL) aircraft will be certified under 14 CFR 21.17(b) as powered lift aircraft. Other companies are trying to efficiently fill the gap between short distance ground transportation and long-range air transportation, designing economically viable Regional Air Mobility (RAM) vehicles. Different manufacturers are following different approaches, ranging from retro-fitting existing conventional flight control designs with AFCSs to exploit the capabilities of Fly-By-Wire (FBW) systems and integrated avionics, to developing completely new configurations capable of quiet, emission-free, vertical and forward flight. Common traits of most of these projects are FBW technology and electric propulsion. Certification of FBW GA aircraft requires the development of dedicated regulations and processes.

The previous National Test Pilot School (NTPS) research conducted for the Federal Aviation Administration (FAA) was aimed at providing guidance and best practices for the whole certification process of GA FBW aircraft. The currently proposed research addresses the verification and validation/qualification phases of the same certification process recommended in the previous research.

Verification is planned to be based on measurement of the vehicle response parameters/characteristics, through the execution of Flying Qualities Task Elements (FQTEs). Validation is based on pilot's evaluation of the vehicle handling qualities, through the execution of Handling Qualities Task Elements (HQTEs). Qualification is based on the assessed capability of the aircraft to satisfy the performance and mission requirements in the most demanding configurations and at the boundaries of the flight envelope. The objective is to ensure that the vehicle will operate properly (i.e., HQ satisfactory without improvement) with the planned margins. Qualification is linked to the vehicle design and it has to be repeated when/if there is a change in the design for which it was performed.

A standardized approach to these phases is particularly relevant in FBW aircraft, because of the available flexibility in shaping the aircraft response, and consequently its handling qualities, as a function of flight phase/task and mission requirements. It is important to consider that in a model-based design approach, both verification and validation can be performed at different aircraft developmental stages. The early implementation of verification and validation criteria can reduce the risk of costly aircraft redesigns, which can occur in the development or even in the production/test stages of the program.

Therefore, it is recommended to perform offline Flying Qualities Assessment (FQA) and HQTE evaluations based on manned simulations prior to the first flight. These steps should be followed with flying qualities verification through the analysis of data collected from in-flight execution of FQAs, which can be performed with the aircraft remotely piloted. The FQA's are intended to be performed by the applicant. FAA personnel should be involved in reviewing the flying qualities assessment and verification process and should perform HQTEs.

This research expanded the results from a previous study, directed at providing guidance and best practices for the certification process of advanced flight controls in general aviation and hybrid aircraft vehicles that the NTPS conducted for the FAA. The research addressed the verification and validation/qualification phases of the recommended certification process with particular attention to Mission Task Elements (MTEs), composed of two classes: Flying Qualities Task Elements (FQTEs) and Handling Qualities Task Elements (HQTEs). The aim of FQTEs and HQTEs is respectively to collect quantitative and qualitative/subjective data for characterization of aircraft dynamics and handling qualities (HQ). The scope was to expand the description of the approach to the design, definition, execution, data analysis of FQTEs and HQTEs, and provide recommendations for certification means of compliance. The study was composed of three main phases:

1. Expansion on Technical Content of FQTEs and HQTEs
2. Scope, Limitations and Analysis Boundaries for FQTEs and HQTEs
3. Recommendation of FQTEs and HQTEs for FQ and HQ Evaluations

In phase 1, the technical content of the FQTEs and HQTEs recommended was expanded. The descriptions were be based on a set of principal components for FQTEs and HQTEs.

Phase 2 (Scope, Limitations and Analysis Boundaries for FQTEs and HQTEs) described the limitations and analysis boundaries for FQTEs and HQTEs.

During phase 3 (Recommendation of FQTEs and HQTEs for FQ and HQ evaluations), one of the aims was to identify MTEs to evaluate the aircraft handling performance in the applicant's manned simulator.

The NTPS- Systems Technology Inc. (STI) research team was formed by experimental test pilots and flight test engineers, with combined experience in aircraft design/development, and developmental and operational test and evaluation. The technical and piloting background of the team was the foundation and source of information for the research. It merged with technical knowledge on hybrid vehicles development and testing available within the aeronautical community. The diverse know-how of the team provided a multidisciplinary approach to proposing new MTEs and to adapt existing MTEs to VTOL, vertical and/or short take-off and landing (V/STOL), hybrid aircraft mission requirements and means of compliance.

Follow-on research was recommended with the scope of developing a high fidelity UAM simulator, to validate the recommended certification process to certify UAM vehicles that FAA can evaluate and potentially incorporate for UAM certification.

1 Introduction

Aircraft manufacturers are currently advancing the implementation of Automatic Flight Control System (AFCS) in General Aviation (GA) aircraft, certifiable under 14 Code of Federal Regulations (CFR) Part 23 regulations. Additionally, several startup companies, often backed by larger manufacturers, are developing an entirely new technology with the ultimate vision of deploying Urban Air Mobility (UAM) to a large scale; electric Vertical Takeoff and Landing (eVTOL) aircraft will be certified under 14 CFR 21.17(b) as powered lift aircraft. Other companies are trying to efficiently fill the gap between short distance ground transportation and long-range air transportation, designing economically viable Regional Air Mobility (RAM) vehicles. Different manufacturers are following different approaches, ranging from retro-fitting existing conventional flight control designs with AFCSs to exploit the capabilities of Fly-By-Wire (FBW) systems and integrated avionics, to developing completely new configurations capable of quiet, emission-free, vertical and forward flight. Common traits of most of these projects are FBW technology and electric propulsion.

Certification of FBW GA aircraft requires the development of dedicated regulations and processes. The previous National Test Pilot School (NTPS) research conducted for the Federal Aviation Administration (FAA) (Lotterio M. , 2022) was aimed at providing guidance and best practices for the whole certification process of GA FBW aircraft. The currently proposed research addresses the verification and validation/qualification phases of the same certification process recommended in the previous research.

Verification is planned to be based on measurement of the vehicle response parameters/characteristics, through the execution of Flying Qualities Task Elements (FQTEs). Validation is based on pilot's evaluation of the vehicle Handling Qualities (HQ), through the execution of Handling Qualities Task Elements (HQTEs). Qualification is based on the assessed capability of the aircraft to satisfy the performance and mission requirements in the most demanding configurations and at the boundaries of the flight envelope. The objective is to ensure that the vehicle will operate properly (i.e., HQ satisfactory without improvement) with the planned margins. Qualification is linked to the vehicle design and it has to be repeated when/if there is a change in the design for which it was performed.

A standardized approach to these phases (verification, validation, qualification) is particularly relevant in FBW aircraft, because of the available flexibility in shaping the aircraft response, and consequently its handling qualities, as a function of flight phase/task and mission requirements. It is important to consider that in a model-based design approach, both verification and validation can be performed at different aircraft developmental stages. The early implementation of verification and validation criteria can reduce the risk of costly aircraft redesigns, which can occur in the development or even in the production/test stages of the program.

Therefore, it is recommended to perform offline Flying Qualities Assessment (FQA) and Handling Qualities Task Element (HQTE) evaluations based on manned simulations prior to the first flight. These steps should be followed with flying qualities verification through the analysis of data collected from in-flight execution of FQAs, which can be performed with the aircraft remotely piloted. These three phases are intended to be performed by the applicant. FAA personnel should be involved in reviewing the Flying Qualities Assessment (FQA) and verification process, and should perform HQTEs.

Similarly, to the previous research, the approach of this work is to leverage and merge the publicly available technical knowledge on AFCS vehicles with the experience of the researchers in industrial and military development and testing of Fixed Wing (FW) and Rotary Wing (RW) FBW aircraft.

2 Specific objectives and method

The technical approach detailed in this document is aimed at the objectives listed below, with reference to FQTEs and HQTEs recommended in (Lotterio M. , 2022):

1. Expansion on Technical Content of FQTEs and HQTEs
2. Scope, Limitations and Analysis Boundaries for FQTEs and HQTEs
3. Identification of the required FQTEs and HQTEs and development of a top-level flow chart for individual ones
4. Mapping of the FQTE/HQTEs developed in (Lotterio M. , 2022) to VTOL regulations provided by the FAA

The purpose was to expand the description of the approach to design, definition, and execution of Mission Task Elements (MTEs). Scopes and limitations, together with potentially new flying qualities boundaries are discussed. In continuity with the research in (Lotterio M. , 2022), this work also aimed at providing the foundation for a handbook for FAA Aeronautical Safety Engineers (ASE). It may serve well to summarize existing techniques in a simple and easy to understand format for engineers specialized in technical fields not strictly related to handling qualities and aircraft flight controls.

The objectives were met by merging the experience of NTPS pilots and STI engineers in MTE design, execution, and data analysis with the extensive technical material available within the aeronautical community.

One RW Test Pilot, one FW Test Pilot, one Flight Test Engineer (FTE) and one Aerospace Engineer were involved in this research, to cover a wide spectrum of experience in different types of aircraft and technical fields. Potential technical uncertainties derived from the fast changes in the hybrid aircraft mission requirements and related configurations led to changes in some of the MTEs. The lack of in-flight or simulator-based validation of the recommended ideas was a limitation to scope. A potential development after completion of the proposed project is the simulator-based validation, which potentially NTPS, together with STI, could perform validating the results. This might be part of further research on this subject.

2.1 Research phases

The research was formed by different phases, which are described as following:

Phase 1: Expansion on Technical Content of FQTEs and HQTEs

Subphase 1a: Detailed Description of FQTEs and HQTEs Flight Test Techniques

This phase was dedicated to a detailed description of the FQTEs and HQTEs recommended in (Lotterio M. , 2022). The descriptions was based on a set of principal components for each class of task elements, respectively FQTEs and HQTEs.

The principal components for the definition of FQTEs were:

- aircraft class (i.e., airplane, powered-lift, rotorcraft/multicopter)
- aircraft mission requirements (to guide the identification of the flight phases in which each FQTE must be performed)
- aircraft handling specification requirements
- minimum set of FAA required Handling Qualities (HQ) prediction criteria applied in design and flight clearance

It was assumed that the FQTEs were performed in flight, as a means to verify that the actual vehicle satisfies the specified Flying Qualities (FQs) requirements. The relevance of the FQTEs for the quantitative part of the certification and the correspondence between FQTEs and FQ requirements was highlighted. This is a fundamental part for the selection of existing FQTEs, or the design of dedicated ones. The application of new, or of current, FQ requirements customized for Urban Air Mobility (UAM) in the design and clearance phases is a significant factor for the set of FQTEs to be executed.

The recommended principal components for the definition of HQTEs were:

- aircraft class (i.e., airplane, powered-lift, rotorcraft/multicopter)
- aircraft mission requirements(conditions in which the mission must be accomplished: turbulence level, day/night and frequency with which the mission has to be performed)
- specific task requirements
- required amplitude and frequency of pilot control inputs

The recommended approach to certification is to execute HQTEs both in the simulator and in flight, depending on the aircraft developmental phase. The first phase of the description included detailed notes on the sub-components for HQTE definition and on the setup of their execution. The research highlighted that the critical objective leading to the definition of each HQTE is to ensure the absence of arbitrary factors affecting the final Handling Qualities assessment and their validation based on pilot evaluations.

Subphase 1b: FQTEs/HQTEs Inputs, Outputs, Flight Phases and Aircraft Dynamic Modes

This phase provided expanded information about the inputs and outputs required for data analysis and the corresponding high priority dynamic modes for each FQTE. Critical data acquisition aspects were highlighted, depending on flight phase and on the dynamic mode to be characterized.

Input and output requirements for HQTEs were focused on the baseline set of data necessary to perform correlation between pilot’s comments and vehicle response, and on additional data, i.e., from support avionics required to perform the task. One example of support avionics is the use of a Head Up Display (HUD), or Head Down Display (HDD), to produce synthetic task scenarios in substitution of real-world settings.

Minimum and optimal data requirements were indicated in terms of sampling rate, range, filtering and other characteristics for an expected standard instrumentation system installed on a typical AFCS aircraft configuration, for each class: airplane, powered/lift, rotorcraft/multicopter.

Where applicable, groups of task elements with comparable data requirements were identified to guide towards a streamlined planning process. In this case, planning involves the design of the vehicle instrumentation and of the different aspects of testing.

Subphase 1c: FQTEs/HQTEs Required Analysis Processes

This subphase illustrated the most common approaches to analysis of data acquired in the recommended FQTEs and HQTEs. Multiple aircraft dynamic modal parameters can be derived from the same FQTE. The recommended analysis techniques for FQTEs were linked to the applicable FQ requirements and criteria, reporting on the expected typical accuracy level of each computed dynamics parameter. This is relevant also for test planning/execution and it can affect the selection of the data analysis software. Recommendations were provided for the minimum set/type of data that the applicant should provide to the FAA, for an adequate FQ assessment, in case the applicant performs part of the analyses independently. This is of high relevance for certification, as it can reduce the amount of FQTEs performed in flight under direct request of the FAA. Both time domain and standard linear system analysis techniques were described, as background information, with relative step-by-step instructions. Recommendations included specific software(s) which is expected to allow accurate and efficient analysis and results.

Descriptions of the analyses of data acquired during the execution of HQTEs included both quantitative and qualitative methods. This derives from the combination of pilots’ provided ratings/comments, and aircraft dynamics data. Recommended types of questions to collect appropriate and consistent pilots’ comments on the principal handling elements were reported. The technical feedback between the two types of data (quantitative and qualitative) used to guide the understanding of the aircraft handling characteristics were explained. This feedback is a data analysis procedural aspect which has to inform the overall approach and must involve all participants in the test.

Approaches to correlation between results of FQTEs and HQTEs performed in the same flight phase were described as a fundamental part of the vehicle HQ characterization. This is essential for both vehicle development and certification, and to ensure that potential handling deficiencies can be traced through the whole process. The identification of the modal parameter(s) of the dynamic modes contributing to produce potential unsatisfactory handling characteristics is considered an important outcome of the handling qualities validation process.

Phase 2: Scope, Limitations and Analysis Boundaries for FQTEs and HQTEs

Subphase 2a: Scope and Limitations of FQTEs and HQTEs

Phase 2a reported the principal objective(s) and potential limitation(s) in terms of FQs verification and handling qualities validation respectively of each FQTE and HQTE recommended in (Lotterio M. , 2022). The different components of predicted (i.e., FQs, and assigned HQs) were considered.

These were mainly formed by:

- inceptor feel characteristics: displacement, force, sensitivity and harmony;
- static stability and maneuvering flight;
- response characteristics: bandwidth, medium and large amplitude;
- response predictability;
- Pilot Induced Oscillations (PIO) prediction/detection; and
- modes transition and lift generation transition, when applicable.

This phase highlighted the links between the described MTEs and the most relevant FQ requirements and criteria. This is considered an important step to establish a functional link between FQTEs, HQTEs and the corresponding aircraft development/certification phases.

Aspects affecting the assigned handling qualities when executing HQTEs in manned simulators were described to underline the reasons of potential differences in assigned handling qualities from simulator based and in-flight evaluations.

Subphase 2b: Boundaries of Analysis Results

Referring to the analyses described in Phase 1c, this phase described concepts for the definition of boundaries to characterize the flying and handling qualities based on the execution of MTEs. Discussion of the boundaries of the current FQ criteria was conducted to propose possible approaches to adapt them to new classes of vehicles, particularly UAMs. The main method is to propose trends of variation of the criteria quantitative values while preserving their background logic. Implementation of additional boundaries, or partial removal of the current ones were considered, when assessed to increase consistency with the requirements of the new class of aircraft. Recommendations were based on the expected range of Concept of Operations (ConOps) for AFCS vehicles.

Updates of boundaries for assigned handling qualities from the execution of HQTEs were proposed in terms of concepts for the definition of task requirements and task setup. This considered both task operational representativeness for the given class of aerial vehicle and the assessment of the presence of a “Handling Qualities cliff”, corresponding to a significant reduction of handling performance in specific areas of the envelope.

Impact of the control laws mode(s) on the execution of the HQTEs was discussed when applicable/relevant for the definition of requirements/boundaries.

Recommendations for the design of updated boundaries accounted for general trends and ranges of expected flying and handling qualities levels. This was based on current trends of the same criteria. The overall scope of this phase was to provide expected directions of variation of the existing criteria boundaries.

Subphase 2c: Mapping of Boundaries to Other FQTEs/HQTEs

The objective of this phase is to expand the application of the results of previous Phase 2b to other MTEs, which do not take part of those recommended in Lotterio (2022), or to blocks of combined recommended FQTEs and HQTEs. Combinations of multiple MTEs, addressing the same or similar handling characteristics, are considered an added value for the possibility to develop a comprehensive assessment of the specific handling qualities element. This derives from the possibility to evaluate the same handling qualities elements with different task set up and requirements.

Intersection of MTE blocks addressing different handling characteristics is a potentially useful method to ensure continuity in the evaluation of contiguous flight phases. This is expected to depend on the aircraft characteristics and operational requirements. Aircraft which require transition between different modes of lift generation/control may require a wider range of MTE types to assess handling performance in the transition phases of flight and in each of the different modes of lift generation.

Phase 3: Recommendation of FQTEs and HQTEs for FQ and HQ Evaluations

Subphase 3a: FQTEs and HQTEs for Manned Simulator Evaluations

The aim of this subphase is to identify MTEs to evaluate the aircraft handling performance in the applicant’s manned simulator. This testing is based on the assumption that the FAA has approved the applicant’s simulator for certification credit and that the FAA might not have full visibility into control system development and the flight clearance process applied by the applicant.

The MTEs were identified by linking them to the core certification process recommended in Lotterio (2022). The identification of FQTEs to be performed in the simulator has mostly an operational value. When available, this is to evaluate how their execution can be combined with the HQTEs in the same phase of flight and assess the level of matching between the results from analysis of data collected from FQTEs execution and the corresponding values calculated from the simulation models.

Under the assumption of limited FAA visibility into the aircraft developmental process, recommendations were provided on the use of FQTEs to detect local non-compliances with respect to standard flying qualities requirements. Margins of MTEs applicability were suggested, based on the aircraft configuration and operational requirements, combined with expected standard pilots' comments/feedback.

Recommendations apply to aircraft in normal and failed operational status for the failures which are expected to be more common in the new class of Part 21 powered-lift designs, which will be treated as "Special Class".

When possible, results were complemented by a flow chart to represent the flow of execution of the different MTEs and their relationship with the phases of the certification process. The underlying concept was to recommend MTE blocks which can ensure continuity between requirements (Phase 2c), execution, and applicability to means of compliance towards flight clearance.

Phase 4: Mapping of FQTEs and HQTEs to Vertical Take Off and Landing Requirements

This phase is used to map the MTEs recommended in the previous phases to certification requirements of aircraft with Vertical Take Off and Landing (VTOL) capabilities. To this scope, the FAA indicated that emerging aircraft for which airworthiness standards have not been issued (those that don't fit into existing Part 23, 25, 27, 29 and 31) will be certified in accordance with Part 21 Certification Procedures, which means powered-lift designs will be treated as "Special Class" aircraft (not Part 23 airplanes). This clarification removed the rulemaking burden of Special Conditions, and these MTE based standards and other airworthiness criteria can be crafted against individual type designs to deliver an appropriate level of safety without entering into the rulemaking process.

Mapping of FQTEs and HQTEs was based on synthesis of the results from previous phases, and it reports links to the MTE flow charts that could be derived in Phase 3a. The results were synthesized in recommendations, discussion of their rationale, and flow charts representing the correlation between MTEs, certification phases, and FQ requirements.

3 Description of different flight controls setup

3.1 Conventional flight controls

For conventional FW Flight Control Systems (FCS) (reversible and irreversible), the pilot inceptors control the following effectors:

- Longitudinal stick (or wheel) deflection controls the elevator deflection.
- Lateral stick deflection (or wheel rotation) controls the aileron (or spoiler) deflection.
- Pedal deflection controls the rudder deflection.

Conventional airplanes are statically stable (longitudinally and directionally): effectors generate moments, which balance the aircraft static stability at trim conditions. The longitudinal static stability causes the elevator deflection to control the angle of attack. The directional static stability causes the rudder deflection to control the angle of sideslip. The lateral static stability is driven by the angle of sideslip, not the bank angle; therefore, the bank angle does not generate rolling moments and the aileron deflection produces a rolling moment that balances the roll damping in a coordinated turn. Thus, the aileron deflection controls the roll rate.

For conventional RW FCS, the pilot inceptors control the following effectors:

- Stick deflection (cyclic) controls the swash plate angle.
- Pedal deflection controls the tail rotor pitch angle.
- Collective deflection controls the main rotor pitch angle.

In forward flight, the control logic is similar to FW aircraft. During hovering, the pilot controls the following rates:

- Cyclic controls pitch and roll rates.
- Pedals controls yaw rate.
- Collective controls vertical rate.

In addition, strong cross coupling effects exist between different inceptors. Basic control of rotorcraft in low airspeed regime is more challenging than forward flight. Furthermore, different control logics apply in different flight phases, increasing workload and requiring more extensive pilot training to proficiently and safely fly conventional rotorcraft.

3.2 Advanced flight controls for VTOL aircraft

Advanced FBW control logics aim at improving the handling qualities of aircraft, leading to several benefits. In particular for VTOL aircraft, one of the challenging objectives of FBW systems is resolving the conflict between aircraft responses in different flight phases by achieving the largest possible degree of commonality between vertical flight, transition, and forward flight. More specifically, the typical goal is controlling the same aircraft state with the same inceptor, regardless of the flight phase. Using the same control inputs in any flight phase significantly reduces the pilot's workload and complexity of transitions. Although the largest commonality is sought, some blending is unavoidable (e.g., between ground speed for hovering and airspeed for forward flight). Effectors may be significantly different than traditional ones, especially for electric VTOL (eVTOL) aircraft designed for Urban Air Mobility (UAM). Multiple vertical rotors and/or thrust vectoring are typically used for advanced eVTOL designs in hovering and transition phases. Control during forward flight is normally achieved with more conventional aerodynamic effectors; forward thrust is produced by dedicated propellers, or by tilting the same rotors used for vertical flight. While FBW is the logical choice for most future designs, hybrid configurations are also being pursued, where an advanced control strategy is used for vertical flight and transition, whereas a simple direct link between inceptors and aerodynamic effectors is used in forward flight.

While different manufacturers are developing different control logics, they can be generally classified into two basic configurations: airplane-centric inceptor and helo-centric inceptor configurations. The former one utilizes inceptor strategies typical of FW aircraft, whereas the latter reflects RW logics. Examples of airplane-centric inceptor mappings are the Unified flight control logic and the EZ-Fly control logic.

It is also worth noting that the end goal of many eVTOL manufacturers is achieving autonomous flight, for which HQ criteria will be obviously irrelevant. Different challenges, certification criteria, and means of compliance will need to be developed for such systems.

3.3 Unified flight controls

The Unified Flight Control inceptor mapping (Figure 1) is considered the closest to the traditional FW logic. The inceptors consist of a stick (typically a sidestick), a lever and optionally a set of pedals:

- Vertical and lateral motions are controlled with the stick motion (fore-aft and left-right); the vertical and lateral motions are achieved through pitch and bank rotations, which are controlled accordingly by the FCS.

- Yaw is controlled either with the stick rotation or through pedal deflection.
- Longitudinal motion is controlled with the left lever.

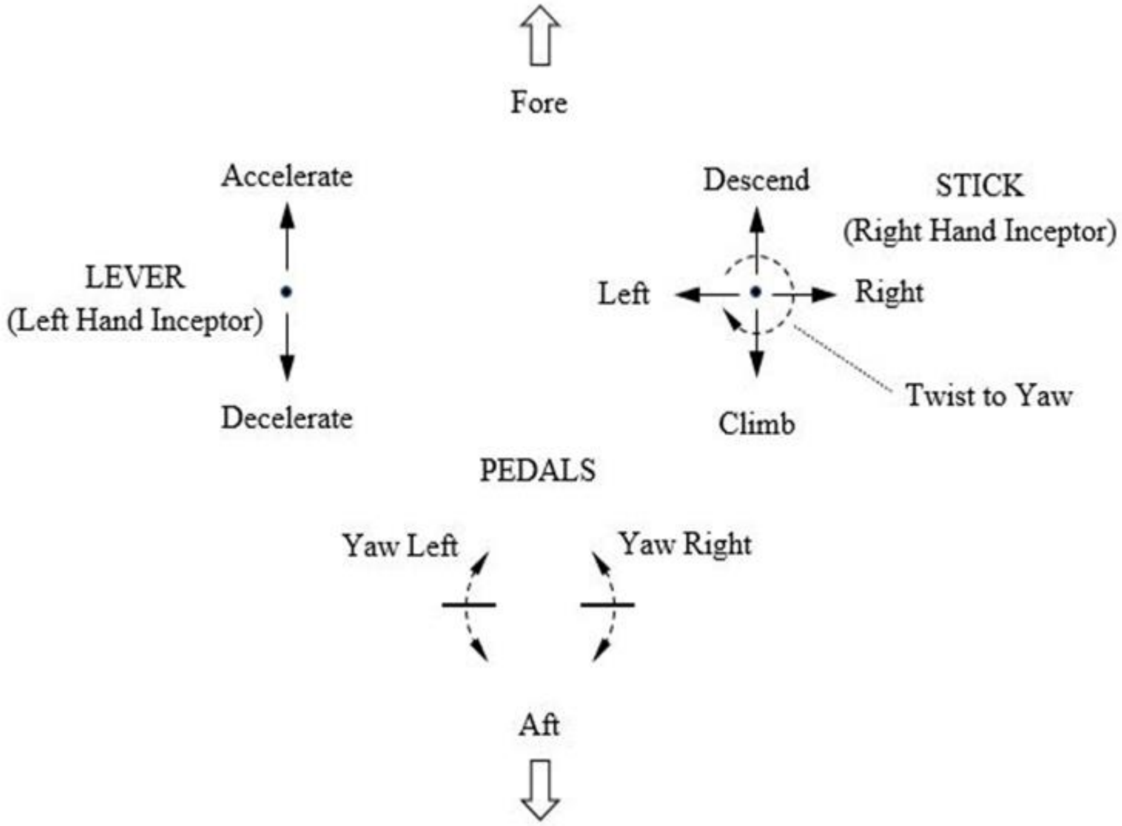

Figure 1. Unified inceptor mapping

The Unified Flight Control System is a flight path command system in forward flight and a translational command system in hover. Ground speed is controlled in hover and airspeed is controlled in forward flight. The transition is a seamless blending between the two modes (with respect to airspeed or ground speed), because the inceptors control the same axes, and the controlled parameters, although not exactly the same, are strictly correlated. Table 1summarizes the Unified inceptor mapping.

Table 1. Unified inceptor mapping

	Vertical Flight	**Transition**	**Forward Flight**
Left-hand inceptor	Ground speed u_{GS}	Acceleration (blended)	Acceleration (airspeed) $\dot{u}_{CAS}$
Longitudinal Right-Hand Inceptor	Vertical speed $\dot{h}$	Blended	Flight path rate $\dot{\gamma}$
Lateral Right-Hand Inceptor	Lateral ground speed v_{GS}	Angle of bank (blended) ϕ	Roll rate p
Directional Right-Hand Inceptor or pedals	Heading rate $\dot{\psi}$	Blended	Angle of sideslip β

3.4 EZ-Fly flight controls

The EZ-FLY Flight Control inceptor mapping (Figure 2) tries to simplify the control logic by maximizing similarity between different flight phases. With minor differences, the same inceptor always controls the same flight parameter.

The inceptors consist of a stick or wheel column, a lever, and a set of pedals:

- The longitudinal stick deflection controls the vertical speed.
- The lateral stick deflection controls the heading rate (turn rate).
- The left lever controls the forward speed.
- The rudder pedals control the lateral speed (i.e., angle of sideslip in forward flight), with potential buildup of aerodynamic loads in sideslip flight, due to this control logic.

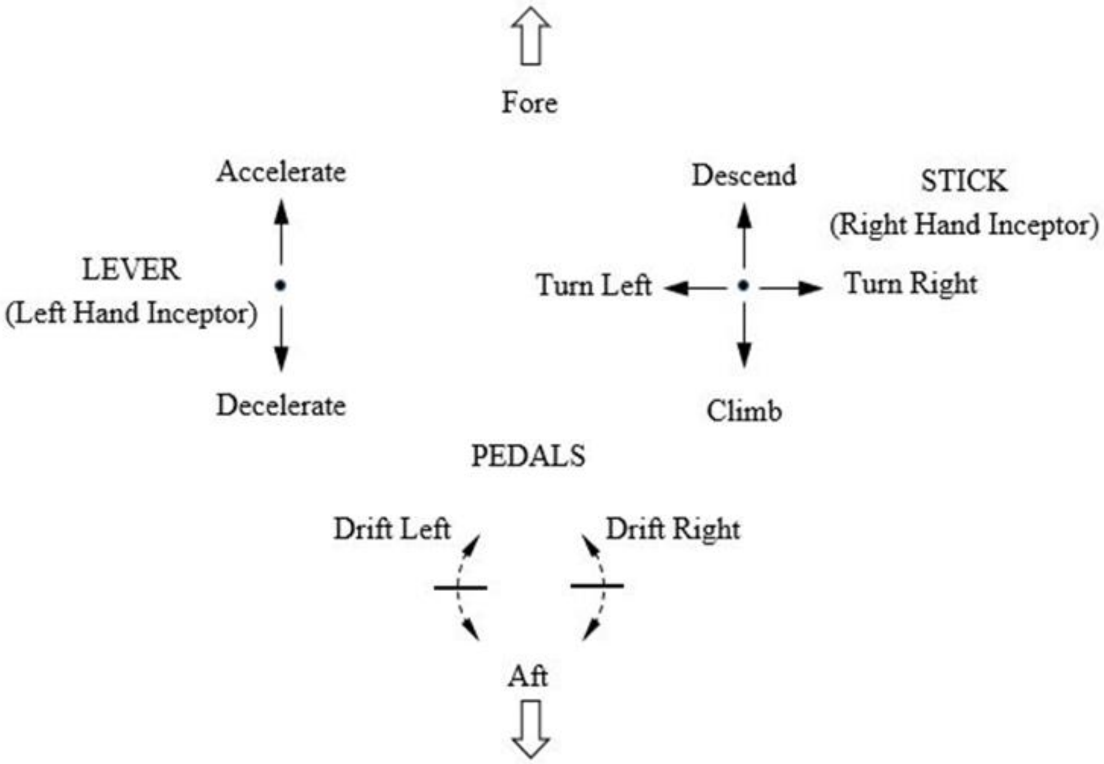

Figure 2. EZ-Fly inceptor mapping

Table 2 summarizes the EZ-Fly inceptor mapping.

Table 2. EZ-Fly inceptor mapping

	Vertical Flight	**Transition**	**Forward Flight**
Left-Hand Inceptor	Forward Speed u_{GS}	Forward Speed Blended	Forward Speed u_{CAS}
Longitudinal Right-Hand Inceptor	Vertical Speed $\dot{h}$	Vertical Speed $\dot{h}$	Vertical Speed $\dot{h}$
Lateral Right-Hand Inceptor	Heading Rate $\dot{\psi}$	Heading Rate $\dot{\psi}$	Heading Rate $\dot{\psi}$
Pedals	Lateral Speed v_{GS}	Lateral Speed Blended	Lateral Speed β

3.5 Helo-centric flight controls

The Helo-Centric inceptor mapping (Figure 3) tries to maximize commonality with traditional RW controls.

The inceptors consist of a left-hand stick and a right-hand stick:

- The left-hand stick controls vertical speed (fore/aft) and heading rate/sideslip (left/right).
- The right-hand stick controls longitudinal acceleration (fore/aft) and bank angle (left/right).

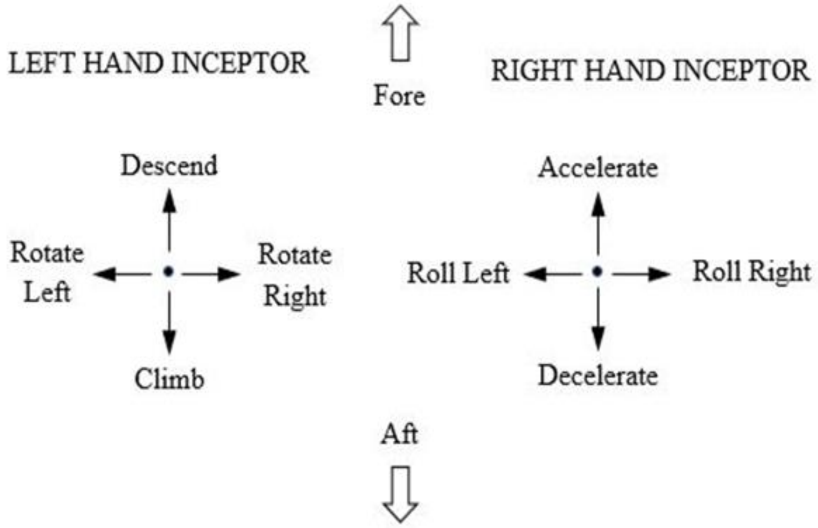

Figure 3. Helo-centric inceptor mapping

Table 3 summarizes the Helo-centric inceptor mapping.

Table 3. Helo-centric inceptor mapping

	Vertical Flight	**Transition**	**Forward Flight**
Longitudinal Right-Hand Inceptor	Forward Speed u_{GS}	Forward Speed Blended	Forward Speed u_{CAS}
Lateral Right-Hand Inceptor	Ground speed v_{GS}	Angle of Bank ϕ	Angle of Bank ϕ
Longitudinal Left-Hand Inceptor	Vertical Speed $\dot{h}$	Vertical Speed $\dot{h}$	Vertical Speed $\dot{h}$
Lateral Left-Hand Inceptor	Heading Rate $\dot{\psi}$	Blended	Sideslip β

A summary of the controlled variables per axis, flight phase/mode and flight controls setup[1] is shown in Table 4.

Table 4. Controlled variables per axis, flight phase/mode and flight controls setup

Flight Controls setup	**Phase/Mode**	$\delta_{\text{RH-Long}}$	$\delta_{\text{RH-Lat}}$	$\delta_{\text{LH-Long}}$ **or** δ_{coll}	$\delta_{\text{LH-Lat}}$ **or** δ_{ped} **or** $\delta_{\text{RH-Rot}}$
Conventional Helicopter	Hover	u	v	$\dot{h}$	r
	Transition	θ	ϕ	$\dot{h}$	$r \rightarrow \beta$
	Forward flight	q	p	$\dot{h}$	β
Unified	Hover	$\dot{h}$	v_{gnd}	u_{gnd}	r
	Transition	$\dot{h} \rightarrow \dot{\gamma}$	ϕ	$u_{gnd} \rightarrow \dot{V}_{cas}$	$r \rightarrow \beta$
	Forward flight	$\dot{\gamma}$	p	$\dot{V}_{cas}$	β
EZ-Fly	Hover	$\dot{h}$	r	u_{gnd}	v
	Transition	$\dot{h}$	r	$u_{gnd} \rightarrow V_{cas}$	v
	Forward flight	$\dot{h}$	r	V_{cas}	v
Helo-Centric	Hover	u_{gnd}	v_{gnd}	$\dot{h}$	r
	Transition	$u_{gnd} \rightarrow V_{cas}$	ϕ	$\dot{h}$	$r \rightarrow \beta$
	Forward flight	V_{cas}	ϕ	$\dot{h}$	β

Legend:

$\delta_{\text{RH-Long}}$	right stick longitudinal deflection
$\delta_{\text{RH-Lat}}$	right stick lateral deflection
$\delta_{\text{LH-Long}}$	left stick longitudinal deflection
$\delta_{\text{LH-Lat}}$	left stick lateral deflection
δ_{coll}	collective deflection
δ_{ped}	pedals deflection
$\delta_{\text{RH-Rot}}$	right stick rotation
u_{gnd}	forward/rearward ground speed component along X-axis

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[1] Thomas Lombaerts, John Kaneshige, Michael Feary, *"Control Concepts for Simplified Vehicle Operations of a Quadrotor eVTOL Vehicle"*, Presented at the virtual AIAA Aviation Conference, 15–19 June 2020.

4 Flying qualities task elements (FQTEs) definitions and requirements for UAMs

4.1 Flying qualities task elements

The objective of executing FQTEs within the aircraft certification process is to collect system identification data in flight for Flying Qualities (FQ) verification. Even if not required for conventional designs characterized by well-known essentially linear local dynamics, performing FQTEs in a simulated environment can be relevant when the aircraft simulation model is not fully characterized, when the aircraft dynamics are highly nonlinear, when the control laws are particularly complex (e.g., Nonlinear Dynamic Inversion augmented by robust outer loop controllers) or when simulated input/output data are not readily accessible for post-test analysis. In this case, the objectives and the approach to execution of simulated FQTEs is similar to that of in-flight execution. The data analysis and synthesis processes are the same for the in-flight and simulation environment. Assuming the availability of an aircraft model of adequate accuracy, highest priority is to extract aircraft modal parameters from model linearization and analysis, with execution of FQTEs in the flight test phase alone.

Note: a consistent aircraft model for offline simulations is necessary and sufficient for all pre-flight assessments, assuming the applicability of the required tools.

In some cases, vehicle models can be used, which reproduce the aerodynamic flow on the aircraft via real time calculation based on Computational Fluid Dynamics (CFD) methods. This introduces a degree of variability which is mostly due to the numerical solution. The simplest applied approach in this case is to consider the model as a gray box and perform the flight test derived FQTEs in the simulator, in place of conducting offline linearization.

A recommended engineering approach to account for the scatter in the results and for the related lower level of the solution predictability is to generate look up tables from a comprehensive set of numerical solutions and to apply tolerances on the calculated values. The amplitude of the tolerances is based on the assessed accuracy of the fluid-dynamic model and on the measured scatter of the numerical solution in correspondence of pre-selected check cases. This last approach leads to higher consistency and repeatability of the results, better assessment of the impact of off-nominal characteristics, and it allows overall time saving.

Results from FQTEs can be directly compared with the flying qualities requirements, in the form of modal parameters and of other relevant metrics derived from the analysis, or used to update the vehicle models. Model updates require additional post processing, which significantly depends on the type of model, their validity envelope, the aircraft flight envelope, and its coverage in the specific flight test campaign.

FQTEs excite aircraft responses/modes in specific flight conditions and configurations. Successful system identification is based on accurate execution of the maneuvers, designed to excite the aircraft dynamic modes and obtain response data containing sufficient information. This requires adequately high Signal to Noise Ratio (SNR), typically SNR > 6 dB, for accurate modeling, subject to practical constraints. Noise is formed by the component(s) of the signal which do not derive from the deterministic part of the system model. The main components are: effects of resolution and accuracy of sensors, quantization, atmospheric disturbances, structural vibrations and the other not modeled nonlinearities. The impact of noise at frequency in the range of the dynamics to be identified is detrimental to the accuracy of the results. High frequency noise, typically due to structural vibrations, is usually not critical, as it can be filtered out without losing information on the aircraft dynamics.

Maneuvers for identification of systems (Figure 4) for which there is “a priori” knowledge are typically square wave inputs close to the predicted natural frequencies of the dynamic modes, or inputs optimized as a function of the vehicle predicted characteristics and of the response sensitivity to them.

Those for identification of systems with unknown dynamic characteristics are the frequency sweep, or a combination of pulse inputs, represented respectively in Figure 4a) and Figure 4d). The input shape in Figure 4 d) is defined as: 3-2-1-1, based on the relative duration of each consecutive input. These FQTEs excite the response over a wide range of frequencies, with an approximately constant power, allowing for identification of dynamic modes which are not known prior to testing.

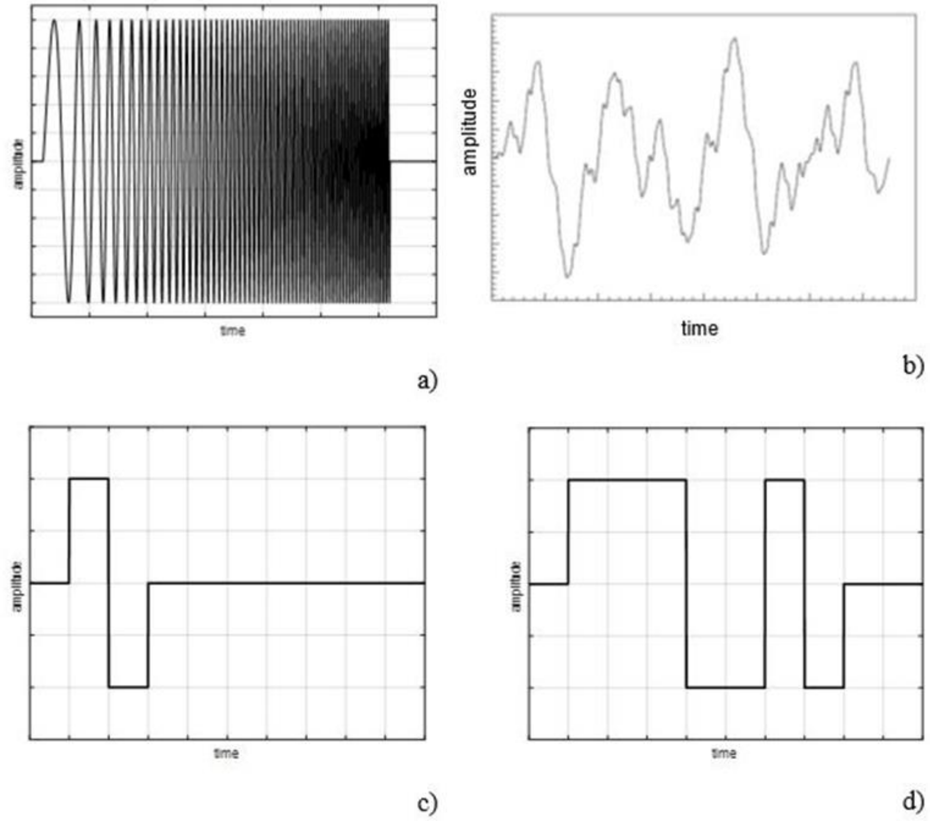


Figure 4. Types of inputs for system identification

FQTEs can be programmed to be performed automatically by the vehicle FCS, or pilot executed. Automatic maneuvers, or Programmed Test Inputs (PTI), are highly repeatable and with constant quality, requiring a lower real time monitoring effort from pilot and FTE with respect to manned maneuvers. Pilot executed maneuvers eliminate the requirement of implementing a programmable, automatic input generator within the primary FCS and allow for their execution at different aircraft developmental stages. This reduces the user's effort to develop dedicated FCS test modes and to conduct related safety reviews. At the same time, this approach poses the challenge of minimizing inherent pilot's distortion of the designed input, of ensuring the planned drift from trim conditions and of respecting flight envelope limits, during the whole execution of the maneuver.

The consolidated FAA practice is to define regulations applicable to the aircraft response to pilot's inceptor inputs. The development of FBW aircraft, equipped with mostly passive artificial feel systems, leads to invariant inceptor feel characteristics throughout the flight envelope. There is an increased priority of the response to control surface/effector for certification purposes which derives from the passive control feel and from the requirement of identifying the aircraft dynamic characteristics at different points of the command path and forward path.

Relevance of control surfaces/effectors authority is high for assessment of flying qualities and for matching vehicle models characteristics with respect to flight test data. The specific approach to certification of UAMs is expected to be the driver for deciding which input(s)/output(s) to consider in the process when performing FQTEs. The following sections provide a description of the main classes of maneuvers mentioned above.

4.2 Aircraft mission requirements

The principal types of missions for UAM vehicles are:

- commercial commuters
- recreational
- emergency first responders
- fire fighting
- police

The mission types listed above are expected to be formed by common flight phases conducted in similar flight conditions. This depends on the mission similarities and on the expected limited performance levels of UAMs, which lead to flight envelopes of limited width. Table 5 of next page reports example of flight phases for each mission type, in broad order of execution.

4.3 Aircraft classification

The aircraft classification reference for this document is that of the Vertical Flight Society (VFS). The main aircraft classes according to the VFS website are:

- Vectored Thrust: an eVTOL aircraft that uses any of its thrusters for lift and cruise
- Lift + Cruise: completely independent thrusters used for cruise as for lift
- Wingless (Multicopter): no thruster for cruise – only for lift
- Hover Bikes: the pilot sits on a saddle, not considered for this research
- Electric Rotorcraft: an electric aircraft that utilizes helicopter flight controls.

Development of new designs might lead to different classes of vehicles, like “Tilt + Cruise” (i.e., powered lift or vectored thrust), in which thrusters rotate to provide lift in vertical flight and forward thrust in wing-borne flight conditions.

Table 5. Examples of mission types and flight phases for UAMs

Mission	**Mission Flight Phases – Nominal Operation**						
Commercial Commuters	Takeoff	Transition*	Cruise			Transition*	Landing
Recreational			Low Level Flying	High Altitude Loiter	Cruise		
Agriculture			Low Level Flying				
Emergency First Responders			Cruise	High Altitude Loiter	Low Level Flying		
Military			Cruise	High Altitude Loiter	Cruise		
Fire Fighting			Cruise	High Altitude Loiter	Cruise		
Police			Cruise	High Altitude Loiter	Cruise		
			Pursuit	Low Altitude Loiter	Cruise		

(*) Applicable to aircraft configurations with different modes of lift generation between the takeoff/landing and the forward flight phases of flight.

4.4 General maneuver requirements

Aircraft class

The maneuvers described in this document are expected to be performed in all classes of aircraft reported in section 4.3, with potential exception for the “hover bike” class. More information has to be collected on “hover bikes” to confirm applicability and relevance of FQTEs for system identification and vehicle characterization.

Aircraft mission

Flight conditions/aircraft configurations typical of the main flight phases in which FQTEs can be performed are takeoff, cruise, loiter, and landing. These are common to the mission profiles reported in section 4.2. Takeoff and landing specifically refer to the aircraft configuration, as FQTEs are not to be performed in the terminal phases of flight, for safety reasons. The transition flight phase is not applicable to wingless aircraft, electric rotorcraft, and hover bikes, and it is expected to present limitations to the execution of FQTEs also for the other aircraft classes. More comprehensive discussion on this subject is provided in section 4.5.

Characteristics and performances

The background elements for the design of effective maneuvers used in aircraft verification can be preliminarily summarized in the list below:

- Safety: the maneuver does not lead to envelope exceedances or departure from controlled flight; the onset of the aircraft response is gradual and the maximum perturbation is predictable.
- Accurate measurement of the initial trim conditions and of the stabilized conditions after execution of the maneuver is possible.
- Maneuvers can be executed manually and/or automatically, with a high degree of repeatability.
- Inputs minimize coupling of commanded control surfaces deflection.
- Inputs maximize the excitation of a specific dynamic mode, while minimizing the response to other dynamic motions.
- Maneuvers designed for data analysis in the time domain excite one dynamic mode at a time.
- The information content allows identification of the most relevant parameters characterizing the targeted aircraft dynamics mode(s).
- Input average is null for oscillatory second order modes. The exception to this requirement occurs when the identification of certain modal parameters/metrics is required. One example is the finite step, or *boxcar* input, performed to measure the high frequency zero of the longitudinal response, the theta *drop-back*, or the flight path angle overshoot.
- Modulation of input amplitude and frequency is possible. This allows specification of the minimum amplitude required to achieve adequate perturbation within the relevant frequency range.

Flight test envelope

The scope of each FQTE is to gather quantitative data relative to a single flight condition. It is important to achieve adequate coverage and discretization of the flight envelope, fundamental requirements of any test and evaluation campaign. This includes potential critical areas known a priori, potentially the envelope “corners”, and those regions identified as critical through execution of the formal flight clearance or equivalent processes based on predictions of the aircraft characteristics. The number of maneuvers and the associated cost is critical, which requires the design and execution of maneuvers that can allow deriving modal parameters relevant for the selected flying qualities criteria. It is important to consider that progress of testing depends highly on the results derived from previously executed FQTEs. Comparison between data trends from prediction models and from flight test is the standard process feedback to ensure safe progression of the test campaign. This implies accurate specification of flight conditions/configurations and the application of post flight analysis processes with average accuracy higher than the estimated error on prediction (Lotterio M. , 2022).

Amplitude of perturbations

Constraints are present on the maximum and minimum amplitude of the perturbations. The principal constraints on the maximum amplitude are:

- Exceedance of envelope limits, with highest priority to aircraft structural limits. This is a critical requirement which should be assessed by means of offline or manned simulations, prior to flight, whenever possible.
- In case reliable aircraft models and simulations are not available, in-flight build up approach with respect to amplitude and flight conditions is required to ensure safe execution of each specific maneuver.
- Respect of the condition of linearity of the response. This is the fundamental requirement to be able to compare the results with most of the current flying qualities criteria. It is the basic requirement to be able to derive increments on linear and nonlinear aircraft models according to the linear “bias + slope” error model.

The principal constraints on the minimum amplitude are:

- Achievement of the minimum acceptable SNR. This requires producing a sufficiently large perturbation with respect to the noise level in the specific flight condition and with the assigned instrumentation system. Details on acceptable values of SNR are reported in section 4.1.

- Presence of software dead-zones in the command path. These are usually implemented to avoid commanding a non-zero input in the inceptor *hands-off* condition, typical of passive inceptor FBW systems, which are inherently irreversible. Implementation of dead-zones is required because the inceptor does not return exactly to center due to the lack of air load acting on it, which leads to a non-zero electrical signal being transmitted to the control system. The need of a dead-zone is also to avoid the "mannequin effect" and integrator windups. The dead-zone prevents the described improper input, minimizing the risk of saturation of the integrator(s).
- Presence of software dead-zones in the forward path. Dead-zones in the forward path can be implemented for example to avoid commanding secondary control surfaces deflection fed by aircraft states, due to the state's minor perturbations with respect to a reference value.
- Presence of physical dead-zones, like the hysteresis cycle in the control surface deflection as a function of the inceptor force produced by control system friction in mechanical control systems, or the mostly small amplitude hysteresis cycle in the aircraft response associated with the deflection of trailing edge surfaces.

Specification of the maneuver

The main parameters for the specification of the maneuver are the amplitude and frequency of the pilot's input and the amplitude of the aircraft dynamics perturbation. FBW aircraft are typically "maneuver demand" systems: accurate specification requires availability of reliable and accurate models, to determine the inputs amplitude leading to the target amplitude of the perturbation. High priority has to be assigned to the selection of the aircraft state(s) with respect to which the amplitude of the perturbation is defined.

Relevant outputs for assessing the amplitude of longitudinal maneuvers are usually Angle of Attack (AoA) in the low airspeed regime and normal load factor (n_z) in the high airspeed regime. The boundaries of the airspeed regimes depend on aircraft characteristics and configuration; in the specific example, they are a function of the value of n_z/α, which is also a reference metric of the Control Anticipation Parameter (CAP) criterion, aimed at predicting analytically the predictability of the longitudinal response to a longitudinal step input.

Note: the statement refers to outputs that are relevant for the execution of the maneuver, independently from the control laws approach. In practice, variation of AoA is usually significant in the low airspeed regime, with corresponding minor load factor variation. In the high airspeed regime, the opposite occurs, where a significant variation of load factor corresponds to a minor variation of AoA. Similar considerations are applicable to the lateral and directional axes, in which the roll angle and the Angle of Sideslip (AoS) are the respective reference states. This induces the specification of the maximum amplitude of the maneuver in function of the airspeed regime.

Specification of the corresponding pilot's input amplitude, usually by quarters of inceptor travel, is fundamental guidance for the pilot, when the maneuvers are executed manually: the open loop nature of FQTEs does not allow input modulation and consequently avoidance of envelope exceedances is a safety concern in case of inappropriate input amplitude. As a consequence, the importance of the appropriate amplitude is both a safety and a technical requirement. Table 6 reports an example of notional maneuver amplitudes and corresponding modifiers, for each of the three axes of FW aircraft dynamics. It is important to notice that flow angles, AoA, and AoS, are respectively relevant for the pitch and yaw axis, in which the aircraft dynamics is characterized by modes defined by perturbations of the same flow angles. Roll angle is the reference perturbation in the roll axis, as the roll mode dominates lateral dynamics.

Table 6. Example of FQTE maneuvers amplitude

FQTE Maneuvers Amplitude		
Axis of Perturbation	**Amplitude Modifier**	**Amplitude of Perturbation**
Pitch	Small	$\Delta AoA \leq 2\ deg$; $\Delta n_z \leq 0.5$
	Medium	$2 < \Delta AoA \leq 4\ deg$; $0.5 < \Delta n_z \leq 1$
	Large	$4 < \Delta AoA \leq 6\ deg$; $1 < \Delta n_z \leq 1.5$
Roll	Small	$\Delta\phi \leq 30\ deg$
	Medium	$30 < \Delta\phi \leq 45\ deg$
	Large	$45 < \Delta\phi \leq 60\ deg$
Yaw	Small	$\Delta AoS \leq 2\ deg$; $\Delta n_y \leq 0.05$
	Medium	$2 < \Delta AoS \leq 4\ deg$; $0.05 < \Delta n_y \leq 0.1$
	Large	$4 < \Delta AoS \leq 6\ deg$; $0.1 < \Delta n_y \leq 0.15$

Based on the table above, requirements have to be designed consistently with the dynamics of the aircraft and the types of maneuvers. Maneuver design and consequent specification can depend on additional constraints, mostly due to aircraft and control system physical limitations. Examples of constraints are provided below:

- control surfaces maximum deflection
- control rate saturation
- actuators bandwidth
- control allocation (allocation of control surfaces deflections command to an assigned input, due to stability and control augmentation)
- capability of maintaining trim conditions (within adequate tolerances during the whole maneuver)
- acceptability of drift of selected aircraft dynamics states/outputs from trim conditions (A significant variation of pressure altitude can be acceptable, when it is necessary to maintain airspeed within the required tolerances, while the perturbations of the other states remain small.)

