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Develop a Method of Compliance to Support Certification of Advanced Flight Controls in General Aviation and Hybrid Vehicles

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16. Abstract

With the current development of Urban Air Mobility (UAM) and hybrid vehicles, fly-by-wire (FBW) flight controls are expected to be the standard for this new class of aircraft and, eventually, for an increasing number of aircraft certifiable under 14 CFR Part 23 regulations. The certification process must directly address the characteristics of FBW systems, and specifically their implementation in aircraft of new design and configuration. This report provides the FAA with a proposed method for certification of advanced flight controls in general aviation, urban air mobility, and hybrid vehicles. The first part of the report provides information on FBW systems and their effect on aircraft response and handling qualities. This report looks at existing handling qualities prediction criteria, providing examples for the description of the proposed certification approach. The central idea is that the FAA should monitor the development of aircraft being certified, to acquire knowledge, require minimum flying/handling qualities standards to progress, and provide guidance towards a successful certification, in a shorter time and at a lower cost than usual. Recommendations are provided on the intermediate requirements for the FAA to authorize the progress of vehicle development. This is expected to reduce the cost of the aircraft by identifying design deficiencies earlier in developmental phases. The last part of the report contains proposed means of compliance, connected to the steps of the presented sample aircraft development and testing, Flying Qualities Task Elements (FQTEs) and Handling Qualities Task Elements (HQTEs). HQTEs are applicable both in the clearance phase and in the in-flight evaluation of the vehicle handling qualities. While additional information, and potentially the evaluation of FQTEs and HQTEs by means of manned simulations and possibly in flight would be ideal, the proposed certification approach is a preliminary guide for the definition of a standardized certification process applicable to the new class of FBW UAMVs and hybrid vehicles

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Note

With the current development of Urban Air Mobility (UAM) and hybrid vehicles, fly-by-wire (FBW) flight controls are expected to be the standard for this new class of aircraft and eventually for an increasing number of aircraft certifiable under 14 CFR Part 23 regulations. The certification process must directly address the characteristics of FBW systems, and specifically their implementation in aircraft of new design and configuration. In response to this task presented by the Federal Aviation Administration (FAA), the National Test Pilot School worked on an FAA FBW research project to address this requirement. This report provides the FAA with a proposed method for certification of advanced flight controls in general aviation, urban air mobility and hybrid vehicles. The evolution of the Part 23 aircraft development, testing, evaluation, and certification processes is expected to be significant, changed by the implementation of fly by wire systems, with the three phases bound with a high degree of interconnection. This work is developed with the primary concept that there are functional and procedural feedback loops between the phases reported above, and that certification must account for the process applied in the development of the vehicle, including its clearance for flight. This is expected to provide the FAA with the required visibility of the intermediate phases that led to define the aircraft configuration under certification. The first part of the work provides background information on FBW systems and on their effect on aircraft response and handling qualities, considering different types of augmentation. The following analysis of the current FAA special conditions for certification of FBW aircraft and airworthiness regulations/standards is aimed at identifying current suitable approaches to ensure airworthiness of augmented aircraft, and of their potential limitations for new classes of aircraft. A part of the work is dedicated to the existing handling qualities prediction criteria, to provide references and examples for the subsequent description of the proposed certification approach. The first part of the description is dedicated to a sample FBW aircraft design process, interconnected with the proposed certification approach. The central idea is that the FAA should monitor the development of the aircraft to be certified, to acquire knowledge on it, require minimum flying/handling qualities standards to progress and provide guidance towards a successful certification, in a shorter time and at a lower cost than usual. The flight clearance process, successfully applied in Part 25 and military FBW aircraft development, is essential for the FAA to monitor that the aircraft is safe to begin the flight test campaign. Recommendations are provided on the intermediate requirements to apply, for the FAA to authorize the progress of the vehicle development. This is expected to reduce the cost of the aircraft, by identifying deficiencies of the design in its earlier developmental phases. The last part of the report contains proposed means of compliance connected to the steps of the presented sample aircraft development and testing, Flying Qualities Task Elements (FQTEs) and Handling Qualities Task Elements (HQTEs). HQTEs are applicable both in the clearance phase and in the in-flight evaluation of the vehicle handling qualities. While additional information and potentially the evaluation of FQTEs and HQTEs by means of manned simulations and possibly in flight would be ideal, the proposed certification approach is a preliminary guide for the definition of a standardized certification process applicable to the new class of FBW UAMVs and hybrid vehicles.

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Acronyms

Acronym	**Definition**
AD	Airworthiness Directive
ADC	Air Data Computer
ADS	Air Data System
AEO	All Engines Operative
AoA	Angle of Attack
AoS	Angle of Sideslip
ASTM	American Society for Testing and Materials
AWFL	Airworthiness Flight Limitations
CAP	Control Anticipation Parameter
CCC	Continuous Compensatory Control
CFR	Code of Federal Regulations
CG	Center of Gravity
CH	Cooper-Harper
CHR	Cooper-Harper Ratings
ConOps	Concept of Operations
DoF	Degrees of Freedom
E	Aerodynamic Efficiency
E-VTOL	Electric Vertical Take Off and Landing
EFCS	Electronic Flight Control System
FAA	Federal Aviation Administration
FBW	Fly-by-wire
FCC	Flight Control Computer
FCS	Flight Control System
FOV	Field of View
FPA	Flight Path Angle
FQTE	Flying Qualities Task Element
FTI	Flight Test Instrumentation
FTOE	Flight Test Only Envelope
GA	General Aviation
GAMA	General Aviation Manufacturers Association
GCAP	Generalized Control Anticipation Parameter

Acronym	**Definition**
GM	Gain Margin
GML	Lower Gain Margin
GMU	Upper Gain Margin
HDD	Head Down Display
HOS	High Order System
HQ	Handling Qualities
HQR	Handling Qualities Rating
HQRM	Handling Qualities Rating Method
HQTE	Handling Qualities Task Element
HUD	Head Up Display
KTAS	Knots True Airspeed
LFE	Limit Flight Envelope
LOC	Loss of Control
LOES	Low Order Equivalent System
MOC	Methods of Compliance
MTE	Mission Task Element
mph	Mile per Hour
MTOW	Maximum Take Off Weight
NASA	National Aeronautics and Space Administration
NTPS	National Test Pilot School
OEI	One Engine Inoperative
OFE	Operational Flight Envelope
OTW	Out-The-Window
PC	Pilot Compensation
PIO	Pilot Induced Oscillations
PM	Phase Margin
PTI	Programmed Test Inputs
PVS	Pilot Vehicle System
RHP	Right Half Plane
SA	Situational Awareness
SC	Special Conditions
S&C	Stability and Control
SM	Static Margin
SVO	Simplified Vehicle Operation

Acronym	**Definition**
UAMV	Urban Air Mobility Vehicles
USAF	United States Air Force
VTOL	Vertical Take Off and Landing
α	Angle of Attack
β	Angle of Sideslip
δ_e	Elevator Deflection
θ	Pitch Attitude
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

With the current development of Urban Air Mobility (UAM) and hybrid vehicles, fly-by-wire (FBW) flight controls are expected to be the standard for this new class of aircraft and eventually for an increasing number of aircraft certifiable under 14 CFR Part 23 regulations. The certification process must directly address the characteristics of FBW systems, and specifically their implementation in aircraft of new design and configuration. In response to this task presented by the Federal Aviation Administration (FAA), the National Test Pilot School worked on a FAA FBW research project to address this requirement. This report provides the FAA with a proposed method for certification of advanced flight controls in general aviation, urban air mobility and hybrid vehicles.

A description of the proposed certification method is contained in section 8, which is subdivided into the different functional phases of application of the proposed means of compliance. These functional phases include the following: aircraft specifications, control laws development and clearance criteria, development of vehicle models, offline design execution, flight clearance execution, and flight test verification and validation. The certification would be that of the aircraft and of the process that led to the definition of the aircraft configuration to be certified. This is expected to provide the FAA with adequate knowledge of the aircraft system at each developmental phase, and to authorize progress to the next phase.

The emphasis of the report is on flying and handling qualities; mentions about aircraft systems have been included for clarification. The fundamental idea is that certification of FBW aircraft/systems requires knowledge of the vehicle operational requirements, and of the criteria applied to satisfy those requirements. This derives from the fact that evidence of stability margins, of the expected aircraft response, consistency of the design and vehicle integration has to be based on quantitative evidence provided by the applicant. The proposed high-level method is based on the definition of different flight envelopes, and the corresponding predicted and assessed handling qualities levels that the aircraft has to satisfy through verification and validation. Different levels are recommended, based on the atmospheric conditions. Table 7 and Table 8, respectively, contain examples of Flying Qualities Task Elements (FQTE) and Handling Qualities Task Elements (HQTE) for verification and validation of the aircraft handling performance. A recommended method for the design of HQTEs is reported, handling qualities, Pilot Induced Oscillations (PIO) and total workload rating scales are recommended.

The first part of this document contains background information on the implementation of FBW systems and on the different types of aircraft response augmentation. Existing FAA special conditions and airworthiness regulations/standards for certification of FBW aircraft are analyzed

to identify current suitable approaches to ensure airworthiness of augmented aircraft, and of their potential limitations for new classes of aircraft like Urban Air Mobility Vehicles (UAMV). An overview of the main flying qualities criteria is part of the background information. This supports the description of a sample control laws development, which is the reference for the correlation of the proposed means of compliance with the aircraft development process under the handling qualities standpoint. An integral part of this process is the preparation and availability of the vehicle dynamics model, for application of a model-based design approach. This Research was based on the merge of the extensive available technical information on FBW system development and testing, and the experience of the author in the field. The proposed certification approach is a preliminary guide for the definition of a standardized certification process applicable to the new class of FBW UAMVs and hybrid vehicles. A suggestion for the development of this research is to expand the description of the proposed FQTEs and HQTEs, and ideally to evaluate them by means of manned simulations and possibly in flight execution.

The performed work completes the scope detailed in the statement of work issued as part of the Broad Agency Announcement (BAA) to Develop a Method of Compliance to Support Certification of Advanced Flight Controls in General Aviation and Hybrid Aircraft Vehicles. (DTFACT-16-R-00054) [1].

1 Introduction

The scope of this work is to provide the Federal Aviation Administration (FAA) with background information and concepts as guidance and support to develop methods of compliance (MOC) and best practices for the certification of aircraft according to 14 Code of Federal Regulations (CFR) Part 23 regulations. Based on current general aviation (GA) vehicles development, particular consideration is given to aircraft with augmented flight path control systems, equipped with envelope protection and dedicated energy management systems.

The evolution of Part 23 aircraft development, testing, evaluation, and certification processes is expected to be significant, with the three phases bound with a high degree of interconnection.

The current work is developed with the primary concept that there are functional and procedural feedback loops between the phases reported above. Extensive technical information is available, in published, public domain documentation and guidance material.

The central idea at the basis of this research is to refer to the available technical knowledge on Advanced Flight Control Systems (AFCS) aircraft, merged with standard practices in industrial development and testing of fly-by-wire (FBW) aircraft.

2 Vehicle mission and characteristics

Implementation of FBW flight control systems on general aviation aircraft is assumed to take place in two principal ways: as the main control system on Urban Air Mobility Vehicles (UAMV) of new design and as a retrofit on existing fixed wing Part 23 airplanes.

Both types of implementation are expected to correspond to non-conventional augmentation and aim at direct flight path control of the aircraft. The impact on the vehicle handling qualities with respect to conventional aircraft state control systems is expected to be significant.

Some of the target key features of a personal aerial vehicle according to the Comparative Aircraft Flight Efficiency (CAFE) foundation [2] are as follows:

- 150-200 mph car that flies above gridlock without traffic delays
- Quiet, safe, comfortable and reliable
- Simplified operation akin to driving a car
- As affordable as travel by car or airliner
- Near all-weather, on-demand travel enabled by synthetic vision
- Highly energy-efficient and non-polluting

- Up to 800 mile range
- Short runway use--Walk to grandma's from small residential airfields

Considering the development of current UAMV designs and the commercial requirements for this type of aircraft, below is a list of potential missions that can be assigned to UAMVs:

- Commercial – Commuters
- Recreational
- Agriculture
- Emergency First Responders
- Military
- Fire Fighting
- Police

Higher priority is given in this document to the commercial and recreational flight missions. Based on information available in [3], the commercial transport mission is expected to require short duration takeoff and landing phases, of the order of one minute each, with a cruise phase of the order of fifteen to twenty minutes and an average fifty statute mile range. This includes a thirty-minute Instrument Flight Rules (IFR) reserve and flight to an alternate location. The required cruise airspeed is between 175 KTAS and 250 KTAS, with lift over drag, or aerodynamic efficiency (E), between 12 and 17. Payload is expected between two and four passengers including the pilot. Figure 1, below, represents the mission profile described above.

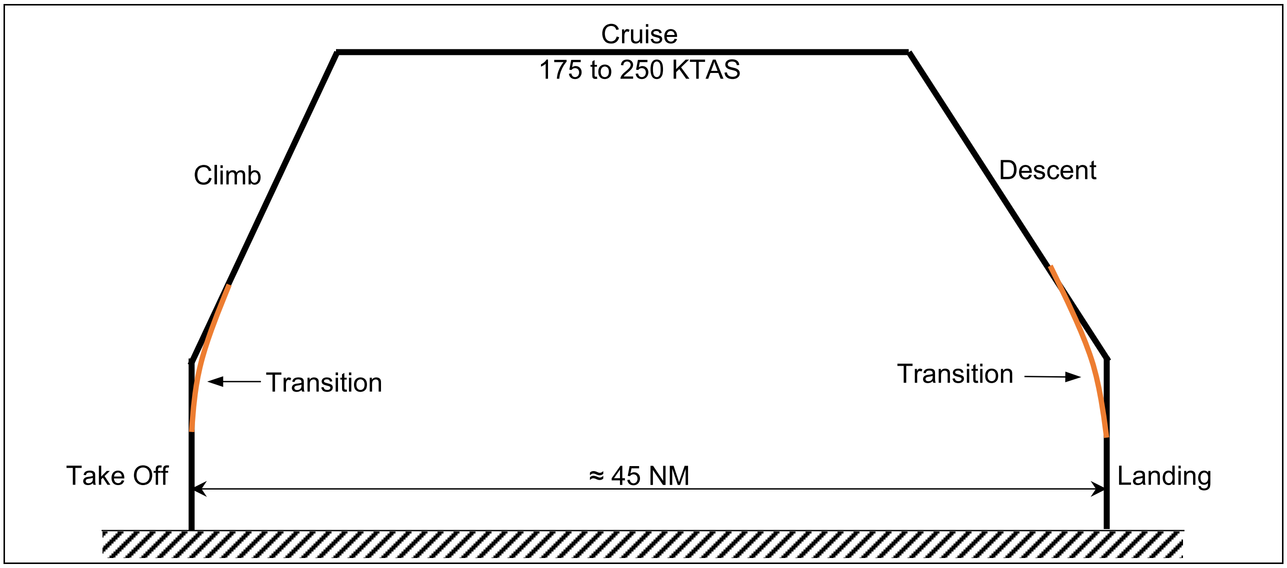

Figure 1. Typical UAMV commercial mission profile

Reference assumptions for this document regarding the vehicle general characteristics are:

- The vehicle can be flown in manned and unmanned control mode and/or remotely piloted.
- Autonomous operation is possible, with full manual control mode when failure of the autonomous system occurs.
- Terminal flight phases and traffic/terrain avoidance maneuvers are flown in manned control mode.
- The aircraft flight control system is fully fly-by-wire, mechanical backup is not available on UAMVs; it can be available on retrofit of conventional GA aircraft.
- Redundancy is present for control effectors, i.e. control surface actuators and/or propellers.
- Redundancy is present for the sensors of the primary augmentation feedback loops.

The typical UAMV configurations that satisfy the mission requirements and the assumptions on the vehicle characteristics reported above are Vertical Take Off and Landing (VTOL) aircraft, in octocopter or hybrid fixed wing/rotary wing configuration, with potential tilt rotor capabilities. Figure 2 below displays examples of vehicle configurations for the class of UAMV aircraft under consideration. Based on information published by the manufacturers, the Maximum Take Off Weight (MTOW) of current UAMVs ranges from 600 lb to 6,000 lb, cruise airspeed ranges from 60 mph to 200 mph, propulsion is fully electric, or a gasoline piston engine drives generators to provide power to propeller motors, airframe structure is mainly composite. The wide range of aircraft characteristics leads to differentiated solutions for the control system architecture and control laws design approach, with the requirement of a high level of generalization of the certification criteria and processes.

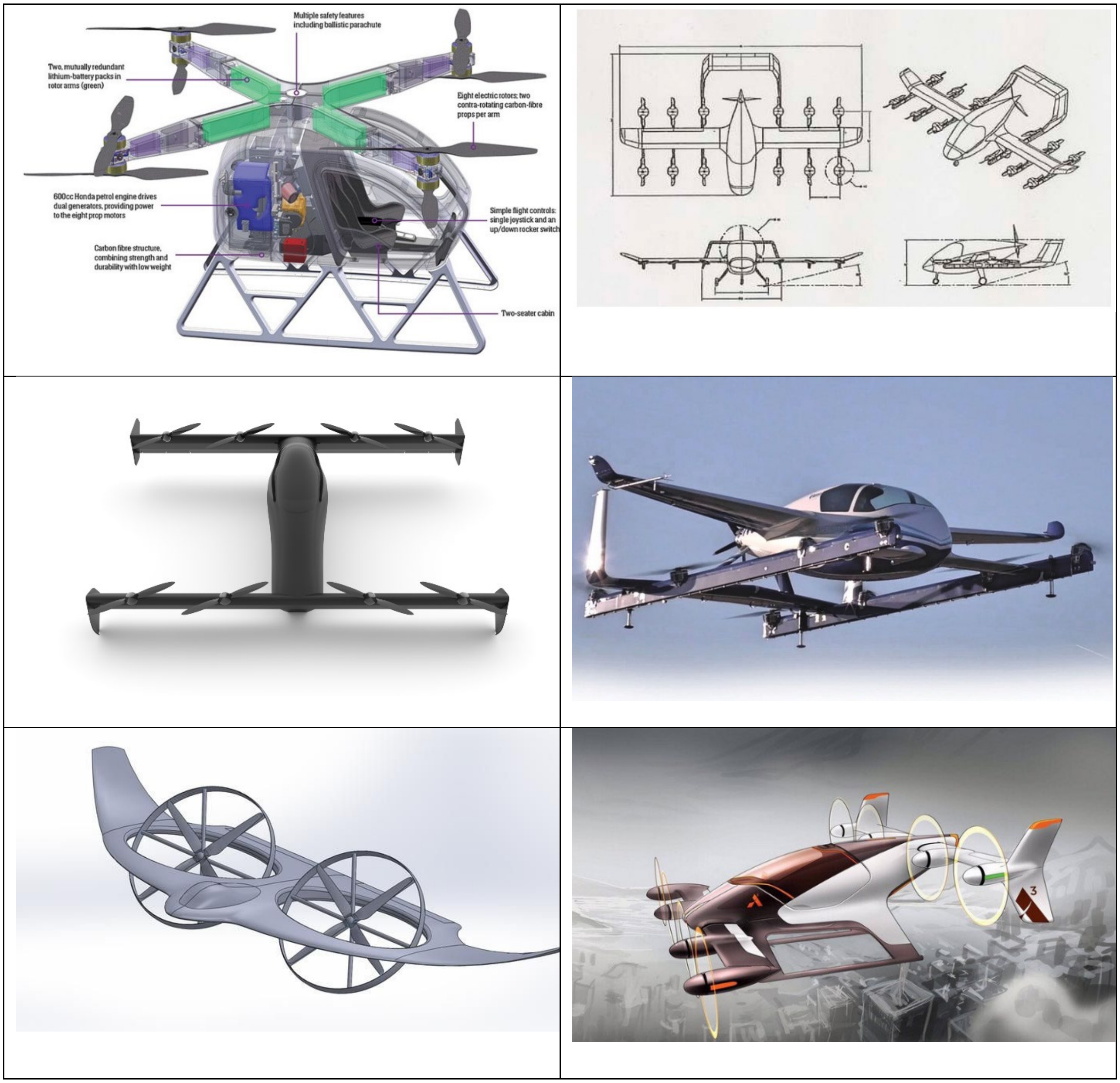

Figure 2. Personal aerial vehicle sample configurations

3 Notes on FBW aircraft

3.1 Background

Under an aircraft flight control and handling qualities point of view, the main differences between a vehicle with a reversible and one with a FBW control system is the lack of a physical link between the inceptor(s) and the effectors/control surfaces, and the implementation of laws to control the aircraft, with reduced pilot authority and situational awareness (SA).

In a reversible control system, the pilot is physically connected with the control surfaces via the cables/push-pull rods, pulleys and bell cranks. This physical connection provides him with direct tactile and visual indication of the deflection of the control surfaces with respect to the center and the stops, of the variation of the dynamic pressure through the control force variation and of the level of vibratory/unsteady phenomena as aerodynamic buffeting, indicating incipient instability of the aerodynamic flow. Together with the visual, proprioceptive and kinesthetic cues, this is a fundamental part of the information used by the pilot to control the aircraft.

In a FBW aircraft, the lack of physical connection between pilot and control surfaces and the consequent loss of natural tactile cues requires the implementation of an artificial feel system. The design of the inceptor and of the feel system is critical to ensure adequate tactile cues, SA and consequently handling qualities. Under the stability and control standpoint, the response of a FBW aircraft can be significantly different from the classical aircraft dynamic modes, with added dynamics and time delay affecting the handling qualities due to the different compensation technique required to the pilot. This is the objective of vast research in the aeronautical community, dealing with the impact of augmentation on handling qualities and on the overall Pilot Vehicle System (PVS); notes about the PVS are contained in section 3.4. This section reports the aspects of the implementation of FBW control systems in aircraft.

In the military and Part 25 transport aircraft industry the gradual transition with time from reversible to boosted, to low authority augmented flight controls, and eventually to high authority FBW control systems, allowed the manufacturers to acquire experience in the development and testing of increasingly complex systems. This evolution was paralleled by research, with development of criteria and best practices to ensure manufacturing, testing and certification procedures for safe and effective FBW aircraft.

The current approach within the general aviation industry is direct transition from reversible aircraft to full authority FBW systems.

This is a critical aspect of the approach to development and certification of GA aircraft, for the significant and fast change of the aircraft characteristics. The next sections contain notes on objectives and different types of FBW control systems.

3.2 Objectives of FBW systems implementation

One of the main objectives of the implementation of FBW systems is to augment stability and to tailor the aircraft response with respect to the mission task requirements, flight condition and operational state. An aircraft construction objective is to reduce the overall control system complexity and the aircraft weight, which can be achieved without implementing specific control laws for stability and/or control augmentation.

According to the current approaches to E-VTOL/UAMV aircraft development, the operational objective for implementation of FBW systems is to achieve Simplified Vehicle Operation (SVO). The underlying concept of SVO is to use automation to support and eventually partially replace the pilot in his different functional skills. The General Aviation Manufacturers Association (GAMA) identified the following nine pilot's skill categories: (1) Planning and decision making, (2) Systems management, (3) Basic airmanship, (4) Takeoff and landings, (5) Terminal procedures, (6) Navigation, (7) Communication, (8) Detect and avoid, and (9) Emergency procedures.

Research published by GAMA in May 2019 [4] states that "over half of the functional skill categories that are part of traditional pilot training curriculum can be more reliably performed by automated systems than by the average pilot." The intended effect of FBW system integration in Part 23 E-VTOL/UAMV aircraft is to reduce the demand on the pilot to fly the vehicle to eventually reduce his/her training time and cost.

3.3 Types of FBW control systems

3.3.1 Un-augmented

The physical connection between pilot's inceptor(s) and control surfaces is replaced with electrical connections to the control surface actuators, or to the effectors. An artificial feel system is implemented to provide the pilot with adequate tactile cues. A limited command augmentation can be implemented as variable command gains scheduled with flight conditions and aircraft configuration. The aircraft free response is unchanged by the system, with minor changes of the command path. This corresponds to the control laws mode of a higher augmentation aircraft in failed operation state, conventionally defined as direct law, and can be a simple approach to retrofit an existing general aviation aircraft with a FBW system.

Figure 3, below, illustrates the conceptual structure of an un-augmented FBW control system.

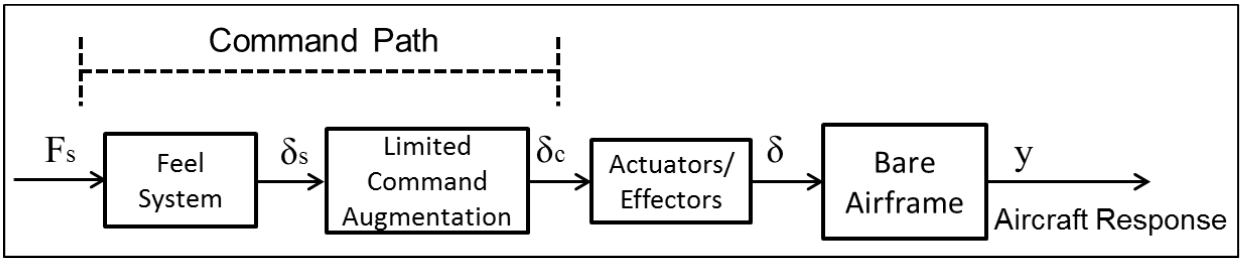

Figure 3. Un-augmented FBW control system

3.3.2 Conventional augmentation

The signal from the pilot's inceptor(s) to the actuators/effectors is electrical as in the previous system, with an artificial feel system. Augmentation feedback is of aircraft states with corresponding aerodynamic derivatives. The feedbacks change the modal parameters (i.e. damping ratio ζ, natural frequency ω_n) of the classical 6 degrees of freedom (DoF) dynamic modes, without changing the order of the aircraft responses. Gain scheduling can be implemented to maintain a constant level of augmentation throughout the flight envelope. Examples of this type of augmentation include the following: yaw damper, pitch damper, roll damper, respectively feedback of perturbations of yaw rate (r) to the rudder command, of pitch rate (q) to the elevator command, of roll rate (p) to the aileron command. There are derivatives of roll, pitch and yaw acceleration, with respect to the corresponding rates perturbations p, q and r, these include: L_p, M_q, N_r. The augmentation feedbacks change the value of these derivatives, not the fundamental modes of the aircraft dynamic response.

Figure 4, below, illustrates conceptually the structure of a Conventional Augmentation FBW Control System.

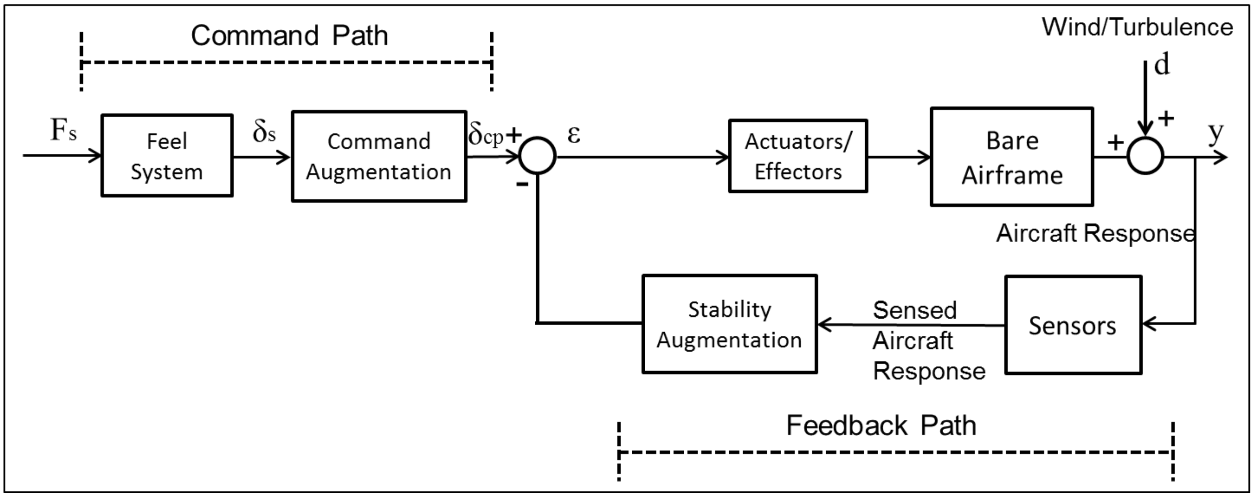

Figure 4. Conventional augmentation FBW control system

As an analytical example, the single degree of freedom linearized pitch aircraft dynamics can be represented in a simplified equation of motion by means of dimensional derivatives:

$$\begin{cases} \dot{q} = M_\alpha \alpha + M_q q + M_{\delta_e} \delta_e \\ \alpha = \theta \end{cases}$$

$$\dot{q} = M_\alpha \theta + M_q q + M_{\delta_e} \delta_e$$

Where:

$M_\alpha = \frac{1}{I_{yy}} \cdot \frac{\partial M}{\partial \alpha} = \frac{\rho S U^2 \bar{c}}{2 I_{yy}} \cdot C_{m_\alpha} \left(\frac{1}{s^2}\right)$ is the change of pitch acceleration per change of angle of attack, which represents longitudinal static stability.

$M_q = \frac{1}{I_{yy}} \cdot \frac{\partial M}{\partial q} = \frac{\rho S U \bar{c}^2}{4 I_{yy}} \cdot C_{m_{\hat{q}}} \left(\frac{1}{s}\right)$ is the change of pitch acceleration per change of pitch rate, which represents pitch damping.

$M_{\delta_e} = \frac{1}{I_{yy}} \cdot \frac{\partial M}{\partial \delta_e} = \frac{\rho S U^2 \bar{c}}{2 I_{yy}} \cdot C_{m_{\delta_e}} \left(\frac{1}{rad \cdot s^2}\right)$ is the change of pitch acceleration per change of elevator deflection, which represents elevator control power.

Where:

ρ	air density
S	reference area
U	trim airspeed
$\bar{c}$	mean aerodynamic chord
I_{yy}	moment of inertia with respect to the y axis
C_{m_α}	derivative of pitching moment coefficient with respect to angle of attack
$C_{m_{\hat{q}}}$	derivative of pitching moment coefficient with respect to non-dimensional pitch rate
$C_{m_{\delta_e}}$	derivative of pitching moment coefficient with respect to elevator deflection

A proportional negative feedback of pitch rate perturbation to elevator command, conceptually representing a pitch damper, modifies the equation in:

$$\dot{q} = M_\alpha \theta + M_q q + M_{\delta_e} \delta_e - M_{\delta_e} \cdot K_q \cdot q$$

Where K_q is the feedback gain.

The modified equation of motion can be written as:

$$\dot{q} = M_\alpha \theta + \left(M_q - K_q \cdot M_{\delta_e}\right) q + M_{\delta_e} \delta_e, \text{ or}$$

$$\dot{q} = M_\alpha \theta + M_q^* q + M_{\delta_e} \delta_e$$

Where $M_q^* = M_q - K_q \cdot M_{\delta_e}$ is the modified pitch damping term augmented by the feedback.

From the expression of M_q^* above, it results that pitch damping varies as a function of the proportional gain K_q and of the elevator control power$\cdot$ M_{δ_e}. This does not alter the fundamental dynamic modes, as the unchanged form of the equation of motion indicates.

The above is an analytical, conceptual example, which does not take into account implementation of possible wash out filters in the feedback path, actuator, or sensor dynamics.

Simplifying the schematics of Figure 4, with one dynamic element for the command path and one for the aircraft, a generalized block diagram is obtained, as displayed in Figure 5.

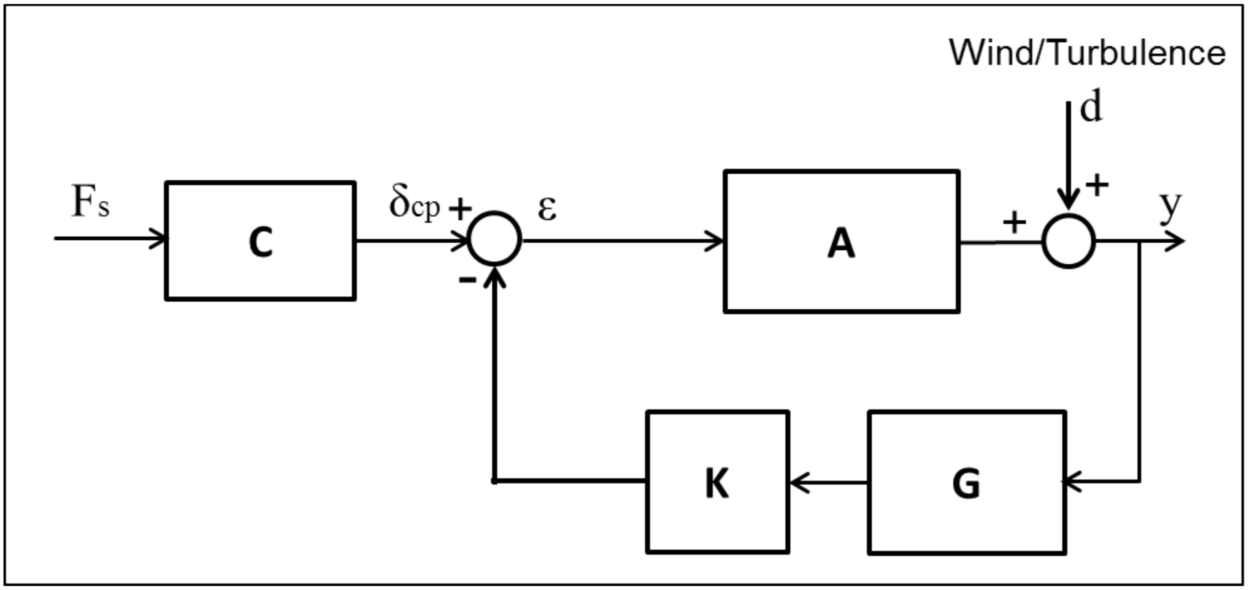

Figure 5. Conventional augmentation generalized block diagram

The transfer function of aircraft response y to pilot's force F_s is:

$$\frac{y}{F_s} = \frac{C \cdot A}{1 + k \cdot A \cdot G} \qquad (d = 0)$$

The feedback gain k affects the denominator of the transfer function alone, demonstrating its effect on the free response alone. $\frac{y}{F_s}$ tends to zero for increasing values of k, making the aircraft more resistant to pilot's inputs as expected for a vehicle with large static and/or dynamic stability. Static stability is augmented by feeding back angles (i.e. α, θ, β), dynamic stability by feeding back angular rates (i.e. p, q, r). Note that the term "augmented" applies to both increase and reduction, depending on the design objective.

The transfer function of aircraft response y to external disturbance d is:

$$\frac{y}{d} = \frac{1}{1+k \cdot A \cdot G} \qquad (F_s = 0)$$

The feedback affects the free response alone. $\frac{y}{d}$ tends to zero for increasing values of k; the aircraft is less sensitive to external disturbances when increasing the feedback gain k.

Implementation of this type of feedback reduces the aircraft controllability and the sensitivity to disturbances, with no significant expected changes required in the pilot's compensation technique.

3.3.3 Non-conventional augmentation

The augmentation algorithm is composed of feedbacks of aircraft states without corresponding aerodynamic derivatives, combined with other design elements, such as command path filters and feed forward paths. The non-conventional algorithms can include the following: Flight Path Angle (FPA) command, pitch attitude limitation, bank angle command and limitation with neutral spiral stability. The order and the dynamic modes of the aircraft response are modified. This type of augmentation is potentially required for Part 23 Electric Vertical Take Off and Landing (E-VTOL) hybrid vehicles.

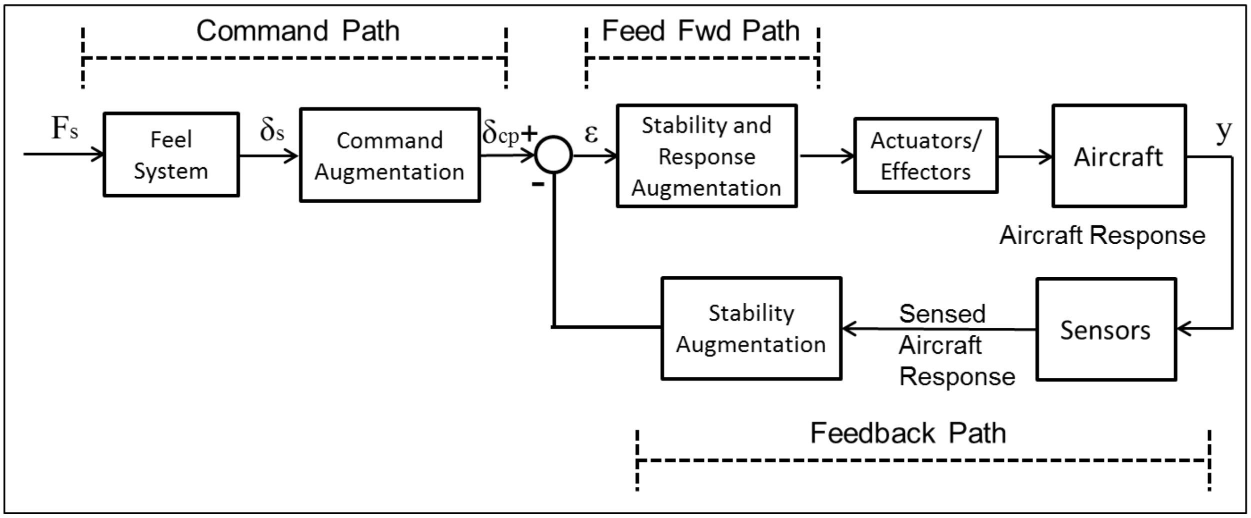

Figure 6. Non-conventional augmentation FBW control system

As for the previous case, simplifying the schematics of Figure 6, leads to the generalized block diagram displayed in Figure 7.

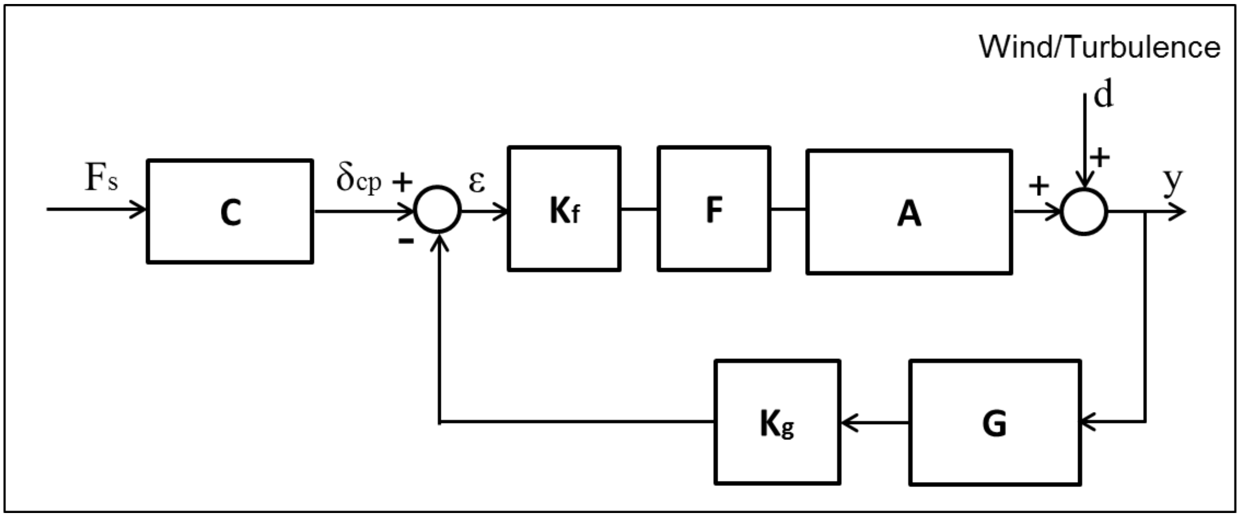

Figure 7. Non-conventional augmentation generalized block diagram

Referring to Figure 7, the transfer function of aircraft response y to pilot's force F_s is:

$$\frac{y}{F_s} = \frac{K_f \cdot F \cdot A \cdot C}{1 + K_f \cdot K_g \cdot F \cdot A \cdot G} \qquad (d = 0)$$

For large values of the feed forward path gain: $\frac{y}{F_s} \approx \frac{C}{K_g \cdot G}$

The transfer function of aircraft response y to external disturbance d is:

$$\frac{y}{d} = \frac{1}{1 + K_f \cdot K_g \cdot F \cdot A \cdot G} \qquad (F_s = 0)$$

For large values of the feed forward path gain, or of the feedback path gain: $\frac{y}{d} \approx 0$.

The results above show that in a highly augmented aircraft the response to the pilot's inputs can become independent from the dynamics of the bare airframe. This is more usual in cases with low, or negative bare airframe stability. This type of control system structure opens the possibility of designing specific dynamics characterized by modes, which are different from the classical bare airframe modes. It increases controllability, stability, and disturbance rejection, and can suppress fundamental classical dynamic modes, like Phugoid in wing-borne flight, or lead to significant reduction of aircraft bandwidth in case of FPA commands. The response is also more exposed to the dynamics of the control system components.

3.3.4 Notes on FBW systems components

This section briefly introduces examples of common dynamic elements and nonlinear components implemented in FBW systems.

The feel system can be passive or active; in general it is expected to be a linear dynamic system of given natural frequency and damping ratio. In a passive feel system/inceptor, the feel is independent from the aircraft states, as the force gradient is constant in the whole envelope. Nonlinearities are implemented in control systems, too. Notional examples are displayed in Figure 8. In an active feel system/inceptor, the feel can vary as a function of the aircraft states, of the control surfaces deflections and of the aircraft configuration. Local discontinuities in the force gradient can be introduced to (a) provide tactile feedback that an envelope limit or a control deflection threshold has been reached. The inceptor of a FBW system does not naturally return to center driven by its physical connection with the control surface. This requires the implementation of artificial break out forces to (b) provide centering cues, and of “dead-zones” to (c) cancel any electrical command due to the inceptor offset from center. This is particularly relevant to avoid integrating a non-zero command over time.

A piecewise or continuously varying command gain (d, e) can be implemented as a function of the inceptor displacement or force. Its scope is to reduce the command sensitivity close to the inceptor center position to improve fine tracking handling performance. The pilot’s command can also be limited by saturations (f). In the forward path, the actuator/effector command can be software rate limited. These nonlinearities are combined with linear elements as a lead-lag, or a lag filter, and with any signal equalization required by the design.

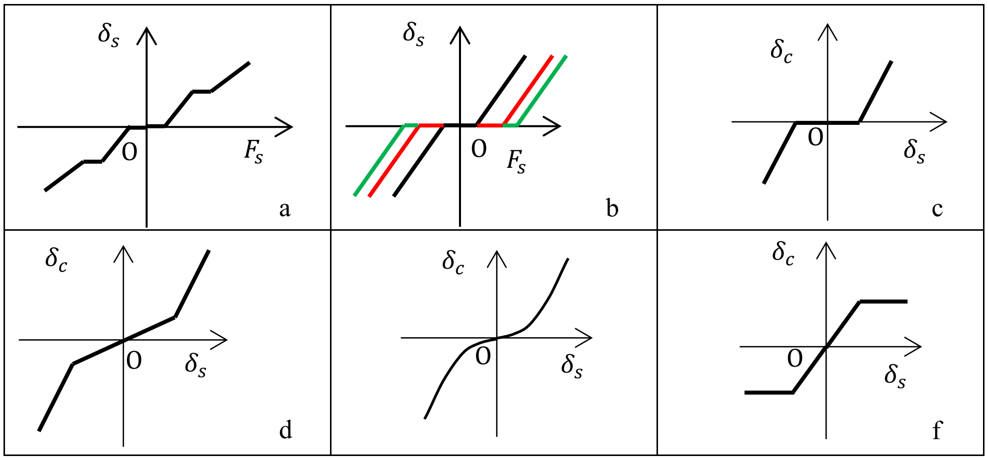

Figure 8. Non-linear control system elements

Rate limiting is a nonlinearity as it is a source of time/phase delay, as displayed in Figure 9. Figure 10 provides a notional example of the location of rate limiting in a control system. The rate limiting block in the command path and the first in the forward path are software defined, typical of digital control systems, the actuator/effector rate limiting depends on its physical dynamic response. The operational state of the vehicle can determine the actuators/effectors physical rate limiting and it has to be taken into account in the assessment of the vehicle handling qualities.

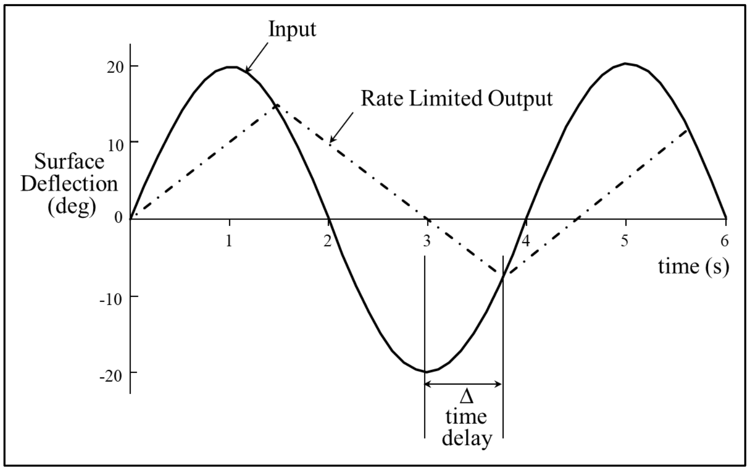

Figure 9. Rate limiting time delay

As can be seen in the block diagram of Figure 10, rate limiting in the command path introduces a time delay in the aircraft response to pilot's inputs, which in the feed forward path affects both the response to pilot's inputs and the stability augmentation.

