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16. Abstract

As fly-by-wire (FBW) flight controls become the norm for commercial transports, the certification process needs to more directly address the unique characteristics of these systems. In response to this challenge presented by the Federal Aviation Administration (FAA), the team of Calspan Corporation and Systems Technology, Inc. worked on the multi-year FAA FBW research program to address this need. This report provides the FAA with proposed revised FBW standards (see table 130) and information to support related guidance materials and the analysis to support the proposed regulations. The key components of any fly-by-wire aircraft design are the cockpit feel system, command augmentation system, and primary control surfaces' actuators characteristics. One of the aspects at the center of this project was the impact of control system nonlinearities introduced to prevent issues of FBW systems implementation. This represents handling qualities (HQ) and safety matters in the design of FBW control systems. Examples of nonlinearities are dead zones, installed to avoid inputs cross-coupling or control integrator windup when the pilot is not in the control loop, or variable command sensitivity, to improve aircraft controllability in the fine tracking phase of pilot's control. Flat zones, which saturate pilots' command, feel system natural frequency and damping ratio, stick shaker, and variable feel active inceptors were also evaluated together with primary control surfaces actuators bandwidth. The increased flexibility gained with the introduction of this type of FBW element requires an understanding of their respective operative margins. The other aspect that was investigated during this research project was the level of augmentation and envelope protection effectiveness that can be achieved with hard envelope protection control system algorithms, maintaining appropriate pilot authority and guaranteeing adequate pilot/system interface. Five test pilots participated in an HQ study that was conducted using the fixed base, hydraulic variable feel system simulator that Calspan developed for the purposes of this project. An aircraft model representative of a twin aisle commercial transport was used in powered approach, maneuver, and cruise flight conditions. The aircraft used for the hard envelope protection evaluations was the Advanced Functionally Integrated Flight Control System augmented transport aircraft provided by the Federal Aviation Administration. Pilots performed continuous compensatory control and discrete and combined tasks in both the longitudinal and lateral plane. The nature of the tasks designed for HQ assessment was also exposed to a limited analysis of the consistency of small versus large control input/output response. Results included pilot ratings and comments as well as a quantitative analysis of task and pilot-vehicle system performance. Design and verification guidelines and recommendations for FBW systems, based on the results of the analysis, were provided. While flight verification of the results presented herein is recommended, the data provided are intended to serve as an initial guide to those concerned with the impact of feel-system characteristics on aircraft HQ.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ACH	Attitude capture and hold
AFI-FCS	Advanced Functionally Integrated Flight Control System
AoA	Angle of attack
ARI	Aileron-to-rudder interconnect
BO	Breakout
BWLAT	Lateral bandwidth
BWLON	Longitudinal bandwidth
CAP	Control anticipation parameter
CCC	Continuous compensatory control
CG	Center of gravity
CLAWS	Control laws
CSLON	Command sensitivity longitudinal
DR	Dutch roll
DLON	Damping longitudinal (feel system)
DLAT	Damping lateral (feel system)
DZLAT	Lateral dead zone
DZLON	Longitudinal dead zone
EP	Evaluation pilot
FAA	Federal Aviation Administration
FBS	Full backstick
FBW	Fly-by-wire
FCS	Flight Control System
FFS	Full forward stick
FFT	Fast Fourier transform
FPA	Flight path angle
FQ	Flying qualities
FREDA	FREquency Domain Analysis
FTE	Flight test engineer
FZLON	Longitudinal flat zone
GPL	General Public License
HDD	Head-down display
HQ	Handling qualities
HQR	Handling Qualities Rating
HUD	Head-up display
KCAS	Knots calibrated airspeed
Kts	Knots
MSL	Mean sea level
NBS	Narrowband signature
ND	Nose-down
NU	Nose-up
n_z	CG Normal Load Factor
n_{zp}	Pilot Station Normal Load Factor
OTW	Out-the-window
PA	Powered approach

PACH	Pitch attitude capture and hold
PIO	Pilot-induced oscillations
PIOR	Pilot-induced oscillations rating
PSD	Power spectral density
PVS	Pilot-vehicle system
rad/s	radians per second
RAPIDS	Rapid Analysis Parameter Identification Software
SM	Static margins
SoS	Sum-of-sines
SOW	Statement of work
SP	Short period
STI	Systems Technology, Inc.
TLA	Throttle lever angle
V_A	Maneuvering Speed
V_C	Cruise Speed
VS	Variable Stability

EXECUTIVE SUMMARY

As Fly-by-wire (FBW) flight controls become the norm for commercial transports, the certification process needs to more directly address the unique characteristics of these systems. In response to this challenge presented by the Federal Aviation Administration (FAA), the team of Calspan Corporation and Systems Technology, Inc. (STI) worked on the multi-year FAA FBW research program to address this need. This report provides the FAA with proposed standards related to FBW flight control systems. These proposed regulations and guidance are found in sections 19 & 20 and in table 130. This work provides the FAA with proposed revised requirements and background technical information addressing certification issues for FBW airplanes to be incorporated in future Federal Aviation Regulations and related guidance materials. This report summarizes the Year 2 (Task 2) Follow-on and Year 3 (Task 3) activities.

Task 2 Follow-on and Task 3 activities expanded the analysis of the FBW design elements and concepts addressing design safety methodologies, evaluating the effects of specific design attributes, characteristics, and envelope protection algorithms on handling qualities (HQ) and pilot-induced oscillation (PIO) tendencies. The evaluation of the design elements was accomplished initially by modeling the up and away characteristics of the transport aircraft model used for the Year 2 task (Task 2) and defining its inner loop control laws (CLAWS) for the Maneuvering Speed (V_A) and Cruise Speed (V_C) flight conditions. The CLAWS resulted in an augmented transport aircraft model with level 1 flying qualities — assessed with respect to MIL-1797B specifications, aircraft bandwidth criteria, and flight path angle (FPA) overshoot criteria. The actuator model, inceptor, and feel system model were concatenated to the augmented aircraft model — establishing the basis for desktop simulations and piloted evaluations using a variable-feel system fixed-base simulator.

A fixed-base simulator was developed by Calspan to be the main simulation device for the piloted evaluations of this project — allowing flexibility in the execution of the simulations, with the same capabilities of the Calspan Learjets in-flight simulators in ground mode. The fixed-base simulator is provided with the standard head-down display used in the Calspan Variable Stability (VS) Learjets and with an out-the-window display. A detailed description of the Calspan simulator is provided in appendix C of this report. The baseline inceptor implemented in the simulator is a hydraulic variable-feel righthand sidestick whose configuration was based on the characteristics of the sidesticks used in the VS Learjets. The various design elements to be evaluated were programmed into the simulator computer and input to the aircraft model and feel system.

Four experienced Calspan test pilots flew the standard augmentation Calspan/STI aircraft and Advanced Functionally Integrated Flight Control System (AFI-FCS) augmented aircraft provided by the FAA, in powered approach, V_A, and V_C flight conditions. A fifth pilot, from the FAA, participated in a limited number of evaluations, focusing mainly on the AFI-FCS augmented aircraft HQ and envelope protection. They performed Continuous Compensatory Control (CCC), discrete, and combined tasks in both the longitudinal and lateral plane. Artificial feel system, CLAWS, and control system parameters were varied to evaluate the effect on HQ and PIO susceptibility. Year 3 (Task 3) evaluations did not require any variation of the AFI-FCS control system, which was tested as provided by the FAA.

Tasks 2 and 3 of the research were divided into the subtasks outlined below in the FAA statement of work (SOW) [1].
Task 2:

Gain further insight into the following additional control system design attributes and characteristics that may affect HQ and control harmony and susceptibility to PIO. Develop design guidelines for determining acceptable design parameter values/variations.

1) Develop recommendations for acceptable/desirable active and passive inceptor characteristics with respect to:

   - Dead zones around the inceptor null position

   - Flat zones (no change in output) at high inceptor deflection

   - Inceptor command sensitivity scheduling as a function of inceptor deflection and flight condition

   - Minimum requirements for passive control inceptors' natural frequency and damping

   - Harmony between the active control inceptor feel force and the control maneuver command sensitivity, as a function of inceptor deflection

   - Harmony between the passive control inceptor feel force and the control maneuver command sensitivity, as a function of inceptor deflection, for various flight conditions

2) Develop guidelines for determining the required control effector bandwidth and maximum rate capability. Consider the effect of center of gravity (CG) or static margin and the need to control atmospheric disturbances without control loop destabilization due to rate saturation.

Task 3:

1) Develop recommendations for envelope protection design requirements by evaluation and analyses of the relative effectiveness and safety of various envelope protection functions:

   - Airspeed
   - Angle of attack
   - Attitudes
   - FPA
   - Normal load factor
   - Implementation concepts (e.g., "hard" and "soft" limiting)

2) Analyze their effect on HQ and operational safety and/or possible interference with normal maneuvering requirements during various flight phases.

3) Analyze pilot evaluations of HQ and PIO ratings, pilot comments, and the time history data performed for all test cases. The results of these analyses are presented as:

- Design safety requirements and best practices design guidance material
- FBW design validation checklist, whose use is for design and the certification process

4) Present suggestions for further development.

The following is a brief synthesis of the results of the research effort. One of the aspects at the center of the SOW is the impact of control system nonlinearities, which were introduced to prevent issues of FBW systems implementation. This represents a HQ and safety matter in the design of FBW control systems. Examples of nonlinearities can be dead zones, installed to avoid inputs cross-coupling; control integrator windup, when the pilot is not in the control loop; and variable command sensitivity, which improves aircraft controllability in the fine-tracking phase of the pilot's control. The increased flexibility gained with the introduction of this type of FBW element requires an understanding of their respective operative margins.

The other aspect investigated during this research project was the level of augmentation and envelope protection effectiveness that can be achieved with highly sophisticated control system algorithms, maintaining appropriate pilot authority and guaranteeing an adequate pilot/system interface.

Independent from the type of tested element/nonlinearity, pilots preferred aircraft response predictability and control authority — directly providing operative guidance in the establishment of the design criteria. An effective example is the stick shaker as a soft envelope protection element. Pilots favored this active stick design with respect to the command path flat zones, conventional variable command sensitivity, and parabolic continuous command gain scheduling, which is implemented in the AFI-FCS hard envelope protection algorithm. The predictability provided by the unmodified command augmentation system and full control authority made the stick shaker preferable, even though there is a possibility of unintentional envelope exceedances. Flat zones caused a highly nonlinear command and limited control authority, which was not evaluated positively. They did, however, provide a certain degree of protection from envelope exceedances.

Variable command sensitivity as a function of stick deflection and flight condition was designed to command limit load factor with full back stick or full forward stick inputs. This implied a piecewise command gain implementation, lower than baseline in the full stick deflection range. As a consequence, it required a slightly higher physical workload and exposed the pilot to a moderate nonlinearity in the command path. These factors were not evaluated positively, even in the presence of full envelope protection from load factor exceedances. A similar implementation present in the AFI-FCS, based on a parabolic command gain, provided excellent envelope protection. On the other side, it introduced a significant nonlinearity around the inceptor null

position, which reduced the aircraft response predictability, causing a tendency for pitch oscillations and an overall lower handling quality level.
Under the production use standpoint, the HQ level degradation cliffs as a function of flat zones amplitude indicates potential criticalities in the implementation of this design element at aircraft production standard level. This is mainly due to the expected low level of robustness with respect to varying flight conditions and the uncertainties in modeling the aircraft characteristics.

Command nonlinearity was an issue with large amplitude dead zones. It did not lead to PIO tendency, given the inherent gain attenuation, but forced the pilot to occasionally command full stick deflection because of the reduction of control authority. This produced a nonlinear nature of the control, which was the reason for the clear limits pertaining to the maximum acceptable dead zones amplitude.

Based on pilots' comments, particular attention has to be dedicated to the design of active sticks in order to minimize both command unpredictability and nonlinearity issues. The active stick implementation used in the evaluations was capable of providing envelope protection—when carefully tuned according to the pilot's requirements—which demonstrates margins of improvement in terms of design robustness.

A moderate impact of the feel system characteristics was derived from the evaluations. The minimum natural frequency ($\omega_{\min} = 10\ /\ 12.5\ rad/s$) and damping ratio ($\zeta_{\min} = 0.3$) derived from the evaluations are expected to be met without criticality by current active or passive inceptors.

On the other end of the airplane's maneuver response capability, actuator natural frequency variation has a noticeable impact on handling qualities ratings, PIO tendency, and task scoring due to the additional phase lag incurred. Low actuator natural frequencies caused additional phase lag near piloted control frequencies, resulting in higher workload, a less responsive aircraft making desired performance harder to achieve, and larger amplitude inputs. These factors all contributed to degraded ratings and an increased tendency to induce oscillations.

The evaluations of the AFI-FCS augmented aircraft, which is based on a vertical FPA rate command/FPA hold augmented manual control algorithm (intended for direct FPA control) provided indications on the appropriate piloting technique and avionics configuration suitable for a highly augmented aircraft with hard envelope protection flight control. Pilots reported that an open-loop piloting technique is most appropriate for this augmented aircraft, as it requires a lower level of compensation and avoids pitch oscillations, thus increasing aircraft response predictability. Visual cues available to the pilot regarding the status of the system are fundamental for good HQ. The availability of the FPA command marker required a significantly lower pilot lead compensation in all tasks performed. The importance of pilot awareness in the control of highly augmented aircraft was also clear in the hard envelope protection system evaluations. Real-time information regarding the control system mode status can eliminate the mismatch perceived by the pilot between the expected functioning of the flight control systems (FCS) and the actual aircraft response at the limits of the envelope. All pilots noted that a deeper knowledge of the system supports the understanding of the most appropriate piloting technique and increases the authority of the pilot. These factors, potentially emphasized by a mainly standard pilot display configuration, negatively impacted the pilot's ratings, even though envelope protection effectiveness was high. In the case of this highly augmented aircraft, predictability and pilot authority were also important factors in the evaluation results. It has to be noted that the system envelope protection functions were rated more positively by pilots with a background in highly augmented large transport aircraft. This is expected to depend on their familiarity with the authority limitations inherent in a full envelope protection system and the consequent attitude to adapt the piloting technique to the control system characteristics.

A recommendation for the further development of this research effort is the in-flight validation of the fixed base simulator results, which can be used as guidance in the definition of the in-flight simulation experiment. Real world visual and motion cues will provide more reliable results and allow for a more complete set of evaluation tasks. The flight testing of a subset of design elements will also allow a degree of extrapolation to be applied to fixed base simulation results in order to match the in-flight ratings.

The evaluations performed complete the most relevant scopes of the Year 2 and Year 3 phases of the project, according to the Year 2 Follow-on (Task 2) and Year 3 (Task 3) SOW [1].

1. INTRODUCTION

The analyses and results reported in this document are valid for the Year 2 Follow-on/Task 2 and Year 3/Task 3 phases, which were conducted to satisfy the requirements of the additional statement of work (SOW) issued by the Federal Aviation Administration (FAA) [1]. These phases form the third and fourth years of effort of the FAA's Fly-by-Wire (FBW) Research Program, which involved investigating Design Safety Validation Methodologies as they apply to Transport Category airplanes with FBW FCS.

The purpose of this research was to propose updated FBW standards and to develop an FBW design validation checklist that could be used in the design and certification process to ensure the proposed FBW design avoids poor practices which can contribute to poor control handling qualities (HQ) and pilot-induced oscillations (PIO). The FBW validation checklist developed may be found in table 130. Recommendations for new FBW standards and guidance may be found in sections 19 and 20.

The scope of this document is to report the analysis and results obtained from the ground-based simulations and the derived quantitative and qualitative guidelines/recommendations for safety validation methodologies of FBW systems design. A description of the aircraft model and an illustration of the stability augmentation approach — and of the ground simulation mechanization — are included to provide the background information on both the vehicle and its representation/interface to the test pilots. The pilot's tasks and scoring logics and the experiment approach are discussed to provide the test's rationale.

During the previous phase of the Year 2 research, a subset of the objectives specified in the SOW was selected to be the principal scope of the investigation. It was based on the set of manned simulations that could be performed depending on the funding to the project. Results of the first phase are valid for a wheel/column control inceptor, the type used in the Year 2 ground simulations.

Variable feel system characteristics, nonlinearities in the command path, variable command sensitivity, and the effect of inner-loop control bandwidth for various combinations of pilot gain were tested and analyzed in this phase. A hard envelope protection system was also evaluated under both HQ and envelope protection effectiveness standpoints. The aircraft used for these evaluations were the AFI-FCS augmented aircraft provide by the FAA. The nature of the tasks designed for HQ assessment was also exposed to a limited analysis of the consistency of small versus large control input/output responses.

Guidelines, FBW design safety requirements, and best practice material are provided in sections 17 and 18. The full set of pilot evaluation logs and time history plots are available in the appendices.

2. AIRCRAFT DESCRIPTION

2.1 AIRCRAFT BACKGROUND INFORMATION

This section provides a broad description of the aircraft characteristics, with brief references to the model and its structure. More detailed information on the model functioning, structure of each model subsystem, and the principal characteristics of the simulated system are provided in appendix A.

The aircraft characteristics (aerodynamic derivatives, mass properties) and reference flight conditions are derived from those of a twin-aisle, medium-size transport aircraft. Command and stability augmentation is implemented to improve HQ and expose issues associated with FBW designs. The model of the augmented aircraft is used for evaluation of the impact of feel system, FCS nonlinearities, and envelope protection algorithms on the HQ.

Different aerodynamic configurations/flight conditions are considered (see table 1):

- Powered approach (PA) at mean sea level (MSL)
- Maneuvering speed (V_A) at Perigree altitude (Hp) = 38,000 ft
- Design Cruise speed (V_C) at Hp = 38,000 ft

A range of longitudinal static margins (SM) of the unaugmented aircraft is considered at each flight condition. Table 2 reports the unaugmented SM, corresponding *x* CG location in the construction axes reference, and respective configuration code used in the document. Feedback and command gains are defined with respect to the reference configuration SM = 5 % ($\bar{c}$). The range of bare airframe SM is intended to require different demands on the augmentation system, mainly to investigate the effect on HQ of a change of the inner-loop bandwidth as a function of unaugmented longitudinal SM.

Table 1. Flight conditions

Flight Condition	Hp (kft)	KCAS	TAS (ft/s)	Mach
Powered Approach (PA)	0	136.3	230.0	0.206
Maneuvering Speed (V_A)	38	234.0	716.4	0.740
Design Cruise Speed (V_C)	38	280.6	847.0	0.875

Kft = thousand feet, Ft/s = feet per second, KCAS = Knots calibrated airspeed, TAS = True airspeed

Table 2. Longitudinal SM and *x* CG locations

Configuration Code	Bare Aircraft SM (% $\bar{c}$)	*x* CG (% $\bar{c}$)	
		Hp = 38 kft Flap = 0 deg	Hp = 0 kft Flap = 45 deg
Cfg 1	5	35	23.2
Cfg 2	2.5	37.5	25.7
Cfg 3	0	40	28.2

The simulation model FAA_FBW_model_nonlinear_forsim.mdl is used to perform offline simulations and is based on the target airframe nonlinear model. The nonlinearities are limited to the lift curve slope, which varies as a function of angle of attack (AoA, alpha). The linear range aerodynamic derivatives of the PA configuration are identical to those of the model used for the Year 2 research project. For detailed information about the aircraft characteristics, see appendix A. The feel system, control laws (CLAWS), actuators, and engine are modeled in separate dedicated subsystems. The sensor dynamics are not modeled. The aircraft model is developed in the MATLAB/Simulink program and is formed by a data set loaded through the MATLAB workspace into a Simulink diagram containing the principal logics and structure of each subsystem. Figure 1 displays the top-level structure of the Simulink diagram, subdivided into the mentioned subsystems. Different modes of the CLAWS configuration can be set by the user, depending on the envelope protection algorithm to be used for the evaluations. The three subsystems for hard, soft, and no envelope protection are visible from top to bottom, respectively, in figure 1— with a light blue background color.

The same simulation model is compiled and run in real-time mode in the Calspan fixed-base/variable-feel simulator for manned evaluations.

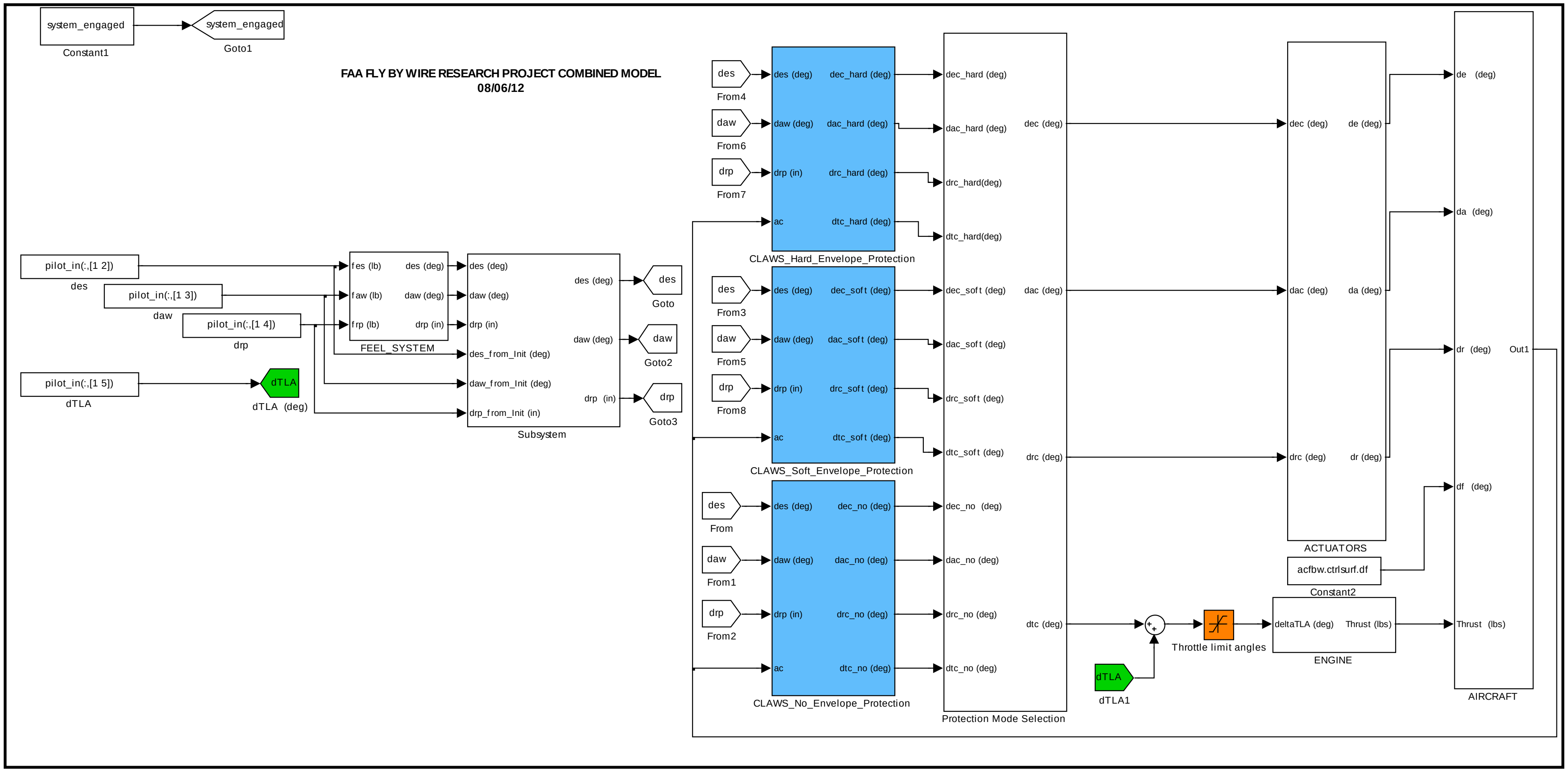


Figure 1. Aircraft simulation model top-level structure

2.2 UNAUGMENTED AIRCRAFT DYNAMICS

2.2.1 Introduction

The scope of the analysis of the unaugmented aircraft dynamics and flying qualities (FQ) evaluations is to identify potential FQ deficiencies and define the stability augmentation strategy necessary to satisfy Level 1 with respect to multiple FQ requirements.

The FQs are assessed according to the following MIL-STD-1797B aircraft and flight phase identification:

Classification:	Class III (large, heavy, low-to-medium maneuverability airplanes, such as heavy transport/cargo/tanker)
Flight Phase:	Nonterminal, Category B/Cruise (CR) Terminal, Category C/Approach (PA)

The flight phase identification is based on the actual aircraft requirements for which the FQ have to be assessed and the augmentation designed, with no direct connection to the tasks performed in the evaluations.

The approach followed in the definition and characterization of the aircraft FQ is to compare the response with multiple FQ requirements defined by modal parameters, frequency domain criteria, and time domain characteristics. This is considered an effective approach for a broader understanding of the FQ, which takes into account different aspects defining them. Each FQ criterion tends to be focused on specific aspects of the aircraft response.

This approach demonstrates consistent results throughout all applied criteria in both the longitudinal and lateral/directional plane.

2.2.2 Longitudinal Plane

2.2.2.1 Modal Parameters and CAP

The unaugmented aircraft modal characteristics are compared with the MIL-F-8785C [2] and MIL-STD-1797B [3] FQ requirements to assess the FQ levels of the un-augmented airframe for each positive longitudinal SM configuration and flight condition.

The set of short period (SP) damping ratio MIL-F-8785C FQ baseline requirements is reported in table 3, with table 4 containing the corresponding FQ levels for all unaugmented aircraft configurations with positive SM. Figures 2 and 3 display the MIL-F-8785C FQ SP requirements for PA and up and away configurations, respectively. The corresponding SP mode control anticipation parameter (CAP) set of requirements, extracted from MIL-STD-1797B, is also reported in figures 4 and 5 for consistency and a comparison between the two requirement sets.

Table 3. The MIL-F-8785C short-period and phugoid damping ratio limits

Damping Ratio Limits					
	Short Period				
	Flight Phase A and C		Flight Phase B		Phugoid
Level	Minimum	Maximum	Minimum	Maximum	Minimum
1	0.35	1.30	0.30	2.00	0.04
2	0.25	2.00	0.20	2.00	0.0
3	0.15*	-	0.15*	-	T_2 at least 55 seconds

* May be reduced at altitudes above 20,000 feet if approved by the procuring activity.

Table 4. The MIL-F-8785C longitudinal damping ratio FQ levels — unaugmented aircraft

Unaugmented Aircraft FQ Levels (Damping Ratio)					
Flight Condition	SM (% $\bar{c}$)	Level		ζ_{SP}	ζ_P
		SP	Ph		
Powered Approach (PA)	+ 5.0	1	1	0.815	0.079
	+ 2.5	1	1	0.900	0.170
Maneuvering speed (V_A)	+ 5.0	1	2	0.707	0.022
	+ 2.5	1	2	0.726	0.031
Cruise speed (V_C)	+ 5.0	1	2	0.598	0.038
	+ 2.5	1	1	0.729	0.049

The short-period requirements displayed in figures 2–5 require the calculation of n_z/a (g/rad), which is the steady-state normal acceleration change per unit change in AoA for an incremental pitch control deflection at constant speed (airspeed and Mach number).

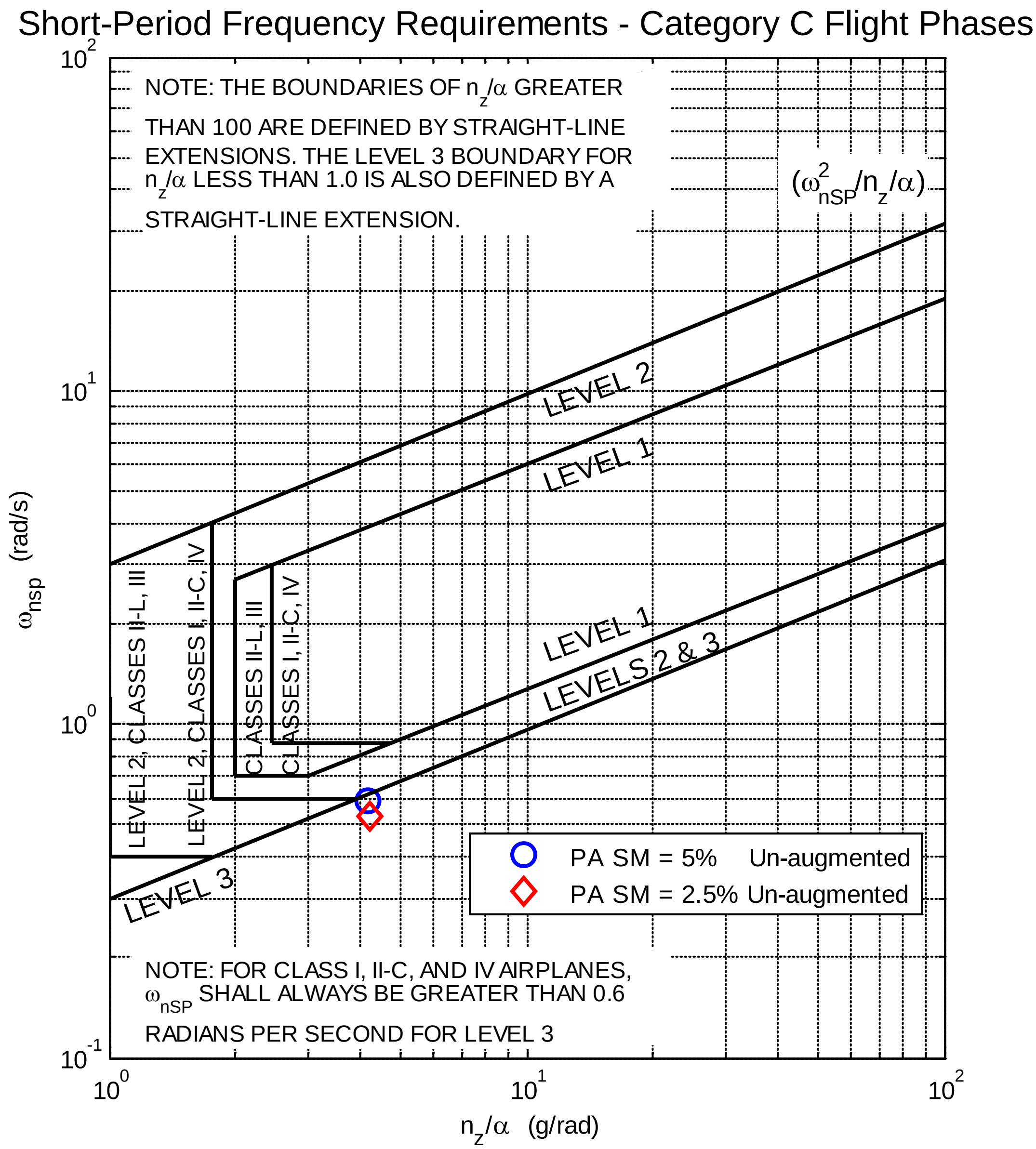
For completeness of the description, the values of n_z/a and CAP were calculated as follows:

$$n_z/a = \frac{V \cdot \frac{1}{T_{\theta_2}}}{g} \quad \text{(g/rad)} \tag{1}$$

$$CAP = \frac{\omega_{n_{SP}}^2}{n_z/\alpha} \left(1/(g \cdot s^2)\right)$$

Where:

V	aircraft true airspeed	(ft/s)
$\frac{1}{T_{\theta_2}}$	higher frequency zero of the $\frac{q}{\delta_e}$ transfer function	$(1/s)$
g	gravity acceleration	(ft/s^2)
$\omega_{n_{SP}}$	short-period natural frequency	(rad/s)



rad/s = radians per second
g/rad = g's per radian
n_z = CG normal load factor

Figure 2. The MIL-F-8785C short-period frequency requirements — PA unaugmented aircraft values

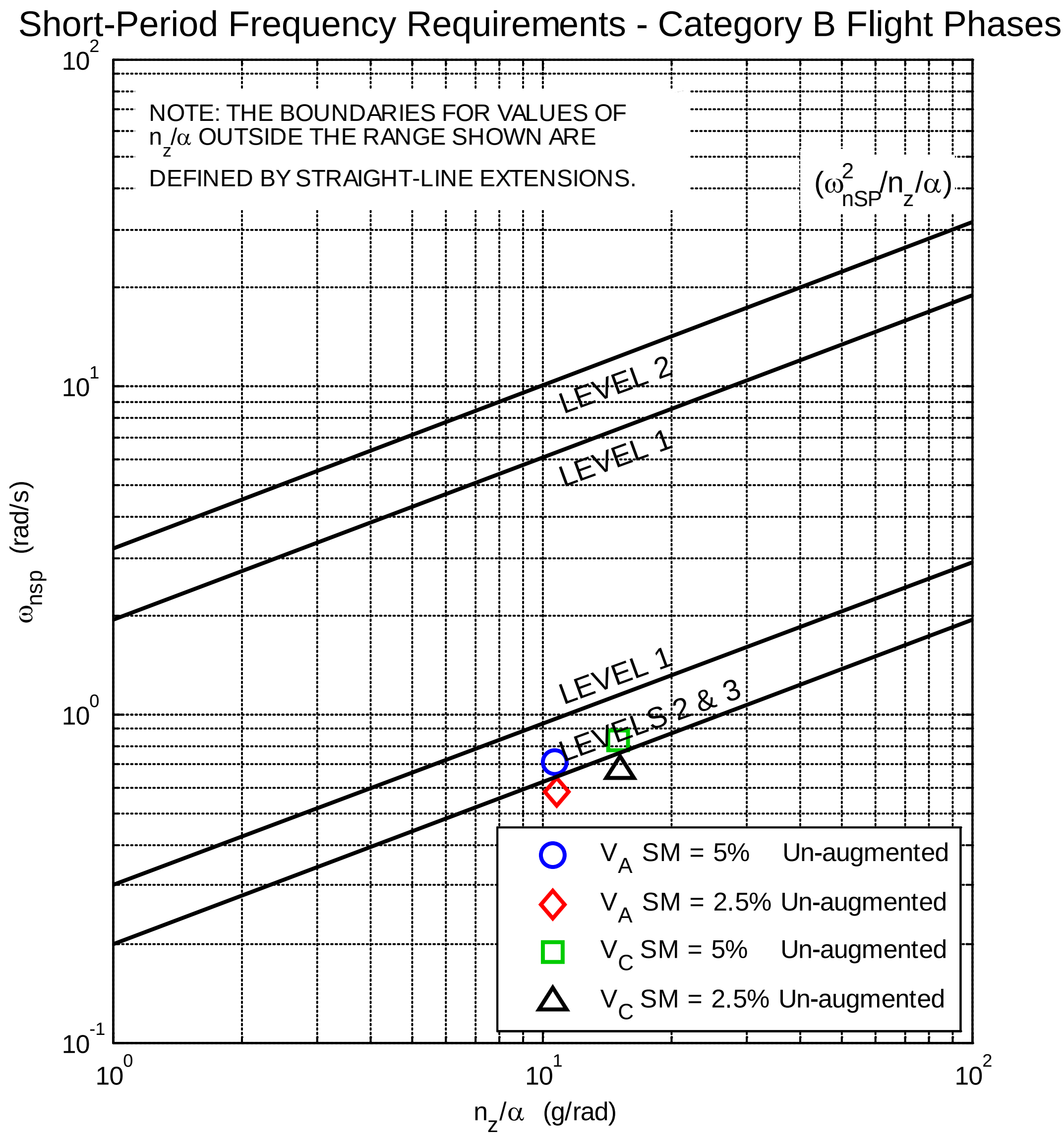


Figure 3. The MIL-F-8785C short-period frequency requirements — V_A, V_C unaugmented aircraft values

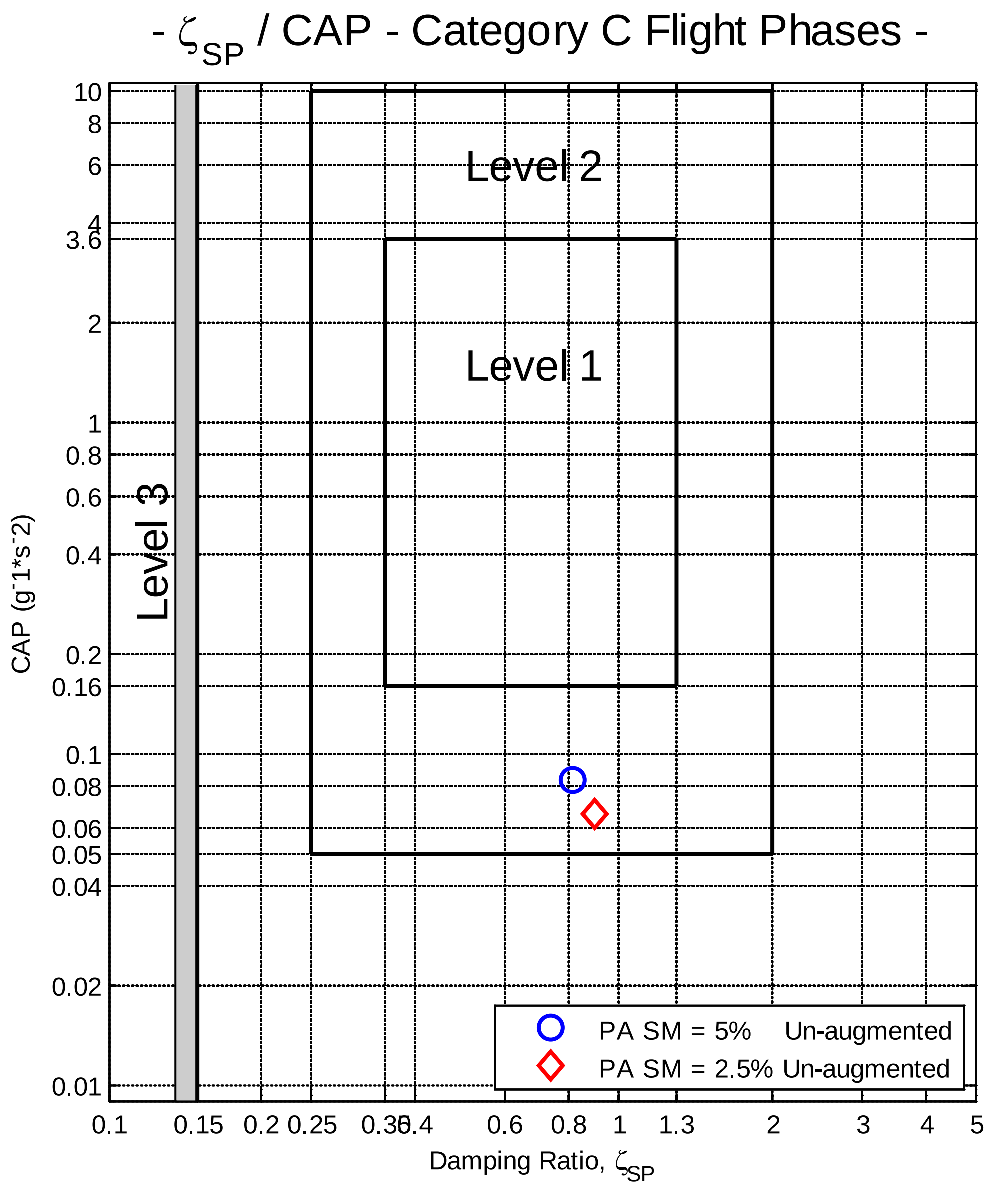


Figure 4. The MIL-STD-1797B ζ_{SP}/CAP requirements — PA unaugmented aircraft values

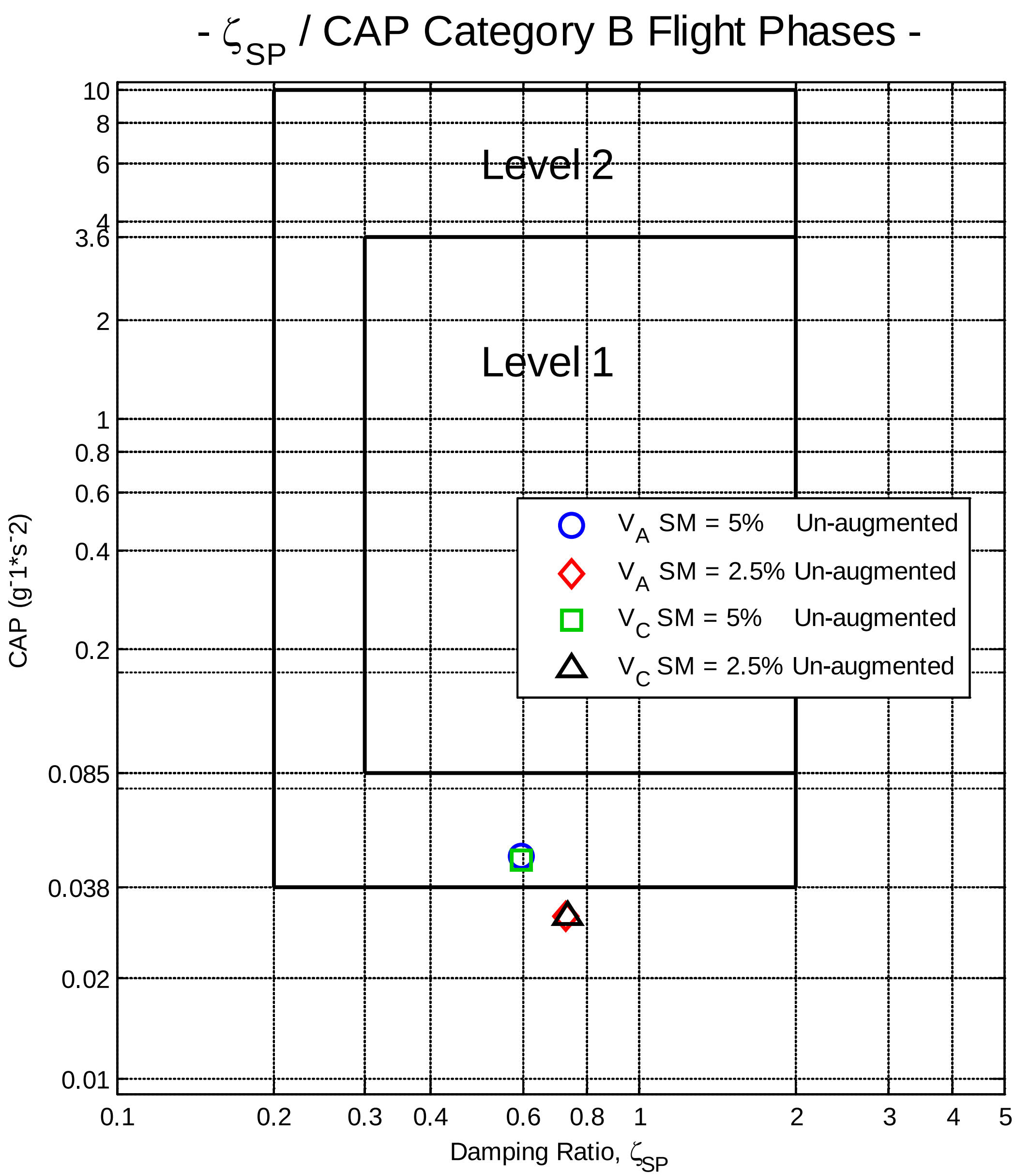


Figure 5. The MIL-STD-1797B ζ_{SP}/CAP requirements — V_A, V_C unaugmented aircraft values

Table 5 contains a synthesis of the unaugmented aircraft longitudinal modal parameters for the flight conditions/configurations with a positive longitudinal SM.

Table 5. Longitudinal modal parameters — unaugmented aircraft

Unaugmented Aircraft Longitudinal Modal Parameters								
Flight Condition	SM (% $\bar{c}$)	$\omega_{n_{SP}}$ (rad/s)	ζ_{SP}	ω_{n_P} (rad/s)	ζ_P	$\frac{1}{T_{\theta_2}}$ $(1/s)$	n_z/a (g/rad)	CAP $(1/(g \cdot s^2))$
PA	+ 5.0	0.59	0.815	0.12	0.079	0.585	4.18	0.083
	+ 2.5	0.53	0.900	0.09	0.170	0.587	4.20	0.066
V_A	+ 5.0	0.71	0.597	0.06	0.022	0.481	10.71	0.047
	+ 2.5	0.58	0.726	0.05	0.031	0.487	10.86	0.031
V_C	+ 5.0	0.83	0.598	0.05	0.038	0.572	15.07	0.046
	+ 2.5	0.68	0.729	0.04	0.049	0.580	15.27	0.031

The next several pages contain figures displaying the bare aircraft pitch rate to elevator $\left(\frac{q}{\delta_e}\right)$ frequency response in the different flight conditions used for the evaluation for all SM.

The following comments apply to the configurations with positive SM. Figure 6 refers to PA flight condition, which shows a lightly damped phugoid and a well-damped SP. The major consequence of this is the significant phase drop occurring at the phugoid mode frequency, which affects the SP response as well and corresponds to a significant phase lag in the aircraft response bandwidth frequency range. The relatively low SP frequency produces a CAP FQ level 2, while the SP damping ratio is adequate for both CG configurations. The $\omega_{n_{SP}}$ values do not change significantly with varying SM (see table 5). For the low SM values considered, the SP natural frequency is mainly determined by the change of normal force with change of vertical speed (Z_w) and total pitch damping $\left(M_q\right)$ when referring to a 2 degrees-of-freedom short-period approximation. A detailed explanation of the hypotheses and simplifications to the equations of motion for aircraft rigid modes approximations is included in [6].

Figures 7 and 8 refer to V_A and V_C flight conditions, respectively. The difference between the short-period and phugoid-mode natural frequencies in both these flight conditions is higher than in PA. This allows for a lower impact of the phugoid-mode phase drop on the phase of the SP, with consequent lower phase lag within the aircraft response bandwidth. It occurs even if the phugoid damping ratio is significantly lower than in PA, as expected ($\zeta_p \approx \frac{1}{\sqrt{2}E}$), with E the aerodynamic efficiency.

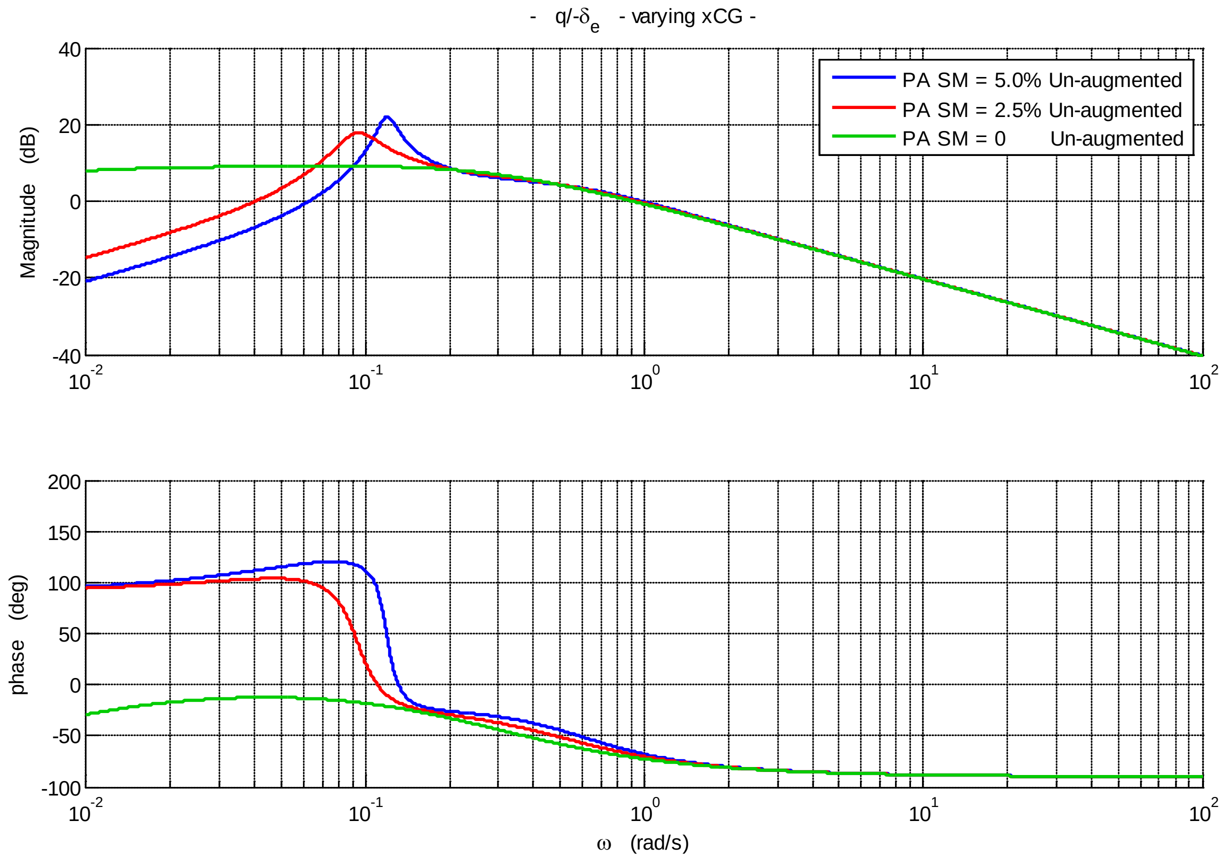


Figure 6. The $\frac{q}{-\delta_e}$ frequency response — PA bare aircraft

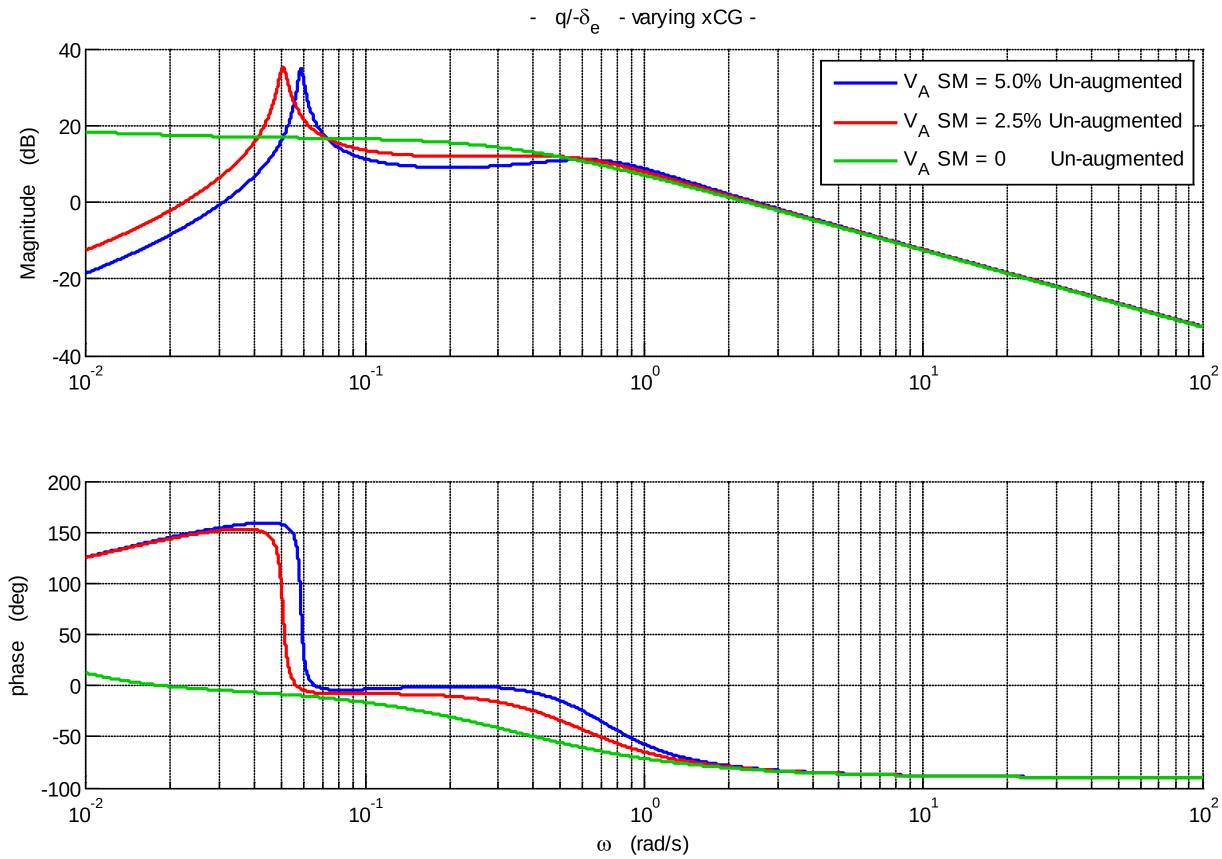


Figure 7. The $\frac{q}{-\delta_e}$ frequency response — V_A bare aircraft

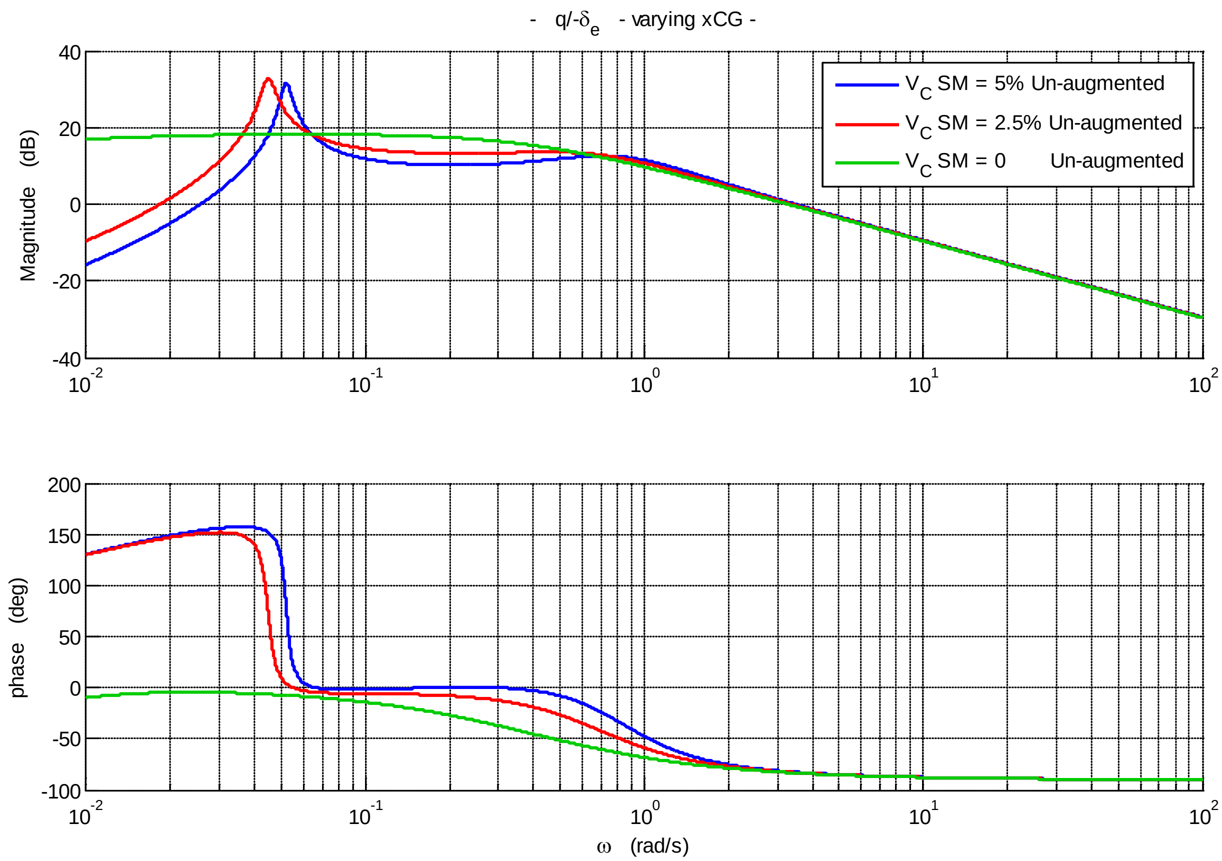


Figure 8. The $\frac{q}{-\delta_e}$ frequency response — V_C bare aircraft

2.2.2.2 Aircraft Bandwidth

The aircraft bandwidth criterion is applied as the metric to quantify and assess the aircraft response characteristics when the pilot is actively controlling the aircraft. Detailed information on this FQ criteria is available in [4 and 7]. Comparisons of the aircraft dynamics response parameters with the longitudinal FQ requirements in the three reference flight conditions are displayed in figures 9–12. The calculated parameters are relative to the aircraft with baseline actuator characteristics and with the feel system dynamics excluded. Table 6 reports the corresponding numerical values.

The results demonstrate that:

- Pitch attitude bandwidth is FQ solid level 2 in all flight conditions and SMs.
- Considering the overall low level of pitch rate overshoot $\Delta G(q)$, no tendency to PIO is expected.
- Flight path angle (FPA) bandwidth versus pitch attitude bandwidth is FQ solid level 3 in PA and in V_A with SM = 2.5%.
- It is FQ level 2, marginal level 3 for the other flight conditions and SMs.

Table 6. Unaugmented aircraft — pitch attitude and FPA bandwidth parameters

Flight Condition	Static Margin (%$\bar{c}$)	θ_{BW} (rad/s)	$\tau_{p\theta}$ (s)	γ_{BW} (rad/s)	$\omega_{\theta c}$ (rad/s)	$\omega_{\theta 180}$ (rad/s)	PM_θ (deg)	$\Delta G(q)$-dB (deg/s/deg)
PA	+5.0	0.50	0.0142	0.29	0.99	4.19	21.40	–
	+2.5	0.40	0.0142	0.26	0.99	4.16	19.26	–
V_A	+5.0	0.81	0.0143	0.39	1.90	4.45	10.69	2.06
	+2.5	0.62	0.0142	0.29	1.86	4.37	9.75	0.19
V_C	+5.0	0.95	0.0143	0.46	2.25	4.85	10.30	2.38
	+2.5	0.73	0.0142	0.34	2.19	4.75	9.37	0.33

The symbols in the table above have the following meanings:

- θ_{BW} — Pitch attitude bandwidth
- $\tau_{p\theta}$ — Pitch attitude equivalent phase delay
- γ_{BW} — Flight path angle bandwidth
- $\omega_{\theta c}$ — Pitch attitude gain cross over frequency
- $\omega_{\theta 180}$ — Pitch attitude phase cross over frequency
- PM_θ — Pitch attitude phase margin
- $\Delta G(q)$ — Pitch rate overshoot

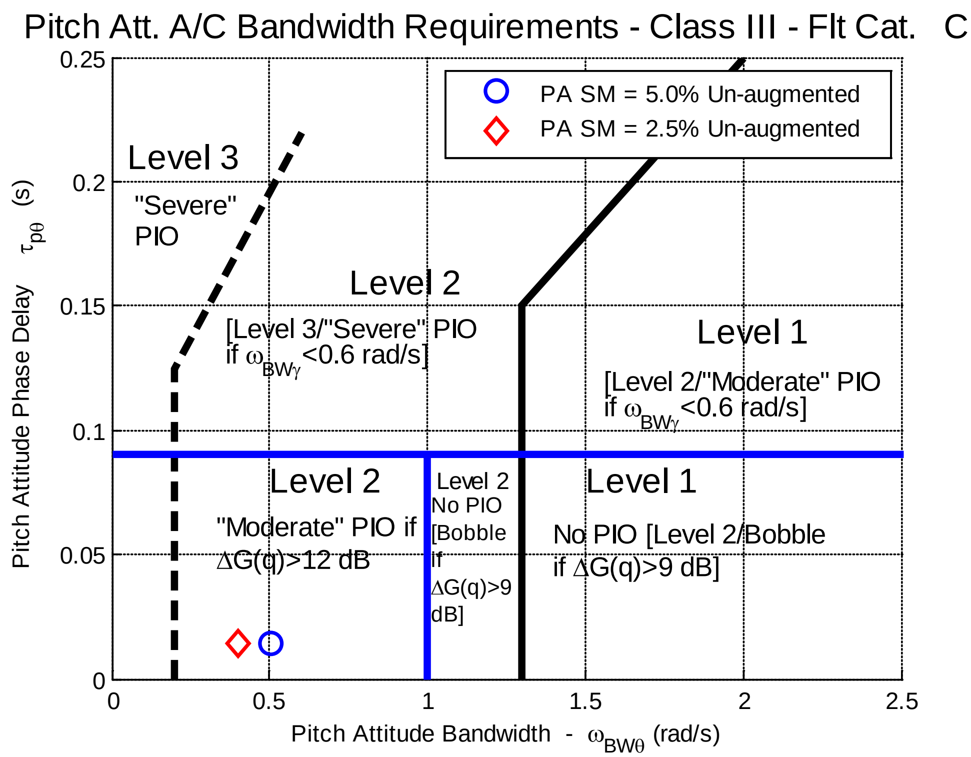


Figure 9. Pitch attitude bandwidth — PA unaugmented aircraft

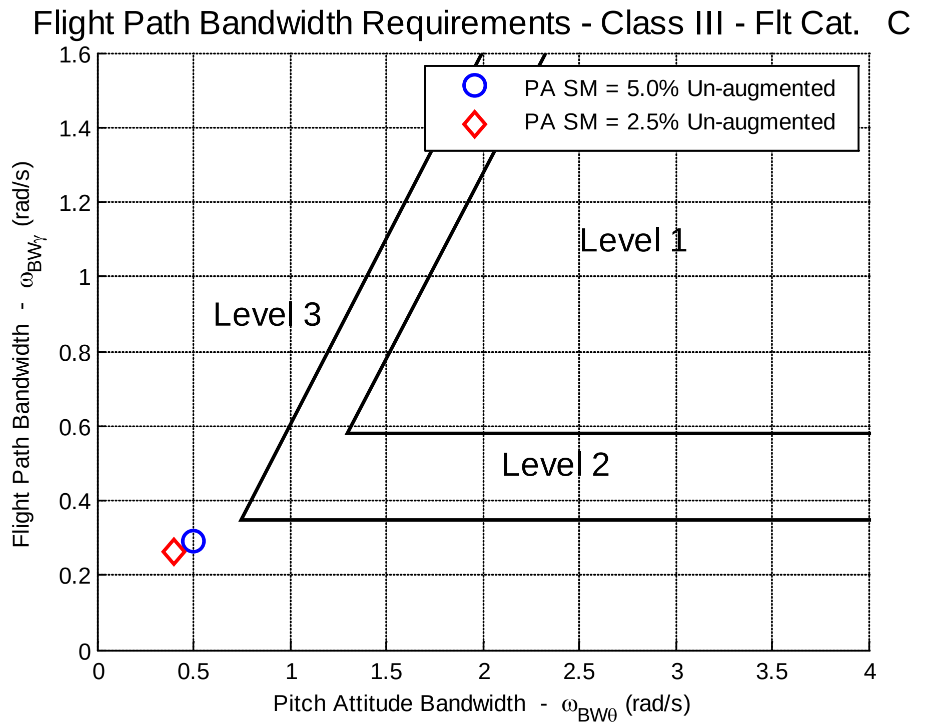


Figure 10. The FPA bandwidth — PA unaugmented aircraft

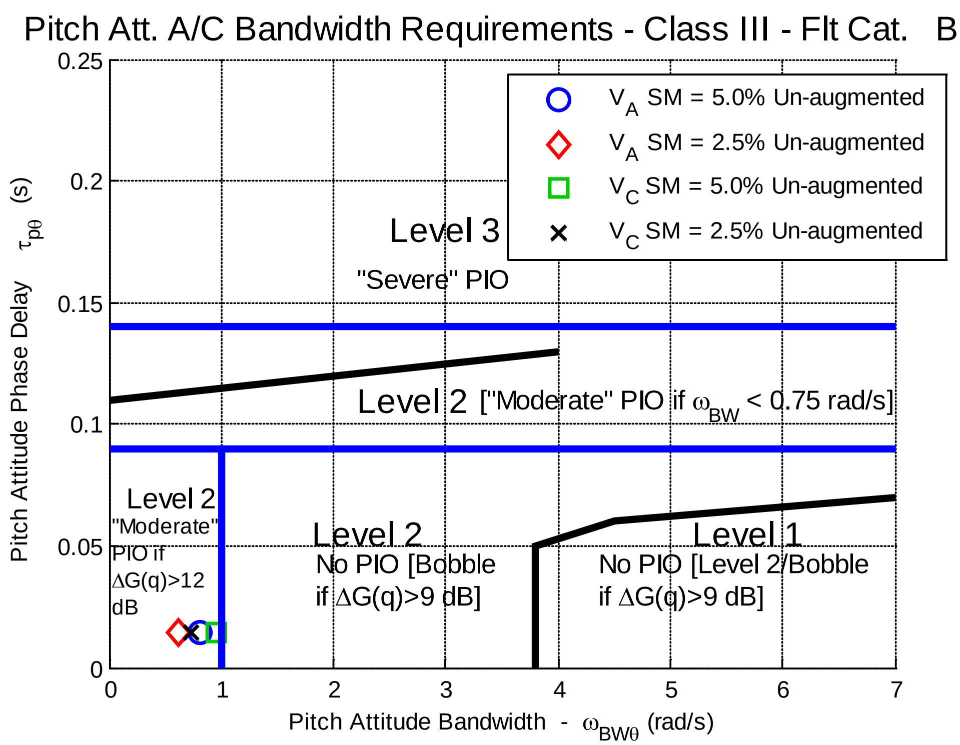


Figure 11. Pitch attitude bandwidth — V_A; V_C unaugmented aircraft

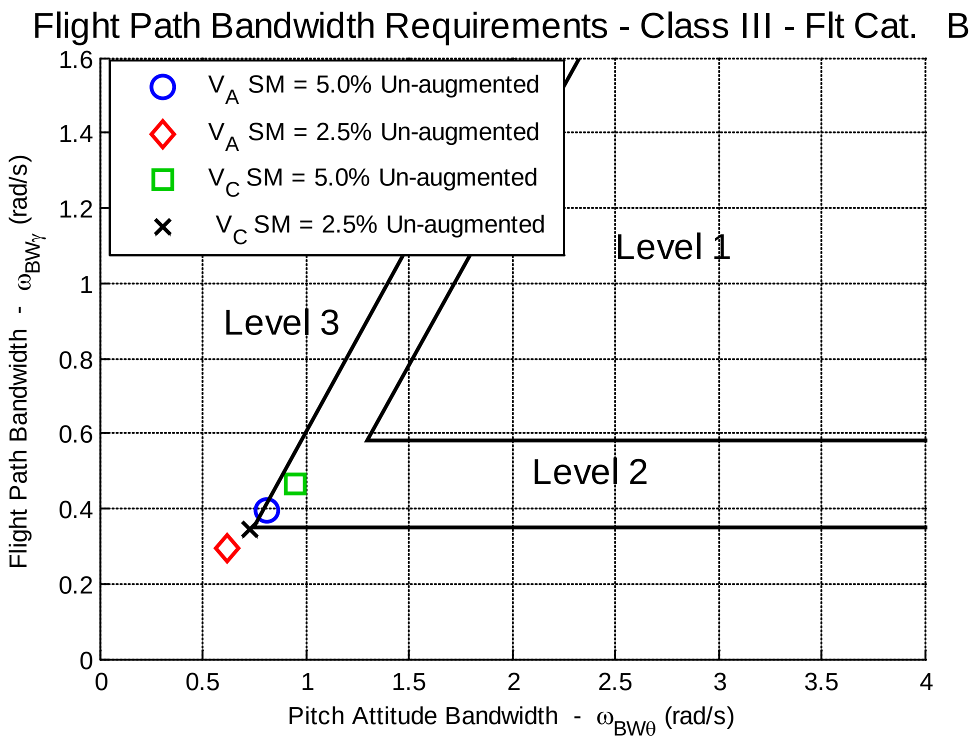


Figure 12. The FPA bandwidth — V_A; V_C unaugmented aircraft

2.2.2.3 Flight Path Overshoot

The flight path overshoot flying quality metric [8 and 9] is applied to the time domain FPA aircraft response. Even if originally designed for the PA flight condition, this metric is considered useful for also exposing potential FPA control deficiencies in cruise conditions. This approach complements the use of the aircraft FPA bandwidth criterion, as an indication of the predictability of the flight path response, which is potentially more applicable to tasks that require a more open loop piloting technique. Time histories of a limited set of signals of the un-augmented aircraft response to a longitudinal stick force step are provided in appendix B. These refer to the positive SM configurations of the three flight conditions under consideration. Plots of more traces from the same aircraft responses, for the SM = 5% $\bar{c}$ configurations, are available in appendix B. The flight path overshoot FQ requirements are reported in table 7, with the relative definitions provided in figure 13.