Specification of the pilot's input frequency depends on the maneuver type: as a broad principle, the frequency of the maneuvers has to be close to that of the dynamics mode to be excited. For example, the frequency of pitch and roll doublets has to be respectively close to that of the short period and of the Dutch roll. This is to excite the maximum amplitude of the mode response for the given amplitude of the input, while minimizing the response to other dynamic modes. The Command Augmentation System (CAS) and the Stability Augmentation System (SAS) can significantly affect respectively the excitation and the aircraft modal response.

For this reason, conventional time domain modal analysis methods, which are not based on optimization methods, like Maximum Likelihood Estimation (MLE) or similar, cannot be directly applied to estimate the bare airframe characteristics from the response of highly augmented vehicles to input types with a relatively narrow frequency band, as doublets. The MLE method, and output error methods in general, compare the response from the real aircraft (obtained through flight testing) with the response from the aircraft model to the same excitation input (the one recorded from the flight test maneuver). The modal parameters are iteratively updated to minimize the error between the two responses (real aircraft and updated model) based on an algorithm aimed at minimizing a specific cost function.

This makes maneuvers designed for analysis in the frequency domain, i.e.: frequency sweeps, or 3-2-1-1, more suitable for the identification of state to inceptor travel/force transfer functions of dynamic modes of FBW, highly augmented aircraft. For frequency sweeps and 3-2-1-1 maneuvers, the relevant frequency range of interest has to be part of the maneuver specification, covering the frequency range of the pilot's inputs and the predicted frequency range of the most important rigid body modes. Discussion of the methods for excitation of structural dynamic modes is outside the scopes of this document, for its lower direct relevance in the assessment of the handling qualities.

It is important to notice that specification of FQTEs is relative to states and outputs defined with respect to the air mass, or to the vehicle local vertical reference system. This is significantly different from the MTEs specification, which includes also pilot's visual cues and ground references.

The notional process of input design and system estimation/identification, adapted from Mulder et al. (1994), is displayed in the flow diagram of Figure 5. The flight test part of the process is key to ensure that the designed maneuvers are valid, considering the different practical and operational constraints.

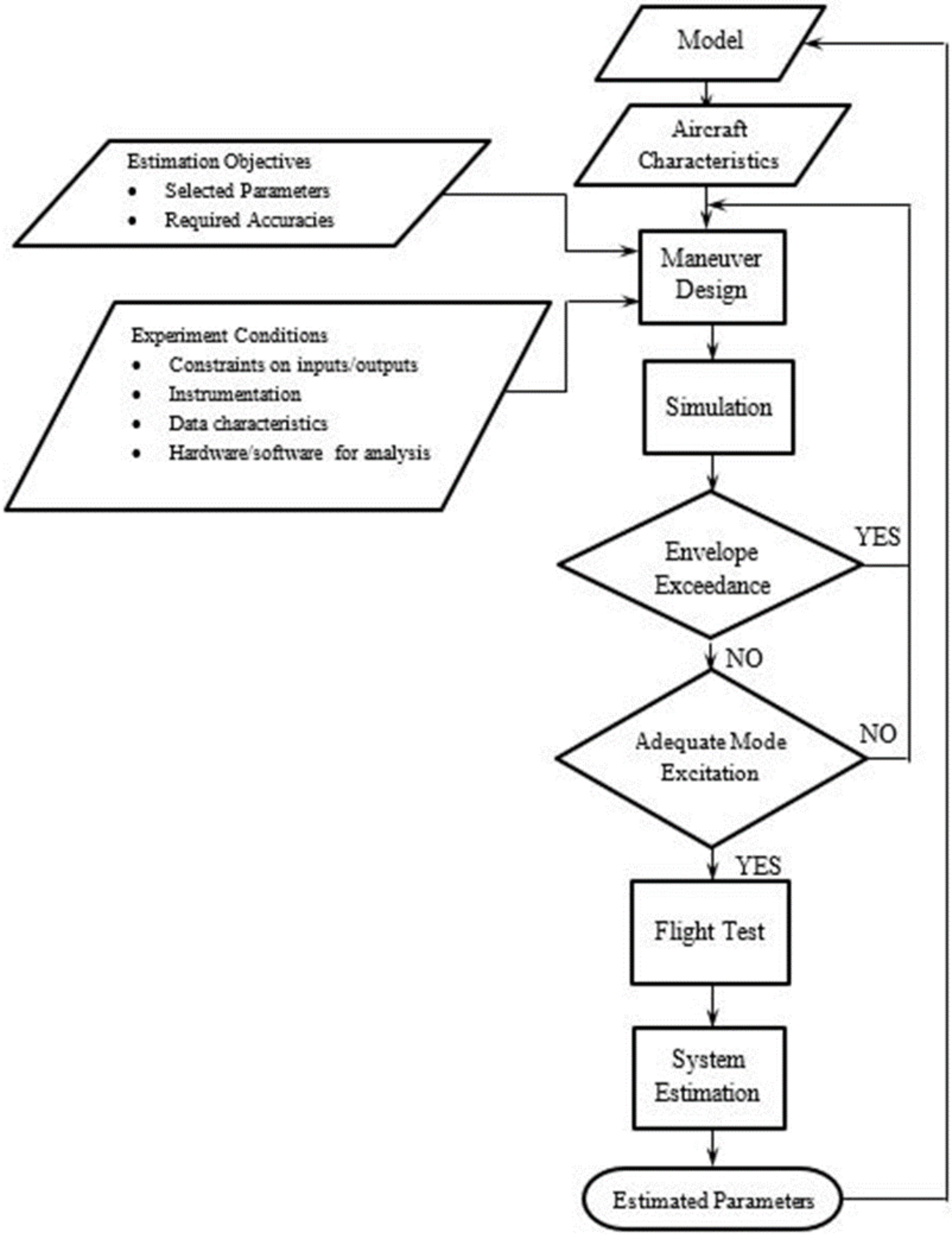


Figure 5. Input design for system estimation/identification

The objective of this class of maneuvers is to identify/estimate the vehicle characteristics, with identifiability of a parameter being the possibility to estimate its value precisely from the inputs and the outputs of the system. Precision is a fundamental aspect, as every estimated value corresponds to one and only one probability distribution. Absence of identifiability occurs when even with an infinite number of observations, it is not possible to estimate the value of the parameter.

It is important to recognize that identifiability is not exclusive and that different degrees of identifiability of a parameter are possible, depending on the maneuver performed. Different maneuvers produce different inputs/outputs sets, corresponding to different contents of information for identification of the given parameter. For this reason, sub-optimal maneuvers under the identifiability standpoint can be considered suitable for the lower time required to perform them, for the lower risk of envelope exceedances, or for the ease of execution.

As an example, square wave doublets or other pulse combinations provide a higher content of information compared to sinusoidal doublets. An automatic system is required for execution of accurate and repeatable square wave doublets; a test pilot can perform sinusoidal doublets with minimal training and with a relatively high level of repeatability. Consequently, sinusoidal doublets are preferable for identification of an aircraft which is not equipped with a Program Test Input (PTI) system. The minimal complexity of their execution, the lower time duration, the possible real time tuning, and the higher feasibility are more relevant for the successful completion of a flight test campaign than the higher information content of the single maneuver. Maneuver duration is a high priority in low power, low autonomy vehicles like the UAMs.

In the initial phases of maneuver design, the feasibility of the maneuver(s), the amplitude of the aircraft response, and the effectiveness of the estimation algorithms can be assessed based on manned simulations. It is best practice to produce simulation data from models with known added off-nominal terms and noise, to verify the accuracy of the estimation algorithms in calculating the increments to be added the nominal values of the model. This exercise allows the test team to practice the full process before flight, increasing safety and reducing the overall flight test time.

Validation and refinement of the designed maneuvers progresses in flight test, based on the actual vehicle response. This is a fundamental phase, to maximize the information content produced by each maneuver type and/or to identify potential deficiencies requiring changes in the design approach.

4.5 Frequency sweep

4.5.1 Specific maneuver requirements

Choice of the inputs and outputs to be measured during the execution of the frequency sweep has to be taken into account under a minimum of three elements:

- relevance of the input control surface, or effector for the excitation of the dynamic modes which are significant for the given flight phase and aircraft configuration;
- relevance of the input control surface, or effector for controlling the aircraft in the given flight phase; and
- achievable power of input and output for analysis.

This is particularly relevant for the over-actuated UAM aircraft, in which the same mode can be excited by means of different control surfaces/effectors and of their combinations.

4.5.2 Detailed description of the test technique

As introduced above, identification of dynamic modes of vehicles for which no models and predictions are available, is usually based on continuous sinusoidal inputs. In the frequency sweep, the input frequency varies continuously, to excite the system/vehicle over a wide frequency band, usually defined by the expected range of relevant frequencies for the dynamics to be identified. An example of this input type is displayed in the bottom time history of Figure 6. The input frequency varies from low to high, linearly or in a logarithmic way.

The input amplitude begins and ends at trim; it is usually symmetric with respect to the trim condition, to obtain symmetric perturbations of a target state with respect to trim. This is to ensure that flight conditions do not vary significantly and that the vehicle characteristics can be considered constant during the execution of the maneuver. Particularly with manual inputs, the average input can be slowly adjusted to maintain the average aircraft state close to trim condition. This is the only closed loop component of the maneuver, which does not practically affect the open loop nature of the frequency sweep input in the frequency range of interest, provided the closed loop compensation is applied very slowly and progressively. The input maximum amplitude is determined to maintain linear system characteristics throughout the maneuver. Results from offline simulations can be used to define the correct input amplitude prior to test, reducing the number of *trial-and-error* cycles for the definition of the maneuver. Linearity is important with system identification performed both in the frequency or in the time domain, which leads to constraints on input and output amplitude.

In the frequency domain, frequency sweeps can be effectively performed to collect data for generation of Bode plots, which require system linearity. In the time domain, the bias + slope linear error model is usually applied for the synthesis of the local increments to the baseline model, derived from the identification/estimation process. This is valid with both conventional time domain equation error and output error techniques.

The input frequency is typically in the range $\omega \approx [0.1, 12]\ rad/s$, with a maximum duration of the whole maneuver from 60 to 90 seconds. The duration is determined by the number of full cycles to be performed at target frequencies within a predefined band and by the flight conditions/configuration. For example, high drag flight conditions and/or aircraft configurations require a lower duration of the maneuver, to ensure maintenance of the trim conditions. A longer maneuver allows a more accurate identification of the low frequency modes and a higher resolution of the Discrete Fourier Transform (DFT) applied to construct the Bode plots (Tischler, 1995; Tischler, 1987).

An example of a good quality Bode Plot resulting from the frequency domain analysis of the maneuver in Figure 7 is displayed in Figure 9. Details on the approach to assess the quality of the results of frequency domain analysis are provided at the end of the section. The distribution of the sweep frequency content is usually linear, i.e.: chirp input, or logarithmic. The logarithmic distribution of frequencies presents significant advantages in the construction of Bode plots, as it is characterized by a more evenly distributed frequency content in the low frequency range. Frequency sweeps can be performed manually by the pilot, or automatically, usually in FBW aircraft. Common characteristics of conventional manual frequency sweeps are:

- higher frequency content than programmed inputs, for the analog and variable nature of the human pilot;
- limited duration/number of cycles in the low frequency range, due to usually large initial drift from trim conditions;
- inconsistent variation of frequency with time, with tendency to dwell at the resonant frequencies;
- small range of input frequencies, often concentrated in the high end of the spectrum, which is usually less relevant for the rigid body dynamics;
- short overall time duration, which reduces the number of cycles per frequency and the resolution of the frequency domain analysis; and
- inputs coupling, highly dependent on the type of inceptor.

The characteristics listed above demonstrate that significant attention has to be dedicated to reducing pilot's distortion of the input and that the negative qualities reported above can be removed by the inputs being generated automatically.

At the same time, the higher frequency content of the manual maneuver makes it preferable for the higher amount of information contained in the data. In this case, the term "frequency content" refers to frequencies below the vehicle bandwidth and human bandwidth is comparable to aircraft bandwidth, which derive from the analog nature of the human body and the small imperfections that a human pilot introduces in the input. This is true for the same frequency sweep and across different sweeps, which are never the same, also providing a more varied base of inputs of the same nature. Having a certain amount of human pilot inputs can be advantageous for these reasons. Adding small amplitude additional frequency content to the programmed frequency sweep is a possible practice to simulate the characteristics of a manually executed maneuver and enrich the input frequency content.

Manually executed maneuvers are preferable also in case of slight aircraft dynamics coupling, due to potential lateral CG offsets in nominally symmetric configurations, as the pilot can cancel the aircraft response in the undesired axis. This applies also at flight conditions close to the boundaries of the envelope, as the pilot can avoid envelope exceedances with relatively low workload, when required. Programming of both secondary control tasks mentioned above in an automated system presents difficulties that, as reported, are significantly attenuated by the manned execution of the maneuver. Another possible approach is combining pilot's inputs with PTIs, where the FCS performs the open loop portion of the task, and the pilot applies the slow closed loop corrections to remain close to trim conditions and cancel undesired cross-coupled responses. Large dynamic coupling has to be dealt with by multiple-input and multiple-output (MIMO) analysis, which is not usual for conventional aircraft, while it is potentially relevant for UAMs, especially in case of failure modes.

Guidelines for consistent manual execution of frequency sweeps aimed at the rigid body frequency range of interest are summarized below:

- Initial and final conditions must be in steady trim, and several seconds of this trim must be included in recorded data. The frequency sweep is considered to be a "transient" in the Fast Fourier Transform (FFT) analysis.
- Initial input period can typically be around 0.25 Hertz; this corresponds to one cycle in 4 seconds.

- The first one/two cycles should be at relatively constant frequency to assure that transients have damped out.
- Each subsequent cycle of the sweep can be about half the period of the previous cycle. It is important to increment the input frequency at a constant pace.
- The pilot may find it useful to count aloud, or have the pilot not flying/FTE count aloud, until frequency gets high, i.e.: about one Hertz.
- For linear aircraft response, maximum on-axis amplitude of the perturbation should be in the following ranges:
    - attitudes within ±10 deg
    - angular rates within ±10 deg/s
    - airspeed within ±10 kts of trim

These limits are not necessarily applied simultaneously, but can be dependent on the maneuver and the flight conditions. Limits on AoA, AoS, Mach number can be specified in parallel with those reported above, even if they are already part of the maneuver specification. The definition of the limits begins from the analysis of the pure aerodynamic data, evolves through offline simulations, and is eventually validated via manned simulations. The sensitivity of the results to angular rates can be high in aircraft with vortical lift generation, which are subject to large aerodynamic hysteresis cycles. This is one of the factors that has to be taken into account in the definition of the maneuver limits.

- The gain usually decreases as frequency increases:
    - Low-damping modes can result in an increase in gain near the modal natural frequencies.
    - A cockpit fixture should help maintain constant input amplitude, alternatively the pilot can limit the input by moving the inceptor with a travel comprised between the thumb and the middle finger of the hand not holding the inceptor. Dedicated visual systems are being developed for implementation in HDDs, to visually guide the pilot in the correct execution of the maneuver.
    - Inputs have to be performed in a single axis.

    - Smaller inputs are potentially required at low frequencies to maintain flight condition. Care should be taken when the amplitude of the input is not constant, as the amplitude of the output is no longer solely driven by the gain of the dynamic mode.
    - The peak in the gain corresponds to the resonant frequency, which may be significantly different from the natural frequency, especially for highly damped modes, as the short period typically is.
- If a large control input is required, it is necessary to start the sweep at a higher frequency, to reduce the drift from the trim conditions.
- Off-axis responses should be regulated only to maintain flight condition:
    - Maintain off-axis inputs at as low a frequency as possible.
    - Bias off-axis control as necessary to maintain flight condition.
- If possible, it is important to repeat the sweep two or three times at the same flight conditions. This allows to concatenate the series of sweeps in the data analysis phase. Details about the higher accuracy of the results obtained from analysis of concatenated sweeps are provided in section 4.5.4.
- Real-time monitoring is useful:
    - Predefine maneuver Knock It Off (KIO) and abort calls.
    - Confirm the required frequency and amplitude ranges are achieved.

Decision of whether performing the maneuver automatically or manually derives from consideration of the different factors reported above, it depends on the specific characteristics of the vehicle control system and on its developmental stage. Full FCS capabilities and implementation of control laws test bed modes are usually not completely established in the initial aircraft developmental stages. This can potentially lead to manual maneuver execution. Installation of tested and reliable PTI systems usually occurs in more mature stages of the vehicle development and it leads to automatic maneuvers being a feasible alternative to manually executed sweeps.

Figure 6 displays a notional FW aircraft response to a linearly distributed frequency sweep (i.e.: chirp signal) of elevator deflection. The plots are of the quantities variation with respect to core of the envelope trim conditions. The input begins and ends at zero, with amplitude of the perturbations broadly symmetric with respect to trim, except for airspeed. The minor asymmetric deviation of airspeed and angle of attack from trim in the initial, low frequency part of the maneuver is characteristic of aircraft responses to frequency sweeps and, as displayed in the figure, tends to be attenuated with the increase of the input frequency. The sine function is the reference for the input definition, as it allows it to begin and to end at zero. Data generated by performing frequency sweeps are usually acquired by a Flight Test Instrumentation (FTI) system for real time or post-test analysis.

Guidelines for the execution of automated frequency sweeps are listed below:

- As for the manually executed maneuver, initial and final conditions must be in steady trim, and several seconds of this trim must be included in recorded data.
- Minimization of drift from trim conditions:
    - Consider starting with a bank angle offset for roll, a different pitch attitude for pitch, to reduce the tendency to asymmetric perturbations produced by symmetric sweep inputs.
    - The pilot can manually minimize trim drift; this will add more signal on top of the sweep.
    - Sweeps from high-to-low frequency have been performed to avoid the initial drift from trim. Their use is not recommended as they potentially lead to rate and position limits at the start.
- Attention is to be dedicated to input amplitudes (application of a buildup approach in frequency and amplitude):
    - Monitor the sweep.
    - Provide the pilot with an immediate input termination method.
    - Shaped sweeps can be used, in which the amplitude of the initial low frequency input is reduced with respect to the higher frequency input.
- Chirp sweeps (linear increase of frequency) rapidly progress from the initial frequency:
    - A fraction of the first cycle occurs at the starting frequency.

    - It is recommended for the initial frequency to be half or less of the lowest desired frequency.

In aircraft not equipped with an FTI system, frequency sweeps can still provide useful information for the detection of natural frequencies and for the qualitative assessment of the aircraft response varying input frequency. In this case, the pilot executes the maneuver by bracketing the inceptor travel within the thumb and the middle finger of the hand not holding the inceptor, to ensure constant input amplitude. This allows the flying crew to derive a qualitative assessment of the frequency domain response. The constant amplitude of the input is a high priority for the adequate quality of the maneuver.

Practical experience of execution of constant amplitude, manual frequency sweeps on non-instrumented general aviation aircraft demonstrated its value for the evaluation team in indicating potential low damping ratio modes and indications regarding the consequent proneness to PIO. This simplified approach is usually applied for initial evaluation of the aircraft response prior to execution of handling qualities testing, in aircraft not equipped with an FTI.

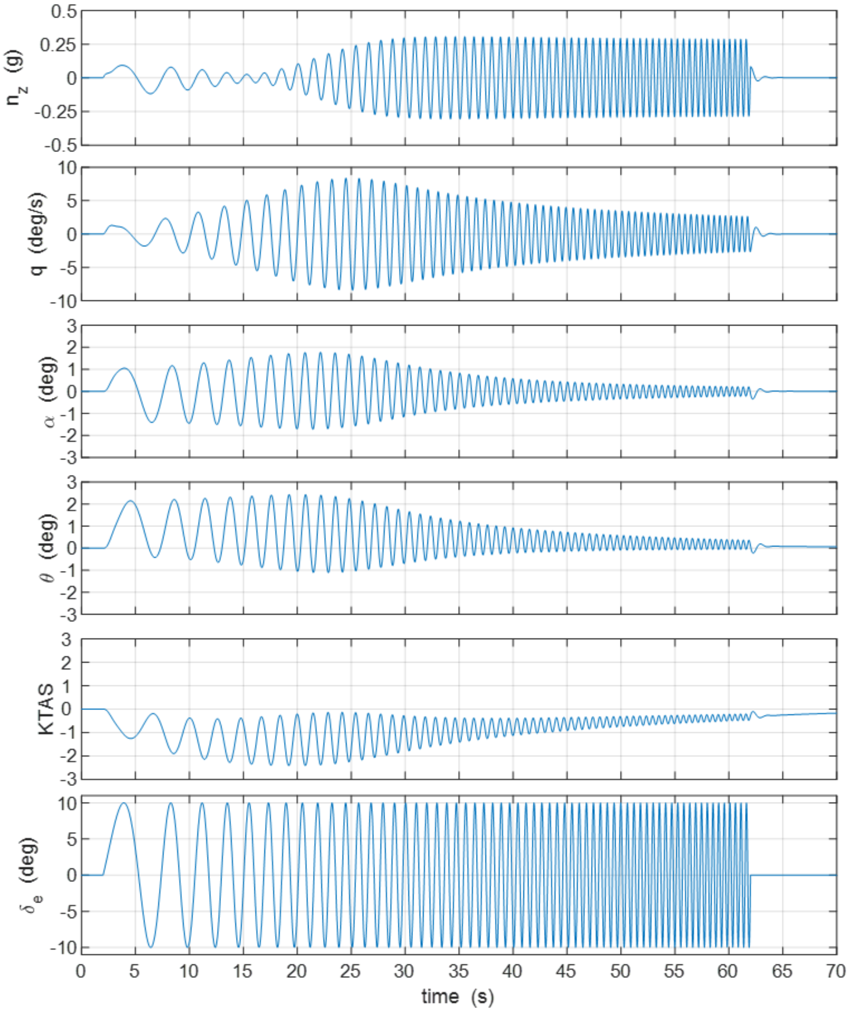


Figure 6. Example of frequency sweep time history

4.5.3 Inputs, outputs, flight phases, and aircraft dynamic modes

The inputs required to excite the aircraft motion depend on its configuration and they do not necessarily coincide with those used in the data analysis. For example, in a conventional FW aircraft configuration, the inputs for longitudinal and lateral frequency sweeps are respectively elevator and aileron. Directional/rudder frequency sweeps are considered safety critical for the buildup of vertical tail loads, potentially leading to structural failure. They are not recommended and they are not treated in this report.

In unconventional aircraft configurations, alternate inputs for longitudinal or lateral frequency sweeps can be respectively symmetric taileron, or differential horizontal tail deflection. The selection of the input control surface depends on the transfer function to be identified and on the type of analysis to be conducted. Identification of the aircraft aerodynamics is strictly dependent on the control surface(s) exciting the aircraft response. Identification of the aircraft response to pilot's inputs depends on the inceptor inputs alone.

As an example, an aircraft is considered in which lateral control is affected by the following combinations of control surfaces deflection:

- aileron deflection at low angle of attack/high airspeed
- combined aileron and differential horizontal tail deflection in the medium alpha range
- differential horizontal tail deflection in the high alpha range

The minimum approach to characterization of the aircraft aerodynamics is to perform a series of frequency sweeps in the three described alpha regimes. The execution and the selection of the input control surfaces depends on the FCS configuration.

Three options can be assumed:

1. The inceptor to control surface command path is not modifiable, the standard control laws command gain scheduling is active. In this case, the combinations of control surface(s) deflections commanded by the inceptor depend(s) on the flight condition. Consequently, the selection of the test flight conditions has to ensure that a lateral inceptor input leads to a target combination of control surfaces deflections in an adequate range of airspeeds. These target combinations are: a) aileron alone, b) differential tail alone c) a set of different aileron/differential tail deflections allocations. Dependency on flight condition of control surfaces deflections combinations is a critical aspect, as it does not allow consistent vehicle identification outside the nominal control surfaces deflection/flight condition envelope. This limits the objective of the system identification to: a) verification of the validity of the aerodynamic tolerances for the progression of testing; b) verification of the flying qualities in nominal vehicle configuration; c) identification of the transfer functions of the aircraft dynamics states to inceptor travel, or to each control system element within the command path; d) feel system identification. The pilot has to manually execute the maneuver; the respect of the target flight conditions is a high priority to ensure the target control surfaces deflection allocation.

2. The inceptor to control surface command path is modifiable, within a control laws test bed mode: the commanded control surface combinations are selectable. The satisfiable objectives of the system identification are those of the previous case, plus the identification of the vehicle aerodynamic/aeromechanic characteristics in the whole

envelope, for each selected command allocation of control surfaces deflections. The pilot has to manually execute the maneuver; the respect of the target flight conditions is a potentially lower priority than for the previous case, as the command allocation is independent from flight conditions.

3. A PTI dedicated test bed mode is implemented in the flight control system. The system identification technical objectives coincide with those of the previous case, except for feel system identification. The maneuver is executed automatically, under pilot's monitoring.

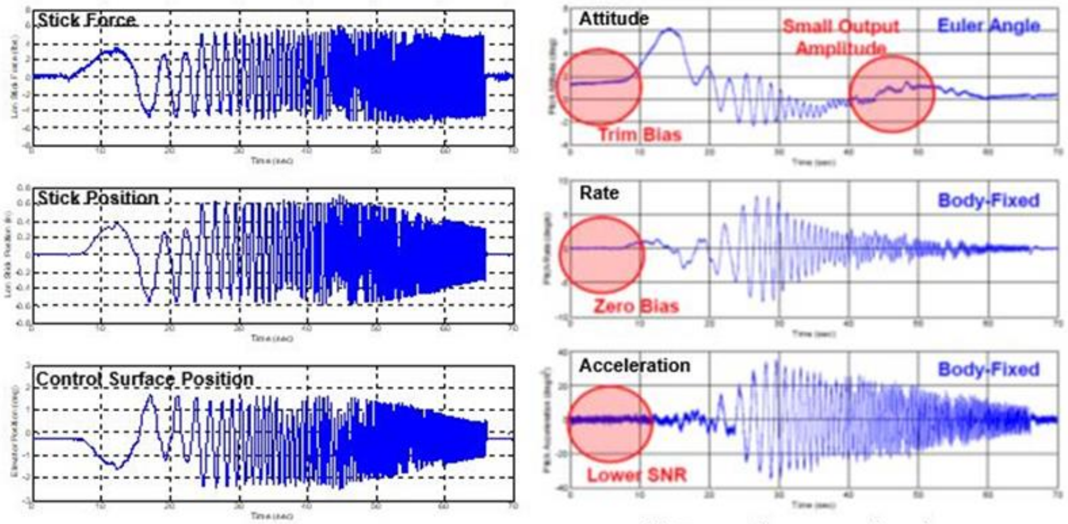
The previous example applies to any FBW aircraft command channel and combination of control surfaces deflection allocation, without loss of generalization. Deep knowledge of control laws implementation and control system mechanization is required to plan for effective testing, real time test monitoring, data analysis, and synthesis. This is a fundamental phase of the overall testing and certification activity. The FAA FCS/system engineering group can support the flight test group in tracing the FCS, control laws and flying qualities requirements throughout the whole design/development/verification and certification process. This would allow the flight test group to plan tests based on the aircraft augmentation and control logics. It is important for safety and for efficiency of the test to approach the vehicle assessment based on predictions and on general expectations of its response. It is essential to avoid a "black box" approach, by directly addressing the potentially critical areas for handling instead. The applicant should provide evidence of the control system architecture, of the control laws design, and of the flight clearance results prior to flight testing. Lotterio (2022) can be useful in tracing these steps through the aircraft development to testing.

The input/output combinations for the different types of system identification analyses reported above are described in detail in section 4.5.5 and 4.5.3.

4.5.4 Required analysis processes

The frequency sweep is designed to conduct frequency domain data analyses. The minimum required analysis process is calculation of the Discrete Fourier Transform of a time-based data series and its synthesis into Bode plots. Example input and output signals of a typical flight test frequency sweep are shown in Figure 7. The example inputs include control inceptor force, control inceptor position, and control surface deflection. It should be noted that for piloted inputs, any of the identified inputs past the inceptor force signal could also be outputs. For example, control inceptor position can be an output with control inceptor force as an input if the objective is to identify the feel system. Typically, stick force is selected as the input when the objective is to identify the entire command path. Stick position is used to identify the command path minus the feel system and the control surface position is used when the objective is to identify the controlled element dynamics. Figure 8 is a schematic of the full aircraft system, which includes bare airframe, actuating, feel and control system, with the principal input/output nodes for analysis. The nodes correspond to the typical data access points in a conventionally instrumented aircraft. It is important to consider that the same schematic applies to simulators with hardware components in the loop, or to iron birds.

Example output signals in the longitudinal plane are angular attitude, rate, and acceleration. As shown in Figure 7b, with an attitude signal there is often a trim bias that should be removed. Furthermore, the attitude signal often has a lower amplitude response at the higher frequencies resulting in reduced output power. The body rate output is often an ideal signal as it will have zero bias and good output response throughout the frequency range of interest. Lateral and rotary accelerations, like rate signals, have good output response but also lower signal-to-noise ratios (SNR). Table 7 reports the system input and output pairs, and the corresponding type of system analysis.



a) Example input signals

b) Example output signals

Figure 7. Example input and output signals

Table 7. Data input-output pairs and analysis type

Input-Output Node Pair		**Analyzed Element**	**Notes**
Input	**Output**		
1	2	Feel system	
1	3	Entire command path	
2	3	Command path minus feel system	
4	5	Actuators	Possible insertion of PTIs at node 4
4	6	Bare airframe plus actuating system	
5	6	Bare airframe	Identification of the aircraft aerodynamics.
2	6	Entire system minus feel system	Example: relevant for validation of the aircraft attitude bandwidth(s), without feel system dynamics.
1	6	Entire system	Example: relevant for validation of the aircraft attitude bandwidth(s), with feel system dynamics.

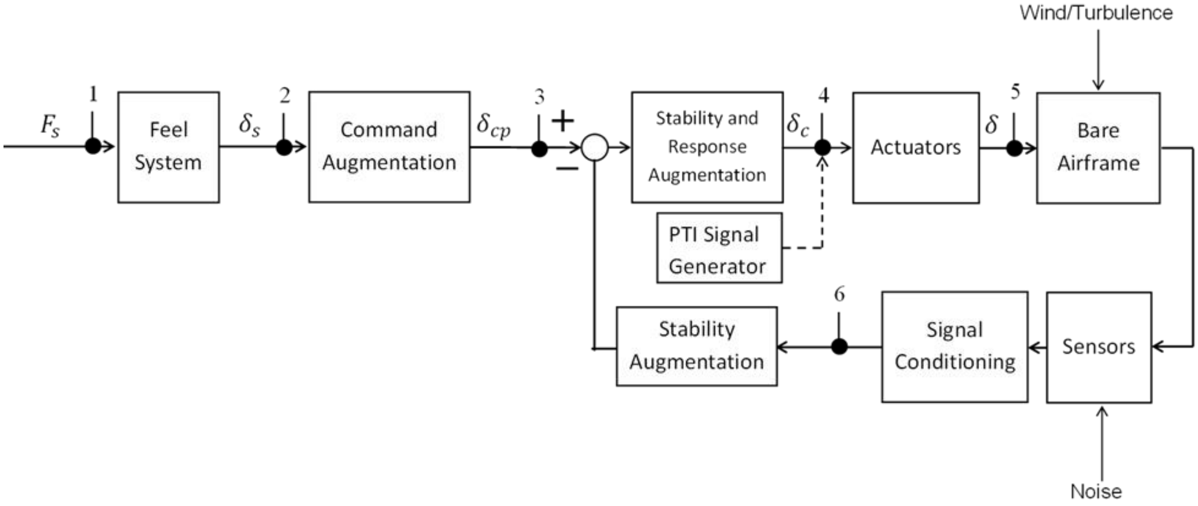
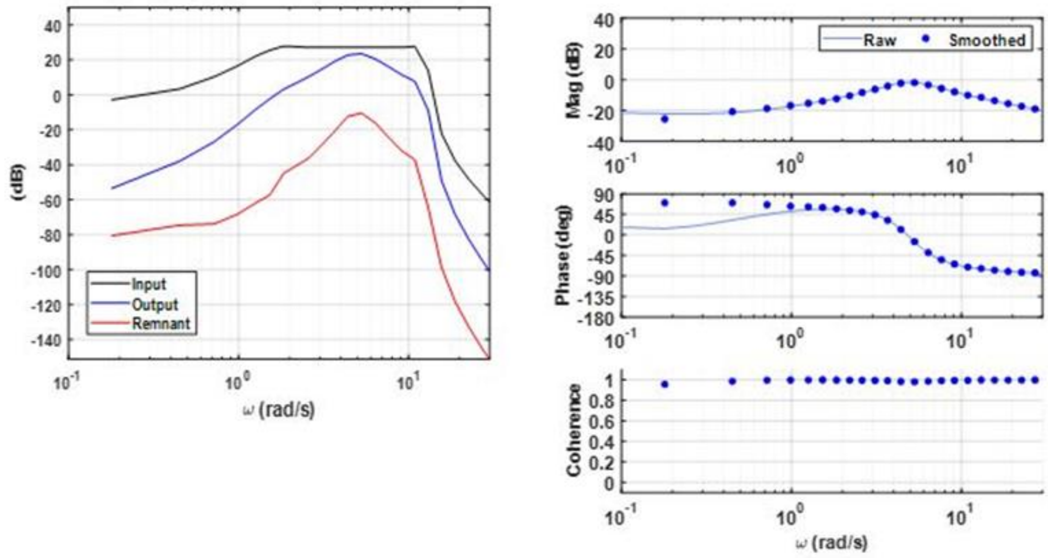


Figure 8. Schematic of aircraft system

Analysis of Figure 9 provides indications of the critical elements to consider for assessing the quality of the analysis in the frequency domain. An important element is the separation between the Power Spectral Density (PSD) of the output and that of the remnant. The remnant is the part of the output that is un-correlated with the input. A significant separation, in the order of 20 dB and higher, ensures that the impact of noise on the results is negligible to minor. The difference between the two PSDs in Figure 9a) is higher than the 20 dB threshold in the whole frequency range, owing to the ideal condition of complete absence of noise. The significant separation between output and remnant is confirmed by the high values of the coherence, close to one, in the whole frequency range of the test. The PSD of the input demonstrates a constant distribution of the input power in the frequency range of interest, $\omega = [1, 10]\ rad/s$, leading to a well discretized Bode plot, displayed in the first two plots of Figure 9b).

This analysis is aimed at discussing the quality of the results and it is independent from the dynamic characteristics of the vehicle resulting from the Bode plot. Discussion of the dynamic response is provided further in the document.

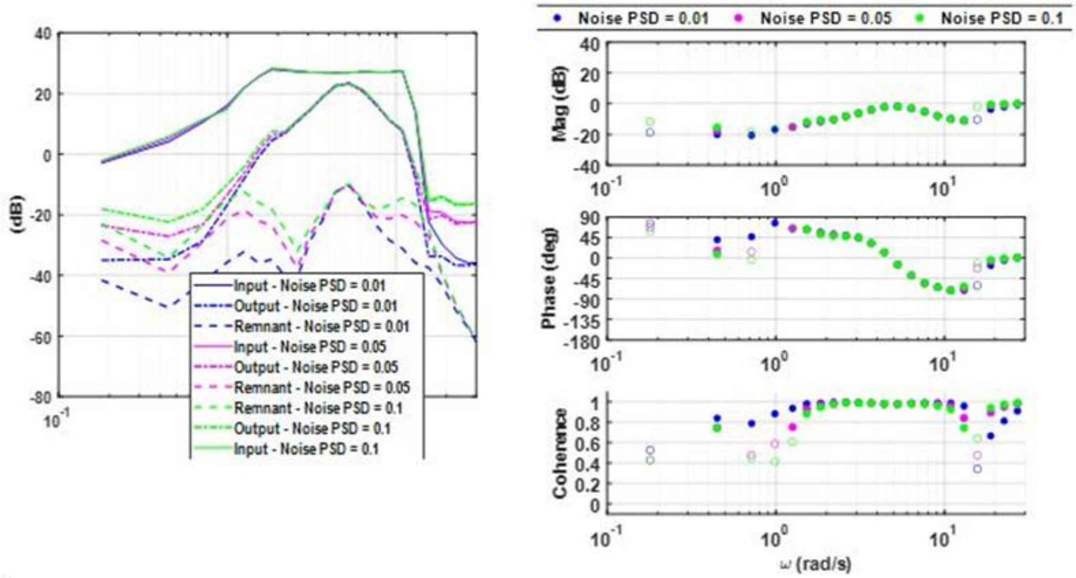


a) b)

Figure 9. PSD & bode plot of generic airplane q/δe transfer function

Experimental data are characterized by the presence of noise, which can negatively affect the accuracy of the results of the system identification, both in the frequency and in the time domain. White noise of increasing power was injected in the input and outputs of the generic FW aircraft simulation model mentioned above. Figure 10 illustrates the resulting effect on the accuracy of the results, which is indicated by the value of the coherence and by the separation between the

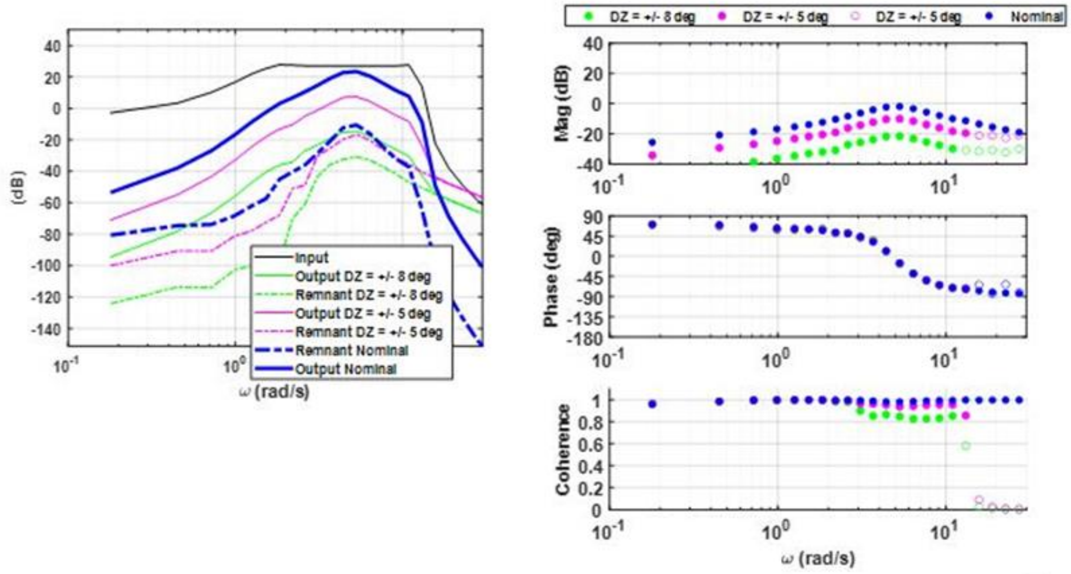
PSDs of output and remnant. The value of the remnant PSD increases significantly increasing the noise power, except for the frequency range in the surrounding of the short period frequency, $\omega = 5\ rad/s$, where the magnitude of the aircraft response is maximum. This corresponds to the reduction of the separation between the PSDs of output and remnant in the same frequency ranges, which do not include the frequencies in the surrounding of the short period. The impact on the input is negligible, as expected for the relatively small magnitude of the noise. The Bode plot of Figure 10b) demonstrates a significant and progressive reduction of the coherence below the acceptable value of 0.66 in the surroundings of $\omega = 1\ rad/s$, with a further localized decrease at $\omega \approx 16\ rad/s$. Decrease in the value of the coherence can be produced by different types of nonlinear components in the signals, derived from sensor characteristics, or from the implementation of nonlinear elements in the control system which include dead zones, saturations, and rate limiters.



a) b)

Figure 10. PSD & bode plot of generic airplane q/δe transfer function, varying noise

Presence of nonlinear elements in the control system affects the overall aircraft response. The following discussion is relative to the variation of the Bode plot and of the PSDs of output and remnant produced by the implementation of a dead zone in the control system command path. The amplitude of the elevator deflection of the sample frequency sweep is $10\ deg$ and that of the dead zone (DZ) is $\pm 5\ deg$ and $\pm 8\ deg$, respectively. Figure 11 illustrates a progressive reduction of the gain with increasing amplitude of the dead zone, with negligible impact on the phase of the response. This is accompanied by a corresponding minor reduction of the coherence in the frequency range $\omega = [0.1, 13]\ rad/s$. The time histories of the sample aircraft response to the frequency sweep, varying dead zone amplitude displayed in Figure 12 confirm the significant reduction of the amplitude of the response. This is produced by the reduction of the amplitude of the control surface deflection, for the same commanded deflection. Output and remnant of the responses of the nonlinear systems coalesce at the same frequency at which there is a major reduction of coherence: the whole output coincides with the remnant and co-linearity is completely lost. It is important to notice that these characteristics depend also on the amplitude of the input, which is typical of nonlinear systems like that of the example. The displayed plots provide an indication of the trend of the response in presence of nonlinearities, they are not intended to be a complete description.



a) b)

Figure 11. PSD & bode plot of generic airplane q/δe transfer function, varying dead zone

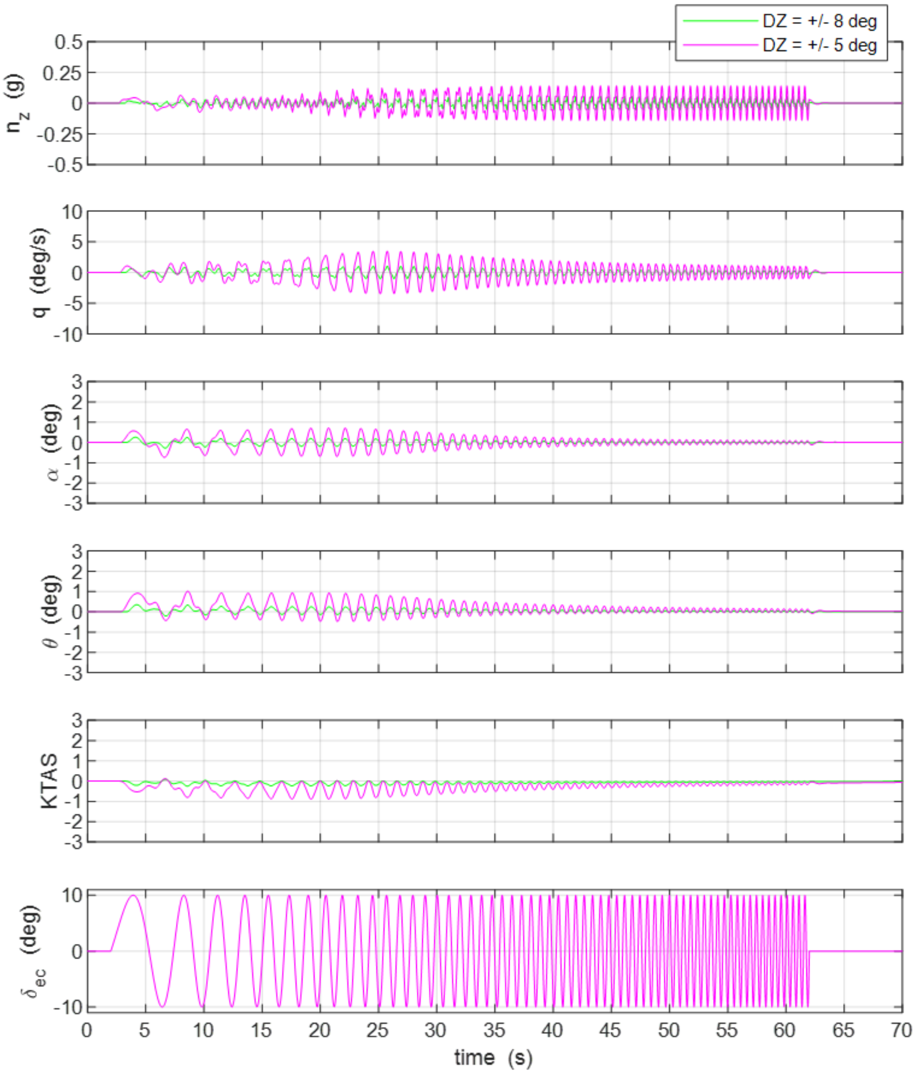


Figure 12. Frequency sweep time history – varying command path dead zone amplitude

Section 4.5.3 contains the recommendation to execute series of frequency sweeps to increase the consistency of the data analysis results. The following is an example from a practical application of the data concatenation concept.

During a system identification campaign on an aircraft, several frequency sweeps were performed in different flight conditions and aircraft configurations. Figure 13 and Figure 14 display the time histories of two frequency sweeps executed in separate instances at the same flight conditions, respectively designated sweep N 1 and sweep N 2 in this document. Angular rate was selected as output of the analysis, for the higher signal power, as indicated in section 4.5.3.

The time interval of each time history was determined to ensure one second of stable flight conditions at the beginning of the maneuver, and null value of angular rate, the output, at the end of the time series. This is to minimize the frequency leakage from the initial step of the data processing. Leakage is typically controlled by data windowing in the further steps of the data analysis. Attention to the initial and final values of the time history is important in the overall process, to proceed consistently at each step of the analysis. This also allows to use "light" windowing, minimizing the distortion of the signal.

It is noticeable how the input shape of both time histories presents irregularities and a narrow frequency range. This is mainly due to the limited time available to complete the maneuver within predefined tolerances with respect to the trim flight conditions. The reported usually lower value of SNR in acceleration signals is confirmed by observation of the load factor time history and its comparison with the angular rate and attitude time histories.

Figure 15 and Figure 16 display the frequency response plots of sweep N 1 and sweep N 2, respectively. The displayed data indicate that the difference between the PSDs of output and input is lower than the recommended value of 20 dB, for $\omega \lesssim 3\ rad/s$ and that the value of coherence is lower than the recommended value of 0.6 for $\omega \lesssim 6\ rad/s$.

Observation of the Bode plot indicates a relatively sparse distribution of valid data points, in a limited range of frequency. The empty circles correspond to low accuracy values, with value of the coherence lower than 0.66. Application of the Aircraft Bandwidth criterion requires identification of the frequency at which the value of the angular rate response phase angle is $\phi = -45\ deg$. This value of the angular rate phase corresponds to the required $\phi = -135\ deg$ for the attitude phase. It is not possible to identify the bandwidth from the data of the first frequency sweep. The aircraft bandwidth derived from the second frequency sweep is $\omega_{BW} = 1.6\ rad/s$. The confidence in the value of the attitude bandwidth is relatively low, considering the sparsity of data points in the vicinity of the intersection with $\phi = -45\ deg$.

The time series of the two sweeps are concatenated in the time domain, obtaining a single time series, displayed in Figure 17. Analysis of the figure confirms the important practice of selecting time slices in which the values of input and output are close to zero, at the beginning and at the end. Minor discontinuities can be noticed at the time of junction between the two maneuvers, occurring at $= 16\ s$. The concatenated time series are analyzed in the frequency domain with the same tools used for the previous analyses. The results of the frequency domain analysis are illustrated in Figure 18, which displays a significant increase of the output PSD values in the low frequency range, with increased separation between the PSDs of output and input in the frequency range $\omega = [0.4, 5]\ rad/s$. This is accompanied by averagely higher values of the coherence in the same frequency range and by a more definite trend of the phase values in the vicinity of $\phi = -45\ deg$, compared to that of the individual sweeps. This provides higher confidence in the results, which indicate $\omega_{BW} = 1.4\ \frac{rad}{s}$.

The presented example of concatenation illustrates the effectiveness of this data preprocessing technique for the accuracy and reliability of the results, even when the concatenated maneuvers are executed in different instances. Consistency of the flight conditions across the preprocessed maneuvers is the critical requirement. Execution of a series of maneuvers at the same flight condition and aircraft configuration is the recommended test approach, to guarantee homogeneous atmospheric conditions and minor variation of aircraft mass properties across the maneuver series. This implies defining the required test technique(s) with significant time margin with respect to the preparation of the test plan, which has to include detailed descriptions of the test approach and of its rationale(s).