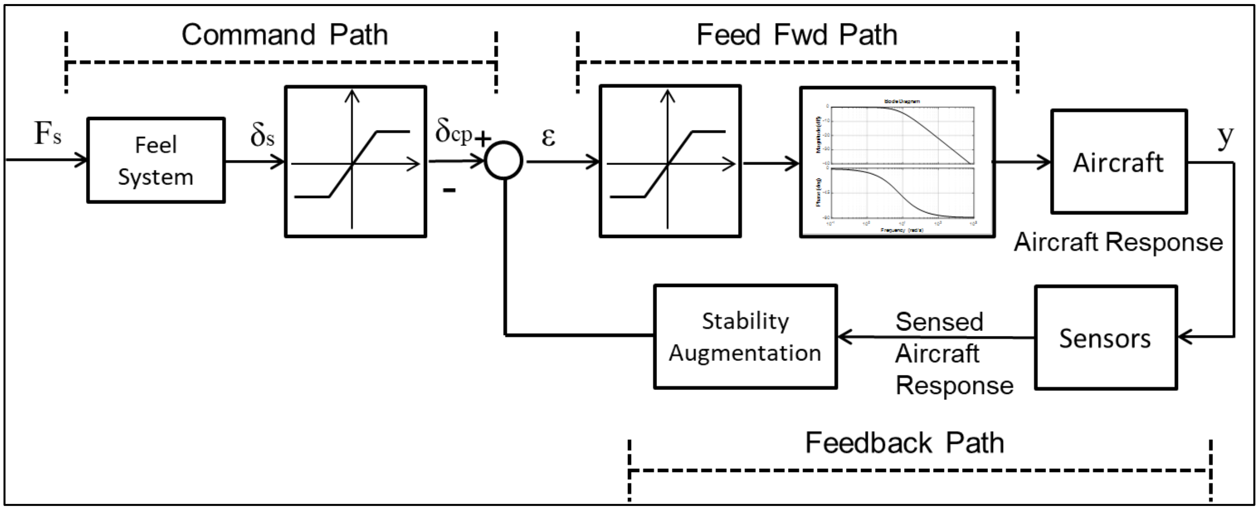

Figure 10. Notional rate limiting in control systems

The relevance for certification of these notes is to cite the effect of nonlinearities on the dynamic system response first and, consequently, on the vehicle handling qualities. At system level, the main effect of nonlinearities is to change the system behavior, reducing its predictability under the linear constant parameter system approach. Reference [5] provides an in-depth description of the effect of nonlinearities on the frequencies, modal parameters, time response and stability of dynamic systems. From an implementation standpoint, dynamic elements commutation is not possible in the presence of nonlinearities. Figure 11 below illustrates two systems that can be obtained by commuting a lag filter and a parabolic gain. Figure 12 displays the time history of each system response to the same step input; the filter introduces a time delay, when implemented before the parabolic command gain, leading to a different response depending on the order in which the two dynamic systems are implemented.

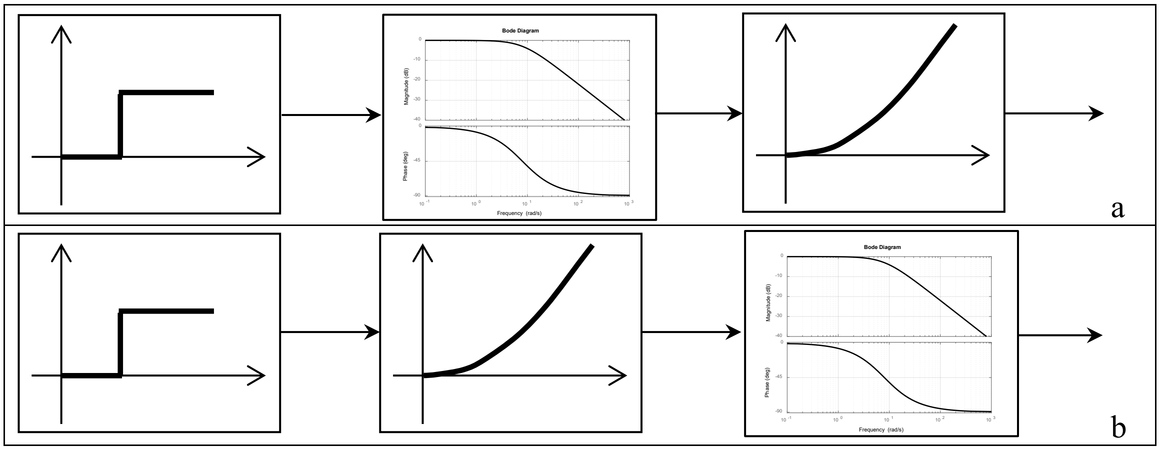

Figure 11. Lag and parabolic gain systems

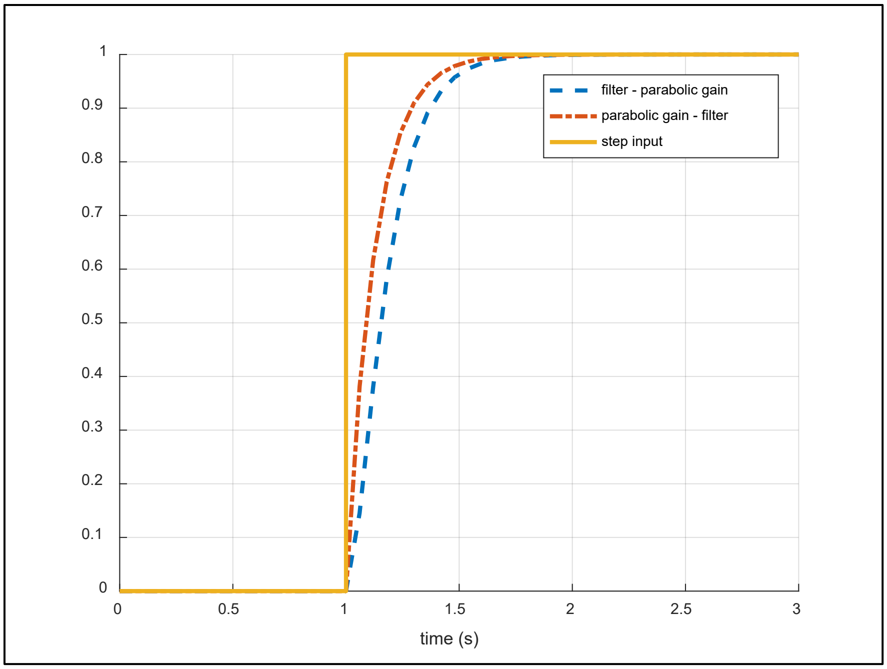

Figure 12. Response of lag and parabolic gain systems to a step input

3.4 Pilot Vehicle System

This section is a brief overview of the Pilot Vehicle System. Figure 13 is a schematic of the PVS, in which the main functional components of the vehicle and of the loop closure(s) are reported. One of the two rectangles identifies the portion of the system that represents the "effective aircraft dynamics" [5], which can be designed and evaluated according to handling qualities prediction criteria. The other rectangle represents the portion that is evaluated by the pilot, the "controlled element" [5]. From observation of the elements enclosed in each of the two rectangles, the full set of real motion and visual cues cannot be explicitly[1] addressed by handling qualities (HQ) prediction criteria. HQ prediction criteria applied in the design phase are based on the effective aircraft dynamics, inner rectangle, to predict the handling performance of the system comprised in the outer rectangle: the controlled element. The necessity of exploring in the simulator and eventually in flight a wide range of different handling qualities tasks, which require different pilot gain, compensation technique, visual cues, with different requirements, arises from the impossibility of accurately predicting the pilot's loop closure, the required compensation and the corresponding handling performance.

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[1] The handling qualities criteria implicitly contains information of these cues, as correlation between the modal parameters and predicted handling qualities was derived from handling qualities databases of HQRs assigned by test pilots to aircraft dynamics with the same modal parameters.

The main reason is the nonlinear, self-adaptive nature of the pilot, who closes the loop around the controlled element.

The importance of considering the PVS can be illustrated by examples. One of the effects on handling qualities evaluations of using fixed base simulators is the lack of acceleration cues. Consequently, the PVS is partially represented and the pilot has to close the loop on the cues provided by the visual system: angular rates and eventually angles.

The time delay between pilot's inputs and accelerations is different from that between the same inputs and rates, or angles, which are the results of integration of the accelerations. This leads to a different sensed delay and potentially different Handling Qualities Ratings (HQRs) between simulator-based and in-flight evaluations.

It is the author's experience that fixed base manned simulations that add indication on the display of the normal acceleration can lead to different HQRs, as compared to simulations where this information was not displayed. This can be correlated with the fact that in in-flight evaluations a larger time delay in a display system is accepted, compared to the time delay in the control system. The time delay in the visual system can be more easily *absorbed* by the pilot, as he derives cues on the motion of the aircraft from its accelerations, for which the physical time delay is inherently lower.

This exemplifies how the cues available to the pilot affect his/her way of controlling the vehicle, related to the PVS concept and it can explain the reason of the less definite HQ trends derived from manned simulations compared to flight tests, for example.

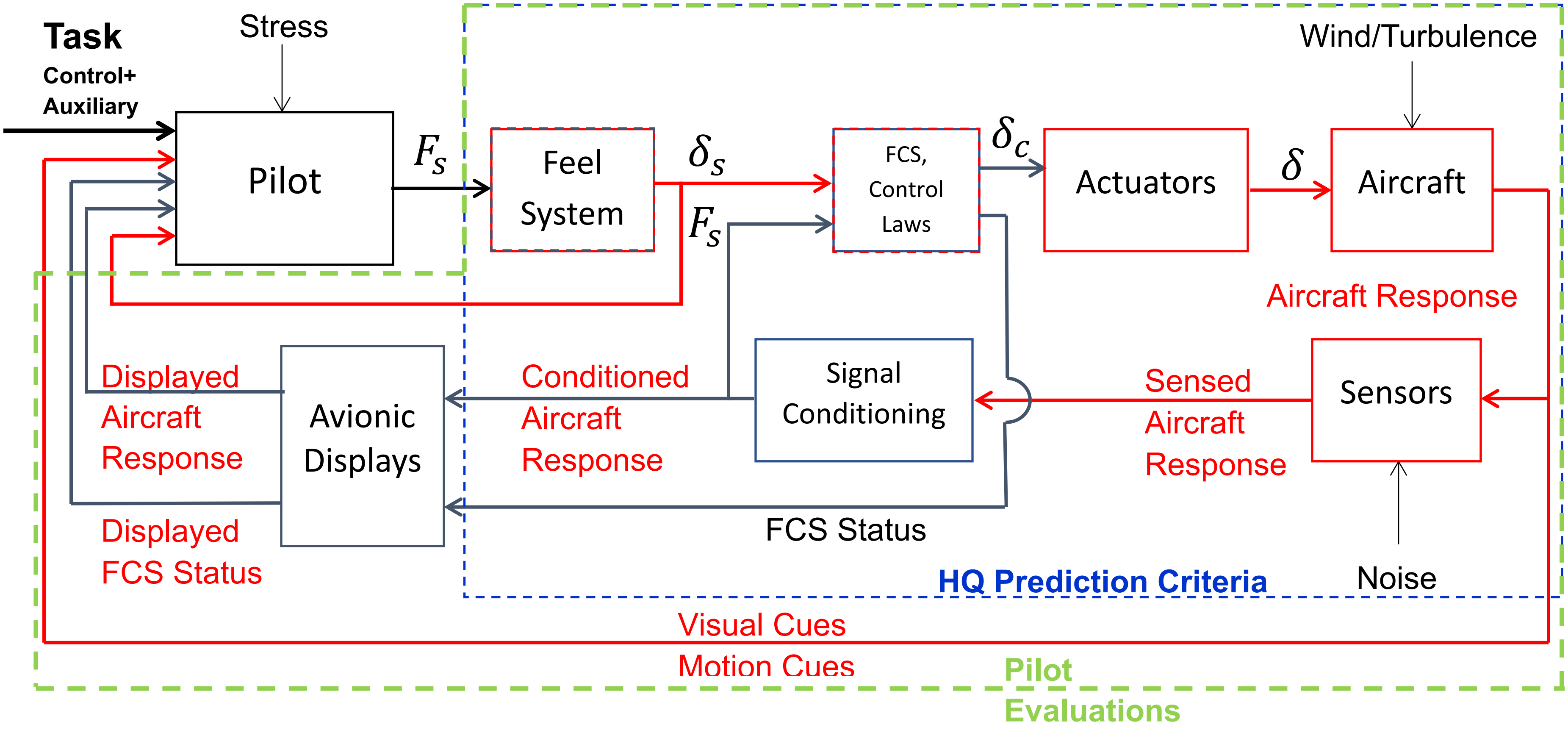


Figure 13. Pilot Vehicle System

Motion cues are composed of the following [42]:

- Vestibular cues, from the inner ear, particularly important when visual cues are reduced.
- Proprioceptive cues, produced by general forces on the body, from sensors in the muscles, joints, and viscera.
- Kinesthetic cues, from small movements of the upper torso and limbs. They make part of the angular and linear accelerations cues.
- Tactile cues, from pressure on the body, normal acceleration.

The consequence of the effect of the acceleration cues on the pilot's loop closure is the higher reliance of the pilot on the display system when flying aircraft with low bandwidth control systems.

A test was conducted during the research documented in [8], in which handling qualities of a conventionally augmented aircraft were compared with those of an aircraft equipped with a flight path angle rate command and hold (FPARCH) control system. The task consisted of series of pitch attitude captures. Degradation in HQRs was observed when the FPA command indication and subsequently the FPA indication were removed from the Head Down Display (HDD). This can be attributed to the low longitudinal bandwidth of the FPARCH aircraft, which required the pilot to rely more on the visual cues provided by the display system.

This aspect can be particularly interesting for the vehicles with augmented flight path control, like SVO UAMVs, as they are expected to be controlled by FPA command systems. Impact on handling qualities of visual system failure(s) is expected to be higher in aircraft with this type of controller.

In Figure 13, the feel system is included in the portion of the effective aircraft dynamics, which can be predicted by HQ criteria. This is true for a few of the criteria, like Neal-Smith and Aircraft Bandwidth, which include the feel system dynamics, not for all. The feel system is an important component of the FBW system, as it provides direct tactile cues to the pilot and it can significantly influence the sensed aircraft dynamics. Pilots' sensitivity to tactile cues can vary widely and can be affected by their background. Variable stability aircraft/in-flight simulators are effective in highlighting the importance of the feel system. It is the author's experience in variable stability aircraft that a significant change in the handling performance can occur by varying the force gradient (lb/in) of a force command system, with varied turbulence levels, or by accomplishing different types of handling qualities tasks, requiring different levels of precision. In a force command system, a higher force gradient increases the sensitivity and can lead to higher bio-mechanical coupling and reduced control precision. This is even more marked when the feel system is initially tuned in a fixed base simulator, which does not reproduce the bio-mechanical coupling due to the aircraft accelerations on the pilot's arm and wrist.

Inceptor configuration is an important factor, too, as center stick, sidestick, wheel/column expose the pilot to different coupling with the aircraft motion, affecting the handling qualities differently.

Command path implementation, as command gain and prefilters can have major effects on handling qualities, related to sensed time delay, bio-mechanical coupling, and unpredictability due to nonlinearities. It was demonstrated that given the same cumulative time delay produced by the feel system dynamics and a prefilter in series, the sensed time delay is higher when the larger amount of time delay (i.e. lower bandwidth) is of the prefilter, compared to the feel system. When the delay is due to the feel system, the pilot's awareness of the time delay is direct while manipulating the controls. When the delay is due to the prefilter, the sensed time delay is larger, as the pilot can assess it from the aircraft response alone, without tactile cues.

"Aggressive" lead compensation can lead to large aircraft accelerations producing bio-mechanical coupling between pilot and aircraft. The author has experienced cases in which the pilot judged the aircraft response as predictable and "crisp" when performing handling qualities tasks in a fixed base simulator. However, when performing the same tasks in flight, the pilot assigned unexpectedly low HQRs and reported difficulties in controlling the aircraft as required. This was due to the angular and linear accelerations developed during the aircraft response, which imposed un-commanded motions on the arm/wrist with which the pilot manipulated the aircraft inceptor.

Pilots who apply a more "closed loop" piloting technique tend to prefer lower breakout force and lower command gain near the stick center position, compared to pilots applying a more "open loop" technique, which requires less continuous manipulation of the controls.

References [6] and [7] describe the impact of feel system break out force, bandwidth, force gradient, and damping ratio on Part 25 aircraft handling qualities, based on fixed base simulator experiments with a sidestick inceptor. As an example, Figure 14, copied from [7], displays the impact of feel system bandwidth variation on HQR and Pilot Induced Oscillations Rating (PIOR) for a Continuous Compensatory Control (CCC) task. The task consisted of maintaining FPA $\gamma = -3\ deg$ flight path angle within desired and adequate FPA task requirements, with the aircraft subject to a sum of sine disturbance. In this case, reduction of the feel system bandwidth produces a degradation of handling qualities and increases the aircraft PIO proneness, as indicated by the PIORs trend. It is an expected result, due to the increase of phase lag in the frequency range in which the pilot controls the aircraft.

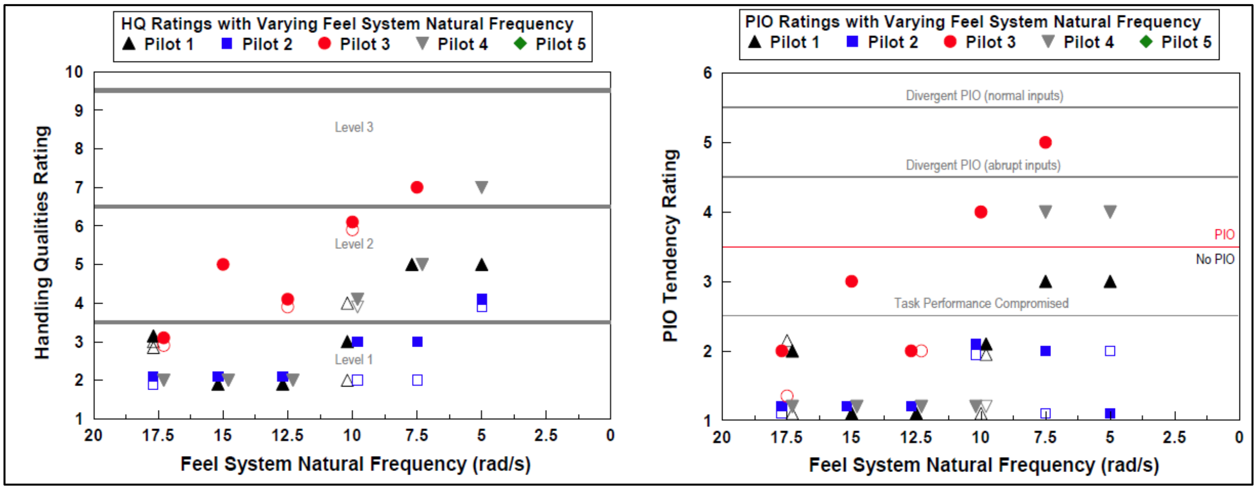


Figure 14. Impact of feel system natural frequency on HQR and PIOR [7]

The dynamic response characteristics of the actuators/effectors implemented in FBW systems can significantly affect the aircraft handling qualities. This adds a further degree of disconnection and potential loss of pilot’s situational awareness (SA), particularly in case of actuators software rate limiting or reduction of the actuators bandwidth due to failure of the actuation system [8]. This can be extended to other types of effectors, such as rotors in E-VTOL aircraft, when loss of power occurs. Figure 16, copied from [7], provides an example of handling qualities ratings from evaluation of a FBW transport aircraft, as a function of actuators bandwidth for the same longitudinal CCC task of Figure 14. A *handling qualities cliff*, which corresponds to a definite degradation of the aircraft handling qualities and increase of assessed PIO proneness, is noticeable for values of the actuator bandwidth $\omega_{BW_{act}} = 10\frac{rad}{s}$. Qualitative trends of HQRs and PIORs as a function of actuator bandwidth are superimposed to the plots, highlighting the change in the slope of the ratings. This frequency is in the range of the frequencies at which the pilot controls the aircraft, so he “feels” that there is another dynamic element in the system, which introduces a time delay and attenuates his inputs and those of the control system. The impact on the capability of the FCS to control the aircraft with degraded actuators is visible from the fact that ratings degraded at higher values of $\omega_{BW_{act}}$ for the aircraft with lower longitudinal stability. The pilot “feels” both the sluggishness of the aircraft in responding to his inputs and the stability degradation due to the reduced capability of the control system to augment it.

The degradation is more evident for the aircraft configuration with Static Margin SM = 0: the HQR and PIOR trend is more marked and affected by a larger scatter, demonstrating a higher sensitivity of the aircraft handling performance to the actuators bandwidth and to the pilot's compensation technique. The combination of time delay sensed by the pilot due to the physical rate limiting and the loss of augmentation is more degrading in configurations with lower inherent bare airframe stability. A similar impact on handling qualities occurs when the actuators are rate limited via software, by design.

The HQR trends displayed in Figure 14 and Figure 16 are part of more generalized trends of HQRs with respect to equivalent time delay. The notional trends of Figure 15 below show both different thresholds in the HQR degradation and different rate of HQR change per amount of equivalent time delay, depending on the type of task, on the source of time delay (i.e. FCS or display) and on performing the task in the air, or in a ground simulator.

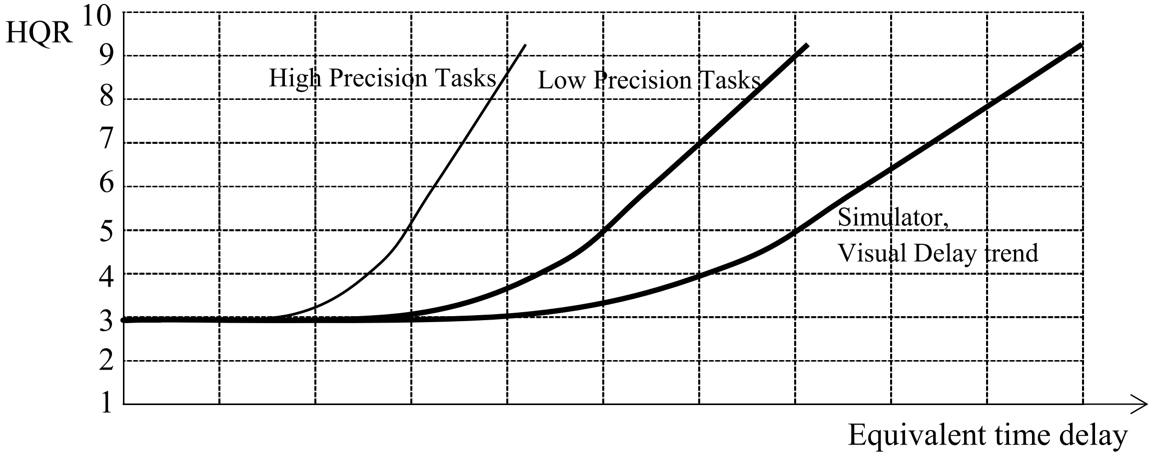
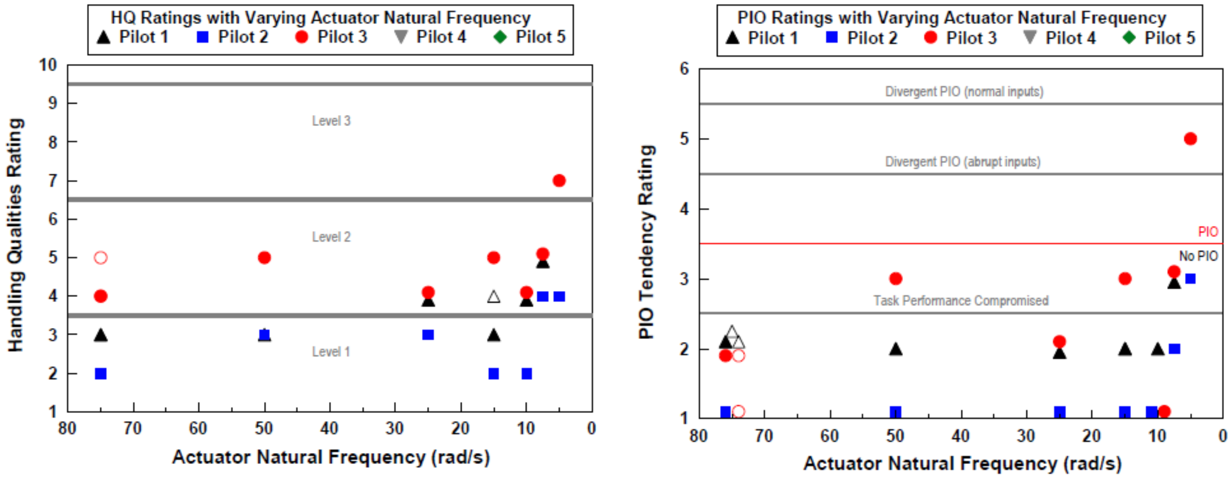


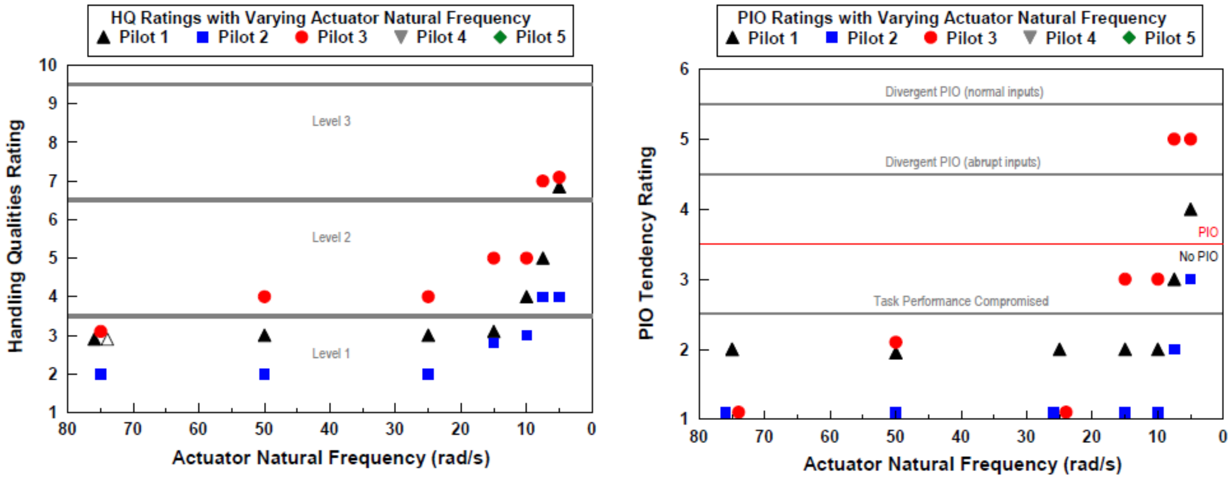
Figure 15. HQR trends vs equivalent time delay

The PVS is continuously studied under many perspectives, demonstrated, and widely treated in the technical literature. These brief notes highlight the importance of structured manned evaluations, both in the simulator and in flight, which include the pilot. He/she is a part of the loop closure system that is not part of the effective aircraft dynamics. The self-adaptive characteristics, the nonlinearity, the variability to responding to inputs and priorities, and the different behavior across different pilots cannot be fully modeled. The test pilot alone can assess performance and compensation, which allows him to assign an HQR for a given task to a given aircraft configuration. This is valid also for highly automated vehicles, for which even a limited interaction of the pilot with the system is required.



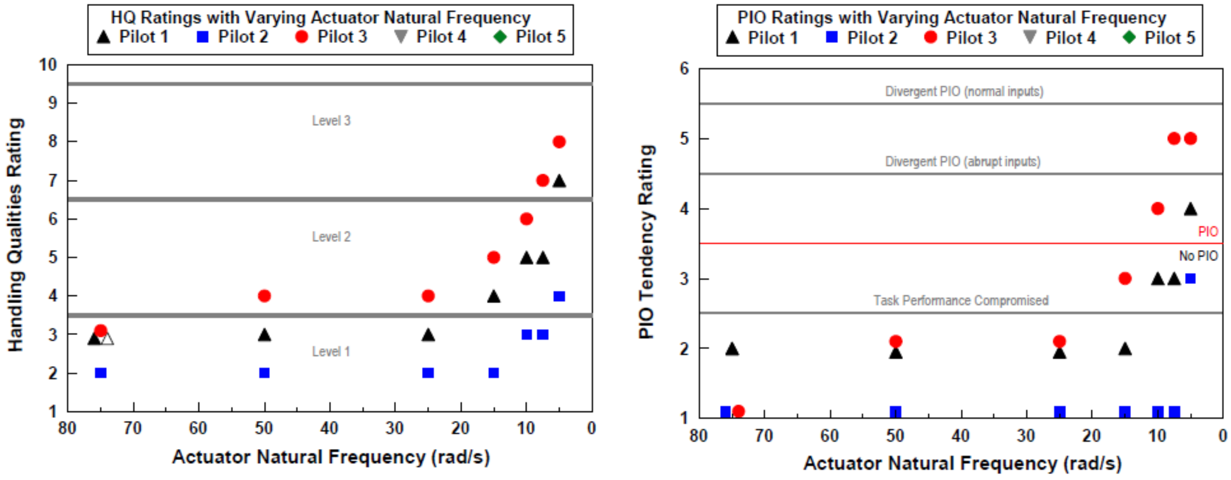
a) Handling Qualities – 5% Static Margin

b) PIO Tendency – 5% Static Margin



c) Handling Qualities – 2.5% Static Margin

d) PIO Tendency – 2.5% Static Margin



e) Handling Qualities – 0% Static Margin

f) PIO Tendency – 0% Static Margin

Figure 16. Impact of actuator natural frequency on HQR and PIOR [7]

3.5 Discussion

An aircraft with a non-conventional augmentation FBW system, and to a limited extent a conventional one, can be identified as a "maneuver demand" vehicle, different from the reversible and the conventional FBW aircraft, which is "control surface demand." A "maneuver demand" vehicle can be defined as one in which the displacement of the inceptor from center corresponds to a predefined variation of a target state (i.e. pitch rate, roll rate, yaw rate, FPA) controlled by the inceptor via the control laws in the given axis. "Response-command" is a definition equivalent to "maneuver demand," applied by the FAA in Special Condition No. 3 of [9]. In a "control surface demand" vehicle (i.e. a reversible and a un-augmented FBW aircraft) a displacement of the inceptor corresponds to a deflection of the control surfaces, with no direct quantitative control of a predefined aircraft state. In this case, the pilot shapes the input to achieve the required aircraft states and consequently FPA control. Requirement for pilot's inputs shaping derives from multiple factors, like aerodynamic or control system nonlinearities, including coupling/interference of two or more dynamic modes (i.e. roll rate oscillations during lateral maneuvers produced by interference of Dutch Roll with roll mode).

The standard FAA aircraft dynamics modal requirements are applicable to the un-augmented and conventionally augmented control system categories, with partial applicability to the non-conventionally augmented. The relevance for this work of the non-conventional augmentation is that Part 23 aircraft pilots might not have been exposed to highly augmented aircraft before and that a significant modification of the aircraft response is potentially critical for safety.

Based on the information of previous sections, the impact of FBW systems is both practical and regulatory. Loss of pilot's SA through tactile cues is a major effect; under the practical standpoint, he/she cannot understand the position and rate of the control surfaces that are commanded by the FCS. With passive feel systems, the force to deflection gradient is constant; the pilot cannot perceive the variation of dynamic pressure and control surfaces deflection through the corresponding variation of inceptor force. Non-conventional augmentation leads to non-conventional dynamic responses, with suppression of natural vehicle dynamic modes and introduction of others requiring different pilot's compensation techniques, or the implementation of envelope protection algorithms, with further complication of the control laws development and testing. Envelope protection can also be required in vehicles with conventional augmentation, as the augmentation itself can prevent the pilot from recovering the aircraft from unusual attitude conditions. This might be particularly critical in aircraft with FPA control, as recovery from out of control situations requires direct control surface control, for SA and vehicle rates/flow angles control. Implementation of nonlinearities makes the aircraft response dependent on the amplitude of the pilot's inputs and on that of the aircraft response, adding another degree of unpredictability and potential disconnection of the pilot with respect to the aircraft, with consequent degradation of handling qualities. An inherent nonlinearity of complex FBW systems is time delay, which has to be addressed under both the design and regulatory standpoint. New displayed variables, like indication of FPA and commanded FPA, can be implemented in FPA command aircraft to support the pilot's loop closure by providing indication of the controlled state. This compensates for the time delay between pitch attitude and flight path angle, T_{θ_2}, and the consequent low bandwidth of FPA command systems. The example above illustrates the critical impact on HQ of losing displayed FPA information in this case. Signal integrity and validity is more critical in FBW systems than in classical reversible aircraft, and the complexity of the systems might require approaches based on system backup, run time assurance, or eventually to full aircraft parachutes, to ensure landing capability in case of failures. A regulatory aspect to consider is the significant difference between FBW un-augmented aircraft and mechanically controlled ones. Applicants should be aware that there are multiple types of FBW system failures, such as electric, sensor, and signal integrity, which do not affect a conventional mechanical system. Even though the response type of an un-augmented FBW aircraft and that of a mechanically controlled one are similar, the two are not equivalent systems from a regulatory point of view. There is not a direct comparison for the Administrator if the applicant removes from the aircraft a mechanical system and retrofits it with a FBW system.

The following sections report the applicability of current standards and special conditions to FBW aircraft.

4 Existing Regulations

4.1 Introduction

This section deals with the applicability of the main existing regulatory requirements to the more representative FBW aircraft configurations, identified in the previous section.

This is an analysis of the Special Conditions (SC) applied for certification of 14 CFR Part 25 aircraft to assess their applicability to Part 23 aircraft, based on their validity for conventional control aircraft and for the three main FBW system type characteristics: un-augmented, conventional augmentation, and non-conventional augmentation.

The rationale in determining a correspondence between FBW system types, relative aircraft response and applicable regulations, is to identify the extent of potential changes to current CFR requirements for their application to the more highly augmented aircraft. Which FBW system design approaches are potentially certifiable with no/minor changes to the regulations are mentioned.

Evaluation of the current compliance with the regulations of the non-conventional augmentation FBW algorithms is especially relevant for Part 23 type aircraft. These system types potentially lead to aircraft dynamic responses significantly different from the standard response that GA pilots are trained for and use. The analysis also supports the understanding of the nominal level of complication of the augmentation algorithms, which is expected to produce minor changes in the pilot situational awareness, and piloting technique, avoiding significant pilot re-training.

These aspects are considered more relevant for highly augmented vehicles, in which the bare airframe stability, control and response characteristics are potentially marginal due to relaxed stability.

4.2 Weight and center of gravity

4.2.1 Notes on standards and regulations

Current 14 CFR Part 23 paragraph 23.2100 “Weight and center of gravity” regulations, [10], and American Society for Testing and Materials (ASTM) standard F3082/F3082M – 17, [11], address the requirements for the definition of weight and center of gravity (CG) envelopes. Section 4.2 of [11] states tolerances to be applied to weight and longitudinal CG travel in flight test.

These tolerances can be referred to in the design, guidance material, and flight clearance phase, as mean of compliance, to prove adequate stability margins of un-augmented and augmented aircraft. The flight clearance process is described in more detail in section 7.5. Tolerances can be added to the nominal mass/CG envelope to determine the worst cases of the mass/CG position combinations. The current regulations are applicable to augmented aircraft, with paragraph 4.2.2 (3) of standard [11], “*The limits at which compliance with each applicable flight requirement is shown,*” providing applicability to each of the requirements that the FAA considers relevant for this class of aircraft. An additional requirement that the FAA should address is the tolerances on moments and products of inertia (i.e. Ixx, Iyy, Izz, Ixz, Ixy, Ixz). This would be a more specific requirement for augmented vehicles. The magnitude of the tolerances on mass properties and specifically on inertias depends on the method applied to calculate the nominal values and on the level of resolution in controlling fuel, payload, and payload distribution. It should be the responsibility of the applicant to report on the method(s) applied to calculate nominal and toleranced moments/products of inertia. A typical 95.5% confidence level should be required in the calculation of tolerances.

4.2.2 Discussion

The limits of the mass/moments of inertia/CG position envelope are critical for both augmented and un-augmented vehicles. Control laws design for target handling qualities level of augmented aircraft is sensitive to the variation of moments of inertia and this should be considered as part of the requirements in [11]. Considering the potential evolution of these tolerance requirements based on the evolution of the vehicles themselves and of the related augmentation strategies, it is technically convenient to update them in [10]. This allows for higher flexibility and adaptation to the stability margins requirements.

Recommendation R1: The FAA should recommend update of ASTM F3082/F3082M – 17, paragraph 4.2.2, to include tolerances on aircraft moments of inertia.

Recommendation R2: The FAA should require the applicant evidence of the methods applied in the calculation of tolerances on aircraft moments of inertia.

4.3 Flight controls

4.3.1 Notes on standards and regulations

The available relevant standard, [12], satisfies the requirements of construction and integration of flight controls in aircraft with reversible control systems and conventional configurations. Implementation of an “Artificial Stall Barrier System” is considered in paragraph 5.3 of [12]. This is assumed to be of the stick pusher type.

A reversible control system is considered here as one in which the aerodynamic forces are transmitted from the control surfaces to the inceptors, through physical linkages. Current UAMVs can be controlled via differential thrust of multiple rotors, combined with conventional control surfaces. Non-conventional control effectors should be included in [12] and criteria equivalent to those contained in paragraphs 4.3, 4.4, 4.6, 4.7 of [12] should be developed to address respectively: control system stops, trim systems, limit load static tests, and operation tests.

The FBW aircraft certification approach based on special conditions is the example of an approach mainly aimed at effectiveness.

SCs were applied to aircraft certified under 14 CFR Part 25 regulations. The flight control system design elements/characteristics addressed by released SCs can form an initial set of references for the development of a comprehensive set of Part 23 aircraft dedicated regulations. References [13], [15], [16], and [17] form a selective, not inclusive list of SCs for this section.

The most relevant design elements and characteristics considered in the indicated SCs are:

1. Operation Without Normal Electrical Power. “A demonstration that the airplane can continue safe flight and landing with inoperative normal and auxiliary power unit generated power (which excludes the battery and any other standby electrical source).”
2. Electronic Flight Control System (EFCS) Failure and Mode Annunciation.
3. Command Signal Integrity.
    a. Stable gain and phase margins are maintained for all aerodynamically closed-loop flight control systems [15].
    b. The control authority characteristics are not degraded to a level that will prevent continued safe flight and landing [15].
    c. Powered Control Integrity. (Continued safe flight and landing after any failure condition to the flight critical powered system which is not shown to be extremely improbable, unless it is associated with a wholly-unrelated failure condition that would itself prevent continued safe flight and landing.) [15].
    d. Maximum Control Surface Displacement [16].
    e. Engine Thrust Levers During Autothrust System Operation [16].
4. Side Stick Controllers.
    a. Pilot Strength. "It must be shown that the temporary and maximum prolonged force levels for the side stick controllers are suitable for all expected operating conditions and configurations, whether normal or non-normal." [16].
    b. Controller Coupling. "The electronic side stick controller coupling design must provide for corrective and/or overriding control inputs by either pilot with no unsafe characteristics. Annunciation of controller status must not be confusing to the flightcrew." [16].
    c. Pilot Control. "It must be shown by flight tests that the use of sidestick controllers does not produce unsuitable pilot-in-the-loop control characteristics when considering precision path control/tasks and turbulence." [16].
    d. Autopilot Quick-Release Control Location. “Quick release (emergency) controls must be on both side stick controllers. The quick release means must be located so that it can readily and easily be used by the flightcrew.” [16].

5. “The change of mode in one of the flight critical control systems must not be greater than 10^{-5}/flt. hr. This applies to the primary flight control systems. A change of mode can be caused by an automatic switching from the normal (i.e., full-up system) to the secondary mode. The effects of latent failures must be considered in demonstrating compliance with this special condition.” [15].

Items 3a, 3b, 3c and 4, as a whole, are conceptually a potential base for new regulations, with significant changes required by the vehicle types. Based on the text of the advisory circular, it is understood that item 5 addresses control laws mode transition(s) from full operational to a degraded mode for minimum safe operational state.

In most of the newly developed Part 23 FBW aircraft, no alternate power source is available. For simplicity of flight crew training, no alternate control laws modes are expected to be available, or selectable, by the pilot. Items 1, 2 and 5 are not expected to be directly applicable.

Items 3d and 3e are considered irrelevant for aircraft with mixed controls, formed by conventional control surfaces and direct lift control through rotors.

4.3.2 Discussion

SCs allow for a certification process dedicated to a specific aircraft type, at the same time the efficiency and the long term guidance and certification value of this approach is reduced by the necessary applicability of each SC to a single aircraft type. As reported in [15]:

- “Special conditions contain the additional safety standards which the Administrator considers necessary to establish a level of safety equivalent to that provided by the airworthiness standards.”
- “The special condition has been written to define the design goal rather than the design detail.”
- “The intent of this special condition is not to define the control laws of the Model, or any other airplane.”

Analysis of the list of design elements addressed by the SCs highlights the focus of the FAA on each of the local non compliances with respect to the 14 CFR Part 25 regulations, singly and not as a combined set of requirements. Harmonization of the requirements can be achieved by referring to the current control laws design criteria used by the industry, combined with the verification that an appropriate FBW aircraft development process is applied, see section 7. For UAMVs in particular, the variety of inceptors, control laws designs, control effectors is expected to be so wide as to require a comprehensive approach, to retain adequate control of the certification process by the Administrator. As an example, item 3a of the list above is inherently connected with 4c and with 1. Under a broader point of view, item 3a is also an essentially critical aspect in all cases of a FBW aircraft operation, and not in case of lack of signal integrity alone. Stable gain and phase margins, when not quantitatively specified, do not necessarily correspond to levels of stability that produce an aircraft response leading to handling qualities *satisfactory without improvement*. It is important to link the stability margins with the predicted handling qualities, by means of recognized standard criteria.

A significant part of the new FBW aircraft designs are expected to be completely different from augmented conventional configuration aircraft. To identify characteristics that allow them "to establish a level of safety equivalent to that provided by the airworthiness standards" is potentially not feasible, when response characteristics alone are addressed. In this case, reliance on special conditions might limit the actual development of novel aircraft designs.

The suggested comprehensive approach would also require merging of flight controls and handling characteristics requirements, as mentioned above for item 3a. . Inceptor dynamics can affect stability margins, with and without occurrence of bio-mechanical coupling. These two aspects are addressed independently in [16] by items 4b and 4c. Merging of requirements would allow addressing the control system, avionics characteristics and the handling qualities as a whole. Closed loop handling qualities, predicted and assessed, would be the principal criterion for certification.

The transition from reversible to irreversible aircraft has proven to be critical due to the reduced direct cueing for the pilot of the region of the envelope in which he is flying. The lack of aerodynamic forces transferred by the control surfaces to the inceptors do not allow pilot's tactile cueing of airspeed and of flow conditions on the control surfaces themselves (i.e. aerodynamic buffet onset). An integrated approach to restore situational awareness through avionics or, potentially, implementation of simple active type inceptors could be considered by the aircraft manufacturers, requiring the FAA to address this approach comprehensively.

Recommendation R3: The FAA should consider implementation of an integrated flight controls/handling characteristics regulations and certification approach.

4.4 Handling characteristics

4.4.1 Notes on standards and regulations

The current regulations [10] and the Standard Specification for Aircraft Handling Characteristics, ASTM standard F3173/F3173M – 17 [14] are considered valid for conventional fixed wing propeller aircraft. Full applicability of these standards is expected for reversible control systems, with partial applicability for irreversible control systems without augmentation or with conventional augmentation. In an irreversible control system, no physical linkages are present between inceptors and control surfaces. Irreversible control systems are potentially installed in conventional aircraft as a retrofit for reversible control system.

The standard is not applicable to vehicles with non-conventional augmentation, such as flight path angle command, direct lift control, or E-VTOL hybrid configurations. This limits the effectiveness of the above standard [14] in the certification of vehicles developed as FBW systems from their inception, UAMVs in particular.

This section lists the handling characteristics elements, which were addressed by Part 25 SCs, and that are considered common to Part 23 aircraft. The selected SCs, not an inclusive group, are: [13] [15], [16], and [17]. Handling characteristics currently addressed include:

1. Flight Characteristic Compliance via Handling Qualities Rating Method (HQRM) for EFCS Failure Cases [15] and [16].
2. Longitudinal Stability [17].
3. Lateral-Directional Stability [17].
4. Design Maneuver Requirements [17].

In this section, it is recommended the assessment of handling characteristics be based exclusively on pilot's evaluation. Separation between predicted handling qualities from control laws design criteria and actual handling qualities assessed by the pilot via manned simulations and in-flight evaluation is essential. Analytical methods are fundamental to guarantee the application of consistent and safe approaches during the design and development phase. Pilot's loop closure strategy cannot be completely predicted via analytical methods, thus requiring manned evaluations.

The concept of the HQRM in item 1 is directly applicable to any vehicle type for which multi-dimensional envelopes, failure levels and required handling qualities levels can be defined. The HQRM approach is a useful conceptual base to develop new regulations in which handling performance is the objective of the certification phase.

The fundamental part for application of an HQRM based method is the specification of test conditions, procedures and HQ tasks, which satisfy the operational requirements of the aircraft. Discretization and relative specification of the flight phases into HQ tasks, sub-tasks or *elements* is considered the necessary device to standardize and guide the identification of potential handling deficiencies.

The AERONAUTICAL DESIGN STANDARD ADS-33E-PRF [18] is another example of an envelope-based approach. The specification and mandatory HQ evaluation through Mission Task Element(s) (MTE) is fundamental for the effectiveness of the evaluation.

This report provides an independent approach of the same certification method.

The term "mission" is applied in [18] to represent the operational requirements with respect to which the evaluation is conducted. This work refers to a definition of "mission" consistent with civilian aircraft operation.

Suitable definitions of the term "mission," "flight phase," and "task" for civilian aircraft are those provided in [24].

Mission: "the composite of pilot-vehicle functions that must be performed to fulfill operational requirements," where operational requirements are "the objectives or delineation of what it is that the pilot-vehicle combination must be able to accomplish" [24].

Flight phases defined in [24] as "a portion of the mission" and applicable to civilian aircraft are:

a. Ground/deck
b. Takeoff
c. Climb
d. Cruise
e. Descent
f. Approach and landing.

Additional flight phases to be added for E-VTOL vehicles are:

a. Hover
b. Translational flight
c. Transition from rotor-borne to wing-borne flight
d. Transition from wing-borne to rotor-borne flight

Task definition: "the actual work assigned a pilot to be performed in completion of, or as representative of, a designated flight segment" [24].

A method combining the detailed definition of the flight envelopes, failures and atmospheric disturbances present in AC 25-7D HQRM and the high discretization of the mission into mission task elements of ADS-33E-PRF is potentially effective for a wide range of aircraft types. Merging the two approaches (AC 25-7D and ADS-33E-PRF) also addresses specific characteristics of both fixed and rotary wing vehicles. Dependency on the classical definitions of longitudinal and lateral/directional stabilities (items 2 and 3) will be reduced as well, when applying a method based on pilot's evaluation.

The longitudinal static stability requirement of [17] is as follows: "These special conditions require that the airplane be shown to have suitable static longitudinal stability in any condition normally encountered in service. In lieu of compliance with Sec. 25.672(c), the HQRM contained in Appendix 7, FAA Handling Qualities Rating Method, (or an equivalent method of compliance found acceptable to the FAA), must be used for evaluation of EFCS configurations resulting from single and multiple failures not shown to be extremely improbable."

The lateral/directional static stability characteristics are addressed in [17] as:

"These special conditions are intended to accomplish the following:

- Provide additional cues of inadvertent sideslips and skids through control force changes.
- Ensure that short periods of unattended operation do not result in any significant changes in yaw or bank angle.
- Provide predictable roll and yaw response.
- Provide acceptable level of pilot attention (i.e., workload) to attain and maintain a coordinated turn."

The essential difference in the approach to certification of static stability characteristics in the three axes between that based on open-loop of the current regulations [10] on one side and the HQRM and SCs on the other side highlights the requirement for developing regulations that address stability and actual aircraft response in the execution of predefined tasks.