Table 7. Flight path overshoot FQ requirements

Flight Path Overshoot Flying Qualities Requirements	
Level	$\gamma_{peak-overshoot}$(%)
1	40
2	100
3	140

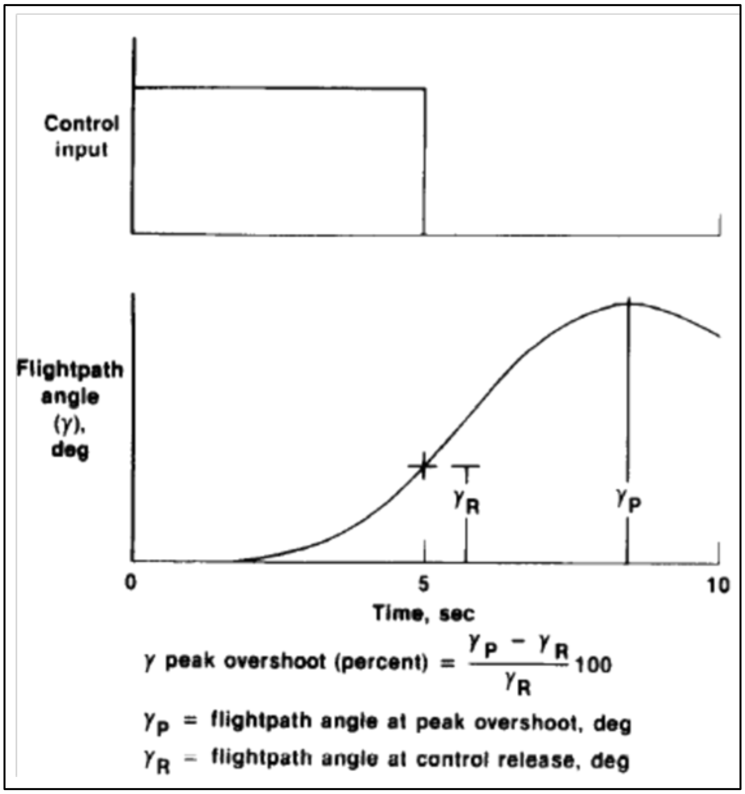


Figure 13. The FPA response definitions

All pitch responses can be defined by the following common time domain characteristics:

- Significant FPA overshoot.
- Lack of a definite pitch rate overshoot, corresponding to a "first order type" response. This confirms the results of the linear analysis conducted in the frequency domain.
- Lack of a definite pitch attitude steady state value, with a continuously increasing dropback (θ_{DB}).
- Lack of a FPA (γ) steady state value, with γ gradually decreasing because of the change of AoA produced by the decrease of airspeed in the pull-up maneuver.

The last two response characteristics are less definite in the up-and-away flight conditions, with a lower decrease of pitch attitude and FPA with time, after application of the step command. See [10] for a detailed explanation of these concepts.

Table 8 contains the values and the corresponding FQ levels of the FPA overshoot derived from the analysis of the time histories.
The overall FQ level 2, marginal level 3 FPA overshoot indicates that the control of the FPA is not accurate and a low predictability of the flight path response in all flight conditions and aircraft configurations.

Table 8. The FPA Overshoot and FQ Levels

Flight Path Overshoot and Flying Qualities Levels			
Flight Condition	SM (% $\bar{c}$)	FQ Level	FPA Overshoot (%)
PA	+ 5.0	2	56
	+ 2.5	3	111
V_A	+ 5.0	2	69
	+ 2.5	3	116
V_C	+ 5.0	2	56
	+ 2.5	2	89

2.2.3 Comments on Unaugmented Longitudinal Aircraft Dynamics

Based on the results reported in the previous sections, the aircraft pitch response across all flight conditions and configurations can be defined by the following characteristics:

- Adequate SP damping.
- Low predictability of the steady state response from the initial pitch acceleration, as indicated by the low CAP values and related FQ levels, due to the insufficient SP natural frequency.
- With the PA flight condition, small difference between phugoid and SP mode natural frequencies; also increases phase lag within the pitch response bandwidth.
- Lack of a pitch rate overshoot in the response to a longitudinal control step.
- Lack of a definite pitch attitude dropback.
- Low predictability of the FPA response, indicated by the significant flight path overshoot.
- Insufficient pitch attitude and FPA bandwidth, as indicated by the aircraft bandwidth criterion.

To improve the FQ, a proportional feedback of alpha to the commanded elevator deflection is required to increase SP natural frequency and CAP. The effect in the PA flight condition, in particular, is to separate phugoid and SP mode and reduce the phase lag in the SP frequency range. This is aimed to achieve FQ level 1 with respect to the relevant CAP requirements in all flight conditions and improve the pitch response bandwidth.

The SP total damping remains constant with the application of the alpha feedback. As a consequence, an augmentation of the SP frequency corresponds to the proportional reduction of the damping ratio. For this reason, a feedback of pitch rate to the elevator is also implemented. This is to maintain an adequate SP damping ratio, which is reduced by the single implementation of the alpha feedback. It also controls the pitch rate overshoot, limiting the tendency to PIO. The guidance requirements for the pitch rate overshoot are the quantitative limits indicated by the aircraft bandwidth criterion.

For these values of the SP modal parameters, CAP is considered constant varying longitudinal command gain $\left(\delta_{e_c}\ per\ \delta_{e_s}\right)$. Regarding the longitudinal control sensitivity, the recommendation is provided in [5] that for high values of $\omega_{n_{SP}}$, $\frac{F_s}{n_z}$ should be high to reduce the sensitivity, abruptness, and pitch oscillations due to small inputs. For a complete description of CAP requirements, see the discussion on SP response in [5].

2.2.4 Lateral/Directional Plane

2.2.4.1 Modal Parameters

The baseline MIL-STD-1797A lateral/directional FQ requirements, based on modal parameters, are reported in tables 9 and 10. Manned evaluations were conducted with the SM = 5% $\bar{c}$ configuration. For this reason, the values of the modal parameters are calculated in this configuration at each flight condition and flight phase.

Tables 11 and 12 contain the values of the bare aircraft lateral/directional modal parameters and the corresponding FQ levels in the different flight conditions.

Table 9. The MIL-F-8785C — minimum dutch roll frequency and damping

Dutch Roll Frequency and Damping for Class III Flight Phase B and C*				
Level	Min ζ_D	Min $\zeta_D \cdot \omega_{n_D}$ (rad/s)		Min ω_{n_D} (rad/s)
		Flight Phase B	Flight Phase C	
1	0.08	0.15	0.10	0.4
2	0.02	0.05		0.4
3	0	-		0.4

* The governing damping requirement is that yielding the larger value of ζ_D, except that a ζ_D of 0.7, is the maximum required for Class III.

Table 10. The MIL-F-8785C roll-mode time constant and spiral stability time to double amplitude

Roll-mode and Spiral Stability for Class III Flight Phase B and C			
Level	Roll-mode Maximum T_R (s)	Spiral-mode Minimum T_2^* (s)	
		Flight Phase B	Flight Phase C
1	1.4	20	12
2	3.0	8	
3	10	4	

* T_2 = time to double amplitude

Table 11. Unaugmented aircraft dutch roll FQ levels

Dutch Roll Modal Parameters and FQ Levels				
Flight Condition	Level	ζ_D	$\zeta_D \cdot \omega_{n_D}$ (rad/s)	ω_{n_D} (rad/s)
PA	1	0.287	0.304	1.06
V_A	2	0.181	0.121	0.67
V_C	2	0.159	0.119	0.75

Table 12. Unaugmented roll and spiral mode FQ levels

Roll and Spiral Modal Parameters and FQ Levels					
Flight Condition	Roll Mode FQ Level	T_R (s)	Spiral Mode FQ Level	$T_{1/2}^{\circ}$ (s)	T_2^* (s)
PA	1	0.41	1	–	73.7
V_A	1	0.53	1	17.4	–
V_C	1	0.44	1	18.3	–

° $T_{1/2}$ = time to half amplitude
* T_2 = time to double amplitude

Based on the comparison of the lateral/directional modal parameter values to the FQ requirements, the following results were derived:

- In PA FQ, level 1 is satisfied at the upper margin for Class III aircraft for all modes.
- In V_A and V_C, roll and spiral mode are FQ level 1.
- In V_A and V_C, Dutch roll (DR) is FQ level 2 due to insufficient damping and index of the time required to damp the mode.
- The spiral mode is unstable in PA and stable in V_A and V_C, within the level 1 FQ requirements in all flight conditions. An unstable spiral mode is acceptable if the time constant of this mode is sufficiently large.

Considering the specific lateral tasks, CCC, and discrete captures formed by a quick sequence of bank angle acquisitions, no significant development of spiral motion is expected.

The roll mode time constant (T_R) requirement represents the precision and predictability of the roll response and the low values of T_R indicate a predictable and well controllable roll response in all considered flight conditions.

The FQ requirements use DR damping ratio (ζ_D) as an index of the number of oscillations and total damping $(\zeta_D \cdot \omega_{n_D})$ as an index of the time required to damp the mode. Natural frequency (ω_{n_D}) provides an indication of the sideslip generated by a yaw perturbation. The scope of these requirements is to ensure that DR motion dissipates in a short time, with no significant interference with the roll mode dynamics.

Frequency responses of the bare aircraft dynamics are provided in figures 14–16.

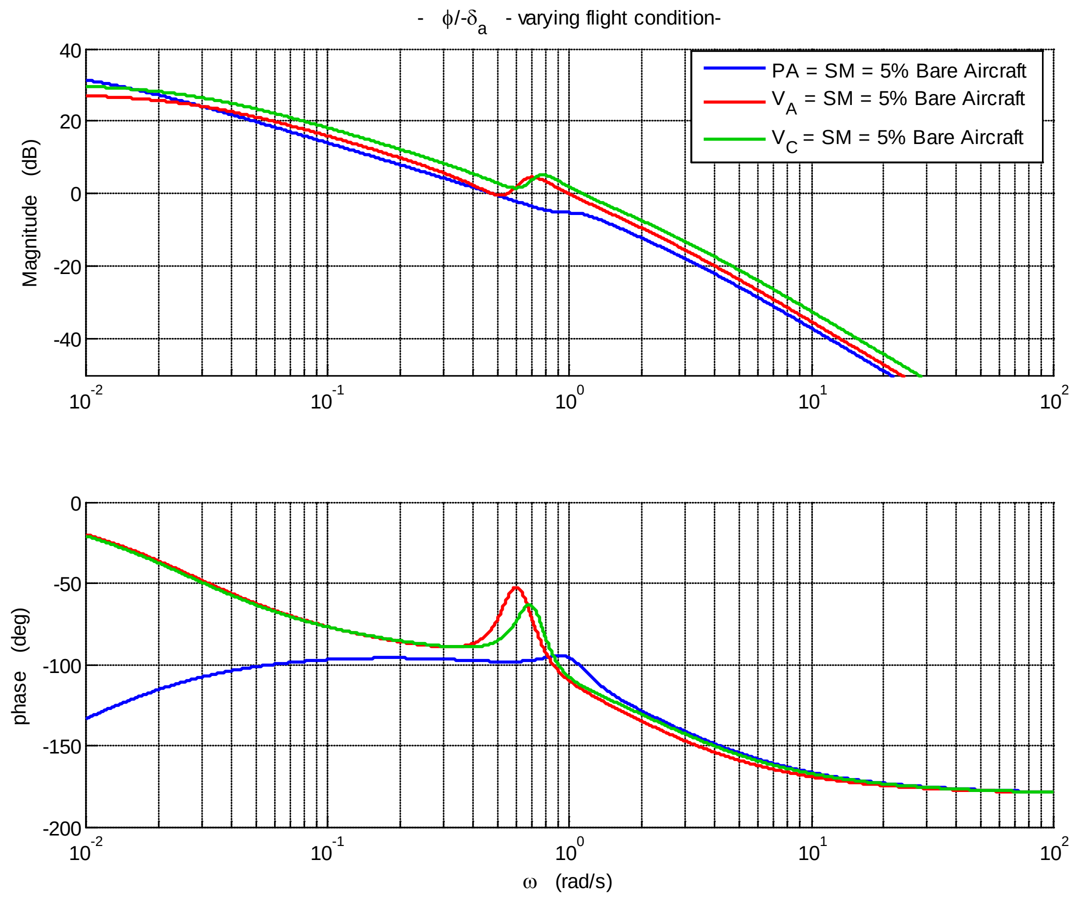


Figure 14. The $\frac{\phi}{-\delta_a}$ frequency response — SM = 5% bare aircraft

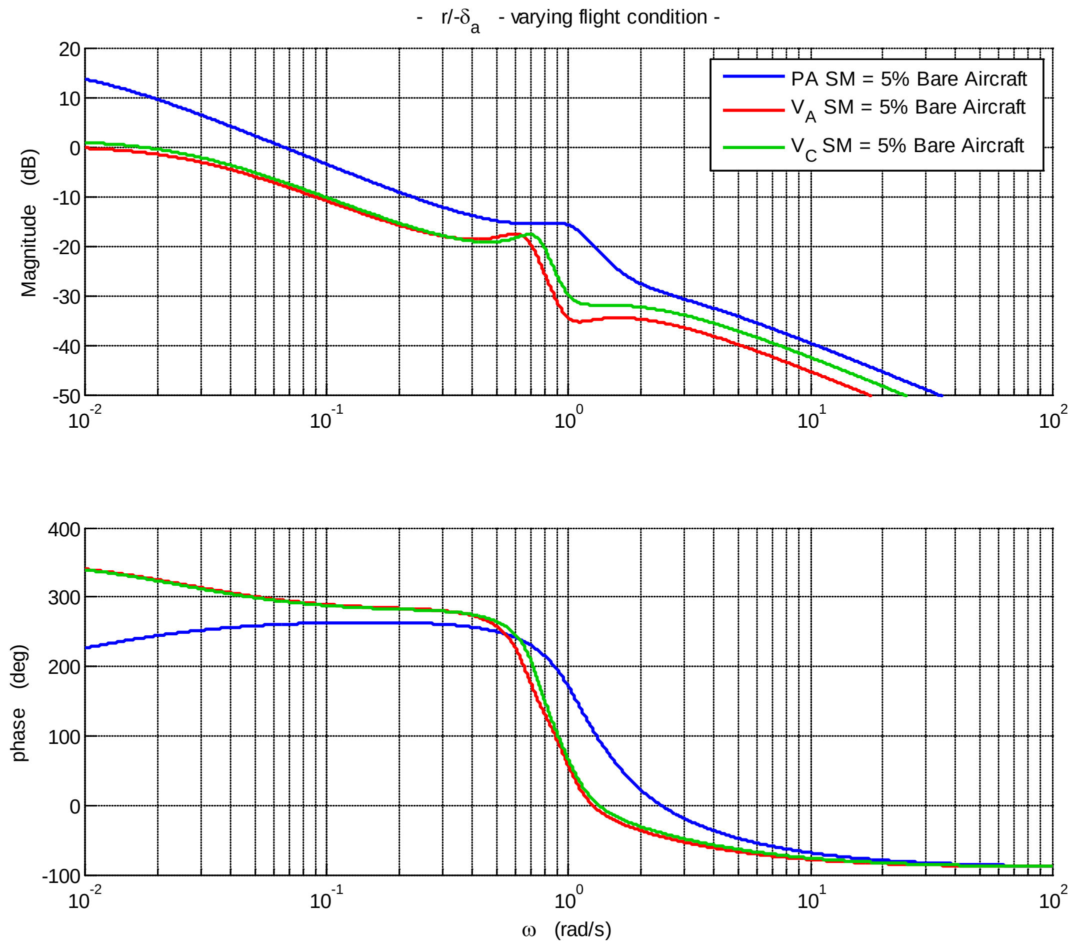


Figure 15. The $\frac{r}{-\delta_a}$ frequency response — SM = 5% bare aircraft

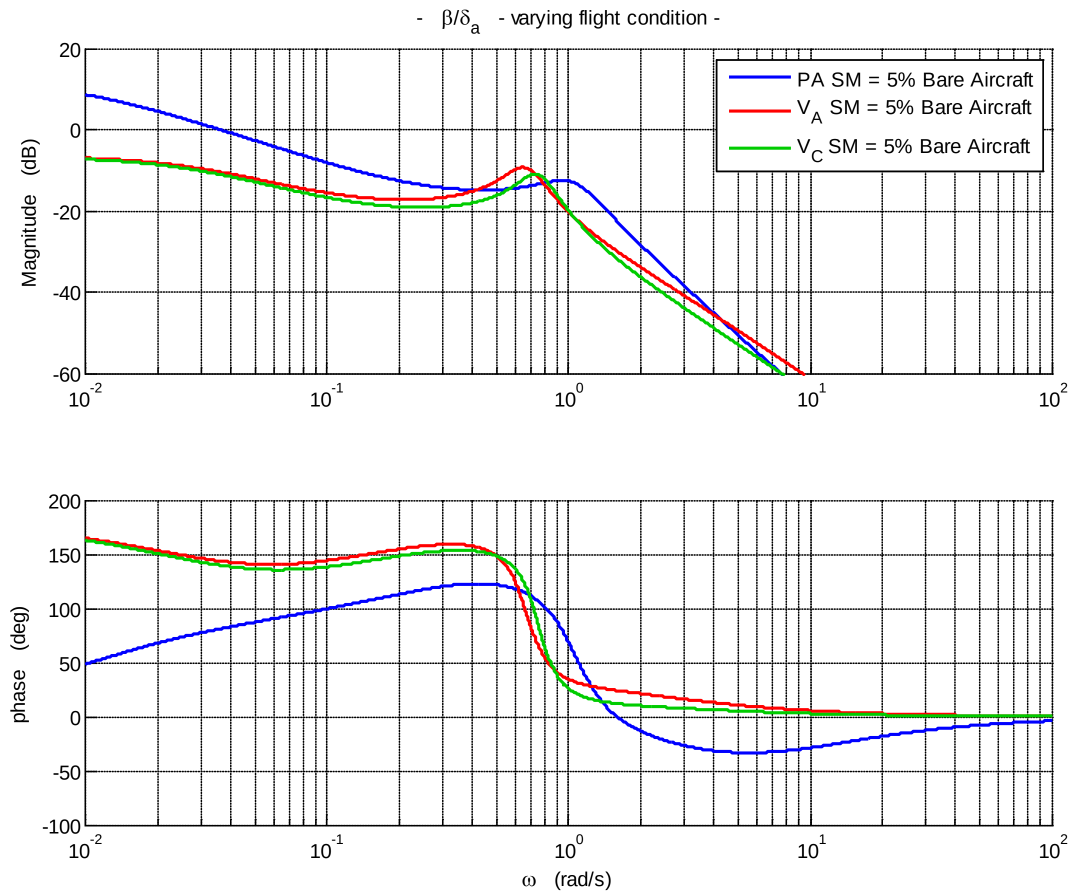


Figure 16. The $\frac{\boldsymbol{\beta}}{\boldsymbol{\delta_a}}$ frequency response — SM = 5% bare aircraft

2.2.4.2 Roll Attitude Bandwidth

As described in section 2.2.2.2, the aircraft bandwidth criterion is mainly applied as the metric to quantify and assess the aircraft response characteristics when operated in a closed-loop pilot-control task. This assessment is required also considering the bank angle regulation task designed for the aircraft evaluations. Comparisons of the aircraft dynamics response parameters with the lateral/directional FQ requirements in the three reference flight conditions are displayed in figure 17. The calculated parameters are relative to the aircraft with baseline actuator characteristics and with the feel system dynamics excluded in the SM = 5% c̄ configuration. Table 13 provides the corresponding numerical values.

The results demonstrate that:

- Roll attitude bandwidth is FQ solid level 1 in all flight conditions for the SM = 5% $\bar{c}$ configuration, with no expected tendency to PIO.

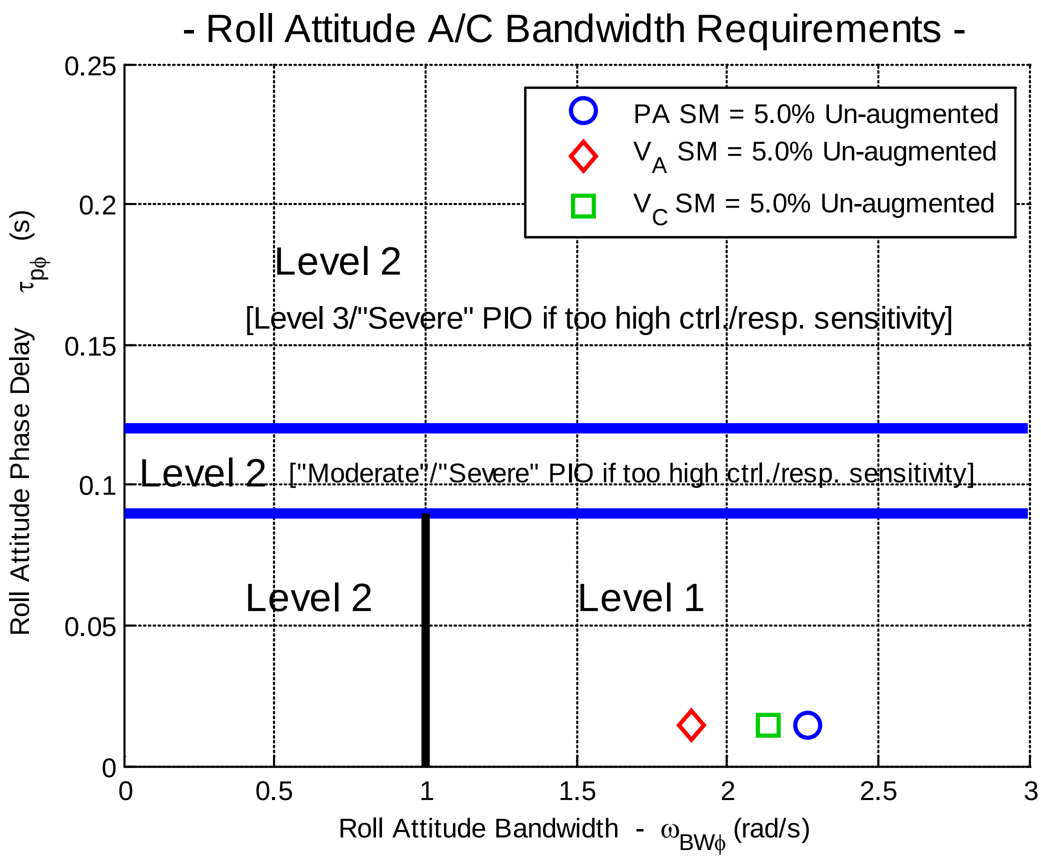


Figure 17. Roll attitude bandwidth — PA; V_A; V_C SM = 5% unaugmented aircraft

Table 13. Unaugmented aircraft — roll attitude bandwidth parameters

Roll Attitude Bandwidth Parameters Cfg 1						
Flight Condition	SM (% $\bar{c}$)	φ_{BW} (rad/s)	$\tau_{p\varphi}$ (s)	$\omega_{\varphi c}$ (rad/s)	$\omega_{\varphi 180}$ (rad/s)	PM_{φ} (deg)
PA	5	2.27	0.0144	1.63	11.24	56.79
V_A	5	1.88	0.0144	2.01	10.10	42.77
V_C	5	2.14	0.0144	2.34	10.96	42.00

Where the symbols in table 13 have the following meaning:

φ_{BW}	Roll attitude bandwidth
$\tau_{p\varphi}$	Roll attitude equivalent phase delay
$\omega_{\varphi c}$	Roll attitude gain cross over frequency
$\omega_{\varphi 180}$	Roll attitude phase cross over frequency
PM_{φ}	Roll attitude phase margin

2.2.5 Comments on Unaugmented Lateral/Directional Aircraft Dynamics

Based on the results reported in the previous sections, the aircraft roll response in the SM = 5% $\bar{c}$ configuration can be defined by the following characteristics:

- The DR is FQ level 1 in PA and level 2 in V_A and V_C because of the low value of total damping.

- Roll mode is FQ level 1 in all flight conditions.

- Spiral mode is FQ level 1 in all flight conditions, stable in V_A and V_C, and unstable in PA.

- Roll attitude bandwidth is FQ level 1 in all flight conditions, as indicated by the aircraft roll response bandwidth criterion.

2.3 FLIGHT CONTROL LAWS

2.3.1 Longitudinal Plane

The augmentation in the longitudinal plane for all configurations and flight conditions is formed by two proportional feedbacks: one of AoA (alpha) and one of pitch attitude rate ($\dot{\theta}$) to the commanded elevator deflection and by longitudinal command gain augmentation. The pitch attitude rate feedback is used to maintain adequate pitch authority in combined longitudinal-lateral/directional maneuvers for which the pitch rate feedback would command additional elevator deflection because of the motion kinematics. The $\dot{\theta}$ feedback is identical to that of pitch rate (q) in straight and level flight. It differs in a constant altitude coordinated turn in which pitch rate is given by: $q = r \cdot \tan(\phi)$ (where r is the yaw rate and ϕ is the turn bank angle). In the turn, the pitch attitude rate is $\dot{\theta} = 0$, with no elevator deflection commanded by the feedback itself.

The CLAWS include an auto-throttle system with proportional-integral feedback of True Airspeed (TAS, V_t) to the commanded throttle lever angle (TLA, δ_{TLA}). The objective is to augment flight path control and maintain the flight condition, thereby reducing the pilot's workload during the evaluation tasks. This is particularly relevant in tasks requiring large amplitude longitudinal maneuvers. Because of the engine thrust limits, there is potential for the actual phugoid dynamics to be slightly different from those determined from linear analysis when large amplitude inputs are performed and maintained for a relatively long time.

The approach followed in the definition of the longitudinal augmentation was to improve the modes of the aircraft to satisfy FQ requirements, maintaining the same type of response of the stable unaugmented aircraft. The potential for lower fidelity in the representation of typical transport aircraft CLAWS structure was thought to be compensated by the simplicity and independence from specific manufacturer augmentation approaches.

The feedback gains were defined based on the combination of the Aircraft Bandwidth Criterion, MIL-F-8785C, MIL-STD-1797B, and Flight Path Overshoot requirements for level 1 FQ. The baseline longitudinal command gain value in PA was determined to maintain a positive longitudinal stick deflection margin at the alpha stall condition. This was defined to expose the pilot to exceedances of the alpha limit ($\alpha_{lim} = 10$ deg) and alpha stall ($\alpha_{st} = 12$ deg) in order to assess the envelope protection effectiveness of the command path design elements to be evaluated with adequate accuracy.

The baseline longitudinal command gain value was determined in order to command maximum positive normal load factor $n_{z_{\max}} = 2.5\ (g)$, with a full backstick (FBS) input at the maneuvering speed flight condition. The command gain is maintained constant in all up-and-away flight conditions. This corresponds to an amplitude ratio of the longitudinal stick deflection to normal load factor response $\left(\frac{n_z}{\delta_{e_s}}\right) G|_{\frac{n_z}{\delta e_s}} \approx -13.5$ dB in the frequency range delimited by the augmented phugoid and SP mode for the Cfg 1 x CG configuration.

All flight conditions are defined for the configuration with the highest unaugmented SM among the ones available (SM = 5.0 ($\%\bar{c}$), configuration 1). Gains are constant varying CG and have been maintained constant through different flight conditions when adequate FQ could be achieved. This is considered consistent with a possibly simple standard transport aircraft implementation assuming robustness to be the higher priority.

In order to be consistent with the augmentation of Year 2 evaluations in PA, the auto-throttle TAS error integral gain K_{Vt_I} is set to zero in PA. This simple auto-throttle implementation can be considered adequate because of the short test runs and discrete captures task profile. It would not be adequate for long-term speed control without an integral control signal path.

The baseline set of longitudinal CLAWS gains at the different flight conditions is provided in table 14.

Table 14. Baseline set of longitudinal control laws gains

Gain Symbol	Flight Condition			Units	Feedback Description
	PA	V_A	V_C		
K_{α}	0.67	1.15		deg/deg	AoA to elevator deflection command
$K_{\dot{\theta}}$	1.0	0.82		deg/deg/s	Pitch attitude rate to elevator deflection command
K_{Vt_P}	1.50	0.50		deg/ft/s	Proportional of true airspeed error to TLA
K_{Vt_I}	0.0	0.005		deg/ft	Integral of true airspeed error to TLA
$K_{\delta e_{c\_}\delta_{e_S}}$	-1.0	-1.40		deg/deg	Longitudinal stick deflection to elevator deflection command

A conceptual block diagram of the longitudinal stability augmentation system is displayed in figure 18. The representation is valid for all tested flight conditions and aircraft configurations. It does not intentionally include the command path design elements to be evaluated, which are illustrated in the next sections.

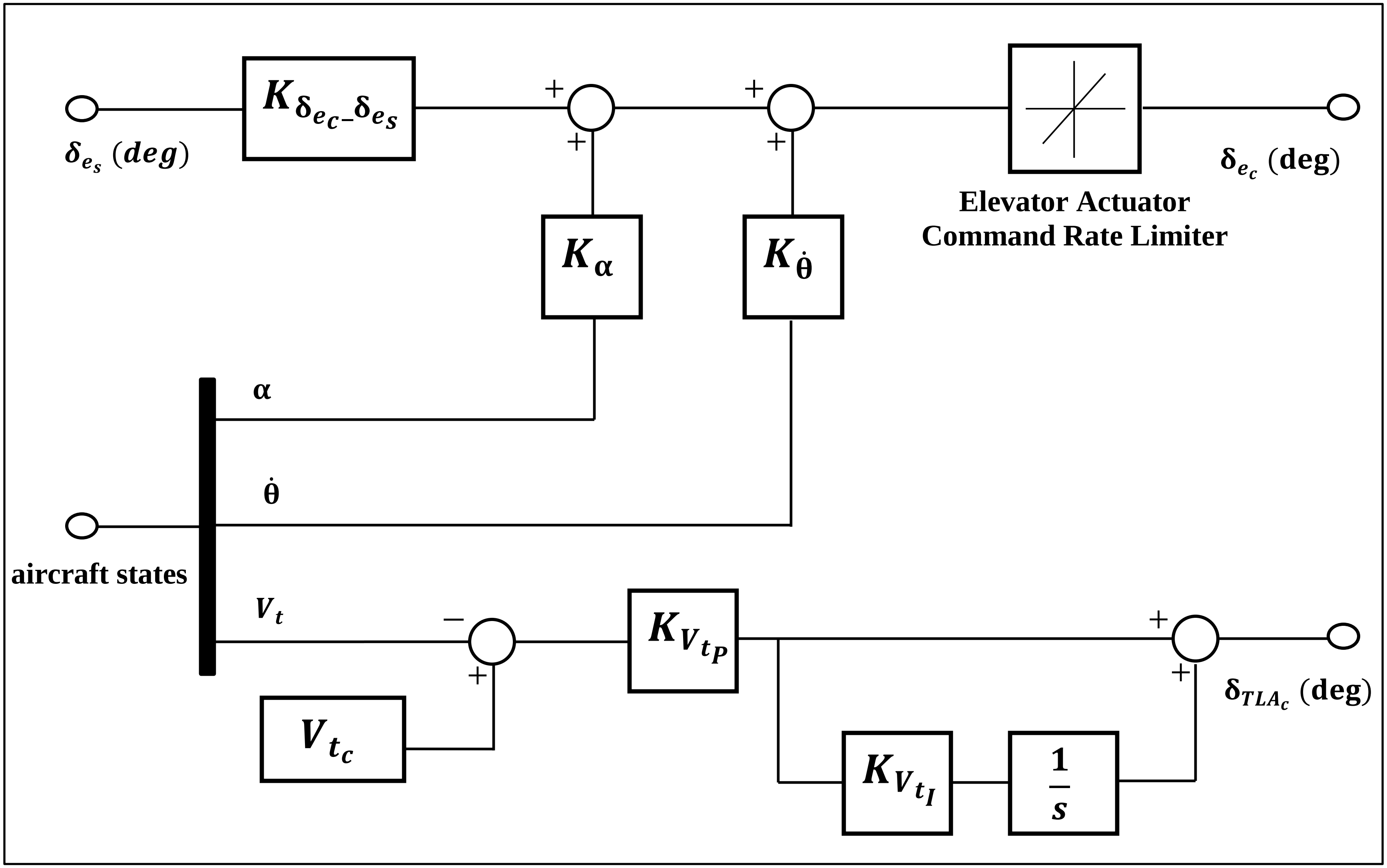


Figure 18. Conceptual block diagram of the longitudinal augmentation

2.3.2 Lateral/Directional Plane

The augmentation in the lateral/directional plane is formed by aileron-to-rudder interconnect (ARI) in all flight conditions and by the feedback of the yaw rate to the commanded rudder deflection (yaw damper) in the up-and-away flight conditions. The ARI is implemented to avoid the use of the rudder pedals and minimize the roll rate oscillations displayed by the time histories of the unaugmented aircraft response. Its purpose is to reduce the generation of sideslip and DR due to lateral inputs, improving roll performance and roll control precision and minimizing pilot workload not related to the specific task. Discussion on the effect of roll/yaw coupling is contained in [5].

In order to maintain the same level of coordination throughout all of the rate-limited configurations, the aileron command downstream of the software rate limits is fed to the rudder command. The software rate limiting of the rudder actuator command is applied downstream of the rudder command's summation point. Lateral/directional command gains are set to default values that were considered appropriate for the type of aircraft so that full inceptor deflection/travel commands maximum control surface deflection.

The implementation of the yaw damper is necessary to augment DR damping in the up-and-away flight conditions. A washout filter is installed in the yaw rate feedback loop to avoid feedback from opposing pilot inputs in steady turns. Table 15 shows a baseline set of longitudinal control law gains at different flight conditions.

Table 15. Baseline set of lateral/directional control laws gains

Gain Symbol	Flight Condition			Units	Feedback Description
	PA	V_A	V_C		
K_{ARI} *	0.4	0.2	0.1	deg/deg	Rudder per aileron commanded deflection
K_r	0	0.82		deg/deg/s	Yaw rate to rudder deflection command
T_{wo}	–	3		s	Yaw rate feedback washout filter time constant
$K_{\delta a_c\_\delta_{a_s}}$	-3.0			deg/deg	Lateral stick deflection to aileron deflection command
$K_{\delta r_c\_\delta_{r_s}}$	15.0			deg/deg	Rudder pedal travel to rudder deflection command

* The value is linearly interpolated with $\bar{q}$, between V_A and V_C.

A conceptual block diagram of the lateral/directional stability augmentation system is displayed in figure 19. The part included in the red rectangle is valid for up-and-away flight conditions. It intentionally does not include the command path design elements to be evaluated, which are illustrated in the following sections.

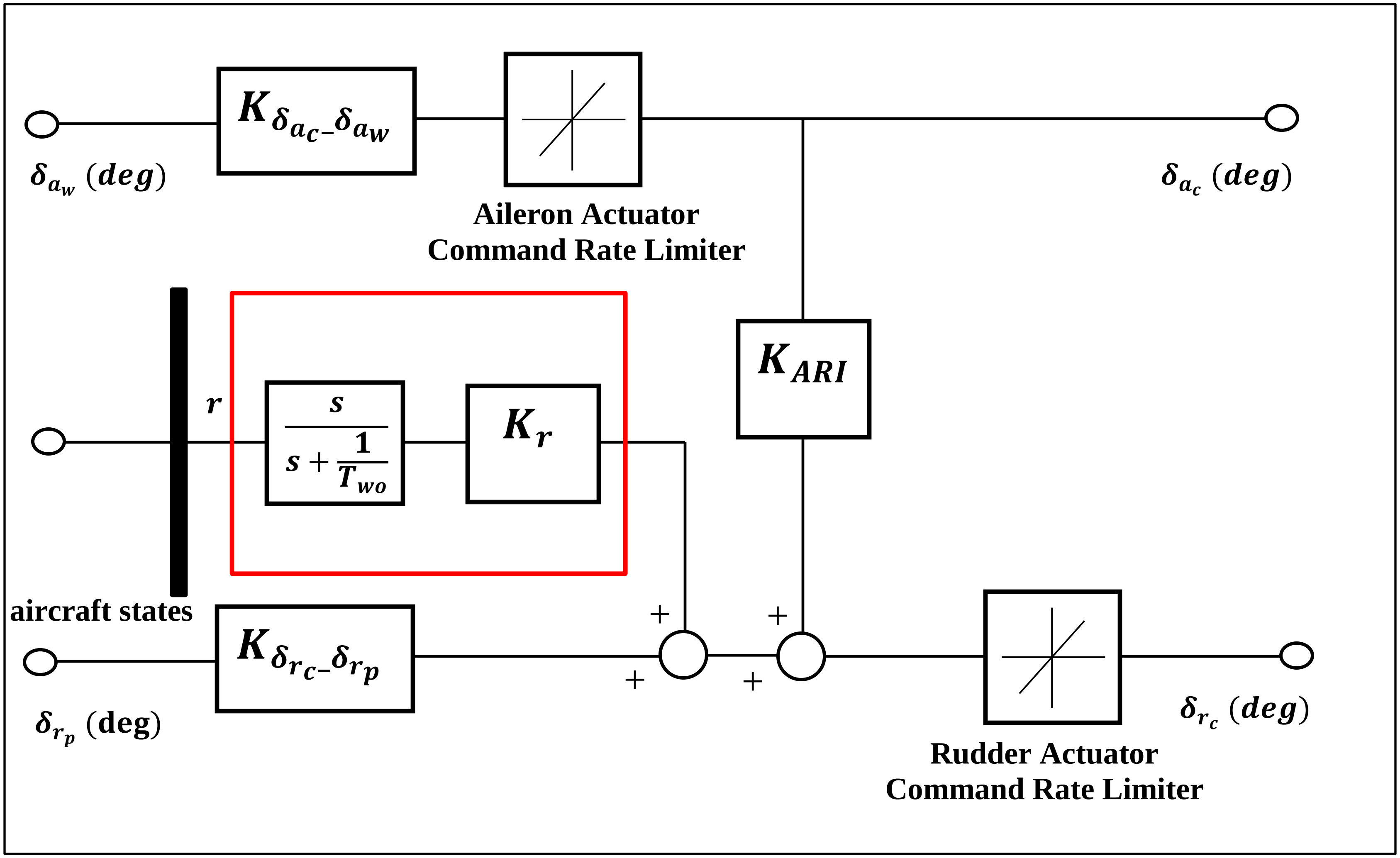


Figure 19. Block diagram of the lateral/directional control laws

2.4 AUGMENTED AIRCRAFT DYNAMICS

2.4.1 Longitudinal Plane

2.4.1.1 Modal Parameters and CAP

This and the subsequent sections provide information on the FQ levels of the augmented aircraft with actuators, dynamics of the feel system excluded.

Table 16 contains the values and correspondent FQ levels of the short-period and phugoid-mode damping ratio of the augmented aircraft in all flight conditions and configurations. Figures 20–23 display the MIL-F-8785C short-period requirements and corresponding MIL-STD-1797B CAP requirements. Bode plots of relevant responses to longitudinal stick inputs are displayed in figures 24–29.

Table 16. The MIL-F-8785C longitudinal damping ratio FQ levels — augmented aircraft

Augmented Aircraft FQ Levels (Damping Ratio)					
Flight Condition	CG Configuration	Level		ζ_{SP}	ζ_P
		SP	Ph		
PA	Cfg 1	1	1	0.766	0.739
	Cfg 2	1	1	0.781	0.744
	Cfg 3	1	1	0.796	0.750
V_A	Cfg 1	1	1	0.706	0.834
	Cfg 2	1	1	0.717	0.834
	Cfg 3	1	1	0.728	0.834
V_C	Cfg 1	1	1	0.782	0.936
	Cfg 2	1	1	0.793	0.937
	Cfg 3	1	1	0.804	0.937

From analysis of the reported numerical data and the following plots, the effect of augmentation on modal parameters, CAP, and its comparison with FQ requirements are synthesized as follows:

- The aircraft response is solid FQ level 1 in all flight conditions and configurations with respect to both MIL-F-8785C and MIL-STD-1797B requirements.
- The impact of x CG position on the response is minimal in PA and minor in V_A and V_C flight conditions.
- Phugoid mode is significantly damped in the PA flight condition ($\zeta_{SP} \approx 0.7$).
- $CAP \approx 0.4$ in all flight conditions and configurations, which is considered acceptable for transport aircraft.

- Pitch rate overshoot is small in PA (figure 24) but significant in V_A and V_C flight conditions (figure 27).

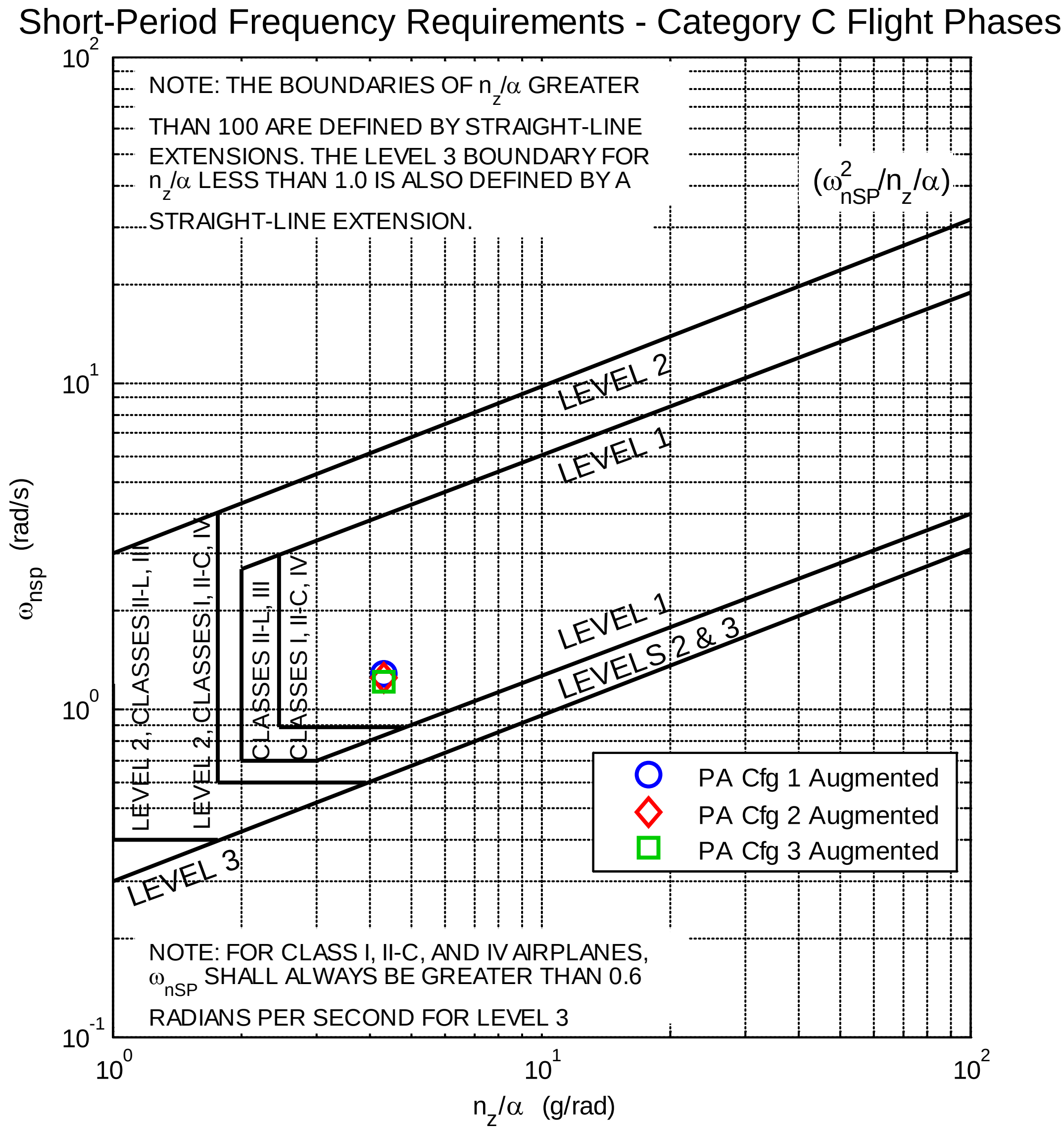


Figure 20. The MIL-F-8785C short period frequency requirements — PA unaugmented aircraft values

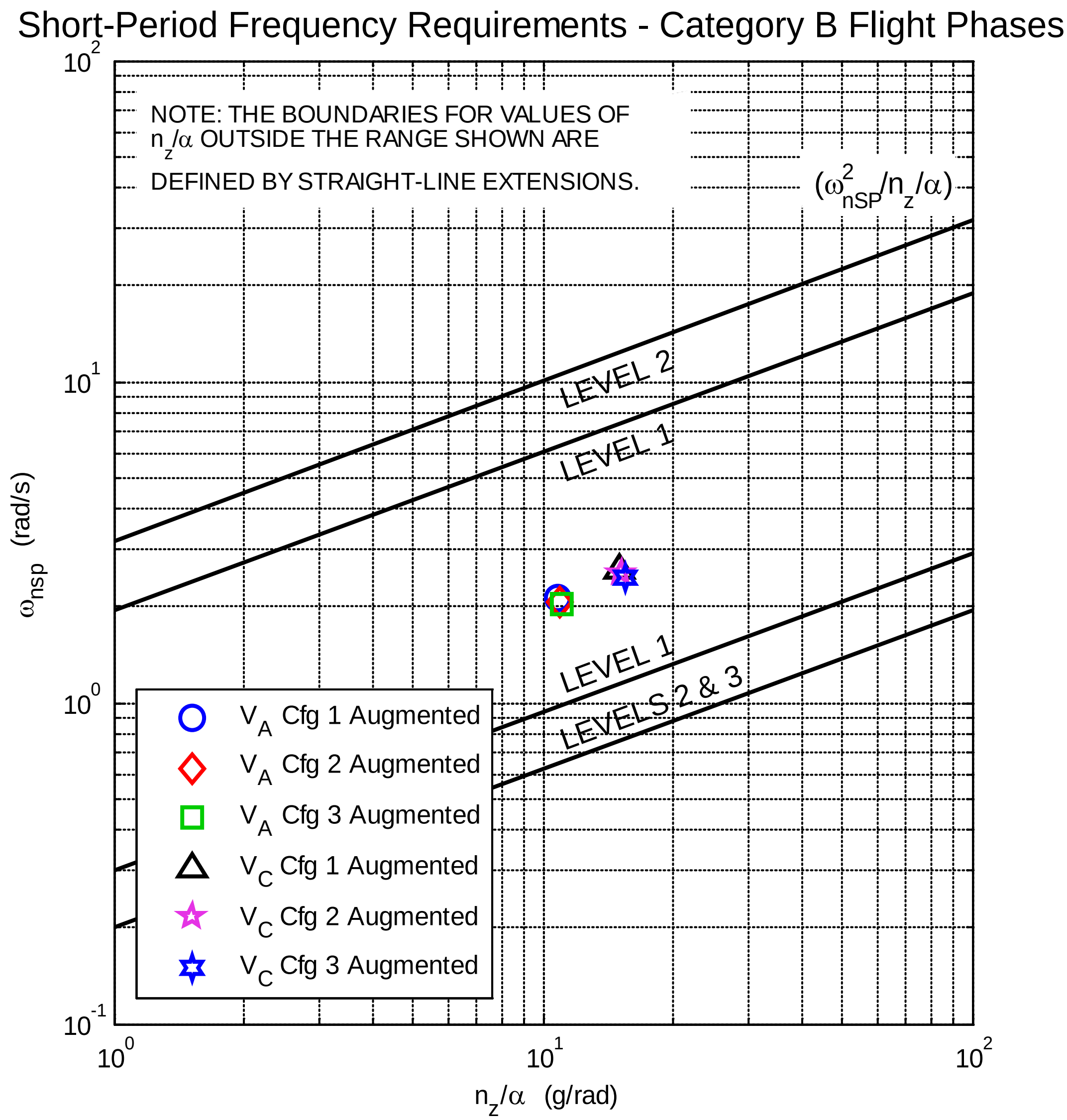


Figure 21. The MIL-F-8785C short period frequency requirements — V_A, V_C unaugmented aircraft values

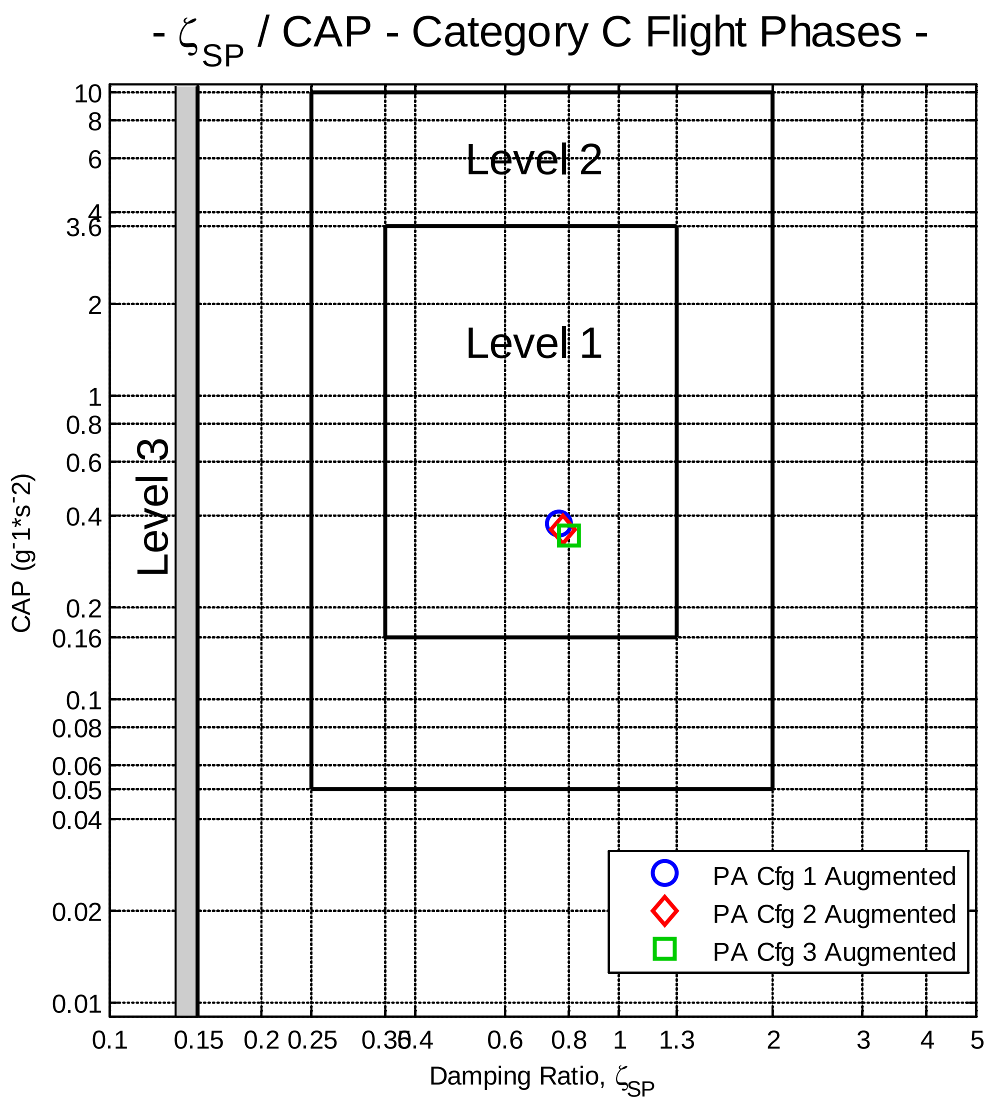


Figure 22. The MIL-STD-1797B ζ_{SP}/CAP requirements — PA unaugmented aircraft values

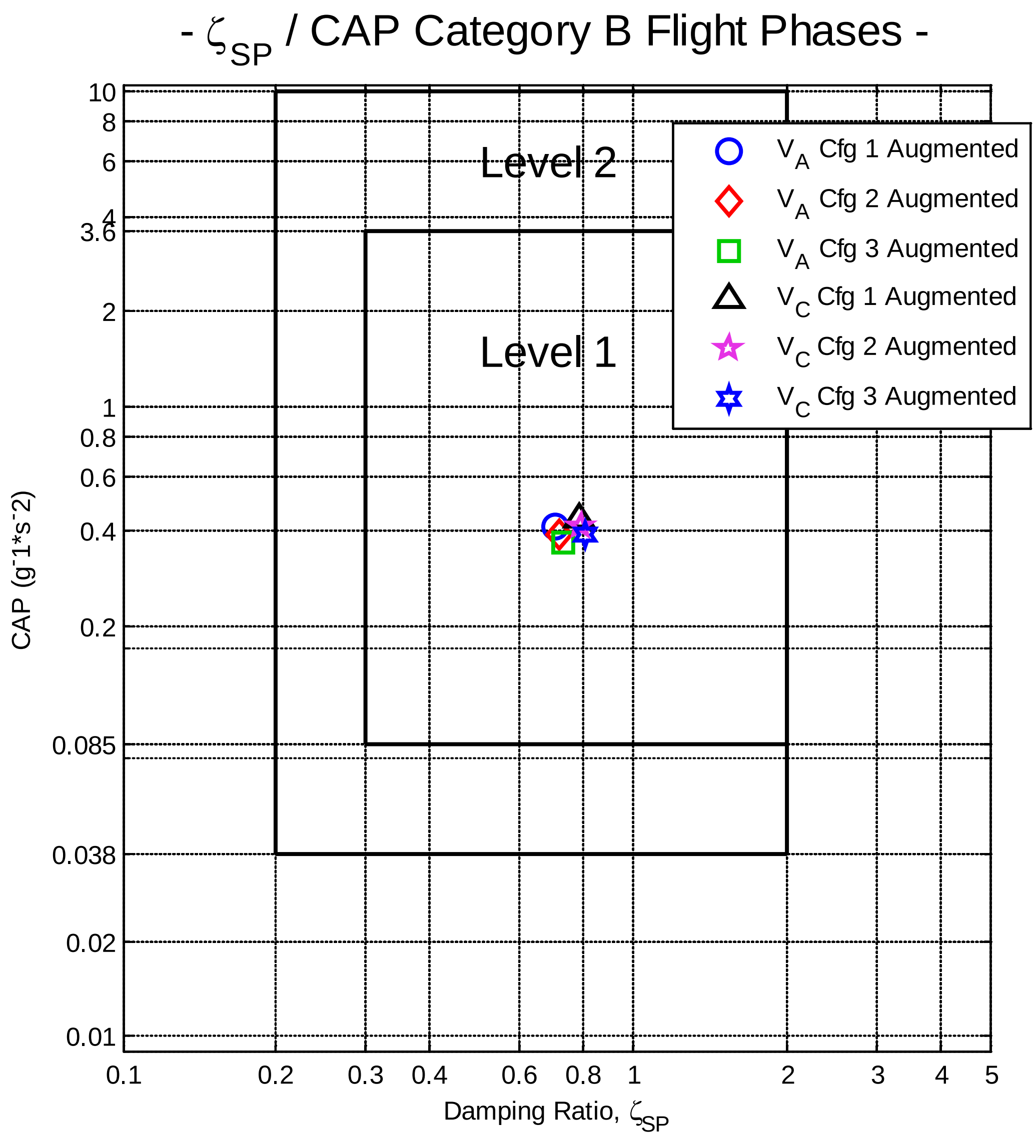


Figure 23. The MIL-STD-1797B ζ_{SP}/CAP requirements — V_A, V_C unaugmented aircraft values

Table 17. Longitudinal modal parameters — unaugmented aircraft

Augmented Aircraft Longitudinal Modal Parameters								
Flight Condition	CG	$\omega_{n_{SP}}$ (rad/s)	ζ_{SP}	ω_{n_P} (rad/s)	ζ_P	$\frac{1}{T_{\theta_2}}$ (1/s)	n_z/a (g/rad)	CAP $(1/(g \cdot s^2))$
PA	Cfg 1	1.28	0.766	0.295	0.739	0.560	4.29	0.379
	Cfg 2	1.25	0.781	0.297	0.744	0.602	4.30	0.362
	Cfg 3	1.22	0.796	0.300	0.750	0.604	4.32	0.345
V_A	Cfg 1	2.12	0.706	0.059	0.462	0.485	10.80	0.415
	Cfg 2	2.07	0.717	0.058	0.467	0.491	10.93	0.391
	Cfg 3	2.02	0.728	0.058	0.473	0.497	11.07	0.368
V_C	Cfg 1	2.58	0.782	0.049	0.465	0.573	15.09	0.440
	Cfg 2	2.52	0.793	0.048	0.471	0.581	15.29	0.415
	Cfg 3	2.46	0.804	0.047	0.478	0.588	15.49	0.340

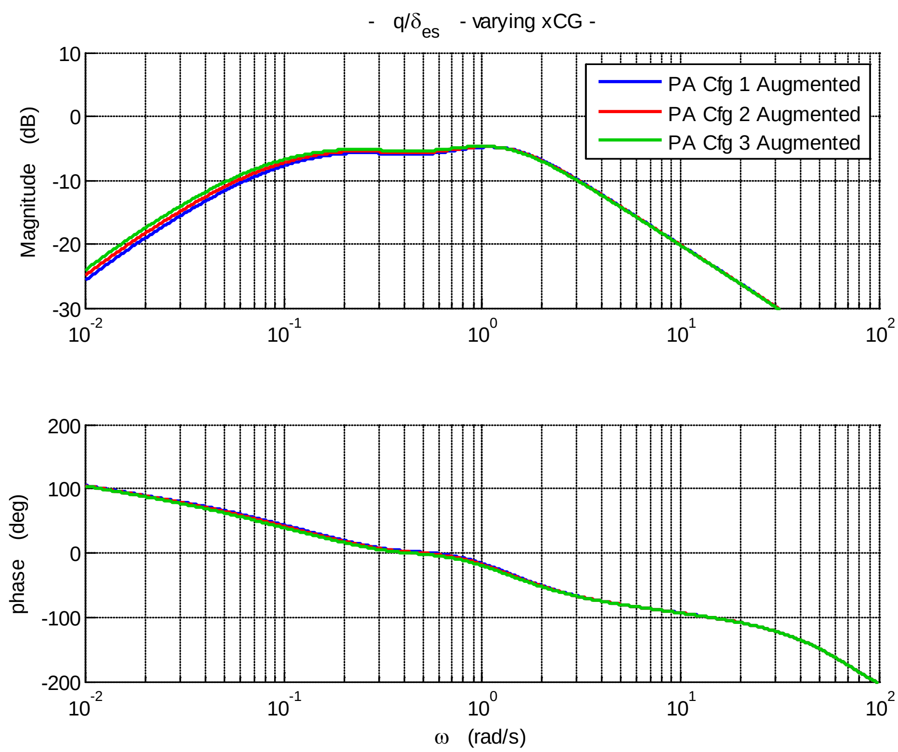


Figure 24. The $\frac{q}{\delta_{es}}$ frequency response — PA augmented aircraft