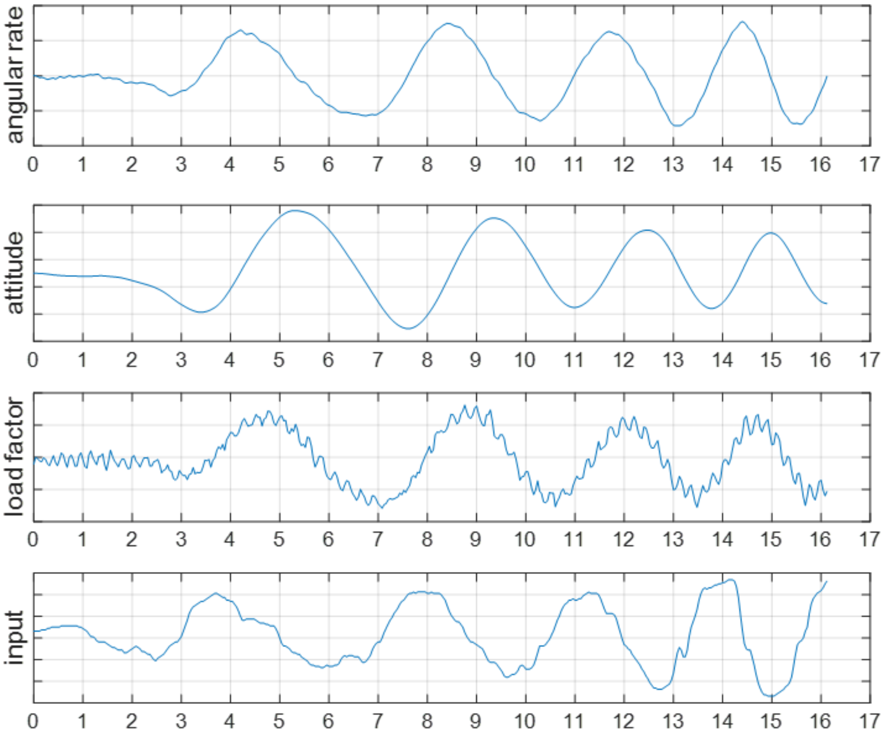


Figure 13. Time history sweep N 1

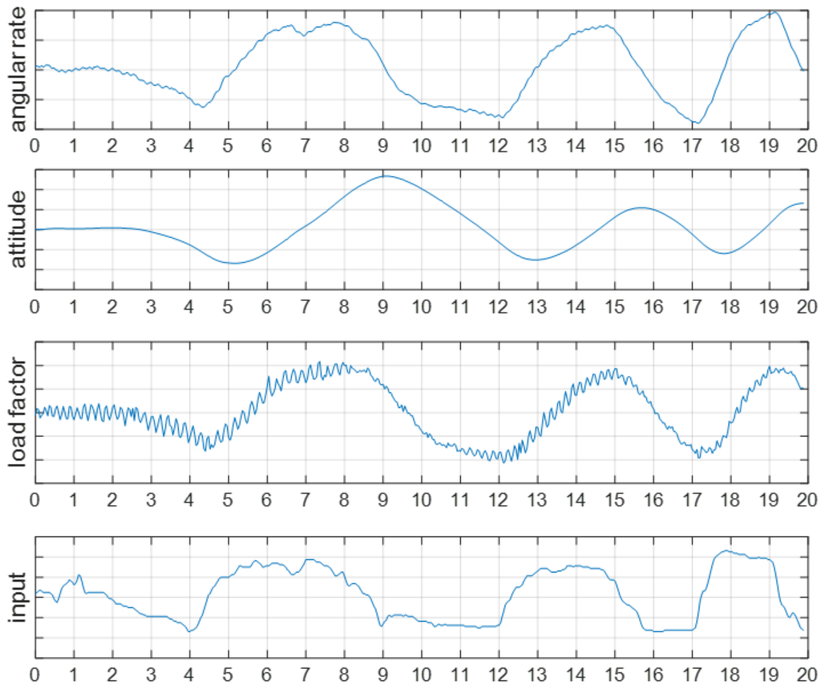
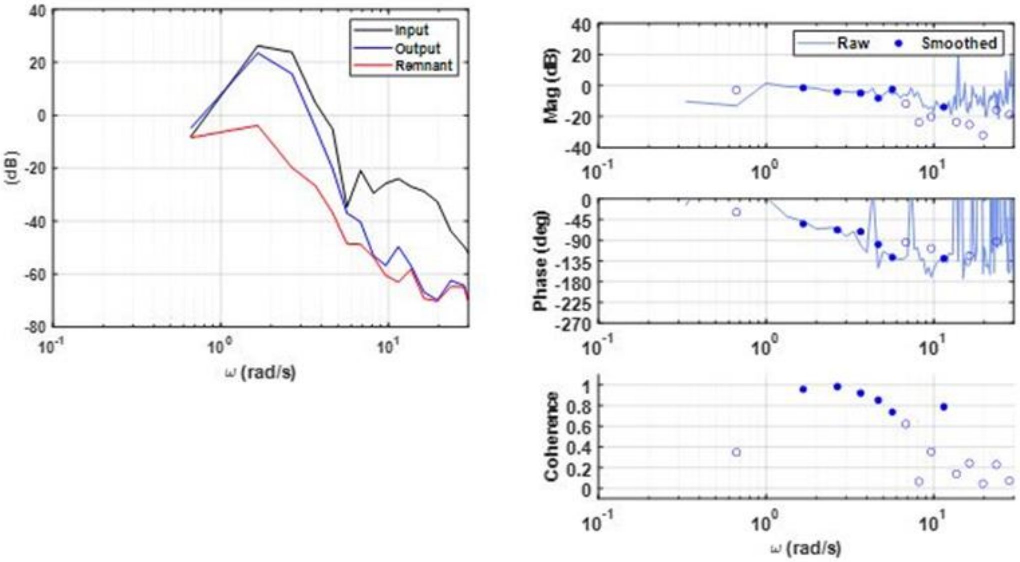


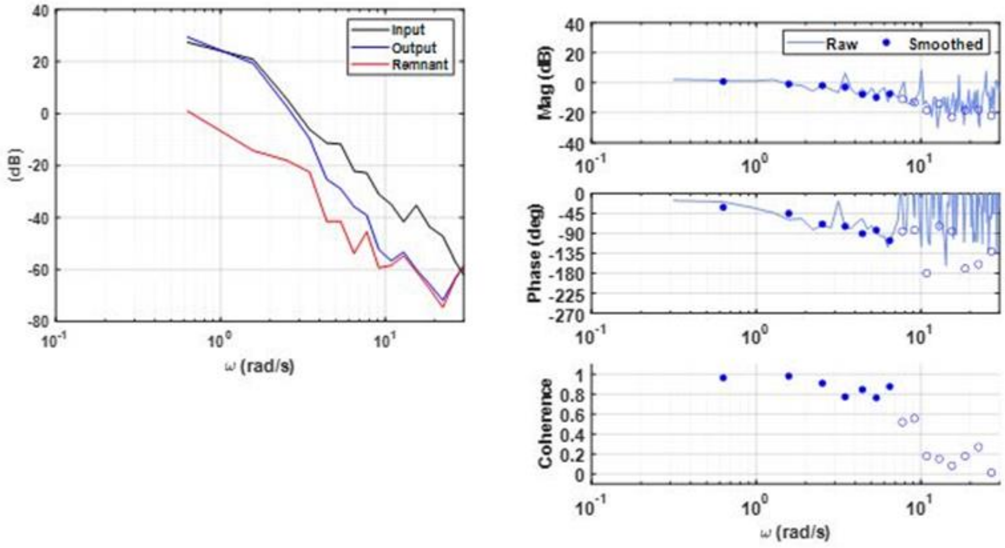
Figure 14.Time history sweep N 2



a)

b)

Figure 15. Bode plot sweep N 1



a) b)

Figure 16. Bode plot sweep N 2

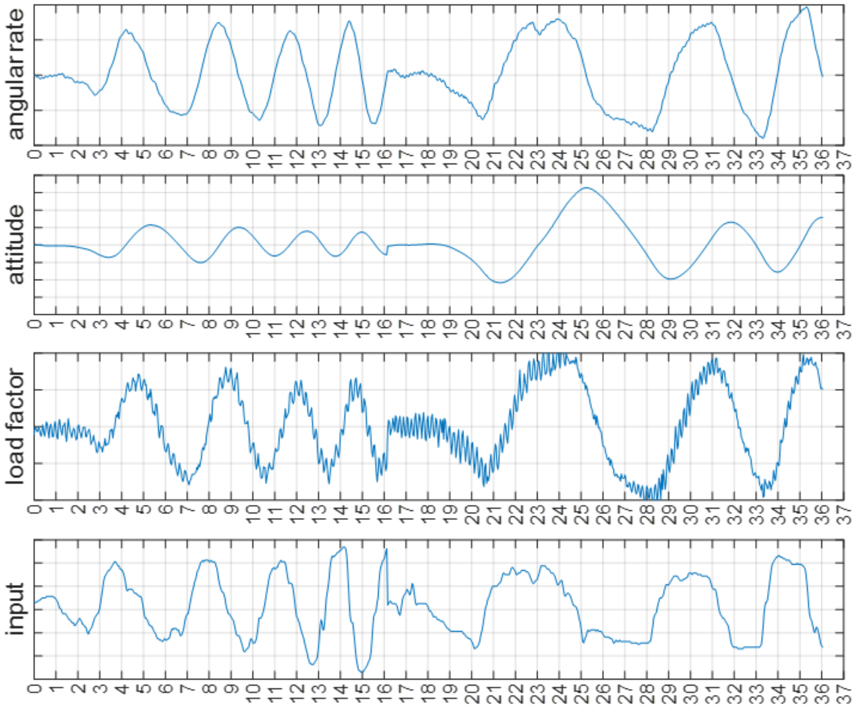


Figure 17. Concatenated time histories of sweep 1 and sweep 2

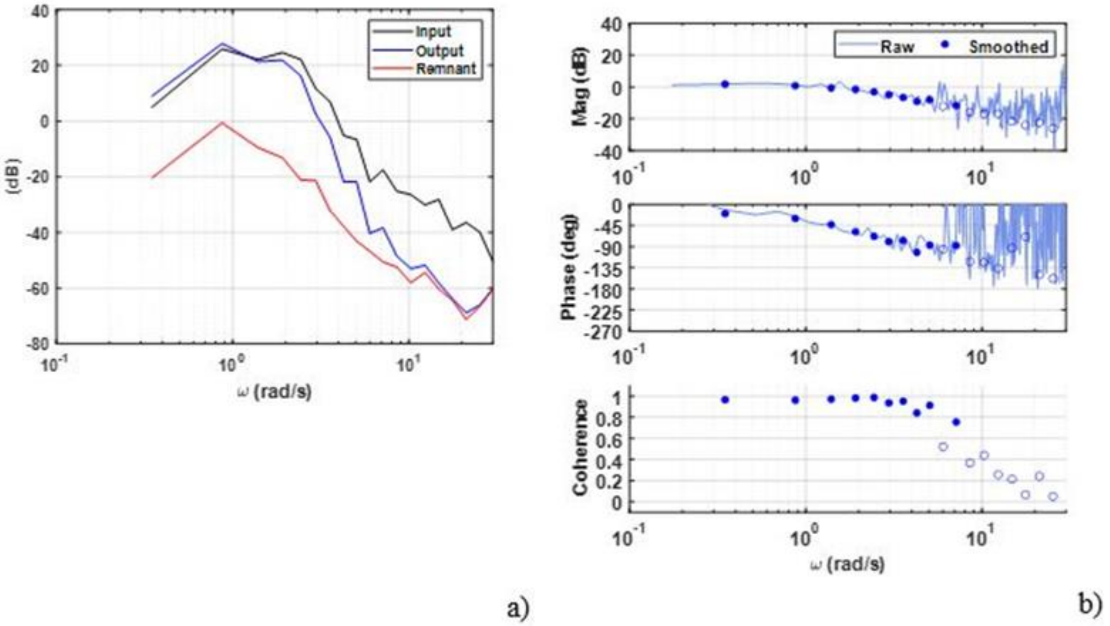


Figure 18. Bode plot of concatenated sweep N 1 and sweep N 2

4.5.5 Important aspects of data analysis

Frequency sweeps data analysis has to include aspects which are not strictly related to the frequency domain system identification alone. Important information regarding the vehicle characteristics and the overall data quality can be derived also from a combined observation of the data in the time domain, with consideration of the causes and of the impact on results of the observed characteristics. This is important to develop knowledge of both the aircraft and the data, based on different analysis approaches.

As an example, Figure 19 displays the stabilizer deflection produced by a frequency sweep of longitudinal stick deflection. Observation of the time history indicates rate limited stabilizer deflection from $t \approx 38\ s$ to the end of the maneuver. Rate limiting is evident by the “sawtooth” shape of the trace enclosed in the black ellipsis. It is important to detect and consider this data characteristic for two main aspects:

1. Input:

- amplitude reduction to avoid actuator/effector rate limiting and allow respect of the condition of linearity
- sweeps with increasing amplitude can be performed to determine the rate limiting onset and investigate the rate limited response of the aircraft.

2. Understanding of the expected impact on the results of the frequency domain analysis, produced by the presence of actuator/effector rate limiting. These are gain attenuation and significant phase lag at the frequencies of rate limiting occurrence. The same effects can be caused by the inherent dynamic characteristics of the vehicle, and it is important to discern between the two causes to identify potential modifications for improvement, which can be applied to the aircraft actuators/effectors, or to the airframe itself.

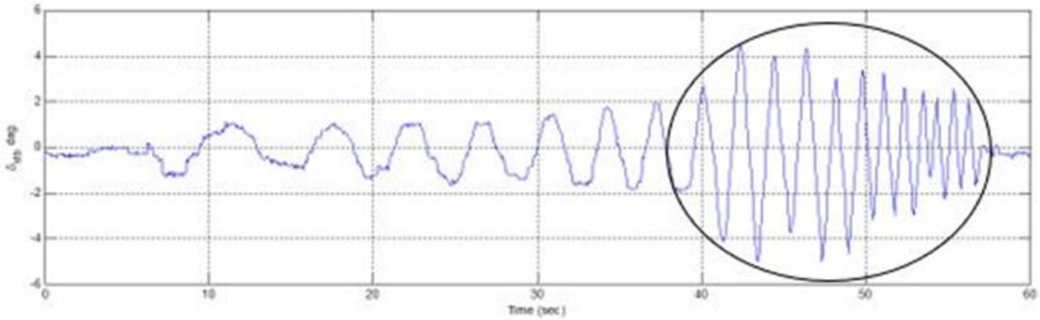


Figure 19. Rate limited stabilizer deflection frequency sweep

The impact of data artefacts on the accuracy of the analyses can be significant. Figure 20 displays one example of consistent sampling rate and three examples of potentially inconsistent, irregular data sampling. This artefact can derive from issues in the analog to digital conversion, from fusion of signals with different sampling rates or of asynchronous signals in networked control systems, and from variations in the system components. In some cases, sampling rate irregularities are the result of a system design choice, which can lead to event-driven sampling, depending on the sensor output with an optional feedback loop from the estimator. This logic is usually chosen to limit resource consumption, accepting a performance reduction. The impact is the incorrect representation of the system as time variant, the insertion of noise, and a consequent reduction of the coherence.

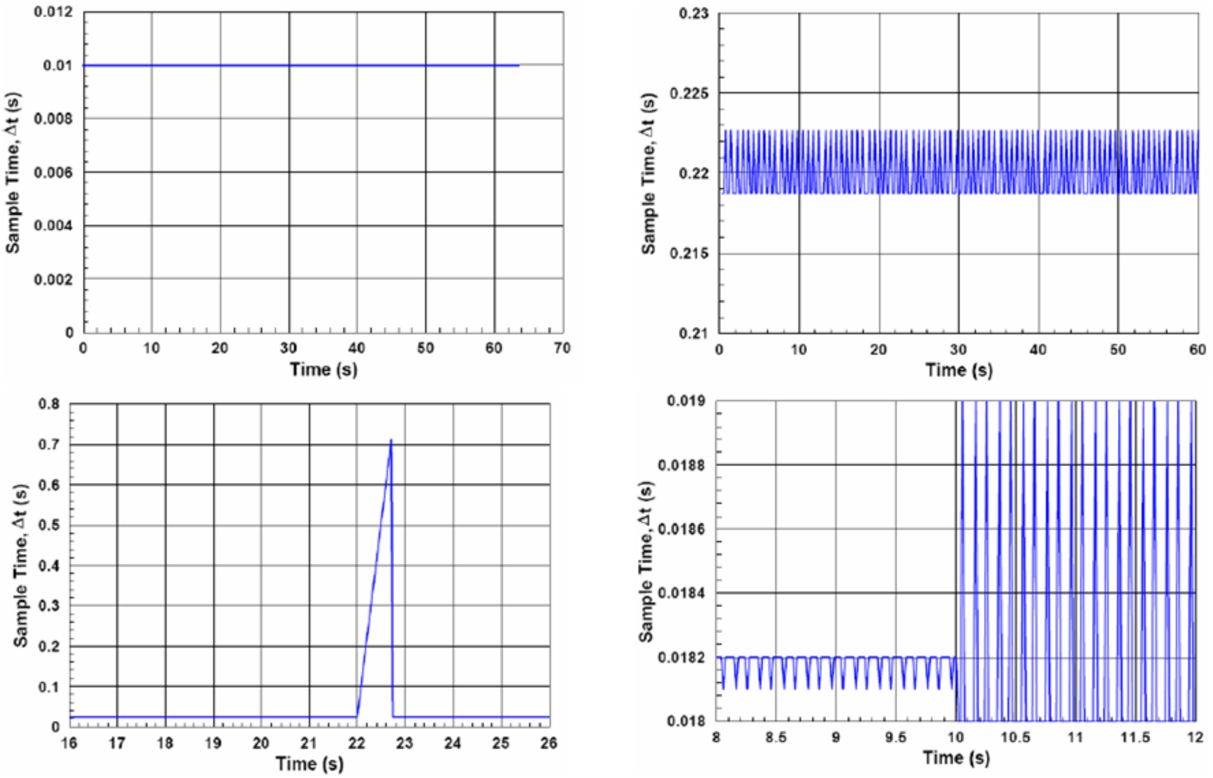


Figure 20. Examples of inconsistent data sample times

Data dropouts, illustrated in Figure 21, can be the result of inconsistent sampling rate or of missing data packets, the second case potentially closer to the phenomenon displayed in Figure 21b). The effect on the signals is of increasing noise, thus reducing SNR and, in the second case, of significantly altering the frequency content of the input and of the response.

Based on the descriptions above, preprocessing to ensure that data are not affected by artefacts independent from the aircraft dynamics is a fundamental step for obtaining high accuracy results.

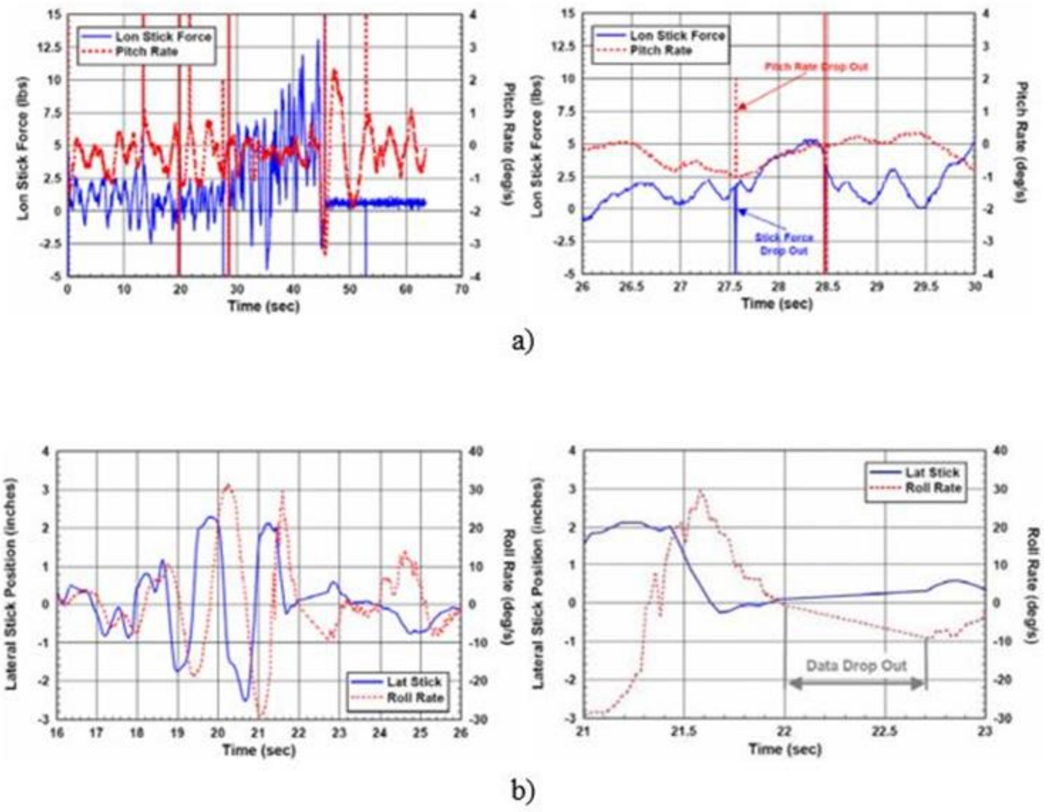


Figure 21. Examples of data dropouts

A data analysis example is provided below, to synthesize in an operative task the concepts described above. The process is divided into multiple steps detailed below:

1. Selection of time interval
2. Frequency domain assessment of the input quality
3. Frequency domain assessment of the output quality
4. Frequency domain analysis of the vehicle response

Selection of time interval

The relevant time interval is selected to coincide with the beginning and the end of the longitudinal stick input. The displayed data are of a conventional FW aircraft, for which the amplitude of the pitch rate response to a high frequency longitudinal input is inherently low. The amplitude of the response can be significant, based on the frequency range of the input and on the type of dynamic response. This requires selecting the end time in correspondence of the null response amplitude, to minimize the risk of injecting high frequency content of the output signal at the end of the time series.

The steadiness of the input amplitude is a useful metric to be considered for preliminary assessment of the input quality, as a constant amplitude is an indication to expect almost constant power.

Frequency domain assessment of the input quality

Analysis of the input PSD, to ensure that the input power is high and almost constant throughout the relevant frequency range of the sweep.

Figure 23 displays the input power of the frequency sweep displayed in Figure 22 and the corresponding frequency range of relevant input data. It is important to notice the slight, but continuous decrease of power with increasing frequency and its abrupt decrease at $\omega \gtrsim 28\, rad/s$, maximum frequency with adequate input power.

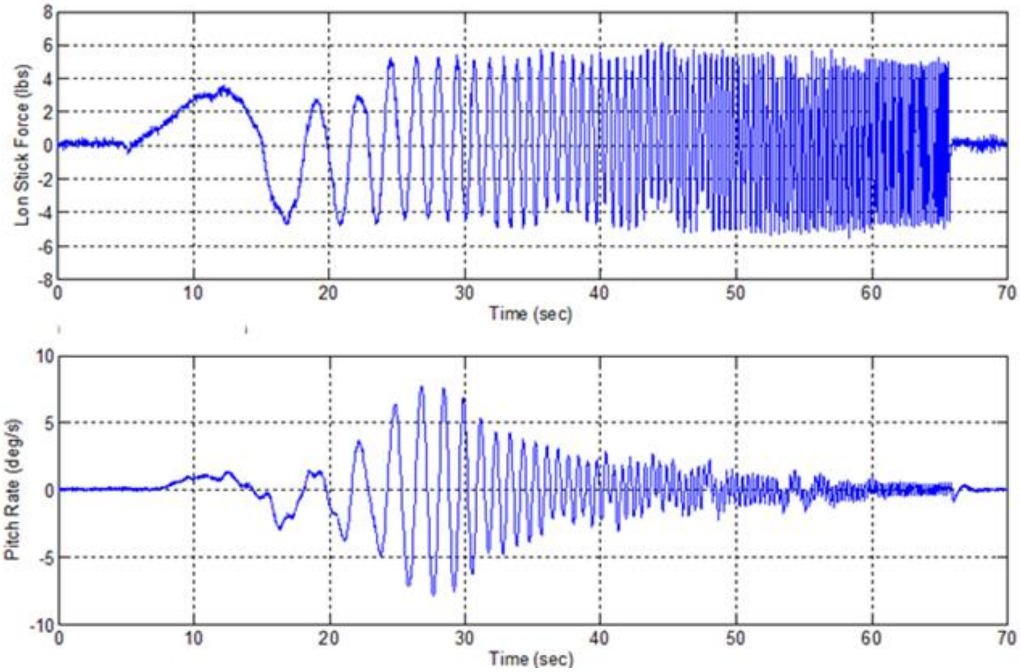


Figure 22. Time histories input-output - frequency sweep

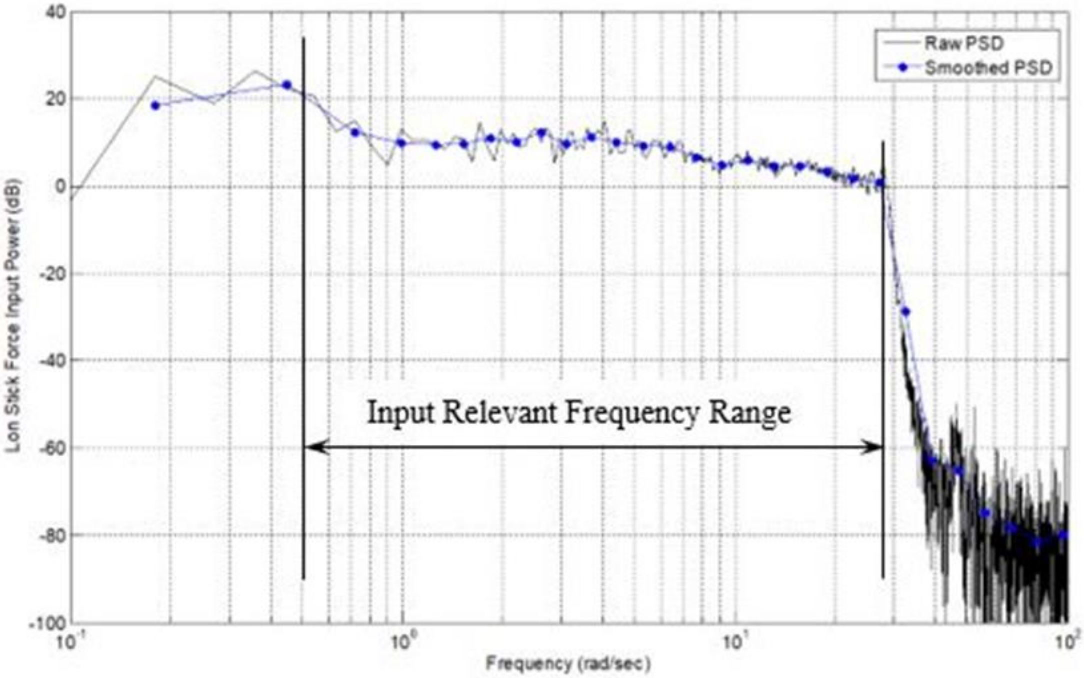


Figure 23. Input power – frequency sweep

Frequency domain assessment of the output quality

Analysis of the PSDs of output and remnant, to ensure that the input produced adequate excitation of the aircraft dynamics. This is based on the analysis of the separation between the power of output and remnant. The output power is expected to be lower than that of the input and to decrease with the increase of frequency, similarly to the input power trend. The requirement is for the output power to be significantly higher than the remnant power, which is the power not correlated with the input. The minimum acceptable difference between the two is in the range of 20 dB. A small difference indicates insufficient amplitude of the perturbation compared with the noise level. This step is also the basis to confirm the choice of the appropriate output signal. As discussed above, the power of angular rates is usually higher than that of the corresponding attitude.

Figure 24 displays the PSD of pitch rate and attitude of the frequency sweep introduced above, and the corresponding remnant. Analysis of Figure 24a) demonstrates that the required minimum separation of 20 dB between PSD of pitch rate and remnant is ensured within the full longitudinal stick force relevant frequency range, highlighted in Figure 23. Figure 24b) illustrates the insufficient separation between PSDs of pitch attitude and remnant for $\omega > 10\ rad/s$. The difference between the usable frequency range of pitch rate and pitch attitude is shaded in Figure 24b): it is a quantitative and qualitative significant difference, as $\omega = 10\ rad/s$ is within the frequency range of pilot control, limiting the capability of identifying the dynamics in its most critical frequency band. It is important to notice the efficiency of selecting pitch rate as the output: it is possible to derive reliable results in the full relevant frequency of the input, with minimal waste of test time and data.

Expected high accuracy of the results in the highlighted frequency range is confirmed by the plots of Figure 25, respectively of coherence and SNR. Their values are higher than the threshold of acceptability within the same frequency range, decreasing abruptly outside of it. The coincidence of the critical frequency values of input and output discussed above demonstrates high quality of the maneuver and of the acquired data, providing a high level of confidence in the results.

Frequency domain analysis of the vehicle response

Analysis of Bode plot(s) and derivation of the corresponding transfer function(s) from the application of system identification programs to the selected input(s) and output(s) pairs.

Figure 26 is an example of pitch rate to longitudinal stick force Bode plot resulting from the data acquired in the frequency sweep described above. The Bode plot analysis is both qualitative and quantitative. The objective of the qualitative part is to ensure that the measured response matches the expected typical one for the class of vehicle to be identified.

It is important to notice that coherence is higher than its acceptance threshold value of 0.6 in the range of displayed data. The relatively high peak in the gain at $\omega \approx 4\ rad/s$ indicates a low damping ratio second order mode at the same frequency, which is expected to be the Short Period. The low frequency peak corresponding to the Phugoid mode is not visible and it is expected to be at a lower frequency than the minimum displayed. Observation of the plot indicates the presence of a high “pitch rate overshoot”, which is the difference between the peak value corresponding to the Short Period mode and the minimum value of the gain between the Phugoid and the Short period frequency. In this specific case, the minimum occurs at $\omega \approx 0.3\ rad/s$ and the pitch rate overshoot is around 15 dB, indicating a potential PIO proneness according to PIO prediction criteria.

The qualitative analysis is the first step in the acceptance of the results and it requires familiarity with the concept of Bode plot, dynamic modes and conceptual knowledge of the flying qualities criteria selected for the specific aircraft. The quantitative part is based on optimization/system identification algorithms which calculate the analytical transfer function. The objective of the quantitative approach is to derive the relevant transfer function(s), to be the base for the derivation of modal parameters and other metrics of the applied flying qualities criteria.

Figure 30 displays the Bode plot of the best fitting pitch rate to longitudinal stick force transfer function obtained from the data of two frequency sweeps performed at the same flight conditions of the one presented above.

The corresponding analytical expression is:

$$\frac{q}{Fes} = \frac{1.212e7(0)(0.01685)(0.9)}{[0.09323, 0.07966][0.375, 3.5][0.7,23][0.7, 75]} e^{-0.11s} \qquad 1$$

Where the following notation applies:

$$[0.7,75] \text{ corresponds to } s^2 + 2\zeta\omega_n s + \omega_n^2, \text{ with } \zeta = 0.7,\ \omega_n = 75\ \frac{rad}{s} \qquad 2$$

$$(0.9) \text{ corresponds to } s + \frac{1}{T_{\theta_2}}, \text{ with } \frac{1}{T_{\theta_2}} = 0.9 \qquad 3$$

A preliminary analysis of the transfer function indicates that the free response dynamics of the vehicle is characterized by the two second order modes of the longitudinal dynamics, Phugoid and Short Period, represented respectively by the terms [0.09323, 0.07966][0.375, 3.5], by the feel system dynamics, term [0.7,23], and by the actuator dynamics, term [0.7, 75].

The forced response is characterized by a low frequency zero, represented by (0.01685), and by a higher frequency zero, (0.9), which is the steady state time delay between pitch attitude and flight path angle in the aircraft response to a longitudinal control step input.

The transfer function also contains an equivalent time delay, to model the effect of the high frequency elements. The delay linearly affects the phase and has no effect on the gain, as displayed in the Bode plot of Figure 24 and expressed by the relationship: $\phi = \omega\tau$.

The effect on the gain of the high frequency control system elements is negligible due to the low value of the aircraft gain itself in the high frequency range. Figure 25 displays the effect of time delay on the phase of a notional system, which is of increasing the phase *roll-off*. The frequency range at which this occurs varies as a function of the delay, as displayed in Figure 26.

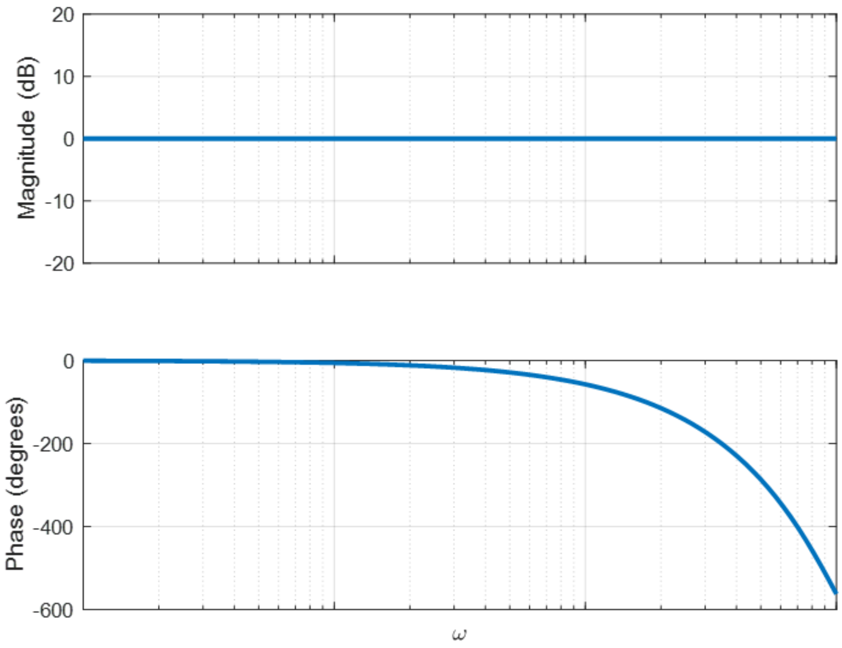


Figure 24. Bode plot of time delay

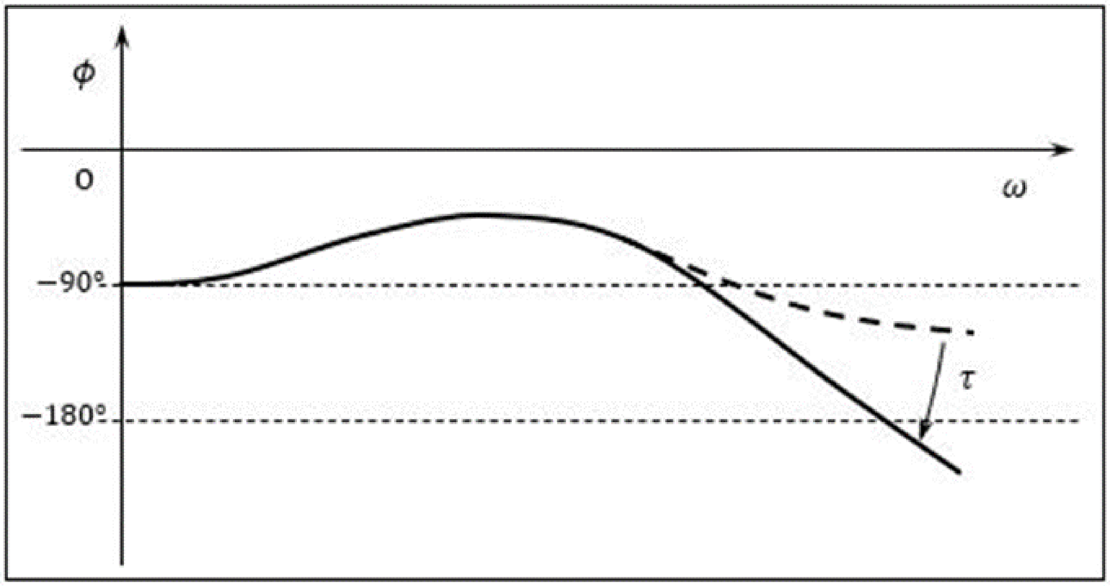


Figure 25. Effect of time delay on the phase of a notional system

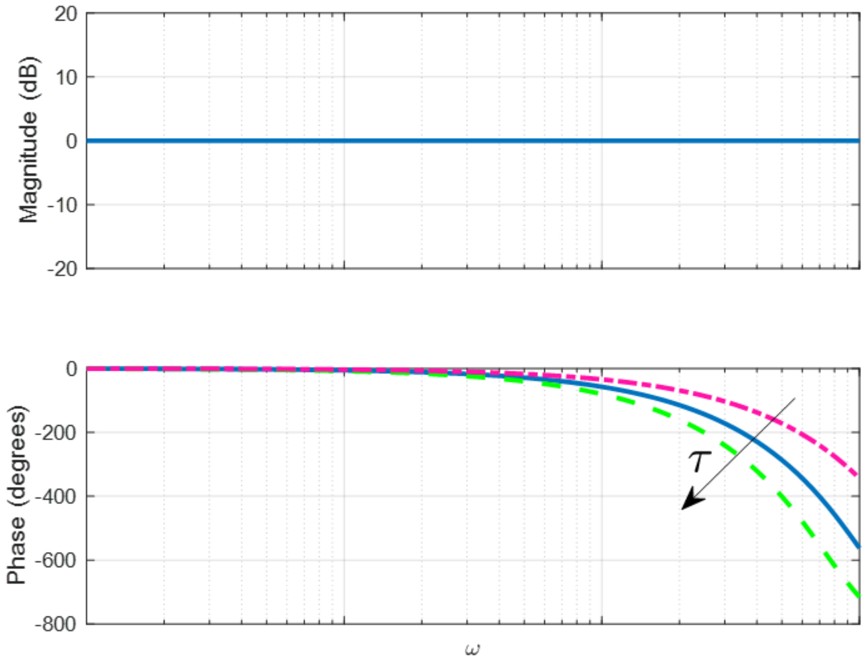


Figure 26. Bode plot of varying time delays

The free response component of a frequency sweep is negligible, as it is a test technique designed for frequency domain analyses of forced responses.

Two quantitative analysis approaches are usually followed:

1. Metrics are extracted from the derived transfer functions, to be compared with the relevant requirement envelopes of the applied flying qualities criteria.
2. Aircraft aerodynamic terms are extracted from the derived modal parameters, based on the measured flight conditions and on the modeled mass properties.

Analysis approach 1: It is mostly aimed at direct verification of flying qualities requirements. This is principally relevant under the contractual standpoint. It can also have a significant impact on the progression of flight testing and aircraft development when predefined requirements and tolerances are specified as part of the developmental testing and evaluation process.

The applied criteria determines the type of required outputs, consequently the analysis approach and the method to calculate the metrics. A combination of modal parameters and other metrics as pitch attitude bandwidth, equivalent phase delay, n/α, and roll mode time constant directly apply to flying qualities requirements and aircraft flying qualities verification.

The Aircraft Bandwidth Criterion can be taken as an example. Calculation of the aircraft bandwidth as the lower frequency between those corresponding to pitch attitude gain margin GM = 6 dB and phase margin PM = 45 degrees requires the derivation of the θ/δ, or θ/F_{es} transfer functions, respectively excluding or including the feel system dynamics.

Execution of a frequency sweep and analysis of the data acquired allows to derive the Bode plot of the transfer function and of the metrics which can be extracted from it. Figure 27 illustrates the bandwidth definition with respect to a notional θ/δ transfer function (Hoh, Mitchell, & Hodgkinson, 1981). Phase delay has to be extracted from the same transfer function, to complete the calculation of the Flying Qualities (FQ) level based on the aircraft bandwidth criterion. A more comprehensive description of this and of the other criteria is available in section 5.5.

Analysis approach 2: Update and validation of the aerodynamic model addresses phases of the aircraft development, which precede verification. This is a fundamental step for the refinement of the control laws design and for the clearance to flight of a specific control laws mode.

Calculation of the aerodynamic terms from the modal parameters derived from frequency sweep data is valid for unaugmented aircraft alone and it is generally approximated. This is a significant limitation to the applicability of frequency sweeps for the derivation of aircraft aeromechanic characteristics. A basic example is provided below.

Applying a 2 Degrees of Freedom (DoF) short period approximation, the short period natural frequency is expressed as a function of the dimensional aerodynamic derivatives by the relationship: $\omega_{n_{sp}}^2 = -M_\alpha + Z_w M_q$, which can be simplified in $\omega_{n_{sp}}^2 \approx -M_\alpha$, assuming $|Z_w M_q| \ll |M_\alpha|$.

The expression of M_α is: $M_\alpha = \frac{\rho U_0^2 S\bar{c}}{2I_{yy}} \cdot C_{m_\alpha}$, which leads to the calculation of the non-dimensional derivative from the expression: $C_{m_\alpha} = \frac{2I_{yy} \cdot \omega_{n_{sp}}^2}{\rho U_0^2 S\bar{c}}$.

From analysis of the expression above, accurate calculation of the nondimensional aerodynamic terms requires accurate values of the short period natural frequency, of the moment of inertia about the y stability axis, of the trim dynamic pressure, and of the geometric characteristics of the wing, or equivalent. For un-augmented aircraft, the modal parameters of the rigid body modes (i.e.: natural frequency, damping ratio, time constant) can be directly derived from fitting of the frequency response, or from analytical methods and specific flight test methods.

These methods are described in depth in the handbooks of the Test Pilot Schools (TPS) recognized by the Society of Experimental Test Pilots (SETP), and in the handbook of the Society of Flight Test Engineers (SFTE).

Figure 28 displays the PSD of the outputted rate and attitude and of the corresponding remnant, respectively in part a) and part b). The acceptable difference of around 20 dB between output and remnant corresponds to a wider frequency range when the output is the rate, thus a wider relevant frequency range. Coherence and SNR are higher in the relevant frequency range, as displayed in Figure 29. Figure 30 shows the Pitch rate to longitudinal stick force bode plot - frequency sweep and Figure 31 displays the high-quality match of the pitch rate to longitudinal stick force transfer function.

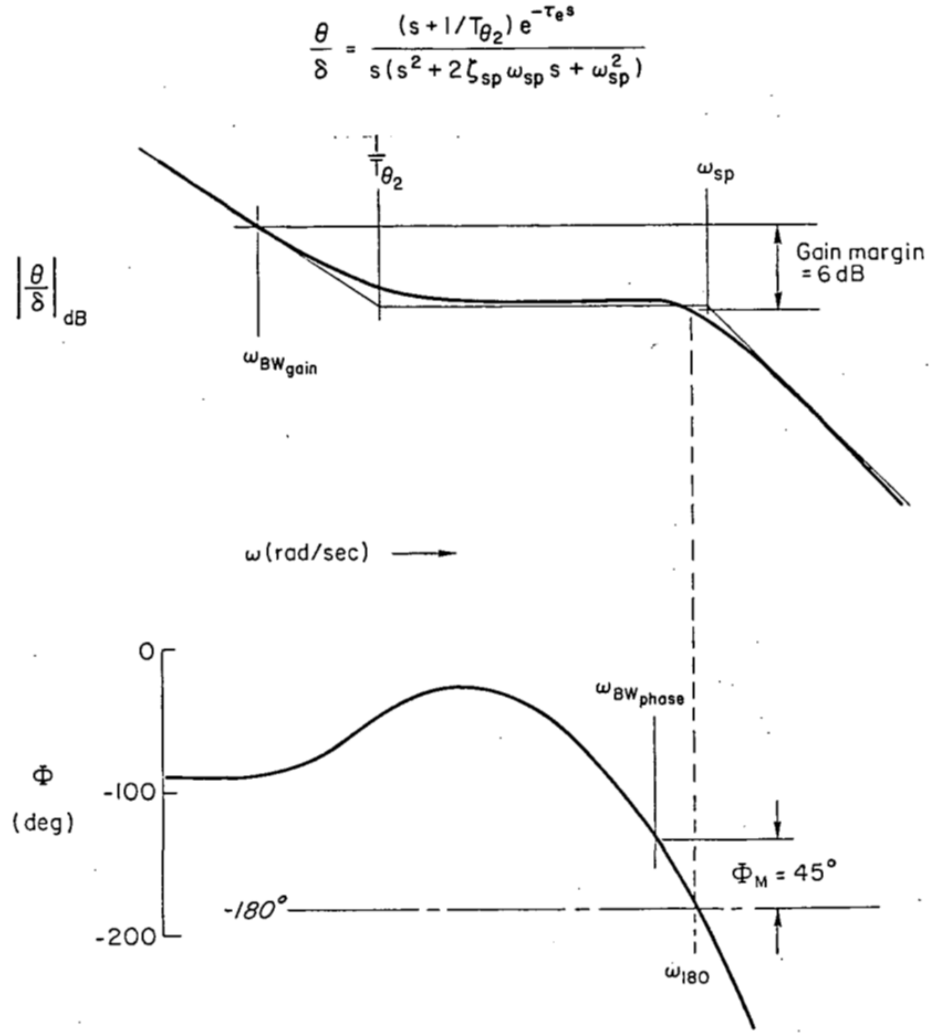


Figure 27. Aircraft bandwidth definition

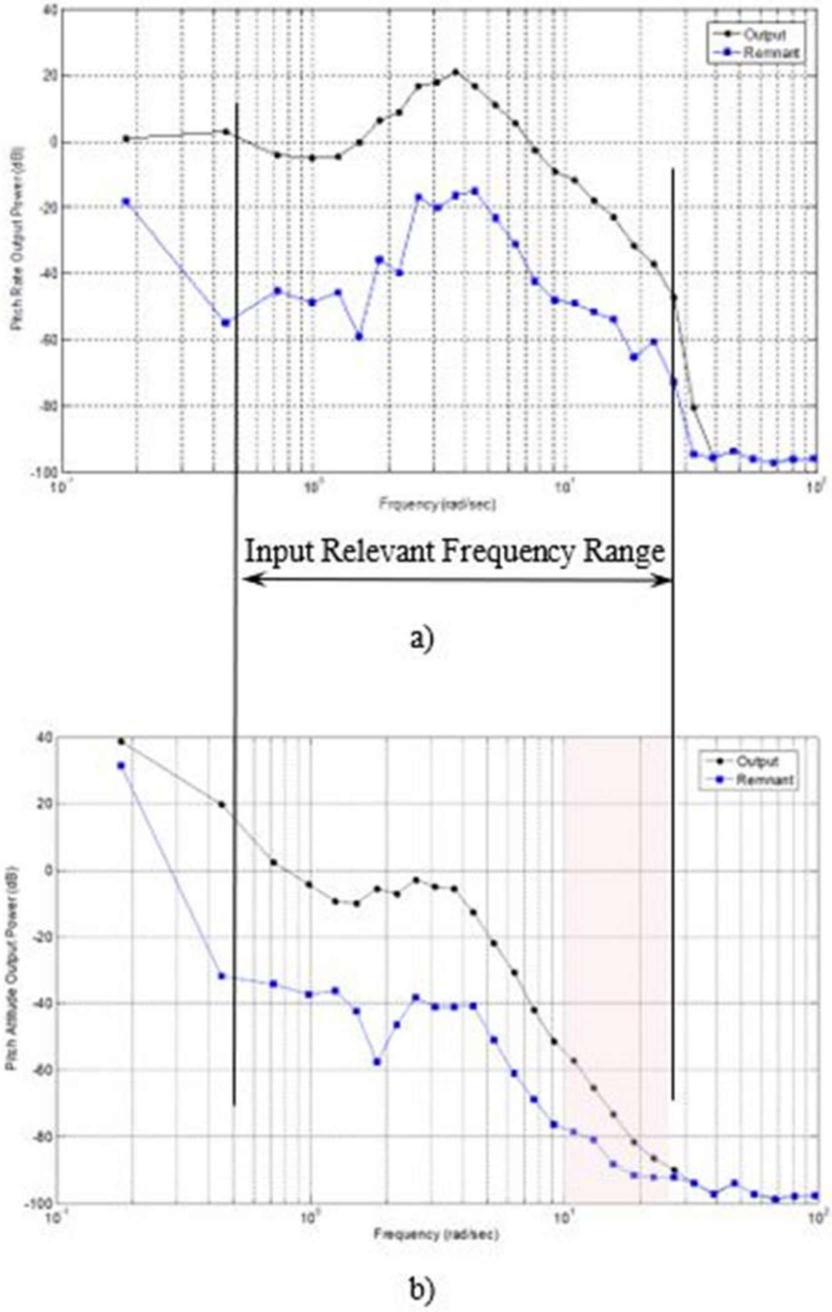
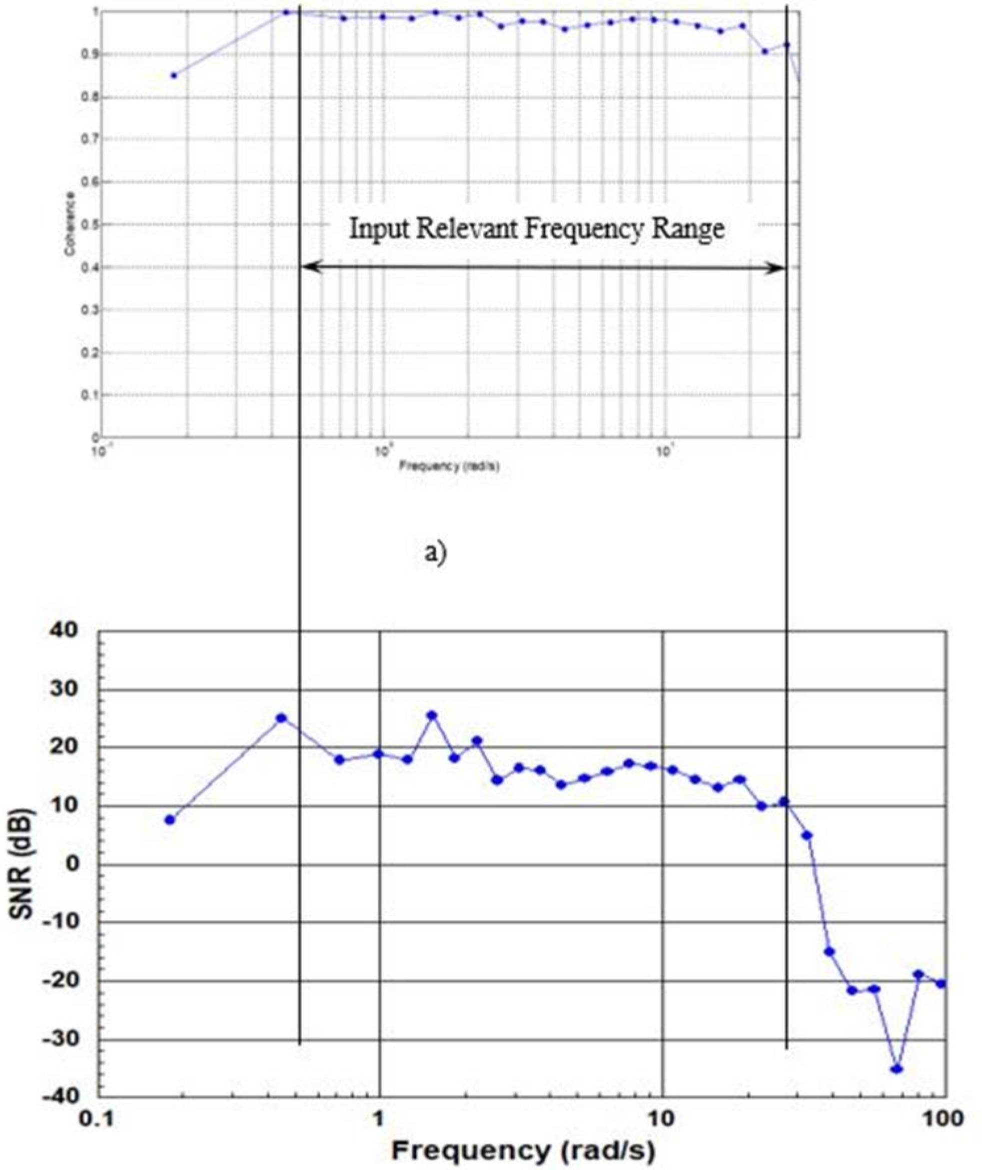


Figure 28. PSD of pitch rate, pitch attitude and remnant – frequency sweep



a)

b)

Figure 29. Coherence and SNR - frequency sweep

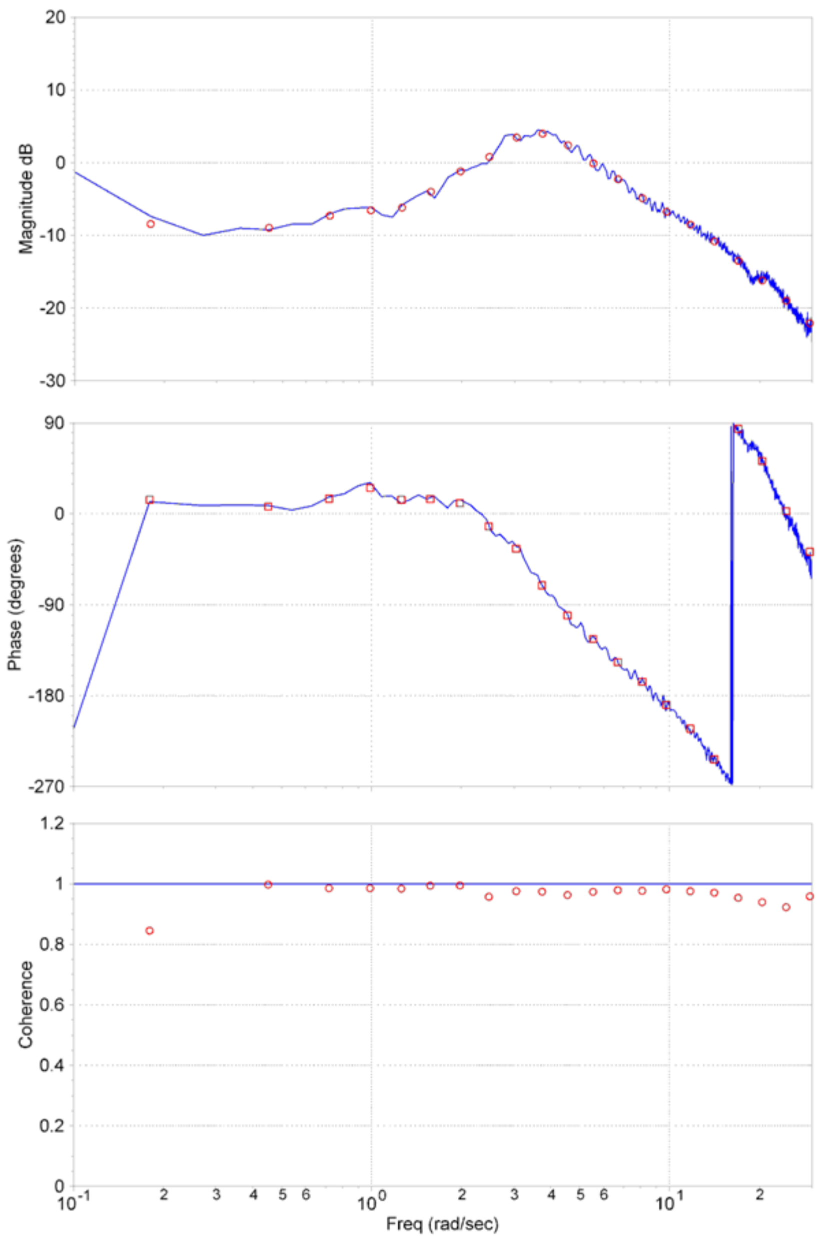


Figure 30. Pitch rate to longitudinal stick force bode plot - frequency sweep

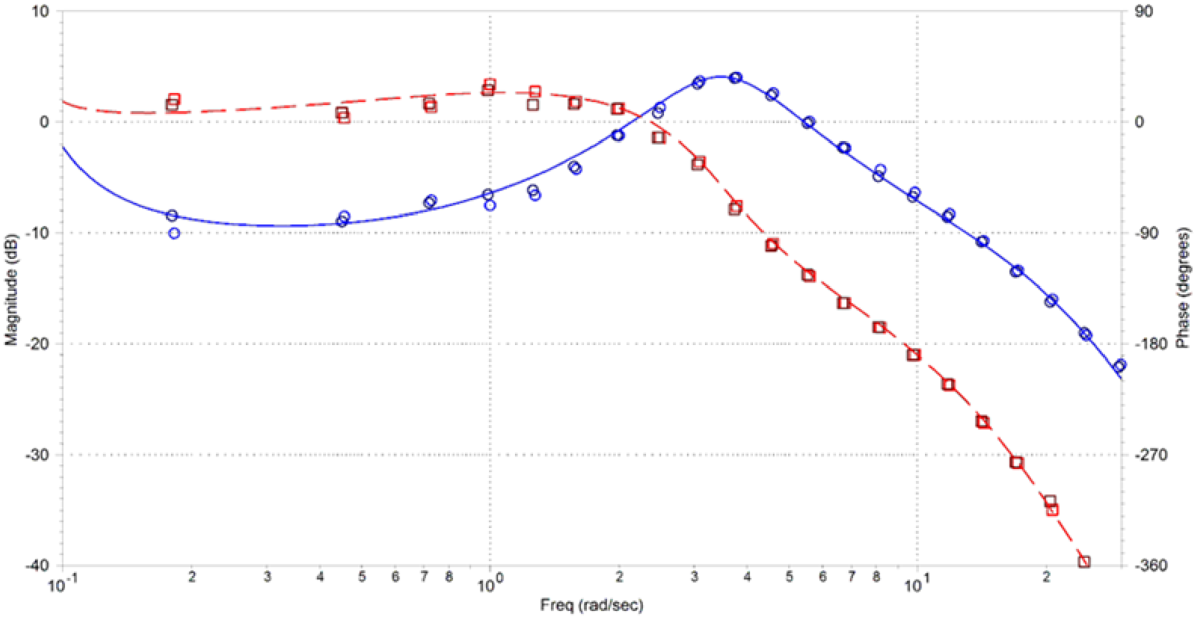


Figure 31. Matched pitch rate to longitudinal stick force transfer function

4.5.6 Scope and limitations of the test technique

The scope of the frequency sweep Flight Test Technique (FTT), as described above, is to acquire data for the derivation of the aircraft forced response in the frequency domain. The assumption of system linearity is underlying both the execution and the analysis phase, leading to limitations due to aircraft configuration, flight conditions, and flight phase. Considering a powered-lift configuration as an example, partial applicability is expected in the transition phases through configurations and/or through different modes of lift generation, i.e.: from rotor-borne to wing-borne flight and vice versa. Limitations derive from the following:

- Relatively long duration of the maneuver, which requires maintenance of the flight condition until completion. This demands high thrust/power levels for the whole duration of the maneuver, in particular in the low aerodynamic efficiency configurations/flight conditions. This limits the execution to level flight conditions and low angles of attack, for both safety and quality of the maneuver.
- Insufficient aerodynamic effectiveness and consequently low control authority of specific control surfaces/effectors for that specific flight phase. As an example, elevator effectiveness is expected to be insufficient to excite longitudinal dynamics of a powered-

lift configuration in the initial part of the transition from hovering (rotor-borne lift generation) to forward flight (wing-borne lift generation).

- Results are valid at the trim condition at which the maneuver is performed. This requires execution of the maneuver at a large number of trim conditions, for an adequate coverage of the flight envelope and/or of the validity envelope of the aircraft model(s).
- Based on the standard analysis approach, results are a linearized model of the aircraft dynamics, which prevents execution of the maneuver in envelope regions with significant nonlinearities. This can limit the amplitude of the perturbation and the flight envelope coverage.

Limitations have to be considered at the flight test plan level, in the definition of flight conditions and aircraft configuration, and during maneuver execution, to ensure respect of the validity of the underlying assumptions.