Recommendation R4: The FAA should develop means of compliance for in-flight assessment of aircraft static stabilities founded on open loop and handling qualities evaluations based on predefined tasks.

The list below summarizes the components that are considered fundamental for handling qualities evaluation:

a. Assigned levels of handling qualities.
b. Definition of limit and operational envelopes as multi-dimensional domains.
c. Definition of atmospheric disturbance levels.
d. Definition of failure types and related probability of occurrence.
e. Definition of mandatory and aircraft configuration specific (fixed wing, rotary wing, hybrid vehicle, tilt rotor) MTEs.

Recommendation R5: The FAA should require the handling qualities assessment to be specified in correspondence of combinations of: assigned HQ levels, pre-defined multi-dimensional envelopes, levels of atmospheric disturbance/probability, operational state, and mandatory and aircraft type specific MTEs.

This is expected to allow a high degree of flexibility, derived from changing each of the evaluation components, singly or in combination, to satisfy the certification requirements of different aircraft types and configurations. More information on the recommended approach is provided in section 7.2.4.

4.4.2 Discussion

Evolution in the approach of the SCs is clear in item 2 of the list in section 4.4.1: “In lieu of compliance with the regulations pertaining to lateral- directional and longitudinal stability, these special conditions ensure that the Model will have suitable airplane handling qualities throughout the normal flight envelope.”. It is understood that in this case the requirement to demonstrate suitable handling qualities has to be *necessary and sufficient* for the type under certification. In a comprehensive review of the regulations, requirement of specific handling qualities evaluation tasks would be mandatory to ensure that the certification objective is achieved. As reported above in item 1 of section 4.4.1, Handling Qualities Rating Method (HQRM) is considered one of the currently most suitable guidance to “determine appropriate minimum handling qualities requirements” [19]. The value of the HQRM approach is mostly in its recognition that “this service [the FAA] experience has shown that compliance with only the quantitative, open-loop (pilot-out-of-the loop) requirements does not guarantee that the required levels of flying qualities are achieved” [19], and in referring to multi-dimensional flight envelopes when assigning the required handling qualities level. Definition of flight envelopes as multi-dimensional domains is particularly valid when certifying hybrid vehicles, with Vertical Take Off and Landing (VTOL) capabilities. This is due to their different modes of flying and corresponding large variation of the states envelopes (i.e. airspeed limits in forward flight mode with respect to vertical flight mode).

Experience of aircraft HQ evaluation according to ADS-33E-PRF requirements by a large number of instructor and student test pilots at the National Test Pilot School (NTPS) demonstrated the effectiveness of an approach based on mission/envelope/MTE(s) to obtain consistent and repeatable Handling Qualities Rating(s) (HQR) and in identifying handling qualities deficiencies. The value of NTPS implicit validation of this approach is that evaluations are performed of known helicopters, flown operationally in different scenarios for a significant amount of time, and that evaluators have a diversified flying and technical background. It was practically demonstrated that HQ evaluation by pilots with a limited number of flight hours match that of pilots with a higher number of flight hours.

NTPS experience also highlighted that the application of the MTE-based approach in manned simulators was partially successful. Based on pilots' reports, this partial success and consequent applicability depends on the differences between aircraft and simulator field of view, lack of ground micro texture cues, partial representation of ground effect aerodynamics and of rotor flow recirculation against buildings, or sloped terrain. Another lesson identified at NTPS is the impossibility for all aircraft, including certified ones, to execute all the applicable ADS-33E-PRF MTEs. This highlights the necessity of adapting MTEs and their requirements to the vehicle characteristics and type.

4.5 Low speed flight characteristics

4.5.1 Notes on standards and regulations

The available relevant standard [20] requirements on stall performance/characteristics and most of those on departure characteristics testing apply to aircraft with conventional fixed wing configuration, as stated in section 1. Scope of the standard. Paragraph 4.2.4 of [20] indicates the possibility of alternate methods to demonstrate compliance with departure characteristics requirements, as follows:

> "Level 1 and Level 2 multi-engine airplanes may demonstrate compliance with 4.2 as follows: 4.2.4.1 At their discretion, the applicant shall utilize an approach acceptable to the local CAA that may utilize aerodynamic design characteristics, systems-based protection features, or a combination thereof to lower the probability of departure from controlled flight after a critical loss of thrust to an acceptable level."

The content of paragraph 4.2.4 indicates the possibility of assessing departure characteristics, and potentially the departure resistance of a vehicle (i.e. "systems-based protection features"), based on envelope protection type devices.

This is considered applicable to FBW aircraft; it is a portion of the standard that could be expanded to more aircraft types, including hybrid E-VTOLs, and directly specify the alternate means of compliance.

Note 2 to paragraph 4.2.4.1 of [20] indicates development towards this recommended approach: "NOTE 2—Proposals are in development for alternate means of compliance to the parent requirement in 4.2. Future revisions of this specification will include those alternate approaches."

Recommendation R6: The FAA should recommend ASTM to expand paragraph 4.2.4 of ASTM F3180/F3180M-17 to include normal operation of E-VTOL vehicles.

Issued SCs address low speed characteristics and high incidence protection function of Part 25 aircraft, common to Part 23 aircraft. The selected SCs, not an inclusive list, include [13], [15], [16], and [17]. Flight characteristics currently addressed are outlined below.

1. Flight Envelope Protection: High Incidence Protection Function [16].
    a. Definitions. For the purpose of this special condition, the following definitions apply:

       Electronic Flight Control System (EFCS) – The electronic and software command and control elements of the flight control system.

       High Incidence Protection Function – An airplane level function that automatically limits the maximum angle of attack that can be attained to a value below that at which an aerodynamic stall would occur.

       Alpha Limit – The maximum angle of attack at which the airplane stabilizes with the high incidence protection function operating and the longitudinal control held on its aft stop.

    b. Capability and Reliability of the High Incidence Protection Function
        (1) It must not be possible to encounter a stall during pilot induced maneuvers, and handling characteristics must be acceptable, as required by paragraphs e and f below, titled High Incidence Handling Demonstrations and High Incidence Handling Characteristics respectively.
        (2) The airplane must be protected against stalling due to the effects of environmental conditions such as windshears and gusts at low speeds, as required by paragraph g, Atmospheric Disturbances, below.
        (3) The ability of the high incidence protection function to accommodate any reduction in stalling incidence resulting from residual ice must be verified.
        (4) The reliability of the function and the effects of failures must be acceptable, in accordance with Sec. 25.1309 and Advisory Circular 25.1309-1A, System Design and Analysis.
        (5) The high incidence protection function must not impede normal maneuvering for pitch angles up to the maximum required for normal maneuvering, including a normal all-engines operating takeoff plus a suitable margin to allow for satisfactory speed control.

c. Minimum Steady Flight Speed and Reference Stall Speed. In lieu of the requirements of Sec. 25.103, the following special conditions apply:
   (1) VMIN: The minimum steady flight speed, for the airplane configuration under consideration and with the high incidence protection function operating, is the final stabilized calibrated airspeed obtained when the airplane is decelerated at an entry rate not exceeding 1 knot per second until the longitudinal pilot control is on its stop.
   (2) The minimum steady flight speed, VMIN, must be determined.

(6) The flight characteristics at the angle of attack for CLMAX must be suitable in the traditional sense at FWD and AFT center of gravity in straight and turning flight at IDLE power. Although for a normal production EFCS and steady full aft stick this angle of attack for CLMAX cannot be achieved, the angle of attack can be obtained momentarily under dynamic circumstances and deliberately in a steady state sense with some EFCS failure conditions.

(2) Failure Cases. Following failures of the high incidence protection function not shown to be extremely improbable, if the function no longer satisfies paragraph b, Capability and Reliability of the High Incidence Protection Function, paragraphs b(1), (2), and (3) of this special condition, stall warning must be provided in accordance with Sec. 25.207. The stall warning should prevent inadvertent stall under the following conditions.

e. High Incidence Handling Demonstrations. In lieu of the requirements of Sec. 25.201, the following special conditions apply:
Maneuvers to the limit of the longitudinal control in the nose up direction must be demonstrated in straight flight and in 30 degree banked turns under the following conditions:

f. High Incidence Handling Characteristics. In lieu of the requirements of Sec. 25.203, the following special conditions apply:

g. Atmospheric Disturbances. Operation of the high incidence protection function must not adversely affect aircraft control during expected levels of atmospheric disturbances or impede the application of recovery procedures in case of windshear. Simulator tests and analysis may be used to evaluate such conditions but must be validated by limited flight-testing to confirm handling qualities at critical loading conditions.

Special Condition No.2 Electronic Flight Control System: Lateral- Directional Stability, Longitudinal Stability, and Low Energy Awareness
[17].

“These special conditions require that adequate awareness be provided to the pilot of a low energy state (low speed, low thrust, and low altitude) below normal operating speeds.” [17]

4.5.2 Discussion

The extracts of the special conditions reported in Section 4.5.1 are directly applicable to Part 23 fixed wing aircraft and to the wing-borne flight phase of hybrid configuration aircraft. Reference to high incidence and CLmax cannot be applied as they are defined in the SCs. They could be adapted to E-VTOLs and more generally non-conventional configuration UAMVs, substituting the high alpha and CLmax conditions with more general low energy flight conditions, relevant for E-VTOLs/hybrid configurations during the transition from wing-borne to rotor-borne flight phase and vice versa.

4.6 Operating limitations

4.6.1 Notes on standards and regulations

The applicable regulations and standards to establish aircraft operating limitations are the Code of Federal Regulations, paragraph 23.153 [10] and the ASTM standard of [21]. The limitations defined in these documents are applicable to fixed wing aircraft not equipped with envelope protection control systems. Issued SCs provide a useful indication for approaching the definition and demonstration of operating limitations of aircraft with envelope protection systems.

Below is a list of requirements on flight envelope protection systems from SC [16]. It is important to notice that the requirements apply to aircraft normal operation and failure states and that their specification applies conceptually to different types of aircraft.

12. Flight Envelope protection [16].

    (a) General Limiting Requirements.

(1) *Normal Operation.*

(i) Onset characteristics of each envelope protection feature must be smooth, appropriate to the phase of flight and type of maneuver, and not in conflict with the ability of the pilot to satisfactorily change airplane flight path, speed, or attitude as needed.

(ii) Limit values of protected flight parameters [---] compatible with:

(A) Airplane structural limits;

(B) Required safe and controllable maneuvering of the airplane; and

(C) Margin to critical conditions. Unsafe flight characteristics/conditions must not result if dynamic maneuvering, airframe and system tolerances (both manufacturing and in-service), and non-steady atmospheric conditions, in any appropriate combination and phase of flight, can produce a limited flight parameter beyond the nominal design limit value.

(iii) The airplane must be responsive to intentional dynamic maneuvering to within a suitable range of the parameter limit. Dynamic characteristics such as damping and overshoot must also be appropriate for the flight maneuver and limit parameter in question.

(iv) When simultaneous envelope limiting is engaged, adverse coupling or adverse priority must not result.

(2) *Failure States.* EFCS (including sensor) failures must not result in a condition where a parameter is limited to such a reduced value that safe and controllable maneuvering is no longer available. The flightcrew must be alerted by suitable means if any change in envelope limiting or maneuverability is produced by single or multiple failures of the EFCS not shown to be extremely improbable.

(3) *Abnormal Attitudes.* In case of abnormal attitude or excursion of any other flight parameters outside the protected flight boundaries, the operation of the EFCS, including the automatic protection functions, must not hinder airplane recovery.

(b) *Angle-of-Attack Limiting.*

This section provides the description of the impact of angle of attack limiting on airspeed definitions in the low speed flight regime.

4.6.2 Discussion

Point 12 (ii) (C) is relevant for the approach to certification based on combined multi-dimensional flight envelopes, operational state and atmospheric conditions. If applied as a regulation, it requires formal definition of “nominal design limit values,” in both nominal and toleranced (i.e. off-nominal) vehicle conditions. This is at design stage, prior to simulated and in-flight assessment of aircraft capability to respect the target “nominal design limit envelope.” A model-based design of the vehicle and the capability to predict its dynamic response with adequate accuracy is required. In this report, sections 5.1, 5.2, and 7.3 address operational state, flight envelopes definition, and model development, respectively.

Point (iii) is considered fundamental to inherently drive the design to the appropriate level of conservativeness and establish envelope margins to ensure the required aircraft maneuvering capabilities within the whole service envelope. This includes the disturbance rejection capability in proximity of the envelope limits.

Recommendation R7: The FAA should consider including in the regulations the concept that *the airplane must be responsive to intentional dynamic maneuvering to within a suitable range of the parameter limit*, by establishing margins applicable to the limit envelope(s), within which no degradation of the maneuvering capabilities occurs. Demonstration maneuvers should be required to ensure respect of the new regulations.

According to the concept of multi-dimensional flight envelope at the basis of points 12 (1), 12 (2) and 12 (3), failures are expected to reduce the range of one or more variables defining the envelope. Departure from controlled flight, of point 12 (3), is highly critical for the large control surface activity demand and the potential negative effect of high authority control laws on the capability of the pilot to regain control of the vehicle. Low to no augmentation control laws modes are usually implemented in aircraft with high authority FBW systems. These selectable modes restore a high level of the pilot’s authority and provide increased pilot’s SA of the commanded control surface deflection through the inceptor’s position. Implementation of similar modes in UAMVs is potentially critical, depending on the inherent stability of the bare airframe and on the expected pilot’s skill requirements. An alternate way to recover the aircraft from uncontrolled flight is the deployment of a full aircraft parachute.

The SCs were designed for Part 25 aircraft, which have different control laws modes and corresponding different flight envelopes. Their applicability is also valid to Part 23 aircraft, for which failures are expected to reduce the range of the flight envelope “nominal design limit values,” even if the type of augmentation remains unchanged. Suitable means of alerting the pilot that reduction of the flight envelope occurred due to a failure is also considered to be fundamental for FBW Part 23 aircraft and it should be one of the elements of updated regulations. This applies even if there is no corresponding change in the mode of aircraft stability augmentation.

Recommendation R8: The FAA should require suitable means of alerting the pilot of a reduction of the flight envelope, following a failure, independently from the transition to a different stability augmentation mode.

The selected SCs, even if applied to different aircraft, are characterized by the following technical and certification requirements common to the largest majority of FBW designs:

1. Model-based design
2. Specification of multi-variable envelopes, basis of the WM method
3. Variation of envelope range as a function of failure modes and operational state
4. Requisite of control laws modes with alternate augmentation, to allow recovery from Loss of Control (LOC) conditions.

This derives from their application to aircraft with similar characteristics, designed according to similar technical processes, for similar mission types, with similar augmentation and handling qualities requirements. This is also applicable to Part 23 aircraft, mostly UAMVs. Standardization of certification requirements is possible with a standardized process to FBW aircraft design, development, testing and certification.

Recommendation R9: The FAA should issue advisory material outlining a conceptual path from preliminary design to certification of Part 23 FBW aircraft.

5 Operational states, envelopes, turbulence levels and HQ levels

5.1 Operational states

The vehicle operational state affects its capability of accomplishing the operational requirements. Reference [22] defines five levels of operational state, three of which are broadly applicable to light FBW vehicles. Adaptations of these are described below.

a. Normal operation: normal state of flight control system performance, safety and reliability.
b. Minimum safe operation: state of degraded flight control system performance, safety and reliability, which permits safe cruise, descent and landing at the destination of original intent or alternate, but where pilot workload is excessive, or mission effectiveness is inadequate.
c. Controllable to an immediate emergency landing.

Association of the vehicle operational states and corresponding flight envelopes, defined in the following section 5.2, has to be specified in the aircraft specification and in the handling specification.

5.2 Flight envelopes

Definitions of operational and limit flight envelopes are based on those of Reference [23], modified as a function of mission requirements, and of the aircraft states defining the envelope boundaries, to adapt them to light FBW aircraft with different configurations.

Operational Flight Envelopes (OFE): the operational flight envelopes define the boundaries in terms of airspeed, pressure altitude, load factors, flow angles, attitude angles and other states within which the aircraft must be capable of operating in order to accomplish its mission. Different operational envelopes can be assigned to different flight phases and missions required to the same aircraft.

Limit Flight Envelopes (LFE): for each aircraft normal operational state, a Limit Flight Envelope has to be established, representing the combinations of airspeed, pressure altitude, load factors, flow angles, and attitude angles derived from aircraft limits, distinguished from mission requirements. For each mission type and flight phase, the boundaries of the LFE shall not be internal to the corresponding OFEs.

Flight Test Only Envelopes (FTOE): this envelope is smaller than the OFE, and defined from restrictions on the target OFE issued after the clearance process. This restricted envelope can be due to low confidence level in the modeled aircraft data, and verified large variation of prediction data, which does not allow for a robust design and sufficient predicted robustness of the controller. The **FTOEs** must be defined by the same states that define the corresponding target **OFEs**.

The scope of the FTOE is to allow data gathering in flight to refine the models, and eventually remove the restrictions based on flight clearance analysis.

The aircraft maneuvering capabilities and the envelopes are linked through the respective envelope definitions and previous recommendation R7.

The approach proposed for Part 23 aircraft matches the application of multi-dimensional flight envelopes and their graphical representation contained in AC 25-7D [19] and in [18].

The FAA could identify aircraft configurations requiring different sets of envelopes. A set of envelopes is formed by LFE, OFE and, when published by the manufacturer, FTOE. The aircraft configuration can be defined by the control laws mode and by the flight mode. In hybrid vehicles, the considered flight modes are, for example, wing-borne, rotor-borne, and transition flight. The assumption is that different flight modes require different vehicle and control laws configurations.

Recommendation R10: The FAA should define the mandatory minimum set of aircraft states and minimum boundaries defining the Limit Flight Envelopes and the Operational Flight Envelopes, as a function of the aircraft configuration and phase of flight.

Figure 17, below, displays the proposed approach applied to notional LFE, OFE, FTOE of a given flight phase and aircraft configuration. The notional states defining the envelopes are indicated as S#. OFE and FTOE values are normalized with respect to the corresponding LFE values. OFE and LFE coincide for $S1_{min}$ and $S4_{min}$, for the other states margin between the two envelopes is positive. FTOE is internal to OFE for the aircraft states limited by flight test only restrictions: $S2_{max}$ and $S3_{min}$ in the example.

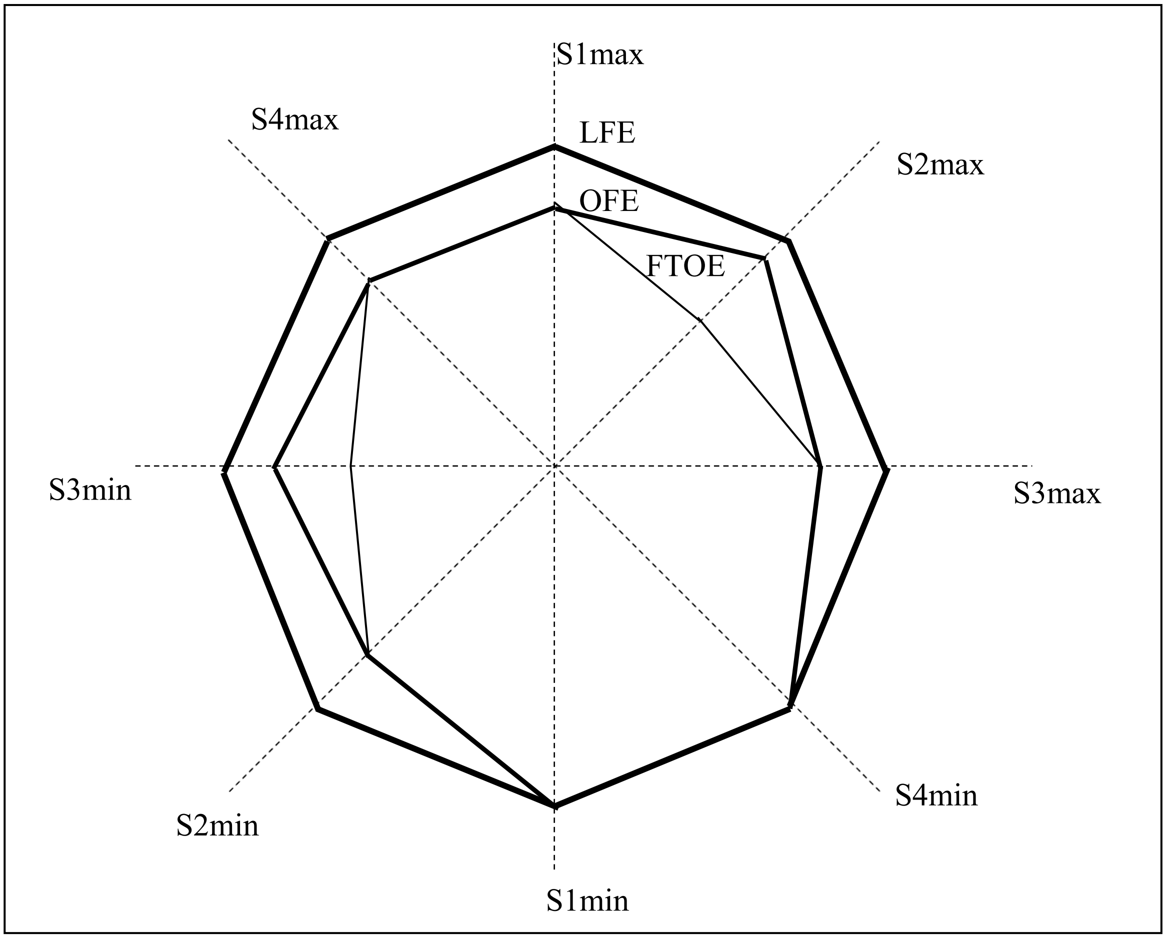


Figure 17. Notional LFE, OFE and FTOE

Procedural aspects related to the defined envelopes are discussed below.

Operational Flight Envelope: to be reported in the aircraft specification. This envelope is the objective of the control laws design to ensure handling qualities *satisfactory without improvement* [24] for the aircraft in full operational conditions. It is also the target envelope for the flight clearance and it can be reduced based on the outcomes of the clearance itself, leading to a temporary Flight Test Only Envelope.

Limit Flight Envelope: the margins that lead this envelope to be wider than the operational envelope can derive from the clearance process. It is based on the aircraft limits and it includes margins deriving from potential mishandling, when this does not lead to exceedance of the airframe structural limitations.

Flight Test Only Envelope: it is internal to the operational flight envelope with respect to one or more of the aircraft states that define it. This envelope is authorized formally by the manufacturer/applicant for flight tests aimed at data gathering for models matching and improvement of their fidelity, or for in-flight evaluation of local mismatch of vehicle characteristics with respect to the requirements.

The scope of its definition is to formalize the impact of the handling deficiencies identified during the clearance phase in terms of restrictions to the operation of the aircraft. Modifications/opening of this envelope can be authorized when sufficient data are gathered to ensure the target level of confidence of the model, or after modification of the control laws based on the data gathered in flight test.

Temporary Airworthiness Flight Limitations (AWFL): during the flight test phase, temporary airworthiness flight limitations with respect to the cleared OFE and LFE can be issued, due to experimentally verified deficiencies of the airframe, engine, or systems. Consequently, the envelopes defined above on the basis of design and clearance can be reduced, leading to specific FTOEs.

This is a procedural mean for the manufacturer/applicant to enforce upon itself respect of a reduced envelope strictly dependent on airworthiness deficiencies identified in flight.

It is also a mean to inform the FAA that the vehicle does not match the specified requirements.

Recommendation R11: The FAA should monitor the occurrence of airworthiness deficiencies through the applicant's issuing of FTOEs.

5.3 Turbulence levels

Atmospheric turbulence level is one of the factors for the definition of the handling qualities requirements. Table 1 below reports the United States Air Force turbulence intensity definitions [25], Table 2 reports the FAA turbulence duration definitions [26]. These definitions are applied in the specfication of the requirements reported in this document.

Slightly different atmospheric disturbance levels are defined in [19] as part of the HQRM method. Their consideration of crosswind velocity make them more specific for application to fixed wing aircraft alone, limiting their application to hybrid aircraft configurations.

Table 1. US Air Force turbulence intensity definitions

AIR FORCE TURBULENCE INTENSITY DEFINITIONS **Meteorological Techniques, Air Force Weather Agency, AFWA/TN-98/002 Revised 21 February 2007**	
LIGHT	The aircraft experiences slight, erratic changes in attitude and/or altitude, caused by a slight variation in airspeed of 5 to 14 knots with a vertical gust velocity of 5 to 19 feet per second.
MODERATE	The aircraft experiences moderate changes in attitude and/or altitude, but the pilot remains in positive control at all times. There are usually small variations in airspeed of 15 to 24 knots; vertical gust velocity is 20 to 35 feet per second.
SEVERE	The aircraft experiences abrupt changes in attitude and/or altitude and may be out of the pilot's control for short periods. There are usually large variations in airspeed greater than or equal to 25 knots and the vertical gust velocity is 36 to 49 feet per second.
EXTREME	The aircraft is violently tossed about and is practically impossible to control. Structural damage may occur. Rapid fluctuations in airspeed are the same as severe turbulence (greater than or equal to 25 knots) and the vertical gust velocity is greater than or equal to 50 feet per second.

Table 2. FAA turbulence duration definitions

TURBULENCE DURATION **FAA Aeronautical Information Manual, 12 October 2017**	
OCCASIONAL	Less than 1/3 of the time
INTERMITTENT	From 1/3 to 2/3 of the time
CONTINUOUS	More than 2/3 of the time

5.4 Handling qualities levels and rating scales

Tools and metrics to assess handling qualities are essential to ensure uniform, repeatable, and reliable subjective evaluations. To clearly establish levels of acceptable/unacceptable and of satisfactory/unsatisfactory handling qualities boundaries.

The definition of handling qualities provided in [24] is:

"Those qualities or characteristics of an aircraft that govern the ease and precision with which the pilot is able to perform the tasks required in support of an aircraft role."

The term "aircraft role" is related to the aircraft mission. "Ease" and "precision" identify the bi-dimensional space in which HQ are rated and that are necessarily connected by the evaluation task. It is fundamental to notice that “tasks” are multiple in the definition. Tasks depend on the flight phase and the aircraft role. The reference handling qualities rating scale is the Cooper-Harper (CH) scale, displayed in Figure 18. Figure 19 contains the definitions accompanying the scale, from [24].

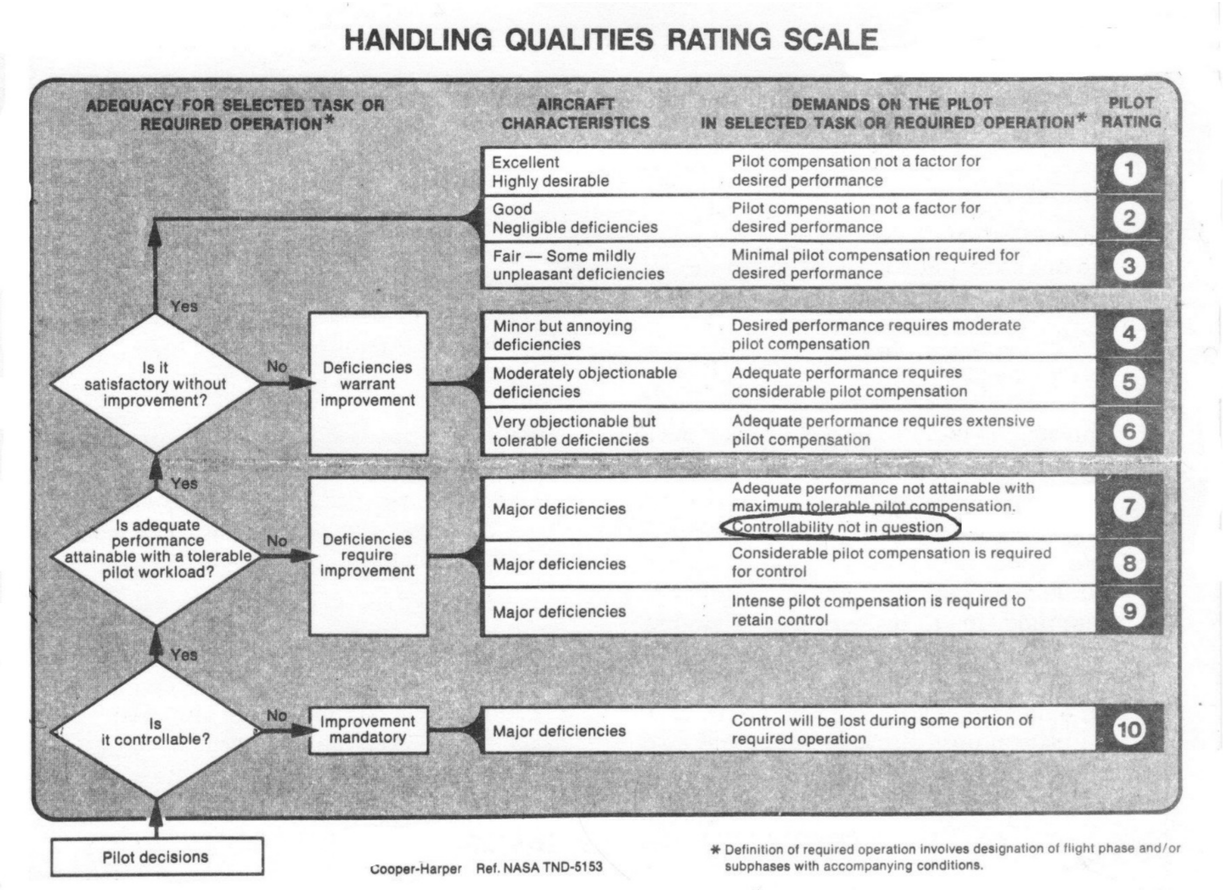
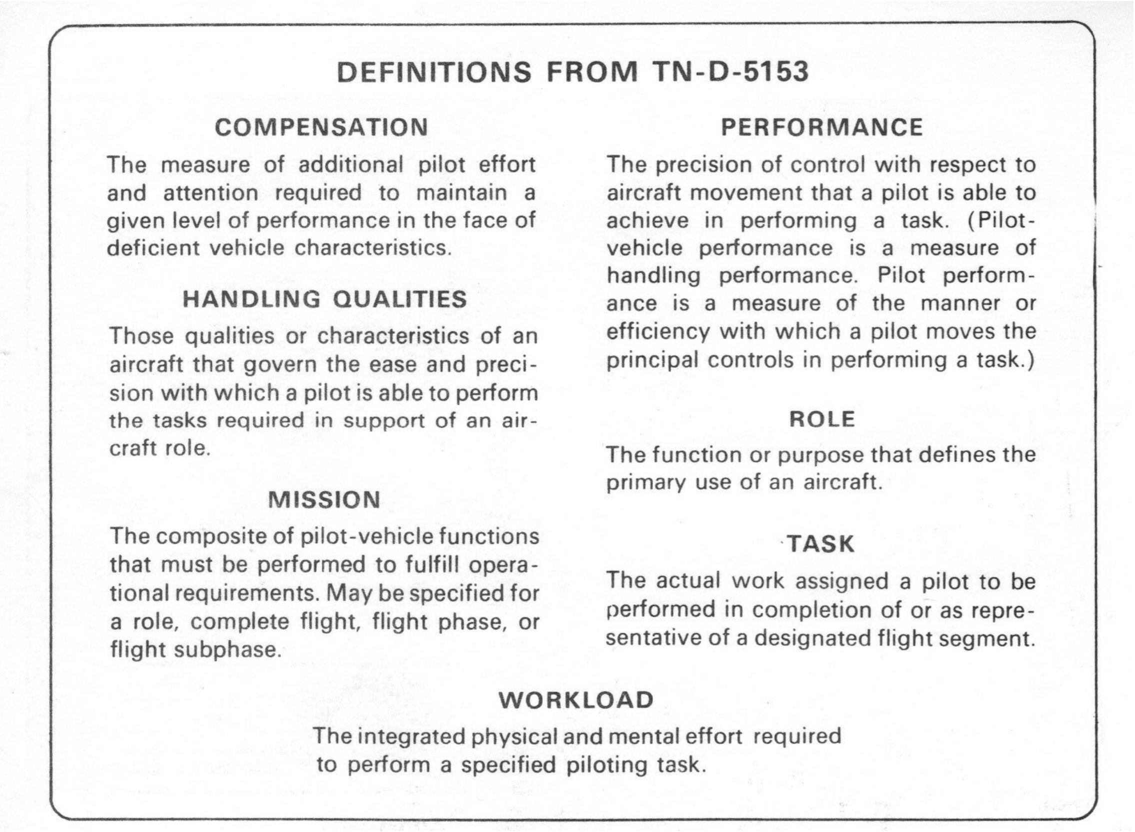


Figure 18. Cooper-Harper handling qualities rating scale

For consistency with the current FAA method of handling qualities evaluation, direct correspondence can be traced between Cooper-Harper Ratings (CHR) and the definitions in Appendix E of Advisory Circular AC-25-7D [19]. The AC contains the correlation between civil and military HQ levels [23] and CHRs [24], which are also the reference of most of the handling qualities prediction criteria. This possibility to link the predicted and subjectively rated HQ levels is crucial for their consistent traceability through the aircraft development from design to certification.



DEFINITIONS FROM TN-D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE

The function or purpose that defines the primary use of an aircraft.

TASK

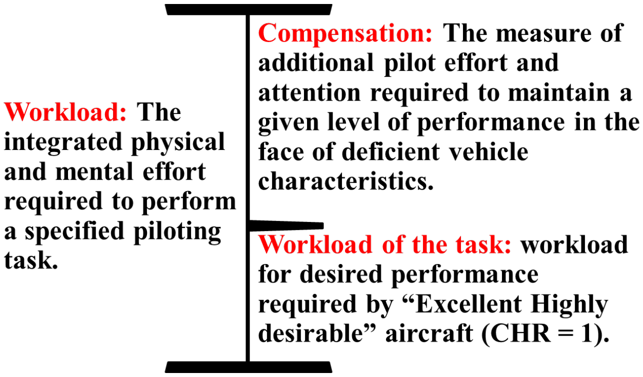
The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

WORKLOAD

The integrated physical and mental effort required to perform a specified piloting task.

Figure 19. Cooper-Harper handling qualities definitions

According to the definition of Figure 19, “compensation” is a function of the “additional pilot effort and attention”. In this case “additional” is with respect to the workload required to achieve desired performance, performing the assigned task with an “excellent, highly desirable” aircraft. This workload amount is defined as “workload of the task”. Figure 20 below represents the relationship between workload, compensation and workload of the task.



Workload: The integrated physical and mental effort required to perform a specified piloting task.

Compensation: The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

Workload of the task: workload for desired performance required by “Excellent Highly desirable” aircraft (CHR = 1).

Figure 20. Workload and compensation

From the definition of "compensation," it derives that different levels of workload of the task lead to different levels of compensation for the same total workload, as displayed in Figure 21.

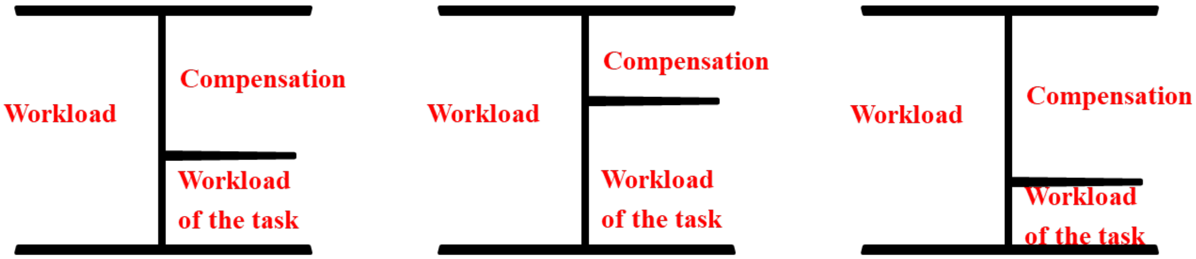


Figure 21. Workload, workload of the task and compensation

Accurate knowledge and experience of the "workload of the task" for different types of tasks is essential to provide a reliable CHR. This restricts the use of the Cooper-Harper rating scale to test pilots.

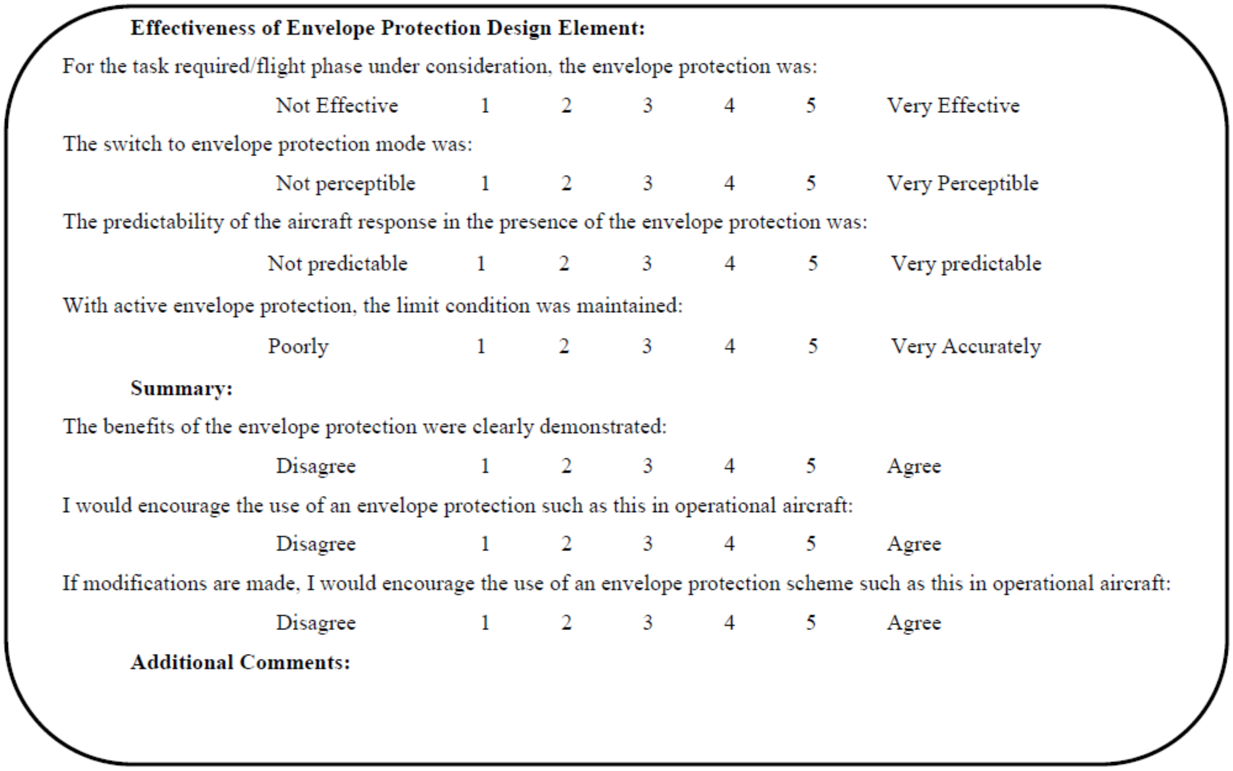
Evaluations of the man-machine interface of vehicles developed according to the SVO concept are potentially conducted in a partially different way from the classical approach. The potential main differences are: (1) assessment of total workload alone, in performing not strictly handling qualities tasks; (2) part of the aircraft HQ evaluation team formed by non test pilots; and (3) evaluation of operationally relevant aircraft functions that do not require the execution of classic handling qualities tasks. This can be the assessment of an envelope protection system effectiveness in preventing flight envelope exceedances.

The Bedford rating scale [27] for total workload and the NASA Task Load Index (TLX) [28] are examples of suitable alternate scales. These scales are reported in Appendix A and Appendix B, respectively.

Both the Bedford and the NASA TLX rating scale are designed to evaluate total workload, being fundamentally different from the Cooper-Harper rating scale, based on compensation. The Bedford scale is aircraft handling related, while the NASA TLX is also expected to be applicable to non-handling related tasks. In the NASA TLX, demands on the pilot/operator are divided into mental, physical, and temporal, each of them characterized by magnitude and importance. These produce emotional, cognitive, and physical responses, which can be measured as overt behaviors; the results of the individual actions can be self-evaluated. The workload definitions are reported in Figure 55, and an example of the estimation process is presented in Figure 56. The process requires weighing of the different components; reliable results have also been obtained by performing a non-weighted average.

An example of questionnaire used in the research reported in [8] to evaluate the effectiveness of an envelope protection system is provided in Figure 22 below. The output of a questionnaire cannot be a single rating and it is important that it is not considered as a rating scale. This questionnaire example contains two main parts: the part dedicated to the envelope protection effectiveness merges quantitative and qualitative components, while the summary is a subjective, qualitative pilot's evaluation. The value of the questionnaire is to provide a common evaluation reference frame for pilots and engineers and to constrain the evaluation to a limited set of key aspects. The example could be improved by reverting the order of the numbers assigned, with 1 for the best and 5 for the worst characteristic. This would match the order of the Cooper-Harper and PIO rating scales.

Recommendation R12: The FAA should consider requiring the use of alternate rating scales and questionnaires to assess the pilot's or operator's effort in performing semi-automated tasks.



Effectiveness of Envelope Protection Design Element:

For the task required/flight phase under consideration, the envelope protection was:

Not Effective 1 2 3 4 5 Very Effective

The switch to envelope protection mode was:

Not perceptible 1 2 3 4 5 Very Perceptible

The predictability of the aircraft response in the presence of the envelope protection was:

Not predictable 1 2 3 4 5 Very predictable

With active envelope protection, the limit condition was maintained:

Poorly 1 2 3 4 5 Very Accurately

Summary:

The benefits of the envelope protection were clearly demonstrated:

Disagree 1 2 3 4 5 Agree

I would encourage the use of an envelope protection such as this in operational aircraft:

Disagree 1 2 3 4 5 Agree

If modifications are made, I would encourage the use of an envelope protection scheme such as this in operational aircraft:

Disagree 1 2 3 4 5 Agree

Additional Comments:

Figure 22. Example of envelope protection evaluation questionnaire

The proposed scale to assess PIO proneness is the standard PIO rating scale, displayed in Figure 23. Table 3, from [19], reports the correspondence between standard PIO rating scale (MIL-STD-1797B) and FAA HQ ratings.

The Chalk-Parrag PIO Tendency rating scale, displayed in Figure 24, is a suggested alternate scale. While the first set of questions leading to the ratings are mainly the same as those of the standard PIOR scale, there is a significant difference in the question discriminating between PIOR=4 and PIOR=5. The question of the standard scale is relative to the aircraft response (i.e. “Divergent”). The corresponding question in the Chalk-Parrag scale is relative to the task (i.e. “is task achievable”). Task performance based PIO modifiers are included in the scale itself. As in the Cooper-Harper scale, modifiers below the rating of achievable task (CHR = 6) deal with aircraft controllability, because the aircraft response prevents the accomplishment of the task. This defines the separation between Level 2 and Level 3. Overall, the Chalk-Parrag PIO rating scale is conceptually similar to the Cooper-Harper rating scale in its being task performance based.

In an approach centered on Mission Task Elements, the Chalk-Parrag PIO rating scale can provide a higher level of PIO rating consistency.

Recommendation R13: The FAA should evaluate the use of the Chalk-Parrag PIO tendency rating scale for certification handling qualities evaluations.