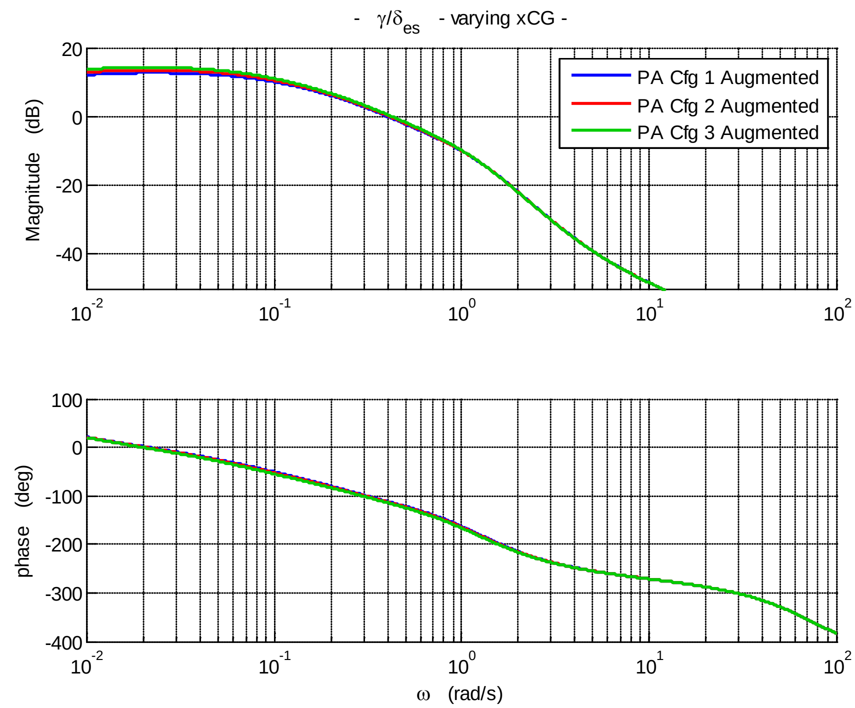


Figure 25. The $\frac{\gamma}{\delta_{es}}$ frequency response — PA augmented aircraft

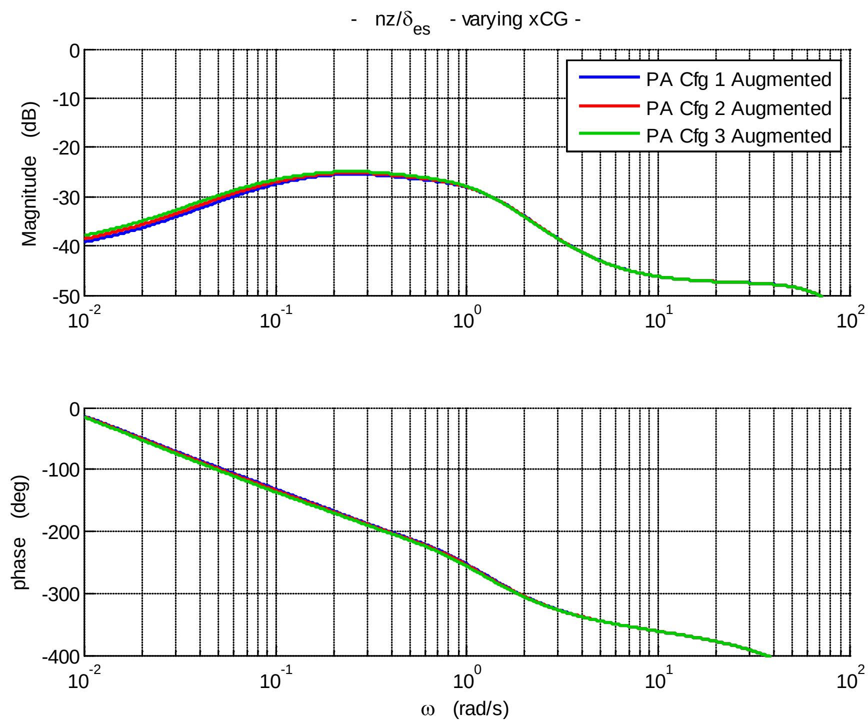


Figure 26. The $\frac{n_z}{\delta_{es}}$ frequency response — PA augmented aircraft

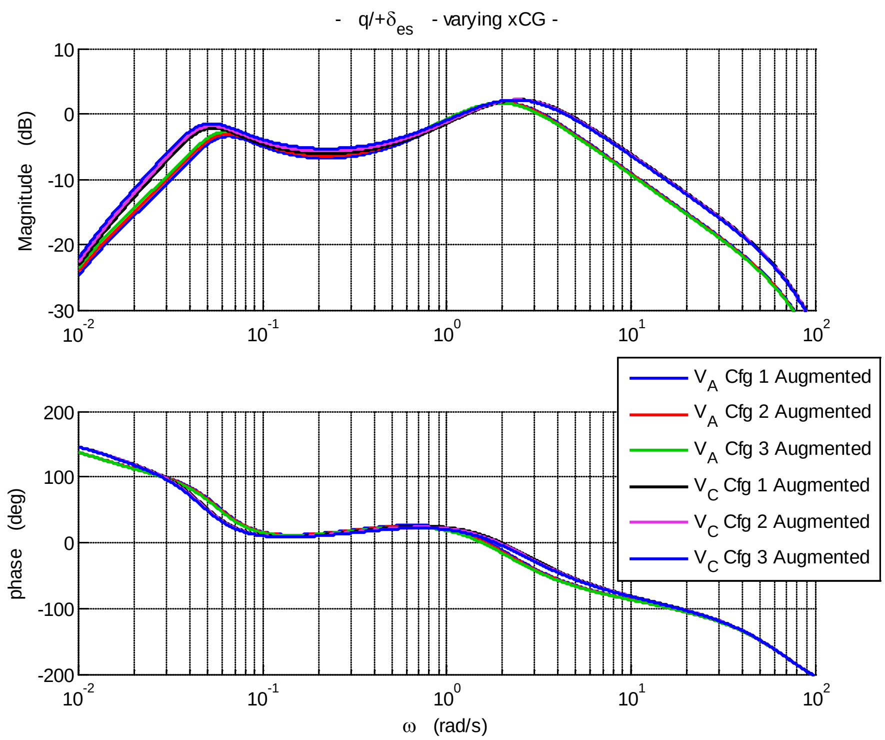


Figure 27. The $\frac{q}{\delta_{es}}$ frequency response — V_A; V_C augmented aircraft

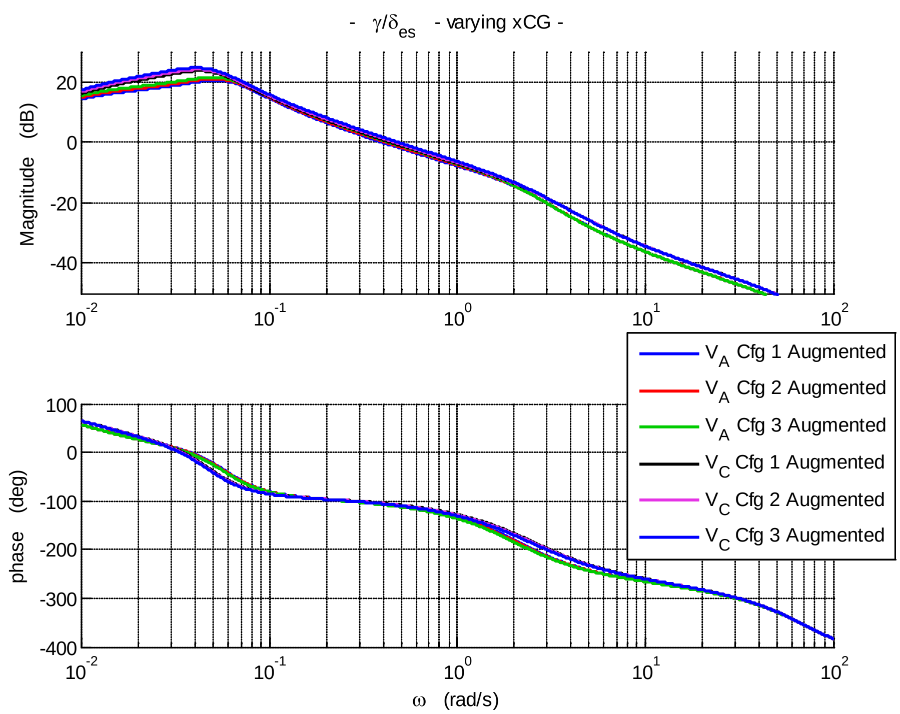


Figure 28. The $\frac{\gamma}{\delta_{es}}$ frequency response — V_A; V_C augmented aircraft

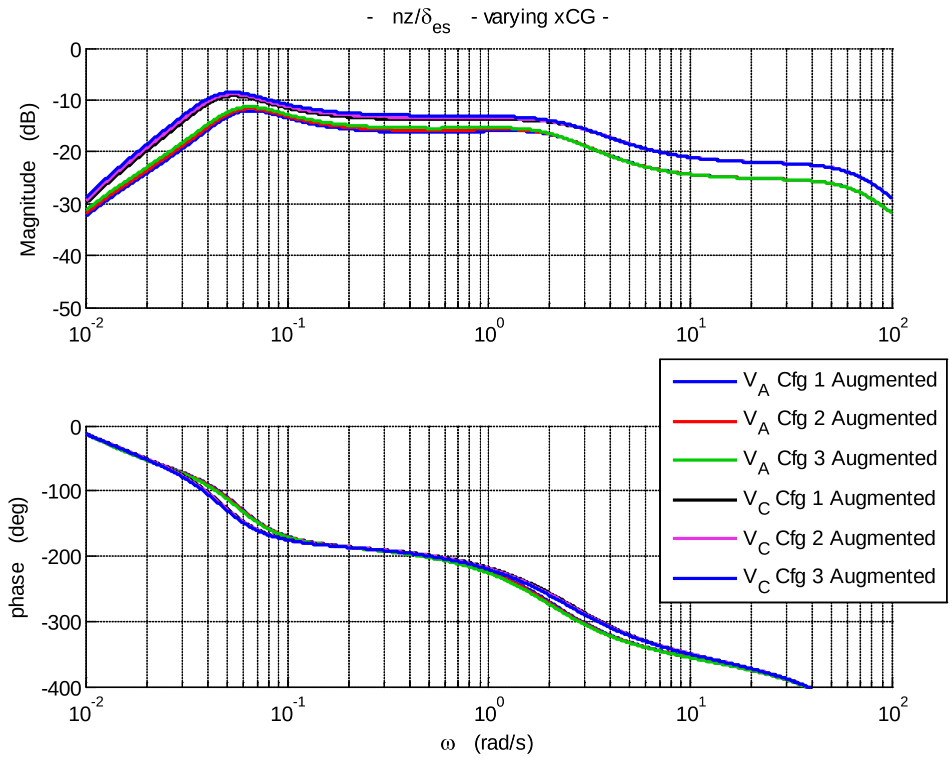


Figure 29. The $\frac{n_z}{\delta_{es}}$ frequency response — V_A; V_C augmented aircraft

2.4.1.2 Aircraft Bandwidth

Comparisons of the aircraft dynamics response parameters with the longitudinal aircraft bandwidth longitudinal FQ requirements in the three reference flight conditions are displayed in figures 30–33. The calculated parameters are relative to the aircraft with baseline actuator characteristics and with the feel system dynamics excluded. Table 18 provides the corresponding numerical values.

The results demonstrate that:

- Pitch attitude bandwidth is FQ solid level 1 in PA with no expected tendency to PIO, considering the small value of pitch rate overshoot (table 18).

- Pitch attitude bandwidth is FQ level 1, marginal level 2 in V_C and level 2 in V_A. Pitch rate overshoot is high in both flight conditions ($\Delta G(q) = 7.46 \div 8.51\ dB$), which is expected to impact the pitch response with a tendency toward bobbling.

- Flight path bandwidth versus pitch attitude bandwidth is FQ level 1 and marginal level 2 in PA. It is solid level 1 in V_A and V_C.

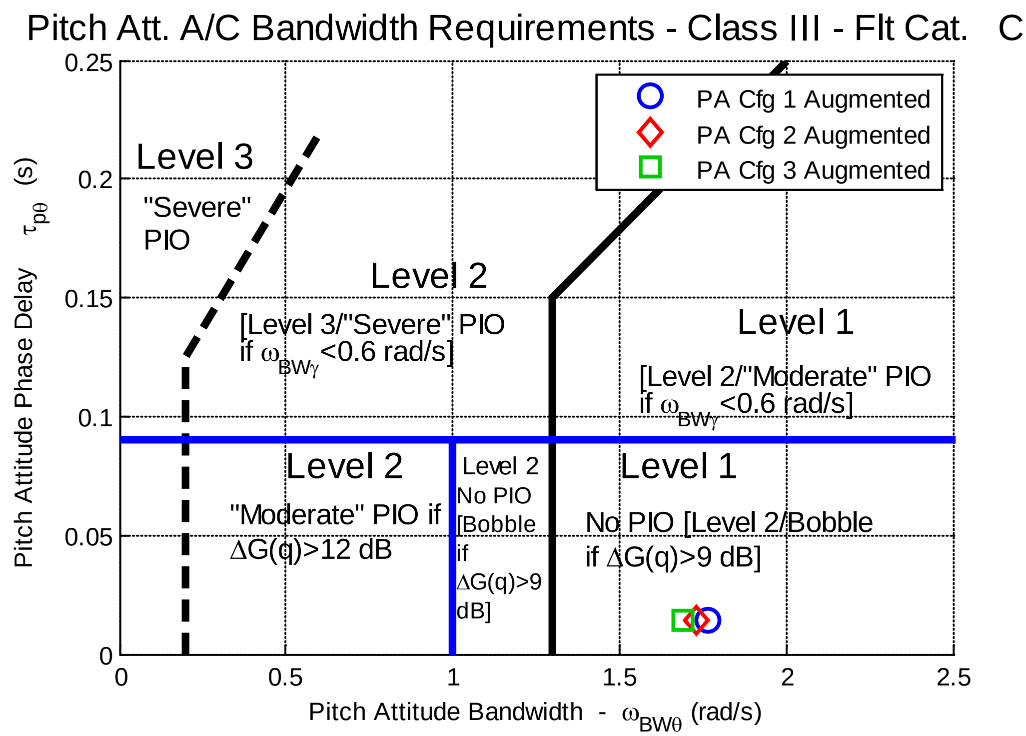


Figure 30. Pitch attitude bandwidth — PA augmented aircraft

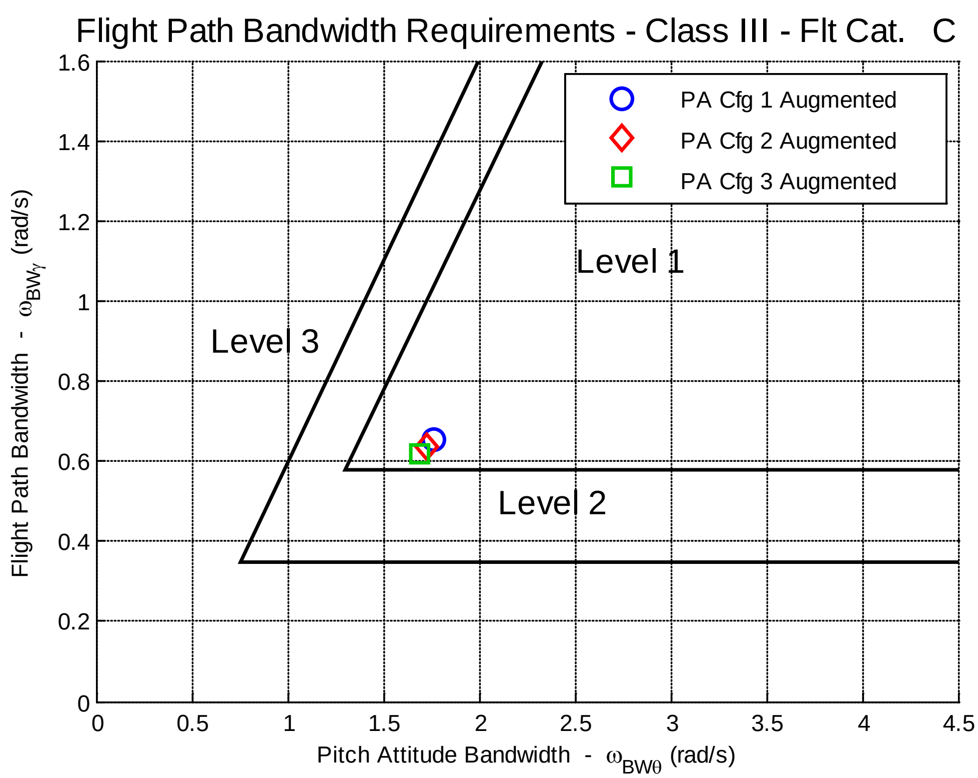


Figure 31. Flight path angle bandwidth — PA augmented aircraft

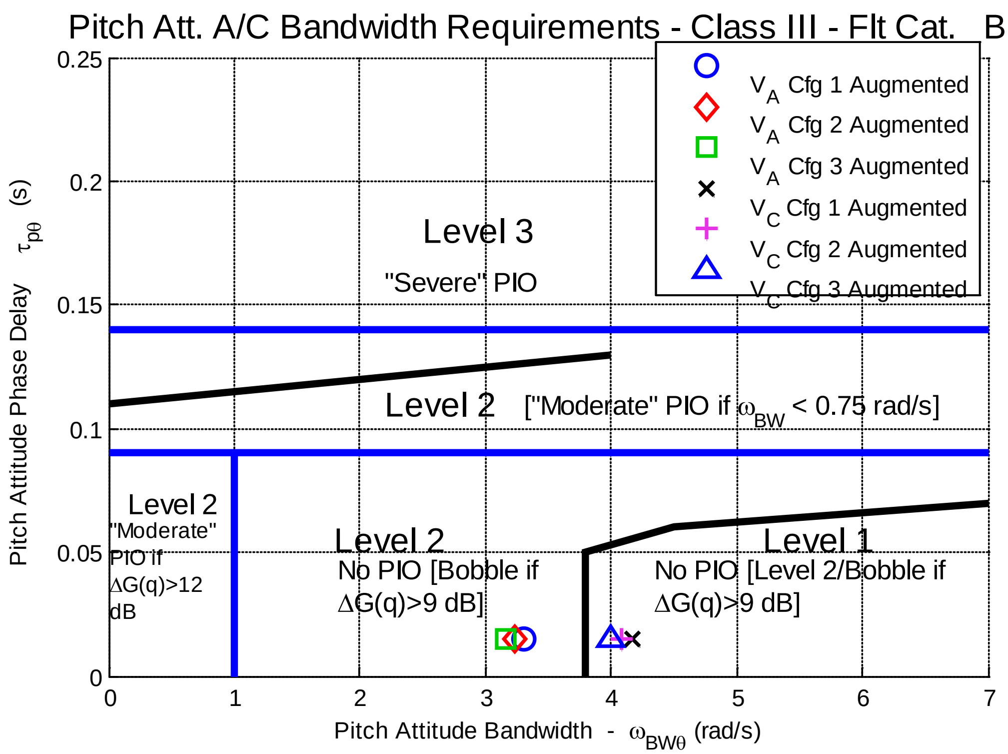


Figure 32. Pitch attitude bandwidth — V_A; V_C augmented aircraft

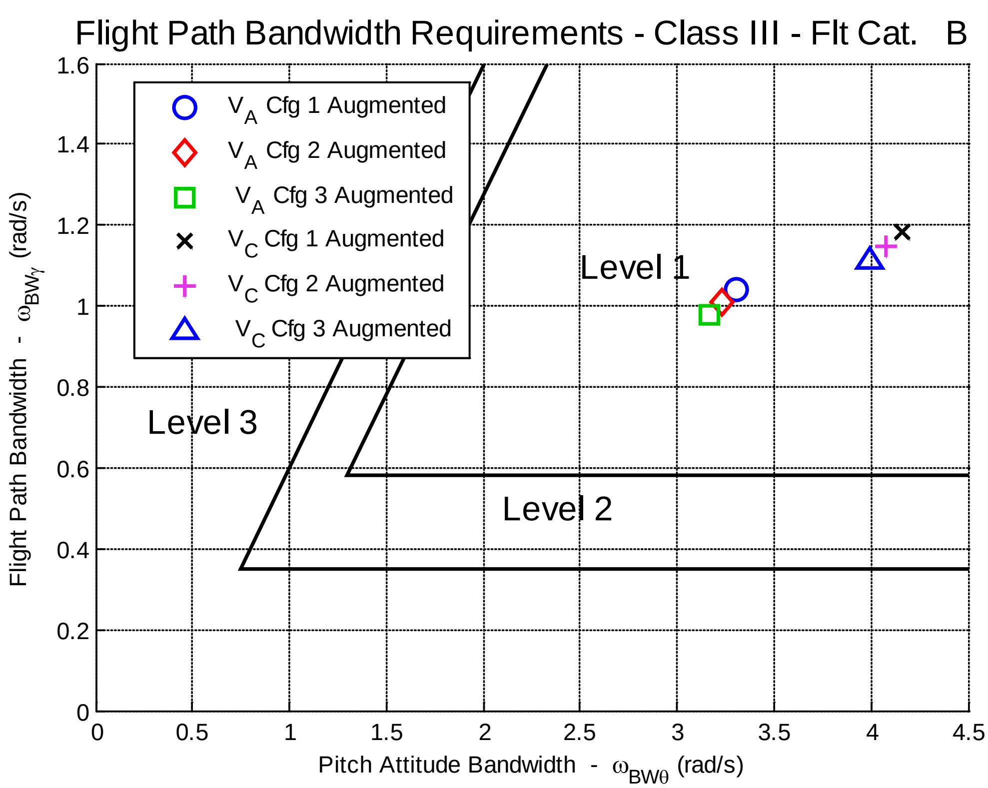


Figure 33. Flight path angle bandwidth — V_A; V_C augmented aircraft

Table 18. Augmented aircraft — pitch attitude and flight path angle bandwidth parameters

Flight Condition	CG	θ_{BW} (rad/s)	$\tau_{p\theta}$ (s)	γ_{BW} (rad/s)	$\omega_{\theta c}$ (rad/s)	$\omega_{\theta 180}$ (rad/s)	PM_θ (deg)	$\Delta G(q)$-dB (deg/s/deg)
PA	Cfg 1	1.77	0.0145	0.65	0.50	8.43	90.93	1.21
	Cfg 2	1.73	0.0145	0.64	0.52	8.41	89.14	1.01
	Cfg 3	1.69	0.0145	0.62	0.54	8.39	87.19	0.80
V_A	Cfg 1	3.30	0.0149	1.04	0.63	11.52	116.44	8.51
	Cfg 2	3.23	0.0149	1.01	0.69	11.44	115.03	8.11
	Cfg 3	3.16	0.0149	0.98	0.76	11.35	112.92	7.70
V_C	Cfg 1	4.16	0.0152	1.18	0.65	13.41	114.60	8.24
	Cfg 2	4.08	0.0152	1.15	0.70	13.31	113.62	7.86
	Cfg 3	4.00	0.0152	1.11	0.76	13.22	112.24	7.46

The symbols in the above table have the following meanings:

- θ_{BW} Pitch attitude bandwidth
- $\tau_{p\theta}$ Pitch attitude equivalent phase delay
- γ_{BW} Flight path angle bandwidth
- $\omega_{\theta c}$ Pitch attitude gain cross over frequency
- $\omega_{\theta 180}$ Pitch attitude phase cross over frequency
- PM_{θ} Pitch attitude phase margin
- $\Delta G(q)$ Pitch rate overshoot

2.4.1.3 Flight Path Angle Overshoot

The assessment of FQ levels with respect to the FPA overshoot requirements is based on the analysis of the time domain responses displayed in appendix B.

The responses can be defined by the following time domain characteristics:

- FPA overshoot is low and the corresponding FQ is solid level 1 in all flight conditions and aircraft configurations.

- Small amplitude pitch rate overshoot in PA flight condition. This is consistent with the magnitude of the δ_{es} to q linear response shown in figure 24 as a function of angular frequency.

- Lack of a definite pitch attitude and FPA steady state value, with a continuously increasing pitch attitude dropback (θ_{DB}) in PA flight condition in particular. Smaller tendency for continuous dropback in V_A and V_C flight conditions.

- No negligible pitch rate overshoot in V_A and V_C flight conditions.

The overall FQ level 1 FPA overshoot indicates accurate control of FPA and a consequent predictability of the flight path response in all flight conditions and aircraft configurations.

Table 19 provides the values and corresponding FQ levels of the FPA overshoot derived from analysis of the time histories.

Table 19. Augmented aircraft FPA overshoot and FQ levels

Flight Path Overshoot and Flying Qualities Levels			
Flight Condition	x CG	FQ Level	FPA Overshoot (%)
PA	Cfg 1	1	24
	Cfg 2	1	26
	Cfg 3	1	27
V_A	Cfg 1	1	18
	Cfg 2	1	19
	Cfg 3	1	19
V_C	Cfg 1	1	16
	Cfg 2	1	16
	Cfg 3	1	17

2.4.1.4 Comments on Augmented Aircraft Longitudinal Dynamics

Based on the data and results reported in the previous sections, the aircraft pitch response can be defined by the following characteristics:

- There is adequate short-period damping, increased with respect to the unaugmented aircraft by the implementation of the feedback of $\dot{\theta}$ to the elevator command (pitch damper).

- There is a predictable steady-state response from the initial pitch acceleration, as indicated by the adequate CAP values and related FQ level 1. This has been achieved through the increase of SP natural frequency with the implementation of the alpha feedback to the elevator command.

- In a PA flight condition, augmentation provides most of the closed-loop stability margin for all cases due to the low longitudinal static stability of the bare aircraft for the configurations with positive SM.

- The pitch rate overshoot is significant in V_A and V_C, while there is a lack of a definite pitch rate overshoot in the response to a longitudinal control step in the PA flight condition.

- There is positive pitch attitude dropback in V_A and V_C flight conditions and lack of pitch attitude dropback in PA flight condition, as pitch attitude does not reach steady state after the input is released.

- There is good predictability of the flight path response, indicated by the overall FQ level 1, with respect to flight path overshoot criterion requirements.

- There is low pitch attitude phase delay in all flight conditions and configurations. In up-and-away flight conditions, the pitch attitude bandwidth is nominally FQ level 1, marginal level 2. Accurate flight path control is expected, given the solid FQ level 1 FPA bandwidth. In PA, pitch attitude bandwidth is FQ solid level 1; flight path control is expected to be less accurate than in up-and-away flight conditions due to the lower FPA bandwidth.

The up-and-away pitch attitude bandwidth requirements are mainly defined for high-performance aircraft and the relative marginality reported above, even if the indication of potentially low tracking precision is considered adequate for the required tasks performed by a Class III aircraft. This is reinforced by the expected good flight path control.

From the assessment of the augmented aircraft longitudinal FQ levels, the manned evaluation tasks are expected to be performed with adequate precision with the baseline aircraft in all flight conditions and configurations. Baseline aircraft dynamics are not expected to affect the pilot's ability to rate the impact on HQ of the installation/change of the specific design elements to be evaluated.

2.4.2 Lateral/directional plane

2.4.2.1 Modal Parameters

Tables 20 and 21 contain the values of the augmented aircraft modal parameters, in CG configuration Cfg 1. Figures 34–36 display the primary aircraft frequency responses.

Table 20. Augmented aircraft DR FQ levels

The DR Modal Parameters and FQ Levels				
Flight Condition	Level	ζ_D	$\zeta_D \cdot \omega_{n_D}$ (rad/s)	ω_{n_D} (rad/s)
PA	1	0.287	0.304	1.06
V_A	1	0.308	0.196	0.64
V_C	1	0.332	0.231	0.70

Table 21. Augmented roll and spiral mode FQ levels

Roll and Spiral Modal Parameters and FQ Levels					
Flight Condition	Roll Mode FQ Level	$T_R\ (s)$	Spiral Mode FQ Level	$T^{\circ}_{1/2}$ (s)	T^{*}_{2} (s)
PA	1	0.41	1	–	73.7
V_A	1	0.53	1	30.4	–
V_C	1	0.44	1	32.6	–

° $T_{1/2}$ = Time to half amplitude
* T_2 = Time to double amplitude

Based on the comparison of the modal parameters with the corresponding MIL-F-8785C FQ requirements:

- All dynamic modes are FQ level 1 in the three flight conditions (PA, V_A, V_C).
- Implementation of the yaw damper and wash out filter in the feedback path in V_A and V_C augments DR damping ratio, total damping, and spiral mode time to half amplitude, with minimal impact on DR natural frequency.
- As expected, there is no impact of the augmentation on the roll mode time constant.

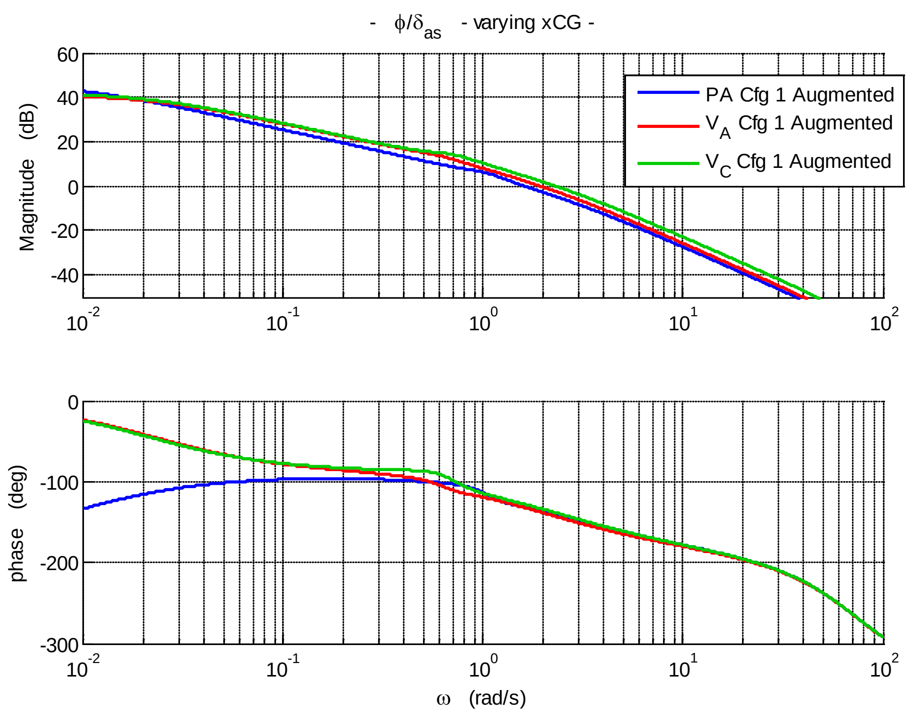


Figure 34. The ϕ/δ_{as} frequency response — Cfg 1 augmented aircraft

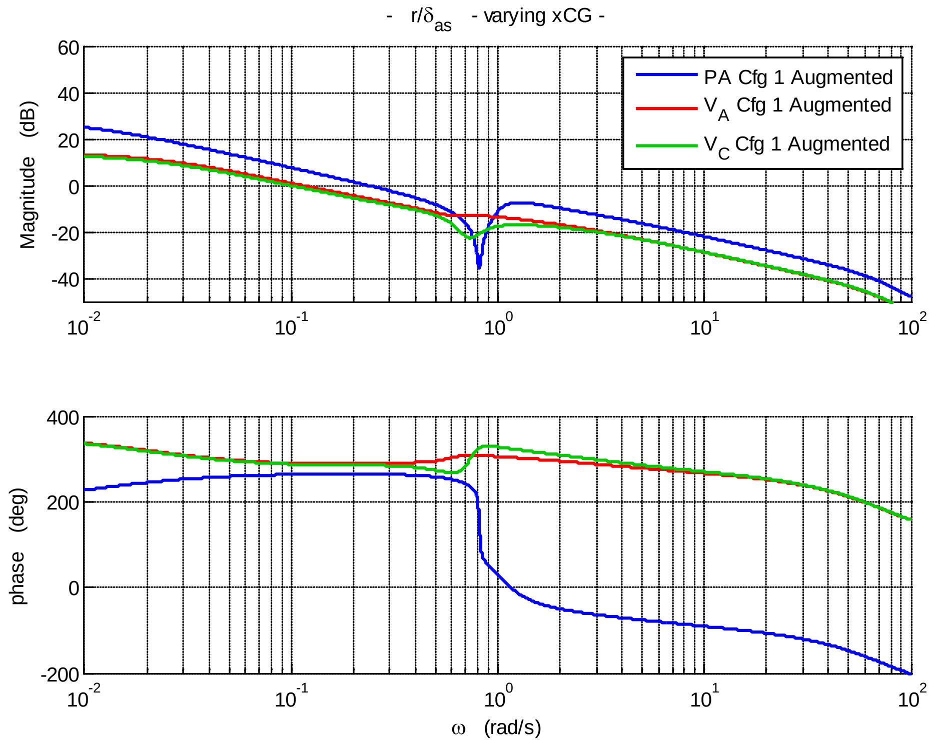


Figure 35. The r/δ_{as} frequency response — Cfg 1 augmented aircraft

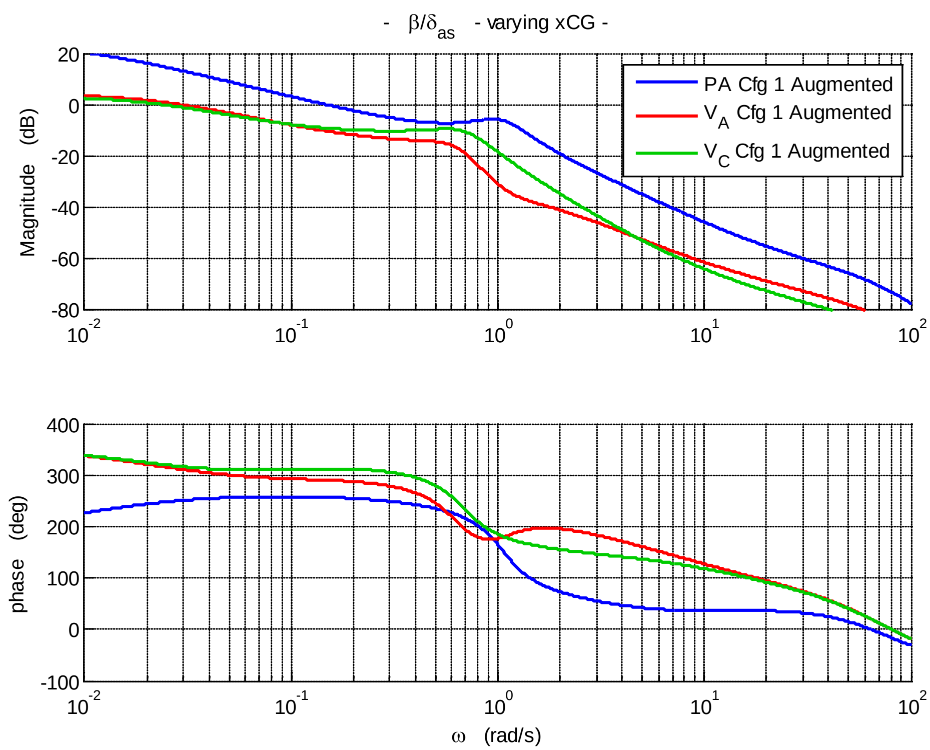


Figure 36. The β/δ_{as} frequency response — Cfg 1 augmented aircraft

2.4.2.2 Roll Attitude Bandwidth

The aircraft roll attitude bandwidth criterion is applied to the augmented aircraft, with feel system dynamics excluded (table 22).

The results demonstrate that:

- Roll attitude bandwidth is FQ solid level 1 in all flight conditions for the Cfg 1 configuration, with no expected tendency to PIO.
- Roll attitude bandwidth in PA is slightly reduced by the implementation of the ARI.

Table 22. Augmented aircraft Cfg 1 — roll attitude bandwidth parameters

Roll Attitude Bandwidth Parameters Cfg 1					
Flight Condition	φ_{BW} (rad/s)	$\tau_{p\varphi}$ (s)	$\omega_{\varphi c}$ (rad/s)	$\omega_{\varphi 180}$ (rad/s)	PM_φ (deg)
PA	1.87	0.0144	1.63	10.90	48.25
V_A	1.78	0.0140	1.95	10.01	42.22
V_C	2.07	0.0144	2.31	10.90	41.62

The symbols in table 22 have the following meanings:

φ_{BW}	Roll attitude bandwidth
$\tau_{p\varphi}$	Roll attitude equivalent phase delay
$\omega_{\varphi c}$	Roll attitude gain crossover frequency
$\omega_{\varphi 180}$	Roll attitude phase crossover frequency
PM_φ	Roll attitude phase margin

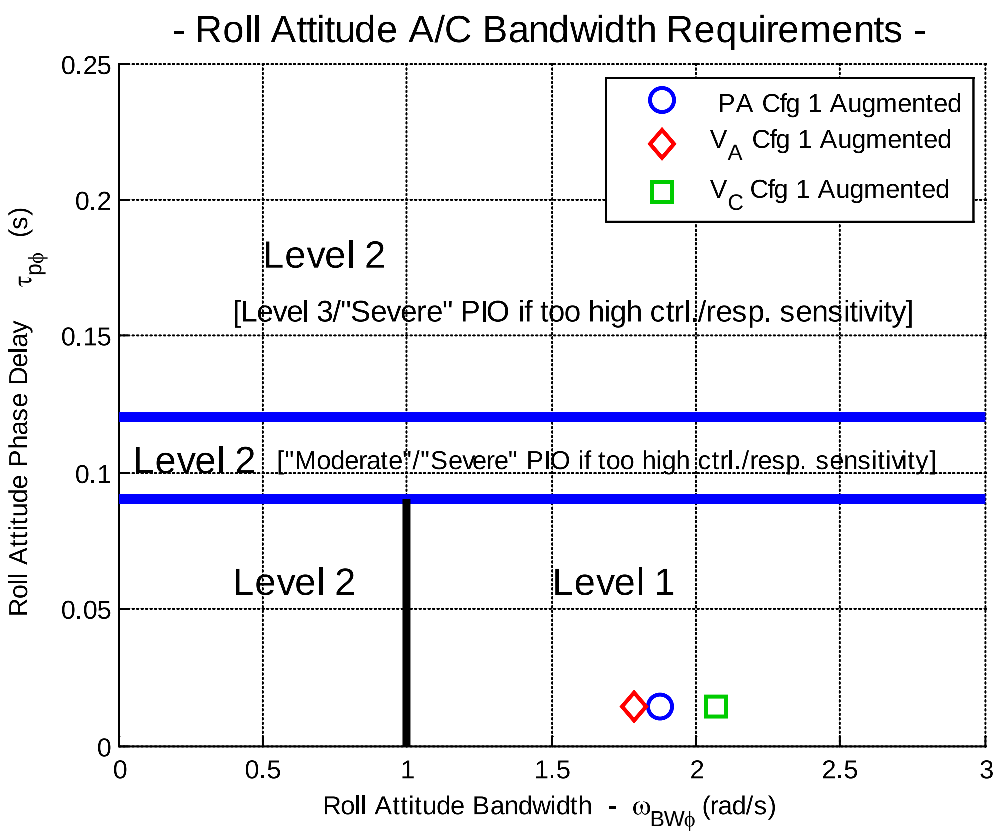


Figure 37. Roll attitude bandwidth — PA; V_A; V_C Cfg 1 augmented aircraft

3. FEEL SYSTEM DESCRIPTION

The feel system used for the evaluations is formed by variable feel side-stick and pedals. The side-stick can be programmed both as an active and passive inceptor. The baseline side-stick characteristics are reported in table 23.

Table 23. Side-stick characteristics

Side-Stick Characteristics					
Axis	Maximum Deflection (deg)	Force/Position Gradient (lb/deg)	Breakout Force (lb)	Natural Frequency (rad/s)	Damping Ratio
Pitch	± 10	1.0	0.25	17.5	0.7
Roll	± 10	0.6	0.25	15	0.7

No evaluations are planned for the pedal feel system.

Figures 38 and 39 show the longitudinal and lateral baseline side-stick spring gradient characteristics.

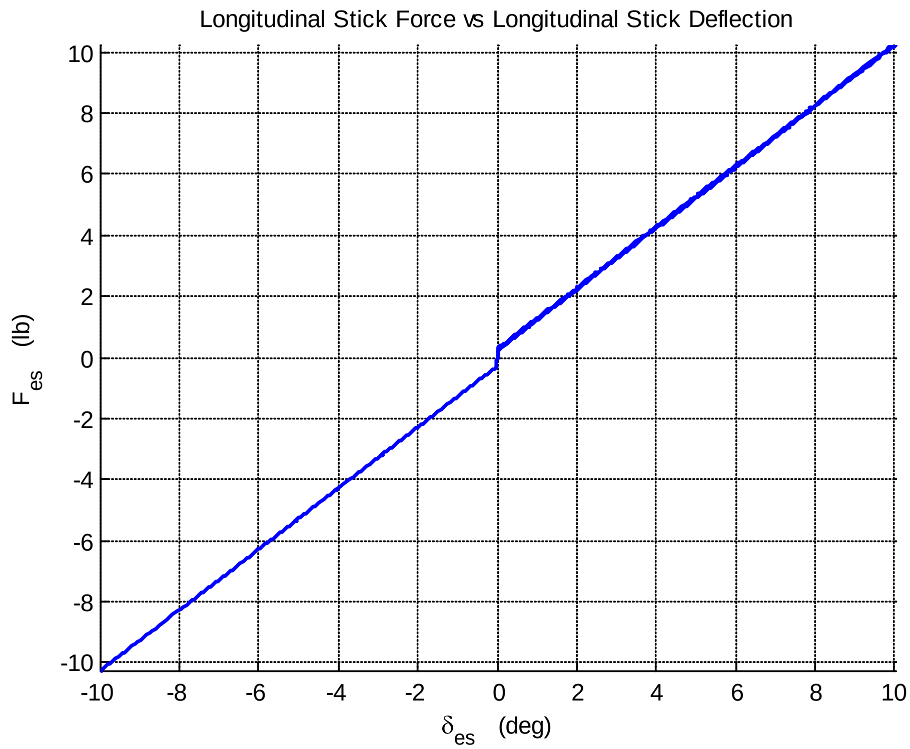


Figure 38. Baseline side-stick longitudinal spring gradient

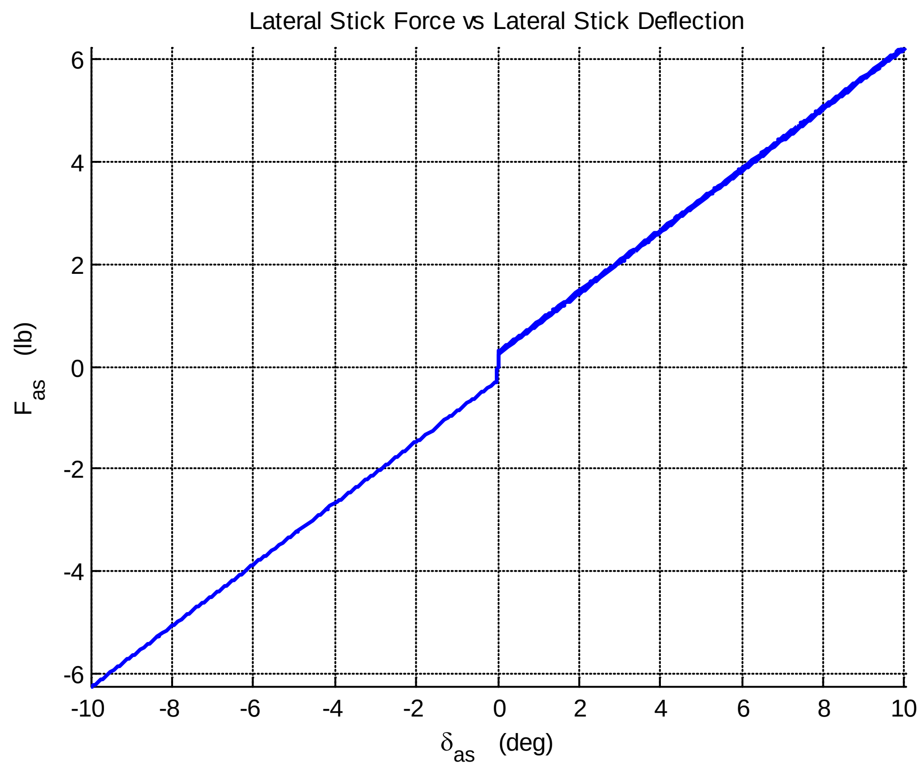


Figure 39. Baseline side-stick lateral spring gradient

4. TASK 2 EVALUATION TEST PLAN

4.1 BACKGROUND INFORMATION

Task 2, or Year 2 Follow-on task, is dedicated to the evaluation of different feel system characteristics, a comparative assessment of the advantages/disadvantages between active and passive control inceptors, and the analysis of the impact of actuators' bandwidth variation on augmented aircraft dynamics.

The scope of the entire work is to provide top-level requirements and define rules for feel system, CLAWS, and FCS design specifications. The understanding of the aircraft states and available signals used by the pilot to close the loop when controlling the aircraft is also relevant to the project.

An additional output of the project is to derive guidance and suggest a control strategy/design approach common to all conditions and control system modes.

The main objectives of this test plan are pitch and roll controls. The impact of the rudder control on HQ can be assessed as a consequence of the evaluations when considered relevant.

The aircraft model and augmentation algorithm used for all feel system evaluations is a side-stick inceptor with conventional CLAWS.

The titles of the sections of this test plan refer to the titles of the subtasks specified in the FAA SOW [1]. All evaluations are based on the following metrics/criteria:

- Handling Qualities (Cooper Harper) Ratings (HQR)
- Pilot-Induced Oscillations Rating (PIOR)
- Evaluation pilot's (EP's) comments
- Task scoring for offline simulations and manned evaluations, when applicable
- Pilot-vehicle system (PVS) measures, when applicable

To reassess the baseline HQ during manned evaluations, the configuration values will be varied by the Flight Test Engineer (FTE), with the EP not knowing the current value unless he specifically requests to fly the baseline configuration.

4.2 BASELINE COMMAND PATH CONFIGURATION

A conceptual diagram of the implementation of dead zones and flat zones in the command path is provided in figure 40. More detailed figures of the actual CLAWS simulation model are included in the next sections. These two non-linearities are implemented in series between the feel system and the relevant control surface command gain. They can be activated individually and in combination, if required.

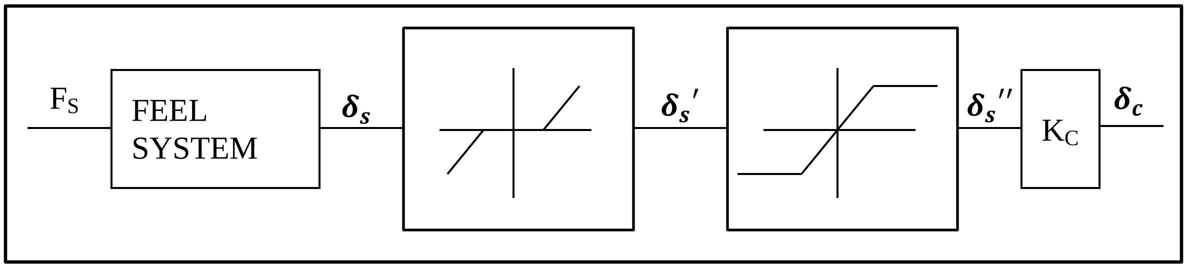


Figure 40. Conceptual implementation of dead zone and flat zone

Where:

F_s	(lb)	stick force
δ_s	(deg)	stick deflection
$\delta_s{}'$	(deg)	output of the dead zone
$\delta_s{}''$	(deg)	output of the flat zone
K_C	(deg/deg)	command gain
δ_c	(deg)	commanded control surface deflection

4.3 DISCRETE TASKS

4.3.1 Pitch Attitude Captures With Sum-of-Sines Disturbance

Objectives:

- Evaluate the ability to maneuver in pitch and capture a pitch attitude.
- Evaluate feel system and control sensitivity characteristics.
- Identify maneuverability limitations and PIO tendencies.

Description:

Aggressively capture the discrete target pitch attitude and regulate against the sum-of-sines (SoS) disturbance.

Desired Performance:

- ±1° of pitch attitude command at least 50% of the time.
- 8.5° ≤ AoA < 9.5° during capture (PA).
- 0 g ≤ n_z ≤ 2.5 g during capture.

Adequate Performance:

- ±2° of pitch attitude command at least 50% of the time.
- 9.5° ≤ AoA < 10.5° during capture (PA).
- 0 g ≤ n_z ≤ 2.5 g during capture.

From steady wings-level flight, the pilot captures the target pitch attitude identified on the head-down display (HDD) and maintains the pitch attitude within the defined tolerances of the task. Additionally, the pilot is instructed not to exceed the 2.5 g or 11° AoA limit. For PA conditions, the pilot must pull to a minimum of 8.5° AoA during the capture so that aircraft limits are approached. Figure 41 depicts the discrete task profile used for this task. Figure 42 depicts the profile for the up-and-away configurations.

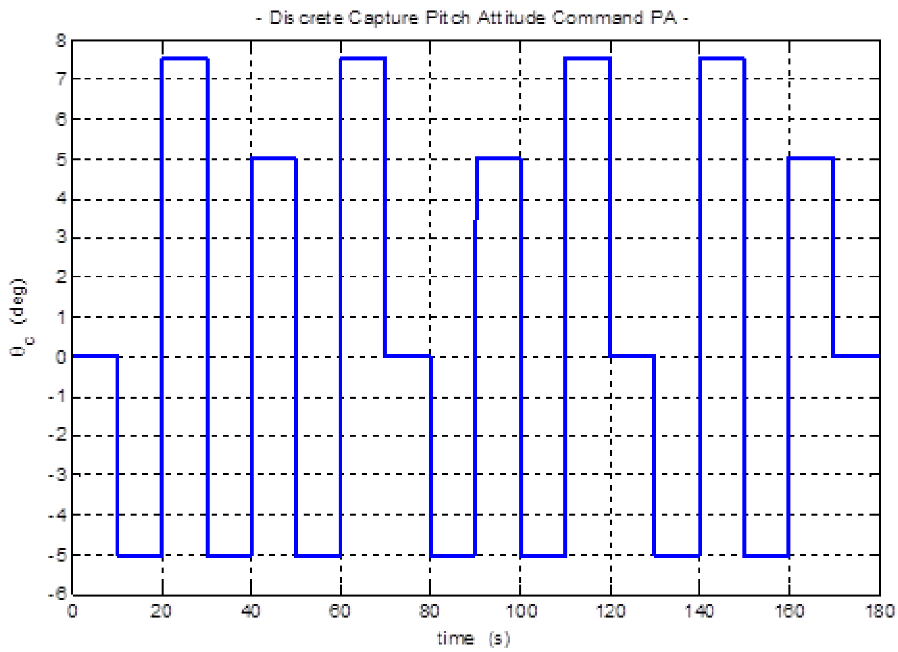


Figure 41. Pitch attitude capture task profile — PA

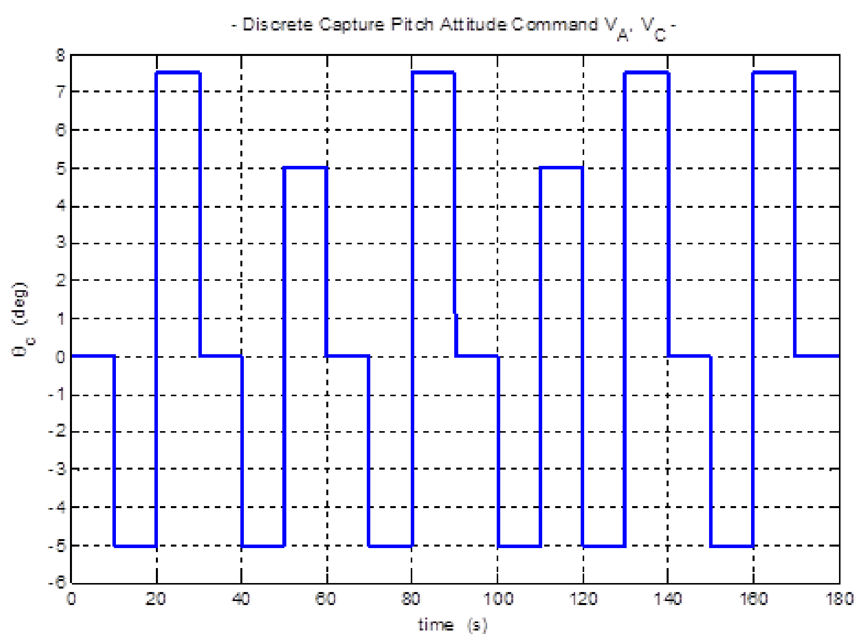


Figure 42. Pitch attitude capture task profile — V_A/V_C

This task was performed with an SoS disturbance optionally on or off. The SoS disturbance input forcing function is used to mimic random atmospheric turbulence with a known input as part of a pilot regulation tracking task. That is, the disturbance continually displaces the vehicle from its path while the pilot attempts to minimize the displayed pitch attitude error within desired performance constraints. The disturbance was injected as an elevator position in the model. This disturbance was implemented as the sum of 13 individual sine waves of varying frequency content, as depicted in table 24. The task profile is illustrated in figure 43. For PA, a gain of 0.9 is used on this signal before injecting it into the elevator; a gain of 0.3 is used for the up-and-away configurations.

Table 24. The SoS task component sine waves

Frequency (rad/s)	Amplitude	Phase (rad)
0.1534	0.9998	0
0.3835	0.9989	0
0.6903	0.9963	0
0.9971	0.9923	0
1.3806	0.9854	0
1.9942	0.9703	0
2.7612	0.9453	0
3.9884	0.8949	3.9750
5.6757	0.8156	4.7527
7.9767	0.7081	6.2269
10.9680	0.5893	2.2955
15.9534	0.4483	1.5522
21.9359	0.3426	6.1735

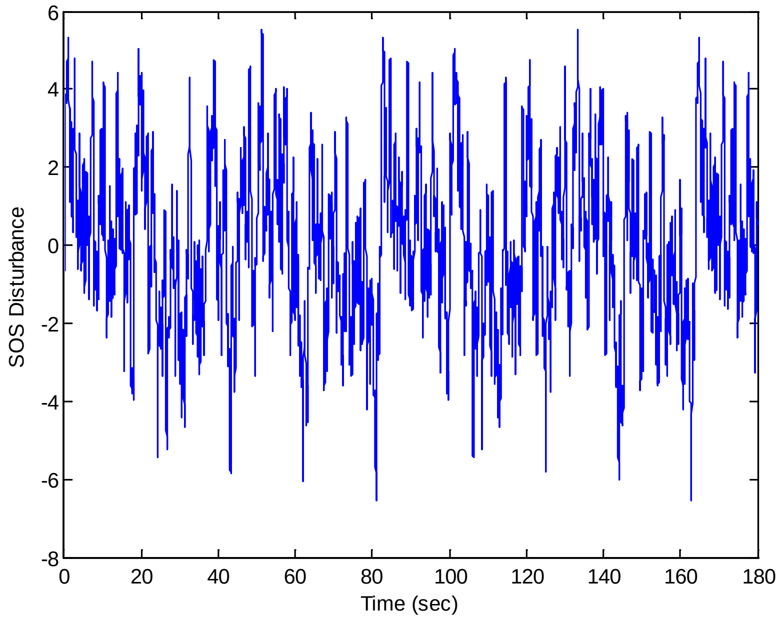


Figure 43. The SoS disturbance profile

4.3.2 Bank Angle Captures and Hold

Objectives:

- Evaluate ability to roll and capture a bank angle.
- Identify maneuverability limitations and PIO tendencies.

Description:

From steady wings-level flight, roll and capture the target bank angle identified on the HDD and maintain this bank angle within the specified tolerance until stable. Capture the bank angle, then capture and hold the next displayed bank angle and maintain within the specified tolerance until stable. The discrete roll task profile is illustrated in figure 44.

Desired Performance:

- ±5° bank angle.
- No more than one bank angle overshoot for each capture. Magnitude of overshoot remains within the desired region.

Adequate Performance:

- ±10° bank angle.
- No more than one bank angle overshoot for each capture. Magnitude of overshoot remains within the adequate region.

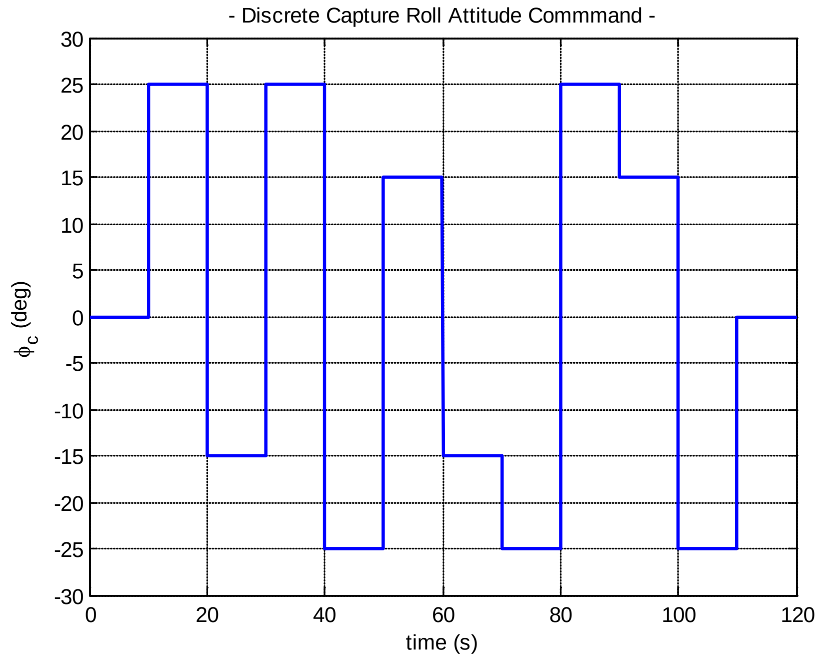


Figure 44. Roll task profile

4.4 THE SOS TRACKING TASK

This section describes the SoS disturbance forcing function, which is one of the tasks that is used for the piloted evaluations. It is used to drive the compensatory tracking task through which the pilot attempts to minimize the displayed error within desired/adequate performance constraints. Table 25 presents the parameters for a Fibonacci series-based SoS input that has been designed to emphasize key vehicle dynamics as well as typical closed-loop control. The input is defined for a 60-second scoring time run length. Thus, each sine wave frequency is defined by f_n (Hz) = N_n (cycles/run)/60 (s/run).

Table 25. Example SoS input forcing function parameters for lower frequency identification

Frequency No.	1	2	3	4	5	6	7
Cycles/Run, N_n	3	5	8	13	21	34	55
Frequency, f_n (Hz)	0.0500	0.0833	0.1333	0.2167	0.3500	0.5667	0.9167
Frequency, (r/s)	0.3142	0.5234	0.8375	1.3616	2.1991	3.5607	5.7598
Amplitude ($A_i = f_1/f_n$)	+1.000	-0.6000	+0.3750	-0.2308	+0.1429	-0.0882	+0.0545
Initial Rate A_n x ω_n	+0.6786	-0.6286	+0.6283	-0.6284	+0.6285	-0.6281	+0.6278

A time history of the SoS input forcing function defined by the parameters of table 25 (with an overall gain of factor 1.1 as used in previous piloted simulations) is shown in figure 45. To provide adequate warm-up time for the pilot, the input function begins with 10 seconds of nonscoring time that includes a 5-second initial linear ramp-up in amplitude. This is followed by the 60 seconds of scoring time (10–70 s) and a 5-second cool down period during which the amplitude is ramped back to zero. Figure 46 presents an input power spectral density (PSD) plot for the 60-second scoring time. This figure illustrates the unique characteristic of the Fibonacci series-based input that provides for equally spaced input power on a log frequency plot. The figure also reveals that the amplitude of the sine waves has been defined to provide a -20 dB/decade slope.

The SoS input forcing function can be summarized as follows:

- The 7-sine wave Fibonacci forcing function defined in table 25 adequately covers the range of frequencies for pilot-vehicle closed-loop from 0.3–6 radians per second (rad/s) over a 60 s scoring time run.

- The alternating initial amplitude signs gave an even distribution function and seven sine waves assure a reasonably Gaussian distribution function.

- Complete runs included a 10-second lead-in or warm-up to the formal scoring time and a 5-second cool down time at the end of the run.

- To prevent pilots from anticipating the input, the phasing of the individual sine waves was varied to produce two input functions. The phasing is constant with time.

An appropriately scaled version of this SoS input is used as the disturbance input for the pitch attitude and bank angle regulatory tracking tasks.
The task will be used in this program as a disturbance-regulation task, so there is no command signal per se. Instead, the pilot (or pilot model in offline simulations) will attempt to reduce the error that results from the SoS disturbance signals, thereby maintaining the steady-state flight condition.

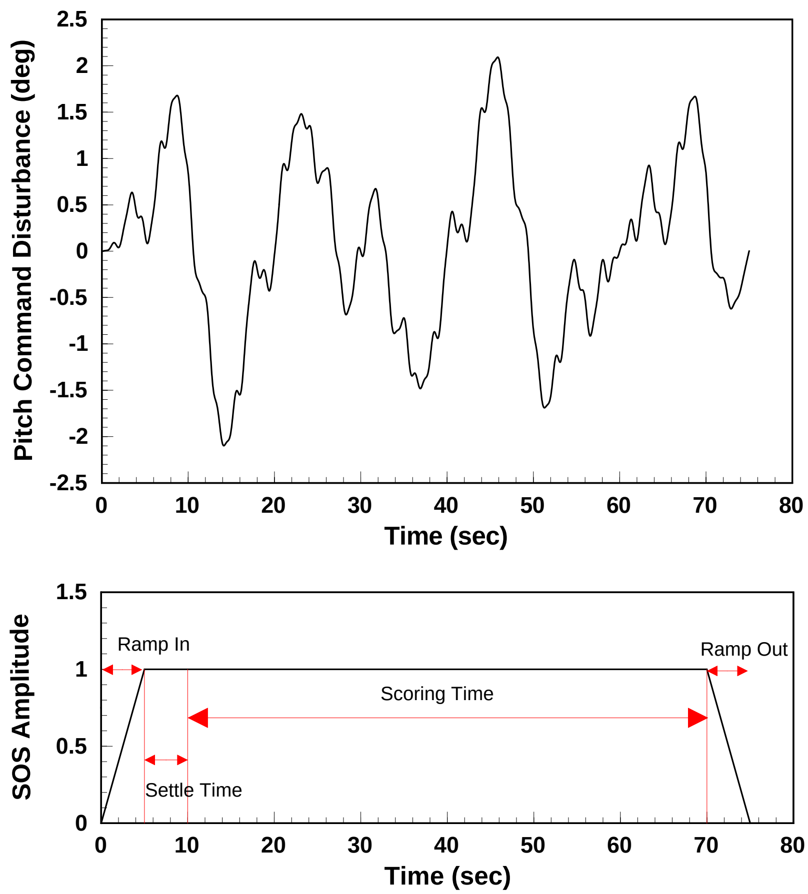


Figure 45. Fibonacci series-based lower frequency SoS input forcing function time history

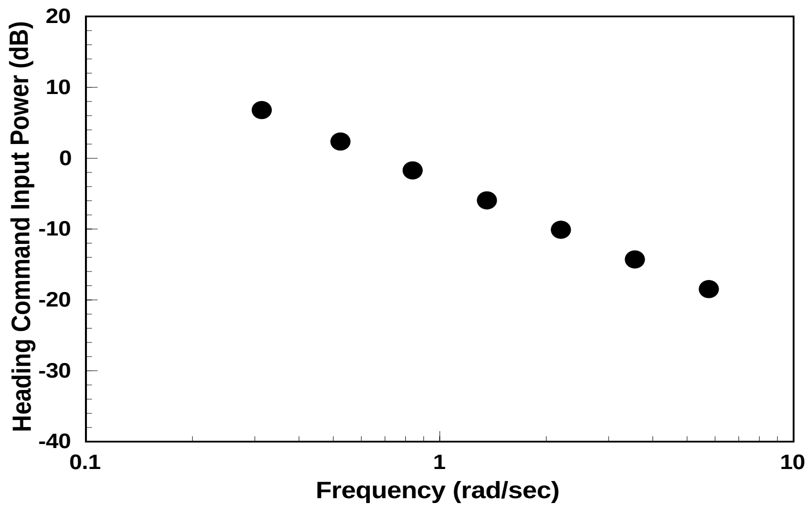


Figure 46. Fibonacci series based lower frequency SoS input forcing function PSD

Figure 47 displays the integration of the pitch or roll attitude SoS task within a generic aircraft model, for which the pilot block can be represented by a transfer function, for offline simulations, or the EP of manned simulations.