4.6 Doublet

4.6.1 Detailed description of the test technique

The doublet input is formed by two consecutive pulses of equal amplitude and opposite sign, as displayed in Figure 32. It is a square wave approximating a sine wave of the same period. The dominant frequency of the example is of 0.5 Hertz. The square wave is preferred to the pure sinusoidal input for its higher frequency content, due to its theoretically infinite frequency spectrum. This makes the input more effective in the excitation of a mode that does not coincide exactly with the input dominant frequency.

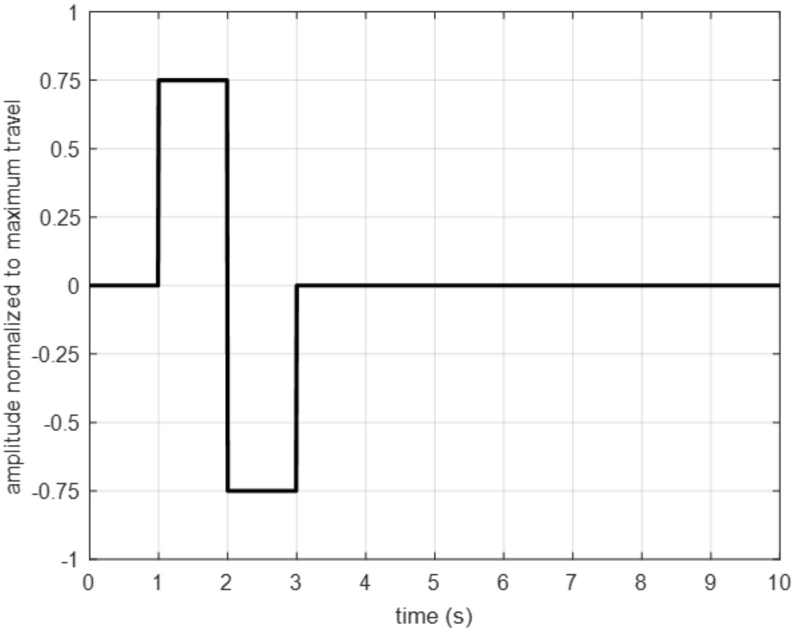


Figure 32. Doublet input

Figure 33 displays the time histories of the response of a generic FW aircraft to the doublet of Figure 32. The relatively high damping ratio of the Short Period leads to a limited number of overshoots and an overall limited duration of the relevant, free response, part of the maneuver. The low duration of the time history is one of the main characteristics of this type of maneuver, which makes it an effective alternative to the frequency sweep when test time is a constraint and analysis is performed mostly in the time domain. Square wave shaped doublets are usually performed automatically, as a PTI; manual execution is possible, which tends to provide single frequency inputs, close to a sinusoidal wave.

The typical sequence for maneuver execution is:

- set of the PTI input amplitude and period/frequency, if an automatic system is available
- trim of the aircraft at the required flight conditions
- maintaining *hands off* trim conditions for at least 2 seconds
- start of the PTI, or manual execution of the maneuver
- wait for the aircraft dynamics to be fully damped before maneuvering

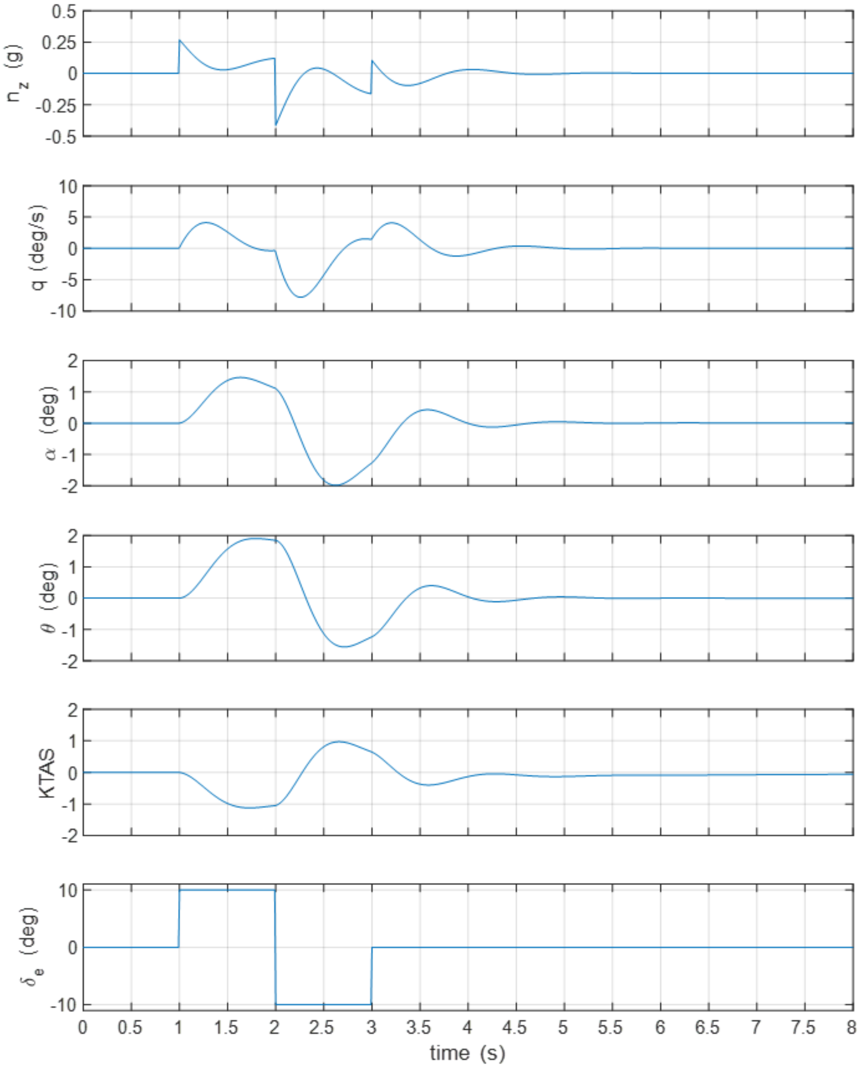


Figure 33. Example of doublet time history

The advantages of a programmed, automatic input are: 1) predictability, 2) repeatability, 3) absence of input distortion, i.e.: execution in the required axis. Maneuver design is in this way mainly an engineering, repeatable and traceable process, which can be performed and validated via offline simulations.

Considering the short duration of the maneuver, the advantage of manual inputs is the possibility for the pilot to gradually adapt the amplitude and frequency of the input to obtain the required amplitude of the perturbation, varying flight conditions and control system mode. This requires repeating the maneuver sequence reported above under real time monitoring for quality assessment by the FTE. The effect on the response of an initially non-ideal, not repeatable, input shape can be compensated by iteratively adapting input frequency and amplitude with a heuristic approach. Criteria for real time monitoring and quality assessment of the maneuver are:

- Respect of the flight envelope limits.
- Adequate duration of the trim conditions prior to input execution.
- Respect of the tolerance on airspeed and/or on other relevant states.
- Respect of the required amplitude of the perturbations of the aircraft states used in the analyses.
- States perturbations remain in the linear range of aircraft characteristics, when maneuvering at the boundaries of known non-linearities.
- Decoupling of longitudinal and lateral/directional inputs, with minimal input distortion.
- Respect of the *hands-off* phase of the maneuver after input execution, ensuring free aircraft response until the transient is completely damped, or neutral/trim position in case of control fixed responses.
- Absence of spurious inputs which can be produced by the abrupt, or by the incomplete release of the inceptor after the input is performed. This is a critical aspect which requires significant pilot's attention.

It is the authors' experience that manually executed doublets can be very effective in parameter estimation flight test campaigns. In this case, it is recommended to conduct post flight analysis and evaluation of the maneuvers, to maintain and improve the standard of execution.

The post flight analysis of the maneuvers can be based on the following guiding principles:

- Grouping of maneuvers by amplitude and axis of aircraft dynamics excitation.
- Determination of the input standardization level by calculation of the deviation with respect to the average maneuver, for each maneuver group.
- Evaluation of the aircraft response for each maneuver group.
- Synthesis of the ideal maneuver referenced to the average maneuver and the aircraft response(s).
- Test of the resulting most effective, or "central", maneuver via offline and manned simulation.

The results of the post flight maneuver analysis has to be applied to guide the pilot towards improving the manual execution and the iterative process performed in flight to achieve optimal input amplitude and frequency. It is important to inform the pilot of the objectives of the test and of the methods to achieve them, from maneuver execution to analysis and final results.

It is highly recommended to perform doublets at different frequencies with respect to the "central" one, for assessing the response sensitivity to the varying input characteristics. Pilots can adapt their input quickly and effectively to mismatch between predicted and actual response characteristics. It is fundamental to continuously monitor the effectiveness of the maneuvers also in case of PTIs, as they are based on predicted aircraft characteristics, which might present local not negligible differences with respect to the actual characteristics.

The effectiveness of a square wave doublet input can be assessed practically by analyzing the aircraft responses in Figure 34. The inputs are two doublets with different dominant frequencies, $\omega = \pi\, rad/s$ and $\omega = 4.7\, rad/s$, respectively for the blue and the red trace in the figure.

The Short Period natural frequency is $\omega_{n_{SP}} = 5\, rad/s$, the longitudinal resonance frequency is $\omega_{n_{SP}} = 4.7\, rad/s$, coincident with the dominant frequency of the second doublet. It is noticeable that the difference between the amplitude of the responses is minor to negligible, owing to the theoretically infinite frequency content of the square wave, which is capable of adequately exciting modes in the relative vicinity of its dominant frequency.

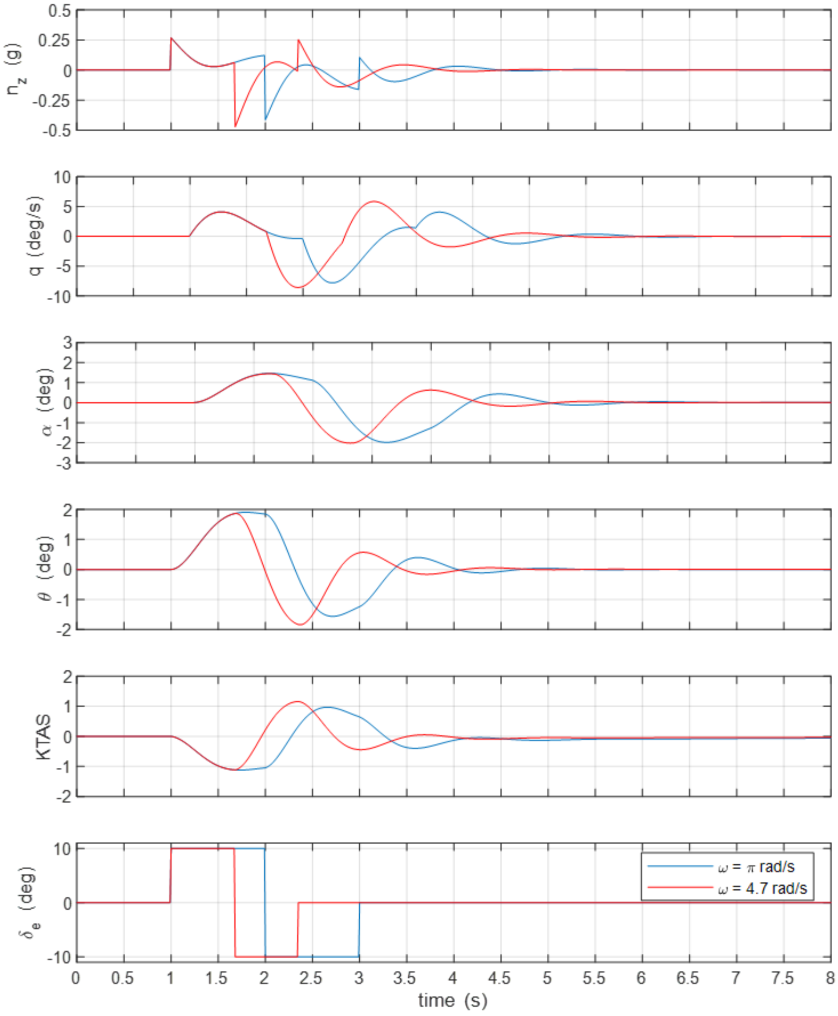


Figure 34. Comparison of square wave doublet time histories

For a comparison, it is useful to analyze the responses to sinusoidal doublets of the same frequency as the previous ones, displayed in Figure 35. It is noticeable that the maximum amplitude of the perturbations produced by the sinusoidal inputs is lower compared to that produced by the square wave doublets and that the difference in the amplitude of perturbations between inputs with different frequencies is higher for sinusoidal inputs, confirming the higher effectiveness of square wave doublets. It is important to consider that typical manual inputs are closer to a sinusoidal wave. The iterative input refinement and the continuous monitoring of the manually executed maneuvers described above ensure adequate modes excitation, even with a relatively low effectiveness input shape like the sinusoidal.

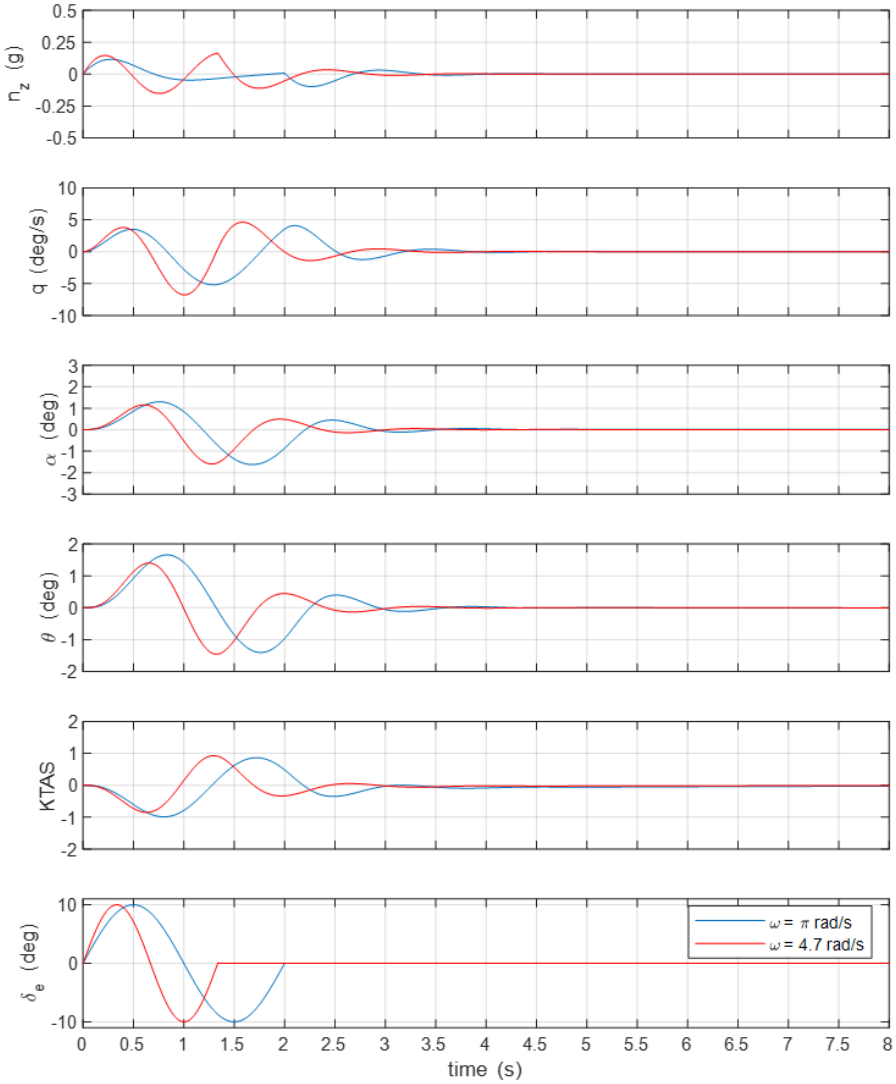
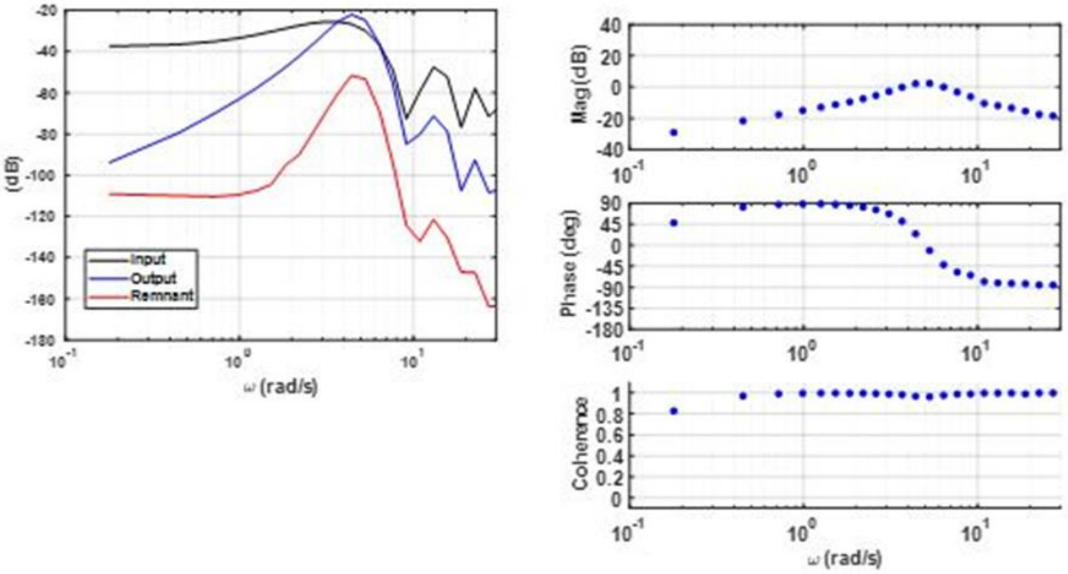


Figure 35. Comparison of sinusoidal doublet time histories

The frequency domain analysis of the aircraft response to a square wave doublet clarifies the information about the spectrum of the input, introduced above. The PSD of the input displayed in Figure 36a) demonstrates that the power peak is slightly lower than the doublet dominant frequency. This is because an isolated doublet is analyzed, instead of a series of doublets at the same frequency. The power at the lower frequencies remains high and local maxima are present at the higher frequencies in correspondence of the odd harmonics of the dominant frequency. This relatively wide frequency spectrum confirms the effectiveness of the square wave doublets in exciting the response of dynamic systems, which was discussed above, relatively to the time domain. As expected, the peak of the output power corresponds to the resonance frequency, with a trend similar to that of the input at the higher frequencies, decaying with the decrease of the frequency with respect to the dominant one. The system dynamics characteristics are confirmed by the Bode plot in Figure 36b). The high values of the coherence and the significant separation between output and remnant derive from the nominal conditions: lack of noise and pure linearity of the model.



a) b)

Figure 36. Square wave doublet frequency domain response

4.6.2 Inputs, outputs, flight phases, aircraft dynamic modes

Simple doublets of the type described in this chapter are typically performed when the aircraft modal characteristics are known based on the aircraft dynamic model. Assuming the vehicle dynamics is of second order, the objective is to estimate the static/aerodynamic gain and the modal parameters natural frequency and damping ratio. Execution of the doublet with dominant frequency in the vicinity of the predicted second order mode natural frequency allows to derive both modal parameters. The static/aerodynamic gain can be calculated from the trim conditions.

The typical application of this maneuver is the parameter estimation of the bare airframe aerodynamics in the time domain. Inputs and outputs are the control surfaces deflections and the aircraft states, respectively. This corresponds to inputs/outputs pair 5-6 of Table 7. The same maneuver can be used for system identification of other aircraft system elements, as reported in Table 5.

Doublets can be executed to excite the dynamics in both the longitudinal and lateral/directional plane, respectively defined as Pitch Doublet (P/D), Roll Doublet (R/D) and Yaw Doublet (Y/D). The maneuvers name addresses the axis in which the perturbation is commanded, not the control surface(s) deflected to produce the perturbation. This is to be consistent with the *maneuver demand* characteristic of FBW aircraft. Perturbation in the pitch axis can be affected by deflection of the elevator/stabilator, elevons, flaperons, and differential rotor RPM in multi rotor configurations, or by a combination of the above. Perturbation in the roll axis can be affected by differential aileron deflection, differential elevons or taileron, differential rotor RPM or angle in multi rotor configurations, or by a combination of the above. Similar concepts are valid for the yaw axis. Perturbations of adequate amplitude in the lateral/directional plane can be produced effectively by lateral controls.

For their short duration, doublets can be effectively performed in all flight phases and aircraft configurations, with minimal drift from the initial flight conditions also in low lift to drag ratio or high load factor conditions. Doublets are not recommended for estimation of first order dynamics, due to their zero average amplitude. First order dynamics is more effectively identified with pulse inputs.

4.6.3 Required analysis processes

A basic approach valid for second order underdamped modes is the calculation of the natural frequency and damping ratio in the time domain. The analysis process is consolidated and extensive descriptions are available in a wide variety of engineering textbooks. Below is a brief, practical example of how the process can be applied to the aircraft response displayed in the previous examples.

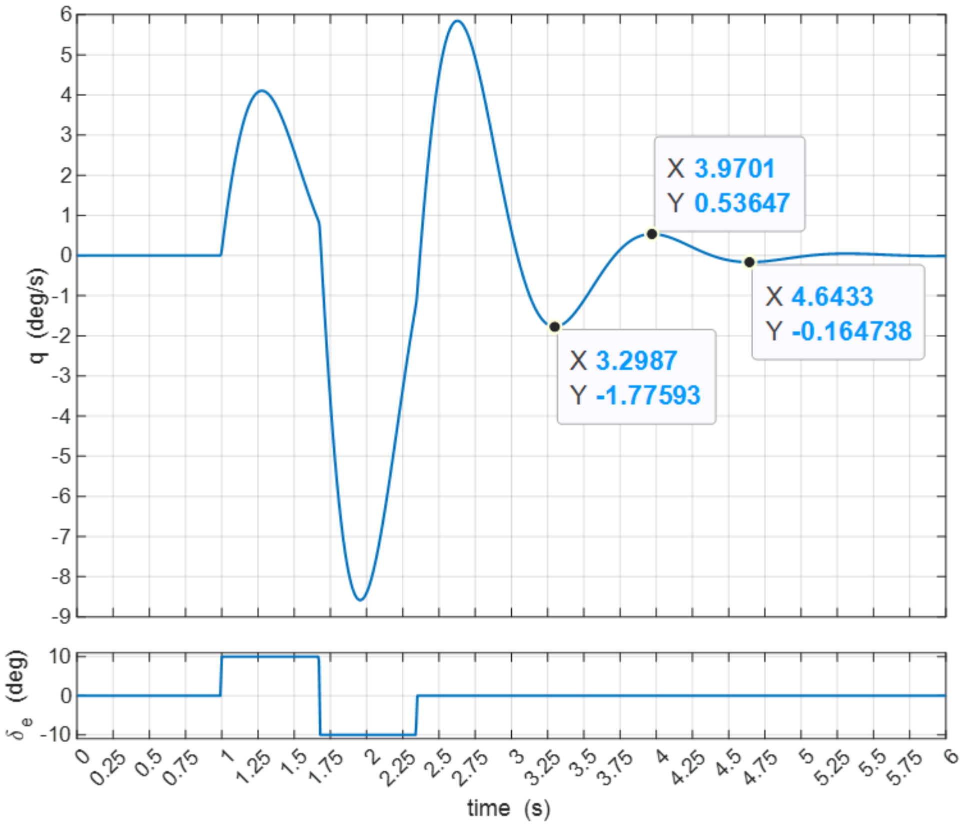


Figure 37. Pitch rate response to elevator doublet

As displayed in Figure 37, pitch rate is selected for the application of the method; any other state can be used without loss of generality. The Transient Peak Ratio (TPR) method (NTPS, 2021) is applied to three overshoots of the free response, whose amplitudes and times are displayed on the figure.

The ratio between the second and first overshoot is: $PR_1 = \frac{0.54}{|-1.78|} = 0.303$

The ratio between the third and second overshoot is: $TPR_2 = \frac{|-0.16|}{0.54} = 0.296$

The damping ratios can be calculated from the TPRs of consecutive overshoots with the formula:

$$\zeta = \sqrt{\frac{[ln(TPR)]^2}{\pi^2 + [ln(TPR)]^2}} \qquad 4$$

This results in: $\zeta_1 = 0.3553$; $\zeta_2 = 0.3613$; the most accurate value of the damping ratio is the average of the two values: $\bar{\zeta} = 0.36$.

Calculation of more than one TPR and averaging of the corresponding ζ is practice for reducing the impact of noise and of local deviations typical of experimental data. The damping ratio formula reported above is valid if and only if the mean of the response is null.

The TPRs can be calculated also from consecutive peak to peak amplitudes, to nullify the effect of bias and reduce the effect of drift of the response on the accuracy of the results.

Calculation of the peak-to-peak TPR is as follows:

$$TPR = \frac{0.54-(-0.16)}{0.54-(-1.78)} = \frac{0.7}{2.32} = 0.302 \qquad 5$$

The damping ratio calculated from the TPR above is:

$$\zeta = \sqrt{\frac{[ln(0.302)]^2}{\pi^2+[ln(0.302)]^2}} = 0.36 \qquad 6$$

This confirms that the value of the damping ratio does not change based on the method with which the TPR is calculated.

The natural frequency can be calculated from the measured damped frequency and the calculated damping ratio.

Based on the times of the overshoots in Figure 37, the damped period results to be: $T_D = (4.6433 - 3.2987)\ s \approx 1.34\ s$

The damped frequency is:

$$\omega_D = \frac{2\pi}{T_D} = 4.69\ \frac{rad}{s} = \omega_n\sqrt{1-\zeta^2} \Rightarrow\ \omega_n = \frac{4.69}{0.93}\ \frac{rad}{s} = \frac{4.69}{0.93}\ \frac{rad}{s} = 5.00\ \frac{rad}{s} \qquad 7$$

Other dynamics analysis methods in the time domain suitable for overdamped systems are the “Time Ratio Method” and the “Maximum Slope Method”, whose description is available in engineering textbooks as the National Test Pilot School Handbook (2021).

Under a practical application standpoint, the “TPR method”, the “Time Ratio Method”, the “Maximum Slope Method”, and other similar methods are relevant for characterization of inner loops dynamics, not applicable to the outer loop of highly augmented aircraft.

Analysis can also be based on output error optimization methods, as the Maximum Likelihood Estimation (MLE). These methods solve an optimization problem, by minimizing the error on the prediction of selected states and outputs of the aircraft dynamics. The objective is to determine the parameters of the system, unknown, so that the difference between measured and simulated states and outputs is “small”. The unknowns are the linearized increments to the aerodynamic model terms, calculated with respect to the trim conditions. This corresponds to a linear error model for the unknowns, while the aerodynamic model can be fully nonlinear.

A cost function J to be minimized is defined, of the form: $J(\Theta) = \frac{1}{KN}\sum_{i=1}^{n} \upsilon(i)^T R^{-1} \upsilon(i)$

Where:

- Θ is the vector of the unknowns
- K is the number of measured states
- N is the number of time samples, or the length of the vector of the measures
- $\upsilon(i) = y_m(i) - y_z(i)$ is the measurement residual, or the residual between current and predicted measurement
- R is the matrix of covariance of the noise

The cost function is minimized through an iterative approach, varying the vector of the unknowns until minimization of $J(\Theta)$ is reached with respect to predefined convergence criteria. Normalization of the cost function with respect to the number of data points, i.e.: the quantity KN, is required for successful application of convergence criteria and for tuning of the optimization routine.

Extensive description of the MLE and of the output error approach is available in Maine & Iliff (1986). When using parameter estimation algorithms, identification of the increments to the lateral/directional aerodynamic terms is critical for the laterally and directionally coupled response. To increase the information that can be extracted from the maneuvers, yaw doublets (Y/D) and roll doublets (R/D) are executed also in series. The roll doublet is usually executed when the Dutch roll is almost completely damped.

This allows to estimate in the same maneuver the effect of rudder and aileron, or more generically of the directional and lateral control, respectively on the lateral and the directional response of the aircraft. In parameter aerodynamic estimation, it corresponds to the effects represented respectively by the cross-control derivatives $C_{l_{\delta_r}}$ and $C_{n_{\delta_a}}$. Accurate matching of $C_{l_{\delta_r}}$ and $C_{n_{\delta_a}}$ is the main objective of the Y/D-R/D sequence, being the other terms, including the primary control derivatives $C_{l_{\delta_a}}$and $C_{n_{\delta_r}}$, obviously identified at the same time, too.

The value of the Y/D-R/D sequence for model matching is of producing residuals for $C_{l_{\delta_a}}$, $C_{l_{\delta_r}}$, $C_{n_{\delta_r}}$ and $C_{n_{\delta_a}}$ contributing to the same cost function, at the same aircraft flight/mass/thrust conditions.

Common practice is to average the values of the respective effectiveness (i.e.: $C_{l_{\delta_a}}$ and $C_{n_{\delta_r}}$) estimated from single doublets (i.e.: Y/D, R/D), and from sequences of doublets Y/D - R/D, for generalization.

It is important to recognize that aerodynamic increments are usually linear, i.e.: represented by derivatives, independently from the formulation of the aerodynamic model, which can be linear or more frequently nonlinear. Synthesis of local increments into an increments dataset which can be implemented in a nonlinear model is beyond the scope of this report, but it is the object of dedicated papers and books available in the public domain. Figure 38 illustrates the time history of a FW aircraft response to a Y/D – R/D sequence. The time interval between the first and the second doublet is defined to establish a balance between overall duration of the maneuver and minimal residual of the aircraft response when the second doublet is executed.

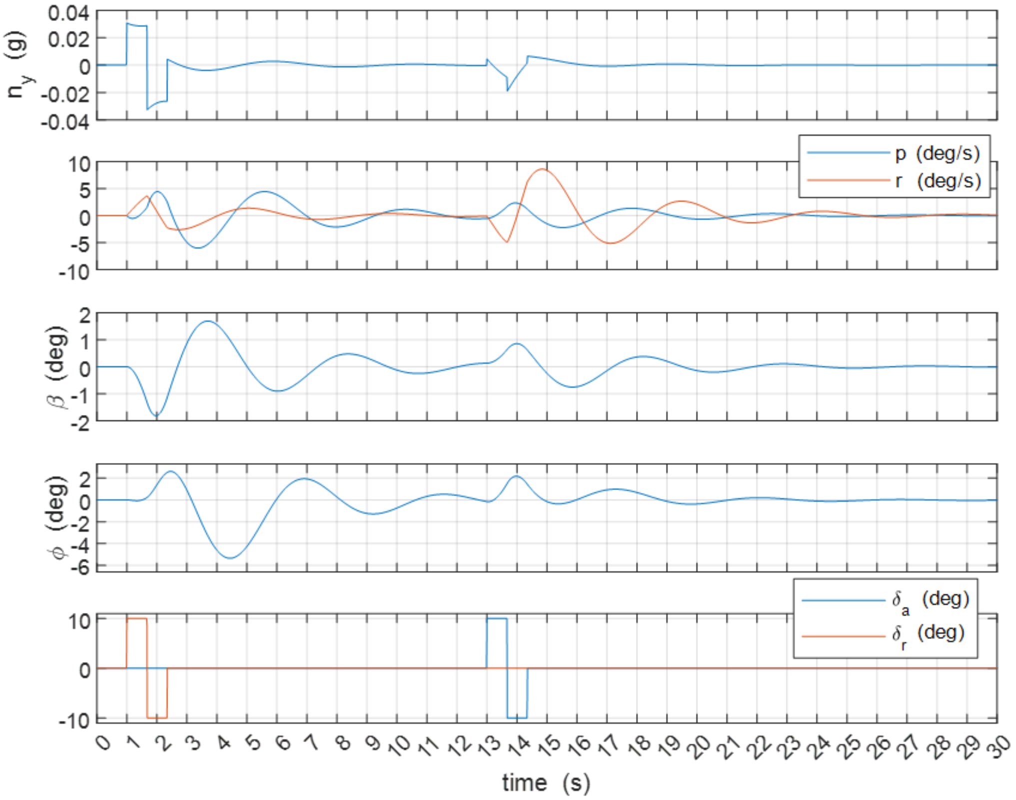


Figure 38. Yaw doublet – roll doublet time history

Under a process standpoint, methods which allow to estimate/identify individual components of the overall aircraft dynamics model, as the aerodynamics, require an analytical approach to calculate the updated modal parameters derived from the analysis (flight matching) procedure. The updated modal parameters are not calculated directly from the time history of the response, as in the example of application of the TPR method. They are calculated from the aircraft model, in which the aerodynamic model updated through application of the methods described above, is implemented.

The verification process, based on comparison of the aircraft modal parameters with the requirements of the selected flying qualities criteria, is the last step of an engineering process, of which flight test is a fundamental part, but not the only one. Identification of the FCS including the actuation system, of the Air Data System and refinement of the mass properties model, are an integral part of the process, to be conducted via ground test.

Close interconnection between the flight test and the data analysis/synthesis phases is required by the structure of the process itself. This tends to require high integration between the flight test and the design functions, both at manufacturer and civil aviation authority level.

4.7 Pulse input combinations

4.7.1 Detailed description of the test technique

Development of the doublet input design elements leads to pulse input combinations, aimed at increasing the power across the nominal frequency spectrum of the standard doublet. One example is the “3-2-1-1” maneuver, introduced in section 4.1 and represented in Figure 39, which contains elements of both the frequency sweep and of the pure doublet.

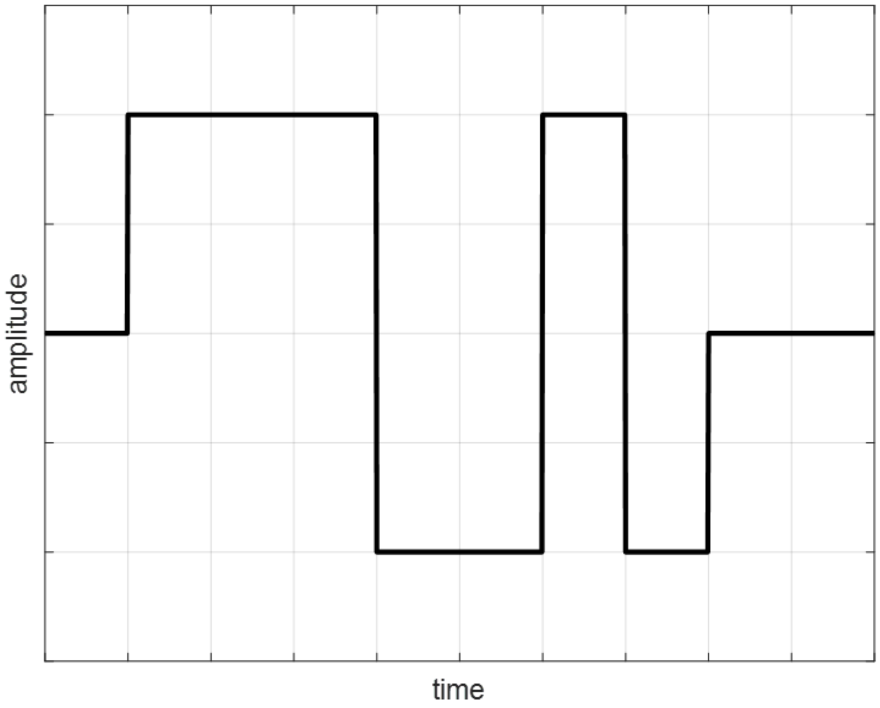


Figure 39. Example of 3-2-1-1 maneuver

The name derives from the time width of the pulses forming the maneuver, normalized with respect to the time width of the last pulse. The square wave shape of the input ensures a relatively wide effective spectrum, the series of pulses of different durations allows to investigate a predefined frequency range of interest.

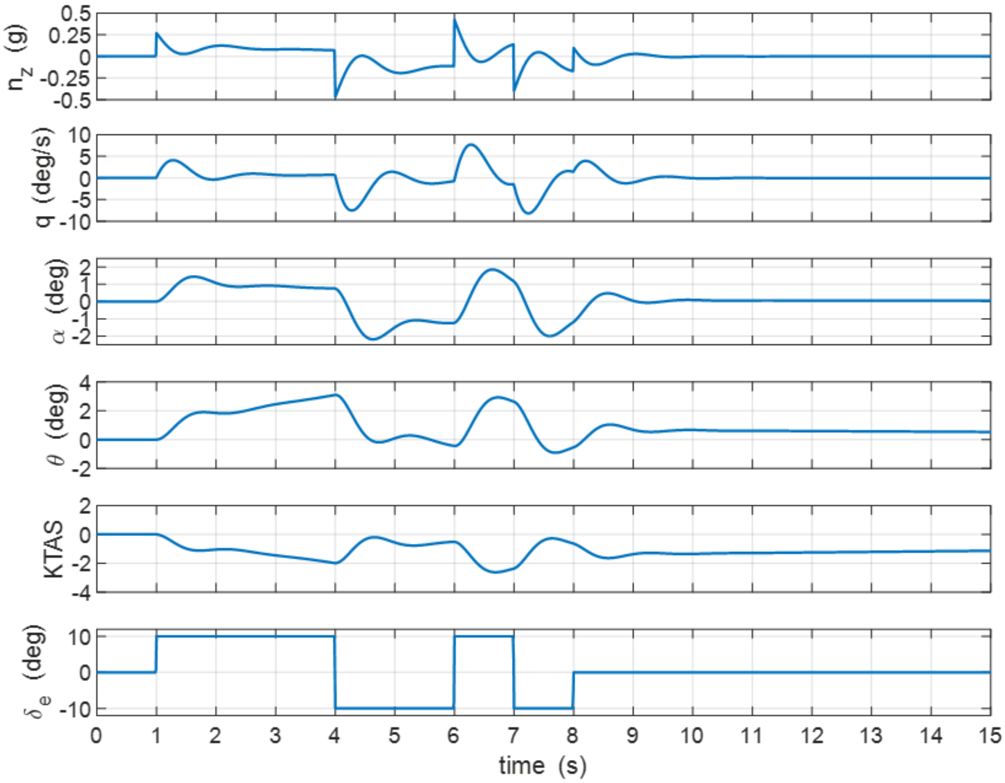


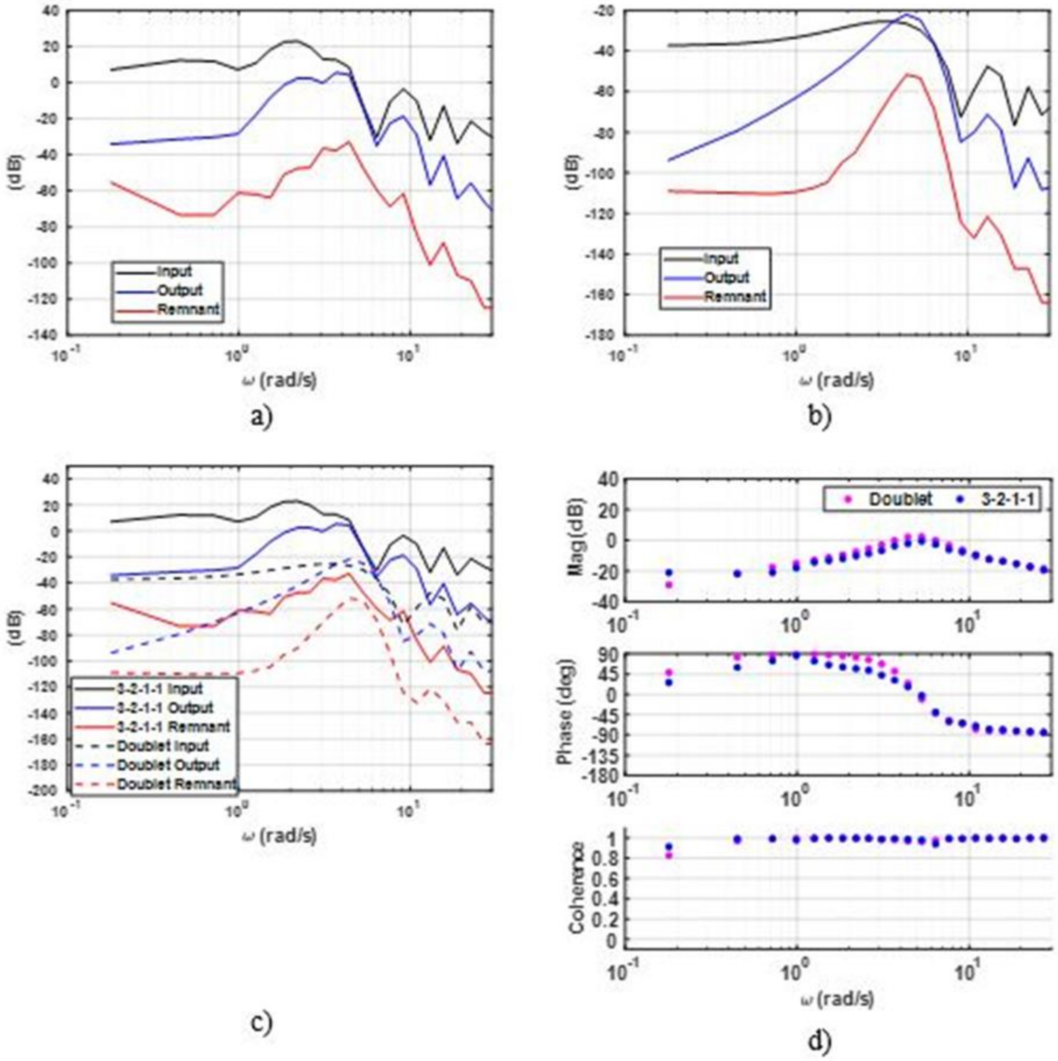
Figure 40. 3-2-1-1 maneuver – time histories example

This type of maneuver is not ideal for high performance aircraft, with wide flight envelopes, as the long width of the initial input can lead to significant deviations from the trim flight conditions with respect to airspeed, pressure altitude, angle of attack, and Mach number when applicable. A not negligible deviation from trim conditions is inherent in the not zero average value of the input. It is advisable for the “3-2-1-1” and the analogous “2-1-1” maneuvers to be programmed as PTIs, for their relatively higher complexity of execution with respect to the pure doublet input, which can lead to a lower degree of repeatability when performed by a test pilot.

4.7.2 Inputs, outputs, flight phases, aircraft dynamic modes

Pulse input combination maneuvers are usually executed starting from straight and level flight, due to the relatively high drift from trim conditions that they produce and their high level of complexity. It is not recommended to perform this type of maneuvers from high load factor, or high angle of attack flight conditions, to minimize the risk of occurrence of envelope exceedances or of departure from controlled flight. The possibility of tuning the frequency spectrum of the maneuver allows to identify the characteristics of all rigid body dynamic modes of the vehicle.

Figure 41 illustrates comparisons of PSDs of input, output, remnant and Bode plots between a standard doublet and a “3-2-1-1” maneuver.



a)

b)

c)

d)

Figure 41. Comparison of PSDs for “3-2-1-1” and doublet maneuvers

As expected, the input power of the “3-2-1-1” is significantly higher with respect to that of the single doublet in the low frequency range, with a similar decrease in magnitude increasing frequency. The trend of the differences in the output power is similar, with an expected higher difference in the low frequency range, owing to the long duration of the initial input of the “3-2-1-1”. The Bode plots resulting from the frequency domain analysis demonstrate a not negligible difference in the phase, in particular in the frequency range of the short period and of pilot’s inputs: $\omega = [2, 5]\ rad/s$.

This is also the frequency range in which the difference of input and output power between "3-2-1-1" and single doublet is maximum. The disadvantages of the longer duration and the higher difficulty of execution of the "3-2-1-1" compared to the single doublet are compensated by a wider frequency range in which the input effectively excites the aircraft rigid body dynamics modes.

Figure 42 displays the power spectrum of the maneuvers discussed in the previous sections. As expected, the maximum value of power and the corresponding frequency range decrease from the frequency sweep through the "3-2-1-1", the "2-1-1", and the doublet maneuver. The constant value of maximum power for the frequency sweep is a significant qualitative difference with respect to the other maneuvers, which exhibit the maximum amplitude peak in correspondence of the dominant frequency and lower local maxima in correspondence of its odd harmonics.

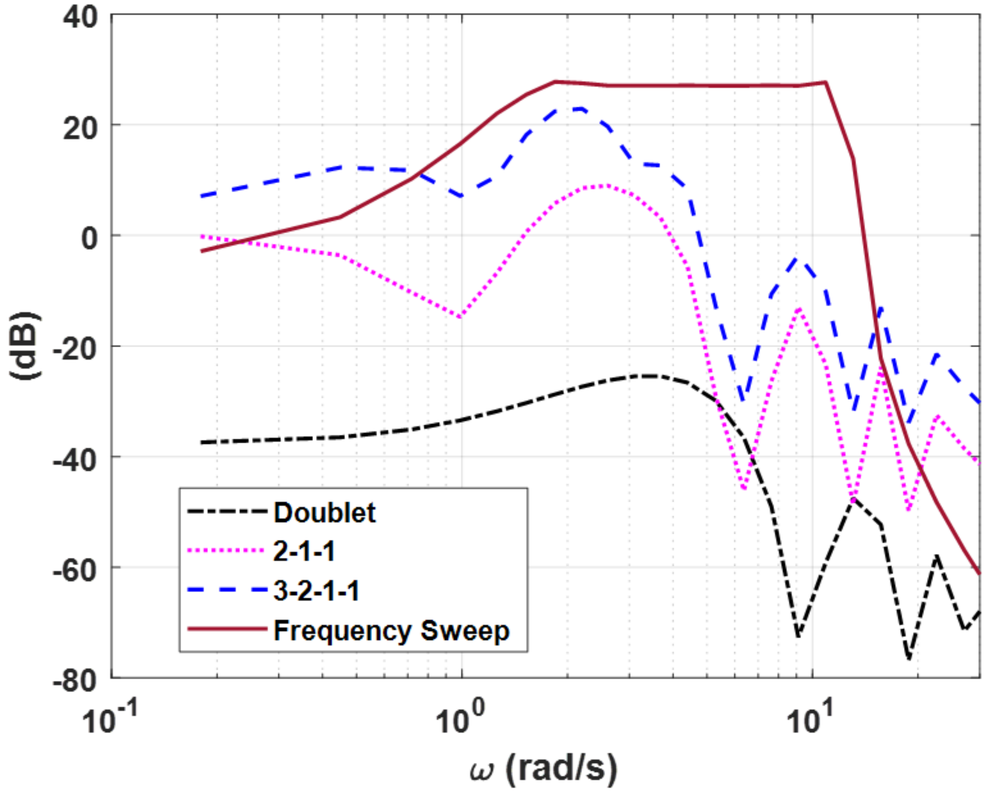


Figure 42. Comparison of input power – different maneuvers

4.7.3 Required analysis processes

The "3-2-1-1" maneuver, and its derivative "2-1-1", are closer to a frequency sweep and the corresponding data analysis processes usually coincide with those of the frequency sweep.

The single doublet is the only maneuver to be performed for analyses in the time domain, the others require a frequency domain-based analysis. Details are provided in previous sections 4.5.4 and 4.5.5.

4.8 Finite step: “Boxcar” input

4.8.1 Detailed description of the test technique

The finite step, or “boxcar” input (Figure 43), is a pulse type input of relatively long duration, in the order of 3 to 5 seconds. The scope of the maneuver is to achieve the steady state of the response, to study its three main phases: a) initial transient, b) steady state, c) final transient. The maneuver is therefore a non-zero average input by design, which leads to limitations on its amplitude and duration. Both are a function of the vehicle characteristics and they are defined to achieve a steady state of measurable amplitude, with non-negligible transients, minimizing the deviation from trim conditions.

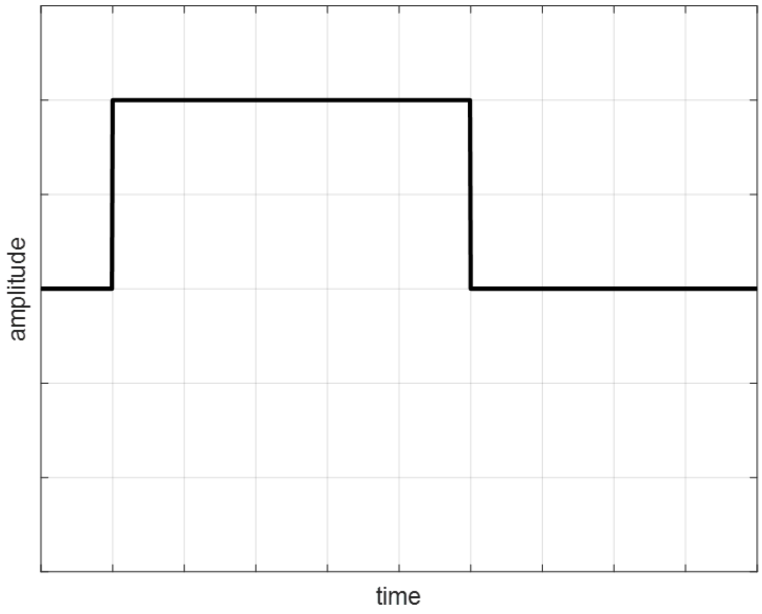


Figure 43. Finite step: “boxcar” input

Difficulties in the execution of the “boxcar” input derive from the required abruptness of its transients and from the required extended duration of the constant part. For these reasons, it is usually performed as a PTI. Potential limitations apply for high performance aircraft, in which deviation from trim can be significant due to the extended duration of the constant input.

4.8.2 Inputs, outputs, flight phases, aircraft dynamic modes

The “boxcar” input is typically performed in the longitudinal plane, for assessment of the following characteristics of the longitudinal response:

- predictability of the steady state from the initial response;
- time delay between pitch attitude and flight path angle at steady state, i.e.: T_{θ_2}; and
- evaluation of the “theta dropback”, which is the tendency of the aircraft to return to the trim pitch attitude at input release.

The maneuver can be performed in the lateral plane, for calculation of the roll mode time constant. Inputs for the analysis can be inceptors force, inceptors travel, and control surface deflection; outputs are the longitudinal aircraft states, in particular pitch rate, pitch attitude, AoA, and flight path angle. Referring to Table 7, the typical input/output pairs are: 1-6, 2-6, and 5-6. The “boxcar” input is applicable to characterize the inner loop response of a vehicle with a conventional dynamic. It can be performed mostly in the forward flight phase beyond transition in lift + cruise aircraft configurations.

4.8.3 Required analysis processes

The analysis processes applicable to data acquired by means of the longitudinal “boxcar” maneuver are mostly based in the time domain. The primary metric which can be derived from the time histories of the aircraft response to this input in the longitudinal plane is the time delay between pitch attitude and flight path angle at steady state, defined as T_{θ_2}. Analytically, T_{θ_2} is the time constant of the high frequency zero in the transfer function of pitch angle, or pitch rate, to elevator deflection.

Below is the transfer function of the 2 DoF approximation of the longitudinal dynamics of a fixed wing aircraft, written in the conventional symbolic form and as a function of the dimensional aerodynamic derivatives:

$$\frac{q}{\delta_e} = \frac{M_{\delta_e}\left(s+\frac{1}{T_{\theta_2}}\right)}{s^2+2\zeta_{SP}\omega_{SP}s+\omega_{n_{SP}}^2} \equiv \frac{M_{\delta_e}(s-Z_w)}{s^2+(-M_q-M_{\dot{\alpha}}-Z_w)s+(-M_\alpha+Z_w M_q)} \qquad 8$$

From comparison of the two forms, it is possible to derive that:

$$\frac{1}{T_{\theta_2}} = -Z_w = -\left(\frac{1}{m}\cdot\frac{\partial Z}{\partial w}\right) = -\left(\frac{\rho S U_0}{2m}\cdot\left(-C_{Z_\alpha}\right)\right) \qquad \left(\frac{1}{s}\right) \tag{9}$$

Where C_{Z_α} is non dimensional and it is the variation of body axes normal aerodynamic force coefficient per change of angle of attack. For small angles of attack, the term $-C_{Z_\alpha}$ can be approximated with C_{L_α}, the lift coefficient curve slope with respect to angle of attack. This leads to the expression:

$$\frac{1}{T_{\theta_2}} = -Z_w = -\left(\frac{1}{m}\cdot\frac{\partial Z}{\partial w}\right) \approx -\frac{\rho S U_0 C_{L_\alpha}}{2m} \tag{10}$$

A more extensive discussion on the significance and derivation of T_{θ_2} is available in Lotterio (2022). Figure 44 illustrates T_{θ_2} with respect to the time histories of pitch attitude and flight path angle. It is important to notice that the displayed time history is of the 3 DoF longitudinal dynamics, leading to a delay between pitch attitude and flight path angle slightly varying with respect to time, due to the variation of airspeed. The delay represented in the figure is measured after the end of the initial transient.