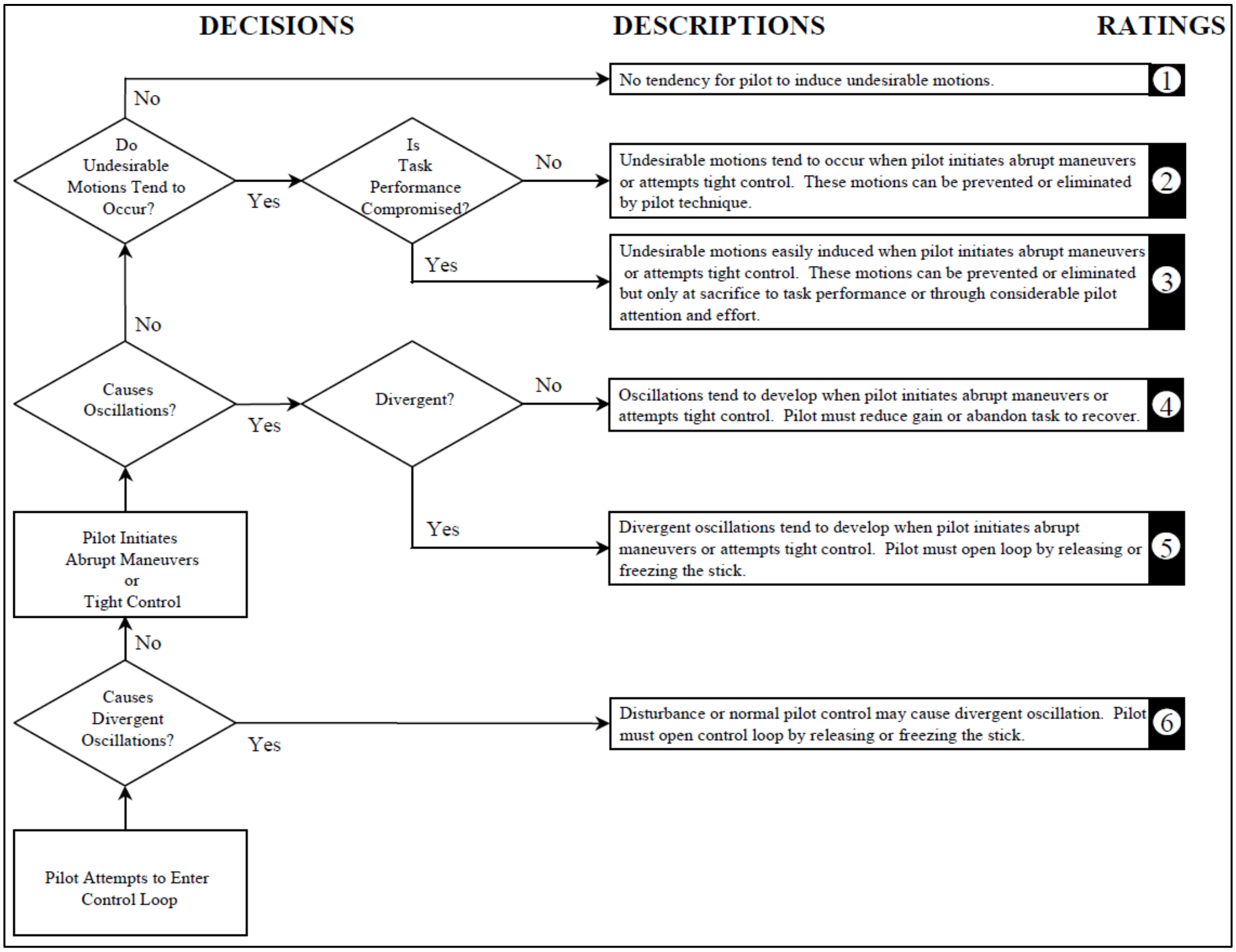


Figure 23. Standard PIO rating scale [29]

Table 3. Standard PIO ratings correlation with FAA HQ ratings

FAA Rating	**PIO Characteristics Description**	**Mil-STD Rating**
SAT	No tendency for pilot to induce undesirable motion	1
	Undesirable motions (overshoots) *tend to occur* when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique. (*No more than minimal pilot compensation is required.)*	2
ADQ	Undesirable motions *easily induced* when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort. (*No more than extensive pilot compensation is required.*)	3
CON	*Oscillations tend to develop* when pilot initiates *abrupt maneuvers* or attempts tight control. Adequate performance is not attainable and pilot has to reduce gain to recover. (Pilot can recover by merely reducing gain.)	4
UNSAT	*Divergent oscillations* tend to develop when pilot initiates *abrupt maneuvers* or attempts tight control. Pilot has to open control loop by releasing or freezing the controller.	5
	Disturbance or *normal pilot control* may cause divergent oscillation. Pilot has to open control loop by releasing or freezing the controller.	6

Where:

SAT:	Satisfactory
ADQ:	Adequate
CON:	Controllable
UNSAT:	Unsatisfactory

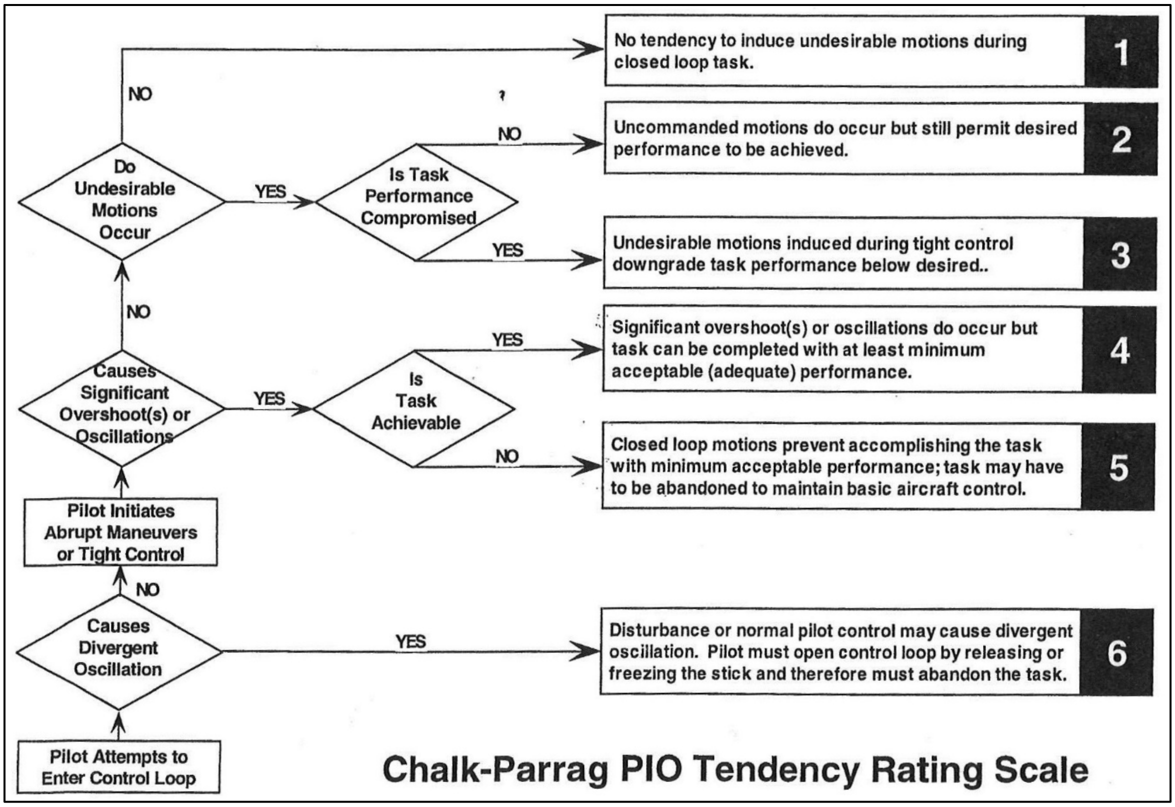


Figure 24. Chalk-Parrag PIO tendency rating scale

5.5 Discussion

The definitions of the envelopes described above are expected to be part of a standard FBW aircraft development. This is fundamental to identify an *a priori* target for the design, clearance, and in-flight verification and validation of the aircraft capability to satisfy its operational requirements.

This ensures that the envelope boundaries are not defined empirically based on the handling qualities levels that can be achieved during flight test. Partitioning of the requirements as a function of different envelopes also avoids the tendency to exceed the minimum required standards.

One of the pilot's primary objectives is to ensure aircraft operation within the limit and operational envelopes.

The role of the FAA is to define the minimum LFE, indicating both mandatory states and their values, and enforce the application of a process based on predefined criteria that allow definition and, if required, further shaping of these envelopes. The margins corresponding to each of the states that the applicant refers to for their definition can be the subject of advisory material and/or MOCs. As an example, margins could be based on the expected potential for mishandling in the specific area of the envelope merged with standard structural margins. The width of the margins is based on the specific aircraft and on the manufacturer's approach to aircraft development. Margins in the order of 10% of the respective flight envelope state can be considered reasonable.

The applicant is responsible for the selection of the envelope relevant states, which must include those required by the FAA, for flexibility in matching the requirements of the different aircraft configurations and the respective observability by the pilot or by the control system. The operational state of the control system and of the vehicle avionics is a significant factor in the appropriate selection of the states by the applicant, which should require consistency check by the FAA.

Recommendation R14: The FAA should ensure that operational, service and the potential flight test only envelope are defined by the applicant, and that the states selected by the applicant to define them match the minimum set required by the FAA. This can be subject of advisory material or MOC.

Recommendation R15: The FAA should verify provision by the applicant of a process to identify airworthiness deficiencies and consequent temporary flight limitations. This can be the subject of a MOC, for which the process has a higher priority than the defined quantitative values. The scope is to ensure flexibility.

6 Notes on HQ prediction criteria

6.1 Introduction

This section describes a selected group of handling qualities prediction criteria. These criteria can be applied in the design and clearance phase to predict handling qualities and they are not a substitute for pilot in the loop assessment of the actual handling qualities. "Open loop" and "closed loop" criteria are presented. Criteria are classified as "open loop" when no pilot's loop closure is assumed, and "closed loop" when they are based on an assumed pilot model and relative loop closure, as in the "Neal-Smith" criterion.

There is vast technical literature reporting the fundamental concepts on which HQ prediction criteria are based and the analyses of their effectiveness. The scope of this section is merely to summarize reference concepts and terminology extracted from the selected examples, for their potential application by the FAA in newly developed, dedicated certification requirements for

UAMVs. The core concepts of the criteria have demonstrated to be valuable in the design of handling qualities evaluation tasks and as a basis of communication and comments between pilots and engineers. The concepts of pitch rate overshoot or that of pitch response predictability as ratio between initial pitch acceleration and steady state load factor are not limited to the analytical applications. They can be used as a qualitative communication metric to substantiate evaluations and/or recommend HQ improvements. The possibility of their experimental/qualitative application increases their value, as it allows continuity from the prediction to the assessment phase and it broadens the knowledge of the concepts themselves.

HQ prediction criteria have a significant value in the control laws design, in handling qualities evaluation test design/planning, and in making available to the aeronautical community the related handling qualities knowledge. Similar to the approach followed in the development of Part 25 and military FBW aircraft, the criteria in this work are intended as analytical tools for the assessment of the consistency of the design with respect to the handling requirements, prior to flight.

Independently from the architecture of the controller, the aircraft handling characteristics are mostly determined by the HQ prediction criteria applied in the design and clearance phase.

Their value and reliability derive from their foundation on handling qualities databases, which retain the experience of many evaluators on a wide range of tested configurations. A second and as important aspect of the application of these criteria is their "neutrality" with respect to the design. This allows their effective application as "gates" for the advancement of the aircraft development, and of its certification.

The application of all the classical, and most of the current HQ prediction criteria, is based on the elements defined in [23], below:

- Aircraft classification
- Flight phase category
- Flying qualities level

It is important to consider that this classification applies to the current criteria and it is not necessarily coincident with that of future criteria, which can be developed independently, or derived from the current ones, for their application to unconventional aircraft configurations, like E-VTOL, or hybrid configurations.

Part 23 aircraft match the following Class I aircraft definition specified in [23]:

"Small, light airplanes such as Light utility, Primary trainer, Light observation."

Below is the verbatim description of flight phase categories and flying qualities (FQ) levels specified in [23].

Flight phase categories:

- Category A – Those nonterminal Flight Phases that require rapid maneuvering, precision tracking, or precise flight-path control.
- Category B – Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required.
- Category C – Terminal Flight Phases that are normally accomplished using gradual maneuvers and usually require accurate flight-path control.

Flying qualities levels:

- Level 1 – Flying qualities clearly adequate for the mission Flight Phase.
- Level 2 – Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.
- Level 3 – Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed.

The requirements on aircraft dynamics of [23] are based on three values of the modal and stability and control parameters. Each value is the minimum condition to match one of the three flying qualities levels reported above, which are levels of acceptability for mission compliance.

For this reason, the definition of "Flying Qualities" for the handling qualities predicted on the basis of aircraft modal and stability and control parameters. The terms "Flying Qualities" requirements, or "predicted handling qualities" requirements have the same meaning, with the second term being possibly preferable to avoid misunderstanding between levels based on modal parameters or test pilot evaluation.

The criteria reported in this section are not necessarily applicable to all UAMVs; dedicated UAMV criteria will be required and will have to be developed, based on aircraft characteristics and mission requirements.

6.2 Control Anticipation Parameter

The Control Anticipation Parameter (CAP) is a classical linear open loop criterion contained in military specifications [23] and [29]. It is a measure of the aircraft pitch response predictability:

pilot capability to predict the steady state response from the initial pitch acceleration due to a longitudinal force step input. For its definition, it applies to wing-borne flying phases. Assuming negligible effect of feel system dynamics, its expression can be derived as the ratio of the transfer functions of pitch acceleration $(\dot{q})$ and normal load factor (n_z) to longitudinal inceptor displacement, as follows:

$$CAP = \frac{\left.\frac{\dot{q}}{\delta_{es}}\right|_{t=0}}{\left.\frac{n_Z}{\delta_{es}}\right|_{t=\infty}} = \frac{\omega_{n_{SP}}^2}{\frac{n_Z}{\alpha}} \qquad \left({}^{1}/_{(gs^2)}\right)$$

Where:

$\omega_{n_{sp}} (rad/s)$ is the short period natural frequency

$\frac{n_z}{\alpha}$ (g/rad) is the variation of normal load factor per variation of angle of attack, or "acceleration sensitivity"

$\frac{n_z}{\alpha} = \frac{U_0 \cdot \frac{1}{T_{\theta_2}}}{g}$; where U_0 is the trim airspeed and T_{θ_2} the time delay between pitch attitude θ and flight path angle γ.

The meaning of T_{θ_2} can be derived from the transfer functions of pitch rate and alpha to elevator deflection, with the assumption of 2 DoF short period dynamics:

$$\frac{\alpha}{\delta_e} = \frac{M_{\delta_e}}{s^2 + 2\zeta_{SP}\omega_{n_{SP}}s + \omega_{n_{SP}}^2}$$

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

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

where C_{Z_α} is the variation of normal aerodynamic force per change of angle of attack

At regime, applying the final value theorem for a step input to $\frac{\alpha}{\delta_e}$ and $\frac{q}{\delta_e}$:

$$\lim_{s\to 0} s\frac{1}{s}\frac{\alpha}{\delta_e} = \frac{\alpha_{ss}}{\delta_e} = \frac{M_{\delta_e}}{\omega_{n_{SP}}^2};\ \lim_{s\to 0} s\frac{1}{s}\frac{q}{\delta_e} = \frac{q_{ss}}{\delta_e} = \frac{M_{\delta_e}\cdot\frac{1}{T_{\theta_2}}}{\omega_{n_{SP}}^2} \Rightarrow q_{ss} = \alpha_{ss}\cdot\frac{1}{T_{\theta_2}}$$

$$\boldsymbol{\alpha_{ss} = T_{\theta_2} q_{ss}}$$

Referring to Figure 25, below, it is derived that T_{θ_2} is the steady state time delay between θ and γ. For the given trim flight condition, T_{θ_2} is a function of the nondimensional derivative of normal aerodynamic force with respect to α $\left(C_{Z_\alpha}\right)$ and of the mass (m).

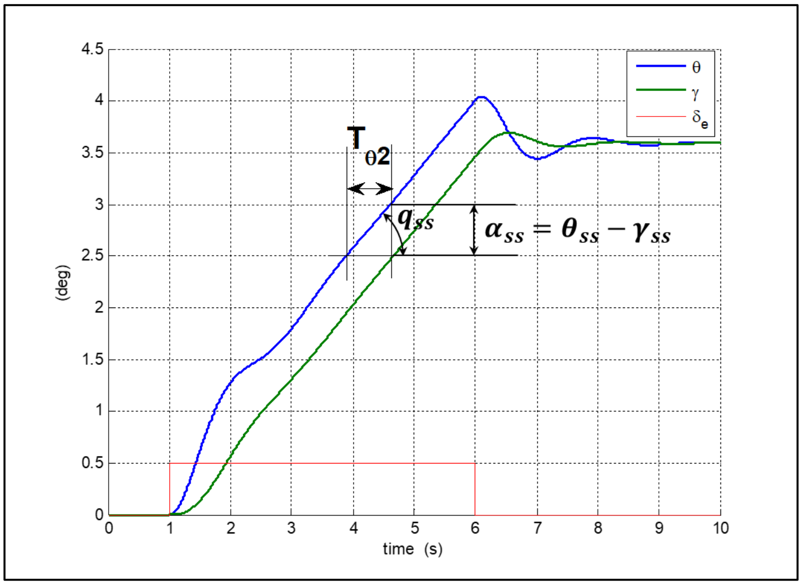


Figure 25. T_{θ_2} as time delay between θ and γ

The meaning of T_{θ_2} can also be derived analytically, given the transfer functions $\frac{\alpha}{\delta_e}, \frac{\theta}{\delta_e}$ and the definition of flight path angle: $\gamma = \theta - \alpha$.

$$\begin{cases} \dfrac{\alpha}{\delta_e} = \dfrac{M_{\delta_e}}{\Delta_{sp}} \\ \dfrac{\theta}{\delta_e} = \dfrac{M_{\delta_e} \cdot \left(s + \dfrac{1}{T_{\theta_2}}\right)}{s \cdot \Delta_{sp}} \end{cases}$$

Where Δ_{sp} is the characteristic polynomial of the 2 DoF short period aircraft dynamics.

From the above transfer functions:

$$\begin{cases} \dfrac{\alpha}{\theta} = \dfrac{s}{s + \dfrac{1}{T_{\theta_2}}} \\ \gamma = \theta - \alpha \end{cases} \Rightarrow \begin{cases} \dfrac{\alpha}{\theta} = \dfrac{s}{s + \dfrac{1}{T_{\theta_2}}} \\ \dfrac{\gamma}{\theta} = 1 - \dfrac{\alpha}{\theta} \end{cases} \Rightarrow \frac{\gamma}{\theta} = 1 - \frac{s}{s + \dfrac{1}{T_{\theta_2}}} = \frac{\dfrac{1}{T_{\theta_2}}}{s + \dfrac{1}{T_{\theta_2}}}$$

$$\frac{\gamma}{\theta} = \frac{1}{T_{\theta_2} s + 1}$$

The above transfer function indicates analytically that T_{θ_2} is the time delay between flight path and pitch attitude change.

The pilot closes the loop on pitch attitude θ as a surrogate of FPA γ, which is the state he/she wants to control. A lower time delay is expected to allow higher predictability of FPA variation through the sensed variation of θ, hence the importance of T_{θ_2}. In a constant airspeed condition, normal acceleration is directly proportional to pitch rate, through the trim airspeed. This time delay has to be commensurate with the initial pitch acceleration, which is represented by $\omega_{n_{SP}}^2$.

Figure 26 below illustrates the qualitative effect of Z_w variation on T_{θ_2} and magnitude of the steady state. Scaling factors of Z_w are intentionally large to magnify the effect. As it can be derived from the symbolic transfer function $\frac{q}{\delta_e}$ above, an increase of Z_w corresponds also to an increase of total damping and consequently damping ratio. The corresponding variation of natural frequency $\left(\omega_{n_{sp}} = -M_\alpha + Z_w M_q\right)$ through the term $Z_w M_q$ is of lower magnitude.

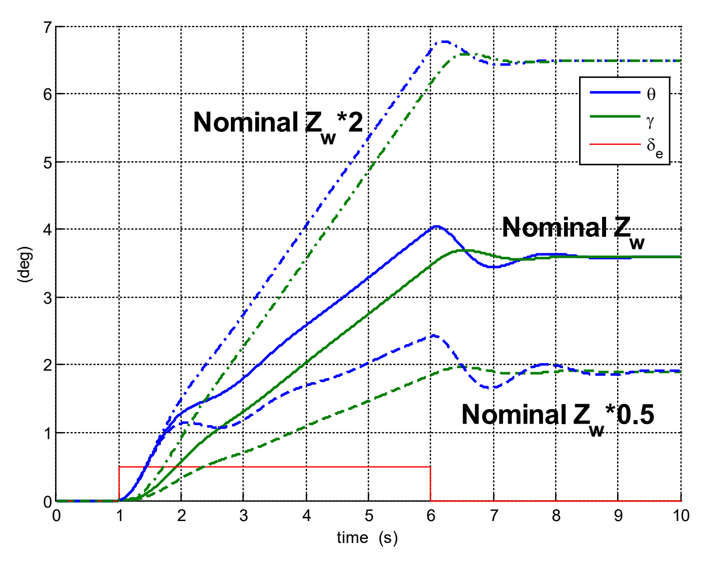


Figure 26. Effect of Zw variation on T_{θ_2}

In the Background Information and User Guide for Mil-F-8785B (ASG) [30] CAP is also defined as:

a. Ratio of the initial pitching acceleration to steady-state normal acceleration, due to a pilot's longitudinal-force step input.
b. A measure of the harmony between rotation and translation in the Short Period.

The predicted HQ boundaries for flight phase category C are displayed in Figure 27, below [23].

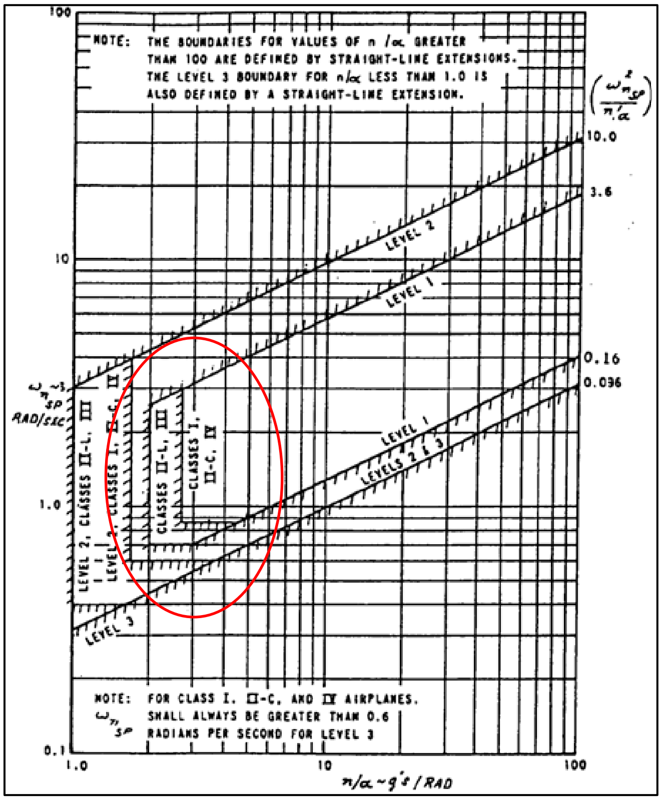


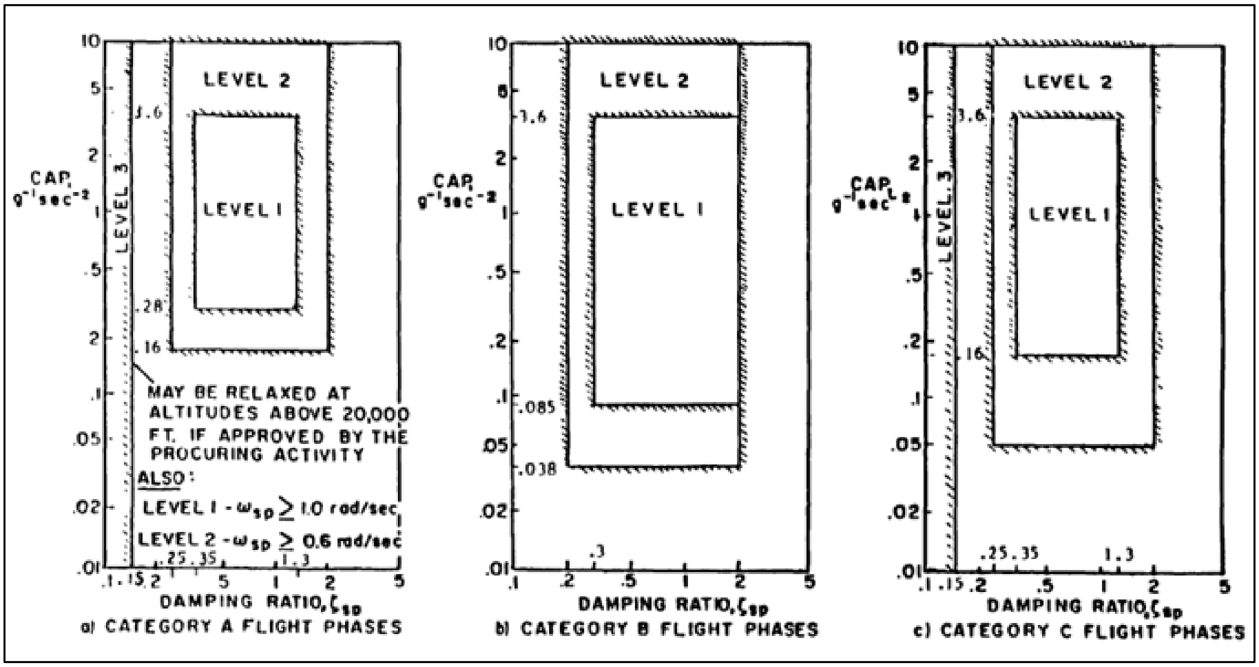
Figure 27. CAP requirements for Flight Phase Category C

The requirements indicate a lower limit value, specifically imposed for Flight Phase Category C, of $\frac{n_z}{\alpha}$, necessary for adequate pilot's tactile and proprioceptive cues: forces and pressure on the body. This can be particularly relevant for Part 23 aircraft, which operate in a low airspeed flight regime and which are potentially characterized by low $\frac{n_z}{\alpha}$ values.

CAP addresses the initial part of the response and its steady state; it is a necessary, but not sufficient criterion and it has to be combined with requirements on short period damping ratio to address the three parts of the response: initial, transient, and steady state. Damping ratio requirements are reported in paragraph 3.2.2.1.1 of [23].

Requirements in Figure 28 [29] report both CAP and damping ratio boundaries in the same chart, with a loss of information on the single components of CAP.

The non-sufficiency of CAP is an important general characteristic of the predicted HQ assessment, as it demonstrates that predictability is an essential characteristic of an aircraft response, but it has to be considered in combination with other characteristics. The fact that the response can be predicted does not imply that it is satisfactory without improvement.



a) CATEGORY A FLIGHT PHASES

b) CATEGORY B FLIGHT PHASES

c) CATEGORY C FLIGHT PHASES

Figure 28. CAP and short period damping ratio requirements

CAP is an effective analytical criterion and practical HQ reference in pilot's assessment of pitch response characteristics. It accounts for both the rotational and heaving nature of short period dynamics. It is useful to expose HQ deficiencies, as a guide for the baseline augmentation strategy. It can also be considered an experimental criterion; the pilot can refer to the concept of CAP, to assess the pitch response predictability in flight, by executing longitudinal force steps. The pilot's comment in flight can be as simple as "good CAP" or "bad CAP". This has a high experimental value, as an assessment of the design with respect to the CAP metric is direct and it can be compared to the results derived from its analytical application. Based on the author's experience with variable stability aircraft, CAP in-flight assessment is effective in screening many configurations in a short time, during the initial phase of the evaluations.

The described formulation of this criterion can be applied in a wing-borne flight phase alone, and it has not been applied to characterize the short period of rotary wing aircraft in forward flight. One of the reasons is that CAP does not assume high order dynamics in the frequency range delimited by $\frac{1}{T_{\theta_2}}$ and $\omega_{n_{sp}}$, which is not true for helicopters. A different formulation based on the same concept, a function of the attitude quickness and agility quickness parameters exist for rotor-borne flight phases. This is defined as Generalized CAP (GCAP), illustrated in reference [31].

A significant limit of CAP application to UAMVs is that it cannot be applied to non-conventional aircraft responses, like pitch attitude or pitch rate command. CAP application to Part 23 aircraft potentially requires refinement of the quantitative requirements; the importance for this document is to stress the relevance of predictability of the steady state longitudinal response, and the awareness that it is not a sufficient metric to ensure satisfactory handling qualities.

6.3 Low Order Equivalent System

The Low Order Equivalent System (LOES) is a method more than a criterion, the scope of which is to approximate a High Order System (HOS) with a lower order model, to verify that the equivalent modal parameters satisfy the classical frequency domain criteria requirements, like CAP and short period damping ratio.

The second order LOES pitch transfer function is:

$$\frac{\dot{\theta}}{F_{es}} = K_{\dot{\theta}} \frac{e^{-\tau_e s}\left(s + 1/T_{\theta_e}\right)}{\left(s^2 + 2\zeta_{sp_e}\omega_{nsp_e}s + \omega_{nsp_e}^2\right)}$$

Where the subscript “e” indicates “equivalent”.

Matching can be performed in the frequency or time domain; discussion of matching techniques is not the scope of this document. Focusing on the concept of equivalent system, the equivalent time delay τ_e represents the cumulative effect of FCS components, like command and feedback path filters, and computational time delay. The lower order model presented above is simplified, and it does not contain the phugoid mode; alternate formulations include the phugoid mode dynamics. For the correct representation of the vehicle dynamics, it is important to consider that matching of a single transfer function is not sufficient as the short period is a two degree of freedom motion. A variation of pitch attitude θ produces a variation of angle of attack α and consequently of flight path angle γ. Simultaneous matching of second order transfer functions of $\frac{\dot{\theta}}{F_{es}}(s)$ and $\frac{\alpha}{F_{e_s}}(s)$, or $\frac{\gamma}{F_{e_s}}(s)$ is required for accurate modeling of the short period dynamics.

Different approaches can be followed in the definition of $1/T_{\theta_e}$. In a conventional aircraft in wing-borne flight mode, pitch rotation and heaving due to a pilot input are coupled through the increase of lift produced by the variation of angle of attack due to the rotation. This response coupling is represented in dimensional form by $Z_w = \frac{\rho S U_0}{2m}\left(-C_{Z_\alpha}\right)$. It is recommended to fix the value of $1/T_{\theta_e} = -Z_w$ to prevent its free identification, which could lead to inconsistent, not physical values and retain the vehicle "natural" pitch/heaving coupling.

In an aircraft with direct lift control, flight path angle and pitch attitude response to a pilot input are not coupled through the vehicle $1/T_{\theta_2}$. In this case $1/T_{\theta_e}$ can be identified freely, for optimal matching, with the condition that $\frac{\dot{\theta}}{F_{es}}(s)$ and $\frac{n_z}{F_{es}}(s)$ are matched simultaneously.

The LOES equivalent time delay is usually determined by accurate matching of the high order system phase lag in the high frequency range, as represented in Figure 29 below.

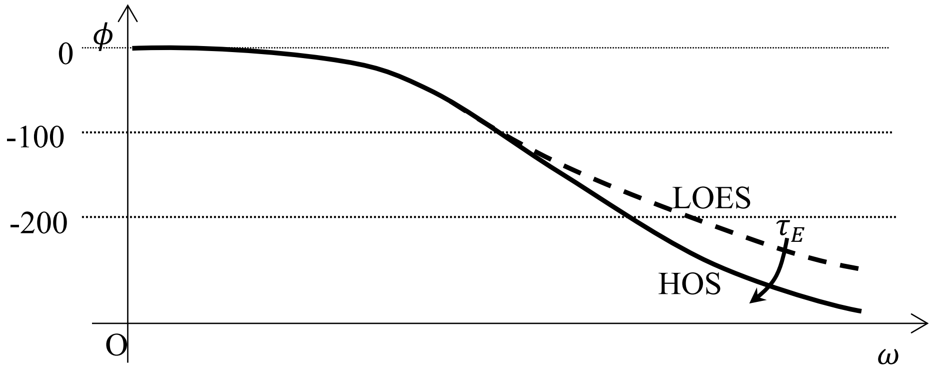


Figure 29. Equivalent time delay and phase lag match

The high frequency dynamics is relevant to the pilot for the phase lag that it introduces, with no noticeable variation of the magnitude of the response. The cumulative lag modeled by τ_e accounts for these high frequency dynamics (i.e. feel system, actuators, filters, digital sampling, and computation).

The LOES method applies also to the lateral directional plane, with the LOES lateral transfer function:

$$\frac{p}{F_{as}} = \frac{e^{-\tau_e s} \cdot L_{F_{a_s}}}{T_{R_e} s + 1}$$

Where:

τ_e	roll equivalent time delay
$L_{F_{a_s}}$	lateral acceleration per change of lateral stick force
T_{R_e}	equivalent roll mode time constant

The lower order model has to be adapted to the vehicle type of response. The dynamics of an inceptor rate command is modeled by a first order lag, with time delay, as in the example below:

$$\frac{y}{u} = \frac{K \cdot e^{-\tau_e s}}{T_e s + 1}$$

Where:

y	generic rate
u	generic input
τ_e	equivalent time delay
T_e	equivalent time constant of the first order lag

In case the inceptor commands attitude, the response can be modeled by a second order lag, with time delay, as below:

$$\frac{y}{u} = \frac{K \cdot e^{-\tau_e s}}{s^2 + 2\zeta_e \omega_{ne} s + \omega_{ne}^2}$$

Where:

y	generic attitude
u	generic input
τ_e	equivalent time delay
ζ_e, ω_{ne}	respectively equivalent damping ratio and natural frequency of the second order lag

The LOES criterion/method allows application of the classical HQ prediction criteria to higher order aircraft, as reported in MIL-STD- 1797A Handbook: "We feel that the ζ_{SP}, ω_{SP}, n/α form of MIL-F-8785 B/C not only fits the data but has demonstrated its effectiveness for a number of highly augmented aircraft as well as for classical response" .

The LOES approach is aimed at guiding design and HQ assessment towards a conventional aircraft response. The additional requirements with respect to the classical ones are the predicted HQ levels as a function of the equivalent time delay and the envelopes of maximum unnoticeable dynamics. Reference [23] reports the time delay requirements for a step control force input, which are presented in Table 4 below. The relevance of the equivalent time delay is relative to the pilot's passband. The effect of a low time delay on phase lag is significant at high frequencies alone, which are potentially outside of the pilot's passband, being so unnoticeable to the pilot.

Table 4. MIL-F-8785C allowable airplane response delay

MIL-F-8785C Allowable Airplane Response Delay	
Level	τ_e **(s)**
1	0.10
2	0.20

MIL-F-8785C Allowable Airplane Response Delay	
Level	$\tau_e\ (s)$
3	0.25

The envelopes of unnoticeable dynamics define the maximum deviation of the LOES with respect to the corresponding HOS, in the frequency domain. They represent the difference HOS – LOES for both gain and phase. They were derived from in-flight simulation and, as stated in [29], correspond to a "pilot rating difference no greater than 1 between the low-order system and the corresponding high-order system," where "pilot rating" is Cooper-Harper rating. Reference [29] reports the corresponding transfer functions. Figure 30 displays the envelopes.

Reference [29] recommends applying criteria directly applicable to the actual system, in case the mismatch between LOES and HOES is outside the boundaries of Figure 30.

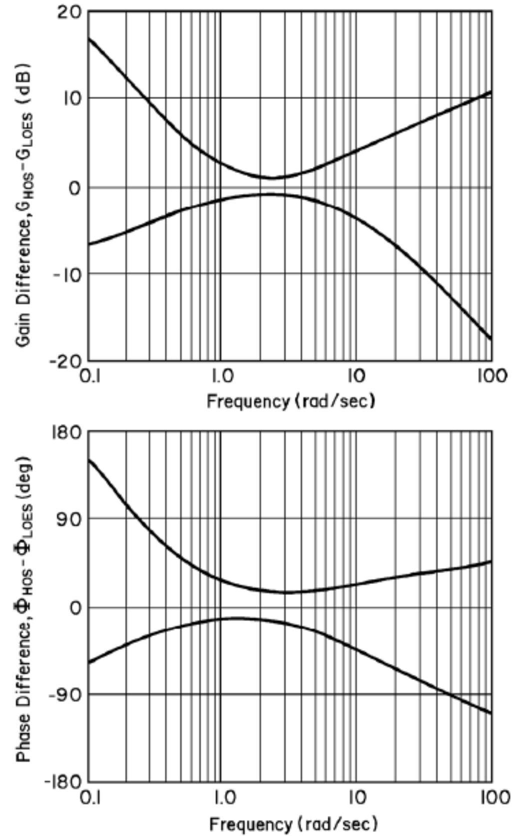


Figure 30. MIL-STD-1797B envelope of maximum unnoticeable added dynamics

As expected, the envelopes are narrower in the pilot's passband, close to the crossover frequency, in the range of frequency in which the differences between HOS and LOES are more noticeable to the pilot. They are applied to ensure that a matched LOES is reliable for HQ prediction in the design phase and to predict the impact on HQ of added dynamics to an FCS. A third application, not directly related to control laws design, is to assess the fidelity of an in-flight simulator with respect to the target aircraft dynamics, for HQ assessments.

6.4 Neal-Smith criterion

The Neal-Smith criterion was derived for predicting HQ in the "combat" phase of a fighter aircraft mission; the reference task is pitch attitude tracking. A pilot model is assumed, which consists of a variable pilot gain K_p, a fixed time delay $\tau = 0.3\ s$ and a variable first order lead-lag compensation network. The time delay τ represents the sum of the time required for the pilot to sense a change in the attitude error θ_e, the decisional time and the neuromuscular time delay.

Figure 31, below, displays the block diagram representing the pilot-vehicle closed loop system.

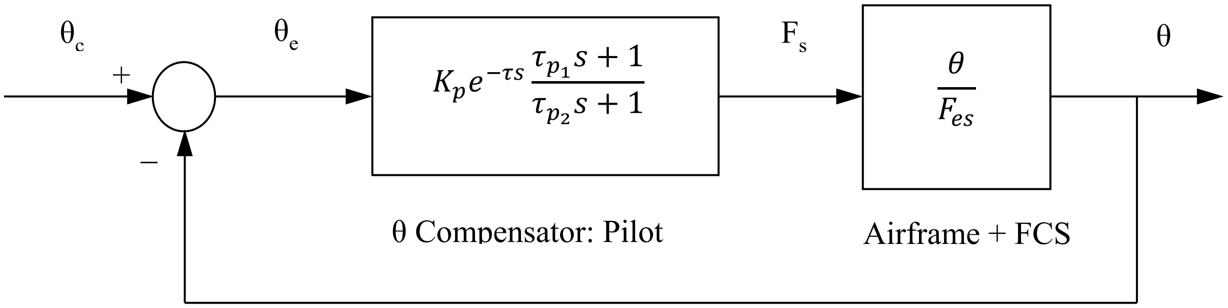


Figure 31. Neal-Smith mathematical model of pitch attitude tracking

The constraints for the application of the criterion were based on pilot's comments, for which good tracking performance is achieved when he can acquire the target quickly and predictably, with minimum overshoot and oscillations. This corresponds to minimizing the phase shift and amplitude attenuation of the closed loop $\frac{\theta}{\theta_c}$ transfer function in a range of frequencies below a fixed value, without amplitude magnification at any frequency.

Closed loop performance is defined as a function of the following terms:

- Bandwidth ω_{BW} – the frequency for which the phase of $\frac{\theta}{\theta_c}$ is equal to $-90°$. It represents how quickly the pilot can point the aircraft nose towards the target.

- Gain droop – maximum deviation of amplitude $\left|\frac{\theta}{\theta_c}\right|$ below the zero dB line for frequencies $\omega < \omega_{BW}$. It is a measure of how slowly the aircraft nose settles down on target.
- Closed loop resonance $\left|\frac{\theta}{\theta_c}\right|_{max}$ – magnitude of the resonant peak of $\left|\frac{\theta}{\theta_c}\right|$, which is a measure of the damping ratio and of the amplitude of pitch attitude oscillations while performing the task.

Figure 32, below, represents the definitions described above.

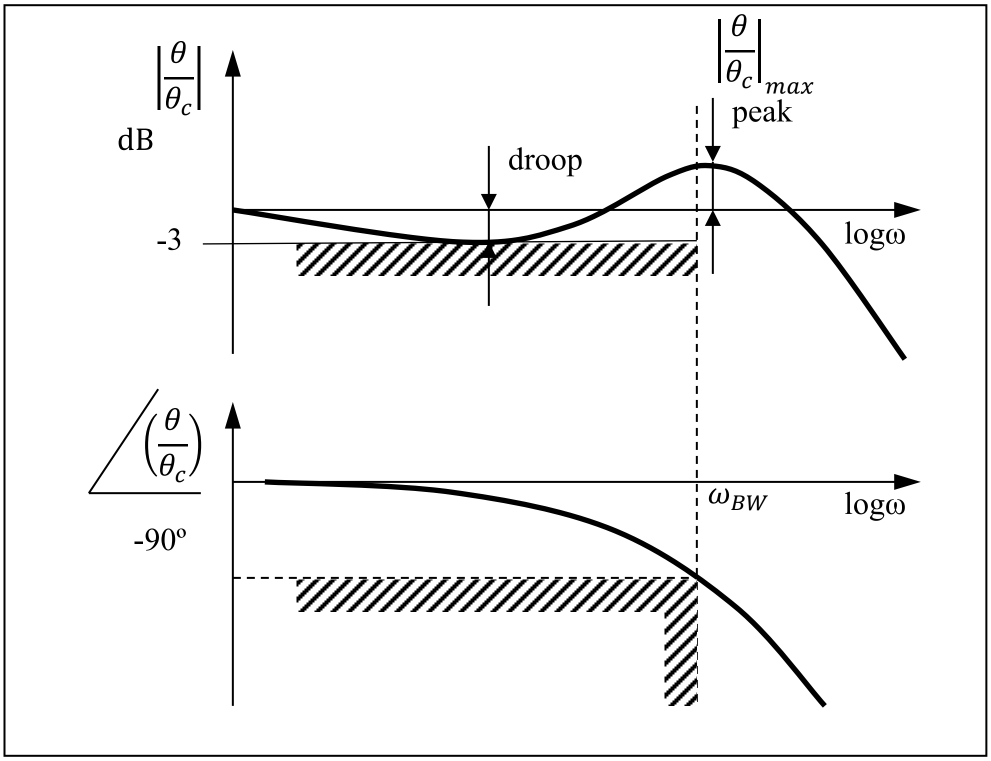


Figure 32. Neal-Smith criterion definitions

The application of the criterion consists in optimizing the pilot's gain and lead/lag compensation to achieve specific closed loop performances, which are the actual constraints of the optimization.

The performance and constraints are as follows:

1. Minimization of the closed loop resonance peak
2. Achievement of a target value of the bandwidth, defined as a function of the task
   - High gain tasks (Category A) – $\omega_{BW} = 3.5\ rad/s$
   - Landing (Category C) – $\omega_{BW} = 2.5\ rad/s$

    - Low gain tasks (Category B) – $\omega_{BW} = 1.5\ rad/s$
3. Maximum value of the closed loop gain droop equal to –3 dB
4. Variable gain K_p within limits consistent with task and controller

The outputs of the optimization to be compared with the criterion requirements are as follows:

1. Phase of the lead/lag pilot compensation (PC), not including the neuro-muscular time delay, in correspondence of the bandwidth frequency of the task

$$arg(PC) = arg\left(\frac{\tau_{p_1} j\omega_{BW} + 1}{\tau_{p_2} j\omega_{BW} + 1}\right)$$

2. Value of the closed loop resonance peak

The criterion requirements are mapped in the chart of Figure 33, below. The phase of the pilot's compensation is reported on the x axis, the magnitude of the closed loop resonance is reported on the y axis. The envelopes superimposed on the chart define the predicted HQ level.

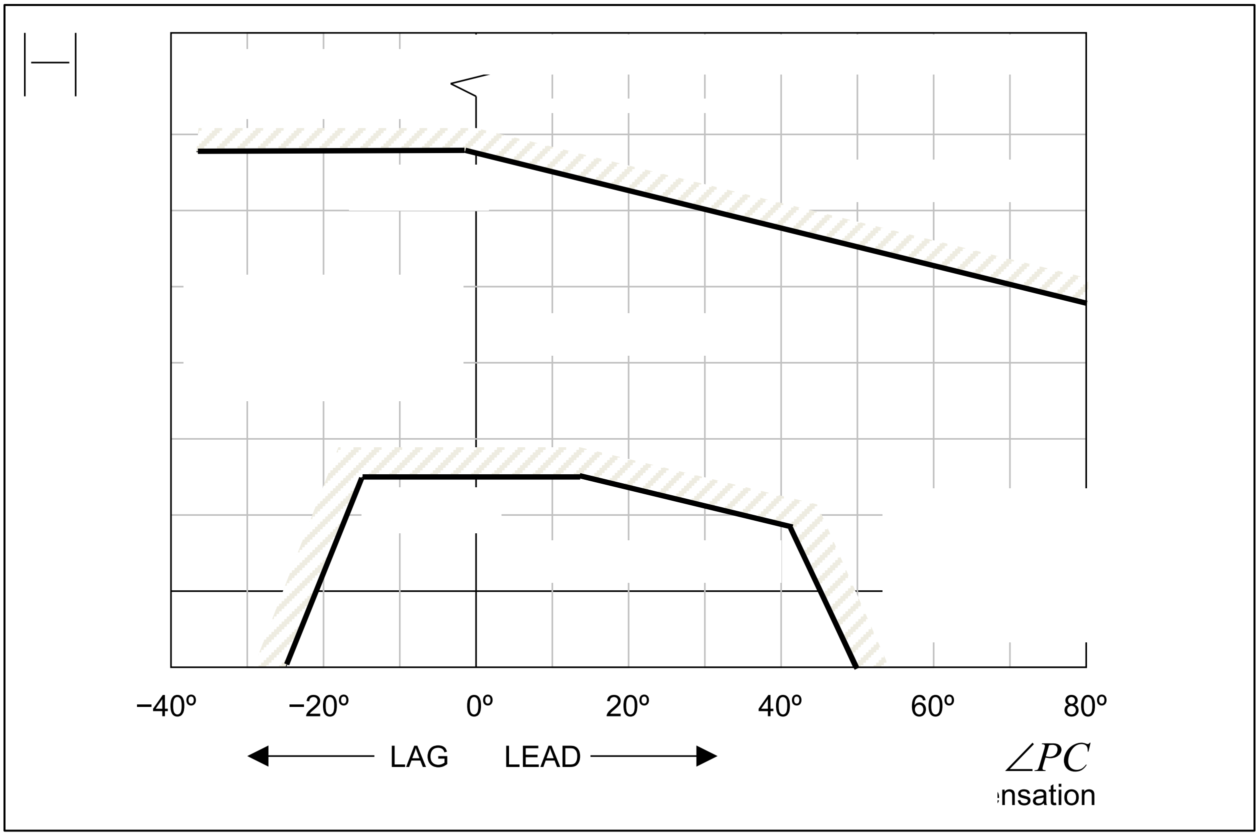


Figure 33. Neal-Smith criterion requirements

Based on the envelopes, pilot's lead compensation is assessed as less degrading than lag compensation for HQ Level 1, with the maximum acceptable closed loop resonance a function of phase compensation. The magnitude of the closed loop resonance is the metric of the aircraft tendency to oscillations and undesirable motions, being an inherent representation of the system damping. Values of the closed loop resonance $\left|\frac{\theta}{\theta_c}\right| = 8\ to\ 12\ dB$ indicate potential for PIO, at 12 dB. This is independent from the phase for lag compensation. In case of lead compensation, indicating sluggishness of the response, the maximum $\left|\frac{\theta}{\theta_c}\right|$ beyond which strong tendency to PIO is expected decreases with the increasing of the phase. This can be assumed to be due to the lower predictability of the response amplitude variation with frequency when sluggishness increases. The importance for handling qualities of the sensitivity of the amplitude of the response to the inputs frequency is a background concept of this criterion, which is common to others, like the aircraft bandwidth criterion. The substantial difference is that Neal-Smith is a closed loop criterion; aircraft bandwidth is an open loop one, as the next sections will illustrate.

The fixed constraint on minimization of the amplitude droop in the frequency range of pilot's control is part of the same concept. An aircraft response amplitude that is less sensitive to frequency reduces the tendency to aircraft undesirable motions when transitioning between phases of the task execution (i.e. from gross acquisition to fine tracking). The lower range of acceptable lag compensation for HQ Level 1 is an indication that abruptness of the response is assessed to be more degrading than sluggishness, for a *good responsive aircraft*. For values of the closed loop resonance higher than 3 dB, the criterion assumes that handling qualities are determined by the resonance itself, independently from the abruptness, or sluggishness of the response (i.e. lag, or lead compensation). The requirement of constraining the optimization to pre-defined bandwidths varying as a function of flight phase category is a potential limit of the criterion, as a result of the optimization depending on the selected bandwidth.

Fixing the bandwidth as a function of the task assumes that the pilot does not accept a degraded overall handling performance in the face of aircraft deficiencies. Experience demonstrates that this actually occurs and that pilots accept handling performance degradation due to aircraft deficiencies, proportionally to the amount of additional compensation.

6.5 Aircraft bandwidth criterion

The aircraft bandwidth is an "open loop" criterion based on the idea that a measure of an aircraft handling qualities is the response characteristics to a compensatory tracking task. The maximum frequency at which the tracking task can be executed without loss of stability is defined as bandwidth ω_{BW}. Aircraft with higher bandwidth exhibit higher handling performance; in aircraft with a lower bandwidth, the pilot executing a tracking task is forced to open the loop and accept a lower handling performance. As mentioned above, the concept of bandwidth is common to the Neal-Smith criterion; at the same time, here it is calculated applying a different definition. The background ideas and application of the criterion are described in reference [32].

Aircraft pitch attitude bandwidth is calculated from the $\frac{\theta}{F_{es}}$ transfer function, as illustrated in Figure 34 below, copied from [29].