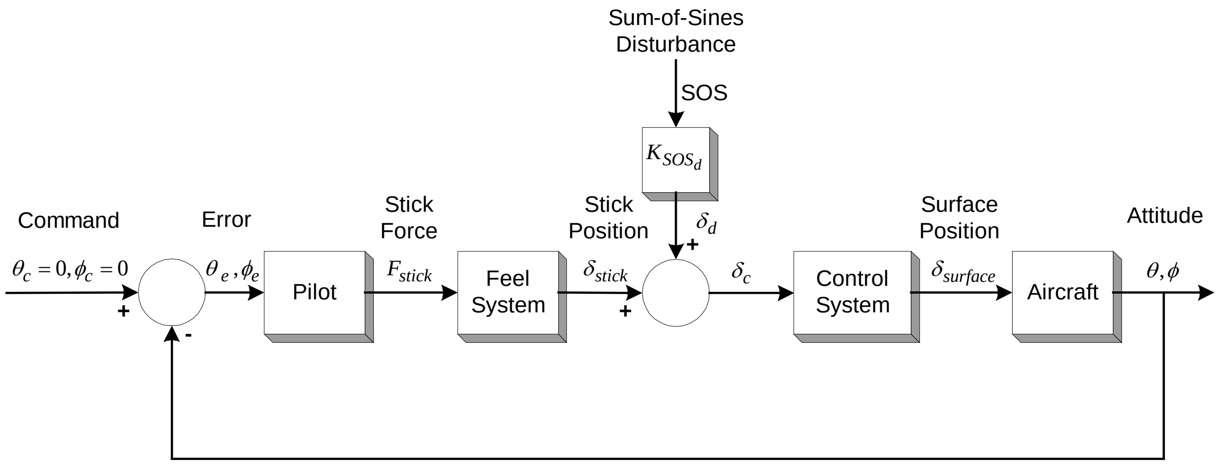


Figure 47. The SoS disturbance regulation task integration

The SoS disturbance input forcing function is used to mimic random atmospheric turbulence with a known input as part of a pilot-regulation tracking task. That is, the disturbance continually displaces the vehicle from its trim condition, while the pilot attempts to minimize the displayed error, with respect to the target state, within desired performance constraints.

The objectives of the SoS task are to:

- Evaluate HQ in a tight, closed-loop disturbance regulation task.
- Evaluate feel system and control sensitivity characteristics.
- Identify bobble or PIO tendencies.

4.5 AIRCRAFT DISPLAYS

Figure 48 is a screenshot of the HDD used by the EPs to perform the pitch attitude capture tasks. The pilot flies the aircraft symbol to try and match the pitch attitude of the target symbol. The target is driving by one of the discrete task profiles discussed in section 4.3.1. The circular gauge at the top-right portion of the screen displays AoA; the top-left displays normal load factor (n_z). While performing the task in PA flight condition/configuration, the pilot is required to achieve alpha = 9° ± 0.5° for desired performance and alpha = 10° ± 0.5° for adequate. The second component of the scoring is given by the time percentage of the target being contained in the inner (desired) and outer (adequate) circle of the aircraft symbol. Individual scorings are assigned to the discrete (first component) and continuous regulation (second component) part of the task.

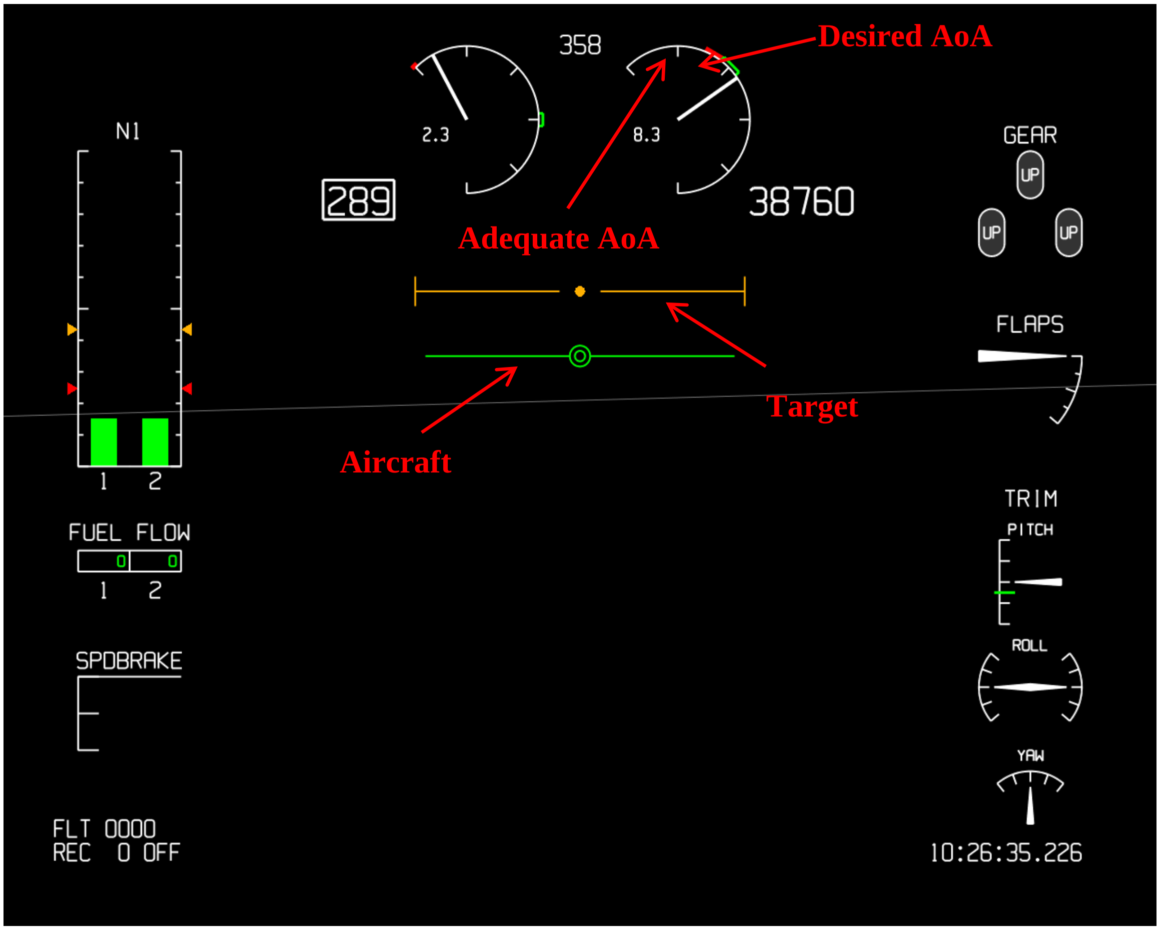


Figure 48. HDD pitch task representation

Figure 49 displays the HDD with the symbols used for the bank angle capture. The wing tip of the aircraft (green) has to be kept at half of the vertical bracket of the target (amber) for desired performance and at the tip of the bracket for adequate performance. One overshoot is allowed for discrete captures without disturbance. The scoring is based on the percentage of time within desired/adequate boundaries for a CCC task.

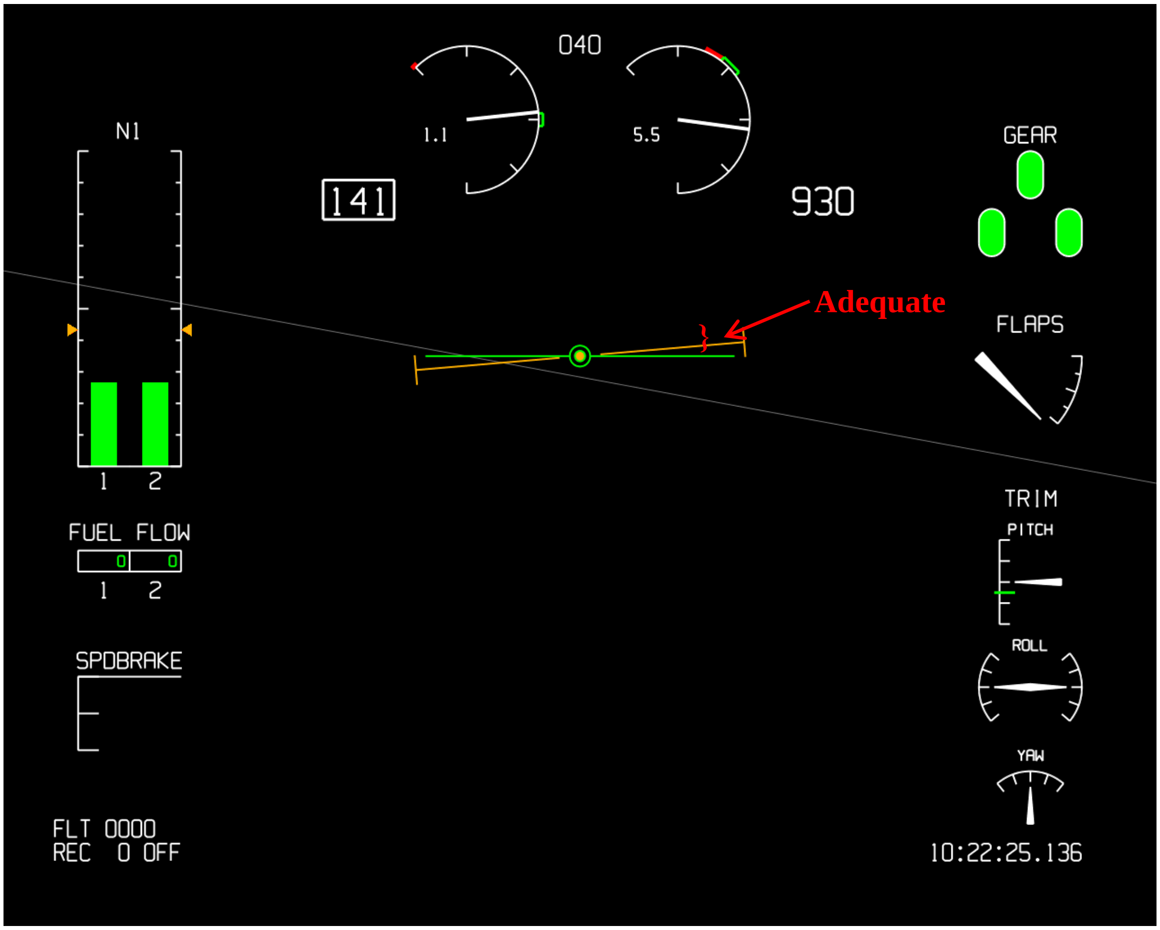


Figure 49. HDD Roll Task Representation

4.6 COMMAND PATH DEAD ZONES AROUND THE INCEPTOR NULL POSITION

4.6.1 Implementation

A dead zone is programmed in the command path as a null command gain around the null inceptor position. Mechanization of the dead zone in both longitudinal and lateral control axes of the feel system includes a breakout (BO) force to provide the pilot with centering cues.

Figure 50 displays the normalized force and control surface command, with the proposed implementation of different values of the longitudinal dead zone (DZLON). The case represented has nominal force gradient and BO force. The same implementation is valid for the lateral dead zone (DZLAT) without loss of generalization.

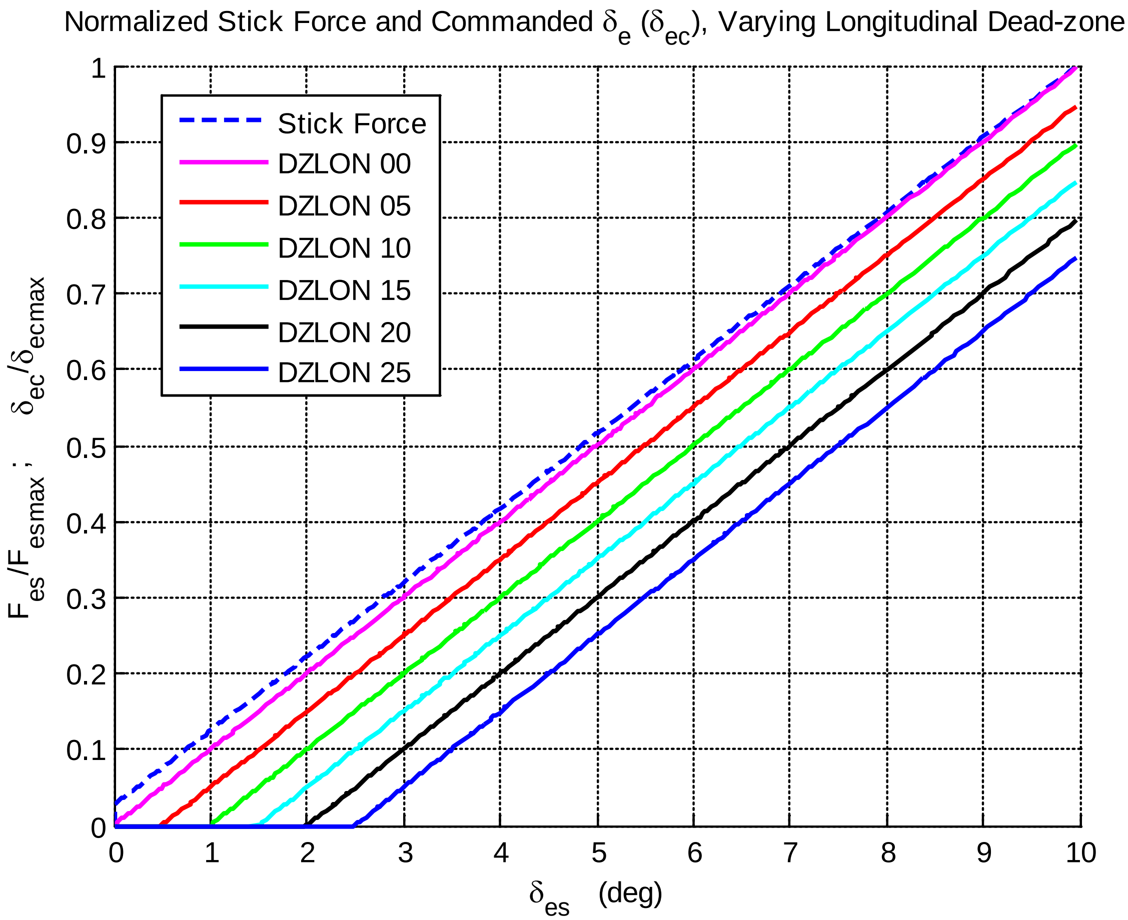


Figure 50. Normalizes side-stick F_{es} (dashed blue lines) and δ_{ec}, varying longitudinal dead zone

Figure 51 displays the implementation of the command path dead zones within the standard Calspan/ Systems Technology, Inc. (STI) Year 2 CLAWS subsystem. Dead zones are external to the feedback loop and upstream of the control surface command gain. This is to decouple the value of the inceptor dead zone from the resulting commanded control surface dead zone, as the command gain value can vary in function of flight condition and aircraft configuration. The lateral command path dead zone is from upstream of the ARI as well to maintain proper turn coordination independently from the lateral command path configuration.

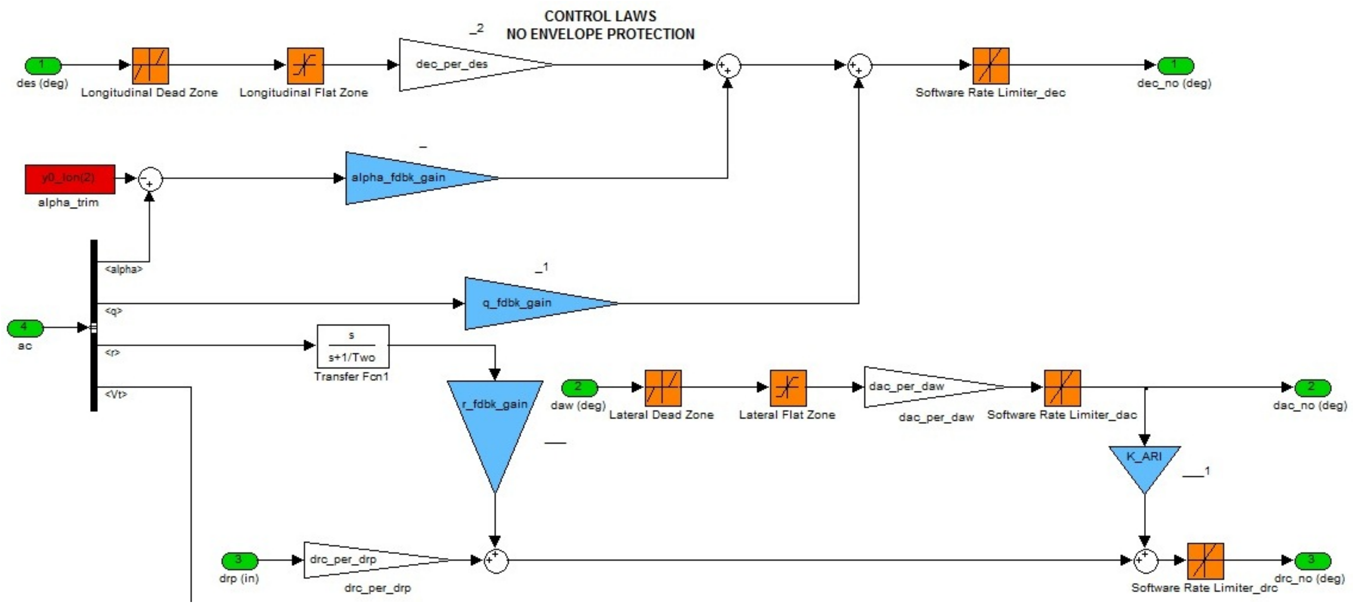


Figure 51. Dead zone implementation within the Calspan/STI year 2 control laws subsystem

4.6.2 Evaluation Task Description

The tasks, to be performed independently, in the longitudinal and lateral plane are the SoS pitch attitude (theta, θ) and bank angle (phi, ϕ) regulation, respectively.

In the lateral plane, the pilot has to maintain wing level when disturbed with respect to the trim condition.

The performance requirements for the longitudinal and lateral tasks are reported in tables 26 and 27, respectively.

Table 26. Pitch attitude SoS longitudinal task performances requirements

Flight Condition	Pitch Attitude Target **θ** (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\theta = \theta_{trim}$ Pitch disturbance: sum-of-sines	$\boldsymbol{\theta_e = \pm 1}$ At least 50% of the time	$\boldsymbol{\theta_e = \pm 2}$ At least 50% of the time	Aggressively minimize the displayed pitch attitude error ($\boldsymbol{\theta_e}$) signal and attempt to keep the error within the specified tolerances
Maneuvering Speed				
Design Cruise Speed				

Table 27. Lateral attitude SoS longitudinal task performances requirements

Flight Condition	Roll Attitude Target $\boldsymbol{\phi}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\phi = \phi_{trim}}$ Roll disturbance: sum-of-sines	$\boldsymbol{\phi_e = \pm 3}$ At least 50% of the time	$\boldsymbol{\phi_e = \pm 6}$ At least 50% of the time	Aggressively minimize the displayed bank angle error ($\boldsymbol{\phi_e}$) signal and attempt to keep the error within the specified tolerances
Maneuvering Speed				
Design Cruise Speed				

4.6.3 Piloted Evaluations

The manned simulations test plan is based on the variation of the dead zone amplitude with a baseline BO force. From Year 2 testing, it was noted that some pilots like to be highly active in controlling the aircraft, with very small amounts of BO force preferred.

As it can be derived from figure 50, an increase of the dead zone amplitude also reduces the control authority. The impact of this authority reduction is not expected to be significant for the small amplitude of the pitch attitude perturbations in the selected task.

Tables 28 and 29 contain the conventional test case identification and dead zone values, which are planned for the evaluations of longitudinal and lateral control, respectively. They are tested separately, the values are the same for both control channels, and they correspond to the same authority ratio of the respective control.

The piloted evaluations are conducted in both pitch and roll in CG configuration Cfg 1 and the selected flight conditions are:

- Maneuvering speed V_A at Hp = 38 kft

Table 28. Longitudinal command path dead zone evaluation cases

Longitudinal Dead Zone (DZLON) Case Identification	Dead Zone Value (deg)
DZLON00 (baseline)	0.0
DZLON05	0.5
DZLON10	1.0
DZLON15	1.5
DZLON20	2.0
DZLON25	2.5

Table 29. Lateral command path dead zone evaluation cases

Lateral Dead Zone (DZLAT) Case Identification	Dead Zone Value (deg)
DZLAT00 (baseline)	0.0
DZLAT05	0.5
DZLAT10	1.0
DZLAT15	1.5
DZLAT20	2.0
DZLAT25	2.5

4.7 COMMAND PATH FLAT ZONES AT HIGH INCEPTOR DEFLECTION

4.7.1 Implementation

Flat zones are implemented in the command path as saturation of the pilot command prior to the stick reaching its forward or aft limit to prevent high maneuver commands at high inceptor deflections [1]. This design characteristic could occur in systems where constant command gains are used, but the authority gets limited. The longitudinal flat zones (FZLON) apply to positive (pitch up) and negative (pitch down) values of the inceptor travel. Tests are principally aimed at understanding the effectiveness of the flat zones in preventing g's and AoA exceedances.

Figure 52 displays the flat zone implementation within the standard Calspan/STI Year 2 CLAWS subsystem. They are upstream of the correspondent control surface command gain and outside the feedback path. The correspondent simulation blocks are circled in red.

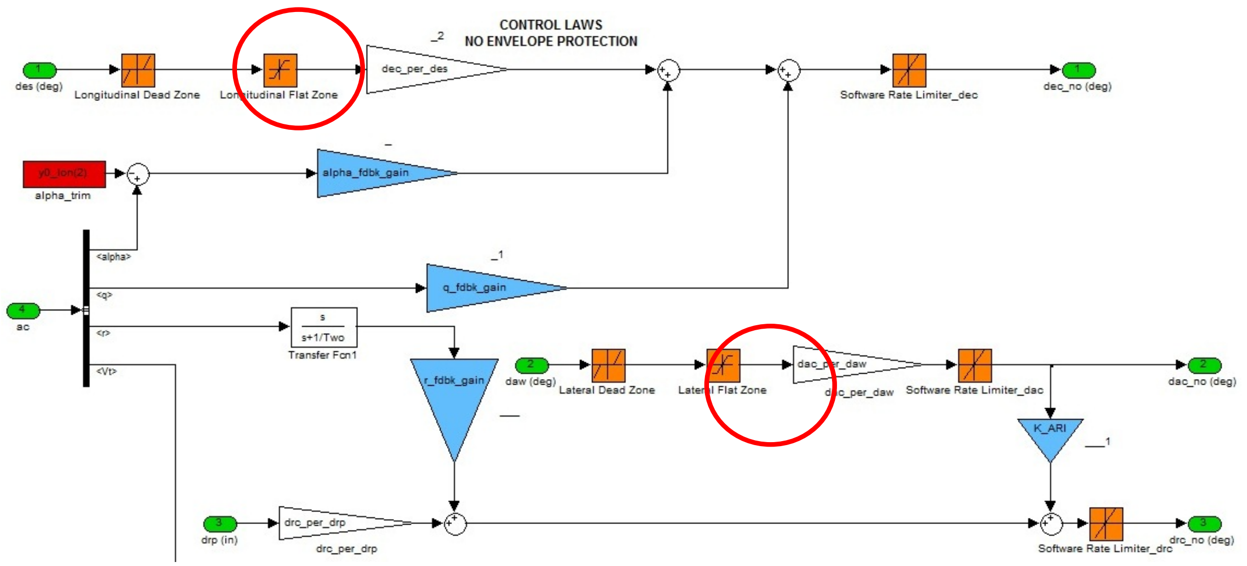


Figure 52. Flat zone implementation within the CLSPAN/STI year 2 control laws subsystem

No specific alpha/*nz* protection is added to the baseline augmentation: the flat zones are considered the CLAWS' design element dedicated to prevent envelope exceedances.

Figure 53 displays the proposed implementation of the baseline FZLON in the command path in terms of commanded control surface deflection and inceptor force, normalized with respect to their maximum value. The cases represented have nominal gradient and BO force with command path flat zones of different amplitude. The conventional case names are those listed in table 30. The same representation, without loss of generalization, is valid for the lateral command path flat zones.

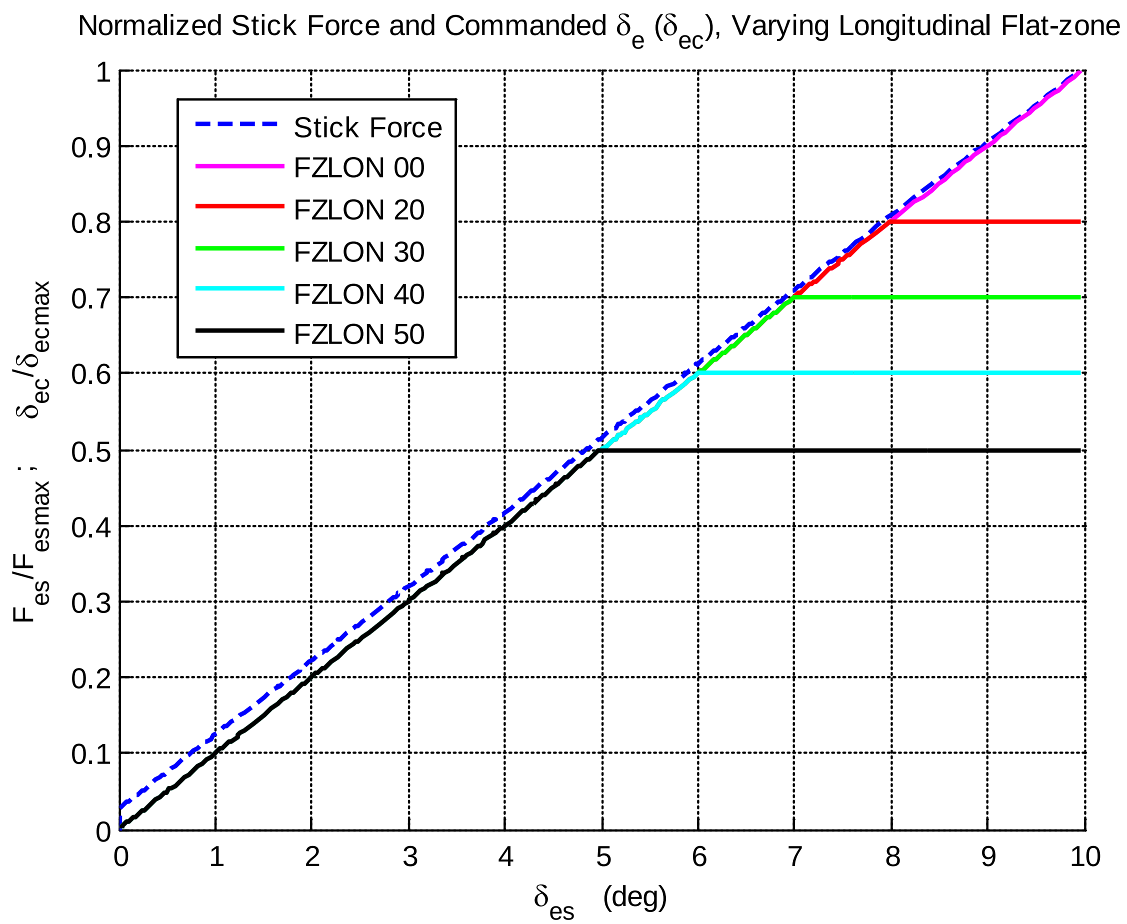


Figure 53. Normalized longitudinal stick F_{es} (dashed blur), and δ_{ec}, varying longitudinal flat zone

4.7.2 Evaluation Task Description

The evaluation will focus on the longitudinal axis. Two flight conditions are considered:

- Powered approach
- Cruise speed

The reference task is a discrete pitch attitude capture with a disturbance injected as SoS control surface deflection summed to the deflection commanded by the pilot and control system. From steady, wings-level flight, the pilot is instructed to capture the target pitch attitude angle identified on the HDD and maintain this pitch angle within the specified tolerance. The tolerance is not to exceed the *nz* = 2.5 g limit or AoA = 11 deg limit. The pilot is then instructed to capture the pitch angle, then capture and hold the trim pitch angle and maintain within the specified tolerance.

The scope of the task for the up-and-away flight conditions is to expose the pilot to potential g exceedances and verify the effectiveness of different flat zone amplitudes in preventing such occurrences.

For the PA flight condition, this task is intended to verify the effectiveness of the flat zones in preventing the pilot from exceeding maximum allowed AoA.

The objectives of this task are to:

- Evaluate the ability to maneuver in pitch and capture a pitch attitude angle.
- Identify maneuverability limitations and PIO tendencies.

Target pitch angle values are discrete. Table 30 summarizes the task principal information.

Table 30. Flat zone pitch attitude capture task requirements

Flight Condition	Pitch Attitude Target $\boldsymbol{\theta}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\theta = \theta_{trim} + \Delta\theta_c\|_{PA}}$	$\boldsymbol{\theta_{err} = \pm 1}$ at least 50% of the time $\boldsymbol{8.5 \le AoA < 9.5}$	$\boldsymbol{\theta_{err} = \pm 2}$ at least 50% of the time $\boldsymbol{9.5 \le AoA < 10.5}$	Aggressively capture the discrete target pitch attitude and regulate against the SoS disturbance
Design Cruise Speed	$\boldsymbol{\theta = \theta_{trim} + \Delta\theta_c\|_{V_A - V_c}}$	$\boldsymbol{\theta_{err} = \pm 1}$ at least 50% of the time $\boldsymbol{0 \le n_z \le 2.5g}$	$\boldsymbol{\theta_{err} = \pm 2}$ at least 50% of the time $\boldsymbol{0 \le n_z \le 2.5g}$	

The values of the desired and adequate performance requirements have been confirmed by means of preliminary manned simulations. Those of the pitch attitude command have been verified by two pilots in the nominal configuration.

For each flat zone configuration evaluation, compliance of each pitch angle capture (except the last one) is verified against the criteria described above. The scoring is based on the time the desired or adequate performance is achieved, with the same logic of the standard SoS tasks, as required by the regulation part of the task.

4.7.3 Piloted Evaluations

The test plan is based on the amplitude variation of the FZLON. Table 31 contains the conventional test case identification and baseline flat zone values that are planned for the evaluations of longitudinal control.

The values refer to the inceptor deflection angle in which the command is saturated. Combined variation of the other feel system parameters is not planned.

Table 31. Longitudinal command path flat zone evaluation cases

Longitudinal Flat Zone Case Identification	Flat Zone Amplitude Value (deg)
FZLON00 (baseline)	0.0 (no command saturation)
FZLON20	2.0
FZLON30	3.0
FZLON40	4.0
FZLON50	5.0

FZLON = Longitudinal Flat Zone

The evaluations are conducted in the longitudinal plane of the aircraft dynamics in CG Cfg 1 and the selected flight conditions are:

- Powered approach
- Cruise speed V_C at Hp = 38 kft

4.8 INCEPTOR COMMAND SENSITIVITY SCHEDULING AS A FUNCTION OF INCEPTOR DEFLECTION AND FLIGHT CONDITION

4.8.1 Command Sensitivity Passive Inceptor Implementation

The command sensitivity scheduling for the passive stick is implemented with a variation of command gain, as a function of stick deflection, at the given flight condition: piecewise command gain. With the single force gradient $\left(\frac{F_{es}}{\delta_{es}}; \frac{F_{as}}{\delta_{as}}\right)$ baseline passive stick, the effect of this implementation is to vary the command sensitivity as a result of the piecewise linear $\left(\frac{\delta_{ec}}{\delta_{es}}; \frac{\delta_{ac}}{\delta_{as}}\right)$ gain and the subsequent different stick travel required to command the same alpha or normal load factor increment.

The command gain breakpoint is set at the inceptor displacement boundaries for small amplitude regulation (i.e., 35% of full stick travel). Figure 54 is a sketch of the commanded load factor

$\left(\Delta n_{z_c}\right)$ versus normalized longitudinal stick travel $\left(\delta_{e_s}\right)$ as a conceptual example of the implementation. The black line represents the baseline command gain.

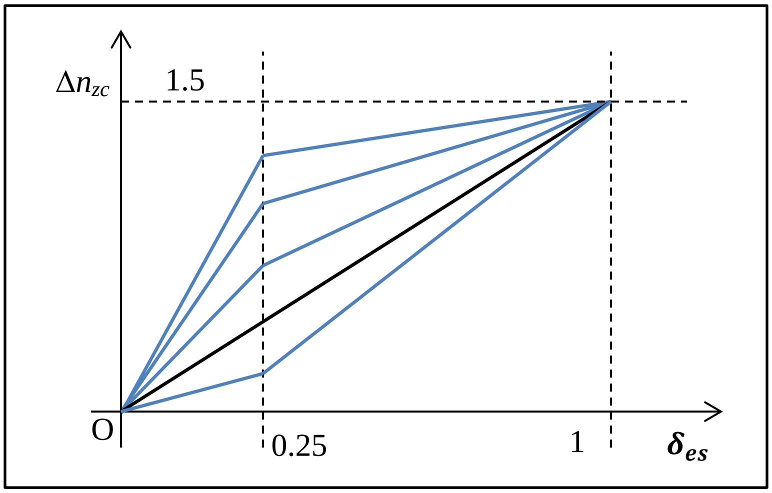


Figure 54. Piecewise Δ*nzc* as a function of $\boldsymbol{\delta_{es}}$

Figure 55 displays the normalized stick force (dashed blue line) and commanded control surface as a function of stick deflection for the passive stick configuration. The test case code reported in the legend is the same as found in section 4.8.4. The value of the reported command gain scaling factor is that applied to the small amplitude range command gain; the value of the second piece command gain is determined to command the same maximum control surface deflection.

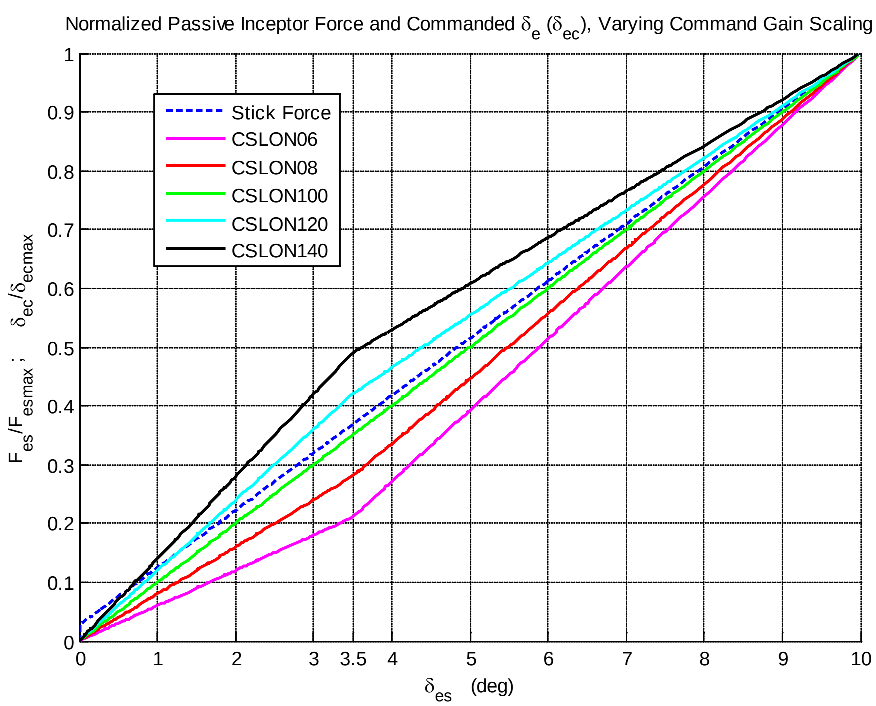


Figure 55. Normalized $\mathbf{F_{es}}$ (dashed blue) and $\boldsymbol{\delta_{ec}}$, varying piecewise longitudinal command gain

The value of the stick travel corresponding to the command gain breakpoint is that used in the evaluations, derived from analysis of offline simulations. If required, the preferred dead zone resulting from previous tests will be used for this evaluation to eliminate unintended pilot inputs caused by inceptor misalignment or position sensors biases. The linear piecewise command gain scheduling is implemented outside of the feedback path, as it is for the dead zone.

Figure 56 displays the implementation of the piecewise command gain simulation within the Calspan/STI Year 2 CLAWS subsystem. The piecewise portion of the command gain is added to the value calculated through the linear baseline command gain. The command gain variation breakpoint and scaling coefficient are set by the FTE during the evaluation.

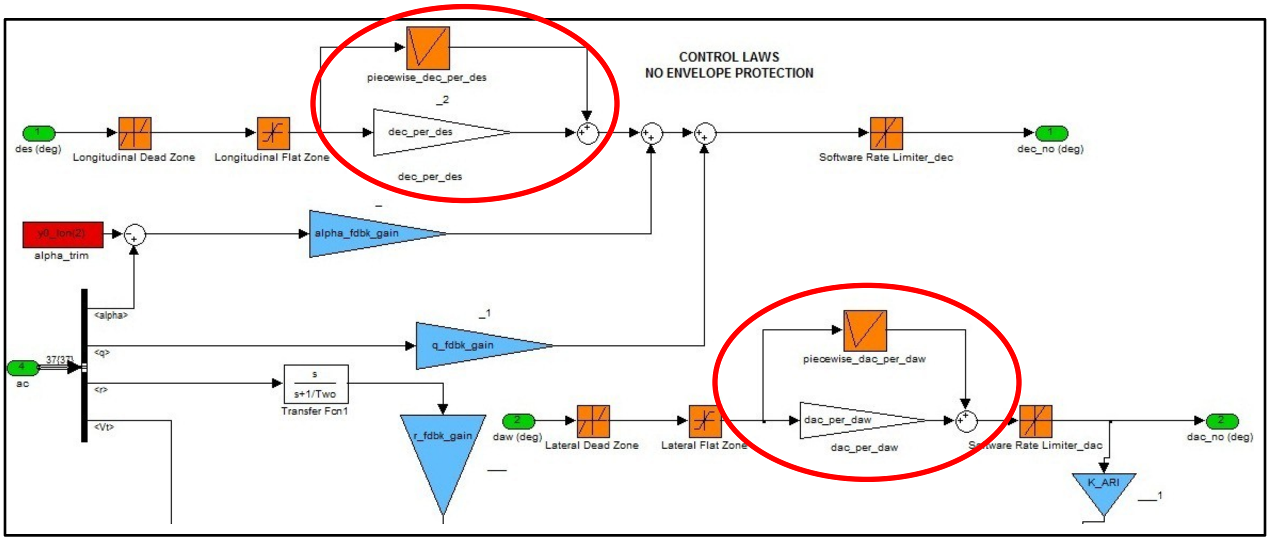


Figure 56. Piecewise command gain implementation within the CALSPAN/STI year 2 control laws subsystem

4.8.2 Command Sensitivity Active Inceptor Implementation

For active inceptors, a baseline variation of the force gradient as a function of normal load factor (n_z) is implemented.

The force gradient variation occurs when given values of the nose-up (NU) (positive) and nose-down (ND) (negative) load factor are exceeded. After transition to the higher gradient, the baseline is restored when:

- A stick displacement is produced that is expected to command a load factor reduction for positive stick deflection.
- A stick displacement is produced that is expected to command a load factor increase for negative stick deflection.

- The load factor varies because aircraft dynamics are within the design n_z breakpoint values.

Figure 57 displays the longitudinal stick force (F_{es}) variation as a function of stick travel (δ_{es}) at a given flight condition. The gradient breakpoint corresponds to the predefined values of n_z and it can occur at any value of the stick displacement, depending on the aircraft response. The arrows in the sketch represent the direction of the stick displacement producing the gradient displayed for given values of the engagement n_z breakpoints. This representation is valid without loss of generalization for positive and negative load factors/stick travel. Where n_{zl} and n_{zh} are the lower and higher normal load factor breakpoint, respectively.

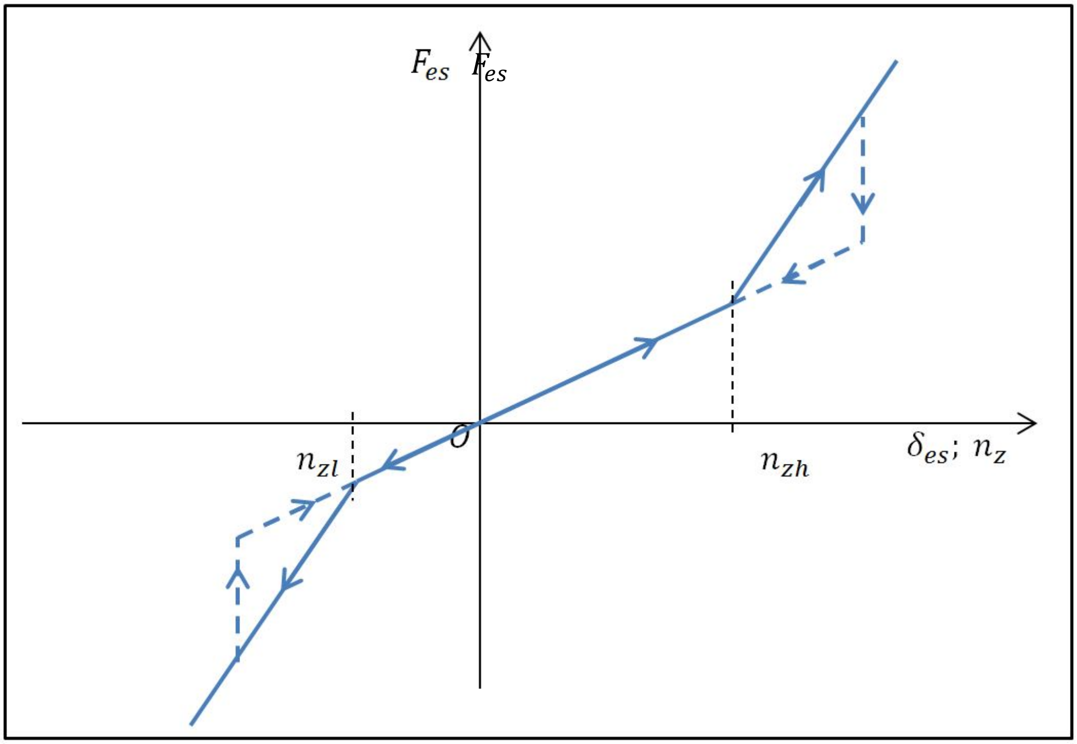


Figure 57. Longitudinal stick F_{es} as a function of δ_{es}, given n_z breakpoints

4.8.3 Evaluation Task

Higher priority is assigned to the longitudinal axis. The task is a sequence of pitch captures in the longitudinal plane (see table 32 for task details). An SoS disturbance is injected as elevator aircraft deflection.

In the longitudinal plane, from steady, wings-level flight, capture the target pitch attitude angle identified on the HDD and maintain this pitch angle within the specified tolerance for desired/adequate performance, regulating against disturbance. The pilot is instructed to capture the pitch attitude angle, then capture and hold the next displayed pitch attitude angle, maintaining this pitch angle within the specified tolerance for desired/adequate performance, regulating against disturbance. The sequences of discrete pitch attitude captures time histories are displayed in figures 41 and 42.

Table 32. Command sensitivity pitch attitude capture task requirements

Flight Condition	Pitch Attitude Target $\boldsymbol{\theta_c}$	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\theta_c} = \boldsymbol{\theta_{trim}} + \Delta\boldsymbol{\theta_c}$ $\Delta\boldsymbol{\theta_c}$: discrete pitch attitude command. See figures 41 and 42.	$\boldsymbol{\theta_e = \pm 1}$ $\mathbf{8.5 \leq AoA < 9.5}$	$\boldsymbol{\theta_e = \pm 2}$ $\mathbf{9.5 \leq AoA < 10.5}$	No more than one pitch attitude overshoot for each capture. Magnitude of overshoot remains within the desired region.
Design Cruise Speed		$\boldsymbol{\theta_e = \pm 1}$ $\mathbf{0 \leq \boldsymbol{n_z} \leq 2.5g}$	$\boldsymbol{\theta_e = \pm 2}$ $\mathbf{0 \leq \boldsymbol{n_z} \leq 2.5g}$	

4.8.4 Piloted Evaluations

The test plan is based on the variation of the command gain and of the force gradient scaling factor for the passive and active side-stick configuration, respectively.

- Table 33 reports the values of the longitudinal command gain scaling.
- Table 34 reports the values of the longitudinal force gradient scaling.

The evaluations are conducted in the longitudinal plane of the aircraft dynamics in xCG configuration Cfg 1 and the selected flight conditions are:

- Powered approach
- Cruise speed V_C at Hp = 38 kft

Table 33. Longitudinal command gain scheduling evaluation cases

Longitudinal Command Sensitivity Case Identification	Command Gain Scaling Factor
CSLON60	0.60
CSLON80	0.80
CSLON100 (baseline)	1.00
CSLON120	1.20
CSLON140	1.40

CSLON = Command sensitivity longitudinal

Table 34. Longitudinal force gradient scheduling evaluation cases

Longitudinal Command Sensitivity Case Identification	Longitudinal Force Gradient Scaling factor
CSLON50	0.50
CSLON75	0.75
CSLON100 (baseline)	1.00
CSLON125	1.25
CSLON150	1.50

CSLON = Command sensitivity longitudinal

4.9 MINIMUM REQUIREMENTS FOR PASSIVE INCEPTORS, NATURAL FREQUENCY, AND DAMPING

4.9.1 Natural Frequency Evaluation Task

The side-stick dynamic parameters are varied directly in the feel system model. The baseline passive side-stick and command gain configuration at each flight condition is used for these evaluations.

The tasks for the evaluation of the varying inceptor natural frequency, for longitudinal and lateral control, respectively, is the pitch attitude and bank angle SoS. The tasks are identical to those for the evaluation of the command gain dead zones. See tables 35 and 36 for the task requirements specifications.

Table 35. Pitch attitude SoS longitudinal task performances requirements

Flight Condition	Pitch Attitude Target $\boldsymbol{\theta}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\theta = \theta_{trim}}$ Disturbance: Sum-of-Sines.	$\boldsymbol{\theta_e = \pm 1}$ at least 50% of the time.	$\boldsymbol{\theta_e = \pm 2}$ at least 50% of the time.	Aggressively minimize the displayed pitch attitude error ($\boldsymbol{\theta_e}$) signal and attempt to keep the error within the specified tolerances.
Maneuvering Speed				
Design Cruise Speed				

Table 36. Lateral attitude SoS longitudinal task performances requirements

Flight Condition	Roll Attitude Target $\boldsymbol{\phi}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\phi = \phi_{trim}}$ Disturbance: Sum-of-Sines.	$\boldsymbol{\phi_e = \pm 3}$ at least 50% of the time.	$\boldsymbol{\phi_e = \pm 6}$ at least 50% of the time.	Aggressively minimize the displayed bank angle error ($\boldsymbol{\phi_e}$) signal and attempt to keep the error within the specified tolerances.
Maneuvering Speed				
Design Cruise Speed				

4.9.2 Damping Evaluation Task

For passive side-sticks, it is expected that damping will be a significant factor affecting HQ. For the inceptor damping evaluation, it is considered necessary to use a task that requires moderate to high frequency and large amplitude pilot inputs with no continuous regulation.

The selected tasks are the attitude captures used for command sensitivity evaluation. See tables 37 and 38 for the task requirement specifications.

Table 37. Command sensitivity pitch attitude capture task requirements

Flight Condition	Pitch Attitude Target $\boldsymbol{\theta}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\theta = \theta_{trim} + \Delta\theta_c}$	$\boldsymbol{\pm 1}$	$\boldsymbol{\pm 2}$	No more than one pitch attitude overshoot for each capture. Magnitude of overshoot remains within the desired region.
Design Cruise Speed				

The values of the desired and adequate performance requirements will be confirmed/tuned by means of preliminary manned simulations.

Table 38. Command sensitivity roll attitude capture task requirements

Flight Condition	Roll Attitude Target ϕ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\phi = \phi_{trim} + \Delta\phi_c$	± 3	± 6	No more than one bank angle overshoot for each capture. Magnitude of overshoot remains within the desired region.
Maneuvering Speed				
Design Cruise Speed				

4.9.3 Natural Frequency Piloted Evaluations

Inceptor frequency variation was evaluated for a wheel/column inceptor configuration during Year 2 Task 2 in PA flight condition. The natural frequency will be evaluated first, keeping the damping ratio constant at a value of $\zeta = 0.7$.

Tables 39 and 40 report the values of both longitudinal and lateral control natural frequency values and corresponding test case identification codes.

The evaluations are conducted in both axes in CG configuration Cfg 1 and the selected flight conditions are:

- Powered approach

Table 39. Longitudinal side-stick natural frequency evaluation cases

Longitudinal Natural Frequency Case Identification	Longitudinal Side-Stick Natural Frequency (rad/s)
FLON175 (baseline)	17.5
FLON150	15.0
FLON125	12.5
FLON100	10.0
FLON075	7.50
FLON050	5.00

FLON = Frequency longitudinal (feel system)

Table 40. Lateral side-stick natural frequency evaluation cases

Lateral Natural Frequency Case Identification	Lateral Side-stick Natural Frequency (rad/s)
FLAT150 (baseline)	15.0
FLAT125	12.5
FLAT100	10.0
FLAT075	7.50
FLAT050	5.00

FLAT = Frequency lateral (feel system)

4.9.4 Damping Piloted Evaluations

The side-stick damping ratio was varied, maintaining the inceptor frequency constant at the nominal baseline values.

Tables 41 and 42 report the values of the longitudinal and lateral side-stick damping ratio and the corresponding test case identification codes.

The evaluations were conducted in both planes of the aircraft dynamics in CG configuration 1 and the selected flight conditions were:

- Powered approach

Table 41. Longitudinal side-stick damping ratio evaluation cases

Longitudinal Damping Ratio Case Identification	Longitudinal Side-Stick Damping Ratio
DLON10	1.0
DLON09	0.9
DLON07 (baseline)	0.7
DLON05	0.5
DLON03	0.3
DLON02	0.2
DLON01	0.1

DLON = damping longitudinal (feel system)

Table 42. Lateral side-stick damping ratio evaluation cases

Lateral Damping Ratio Case Identification	Lateral Side-Stick Damping Ratio
DLAT10	1.0
DLAT09	0.9
DLAT07 (baseline)	0.7
DLAT05	0.5
DLAT03	0.3
DLAT02	0.2
DLAT01	0.1

DLAT = damping lateral (feel system)

4.10 HARMONY BETWEEN THE PASSIVE CONTROL INCEPTOR FEEL FORCE AND THE CONTROL MANEUVER COMMAND SENSITIVITY

4.10.1 Variable Control Maneuver Command Sensitivity Implementation

One of the objectives of this subtask is to evaluate the importance of commanding maximum n_z at maximum inceptor deflection. Linear command gains, to prevent envelope limits (AoA, n_z) at different flight conditions, are defined in the Calspan/STI aircraft model. The passive side-stick/command gain configuration to be tested has variation of the command gain to command maximum n_z at maximum deflection with constant force gradient. Different values of the command gains are defined at a discrete number of flight conditions (V_A and V_C) and calculated with linear interpolation with respect to dynamic pressure for the intermediate flight conditions. The sketch in figure 58 displays the conceptual implementation of the variable command gain with flight condition (true airspeed V) in terms of commanded elevator deflection as a function of stick travel. The V_A command gain (black line in figure 58) is maintained constant at airspeeds lower than V_A, as no g exceedances are possible at those flight conditions. For $V < V_A$, the AoA is the limiting condition, so maximum commanded load factor $-1 < \Delta n_{zc} < 2.5$. The actual stick travel is represented in the figure. The values reported are those normalized independently for positive and negative displacement.

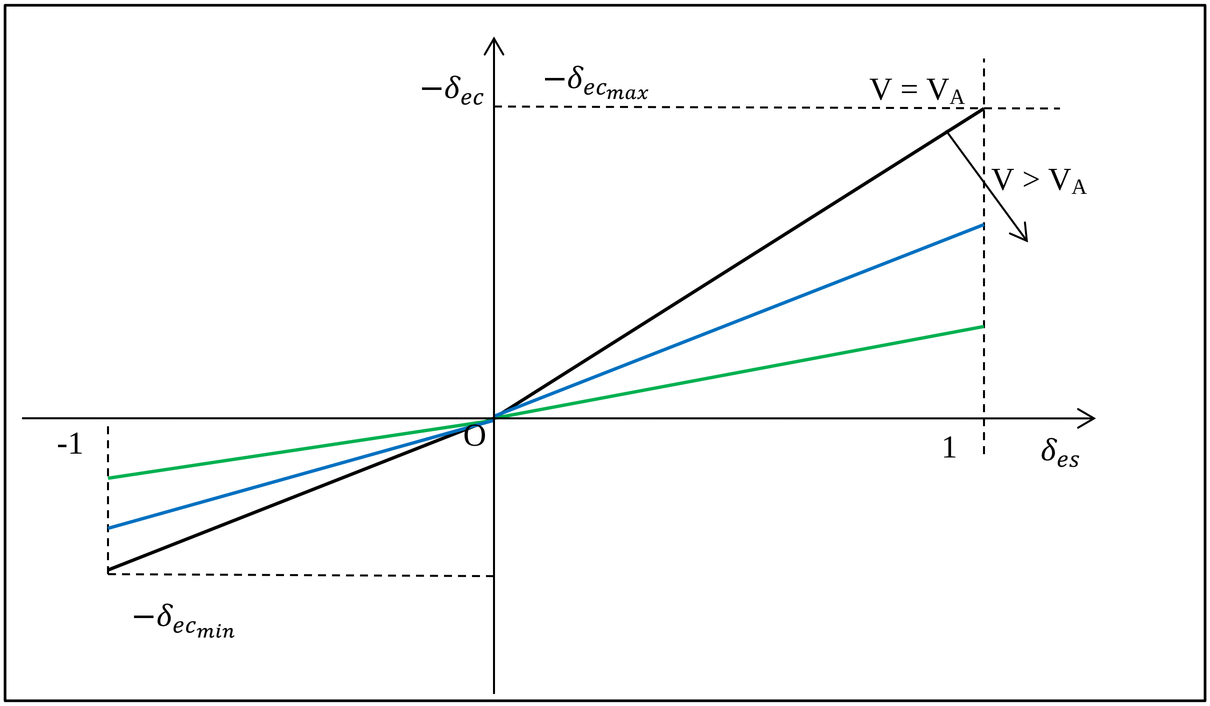


Figure 58. Conceptual implementation of a variable command gain with flight condition

An alternate solution, contained in the simulation models provided by the FAA is a "parabolic command sensitivity schedule" with continuous variation of the command gain with true airspeed (V) to command the maximum n_z achievable at the actual speed. The maneuver command varies as a function of both deflection and airspeed ($V^2/Vstall^2$) without a gradient discontinuity at zero inceptor deflection [1]. The command gain is calculated with a parabolic interpolation through three points corresponding to the limits of the inceptor travel and the inceptor null position, respectively corresponding to maximum, minimum, and null commanded load factor. The acceptability of the resulting HQ for these two approaches is evaluated. Also, the need or advisability of using more than a single force gradient or other nonlinear force/displacement characteristic will be assessed, keeping in mind the merits of a simple/reliable and inexpensive inceptor design.

4.10.2 Evaluation Task

For both inceptor/command path configurations, the scope of the task is to expose the pilot to potential envelope exceedances and require finer control around the inceptor null position/command gain. A sequence of pitch attitude captures is used to investigate the effect of the piecewise command gain discontinuity around the stick null deflection for the classical Calspan/STI augmentation. Evaluations will also be made with the continuous variation implemented in the FPARCH model.

The task is the same pitch attitude capture used for the command sensitivity evaluations, constrained to not exceed the *nz* = 2.5 g or the maximum AoA = 11 deg limit at the different flight conditions. See table 43 for task specification.

Table 43. Command sensitivity pitch attitude capture task requirements

Flight Condition	Pitch Attitude Target $\boldsymbol{\theta}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\theta} = \boldsymbol{\theta}_{trim} + \Delta\boldsymbol{\theta}$ Disturbance: Sum-of-Sines.	$\pm \mathbf{1}$	$\pm \mathbf{2}$	No more than one pitch attitude angle overshoot for each capture. Magnitude of overshoot remains within the desired region.
Design Cruise Speed				

4.10.3 Piloted Evaluations

Evaluations are focused on the longitudinal axis. The test plan requires at least three repetitions of the specified task with both classical Calspan/STI and FAA models in sequence. The baseline feel system characteristics are defined based on the previous evaluations and no specific changes are planned. It is also important to evaluate whether either gain variation configuration is PIO-prone when the command gain is low.

The evaluations are conducted in xCG configuration Cfg 1 and the selected flight conditions are:

- Cruise speed V_C at Hp = 38 kft

4.11 GUIDELINES FOR DETERMINING THE REQUIRED CONTROL EFFECTOR BANDWIDTH

4.11.1 Control Effector Implementation

Second-order dynamics control effectors models are used in the Calspan/STI aircraft model. The value of the control effectors' bandwidth is changed as part of the model initialization values. The maximum rate capability of the control effectors was tested during Year 2 evaluations as a software rate limit on the actuator command.

4.11.2 Evaluation Task

The task for the evaluation of varying inceptor natural frequency is the pitch attitude and bank angle SoS—selected for the evaluation of the command gain dead zones. See tables 44 and 45 for the task requirements specifications.

Table 44. Pitch attitude SoS longitudinal task performances requirements

Flight Condition	Pitch Attitude Target $\boldsymbol{\theta}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\theta = \theta_{trim}}$ Disturbance: sum-of-sines.	$\boldsymbol{\theta_e = \pm 1}$ at least 50% of the time.	$\boldsymbol{\theta_e = \pm 2}$ at least 50% of the time.	Aggressively minimize the displayed pitch attitude error ($\boldsymbol{\theta_e}$) signal and attempt to keep the error within the specified tolerances.
Maneuvering Speed				
Design Cruise Speed				

Table 45. Lateral attitude SoS longitudinal task performances requirements

Flight Condition	Roll Attitude Target $\boldsymbol{\phi}$ (deg)	Desired Performance (deg)	Adequate Performance (deg)	Notes
Powered Approach	$\boldsymbol{\phi = \phi_{trim}}$ Disturbance: sum-of-sines.	$\boldsymbol{\phi_e = \pm 3}$ at least 50% of the time.	$\boldsymbol{\phi_e = \pm 6}$ at least 50% of the time.	Aggressively minimize the displayed bank angle error ($\boldsymbol{\phi_e}$) signal and attempt to keep the error within the specified tolerances.
Maneuvering Speed				
Design Cruise Speed				

4.11.3 Piloted Evaluations

The objective of the evaluations is to assess how the *x*-axis CG location and airspeed range affect the required actuators' bandwidth to satisfy HQ Level 1, studying the effect of increasing the demand on the required actuators' bandwidth. Bandwidth is changed by varying natural frequency, with a constant damping ratio value deriving from offline simulations. Tables 46 and 47 report elevator and aileron actuator for bandwidth natural frequencies and corresponding test case identification codes.

The longitudinal axis evaluations are conducted in the three xCG configurations (Cfg 1, Cfg 2, Cfg 3); in the lateral/directional axis, a single xCG configuration is selected: Cfg 1.

The flight conditions for evaluation in both planes of the dynamics are:

- Powered approach
- Maneuvering speed V_A at Hp = 38 kft

Table 46. Elevator actuator bandwidth evaluation cases

Elevator Actuator Bandwidth Case Identification	Natural Frequency Value (rad/s)
BWLON75 (baseline)	75.0
BWLON50	50.0
BWLON25	25.0
BWLON15	15.0
BWLON10	10
BWLON7.5	7.5
BWLON5.0	5.0

BWLON = Longitudinal Bandwidth

Table 47. Aileron actuator bandwidth evaluation cases

Aileron Actuator Bandwidth Case Identification	Natural Frequency Value (rad/s)
BWLAT75 (baseline)	75.0
BWLAT50	50.0
BWLAT25	25.0
BWLAT15	15.0
BWLAT10	10
BWLAT7.5	7.5
BWLAT5.0	5.0

BWLAT = Lateral Bandwidth

4.12 HARMONY BETWEEN THE ACTIVE CONTROL INCEPTOR FEEL FORCE AND THE CONTROL MANEUVER COMMAND SENSITIVITY

This task is required in the SOW issued by the FAA [1]. The lack of acceleration cues in the Calspan fixed-base ground simulator is considered a significant limitation to the reliability of the evaluations. For this reason, evaluation of F_{es}/n_z command sensitivity is not possible in a fixed base simulator and Calspan/STI cannot feasibly examine any feature properly in the current funds/simulation systems constraints.

This task can be performed with adequate fidelity and accuracy of the results with in-flight simulation and Calspan VS aircraft can be used for the purpose. It is proposed to provide for the requirement of an in-flight simulation feasibility plan to complete the analysis and derive indications for future systems development.

4.13 TEST PLAN MATRIX

This section reports the longitudinal and lateral/directional plane evaluation test plan matrices, including flight conditions and CG configurations for manned simulation specifications (see tables 48 and 49). Each dot in the tables on the next two pages represents the evaluation of the corresponding design element.

Table 48. Longitudinal plane test plan matrix

LONGITUDINAL PLANE TEST PLAN MATRIX								
Flight Condition	CG Configuration Code	Dead Zones	Flat Zones	Active Inceptor Command Sensitivity	Passive Inceptor Command Sensitivity	Inceptor Natural Frequency	Inceptor Damping Ratio	Control Effector Bandwidth
PA	Cfg 1	•	•	•	•	•	•	•
	Cfg 2							•
	Cfg 3							•
V_A	Cfg 1							•
	Cfg 2							•
	Cfg 3							•
V_C	Cfg 1		•	•	•			
	Cfg 2							
	Cfg 3							

Table 49. Lateral/directional plane test plan matrix

LATERAL/DIRECTIONAL PLANE TEST PLAN MATRIX								
Flight Condition	CG Configuration Code	Dead Zones	Flat Zones	Active Inceptor Command Sensitivity	Passive Inceptor Command Sensitivity	Inceptor Natural Frequency	Inceptor Damping Ratio	Control Effector Bandwidth
PA	Cfg 1	•	•			•	•	•
	Cfg 2							
	Cfg 3							
V_A	Cfg 1							•
	Cfg 2							
	Cfg 3							
V_C	Cfg 1		•					
	Cfg 2							
	Cfg 3							

4.14 EVALUATION TEST CARD

Table 50 shows the evaluation test card, which is used to record the HQR, PIORs, and pilot's comments for each test case. One card is used for the evaluation of each design element.