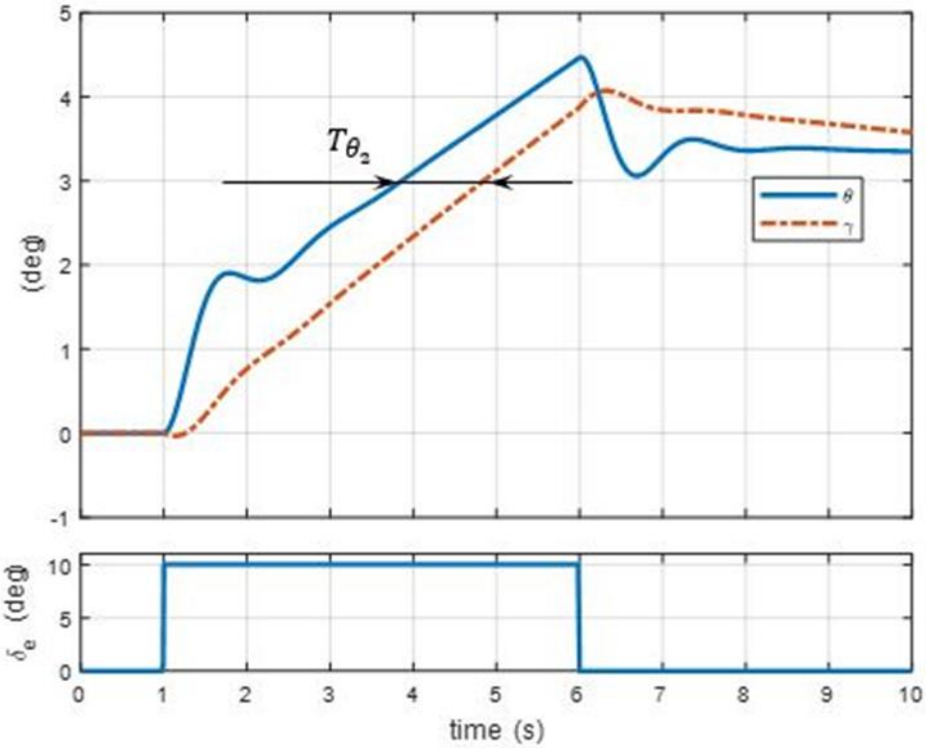


Figure 44. Tθ2- "Boxcar" input

The relevance of T_{θ_2} is in the calculation of $\frac{n_z}{\alpha}$, representing the variation of normal load factor per variation of angle of attack in radians: $\frac{n_z}{\alpha} = \frac{U_0 \cdot \frac{1}{T_{\theta_2}}}{g} \qquad \left(\frac{g}{rad}\right)$.

Under a physical standpoint, a higher lift curve slope, approximated by C_{Z_α},or a lower wing loading, produce a lower time delay, leading to a higher predictability of the aircraft flight path response.

The term $\frac{n_z}{\alpha}$ is present also in the expression of CAP: $CAP = \frac{\omega_{n_{SP}}^2}{\frac{n_z}{\alpha}}$, which is intended to represent the predictability of the steady state response (steady state flight path) from the initial response (initial pitch acceleration) to a step longitudinal input. Also, for CAP, the predictability is mainly intended of the flight path variation, which is a function of the load factor variation. The input release part of the maneuver allows to derive a second metric, defined as “theta dropback”. Figure 45 displays the time histories of the response to the same “boxcar” input of Figure 44.

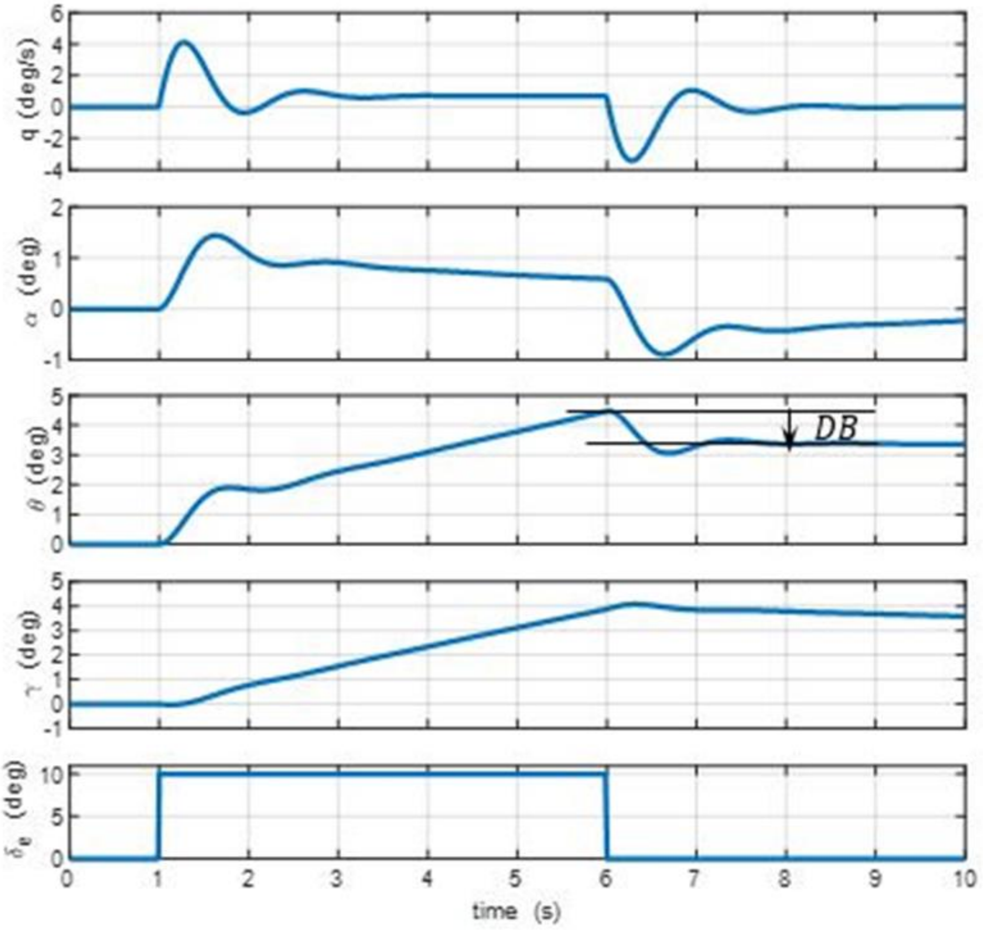


Figure 45. Time histories – “boxcar” input

The concepts described above are applicable to a conventional aircraft response, this being relevant for the inner loop of the stability and control augmentation in UAM vehicles. More information on the theta drop-back metric is provided in section 5.

4.9 Definition of test points

Maneuver specification includes the definition of the flight conditions at which each maneuver type has to be specified. Within the test plan frame, the selected flight conditions have to ensure adequate flight envelope coverage for each of the aircraft configurations under test. Envelope is in this case a multidimensional space, which can be delimited by airspeed, pressure altitude, flow angles, load factors, attitude angles, and the other variables that define the state of the specific vehicle in the given configuration. The accuracy of the aircraft FQ assessment is highly dependent on the discretization of the envelope with respect to each of the variables defining it, which is obtained by means of the test points. An adequate number and appropriate location of test points allows to measure the FQ metrics in correspondence of the main variations of the aeromechanic characteristics. The aircraft characteristics determine the priority and the feasibility of a given maneuver type, and indirectly the flight conditions. As an example, nonlinearities are usually one of the principal factors delimiting the envelope regions where FQTEs can be performed, and driving their amplitude requirements, as FQTEs are constrained to respect the conditions of vehicle linearity.

Figure 46 illustrates a generic aerodynamic coefficient, varying AoA, from a notional aircraft aerodynamic model. FQTEs have to be executed so that angle of attack remains in its linear region for the full duration of the maneuver. This requires defining trim airspeed, pressure altitude, and amplitude of the maneuver to ensure respect of linearity. The dot on the figure represents one trim point, and the bars represent the maximum achievable amplitude of a maneuver performed starting from that trim point. It is important to notice the margin with respect to the nonlinear region, to account for the potential mismatch between predictions and actual values.

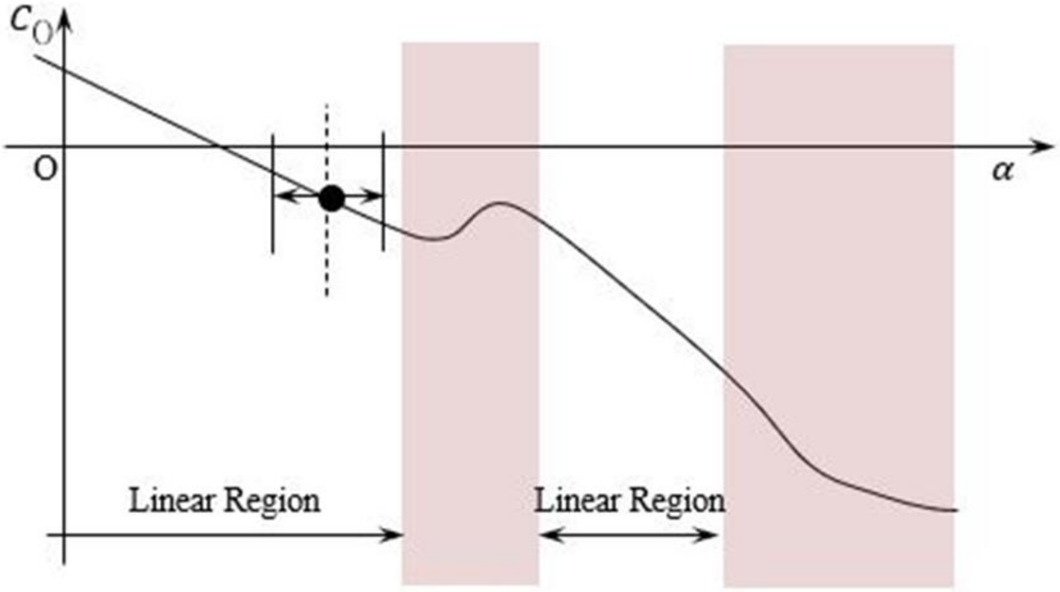


Figure 46. Regions of linearity for a notional aerodynamic coefficient

Assuming negligible compressibility effects, the target AoA leads to the specification of the airspeed and of the pressure altitudes at which the maneuver has to be performed. The boundaries of the linear regions lead to the specification of the amplitude(s) of the perturbation and consequently of the input.

Efficient flight test execution requires to perform multiple maneuvers and of different types at the same flight condition. This demands the definition of groups of maneuvers, conventionally defined as “Maneuver Blocks”, to facilitate their specification in the test plan. Table 8 reports examples of definition of three different maneuver blocks. Figure 47 illustrates a notional distribution of maneuver blocks within a KCAS/Hp flight envelope.

Table 8. Examples of maneuver blocks

	Maneuver Block 1	**Maneuver Block 2**	**Maneuver Block 3**
Maneuvers	Pitch Doublet Yaw Doublet Roll Doublet Roll + Yaw Doublet SHSS*	Pitch Doublet Yaw Doublet Roll Doublet Roll + Yaw Doublet Pitch Frequency Sweep Level Acceleration	Pitch Doublet Pitch 3-2-1-1 Roll Frequency Sweep Roll Step Level Deceleration

(*) Steady Heading Side Slip

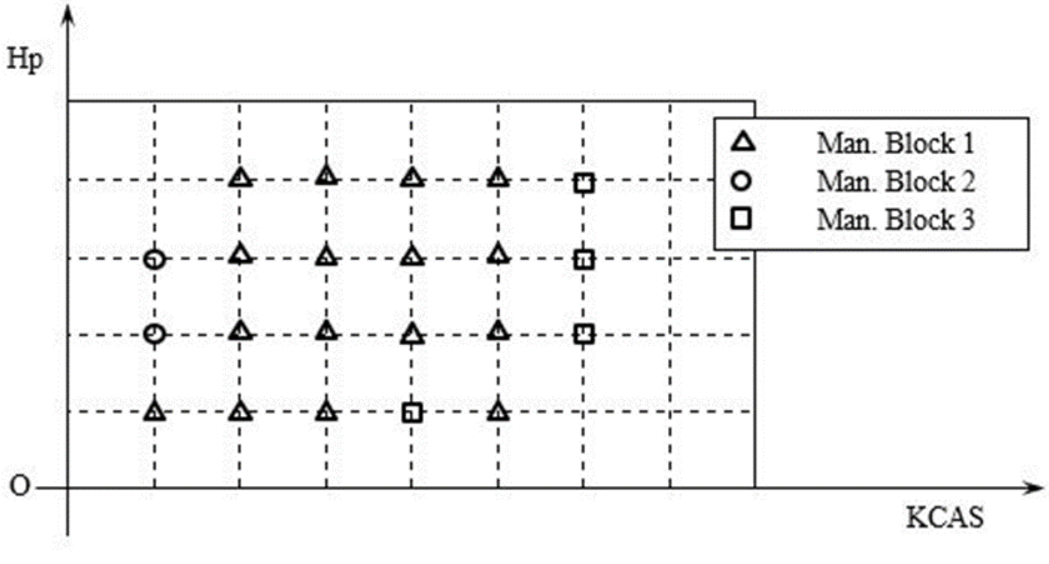


Figure 47. Example of maneuver blocks envelope coverage

A practical approach is to specify the maximum amplitude allowed by the various constraints, to maximize the SNR and the amount of available information. In case of manually executed maneuvers, feasibility is higher for the larger inputs.

5 Boundaries of analysis results and flying qualities criteria

5.1 Background

The main objective for the execution of FQTEs is to produce and gather data to be analyzed, synthesized and compared with the requirements of selected flying qualities criteria. The result of the whole process is to obtain flying qualities, i.e.: predicted handling qualities, levels which can be mapped onto the flight envelope. The standard applicable boundaries of the results are analytical. They correspond to the requirements on modal parameters and on other metrics specific to the flying qualities criteria selected for the assessment of the vehicle dynamics and eventually of the flying qualities, or predicted handling qualities.

This process verifies that flying qualities levels derived from the results of offline analysis/synthesis of the aircraft modeled characteristics match those obtained from analysis/synthesis of experimental data gathered from FQTEs. A consistent match of the flying qualities in correspondence of selected areas of the flight envelope verifies that the aircraft satisfies the specification and/or certification requirements and provides good confidence that the handling qualities levels are expected to match those for which the aircraft was designed. This allows the safe progress of flight testing aimed at handling qualities evaluation/assessment and provides fundamental feedback on the validity of the process conducted from aircraft modeling, control laws design and flight clearance. The value is also in the use of the test and evaluation experience that the aeronautical community accumulated and synthesized in the flying qualities criteria.

The next sections describe the definitions and the main flying qualities criteria, their requirements and the applicable FQTEs, grouped into airworthiness and military specification requirements. Most of the requirements have been extracted from FAA Title 14 CFR Parts 23, 25, 27 and 29, SAE AS94900 (SAE , 2007), ADS-33E-PRF for piloted military rotorcraft and MIL-STD-1797B for piloted military FW aircraft (DOD, 2012). The wider variety of criteria listed are for pitch control; few choices are documented for roll, yaw, flight path, or speed control.

The following sections present a significant number of diversified criteria, which can be applied singly or in combination. Their relevance for aircraft certification is in collectively addressing the vehicle characteristics and performances which form part of the expected aircraft certification basis. Specific means of compliance can be derived from these criteria, or the criteria themselves can be adopted as means of compliance, when consistent with the certification approach.

It is useful to define the effectiveness of the criteria using a set of three prerequisites for their application, as defined by McRuer (McRuer, 1997) in his past work at STI:

1. Validity: it implies that the metrics are associated with properties and characteristics that define the environment of interest. Specifically, in this application, valid metrics will differentiate between desirable, acceptable, and unacceptable handling qualities.
2. Selectivity: it demands that the metric differentiates sharply between “desirable” systems and those that are merely “acceptable.” This assures that there will be no question about selecting between “desirable” and “unacceptable” per se.
3. Ready Applicability: it requires that the metric be easily and conveniently applied. Its expression in terms of readily available system parameters should be compact; procedures for its analytical evaluation should be convenient; and it should be easily measured in terms of either simulation models and/or empirical operations on the actual airplane and its systems.

Considering the wide variety of aircraft configurations within the UAM class, grouping and separation of criteria based on the prerequisites reported above can be critical for the success of their application and of a potential certification process based on selected groups of them.

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5.2 14 CFR Airworthiness requirements

The main FQ requirements contained in 14 CFR Part 23, 25, 27 and 29 are reported below in Table 9, together with the applicable FQTEs described in the previous sections and in public domain publications.

Table 9. 14 CFR Airworthiness requirements

14 CFR Airworthiness Requirements		
Requirement	**Description**	**Applicable FQTEs**
§ 23.2145 Stability	(a) Airplanes not certified for aerobatics must - (1) Have static longitudinal, lateral, and directional stability in normal operations; (2) Have dynamic short period and Dutch roll stability in normal operations; and	Classical longitudinal stabilized, or longitudinal level acceleration/deceleration techniques, and SHSS to demonstrate respectively longitudinal and

14 CFR Airworthiness Requirements		
Requirement	**Description**	**Applicable FQTEs**
	(3) Provide stable control force feedback throughout the operating envelope. (b) No airplane may exhibit any divergent longitudinal stability characteristic so unstable as to increase the pilot's workload or otherwise endanger the airplane and its occupants.	lateral/directional static stability. Pitch frequency sweep or 3-2-1-1 and single doublet for short period and phugoid dynamic stability. Yaw or roll doublet
§ 23.181 Dynamic stability	(a) Any short period oscillation not including combined lateral-directional oscillations [---] must be heavily damped with the primary controls— (1) Free; and (2) In a fixed position. (b) Any combined lateral-directional oscillations (Dutch roll) [---] with the primary controls in both free and fixed position, must be damped to 1/10 amplitude in: (1) Seven (7) cycles below 18,000 feet and (2) Thirteen (13) cycles from 18,000 feet to the certified maximum altitude. (c) If it is determined that the function of a stability augmentation system, reference §23.672, is needed to meet the flight characteristic requirements of this part, the primary control requirements of paragraphs (a)(2) and (b)(2) of this section are not applicable to the tests needed to verify the acceptability of that system. (d) During the conditions as specified in §23.175, when the longitudinal control force required to maintain speeds differing from the trim speed by at least plus and minus 15 percent is suddenly released, the response of the airplane must not exhibit any dangerous characteristics nor be excessive in relation to the magnitude of the control force released. Any long-period oscillation of flight path, phugoid oscillation, that results must not be so unstable as to increase the pilot's workload or otherwise endanger the airplane. [Amdt. 23–21, 43 FR 2318, Jan. 16, 1978, a	Pitch frequency sweep or 3-2-1-1 and single doublet.
§ 25.173 Static longitudinal stability	Under the conditions specified in § 25.175, the characteristics of the elevator control forces (including friction) must be as follows:	Classical longitudinal stabilized, or longitudinal level acceleration/deceleration

14 CFR Airworthiness Requirements		
Requirement	**Description**	**Applicable FQTEs**
	(a) A pull must be required to obtain and maintain speeds below the specified trim speed, and a push must be required to obtain and maintain speeds above the specified trim speed. [---] (b) The airspeed must return to within 10 percent of the original trim speed for the climb, approach, and landing conditions [---], and must return to within 7.5 percent of the original trim speed for the cruising condition [---]. (c) The average gradient of the stable slope of the stick force versus speed curve may not be less than 1 pound for each 6 knots. (d) Within the free return speed range [---], it is permissible for the airplane, without control forces, to stabilize on speeds above or below the desired trim speeds if exceptional attention on the part of the pilot is not required to return to and maintain the desired trim speed and altitude.	techniques and SHSS to demonstrate longitudinal and lateral/directional static stability. Frequency sweep or 3-2-1-1 and single doublet for short period and phugoid dynamic stability.
§ 27.143 Controllability and maneuverability	(a) The rotorcraft must be safely controllable and maneuverable - (1) During steady flight; and (2) During any maneuver appropriate to the type, including - [---] (b) The margin of cyclic control must allow satisfactory roll and pitch control at V_{NE} with – [---] (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 – [---] (d) 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 out-of-ground-effect, with – [---]	

14 CFR Airworthiness Requirements		
Requirement	**Description**	**Applicable FQTEs**
	(e) The rotorcraft, after (1) failure of one engine in the case of multiengine rotorcraft that meet Transport Category A engine isolation requirements, or (2) complete engine failure in the case of other rotorcraft, must be controllable over the range of speeds and altitudes for which certification is requested when such power failure occurs with maximum continuous power and critical weight. No corrective action time delay for any condition following power failure may be less than - (i) For the cruise condition, one second, or normal pilot reaction time (whichever is greater); and (ii) For any other condition, normal pilot reaction time. (f) For helicopters for which a V_{NE} (power-off) is established under § 27.1505(c), compliance must be demonstrated with the following requirements with critical weight, critical center of gravity, and critical rotor r.p.m.: [---]	
§ 29.173 Static longitudinal stability	(a) The longitudinal control must be designed so that a rearward movement of the control is necessary to obtain an airspeed less than the trim speed, and a forward movement of the control is necessary to obtain an airspeed more than the trim speed. (b) Throughout the full range of altitude for which certification is requested, with the throttle and collective pitch held constant during the maneuvers specified in § 29.175(a) through (d), the slope of the control position versus airspeed curve must be positive. However, [---], the slope of the control position versus airspeed curve may be neutral or negative if the rotorcraft possesses flight characteristics that allow the pilot to maintain airspeed within ±5 knots of the desired	

14 CFR Airworthiness Requirements		
Requirement	**Description**	**Applicable FQTEs**
	trim airspeed without exceptional piloting skill or alertness.	

5.3 Military specification requirements

5.3.1 MIL-STD-1797B

This section reports MIL-STD-1797B FW aircraft military specification requirements. MIL-STD-1797B defines six Classes of aircraft; requirements relevant for UAMs are those relative to Class I, i.e.: small, light aircraft such as light observation. The reasons for this are that Class II and Class III aircraft are significantly heavier than the standard UAM; Class IV aircraft are more maneuverable and with significantly different mission requirements with respect to UAMs; Class V (rotorcraft) and Class VI (V/STOL aircraft) requirements are considered more extensively covered by ADS-33E-PRF. Table 10 reports Class I requirements, where applicable.

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Quoting material from it in this document would imply that the document must also carry the limitation, and in accordance with NIST SP-800-171 must be protected and transmitted only by the guidelines established for Controlled Unclassified Information (CUI). For this reason, the requirements are not quoted in detail; the information provided in Table 10 is of a general nature or it can be found in open literature, reference Mitchell et al. (1994).

Table 10. MIL-STD-1797B Requirements

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
5.2.2 Longitudinal flying qualities requirements 5.2.2.1 Longitudinal	"The longitudinal response of the air vehicle to the pitch controller shall meet the requirements of 5.2.2.1.1 through 5.2.2.1.8.8." It is a group of requirements: equivalent systems; time response criteria; $d\gamma/dV$; speed stability; pitch attitude Bandwidth; frequency response envelopes;	The dynamic response requirements might be used for two cases: 1) aircraft with no more than a simple SAS, i.e.: basic dynamic responses resemble a conventional airplane; 2) inner-loop design objectives for semi-autonomous aircraft. In the second case, the	

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
response to the pitch controller	flight path response to attitude changes; highly modified Neal-Smith criterion; Smith-Geddes criterion (pitch PIO); n_z at pilot station; control power and controller force/deflection limits; and Fs/n.	requirements are design goals, not pass/fail flying qualities criteria. The following is an overview of selected requirements and their limitations.	
5.2.2.1.1 Longitudinal lower-order equivalent system dynamics	Specifies multiple steps to obtain Low Order Equivalent System (LOES) parameters depending on the number of control effectors; the discussion of methods is not included in the document.	These requirements apply if no advanced command augmentation system is implemented. As an example, it does not apply to an Attitude Command system. Criteria based on LOES are not applicable to non-classical response types. With an outer loop, short period mode characteristics are overridden by the outer-loop controller.	
5.2.2.1.1.1 Phugoid dynamics	Minimum damping ratio requirements on “Any oscillatory mode with a frequency of 0.42 rad/s or less.”	Potentially relevant for flight path modes for, also in case of semi-autonomous UAMs. Low-frequency oscillatory modes might not be present in highly-augmented UAMs.	
5.2.2.1.1.2 Short-period dynamics	Limits on short-period modal parameters, CAP, equivalent time delay.	Relevant for classical responses, not relevant if outer (path) loops are applied, especially if the form of the response has been changed.	
5.2.2.1.2.1 Long-term longitudinal response	Same damping ratio requirements as the phugoid modes above for “Any oscillation with a period of 15 s or longer.”	Potentially relevant for flight path modes for, also in case of semi-autonomous UAMs. Low-frequency oscillatory modes might not be present in highly-augmented UAMs.	
5.2.2.1.2.2 Short-term pitch response	Requirements/limits on time responses of pitch rate to a step and a pulse pitch control input: effective time delay, rise time,	Relevant for augmented UAMs that employ a pitch rate command/pitch attitude hold CAS. Not applicable to any	

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
to pitch controller	pitch rate overshoot, theta dropback, TPR, [---]. It includes a comprehensive discussion of theta drop-back by J. Gibson.	other control laws, especially those with no augmentation.	
5.2.2.1.2.3 Steady-state flight-path response to pitch controller	Sets limits on dγ/dV to assure flight path stability. Flight path controlled primarily through the pitch controller and through “some designated flight path controller other than the pitch controller”.	Not applicable to vehicles with speed control or auto-thrust control. Potentially applicable to UAMs in low-speed regime without automatic airspeed controller.	
5.2.2.1.2.4 Speed response to attitude change	This requirement and related sub-requirements establish speed stability requirements.	Potentially applicable to UAMs without automatic speed controller.	
5.2.2.1.3 Longitudinal frequency response to the pitch controller. 5.2.2.1.3.1 Pitch attitude bandwidth	Sets limits on pitch attitude Bandwidth and Phase Delay. Note: requirement boundaries are very close to the most current set. It applies to “the pitch attitude response to pilot pitch control input” but does not specify force or position input. Refer to AFRL-VA-WP-TR-2000-3046 for boundaries when input is position only.	Applicable to any manually-controlled aircraft, unaugmented, with simple SAS or advanced CAS. All control loops should be closed, it might be difficult to isolate “pitch controller”, as multiple effectors (including thrust) might change. The response to pitch controller could be considered as a whole, following a "maneuver demand" approach.	
5.2.2.1.3.2 Pitch attitude frequency response envelopes.	Nichols chart limits without definition of FQ Levels.	Material intended to be initial design guidance alone.	
5.2.2.1.4 Closed-loop analysis with a pilot model	Apply one or more of several pilot model forms at one or more assumed control frequencies to determine pilot compensation and closed-loop resonance.	Reference for application of the Neal-Smith criterion. Direct application of the criterion is preferable.	
5.2.2.1.5 Pitch PIOs	Smith-Geddes PIO criterion.	Relative validity.	
5.2.2.1.6 Normal	Qualitative requirement.	Requirement of potential high value for over actuated aircraft	

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
acceleration at the pilot station		like UAMs. It includes an interesting discussion on the effect of Direct Lift Control (DLC) on heave effects at pilot's station and on impact of aeroelastic modes.	
5.2.2.1.7 Longitudinal control power. 5.2.2.1.7.1 to 5.2.2.1.7.6	Set of requirements on control power for maneuvering, takeoff, landing, and commanding load factor.	To be considered that the formulation of the requirement is aimed at tactical aircraft maneuvering, which is not completely applicable in all its parts to UAMs.	
5.2.2.1.8 Longitudinal control forces and displacements in maneuvering flight	Several requirements on controller characteristics, Fs/n, [---].	The structure of the requirement could be adapted to vehicles with a smaller n_z envelope. A significant amount of data of Class I aircraft is provided.	
5.2.2.2 Longitudinal response to the designated flight path controller 5.2.2.2.1 Flight path response to designated flight path controller 5.2.2.2.2 Flight path control power	Short-term (rise time and overshoot) limits, and minimum change in flight path angle, for flight path response to a designated flight path controller.	These requirements are intended for piloted STOLs, they could be applicable to powered-lift STOL UAMs, as long as there is a controller that has direct commands to flight path angle.	

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
5.2.2.2.3 Flight path controller characteristics			
5.2.3 Lateral-directional flying qualities 5.2.3.1 Lateral-directional modal characteristics	"The lateral-directional modal characteristics (roll mode, spiral mode, Dutch roll, etc.) shall meet the requirements of 5.2.3.1.1 through 5.2.3.1.6."	This is a relevant set of requirements and the only available for lateral/directional dynamics in MIL-STD-1797B. Combined application of roll attitude Bandwidth/Phase Delay requirements should be considered. Attitude bandwidth could be the primary requirement. Highly augmented aircraft can refer to the Bandwidth criterion alone, as they will not exhibit discernable lateral/directional modes.	
5.2.3.1.1 Roll mode	Limits on maximum allowable equivalent roll mode time constants.	The method is applicable, the limits have to be updated to match UAMs requirements. The specification suggests to apply Roll Attitude Bandwidth criterion for aircraft with a roll response which cannot be approximated by a first order equation alone.	
5.2.3.1.2 Dutch roll frequency and damping	Limits on Dutch Roll minimum frequency, damping ratio, total damping, as well as the delta total damping for large phi/beta.	Same comment as for roll mode.	
5.2.3.1.3 Spiral stability	Allows divergent spiral.	Same comment as for roll mode.	
5.2.3.1.4 Coupled roll-spiral oscillation	Limits on total damping of coupled roll-spiral mode.	Same comment as for roll mode.	
5.2.3.1.5	Limits on equivalent time delays in roll and yaw responses.	Same comment as for roll mode.	

MIL-STD-1797B REQUIREMENTS

Requirement	Description	Discussion	Applicable FQTEs
Roll time delay 5.2.3.1.6 Yaw time delay			
5.2.3.2 Lateral-directional dynamic response characteristics	“The lateral-directional time responses shall meet the requirements of 5.2.3.2.1 through 5.2.3.2.8.”	These requirements are aimed at the forced response (zeros of the transfer functions) of the aircraft. In general, the requirements are met by default, if there are no detectable roll rate or sideslip oscillations. Most of these requirements are not applicable to highly augmented aircraft. Determination of parameters for these requirements is complicated and potentially subject to errors.	
5.2.3.3 Roll PIO	“There shall be no tendency for sustained or uncontrollable roll oscillations resulting from efforts of the pilot to control the aircraft. The phase angle of the bank angle frequency response to roll stick force at the criterion frequency, ω_c, shall be greater than or equal to -180 deg [---]”	This paragraph refers to the Smith-Geddes criterion, which might be removed in next revisions, and to the other roll requirements of the specification.	
5.2.3.4 Yaw PIO	“There shall be no tendency for sustained or uncontrollable yaw oscillations resulting from the efforts of the pilot to control the aircraft in the air or on the ground [---]”	The requirements are qualitative, based on pilot’s evaluation. There is a reference to the ω_ϕ/ω_D effect, which determines the phase of the AoS response.	
5.2.3.5 Roll control effectiveness 5.2.3.5.1 Additional roll	The requirements are the times to roll through specified bank angle changes in specified times, for specified airspeed ranges, separated by Class of aircraft.	The concept is important for any air vehicle. Update of the requirements values for UAMs to be evaluated.	

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
requirements for Class IV air vehicles 5.2.3.5.2 Roll termination 5.2.3.5.3 Roll control power with asymmetric loads	Values for Class I aircraft could be considered as an initial reference.		
5.2.3.6 Lateral-directional control with speed changes 5.2.3.7 Yaw control forces in waveoff (go-around) 5.2.3.8 Lateral-directional control forces and displacements	A set of requirements on cockpit control forces and displacements.	Integration in the requirement of fraction of maximum control surface deflection at the given trim flight condition is potentially useful. A single requirement valid for all aircraft types is preferable, for the absence of exceptions.	
5.2.3.9 Steady sideslips	Several requirements to assure static stability and control power in sideslips.	The requirement concept is useful to ensure that significant lateral/directional non linearities are not present. Wave-off requirements can be highly relevant for operation in constrained space.	

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
5.2.3.10 Lateral-directional control in crosswinds	Limits on control forces and displacements in crosswinds.	Requirements include limits for takeoff, taxi, and landing that should be checked for UAMs. Parts of the requirements are related to control surfaces deflection and overall controllability.	
5.2.3.11 Lateral-directional control with asymmetric thrust	Limits on control forces and displacements for multi-engine aircraft.	This is a potentially highly relevant requirement, mostly for the multi-engine concept. Modifications might be necessary to adapt it to the UAM characteristics. Force values could be complemented by control surface deflections.	
5.2.3.12 Wings-level turn. 5.2.3.13 Lateral translation	Series of requirements on aircraft designed to perform wings-level turns or nose pointing in straight flight.	The requirements provide implicit guidance on implementation of the direct side force control on unmanned aircraft. Based on pilots' reports, this controller can impact negatively the HQ. Significant decrease of airspeed when turning with the direct side force controller to be evaluated.	
5.2.4.3 Cross-axis coupling in roll maneuvers	Generally qualitative requirement to minimize the chances of cross-coupling in maneuvering flight.	Qualitative requirements: "neither exceed structural limits nor cause other dangerous flight conditions such as uncontrollable motions or roll autorotation," "yawing and pitching shall not be so severe as to impair the tactical effectiveness of the maneuver". It is designed to prevent aero and inertial cross-coupling. It can be generalized to retain validity for application to UAMs, discarding references to high performance/high maneuverability tactical aircraft.	

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
5.2.4.4 Crosstalk between pitch and roll controllers 5.2.4.5 Control harmony 5.2.4.6 Control cross-coupling	Pitch-, roll-, and yaw-control force and displacement requirements.	Application to UAMs can be critical for the fully passive nature of the inceptors and for the high level of the control modes.	
5.2.5 High angle of attack requirements	A comprehensive set of requirements on stall, departure, and spin prevention and recovery.	The set of requirements is aimed at high performance tactical aircraft. It is not applicable to UAMs in the current form, as AFCS is expected to prevent high AoA operation, in full carefree mode or with automatic recovery. The value for any type of manned (and unmanned) aircraft is high, to ensure departure resistance and to improve SA in low energy flight conditions.	
5.2.6 Carrier Operations	Includes candidate MTEs for carrier-based aircraft; minimal requirements for shipboard operations.	These requirements are of high value for the specification of MTEs for operation with space and time constraints. Quantitative values have to be defined, for the requirements to be practically applicable.	N/A
5.2.6.1 Deck handling	"The air vehicle shall have ground handling characteristics that allow operation from the constricted spaces aboard ships in degraded environmental conditions."	The requirement includes specific elements of ship operation like the catapult. Evaluation of its adaptation to the UAMs is suggested, for its relevance for operation in "constricted spaces".	N/A

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
5.2.6.2 Catapult launch	"With __(1)__ wind-over-deck (WOD), Level 1 flying qualities shall be achieved during catapult launches from all in-service catapult types, for all operating weights and center of gravity location combinations, subject to constraints on catapult minimum end speed. Sink off bow shall be no more than __(2)__ and pitch rate shall be no more than __(3)__ following catapult launch."	These qualitative requirements are reported for completeness, they are not directly applicable to UAMs and they are MTE based, not relevant for FQTE execution.	N/A
5.2.6.3 Carrier approach and landing	"Level 1 flying qualities shall be achieved during approach and landing on carrier decks for all recovery weights, with airspeed slow enough to require a WOD of no more than __(1)__."	These qualitative requirements are reported for completeness, they are not directly applicable to UAMs and they are MTE based, not relevant for FQTE execution.	N/A
5.2.6.4 Bolter	"From a 4º glideslope at approach speed, it shall be possible to achieve nosewheel liftoff and attain flyaway attitude by the end of the angle deck, assuming the arresting hook just misses the last wire on the classes of carriers from which it is required to operate."	These qualitative requirements are reported for completeness, they are not directly applicable to UAMs and they are MTE based, not relevant for FQTE execution.	N/A
5.2.6.5 Waveoff.	"The air vehicle shall possess __(1)__ flying qualities during waveoff in order to enable timely and safe termination of a shipboard approach. Loss of altitude following waveoff initiation shall be no more than __(2)__."	Recommended potential requirements are: (1) level 1 and (2) 30 ft. Different UAM configurations can perform the required MTE in different ways, depending on their capability to hover.	N/A
5.2.6.6 Single engine failure (multi-engine air vehicles)	No specific requirements, just says that it should be possible to recover to single-engine conditions. Implies two-engine aircraft specifically.	These qualitative requirements are reported for completeness, they are not directly applicable to UAMs and they are MTE based, not relevant for FQTE execution.	N/A

MIL-STD-1797B REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs**
5.2.7 V/STOL specific requirements	This is a set of requirements on dynamic response, and suggested MTEs, primarily oriented towards fixed-wing V/STOL aircraft.	Requirements from ADS-33E-PRF overlap with these.	N/A
5.2.8 Characteristics of the primary flight control system	These requirements apply to forces in mode transfer, operation of augmentation systems, control surface rates, cockpit controller characteristics (breakout force, forces and displacements, freeplay, dynamics)	Similar FCS requirements are available in AS94900 or ARP94910, to be evaluated the most convenient set amongst the three documents.	
5.2.9 Characteristics of secondary flight control systems	Requirements on trim systems, motions during configuration changes, dive recovery devices.	Similar FCS requirements are available in AS94900 or ARP94910, to be evaluated the most convenient set amongst the three documents.	

5.4 ADS-33E-PRF

This section reports ADS-33E-PRF RW aircraft military specification requirements. ADS-33E-PRF is the United States Army's Aeronautical Design Standard (ADS) for handling qualities requirements for military rotorcraft. It has been adopted also by the United States Navy and it has become the single reference for handling qualities of Vertical Take Off and Landing (VTOL) aircraft. There is a gap in requirements for transition between wingborne and rotorborne flight; Class VI (V/STOL) requirements in section 5.2.7, paragraphs 5.2.7.2.1.1 to 5.2.7.2.2, of MIL-STD-1797B, reflect the work performed to update them, not including knowledge gained from V-22 or F-35B aircraft development.

ADS-33E-PRF consists of quantitative and qualitative requirements. Table 11 reports the quantitative requirements. The qualitative ones are expressed in the form of Mission Task Elements (MTEs) and they are not listed here, as their development constitutes another part of this research, dedicated to MTEs for UAMs. Full applicability of MTEs contained in ADS-33E-PRF to UAM aircraft is not guaranteed.

Table 11. ADS-33E-PRF Requirements

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3. Requirements 3.1 General	This section includes several requirements which mark an advancement in the specification of aircraft handling qualities. The most important of them are reported below.	All of 3.1 content should be the foundational information in a handling qualities document for hybrid configuration vehicles. The requirements specific to near-future application are reported.	N/A
3.1.5 Levels of handling qualities	It defines Predicted Levels, from analytical criteria, and Assigned Levels, from execution of MTEs.	It provides a useful structure for means of compliance, which can even be used as it is now, for initial application and evaluation of its validity.	Valid for all FQTE/HQTEs, depending on the modal parameters and aircraft dynamics metrics.
3.1.6 Flight envelopes	It defines envelopes similar to definitions applied before MIL-STD-1797B: Operational and Service envelopes. It also reports what is required for flight outside the Service Flight Envelopes.	The concept is critical to formation of usable requirements and means of compliance (Tischler, 1995). The application of envelopes is important, instead of the definition of "regions of handling" as applied in MIL-STD-1797B. It leads to a potentially more straightforward application of the requirements: handling is decoupled from aircraft operation.	N/A

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3.2 Response-Types	It defines the method to determine Usable Cue Environment (UCE), Visual Cue Rating (VCR) and minimum Response-Types to operate in the UCE.	This can be limited by the Response-Type being a pilot-centric concept that applies to inner-loop dynamics; guidance loops do not strictly require a specific Response-Type. ADS-33 defines responses in terms of pilot control inputs, of three general types in hover and low speed: Rate, Attitude, and Translational Rate Command. Responses that do not match the last two are identified as Rate by default. For autonomous aircraft, the outer/guidance loops can alter one of the standard responses above – that are not addressed in ADS-33, with few exceptions.	N/A
3.2.7 Character of Attitude Hold and Heading Hold Response-Types 3.2.7.1 Additional requirement for Heading Hold	These requirements define dynamic response characteristics for the specific "outer-loop" modes identified in the respective titles.	These three paragraphs are in the Response-Type section, they can be considered more hybrids, as they address both pilot-applied and system-applied guidance loops. These short-term requirements are potentially useful in combination with the select and hold specifications of ARP94910. ADS-33 sets limits on quickness and initial accuracy of the	Pulse input, Hover, Hover Taxi, Lateral Reposition.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3.2.10.1 Character of Vertical Rate Command with Altitude (Height) Hold		response, ARP94910 sets limits on the quality of the response over time.	
3.3 Hover and low speed requirements	This section contains a series of requirements, the most relevant of which are discussed below.	This section of ADS-33 requires a different approach from the other military specifications. Simplification of the requirements can be considered, in particular to generalize them with respect to the inceptor configuration of UAMs. The advantage is in being a flying qualities centered approach that can be applied to verification in different phases of the aircraft development.	Hover, Hover Taxi.
3.3.1 Equilibrium characteristics	It requires that no-wind hover, and “equilibrium flight” in a 35-kt relative wind, does “not result in pilot discomfort, disorientation, or restrictions to the field-of-view that would interfere with the	Not all of the UAMs are expected to satisfy the 35 kt requirement. Different ranges of relative wind speed can be specified, based on the UAM type, or class. Upper limits should be specified for all ranges. Specification of different FQ levels based on the wind speed range could also be considered, to attenuate the current nature of pass/fail	Hover related MTEs.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
	accomplishment of the Mission-Task-Elements [---]”	criterion. Consideration of turbulence levels is possible, given its impact on the limited powered UAMs.	
3.3.2 Small-amplitude pitch (roll) attitude changes 3.3.2.1 Short-term response to control inputs (bandwidth)	These requirements are the core of the specification: pitch/roll Bandwidth and Phase Delay requirements.	These requirements are valid before the guidance loops are closed, which makes it potentially difficult to obtain data. Matching these requirements is expected to ensure adequate response characteristics in case of flight guidance degradation and to reduce the demand on the control system. Their main application is offline, to models. Considering a standard aircraft development process, all FQ requirements will be applied offline first, for flight clearance. Stating their required offline application can clarify their guidance value, too. Overall, these requirements can be more guidelines for the designer and to define intermediate *gates* in the development process.	Frequency sweep, 3-2-1-1.
3.3.2.2 Short-term pitch and roll	It requires Attitude Bandwidth check through control surface actuator.	The relevance of this requirement is its validity as an offline requirement, too.	Frequency sweep, 3-2-1-1.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
responses to disturbance inputs			
3.3.2.3 Mid-term response to control inputs	This requirement states limits on oscillations below the Bandwidth frequency.	The gain/phase margin requirements from ARP94910, combined with a limit on residual oscillations can be applied in place of this requirement. It could also be substituted by a metric similar to the pitch rate overshoot, i.e.: variation of the gain as a function of frequency, representing an *effective* damping ratio.	Frequency sweep, 3-2-1-1.
3.3.3 Moderate-amplitude pitch (roll) attitude changes (attitude quickness)	This requirement limits peak angular rate per unit attitude change for larger magnitude responses.	Actuator rate/position saturation is to be avoided. At the same time, their potential effect on the outer-loop response is more important.	Frequency sweep, 3-2-1-1.
3.3.4 Large-amplitude pitch (roll) attitude changes	This requirement states the minimum attainable angular attitudes (for Attitude Command) or rates (for Rate Command).	The concept is applicable to UAMs, potentially updating the values to match UAM mission requirements. The three agility categories can be reduced to two.	Boxcar, step input, Sidestep.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3.3.5 Small-amplitude yaw attitude changes 3.3.5.1 Short-term response to yaw control inputs (bandwidth)	These are requirements on Heading Bandwidth and Phase Delay.	Similar to section 3.3.2.1: these can be used as inner-loop design guidance, with limited utility for outer-loop control. Overall, it is useful to retain requirements based on bandwidth and phase delay, which form the core of a potential new way of certification means of compliance, closer to the criteria applied also in the aircraft design and development phase.	Frequency sweep, 3-2-1-1.
3.3.5.2 Mid-term response to control inputs 3.3.6 Moderate-amplitude heading changes (attitude quickness) 3.3.7 Short-term yaw response to disturbance inputs 3.3.8 Large-amplitude heading changes	These requirements are conceptually very close to those in the pitch/roll paragraphs 3.3.2.2 through 3.3.4 presented above.	Similar discussion to that for the pitch/roll requirements applies.	Frequency sweep, 3-2-1-1.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3.3.9 Interaxis coupling	These are three specific requirements dealing with typical coupling responses for helicopters. This paragraph is a generic statement: “Control inputs to achieve a response in one axis shall not result in objectionable responses in one or more of the other axes.”	The coupling requirements can be extended to outer-loop response for UAMs. This overarching requirement can be very useful for UAMs, considering their different configurations. The term “objectionable” can be replaced by “excessive” in case of autonomous vehicles.	Step, boxcar input, Longitudinal/Lateral/Combined reposition and hold.
3.3.9.1 Yaw due to collective for Aggressive agility	This requirement states limits on yaw rate time responses as a function of vertical rate.	This can be a useful requirement for hybrid configurations. For generalization, the inputs should be renamed, from collective to vertical acceleration command, for example. As a consequence, the requirement could be renamed as “yaw due to vertical-axis commands”. This is potentially one of the most operationally relevant set of requirements for UAMs.	Abrupt step.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3.3.9.2 Pitch due to roll and roll due to pitch coupling for Aggressive agility	This requirement states limits on the ratio of peak off-axis response in the first 4 seconds to on-axis response at 4 seconds for abrupt control inputs.	The term “Aggressive agility” should be clarified for UAMs, when considered mission representative. Values are potentially to be updated. An approach similar to MIL-STD-1797B could be initially applied, leaving the quantitative values blank, to be later assigned by the certification authority. This would allow gathering data while enabling the application of the requirement, implicitly guiding aircraft development to minimization of axis coupling. An example of "open" quantitative requirements can be: "The ratio of peak off-axis attitude response from trim within [---] seconds to the desired (on-axis) attitude response from trim at [---] seconds, $\Delta\theta pk / \Delta\phi 4$ ($\Delta\phi pk / \Delta\theta 4$), following an abrupt lateral (longitudinal) cockpit control step input, shall not exceed ±[---] for Level 1 or ±[---] for Level 2. Heading shall be maintained essentially constant."	Abrupt lateral (longitudinal) cockpit control step input.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3.3.9.3 Pitch due to roll and roll due to pitch coupling for Target Acquisition and Tracking	These requirements are aimed at limiting frequency response of off-axis/on-axis dynamics.	This requirement is potentially not applicable to UAMs, for the low relevance of "Target Acquisition and Tracking" tasks for this class of vehicles. "Target Acquisition and Tracking" is not expected to be a representative task for the majority of UAMs operation. Significant flight test time is expected to be necessary to define the values of requirement 3.3.9.2, which will allow to comprehend the validity of this requirement for UAMs. These requirements were generated from a DLR/US Army flight test program (Blanken, Pausder, & Ockier, 1995). The basic concept was found in a US Air Force Test Pilot School program to be applicable to conventional manned airplanes (Lemery, et al., 2011; Mitchell & Nicoll, 2010) . The requirement is to be considered for its versatility, as it can be applied to different types of vehicle configurations.	N/A
3.3.10 Response to collective controller	This requirement states time-domain measures of the	The objective of this requirement is to assess if the vertical rate response to vertical commands	Boxcar, step input.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
3.3.10.1 Height response characteristics	vertical rate response to a step collective input. It attempts to assure an approximately first-order response with limits on rise time and time delay.	is *clean*. It can be applicable in form to UAMs, updating the values to match UAM mission requirements, with application to vertical commands, in addition to collective alone. The value of the first order response time constant is expected to be lower than 5 s, for small aircraft in particular. Data have to be collected, to match the quantitative values with operational requirements and aircraft class. In this case the aircraft class is important, for the different expected quickness of the response varying aircraft size, and for requiring full use of the altitude rate capabilities of each aircraft class.	
3.3.10.2 Torque response	This requirement states limits on displayed torque.	It is of potentially low relevance for UAMs, depending on the aircraft configuration and powertrain.	N/A
3.3.10.3 Vertical axis control power	This requirement states minimum achievable vertical rates in response to collective inputs.	The requirement concept is relevant, quantitative requirements have to be updated. It is more connected to pure performance, even if it requires that "Pitch, roll, and heading	Rapid displacement of the collective/vertical rate control from trim.

ADS-33E-PRF REQUIREMENTS			
Requirement	**Description**	**Discussion**	**Applicable FQTEs/HQTEs**
		shall be maintained essentially constant.". Considering the significant difference in specific excess power, mass, aeromechanic characteristics, between the different types of UAMs, there is potential for subdividing the requirements by vehicle class. To be evaluated, as this is different from the fundamental concept of ADS-33 and of potential new airworthiness requirements.	
3.3.10.4 Rotor RPM governing	This requires rotor RPM to remain within the SFE when flying required MTEs.	This requirement is potentially irrelevant for vehicles with AFCS. It is mainly a system design best practice rather than an FQ requirement.	All operational MTEs.

5.5 Notes on aircraft attitude bandwidth criterion

5.5.1 Background

The Aircraft Bandwidth criterion, based on the Bode plot of the frequency response of attitude to control input (position or force), were developed for evaluation of the handling qualities of highly augmented airplanes where more conventional criteria cannot be easily applied (Hoh, Mitchell, & Hodgkinson, 1981). The criteria are included in MIL-STD-1797A (DOD, 1995) and, as reported in section 5.4 form the basis of the United States Army's rotorcraft airworthiness standard ADS-33E-PRF (DOD, 2000). The criterion requirements reported in MIL-STD-1797A have been found to be too stringent and have been adjusted, especially with the addition of a requirement on pitch rate overshoot (Mitchell D. G., Hoh , Aponso, & Klyde, 1994), representing the metric of an effective damping ratio.

The fundamental theory at the basis of the "Aircraft Bandwidth", different from the "bandwidth" as defined in other control systems applications – is that the principal stability characteristics of the aircraft can be described by the frequency response of angular attitude for control inputs. This is valid for continuous pilot's closed-loop control of attitude and when attitude is used as an inner loop to generate changes in load factor or flight path. The concept of "Aircraft Bandwidth" is that the aircraft should have good inherent stability, whether from basic design or by augmentation with SAS. The lower this inherent stability, the more stability the pilot must provide to perform required tasks, resulting in increasing workload, degraded handling performance, poor flying qualities, and ultimately, PIO.

5.5.2 Parameters for the bandwidth criterion

Three metrics in the criterion capture the basic pitch attitude characteristics of the airplane, displayed in Figure 48 (DOD, 2000). The first is the "phase margin Bandwidth frequency," the lowest frequency for which there is a phase margin of 45 degrees. The higher this frequency, the better attitude follows control inputs: if phase margin is 180 degrees, that is, phase angle is zero, then output follows input exactly. At the frequency for 0 degrees phase margin – the "neutral-stability" or 180-degree frequency – attitude is in phase opposition with inputs. If the phase margin Bandwidth frequency is very low, the pilot must generate lead to improve the overall response of the pilot-plus-aircraft system in order to do a task.

The second measure is the "gain margin Bandwidth frequency": it is basically the same type of measure, except it determines the change in effective-aircraft dynamics the pilot will encounter if closed-loop gain is increased by a factor of two, or 6 decibels.

The third measure, broadly named “Phase Delay,” is really a measure of how rapidly the phase angle of attitude/control inputs degrades at high frequencies. The assumption is that, if the pilot found it necessary to operate at higher frequencies – which can be done with closed-loop stability only if the pilot generates lead compensation – a gradual phase roll off is much better than a steep one.

There are fixed-wing aircraft for which assessed poor handling qualities are unlikely on the basis of the attitude Bandwidth characteristics alone. In some instances, high pitch rate overshoot is a contributor, and limits are placed on the corresponding frequency-domain-based metric, $\Delta G(q)$ as shown in Figure 49. The pitch rate overshoot metric provides a general indication of pitch rate damping ratio; it indicates the inherent sensitivity of the response to the frequency of the input, relevant for the predictability of the response itself. Inadequate flight path control is addressed by the limits placed on flight path Bandwidth frequency, ω_{BW_γ} .

These limits indicate the importance of harmony between attitude and flight path angle bandwidths. This requirement may be applicable to VTOL aircraft in a high-speed airplane mode, not applicable at low speed or hover.