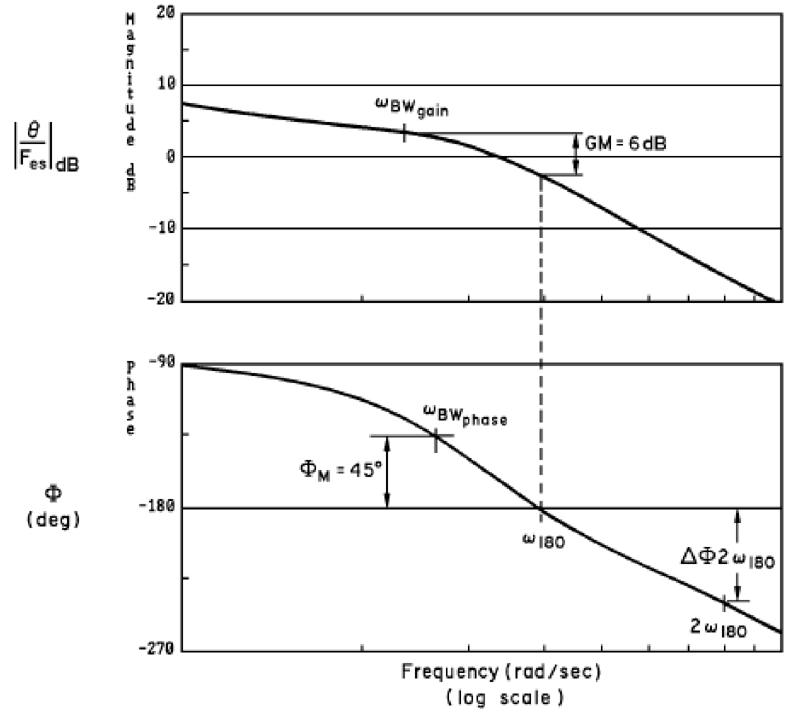


Figure 34. Aircraft bandwidth criterion definitions

The pitch attitude gain bandwidth $\omega_{BW\theta_{gain}}$ is the frequency corresponding to a gain margin GM=6 dB, the phase bandwidth $\omega_{BW\theta_{phase}}$ is the frequency corresponding to a phase margin PM=45˚. The pitch attitude bandwidth $\omega_{BW\theta}$ is defined as the lowest of the two: $\omega_{BW\theta_{gain}}$ and $\omega_{BW\theta_{phase}}$.

Flight path angle bandwidth $\omega_{BW\gamma}$ is calculated with the same method, referred to the phase alone: $\omega_{BW\gamma} = \omega_{BW\gamma_{phase}}$.

The second metric is the phase delay τ_p, which represents the cumulative effect on the response of high frequency dynamics, assuming negligible impact on the amplitude. It is an approach similar to that applied to calculate the equivalent time delay in the LOES method.

The way in which τ_p is calculated matches the assumption:

$$\tau_p = \frac{\Delta\phi_{2\omega 180}}{2 \cdot \omega_{180}}$$

Where:

ω_{180} is the frequency of the phase for neutral stability ($\phi = -180°$)

$\Delta\phi_{2\omega 180}$ is the variation of the phase between that at $2 \cdot \omega_{180}$ and that at ω_{180}

Based on its definition, the phase delay is a function of the phase roll off at $\omega > \omega_{BW}$: a high rate of change of the phase as a function of frequency, produced by high frequency dynamics, corresponds to large values of τ_p.

The requirements of the criterion for the pitch axis including feel system, for Category C flight phase, are displayed in Figure 35. Decreasing $\omega_{BW\theta}$ and increasing τ_{p_θ} corresponds to degradation of HQ levels.

For $\tau_{p_\theta} \gtrsim 140\ ms$, the degrading effect of the phase delay increases and it becomes predominant with respect to the bandwidth requirement, as represented by the slope of the HQ level boundaries in the $\omega_{BW\theta}$ and τ_{p_θ} plane.

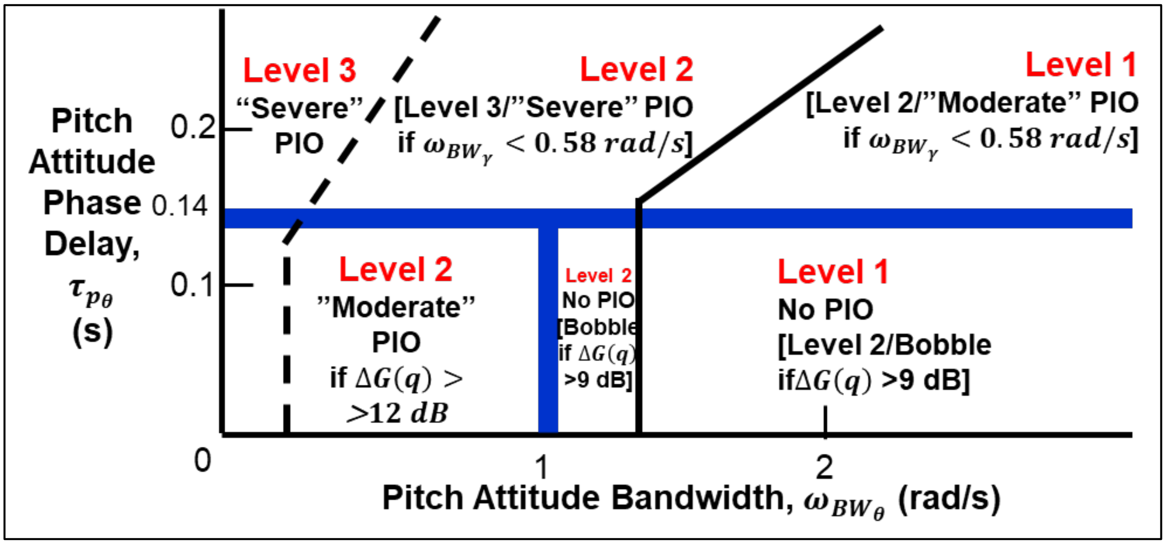


Figure 35. Aircraft bandwidth criterion $\omega_{BW\theta}$ and τ_{p_θ} requirements, no feel system

Pitch rate overshoot is a third metric, reported on the chart of Figure 35 as $\Delta G(q)$, to provide indication of the aircraft PIO proneness. $\Delta G(q)$ is the difference in dB between the maximum and minimum value of $\left|\frac{q}{F_{es}}\right|$ in the pilot passband frequency, as represented in Figure 36, below.

Pitch rate overshoot is an indication of the sensitivity of the amplitude of the pitch rate response to the inputs frequency and an inherent measure of the equivalent damping ratio. It is an analogous concept to the amplitude resonance of the Neal-Smith criterion, with the significant difference that it is relative to the open loop response, that the gain droop is not constrained, and that it is referred to pitch rate perturbation, instead of pitch attitude. $\Delta G(q)$ is not strictly limited to small amplitudes and it is a functional complement to the bandwidth concept, which is more typical of small amplitude inputs. It is the author's understanding that referring to pitch rate is more closely related to the pilot's motion cues, instead of to the objective of the task, making this "open loop" criterion of potentially wider application with respect to others. High values of $\Delta G(q)$ indicate low damping, $\Delta G(q) > 9\ dB$ is associated to the tendency to "bobbling", $\Delta G(q) > 12\ dB$ to "Moderate" PIO when bandwidth is low.

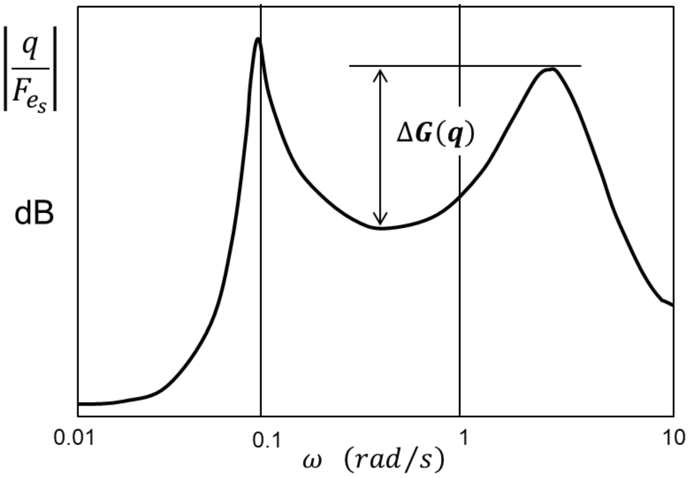


Figure 36. Aircraft bandwidth criterion pitch rate overshoot

The pitch response is also characterized by the $\omega_{BW\theta}$ and $\omega_{BW\gamma}$ requirements envelope of Figure 37, below. Those displayed are for flight phase Category C. This part of the criterion addresses the dual heaving and rotational nature of the short period, respectively represented by $\omega_{BW\gamma}$ and $\omega_{BW\theta}$. It is the author's understanding of the requirement that a minimum threshold of $\omega_{BW\gamma}$ is required to ensure adequate FPA control (lower boundaries); at the same time $\omega_{BW\gamma}$ and $\omega_{BW\theta}$ have to be commensurate, and an increasing value of $\omega_{BW\gamma}$ has to correspond to increasing values of $\omega_{BW\theta}$ (sloped boundaries).

The criterion is also applied to the roll response, whose requirements are displayed in Figure 38, below. The roll attitude bandwidth $\omega_{BW\phi}$ is calculated with the same approach of the pitch attitude bandwidth $\omega_{BW\theta}$.

Different requirements are specified for responses with and without feel system dynamics. This is a significant advantage, as it allows designing control laws and control system independently from the feel system dynamics, which can be refined in a second phase of the aircraft design.

One of the shortcomings of this criterion is the inapplicability to responses with a shallow slope of the amplitude in the frequency range of pilot's control. This can lead to low values of the gain bandwidth, and consequently of the aircraft bandwidth, which do not fully correspond to the actual aircraft characteristics. A second drawback is the lack of a maximum value of the bandwidth, which does not allow accurate detection of potentially abrupt responses.

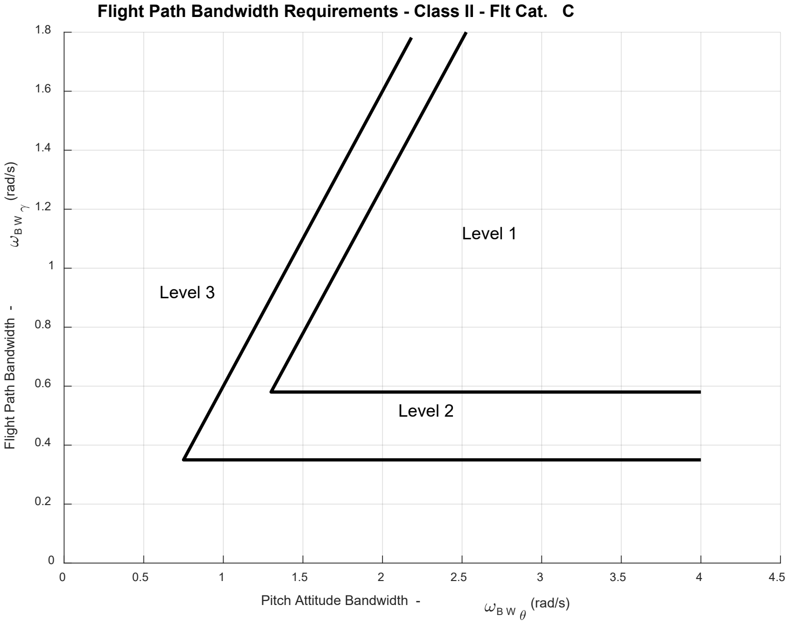


Figure 37. Aircraft bandwidth criterion $\omega_{BW\theta}$ and $\omega_{BW\gamma}$ requirements, no feel system

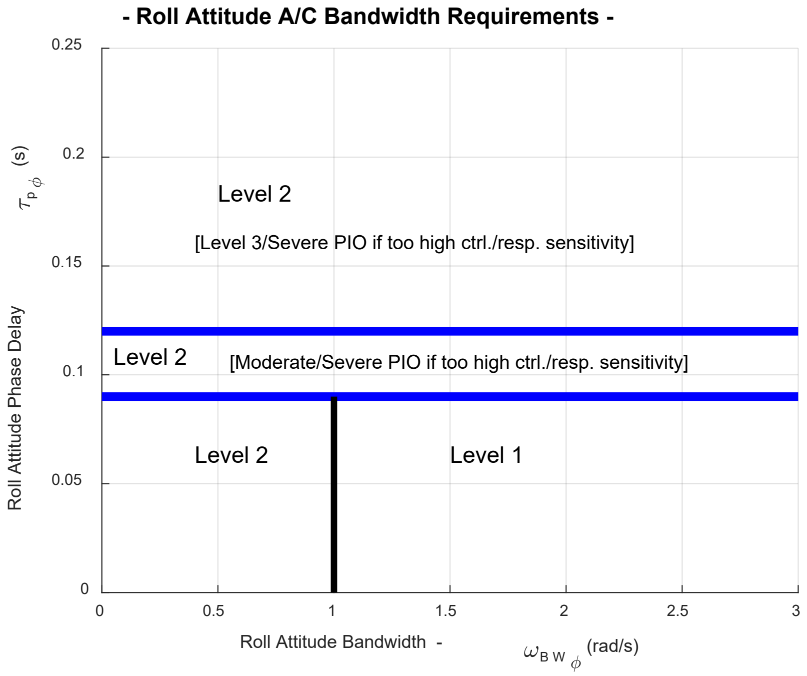


Figure 38. Aircraft bandwidth criterion - roll requirements, no feel system

The background concepts of the criterion and the same definitions of bandwidth and phase delay were applied to specify metrics in the rotary wing military specification ADS-33E-PRF [18]. Requirements boundaries in the bandwidth-phase delay plane are specified for pitch, roll, and yaw attitude, with and without feel system dynamics.

The applicability of the criterion to both fixed and rotary wing aircraft makes the Aircraft Bandwidth an effective metric for UAMVs, which can usually operate both in wing-borne and rotor-borne flight, depending on the mission phase.

The benefit of the Aircraft Bandwidth is of being an “open loop” criterion, which does not require assumptions on the pilot’s dynamics/compensation and on the required bandwidth to accomplish specific tasks. It includes the background concepts of Neal-Smith, CAP, and LOES criteria, with a higher degree of flexibility and adaptability to the different aircraft responses. Its application is necessary and sufficient, and it allows accurate prediction of aircraft handling qualities, including PIO proneness. Similar to the Neal-Smith criterion, it does not depend on the calculation of the aircraft modal parameters, making its application straightforward for both un-augmented and highly augmented aircraft. This is a significant advantage for the simplicity of the analytical tools required in its application.

In case no model data are available, it is relatively easy to measure the required data in flight to derive the transfer functions for the application of the criterion. A qualitative pitch rate overshoot assessment can be performed by the pilot, executing a constant amplitude pitch frequency sweep, and noting the amplitude of the pitch rate response. This approach has a significant value in identifying the potential for exceeding aircraft limits and for entering PIO conditions, increasing safety. Even if the highest technical value of applying HQ prediction criteria is in their application prior to flight, a post flight calculation of the criterion metrics can be a useful support to the characterization of the aircraft response and to complement the pilot's comments with quantitative values. This can be an effective approach to identify control laws/FCS deficiencies and provide guidance for their improvements.

It is the author's opinion that prediction of aircraft handling qualities should always include application of the Aircraft Bandwidth criterion amongst the ones utilized.

Recommendation R16: The FAA should adopt the Aircraft Bandwidth criterion as the reference one for handling qualities prediction. This can be part of a MOC.

6.6 Other criteria

Several other criteria are available, specifically for fixed wing aircraft HQ prediction, including the Flight Path Angle Overshoot criterion, the Gibson criterion, C-star (C*), and the Calspan time domain criterion. Some of the underlying concepts of these criteria, like that of theta "dropback" and "overshoot", related to FPA predictability, are more typical of conventional fixed wing aircraft and aimed in particular to their landing phase. They are not all discussed in this work, for their lower expected relevance for E-VTOL aircraft.

6.7 Discussion

The HQ prediction criteria presented in the previous sections are a small, selected list of those available to the designer. As mentioned in the introduction, their value is composite.

Criteria of this type have to be applied in any model-based design process to avoid application of empirical methods, which are increasingly facilitated by the large computational power of the tools available for design. They provide fundamental metrics to understand and characterize the aircraft response, both analytically and experimentally.

Their value is funded in the design phase and it propagates throughout the flight clearance and the testing phase of a new vehicle. Knowledge of the criteria on which an aircraft response is designed allows pilots and engineers to have a common reference to exchange information in the different phases of the aircraft design, development, and testing. It supports the design/specification of handling qualities evaluation tasks and pilot's reporting of aircraft characteristics through comments.

The selection of the criteria to present was based on their relevance for hybrid configuration aircraft and on the applicability of their metrics to possible new criteria specifically developed for UAMVs.

They are also a fundamental tool during the aircraft certification process proposed in this work, to provide the FAA with quantitative gates to allow the progress from the design to the flight phase, to assess open loop vehicle characteristics, and to guide improvements of handling qualities deficiencies. The scope is to avoid certification of a FBW aircraft with a "black box" approach.

In their practical use, several different criteria are applied. This is done to analyze the aircraft response from different standpoints (i.e. response to continuous pilot's compensation, to combined gross acquisition and fine tracking, predictability, and FPA control). This concurs to develop a "mental picture" of the predicted handling qualities and of the nature of the potential deficiencies.

One critical aspect of these criteria is that the predicted handling qualities levels are based on the aircraft classification and flight phase category. The aircraft classification (section 6.1and [23]) is a function of the aircraft size, weight, maneuverability, and overall mission. As an example, Part 23 aircraft broadly match the definition of Class I: "Small, light airplanes such as Light utility, Primary trainer, Light observation," which is a function of size, weight and general mission requirements.

Class III: "Large, heavy, low-to-medium maneuverability airplanes such as Heavy transport/cargo/tanker - Heavy bomber - Patrol/early warning/electronic countermeasures/airborne command, control, or communications relay - Trainer for Class III" is also a function of maneuverability, which is somehow inherent in the scope of handling qualities prediction.

This fits the military aircraft classification; at the same time, this classification is not expected to be as effective for aircraft with the same mission requirements and significantly different configurations, like UAMVs.

A possible approach for the application of the current criteria to hybrid configuration aircraft is to remove the current aircraft classification. Combination of aircraft class and flight phase category could be substituted by the definition of Mission Task Elements, as in ADS-33E-PRF.

This change is expected to be effective in manned simulations during the design and flight clearance phase, and in the flight test phase. This allows certification based on the actual mission/operational requirements.

A potentially critical aspect is mapping the MTE requirements to the analytical ones. It is fundamental to retain analytical HQ prediction criteria to guide design, and consequently, the early stages of certification. While the mission requirements and concepts of operation are fundamental for the end user, consistency of the design with the aircraft specification must also be based on analytical methods. Both rotary and fixed wing criteria will have to be part of the reference criteria, with the Aircraft Bandwidth criterion being the reference for its applicability to both types of aircraft.

Recommendation R17: The FAA should define new aircraft classifications for handling qualities prediction criteria, linked to the mission task requirements and not to the size or physical properties of the aircraft.

7 Sample steps in the control laws design/development process

7.1 Introduction

This section illustrates a sample control laws design process as a list of activities. The scope is to provide a reference for the proposed certification process.

It includes the required documentation to be issued formally as a preliminary step. Procedurally, this is the internal specification for the implementation of the design and clearance process. Under a certification point of view, the value of the documentation is double: (1) the FAA verifies that the process is implemented correctly by ensuring the existence of the formally documented criteria and (2) that the criteria themselves are consistent with the certification requirements of the FAA and with industry standard practice.

The described applicative steps of the process are generalized, as placeholders for a notional development process. Quantitative values are reported as a general guidance, where they are widely accepted as part of a standard practice, or as examples.

The scope of the FAA should be to ensure that the process exists, and it is technically and regulatory consistent.

7.2 Formal preliminary steps

7.2.1 Aircraft specification

The aircraft specification contains the requirements as design objectives. The specification describes the vehicle mission(s), required vehicle characteristics and performances, and related flight envelope(s). Characteristics requirements are expected to include the following: aircraft configuration, weight, type of propulsion system, take-off and landing modes, crew, capabilities, constraints, and other functions necessary to satisfy the objectives. Performance requirements are quantitative values applied to the satisfaction of the objectives. These can include stability & control properties, flying and handling qualities, range, endurance, and take-off and landing performance. Concept of Operations (ConOps) can be included in the specification, defining the aircraft life-cycle operation to meet the stakeholder requirements. ConOps describe the aircraft characteristics from an operational perspective and supports the definition of the aircraft mission.

The aircraft specification reports also the applicable documents as guides in the design of the aircraft detailed by the specification itself. These documents are civil aviation authority regulations, advisory material, industry standards and criteria, military specifications, and internal best practices.

7.2.2 Handling specification

The handling specification document contains the requirements of the vehicle handling characteristics. This document can be a part of, or be derived from, the aircraft specification. As a minimum, the handling specification reports the required handling qualities levels, typically defined according to NASA TN D-5153 [24], as a function of:

a. Flight envelope
b. Operational state
c. Flight phase
d. Configuration
e. Atmospheric conditions

For Part 23 aircraft, the configuration might be a combination of payload distribution and secondary control surfaces/effectors deflection/configuration. As for the general aircraft specification, handling specification is mainly based on ConOps/mission requirements. The scope is to ensure that handling qualities do not lead to any limitations on flight safety or on the aircraft capability to perform the required mission(s).

This means that HQ must be Level 1, “satisfactory without improvement,” in the whole Operational Flight Envelope.

HQ degradation to Level 2, “deficiencies warrant improvement,” is typically allowed in the Operational Flight Envelope for minimum safe operation failure states and for adverse atmospheric conditions.

HQ can be Level 2 in full operational state, between the Operational Flight Envelope and the Limit Flight Envelope.

HQ Level 3, “deficiencies require improvement,” are not usually allowed in any region of the flight envelope. Exceptions can be the flight phases following a recovery from out of control situation, with an associated failure state. In this case, the main objective is to maintain control of the aircraft and attempt to restore its full operational state. Level 3 corresponds to a reduction of the flight safety level and to the abandonment of any specific task, with the aircraft still controllable, as respectively stated in the Cooper-Harper rating scale definitions of (1) aircraft characteristics and (2) demands on the pilot.

The high importance of the handling specification is to define the boundaries of the handling qualities levels, and consequently of the flight envelopes, to drive the aircraft development until the production phase. The constraints are the HQ levels, the operational state, the envelopes, and the atmospheric conditions.

7.2.3 Guidelines for control laws design and flight clearance criteria

This phase consists of the selection, development, and synthesis of guidelines for control laws design and for clearance criteria. The result is the official release of documents describing the control laws design approach and the criteria applied for flight clearance. The scope of these documents is to provide requirements based on the combination of flight envelope and operational state, for nominal and tolerance cases. The information they provide can be grouped in the following categories:

1. Design criteria and technical guidance to optimize aircraft stability and handling qualities. These do not usually correspond to formal *gates* for the advancement of the design.
2. Requirements to guarantee the stability of the FCS aerodynamic feedback loops, both in the linear and non-linear regimes. These requirements are not explicitly related to handling qualities, and for the linear regime can be generally identified as:
    a. All eigenvalues of the electronically closed loop system have to be stable – their real part has to be negative.

b. Requirements on the values of Gain Margin (GM) and Phase Margin (PM) of the control aerodynamic feedback loop(s) open in correspondence of each actuator input, with all the other feedback loops closed. Quantitative values of GM and PM for aerodynamically closed loop flight control systems are provided in MIL-DTL-9490E [22], in particular in paragraphs 3.1.3.6.1, 3.1.3.6.2, 3.1.3.8 and SAE-AS94900 [33].

Table 5 below is extracted from SAE-AS94900; it reports the numerical values of gain and phase margin required in the whole OFE, in the most adverse center of gravity and mass distribution conditions.

Table 5. MIL-DTL-9490E open loop stability requirements

Mode Frequency (Hz)	Below $V_{o_{min}}$	$V_{o_{min}}$ to $V_{o_{max}}$	At Limit Airspeed (V_L)	At $1.15V_L$
$f_M < 0.06$	$GM = 6dB$ No Phase Requirement	$GM = \pm 4.5dB$ $PM = \pm 30\ deg$	$GM = \pm 3.0dB$ $PM = \pm 20\ deg$	$GM = 0$ $PM = 0$ Stable at Nominal Phase and Gain
$0.06 \leq f_M <$ First Aeroelastic Mode		$GM = \pm 6.0dB$ $PM = \pm 45\ deg$	$GM = \pm 4.5dB$ $PM = \pm 30\ deg$	
$f_M >$ First Aeroelastic Mode		$GM = \pm 8.0dB$ $PM = \pm 60\ deg$	$GM = \pm 6.0dB$ $PM = \pm 45\ deg$	

Where:

V_L is the Limit airspeed as defined in MIL-A-8860 [34].

$V_{o_{min}}$ is the Minimum Operational airspeed as defined in MIL-F-8785 [23].

$V_{o_{max}}$ is the Maximum Operational airspeed as defined in MIL-F-8785 [23].

Mode is a characteristics aeroelastic response of the aircraft as described by an aeroelastic characteristic root of the coupled aircraft/FCS dynamic equation of motion.

f_M is the mode frequency in Hz.

Nominal Phase and Gain are the contractor's best estimate or measurement of FCS and aircraft phase and gain characteristics available at the time of requirement verification.

It is important to notice that the values of gain and phase margins are those available "at the time of verification." This implies that they can be derived from prediction models, from models matched and validated versus flight and from flight data, depending on the developmental stage of the aircraft. This highlights the importance of model-based design and the value of models to assess and demonstrate the respect of the requirements, in this case to the FAA.

c. Positive margins with respect to the *Nichols criterion* exclusion zone of the Nichols plot, with the control feedback loop(s) open in correspondence of each actuator input, one at a time. The frequency range of validity of the exclusion zone criterion is usually comprised between those of the minimum and maximum six degree of freedom modes of the aircraft. Figure 39, below, illustrates the point at which the loop is opened to conduct the analysis.

   An example of how the exclusion zone can be graphically defined is provided in Figure 40, below. It represents the GM and PM requirements for systems with possible conditional stability, i.e. poles with positive real part, which are in the Right Half (Gauss) Plane (RHP). There is a Lower Gain Margin (GML) and an Upper Gain Margin (GMU), where lower and upper refer to the lower phase crossover frequency ω_{PCL} and the upper phase crossover frequency ω_{PCU}. The upper boundary of the exclusion zone is the required GML, the lower one is the required GMU, and the right boundary defines the phase margin.

In these requirements, the aerodynamic loop is based on aerodynamics and/or thrust vectoring forces and moments for loop closure.

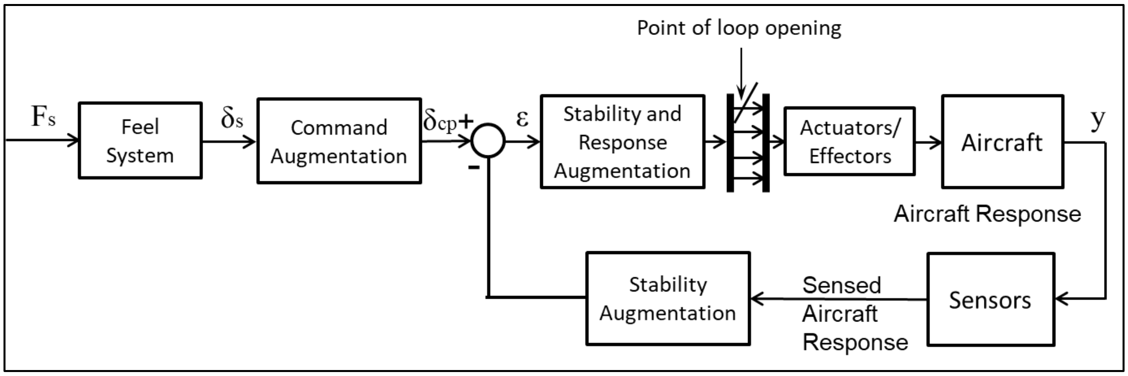


Figure 39. Point of loop opening for stability analysis

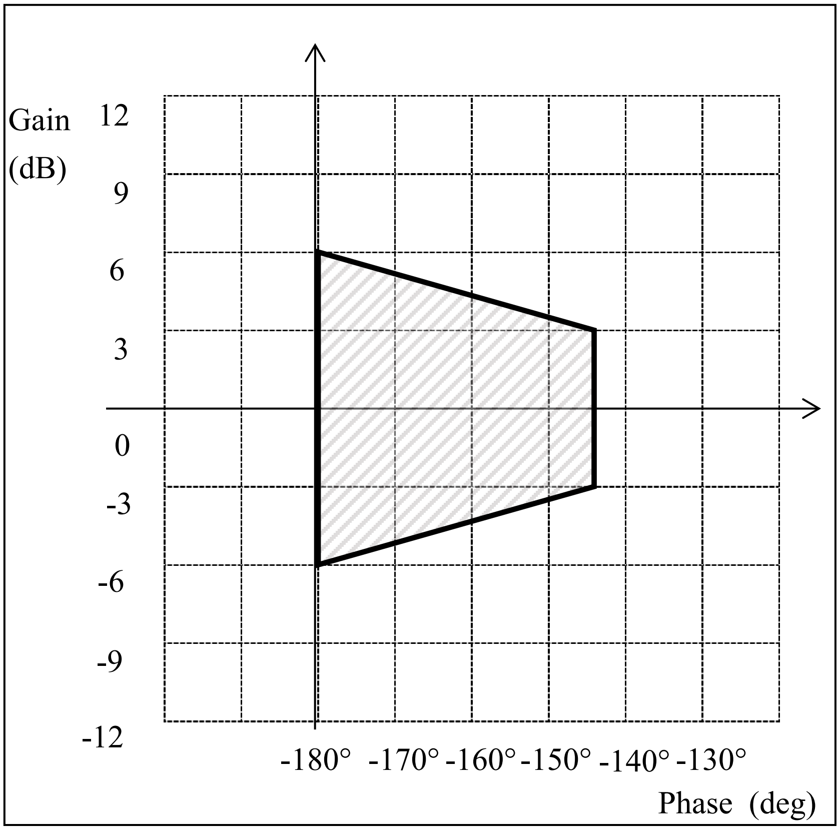


Figure 40. Nichols plot exclusion zone

Different exclusion zones are applied for stability analysis of failure and off-nominal configurations. In this case, zones are smaller, with less stringent margins, in particular for GMU and GML. Failures include actuators, air data system, sensors and landing gear. Off-nominal correspond to toleranced airframe and systems models, i.e. aerodynamics, FCS including actuators and sensing characteristics of air data system(s). Figure 41 and Figure 42 below show two examples of possible exclusion zones for failure and off-nominal conditions, traced with dashed lines.

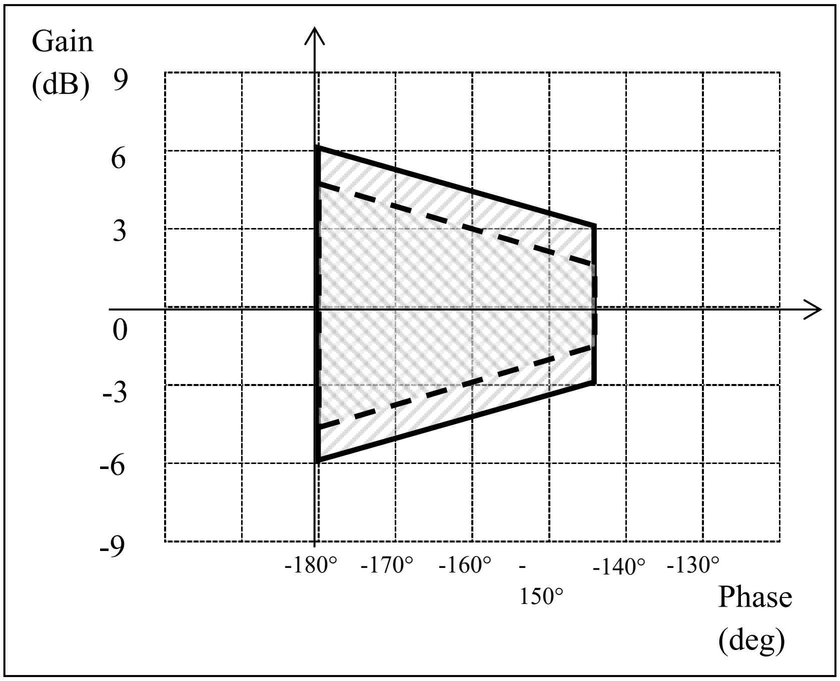


Figure 41. Failure and off-nominal configurations exclusion zone example 1

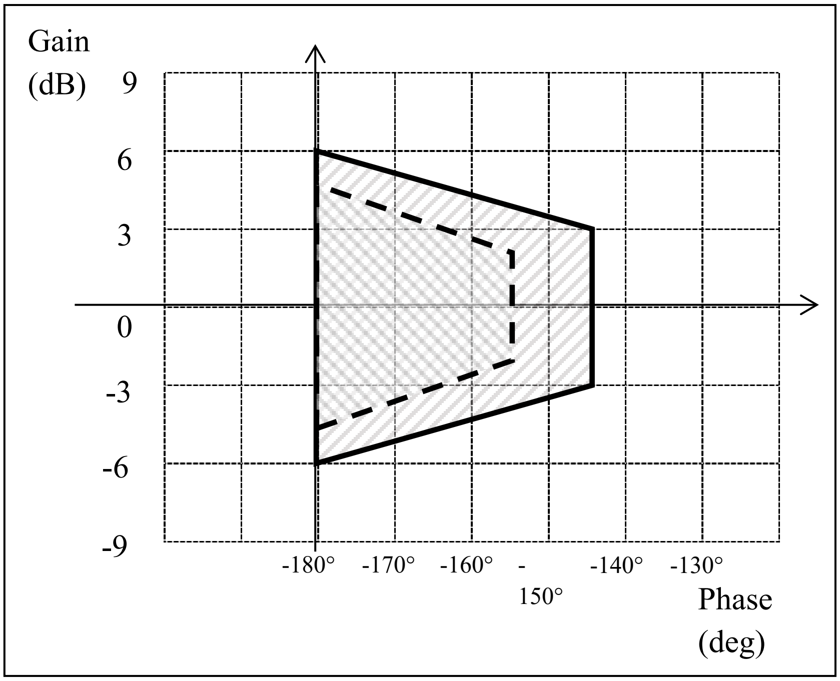


Figure 42. Failure and off-nominal configurations exclusion zone example 2

In the first example, the GML and GMU requirements are relaxed, maintaining the same requirement for PM. In the second example, all three requirements are relaxed.

The Nichols plot exclusion zones are particularly valuable to assess the stability of systems with unstable poles, as they inherently require the value of the gain crossover frequency ω_{GC} to be between the upper and lower phase crossover frequency, with predefined margins.

The requirement for augmented systems with unaugmented unstable dynamics is:

$$\omega_{PCL} < \omega_{GC} < \omega_{PCU}.$$

Figure 43 and Figure 44 are examples of application of the nominal configuration/full operational state exclusion zone to the open elevator actuator-to-actuator loop of a fixed wing aircraft with unstable short period dynamics.

Figure 43 shows that the impact of the reduction of actuator bandwidth $\omega_{BW_{act}}$ is significant at the higher frequencies, reducing the GMU and PM, as expected. This is due to the reduction of the open loop phase cross-over frequency ω_{GC}. A parallel can be done with the results of the handling qualities evaluations presented in section 3.4. Handling qualities of augmented aircraft with lower actuator bandwidth were rated lower, due to the lower stability and the higher phase lag of the augmented system. See section 6.5 for impact of the phase crossover frequency on the aircraft bandwidth. In Figure 43 the system with the lowest $\omega_{BW_{act}}$ does not satisfy the stability requirements: $\omega_{BW_{act}}$ has to be adequately higher than the frequency of the unstable dynamics to ensure adequate stability of the system. The performance of the closed loop system (i.e.: augmented aircraft) is mainly determined by the actuators bandwidth and by the unstable dynamics.

The Bode plot of Figure 45 illustrates the significant effect of the reduction of ω_{PCU} on the reduction of GMU, with GML remaining unchanged.

Figure 44 shows that variation of the aerodynamic gain M_{δ_e}, due to a reduction of the elevator aerodynamic effectiveness, leads to variation of the open loop gain, with unchanged phase characteristics. This produces a vertical translation of the Nichols plot, a reduction of the GML and an increase of the GMU when decreasing M_{δ_e}. The system with the lowest M_{δ_e} does not satisfy the GML requirements.

The Bode plot of Figure 46 illustrates the variation of GML, GMU, of the gain cross-over frequency ω_{GC}, and the unchanged system phase. The impact of the variation of ω_{GC} on PM is noticeable, with no monotonic variation as a function of M_{δ_e}.

From the observation of both the Nichols and the Bode plots, it is noticeable that the Nichols plots are a more effective way to assess the stability of the closed loop system with respect to predefined margins.

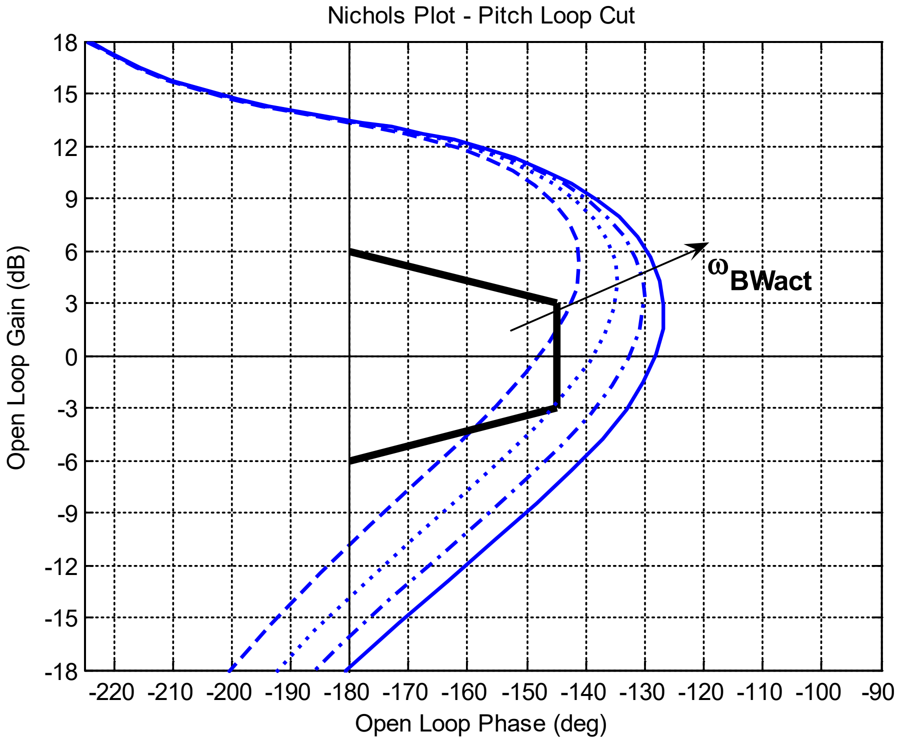


Figure 43. Effect of variation of actuators bandwidth on stability- Nichols plot

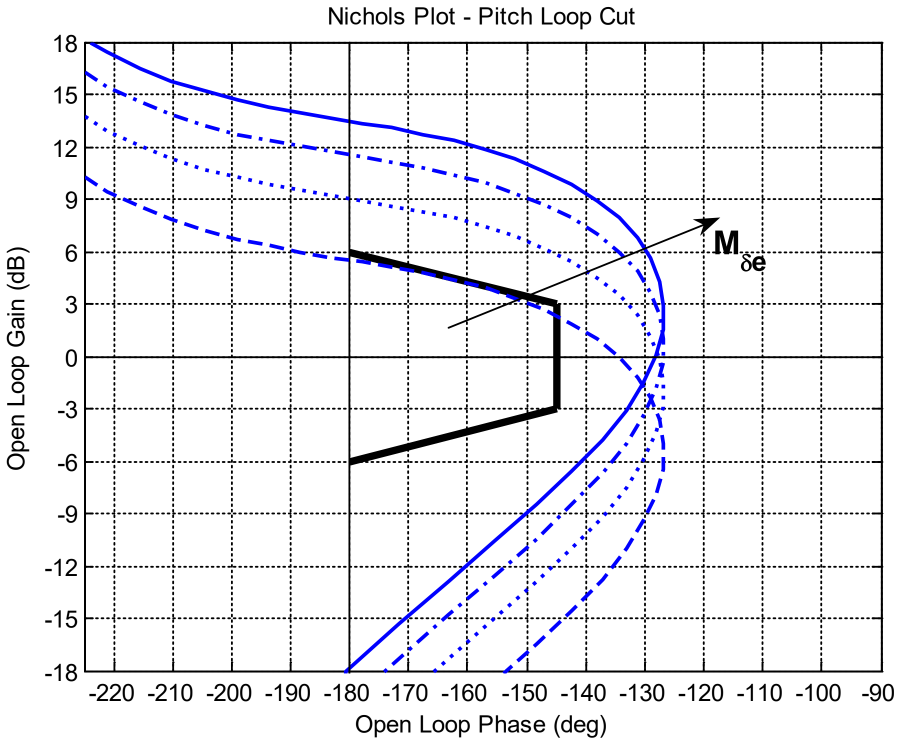


Figure 44. Effect of variation of M_{δ_e} on stability

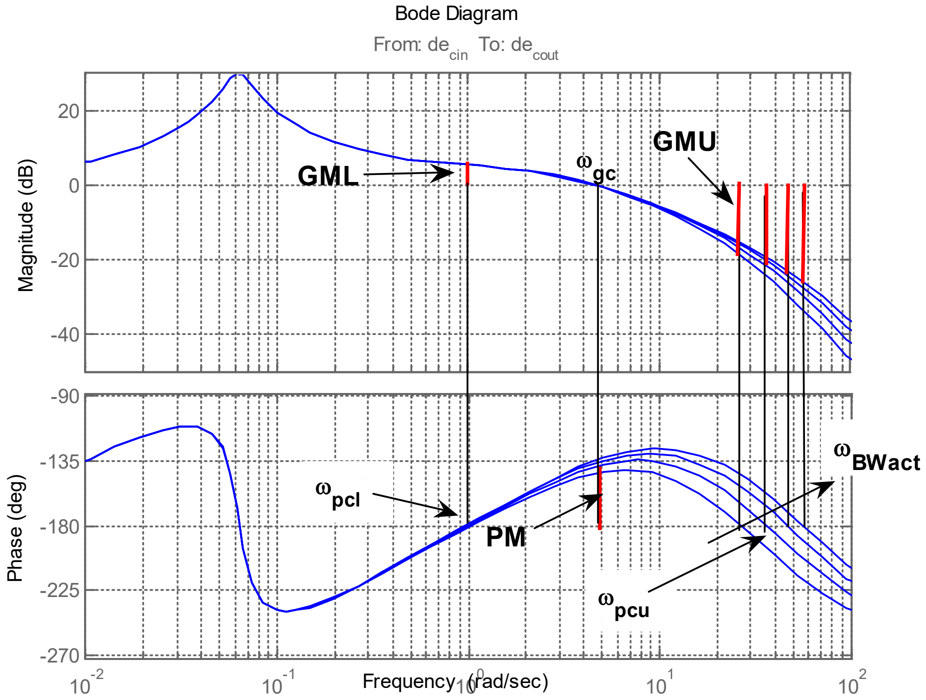


Figure 45. Effect of variation of actuators bandwidth on stability – Bode plot

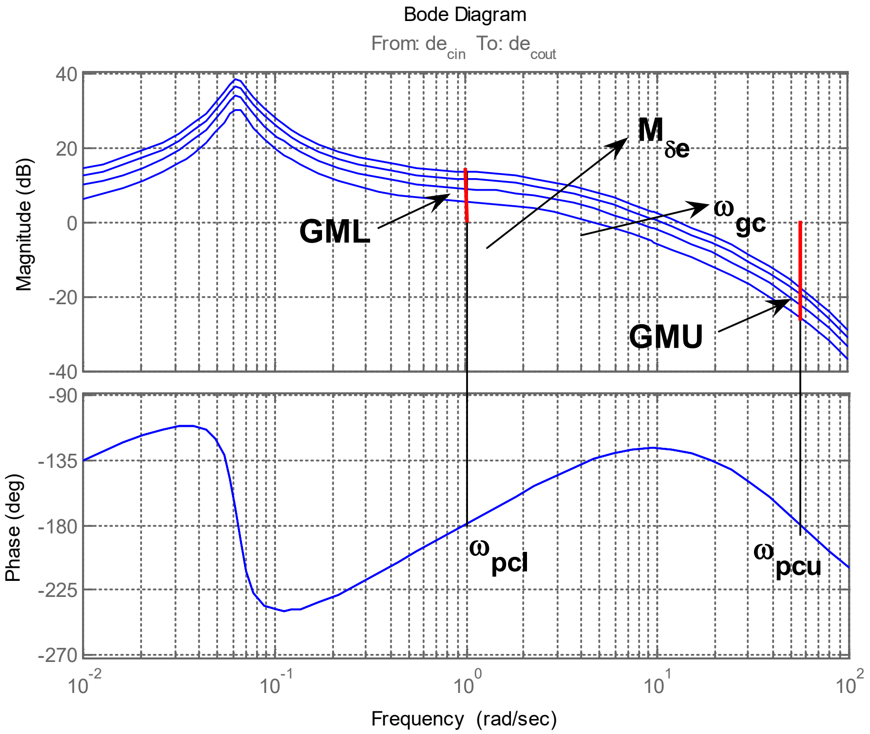


Figure 46. Effect of variation of M_{δ_e}on stability – Bode plot

Considering the two notional examples of Figure 43 and Figure 44, two different ways for application of the requirements are possible, depending on the aircraft development phase.

In the design phase the full operational stability requirements of Figure 40 would be applied to the varying parameters $\omega_{BW_{act}}$ and M_{δ_e}, for example. This would ensure appropriate selection of the actuators and of the design of the longitudinal control surface to guarantee proper stability.

In the clearance phase, the failure/off-nominal conditions requirements of Figure 41 or Figure 42 would be applied to assess the respect of the stability margins with degraded actuators performance due to failure, varying $\omega_{BW_{act}}$, and with uncertainties on the aircraft aerodynamics, varying M_{δ_e}. In the design phase, the margin with respect to the requirement is valuable information for design refinements, while in the clearance phase the exclusion zone requirements would be applied as a pass/fail criterion.

The clearance approach can be applied by the FAA, as a pass/fail criterion for a potential stability gate applied by the FAA during certification.

Operatively, using the exclusion zone of the Nichols plots, allows for a quick graphical assessment of the pass/fail status of the augmented vehicle. As stated above, the margin with respect to the exclusion zone is not relevant in this case.

Recommendation R18: The FAA should use the Nichols exclusion zones as a baseline method for quantitative assessment of closed loop stability in the certification process.

7.2.4 Critical flight clearance criteria

Critical flight clearance criteria: this is the set of minimum handling qualities requirements. They are mandatory and a subset of the design criteria, potentially less stringent. They are a combination of non-handling related (i.e. GM, PM discussed above) and handling related requirements, linear and nonlinear. For example:

- Minimum value of eigenvalues damping ratio and natural frequency.
- Disturbance rejection bandwidth and disturbance rejection peak.
- Handling qualities prediction criteria. These include the criteria publicly issued and those that the applicant/manufacturer will define.