Table 50. Pilot legend for rating summary plots

Flight #: ________ Pilot: _______________Evaluation of: _____________ Axis: ______________ Date: ______________

Run #	Configuration	HQR	PIOR	Comments

5. RATING SCALES USED FOR EVALUATIONS

Cooper-Harper HQR [11] and PIO tendency ratings were collected using the rating scales shown in figures 59 and 60. The EPs have been strongly encouraged to talk their way through the rating scale decision trees as a means of extracting additional commentary.

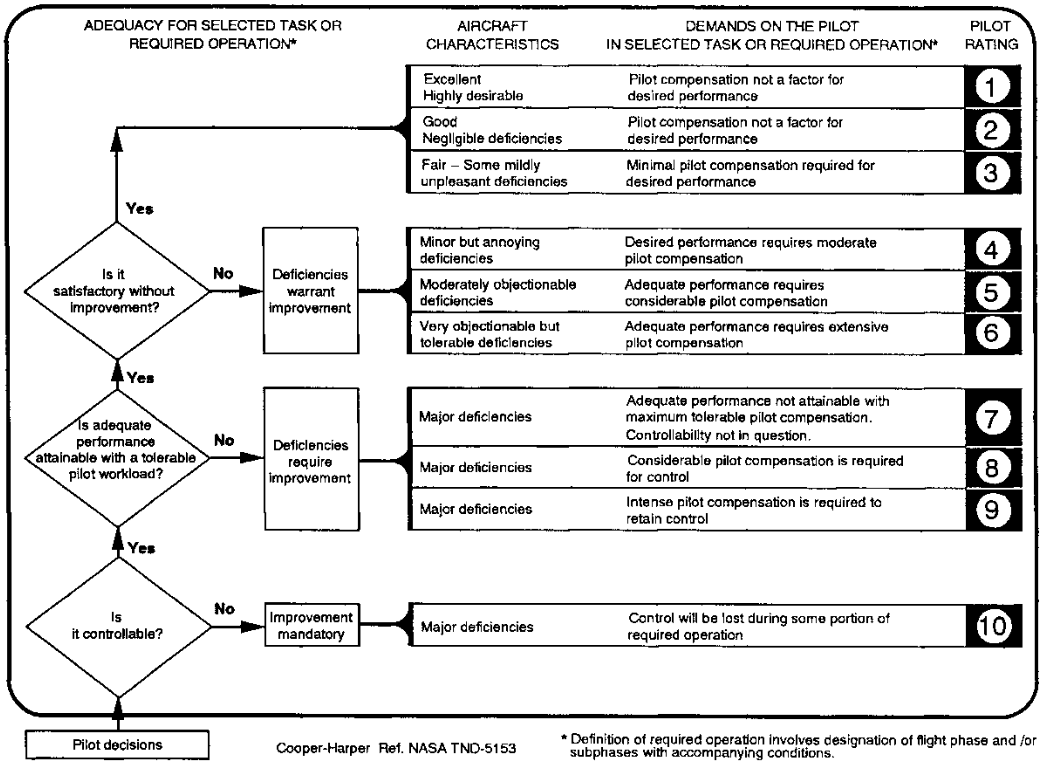


Figure 59. Cooper-Harper handling qualities rating scale

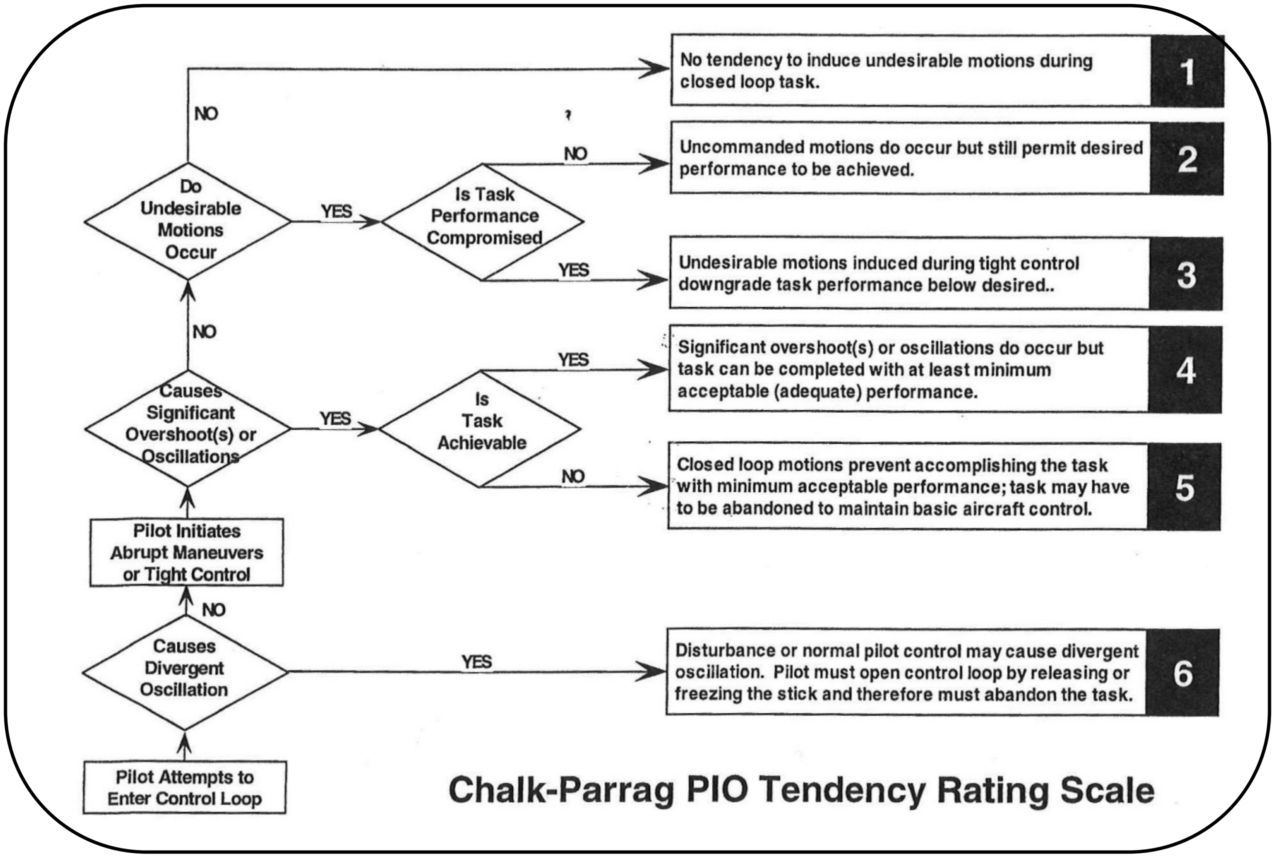


Figure 60. Chalk-Parrag PIO tendency scale

6. TEST PILOTS' BACKGROUNDS

Five pilots were used as subjects for this experiment, with three of them performing all evaluations. Each is an experienced test pilot. For purposes of reporting and analysis, the identity of each pilot remains anonymous. Brief details on each pilot's background and flying experience are presented here.

Pilot 1

Pilot 1 is a graduate of the US Naval Academy. Pilot 1 has a B.S. in physics and an M.S. in aerospace engineering. Pilot 1 has over 30 years of experience as a test pilot. Aircraft this pilot has flown include the A-6, A-10, NT-33A, and variable stability (VS) Learjets.

Pilot 2

Pilot 2 is a graduate of the U.S. Air Force Test Pilot School and has 17 years of experience as a test pilot. Pilot 2's flight experience was primarily in transport and trainer aircraft, including the T-37, C-5, C-17, C-23, and C-12. He has a B.S. in electrical engineering and an M.S. in engineering.

Pilot 3

Pilot 3 is a graduate of the U.S. Air Force Test Pilot School with almost 40 years of experience as a test pilot. Pilot's flight experience was primarily in fighter and attack aircraft, including the F-100, F-104, F-105, F-106, F-4, F-15, A-4, A-7, and A-37. Pilot 3 also has experience with NT-33A and VS Learjets. Pilot 3 holds a B.S. in engineering science and an M.S. in aerospace engineering.

Pilot 4

Pilot 4 graduated with distinction from the U.S. Naval Test Pilot School. Pilot 4 has more than 25 years of experience as a test pilot. Pilot 4 has flown a variety of aircraft, including the T-28, T-44, P-3, T-2, T-38, TA-4, OV-1, X-26, the Total In-Flight Simulator, and VS Learjets. Pilot 4 also holds a B.S. in electrical engineering.

Pilot 5

Pilot 5 is a U.S. Air Force TPS Graduate (June 1981) with 30+ years in flight test and 40+ years flying. Aircraft flown include T-38, F-4, F-15, T-39, E-3 AWACS, and sampling of variety of other aircraft in military. National Test Pilot School Instructor flying MB-326 and variety of multiengine and single-engine General Aviation aircraft. Ranger 2000 trainer with Deutsche Aerospace. FAA Project pilot on Lancair Columbia 300 (Spin Resistant Cert); Boeing 737, 747-400/800, 757, 767, 777, and 787; Airbus A320, A330, A340, and A380; Dassault Falcon 900, 2000, and F-7X; and Embraer 170. Pilot 5 holds a BS degree in math and physics and an MS in information systems technology.

7. SUMMARY OF TEST POINTS COMPLETED

A summary of the number of evaluation runs completed for each pilot is listed in table 51. Pilots 1 and 2 completed the entire test matrix. Pilot 3 was not available to complete the active inceptor and the scheduled command sensitivity evaluation. Pilots 4 and 5 completed a subset of evaluations, with Pilot 4 evaluating command path and feel system characteristics and pilot 5 more dedicated to the AFI-FCS evaluation. Pilot 5 was available for five days.

Table 51. Test runs completed by each pilot

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Total
Longitudinal Dead Zone	14	11	8	6	-	39
Longitudinal Flat Zone PA	9	6	6	7	-	28
Longitudinal Flat Zone V_C	9	10	13	6	-	38
Longitudinal Command Sensitivity PA	10	10	11	-	-	31
Longitudinal Command Sensitivity V_C	8	8	15	-	-	31
Active Inceptor Longitudinal Sensitivity PA	5	6	-	-	-	11
Active Inceptor Longitudinal Sensitivity V_C	13	14	-	-	-	27
Inceptor Longitudinal Natural Frequency	15	11	9	7	-	42
Inceptor Longitudinal Damping Ratio	11	8	9	-	-	28
Scheduled Longitudinal Command Sensitivity	3	3	-	-	-	6
Elevator Actuator Natural Frequency PA Unaugmented SM = 5%	9	7	9	-	-	25
Elevator Actuator Natural Frequency PA Unaugmented SM = 2.5%	9	7	7	-	-	23
Elevator Actuator Natural Frequency PA Unaugmented SM = 0	8	7	7	-	-	22
Elevator Actuator Natural Frequency V_A Unaugmented SM = 5%	9	9	8	-	-	26
Elevator Actuator Natural Frequency V_A Unaugmented SM = 2.5%	9	9	9	-	-	27
Elevator Actuator Natural Frequency V_A Unaugmented SM = 0	10	10	10	-	-	30
AFI-FCS Handling Qualities PA	7	7	7	-	3	24
AFI-FCS Handling Qualities V_A	7	7	9	-	3	26
AFI-FCS Handling Qualities V_C	3	3	2	-	-	8
AFI-FCS Envelope Protection Alpha	5	4	4	-	9	22
AFI-FCS Envelope Protection V_{min}/V_{max}	-	4	7	-	4	15
Total Pitch	173	161	150	26	19	529
Lateral Dead zone	11	9	9	8	-	37
Inceptor Lateral Natural Frequency	10	10	5	7	-	32
Inceptor Lateral Damping Ratio PA	9	6	9	-	-	24
Aileron Actuator Natural Frequency PA	9	8	13	-	-	30
Aileron Actuator Natural Frequency V_A	9	10	11	-	-	30
Total Roll	48	43	47	15	0	153
Total Pitch and Roll	221	204	197	41	19	682

8. PILOT MODEL DEVELOPMENT AND INTEGRATION

8.1 INTRODUCTION

This section documents the preliminary integration of a basic analytical pilot model into the Calspan/STI FAA FBW Simulink model described in previous sections. Though feel system and control law parameters can be modified for analysis, the work described herein focuses on a baseline set of feel and control system characteristics at a cruise flight condition of Vt = 480 ft/s true airspeed at Hp = 20,000 ft.

The section begins with a description of the pilot modeling methodology. The SoS disturbance tracking task used to predict piloted performance is described in section 4.4. An analysis of the PVS follows that includes a basic FQ study, FREquency Domain Analysis (FREDA), and example task performance time histories for two candidate pilot model cases. All analysis is performed on the pitch axis for a pitch attitude disturbance tracking task.

8.2 COMPENSATORY PVS

The crossover model is applied as a truth model for assessment of pilots performing precision tracking tasks, such as the SoS tracking task. There is a wealth of research concerning the development of pilot behavior models, including the crossover model [12]. The crossover model is valid for single-loop compensatory control (e.g., precision tracking). A block diagram for the compensatory control scenario is shown in figure 61. Here, the pilot controls the system output, *m*, in response to the displayed PVS error, *e*.

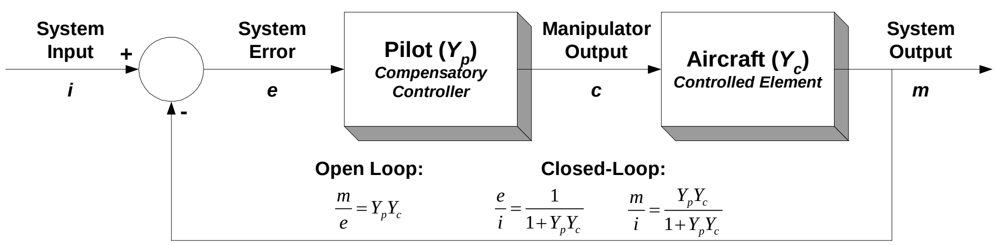


Figure 61. Compensatory control scenario

In short, the crossover model states that the pilot adjusts his or her characteristics so the PVS can be represented by the following open-loop transfer characteristics:

$$Y_p(j\omega)Y_c(j\omega) = \frac{\omega_c e^{-j\omega\tau_e}}{j\omega} = \frac{m}{e} \qquad (2)$$

In the above equation and figure, Y_p is the pilot describing function, Y_c is the controlled element, ω_c is the crossover frequency, and τ_e is the effective system time delay. The key variables, ω_c and τ_e, are functions of the controlled element dynamics (airplane model), mission task variables, and environment (system delays, field-of-view, etc.). The crossover frequency is defined as the frequency on a Bode plot at which the PVS open-loop describing function amplitude ratio crosses the 0 dB line. It has been demonstrated through extensive research that those controlled elements that are most "k/s–like" in the region of crossover require the least compensation by the pilot. In turn, as pilot compensation increases, the achieved crossover frequency decreases.

The effective system time delay is a function of fundamental pilot latencies, the high-frequency FCS and aircraft dynamics (e.g., actuators, structural filters, structural modes, etc.), and added incremental time delays due to pilot compensation. Once again, the more "k/s–like" the controlled element is in the region of crossover, the less pilot compensation will be required and the smaller the effective time delay. When little or no compensation is required by the pilot and the higher frequency dynamics are negligible, the effective time delay will consist solely of the delay in the pilot's response. This delay has been shown to be in the neighborhood of 0.2–0.25 seconds.

For this analysis, a compensatory pure-gain pilot was assumed and vehicle frequency responses for the flight condition of interest were used to determine a transfer function model for the pilot. A 250-msec delay is included to model the pilot's reaction time. In this preliminary implementation, it is assumed that the pilot will behave with a simple gain adjustment to achieve the crossover necessary to achieve desired performance. Future analysis will determine whether additional pilot compensation, such as a combination of gain and lead/lag compensation to tailor the open-loop Y_pY_c response to be "k/s-like" in the region of crossover, will be beneficial to piloted task performance. Furthermore, the task used herein is a disturbance regulation task, so there is no command signal per se. Instead, the pilot model will attempt to reduce the error that results from the SoS disturbance signal, thereby maintaining the steady state flight condition.

8.3 SYSTEM ANALYSIS APPROACH

Representations of the controlled element are necessary for the development of a compensatory pilot model. For linear systems, this representation is readily available as a state-space or transfer function representation. Modern modeling and simulation tools, such as Simulink, allow for the linearization of nonlinear models; however, this ability is limited and possible only for straightforward or simple nonlinear systems.

Because of the nonlinearities in the aircraft and feel system dynamics, linearized representations were either not available or did not accurately represent the dynamics of the aircraft. In lieu of linear models for the aircraft, feel system, and PVS, frequency sweep inputs were used to identify the frequency responses for the system and system components. Linear systems are shown where available and differences in extracted linear and identified nonlinear systems are highlighted, but the majority of the analysis presented herein utilizes the nonlinear frequency response identification.

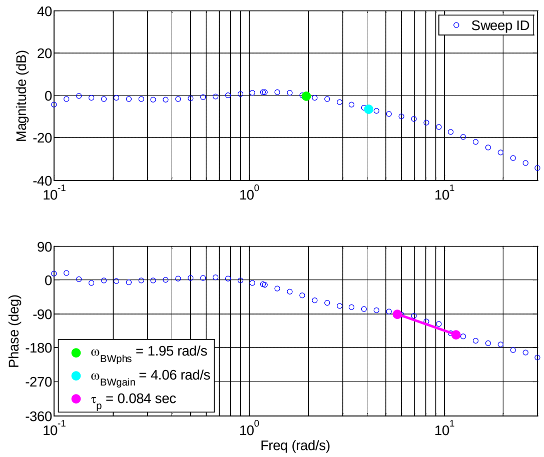
The next section provides a description of the development and analysis of the preliminary pilot model. For brevity, details on the tools and methods used to produce the analytical data and figures are omitted.

8.4 CLOSED-LOOP AIRCRAFT

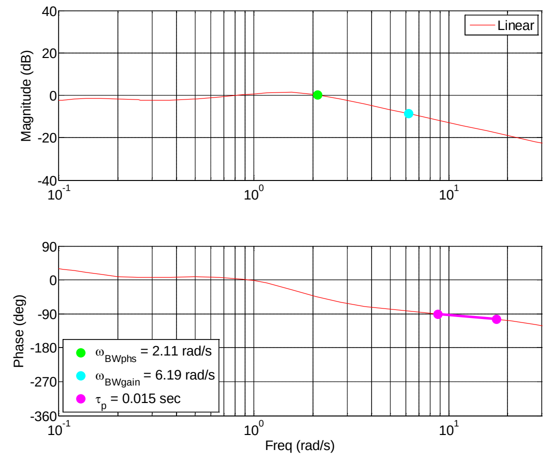
To develop and implement a pilot model, an accurate representation of the controlled element (Y_c) dynamics was required. In this case, Y_c refers to the closed-loop augmented aircraft that includes the CLAWS and vehicle dynamics. The feel system is treated as separate and, therefore, not included in the controlled element for this analysis.

Because the analysis is based on identified responses from frequency sweep inputs, the pitch rate response of the aircraft is used. The rate output signal contains much more energy than the attitude signal and, thus, is easier to identify. Though the airplane bandwidth criteria are based on column-to-attitude frequency responses, equivalent HQ metrics can be derived by using phase points that are offset by the 90 degrees that is representative of a rate-to-attitude integration. Frequency responses provided in this section show the equivalent rate response phase points used to determine HQ parameters.

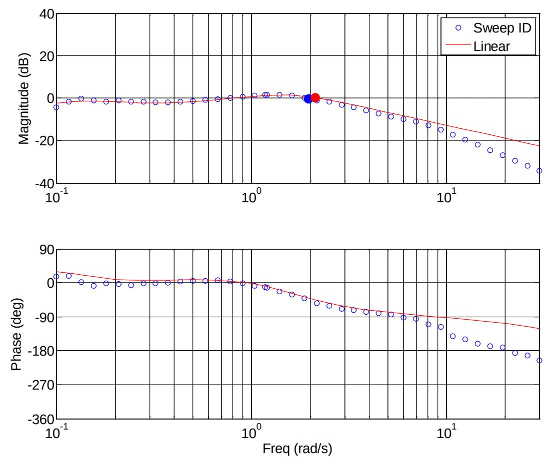
The extracted linear system and identified nonlinear system for the flight condition of interest are shown in figure 62. In the figure, the identified nonlinear system is overlaid with identified airplane bandwidth frequencies. In addition, related parameters for both systems are shown as colored dots. At low frequencies, both systems are similar, but at frequencies above 8 rad/s, the nonlinear behavior becomes evident as both gain and phase loss are significantly present in the nonlinear system response. This result demonstrates that the linearization process used by Simulink does not adequately account for the nonlinearity in the system and therefore cannot be trusted to provide models for the pilot model development.



a) Frequency Sweep Identification



b) Linearized Model



c) Overlay

Figure 62. Closed-loop aircraft linear and identified nonlinear frequency responses and FQ metrics

A well-damped vehicle response with an airplane bandwidth near 2 rad/s and fairly predictable behavior up to the 8 rad/s threshold where nonlinearities become evident is also evident in figure 62. Note that there is a much higher gain bandwidth for the linear system and less phase delay because of the shallow phase response near the ω_{-180} frequency (shown as -90 degrees for the equivalent rate response in figure 62).

Assessing the HQ for the closed-loop aircraft (figure 63), both systems predict Level 2 HQ, with the nonlinear identification showing a possible PIO susceptibility due to the amount of phase delay present. Figure 63 also shows that the additional delay introduced by the nonlinearities in the system can create a significant HQ issue despite affecting bandwidth frequency by only 1%.

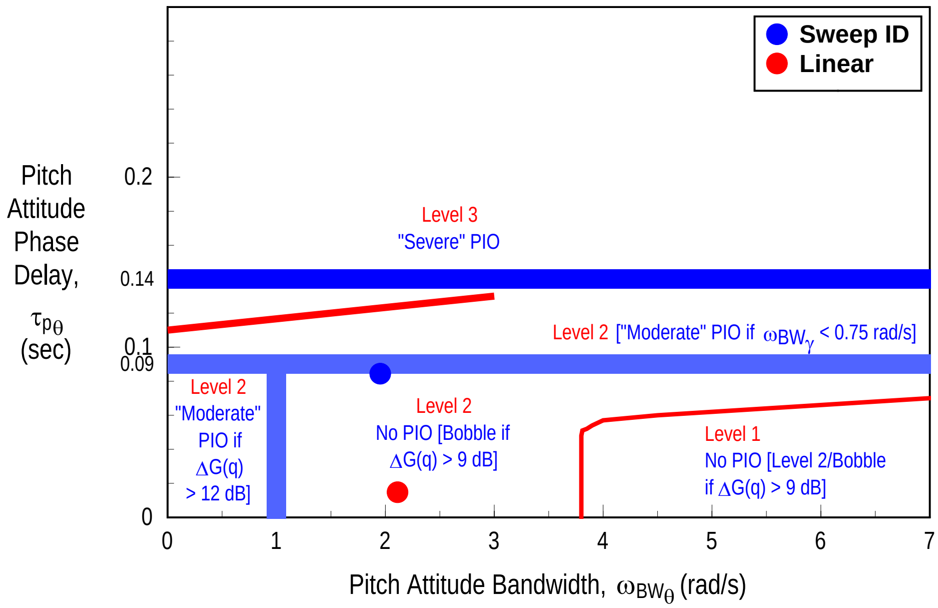


Figure 63. Pitch attitude bandwidth/PIO summary, cruise configuration [13]

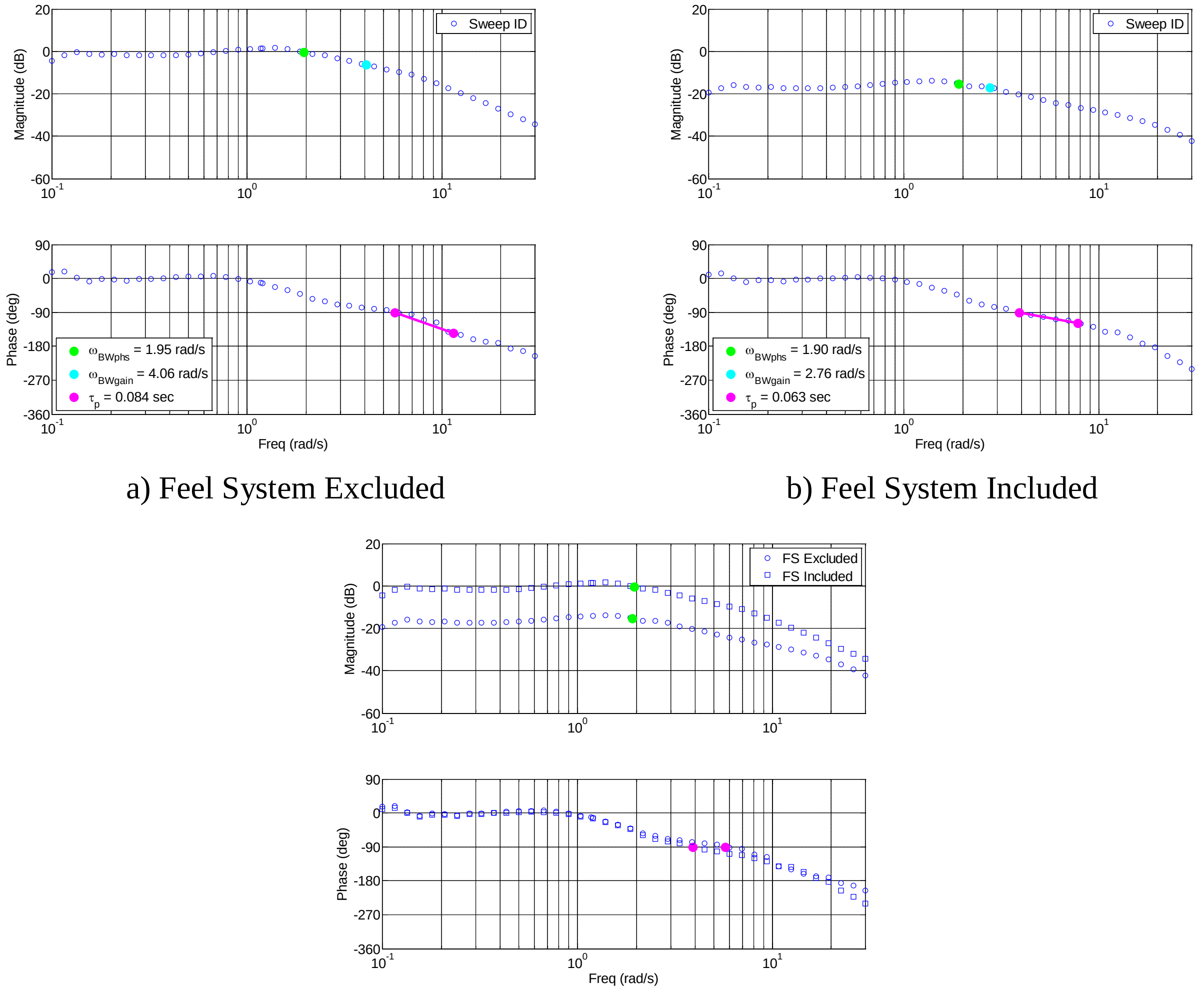
8.5 FEEL SYSTEM EFFECTS

The feel system dynamics are modeled as a nonlinear gradient with BO and friction. For this analysis, the parameters were left at their baseline values, with no friction force and a 2-lb. BO.

There is a significant DC gain difference of about 20 dB between the two cases shown in figure 64. The feel system with the BO and nonlinear gradient attenuates gain by a factor of nearly 10 as well as introduces nonlinearities that alter the high-frequency dynamics.

Though phase differences are minimal, there is a slight shallowing of the phase response for the feel system excluded case, which results in a higher ω_{-180} frequency. This frequency resides in a region of steeper roll-off in the phase response and the resulting phase delay calculation for this case is higher. Despite the additional nonlinearity introduced by the feel system, this effect results in a net improvement in controlled element dynamics as seen by the pilot.

Figure 65 shows the pitch attitude bandwidth cruise configuration with feel system.



a) Feel System Excluded

b) Feel System Included

c) Overlay

Figure 64. Aircraft plus feel system identified frequency responses and FQ metrics

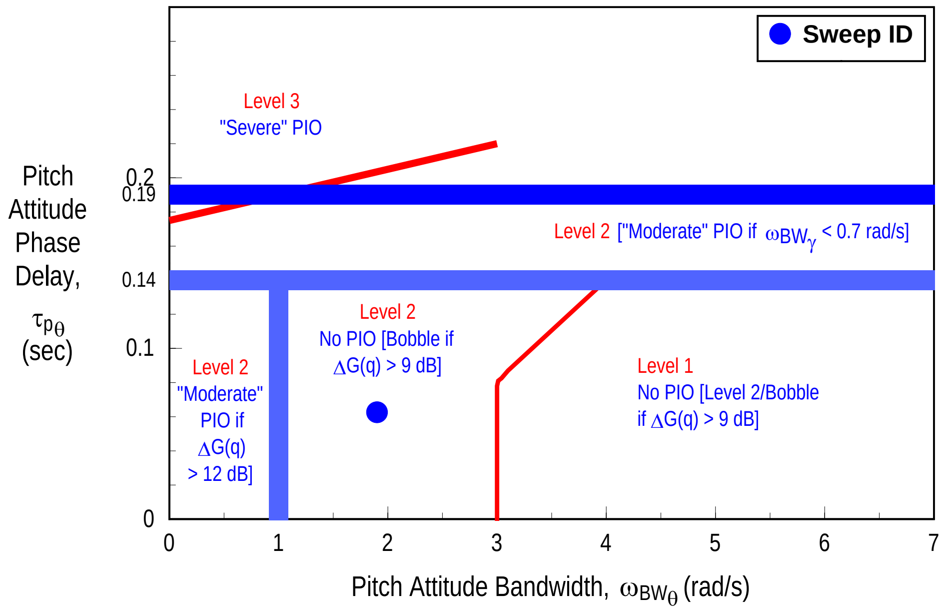


Figure 65. Pitch attitude bandwidth/PIO summary, cruise configuration with feel system [13]

8.6 THE PVS

The pilot model is introduced as an outer-loop regulator acting on pitch attitude error. This architecture for a generic regulatory task is shown in figure 66. The implementation allows for lead or lag compensation, but for the current analysis with a baseline aircraft that possesses adequate response characteristics and baseline HQ, a pure-gain-plus-delay pilot model was used.

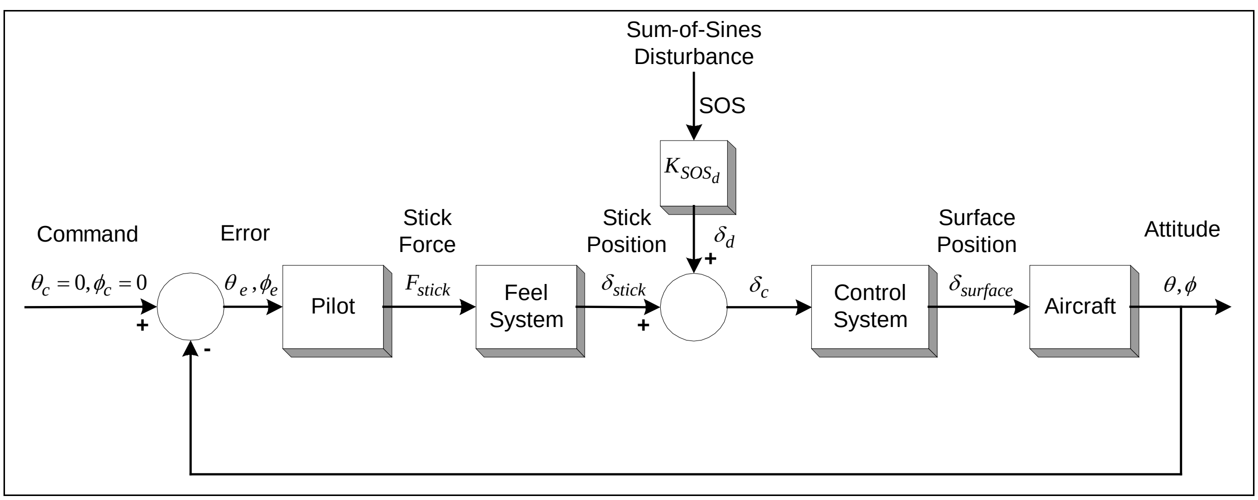


Figure 66. Sum-of-sines disturbance regulation task integration

Figure 67 shows the Y_pY_c response overlaid onto the baseline aircraft with feel system effects included. Note that this response is shown as an attitude response to column input, as this is the response relevant to the pilot's attitude tracking task and, thus, will determine his or her gain. The Y_pY_c response shown in figure 67 utilizes a pilot model with a 250-msec delay and unit gain so that the effects of the delay can be visualized in the phase response. For both cases, crossover frequency (ω_c) is about 0.11 rad/s, which is considered very low.

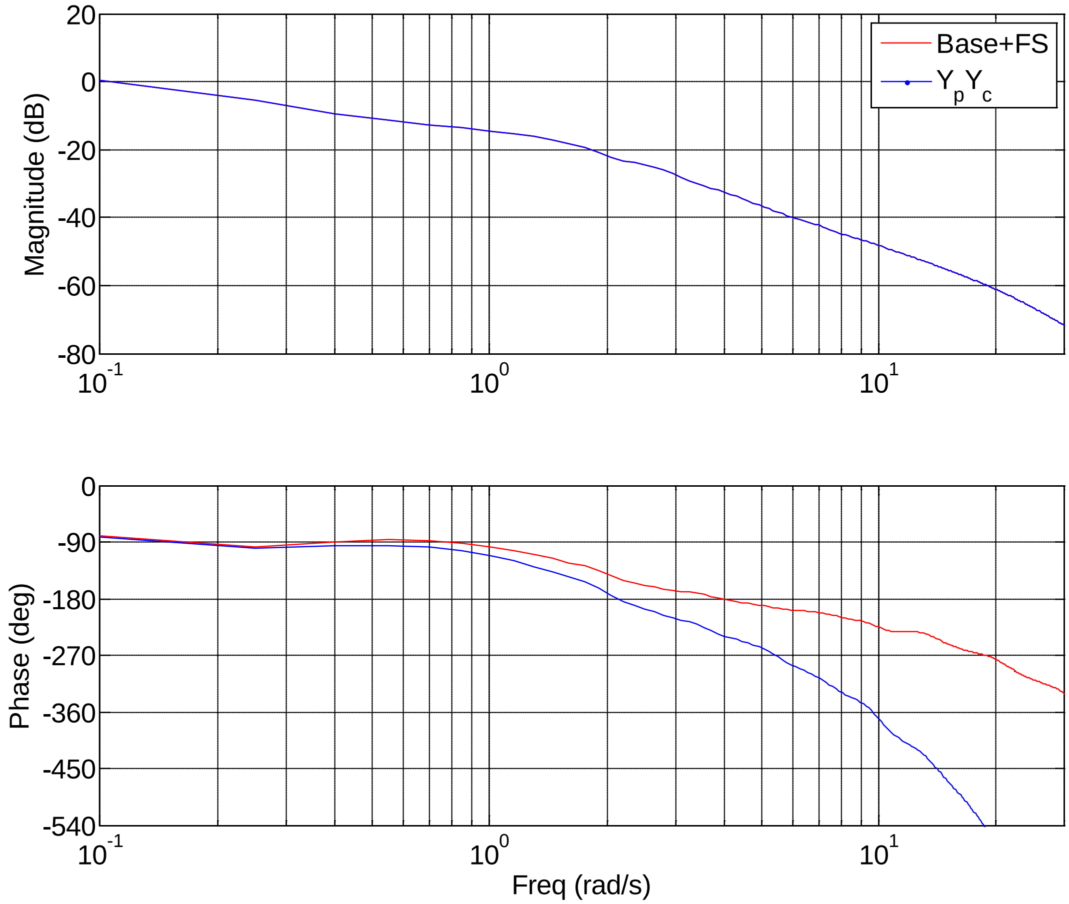
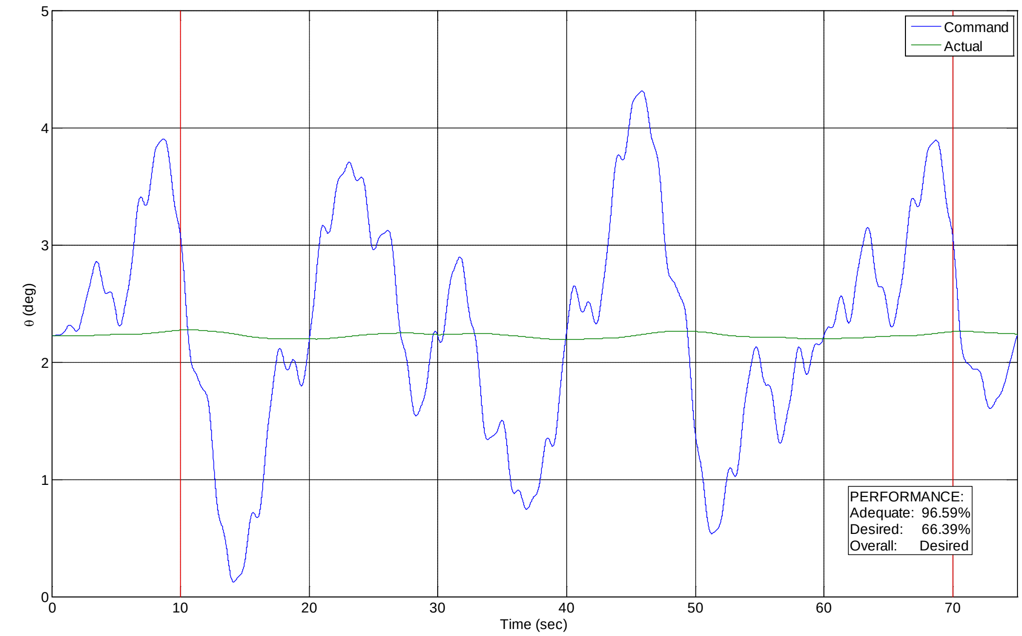


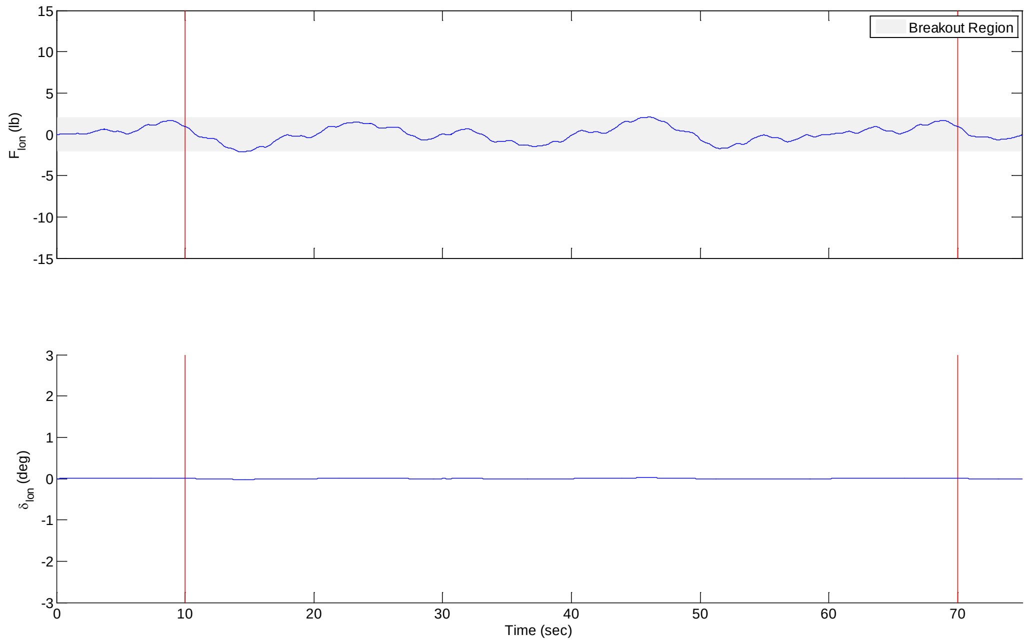
Figure 67. Comparison of baseline aircraft with feel system and YpYc PVS with unit gain

Figure 68 gives a summary of the task performance achieved by a pilot model that is not attempting to control with additional gain compensation. This is representative of a pilot who is simply reacting to errors with unit proportional inputs after a response delay.

Looking first at figure 68(b), almost no stick activity results from the tracking error. Though the pilot model reacts to the error introduced, the gain is sufficiently low that the force applied on the stick does not overcome the BO force required to take the stick out of detent. There is a slight amount of movement allowed in BO (a 100 lb/deg gradient is present), driving a slight change in pitch attitude as a result of the forces applied, but the tracking task is effectively ignored by this pilot model. Still, the nature of the task requirements—of ±2 degrees 50% of the time for adequate and ±1 degree 50% of the time for desired—allows the end of run performance to fall within desired.



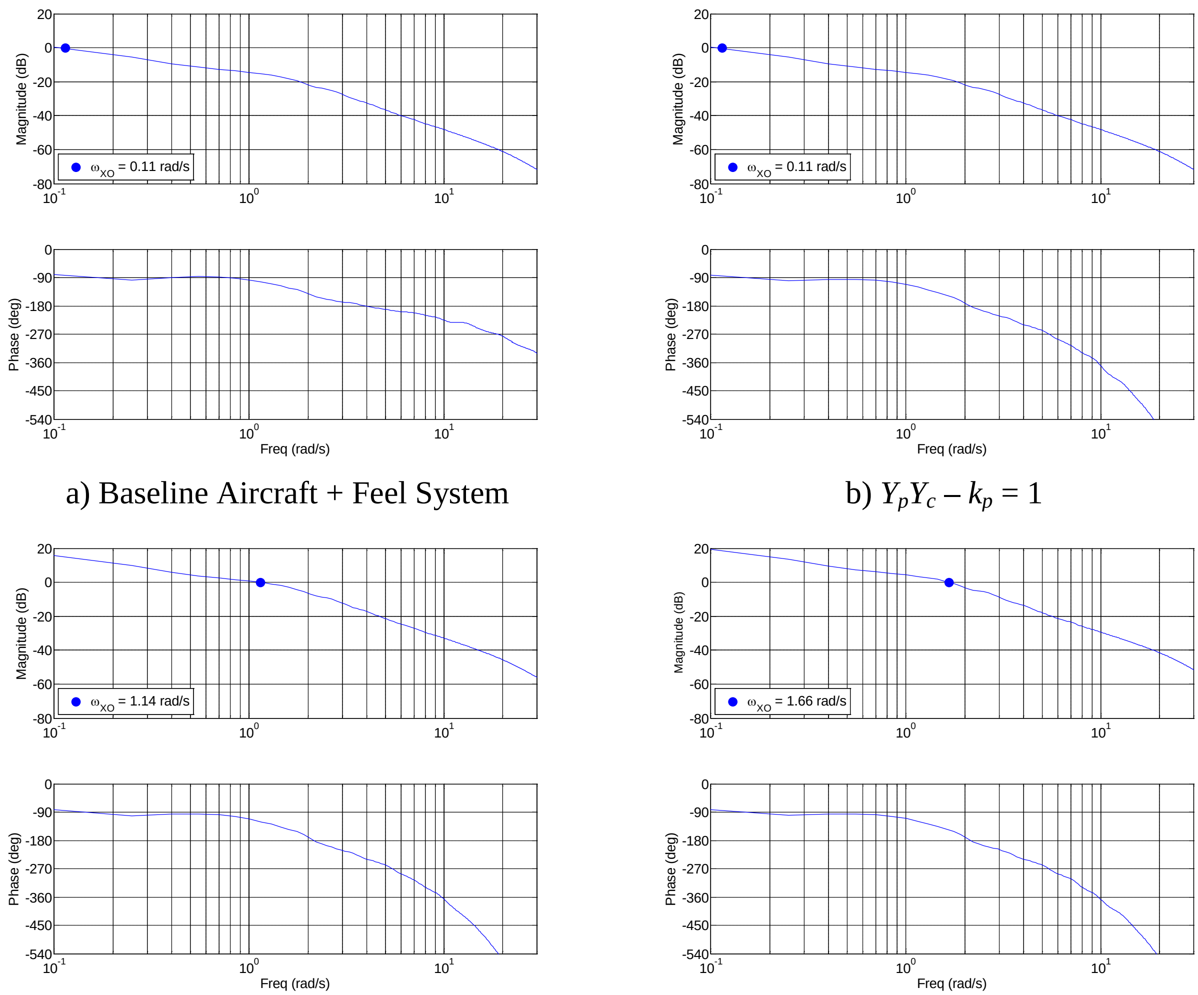
a) Task Performance



b) Resultant Stick Activity

Figure 68. Unit gain PVS task summary

A systematic study of possible pilot behavior was conducted and two pilot gain (k_p) representations were selected. The results of this study are summarized in figure 69.



a) Baseline Aircraft + Feel System

b) $Y_pY_c - k_p = 1$

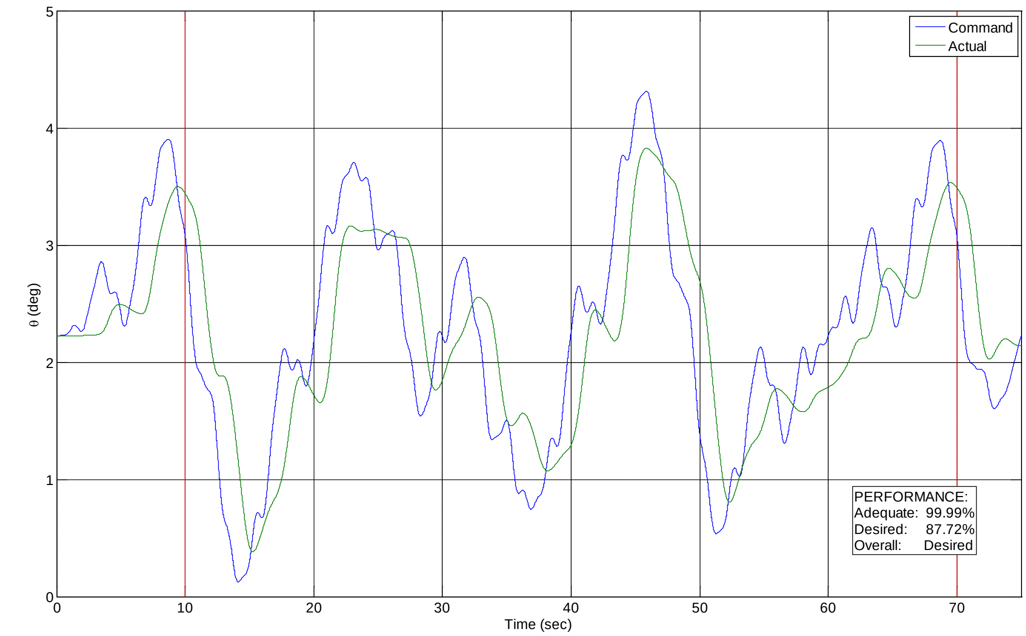
c) $Y_pY_c - k_p = 6$ (Low Gain Pilot)

d) $Y_pY_c - k_p = 10$ (High Gain Pilot)

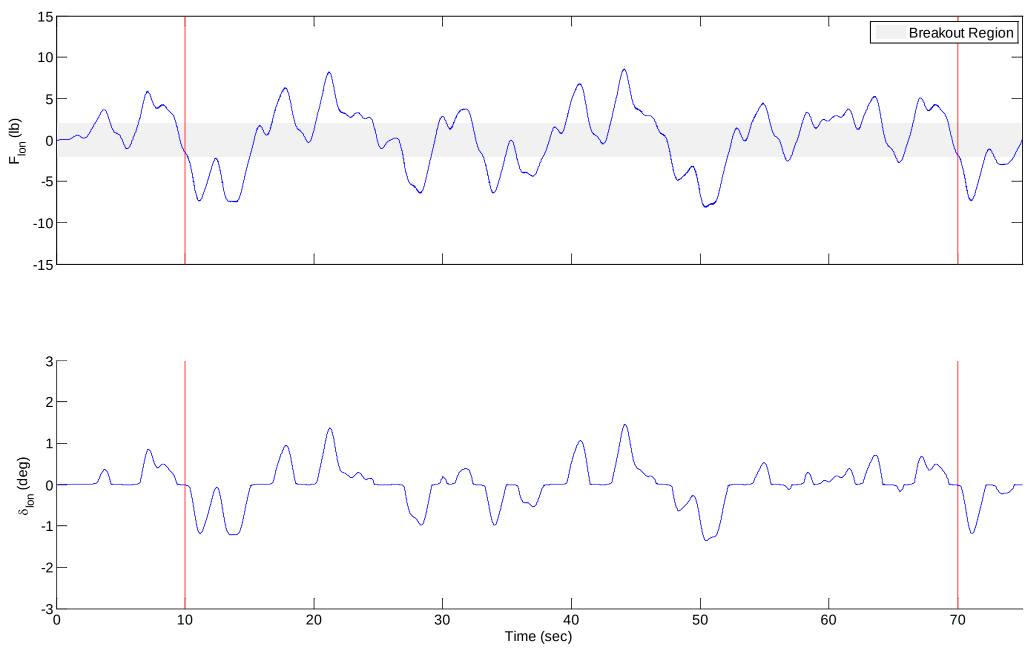
Figure 69. Pilot gain effects on crossover

The first represented an average pilot looking to close the loop and achieve a Y_pY_c crossover of about 1.1 rad/s, typical of a pilot flying a transport aircraft in a closed-loop task. This crossover also allows the pilot to achieve the “k/s-like” crossover described previously without encountering the augmented short-period dynamics.

We see in figure 70 that the low-gain pilot is able to achieve desired performance and can adequately track the lower frequency disturbances. The stick activity in figure 70(b) indicates that the pilot is controlling outside of the BO force with moderately low-amplitude stick displacements.



a) Task Performance



b) Resultant Stick Activity

Figure 70. Low gain PVS task summary

9. BACKGROUND INFORMATION ON PILOT RATINGS REPORTING

Pilots' HQ and PIO tendency ratings are reported for each evaluation in the form of plots of ratings as a function of the design element value and HQR and PIOR crossplots.

To distinguish between the large number of runs presented in each figure, a different symbol was used for each pilot and also assigned a color (see table 52). This color designation applies throughout the document, though symbol designations vary between figures of different type. A legend is included with each figure to distinguish symbol meanings. Repeated configurations are shown as open symbols unless otherwise noted. This representation is valid for both pitch and roll axis testing.

Table 52. Pilot legend for ratings summary plots[1]

Pilot	Symbol Color
1	Black
2	Blue
3	Red
4	Gray
5	Green

10. RESULTS OF TASK 2 PITCH AXIS TESTING

10.1 BASELINE AIRCRAFT

10.1.1 Introduction

This section presents an overview of the fixed-base simulation evaluations of longitudinal baseline configurations [14]. Five pilots participated in the evaluations of this configuration. The evaluations were SoS and discrete attitude capture and hold (ACH) tasks in PA, V_C, and V_A configurations. The bare airframe SM was 5%, with the exception of the actuator bandwidth evaluations, where 2.5% and 0% SM cases were evaluated. HQ and PIO tendency ratings were recorded after each evaluation run. In figures 71 and 72, the text annotations denote the number of times the baseline run was given that rating.

10.1.2 Analysis Summary

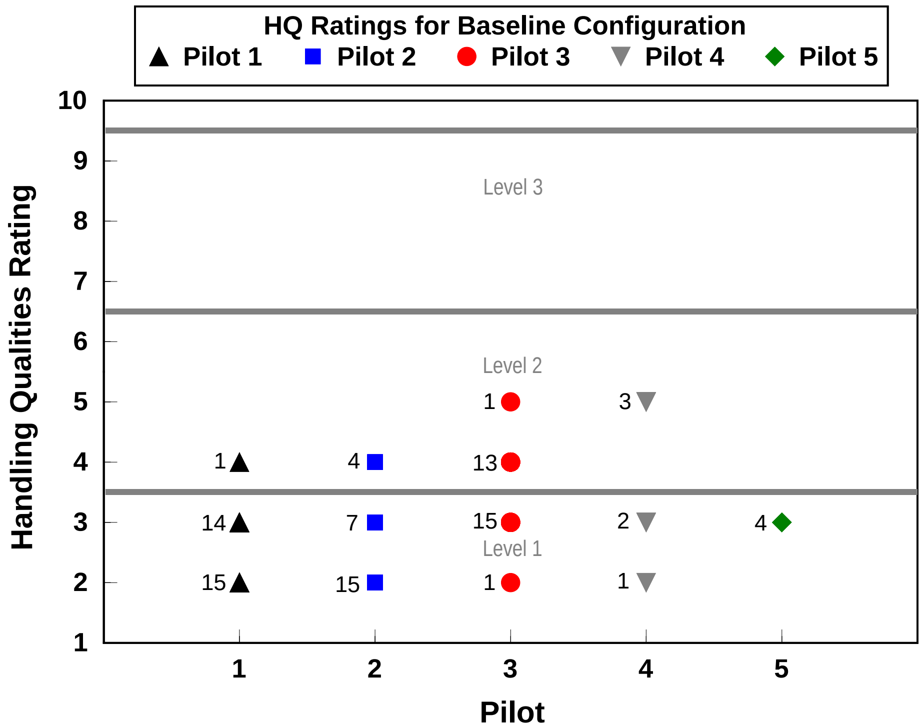
Figures 71 and 72 give a summary of the HQ and PIO tendency ratings for the five pilots that participated in the evaluations. Each pilot flew the baseline configuration to begin each session and often repeated the baseline configuration both known and blind during each session for ratings through the duration of the experiment. Pilot 1 evaluated the baseline 30 times; pilot 2, 26 times; pilot 3, 30 times; pilot 4, 6 times; and pilot 5, 4 times.

---

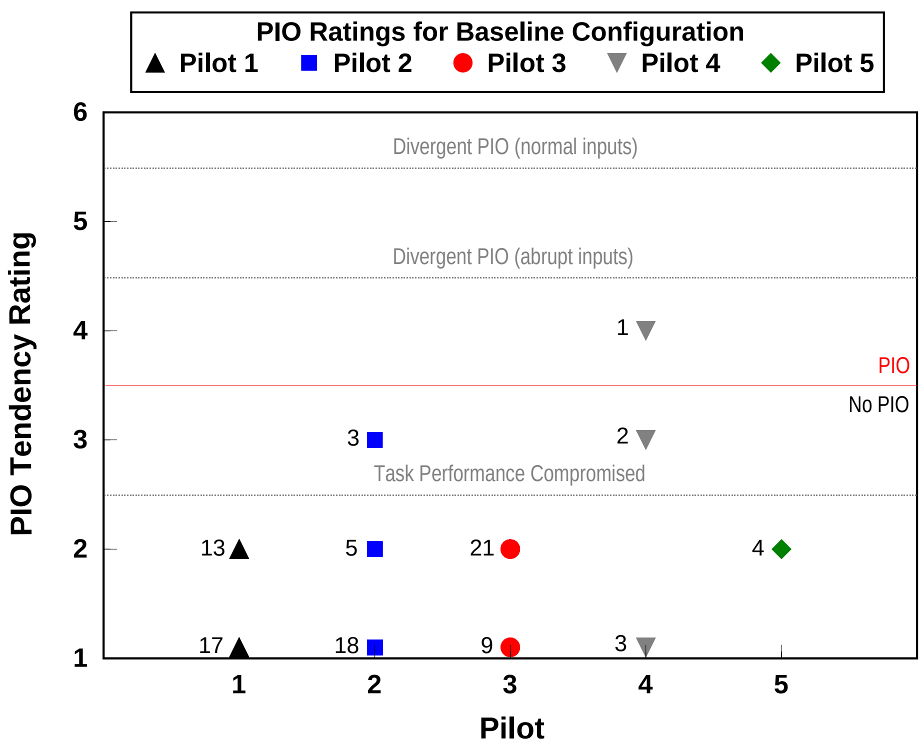
[1] Repeated runs are shown as open symbols.

Figures 71 and 72 show that pilots generally rated the baseline Level 1, with pilot 3 giving borderline Level 1/2 ratings. The aircraft model used in the evaluation was designed to be Level 1 (HQR = 3 or better) at all flight conditions, and the ratings shown in figures 71 and 72 are consistent with the design objectives.

PIO tendency is not an issue for the baseline configuration, with only one PIO rating of 4 and six total ratings of 3 or worse in the 96 total baseline runs. The results in figure 72 show that each pilot rated the configuration favorably, with only a few outlier ratings for each pilot, which were likely due to blind runs after poor configurations. Evaluating the baseline configuration after evaluating a poorly performing configuration led to pilots altering control schemes and perceiving the baseline differently than when originally evaluated at the beginning of each section. Overall, the baseline configuration in the pitch axis is Level 1 with minimal PIO tendency.

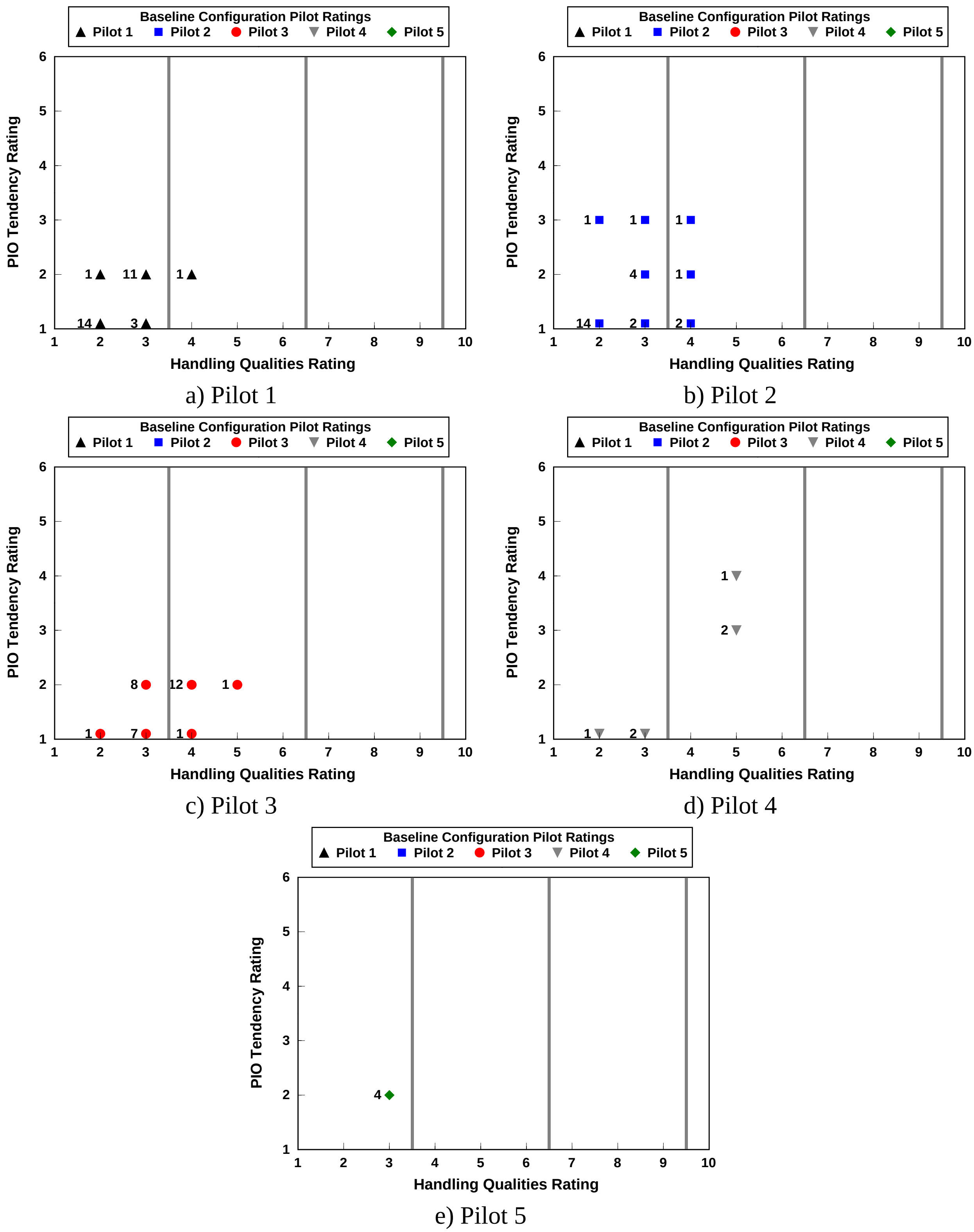


a) Handling Qualities



b) PIO Tendency

Figure 71. Ratings summary, pitch baseline configuration



a) Pilot 1

b) Pilot 2

c) Pilot 3

d) Pilot 4

e) Pilot 5

Figure 72. Pilot ratings, pitch baseline configuration

10.1.3 Piloted Evaluations, Observations, and Conclusions

- The baseline configuration in the pitch axis was flown a total of 96 times by five pilots. Pilots 1, 2, and 3 participated in the majority of the evaluations, while pilots 4 and 5 participated in a limited number.
- HQR were mostly Level 1 with Pilot 3 rating the configuration borderline Level 1/2.
- PIO tendency was not an issue, with only six of the 96 runs rated a PIOR of 3 or higher.
- Outlier ratings were most likely due to blind evaluations following a poorly performing configuration.

10.2 COMMAND PATH DEAD ZONE

10.2.1 Introduction

This section extends the work described in section 7 to include offline analysis of the side stick and effects of a command path dead zone on task performance and pilot workload. In the previous work, an analytical pilot model was developed that used the feel system characteristics for a control column with a nonlinear gradient and BO (i.e., the baseline system from the Year 2 piloted simulation study). The analysis shown herein details the revision of the compensatory pilot model to account for the side stick characteristics, which differed significantly from the column in both gradient and BO force and were based on those used previously by Calspan on the Learjet in-flight simulator.

In addition to the adjusted feel system dynamics, a command path dead zone is also included in the analysis. Though this dead zone behaves similarly to a BO force, the effects are on stick displacement rather than force and are not felt by the pilot. This lack of cueing can lead to unexpected results as pilots adapt differently to the reduced command authority. Though pilot adaptation can be difficult to predict, this section attempts to identify possible adaptation techniques and the effects these changes may have on task performance.

The same model used for the piloted evaluations was used for these offline simulations.

The second part of this section presents an analysis of the fixed-base simulation evaluations investigating the effects of the same pitch feel system dead zones on longitudinal HQ. Four pilots participated in the pitch dead zone evaluations [14]. The evaluations were SoS tracking tasks (section 4.4) in PA configuration with a bare airframe SM of SM = 5% ($\bar{c}$). HQ and PIO tendency ratings were recorded after each evaluation run and task performance data were recorded for offline analysis. Dead zones were varied from not present (baseline) to ±2.5 degrees, which represents 25% of total stick travel.

10.2.2 Offline Analysis

10.2.2.1 Closed-Loop Aircraft

The primary objective of this analysis was to determine the effects of command path dead zone on task performance and pilot behavior. A baseline pilot model was determined using frequency sweep identifications of the baseline aircraft at maneuvering speed. The command path dead zone was then varied from 0–2 degrees to determine the effects on the system frequency response and task performance.

For this analysis, the controlled element Y_c refers to the closed-loop augmented aircraft that includes the CLAWS and vehicle dynamics. The feel system is not considered part of the controlled element for the analysis shown in this section.