Phase delay:

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

Rate response-types: ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$

Attitude response-types: $\omega_{BW} = \omega_{BW_{phase}}$

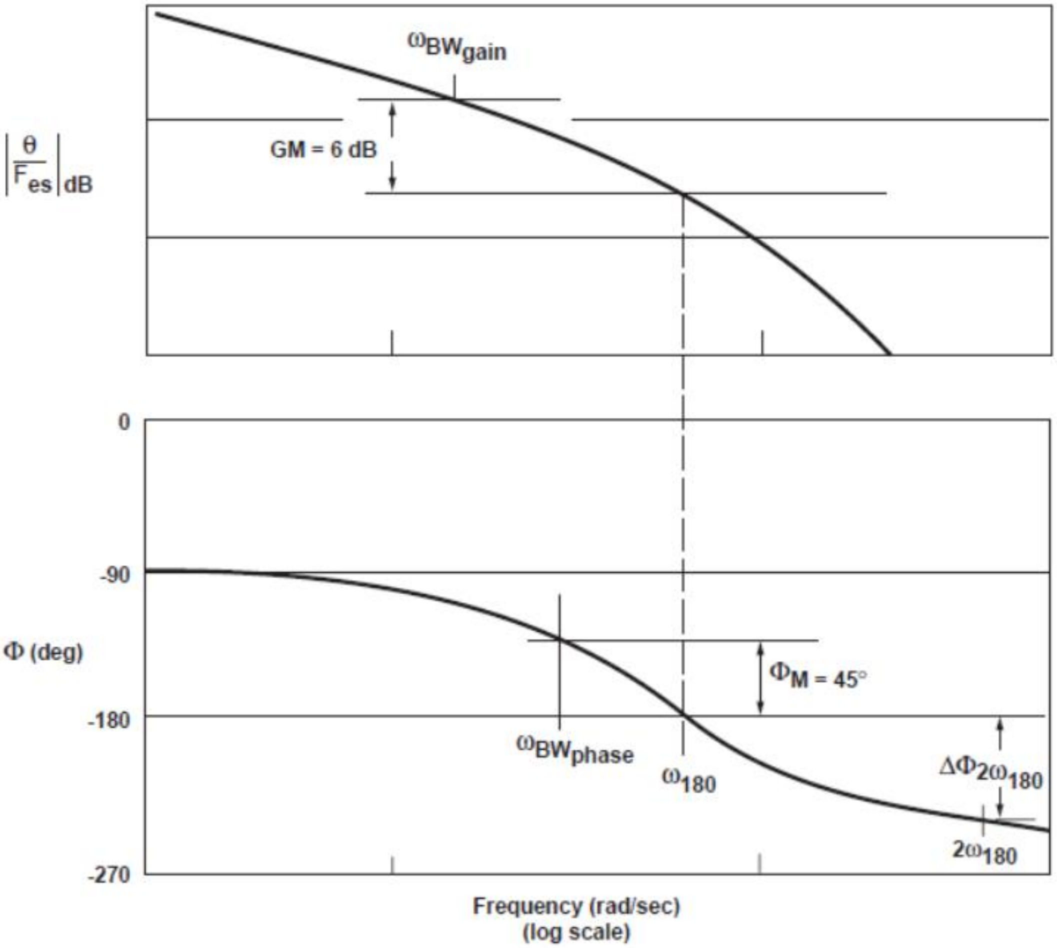


Figure 48. Parameters for pitch attitude bandwidth and phase delay

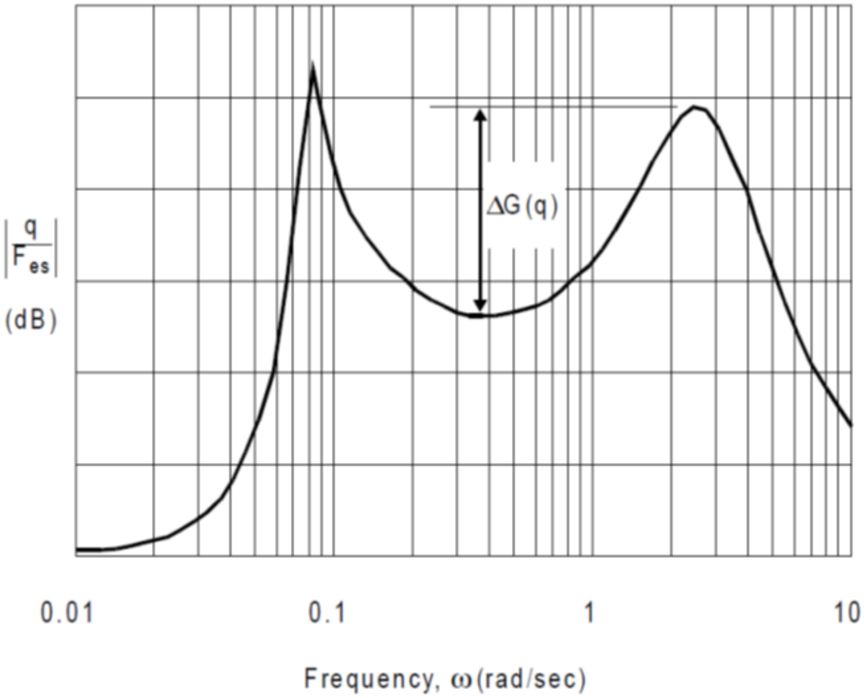


Figure 49. Pitch rate overshoot parameter

5.5.2.1 Strengths of the bandwidth criterion

Strength of the Bandwidth criterion is its applicability through all stages of aircraft development, and especially to flight testing. No assumptions, linearization, or simplification are required. It can be applied to all attitude-based response types.

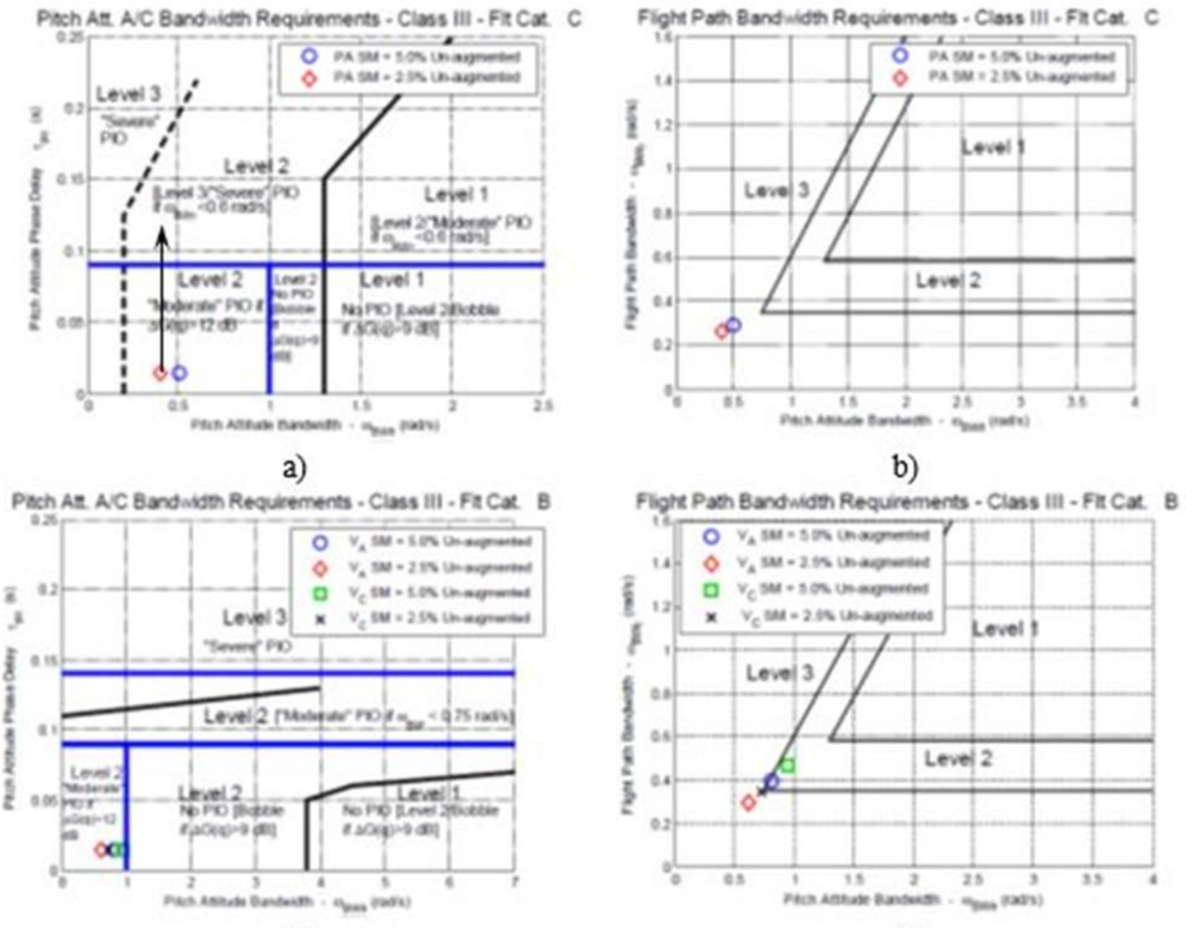
5.5.2.2 Shortcomings of the bandwidth criterion

The Phase Delay parameter is a measure defined for a rigid body system. Thus, the impact of additional dynamics (i.e., rotor dynamics, structural mode dynamics), can disrupt measurements of the phase roll off at higher frequencies. While a known issue, more research has to be developed to address this shortcoming.

5.5.3 Notes on the fixed wing aircraft requirement

Figure 50 illustrates the current boundaries of the Aircraft Bandwidth Criterion for the longitudinal dynamics of a transport aircraft in flight phase category C, terminal flight phases, and category B, non-terminal flight phases requiring gradual maneuvering. These provide an example of composite boundaries, based on metrics which can be calculated from data acquired from a frequency sweep. Analysis of Figure 50a) demonstrates that the requirements are a function of the combination of Pitch Attitude Bandwidth ($\omega_{BW\theta}$) and phase delay ($\tau_{p\theta}$), black lines, with superimposed requirements based on pitch rate overshoot ($\Delta G(q)$), blue lines, and flight path angle bandwidth, $\omega_{BW\gamma}$.

The combination of $\Delta G(q)$ and $\omega_{BW\theta}$ determines the prediction of “Moderate” PIO, or pitch “bobbling” for $\tau_{p\theta} < 0.09\ s$. Low pitch attitude bandwidth and high values of pitch rate overshoot correspond to PIO proneness, which decreases to tendency to “bobbling” for $\omega_{BW\theta} > 1\ \frac{rad}{s}$ and slightly reduced values of pitch rate overshoot, i.e.: $\Delta G(q) > 9\ dB$. Higher values of phase delay correspond to a more pronounced PIO proneness with Level 2 flight path angle bandwidth, i.e., $\omega_{BW\gamma} < 0.6\ \frac{rad}{s}$. Severity of PIO proneness increases with reduction of $\omega_{BW\theta}$, confirming the significance of bandwidth for precision of control of a vehicle. These requirements are applied concurrently with those of Figure 50b), which present boundaries based on a different combination of $\omega_{BW\gamma}$ and $\omega_{BW\theta}$. The requirements of Figure 50b) demonstrate the relevance assigned by the criterion to the harmony between pitch attitude and flight path angle bandwidths, and the importance of achieving a minimum value of $\omega_{BW\gamma}$ to ensure satisfactory flying qualities, i.e.: predicted handling qualities.



a)

b)

c)

d)

Figure 50. Boundaries of aircraft pitch attitude bandwidth criterion

The state of the sample aircraft dynamics with respect to the requirements is represented by the symbols plotted on the corresponding plane. The sample case of Figure 50 is of an un-augmented aircraft with low pitch attitude and flight path angle bandwidths, and pitch rate overshoot value $\Delta G(q) < 12\ dB$. The position of the symbols in the requirements plane corresponds to low FQ Level 2 with respect to the requirements in a) and FQ Level 3 with respect to those in Figure 50b). Observation of the position of the symbols varying static margin (SM) demonstrates the general tendency to increase of both pitch attitude and flight path angle bandwidth with the increase of static margin, i.e.: short period natural frequency. Based on its definition (Tischler, 1995), phase delay increases due to the implementation in the control system of elements with high frequency dynamics, which produce a “steep” phase roll-off. The pilot perceives these dynamics as a delay due to the corresponding low amplitude of the aircraft response in the high frequency range. The increase of phase delay leads to the degradation of flying qualities, which is represented by the arrow indicating the corresponding trend for one configuration in the FQ requirements plane of Figure 50a).

The Aircraft Bandwidth Criterion evolved with time, as displayed by the series of requirements presented in this section. The boundaries for the landing phase reported in the AIAA paper “Bandwidth - A Criterion for Highly Augmented Airplanes” (1981), in which it was first introduced, are displayed in Figure 51. The current corresponding pitch attitude boundaries for fixed wing aircraft displayed in Figure 50a) are superimposed on it, in dashed black lines. Analysis of Figure 55 demonstrates the significant reduction of both Level 1 and Level 2 pitch attitude bandwidth requirements from the initial to the current values and the corresponding relaxation of the phase delay requirements.

The evolution of the criterion led also to the introduction of the pitch rate overshoot, adding one dimension to the requirements envelope and increasing its effectiveness in predicting handling qualities. The pitch rate overshoot metric was introduced to include the pitch attitude drop-back concept, discussed by Gibson (1999) and expanded in Mitchell et al. (1994). A high value of the pitch rate overshoot corresponds to an excessive theta drop back, due to a too low value of the damping ratio in the frequency range of the aircraft short period, which indicates a higher tendency to pitch oscillations and potential accumulation of residual dynamics/oscillations in the aircraft response in Continuous Compensatory Control (CCC) or tracking tasks. High values of pitch rate overshoot are associated in the criterion to higher PIO proneness. Figure 55 displays pilot’s evaluation data used to define the FQ boundaries, providing the experimental substantiation of the requirements.

A similar approach to the structure of the FQ requirements was applied to the roll attitude bandwidth, whose boundaries for transport aircraft are displayed in Figure 52. A useful approach to demonstrate traceability of requirements across different criteria is described in Kivioja (1996).

The Aircraft Bandwidth Criterion is foundational for the rotorcraft flying qualities military specification ADS-33E-PRF (DOD, 2000) and a demonstrated effective criterion for FW aircraft flying qualities. Hoh & Mitchell (1981) reports a fundamental review and discussion of the available FW aircraft FQ criteria, underlining the applicability of the Aircraft Bandwidth Criterion to the different types of responses.

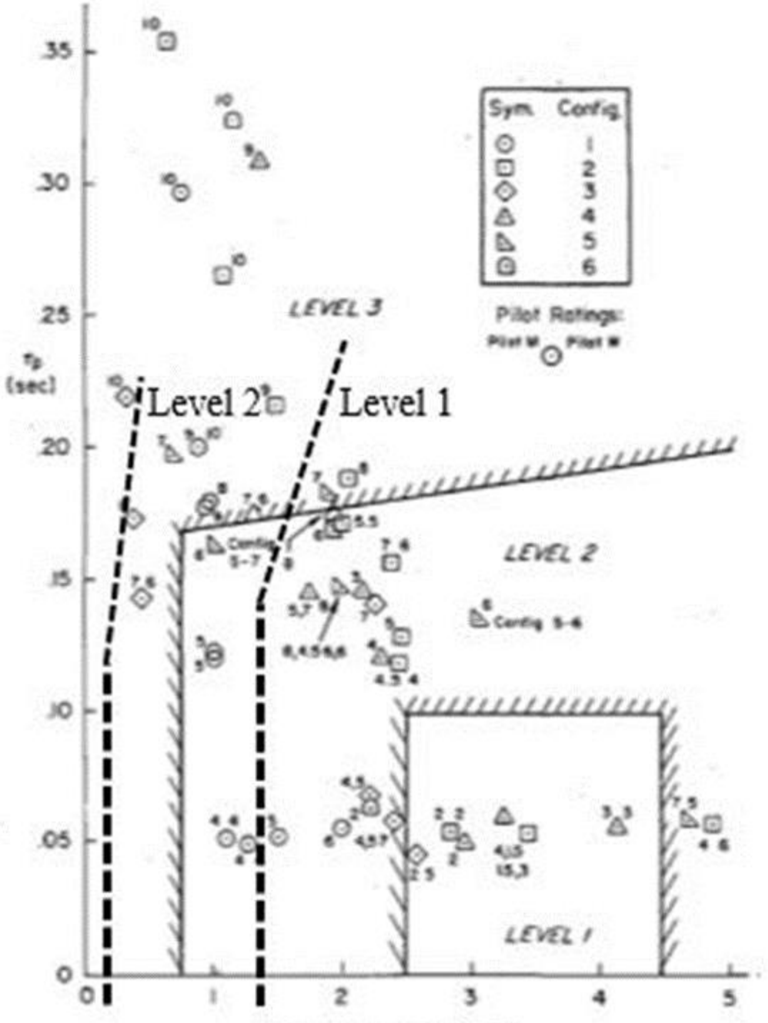


Figure 51. Original boundaries of aircraft bandwidth criterion – approach and landing

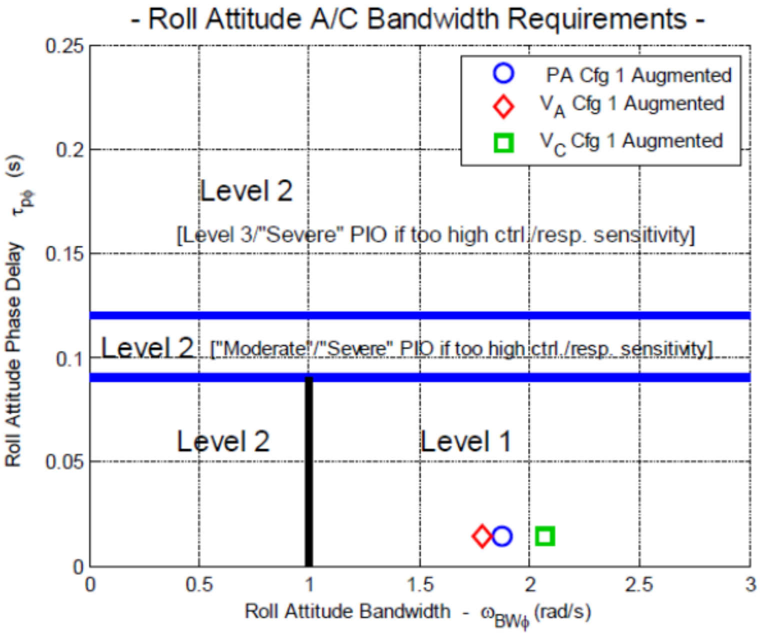
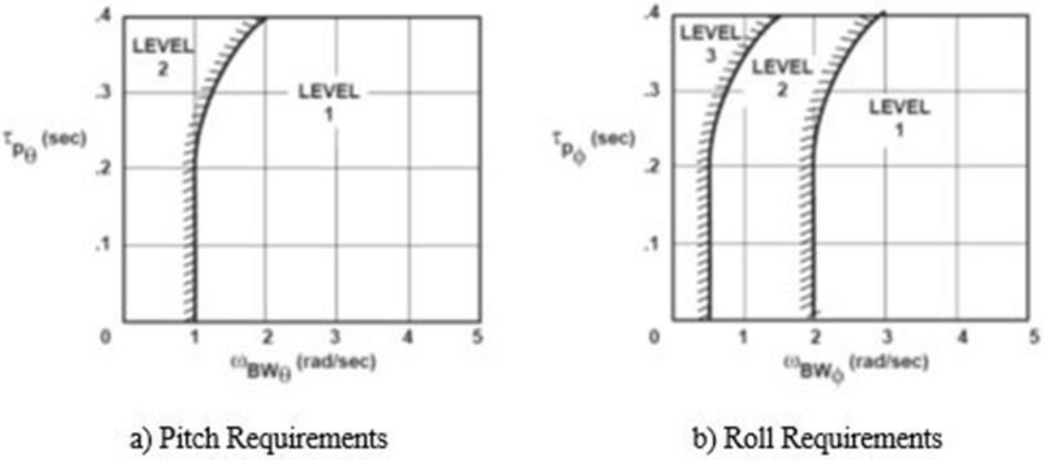


Figure 52. Boundaries of aircraft roll attitude bandwidth criterion

5.5.4 Low airspeed bandwidth requirements for VTOL aircraft

For low-speed operations, the pitch and roll Aircraft Bandwidth requirements for Usable Cue Environment (UCE) UCE =1 (GVE) from ADS-33E-PRF are displayed in Figure 53 (US ARMY, 2000). These requirements apply to all of the mission tasks that are expected to be associated with civilian small VTOL vehicles including urban air taxis. Pitch and roll requirements for UCE > 1 (DVE) are shown in Figure 54 (US ARMY, 2000).



a) Pitch Requirements

b) Roll Requirements

Figure 53. Pitch and roll aircraft bandwidth requirements for UCE 1

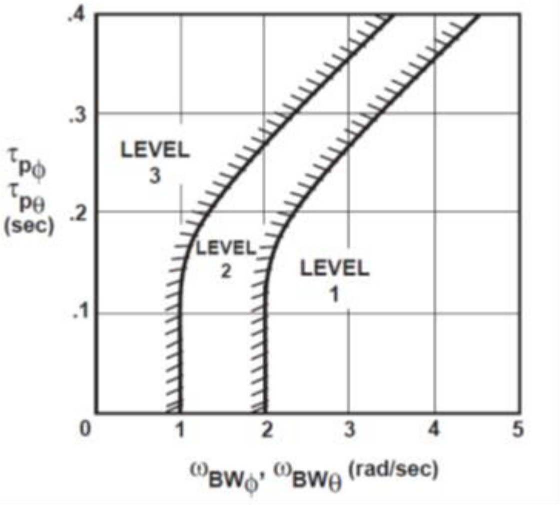
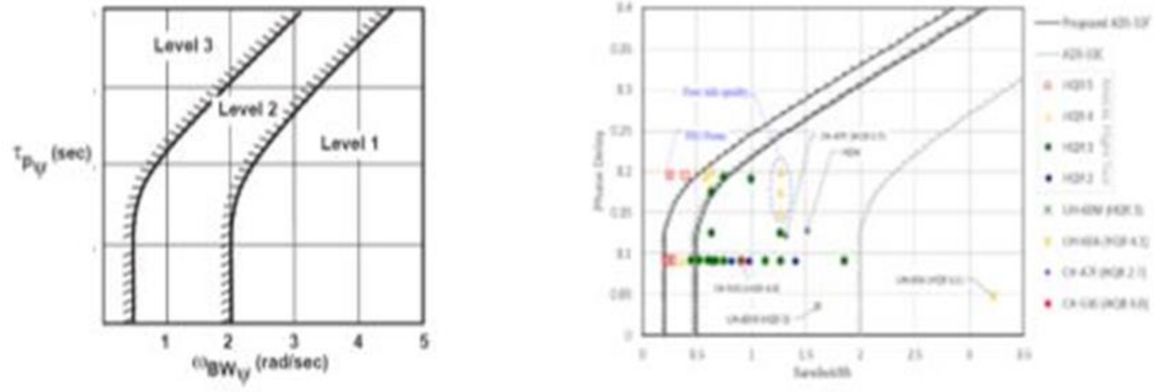


Figure 54. Pitch and roll aircraft bandwidth requirements for UCE > 1

The current yaw attitude Bandwidth requirements are shown in Figure 55a. Concerns have been raised on the excessive conservativeness of the required Level 1 and Level 2 bandwidth frequency boundaries. It has been noted that the allowable phase delay should be limited at values that protect against PIO susceptibility. The US Army has proposed revisions to the Figure 55a requirements in work documented in Lehmann et al. (2016). The revised “All Other MTEs” requirements from Hoh et al. (1981) are shown in Figure 55b from which the following observations derive:

- The required relaxation in the specification of yaw attitude bandwidth is founded on flight test data.
- The relaxation of the requirement from 2 rad/s to slightly above 0.5 rad/s suggests concerns that the new Level 1/Level 2 boundary is too low. Data are available to support the validity of this boundary; with a so large change proposed, additional data generated by an independent source would add confidence to the results.
- The “HQR 3” flight test are results displayed in Figure 55. The proposed revision to yaw requirements (Figure 55b) are spread over a wide region of bandwidth frequencies and phase delay values. With a preliminary review of the data, it should be confirmed that bandwidth - phase delay values of [1.8 rad/s - 0.09 s], [0.5 rad/s - 0.09 s], and [0.7 rad/s - 0.19 s] would all receive HQR ratings of 3 from 3 different pilots. More details would be required for a better understanding of the assigned pilot ratings.
- Evaluation should be conducted for the specification of an upper boundary on phase delay, to clarify whether phase delay values higher than 0.3 s are acceptable in the Level 1 region.

- The proposed Level 2 bandwidth range is potentially excessively narrow, to assume that the full range of ratings from HQR 4 to HQR 6 can be assigned to vehicles with bandwidth in such limited range.



a) Existing yaw requirements

b) Proposed revision to yaw requirements

Figure 55. Yaw aircraft bandwidth requirements

The value of the presented proposed yaw requirements, which necessitate wider consensus for their adoption in the current criterion, is in indicating requirement trends based on the vehicle class, on the related type of augmentation, and on the data available from pilots' evaluations. Section 5.5.3 confirms evolutionary trends for FW aircraft. The Aircraft Bandwidth criterion provides a suitable and flexible reference frame to predict handling qualities of aircraft with significantly different configurations and response types, as it addresses the fundamental dynamic system characteristics relevant for pilot's control. The values of its metrics can be adapted as required by aircraft, response type, and certification requirements, with the possibility of rendering it one of the foundational criteria for certification of FBW and specifically UAM aircraft. Four examples of FQTE maneuvers cards, including "Frequency Sweep", "Doublet", 3-2-1-1" and "Finite step (Boxcar)" are presented in Appendix A.

5.6 HQTEs definitions and requirements for UAMs repeatability

5.6.1 Background

Every pilot should attempt exactly the same task. Ideally, several pilots should be used for the evaluation, to minimize bias and subjectivity. Pilots should be proficient with the task, although not overly experienced in the specific task and type of aircraft, to avoid precognitive, effortless and unrecognized compensation for the deficiencies of the test item. In order to ensure repeatability, the task must be clearly defined in details. Examples are clearly defining the configuration, final approach speed, glide path, usable aids (e.g., ILS, PAPI, velocity vector, etc.), flaring technique, power management, and braking effort.

5.6.2 Measurability

Performance criteria must be identified and they must be measurable. The choice of criteria and tolerances should be driven by mission considerations. The target is achieving desired criteria with minimal or insignificant pilot compensation (workload in excess of the workload of the task, compensation for the deficiencies of the test item compared to an excellent aircraft). Desired performance, not perfection, is what the pilot should try to achieve. If only adequate performance is achieved, the test item might still be marginally acceptable, provided no more than extensive compensation is required. Examples of performance criteria are airspeed maintenance, glide path maintenance, lateral deviation on final, touchdown longitudinal deviation, touchdown lateral deviation. The performance criteria should be easy to assess in flight by the pilot, without the use of additional non-production instrumentation (e.g., touchdown within the aiming point markings, rather than ±75 ft).

5.6.3 High gain tasks

In order to reveal handling qualities deficiencies, the task must require evaluation pilots to apply high amplitude and high frequency inputs. If the task can be satisfactorily executed with small infrequent inputs, latent HQ problems might remain undetected, especially in the presence of HQ cliffs. Typical examples are rate saturation limits, which can only be triggered with large amplitude and frequency inputs, leading to sudden and unexpected HQ problems, often leading to Pilot Induced Oscillations (PIO). High pilot's gain tasks can be achieved tightening performance criteria and/or introducing time limits for the execution of the task. While the task should remain mission representative, the pilot's gain can be increased simulating the worst possible operational situation (e.g., a reduction of the area size for precision landing task) and boundary conditions (e.g., proximity to the ground or time pressure due to weather or system malfunctions).

5.6.4 Inputs/outputs/data requirements

Once the task is properly defined, all participating pilots and crewmembers must be thoroughly briefed, to ensure clear comprehension of the task and standardization. The Flight Test Instrumentation (FTI) should include sensors measuring critical parameters indicative of pilot's activity. While pilot's ratings should be assigned exclusively based on the pilot's perception of the attained performance, measuring the actual performance is important to validate the task and ensure all pilots are effectively aiming at the same criteria. For a spot landing task, typical parameters to record would be airspeed, altitude, GPS (or Differential Global Positioning System (DGPS)) position, control effectors positions, inceptor displacements and force.

While these parameters may be sufficient to substantiate and complement qualitative comments from the pilots, additional signals may be invaluable for troubleshooting undesirable responses, especially for highly augmented FBW aircraft. For example, tracing the pilot's input through the flight control system, to identify sources of nonlinearities, latencies, unmodeled dynamics or disturbances. Sample rates should be at least 5 times the highest frequency range of interest, preferably 10 times. Assuming rigid body dynamic responses and pilots' inputs are below 2 Hz, a sample rate of 20 Hz is adequate for most application, although 50 Hz is common given the current data acquisition systems capabilities. As a minimum, anti-aliasing filters must be applied prior to sampling; digital filters may be applied to remove high frequency noise. Any filtering within the aircraft and pilot bandwidth should be avoided or used with extreme care. Data ranges should be chosen to cover the entire data band of interest while optimizing resolution, based on the characteristics of the digital acquisition system.

5.7 Data analysis

The primary source of information for HQ tests is pilots' comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not to be averaged or altered based on quantitative data analysis, and task requirements shall not be changed after task execution. For example, three pilots providing HQRs of 3, 5, and 7 is very different than three pilots all providing a consistent rating of 5. The former case is most likely the result of a poorly defined task (non-repeatable) with different pilots executing the same maneuver differently, or possibly the result of different external conditions.

The Cooper Harper Rating Scale (CHRS) is the most popular and widely accepted scale for assessing aircraft HQs. HQRs must always be accompanied by qualitative comments in order to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety, for example the spot landing task, as it is much easier for the pilot to assess the overall compensation during the execution of the maneuver, rather than trying to correlate performance and compensation for different portions of the task performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. For example, a quantitative measurement of the actual performance ensures that pilots' feedback can be detected and all participant pilots were actually attempting the same level of performance.

The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload, but it is also true that low pilot activity is not necessarily an indication of low workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

5.8 Guidance for unexpected response

In case HQ testing reveals undesired and/or unexpected characteristics, the quantitative and qualitative results can help identifying the issues, but most likely further testing will be necessary to validate possible theories.

In general, for unexpected responses/HQ cliffs, the following approach should be considered:

1. Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
2. Once the condition and aggressiveness level have been determined, isolate the axis on which the unexpected response is experienced.
3. Analyze choice of effectors, control power and priorities (e.g., spoilers, outboard ailerons, inboard ailerons, flaperons, spoilers, thrust vectoring). Particularly critical is the control allocation (e.g., control distribution among redundant effectors or same effector controlling different axis, potentially saturating controls and resulting in problems like momentarily exclusion of one axis resulting in latencies or undesired cross coupling effects).

Additionally, the following examples of possible further testing when unsatisfactory Handling Qualities are found during HQ testing should be addressed.

Difficulty controlling the flight path:

- Verify flight path stability; marginal or negative flight path stability increase pilot's workload during approach.

- Analyze the short period response in the approach configuration and the Control Action Parameter (CAP) in particular; some aircraft exhibit very low bandwidth (short period natural frequency) at slow speeds, rendering the vehicle sluggish and more challenging to control in a high gain task.
- Assess engine response (e.g., spool up time from low RPM).
- Assess display latencies and/or filtering of airspeed, altitude or velocity vector cues.

Pitch oscillations during flare:

- Explore short period characteristics in the landing configuration at approach speeds.
- Verify actuator bandwidth and saturation limits (especially rate limits).
- Verify the force feel system characteristics and sensitivity (forces are expected to be very low, with cueing derived from avionics).
- Analyze control logic during flare (including control strategy, blending of control laws, triggering parameters, command gains, etc.).
- Assess pitch (or any multi-axial) response to engine.
- Assess transition from out of ground effect to in ground effect.

Roll oscillations during flare:

- Assess cross-coupling effects.
- Explore the roll mode characteristics in the landing configuration at approach speeds.
- Explore the Dutch roll characteristics in the landing configuration at approach speeds.
- Explore the adverse (or proverse) yaw in the landing configuration at approach speeds.
- Verify actuator characteristics.

Excessive lag in aircraft response:

- Verify controls allocation.
- Analyze time histories comparing pilot inputs with the effectors response.
- If effectors are saturated, assess prioritization logic and actuators performance (rate limit).

Difficulty in capturing and controlling the ground speed and/or height:

- Assess engine response (RPM control), display latencies and/or filtering of airspeed, height or velocity vector cues.

Diagrams for Handling Qualities unexpected responses are presented in Appendix A of this report. A description of relevant new HQTEs is presented in Appendix B of this report, using the following format:

- Objective
- Maneuver Test Conditions
- Maneuver Description
- Reference Guidance
- Test Course Description
- Evaluation Criteria (Desired and Adequate requirements)
- Inputs/Ouputs/Data Requirements
- Data Analysis
- Guidance for Unexpected Response

The new HQTEs presented in Appendix B are:

1. Ground steering
2. Ground deceleration
3. Hover taxi
4. Climbout stability and control
5. Envelope protection limiting (Climb)
6. Envelope protection limiting (Descent)
7. Envelope protection limiting (Takeoff)
8. Level acceleration from vertical takeoff
9. Longitudinal/Lateral/Combined reposition and hold
10. Pitch and roll control (Cruise)

6 Conclusions

The present report illustrated a proposed technical approach to the design and development of MTEs, as a basis to satisfy the FAA requirements for the Broad Agency Announcement (BAA) 692M15-20-R-00004 R7, Topic Number: ARSS0002. The scope was an Aviation Safety Research focusing on developing MTEs, Means of Compliance/Methods of Compliance (MOC), to assist in the certification of General Aviation, VTOL, VSTOL, or Hybrid aircraft. Background technical information, actions and activities considered necessary to provide the FAA with technical support in the verification and validation/qualification phases of the certification were provided.

The research expanded the results from a previous study, directed at providing guidance and best practices for the certification process of advanced flight controls in general aviation and hybrid aircraft vehicles that NTPS conducted for the FAA. The research addressed the verification and validation/qualification phases of the recommended certification process with particular attention to MTEs, composed of two classes: FQTEs and HQTEs. The aim of FQTEs and HQTEs is respectively to collect quantitative and qualitative/subjective data for characterization of aircraft dynamics and handling qualities. The scope was to expand the description of the approach to the design, definition, execution, and data analysis of FQTEs and HQTEs, and provide recommendations for certification means of compliance. The study was composed of three main phases:

1. Expansion on Technical Content of FQTEs and HQTEs;
2. Scope, Limitations and Analysis Boundaries for FQTEs and HQTEs;
3. Recommendation of FQTEs and HQTEs for FQ and HQ Evaluations.

In phase 1, the technical content of the FQTEs and HQTEs recommended was expanded. The descriptions were be based on a set of principal components for FQTEs and HQTEs. The relevance of the FQTEs for the quantitative part of the certification and the correspondence between FQTEs and Flying Qualities requirements was highlighted. Possible approaches to derive generalized design techniques for FQTEs was discussed as a synthesis of the different types discussed in this work. The critical objective leading to the definition of each HQTE was to ensure the absence of arbitrary factors affecting the final HQ assessment and their validation based on pilot’s evaluations. The FQTEs/HQTEs required inputs, outputs, flight phases and aircraft dynamic modes were also addressed. Minimum and optimal data requirements were indicated for each aircraft class: airplane, powered/lift, rotorcraft/multicopter. Where applicable, groups of task elements with comparable data requirements were identified, to guide towards a streamlined planning process. The recommended analysis techniques for FQTEs was linked to the applicable FQ requirements and criteria, reporting on the expected typical accuracy level of each computed dynamics parameter. There were recommendations for the minimum set/type of data for an adequate FQ assessment, in case the applicant performs part of the analyses independently. Recommendations included specific software(s), which is expected to allow accurate and efficient analysis and results.

Descriptions of both quantitative and qualitative methods for analyses of data acquired during the execution of HQTEs were also included. Recommended types of questions to collect appropriate and consistent pilots' comments on the principal handling evaluation elements were reported. The technical connection between the two types of data (quantitative and qualitative) used to guide the understanding of the aircraft handling characteristics was explained. Approaches to correlation between results of FQTEs and HQTEs performed in the same flight phase were described as a part of the vehicle handling qualities characterization. The identification of the modal parameter(s) of the dynamic modes contributing to produce potential unsatisfactory handling characteristics is an important outcome of the handling qualities validation process.

Phase 2 (Scope, Limitations and Analysis Boundaries for FQTEs and HQTEs) described the limitations and analysis boundaries for FQTEs and HQTEs. The principal objectives and potential limitations for FQs verification and HQs validation respectively of each FQTE and HQTE recommended were reported. The links between the described MTEs and the most relevant FQ requirements and criteria were highlighted. This is an important step to establish a functional link between FQTEs, HQTEs and the corresponding aircraft development/certification phases. Additionally, concepts for the definition of boundaries to characterize the flying and handling qualities based on MTEs were reported. Boundaries of the current FQ criteria were analyzed to propose possible approaches for their adaptation to UAM Vehicles. The main method was to propose trends of variation of the quantitative values of the criteria, while preserving their background logic. Implementation of additional boundaries, or partial removal of the current ones were considered, to increase consistency with the requirements of the new class of aircraft. Updates of boundaries for assigned handling qualities from the execution of HQTEs were proposed in terms of concepts for task requirements and task setup. This considered both task operational representativeness for the given class of aerial vehicle and the assessment of the presence of a "handling qualities cliff": a significant reduction of handling performance in specific areas of the envelope. Impact of the control laws modes on the execution of the HQTEs was discussed when applicable/relevant for the definition of requirements/boundaries. Recommendations for the design of updated boundaries accounted for general trends and ranges of expected flying and handling qualities levels, current trends of the same criteria. The overall scope of this phase was to provide expected directions of variation of the existing criteria boundaries.

Another objective of this phase was to expand the application of the results to MTEs which are not part of those recommended, or to blocks of combined recommended FQTEs and HQTEs. Intersection of MTE blocks addressing different handling characteristics is a useful further method to ensure continuity in the evaluation of contiguous flight phases. This depends on the aircraft characteristics and operational requirements. Aircraft transitioning between different modes of lift generation/flight control can require a wider range of MTE types to assess handling performance in the transition phases of flight and in each of the different modes of lift generation.

During phase 3 (Recommendation of FQTEs and HQTEs for FQ and HQ Evaluations), one of the aims was to identify MTEs to evaluate the aircraft handling performance in the applicant's manned simulator. The assumption was that the FAA has approved the applicant's simulator for certification credit, not having full visibility into control system development and the flight clearance process applied by the applicant. The MTEs were identified by linking them to the core of the certification process recommended. The identification of FQTEs to be performed in the simulator has mostly an operational value. When a simulator is available, it is to evaluate how FQTEs and HQTEs execution can be combined in the same phase of flight and assess the level of matching between the results from analysis of data collected from FQTEs and the corresponding values calculated from the simulation models. Assuming limited FAA visibility into the aircraft developmental process, recommendations addressed the use of FQTEs to detect local non-compliances with respect to standard flying qualities requirements. Margins for applicability of MTEs were suggested, based on the aircraft configuration and operational requirements, combined with expected pilots' comments. A flow chart complemented the results, to represent the flow of execution of the MTEs, their relationship with the phases of the certification process and the means of compliance. The underlying concept is to recommend MTE blocks which can ensure continuity between requirements, execution and applicability to means of compliance towards flight clearance. Evaluations performed in the manned simulator are in support of the formal flight clearance conceded by the FAA to begin the flight test campaign. Means of compliance were recommended for this phase, and FQTEs and HQTEs for in flight evaluations were recommended. The methodological approach and assumptions remained unchanged at certification process level; these recommendations are functionally independent from previous results. This is to ensure applicability if a manned simulator is not available, or in the more advanced phases of aircraft certification. The continuity of the requirements/execution/means of compliance process is a fundamental component for the definition of MTEs performed in flight. In-flight evaluations based on the recommended MTEs are the final end-to-end integrated handling qualities evaluation for certification credit. The next step was mapping the recommended MTEs in the previous phases to certification requirements of aircraft with Vertical Take Off and Landing (VTOL) capabilities.

The NTPS-STI research team was formed by Experimental Test Pilots and Flight Test Engineers, with combined experience in aircraft design/development, and developmental and operational test and evaluation. The technical and piloting background of the team was the foundation and source of information for the research. It merged with technical knowledge on hybrid vehicles development and testing available within the aeronautical community. The diverse know-how of the team provided a multidisciplinary approach to proposing new MTEs and to adapt existing MTEs to VTOL, VSTOL, and hybrid aircraft mission requirements and means of compliance.

The validity of the method was shown by the application of concepts proven by the researchers' experience in different RW and FW operational environments, and by merging these concepts with results from other research works in the same field. NTPS could access a database of handling qualities evaluations conducted by test pilots and student test pilots, including those of ADS-33-PRF mission task elements. This provided the research with further consistency and depth, as recommendations will be substantiated by references to the available known results.

A further and follow-on research is recommended with the scope of developing a high fidelity UAM simulator, to validate the recommended certification process to certify UAM vehicles that the FAA can evaluate and potentially incorporate for UAM certification.

Specifically, the follow-on research should be focused on:

- development of an UAM aircraft simulation model
- implementation of the model in a manned simulator
- MTEs evaluation in the manned simulators, based on pilot's ratings, comments and data analysis
- MTEs evaluation, based on pilot's ratings, comments and data analysis
- replication of the process leading to the UAM aircraft qualification and certification, with specific reference to:
    - aircraft aeromechanic characterization;
    - design of experiment and test plan;

  - handling qualities evaluation in the manned simulator;
  - use of model predictions based on aircraft offline characterization and manned simulations to finalize flight test plan;
  - in-flight handling qualities evaluation;
  - data analysis and synthesis; and
  - comparison of assessed aircraft characteristics with requirements valid for: verification, validation, qualification and certification.

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A FQTEs Maneuver Cards

Tables

FQTE MANEUVER CARD

FQTE NO.	MANEUVER TITLE	CONFIGURATIONS	OP. STATE
1	Frequency Sweep	All	Normal

MANEUVER OBJECTIVES

Excitation of the aircraft response from low to high frequency, to obtain symmetric perturbations of a target state with respect to trim, within a predefined frequency range, minimizing long term drift away from trim conditions.

DESCRIPTION OF THE MANEUVER

After establishing stable trim conditions, perform continuous sinusoidal input, varying from low to high frequency, linearly or logarithmically. The input amplitude begins and ends at trim, usually symmetric with respect to the trim condition. The average input can be slowly adjusted to maintain the average aircraft state close to trim conditions.

MANEUVER PARAMETERS AND CONSTRAINTS

Amplitude of the input chosen to maximize the SNR while maintaining linear aircraft/system characteristics throughout the maneuver.

Typical input frequency: $\omega \approx [0.1, 12]\,\frac{rad}{s}$

Typical maximum duration: 60 to 90 seconds. Duration determined by the number of full cycles to be performed at target frequencies within a predefined band and by the flight conditions/configuration. Results from offline simulations can be used to define the correct input amplitude prior to test.

ANALYSIS OBJECTIVES

Identification of vehicle transfer function(s) and dynamic modes, directly in the frequency domain, generation of Bode plots. Assessment of aircraft flying qualities from comparison of vehicle modal parameters and metrics with respect to envelopes of flying qualities criteria.

ANALYSIS PRACTICES AND CONSTRAINTS

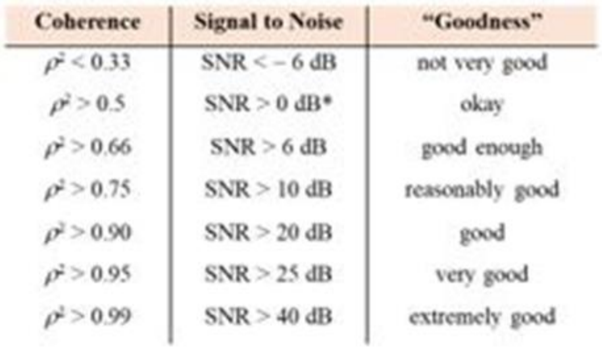
Minimum one second of stable trim conditions before and after input application.

Preferred output: angular rates, for modal analysis, zero bias and good output response.

Required calculation of coherence ρ, index of input/output co-linearity, for each measured frequency response. Application of data windowing to attenuate insertion of high frequency or spurious signal content at the beginning and at the end of the maneuver. Difference between output and remnant higher than 20 dB within the target frequency range.

Minimum value of coherence ρ^2 for acceptability of the results: $\rho^2 > 0.66$.

$$SNR|_{dB} = 20\, log_{10} \frac{\rho^2}{1-\rho^2}$$



Coherence	Signal to Noise	"Goodness"
$\rho^2 < 0.33$	SNR < – 6 dB	not very good
$\rho^2 > 0.5$	SNR > 0 dB*	okay
$\rho^2 > 0.66$	SNR > 6 dB	good enough
$\rho^2 > 0.75$	SNR > 10 dB	reasonably good
$\rho^2 > 0.90$	SNR > 20 dB	good
$\rho^2 > 0.95$	SNR > 25 dB	very good
$\rho^2 > 0.99$	SNR > 40 dB	extremely good

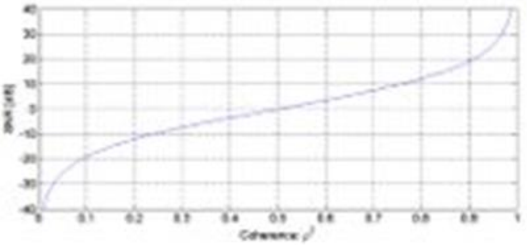


Figure A- 1. Signal to noise ratio acceptability

INPUT/OUTPUT PAIRS

Table A- 1. Frequency Sweep Input-Output Node Pairs

Input-Output Node Pair		**Analyzed Element**	**Notes**
Input	**Output**		
1	2	Feel system	
1	3	Entire command path	
2	3	Command path minus feel system	
4	5	Actuators	Possible insertion of PTIs at node 4
4	6	Bare airframe plus actuating system	
5	6	Bare airframe	Identification of the aircraft aerodynamics.
2	6	Entire system minus feel system	Example: relevant for validation of the aircraft attitude bandwidth(s), without feel system dynamics.
1	6	Entire system	Example: relevant for validation of the aircraft attitude bandwidth(s), with feel system dynamics.

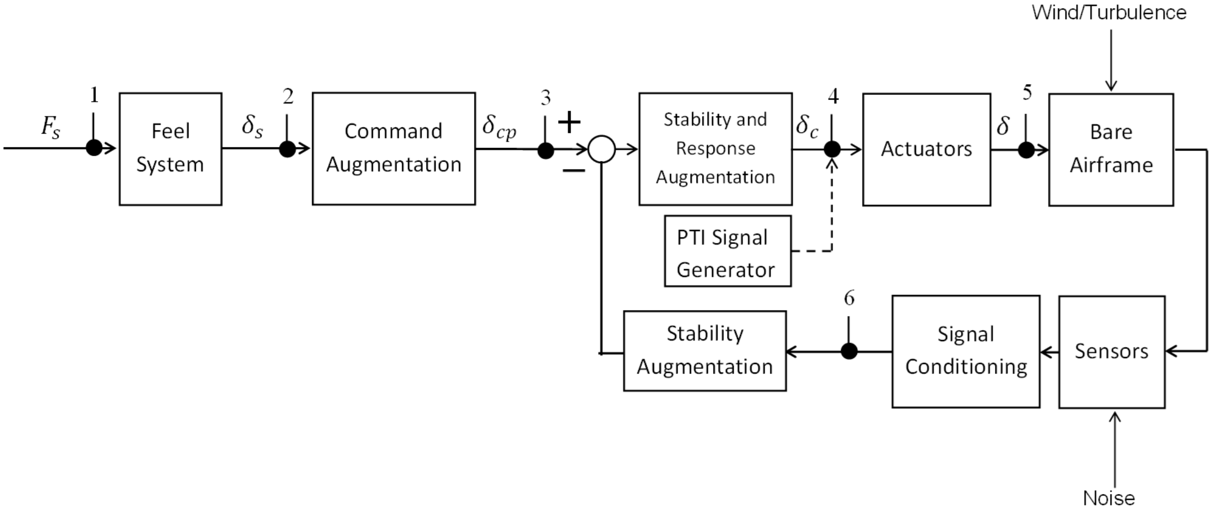


Figure A- 2. Flight control system notional block diagram

STANDARD ANALYSIS OUTPUT FORM

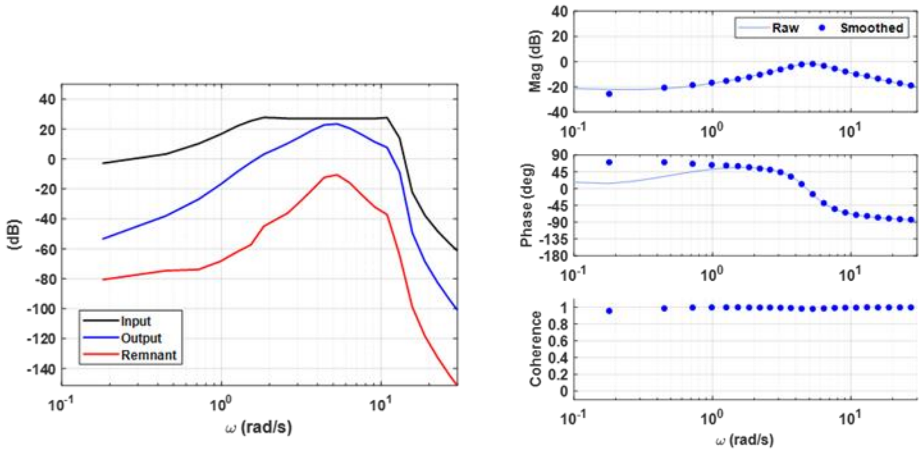


Figure A- 3. Frequency domain analysis

SAMPLE MANEUVER TIME HISTORY

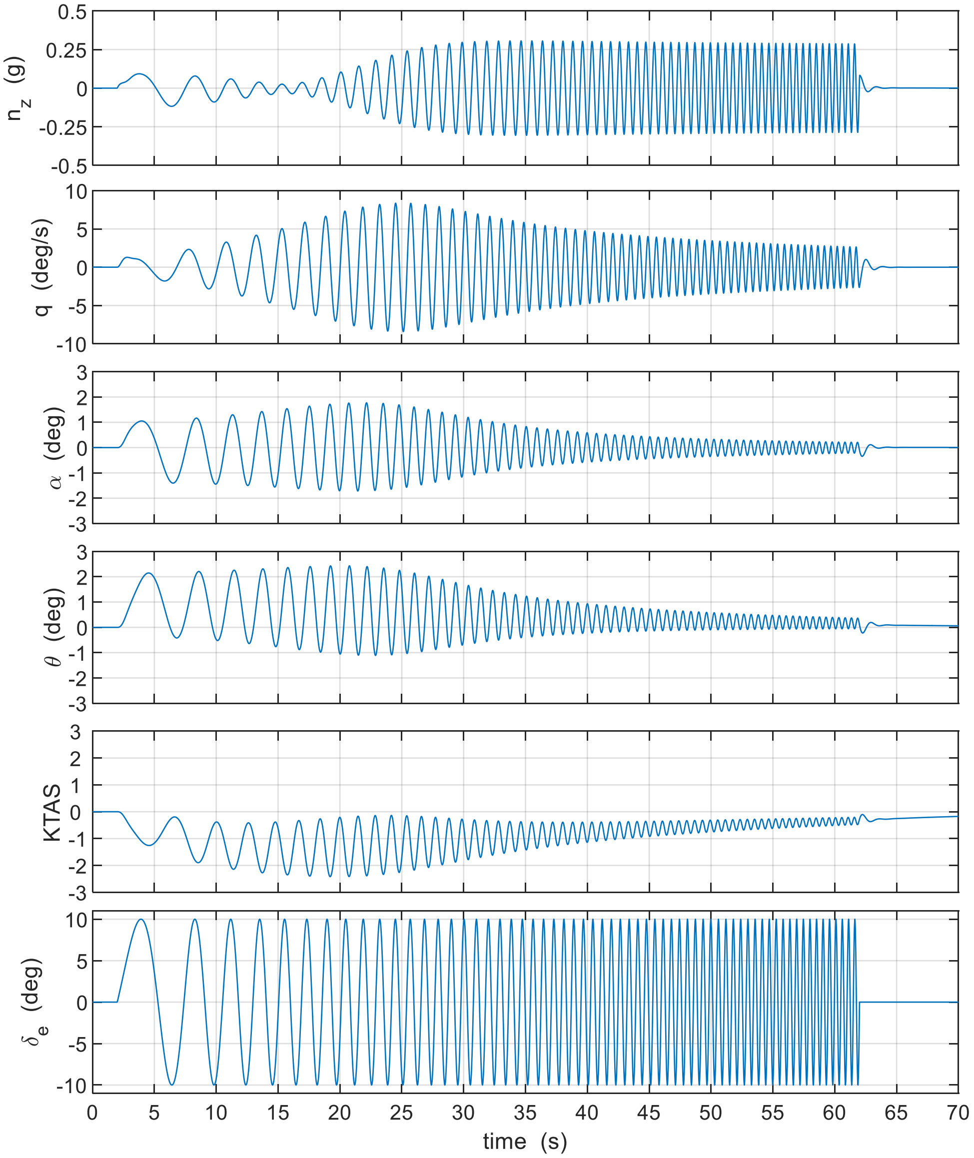


Figure A- 4. Frequency sweep time histories

SAFETY ISSUES

Maneuver not to be executed with directional input, to minimize the risk of vertical tail structural failure. Envelope exceedance, specifically of maximum load factor and flow angle(s).

FQTE MANEUVER CARD

FQTE NO.	MANEUVER TITLE	CONFIGURATIONS	OP. STATE
2	Doublet	All	Normal

MANEUVER OBJECTIVES

Excitation of aircraft high frequency dynamic modes, with symmetric perturbations of a target state with respect to trim, at constant flight conditions.

DESCRIPTION OF THE MANEUVER

After establishing stable trim conditions, perform two consecutive pulses of equal amplitude, duration and opposite sign. The maneuver is complete with zero input and aircraft free dynamics completely damped.

MANEUVER PARAMETERS AND CONSTRAINTS

Input maximum amplitude determined to maintain linear aircraft/system characteristics throughout the maneuver.

Typical duration: 1 to 5 seconds.

Input frequency close to the target modal frequency. Square pulse shape is a high priority, advisable for doublets to be programmed as PTIs, to obtain square wave shaped input. The square wave approximates a sine wave of same period, preferred to the pure sinusoidal for its higher frequency content: theoretically infinite frequency spectrum.

Square input more effective in the excitation of modes with frequency not exactly coincident with the input dominant frequency.

Execution with zero average input is fundamental.

ANALYSIS OBJECTIVES

Time domain identification of vehicle aerodynamic characteristics and modal parameters.

Assessment of aerodynamic model fidelity and of aircraft flying qualities from comparison of vehicle modal parameters with respect to envelopes of flying qualities criteria.

ANALYSIS PRACTICES AND CONSTRAINTS

Minimum one second of stable trim conditions before input application, free dynamics completely damped at the end of the maneuver.

Maximum Likelihood Estimation (MLE), output error approach. The unknowns are the linearized increments to the aerodynamic model terms, with respect to trim conditions.

Linear error model for the unknowns, while the aerodynamic model can be fully nonlinear.

A cost function J to be minimized is defined, of the form: $J(\Theta) = \frac{1}{KN}\sum_{i=1}^{n} \upsilon(i)^T\, R^{-1}\upsilon(i)$

Where:

Θ is the vector of the unknowns

K is the number of measured states

N is the number of time samples, or the length of the vector of the measures

$\upsilon(i) = y_m(i) - y_z(i)$ is the measurement residual, or the residual between current and predicted measurement

R is the matrix of covariance of the noise.

Time domain methods for calculation of modal parameters, i.e.: Transient Peak Ratio (TPR) method.