The formal flight clearance stability requirements of the augmented aircraft, the predicted handling qualities levels required in correspondence of different combined (1) operational states, (2) control system modes, (3) flight envelopes, and (4) nominal and toleranced conditions, is fundamental information for the process. Less stringent linear and nonlinear stability and predicted HQ level requirements are expected for degraded operational states and for toleranced cases, as described in point 2 (c) of section 7.2.3.

This step contains specification of the type of open loop inputs for offline simulations for the linear and nonlinear stability and controller performance analysis.

Design of the inputs will have to expose the response to the required metrics and criteria specified for given parts of mission flight phases, or MTEs. For the open loop and HQ predictive nature of the criteria, this group of MTEs is defined in [35] as FQTEs. This marks the distinction between Flying Qualities/open loop and Handling Qualities/closed loop MTEs.

Multiple *first flights* have to be planned in the development of the aircraft, corresponding to clearance of a specific control laws mode and/or within a specific envelope. As a consequence, different experimental airworthiness certificates might be required.

The following is a suggested list of requirements to ensure that the FBW system is designed and cleared according to certification standards.

a. Software certification.
b. System integration tests, such as avionics and electrical “hot benches,” “rig tests,” avionics manned simulator.

c. Linear, nonlinear stability, controller performance, robustness.
d. HQ prediction.
e. Execution of manned evaluations. The last step of the clearance process is the handling qualities manned evaluations: the pilot is responsible for the final decision on authorizing the aircraft to be flown, based on safety and respect of the mission requirements. The main part of these requirements is the specification of the handling qualities tasks in each area of the flight envelope. Tasks are typically (1) operationally representative, (2) tightest of the operational requirements, for investigation of the *HQ cliff*, and (3) what could be called *synthetic tasks.* These are designed by extracting a single HQ element from a more complex and composite task. Examples of *synthetic tasks* are the pitch attitude and roll attitude captures, mostly conducted by tracking a target in the Head Up Display (HUD), for high performance military aircraft. While they are not fully operationally representative, they can expose potential handling qualities deficiencies critical to operational air-to-air tracking tasks. The pitch and roll attitude capture profiles are reported in [29]. A similar approach can be applied to Part 23 aircraft, including UAMVs, based on their specific mission characteristics.

   Overall, tasks have to be designed in order to require different control techniques (i.e. gross acquisition + fine tuning, continuous compensatory control) and maneuvers' amplitudes, including large amplitude maneuvers and carefree maneuvers, if a hard envelope protection system is part of the control laws.

   Main scopes of the specified tasks are: (1) to verify that the required handling qualities requirements are met, in full operational state and failure states, (2) the absence of PIO proneness, and (3) the effectiveness of the envelope protection.

   These tasks are defined in [35] as HQTEs, which is the part of the MTEs addressing the actual vehicle handling qualities, as evaluated by the pilot.

The design of specific MTEs, which address the aircraft ConOps, is the highest priority for this phase, for both developmental and certification scopes. Considering the level of automation of vehicles developed according to SVO concepts, part of the MTEs requiring pilot's evaluation are potentially not pure handling qualities task elements.

The content of the document reporting the critical flight clearance criteria is both quantitative and qualitative. Stability and predicted handling qualities metrics are defined, together with the engineering process and requirements that will be applied in the design phase to match the quantitative portion of each metric. Required metrics applicable in the design phase provide guidance to ensure adequate handling qualities level and robustness.

Those applicable in the flight clearance process are the mandatory stability and handling qualities gates to be satisfied to authorize the aircraft to begin the flight testing phase.

The metrics in this document are not necessarily coincident with those reported in the aircraft handling specification, which define the handling performance.

Consequently, an exact correlation is not expected between handling specification and flight clearance specification requirements.

The level of detail of the design and clearance criteria can be locally higher than that applicable to the aircraft handling performance of the aircraft specification. They are aimed at ensuring the robustness of the design, according to principles verified by the manufacturer or by recognized sources within the aeronautical industry.

As a generalized example, the gain and phase margin are the standard hard, mandatory criteria to define the stability of a system. The developer of the system defines the metric (i.e. gain and phase margin) and the values of both margins required to achieve an adequate level of stability (i.e. GM=6 dB, PM=45 deg) to ensure satisfaction of higher-level system requirements. Actions to be taken in case of non-compliance with the criteria in both the design and clearance phase are described. Different priority levels, from mandatory to advisory are defined.

The higher-level requirements are those related to predicted handling qualities, usually developed in military specifications, by industry, research organizations, or proprietary of the aircraft manufacturer. This subject is treated in section 6 above.

7.2.5 Discussion

From the developmental and procedural standpoint, the formalization and documentation of steps a. and b. of section 7.2.4 is fundamental to the manufacturer/applicant to ensure that the aircraft performance, including handling performance and mission requirements, are first identified and consequently officially defined. Traceability of the requirements and engineering practice of design per requirements is expected to ensure a minimum standard for adequacy of the design.

Recommendation R19: The FAA should verify the existence and the formal release by the applicant of the vehicle specification and of the handling specification. The handling specification can be standalone, or a part of the aircraft specification. This can be the subject of a dedicated MOC.

Steps c. and d. of section 7.2.4 are relevant for the aircraft handling requirements. The applicant must identify criteria and corresponding values prior to the design phase.

Selection of appropriate HQ prediction criteria is as important as applying them.

Under a broad standpoint, reliability and neutrality of the results of the predicted handling qualities assessment is ensured by the application of standard criteria developed by third parties through research and verification. The success of the design and of the subsequent clearance process derives in this approach from referring to widely used and verified criteria, which can be the reference throughout all phases of the aircraft development and operation.

The update of the aircraft models, the reduction of the relative tolerances, which derive from their matching with flight test, shall require a continuous re-application of the predefined criteria.

It is important that these are merged with quantitative assessment with respect to the criteria. This provides a neutral, and particularly quantitative, component in the evaluations based on the experience of all the previous evaluators who contributed to the definition of these metrics and criteria.

This is particularly relevant for the general aviation aeronautical community, which is currently experiencing a significant and fast technological change in a field in which it has no specific technical background.

Potential limitations in the applicability of metrics/criteria developed for other vehicle types are preferable to the absence of them.

The correct technical and engineering attitude, which should also be supported by the FAA, is towards an adaptation of the current criteria to the characteristics of the new vehicles, instead of neglecting them for their partial applicability.

Recommendation R20: The FAA should release guidance material and recommendations towards the application of current handling qualities prediction criteria, guiding adaptation of the quantitative part of the requirements to the new class of vehicles, when necessary.

Involvement of the certification authority in the selection of a minimum subset of mandatory requirements would be beneficial. This approach would match the current 14 CFR Part 23 Amendment 64 approach, which is ASTM based. As an example, there is potential for the FAA to include in the mandatory list standard handling qualities criteria as Aircraft Bandwidth, MIL-STD-1797B and ADS-33E-PRF derived ones, attitude and agility quickness for rotor-borne flight.

Considering the types of personal aerial vehicles under certification, third party tests will be necessary to refine the requirements, as standard criteria are based on vehicle and task elements that are significantly different from the current aircraft developed for Part 23 certification.

Recommendation R21: The FAA should ensure the existence and the formal release by the applicant of an official document defining design, flight clearance principles and criteria, together with the related compliance verification process. This can be the subject of a dedicated MOC.

Recommendation R22: The FAA should identify a minimum set of stability and flying qualities requirements, selected between the current industry standard ones, which must be satisfied by the design as part of the flight clearance. Required verification must be analytical. This can be the subject of advisory material and a dedicated MOC.

Recommendation R23: The FAA should define a minimum set of MTEs for certification of Urban Air Mobility Vehicles. These should include open loop (FQTE) and closed loop (HQTE) MTEs.

7.3 Development of the vehicle models

7.3.1 General process

The availability of a high-fidelity aircraft simulation model is the most important component for the design of flight control system, control laws, and to predict aircraft performance. The technical methods applied to develop the model will depend on the manufacturer, based on the different target level of accuracies, depending on the region of the flight envelope, the control laws design approach, and the aircraft characteristics. Below is a list of steps into which the development of aircraft simulation models can be divided, specifically oriented to control laws design:

a. Aircraft simulation model specification – requirements for validity envelope and corresponding fidelity level of the aircraft model used for control laws design and subsequently flight clearance.
b. Formalization and issue of the specification of the accuracy and validity envelope(s) of each of its component models.

   This applies to each model which is part of the aircraft model and whose functioning/fidelity affects the aircraft handling characteristics. The level of fidelity of the component models has to be comparable across all of them, in particular in the cross-over frequency range of the vehicle dynamics.

c. Development of the bare airframe and aircraft systems models in accordance with the required level of fidelity. The principal models are outlined below.

    - Airframe:
        - Aerodynamics Stability and Control (S&C)
        - Mass properties
        - Air data system (ADS)
        - Hinge moments
        - Landing gear, ground reaction
    - Feel System and Flight Control System:
        - Inceptors
        - Hydraulic and/or electrical system
        - Actuators/effectors, including rotors for UAMVs
        - Sensors (inertial, air data, control surfaces)
        - Command path and feedback path filters
        - Structural modes filters
        - Time delays
    - Standard atmosphere model, including atmospheric disturbances

After development of the individual models, they have to be implemented into the aircraft simulation model. This is the reference model for the control laws design and assessment of the handling characteristics, offline analysis and simulations, and manned simulations. The model has to be valid for all aircraft operational states, nominal and off-nominal (toleranced) cases.

Each model has to include the set of tolerances required to represent off-nominal characteristics for robust design.

When the propulsion model is not developed by the aircraft manufacturer, accuracy requirements for the different phases of flight and of operation are issued by the aircraft manufacturer to the manufacturer of the propulsion system.

The propulsion system can also be designed and manufactured by the aircraft manufacturer, in particular for E-VTOL vehicles. In this case, the manufacturer should issue a formal release of the propulsion model, including a statement of its accuracy.

The requirements on the models fidelity level are based on a combination of the source of the data (i.e. flight test, wind tunnel test, CFD, analytical methods, similarity/scaling methods with other models or vehicles) and on the statistical level of confidence, which determines the magnitude of the applicable tolerances. The target of the required validity envelope of each model must be the service flight envelope, including margins to cover potential mishandling and modeled inaccuracies of the air data system measurements. Margins have to be defined with respect to each of the states describing the aircraft flight envelopes, see section 5.2 for envelope definitions.

7.3.2 Procedural aspects related to aircraft modeling

Relevance for Handling Characteristics – The aircraft model must be formed by all the component models (i.e. actuators/effectors, air data, ground reaction, propulsion, and feel system), including failure states, which determine the aircraft handling characteristics.

Recommendation R24: The FAA should verify that the aircraft model used for control laws/FCS design and flight clearance is formed by all models that affect the aircraft handling characteristics. This can be the subject of advisory material.

Version Control – The ability to implement model updates derived from further testing/calculations and flight data matching is fundamental for model-based design. Provision for version-controlled updates has to be planned in the technical model development and in the overall design and clearance process, through a system of official releases. Every release of each model has to be accompanied by check cases to ensure the proper installation of the model in the target computer(s).

It is important that the models used in the design of the control system and the control laws satisfy the minimum fidelity requirements before the design begins, and that they are version controlled. Version controls require that each of the component models and the aircraft model are officially released and that changes are incorporated as new official releases. When possible, software for version control of files should be used.

Each phase of the design should be based on a single official release of the aircraft model for efficiency, and to reduce the risk of inconsistencies. Improvement of the aircraft models during the design phase have to be possible: the updated release(s) are used in further phases of the design or of the flight clearance cycle. Usually, it is not required for the flight clearance to be based on the same aircraft model release of the corresponding design phase.

Tolerances Application – The availability of a set of tolerances applicable to the main terms of each model is fundamental to allow for robust design and for verification of handling characteristics in off-nominal conditions. Each tolerance amplitude expressed as a function of standard deviation, and of the combinations in which they are applied, have to be stated in the model technical report, or in a separate *Tolerance Report* specifying the data source and the criteria of application of the given tolerances.

Tolerances Amplitude – The industry practice for models is to issue tolerance amplitudes corresponding to two times the standard deviation of each term: 2σ amplitude.

When multiple tolerances are applied simultaneously, each of them has to be multiplied by a weighting factor, which is a function of the number of applied tolerances. These factors are defined on a statistical basis to achieve the equivalent combined amplitude of a single tolerance. Table 6 below reports the numerical values of the tolerance weighting factor.

Table 6. Weighting factors for simultaneous application of tolerances

Number of Simultaneously Applied Tolerances	**Weighting Factor Value**
2	0.62
3	0.46
4	0.37
5 or more	0.31

The design and flight clearance criteria have to include logics for scaling of the individual tolerance amplitude as a function of the model development stage.

The standard scaling factor of the 2σ amplitude tolerances is *1.5*, 3σ amplitude, for control laws design and flight clearance models that are not matched and validated with respect to flight data. The nominal 2σ amplitude tolerances are applied, scaling factor of *1*, for the first release of models matched and validated with respect to flight. Tolerances at 1σ amplitude (i.e.: scaling factor of *0.5*) are usually applied to models matched and validated through multiple flight matching campaigns, for which confidence in their fidelity is high.

Importance of the air data system model

The air data system model is critical for the control laws development, for robustness of the design with respect to incorrect sensing of the flight conditions and with respect to system failures. A high fidelity model is required to design failure management algorithms within the air data system itself and to design dedicated control laws modes. As in the case of the other vehicle models, application of a set of tolerances allows the assessment control laws robustness. Accurate modeling of the sensed quantities by each individual sensor is fundamental to design failure management algorithms. Typically, tolerances are calculated and released for each individual sensor. The presence of more than one sensor requires the design of dedicated tolerance application algorithms to ensure considering the most conservative cases. Scaling of tolerance values follows the criteria described above.

7.3.3 Discussion

The adequate accuracy of the aircraft model is a high priority to ensure that the aircraft is safe for flight testing, and to achieve the required handling performance. In a model-based process like that required in FBW aircraft development, the model is the only representation of the aircraft, before and after the first flight. Availability of an aircraft model specification is fundamental, with formalization of the minimum validity envelopes, to ensure that they respect the target limit (LFE) and operational envelopes (OFE), with the necessary margins. These requirements are the basis for planning of wind tunnel tests, Computational Fluid Dynamics (CFD) campaigns, or analytical modeling processes, and minimize the risk of producing models with inadequate accuracy and flight envelope coverage.

This is a key point in the aircraft certification process: certification of designs even partially based on empirical approaches should not be granted.

The source of data is the main factor determining the accuracy; for aerodynamic models in the design phase, wind tunnel tests can be combined with CFD results and recognized analytical methods. Increments from flight data are expected to be implemented in each of them, after dedicated ground and flight test campaigns of system identification involving all models composing the aircraft model. This is to increase the accuracy of the nominal terms and reduce the amplitude of the corresponding tolerances.

The possibility reported above of remotely flying UAMVs is a significant opportunity to develop high fidelity aircraft models in the early stages of aircraft development, reducing the initial costs, too. This is a phase of flight testing dedicated to engineering development of the vehicle and it is recommended to not consider it an inherent demonstration of characteristics more strictly related to airworthiness, such as handling qualities and systems reliability. The results of these test campaigns can be used in the portion of the certification where compliance with the regulations can be demonstrated by analysis.

Recommendation R25: The FAA should ensure the existence of an aircraft model specification. This can be the subject of advisory material and MOC.

Recommendation R26: A core formed by data from wind tunnel testing is highly recommended for the aerodynamic models: S&C, ADS and hinge moments. It is

recommended to base all the other models on experimental data, when available. This can be the subject of FAA advisory material.

Recommendation R27: The implementation of a version controlled development of the aircraft model and of corresponding control laws is recommended. This ensures traceability and consistency of the design. This can be the subject of FAA advisory material.

Recommendation R28: The FAA should ensure that each model is equipped with a set of tolerances. Tolerances application is a high priority for each of the airframe models: S&C, ADS, and mass properties. This can be the subject of advisory material and MOC.

Recommendation R29: Indications related to the airworthiness of the aircraft should not be derived from remotely flown, sub scale vehicle tests.

7.4 Off-line design

7.4.1 General process

The scope of this section is to provide a minimal list of steps usually performed in the control laws design process. As stated in the previous sections, it is important for the FAA to ensure that control laws design is model based, and guided by pre-defined criteria, formalized in dedicated documentation. The combination of the aircraft simulation model and design criteria is fundamental. This is to avoid the application of empirical methods, which, even if based on models, do not require a deep knowledge of the vehicle characteristics, and are not constrained by different levels of stability and required performance.

The overall scope of the design is to define a feedback architecture so that the augmented vehicle (1) is stable, (2) has satisfactory transient response to inputs, (3) has a low regulation error, (4) attenuates external disturbances, and (5) has low sensitivity to system variations (i.e. off-nominal conditions and failures). Analysis for design within each envelope/flight phase/configuration can be divided as follows:

a. Bare airframe stability and control assessments.
b. Linear stability, based on requirements of the type specified in section 7.2.3 (2).
c. Linear handling, based on time or frequency domain prediction handling qualities requirements, such as aircraft bandwidth, CAP, GCAP, Neal-Smith.
d. Non-linear stability, mostly based on off-line simulations with inputs of the type specified in documentation required in section 7.2.4.

e. Non-linear handling, based on manned simulations and handling qualities evaluations, according to specified rating scales, see section 7.2.3.
f. Systems failures (i.e.: actuators/effectors, air data system, and sensors).
g. An additional constraint is the minimization of the demand on the actuators/effectors.

As introduced in section 7.2, management of non-compliances should be described in the official documents reporting the control laws design principles and criteria. Listing the different steps highlights the link between each phase and the type of corresponding requirements. It is also important to stress that priority is always given to stability, as it is not possible to apply higher-level requirements to an unstable aircraft.

The necessity and application of predefined criteria and requirements is fundamental for the success of the design, and consequently it is relevant for the certification authority. The aircraft handling qualities of the finalized design are mostly determined by the applied design criteria and the corresponding level of compliance with them, independently from the synthesis and architecture of the controller. This is valid whether the controller architecture is a gain scheduled Proportional Integral Derivative (PID) designed with analytical methods, or it is based on model-following techniques typical of in-flight simulators, or on Dynamic Inversion (DI).

Optimization of the control laws should be performed with respect to all criteria simultaneously to achieve simultaneous satisfaction of their requirements.

Recommendation R30: non compliance with respect to the requirements of even one HQ prediction criterion should not be acceptable in the control laws/FCS design phase.

This is true for criteria applied to different planes of the aircraft dynamics and for those that are applied simultaneously to one plane of the dynamics. An example in the longitudinal plane is to require simultaneous satisfaction of stability requirements and of Level 1 HQ based on CAP, aircraft bandwidth, and short period damping ratio requirements.

Optimization algorithms to ensure simultaneous satisfaction of a set of predefined criteria and constraints, such as CONDUIT [36] and MOPS [37], have been extensively used for the design of control systems structure and control laws.

An example of a similar approach applied to the handling qualities requirements for a variable stability Part 23 aircraft was presented [38] at the 2016 "FAA summit on Augmented Flight Path Control (AFPC) For Part 23 and Hybrid Vehicles." An optimal envelope of the modal parameters $\omega_{n_{SP}}$ and T_{θ_2} was presented for a Diamond DA42 aircraft. This was obtained as the intersection of the envelopes corresponding to predicted Level 1 handling qualities according to ten different linear handling qualities prediction criteria.

For the certification process, the concept of simultaneous optimization and the appropriate selection of the related criteria are more important aspects than the actual numerical implementation of the optimization routine.

7.4.2 Discussion

In this phase the FAA should ensure that the control laws design process is consistent with the principles and criteria stated by the applicant and that the finalized design respects the corresponding requirements.

The scope is to verify the appropriate technical application of the design process, leading to flight clearance.

The FAA should define certification control gates in correspondence of critical phases, which can correspond with those of the list above. This is to minimize the risk of deviation of the final design performance from requirements/standards, leading to a subsequent clearance failure, or to a reduced clearance envelope with respect to target. This approach is expected to guarantee the validity of the certification and it can be accomplished by the FAA through localized checks of the process.

Monitoring at this stage has a dual importance: consistency of the certification and technical support to the applicant.

Recommendation R31: Compliance with the set of minimum stability and handling requirements should be demonstrated by the applicant as part of the design phase, or independently by the FAA. This can be the subject of a dedicated MOC.

Optimization algorithms decrease the time required to finalize the design and increase the number of possible design points, at the same time a fully automated optimization process reduces visibility of the design path towards optimization.

7.5 Flight clearance

7.5.1 General process

Under an industrial application point of view, the flight clearance is the multi-disciplinary process to prove that the design of the control laws and of the flight control system in general produced an aircraft that is safe to fly within the target flight envelope. It demonstrates that the control laws are robust with respect to variation of the system parameters and to the occurrence of failures, separately and in combination. This process is based and founded on the experience and results gathered through the design phase. It is composed of an offline phase, by rig tests and by manned simulations, both in the handling qualities research simulator and in the system integration rig(s). Its scope is to authorize flight testing of a new aircraft and/or control laws and/or FCS design. The process is well established for FBW aircraft development and documented in a wide range of technical publications.

The scope of this section is to provide a brief overview of the process, with particular attention to the connections with certification.

Flight clearance should be formed by the following steps:

- Overview of aircraft and controller characteristics, offline model based.
- Linear stability analysis, offline model based. The type of requirements is reported in section 7.2.3 2 (a), (b), and (c).
- Linear handling analysis, offline model based. The type of applicable requirements is reported in section 6.
- Assessment of the impact on stability and handling of off-nominal (i.e. toleranced) aircraft, sensors and actuators characteristics, offline.
- Nonlinear nominal and toleranced control laws verification, offline.
- Manned simulations for handling qualities evaluation.
- Rig tests for verification of systems integration.
- Flight clearance report.
- Flight clearance refinement in the regions of local non-compliance, identified after the beginning of flight testing.

7.5.2 Technical output

The output of the clearance process is expected to be a cleared multi-dimensional flight envelope in which the clearance criteria are verified by analysis and manned simulations, including rig tests.

Management of local non-compliances, where robustness of the design cannot be demonstrated for off-nominal aircraft characteristics, has to be described.

Official release of the flight clearance document is particularly important. This document must describe the following outcomes of the flight clearance analysis:

a. Stability margins violations within the LFE, for each of them reporting on the violation magnitude, the region of the envelope and the tolerance combination leading to it.
b. Unstable eigenvalues outside of the required limits and corresponding tolerance combination.
c. Occurrence of limit cycles, the region of the envelope and corresponding tolerance combination.
d. Rate or position effector saturation, corresponding tolerance combination and potential for aircraft control problems (i.e. PIO).
e. Identification of the handling qualities prediction criteria indicating predicted Level 3 HQs. Region of the envelope and corresponding tolerance combination.
f. Identified and repeated LFE envelope exceedance(s), for which maneuver(s) and corresponding tolerance combination.
g. Handling qualities level(s) with atmospheric disturbances: turbulence, gust and crosswind, where applicable.

Envelope regions where restrictions apply (**restricted**) and where it is not possible to fly the aircraft (**prohibited**), which are effectively areas of unresolved non-compliance, have to be clear to the pilot and to all personnel involved with the aircraft operation.

Prohibited areas must be defined in terms of fight conditions and report the reason of the non-compliance (i.e. airspeed and pressure altitude - GMU requirements not met by the elevator loop).

Restricted areas must be defined in terms of flight conditions, of the restricted aircraft states, and report the reason for the restriction, i.e.: Angle of Attack (AoA), Angle of Sideslip (AoS) - PM requirements not met by the rudder loop.

The aircraft operational state, the configuration, and the off-nominal conditions must be reported for all identified prohibited and restricted areas of the envelope.

Optimization algorithms as mentioned in section 7.4.1 can be used to reduce the time required to complete the offline part of the clearance.

7.5.3 Discussion

The importance of the clearance process for the FAA is its structured approach and the information that it provides about the predicted and assessed handling performance of the aircraft contained in the clearance report.

The flight clearance process ensures correct system integration, adequate predicted handling qualities within the target flight envelope, and identifies and documents potential deficiencies and regions of non-compliance with respect to the pre-defined stability and handling qualities criteria.

Like in the design phase, the most important aspect for the FAA is to ensure that the manufacturer applies the clearance process to the combination of control laws, FCS design and systems integration, respecting the criteria stated in the clearance criteria document, described in section 7.2.3 and 7.3.

The FAA should follow the progression of the flight clearance and conduct a detailed analysis of its results. The objective is to have adequate visibility of the process to guarantee that it is implemented correctly, and to be informed on the predicted handling performance of the vehicle prior to first flight, including restricted and prohibited areas of the envelope.

The monitoring role of the FAA could be complemented by issuing specific clearance requirements. These requirements could be at stability, handling qualities criteria level and at procedural level, specifying minimum standards for systems integration tests, manned simulations, management of non-compliances. Stability and handling qualities criteria are of the type reported respectively in sections 7.2.3 and 6, which would require the update of current regulations and ASTM standards. Aircraft systems integration requirements could be based on existing regulations and advisory material (i.e.: 14 CFR Part 23, paragraph 23.1309, AC 23.1309-1E [39]), or on dedicated ASTM standards. The option of applying run time assurance concepts could be part of the approach to certification of systems integration, as reported in [40] and [41].

A clearance failure corresponds to a significant delay and extra costs in the development of the vehicle and it can lead to the termination of a program.

The FAA monitoring and advisory role at clearance level allows acquiring fundamental knowledge on the aircraft and its systems in support of the overall certification, minimizing the risk of a clearance failure and verify the appropriate management of non-compliances, avoiding reduction of the levels of safety.

Recommendation R32: The FAA should monitor and advise the manufacturer during execution of the flight clearance process, through the application of a set of dedicated clearance requirements. This is to verify appropriate application of the process and ensure its success. This can be the subject of a MOC.

Recommendation R33: The FAA should require the applicant formal release of the flight clearance report, prior to authorize manned flights of the vehicle. This can be the subject of a MOC.

Recommendation R34: The FAA should issue requirements at stability, handling qualities criteria level and at procedural level, specifying minimum standards for systems integration tests, manned simulations, and management of non-compliances.

7.5.4 Notes on manned simulations

Pilot in the loop evaluations through simulations are a fundamental step to ensure that the aircraft is safe to fly. The aircraft models used for the manned simulations have to be the same used for the analytical offline flight clearance, including delays representative of the implemented FCS. The simulator integration has to take into account also the delays of the simulator itself.

The cockpit of the simulator, including inceptor and feel system, has to be representative of that of the aircraft. It is important to include motion cues, providing the simulator with a motion base. This is to reproduce both the short-term acceleration cues and the long-term rates and angles cues, which the pilot can derive from the visual. An accurate Out-The-Window (OTW) display with a representative Field of View (FOV) is required for this scope.

The importance of the simulator inceptor and feel system matching those of the real aircraft is high, as tactile cues are a fundamental part of the aircraft feedback to the pilot and full representativeness can be achieved by installing aircraft hardware in the simulator.

The scope is to reach an adequate level of "handling fidelity," defined in [42] as "quick and accurate operation of the flight control movements and forces in a way similar to the aircraft."

Recommendation R35: The FAA should require a minimum standard for the fidelity of the simulators used for flight clearance. This can be the subject of advisory material.

A potential deficiency of fixed base simulators is their reduced capability to represent bio-mechanical coupling due to interaction of the pilot's arm, aircraft and inceptor when subject to acceleration. This is usually more pronounced in roll maneuvers and produced by lateral acceleration. Based on the author's experience, in particular with variable stability aircraft, this lack of simulator representativeness impairs detection of degraded handling qualities due to bio-mechanical coupling, leading to unexpected and degraded aircraft response in flight.

Based on observation of the execution of given a handling qualities tasks, the scatter of handling qualities comments and ratings assigned by different pilots is larger when executed in a fixed base ground simulator compared to in-flight execution. This is potentially due to the different compensation techniques applied by the pilots in the face of reduced dynamic cues.

The two phenomena exemplified above can be critical for the flight clearance phase, as they can lead to inconsistent evaluations and to difficulties in the assessment of the predicted handling qualities.

The evaluation tasks and their objectives are those specified in the clearance criteria report. As reported above, manned simulations are the mean that test pilots use to authorize the aircraft to fly. The output of the clearance process can include local non-compliances, mostly deriving from the linear analysis. An important function of manned simulations is to assess how critical these non compliances are for the actual aircraft handling. Usually, when confined to a limited region of the envelope, the pilot is capable of compensating for them, with minor to negligible impact on handling qualities. This is due to the pilot’s adaptive capabilities, for which minimal to negligible additional compensation is required. Management of non compliances is a critical process, which has to be formalized prior to the evaluations.

Refinements of the control laws following the results of manned simulations require the same design steps of the original design phase, beginning from the offline phase through the whole process up to a new clearance.

Manned simulations are to be carried out for all relevant flight phases, FCS modes, off-nominal conditions, and failure modes. They reduce the risk of handling qualities evaluation of failure configurations.

Manned simulations are also effective in maneuver rehearsal and in training the team of pilot, test conductor, and discipline engineers prior to first flight and to high-risk phases of the flight test campaign.

Availability of full-scale in-flight simulators: in UAMVs this potentially coincides with the prototype itself, with the advantage of being flown remotely.

Recommendation R36: The FAA should limit the validity of the results from full-scale remotely flown tests to system identification, open loop verification of models fidelity and systems reliability.

7.5.5 Notes on rig and ground testing

Rig testing is conducted with the actual control laws software and hardware in the loop, which includes Flight Control Computer(s) (FCC), Air Data Computers (ADC), actuators/effectors, sensors (inertial, air data, and control surfaces), hydraulics and/or electrical system. The main scope is to verify integration of the whole FBW system under the following aspects: (1) FCS hardware and software, (2) response to failures, (3) fault tolerance, and (4) redundancy management. The verified level of integrity of the FCS and of the other systems must be equivalent. Dedicated avionics integration simulators can be used. Tests can preliminarily begin on isolated test benches of each of the principal aircraft systems.

In a subsequent phase, verification of the control system software implementation in the FCC is conducted by means of tests with hardware in the loop simulators. These simulators are formed by the FCS and the hardware, which must be interfaced with the software in the real aircraft. Hydraulic, electrical systems and actuators/effectors are not part of them. The control laws and related commands are produced by the FCC; the input signals, actuator/effector commands, and aircraft response are simulated.

Tests are subsequently performed on the fully integrated FBW system, which includes, in addition, avionics and Flight Test Instrumentation (FTI). Rig tests allow running the FCS hardware as a fully integrated system. The initial phases are typically dedicated to characterization of the FCS components, ensuring that they satisfy the specification requirements. Software validation tests follow, conducted with an incremental approach, open and closed loop, normal operation and failure modes. The subsequent system integration testing phase is aimed at clearing the integration of the FCS with the other aircraft systems, like avionics, propulsion, and FTI. Actual flight profiles are flown to exercise the system in conditions representative of the aircraft operation. Endurance tests can also be run, during which simulated sorties of general handling maneuvers are performed in turn by pilots and experienced engineers to verify the stability of the system over time.

The Iron Bird is the tool for testing the full FCS integration described above, formed by the flight control hardware and software, and integrated with the actuators/effectors, hydraulic, electrical systems and sensors. Physical sensors can be integrated, requiring accurate modeling of their inputs. Accuracy of the sensors inputs is critical, for the system to calculate the correct values of the gains, when these are scheduled as a function of flight conditions and configuration. The systems are those implemented in the aircraft, including their physical mutual position and their interface connections. The rigid body aircraft response is simulated by means of the same aircraft model implemented in the handling qualities evaluation simulator. The value of the iron bird for the verification process is to contain the actual mechanical and electrical nonlinearities of the aircraft systems. It is important that any modification to the systems and their layout in the actual aircraft are matched in the iron bird. It can be replaced by an actual aircraft, representative of the configuration under test, when it is not possible to develop a standalone iron bird.

Ground vibration tests (GVT) are conducted on the actual aircraft in the relevant configurations to identify the structural modes and validate the structural dynamics model. Dedicated suspension rigs and exciters applied on different parts of the aircraft are used. The aircraft is instrumented with accelerometers to characterize the modes of structural vibrations. Results of this test are used to refine the aircraft structural dynamic model, integrated with the FCS and aerodynamics model, to simulate the vehicle structural response in flight.

Servoelasticity tests conducted on the actual aircraft are aimed at verifying the stability of the FCS, by ensuring that structural modes are filtered by the notch filters implemented in the control paths, and that the sensed structural oscillations do not couple with the control system, in turn amplifying the structural oscillations. Open and closed loop aervoelasticity resonance tests are conducted to derive experimentally the frequency response of the fully implemented system. A gain margin GM = 6 dB is the minimum required in the frequency range of interest. It is important to consider that steady and unsteady aerodynamic effects are not part of the test, while they are present in flight. For aircraft with high structural stiffness, the frequency range of interest of servoelastic tests is higher than the maximum rigid body motion frequency, due to the high structural modal frequencies. For vehicles with low structural stiffness, the servoelastic frequency range of interest and the 6-dof rigid body motion frequency range can overlap, due to the low frequency range of the structural modes. This has potential significant implications in the design of the FCS, which has to ensure adequate stabilization of the closed loop system, with the impossibility of implementing notch filters in the rigid body motion frequency range.

Rigid body limit cycle testing is performed to account for the effect of nonlinearities to identify the margin with respect to the occurrence of small amplitude oscillations, or to ensure that a gain increase of 8 dB with respect to the nominal loop gain does not lead to oscillations. The test is a combination of actual vehicle hardware and simulation of the aircraft and sensor response.

Consistent application of the standard ground testing process, for verification and validation of FCS software and hardware, is critical to issue flight clearance. The same process must be repeated for any software or hardware change. Usually software changes occur with a higher frequency and according to a predefined schedule, based on the aircraft developmental phases. It is fundamental to identify any variant of the software as a completely independent release, which must undergo the same cycle of ground testing, to achieve a separate flight clearance from that of the releases preceding it. Flight clearance is the integrated process of offline analyses, handling qualities evaluations, and ground test.

Recommendation R37: The FAA should require the applicant to report the results of the applied ground testing process, for verification and validation of the FCS software and hardware, as an integral part of the flight clearance process.

7.6 Flight test

7.6.1 Background

Flight testing of a FBW aircraft can be considered as an integrated process of ground and flight testing, in which the ground phase includes manned simulations for handling qualities evaluations and rig tests for FCS integration, see previous section.

The overall scope is to verify that the aircraft, considered as a system, satisfies the specification requirements. The detail scopes are as follows:

a. Matching/cross-validation of the aircraft model with respect to flight data.
b. In-flight verification of the predicted handling qualities (flying qualities) with respect to specification requirements, accomplished through FQTEs.
c. Handling qualities qualification with respect to handling qualities requirements, accomplished through HQTEs.
d. Handling qualities validation with respect to mission specification requirements by determining the effectiveness and suitability of the aircraft for use in the specified mission operations by a typical user.

The rationale is to perform verification in two ways: (1) model based, resulting from the matched aircraft model from data gathered in the model estimation phase, section 7.6.2, and (2) from flight test, in the most critical conditions, section 7.6.3.

Flight matching and cross-validation of the models used for design and flight clearance allows the identification of deficiencies and for refining the overall FCS/control laws design by means of the same model-based approach applied to achieve first flight. Accurate quantification of the aircraft aeromechanic characteristics and modal parameters requires a dedicated Flight Test Instrumentation (FTI), designed based on the aircraft model matching requirements, as the reference standard to define instrumentation accuracy.

Handling qualities are an integral part of the system, as they respond to specification requirements like all other aircraft/system components. Their verification, qualification, and eventual validation is required for aircraft certification, as a part of the design safety assurance, assuring the vehicle handling performance.

For these reasons, flight testing of FBW aircraft requires a change in the approach to testing, required by the close interconnection between design and testing. The complexity of the system, the number of criteria, and requirements that the aircraft must satisfy is large and interconnected. Any aircraft modification has to be approached by updating the models that represent the vehicle, and on which the design and clearance criteria are applied.

On the other side, the scope of handling qualities evaluations is to ensure the validity of the overall design approach by assessing satisfaction of the mission requirements through the pilot's evaluation.

This is a significant change in the aircraft development, test, and evaluation process of Part 23 aircraft, which is historically based on proven standard practices and consolidated design approaches derived from the manufacturer's experience.

This section addresses these two main aspects, considered more relevant for FBW aircraft and their certification.

Testing is planned from the early stages of the design phase, progress to manned simulations, rig and ground tests before achieving full flight clearance and eventually beginning the actual flight test campaign. A relevant part of this approach under the aircraft development and operational standpoint is the definition of possible FCS test bed modes required for specific flight test tasks, like aerodynamics parameter estimation and flutter testing. The specification of test bed modes requirements, which include dedicated Programmed Test Inputs (PTI), stability and control augmentation and avionics, has to begin at the design phase. This is because each test bed mode requires dedicated design, safety analysis, flight clearance, and ground test processes. Implementation of test bed modes at later stages of the aircraft development requires modification of a consolidated FCS architecture and control laws design, requiring longer time and achieving reduced safety margins and technical objectives.

The evaluation pilots provide fundamental information regarding the vehicle handling characteristics and indications towards improvement throughout the whole flight test process. Also, in highly automated/autonomous vehicles, pilot's evaluations are required to address the pilot's interfacing with the displays, inceptors, and control laws in the different flight phases. The typical pilot will have to take full control of the aircraft in case of automation failure. Pilot's evaluations of the transition to full piloted operation and of the handling qualities when the aircraft is hand flown is primary information for the aircraft development, fulfillment of the mission requirements, validation, and certification.

In addition, in fully automated mode, the pilot/operator's evaluation should still be the decisive metric to assess the satisfaction of the mission requirements and the suitability of the vehicle. The evaluations are of the combined pilot-vehicle handling performance. The main aspects of the Pilot Vehicle System (PVS) are described in the summary of section 3.4.

The diagram on the next page (Figure 47) is a notional schematic representation of the flow of the modeling/design/clearance/flight test processes for a FBW aircraft. It illustrates the functional relationships and the feedback between phases. Aircraft systems testing and details are intentionally omitted. The actual flight test phase, yellow rectangle, occurs downstream of a series of mostly analytical steps. It is important to notice that the feedback from the flight test phase to the process is dual, based on model matching/cross-validation and on specification requirements, which include flying qualities, handling qualities, and their validation.

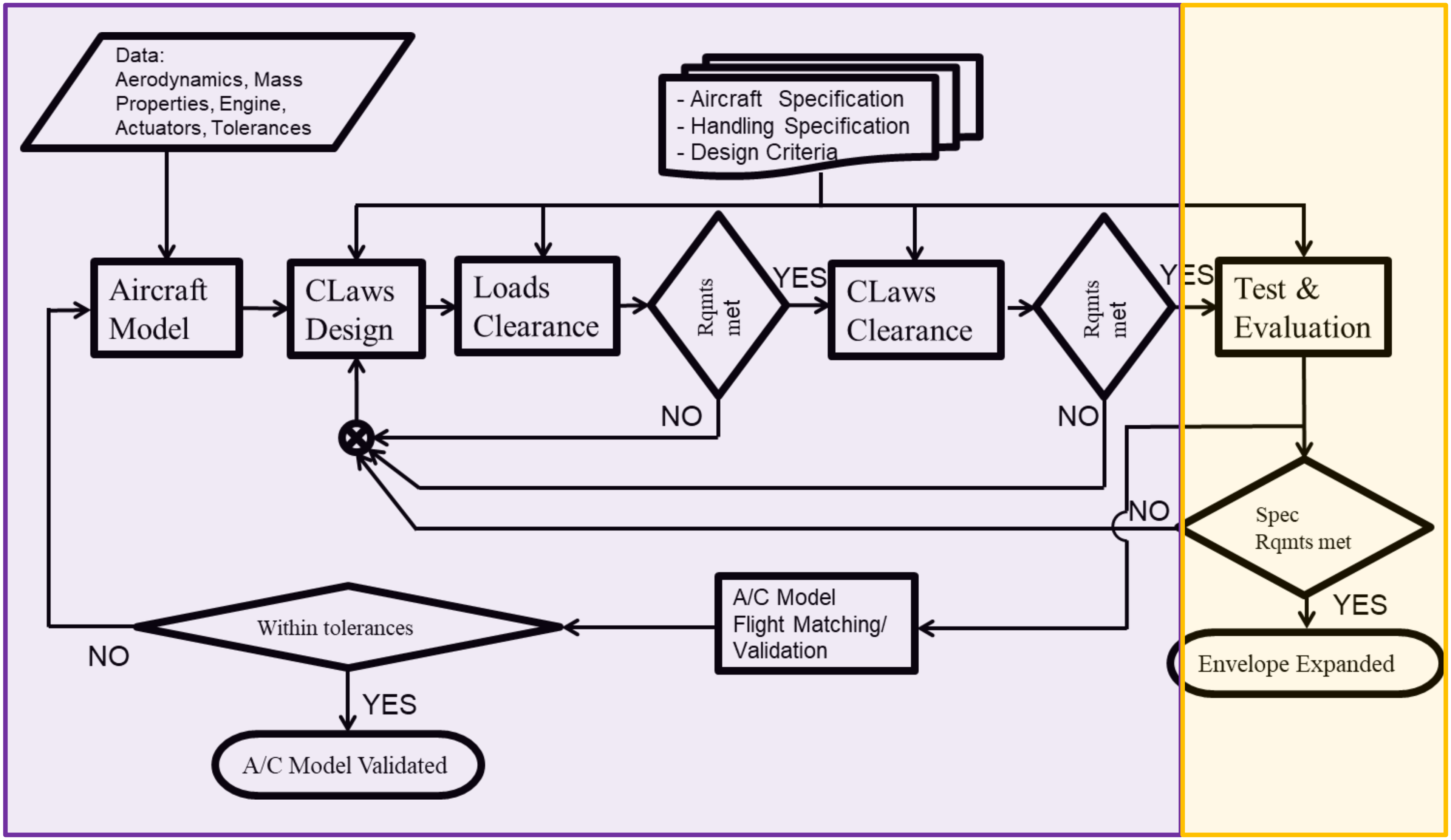


Figure 47. Notional sample control laws development and evaluation process

7.6.2 Aircraft models estimation from flight test

The process of identifying the aircraft/system model is one of the highest priorities in the development of FBW aircraft. As mentioned above, a consistent and reliable aircraft design and development process is based on models, for safety, traceability, and technical consistency. This is one of the primary factors of the proposed certification process and one of the main objectives of the flight test campaign. This ensures technical confidence in the basis of the process and in its repeatability. Identification is of all the individual models that compose the aircraft model used in design and clearance.

The scope of this section is to introduce the procedural aspects of model flight matching considered relevant for certification, independently from the algorithm used for estimation.

A practical definition of system identification is provided in [43], as follows:

> "System identification is the determination, on the basis of observation of input and output, of a system within a specified class of systems to which the system under test is equivalent."

From the definition above, one derives that more than one mathematical model of a physical system exists, that inputs and outputs have to be observed (i.e.: measured), and that the applied definition of equivalency determines the way in which the model represents the aircraft/system.

In the classical industry standard approach, the structure of an aircraft model is pre-defined, based on the knowledge of the aircraft configuration. This transforms the process from the more general one of identification to the more specific one of estimation of a set of pre-defined parameters. As an example, in the case of the estimation of the aerodynamics, the parameters are the pre-defined aerodynamic terms that represent the characteristics of the vehicle, linearized with respect to the trim condition. Algorithms that allow nonlinear modeling from flight will be reported in the latter part of this section.

Identification is applied to aircraft configurations for which it is difficult to pre-define a model structure. For this reason, it is expected to have a wide application to UAMVs, for their novel and hybrid fixed/rotary wing configurations.

Independently from the estimation algorithm itself, different technical approaches can be followed, with respect to what the model has to represent. These are for example: (1) separate estimation of each single model composing the aircraft model, or (2) estimation of the dynamic response of the whole aircraft, with respect to specific input-output channels.

The first approach is typically applied to aircraft models in which the degree of non-linearity is different across the component models, and/or when one of the component models is expected to change significantly more than the others throughout the development of the aircraft. All component models have to be available, with a relatively high fidelity. The outputs of each estimation are the increments to the corresponding prediction model. This is the approach applied historically to modeling of manned fixed wing Part 25 or military aircraft.

The second approach, more typical of the frequency domain estimation, is effective for vehicles with mainly linear dynamic characteristics, because it allows direct extraction of the transfer functions of the dynamics, i.e. $\frac{q}{\delta_e}(s), \frac{p}{\delta_a}(s), \frac{r}{\delta_r}(s)$. These can be highly augmented vehicles, in which it is not possible to reduce the level of augmentation to match the bare airframe model based on the un-augmented response. An advantage of this method is its lower reliance on prediction models and the relatively short time required to release a cross-validated vehicle model. The disadvantage is the impossibility to separate the contributions of the different components of the dynamics; the main focus is on the input-output dynamic response of the vehicle, without specific characterization of the aerodynamics, of the actuators/effectors, or of the sensors.

There are different operational approaches to model identification from flight test, including:

a. Estimation of the increments with respect to the prediction model(s), derived from flight testing of the full-scale vehicle.
b. Derivation of a high fidelity model from full scale testing of the vehicle, without a prediction model.
c. Derivation of a high fidelity model from testing of a sub scale vehicle, without a prediction model.

The first approach is required for highly augmented manned aircraft, with low inherent stability, for which model-based flight clearance is essential, for both safety and technical consistency. **It is not possible to apply the *build-fly-fix-fly* design method to manned aircraft.**

The second approach can be applied to known inherently stable aircraft, which do not require augmentation to be pilot flown (i.e. all standard configuration Part 23 general aviation aircraft). It can be a viable approach for optionally piloted or unmanned aircraft, when the economic impact on the program of losing one vehicle is lower than the cost required to develop its model before flight. This is expected to be technically possible for UAMVs, which can be flown remotely for system identification/estimation and control laws verification.

The third approach is applicable to a large number of aircraft types, and it is applied in the identification/estimation of UAMVs and Unmanned Aerial Vehicles (UAVs).

The required output of the flight matching process of each model consists of the updated nominal terms and corresponding set of tolerances.

Under a flight test execution standpoint, model estimation requires dedicated inputs. Different approaches can be followed to determine the optimal, or the most cost/time effective ones. The accurate knowledge of the vehicle characteristics allows specific maneuver design, based on the outputs sensitivity to the vector of the unknown parameters. When an accurate prediction model is not available, or specific maneuver design is not considered cost effective, standard broad frequency spectrum maneuvers are usually performed. These are frequency sweeps, doublets, specific square wave sequences like the 3-2-1-1 maneuver.