Because the analysis is based on identified responses from frequency sweep inputs, the pitch rate response of the aircraft is used. The rate output signal contains much more energy than the attitude signal, making it easier to identify. Though the airplane bandwidth criteria are defined for stick-to-attitude frequency responses, equivalent HQ metrics can be derived by using phase points that are offset by the 90 degrees typical of a rate-to-attitude integration. Frequency responses provided in this working paper show the equivalent rate response phase points used to determine HQ parameters.

The frequency response for the maneuvering speed flight condition is shown in figure 73. In the figure, the identified nonlinear system is overlaid with identified airplane bandwidth frequencies and related parameters shown as colored dots.

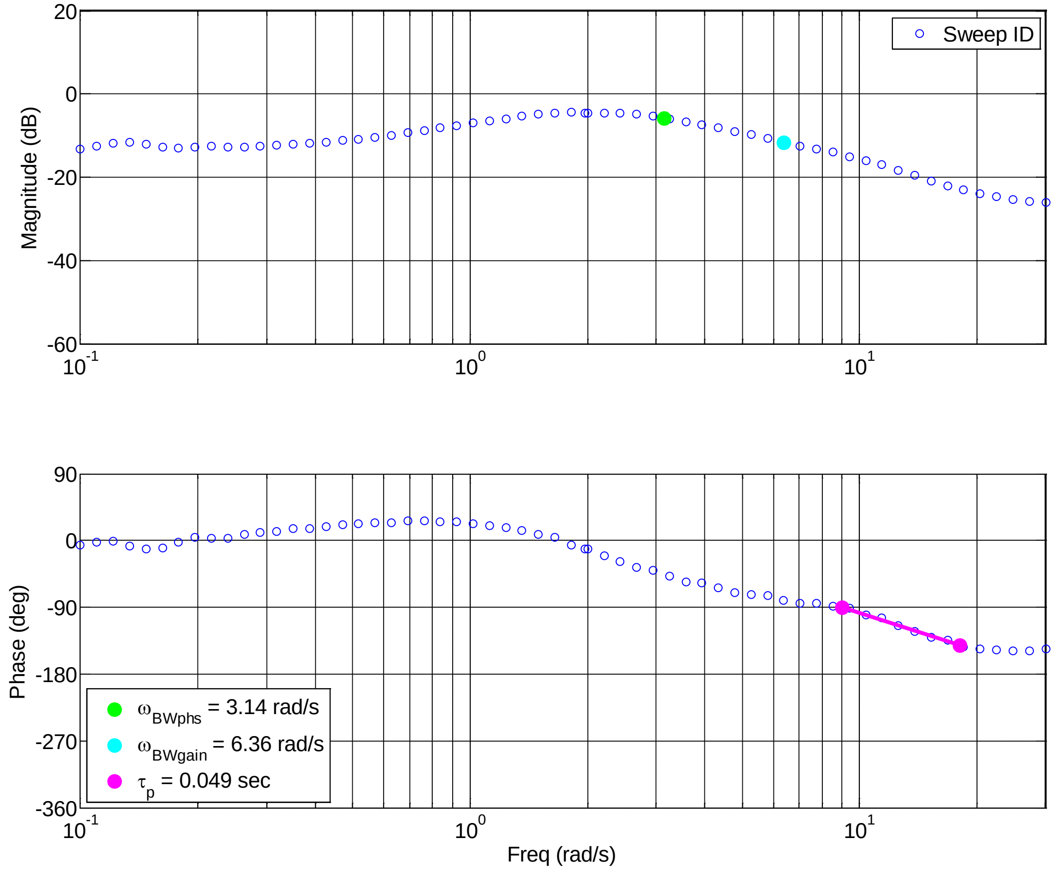


Figure 73. Closed-loop aircraft identified frequency response and FQ metrics

A well-damped vehicle response with an airplane bandwidth over 3 rad/s indicates highly responsive vehicle dynamics. Note that the ω_{-180} frequency is shown as -90 degrees for the equivalent rate response in figure 73.

Assessing the HQ for the closed-loop aircraft (figure 74), Level 2 HQ are predicted, with no significant PIO risk shown for the current configuration. Though the points used to determine the phase delay metric lie in a region of increased phase roll off, the resulting amount of phase delay is not enough to push the system into the region of moderate PIO susceptibility for the current configuration.

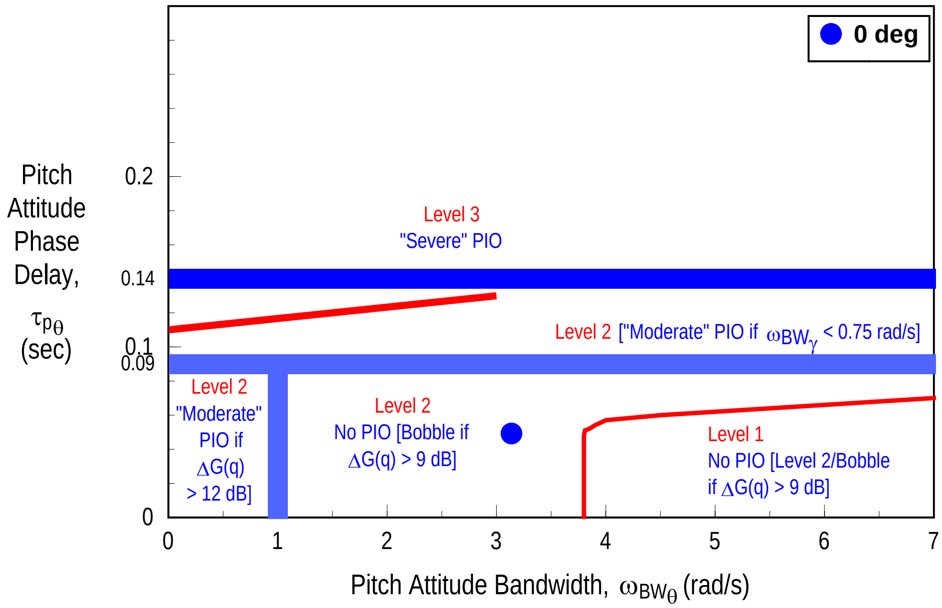


Figure 74. Pitch attitude bandwidth/PIO summary, cruise configuration/maneuver Speed [14]

10.2.2.2 Feel System Effects

The feel system dynamics are modeled as a linear gradient with BO and friction. Additionally, there are dead zones and flat zones that can be inserted into the command path. For the work described in this section, the parameters were left at their baseline values, with no friction force and a 0.25 lb. BO. The dead zone is set to four discrete values of 0, 0.5, 1.0, and 2.0 degrees to determine the threshold, if any, that compromises pilot performance. Flat zones were not present for any of the analysis runs performed.

Figure 75 shows an overlay of the feel system identifications while figure 76 shows the identified Y_c frequency responses with feel system included for the various dead zone settings. The system gain decreases proportionally with increasing dead zone, which is expected as the sensed deflection of the stick is decreased as the dead zone increases. Of note is the lack of variation in HQ parameters. Both phase and gain bandwidths are almost invariant, even for large dead zones, which represent 10% of total stick travel. Phase delay is also largely invariant, though there is a slight decrease when the dead zone is introduced.

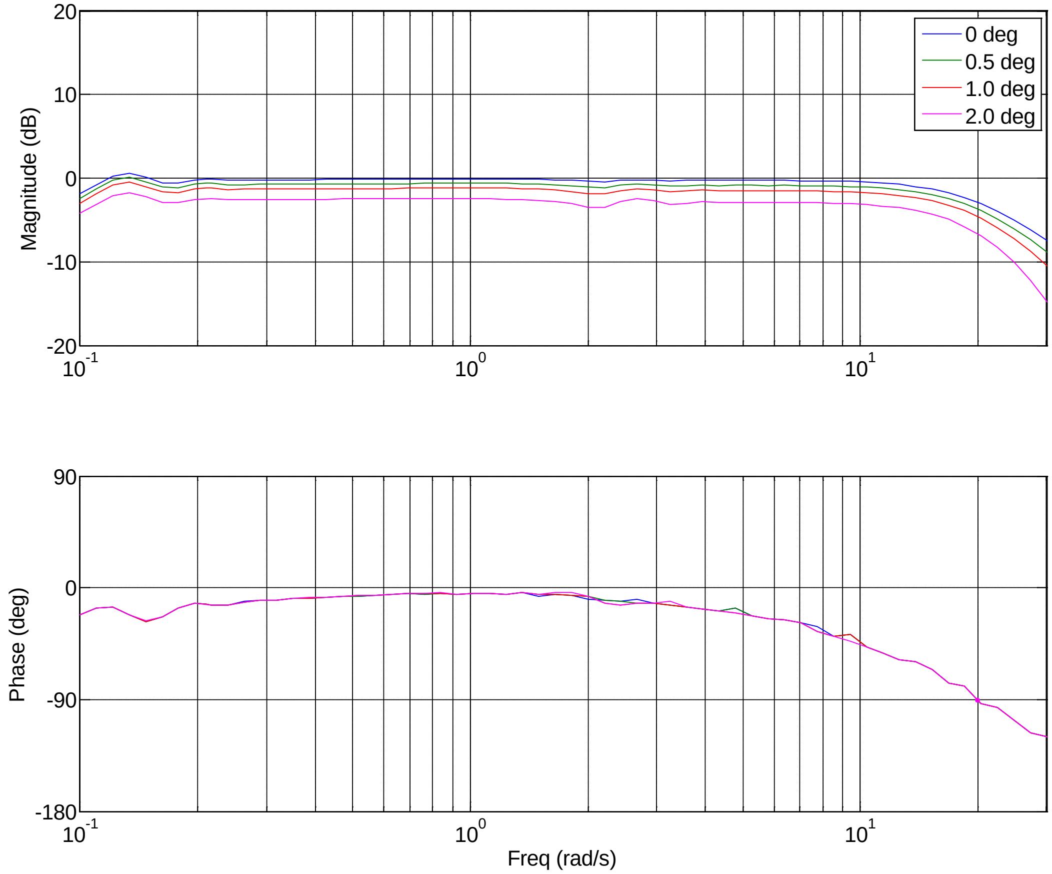
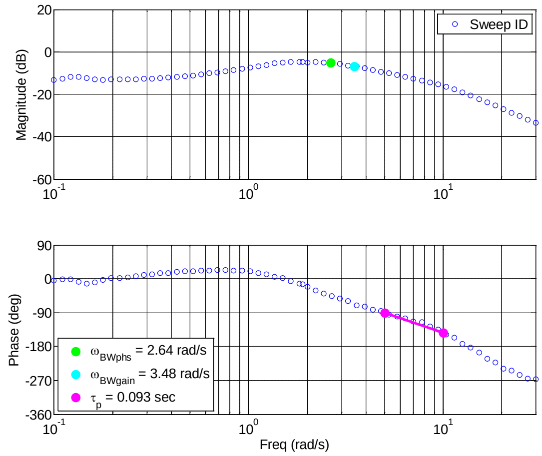
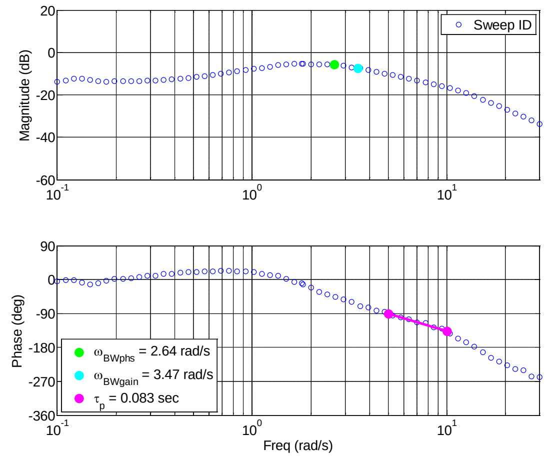


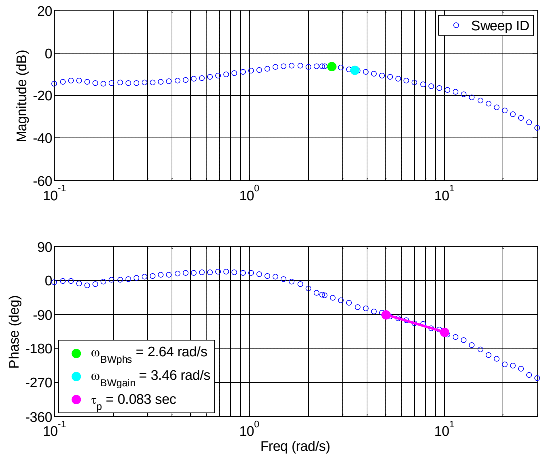
Figure 75. Feel system frequency response as a function of dead zone



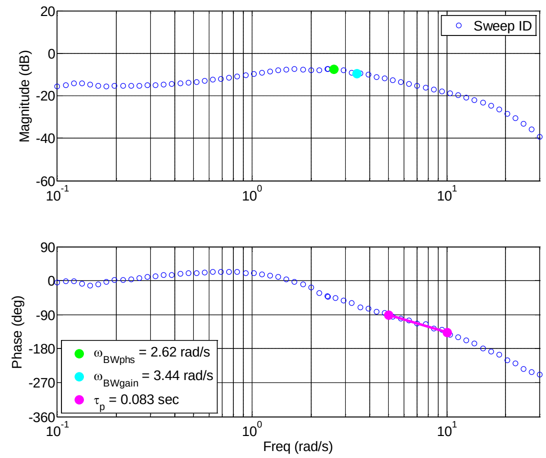
a) DZ = 0 deg



b) DZ = 0.5 deg



c) DZ = 1.0 deg



d) DZ = 2.0 deg

Figure 76. Aircraft plus feel system identified frequency responses and FQ metrics

A hypothesis for the lack of variation is that the high amplitude sweep input used for identification is too large to show sensitivity to the nonlinear effects of the dead zone. Though there is a gain reduction for the dead zone cases, this is due to the stick deflection signal being scaled by the deflection dead zones. The lack of phase differences shows that the aircraft responds well to the inputs it receives and the only effect of the dead zone is a loss of input gain (see figure 77). This implies that the pilot can accommodate for the dead zone by increasing his gain by a corresponding amount, but because nonlinearities are heavily dependent on input amplitude, it remains to be seen whether the effects are similar for a small amplitude forcing function, such as the error signal driven by the SoS disturbance (see table 53).

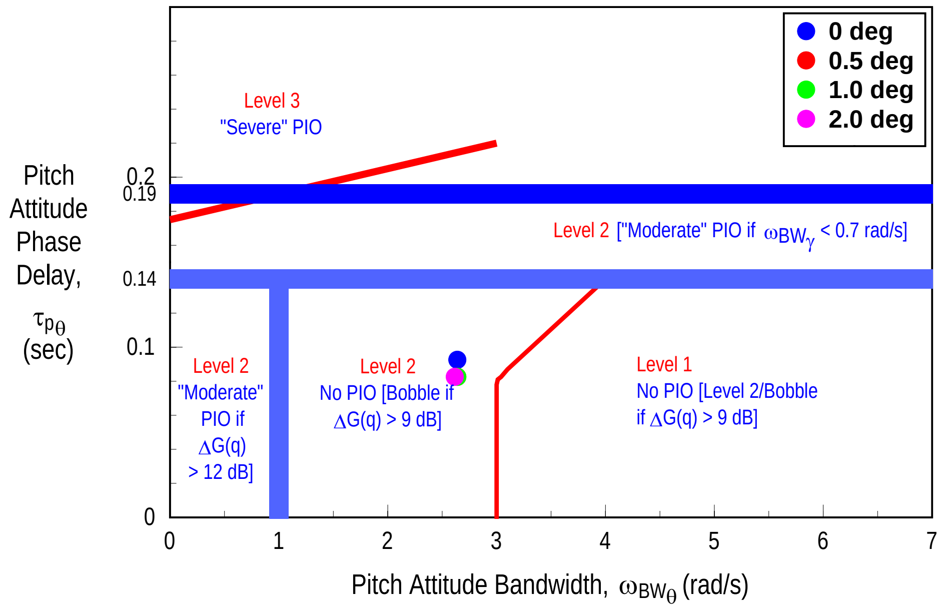


Figure 77. Pitch attitude bandwidth/PIO summary (with feel system) for varying dead zone [13]

Table 53. Summary of closed-loop aircraft handling qualities

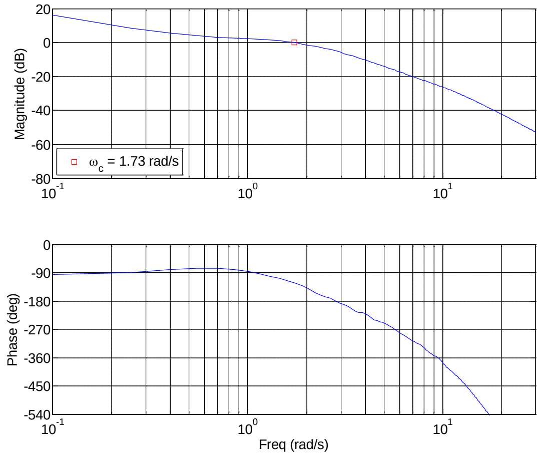
Dead Zone (deg)	Bandwidth (rad/s)	Phase Delay (msec)
0	2.6394	92.599
0.5	2.6394	82.588
1.0	2.6394	82.588
2.0	2.6159	82.588

10.2.2.3 The PVS

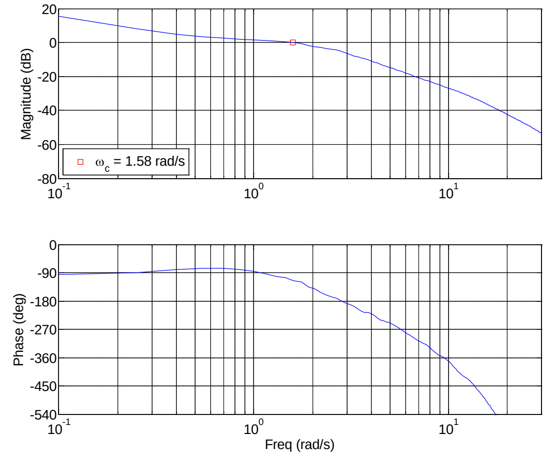
10.2.2.3.1 Frequency Sweep Identification

The pilot model is introduced as an outer-loop regulator acting on pitch attitude error. This architecture is shown in figure 47 for a generic regulation task. The implementation allows for lead or lag compensation by the pilot as well as a pure-gain-plus-delay pilot model.

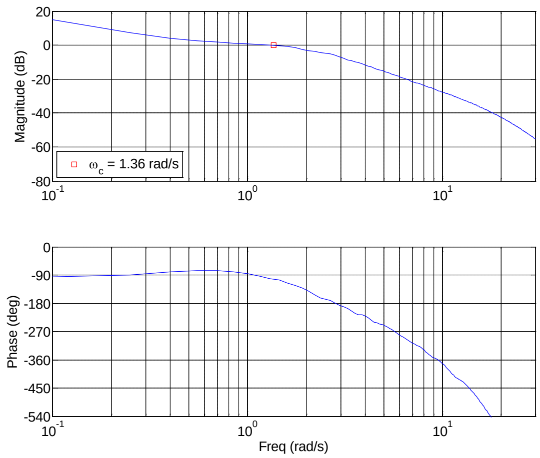
Based on the system responses shown in figure 64, a pilot gain (K_P) of 3 was selected. A frequency sweep with an amplitude equivalent to 3 degrees of pitch attitude error was utilized to generate data that was used to identify the PVS (Y_pY_c) for the four dead zone cases, shown in figure 78. Crossover frequency and task performance were used to gauge the effects of the dead zone on PVS performance.



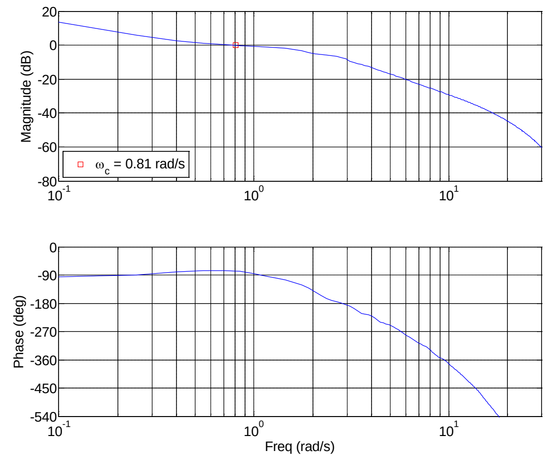
a) DZ = 0 deg



b) DZ = 0.5 deg



c) DZ = 1.0 deg



d) DZ = 2.0 deg

Figure 78. The PVS responses for varying dead zone

Crossover frequency decreases with increasing dead zone, corresponding directly to the gain loss associated with the introduction of the dead zone in the command path (see table 54). Taking into consideration that pilot gain is held constant for all of the PVS responses in figure 78, the effects on crossover are readily apparent.

Table 54. Summary of identified PVS crossover frequencies

Dead Zone (deg)	Crossover (rad/s)
0	1.73
0.5	1.58
1.0	1.36
2.0	0.81

10.2.2.3.2 Describing Function Analysis

In addition to using frequency sweep data to estimate the frequency response of the system, the regulation task time history can be used to determine system crossover. Because the pilot is compensating for an error signal driven by a known forcing function, a describing function analysis can be performed that identifies the system at the forcing function frequencies. When flight or simulation data are used, this analysis can extract pilot behavior in relation to changes in the vehicle, feel system, or task. For the current analysis investigating simple changes in feel system parameters, this analysis is used to determine how changes in the pilot model affect system crossover and, ultimately, task performance. These results can be used to predict pilot adaptation to changes in dead zone and help determine realistic limits for the dead zone variations used for piloted evaluation.

Figure 79 gives an example time history for the pitch attitude disturbance regulation task. This run has no dead zone present. We see the pilot compensating for the SoS disturbance-driven error from the reference pitch attitude of 4.59 degrees with pure gain compensation. From this, we can extract the PVS describing functions shown in figure 80.

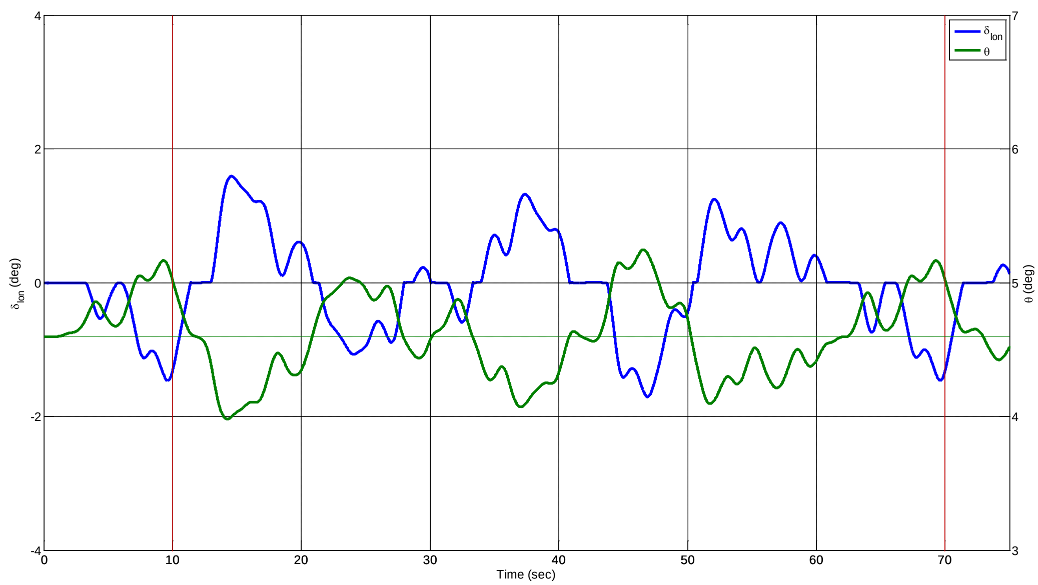
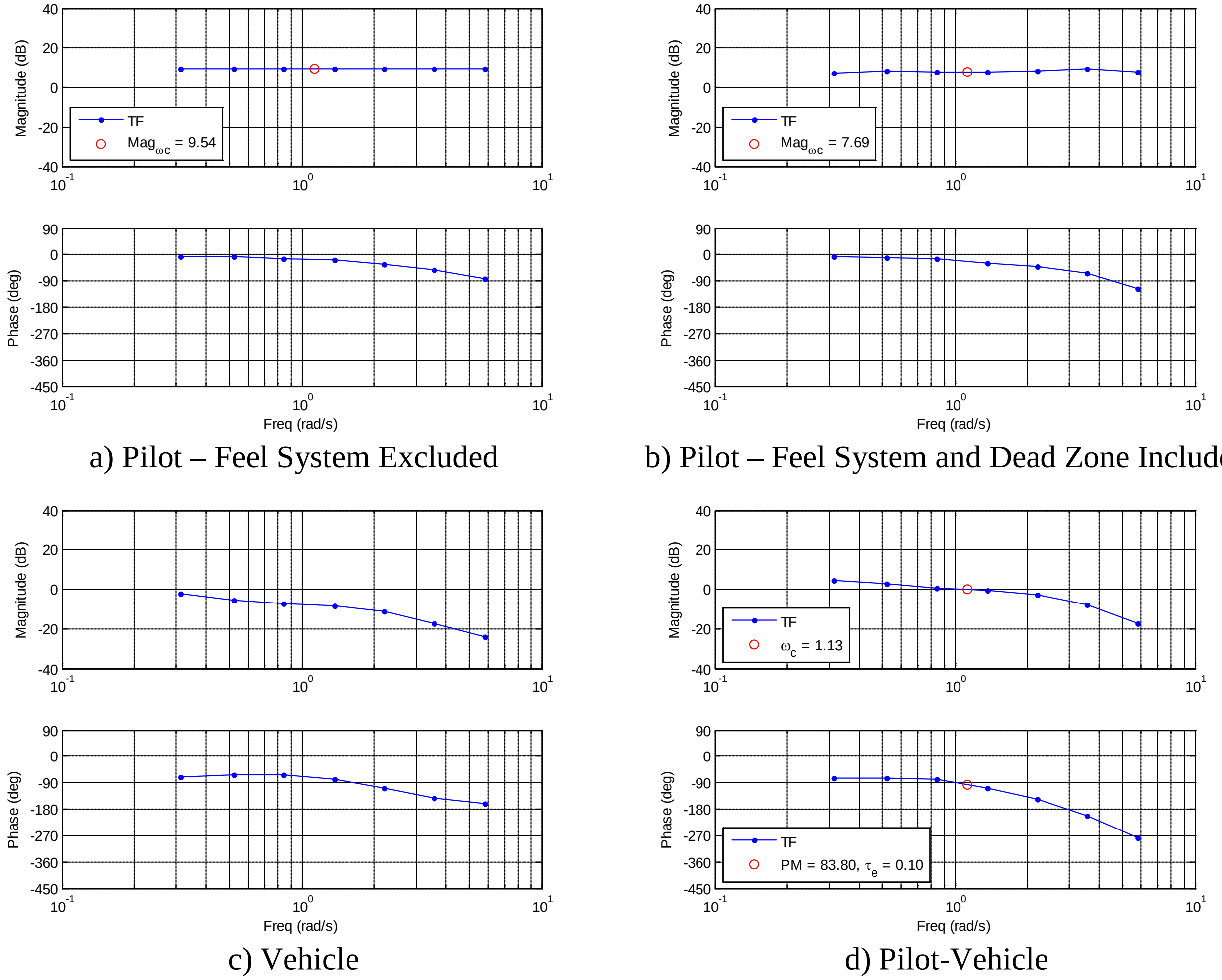


Figure 79. Example regulation task time history; DZ = 0 deg



a) Pilot – Feel System Excluded

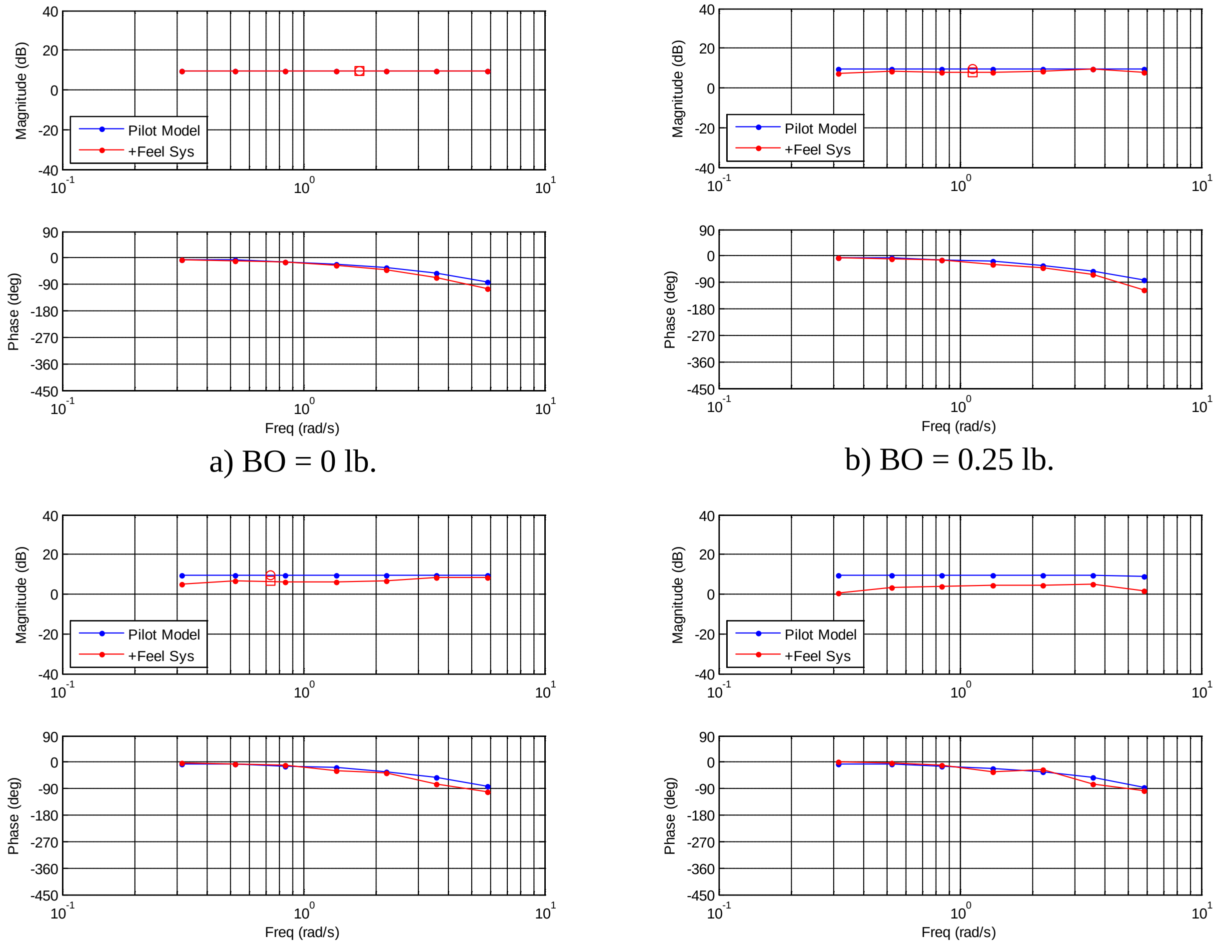
b) Pilot – Feel System and Dead Zone Included

c) Vehicle

d) Pilot-Vehicle

Figure 80. Describing functions for SoS regulation task; DZ = 0 deg

The magnitude at the 1.13 rad/s crossover frequency (shown in figure 80(d)) when including the feel system is 7.69 dB, despite the lack of a dead zone for the case shown, slightly less than the expected 9.54 dB expected with our pure gain pilot model. This is due to the gain loss through the feel system dynamics, likely due to the BO force of 0.25 lb. The gain loss effect due to the BO force is demonstrated in figure 81. None of the cases in figure 81 had any dead zone present.



a) BO = 0 lb.

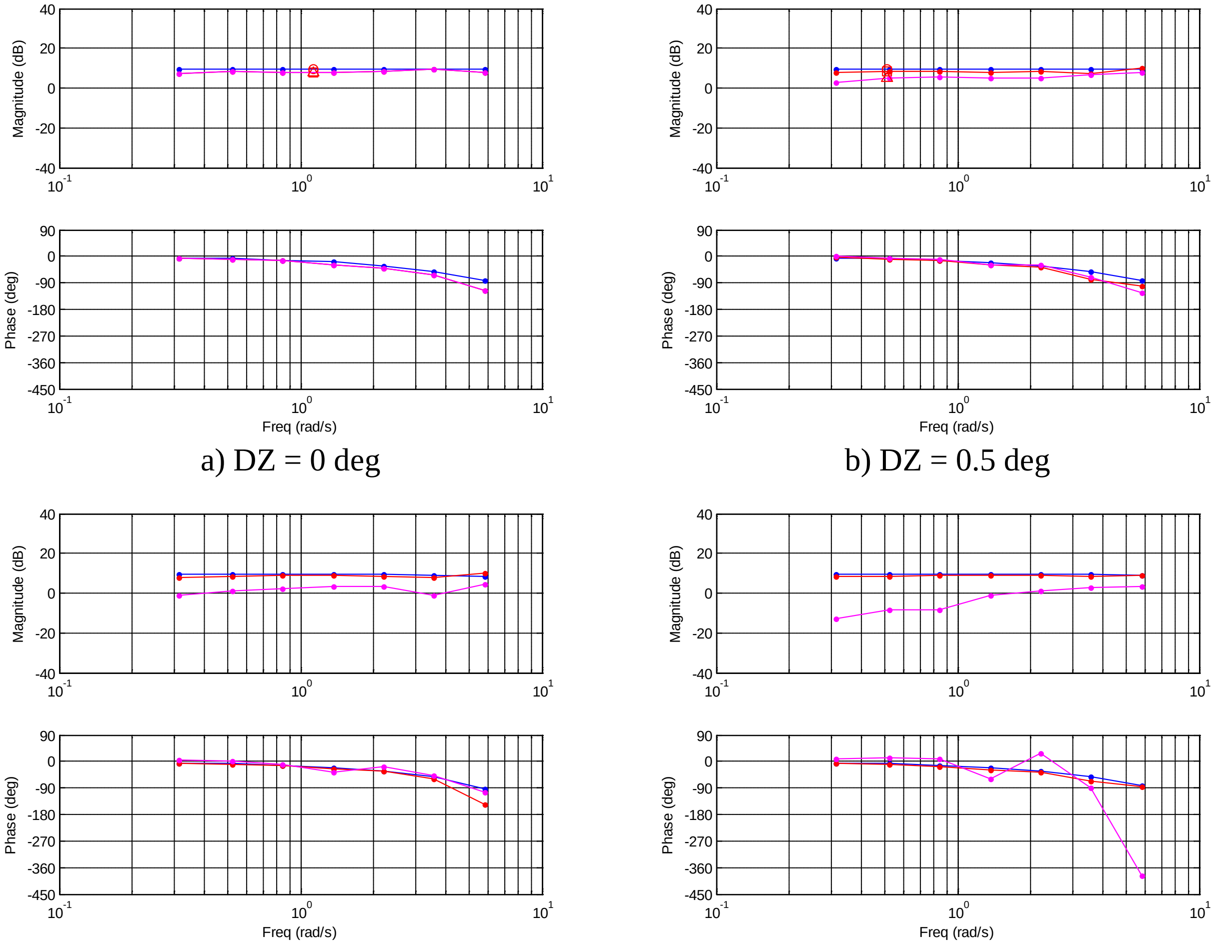
b) BO = 0.25 lb.

c) BO = 0.5 lb.

d) BO = 1.0 lb.

Figure 81. Pilot describing functions with varying breakout force

Figure 82 gives the pilot describing functions for the various dead zone settings. For all cases, we see a slight gain loss across the feel system associated with the BO force. At higher frequencies, we also note a slight phase loss due to the feel system dynamics. The magenta lines show the gain loss due to the dead zone, which rises with the increasing dead zone setting, an indicator of the nonlinear behavior that becomes more significant as the dead zone increases. Another interesting observation is that the dead zone does not add any phase lag to the system but contributes to lower gain across the command path.



a) DZ = 0 deg

b) DZ = 0.5 deg

c) DZ = 1.0 deg

d) DZ = 2.0 deg

Figure 82. Pilot describing functions — pilot model (blue) with feel system effects (red) and dead zone (magenta) included

We also note from table 55 that the PVS crossover frequency is 1.13 rad/s for the SoS disturbance run—less than the 1.73 rad/s reported for the same system when using the sweep identification. Examining the PVS crossover frequencies for all of the dead zone cases, we see that this crossover mismatch is present for the 0- and 0.5-degree cases, while the 1.0- and 2.0-degree cases could not be determined because of the frequency limits applied to the SoS-describing functions and nonlinear behavior exhibited by the PVS system.

Table 55. Comparison of PVS crossover frequencies

Dead Zone (deg)	Sweep ω_{co} (rad/s)	SoS ω_{co} (rad/s)
0	1.73	1.13
0.5	1.58	0.51
1.0	1.36	N/A
2.0	0.81	N/A

Taking the 0.5-degree dead zone case as an example, the sweep input used to generate the data for identification has an amplitude of 3 degrees (see figure 83). This was done to produce enough output energy to properly identify the system at higher frequencies. The corresponding frequency response for this identified PVS shows a crossover of 1.73 rad/s.

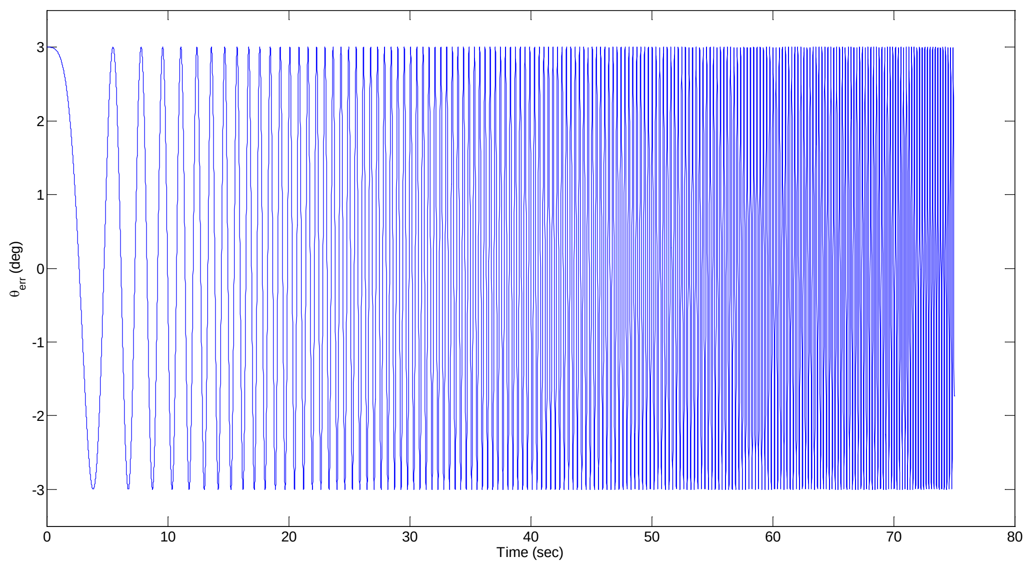


Figure 83. Sweep input used for PVS identification

When examining the pitch attitude error signal resulting from the SoS regulation task, we see that the amplitude is about 20% of the sweep amplitude used for identification, bound roughly between -0.7 degrees and 0.7 degrees. Because gain and phase loss due to nonlinearities, such as dead zone, are known to be input-dependent, it was hypothesized that the difference in crossover frequency was due to the amplitude of the error signal (see figure 84).

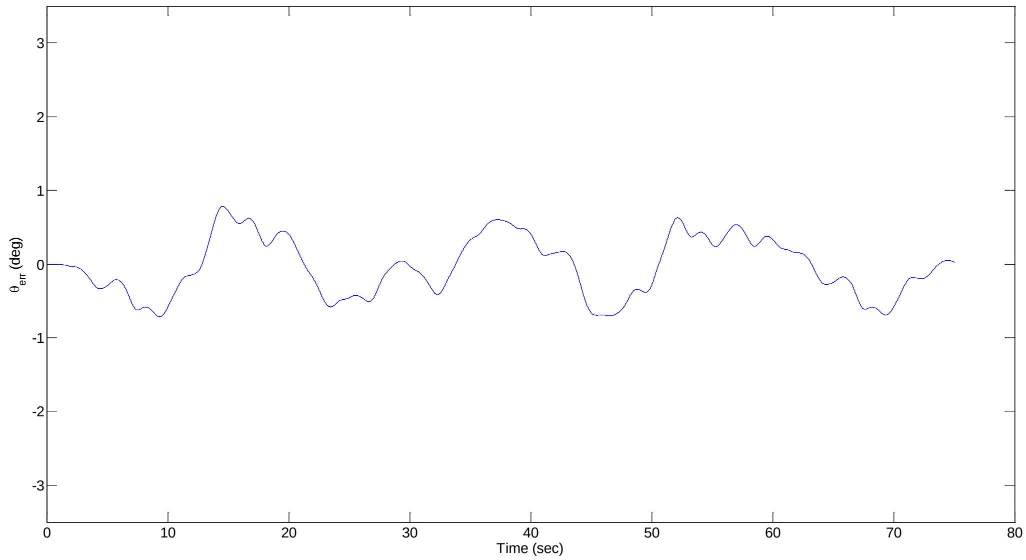
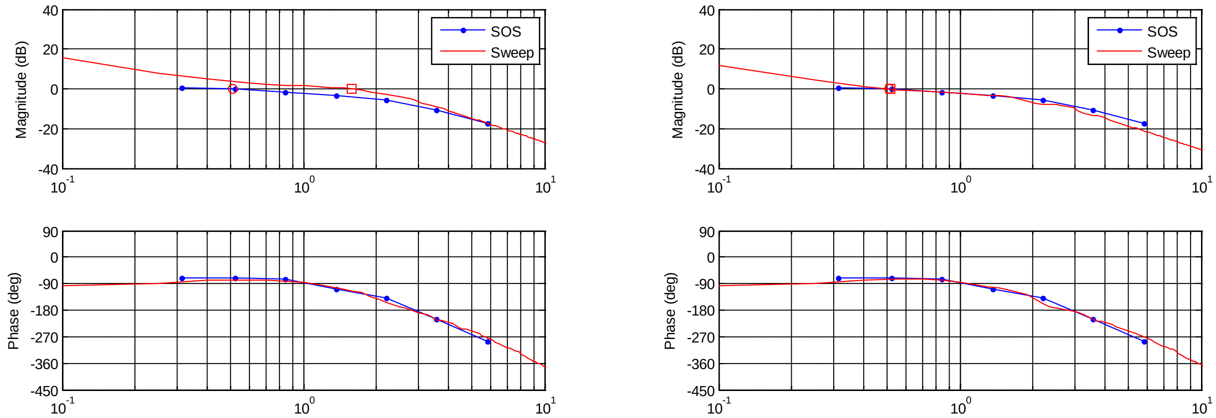


Figure 84. Error signal resulting from SoS regulation task, DZ = 0.5 deg

To test this hypothesis, the sweep input amplitude was set to ±0.7 degrees and the identification performed on the new data. Overlays are shown in figure 85 for the original high and revised low-amplitude frequency sweeps when compared to the SoS describing function response. For the reduced amplitude sweep, both the frequency response and crossover frequency overlay almost exactly.



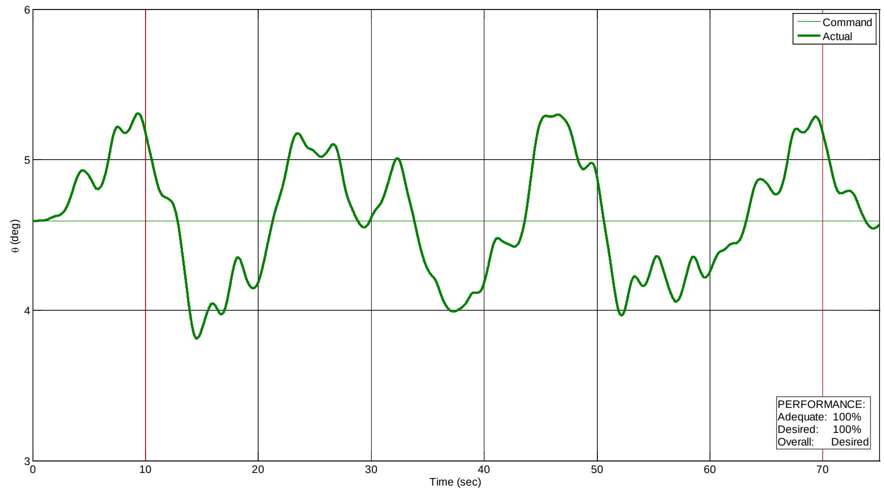
a) 3° sweep b) 0.7° sweep

Figure 85. Comparison of PVS frequency responses for varying sweep amplitude

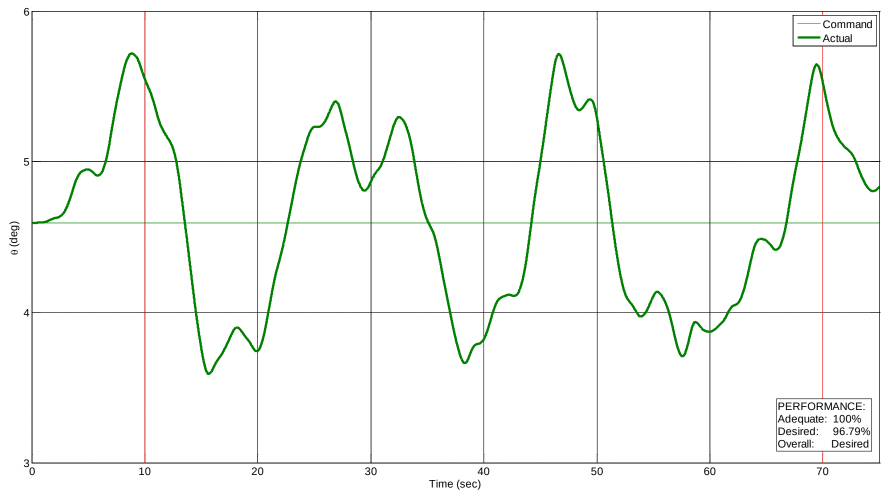
The conclusion to be drawn is that input amplitude has a profound effect on the overall PVS gain and, thus, crossover frequency. This would imply that for large amplitude tasks that produce large tracking errors, the pilot would have to use less gain to achieve similar performance to that of a smaller amplitude task. This is true of proportional control in which larger errors produce larger compensatory inputs and, thus, higher effective pilot gain.

10.2.2.4 Task Performance

Using the SoS disturbance signal described in section 4.3, the ability of the pure gain pilot model to regulate pitch attitude error was determined using a ±1 degree bound for desired performance and ±2 degree bound for adequate. With these bounds and the pilot models described above, 100% desired performance was achievable for all dead zone configurations, except for the 2.0 degree case, which achieved only 96.79% desired. Figure 86 shows a comparison of the tracking performance for the 0.5-degree and 2.0-degree dead zone cases; the 2.0-degree case shown in figure 86(b) indicates a lack of high-frequency tracking as well as higher errors between the reference and actual pitch attitudes.



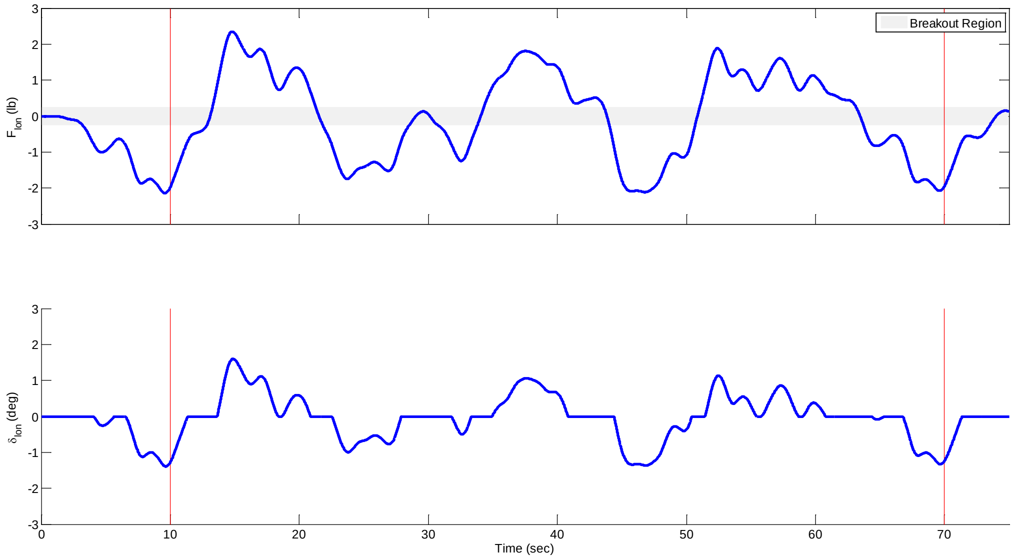
a) DZ = 0.5 deg



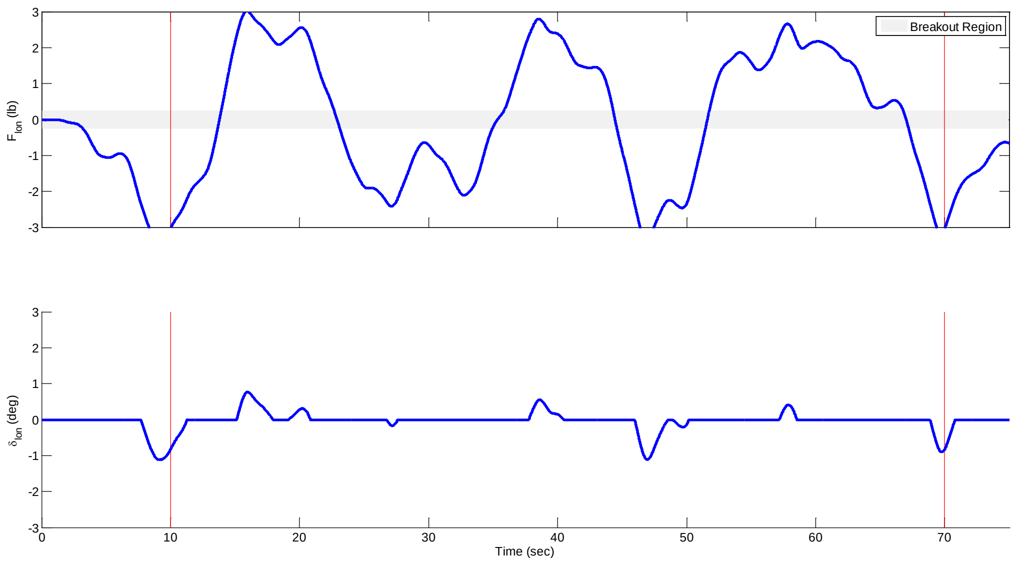
b) DZ = 2.0 deg

Figure 86. Task performance time histories

The corresponding stick activity shown in figure 87 shows the effects of the dead zone on task performance. For the 2-degree case, the pilot is controlling with much more stick input (force) in response to the pitch attitude error, but the dead zone does not allow any deflection input to the aircraft. The result is a much more open-loop type of control with inputs that are representative of a pulse-and-wait style of inputs that results in a much lower PVS crossover and degraded task performance.



a) DZ = 0.5 deg



b) DZ = 2.0 deg

Figure 87. Stick activity time histories

10.2.3 Offline Analysis Observations and Conclusions

- The baseline case showed some gain and phase loss due to the BO force nonlinearity in the feel system. The introduction of the dead zone produced increasing amounts of gain loss, but no additional phase lag was noted.

- Task performance was generally satisfactory due to the low amplitude of the disturbance and large bounds on adequate and desired performance. Pilots would not need to increase gain to achieve desired performance, even with very large command path dead zones.

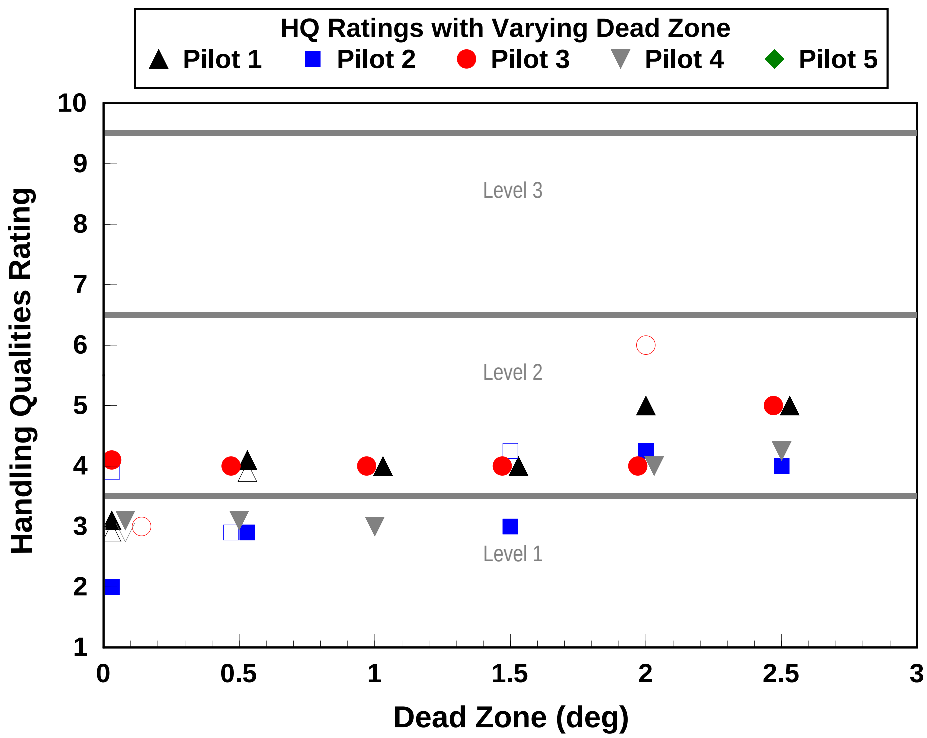
- Dead zones effectively negate pilot gain and produce control inputs and, when large enough, result in inputs that mimic more open-loop control techniques. Pilots can compensate for this effect by increasing their gain. Higher crossovers and improved task performance are achievable.

10.2.4 Piloted Evaluations Analysis Summary

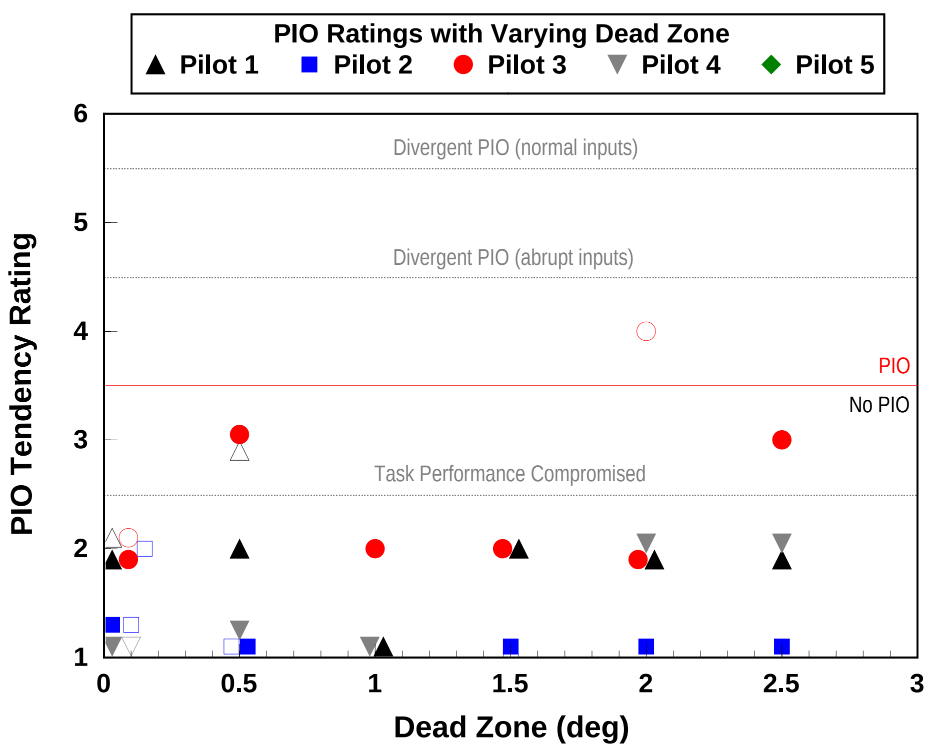
Figure 88 gives a summary of the HQ and PIO tendency ratings for the four pilots who participated in the pitch dead zone evaluations.

Though variations exist between pilots because of personal preference or ratings scale interpretation, a distinct drop in HQR occurs for dead zones above 1.5 degrees for all pilots. Pilots 1 and 3 rated the baseline airplane level 1, while moderate dead zones of 0.5–1.5 degrees degrade the airplane characteristics slightly, with ratings moving to level 2. Pilots 2 and 4 also rated the baseline airplane level 1 and though moderate dead zones degraded the airplane a similar amount, they still felt the airplane was satisfactory without improvement.

For dead zones above 1.5 degrees, all pilots saw a degradation in HQ. Pilots 1 and 4 also note an increase in PIO tendency for dead zones above 1.5 degrees, while pilot 3 showed an increased PIO tendency due to dead zone for the repeated 2.0 degree run. Though pilot 2 did not show an increased PIO sensitivity due to dead zone, examination of the HQ and PIO tendency ratings together indicates a degraded pilot opinion for dead zones above 1.5 degrees, similar to those of the other pilots. Dramatic increases in PIO tendency are not expected for dead zone cases because increased dead zone attenuates commands.



a) Handling Qualities



b) PIO Tendency

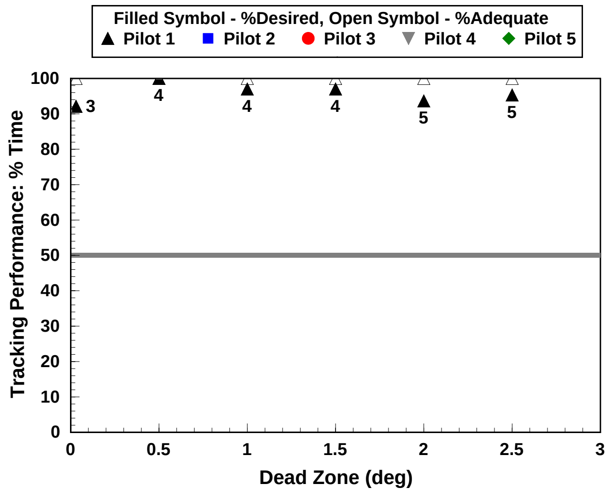
Figure 88. Pilot ratings, all pilots, pitch dead zone variations

As shown in table 56 and figure 89, task performance is not significantly impacted by dead zone. All pilots were able to achieve 90% or better desired performance for all configurations, with only pilot 3 showing slightly degraded performance for the most severe 2.5 degree dead zone case. All pilots were able to keep the aircraft within adequate bounds 100% of the time for all runs. Thus, the degradations in ratings clearly resulted from the increased compensation required when the dead zones became large.

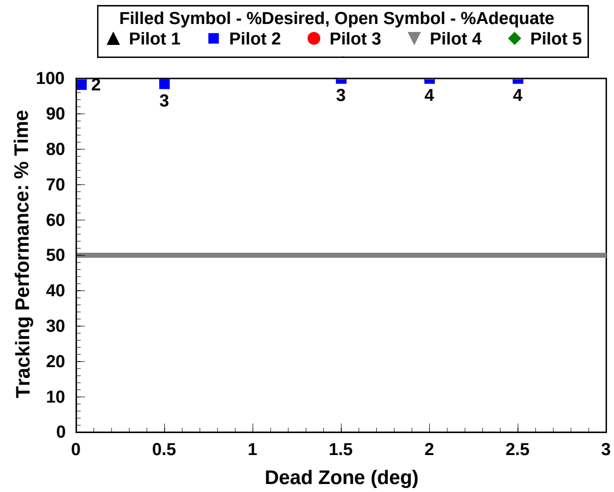
Symbol annotations in figure 89 indicate HQR for each run.

Table 56. Task performance summary, all pilots, pitch dead zone variations

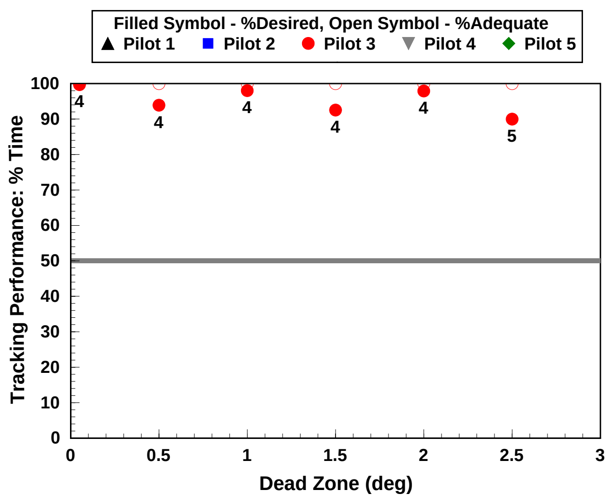
Dead Zone (deg)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
0.0	92.13	98.23	99.70	97.90
0.5	100	98.48	93.90	94.80
1.0	97.00	-	98.02	93.83
1.5	97.00	100	92.52	-
2.0	93.63	100	97.90	97.07
2.5	95.32	99.08	89.97	96.35



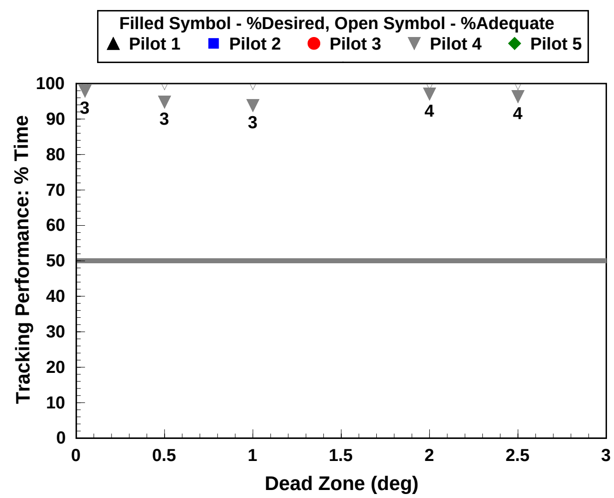
a) Pilot 1



b) Pilot 2



c) Pilot 3



d) Pilot 4

Figure 89. Tracking task performance, pitch dead zone variations

10.2.5 Detailed Analysis of Selected Cases

10.2.5.1 Introductory Notes

Examination of variations among pilots or multiple runs by the same pilot can provide insight into the effects of dead zone on pilot behavior and the level of compensation necessary to perform the task. Correlations between degraded ratings for larger dead zones and increased pilot compensation or changes in pilot behavior further emphasize the impact of the dead zone on the pilots' ability to perform a task.

The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which may be inadequate to accurately predict the impact of command path parameter changes in real aircraft due to a lack of motion cueing.

10.2.5.2 Pilot 2 — Session 2 Evaluations

10.2.5.2.1 Overview

Pilot 2 participated in pitch dead zone evaluations on June 15, 2012. The data was collected during session 2 of the Year 2 Follow-On evaluations. A total of 11 runs were completed in the pitch axis, with two unrated warm-up runs in the baseline configuration and nine scored runs that were rated by the pilot. The baseline configuration was repeated twice during the session, once blind and once known to the pilot. The 1.5- and 0.5-degree dead zone cases were also repeated but are left out of this analysis for brevity. A full listing of the configurations flown and ratings given by pilot 2 are provided in table 57 and shown in figure 90.