INPUT/OUTPUT PAIRS

Table A- 2. Doublet input-output node pairs

Input-Output Node Pair		**Analyzed Element**	**Notes**
Input	**Output**		
4	5	Actuators	Possible insertion of PTIs at node 4
4	6	Bare airframe plus actuating system	
5	6	Bare airframe	Identification of the aircraft aerodynamics.
2	6	Entire system minus feel system	Example: relevant for validation of the aircraft attitude bandwidth(s), without feel system dynamics.

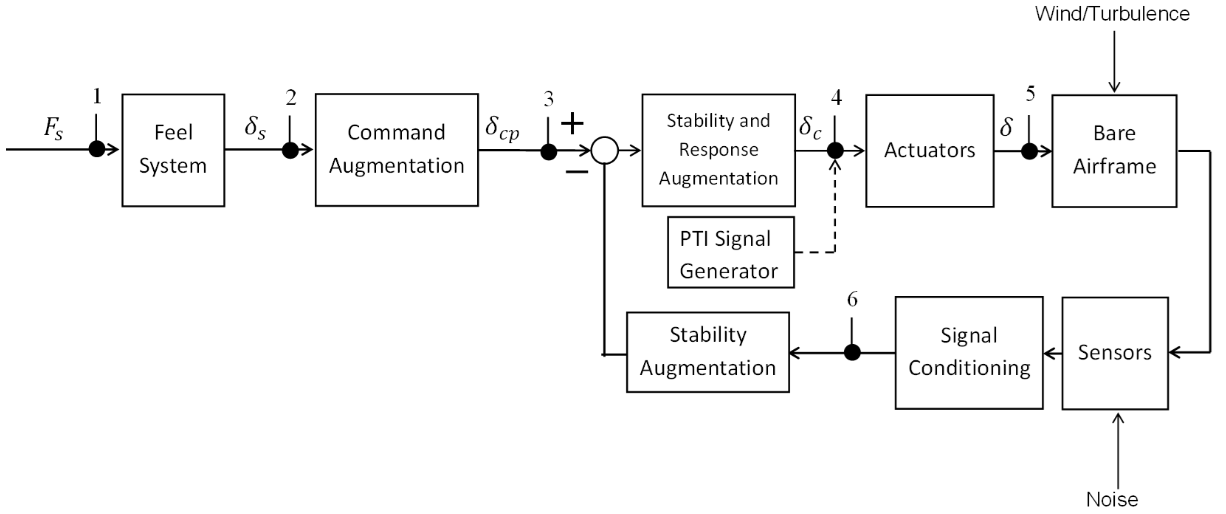


Figure A- 5. Flight control system notional block diagram

STANDARD ANALYSIS OUTPUT FORM

$$\zeta = \sqrt{\frac{[ln(TPR)]^2}{\pi^2 + [ln(TPR)]^2}}$$

$$\omega_n = \frac{\omega_D}{\sqrt{1-\zeta^2}} = \frac{2\pi}{T_D\sqrt{1-\zeta^2}}$$

Results from time domain Maximum Likelihood Estimation Output error analysis

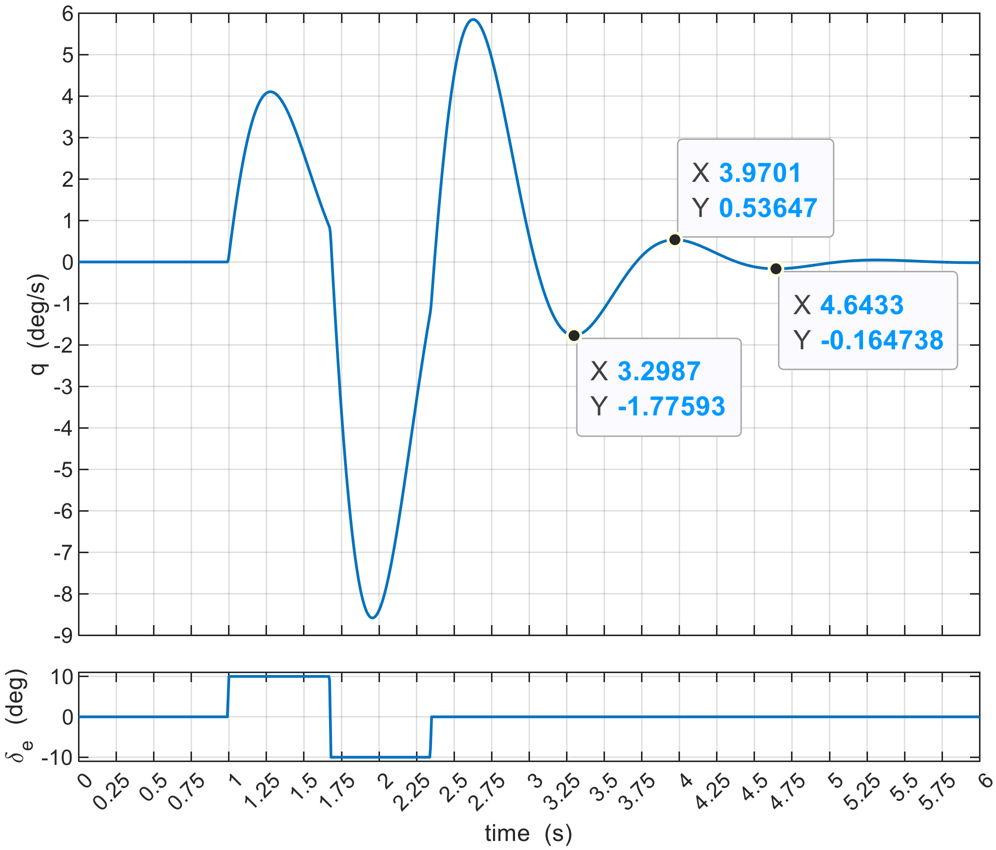


Figure A- 6. Transient peak ratio method

SAMPLE MANEUVER TIME HISTORY

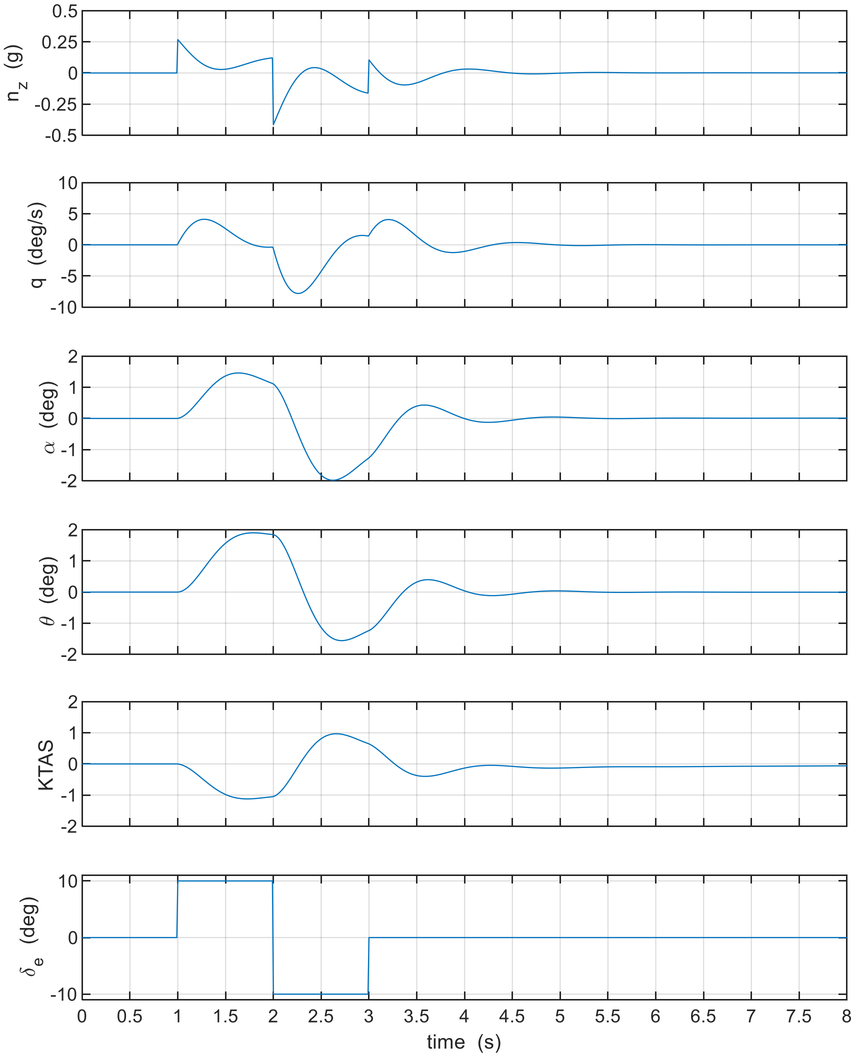


Figure A- 7. Doublet time histories

Plots are of the deltas with respect to trim.

SAFETY ISSUES

Directional input: maneuver not to be executed at airspeed higher than maneuvering speed V_A, or equivalent, to minimize the risk of vertical tail structural failure. Application of buildup approach, with real time structural loads monitoring, for execution at airspeed lower than maneuvering speed V_A, or equivalent. Envelope exceedance, specifically of maximum load factor and flow angle(s), in the high airspeed flight regime.

FQTE MANEUVER CARD

FQTE NO.	MANEUVER TITLE	CONFIGURATIONS	OP. STATE
3	3-2-1-1 (2-1-1)	All	Normal

MANEUVER OBJECTIVES

Short duration excitation of the aircraft response from low to high frequency, within a predefined frequency range.

DESCRIPTION OF THE MANEUVER

After establishing stable trim conditions, perform a pulse input combination. Pulse duration decreases from first to last in the ratio of 3-2-1 / 2-1-1 expressed as a multiple of the duration of the last pulse. The maneuver is complete with null input at the end of the last pulse.

MANEUVER PARAMETERS AND CONSTRAINTS

The amplitude of the input should be chosen to achieve an observable response for post-flight analysis while maintaining linear aircraft/system characteristics throughout the maneuver and minimizing deviation from trim conditions.

Typical duration: 2 to 12 seconds.

Square pulse shape a high priority

A not negligible deviation from trim conditions is inherent in the not zero average value of the input.

It is advisable for the “3-2-1-1” and the “2-1-1” maneuvers to be programmed as PTIs, for their relatively high complexity of execution, leading to a lower degree of repeatability when performed manually.

ANALYSIS OBJECTIVES

Identification of vehicle transfer function(s) and dynamic modes, directly in the frequency domain, generation of Bode plots.

Assessment of aircraft flying qualities from comparison of vehicle modal parameters and other metrics with respect to envelopes of flying qualities criteria.

ANALYSIS PRACTICES AND CONSTRAINTS

Minimum one second of stable trim conditions before and after input application.

Preferred output: angular rates, for modal analysis, zero bias and good output response.

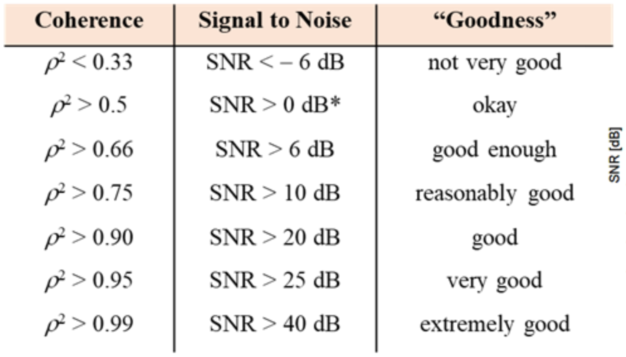
Required calculation of coherence ρ, index of input/output co-linearity, for each measured frequency response.

Application of data windowing to attenuate insertion of high frequency or spurious signal content at the beginning and at the end of the maneuver.

Difference between output and remnant higher than 20 dB within the target frequency range.

Minimum value of coherence ρ^2 for acceptability of the results: $\rho^2 > 0.66$.

$$SNR|_{dB} = 20\,log_{10}\frac{\rho^2}{1-\rho^2}$$



Coherence	Signal to Noise	"Goodness"
$\rho^2 < 0.33$	SNR < – 6 dB	not very good
$\rho^2 > 0.5$	SNR > 0 dB*	okay
$\rho^2 > 0.66$	SNR > 6 dB	good enough
$\rho^2 > 0.75$	SNR > 10 dB	reasonably good
$\rho^2 > 0.90$	SNR > 20 dB	good
$\rho^2 > 0.95$	SNR > 25 dB	very good
$\rho^2 > 0.99$	SNR > 40 dB	extremely good

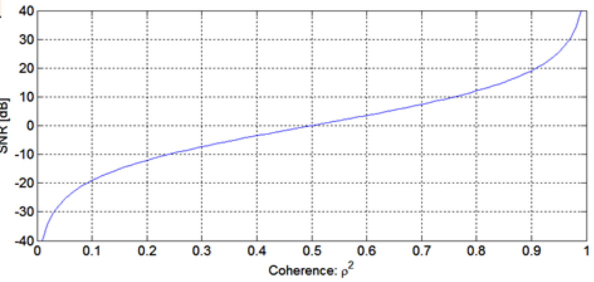


Figure A- 8. Signal to noise ratio allowances

INPUT/OUTPUT PAIRS

Table A- 3. 3-2-1-1 Input-output node pairs

Input-Output Node Pair		**Analyzed Element**	**Notes**
Input	**Output**		
1	2	Feel system	
1	3	Entire command path	
2	3	Command path minus feel system	
4	5	Actuators	Possible insertion of PTIs at node 4
4	6	Bare airframe plus actuating system	
5	6	Bare airframe	Identification of the aircraft aerodynamics.
2	6	Entire system minus feel system	Example: relevant for validation of the aircraft attitude bandwidth(s), without feel system dynamics.
1	6	Entire system	Example: relevant for validation of the aircraft attitude bandwidth(s), with feel system dynamics.

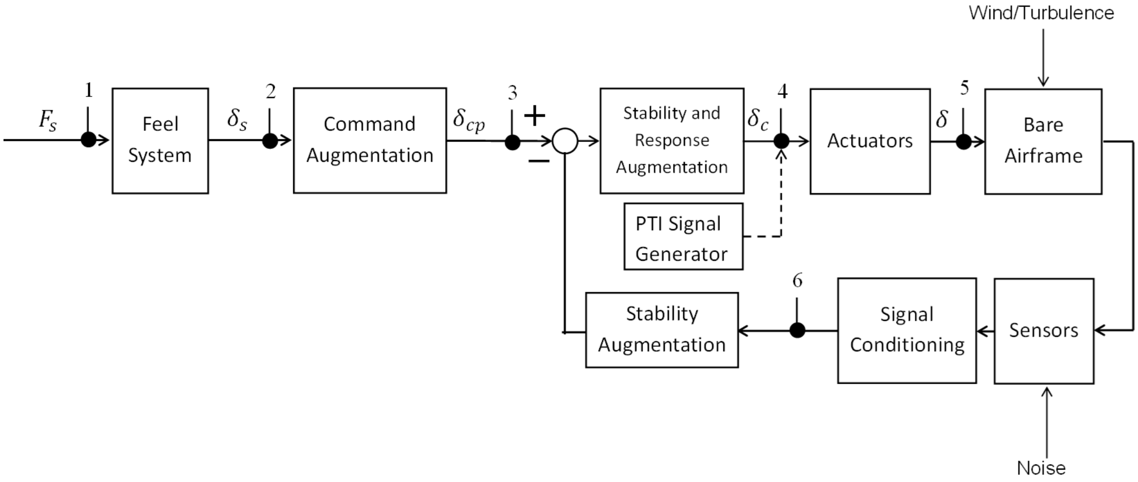


Figure A- 9. Flight control system notional block diagram

SAMPLE ANALYSIS OUTPUT

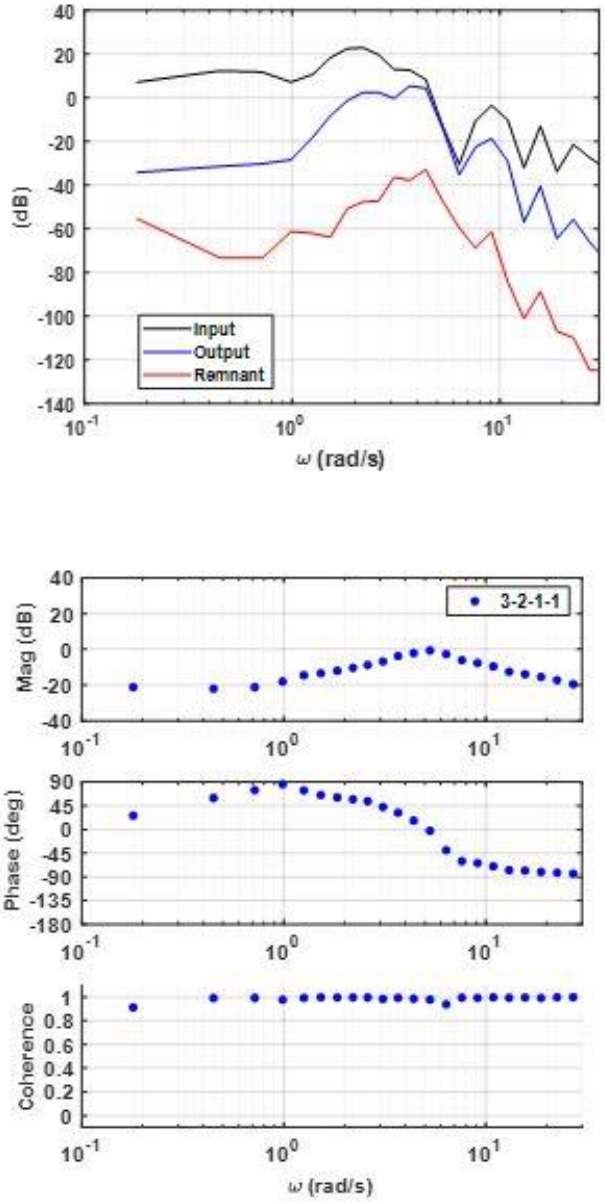


Figure A- 10. Frequency domain analysis

SAMPLE MANEUVER TIME HISTORY

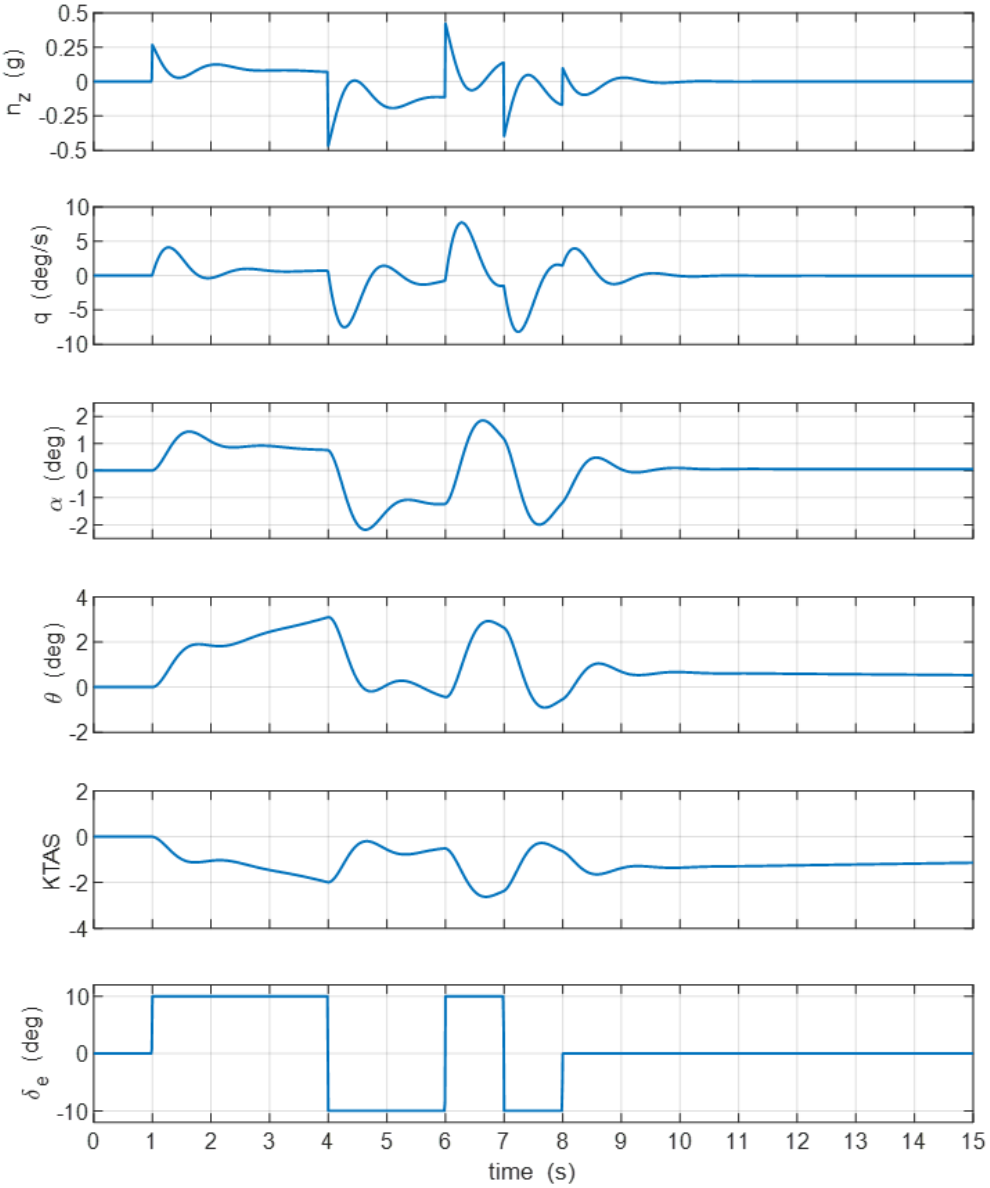


Figure A- 11. 3-2-1-1 Time Histories

Plots are of the deltas with respect to trim – 3-2-1-1 maneuver.

SAFETY ISSUES

Maneuver not to be executed with directional input, to minimize the risk of vertical tail structural failure.

Envelope exceedance, specifically of maximum load factor and flow angle(s).

FQTE MANEUVER CARD

FQTE NO.	MANEUVER TITLE	CONFIGURATIONS	OP. STATE
4	Finite Step (Boxcar)	All	Normal

MANEUVER OBJECTIVES

Short duration excitation of the aircraft response from low to high frequency, within a predefined frequency range.

MANEUVER OBJECTIVES

The scope of the maneuver is to assess the transition to a new steady state condition and study its three main phases: a) initial transient, b) steady state, c) final transient.

DESCRIPTION OF THE MANEUVER

After establishing stable trim conditions, perform a step input of relatively long duration, in the order of 3 to 5 seconds. The input to be held until steady state is reached, transient completely damped. Abruptly return input to zero and hold it at zero. The maneuver is complete with null input and response final transient completely damped.

MANEUVER PARAMETERS AND CONSTRAINTS

The maneuver is a non-zero average input by design, leading to limitations on its amplitude and duration. Both are a function of the vehicle characteristics, and defined to achieve a steady state of measurable amplitude, with non-negligible transients, limiting deviation from trim conditions and minimizing the risk of envelope exceedance.

Typical duration: 3 to 5 seconds. Square input shape is a high priority. Lateral and directional inputs are typically shorter, to limit roll, yaw angle perturbations and vertical tail structural loads. The maneuver is principally designed for longitudinal and lateral inputs. Lateral inputs can require coordination with directional control.

Difficulties in the execution of the “boxcar” input derive from the required abruptness of its transients and from the required extended duration of the constant part.

PRINCIPAL ANALYSIS OBJECTIVES

Calculation of time constant of the high frequency zero in the pitch attitude, pitch rate transfer function: T_{θ_2}. Calculation of “theta dropback”. Calculation of damping ratio of highly damped modes. Calculation of roll mode time constant. Measurement of time delay at different nodes in the system.

ANALYSIS PRACTICES AND CONSTRAINTS

Required sharp input shape. Application of standard time domain methods for calculation of modal parameters, damping ratio in highly damped modes.

The following is an example of a time domain method for heavily damped systems, the time ratio method:

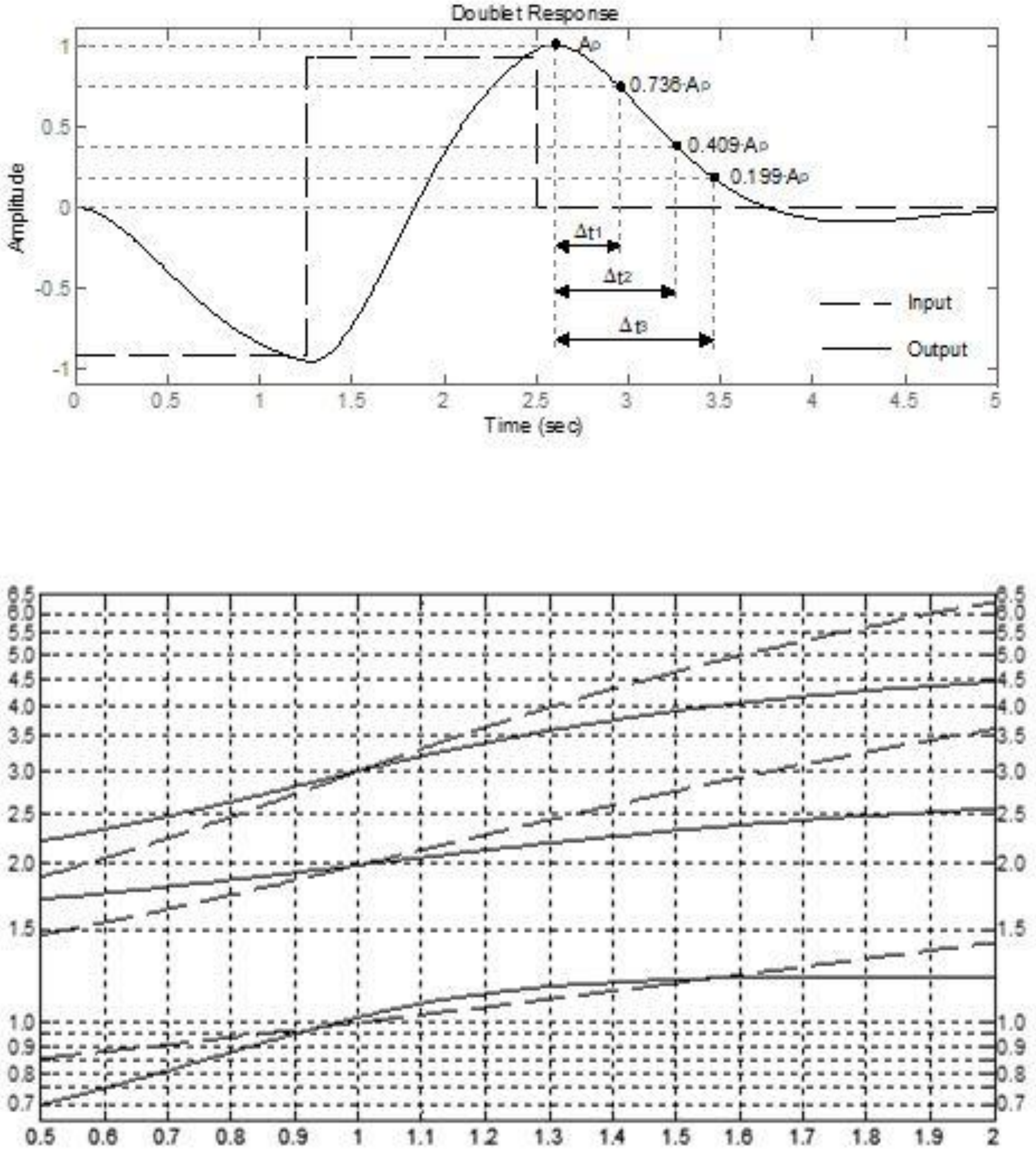


Figure A- 12. Time ratio method

INPUT/OUTPUT PAIRS

Table A- 4. Boxcar input-output node pairs

Input-Output Node Pair		Analyzed Element	Notes
Input	Output		
2	3	Command path minus feel system	
4	5	Actuators	Possible insertion of PTIs at node 4
4	6	Bare airframe plus actuating system	
5	6	Bare airframe	Identification of the aircraft aerodynamics.
2	6	Entire system minus feel system	Example: relevant for validation of the aircraft attitude bandwidth(s), without feel system dynamics.
1	6	Entire system	Example: relevant for validation of the aircraft attitude bandwidth(s), with feel system dynamics.

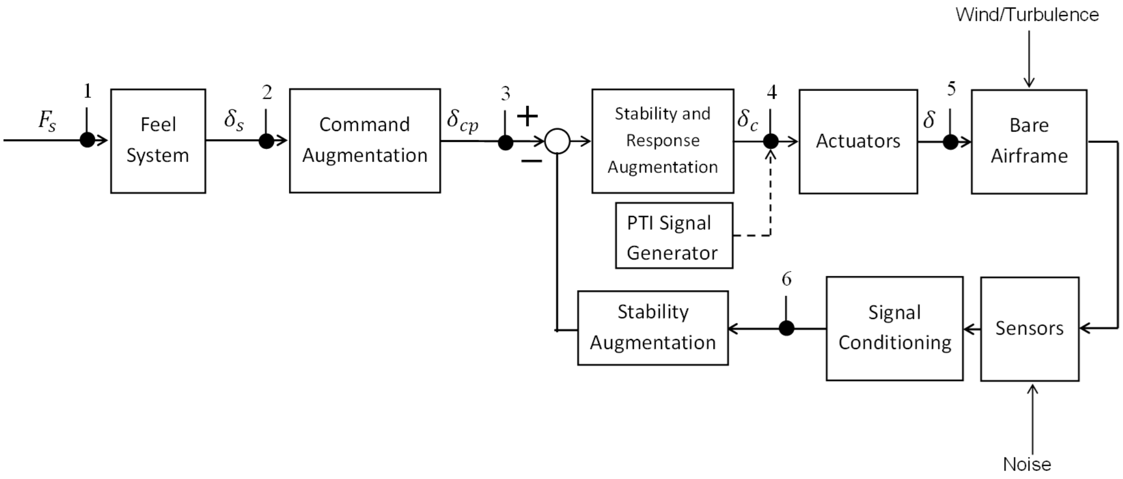


Figure A- 13. Flight control system notional block diagram

SAMPLE STANDARD ANALYSIS OUTPUT

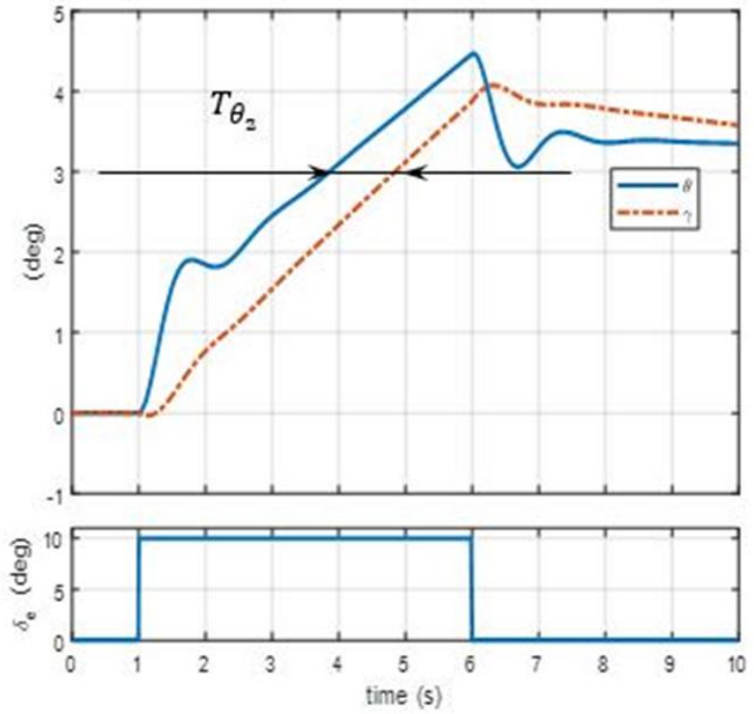


Figure A- 14. Roll rate response to lateral input

SAMPLE MANEUVER TIME HISTORY

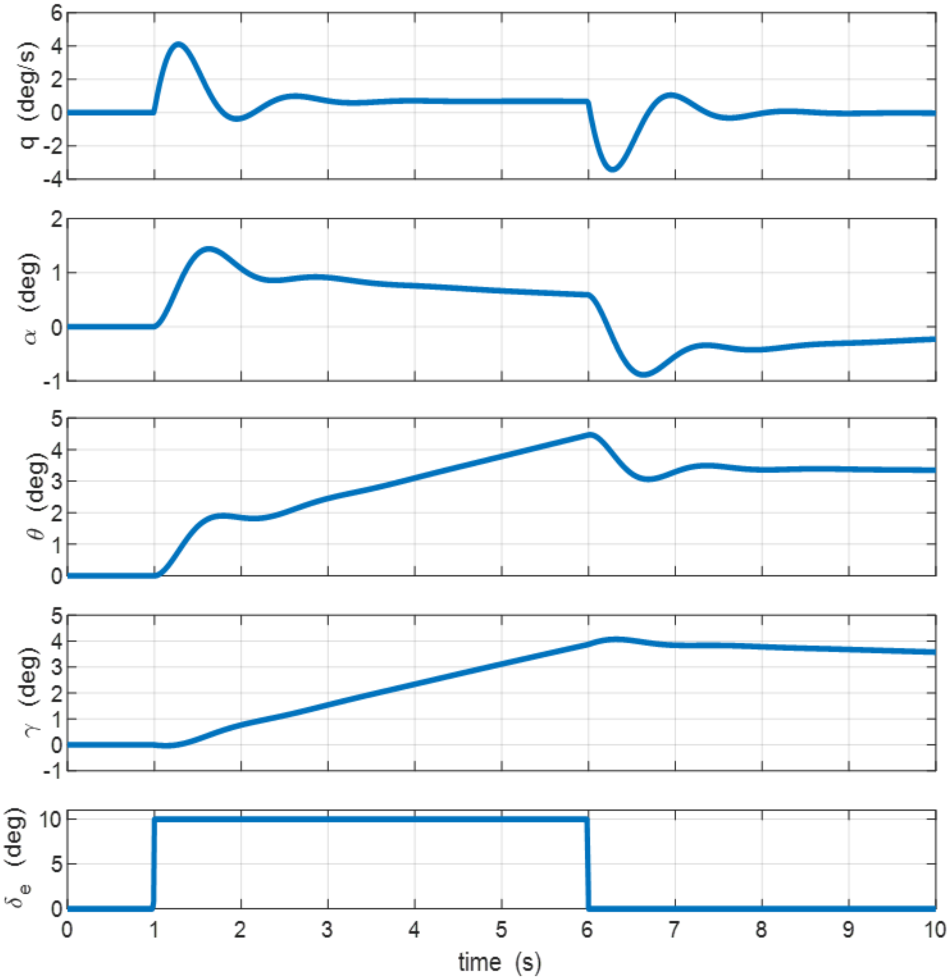


Figure A- 15. Boxcar input time histories

Plots are of the deltas with respect to trim for longitudinal boxcar input

SAFETY ISSUES

Longitudinal input: departure from controlled flight due to adverse stall characteristics/spin following large angle of attack perturbation; flight envelope exceedance, specifically maximum normal load factor exceedance, maximum angle of attack exceedance, particularly in case of unpredicted nonlinearity of the response and/or relaxed stability.

Lateral input: excessive bank angle perturbation, departure from controlled flight due to "wing slice" and spin following large bank angle perturbation.

B Unexpected response flow charts

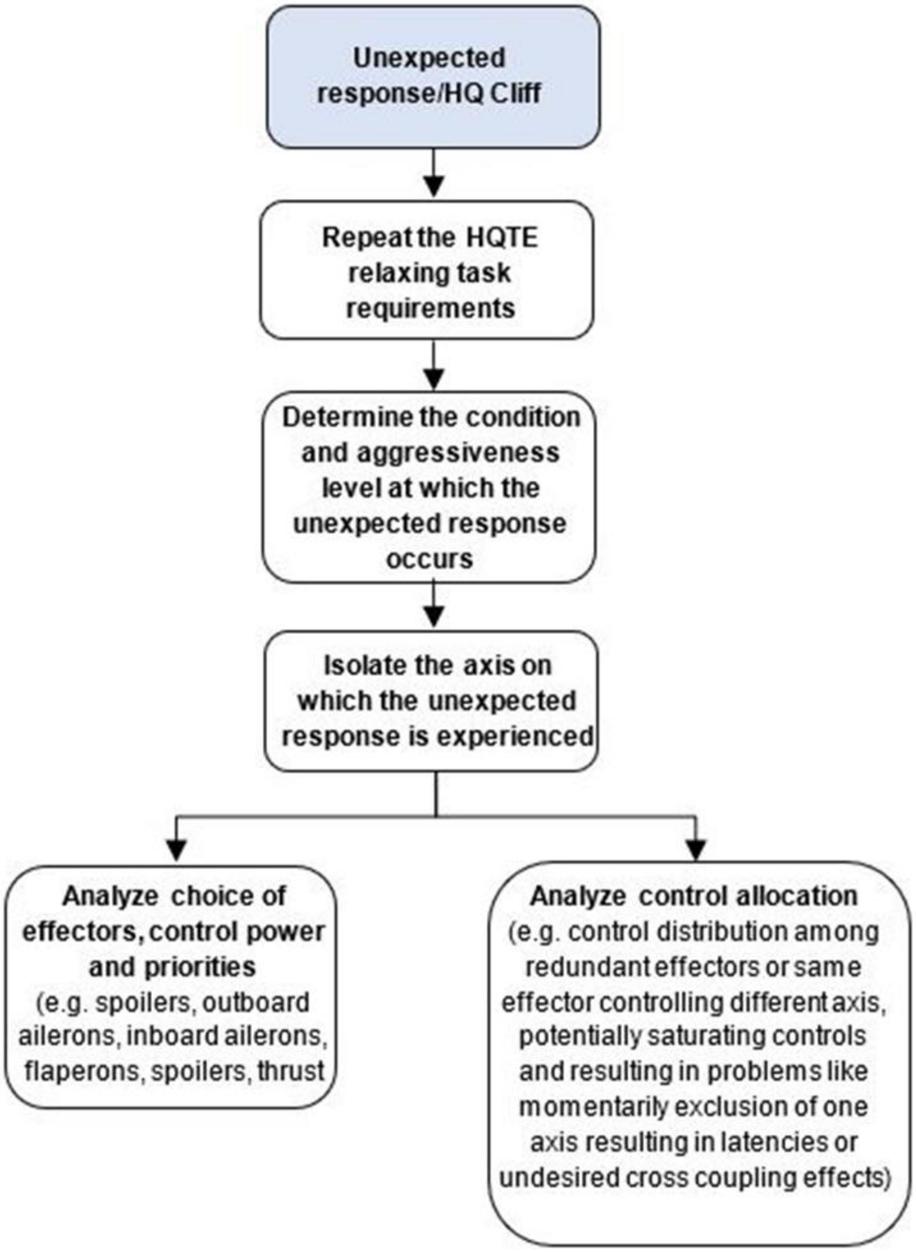


Figure B- 1. Unexpected response/HQ Cliff

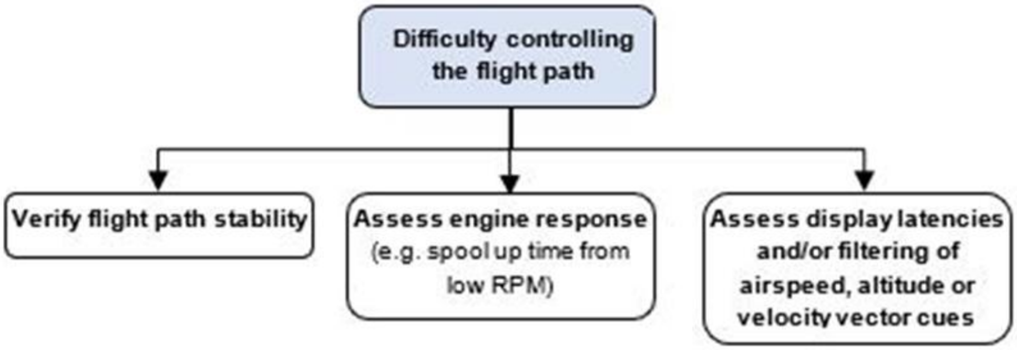


Figure B- 2. Difficulty controlling the flight path diagram

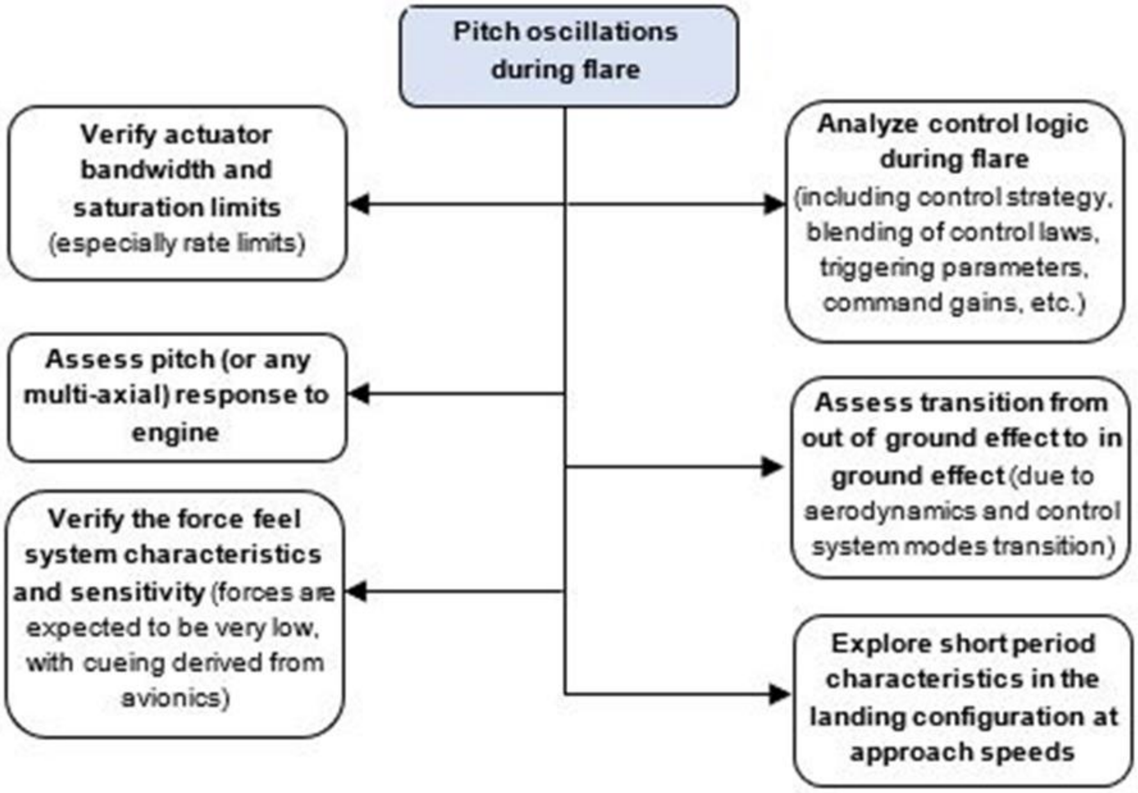


Figure B- 3. Pitch oscillations during flare diagram

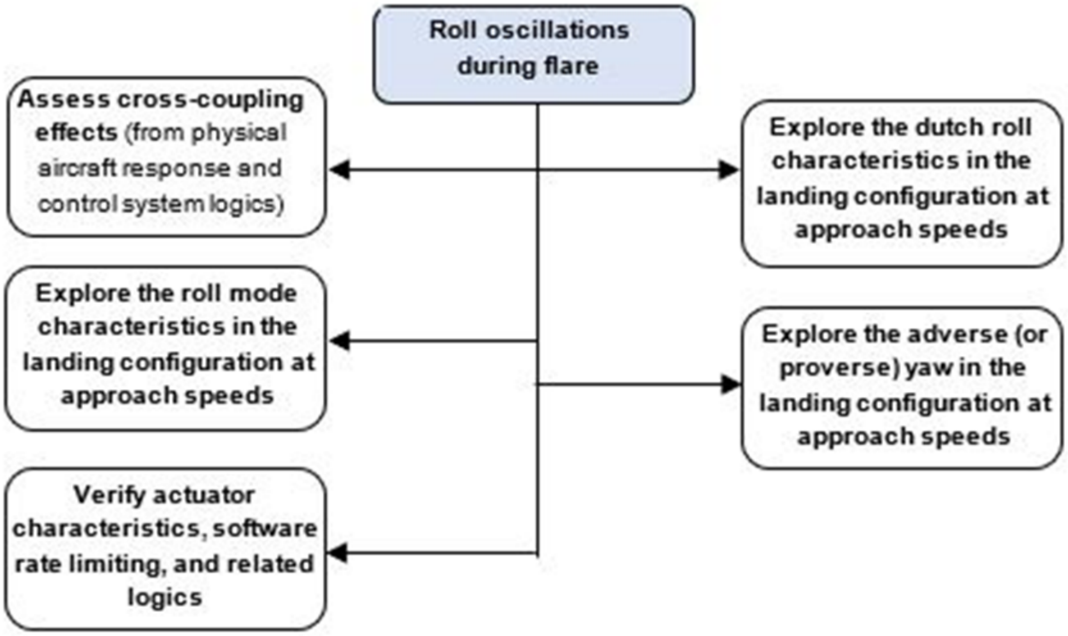


Figure B- 4. Roll oscillations during flare diagram

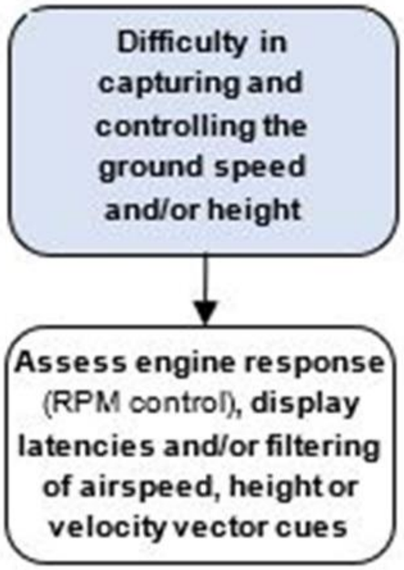


Figure B- 5. Difficulty in capturing and controlling ground speed and/or height diagram

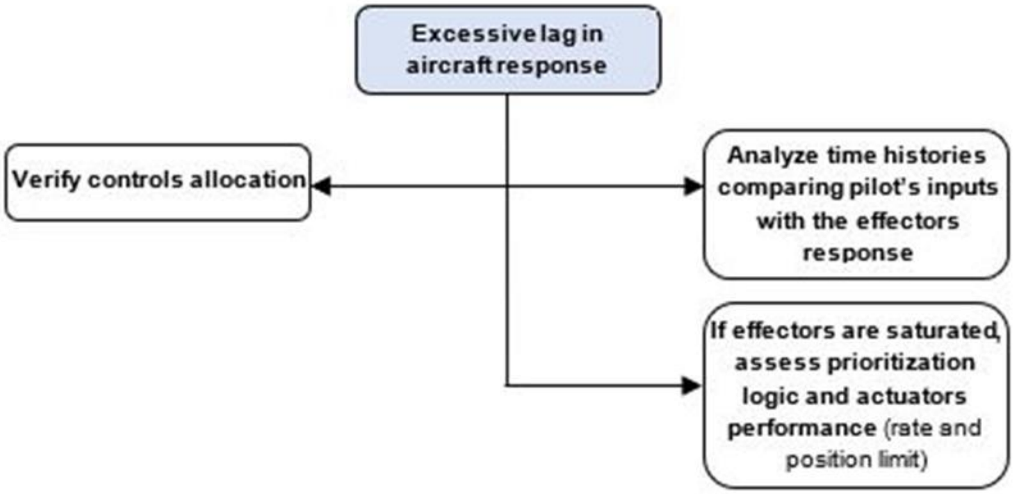


Figure B- 6. Excessive lag in aircraft response diagram

C Handling qualities task elements

Figures

Tables

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
1	Ground Steering	Taxi	Normal State

OBJECTIVE

Assess vehicle controllability and stability during the ground aircraft task of taxiing. The task demonstration points are designed to check directional control characteristics using available effectors (nose wheel steering, differential braking, differential power or a combination as applicable). The task is designed to maneuver the vehicle in a moderately aggressive manner up to what would be considered operationally relevant in a high gain situation.

MANEUVER TEST CONDITIONS

Maximum Ramp Weight and minimum operationally representative weight. Smooth and rough surface.

1. Calm winds
2. TBD knot headwind
3. TBD knot tailwind
4. TBD knot crosswind
5. TBD knot quartering tailwind

MANEUVER DESCRIPTION

1. Centerline capture.
    a. Stabilize the aircraft 10 ft offset the centerline (left and right) at 10 knots ground speed.
    b. Capture the centerline within 4 seconds.
2. Centerline maintenance.
    a. Stabilize the aircraft on the centerline at 10 knots ground speed.
    b. Maintain the centerline for 30 seconds with no more than occasional braking (no more than 1 brief and light application every 10 seconds).
3. Heading reversal.
    a. Stabilize the aircraft at 5 knots ground speed.
    b. Apply maximum permissible control inputs (left and right) to minimize turn radius.
    c. Reverse the heading (180 degrees change).
    d. Maintain maximum permissible control inputs until the heading capture is initiated.
    e. Capture the opposite heading within 3 seconds from the heading capture initial control application.

MANEUVER NOTES

This task is to evaluate the aircraft response characteristics to control track during ground operations. The maneuvers are designed to unveil directional control deficiencies that may affect the pilot's ability to accurately control ground track in normal condition and in confined areas.

Table C- 1. Ground steering maneuver notes

Operations	Normal operation, no degraded performance No Degraded Visual Environment
Aircraft Model Performance	Ground reaction modeling No density altitude performance modeling
Inceptors	Nose wheel steering (as applicable to the specific vehicle) Differential braking (as applicable to the specific vehicle) Differential thrust (as applicable to the specific vehicle)
Display Guidance	GPS speed, heading
Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), Ground and Water Handling Characteristics (23.2155, 27.235).

TEST COURSE DESCRIPTION

The test course shall consist of any reference lines or markers on the ground indicating the desired track. The taxiway must be wide enough to safely execute the heading reversal with adequate margins. Refer to Figure C- 1, Figure C- 2, and Figure C- 3 for an example course.

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)

Moderate turbulence and crosswind or tailwind in excess of 20 knots: Level 2 – Adequate (CHR 4 to 6)

DESIRED PERFORMANCE METRICS

Capture centerline within:	+/- 1 ft
Capture centerline with:	1 or less overshoots
Maintain ground speed within:	+/- 2 kts

Maintain centerline within: +/- 1 ft for at least 80% of the time
Maintain ground speed within: +/- 2 kts

Capture heading within: +/- 2 degrees
Capture heading with: 1 or less overshoots
Maintain ground speed within: +/- 1 kt

ADEQUATE PERFORMANCE METRICS

Capture centerline within: +/- 2 ft
Capture centerline with: 2 or less overshoots
Maintain ground speed within: +/- 4 kts

Maintain centerline within: +/- 2 ft for at least 80% of the time
Maintain ground speed within: +/- 4 kts

Capture heading within: +/- 5 degrees
Capture heading with: 2 or less overshoots
Maintain ground speed within: +/- 2 kt

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 2. Ground steering inputs/outputs data requirements

PARAMETER	**MIN SAMPLE RATE**	**MIN RESOLUTION**
CHR and Pilot’s comments on compensation	N.A.	N.A.
Ground speed	1 Hz	1 kts
Heading	20 Hz	0.2 deg
Longitudinal and lateral position	1 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots’ comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Analyze choice of effectors, control power and priorities (e.g. nose wheel steering, differential braking, differential thrust). Particularly critical is the control allocation (e.g., control distribution among redundant effectors or same effector controlling different axis, potentially saturating controls and resulting in problems like momentarily exclusion of one axis resulting in latencies or undesired cross coupling effects).
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Repeat the HQTE using selective inceptors only as applicable (e.g., nose wheel steering only, differential braking only and differential thrust only) to isolate the potential source of HQ deficiency.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.
- Difficulty in capturing and controlling the ground speed: assess engine response, display latencies and/or filtering of ground speed.
- Lateral oscillations: assess landing gear strut response.