A large amount of technical literature is available on the subject. The scope of this section is to consider the aspects that are most related to certification. One of the possible approaches to generate the inputs is to program and inject them directly as commands to the actuators, summed downstream of the control laws command to the actuators. In some cases, they can also be generated directly by the pilot. The notional schematics of Figure 48 displays the PTI panel used by the pilot to select programmed inputs and the alternate command path, dashed line, by-passing the control laws. The scope of this type of implementation is to be able to produce adequate excitation of the vehicle dynamic response and/or to obtain repeatable inputs. In case of highly augmented aircraft, this can be coupled with a reduction of the augmentation, aimed at ensuring adequate amplitude of the perturbations, which otherwise would be minimized by the augmentation itself. This approach is particularly relevant in the estimation of the bare airframe aerodynamic model.

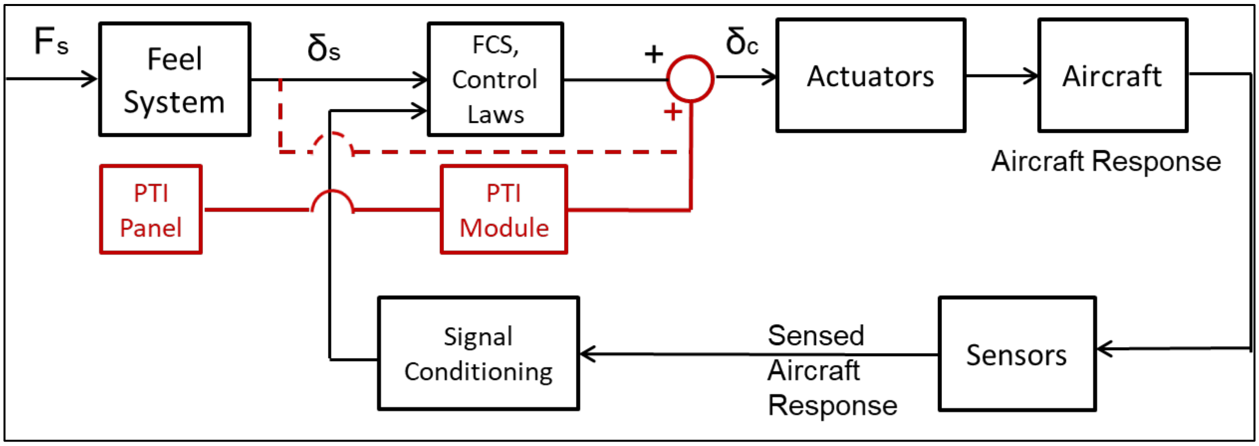


Figure 48. Notional schematic of PTI implementation

An implementation of this type of FCS test bed modes is critical in aircraft with low or negative inherent stability, due to the reduction of the stability margins produced by the lower augmentation and the potential for envelope exceedance due to the alternate inputs path.

Recommendation R38: The FAA should ensure that a dedicated flight clearance is carried out for each of the test bed FCS modes.

The main objectives of the flight matching process are as follows:

- To ensure that the accuracy of the models used for design and flight clearance is sufficient to guarantee the target stability margins and to progress with flight testing: model cross-validation.
- To improve the design based on a set of reduced amplitude tolerances, without requiring a full update of the nominal terms.
- To update the nominal terms of the model, for increased fidelity of the vehicle representation.
- To verify that the calculated metrics of the handling qualities prediction criteria applied to the updated aircraft model continue to match the clearance and specification requirements.

Under the modeling standpoint, the application of the tolerance scaling factor logic described above in section 7.3.2 is aimed at refinement of the design. This is also an effective way to reduce the time required to proceed with envelope expansion and to release an updated version of the model with its accompanying set of tolerances, as it does not require calculating updated tolerance values in correspondence of each release of the updated model.

The applicability of the tolerances scaling logic described above depends on the magnitude of the differences between the nominal terms of subsequent model releases. Reduction of the tolerances amplitude can be performed when the updated nominal term + scaled tolerance amplitude is comprised within the previous nominal term + previous tolerance amplitude. Figure 49 below illustrates a case in which tolerance scaling is marginally acceptable. The tighter tolerance amplitude of the flight matched model, thin dashed line, is locally tangent to the wider tolerance band, thin continuous line, of the prediction model. This is due to the associated variation of the value of the matched nominal term. As the uncertainty band of the flight matched model is contained within the uncertainty band of the prediction model, the second is considered to be still adequately representative of the aircraft.

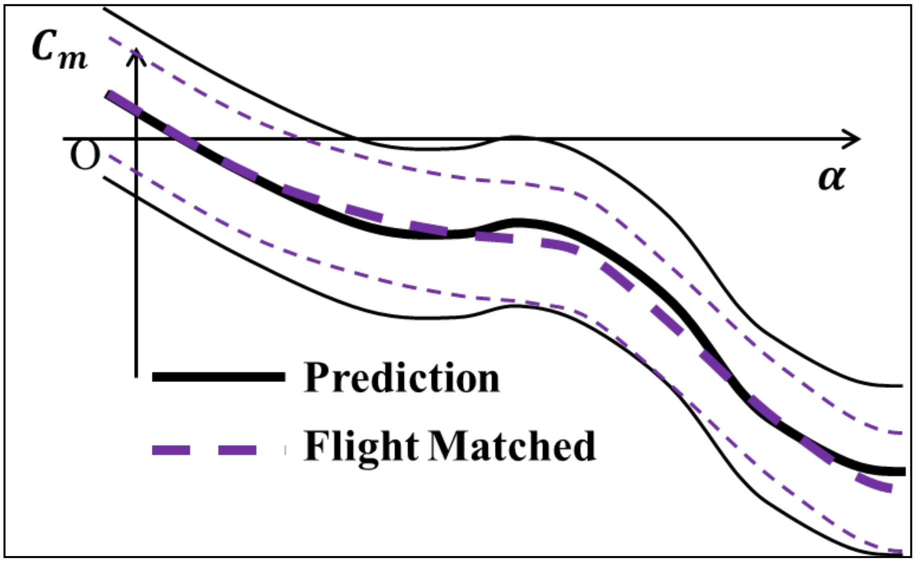


Figure 49. Matched/unmatched aerodynamic terms comparison

In case the uncertainty band of the flight matched model is external with respect to that of the prediction model, potential lack of robustness of the control laws designed and cleared based on the prediction model must be addressed as a flight clearance non compliance.

This should lead to temporary flight limitations; the regions of the flight envelope that correspond to the local interval of non compliance should be identified as “flight test only” (FTOE) to allow for the local refinement of the model.

The highest level of inaccuracy occurs in case the nominal term derived from flight matching/identification is external with respect to its toleranced value used for design and flight clearance.

Recommendation R39: The FAA should verify the existence of a formal procedure to establish supplemental flight envelope limits when model inaccuracies identified from the flight test matching process do not guarantee adequate robustness of the control laws.

Under an aircraft program standpoint, flight matching of the aircraft models, aerodynamics in particular, is one of the primary, most demanding and time-consuming activities, as it involves operational, design, and clearance engineering functions, and requires multiple modeling and matching iterations. The National Aeronautics and Space Administration (NASA) developed and flight tested at the National Test Pilot School, a real time nonlinear aerodynamic modeling technique from flight data [44], [45]. This technique allows a significant reduction of the time to achieve a fully characterized nonlinear aerodynamic model, leading to an expected considerable economical and time advantage for aircraft programs development.

Recommendation R40: The FAA should promote the application of the NASA real time nonlinear aerodynamic modeling technique to increase modeling accuracy and reduce the development cost of Part 23 aircraft. References [44] and [45].

7.6.3 Flying and handling qualities evaluation

Current FAA regulations address flying qualities requirements. These are grouped as a function of a mix of aircraft configuration, performance, maximum seating capacity and maximum take-off weight through Part 23, 25, 27 (Cat. A and B) and 29 (Cat. A and B) requirements.

The proposed method of this work is to link the FQTEs and the HQTEs through the mission requirements.

The applicant flying and handling qualities testing is expected to be based on the set of FQTEs and HQTEs required for flight clearance. The scope is to achieve in-flight verification (FQTEs) of the aircraft dynamic response parameters and qualification of the handling qualities (HQTEs).

Qualification requires execution of the HQTEs in the most critical cases for flight conditions (i.e. altitude, airspeed, outside air temperature), mass properties, atmospheric disturbances, and operational state.

Qualification substantiates the consequent validation of the aircraft with respect to the user mission requirements contained in the aircraft specification, which is the objective of certification.

Analysis of the aircraft characteristics compared with flying qualities (FQ) requirements is fundamental to avoid that the aircraft overall validation based on pilot's evaluation is a mere experimental process.

At the same time, pilot's evaluation is unquestionably required to account for the pilot's nonlinear adaptive characteristics, and for the necessity to combine different types of metrics into a single, continuous mission representative task.

Pilot evaluation is the only method to assess the interaction between pilot-vehicle performance, workload and compensation, and aircraft mission suitability. The consequent added value is the possibility to define quantitative handling performance standards related to mission suitability, through correlation between response modal parameters and results of pilot's evaluation.

Recommendation R41: The FAA should require compliance by test with a minimum set of FQTEs and HQTEs, which are not necessarily coincident with those used by the applicant in its internal aircraft validation process. These minimum sets should be published as part of a Mean of Compliance.

Components for the definition of the FQTEs are:

a. Aircraft class, i.e. airplane, powered-lift, rotorcraft/multicopter.
b. Mission requirements, for the definition of the relevant flight phases.
c. Aircraft handling specification requirements.
d. Minimum set of FAA required HQ prediction criteria for design and flight clearance: traceability from design to clearance to verification is fundamental.

Table 7, below, reports an example of required minimum FQTEs for three aircraft classes. Applicability to hover or forward flight of rotorcraft and multicopters FQ requirements is intentionally not indicated, for simplicity. Satisfaction of the handling qualities prediction criteria is by analysis, with data gathered from each FQTE. Performing in-flight FQTES in selected regions of the envelope, and for specific configurations, provides confidence that the aircraft itself, under actual conditions, satisfies the requirements, and that potentially unmodelled effects did not alter the HQ predictions. This is fundamental for certification, as it supports verification of design and clearance results. Table 7 contains examples of stability and HQ prediction criteria to support the description of the overall approach.

As reported in previous recommendations, it is fundamental to perform FQTEs referred to stability requirements and to require compliance with the Aircraft Bandwidth criterion.

Recommendation R42: As part of the Mean of Compliance, the FAA should define the configurations and the envelope regions in which to perform the FQTEs, based on the documented results of the flight clearance. Higher priority should be given to cases with lower documented margins with respect to the clearance requirements.

Recommendation R43: The FAA should require in-flight execution of the minimum required set of FQTEs in pre-defined configurations in the core of the envelope and in envelope regions at the boundaries of the OFE and of the LFE. This can be the subject of a MOC.

Table 7. Example of minimum FQTE requirements

Execution of the listed FQTEs is required for each flight phase in which the mission can be subdivided. Not all FQTEs are applicable and relevant for each flight phase.				
Requirement/ HQ Prediction Criterion	**Aircraft Class**			
	Aeroplane	**Powered-lift**		**Rotorcraft/ Multicopter**
		Wing-Borne	**Rotor-Borne**	
Longitudinal Static Stability	Stabilized Technique	Stabilized Technique	Stabilized Technique	Stabilized Technique
Maneuvering stability/ Stick Force per g	Pull up/Push over	Pull up/Push over	Pull up/Push over	Pull up/Push over
	Steady Turn	Steady Turn	Steady Turn	Steady Turn
Dynamic Stability Requirements	Pitch Frequency Sweep	Pitch Frequency Sweep	Pitch Frequency Sweep	Pitch Frequency Sweep
	Roll Frequency Sweep	Roll Frequency Sweep	Roll Frequency Sweep	Roll Frequency Sweep
Aircraft Bandwidth (inceptors position and inceptors force)	Pitch Frequency Sweep	Pitch Frequency Sweep	Pitch Frequency Sweep	Pitch Frequency Sweep
	Roll Frequency Sweep	Roll Frequency Sweep	Roll Frequency Sweep	Roll Frequency Sweep
CAP	Pitch Step	Pitch Step	N/A	N/A
Attitude Quickness/ GCAP	N/A	N/A	Pitch Pulse	Pitch Pulse
			Roll Pulse	Roll Pulse
			Yaw Pulse	Yaw Pulse
	Pitch Doublet	Pitch Doublet	Pitch Doublet	Pitch Doublet

Execution of the listed FQTEs is required for each flight phase in which the mission can be subdivided. Not all FQTEs are applicable and relevant for each flight phase.				
Requirement/ HQ Prediction Criterion	**Aircraft Class**			
	Aeroplane	**Powered-lift**		**Rotorcraft/ Multicopter**
		Wing-Borne	**Rotor-Borne**	
Short Period Modal Parameters and PIO Criteria	Pitch Frequency Sweep	Pitch Frequency Sweep	Pitch Frequency Sweep	Pitch Frequency Sweep
Phugoid Mode Modal Parameters/ Phugoid Stability	Gradual airspeed offset from trim	Gradual airspeed offset from trim	Gradual airspeed offset from trim	Gradual airspeed offset from trim
Lateral-Directional Modal Parameters and PIO Criteria	Yaw Doublet	Yaw Doublet	Yaw Doublet	Yaw Doublet
	Roll Doublet	Roll Doublet	Roll Doublet	Roll Doublet
	Roll Frequency Sweep	Roll Frequency Sweep	Roll Frequency Sweep	Roll Frequency Sweep
	Roll Step	Roll Step	Roll Step	Roll Step
Lateral-Directional Characteristics	Steady Heading Sideslip	Steady Heading Sideslip	Steady Heading Sideslip	Steady Heading Sideslip
Roll Oscillations	Roll Step	Roll Step	Roll Step	Roll Step

Components for the definition of the HQTEs are:

a. Aircraft class, i.e. airplane, powered-lift, and rotorcraft/multicopter.
b. Mission requirements. These include the conditions in which the mission and its phases must be accomplished: turbulence level, day/night, frequency with which the mission has to be done. Differences between expected mission conditions and actual evaluation conditions.
c. Specific task requirements.
d. Required amplitude of pilot's control inputs: (1) small, (2) moderate, and (3) large, corresponding to (1) linear/fine-tracking, (2) general handling, and (3) gross acquisition/gross maneuvering.

General background concepts for the design of HQTEs for flight clearance are contained in section 7.2.4 point (e). It is important that a similar approach be applied also to the HQTEs performed in flight, for traceability of the requirements from flight clearance to qualification and validation. The overall development process, including functional feedbacks, for the HQTEs definition is represented in Figure 50, copied from reference [35].

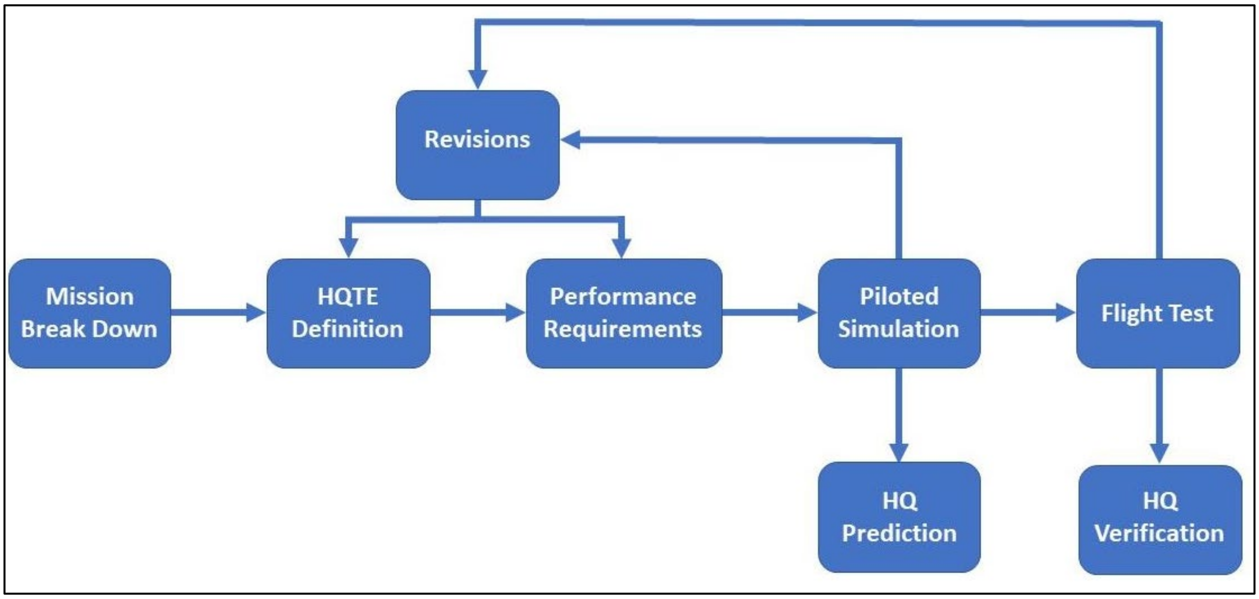
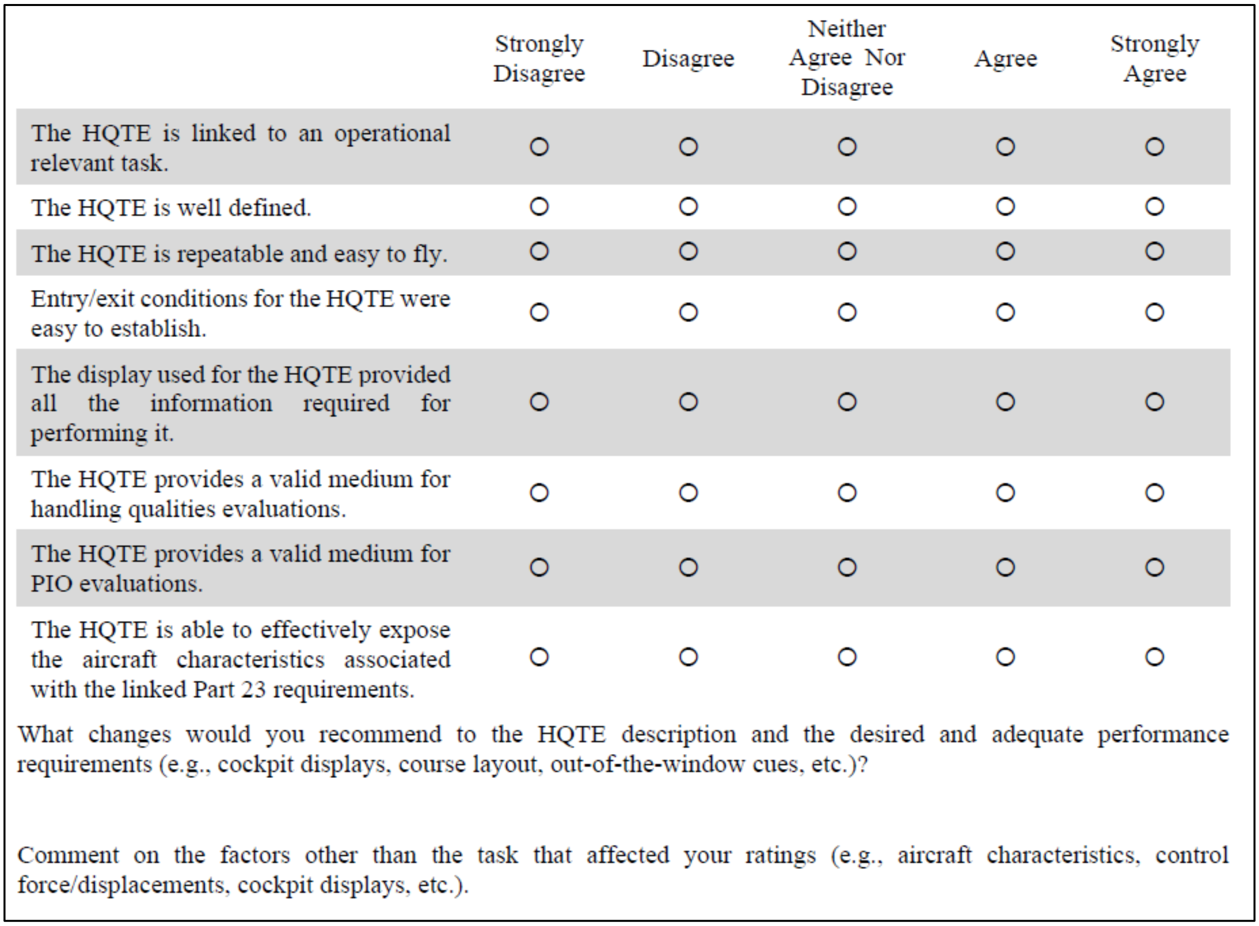


Figure 50. HQTE development process, copied from reference [35]

Reference [35] provides guidance for the evaluation of HQTEs; the proposed "Example HQTE assessment pilot questionnaire" of Figure 51, copied from [35], allows assessing the effectiveness of HQTEs, based on their actual in-flight execution. A second outcome of this assessment is the evaluation of the representativeness of the HQTEs flown in the manned simulator. It is important to maintain the functional feedback between in-flight and simulator execution to refine the HQTEs design and increase the effectiveness of parts of the clearance based on them.



	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
The HQTE is linked to an operational relevant task.	○	○	○	○	○
The HQTE is well defined.	○	○	○	○	○
The HQTE is repeatable and easy to fly.	○	○	○	○	○
Entry/exit conditions for the HQTE were easy to establish.	○	○	○	○	○
The display used for the HQTE provided all the information required for performing it.	○	○	○	○	○
The HQTE provides a valid medium for handling qualities evaluations.	○	○	○	○	○
The HQTE provides a valid medium for PIO evaluations.	○	○	○	○	○
The HQTE is able to effectively expose the aircraft characteristics associated with the linked Part 23 requirements.	○	○	○	○	○

What changes would you recommend to the HQTE description and the desired and adequate performance requirements (e.g., cockpit displays, course layout, out-of-the-window cues, etc.)?

Comment on the factors other than the task that affected your ratings (e.g., aircraft characteristics, control force/displacements, cockpit displays, etc.).

Figure 51. Example of HQTE assessment questionnaire, copied from reference [35]

The HQTEs definition process can be drafted as follows:

1. Mission breakdown in its flight phases, as a function of aircraft class
    - Ground/deck
    - Takeoff
    - Climb
    - Cruise
    - Descent
    - Approach and landing

   Additional flight phases for E-VTOL UAMVs, not all considered simultaneously
    - Hover
    - Translational flight
    - Transition from rotor-borne to wing-borne flight
    - Transition from wing-borne to rotor-borne flight
2. Individual flight phase breakdown into handling qualities tasks

- The principal objective of the task is to require the pilot to explore and evaluate the key handling characteristics necessary to accomplish the given flight phase without mission effectiveness degradation. The potential handling deficiencies that the pilot identifies.
- The task is based on the same set of cues that the pilot would refer to during the actual operational flight phase. It is suggested to avoid using support cueing devices like HUD, HDD, and aural cues, which are not available on the production aircraft, or, if available, change their function in support of the execution of the task.
- Some of the flight phases, like approach and landing, or transition from rotor-borne to wing-borne flight or vice versa, should be performed as a single task, for full representativeness of the mission phase.
- Task repeatability ensures that potential differences of HQRs and evaluations depend on the evaluator and not on different task boundary conditions, which are not addressed in the task definition.

3. Pilot's control amplitude regimes definition. Design of the HQTEs is aimed at evaluating handling qualities in three main pilot's control regimes. Depending on the flight phase, one or more control regime is required for each HQTE.
    - Small amplitude, less than 10% inceptor displacement, fine tracking. This exposes linear handling characteristics.
    - Moderate amplitude, higher than 10%, lower than 50% inceptor displacement.
    - Large amplitude, higher than 50% inceptor displacement. This exposes nonlinear/gross maneuvering handling characteristics.
4. Task requirements definition
    - Clear definition of desired and adequate requirements. It is recommended to limit application of the requirements to a maximum of two to three aircraft states/response conditions, i.e. pitch attitude, pitch attitude overshoots and airspeed; bank angle, bank angle overshoots. Requirements for CCC tasks can be a function of time, i.e. deviation from glide slope, airspeed and time within desired/adequate criteria.

      Different sets of desired and adequate requirements values can be defined to match different levels of operational precision for the given flight phase, and to explore the boundaries of the *handling qualities cliff*.

  - The task must require sufficient pilot's control input frequency to evaluate the system in the bandwidth representative of the demand on the pilot for the given mission phase.
  - Adequate duration to differentiate transient from steady state.
  - It is recommended to also require a single rating for tasks requiring control in different axes and with a wide pilot's control input frequency. This leads to a more robust rating assignment and synthesis of the evaluation.
  - Specific environmental and task set up conditions must be indicated.
  - Variation of the task initial conditions should be defined, when possible, to address evaluation of the aircraft tolerance to mishandling. Robustness of the aircraft response to the individual pilot compensation technique is an important part of the evaluation. No special techniques should be allowed.
5. Execution of the HQTE
   - The task should be executed as planned. It is important to consider that handling qualities evaluation is a form of scientific experiment.
   - The engineer(s) should follow the evaluation in first person to witness the pilot's difficulties and collect the pilot's feedback on them in real time.
   - The communication flow between pilot(s) and engineer(s) should always be maintained open.
   - When possible, it is important not to communicate to the pilot the characteristics of the configuration under test to avoid undesired bias in the evaluation: single blind experiment.
6. Pilot's requirements, for consistent evaluation and ratings assignment
   - Current.
   - Proficient, which requires multiple executions (at least three) of the task before proceeding to the handling qualities evaluation.
   - Knowledgeable of the specific task, which requires detailed briefings of the task requirements from the task designers.
7. Identification of each designed task with a clearly defined name. This is important to achieve a wide application of the HQTEs across multiple phases and aircraft programs.
8. Output of each HQTE evaluation should be formed by one HQR, one PIOR and by pilot's comments. Comments are fundamental to identify the deficiencies that the pilot reports, and to guide the engineer towards their solution. In case the actual evaluation conditions do not match the expected mission conditions, ratings and comments have to take this into account and address it openly. Comments should be provided during the evaluation itself, or immediately after, depending on pilot's workload and spare capacity.

A list of questions can be prepared to extract relevant information from the pilot in a repeatable way, addressing the critical handling aspects. Assignment of half ratings should not be allowed, particularly 3.5, 6.5 and 9.5, as this corresponds to failure to assigning a handling qualities level. Ratings and comments should be given *on the spot*.

9. Synthesis of the evaluation data: it is not correct to average HQRs and/or PIORs. Averaging would assume that the rating scales are linear, which has not been demonstrated and which is not necessary. The scatter in the ratings is to be used as an indication of potential handling qualities deficiencies, or of inconsistent task design, or of inconsistent task definition. Correlation between HQRs and PIORs should be performed to ensure consistency and identify ratings to be discarded.

The reference handling qualities rating scales are the Cooper-Harper and the PIO rating scales, described in section 5.4. The evaluation process applied in the clearance phase should be similar to that applied in flight. A cadre of three to five test pilots with possibly diversified background, fixed and rotary wing for UAMVs, should be part of the evaluation team.

Requiring use of widely recognized and established rating scales, like Cooper-Harper, is important for the accuracy of the evaluation. Pilots are used to these scales, they are proficient in their application, understand the terminology and the background concepts. A direct relationship exists between predicted and assessed handling qualities levels when using the Cooper-Harper rating scale. This aspect is particularly important, as it is one of the components allowing traceability of the handling requirements (predicted and actual) throughout the whole aircraft development, testing, and certification process.

Depending on the aircraft mission, non-pilot evaluators might be part of the team, too. Their assessments could be based on scales like the NASA TLX, which does not strictly require test pilot background, see sections 5.4 and Appendix B for more details. This is a critical aspect of UAMVs and Personal Aerial Vehicles (PAVs), because this type of aircraft are not designed for exclusive use by pilots, contrary to what is currently required and accepted by the regulations.

Table 8, below, reports examples of minimum required HQTEs grouped by flight phase for the generic mission described in section 0When multiple tasks, which are also aircraft type specific, can be performed for a given flight phase, Table 8 reports the handling evaluation objective, in place of the actual task element.

Table 8. Example of minimum HQTE requirements

Flight Phase	**Aircraft Class**			
	Aeroplane	**Powered-lift**		**Rotorcraft/ Multicopter**
		Wing-Borne	**Rotor-Borne**	
Ground/deck	Ground Steering	Ground Steering	Ground Steering	Ground Steering
	Ground Braking	Ground Braking	Hover Taxi	Hover Taxi
Takeoff	Normal Takeoff	Normal Takeoff	Rolling Takeoff	Rolling Takeoff
	FBS Takeoff		Vertical Takeoff	Vertical Takeoff
	Envelope Protection Limiting *	Envelope Protection Limiting *	Level Accel Takeoff	Level Accel Takeoff
	Command Crossfeed^	Command Crossfeed ^		
Climb	Climbout Stability and Control	Climbout Stability and Control	Climbout Stability and Control	Climbout Stability and Control
	Envelope Protection Limiting *	Envelope Protection Limiting *		
Cruise	Pitch and Roll Control - PIO	Pitch and Roll Control - PIO	Pitch and Roll Control - PIO	Pitch and Roll Control - PIO
	Yaw Control	Yaw Control	Yaw Control	Yaw Control
	Mode-Switch Transients	Mode-Switch Transients	Mode-Switch Transients	Mode-Switch Transients
Descent	Flight Path Stability	Flight Path Stability	Flight Path Stability	Flight Path Stability
	Envelope Protection Limiting *	Envelope Protection Limiting *		
Approach and Landing	Low Airspeed Static Stability	Low Airspeed Static Stability	Low Airspeed Static Stability	Low Airspeed Static Stability
	Normal Landing-PIO	Normal Landing-PIO	Decelerating Approach	Decelerating Approach
	Offset Landing-PIO	Offset Landing-PIO	Hover Landing	Hover Landing
	Command Crossfeed^	Command Crossfeed ^	Rolling Landing	Rolling Landing
	Crosswind Landing	Crosswind Landing	Pirouette	Pirouette
	OEI Missed Approach-PIO-Command Limiting	OEI Missed Approach-PIO-Command Limiting	OEI Landing	OEI Landing
	Envelope Protection Limiting *	Envelope Protection Limiting *	OEI Missed Approach	OEI Missed Approach
Hover	N/A	N/A	Pirouette	Pirouette
Translational flight	N/A	N/A	Side Step	Side Step

Flight Phase	Aircraft Class			
	Aeroplane	Powered-lift		Rotorcraft/ Multicopter
		Wing-Borne	Rotor-Borne	
Transition from rotor-borne to wing-borne flight	N/A	N/A	To be Defined	N/A
Transition from wing-borne to rotor-borne flight	N/A	To be Defined	N/A	N/A

(^) Test of command crossfeed is critical for terminal phases and for tasks requiring a different piloting technique with respect to that of the crossfeed design requirements. This is particularly relevant in the transition between flight phases. One example is the effect of command limiting of the Aileron to Rudder Interconnection (ARI), which feeds the lateral control input to the directional controls. While ARI is beneficial for turn coordination in up and away flight phases, it is potentially detrimental in terminal phases, when de-coordination is necessary. It must be evaluated with manned simulations and in flight to validate adequate directional authority in All Engines Operative (AEO) crosswind landings and One Engine Inoperative (OEI) missed approaches. The refinement of the design might require a reduction or the complete cancellation of the crossfeed gain, when landing gear and/or trailing edge flaps are deployed.

(*) Test of aircraft response to envelope protection limiting has two scopes: (1) validate the envelope protection system capability to prevent envelope exceedances with respect to the limited aircraft state(s), i.e. AoA, airspeed, and attitudes, and (2) validate that the envelope protection system allows full aircraft control and satisfactory handling characteristics within the full LFE.

Validation of (1) is by requiring the pilot to intentionally demand an envelope exceedance and evaluating the protection by means of questionnaires of the type of that in Figure 22.

Validation of (2) is by performing gross maneuvering + fine tracking tasks capturing the system limited state(s) at an initial approximate 20% margin with respect to the limit. Margin can be reduced to refine the evaluation. Gross maneuvering + cyclic inputs can be used, as well, to demonstrate robust stability. Handling qualities evaluations are conducted for these scopes with and without atmospheric disturbances to assess the protection system with respect to robustness, effectiveness and no degradation of the handling qualities in proximity of the protected envelope boundaries.

Comment on point 3 of the HQTEs definition process: "Pilot's control amplitude regimes definition." HQTEs requiring different pilot's control amplitude regimes allow addressing potential handling qualities deficiencies with more direct reference to the control system elements. Small control amplitude HQ deficiencies, typical of the linear handling regime, can be resolved by modifying the command path: control sensitivity by varying command gain, prefilters, and feel system characteristics. Moderate control amplitude HQ deficiencies can be resolved by modifying the command path as for the small control amplitude, and by extending the boundaries of nonlinearities inserted in the command path, when they limit the predictability of the aircraft response. It is important to consider that most of the operational tasks, including approach and landing, are accomplished with moderate control amplitude. Large control amplitude handling qualities are linked to the small to moderate amplitude characteristics on one side and derive from aerodynamic and FCS nonlinearities. Stability problems in the large pilot's control amplitude regime are addressed, for example, by reducing the effector position and rate saturation, the tendency to saturation of the controls in the different axes, the inertia coupling effects through feedforward compensation.

8 High level certification process

8.1 Background

The reference for certification of Part 23 FBW aircraft is 14 CFR Part 23 Amendment 64 and 14 CFR Part 27. The method stated in 14 CFR Part 23 Amendment 64 is similar to the overall approach to certification proposed in this work. The main similarity is the presence of criteria that are not directly part of the regulations and that can be updated/changed based on the evolution of the requirements driven by that of the aircraft types.

The technical and procedural differences between development of a FBW system and that of a conventional control aircraft require the certification process to be intertwined with the development process itself and to contain regulations directly applicable to different phases of it, not exclusively to the final product. The objective of a FBW aircraft certification process must be to reach a comprehensive assessment of the airworthiness of the design, addressing its components that affect safety of flight. Section 7 drafts the relevant steps of a FBW aircraft development and particularly the process of flight clearance.

Under a civil aviation authority certification point of view, issuance of an experimental certificate for flight test is the first official step towards full certification of the vehicle.

Once the aircraft developmental phase is complete, it is not possible and economical for the certification authority to reproduce, for certification purposes, even a minor portion of the activities that led the manufacturer to assess their new FBW design as mature and safe for flight.

Therefore, it is important that the applicant/manufacturer keep the certification authority technically informed and involved throughout the whole aircraft developmental process. The applicant/manufacturer must ensure application of correct standard engineering processes, transparency, accurate documentation, verification and validation of the results throughout the aircraft development. Manufacturers implement this process independently from certification scopes to accurately capture the customer requirements and guarantee their satisfaction. The recommended role of the FAA is to apply a structured approach to intercept critical airworthiness information from design to operation.

Involvement of the certification authority for certification of UAMV FBW aircraft is required from the initial stages of the aircraft/system design and development. Specific requirements and close monitoring of the process, as well as of the end result, is expected to reduce the occurrence of un-detected design deficiencies not evident through a conventional certification approach, and to mitigate the risk of costly re-designs in case of non-compliances. Figure 52, below, displays the notional life-cycle cost versus time of a notional system. The diagram is applicable to civilian aircraft programs up to the "production and test" phase. The difference between military and civilian systems is that costs of "operation through disposal" of a civilian aircraft are not all incurred by the manufacturer; their largest portion is faced by the customer. The exceptions are the actions mandated by FAA Airworthiness Directives (AD), "to correct an unsafe condition in a product." According to Figure 52 the costs to extract defects is 20-100 times higher in the development phase, when 85% of the costs are committed, and 500-1,000 times in the production/test phase, when 95% of the costs are committed, with respect to those required in the conceptual phase.

The standard certification process begins in the production/test phase. Considering the cost figures mentioned above, correction of major defects identified in the standard certification phase is a significant financial risk for the manufacturer, potentially leading to the cancellation of the program due to cost overrun.

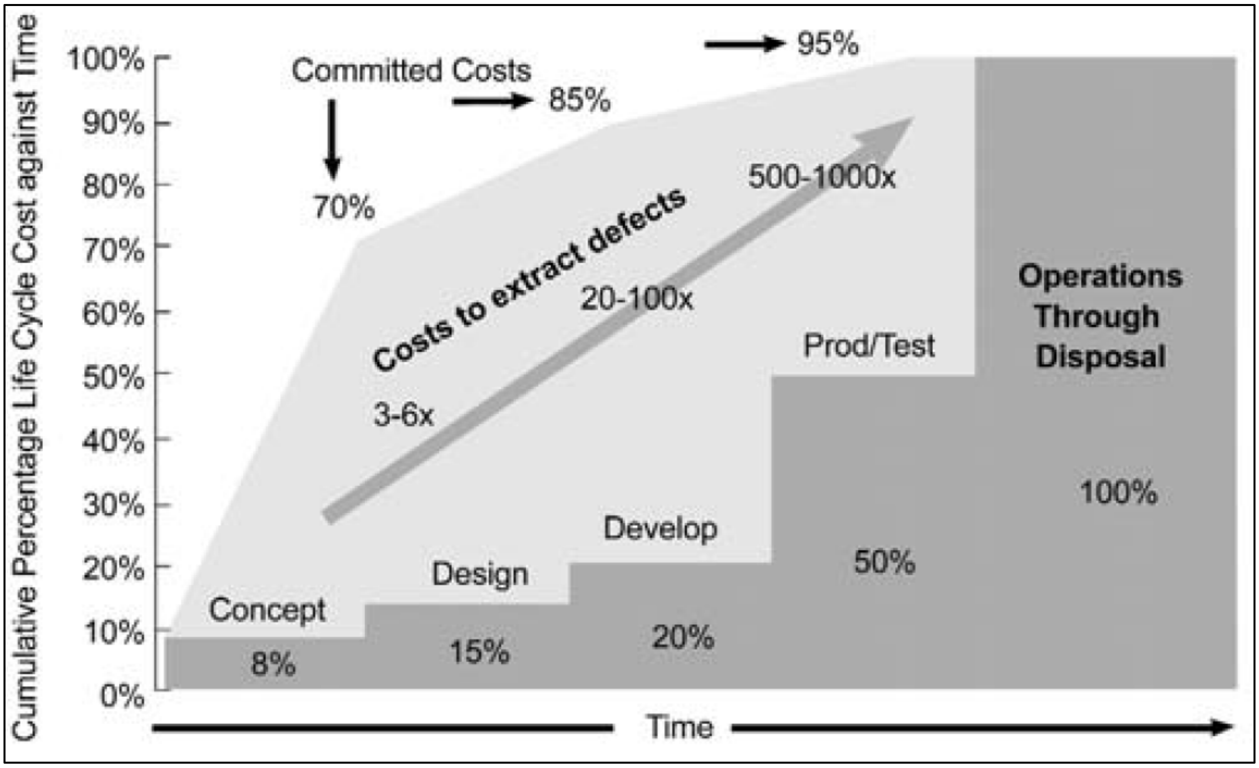


Figure 52. Life-cycle cost vs time [46]

The risk would not involve just the single manufacturer, but the developing UAMV industry as a whole. This is expected to be even more critical for hybrid and E-VTOL vehicles. Implementation of FBW technology in air vehicles, which are required to fulfill a large number of functions usually performed by the pilot, poses a higher level of uncertainty compared with classical FBW aircraft, as it requires a higher level of system integration. Confidence level in prediction models of complex and hybrid aircraft configurations is lower than that typical of conventional fixed or rotary wing aircraft. This implies a higher risk of identifying defects in the developmental, or in the production/test phase, when cost of extracting and correcting them is higher.

The high level result of the recommended certification process is expected to be a reduction of fatal accidents achieved by implementing reliable FBW systems to control the aircraft energy state, harmonize handling qualities throughout different flight regimes and tasks, provide the pilot with additional visual and/or tactile cues in support of his/her compensation technique(s).

One of the main objectives is to ensure that the margins with respect to pilot in the loop vehicle instability and to the boundaries of the *handling qualities cliff* are known along the whole development and certification process through a rigorous and documented engineering procedure.

The FAA should require compliance with the accepted industry standard process of FBW aircraft development, satisfying the functional (non-quantifiable) and performance (quantifiable) requirements that the applicant identified at the beginning of the developmental phase.

The proposed approach is also a certification of the process; the FAA can require applicant evidence of the results of each developmental phase: design, clearance, verification, and validation. This will minimize the application of empirical methods (*black box approach* or *build-fly-fix-fly*) to design, testing, and evaluation, which are now made easier to perform by the computational power currently available to designers, analysts, and evaluators.

Under the economic efficiency standpoint, expected outcomes of a structured approach is the reduction of the development and certification costs.

The following sections draft the certification process, each dealing with the proposed means of compliance applicable to the main steps of the aircraft development and production process:

a. Aircraft specifications
b. Control laws design and clearance criteria guidelines
c. Vehicle models
d. Offline design
e. Flight clearance
f. Flight test verification and validation

Selection of the criteria and derived MOCs are based on the following guiding principles:

- Level of applicability to the different stages of the process proposed in the previous phase.
- Documented validity of their application across major industrial and research aircraft programs.
- Public domain availability of the related background information and user guidance, when necessary.

8.2 Aircraft specifications

Proposed Mean of Compliance MOC1: Release of aircraft specifications. The applicant must provide an officially released aircraft specification and handling specification, if separate documents. The specification must describe the vehicle mission(s), required vehicle characteristics and performances, and related flight envelope(s). The handling specification must describe the required vehicle handling qualities level, as a function of the following:

a. Operational state
b. Flight envelope
c. Flight phase
d. Configuration
e. Atmospheric conditions

Compliance is required to conform to past engineering practice of design for requirements, critical for aircraft with significant design flexibility. This MOC can be satisfied by an applicant with the technical ability required to design, develop, and produce a fly-by-wire aircraft. Capture and analysis of the relevant requirements is potentially critical, and it entails an approach open to an iterative process until completion of the preliminary design. The safety risk of this MOC is an incorrect definition of the specification requirements, leading to mismatch between the production aircraft capabilities and the required ConOps. Best practice history confirms application of an iterative process during execution of the preliminary design, for consolidation of the specification requirements. Operational states are defined in section 5.1, and flight envelopes in section 5.2.

Proposed Mean of Compliance MOC2: The applicant must define the aircraft Operational Flight Envelope and the Limit Flight Envelope, as a function of aircraft states relevant for the mission requirements. Mandatory states defining the envelopes are [to be defined by the FAA].

Margins with respect to the limit envelope must be defined as a function of the envelope states (parameters), in which *the airplane must be responsive to intentional dynamic maneuvering to within a suitable range of the parameter limit* [19]. See Recommendation R7. The specified envelopes are the target for FCS/control laws design, flight clearance, and qualification.

The applicant must allow provision for a Flight Test Only Envelope, when required due to airworthiness limitations identified as result of the flight clearance, and/or of flight testing.

Compliance is required to match the flight envelope based approach of the FAA HQRM, demonstrating compliance with the intent of FAA advisory material defined for FBW aircraft. This MOC can be satisfied by an applicant with standard technical ability for production of aircraft, without any expected technical issues. The safety risk of the proposal derives from the selection of envelope states not representative of the aircraft mission. Envelope definition for application of requirements is aeronautical industry best practice.

Proposed Mean of Compliance MOC3: The applicant must define in the handling specification the handling qualities and PIO rating scales planned to be applied in the handling qualities evaluation. When required by the aircraft and FCS characteristics, criteria applied in the definition of questionnaires for evaluation of systems effectiveness must be included.

If no rating scales are specified, the FAA will require application of the Cooper Harper Rating scale and of the MIL-STD-1797B PIO rating scale.

Proposed Mean of Compliance MOC4: The applicant must specify, in the handling specification, minimum handling qualities level requirements compliant with those reported in Table 9, for the most adverse Center of Gravity position and mass distribution of each aircraft configuration. Where OFE and LFE boundaries coincide, requirements for OFE apply. The specified levels are the target for handling qualification.

Intended operation in the restricted FTOE is not allowed with moderate, severe, and extreme turbulence levels; the HQ level requirements for FTOE apply in case of unintended flight into those conditions. FTOE requirements for minimum safe operational state apply when performing in-flight verification of aircraft aeromechanic characteristics in selectable failed op aircraft and systems configurations.

Table 9. Minimum qualification handling qualities levels

Operational State	**Turbulence Level**								
	Light			**Moderate**			**Severe, Extreme**		
	FTOE	**OFE**	**LFE**	**FTOE**	**OFE**	**LFE**	**FTOE**	**OFE**	**LFE**
Normal	2	1	2	2	1	2	3	2	2
Minimum Safe	2	2	2	3	2	3	3	3	3
Controllable	N/A	3	3	N/A	3	3	N/A	3	3

8.3 Control laws development and clearance criteria

Proposed Mean of Compliance MOC5: The applicant must release official document(s) describing the control laws design approach and requirements, and the separate criteria applied for flight clearance.

Requirements must be identified for the following:

a. Linear stability. Baseline mandatory stability requirements are those reported in Table 5 of this document, specified in SAE-AS94900 [32]. The stability GM and PM requirements are “at the time of verification”. They apply to prediction models, to models matched and validated versus flight and to data acquired in flight, depending on the developmental stage of the aircraft.

b. Nonlinear stability. Impact on stability due to airframe and system non-linearities, to include effector rate and position limiting, aerodynamic non-linearities, inertia coupling, and effect of large atmospheric disturbances.
c. Controller performance (transient response, steady state response) to clinical inputs and disturbances.
d. Robustness.
e. HQ prediction criteria for flying qualities determination. A set of different criteria is allowed; the aircraft bandwidth criterion must be included in the set. Compliance with the FAA-specified values of the aircraft bandwidth criterion is mandatory.
f. Manned evaluations.
g. Verification maneuvers, FQTEs. FAA specified minimum set of mandatory FQTEs are to be defined by the FAA.
h. Design/clearance qualification maneuvers, HQTEs. FAA specified minimum set of mandatory HQTEs are to be defined by the FAA.
i. Software certification.
j. System integration tests, such as avionics and electrical "hot benches," "rig tests" and avionics manned simulator.
k. Internal compliance verification process with the requirements above.
l. Internal flight clearance non compliance management process.

Comment: This MOC addresses the requirement for application of a FBW dedicated process. The key mandatory elements of this MOC are the application of SAE AS94900 stability requirements, of aircraft bandwidth criterion as part of the HQ prediction criteria, the set of FAA specified verification maneuvers (FQTE), and the set of FAA specified qualification maneuvers (HQTE). In this case the term "qualification" is relative to the phase under consideration, in which manned evaluations are required.

This MOC requires the development by the FAA of handling qualities databases relevant for the class of aircraft under certification. This is to derive FQ and HQ requirements, respectively linked to the specific minimum sets of FQTEs and HQTEs. Development of HQ databases is part of the FAA "National Challenge".

8.4 Development of vehicle models

Proposed Mean of Compliance MOC6: The applicant must release an official aircraft model specification, containing requirements on the following:

a. Minimum set of models composing the overall aircraft model.
b. Accuracy and validity envelopes tracked on the aircraft flight envelopes compliant with proposed MOC2.
c. Fidelity level corresponding to each validity envelope.
d. Model tolerances amplitude and corresponding confidence level.

Proposed Mean of Compliance MOC7: The applicant must demonstrate that the aircraft model used for control laws/FCS design and flight clearance is formed by all the models that affect the aircraft handling characteristics.