Table 57. Pilot ratings and comments, pilot 2/session 2

Session	Run	Configuration	HQR	PIOR	Comments
2	3	DZLON00 (baseline)	2	1	A bit more difficult task
2	4	DZLON15	3	1	Very similar, but a bit more difficult than before; very close. Workload higher
2	5	DZLON05	3	1	That one seemed different. The task looked different. Not too different configuration. Two big inputs
2	6	DZLON20	4	1	Larger amplitude inputs. Disconcerting to be on the stop one time. Larger inputs to track
2	7	DZLON00 (baseline-blind)	4	2	More PIO tendency. Easier to track than the last. More fighting for target
2	8	DZLON25	4	1	Larger amplitude inputs. Task seems inconsistent. Similar to (6)
2	9	DZLON00 (baseline)	2	1	Similar to baseline before
2	10	DZLON15	4	1	Larger inputs than baseline. Not too bad. Hit stop one time. He is at least 50% less on target
2	11	DZLON05	3	1	Somewhere between. Better than the last one. Tracks pretty well

DZLON = Longitudinal Dead Zone

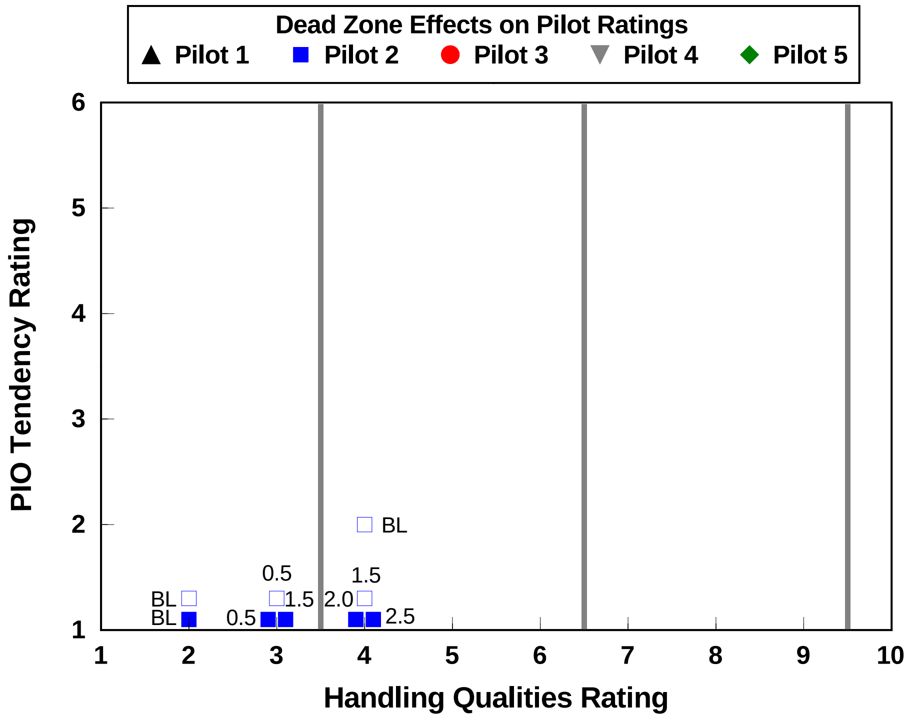


Figure 90. Ratings summary, pitch dead zone variations, pilot 2/session 2

10.2.5.3 Baseline Case

Pilot 2 evaluated the baseline pitch dead zone configuration on run 3 of session 2. This case received an HQR of 2 and a PIO tendency rating of 1. Desired performance was achieved 98.23% of the time and the aircraft was generally well-behaved for the duration of the run. Figure 91 gives a time history of the pitch disturbance regulation task for the baseline dead zone configuration.

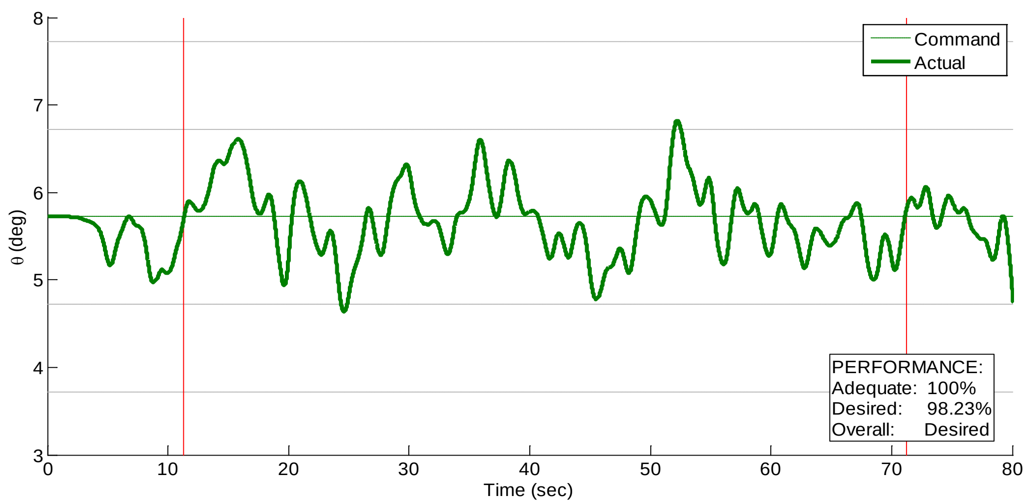
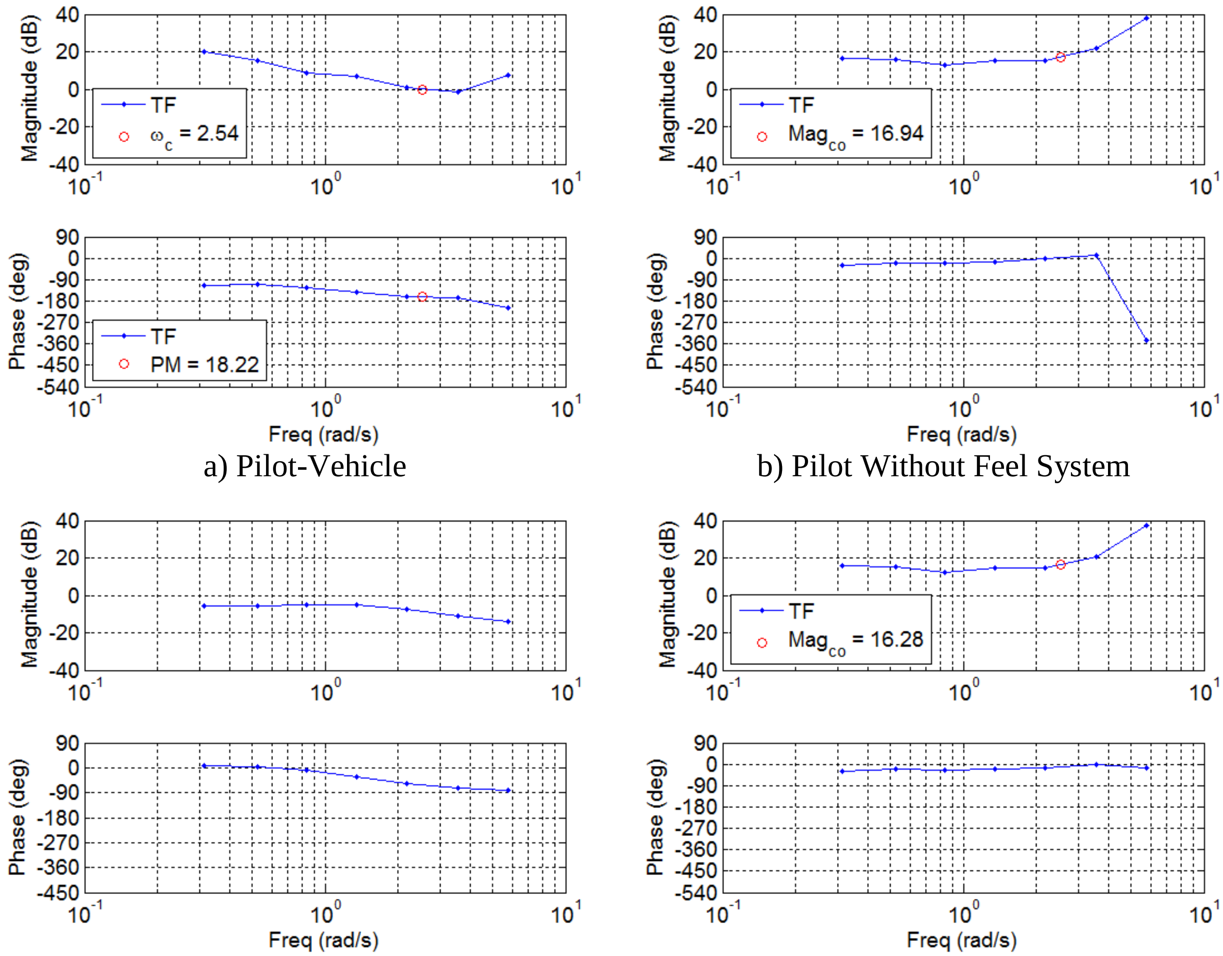


Figure 91. Task performance, session 2/run 3 (HQR 2/PIOR 1)

The PVS analysis for this run shows that the pilot exhibited pure gain behavior at low-to-moderate frequencies with lead compensation at higher frequencies, starting just below crossover and rising with increasing frequency. Note the "k/s-like" behavior near crossover in figure 92(a) with a relatively high crossover frequency of 2.54 rad/s. This indicates a significant pilot aggressiveness, with a PVS phase margin of only 18.22 degrees. There is only a minimal difference in pilot gain at crossover in figures 92(b) and figure(d), as the only nonlinearity present for the baseline case is the relatively small BO of 0.25 lb.



a) Pilot-Vehicle b) Pilot Without Feel System
c) Vehicle d) Pilot With Feel System and Nonlinearities

Figure 92. Identified describing functions, session 2/run 3 (HQR 2/PIOR 1)

<u>10.2.5.4 Large Dead Zone — 2.0 Degrees</u>

Run 6 of session 2 was a DZLON case that had 2.0 degrees of dead zone in the pitch axis feel system. There are significant differences in pilot behavior for the 2.0 degree case when compared with the baseline, as the large amount of dead zone present required additional gain compensation. Despite the additional pilot gain, the resulting compensatory command was of lower magnitude and, therefore, crossover decreased while phase margin increased. This was reflected in the pilot ratings and comments, where the vehicle was given an HQR 4/PIOR 1, with the comments, “larger amplitude inputs, disconcerting to be on the stop one time, larger inputs to track” being made by the pilot. The gain attenuation caused by the dead zone required sufficiently large inputs causing the pilot to encounter the stick position stops, which negatively impacted the HQ of the aircraft. This is shown in the time history in figure 93.

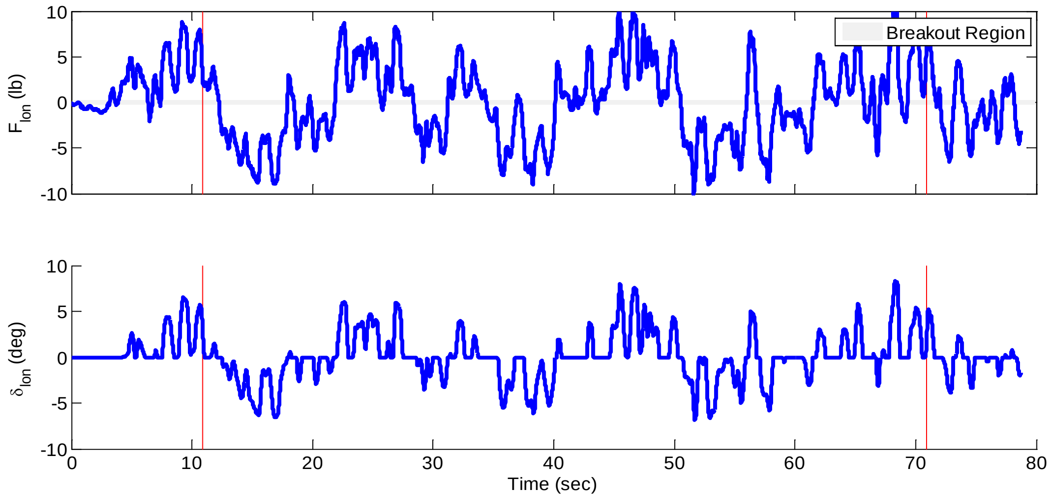
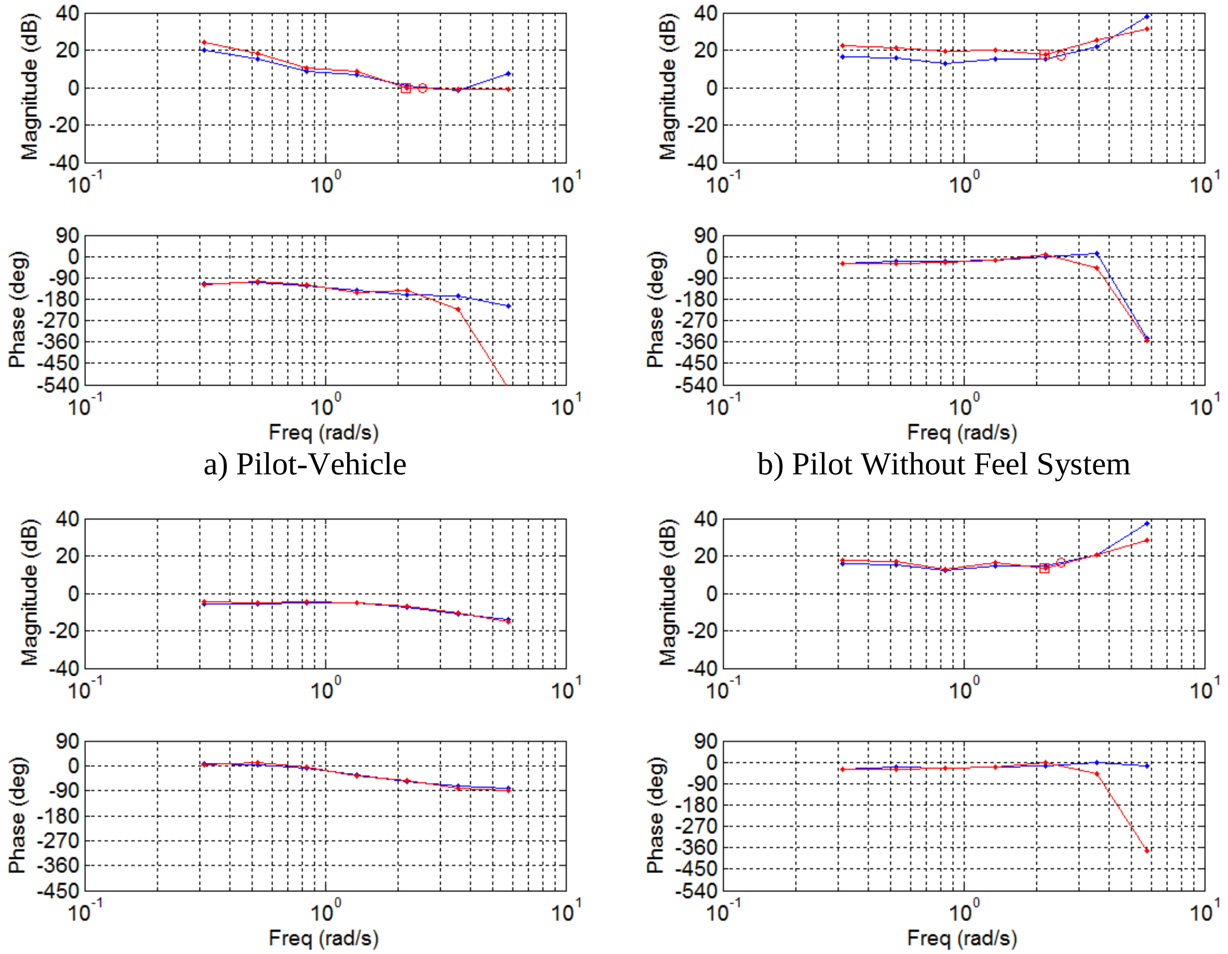


Figure 93. Stick activity, session 2/run 6 (HQR 4/PIOR 1)

When comparing the PVS analysis for the two runs (figure 94), we see the increased gain compensation required by the pilot to offset the dead zone attenuation. Figure 94(b) shows the pilot’s compensation without the effects of the feel system — and the additional gain at low frequencies is easily recognized. Also, the high-frequency lead compensation is less pronounced for run 6 compared to the baseline. Figure 94(d) shows the effect of the dead zone, as the additional pilot gain is not present after passing through the feel system and command path. The crossover frequency is slightly lower and phase margin slightly higher, but the effective pilot compensation through the dead zone is very similar, as is the overall PVS. There is a loss of roughly 4.4 dB of pilot gain due to the dead zone as well as an additional lag roll off at higher frequencies due to the increased pilot compensation.



a) Pilot-Vehicle b) Pilot Without Feel System

c) Vehicle d) Pilot With Feel System and Nonlinearities

Figure 94. Identified describing functions, overlay (run 3 – blue, run 6 – red)

The results observed in this analysis show that the pilot was required to provide additional gain compensation in the presence of the dead zone. This implies a higher workload and increased compensation, leading to the degraded ratings. The brief encounters with the stick travel limits also contributed to the increase in ratings for the 2.0 degree dead zone case.

<u>10.2.5.5 Baseline Case — Blind</u>

The baseline case was repeated blind in run 7 of session 2, with the pilot unaware that the configuration being evaluated was the baseline. This provided an interesting contrast to the run 3 baseline, which was known to the pilot, as differences in pilot behavior following the large dead zone configuration of run 6 affected the pilot's ratings of the baseline (see figure 95).

Run 7 showed a significantly higher crossover frequency (3.31 rad/s) than the run 3 known baseline case (2.54 rad/s), with only 10 degrees of phase margin. Since this run immediately followed a large dead zone case, the pilot used larger amplitude inputs than were seen in the known baseline case. The high crossover indicates that the pilot was comfortable with the configuration, yet it would appear very responsive when compared to a large dead zone configuration.

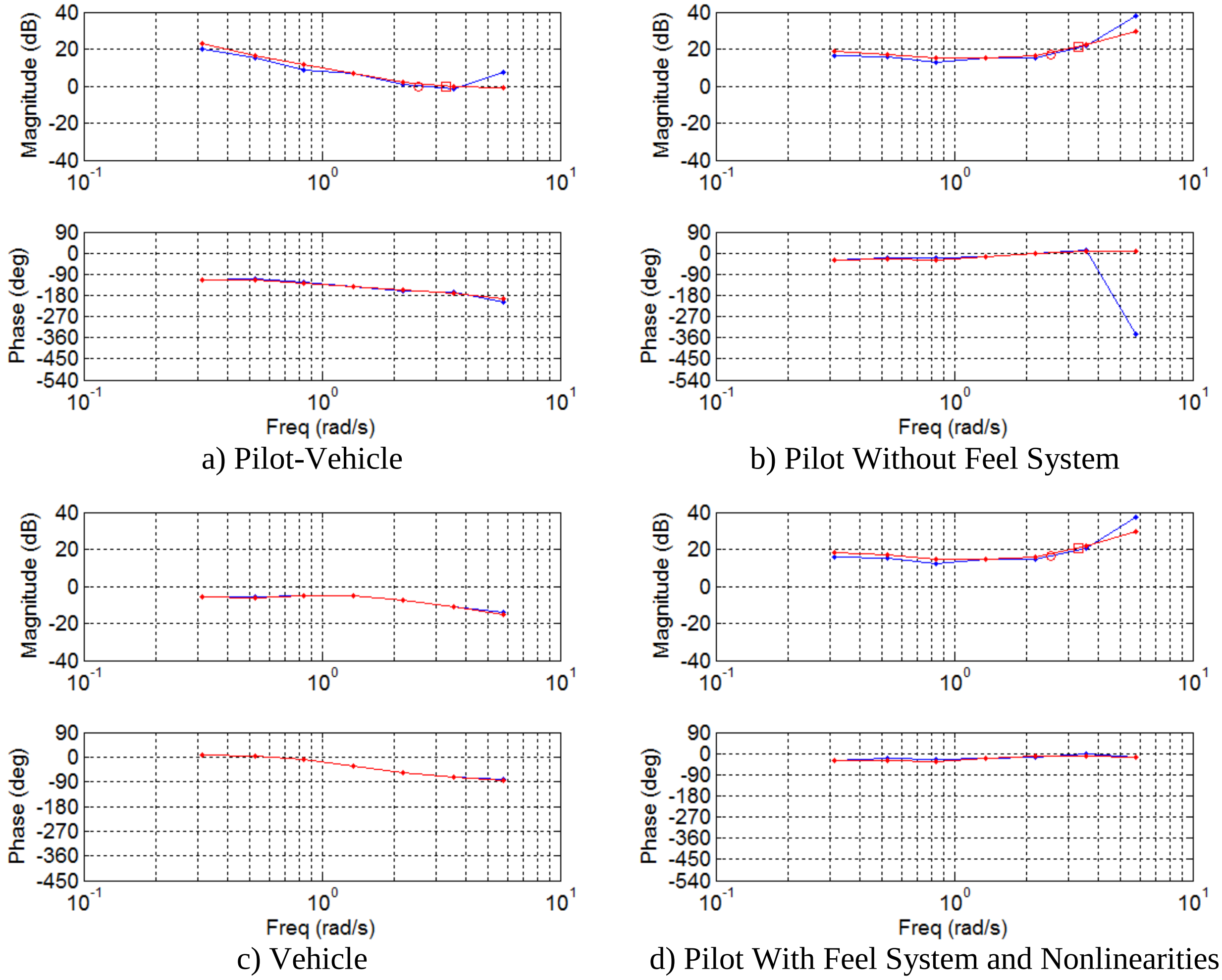


Figure 95. Identified describing functions, overlay (run 3 – blue, run 7 – red)

The pilot noted that the blind baseline case was “easier to track than the last” but that it exhibited “more PIO tendency.” This is a direct result of the restored responsiveness of the aircraft with the large dead zone removed. The results in table 76 show that repeating the baseline as a known baseline case (run 9) restored the original ratings (HQR 2/PIOR 1).

<u>10.2.6 Piloted Evaluations, Observations, and Conclusions</u>

- Based on the results of the limited fixed-base simulation study, it is not recommended that dead zones greater than 1.5 degrees be used for sidestick inceptor configurations, as HQ may be compromised.

- PIO tendency is not a significant issue for large dead zones because of the command attenuation effect. PIO susceptibility is inherently tied to large input amplitudes and dead zone increases generally negate these larger inputs.

- Task performance was not significantly affected by increases in dead zone, likely due to the generous desired and adequate bounds of ±1 and ±2 degrees and relatively low amplitude disturbance.

- The introduction of a large dead zone of 2.0 degrees shows a degradation in HQR due to increased pilot workload and brief encounters with the stick travel limits. PIO tendency is not an issue, as the resulting compensation is similar to the baseline.

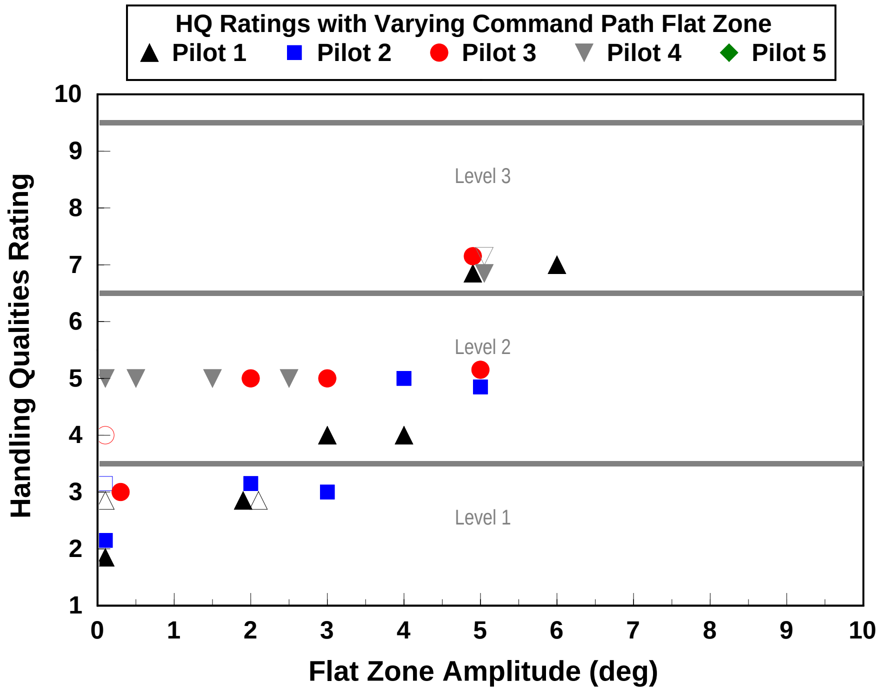
- Evaluation of a blind baseline run after a run with a large dead zone led to modified pilot behavior, which resulted in degraded HQ and an increased PIO tendency for pilot 2. Repetition of a known baseline run resulted in the same ratings as the first baseline run.

10.3 COMMAND PATH FLAT ZONE

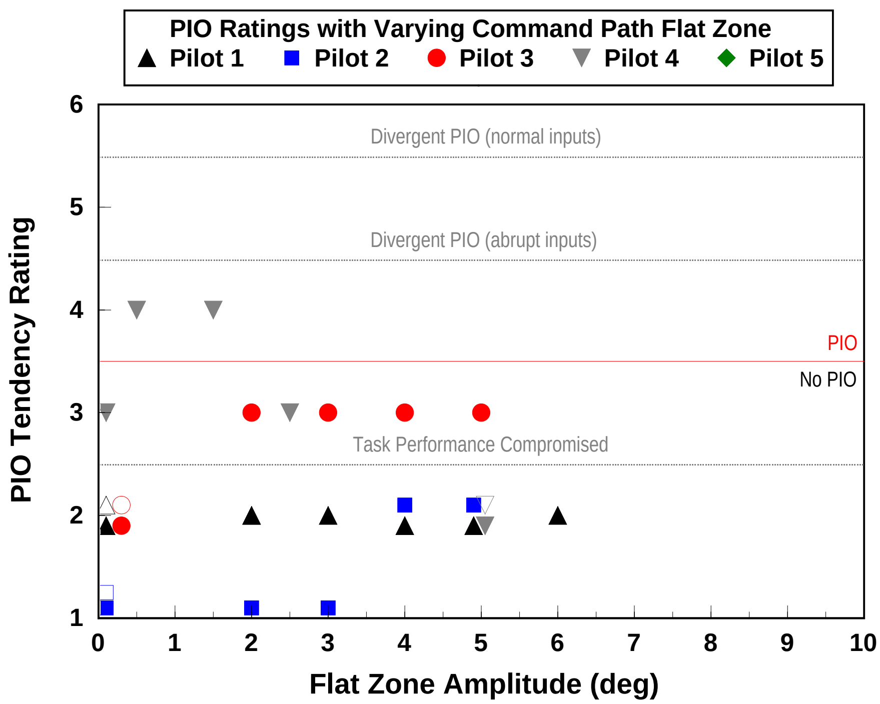
10.3.1 PA Flight Condition

10.3.1.1 Principal Outcomes

The command gain of baseline configuration is constant through the entire stick deflection. The command gain saturation was varied by changing the gain flat zone amplitude in the range FZLON = [0, 6.0] (deg), corresponding to a pitch authority variation PAUTH = [100%, 40%]. The variation range is the same for all pilots, except for pilot 1, for whom maximum amplitude was FZLON = 6.0 (deg). Figures 96(a) and 96(b) represent the HQ and PIO tendency ratings (HQR, PIOR) assigned by the different pilots on the basis of the ground simulations. Figures 97 and 98 contain the plots of the individual HQR and PIORs for each pilot as a function of flat zone amplitude. Figure 99 displays the correlation plots of PIORs versus HQR for each pilot.

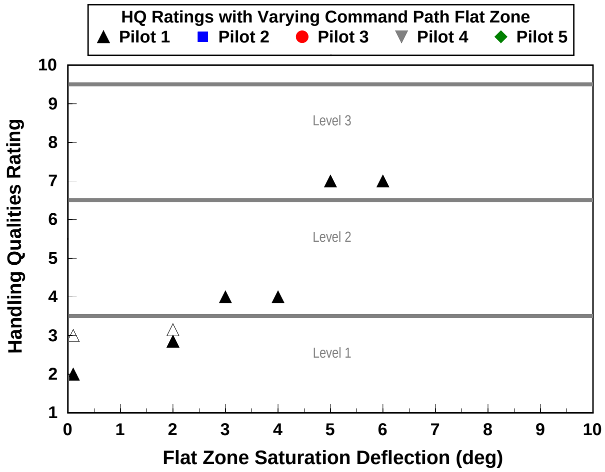


a) Handling Qualities

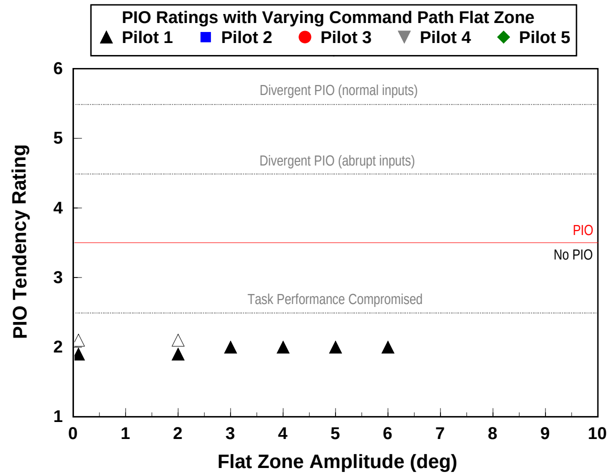


b) PIO Tendency

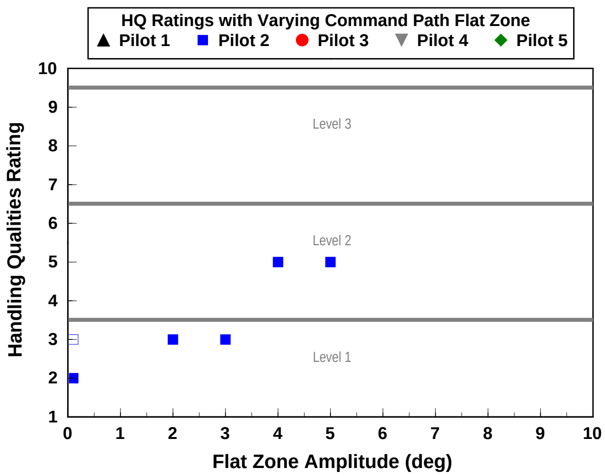
Figure 96. Ratings summary, all pilots, pitch PA flat zone evaluations



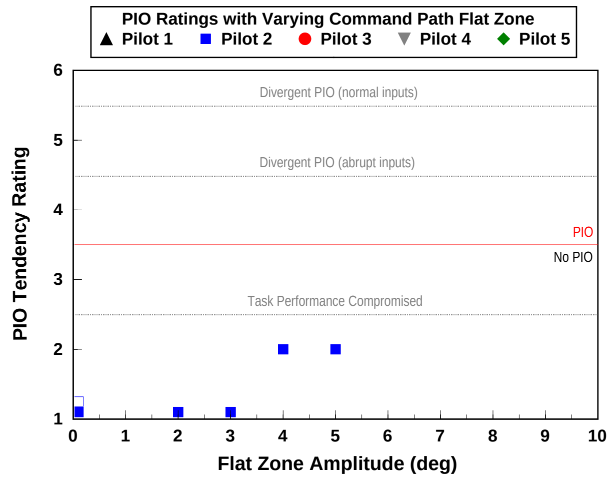
a) Handling Qualities – Pilot 1



b) PIO Tendency – Pilot 1



c) Handling Qualities – Pilot 2



d) PIO Tendency – Pilot 2

Figure 97. Individual pilot ratings, pitch PA flat zone evaluations, pilots 1 and 2

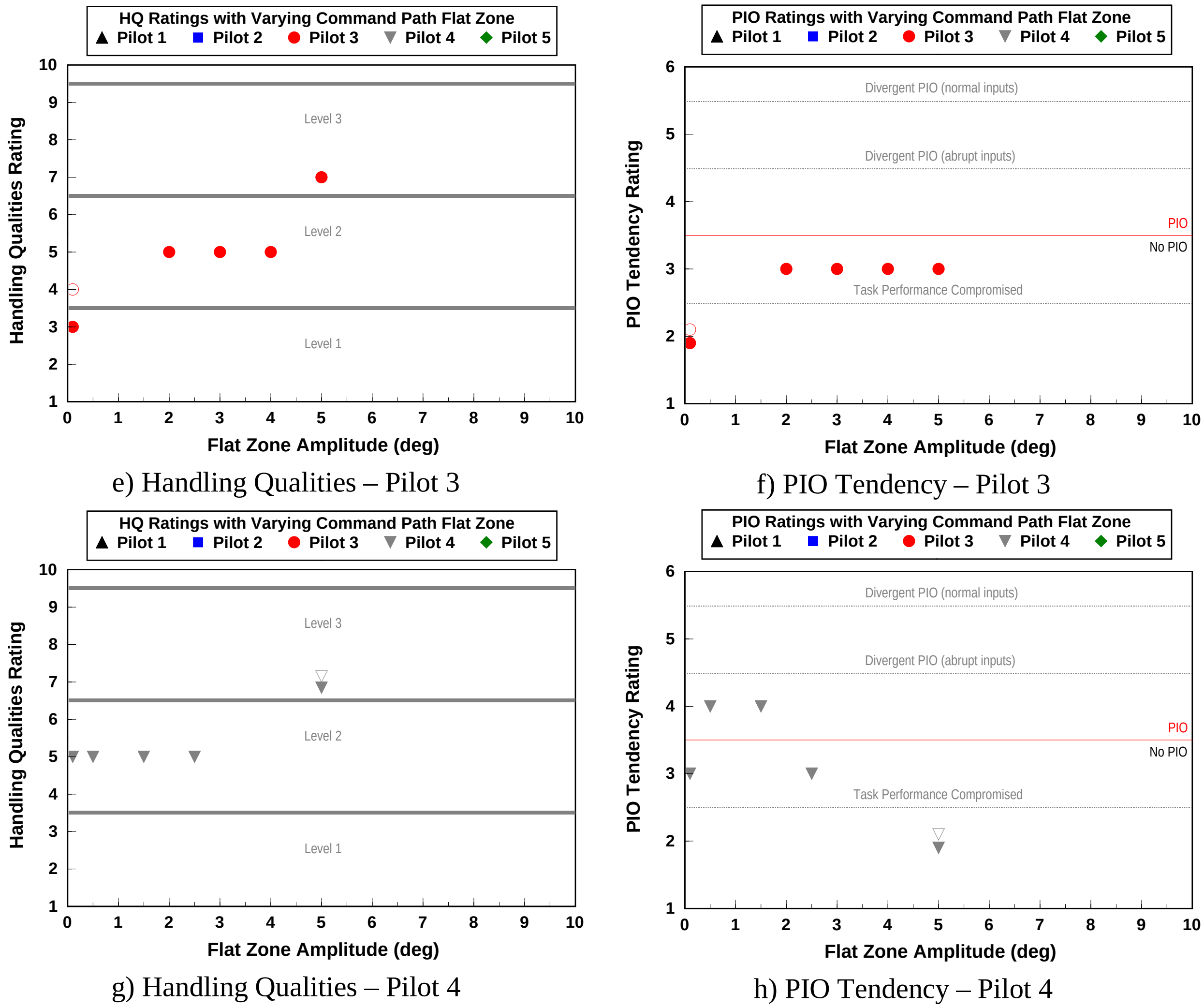


Figure 98. Individual pilot ratings, pitch PA flat zone evaluations, pilots 3 and 4

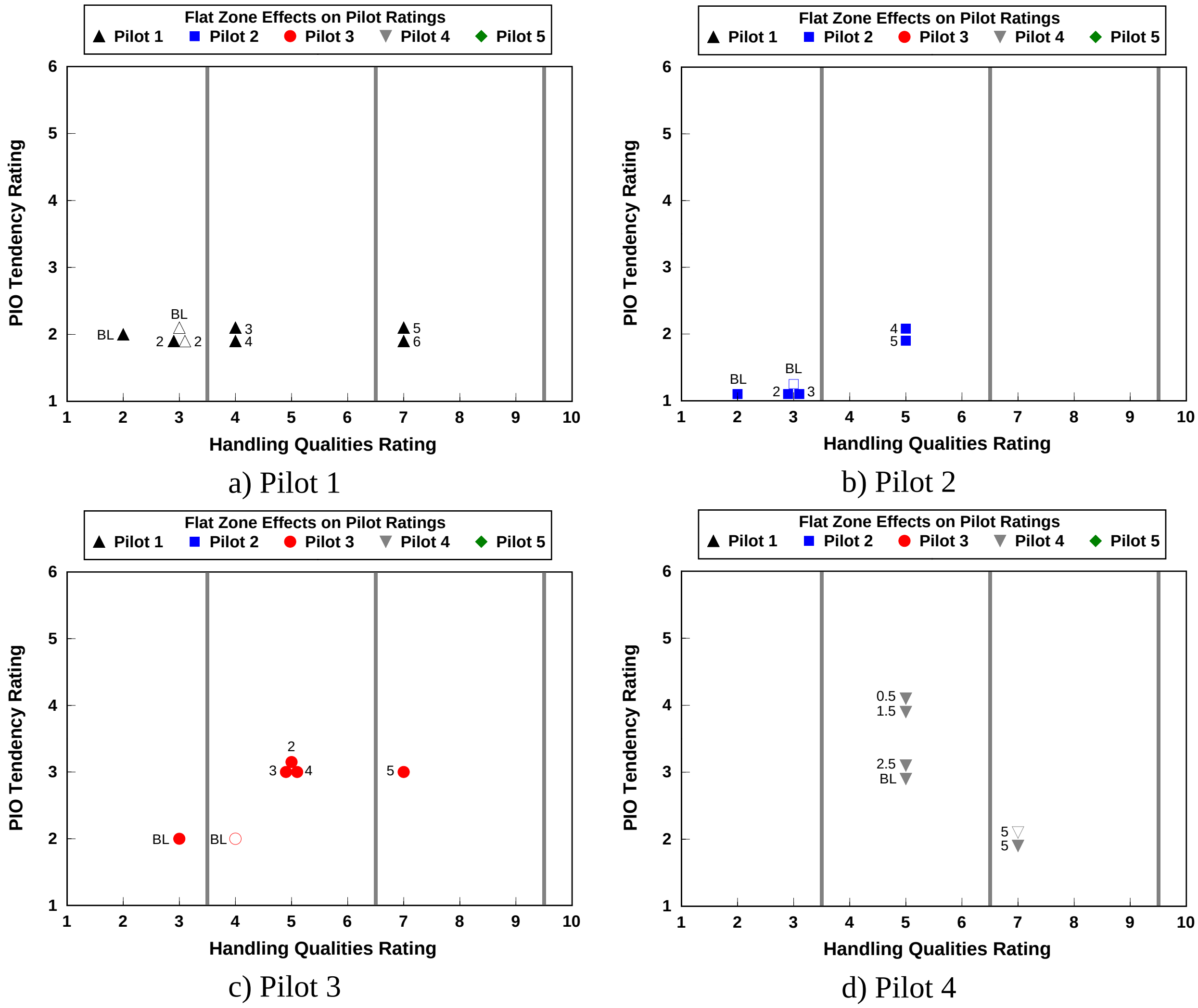


Figure 99. PIOR vs. HQR, all pilots, pitch PA flat zone evaluations

From the analysis of the pilots' ratings and simulation data, the following indications can be derived for the specific pitch attitude capture task, with SoS disturbance:

- There is a significant scatter in baseline configuration HQR and PIORs across all pilots.

- The flat zone amplitude has significant impact on all pilots' HQR, leading from HQ level 1 for the baseline configuration to level 3 for the configuration with the largest flat zone amplitude (HQR = 7). The lowest HQ level of each pilot is associated with task performance compromised because of insufficient pitch authority.

- HQR sensitivity to flat zone variation is different for each pilot. Pilot 1 demonstrates higher sensitivity and consistent correlation between HQR and flat zone amplitude.

- Minimal dependency of PIORs on flat zone amplitude is common to all pilots except for pilot 4, for whom there is a reduction of PIORs with increase of flat zone amplitude. This is considered to be due to the reduction of pitch authority, which prevents bobbling and oscillations.

- No correlation between PIORs and HQR is present for pilot 1; it is minimal for pilot 2 and 3 and consistent for pilot 4. In the last case, the HQR increase (lower HQ level) corresponds to a lower PIO proneness because of the related reduction of pitch authority.

- For values FZLON ≥ 5.0 deg, all pilots report that the task is compromised. This is the main reason for a significant degradation of HQ and transition to HQ level 2 for all pilots, except pilot 2. This does not show a correspondent significant reduction of task scoring.

- From analysis of the stick inputs PSD [15] plots of figures 100–103, it is possible to identify different piloting techniques: stick inputs of pilot 1 have larger amplitude than those of the other pilots throughout the whole frequency range. Inputs of pilots 1 and 2 are characterized by higher energy content at two definite angular frequencies ($\omega \approx 0.25; 0.4\ \frac{\text{rad}}{\text{s}}$), with local peaks of significantly relative lower amplitude in the range $\omega \approx [0.6, 1]\ \frac{\text{rad}}{\text{s}}$. This is considered an indication of a combined open- and closed-loop piloting technique for gross acquisition and fine tracking, respectively.

  Pilot 4 stick inputs are characterized by a higher input energy content in the range of frequencies delimited by the values reported above (no split), with low/negligible levels in the higher frequency range. This indicates the tendency to a smoother and more open loop-type piloting technique. Pilot 3 inputs have a low frequency content similar to pilots 1 and 2, with low to negligible higher frequency content, similar to pilot 4. Pilot 3's technique can be considered intermediate between pilots 1 and 4 for this task.

  The lower frequency amplitude is directly proportional to the amplitude of the flat zone: higher flat zone amplitude corresponds to higher inputs amplitude, consistent with the dual nature of the task. This is an indication of the tendency to perform gross acquisitions with larger inputs when pitch authority is limited by the flat zone.

- HQR are not consistently correlated with task scoring, which is, on average, higher than 60% desired for the continuous regulation part of the task and higher than 70% for the discrete captures, for all pilots. A slight tendency to the reduction of the discrete captures scoring with lower HQR has been identified, for pilot 1 in particular.

From the points illustrated above, it is derived that flat zones' impact on HQ is mostly related to control authority. A reduced-pitch authority is associated by the pilot with a lower performance. The performance evaluation conducted by the pilots for the HQR includes more subjective factors, among which the gross acquisition pitch rate and the relative compensation required. The discrete part of the task is more relevant than fine tracking for the HQ assessment. The inability to accomplish a single capture due to authority limitation leads to a significantly degraded HQR.

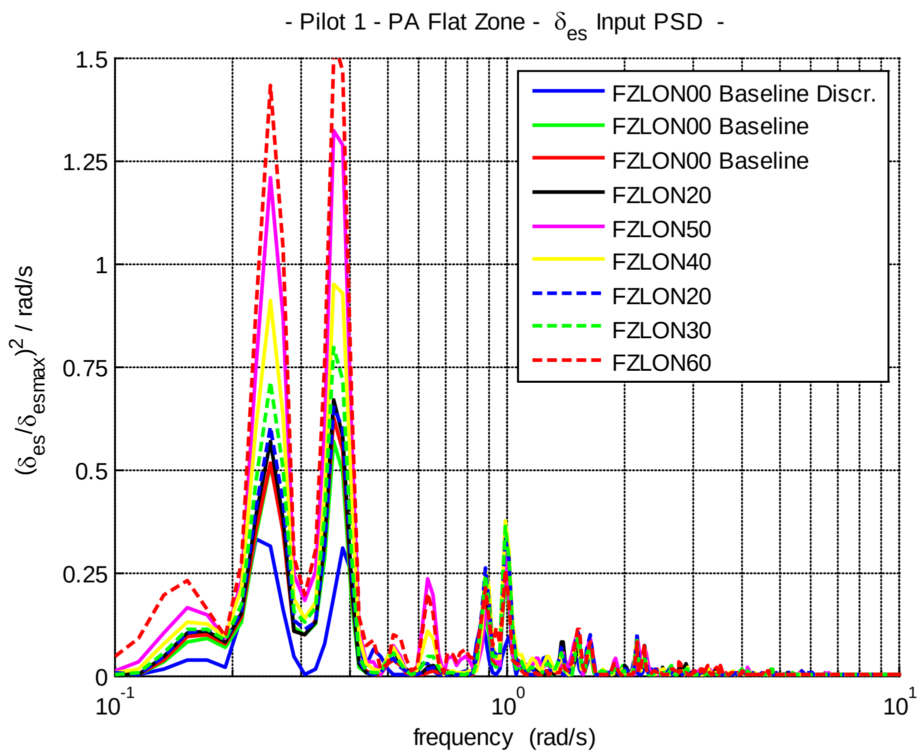


Figure 100. PSD of pilot 1 δ_{es} INPUT — PA flat zones

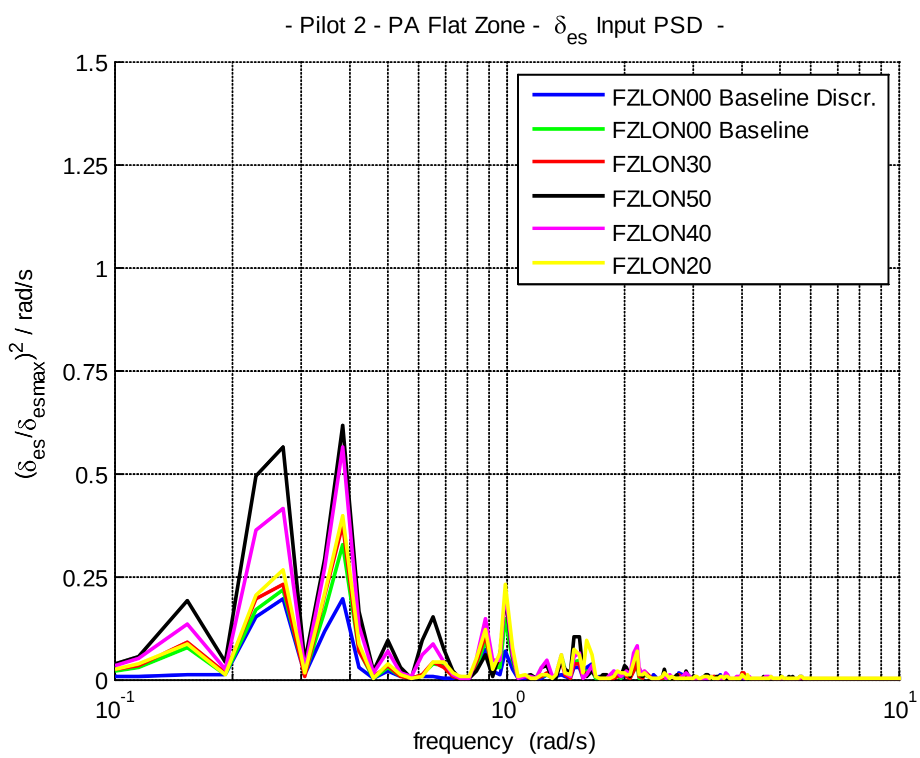


Figure 101. PSD of pilot 2 δ_{es} input — PA flat zones

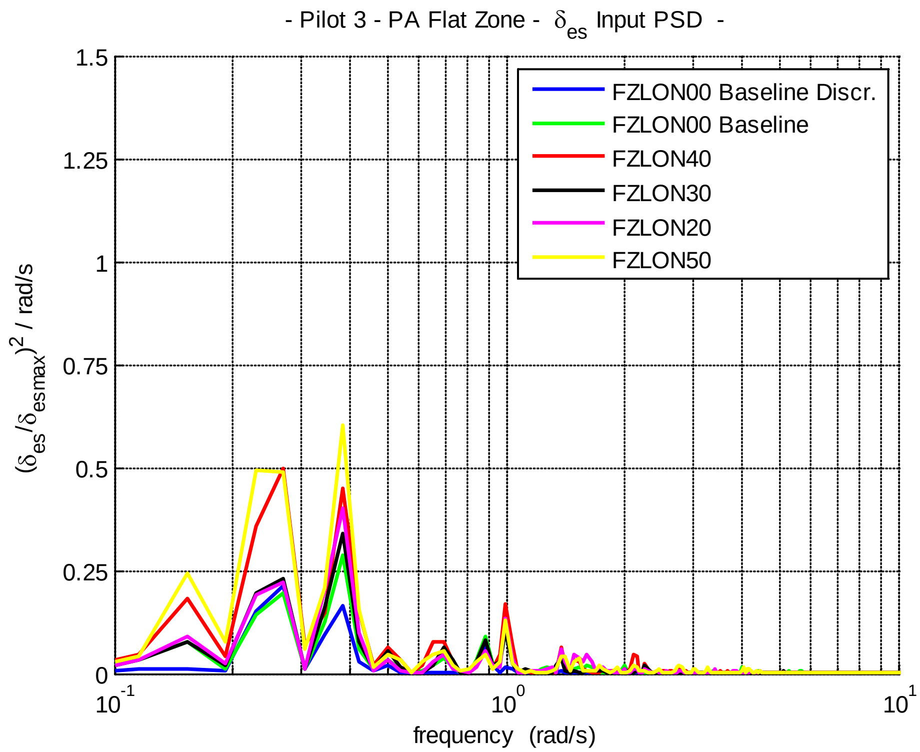


Figure 102. PSD of pilot 3 δ_{es} input — PA flat zones

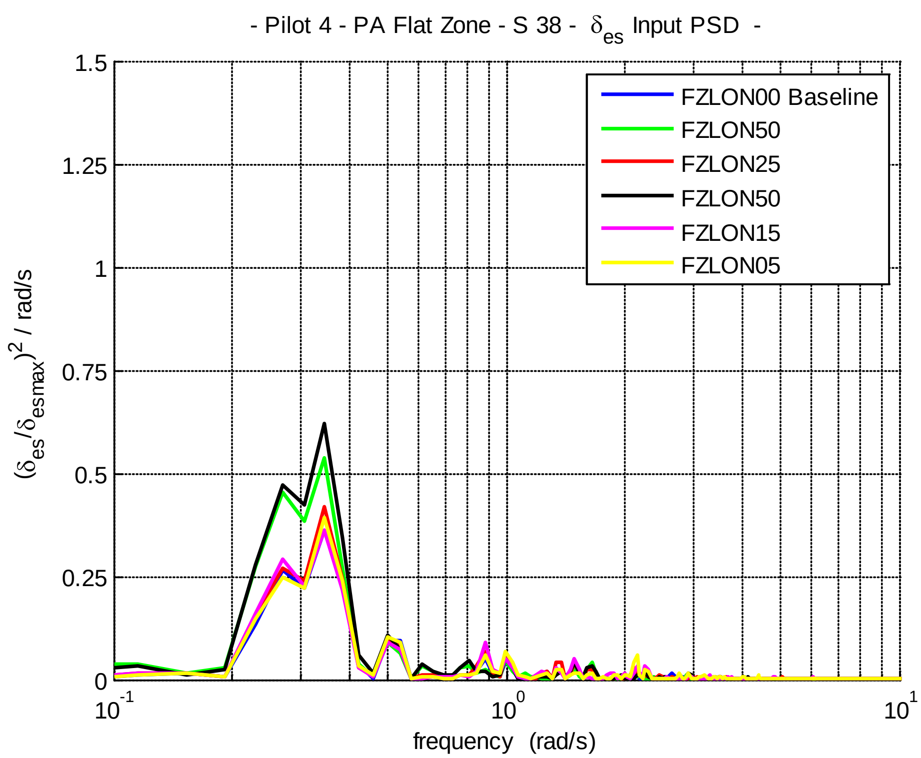


Figure 103. PSD of pilot 4 δ_{es} input — PA flat zones

10.3.1.2 Pilot Ratings, Comments, and Task Scoring

10.3.1.2.1 Pilot 1

Pilot Ratings and Comments — Baseline configuration is rated HQ level 1 with respect to both pure discrete tracking task and discrete task + SoS disturbance. A consistent correlation between HQR and flat zone amplitude can be identified, with ratings worsening increasing amplitude. The higher amplitude flat zones (FZLON = 5.0; 6.0 deg) are rated HQ low level 2, HQR = 7. This is related to the impossibility to reach maximum AoA: "Can't get to the maximum alpha, this is a problem." Lower values of flat zone amplitude are rated HQ marginal level 1/2 (HQR = 3/4); also, when a control authority limitation is perceived, as long as it is possible to achieve the target AoA: "I can tend to accept whatever rate to capture as long as it is not too heavy." In this case, the authority limitation is related by the pilot to increased heaviness of the stick.

Task Performance — Task performance is, on average, 60% desired and 70% adequate for the continuous regulation task. It is 85% desired, and 90% adequate for the tracking task, except for the configuration FZLON = 6 deg, where it is 40% desired = adequate. This is a quantitative indication of the impact of flat zones on task performance, confirmed by the lowest rating (HQR = 7).

Piloting Technique and Time Histories — Time histories show large amplitude, FBS inputs for gross acquisition and low amplitude/closed loop inputs for capture refinement and regulation. The large amplitude inputs are sustained in time in the configurations with maximum flat zone amplitude (minimum authority) until pitch attitude is captured.

10.3.1.2.2 Pilot 2

Pilot Ratings and Comments — Pilot 2 stressed in his comments the dual nature of the task (gross acquisition and continuous regulation), which required him to "divert attention to two different tasks." Large amplitude flat zones are associated with unpredictability and rated HQ level 2 (HQR = 5). Lower amplitude ones are related to higher compensation: "I have to modulate input for going past green [i.e., alpha target]." However, the slight amount of additional compensation does not lead to HQ degradation. They are rated HQR = 3, the same rating as baseline with SoS disturbance.

Task Performance — Task performance is, on average, 60% desired and 68% adequate for the regulation part of the task and 77% desired and 88% adequate for the discrete part of the task. No correlation between task performance and HQR, PIORs can be identified.

Piloting Technique and Time Histories — Time histories confirm the combined open loop/closed loop piloting technique identified through the stick inputs PSD of figure 101, with lower amplitude with respect to pilot 1. With the largest amplitude flat zone configuration and pitch authority reduced 50%, gross acquisition is performed with FBS inputs until the target pitch attitude is captured. The subsequent closed-loop inputs are of average large amplitude as well (see figure 104).

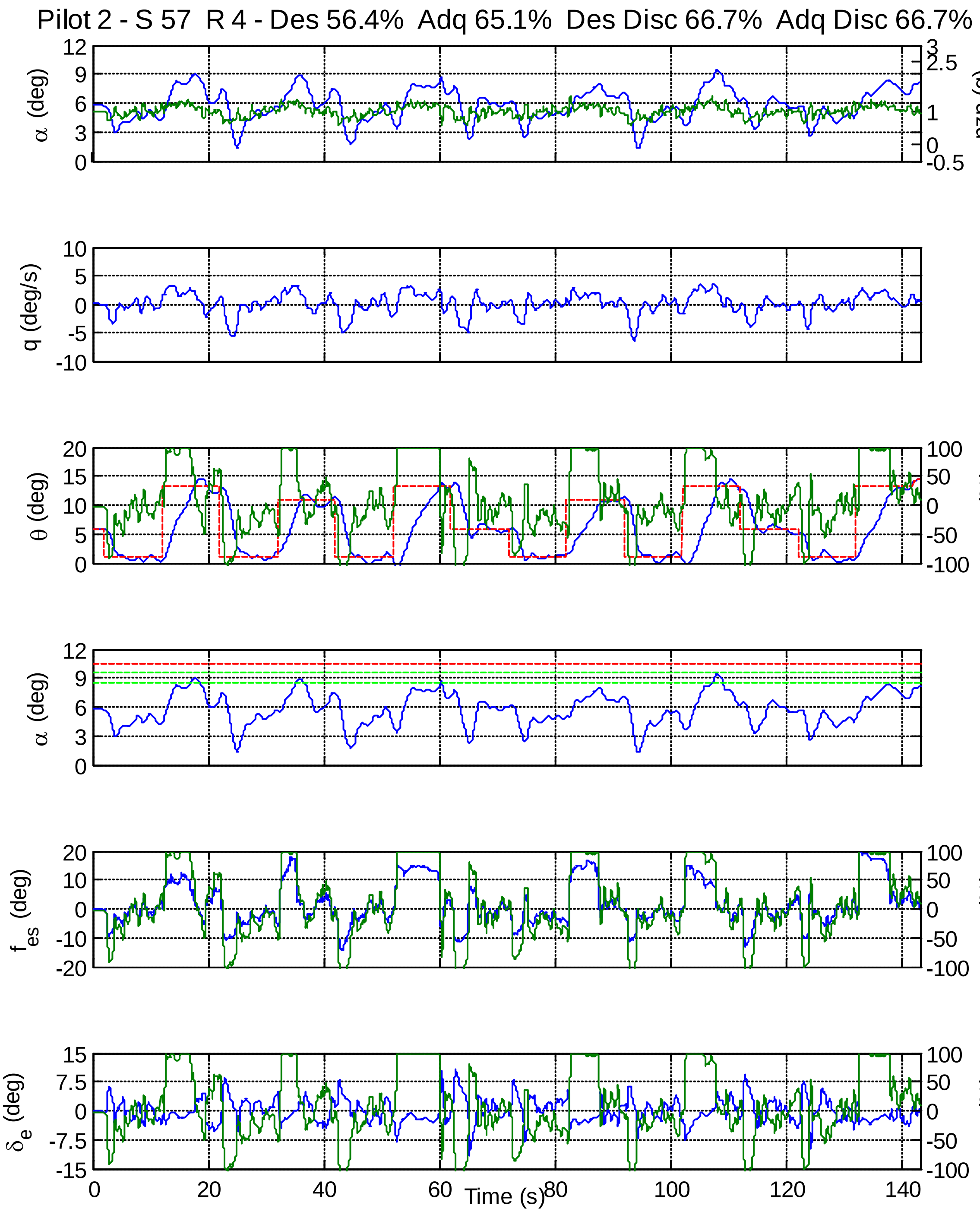


Figure 104. Pilot 2 FZLON = 5.0 deg captures time history plot — PA

10.3.1.2.3 Pilot 3

Pilot Ratings and Comments — Baseline configuration is rated low HQ level 1 (HQR = 3) with pure discrete captures task and HQ level 2 (HQR = 4) with discrete + SoS disturbance. The impact of varying flat zone amplitude on HQ level is minor, as all configurations except the one with largest flat zone amplitude are HQR = 5. Significant impact on HQ is rated for the largest amplitude flat zone, which is level 2 (HQR = 7). This derives from the insufficient pitch authority, which does not allow the pilot to satisfy the discrete capture requirement of achieving AoA = 9 ± 0.5 deg: "Full back stick, on the stops still doesn't get there, for a while extensive compensation. Much less alpha and g than target." In this case, "adequate performance is not attainable with a tolerable pilot workload" and "adequate performance is not attainable with maximum tolerable pilot compensation. Controllability not in question," as no combination of workload and compensation allows the pilot to complete the task successfully. See HQR scale in figure 59. The HQR is the lowest for controllable aircraft. This demonstrates high correlation of HQR with local task performance, determined by the discrete part of the task. It is important to note that the rating is based on two unsuccessful captures, which do not significantly affect the overall performance quantitatively.

Task Performance — In the regulation part of the task, the average performance is 50% desired and 60% adequate, with 70% desired and 90% adequate for the discrete captures. There is a slight correlation between discrete task performance and flat zone amplitude, with the slightly higher ratings for the configurations associated with lower amplitude flat zones.

Piloting Technique and Time Histories — The analysis of the time histories demonstrates that pilot 3's inputs are FBS in the configuration with minimal pitch authority, with the tendency to capture the required pitch attitude and AoA. In all other configurations, inputs are modulated also for gross acquisitions and closed loop inputs can have large amplitude: higher frequency content displayed by the PSD of figure 100. Figure 105 provides an example of pilot 3's technique.

10.3.1.2.4 Pilot 4

Pilot Ratings and Comments — Baseline is rated HQ level 2 for the amount of lead and the concentration required to achieve the desired AoA. The relative comment is, "I have to concentrate on the AoA. I have to predict where it is going to stop. I need low gain. I have to lead." Pilot 4's ratings range is reduced (HQR = 5; 7); however, they demonstrate a correlation with the flat zones' amplitude. There is a reduction of HQR and PIORs with increasing amplitude, indicating a lower HQ level and corresponding lower PIO proneness of the configurations with reduced pitch authority: PIOR = 2 for FZLON = 5.0 deg, while PIOR = 4 for the baseline configuration. As a result, there is good correlation between HQR and PIORs. The worst rating is HQR = 7, assigned to the FZLON = 5.0 deg configuration. As for the other pilots, this depends on the reduced authority and the inadequate performance achieved. "Full stick and I do not get what I want. I do not like that … Problem to get into the green."

Task Scoring — Scoring is, on average, 78% desired, 83% adequate for the discrete captures and 61% desired, 69% adequate for the continuous regulation task, with small variations across the different configurations. It is not strictly correlated to HQR and PIORs. Scoring is 100% desired/adequate for the discrete task and 63% desired, 71% adequate (second highest) for one configuration with HQR = 7, indicating that the performance is assessed by the pilot based on the subjective evaluation of the aircraft capability to accomplish the task—with respect to both task guidelines and comparison with expected adequate dynamics response.

Piloting Technique and Time Histories — Analysis of the time histories shows that pilot 4 has a low-frequency input shaping technique, also in the gross acquisition phase of the task, indifferently for large and small flat zone amplitudes. There is no tendency to hold FBS in an open-loop technique until the capture is completed. This is considered to be the reason for most of the input energy to be distributed in the frequency range $\omega = [0.2, 0.42]\ \frac{\text{rad}}{\text{s}}$, with a single absolute maximum at $\omega = 0.34\ \frac{\text{rad}}{\text{s}}$. Closed-loop, higher frequency inputs have smaller amplitude. Figure 106 provides the time history of session 38, record 7, FZLON = 5.0 deg.