EXAMPLE COURSE

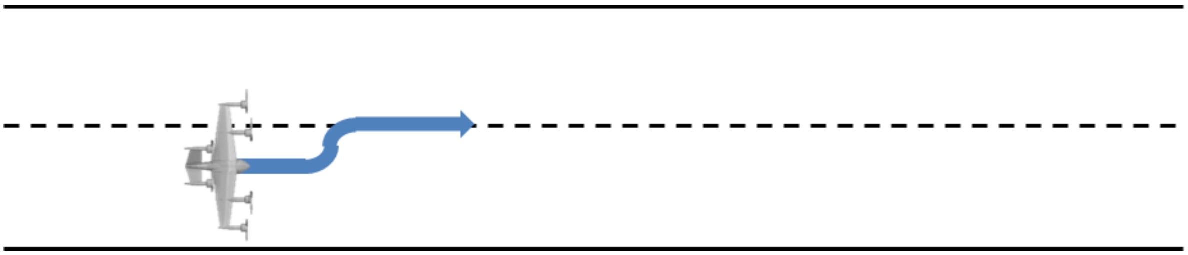


Figure C- 1. Centerline capture

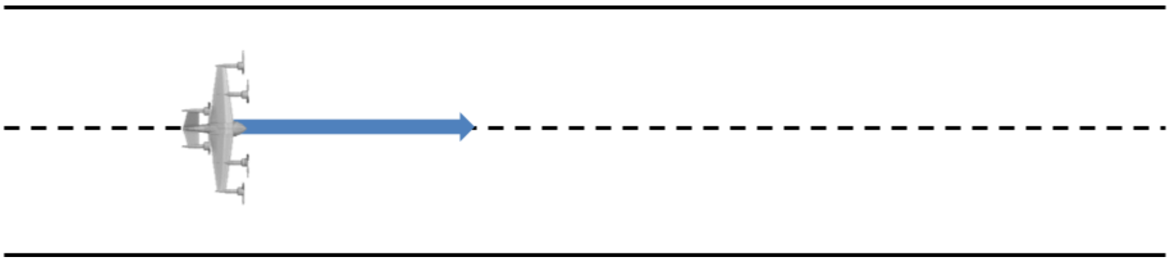


Figure C- 2. Centerline maintenance

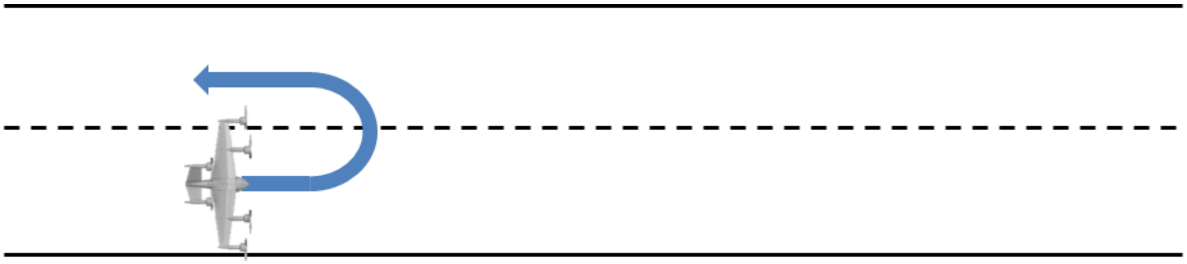


Figure C- 3. Heading reversal

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
2	Ground Deceleration	Landing	Normal State

OBJECTIVE

Assess vehicle controllability and stability during the landing rollout. The task demonstration points are designed to check directional control characteristics using available deceleration means (e.g., brakes and reverse thrust). The task is designed to maneuver the vehicle in a moderately aggressive manner up to what would be considered operationally relevant in a high gain situation.

MANEUVER TEST CONDITIONS

Maximum Landing Weight and minimum operationally representative weight. Smooth and rough surface.

1. Calm winds
2. TBD knot crosswind (maximum demonstrated crosswind)

MANEUVER DESCRIPTION

1. Centerline capture.
    a. Stabilize the aircraft 10 ft offset the centerline (left and right) at 10 knots ground speed.
    b. Capture the centerline within 4 seconds.
2. Centerline maintenance.
    a. Position the aircraft on the centerline 10 knots slower than touchdown speed with idle thrust.
    b. Maintain the centerline until complete stop while applying normal braking for deceleration and differential braking and/or differential reverse thrust for directional control.

MANEUVER NOTES

This task is to evaluate the aircraft response characteristics to control track during landing rollout. The maneuvers are designed to unveil directional control deficiencies that may affect the pilot’s ability to safely execute conventional landing in calm air and up to 25 knots crosswind.

Table C- 3. Ground deceleration maneuver notes

Operations	Normal operation, no degraded performance No Degraded Visual Environment
Aircraft Model Performance	Ground reaction modeling No density altitude performance modeling
Inceptors	Differential braking
Display Guidance	Airspeed
Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), Ground and Water Handling Characteristics (23.2155, 27.235).

TEST COURSE DESCRIPTION

The test course shall consist of a runway with standard markings, long and wide enough for the safe execution of the test depending on the specific aircraft performance and characteristics. Refer to Figure C- 4 and Figure C- 5 for an example course.

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)

Moderate turbulence and crosswind or tailwind in excess of 20 knots: Level 2 – Adequate (CHR 4 to 6)

DESIRED PERFORMANCE METRICS

1. Centerline Capture Task

Capture centerline within:	+/- 2 ft
Capture centerline with:	1 or less overshoots

2. Centerline Maintenance Task

Maintain centerline within:	+/- 5 ft for at least 80% of the time

ADEQUATE PERFORMANCE METRICS

1. Centerline Capture Task

Capture centerline within:	+/- 5 ft
Capture centerline with:	2 or less overshoots

2. Centerline Maintenance Task

Maintain centerline within:	+/- 5 ft for at least 80% of the time

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 4. Ground deceleration inputs/outputs data requirements

PARAMETER	MIN SAMPLE RATE	MIN RESOLUTION
CHR and pilot's comments on compensation	N.A.	N.A.
Indicated airspeed	1 Hz	1 kt
Ground speed	1 Hz	1 kt
Heading	20 Hz	0.2 deg
Longitudinal and lateral position	1 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots' comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Assess deceleration control logic, particularly open-loop vs closed loop (pilot in the loop).
- Assess control effort prioritization in case of multiple effectors (e.g. brakes and reverse thrust).
- Verify potential intervention of anti-skid and/or any wheel lock occurrence.
- Verify brake effectiveness in accordance with specification and maintenance procedures.
- Analyze lags in brake system and correlate potential HQ cliffs with frequency of inputs in relation to phase lags.
- Assess human factors with pilot’s inceptors available for differential braking.
- Lateral oscillations: assess landing gear strut response.

EXAMPLE COURSE

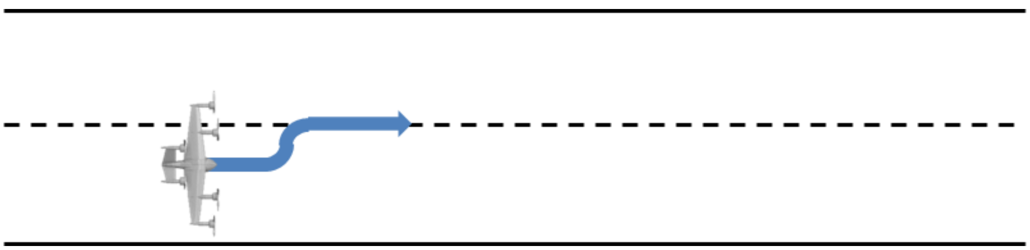


Figure C- 4. Centerline capture

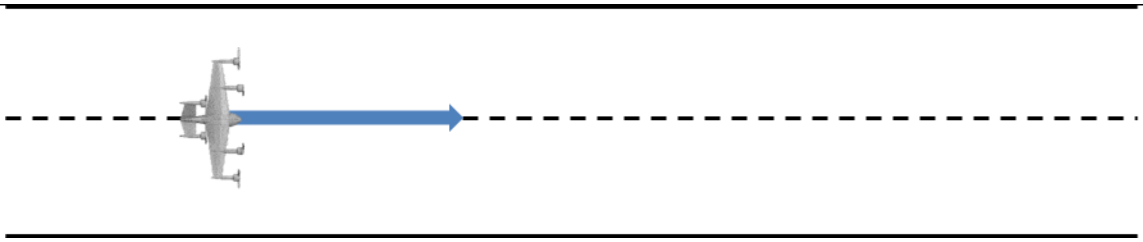


Figure C- 5. Centerline maintenance

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
3	Hover Taxi	Gear/flaps down Rotors vertical	Normal State

OBJECTIVE

Assess vehicle controllability and stability during hover taxi. The task demonstration points are designed to check each axis of control in a combined maneuver to evaluate cross axis harmony and coupling characteristics. The task is designed to maneuver the vehicle in a moderately aggressive manner up to what would be considered operationally relevant in a high gain situation.

MANEUVER TEST CONDITIONS

AUW or maximum permissible hover weight if lower

1. Calm winds
2. Maximum recovery headwind
3. 17 knot wind from critical azimuth
4. 17 knot wind from critical azimuth with light turbulence

MANEUVER DESCRIPTION

1. Start in a stabilized IGE hover in headwind with the longitudinal axis centered over the desired reference line. Maintain hover height throughout all maneuvering.
2. Initiate a longitudinal control input to accelerate the vehicle to 10 knots groundspeed for a steady state forward translation along the reference line (heading aligned with the reference line) no less than 100’.
3. Reduce the speed to 5 knots groundspeed before completing the 100’ forward taxi and perform a tight heading reversal (180 degrees change) applying directional control input as required, maintaining 5 kts during whole heading reversal.
4. Capture the opposite heading and accelerate to 10 knots groundspeed while maintaining height and the new reference line for no less than 100’.
5. Perform the maneuver twice executing the heading reversals in both directions (left and right).

MANEUVER NOTES

This task is to evaluate the air vehicle control response characteristics to command steady translations in each axis precisely and predictably along a reference line. The maneuver is designed to assess each axis of control in a combined maneuver to assess precision of control, axes harmony and evaluate any cross axis coupling that may impact the pilot’s ability to accurately capture a ground speed and heading while translating along a fixed reference line. The pilot is to also assess the pilot’s ability to remain at the desired hover height.

Table C- 5. Hover taxi maneuver notes

Operations	Normal operation, no degraded performance No Degraded Visual Environment
Aircraft Model Performance	No IGE/OGE modeling No density altitude performance modeling
Inceptors	DIM 1 (see ref.) No inceptor trim
Display Guidance	Hover Display Guidance on Primary Flight Display, GPS speed, heading
Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), stability (23.2145, 27.171) **other applicable part 27.**

TEST COURSE DESCRIPTION

The test course shall consist of 2 main parallel reference lines or markers on the ground indicating the desired track. The course should also include intermediate reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate tracking performance. The course must be wide enough to safely execute the heading reversal with adequate margins. Refer to Figure C- 6 and Figure C- 7 for an example course.

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)

Moderate turbulence: Level 2 – Adequate (CHR 4 to 6)

DESIRED PERFORMANCE METRICS

Maintain Ground Track within +/- 10 ft
Maintain Ground Speed within +/- 2 knots
Maintain altitude within: +/- 10 ft
Maintain heading within: +/- 10 deg
Capture heading within: 1 or less overshoots

ADEQUATE PERFORMANCE METRICS

Maintain Ground Track within +/- 20 ft
Maintain Ground Speed within +/- 4 knots
Maintain altitude within: +/- 15 ft
Maintain heading within: +/- 20 deg
Capture heading within: 1 or less overshoots

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 6. Hover taxi inputs/outputs data requirements

PARAMETER	MIN SAMPLE RATE	MIN RESOLUTION
CHR and Pilot’s comments on compensation	N.A.	N.A.
Ground speed	1 Hz	1 kts
Altitude AGL	1 Hz	1 ft
Heading, pitch, roll	20 Hz	0.2 deg
Longitudinal and lateral position	1 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots’ comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not to be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Analyze choice of effectors, control power and priorities (e.g. nose wheel steering, differential braking, differential thrust). Particularly critical is the control allocation (e.g., control distribution among redundant effectors or same effector controlling different axis, potentially saturating controls and resulting in problems like momentarily exclusion of one axis resulting in latencies or undesired cross coupling effects.
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Excessive lag in aircraft response: verify controls allocation and analyze time histories comparing pilot's inputs with the effectors response. If effectors are saturated, assess prioritization logic and actuators performance (rate limit).

- Difficulty in capturing and controlling the ground speed and/or height: assess propulsive response (RPM control), display latencies and/or filtering of airspeed, height or velocity vector cues.

- Pitch oscillations: verify actuator bandwidth and saturation limits (i.e., rate limits). Verify inceptors displacements, characteristics and sensitivity. Assess any different response when transitioning from/to out of ground effect to/from in ground effect.

- Roll/Yaw oscillations: assess cross-coupling effects due to the control logic and effectors, as several of these vehicles are characterized by controls redundancy (i.e.: control surfaces + rotors). Explore the roll mode characteristics in hover. Verify actuators bandwidth and saturation limits (i.e., rate limits).

EXAMPLE COURSE

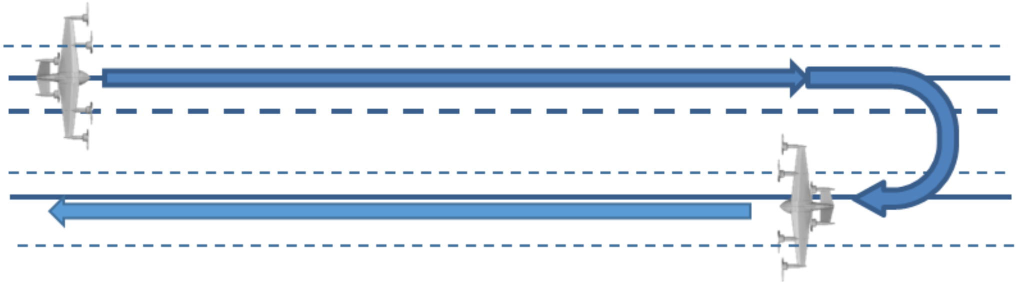


Figure C- 6. Hover taxi with right heading reversal

Figure C- 7. Hover taxi with left heading reversal

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
4	Climbout (Stability & Control)	As required for forward climb	Normal State

OBJECTIVE

Assess vehicle controllability and stability during forward climb. The task demonstration points are designed to check each axis of control to evaluate cross axis harmony and coupling characteristics. The task is designed to maneuver the vehicle in a moderately aggressive manner up to what would be considered operationally relevant in a high gain situation.

MANEUVER TEST CONDITIONS

Maximum Takeoff Weight and minimum operationally representative weight, forward and aft CG.

1. Low Density Altitude (Sea Level)
2. High Density Altitude (10,000 ft)
3. No wind
4. Greater than 20 kts crosswind and turbulence

MANEUVER DESCRIPTION

1. Start in a stabilized OGE hover with the longitudinal axis centered over the desired forward path.
2. Apply full power with forward longitudinal control input to accelerate the vehicle to TBD knots for a steady state forward climb task along the intended path (GPS track and airspeed constant) up to 500’ AGL.
3. At 500’AGL perform 2 turns (left and right) for 90 degrees heading change for each turn, maintaining the new heading for 15 seconds, while continuing the climb at full power to 1,000’ AGL.
4. Level off at 1,000’ AGL.

MANEUVER NOTES

This task is to evaluate the air vehicle control response characteristics and handling qualities to command forward climb along a reference path. The maneuver is designed to assess control precision and harmony in each axis and evaluate any cross axis coupling that may impact the pilot’s ability to accurately capture and maintain an airspeed and heading while climbing.

Table C- 7. Climbout maneuver notes

Operations	Normal operation No Degraded Visual Environment	
Aircraft Model Performance	Density altitude performance modeling required	
Inceptors	All	
Display Guidance	Airpeed, Altitude MSL, Altitude AGL, Angle of Attack, Vertical speed, Pitch Angle, Bank angle, GPS Track	
Automation/Control Laws	C-law: Rotary Wing Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS	

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), stability (23.2145, 27.171) **other applicable part 27**.

TEST COURSE DESCRIPTION

N/A

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)

Moderate turbulence and crosswind in excess of 20 knots: Level 2 – Adequate (CHR 4 to 6)

DESIRED PERFORMANCE METRICS

Capture forward speed with:	1 or less overshoots
Maintain forward speed within:	+/- 1 kt
Capture heading within:	1 or less overshoots
Maintain heading within:	+/- 10 deg
Maintain GPS track within:	+/- 50 ft

ADEQUATE PERFORMANCE METRICS

Capture forward speed with:	2 or less overshoots
Maintain forward speed within:	+/- 2 kt
Capture heading within:	2 or less overshoots
Maintain heading within:	+/- 20 deg
Maintain GPS track within:	+/- 100 ft

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 8. Climbout inputs/outputs data requirements

PARAMETER	MIN SAMPLE RATE	MIN RESOLUTION
CHR and Pilot's comments on compensation	N.A.	N.A.
Torque (or relevant engine parameter)	10 Hz	0.1% of Limit Value
Indicated Airspeed	10 Hz	1 kt
Ground Speed	10 Hz	1 kt
Vertical Speed	10 Hz	20 fpm
Pitch Angle	20 Hz	0.2 deg
Bank Angle	20 Hz	0.2 deg
Heading	20 Hz	0.2 deg
Longitudinal and lateral position	10 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots' comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not to be averaged or altered based on quantitative data analysis. Qualitative comments will be used to identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections can be indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Analyze choice of effectors, control power and priorities (e.g., nose wheel steering, differential braking, differential thrust). Particularly critical is the control allocation (e.g., control distribution among redundant effectors or same effector controlling different axis, potentially saturating controls and resulting in problems like momentarily exclusion of one axis resulting in latencies or undesired cross coupling effects).
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Excessive lag in aircraft response: verify controls allocation and analyze time histories comparing pilot's inputs with the effectors response. If effectors are position or rate saturated, assess prioritization logic and actuators performance (rate limit).
- Difficulty in capturing and controlling the airspeed and/or altitude: assess propulsive response (RPM control), display latencies and/or filtering of airspeed, height or velocity vector cues.
- Pitch oscillations: verify actuator bandwidth and saturation limits (i.e. rate limits). Verify inceptors displacements, force gradients, dynamic characteristics and sensitivity.
- Roll/Yaw oscillations: assess cross-coupling effects due to the control logic and effectors, as several of these vehicles are characterized by controls redundancy (i.e.: control surfaces + rotors). Explore the roll mode characteristics. Verify actuators bandwidth and saturation limits (i.e., rate limits).

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
5	Envelope Protection Limiting (Climb)	Conventional (wing borne)	Normal State

OBJECTIVE

Assess the effectiveness of the envelope protection system and its impact on the HQs of the vehicle. The assessment of the visual and aural cues provided to the pilot is an integral part of the evaluation. The task is designed to demand performance beyond the operational capabilities of the vehicle to assess the ability of the system to prevent departure from controlled flight, the development of unsafe conditions and/or structural damage to the airframe.

MANEUVER TEST CONDITIONS

Maximum Takeoff Weight and minimum operationally representative weight, forward and aft CG.

1. Low Density Altitude (Sea Level)
2. High Density Altitude (10,000 ft)

MANEUVER DESCRIPTION

1. Engine limit
    a. Stabilize best rate of climb airspeed.
    b. Command maximum effort climb with available inceptors.
    c. Verify engine limits are not exceeded.
    d. Verify envelope protection annunciation adequate
2. Total energy balance
    a. Start from 1b initial conditions.
    b. Command maximum acceleration with available inceptors.
    c. Verify total energy balance logic
3. Handling qualities at maximum effort
    a. Start from 2b initial conditions.
    b. Capture half of the current pitch angle within xx seconds and maintain for 20 seconds.
    c. Capture 45 degrees bank angle within xx seconds and maintain for 20 seconds

4. Underspeed protection
    a. Start from 3c initial conditions.
    b. Command maximum effort climb with available inceptors.
    c. Command maximum deceleration with available inceptors.
    d. Verify underspeed protection.
    e. Capture half of the current vertical speed within xx seconds.
    f. Roll back to wings level within xx seconds

MANEUVER NOTES

This task is to evaluate the aircraft envelope protection system during climb and the handling qualities as the pilot is alerted of the envelope protection activation and maneuvers the aircraft to return to normal operating conditions. This task is also aimed at evaluating the handling qualities at maximum effort performance. The maneuvers are designed to unveil longitudinal and lateral control deficiencies that may affect the pilot's ability to safely conduct climbs in normal and marginal performance conditions.

Table C- 9. Envelope protection limiting (climb) maneuver notes

Operations	Normal operation, no degraded performance No Degraded Visual Environment
Aircraft Model Performance	Density altitude performance modeling required
Inceptors	All
Display Guidance	Airspeed, Airspeed Trend, Commanded Airspeed (if applicable), Altitude MSL, Altitude Trend, Angle of Attack, Vertical Speed, Pitch Angle, Flight Path Angle, Commanded Vertical Speed or Flight Path Angle (as applicable), Bank angle
Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), Stability (23.2145), Climb Requirements (23.2120), Stall characteristics, stall warning, and spins (23.2150).

TEST COURSE DESCRIPTION

The test should be conducted in smooth air and perpendicular to the prevailing winds.

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)
Level 2 – Adequate (CHR 4 to 6) at the boundaries of the envelope

DESIRED PERFORMANCE METRICS

Capture bank angle within: +/- 2 degrees
Capture bank angle with: 1 or less overshoots

Maintain bank angle within: +/- 2 degrees 80% of the time for 20 seconds

Capture vertical speed within: +/- 100 fpm
Capture vertical speed with: 1 or less overshoots

Maintain vertical speed within: +/- 100 fpm 80% of the time for 20 seconds

Capture pitch angle within: +/- 1 degree
Capture pitch angle with: 1 or less overshoots

Maintain pitch angle within: +/- 1 degree 80% of the time for 20 seconds

ADEQUATE PERFORMANCE METRICS

Capture bank angle within: +/- 5 degrees
Capture bank angle with: 2 or less overshoots

Maintain bank angle within: +/- 5 degrees 80% of the time for 20 seconds

Capture vertical speed within: +/- 200 fpm
Capture vertical speed with: 2 or less overshoots

Maintain vertical speed within: +/- 200 fpm 80% of the time for 20 seconds

Capture pitch angle within: +/- 2 degree

Capture pitch angle with: 2 or less overshoots

Maintain pitch angle within: +/- 2 degree 80% of the time for 20 seconds

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 10. Envelope protection limiting (climb) inputs/outputs data requirements

PARAMETER	**MIN SAMPLE RATE**	**MIN RESOLUTION**
CHR and Pilot's comments on compensation	N.A.	N.A.
Relevant engine parameters	10 Hz	0.1% of Limit Value
Indicated Airspeed	10 Hz	1 kt
Vertical Speed	10 Hz	20 fpm
Pitch Angle	20 Hz	0.2 deg
Bank Angle	20 Hz	0.2 deg
Heading	20 Hz	0.2 deg
Longitudinal and lateral position	10 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots' comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

Videos of the pilot's displays should be recorded to assess effectiveness and timeliness of envelope protection annunciations, along with adequacy of suggested corrective actions. Time histories of the relevant parameters are required to ensure the envelope protection actually prevents exceedance of critical parameters. Time histories are also vital to troubleshoot unexpected responses, particularly when control allocation is critical in the presence of saturation.

Recordings of displayed information is also important to verify effectiveness of guidance, annunciation and state of the aircraft. Particularly critical are data filtering, lags and display decluttering, particularly when critical safety information are presented.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Verify control prioritization logic following saturation of one or more effectors.
- Verify the envelope protection system actually prevents any exceedances beyond safe margins.
- Verify effectiveness of annunciations.
- Assess dynamics of the saturated FCS response during envelope protection intervention.
- Assess cross coupling effects.
- Assess potential performance degradation compared to published charts due to the intervention of the envelope protection.

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
6	Envelope Protection Limiting (Descent)	Conventional (wing borne)	Normal State

OBJECTIVE

Assess the effectiveness of the envelope protection system and its impact on the HQs of the vehicle. The assessment of the visual and aural cues provided to the pilot is an integral part of the evaluation. The task is designed to stress the envelope protection system in situations where conflicting demands may occur and evaluate the impact on the handling qualities when the system intervenes to protect the aircraft.

MANEUVER TEST CONDITIONS

Maximum Takeoff Weight and minimum operationally representative weight, forward and aft CG.

MANEUVER DESCRIPTION

1. Wings level dive
    a. Apply simultaneously full demand on the vertical and forward degree of freedom inceptors (maximum descent rate and forward acceleration).
    b. Verify propeller RPM limits are not exceeded.
    c. Verify adequacy of airspeed protection and effectiveness of cautions and warnings.
    d. If the system commands a pull up maneuver to avoid over speed, verify limit load factor is not exceeded.
    e. Command maximum deceleration while maintaining pitch angle.
    f. Apply again full demand on the vertical degree of freedom inceptor and capture maximum allowable angle of bank (or 45 degrees AoB, whichever is lower) within 3 seconds.
2. Spiraling dive
    a. Capture and maintain 45 degrees bank angle.
    b. Apply simultaneously full demand on the vertical and forward degree of freedom inceptors (maximum descent rate and forward acceleration).
    c. Verify propeller RPM limits are not exceeded.
    d. Verify adequacy of airspeed protection and effectiveness of cautions and warnings.

e. If the system commands a pull up maneuver to avoid over speed, verify limit load factor is not exceeded.
f. If the system automatically reduces the bank angle to recover from spiraling dive, verify effectiveness of annunciation and impact on handling qualities.
g. Command maximum deceleration while maintaining pitch angle and bank angle.
h. Capture wings level within 3 seconds.

MANEUVER NOTES

This task is to evaluate the aircraft envelope protection system during a dive and the handling qualities as the pilot is alerted of the envelope protection activation and maneuvers the aircraft to return to normal operating conditions. The maneuvers are designed to trigger conflicting conditions where a recovery maneuver could potentially affect multiple limits and different axes. Cross coupling effects are to be carefully evaluated.

Table C- 11. Envelope protection limiting (descent) maneuver notes

Operations	Normal operation, no degraded performance No Degraded Visual Environment
Aircraft Model Performance	High alpha modeling required
Inceptors	All
Display Guidance	Airspeed, Altitude MSL, Altitude AGL, Angle of Attack, Vertical speed, Pitch Angle, Flight Path Angle, Bank angle
Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), Stability (23.2145), Structural Strength (23.2235).

TEST COURSE DESCRIPTION

The test should be conducted in smooth air and medium altitudes

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)

During activation of envelope protection: Level 2 – Adequate (CHR 4 to 6)

DESIRED PERFORMANCE METRICS

Wings Level Dive

Maintain pitch angle for 30 sec within:	+/- 1 degree for 80% of the time
Capture 45 degrees bank angle within:	+/- 2 degrees in 3 seconds
Capture 45 degrees bank angle with:	1 or less overshoots

Spiraling Dive

Maintain pitch angle for 30 sec within:	+/- 1 degree for 80% of the time
Capture wings level within:	+/- 2 degrees in 3 seconds
Capture wings level with:	1 or less overshoots

ADEQUATE PERFORMANCE METRICS

Wings Level Dive

Maintain pitch angle for 30 sec within:	+/- 2 degree for 80% of the time
Capture 45 degrees bank angle within:	+/- 5 degrees in 3 seconds
Capture 45 degrees bank angle with:	2 or less overshoots

Spiraling Dive

Maintain pitch angle for 30 sec within:	+/- 2 degree for 80% of the time
Capture wings level within:	+/- 5 degrees in 3 seconds
Capture wings level with:	2 or less overshoots

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 12. Envelope protection limiting (descent) inputs/outputs data requirements

PARAMETER	MIN SAMPLE RATE	MIN RESOLUTION
CHR and Pilot’s comments on compensation	N.A.	N.A.
RPM	10 Hz	0.1% of Limit Value
Indicated Airspeed	10 Hz	1 kt
Vertical Speed	10 Hz	20 fpm
Pitch Angle	20 Hz	0.2 deg

Bank Angle	20 Hz	0.2 deg
Heading	20 Hz	0.2 deg
Load Factor	10 Hz	0.02 g
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots' comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

Videos of the pilot's displays should be recorded to assess effectiveness and timeliness of envelope protection annunciations, along with adequacy of suggested corrective actions. Time histories of the relevant parameters are required to ensure the envelope protection actually prevents exceedance of critical parameters. Time histories are also vital to troubleshoot unexpected responses, particularly when control allocation is critical in the presence of saturation

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Verify adequacy of response in the presence of conflicting requirements, such as airspeed and load factor limits.
- Verify the envelope protection intervention does not impair pilot’s ability to positively control the aircraft.
- Verify the envelope protection system actually prevents any exceedances beyond safe margins.
- Verify effectiveness and nuisance potential of annunciations.
- Assess dynamics of the saturated FCS response during envelope protection intervention.
- Assess cross coupling effects.
- Assess potential performance degradation compared to published charts due to the intervention of the envelope protection.

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
7	Envelope Protection Limiting (Takeoff)	Conventional takeoff (wing borne), Vertical takeoff (rotor borne)	Normal State

OBJECTIVE

Assess the effectiveness of the envelope protection system and its impact on the HQs of the vehicle. The assessment of the visual and aural cues provided to the pilot is an integral part of the evaluation. The task is designed to demand performance beyond the operational capabilities of the vehicle to assess the ability of the system to prevent the development of unsafe conditions and/or damage to the airframe.

MANEUVER TEST CONDITIONS

Maximum Takeoff Weight and minimum operationally representative weight, forward and aft CG.

1. Low Density Altitude (Sea Level)
2. High Density Altitude (10,000 ft)

The initial condition for all maneuvers is static condition in the takeoff configuration

MANEUVER DESCRIPTION

1. VTOL (torque limit)
    a. Demand maximum vertical rate.
    b. Verify engine limits are not exceeded.
    c. Verify envelope protection annunciation adequate.
    d. Capture 10 kts forward speed within 5 seconds.
    e. Capture 10 kts lateral speed within 5 seconds.
    f. Capture a vertical rate below saturation within 5 seconds
2. VTOL (pitch attitude limit)
    a. Hover outside of ground effect.
    b. Apply full forward acceleration input.
    c. Verify pitch limits are not exceeded.
    d. Verify envelope protection annunciation adequate.
    e. Return to hover within 5 seconds

3. VTOL (roll attitude limit)
    1. Hover outside of ground effect.
    2. Apply full lateral acceleration input.
    3. Verify roll limits are not exceeded.
    4. Verify envelope protection annunciation adequate.
    5. Return to hover within 5 seconds
4. Conventional Take Off and Landing (CTOL) (premature rotation)
    1. During ground acceleration, apply full back stick.
    2. Verify pitch limits are not exceeded.
    3. Verify envelope protection annunciation adequate.
    4. Capture nominal pitch attitude within 2 seconds
5. CTOL (angle of attack protection)
    1. Accelerate to nominal rotation speed.
    2. Apply full back stick.
    3. Verify angle of attack limit is not exceeded.
    4. Verify envelope protection annunciation adequate.
    5. Capture nominal pitch angle within 2 seconds

MANEUVER NOTES

This task is to evaluate the aircraft envelope protection system during takeoff and the handling qualities as the pilot is alerted of the envelope protection activation and maneuvers the aircraft to return to normal operating conditions. The maneuvers are designed to unveil longitudinal and lateral control deficiencies that may affect the pilot's ability to safely conduct CTOL and VTOL in normal and marginal performance conditions.

Table C- 13. Envelope protection limiting (takeoff) maneuver notes

Operations	Normal operation, no degraded performance No Degraded Visual Environment
Aircraft Model Performance	Ground reaction modeling Density altitude performance modeling required
Inceptors	All
Display Guidance	Airspeed, Altitude MSL, Altitude AGL, Angle of Attack, Vertical speed, Pitch Angle, Bank angle

Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), Stability (23.2145), Takeoff Performance (23.2115).

TEST COURSE DESCRIPTION

The test course shall consist of a runway with standard markings, long and wide enough for the safe execution of the test depending on the specific aircraft performance and characteristics. Runway elevation and temperature must allow achieving the target density altitude for the test.

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)

Moderate turbulence and crosswind in excess of 20 knots: Level 2 – Adequate (CHR 4 to 6)

DESIRED PERFORMANCE METRICS

VTOL (torque)

Capture forward speed within: +/- 1 kt
Capture forward speed with: 1 or less overshoots
Capture lateral speed within: +/- 1 kt
Capture lateral speed with: 1 or less overshoots
Capture vertical speed within: +/- 100 fpm
Capture vertical speed with: 1 or less overshoots

VTOL (pitch angle)

Return to hover within: +/- 1 kt
Return to hover with 1 or less overshoots

VTOL (roll angle)

Return to hover within: +/- 1 kt
Return to hover with: 1 or less overshoots

CTOL (premature rotation)

Capture pitch angle within: +/- 1 degree
Capture pitch angle with 1 or less overshoots

CTOL (angle of attack)
Capture pitch angle within: +/- 1 degree
Capture pitch angle with 1 or less overshoots

ADEQUATE PERFORMANCE METRICS

VTOL (torque)
Capture forward speed within: +/- 2 kt
Capture forward speed with: 2 or less overshoots
Capture lateral speed within: +/- 2 kt
Capture lateral speed with: 2 or less overshoots
Capture vertical speed within: +/- 200 fpm
Capture vertical speed with: 2 or less overshoots

VTOL (pitch angle)
Return to hover within: +/- 2 kt
Return to hover with 2 or less overshoots

VTOL (roll angle)
Return to hover within: +/- 2 kt
Return to hover with: 2 or less overshoots

CTOL (premature rotation)
Capture pitch angle within: +/- 2 degree
Capture pitch angle with 2 or less overshoots

CTOL (angle of attack)
Capture pitch angle within: +/- 2 degree
Capture pitch angle with 2 or less overshoots

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 14. Envelope protection limiting (takeoff) inputs/outputs data requirements

PARAMETER	MIN SAMPLE RATE	MIN RESOLUTION
CHR and Pilot’s comments on compensation	N.A.	N.A.
Torque (or relevant engine parameter)	10 Hz	0.1% of Limit Value
Indicated Airspeed	10 Hz	1 kt
Ground Speed	10 Hz	1 kt
Vertical Speed	10 Hz	20 fpm
Pitch Angle	20 Hz	0.2 deg
Bank Angle	20 Hz	0.2 deg
Heading	20 Hz	0.2 deg
Longitudinal and lateral position	10 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots’ comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots’ ratings and comments. A quantitative measurement of the actual performance ensures that pilots’ feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot’s activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

Videos of the pilot's displays should be recorded to assess effectiveness and timeliness of envelope protection annunciations, along with adequacy of suggested corrective actions. Time histories of the relevant parameters are required to ensure the envelope protection actually prevents exceedance of critical parameters. Time histories are also vital to troubleshoot unexpected responses, particularly when control allocation is critical in the presence of saturation.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Verify control prioritization logic following saturation of one or more effectors.
- Verify the envelope protection system actually prevents any exceedances beyond safe margins.
- Verify effectiveness of annunciations.
- Assess dynamics of the saturated FCS response during envelope protection intervention.
- Assess cross coupling effects.
- Assess potential performance degradation compared to published charts due to the intervention of the envelope protection.

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
8	Level Acceleration from Vertical T/O	Rotor Borne / Wing borne	Normal State

OBJECTIVE

Assess vehicle controllability and stability during level acceleration from vertical take-off. The task is designed to check each axis of control to evaluate cross axis harmony and coupling characteristics, and to maneuver the vehicle in a moderately aggressive manner up to what would be considered operationally relevant.

MANEUVER TEST CONDITIONS

AUW or maximum permissible hover weight if lower

1. Calm winds
2. Maximum recovery headwind
3. 17 knot wind from critical azimuth
4. 17 knot wind from critical azimuth with light turbulence

MANEUVER DESCRIPTION

1. Start in a stabilized OGE hover with the longitudinal axis centered over the desired reference line.
2. Initiate a longitudinal control input to accelerate the vehicle to cruise airspeed for a steady state forward translation task along the reference line (heading aligned with the reference line) no less than 1000’.
3. Maintain the initial height throughout all maneuvering applying the appropriate power control input.

MANEUVER NOTES

This task is to evaluate the air vehicle control response characteristics to command steady translations in each axis precisely and predictably along a reference line. The maneuver is designed to assess each axis of control in a maneuver to assess precision of control, axes harmony and evaluate any cross axis coupling that may impact the pilot’s ability to accurately capture an airspeed and maintain constant heading while translating along a fixed reference line. The pilot is to also assess the ability to remain at the desired constant height.

Table C- 15. Level acceleration from vertical T/O maneuver notes

Operations	Normal operation, no degraded performance No Degraded Visual Environment
Aircraft Model Performance	No IGE/OGE modeling No density altitude performance modeling
Inceptors	DIM 1 (see ref.) No inceptor trim
Display Guidance	Airspeed, Altitude MSL, Altitude AGL, Vertical speed, Pitch Angle, Bank angle, Heading
Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), stability (23.2145, 27.171) **other applicable part 27**.

TEST COURSE DESCRIPTION

The test course shall consist of 1 main reference line or markers on the ground indicating the desired track. The course should also include intermediate reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate tracking performance. Refer to Figure C- 8 for an example course.

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)

Moderate turbulence: Level 2 – Adequate (CHR 4 to 6)

DESIRED PERFORMANCE METRICS

Maintain Ground Track within:	+/- 10 ft
Capture Cruise airspeed with	1 or less overshoots
Maintain Cruise airspeed within:	+/- 2 knots
Maintain altitude within:	+/- 10 ft
Maintain heading within:	+/- 10 deg

ADEQUATE PERFORMANCE METRICS

Maintain Ground Track within	+/- 20 ft
Capture Cruise airspeed with	2 or less overshoots
Maintain Cruise airspeed within	+/- 4 knots
Maintain altitude within	+/- 15 ft
Maintain heading within	+/- 20 deg

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 16. Level acceleration from vertical T/O inputs/outputs data requirements

PARAMETER	MIN SAMPLE RATE	MIN RESOLUTION
CHR and Pilot’s comments on compensation	N.A.	N.A.
Airspeed	1 Hz	1 kts
Altitude AGL	1 Hz	1 ft
Heading, pitch, roll	20 Hz	0.2 deg
Longitudinal and lateral position	1 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots’ comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots’ ratings and comments. A quantitative measurement of the actual performance ensures that pilots’ feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot’s activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Analyze choice of effectors, control power and priorities. Particularly critical is the control allocation (e.g., control distribution among redundant effectors or same effector controlling different axis, potentially saturating controls and resulting in problems like momentarily exclusion of one axis resulting in latencies or undesired cross coupling effects).
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses.

Specific for the HQTE

- Excessive lag in aircraft response: verify controls allocation and analyze time histories comparing pilot’s inputs with the effectors response. If effectors are saturated, assess prioritization logic and actuators performance (rate limit).
- Difficulty in capturing and controlling the ground speed and/or height: assess propulsive response (RPM control), display latencies and/or filtering of airspeed, height or velocity vector cues.
- Pitch oscillations: verify actuator bandwidth and saturation limits (i.e. rate limits). Verify inceptors displacements, characteristics and sensitivity. Assess any different response when transitioning from/to out of ground effect to/from in ground effect.
- Roll/Yaw oscillations: assess cross-coupling effects due to the control logic and effectors, as several of these vehicles are characterized by controls redundancy (i.e.: control surfaces + rotors). Explore the roll mode characteristics in hover. Verify actuators bandwidth and saturation limits (i.e., rate limits).

EXAMPLE COURSE

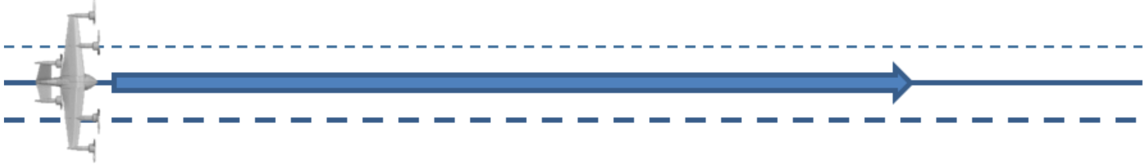


Figure C- 8. Level acceleration from vertical take-off

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S) / CONDITIONS
9	Longitudinal/Lateral/Combined Reposition and Hold	Landing Approach configuration (gear/flaps down/thrust borne lift)	Normal State

OBJECTIVE

Assess vehicle controllability and stability during the VTOL aircraft task of longitudinal and lateral repositioning. The task demonstration points are designed to check each axis of control individually and then in a combined maneuver to evaluate cross axis harmony and coupling characteristics. The task is designed to maneuver the vehicle in a moderately aggressive manner up to what would be considered safe in an operational context

MANEUVER TEST CONDITIONS

AUW or maximum permissible hover weight if lower

1. Calm winds
2. Maximum recovery headwind
3. 17 knot wind from critical azimuth
4. 17 knot wind from critical azimuth with light turbulence

MANEUVER DESCRIPTION

1. Start in a stabilized IGE hover or no higher than 35 ft skid/wheel height with the axis to be assessed centered over the desired reference line. Maintain hover height throughout all of translational maneuvering.
2. Initiate a (lateral/longitudinal/combined) control input to accelerate the vehicle to 10 knots groundspeed for a steady state translation task along the reference line no less than 100’. For the longitudinal reposition aircraft heading shall be aligned with the reference line. For the lateral reposition aircraft heading shall be 90 degrees off the reference line. For the combined reposition aircraft heading shall be 45 degrees off the reference line.
3. Decelerate the vehicle to capture the desired new hover position. The entire maneuver shall be completed within 18 sec.

MANEUVER NOTES

This task is to evaluate the air vehicle control response characteristics to command steady translations in each axis precisely and predictably along a reference line. The maneuver is designed to points are designed to assess each axis of control individually and then in a combined maneuver to assess precision of control, axes harmony and evaluate any cross axis coupling that may impact the pilot's ability to accurately capture a ground speed while translating along a fixed reference line. Since this is a horizontal repositioning task, the pilot is to also assess the pilot's ability to remain in the desired at the desired hover height.

Table C- 17. Long/Lat/Combined reposition and hold maneuver notes

Operations	Normal operation, no degraded performance No agility limits No Degraded Visual Environment
Aircraft Model Performance	No IGE/OGE modeling No density altitude performance modeling
Inceptors	DIM 1 (see ref.) No inceptor trim
Display Guidance	Hover Display Guidance on Primary Flight Display
Automation/Control Laws	C-law: Unified (see ref.), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17B, Controllability (23.2135, 27.143), stability (23.2145, 27.171) **other applicable part 27**.

TEST COURSE DESCRIPTION

The test course shall consist of any reference lines or markers on the ground indicating the desired track. 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 tracking performance and hover position capture. Refer to Figure C- 9 for an example course.

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: CHR 1 to 3

Moderate turbulence and crosswinds targets: CHR 4 to 6

DESIRED PERFORMANCE METRICS

Maintain Ground Track within	+/- 10 ft
Maintain Ground Speed within	+/- 2 knots

Maintain altitude within: +/- 10 ft
Maintain heading within: +/- 10 deg
Hover position capture: +/- 10 ft
Time to complete maneuver 18 sec

ADEQUATE PERFORMANCE METRICS

Maintain Ground Track within +/- 20 ft
Maintain Ground Speed within +/- 4 knots
Maintain altitude within: +/- 15 ft
Maintain heading within: +/- 20 deg
Hover position capture: +/- 20 ft
Time to complete maneuver 18 sec

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 18. Long/Lat/Combined reposition and hold inputs/outputs data requirements

PARAMETER	MIN SAMPLE RATE	MIN RESOLUTION
CHR and Pilot’s comments on compensation	N.A.	N.A.
Ground speed	1 Hz	1 kts
Altitude AGL	1 Hz	1 ft
Heading, pitch, roll	20 Hz	0.2 deg
Longitudinal and lateral position	1 Hz	1 ft
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots’ comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Once the condition and rate has been determined, isolate the axis on which the unexpected response is experienced.
- Analyze choice of effectors, control power and priorities (e.g. spoilers, outboard ailerons, inboard ailerons, flaperons, spoilers, thrust vectoring, including tilt angle, propeller angle and RPM). Particularly critical is the control allocation (e.g. control distribution among redundant effectors or same effector controlling different axis, potentially saturating controls and resulting in problems like momentarily exclusion of one axis resulting in latencies or undesired cross coupling effects.

Specific for the HQTE

- Excessive lag in aircraft response: verify controls allocation and analyze time histories comparing pilot's inputs with the effectors response. If effectors are saturated, assess prioritization logic and actuators performance (rate limit).
- Difficulty in capturing and controlling the ground speed and/or height: assess propulsive response (RPM control), display latencies and/or filtering of airspeed, height or velocity vector cues.
- Pitch oscillations: verify actuator bandwidth and saturation limits (i.e. rate limits). Verify inceptors displacements, characteristics and sensitivity. Assess any different response when transitioning from/to out of ground effect to/from in ground effect.
- Roll/Yaw oscillations: assess cross-coupling effects due to the control logic and effectors, as several of these vehicles are characterized by controls redundancy (i.e.:

control surfaces + rotors). Explore the roll mode characteristics in hover. Verify actuators bandwidth and saturation limits (i.e. rate limits)..

- Pitch oscillations: verify actuator bandwidth and saturation limits (i.e. rate limits). Verify inceptors displacements, characteristics and sensitivity. Assess any different response when transitioning from/to out of ground effect to/from in ground effect.

- Roll/Yaw oscillations: assess cross-coupling effects due to the control logic and effectors, as several of these vehicles are characterized by controls redundancy (i.e.: control surfaces + rotors). Explore the roll mode characteristics in hover. Verify actuators bandwidth and saturation limits (i.e., rate limits).

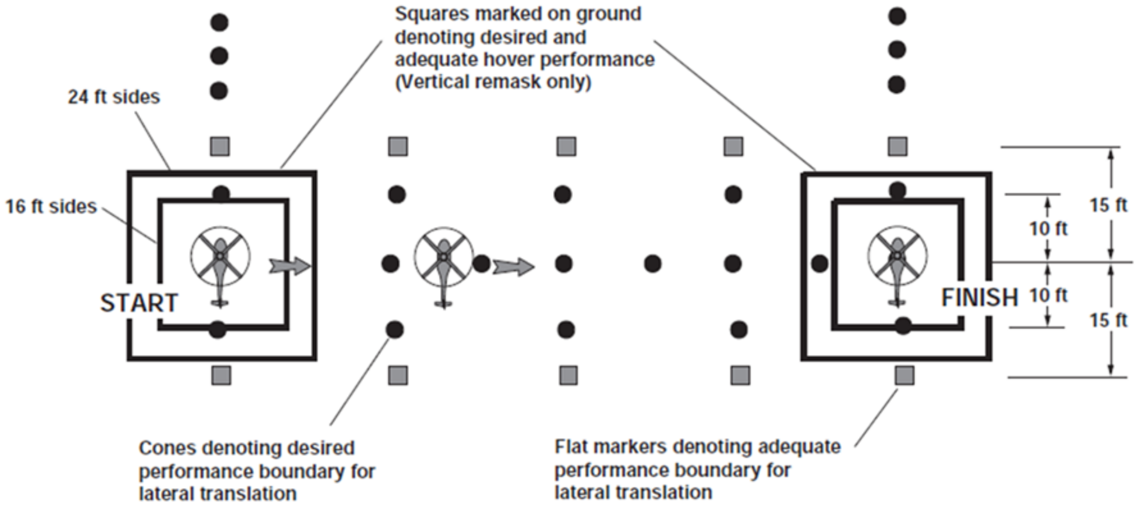


Figure C- 9. Lateral reposition and hold test course

HQTE MANEUVER DESCRIPTION

HQTE NO.	MTE MANEUVER TITLE	CONFIGURATION	OP. STATE(S)/ CONDITIONS
10	Pitch and Roll Control (Cruise)	Conventional (wing borne)	Normal State

OBJECTIVE

Assess the HQs of the vehicle during cruise and unveil any PIO tendencies. The task is designed to stress the system beyond normal operating conditions, which typically involve the use of autopilots. Abnormal situations include aggressive maneuvering to avoid a traffic conflict (e.g. in response to TCAS annunciation) or the unexpected disengagement of the autopilot in out of trim conditions.

MANEUVER TEST CONDITIONS

1. Heavy weight and forward CG
2. Light weight and aft CG

MANEUVER DESCRIPTION

1. Pitch angle capture
    a. Stabilize the aircraft at normal cruising airspeed.
    b. Capture 10 degrees nose up in less than xx seconds.
    c. After new pitch is stabilized, recapture the initial pitch angle in less than xx seconds
2. Bank angle capture
    a. Stabilize the aircraft at normal cruising airspeed.
    b. Capture maximum allowable angle of bank (or 45 AoB, whichever is lower) in less than xx seconds.
    c. After new bank angle is stabilized, return to wings level in less than xx seconds
3. Level altitude heading capture
    a. Stabilize the aircraft at normal cruising airspeed.
    b. Perform 60 degrees heading change in less than xx seconds while maintaining level altitude
4. MIL-STD-1797B longitudinal task
    a. Track the synthetic target through its combination of discrete and continuous motion
5. MIL-STD-1797B lateral task

    a. Track the synthetic target through its combination of discrete and continuous motion

6. Unexpected Autopilot disengagement
    a. Stabilize the aircraft at normal cruising airspeed.
    b. Maintain level flight with pitch control while trimming the aircraft nose up (up to the maximum mistrim required for triggering autopilot disengagement).
    c. Release controls for 2 seconds.
    d. Recover the aircraft to the initial pitch angle in less than xx seconds.
7. Handling Qualities During Tracking (HQDT)
    a. Stabilize the aircraft at normal cruising airspeed.
    b. Apply a brief and small nose up input (2 degrees) and then aggressively capture and track the initial pitch angle.
    c. Do not accept any deviations, as soon as a minimal error is detected, immediately apply a correction.

MANEUVER NOTES

This task is to evaluate the HQs during cruise. Normal and abnormal situations are considered when designing the tasks. An aggressive pitch and roll capture may be required to avoid a traffic conflict, even if the aircraft is designed for smooth normal operations. The MIL-STD-1797B tracking task is excellent because it combines discrete and continuous maneuvering, while adding unpredictability as the pilot should not be aware of the next step in the sequence. The autopilot disengagement task is a realistic and operationally representative one, as many accidents happened as the pilot was unexpectedly given control of an out of trim airplane and had problems regaining control of the vehicle. The HQDT task is an extremely aggressive one; while not a realistic task in an operational environment, it is useful to unveil potential PIO tendencies of the aircraft.

Table C- 19. Pitch and roll control maneuver notes

Operations	Normal operation, no degraded performance No agility limits No Degraded Visual Environment
Aircraft Model Performance	No specific performance modeling required.
Inceptors	All

Display Guidance	Conventional flight instruments. Reticles of adequate size for desired and adequate performance. Synthetic moving target following the MIL-STD-1797B sequence. A HUD is desired, although a Head Down Display may be used.
Automation/Control Laws	C-law: Conventional, Unified, EZ-Fly, Helo-Centric (as applicable), No Autopilot, No FMS

REFERENCE GUIDANCE

14 CFR part 21.17(b), Controllability (23.2135, 27.143), Stability (23.2145).

TEST COURSE DESCRIPTION

The test should be conducted in smooth air at a safe altitude.

EVALUATION CRITERIA

HQ LEVEL REQUIREMENTS

Target: Level 1 – Satisfactory (CHR 1 to 3)
No PIO tendency (PIO rating 1 or 2)

DESIRED PERFORMANCE METRICS

Capture pitch angle within:	+/- 1 degree
Capture pitch angle with:	1 or less overshoots
Capture bank angle within:	+/- 2 degrees
Capture bank angle with:	1 or less overshoots
Capture heading within:	+/- 2 degrees
Maintain altitude within:	+/- 50 ft
MIL-STD-1797B longitudinal task:	Pipper within 5 mils for 50% of the task Pipper within 25 mils for the 95% of the task
MIL-STD-1797B lateral task:	Pipper within 5 mils for 50% of the task Pipper within 25 mils for the 95% of the task

ADEQUATE PERFORMANCE METRICS

Capture pitch angle within: +/- 1 degree
Capture pitch angle with: 1 or less overshoots

Capture bank angle within: +/- 2 degrees
Capture bank angle with: 1 or less overshoots

Capture heading within: +/- 2 degrees
Maintain altitude within: +/- 50 ft

MIL-STD-1797B longitudinal task: Pipper within 5 mils for 50% of the task
Pipper within 25 mils for the 95% of the task

MIL-STD-1797B lateral task: Pipper within 5 mils for 50% of the task
Pipper within 25 mils for the 95% of the task

INPUTS/OUTPUTS/DATA REQUIREMENTS

Table C- 20. Pitch and roll control inputs/outputs data requirements

PARAMETER	**MIN SAMPLE RATE**	**MIN RESOLUTION**
CHR, PIO and Pilot’s comments on compensation	N.A.	N.A.
Relevant engine parameters	10 Hz	0.1% of Limit Value
Indicated Airspeed	10 Hz	1 kt
Pitch Angle	20 Hz	0.2 deg
Bank Angle	20 Hz	0.2 deg
Heading	20 Hz	0.2 deg
Synthetic Target Position	20 Hz	0.2 deg
Inceptors/Effectors position	20 Hz	0.1% of full range

DATA ANALYSIS

The primary source of information for HQ tests is pilots' comments. Handling Qualities Ratings (HQRs) are collected from different pilots; those ratings are not be averaged or altered based on quantitative data analysis. Qualitative comments will be used to clearly identify the deficiencies which degraded performance and/or increased the required compensation to execute a task. The HQR should be assigned to the task in its entirety rather than trying to correlate performance and compensation for different task elements performed at the same time. Comments are used to identify which specific area was problematic. Recorded time histories can be used to corroborate and validate pilots' ratings and comments. A quantitative measurement of the actual performance ensures that pilots' feedback is not biased and all participant pilots were actually attempting the same level of performance. The time histories can also confirm that the pilot was actually performing the task as intended and briefed. Additionally, the pilot's activity on the controls provides valuable information too, as large and frequent corrections are indicative of high workload. In case problems are detected in the execution of the maneuver, the HQR are not to be adjusted, but the task will likely need to be repeated.

Videos of the pilot's displays should be recorded to assess effectiveness and timeliness of envelope protection annunciations, along with adequacy of suggested corrective actions. Time histories of the relevant parameters are required to ensure the envelope protection actually prevents exceedance of critical parameters. Time histories are also vital to troubleshoot unexpected responses, particularly when control allocation is critical in the presence of saturation.

Recordings of displayed information is also important to verify effectiveness of guidance, annunciation and state of the aircraft. Particularly critical are data filtering, lags and display decluttering, particularly when critical safety information are presented.

GUIDANCE FOR UNEXPECTED RESPONSES

General

In case of unexpected response/HQ cliff, proceed as follows:

- Repeat the HQTE relaxing the task requirements in order to determine the condition and aggressiveness level at which the unexpected response occurs.
- Re-evaluate the performance criteria to ensure they are realistic, operationally representative and within the performance capabilities of the vehicle.
- Analyze time histories of inceptors and effectors to detect potential FCS instabilities or undesirable responses

Specific for the HQTE

- Verify control prioritization logic following saturation of one or more effectors.

- Verify absence of actuator rate limits.
- Verify adequacy of actuator bandwidth.
- Assess potential sources for time delays and phase lags.
- Reduce aggressiveness during HQDT to identify potential HQ cliffs.