Proposed Mean of Compliance MOC8: the applicant must demonstrate model tolerances application criteria, based on Monte Carlo method or equivalent, for control laws/FCS design and fight clearance.

8.5 Offline design execution

Proposed Mean of Compliance MOC9: The applicant must demonstrate, by documentation and analysis, the execution of the control laws design for each aircraft configuration in normal, minimum safe and controllable operational states, according to the following phases:

a. Bare airframe stability and control assessments.
b. Linear stability, based on requirements of MOC5 a.
c. Non-linear stability, based on off-line simulations with verification FQTEs specified in MOC5 b.
d. Linear handling, based on requirements of MOC5 e.
e. Non-linear handling, based on manned simulations and handling qualities evaluations, according to required validation HQTEs specified in MOC5 g.

Proposed Mean of Compliance MOC10: The applicant must provide evidence by analysis that the design satisfies the handling specification requirements of MOC5 a., MOC5 b., and MOC5 d. FQTEs.

Proposed Mean of Compliance MOC11: The applicant must provide evidence by analysis and documentation that the design satisfies the handling specification requirements of MOC5 g. HQTEs.

Comment: Considering the expected required involvement of the FAA in this process, this proposed MOC could be transformed in content of advisory material. The scope is to require the applicant to provide evidence of the results of the design by manned simulations, using FAA pilots' evaluations.

Proposed Mean of Compliance MOC12: The applicant must demonstrate, by documentation, the application of target design minimum handling qualities level requirements according to the structure of Table 10. Requirements apply to each CG position and mass distribution of each aircraft configuration. Where OFE and LFE boundaries coincide, requirements for OFE apply.

Table 10. Design handling qualities levels structure

Operational State	**Turbulence Level**																	
	Light						**Moderate**						**Severe, Extreme**					
	FTOE		**OFE**		**LFE**		**FTOE**		**OFE**		**LFE**		**FTOE**		**OFE**		**LFE**	
	N	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**
Normal																		
Minimum Safe																		
Controllable																		

Where:

N stands for nominal.

T stands for toleranced, i.e.: off-nominal aircraft characteristics.

Tolerances apply to stability and control, air data, mass properties, actuators and all other models affecting handling qualities characteristics.

Comment: This MOC does not require specific design target handling qualities levels. The scope is to require the applicant to specify target HQ levels according to the predefined industry standard structure of Table 10. It is fundamental for design to address nominal and toleranced (off-nominal) vehicle characteristics. The scope of the MOC is to ensure that the process is applied consistently and to guarantee traceability in case of non compliances in the clearance phase. The applicant defines the target design handling qualities levels that match the internal approach to control laws and FCS design, refer to MOC5.

8.6 Flight clearance execution

Proposed Mean of Compliance MOC13: The applicant must demonstrate, by documentation and analysis the execution of the flight clearance process according to the following steps:

a. Overview of aircraft and controller characteristics, offline model based.
b. Linear stability analysis, offline model based. The type of requirements are those reported in section 7.2.3 2. (a), (b), (c).
c. HQ prediction criteria for linear handling characteristics analysis, offline model based. The type of applicable requirements are those reported in section 6.
d. Assessment of the impact on stability and predicted handling qualities of toleranced (i.e. off-nominal) aircraft, sensors and actuators characteristics, offline.
e. Nonlinear nominal and toleranced control laws verification, offline.
f. Manned simulations for handling qualities evaluation.
g. Rig tests for verification of systems integration.
h. Flight clearance report.
i. Flight clearance refinement in the regions of local non-compliance, if identified after the beginning of flight testing.

Release of the formal flight clearance report is mandatory to satisfy this MOC.

Comment: The scope of this MOC is to ensure consistent application of the flight clearance process to substantiate the results of MOC14 and MOC15.

Proposed Mean of Compliance MOC14: The applicant must submit for FAA approval the test matrix of the hardware in the loop/iron bird verification and validation campaign of the control laws software compiled in the target Flight Control Computer (FCC), including ground structural coupling tests.

Proposed Mean of Compliance MOC15: In case an iron bird is not available, the applicant must designate an aircraft prototype, representative of the production vehicle, for ground verification and validation of the compiled control laws software and FCS implementation, and for ground validation of the aircraft structural dynamics characteristics Ground Vibration Test (GVT), and ground structural coupling.

Proposed Mean of Compliance MOC16: The applicant must demonstrate, by experiment, successful verification with respect to specification requirements of the control laws software compiled in the target Flight Control Computer (FCC). This must be achieved by hardware in the loop simulation, with the control laws and control system commands generated via the actual FCC; and the input signals, actuation commands, and resulting aircraft dynamics obtained via simulation.

Proposed Mean of Compliance MOC17: The applicant must demonstrate, by experiment in the iron bird, the verification and validation of the rigid-body, total-system models, and fully integrated FCS design.

Proposed Mean of Compliance MOC18: The applicant must demonstrate, by documentation analysis, and offline simulation that the aircraft satisfies the flight clearance flying qualities requirements of MOC5 e. . The required flying qualities levels coincide with those applicable to handling qualities in MOC15.

Proposed Mean of Compliance MOC19: The applicant must demonstrate, by documentation and mannned simulation, that the aircraft matches the flight clearance minimum handling qualities level requirements as reported in Table 11. Requirements apply to each CG position and mass distribution of each aircraft configuration. The specific method of compliance for evidence by simulation requires FAA test pilots to evaluate the aircraft handling qualities by execution of the minimum set of MOC5 h. HQTEs must be performed in the same ground simulator, running the same aircraft model, used by the applicant to perform the design.

Table 11. Target flight clearance minimum handling qualities level requirements

Operational State	**Turbulence Level**																	
	Light						**Moderate**						**Severe, Extreme**					
	FTOE		**OFE**		**LFE**		**FTOE**		**OFE**		**LFE**		**FTOE**		**OFE**		**LFE**	
	N	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**	**N**	**T**
Normal	2	3	1	2	2	3	2	3	1	2	2	3	3	3	2	3	2	3
Minimum Safe	2	3	2	3	2	3	3	3	2	3	3	3	3	3	3	3	3	3
Controllable	N/A		3	3	3	3	N/A		3	3	3	3	N/A		3	3	3	3

Comment: This is the first MOC addressing aircraft airworthiness directly, along the proposed certification process. Compliance with this MOC is a potential component of the basis for issuing an Experimental Airworthiness Certificate. Flight clearance results are the only mean to predict aircraft handling before flight. This is considered a fundamental aspect to approach FBW aircraft certification. In a FBW aircraft, no evidence of potential stability, control and handling qualities issues can be derived from observation of the aircraft general configuration and level of craftmanship.

Proposed Mean of Compliance MOC20: The applicant must issue an official flight clearance report containing the following critical flight clearance outcomes:

a. Compliance with the clearance criteria in the required clearance envelope, see MOC19.
b. Stability margins violations within the LFE, reporting on the violation magnitude, the region of the envelope, and the tolerance combination leading to it for each of them.
c. Unstable eigenvalues outside of the required limits, the region of the envelope and corresponding tolerance combination.
d. Occurrence of limit cycles, the region of the envelope and corresponding tolerance combination.
e. Rate or position effectors saturation, corresponding tolerance combination, and potential for aircraft control problems (i.e. PIO).
f. Identification of the handling qualities prediction criteria, predicting non-compliance with HQ requirements. Region of the envelope and corresponding tolerance combination.
g. Identified and repeated LFE envelope exceedance(s), corresponding maneuver(s) and tolerance combination.
h. Envelope region(s) and tolerance combination(s) corresponding to compliance and non-compliance with the handling requirements of Table 11, MOC 14.
i. Definition of **restricted** envelope regions, defined in terms of flight conditions, of the restricted aircraft states, reporting the reason for the restriction.
j. Definition of **prohibited** envelope regions, or regions of unresolved non-compliance, defined in terms of fight conditions, reporting the reason of the non-compliance.
k. Aircraft operational state, configuration, and off-nominal conditions of all identified prohibited and restricted areas of the envelope.

Proposed Mean of Compliance MOC21: The applicant must demonstrate, by documentation, the process applied to manage and resolve each individual noncompliance with respect to the flight clearance requirements. The applicant must perform the same process as the original design and clearance, beginning from the offline phase for each non-compliance.

Proposed Mean of Compliance MOC22: The applicant must issue an addendum to the clearance report for each resolved non compliance with respect to the flight clearance requirements. This must contain the description of the process and of the results of the supplemental local clearance to fly in the envelope region of previous non compliance.

8.7 Flight test verification and validation

Proposed Mean of Compliance MOC23: The applicant must demonstrate, by analysis, compliance with the accuracy and validation requirements of the aircraft models used for flying qualities prediction, as stated in the aircraft model specification.

Proposed Mean of Compliance MOC24: The applicant must submit for FAA approval the test matrix of the flying qualities in-flight verification campaign for certification.

Comment: This MOC is aimed at ensuring that the applicant's approach to testing for compliance demonstration with verification requirements is consistent with the FAA regulations. The applicant can obviously proceed to internal flying qualities verification, prior to submitting the test matrix for approval by the FAA. The structure of this test matrix can be derived from the flight clearance phase.

At the same time, submitting the test matrix before flight test allows the applicant to receive FAA technical guidance.

Proposed Mean of Compliance MOC25: The applicant must designate an instrumented test aircraft to conduct the certification tests. Flight Test Instrumentation must allow measurement of the pilot's controls position, effectors position and rate, aircraft states, to prove compliance with the verification quantitative requirements, under the test conditions specified in the verification test matrix.

Proposed Mean of Compliance MOC26: The applicant must demonstrate, by analysis and by in-flight experiment, compliance with respect to the required minimum set of FAA FQTEs. Flying qualities levels are those required for handling qualities in MOC 4. Analysis must derive from results based on aircraft models matched/updated with respect to data acquired during the flying qualities verification campaign. Experimental evidence must be based on flight data acquired during the same campaign.

Comment: A proposed example of the minimum set of required FQTEs is provided in Table 7. This MOC is to ensure traceability and continuity of the flying qualities requirements in terms of FQ criteria and levels from clearance to in-flight verification.

Proposed Mean of Compliance MOC27: The applicant must perform high priority FQTEs after submission and FAA approval of the corresponding test matrix. This set is required by the FAA, based on the documented results of the flight clearance. Higher priority is assigned to cases with lower margins with respect to the clearance requirements, documented in the flight clearance report.

Comment: These FQTEs can be a subset of the minimum required set of FQTEs of MOC25 and/or additional FQTEs selected on the basis of the result of the flight clearance. The FAA is responsible for selecting and requiring execution of these additional FQTEs.

Proposed Mean of Compliance MOC28: The applicant must submit for FAA approval the test matrix of the handling qualities in-flight qualification campaign for certification.

Comment: As for the in-flight verification test plan, there is no requirement to execute the qualification test and evaluation after FAA approval. This MOC is aimed at providing to the FAA visibility of the approach to qualification, leaving the applicant the flexibility of beginning the tests before submission of the test matrix.

Proposed Mean of Compliance MOC29: The applicant must demonstrate, by flight test, compliance with respect to the minimum set of required FAA HQTEs for handling qualities qualification. Handling qualities levels are those required in MOC4. Experimental evidence must be based on pilot's evaluation, through handling qualities ratings and comments.

Comment: This MOC would require specific research into the design of relevant HQTEs for different classes of aircraft, addressing potential significant differences between types of the same class of vehicles. Proposed examples of flight sub-phases for handling qualities evaluation through HQTEs are contained in Table 9 of this document. The task design and the identification of the states with respect to which task requirements are specified is a priority with respect to the quantitative requirements.

Proposed Mean of Compliance MOC30: The applicant must perform high priority HQTEs after submission and FAA approval of the corresponding test matrix. This set is required by the FAA, based on the documented results of the flight clearance HQTEs and of the flying qualities in-flight verification FQTEs. Higher priority is assigned to HQTEs with lower margins with respect to the clearance requirements, documented in the flight clearance report, and to those based on flight phases for which lower margin has been verified in flight with respect to the required FQTEs.

Proposed Mean of Compliance MOC31: FAA test pilots and engineers must perform test and evaluation for handling qualities qualification in selected HQTEs, aircraft configurations, and flight conditions. The criterion for their selection is their relevance/criticality with respect to the mission requirements and the results of the previous certification phases. The FAA must verify compliance of the aircraft with MOC28 for the selected HQTEs.

Figure 53 displays the application of the proposed MOCs to the different phases of aircraft development and certification.

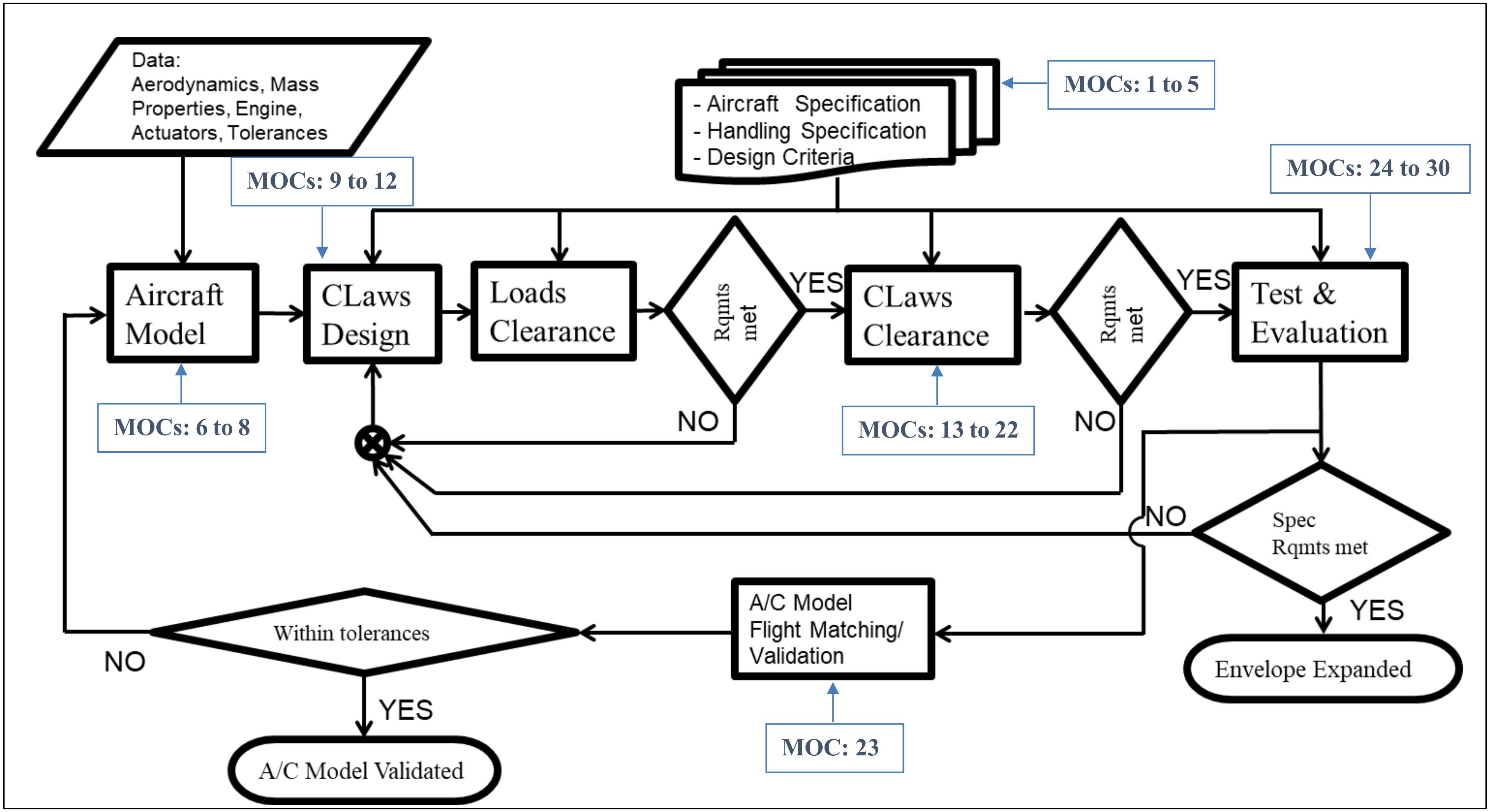


Figure 53. Applicability of proposed certification MOCs

9 Conclusions

The overall proposed approach to certification is that of combined certification of the aircraft and of the developmental process. The proposal is to achieve this gradually, from the initial aircraft developmental phases to its complete qualification, and validation with respect to customer requirements.

The scope is to propose the application of proven, public domain criteria and practices for the FAA to assess certifiability of the FBW system design, when these criteria and practices are applicable. When feasible, multiple criteria are proposed for each stage of the process, with the intent of providing a comprehensive approach to design and testing and a broad spectrum basis for certification. Selection of the criteria is based on the following guiding principles:

- Level of applicability to the different stages of the proposed developmental and certification process.
- Documented validity of their application across major industrial and research aircraft programs.
- Public domain availability of the related background information and user guidance.

The proposed approach is to include flight clearance in the certification process to minimize and quantify the risk of authorizing a new aircraft design to fly test, and to establish a traceable set of requirements and related analysis throughout the whole aircraft development/certification. For this reason, FAA oversight of the aircraft development, testing, and evaluation is considered essential to guide the applicant throughout the process, saving time, and to collect fundamental information leading to a fully traceable certification.

The scope of the combination of handling qualities verification based on FQTEs and qualification based on HQTEs is to combine compliance with the quantitative requirements of the FQ criteria and assessment of mission suitability based on subjective evaluations.

The references and rationale for deriving or suggesting new proposed MOCs have been the current 14 CFR Part 23 regulations, industry standard and military specification criteria. The background concept of this phase is that compliance, with both process and aircraft/system specific quantitative requirements, must be demonstrated as a minimum requirement for certification.

Applying means of compliance to the developmental, test and evaluation process allows: (1) flexibility and adaptability to the range of different vehicle designs deriving from FBW implementation, and (2) control that a process consistent with a mandatory minimum standard has been applied. The scope of means of compliance containing quantitative requirements is to ensure a minimum level of performance, with respect to the metrics relevant for the aircraft characteristics under consideration.

The existence of a reference formal process for airworthiness assessment by the manufacturer and its certification by the airworthiness authority allows for reliable use of the results obtained by the applicant in the aircraft certification process. It is proposed for the certification authority to perform directly a portion of the airworthiness assessment based on flight test, simulation and analysis by, to streamline the process and ensure objectivity.

Table 12 on the next page shows the list of recommendations for the FAA that were discussed in this document.

Table 12. List of recommendations

LIST OF RECOMMENDATIONS		
N	**Recommendation**	**Notes**
1	**The FAA should recommend update of ASTM F3082/F3082M – 17, paragraph 4.2.2, to include tolerances on aircraft moments of inertia.**	
2	**The FAA should require the applicant evidence of the methods applied in the calculation of tolerances on aircraft moments of inertia.**	
3	**The FAA should consider implementation of an integrated flight controls/handling characteristics regulations and certification approach.**	An "integrated" approach is in this case alternate to that of special conditions. It is the scope of this work.
4	**The FAA should develop means of compliance for in-flight assessment of aircraft static stabilities founded on open loop and handling qualities evaluations based on predefined tasks.**	This recommendation is addressed by the MOCs based on FQTEs and HQTEs.
5	**The FAA should require the handling qualities assessment to be specified in correspondence of combinations of: assigned HQ levels, pre-defined multi-dimensional envelopes, levels of atmospheric disturbance/probability, operational state, and mandatory and aircraft type specific MTEs.**	This recommendation is founded on the HQRM applied for certification according to 14 CFR Part 25 regulations.
6	**The FAA should recommend ASTM to expand paragraph 4.2.4 of ASTM F3180/F3180M-17 to include normal operation of E-VTOL vehicles.**	
7	**The FAA should consider including in the regulations the concept that *the airplane must be responsive to intentional dynamic maneuvering to within a suitable range of the parameter limit*, by establishing margins applicable to the limit envelope(s), within which no degradation of the maneuvering capabilities occurs. Demonstration maneuvers should be required to ensure respect of the new regulations.**	This is important to ensure adequate margins with respect to the "handling qualities cliff," and also in case of mishandling, or envelope exceedance due to atmospheric conditions.
8	**The FAA should require suitable means of alerting the pilot of a reduction of the flight envelope, following a failure, independently from the transition to a different stability augmentation mode.**	

LIST OF RECOMMENDATIONS		
N	**Recommendation**	**Notes**
9	**The FAA should issue advisory material outlining a conceptual path from preliminary design to certification of Part 23 FBW aircraft.**	This is important, to ensure adequate applicant's preparation to the FBW aircraft certification process.
10	**The FAA should define the mandatory minimum set of aircraft states and minimum boundaries defining the Limit Flight Envelopes and the Operational Flight Envelopes, as a function of the aircraft configuration and phase of flight.**	This can be based on the aircraft class and overall mission, i.e. PAV, or UAMV.
11	**The FAA should monitor the occurrence of airworthiness deficiencies through the applicant's issuing of FTOEs.**	
12	**The FAA should consider requiring the use of alternate rating scales and questionnaires to assess the pilot's or operator's effort in performing semi-automated tasks.**	
13	**The FAA should evaluate the use of the Chalk-Parrag PIO tendency rating scale for certification handling qualities evaluations.**	
14	**The FAA should ensure that operational, service and the potential flight test only envelope are defined by the applicant, and that the states selected by the applicant to define them match the minimum set required by the FAA. This can be subject of advisory material or MOC.**	
15	**The FAA should verify provision by the applicant of a process to identify airworthiness deficiencies and consequent temporary flight limitations. This can be the subject of a MOC, for which the process has a higher priority than the defined quantitative values. The scope is to ensure flexibility.**	
16	**The FAA should adopt the Aircraft Bandwidth criterion as the reference one for handling qualities prediction. This can be part of a MOC.**	The aircraft Bandwidth criterion is the basis for ADS-33E-PERF and demonstrated to be reliable also for fixed wing aircraft.

LIST OF RECOMMENDATIONS		
N	**Recommendation**	**Notes**
17	**The FAA should define new aircraft classifications for handling qualities prediction criteria, linked to the mission task requirements and not to the size or physical properties of the aircraft.**	This is would be a major change, differentiating CFRs and MIL Specifications, in particular for fixed wing aircraft.
18	**The FAA should use the Nichols exclusion zones as a baseline method for quantitative assessment of closed loop stability in the certification process.**	
19	**The FAA should verify the existence and the formal release by the applicant of the vehicle specification and of the handling specification. The handling specification can be standalone, or a part of the aircraft specification. This can be the subject of a dedicated MOC.**	
20	**The FAA should release guidance material and recommendations towards the application of current handling qualities prediction criteria, guiding adaptation of the quantitative part of the requirements to the new class of vehicles, when necessary.**	This is expected to require additional research, to develop dedicated handling qualities databases.
21	**The FAA should ensure the existence and the formal release by the applicant of an official document defining design, flight clearance principles and criteria, together with the related compliance verification process. This can be the subject of a dedicated MOC.**	
22	**The FAA should identify a minimum set of stability and flying qualities requirements, selected between the current industry standard ones, which must be satisfied by the design as part of the flight clearance. Required verification must be analytical. This can be the subject of advisory material and a dedicated MOC.**	
23	**The FAA should define a minimum set of MTEs for certification of Urban Air Mobility Vehicles. These should include open loop (FQTE) and closed loop (HQTE) MTEs.**	

LIST OF RECOMMENDATIONS		
N	**Recommendation**	**Notes**
24	**The FAA should verify that the aircraft model used for control laws/FCS design and flight clearance is formed by all models that affect the aircraft handling characteristics. This can be the subject of advisory material.**	
25	**The FAA should ensure the existence of an aircraft model specification. This can be the subject of advisory material and MOC.**	
26	**A core formed by data from wind tunnel testing is highly recommended for the aerodynamic models: S&C, ADS and hinge moments. It is recommended to base all the other models on experimental data, when available. This can be the subject of FAA advisory material.**	Modeling methods depend on the applicant; guidance could lead to higher fidelity models, with expected lower risk of re-design/flight limitations.
27	**The implementation of a version controlled development of the aircraft model and of corresponding control laws is recommended. This ensures traceability and consistency of the design. This can be the subject of FAA advisory material.**	
28	**The FAA should ensure that each model is equipped with a set of tolerances. Tolerances application is a high priority for each of the airframe models: S&C, ADS, and mass properties. This can be the subject of advisory material and MOC.**	
29	**Indications related to the airworthiness of the aircraft should not be derived from remotely flown, sub scale vehicle tests.**	
30	**Non-compliance with respect to the requirements of even one HQ prediction criterion should not be acceptable in the control laws/FCS design phase.**	
31	**Compliance with the set of minimum stability and handling requirements should be demonstrated by the applicant as part of the design phase, or independently by the FAA. This can be the subject of a dedicated MOC.**	

LIST OF RECOMMENDATIONS		
N	**Recommendation**	**Notes**
32	**The FAA should monitor and advise the manufacturer during execution of the flight clearance process, through the application of a set of dedicated clearance requirements. This is to verify appropriate application of the process and ensure its success. This can be the subject of a MOC.**	The same minimum required set of in-flight FQTEs and HQTEs can be applied to fight clearance.
33	**The FAA should require the applicant formal release of the flight clearance report, prior to authorize manned flights of the vehicle. This can be the subject of a MOC.**	The clearance report can be considered the first airworthiness document of the certification process.
34	**The FAA should issue requirements at stability, handling qualities criteria level and at procedural level, specifying minimum standards for systems integration tests, manned simulations, and management of non-compliances.**	
35	**The FAA should require a minimum standard for the fidelity of the simulators used for flight clearance. This can be the subject of advisory material.**	
36	**The FAA should limit the validity of the results from full-scale remotely flown tests to system identification, open loop verification of models fidelity and systems reliability.**	
37	**The FAA should require the applicant to report the results of the applied ground testing process, for verification and validation of the FCS software and hardware, as integral part of the flight clearance process.**	
38	**The FAA should ensure that a dedicated flight clearance is carried out for each of the test bed FCS modes.**	
39	**The FAA should verify the existence of a formal procedure to establish supplemental flight envelope limits when model inaccuracies identified from the flight test matching process do not guarantee adequate robustness of the control laws.**	
40	**The FAA should promote the application of the NASA real time nonlinear aerodynamic modeling technique to increase modeling accuracy and reduce the development cost of Part 23 aircraft.**	Novel modeling techniques are expected to have a significant impact on the time and costs of the aircraft development and certification.

LIST OF RECOMMENDATIONS		
N	**Recommendation**	**Notes**
41	**The FAA should require compliance by test with a minimum set of FQTEs and HQTEs, which are not necessarily coincident with those used by the applicant in its internal aircraft validation process. These minimum sets should be published as part of a Mean of Compliance.**	
42	**As part of the Mean of Compliance, the FAA should define the configurations and the envelope regions in which to perform the FQTEs, based on the documented results of the flight clearance. Higher priority should be given to cases with lower documented margins with respect to the clearance requirements.**	Traceability of the requirements and of the related results is fundamental to define a certification plan addressing the high priorities airworthiness aspects of each aircraft.
43	**The FAA should require in-flight execution of the minimum required set of FQTEs in pre-defined configurations in the core of the envelope and in envelope regions at the boundaries of the OFE and of the LFE. This can be the subject of a MOC.**	

10 References

1. Broad Agency Announcement (BAA) to Develop a Method of Compliance to Support Certification of Advanced Flight Controls in General Aviation and Hybrid Aircraft Vehicles. (DTFACT-16-R-00054).

2. https://cafe.foundation/v2/pav_archive.php

3. "Fast- Forwarding to a Future of On-Demand Urban Air Transportation"; UBER Elevate; 27 October 2016.

4. "A Rational Construct for Simplified Vehicle Operations (SVO)"; GAMA EPIC SVO Subcommittee Whitepaper, Version 1.0; 20 May 2019.

5. "ANALYSIS OF NONLINEAR CONTROL SYSTEMS"; D. Graham, D. McRuer; 1961 John Wiley & Sons.

6. "Piloted Simulation Evaluation of Pitch Axis Feel System Characteristics"; January 2013; D. H. Klyde, D. J. Alvarez, M. Lotterio, P. Schifferle, T. Lambregts.

7. "Fixed-Base Piloted Simulation Evaluation of Pitch Axis Fly-By-Wire Flight Control System Characteristics"; August 2013; D. H. Klyde, D. J. Alvarez, M. Lotterio, T. Lambregts.

8. "FAA Fly-By-Wire Research Program — Year 2 Follow-On"; M. Lotterio, R. McMahon, P. Schifferle; D. Alvarez, D. Klyde, and P. C. Schulze.

9. Special Condition No. 3. Electronic Flight Control System: Flight Control Surface Position Awareness".

10. Code of Federal Regulations: Title 14 Aeronautics and Space.

11. American Society for Testing and Materials "Standard Specification for Weights and Centers of Gravity of Aircraft", Designation: F3082/F3082M – 17.

12. American Society for Testing and Materials "Standard Specification for Flight Controls in Small Aircraft", Designation: F3232/F3232M – 17.

13. "Special Conditions: Embraer S.A., Model EMB-550 Airplanes; Flight Envelope Protection: Pitch and Roll Limiting Functions"; Docket No. FAA-2012-1211; Special Conditions No. 25-486-SC; April 3, 2013.

14. American Society for Testing and Materials "Standard Specification for Aircraft Handling Characteristics", Designation: F3173/F3173M – 17.

15. "Special Conditions: Boeing Model 777 Series Airplanes"; Docket No. NM-79; Special Conditions No. 25-ANM-78; December 10, 1993.

16. “Special Conditions: Airbus Industrie Model A320 Series Airplane”; Docket No. NM-26; Special Conditions No. 25-ANM-23; December 15, 1988.

17. Docket No. NM370; Special Conditions No. 25-349-SC; “Special Conditions: Dassault Aviation Model Falcon 7X Airplane [---]”; April 4, 2007.

18. ADS-33E-PRF; “AERONAUTICAL DESIGN STANDARD PERFORMANCE SPECIFICATION HANDLING QUALITIES REQUIREMENTS FOR MILITARY ROTORCRAFT”; 21 March 2000.

19. “Flight Test Guide For Certification of Transport Category Airplanes - Advisory Circular 25-7D”; U.S. Department of Transportation – Federal Aviation Administration; 05/04/18.

20. American Society for Testing and Materials “Standard Specification for Low-Speed Flight Characteristics of Aircraft”, Designation: F3180/F3180M – 17.

21. American Society for Testing and Materials “Standard Specification for Low-Speed Flight Characteristics of Aircraft”, Designation: F3174/F3174M – 18.

22. MIL-DTL-9490E (USAF) “FLIGHT CONTROL SYSTEMS - DESIGN, INSTALLATION AND TEST OF PILOTED AIRCRAFT, GENERAL SPECIFICATION FOR”; 22 April 2008.

23. MIL-F-8785C “MILITARY SPECIFICATION - FLYING QUALITIES OF PILOTED AIRPLANES”; 5 November 1980.

24. NASA TN D-5153 “THE USE OF PILOT RATING IN THE EVALUATION OF AIRCRAFT HANDLING QUALITIES”; April 1969; G. E. Cooper, R. P. Harper Jr. .

25. “Meteorological Techniques”; Air Force Weather Agency; AFWA/TN-98/002 Revised 21 February 2007; M. R. Mireles, Capt K. L. Pederson, MSgt C. H. Elford.

26. “FAA Aeronautical Information Manual”; 16 July 2020.

27. “A Subjective Rating Scale for Assessing Pilot Workload in Flight: A Decade of Practical Use”; Roscoe Dr. Alan H., Ellis George; ROYAL AEROSPACE ESTABLISHMENT TR 90019; March 1990.

28. “Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research”; Hart Sandra G., Staveland Lowell E.; HUMAN MENTAL WORKLOAD P.A. Hancock and N. Meshkati (Editors) Elsevier Science Publishers B.V. (North-Holland), 1988.

29. MIL-STD-1797B “FLYING QUALITIES OF PILOTED AIRCRAFT”; DEPARTMENT OF DEFENSE INTERFACE STANDARD; 15 February 2006.

30. “BACKGROUND INFORMATION AND USER GUIDE FOR MIL-F-8785B(ASG), "MILITARY SPECIFICATION -FLYING QUALITIES OF PILOTED AIRPLANES”;

August 1969; C. R. Chalk, T. P. Neal, T. M. Harris, F. E. Pritchard Cornell Aeronautical Laboratory, Inc.; R. J. Woodcock Air Force Flight Dynamics Laboratory.

31. “PROGRESS IN THE DEVELOPMENT OF COMPLEMENTARY HANDLING AND LOADING METRICS FOR ADS-33 MANOEUVRES”; M. D. Pavel, Gareth D. Padfield; American Helicopter Society 59th Annual Forum, Phoenix, Arizona; May 6 – 8, 2003.

32. “Bandwidth – A Criterion for Highly Augmented Aircraft”; R. H. Hoh, D. G. Mitchell, J. Hodgkinson; AIAA Atmospheric Flight Mechanics Conference; 19-21 August 1981.

33. “Aerospace - Flight Control Systems - Design, Installation and Test of Piloted Military Aircraft, General Specification For”; AS94900 SAE Aerospace; July 2007.

34. MIL-A-8860 B “MILITARY SPECIFICATION AIRPLANE STRENGTH AND RIGIDITY GENERAL SPECIFICATION FOR”; 20 May 1987.

35. “Mission Task Element Development Process: An Approach to FAA Handling Qualities Certification”; Klyde D. H., Schulze P. C., D. G. Mitchell, Sizoo D., Schaller R., McGuire R.; 2020 AIAA Aviation Forum.

36. “CONDUIT A New Multidisciplinary Integration Environment for Flight Control Development”; Tischler Mark B., Colbourne Jason D., Morel Mark R., Biezad Daniel J., Levine William S., Moldoveanu Veronica; NASA Ames Research Center, Aeroflightdynamics Directorate; Moffett Field CA 94035-1000; June 1997.

37. “A methodology for multi-objective design assessment and flight control synthesis tuning”; Joos Hans-Dieter; Aerospace Science and Technology, Elsevier, Paris; April 1999.

38. “Summit on Augmented Flight Path Control (AFPC)”; Lauffs Patrick J., Schatz Simon P., Holzapfel Florian; Technical University Munich Institute of Flight System Dynamics; May 2016.

39. “SYSTEM SAFETY ANALYSIS AND ASSESSMENT FOR PART 23 AIRPLANES” – Advisory Circular; Federal Aviation Administration; 17 November 2011.

40. “Initial Investigations Into Alternate Certification Approaches Using Run-Time Assurance for Small Aircraft Autopilots”; Skoog Mark A., Hook Loyd R. IV; Federal Aviation Administration; January 2018.

41. “Initial considerations of a multi-layered run time assurance approach to enable unpiloted aircraft”; Hook Loyd R. IV, Skoog Mark A., Garland Michael, Ryan Wes, Dave Sizoo, John VanHoudt; 2018 IEEE.

42. “MOTION AND VISUAL CUES IN THE REAL WORLD AND IN SIMULATORS - PRINCIPLES AND PRACTICE”; Strachan Ian W. MBE AFC FRAeS; May 2010.

43. “Aircraft System Identification”; Klein Dr. Vladislav, Morelli Dr. Eugene A.; American Institute of Aeronautics and Astronautics, AIAA Education Series 2006.

44. “Nonlinear Aerodynamic Modeling From Flight Data Using Advanced Piloted Maneuvers and Fuzzy Logic”; Brandon Jay M., Morelli Dr. Eugene A.; Langley Research Center, Hampton, Virginia; October 2012.

45. “Real-Time Onboard Global Nonlinear Aerodynamic Modeling from Flight Data”; Brandon Jay M., Morelli Dr. Eugene A.; Langley Research Center, Hampton, Virginia; June 2014, Atlanta GA.

46. “INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities”; John Wiley and Sons Inc.; January 2015.

A Appendix A

Pilot workload rating scale (Bedford) [27]:

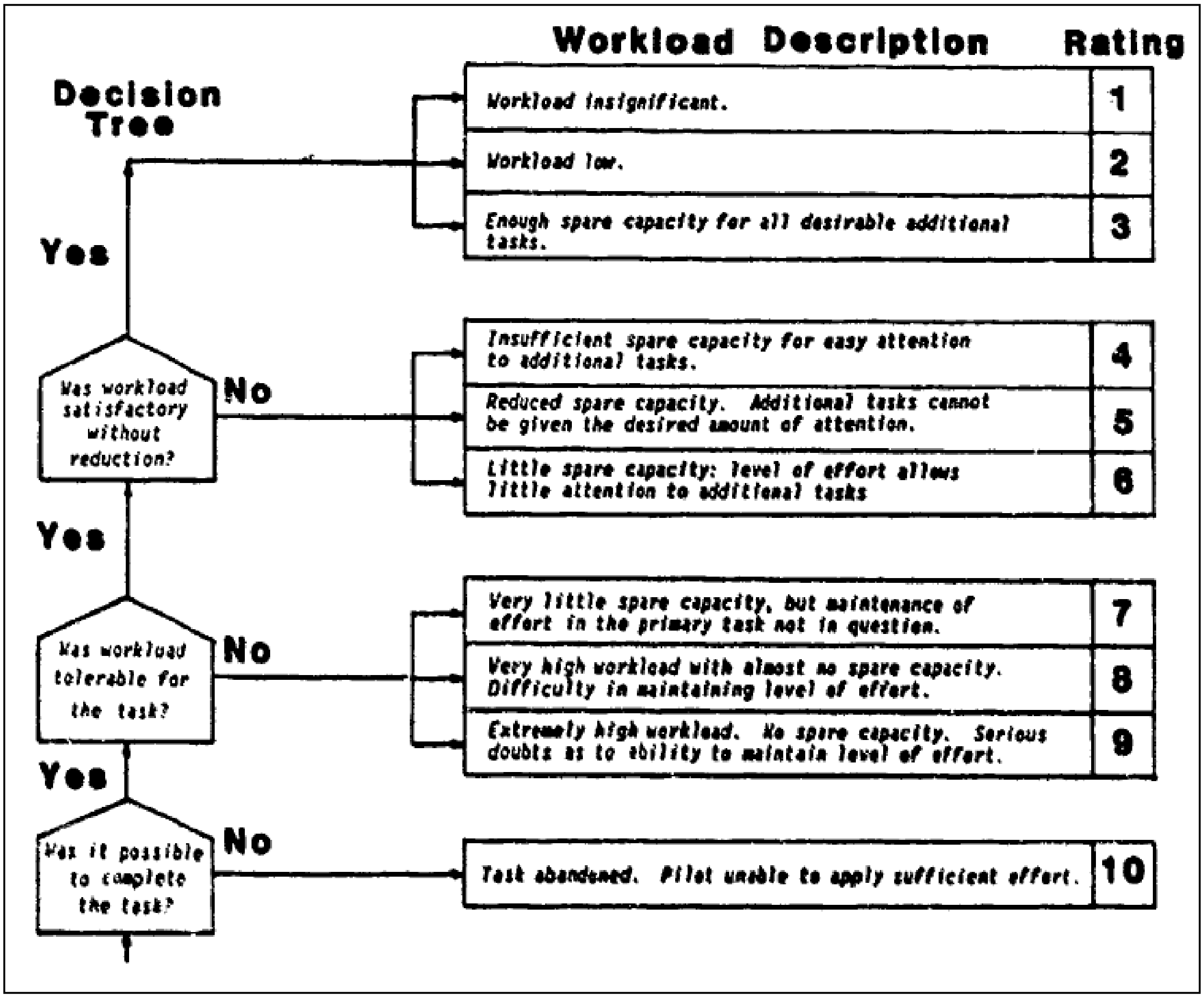


Figure 54. Bedford workload rating scale [27]

B Appendix B

NASA Task Load Index [28]:

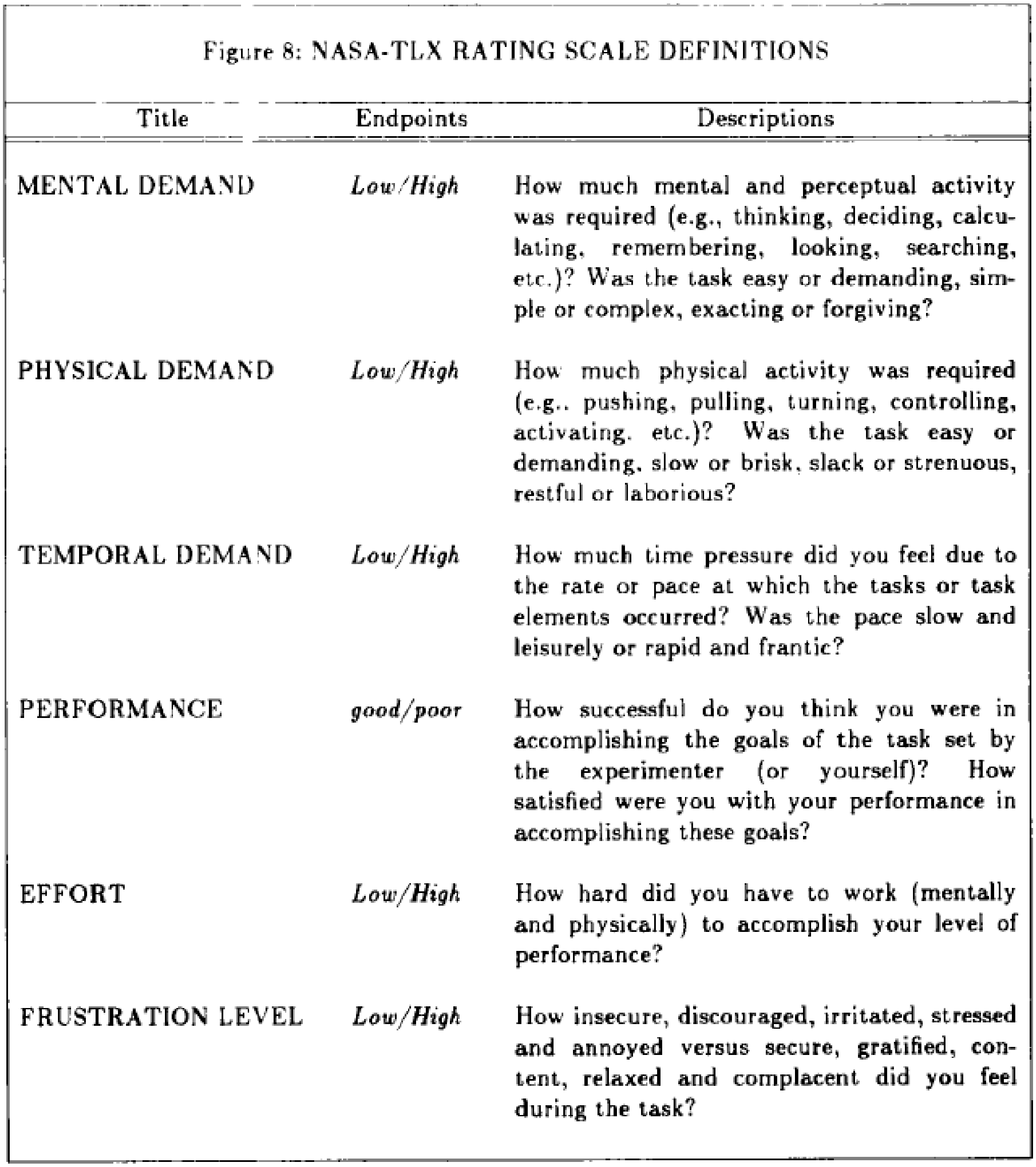
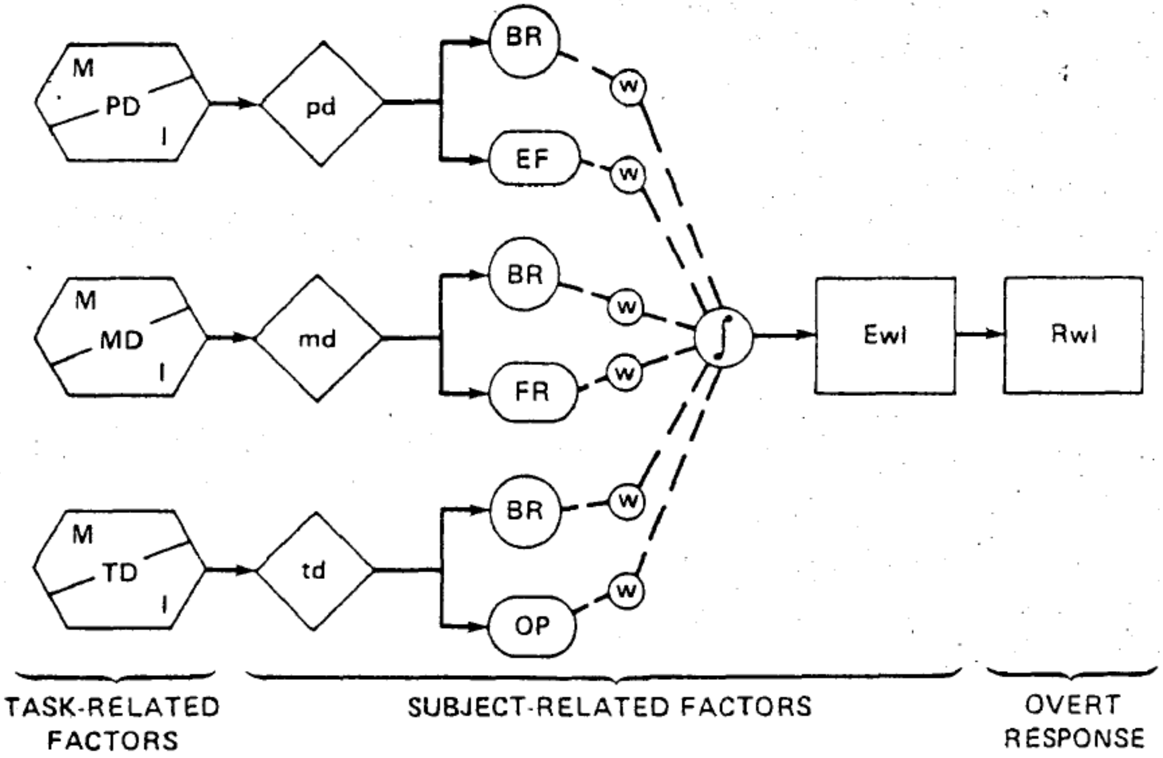


Figure 8: NASA-TLX RATING SCALE DEFINITIONS

Title	Endpoints	Descriptions
MENTAL DEMAND	*Low/High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	*Low/High*	How much physical activity was required (e.g.. pushing, pulling, turning, controlling, activating. etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	*good/poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Figure 55. NASA-TLX rating scale definitions [28]



PD, MD, TD	Objective physical, mental and temporal task demands
M, I	Objective magnitudes and importance of sources of demands
pd, md, td	Psychological representations of task demands
BR	Behavioral responses to task demands
OP, EF, FR	Subjective responses/evaluations of behavioral responses
w	Subjective weighting of factors
Ewl	Integrated subjective experience of workload
Rwl	Formal numeric or verbal evaluation of workload

Figure 56. NASA-TLX subjective workload estimation process [28]