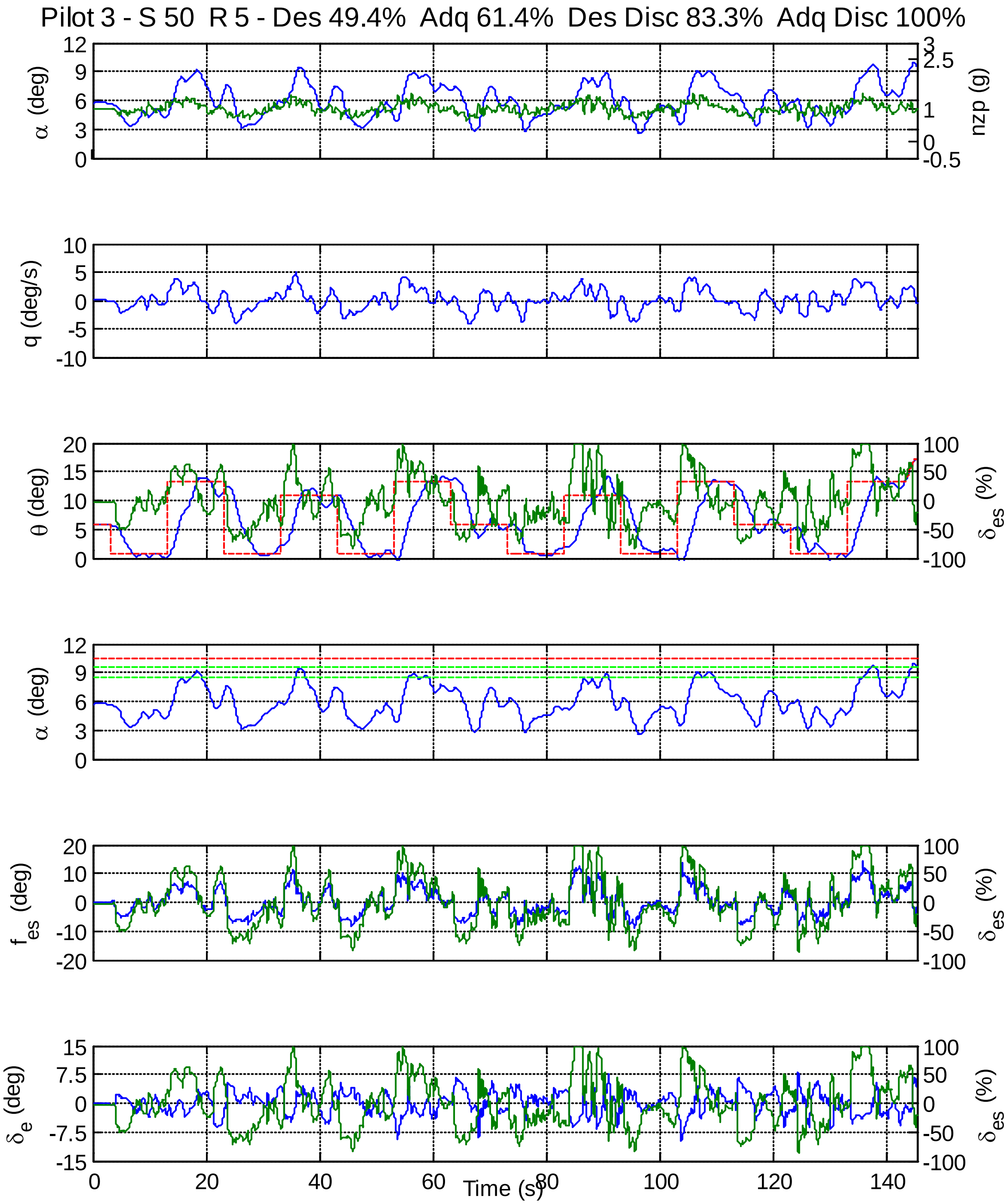


Figure 105. Pilot 3 FZLON = 2.0 deg captures time history plot — PA

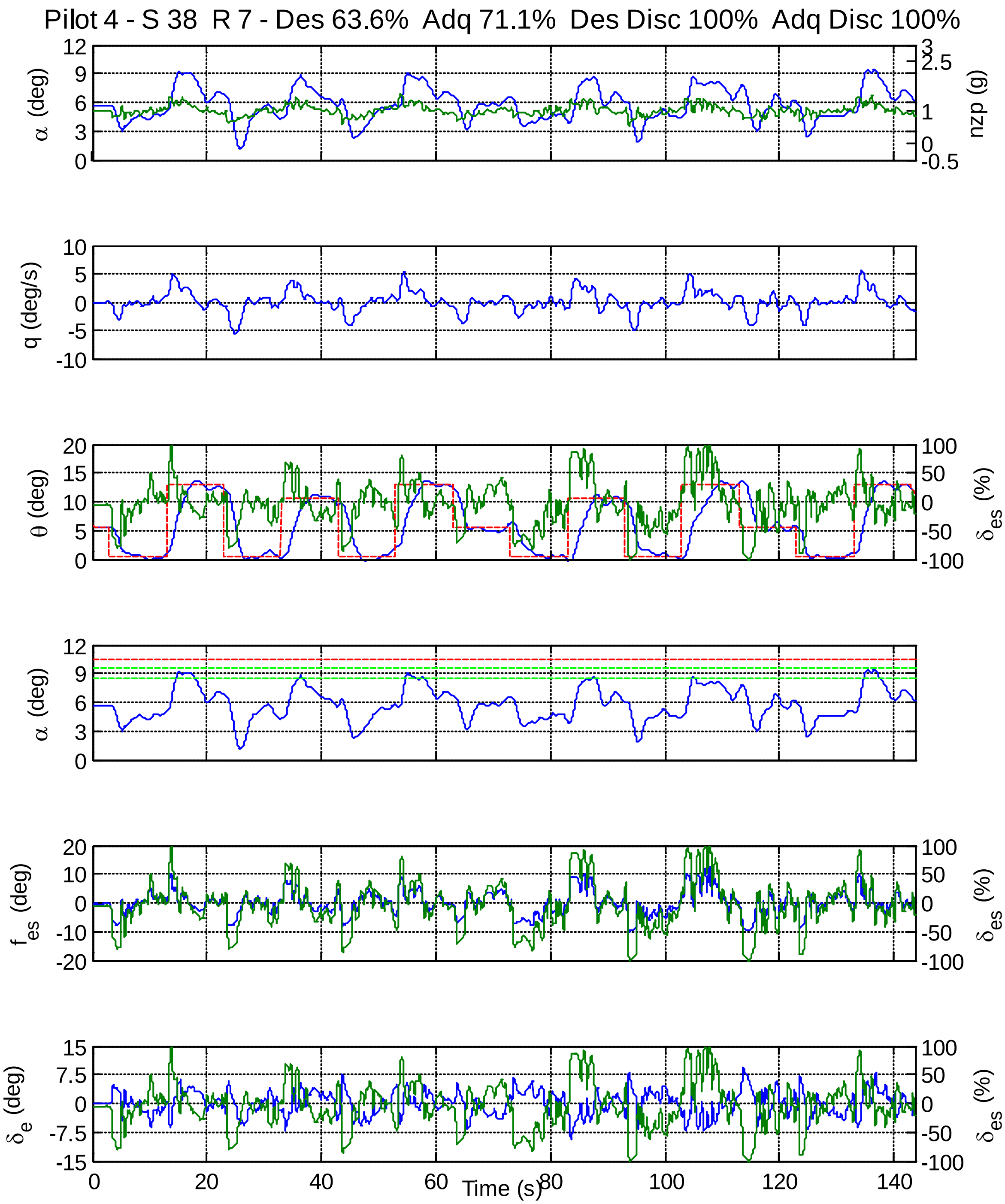


Figure 106. Pilot 4 FZLON = 5.0 deg captures time history plot — PA

10.3.2 V_C Flight Condition

10.3.2.1 Principal Outcomes

As for the PA flight condition, the command gain of baseline configuration is constant through the whole stick deflection. The flat zone was varied for both positive and negative stick deflection. The variation was in the range of FZLON = [0, 8.0] (deg), corresponding to a pitch authority variation of PAUTH = [100%, 20%] for positive stick inputs and FZLON = [0, -7] (deg), corresponding to authority variation PAUTH = [100%, 30%] for negative stick inputs. Evaluations of the positive flat zones was performed first in order to assess the pilot's preferred value. The preferred value was then kept constant and negative values of the flat zones were tested in combination. The range of variation is slightly different among the pilots, as the values to be tested were also based on the pilot's comments during the evaluation. Figures 107 and 108 display the HQR as a function of positive flat zone amplitude. The value of the combined negative flat zone is noted near the symbol in all the plots. Figure 109 displays the correlation between PIORs and HQR for all the pilots.

From the analysis of the pilots' ratings and simulation data, the following indications can be derived for the specific pitch attitude capture task with SoS disturbance:

- There is no scatter in baseline configuration HQR across all the pilots. Slightly higher scatter is occasionally present for baseline PIORs with a single case rated to be PIO prone (PIOR = 4) for pilot 4.

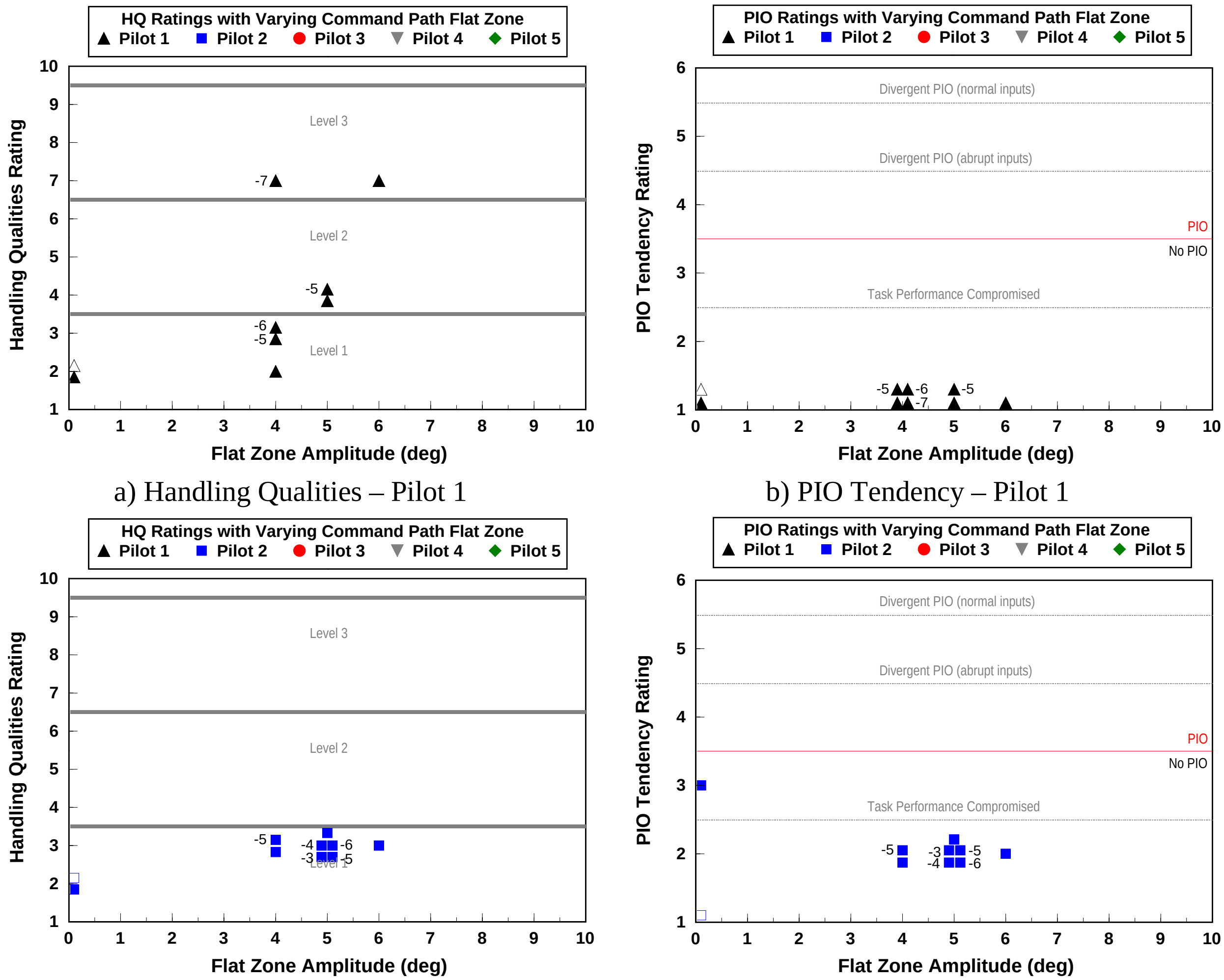
- As for the PA flight condition, the impact of the flat zone on HQ is due to the pitch authority limitation, which can impact the capability of performing the task with the desired performance and affects the predictability of the response. Pilot 3 indicated that the deriving longer time to acquire the target affects the fine-tracking precision as well since less time is available for the transition from gross acquisition to tracking.

- No correlation can be identified between PIORs and HQR. In a single case, pilot 3 indicated a lower tendency to PIO in the presence of the flat zone (FZLON = 5.0 deg).

- Piloting technique can affect the ratings scatter and the exposure of the effect of the flat zone. Pilots who use smaller amplitude inputs in gross acquisition (pilots 2 and 4) show the minimum HQR dependency and scatter on the flat zone amplitude. Their comments may occasionally not be in complete agreement with what is expected for the given configuration.

- There is no significant direct correlation between ratings and task scoring; however, scoring can be used as an indication of average piloting technique, which can affect the ratings of some configurations.

- The intended broad envelope protection function provided by the flat zone is not assessed as an HQ improvement by any pilot. The limitation of pitch authority and the reduction of response predictability overcomes the potential advantage of a more carefree maneuvering piloting technique (see figures 110–113).



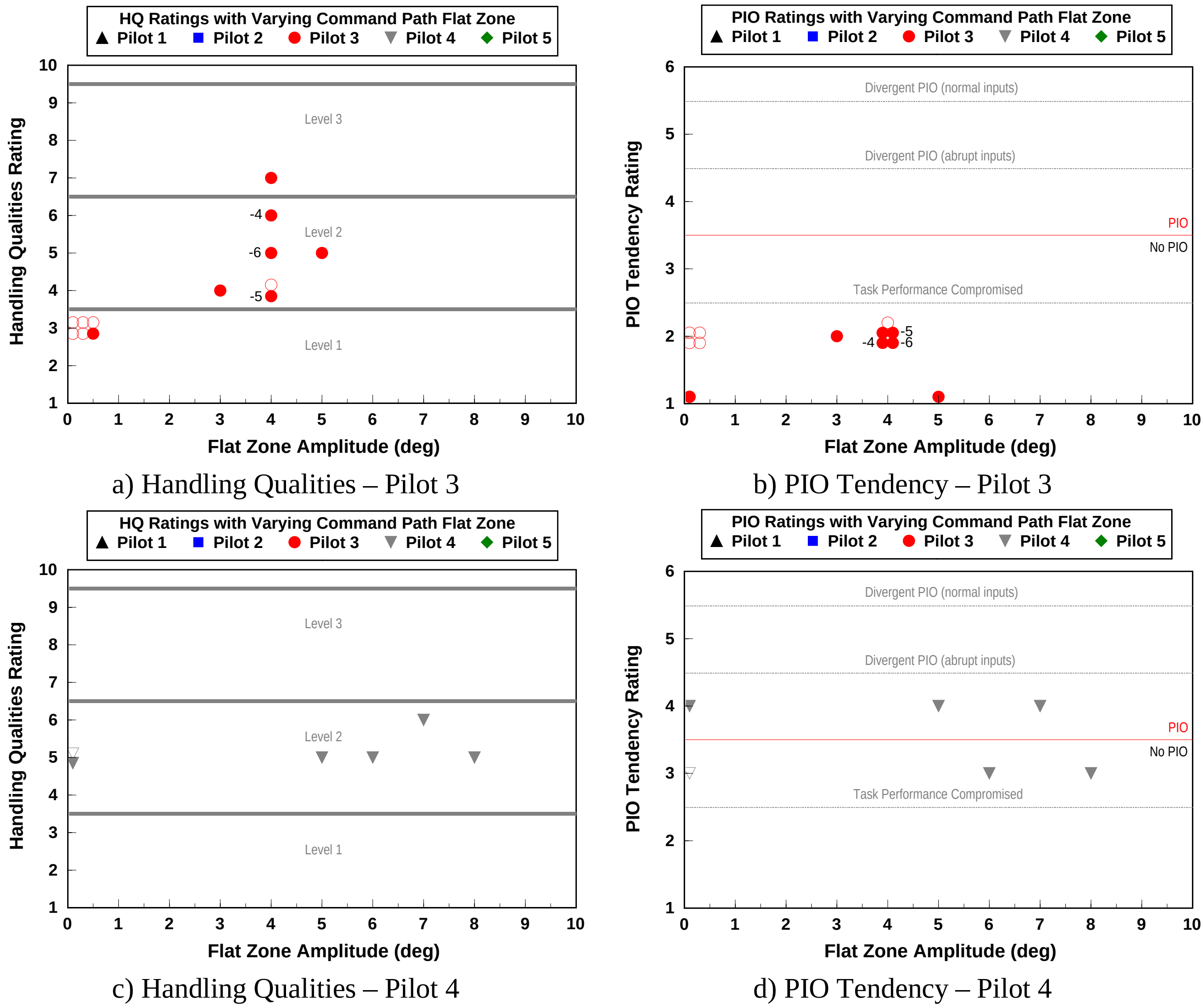
a) Handling Qualities – Pilot 1

b) PIO Tendency – Pilot 1

c) Handling Qualities – Pilot 2

d) PIO Tendency – Pilot 2

Figure 107. Individual pilot ratings, pitch V_C flat zone evaluations — pilots 1 and 2



a) Handling Qualities – Pilot 3

b) PIO Tendency – Pilot 3

c) Handling Qualities – Pilot 4

d) PIO Tendency – Pilot 4

Figure 108. Individual pilot ratings, pitch V_C flat zone evaluations — pilots 3 and 4

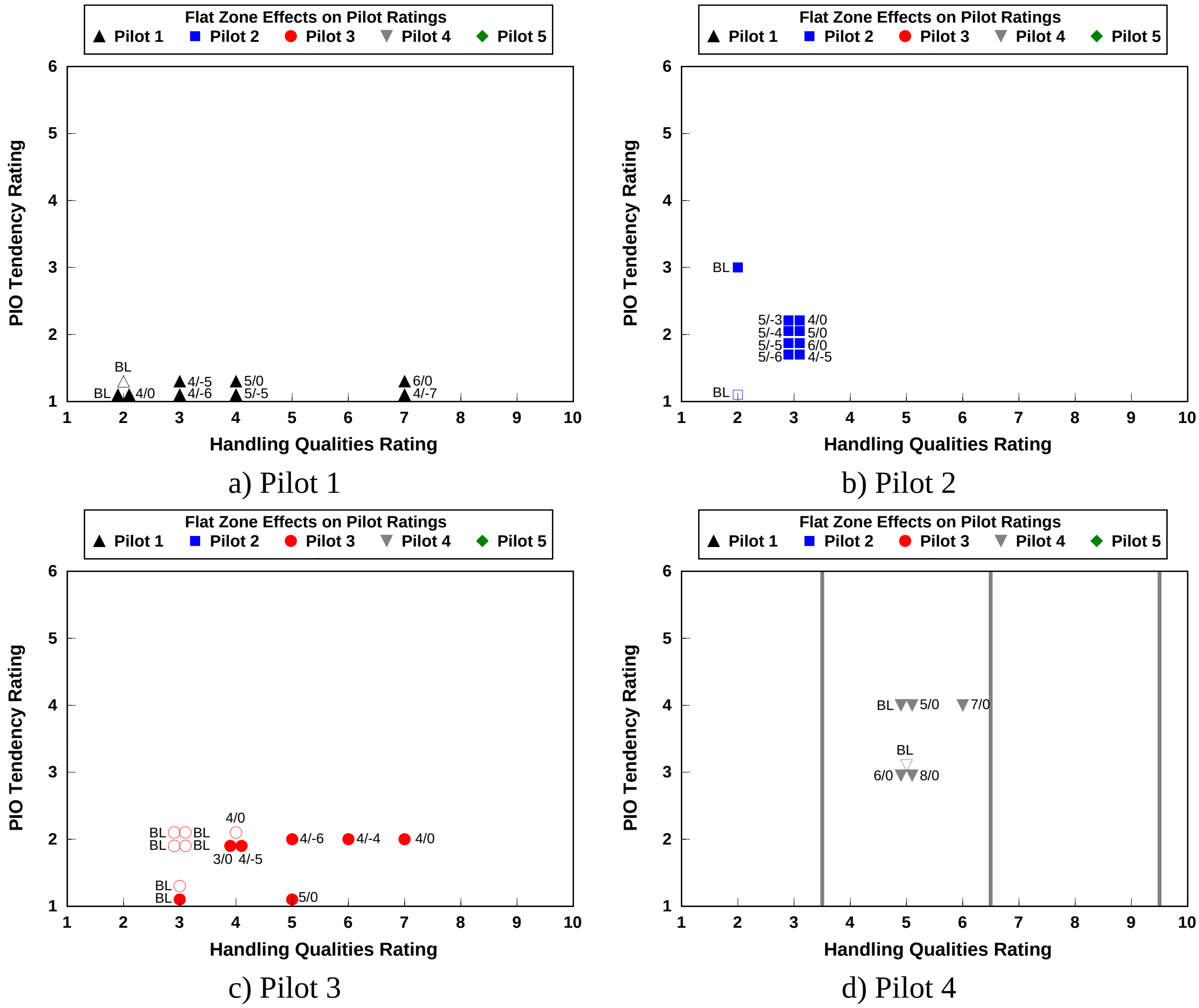


Figure 109. Ratings summary, all pilots, pitch V_C flat zone evaluations

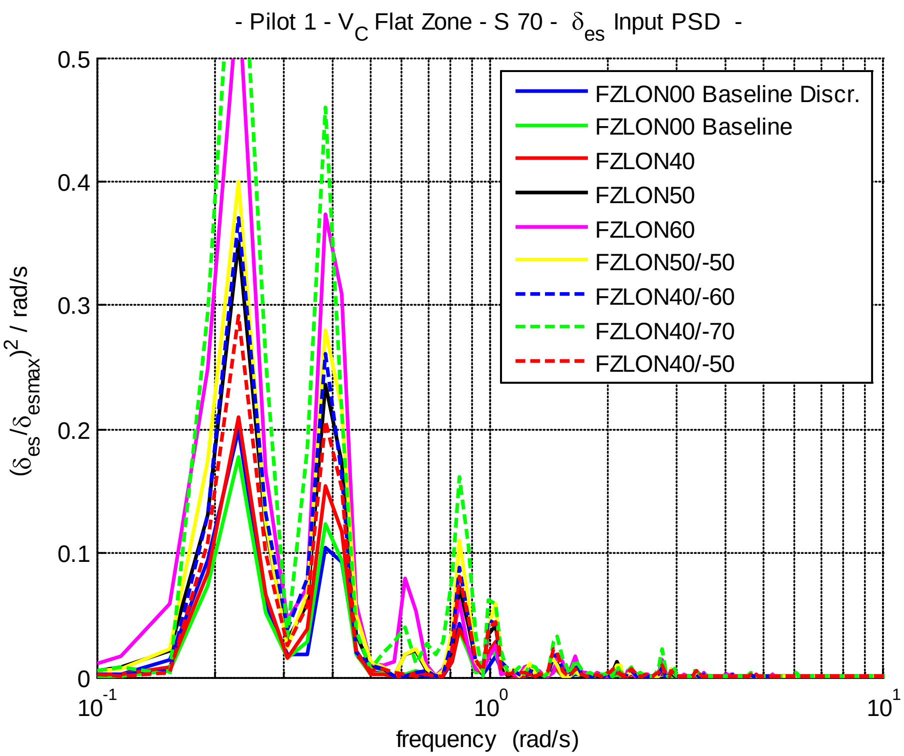


Figure 110. The PSD of pilot 1 δ_{es} input — VC flat zones

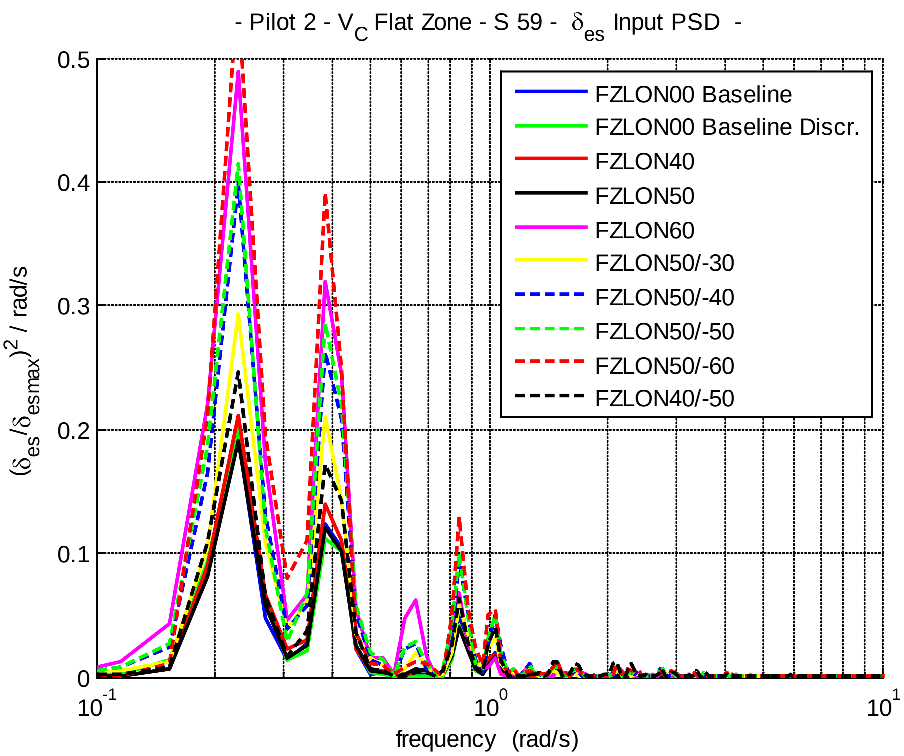


Figure 111. The PSD of pilot 2 δ_{es} input — VC flat zones

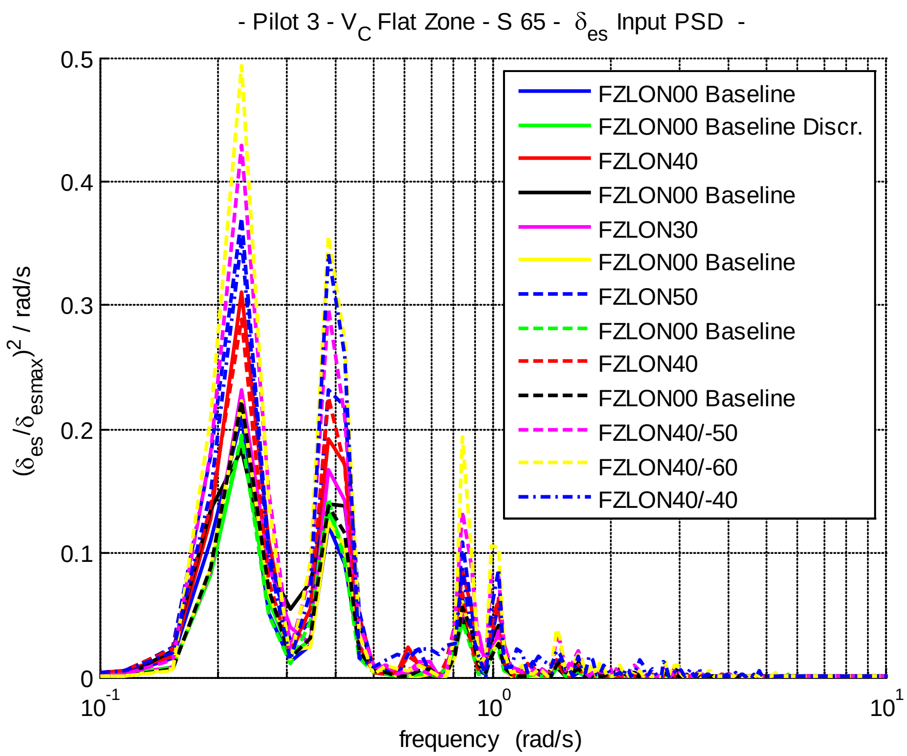


Figure 112. PSD of pilot 3 δ_{es} input—VC flat zones

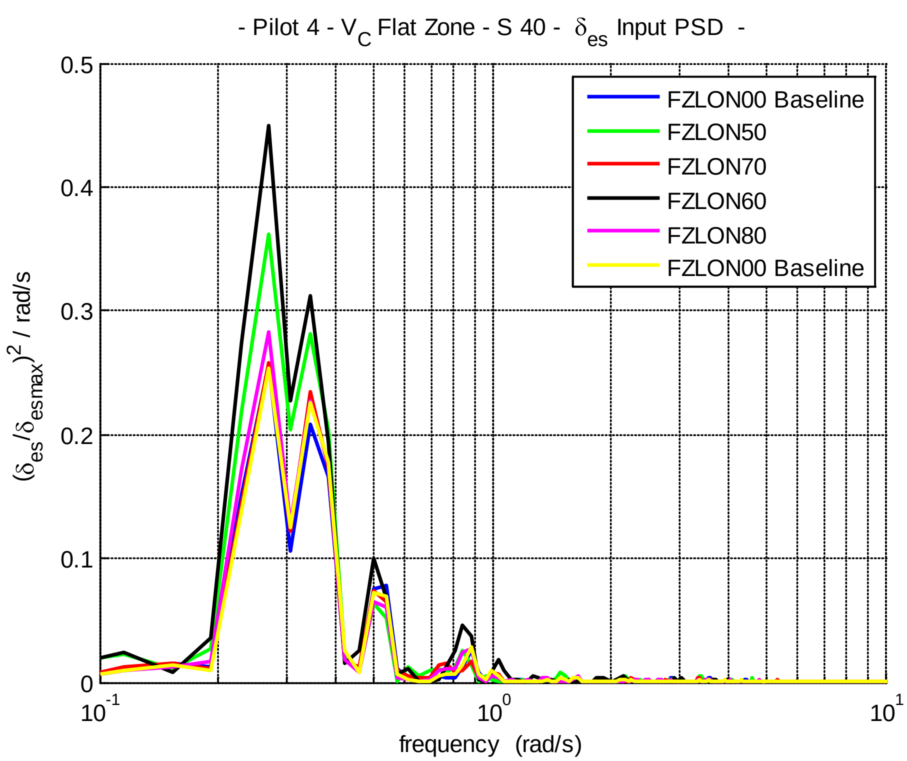


Figure 113. PSD of pilot 4 δ_{es} Input—VC flat zones

10.3.2.2 Pilot Ratings, Comments and, Task Scoring

10.3.2.2.1 Pilot 1

Pilot Ratings and Comments — Baseline configuration is rated HQ level 1 consistently (HQR = 2), and PIOR = 1. Correlation exists between HQR and flat zone amplitude, both positive and negative. HQ level degradation occurs for values FZLON > 4.0°, with HQR = 7 for FZLON = 6.0°. This is related to a lack of pitch authority to accomplish the gross acquisition part of the task. The comment for FZLON = 6.0° is: "Cannot get there even with full back stick. Cannot do the task. Performance issue. Fine tracking okay." The discrete impact of the pitch authority issue on ratings and performance is confirmed by the rating and comments assigned to FZLON = 4.0°, which is still HQ level 1 (HQR = 3): "Still getting the g's I want. No difference [with baseline]. Couldn't sense a rate change." The impact of the positive flat zone is relatively lower and a larger reduction of the pitch authority is tolerated, mostly depending on the task demand. The discrete nature of the effect is more pronounced than for the positive flat zones. FZLON = 4.0° is HQR = 2 without negative flat zone, HQR = 3 with FZLON = -5.0°; -6.0° and HQR = 7, with FZLON = -7.0°. The corresponding comment is: "Too heavy ND. Very slowly moving. Not enough command authority. NU is okay." From the comments and ratings, it can be derived that the best configuration with combined flat zones is FZLON = 4.0°/-6.0° (HQR = 3). The relative comment: "More command authority. Similar to baseline. ND a little heavier than baseline." In this case, the pilot tolerates a reduction of pitch authority, which protects from exceeding g limits. There is no impact of flat zones on PIORs.

Task Scoring — For the task guidelines, which are required not to exceed the g limits (n_z = [0, 2.5]), with no requirements modulation, desired scoring coincides with adequate scoring. Discrete scoring is, on average, 90% desired is defined as (≡) adequate. Continuous task scoring is, on average, 76% desired and 71% adequate. Small scoring variations occur across the different configurations and no correlation can be derived with HQR and PIORs.

Piloting Technique and Time Histories—Analysis of time histories shows that pilot 1 is able to satisfy the g task requirements with margin and that g's exceedances are small. The piloting technique is sensitive to the presence of flat zones and there is a pilot tendency to use a more closed-loop technique with nonzero flat zone amplitude. This is also confirmed by the PSD of the stick inputs displayed in figure 110, which do not show negligible higher frequency content for the limited authority configurations, more pronounced for those with positive and negative flat zones. The amplitude of low-frequency stick activity is directly proportional to the amplitude of the flat zones. The pilot controls the aircraft maintaining a margin with respect to the required g limits $\Delta_{n_z} \approx -0.1; +0.25\ (g)$, for positive and negative g's, respectively. The higher-frequency stick activity is evident from the traces. This is not impacting the rated HQ level and it confirms that the pilot's evaluations are driven by pitch authority related to the capability to perform the task.

10.3.2.2.2 Pilot 2

Pilot Ratings and Comments—Baseline configuration is HQR = 2 and PIOR 3. The comment relative to the baseline with discrete + SoS task is: "Bobbling. The gross acquisition is good. Bobbling for fine tracking. Predictable for large tracking." The same configuration against the discrete task without SoS disturbance is HQR = 2 and PIOR = 1, with the comment: "Less PIO tendency for fine tracking. Nose down not as predictable as NU. A split task for gross acquisition. Initial attention to the g, then start to decrease the pull angle to refine the tracking and capture." All configurations with flat zones are rated less prone to PIO than baseline with the same task: PIOR = 2 for all. HQR are not affected by the flat zone amplitude and all configurations are HQ level 1 (HQR = 3). Indication can be derived from the comments of the impact of flat zones on HQ. The comment relative to configuration with FZLON = 6.0° is: "Inconsistent ND pitch rate. ND pitch rate slows down faster than expected. Large inputs. Noticeable flat zone, no impact on the task but on the performance." The comment for FZLON = 5.0°/-5.0° is: "Pitch rate inconsistencies. Not fully predictable. Slight oscillations for fine tracking. Have to look at the G meter for ND. Divide attention in gross acquisition." These comments indicate an HQ degradation due to the presence of large flat zones, corresponding to pitch authority reduction higher or equal to 50% in both NU and ND. It is noticeable that the reported issues are not considered by pilot 2 a reason for HQ degradation: He decoupled the performance from the task execution, as reported in the comment to FZLON = 6.0° configuration.

Task Scoring — Discrete captures task scoring is 95% desired ≡ adequate, continuous regulation task scoring is 70% desired and 75% adequate. Scoring is not correlated to HQR and PIORs, the high continuous task scoring denotes a low impact of the flat zone on the time to acquire the target and on the fine tracking part of the task.

Piloting Technique and Time Histories—Low frequency stick activity is principally concentrated at the frequencies $\omega = 0.23;\ 0.38\ \frac{\text{rad}}{\text{s}}$, associated to the discrete captures task. Not negligible content is present at higher frequencies ($\omega = 0.85\ \frac{\text{rad}}{\text{s}}$), for the configurations with the highest flat zone amplitudes, in particular. In the same configurations, tendency to a reduced modulation of the gross acquisition input is detected with respect to baseline.

10.3.2.2.3 Pilot 3

Pilot Ratings and Comments — Baseline is HQR = 3, with no scatter in the ratings; PIOR = 1 with the pure discrete task and PIOR = 2 with discrete + SoS task. As displayed in figure 108(a), HQR are slightly correlated with FZLON, with all the gain limited configurations being HQ level 2. A significant amount of scatter is present in HQR, particularly when a negative flat zone (ND) is inserted. As for pilot 1, HQ degradation occurs because of the reduced pitch authority and the impact that it has on the transition between gross acquisition and fine tracking. An example is the comment for FZLON = 4.0/-5.0 deg: "Full aft stick. Not much time to modulate and then settle in. Pretty well protected on both ends." Based on the pilot's comments and ratings, this can be considered the best configuration in terms of HQ level and envelope protection effectiveness.

PIORs are broadly uncorrelated with flat zone amplitude. The configuration with FZLON = 5.0° is associated with a lower PIO proneness than the others (PIOR = 1): "A little less aggressive. Full aft and still cannot get to desired g. Uncommanded motions less this time. Considerable compensation." This confirms the tendency reported by the other pilots as well.

Pilot 3 tested the baseline configurations several times to reassess the reference HQ. A learning curve or adaptation trend can be identified in the HQR scatter for the configuration with FZLON = 4.0°, which is the first pitch authority limited configuration tested. The HQR = 7 at the first evaluation (3rd run) and the HQR = 4 at the second evaluation (9th run).

Task Scoring — Task scoring is averagely desired ≡ adequate = 74% for the discrete captures, it is averagely desired = 70% and adequate = 77% for the continuous scoring, with a minimum desired = 62% and adequate = 73% for the FZLON = 4.0°/-6.0° configuration. There is no correlation between scoring and HQR.

Piloting Technique and Time Histories — The plot of the stick input PSD of figure 112 confirms the consistent direct relationship between flat zone amplitude and low-frequency stick activity, which is larger for larger amplitudes. Two well-defined higher frequency stick activity peaks are present at $\omega = 0.84; 1.03\ \frac{\mathrm{rad}}{\mathrm{s}}$ for all configurations. As for the low frequency inputs, the values of the peaks are higher for the more limited configurations. This indicates a combination of open-loop and closed-loop piloting techniques, which are required by the nature of the task and dependent on the approach followed by the pilot. The time history of figure 116 is relative to the configuration FZLON = 4.0°, which has the worst HQR (HQR = 7). It displays how the flat zone reduces the requirement for positive stick inputs shaping, while significant shaping is evident for negative stick deflections, potentially due to the non-limited NU authority. Figure 85 is relative to the baseline configuration. In this case, input shaping is present for both positive and negative stick input displacement. Lower amplitude closed-loop inputs are also present in both cases for the fine tracking, as expected.

10.3.2.2.4 Pilot 4

Pilot Ratings and Comments — Baseline is consistently HQR = 5 for both evaluations. There is no significant correlation between HQR, PIORs, and flat zone amplitude. Pilot 4 is not significantly affected by the flat zone implementation in V_C flight condition. This is potentially due to his different overall piloting technique, as described below.

Task Scoring — Scoring of the discrete part of the task is averagely desired ≡ adequate = 100%, the continuous scoring is averagely desired = 50%, adequate = 61%. The minimum continuous scoring is desired = 45%, adequate = 56% for the baseline configuration. No significant scoring differences are present across the different configurations.

Piloting Technique and Time Histories — Analyses of the time histories, inputs frequency content, and scoring indicate that pilot technique is characterized by smaller amplitude and less abrupt inputs for the gross acquisition part of the task, with continuous and small amplitude shaping. The low frequency stick activity is more distributed across the frequency range $\omega = [0.2, 0.4]\ \frac{\mathrm{rad}}{\mathrm{s}}$ than the other pilots. Based on the scoring and the time histories, it can be derived that the pilot keeps a larger margin with respect to the normal load factor task requirements, which allows him to not exceed the g limits, thus reducing the continuous scoring and slightly increasing the time to acquire the target. Pilot 4 accepts this overall reduced quantitative part of the task performance and this is the potential reason for his lower sensitivity to pitch authority limitation.

Figure 114 displays the longitudinal stick input of the different pilots and the flat zone amplitude for one run with FZLON = 5.0°. It is clear how pilot 1 and pilot 3 exceed the flat zone amplitude at all NU captures, while pilot 2 and pilot 4 exceed it occasionally and for a much lower amplitude and duration than the other two pilots. This can derive from the piloting background, with pilots 1 and 3 being mainly fighter aircraft pilots and pilots 2 and 4 being mainly large aircraft pilots. Reference to the background is important in this case, as the evaluations are of a transport aircraft.

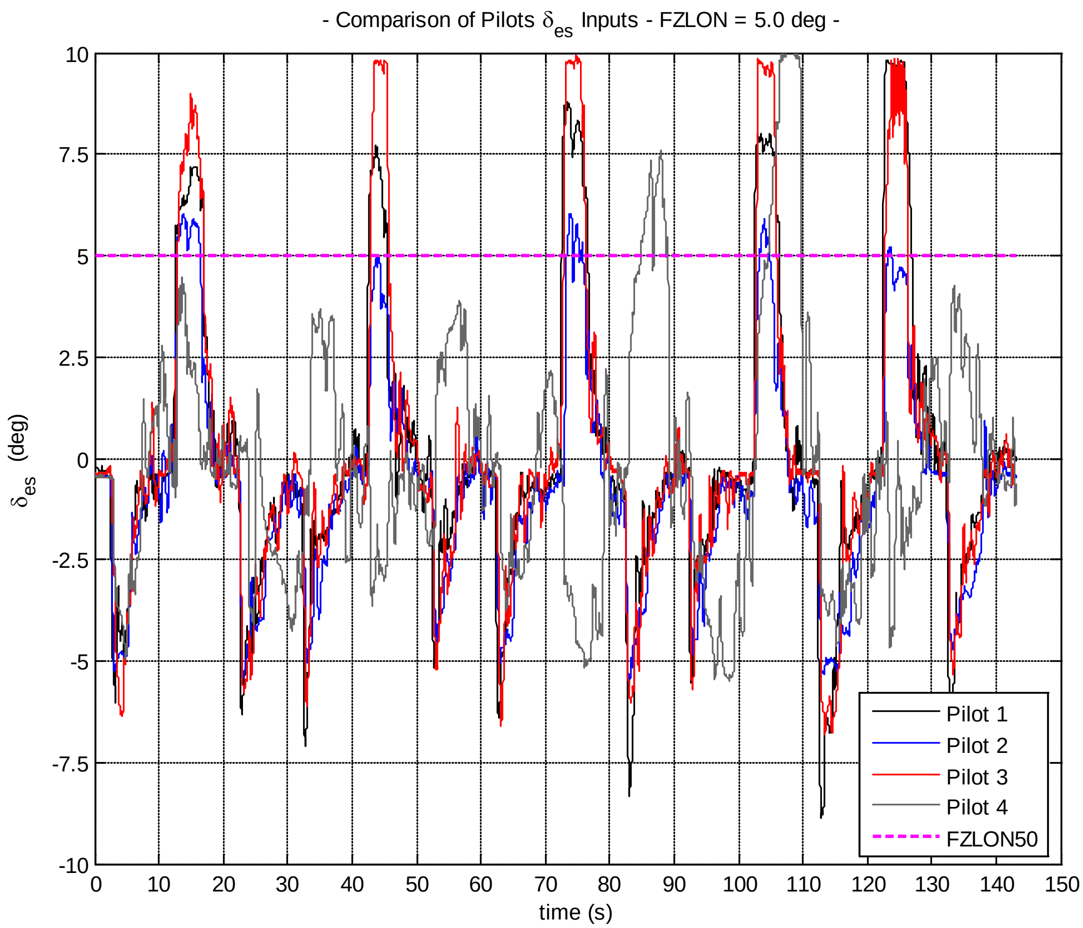


Figure 114. Comparison of Pilots' $\boldsymbol{\delta_{es}}$ inputs FZLON = 5.0° — $\mathbf{V_C}$

Figures 115–117 show time history plots for pilots 1 and 3.

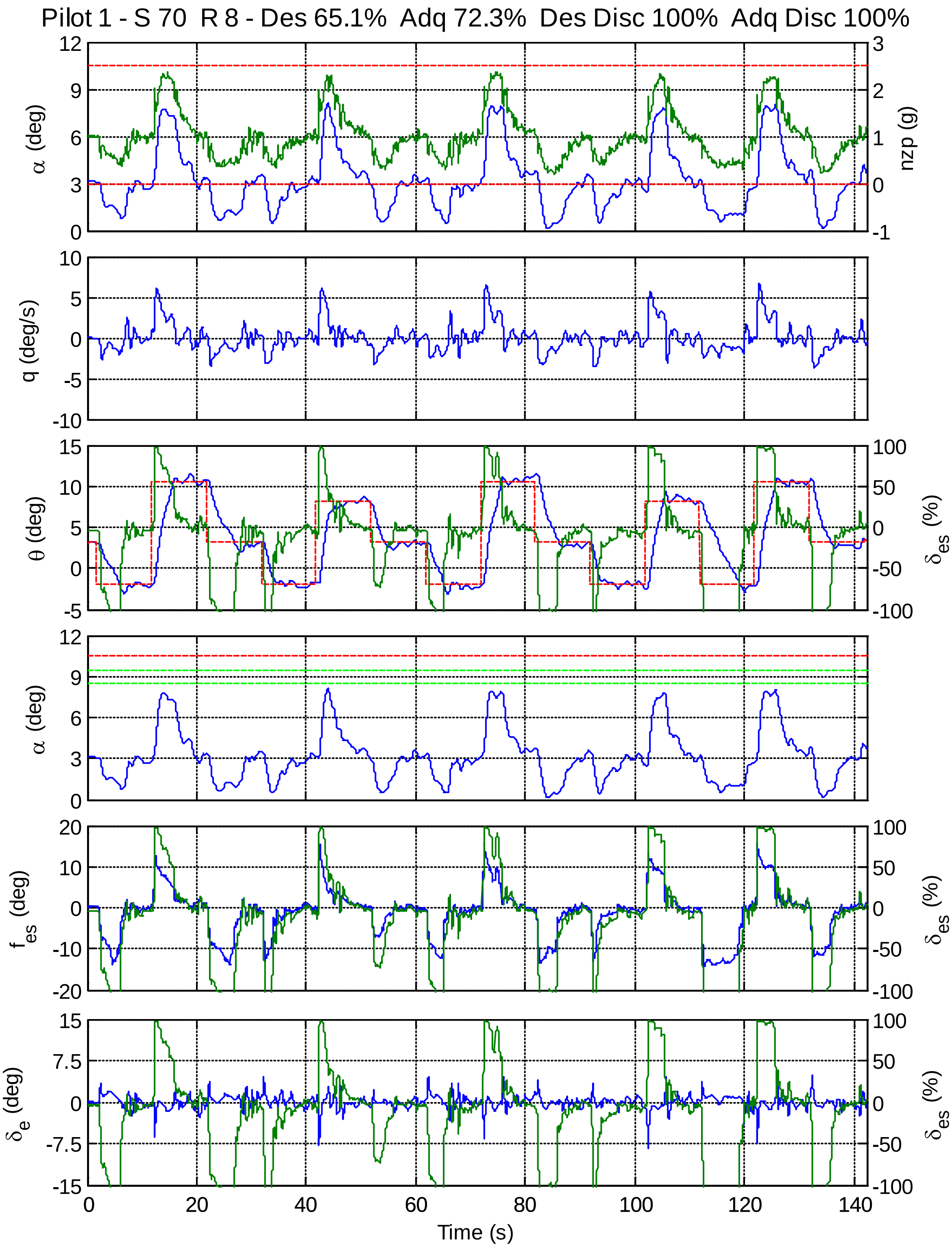


Figure 115. Pilot 1 FZLON = 6.0°/-4.0° captures time history plot — V_C

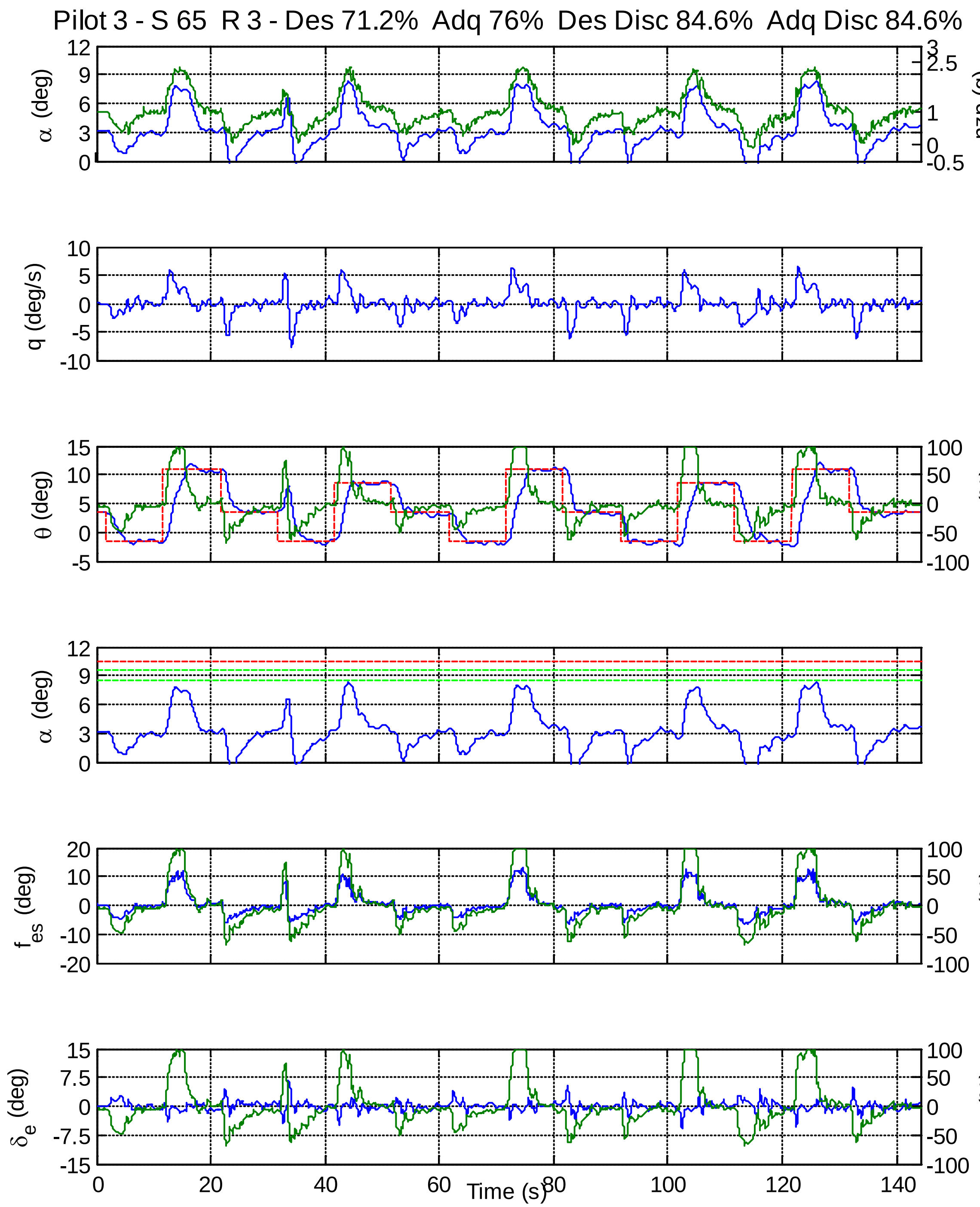


Figure 116. Pilot 3 FZLON = 4.0° captures time history plot — V_C

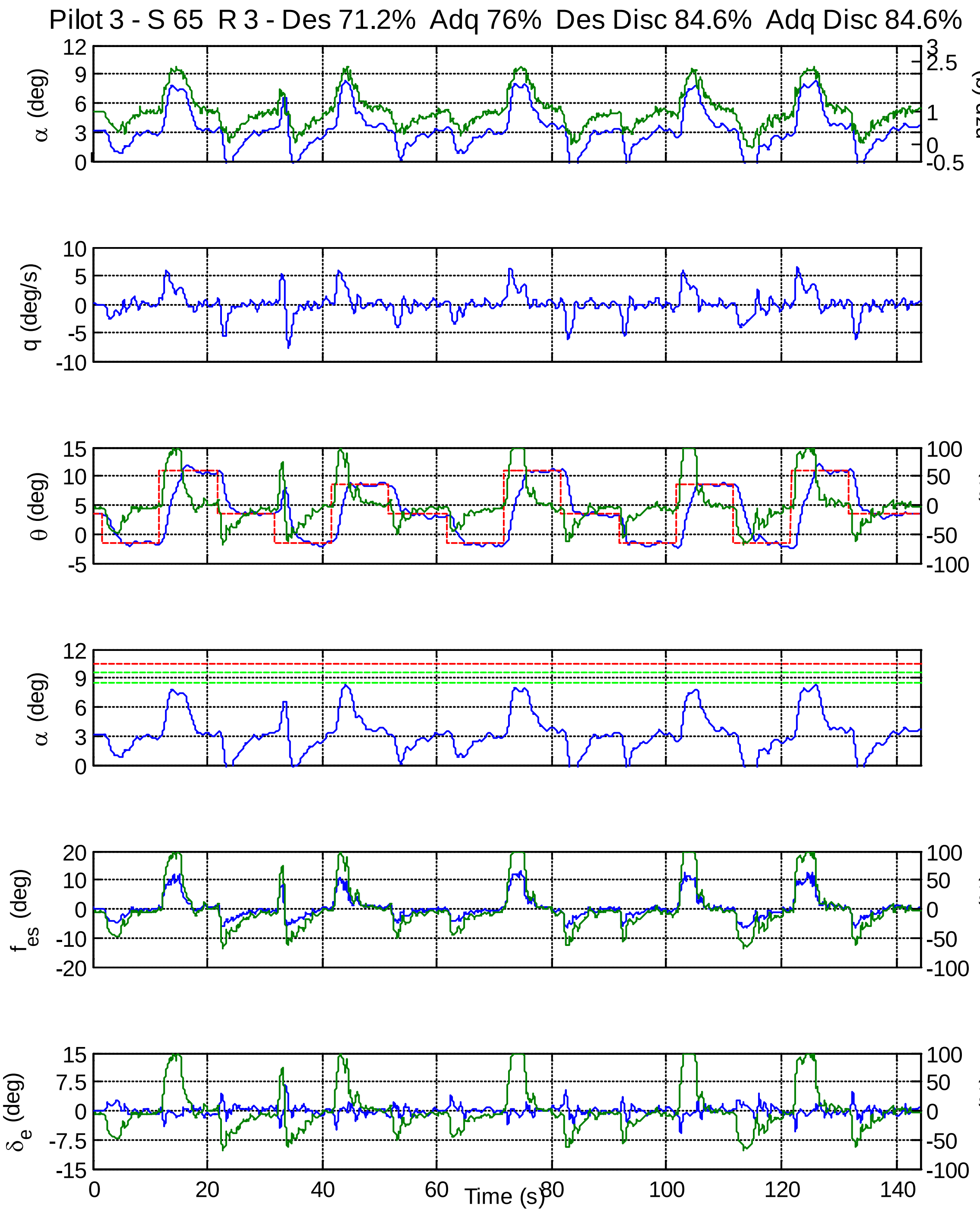


Figure 117. Pilot 3 FZLON = 0.0° captures time history plot — V_C

10.3.3 Piloted Evaluations Observations and Conclusions

From the previous analysis and synthesis of the command-path flat zone HQ evaluations, the following conclusions can be derived:

- Flat zones generally degrade HQ in both PA and V_C flight conditions, even if the aircraft response and dynamics are significantly different in the two flight conditions.

- The principal effect on aircraft response perceived by the pilot is the pitch authority limitation and unpredictability.

- Piloting technique affects HQR, with lower correlation between HQR and flat zone amplitude for the pilots with more progressive inputs in the gross acquisition part of the task (discrete capture).

- The large scatter between HQR of the same flat zone configuration for the same pilot and across different pilots indicates the potential for a critical implementation of this design element. Significant difficulties are expected in the definition of a centralized value or design, which provides an adequate degree of robustness of flat zones in production mode.

- It is recommended that further investigations be conducted (with particular emphasis on in-flight testing) as additional visual and acceleration cues potentially improve the pilot's awareness of the aircraft condition with respect to the task limits and correlation of its dynamics with pilots' inputs. Pilots noted that real-world acceleration cues would have allowed correlation of a given load-factor value at a given flight condition with incipient saturation of the pitch authority. This would have potentially reduced the nonlinear nature of the control perceived by the pilot by providing a predictable reference for the amplitude of the flat zone.

10.4 PASSIVE INCEPTOR COMMAND SENSITIVITY

10.4.1 Offline Analysis

10.4.1.1 Introductory Notes

Regarding the "inceptor command sensitivity scheduling as a function of inceptor deflection and flight condition," a survey has been conducted of the command-gain sensitivity and stick-force gradient breakpoint using the Calspan/STI aircraft model described in previous sections.

This offline analysis was conducted with two goals in mind:

1. Develop a better understanding of the effect of the command-gain variation on task performance.

2. Examine the effect that the stick-force gradient breakpoint has on task performance and stick activity in preparation for an eventual piloted simulation.

Ideally, the final breakpoint location and command-gain values will result in a system that provides good small amplitude control about the inceptor null position, while the large-amplitude maneuver command gain will be automatically determined from these values to provide full-control surface deflection for full-stick deflection. To evaluate these items, a simple pilot model was implemented and a pitch attitude capture and hold (PACH) task was defined. The pilot model and PACH task are the same as those used previously [16].

10.4.1.2 Tasks

The PACH task is intended to investigate three parameters: 1) the ability of the aircraft to pitch and capture a defined attitude, 2) maneuverability limitations, and 3) PIO tendencies. Two pitch attitude capture configurations were defined: the first used captures of -5, 0, and 5 degrees about the trim attitude and the second used -5, 0, and 10 degrees about the trim attitude. A sample PACH task is presented in section 13.2.2. The first 10 seconds of the task are reserved for the model to trim, after which the task begins. Each capture attitude is commanded for 10 seconds, allowing time for the PVS to achieve the designated attitude and maintain this attitude for at least five seconds. For adequate and desired performance, the pilot model must achieve and maintain an attitude within ± 2 degrees and ± 1 degree, respectively, of the commanded attitude.

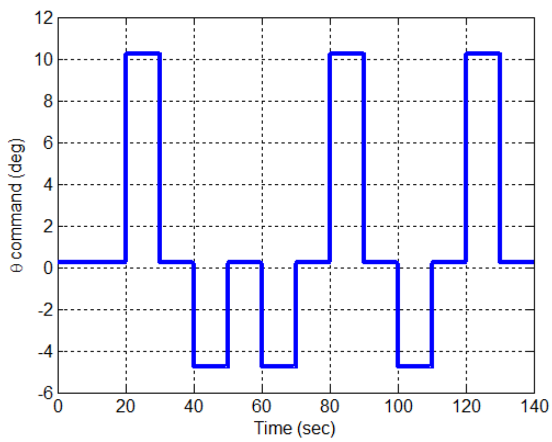


Figure 118. Example PACH command signal

10.4.1.3 Flight Conditions

This evaluation was performed at the cruise condition only using the parameters listed in table 58. The breakpoint and command gain combinations evaluated are given in table 59.

Table 58. Flight condition

	Cruise
Altitude (feet)	38,000
Velocity (feet/second)	847
Static Margin (% chord)	5

Table 59. Test matrix

Breakpoint (% max stick deflection)	Command Gain
0.15	0.5
0.15	1
0.15	1.5
0.25	0.5
0.25	1
0.25	1.5
0.35	0.5
0.35	1
0.35	1.5

10.4.1.4 Effects of Breakpoint and Command Gain Adjustments

Figure 119 shows the effect of adjusting the command gain value. Stick deflection is shown on the *x* axis, with the normalized command output shown on the *y* axis. The baseline command gain (1) is shown as a solid black line, the higher command gain (1.5) is shown as a dashed blue line, and the smaller command gain (0.5) is shown as the dotted red line. The breakpoint for this example is shown using the dashed black vertical line at a stick deflection of 4°. At the breakpoint location, the stick deflection specifies an output command value; increasing the command gain increases the output command value at that breakpoint location. For the higher command gain (1.5) example shown in figure 119, instead of commanding 20% of the maximum output for a 4° deflection, 30% is now commanded for the same stick deflection. The necessary adjustments to retain the stick neutral position, commanding 0%, and the full stick deflection, commanding 100% of the maximum output, are then applied to create the gradients seen here. Similarly, if the breakpoint had been located at 8° of stick deflection and the same command gain applied, instead of 8° commanding 40% of the maximum output, 60% of the maximum output would be commanded. As should be obvious from these trends, increasing the command gain value at a fixed breakpoint location increases the commanded output; conversely, reducing the command gain will do the opposite.

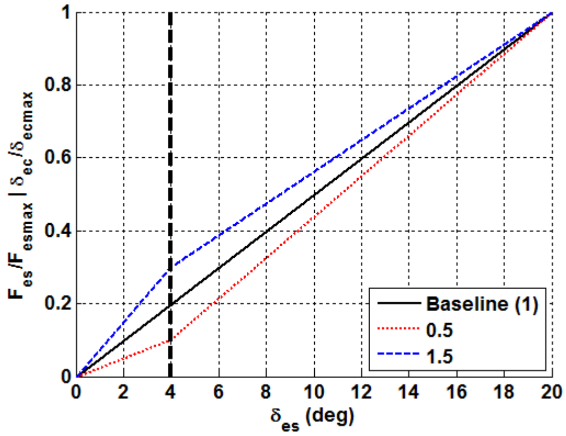
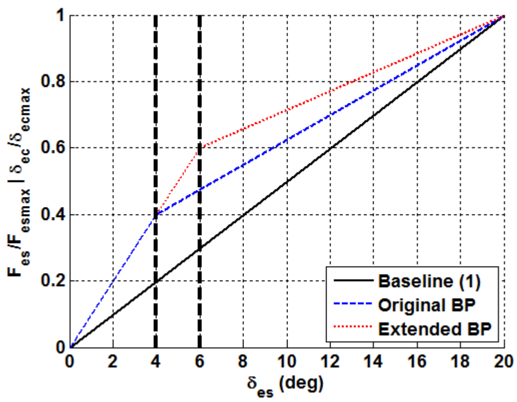
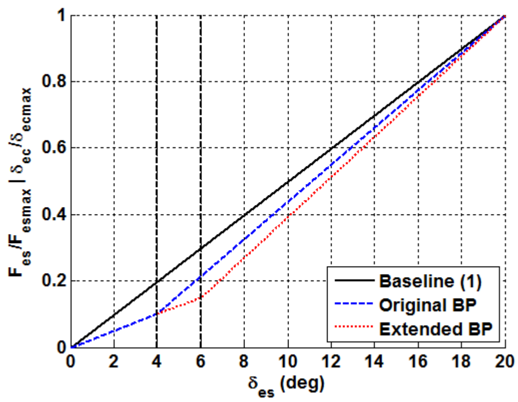


Figure 119. Command gain variation example

Figure 120(a) shows the effect of maintaining the higher command gain (2) but adjusting the breakpoint location. The original breakpoint location is at 4° stick deflection and the new breakpoint is at 6° stick deflection. The original command gain is again shown as the solid black line, the new command gain at the original breakpoint is shown as the dashed blue line, and the new command gain at the new breakpoint location is shown as the dotted red line. As discussed previously, increasing the command gain at a fixed breakpoint increases the command output. If that breakpoint is then shifted, as shown in figure 120(a), from 4° to 6° stick deflection, the command gain remains the same, but the gradient of the command for stick deflections larger than the breakpoint amount changes. As with the alteration of the command gain itself, adjusting the breakpoint also has an effect on the commanded output. Looking at 6° of stick deflection, it can clearly be seen that by increasing the breakpoint value, the commanded output is increased; instead of getting ~47% of the maximum command for 6° of stick deflection, as was commanded with the original breakpoint location, 60% of the maximum command is now used. Similarly, for the command gain that is smaller than the baseline value case seen in figure 120(b), increasing the breakpoint location will result in a commanded output that is smaller than was commanded at the original breakpoint.



a) Command gain 2



b) Command gain 0.5

Figure 120. Breakpoint variation example

10.4.1.5 System Analysis

The results of this study are presented in figures 121–124, which show the trends of pitch attitude and longitudinal stick displacement for the different cases. Figures 121 and 123 show these signals for a fixed breakpoint value with a varying command gain, while figures 122 and 124 show these signals for a fixed command gain and varying breakpoint.

10.4.1.5.1 5° Captures

As the command gain increases for a fixed breakpoint value, the initial capture attitude tends to go from undershooting to overshooting the desired attitude; the neutral command gain (1) case appears to capture the attitudes with little appreciable over/undershoot. The higher command gain (1.5) case also tends to achieve the capture attitude faster than the lower command gain (0.5) case, although minor oscillations about the capture attitude are observed before settling.

With the exception of the neutral command gain (1) case, increasing the breakpoint value tends to exaggerate the tendencies of the other command gain values; the lower command gain (0.5) tends to see greater undershoot values while the higher command gain (1.5) case tends to see higher amplitude overshoots and oscillations. These trends are in line with those seen in figure 120 and discussed in section 10.4.1.4. Capture times did not seem to be affected by this trend, though, because the higher command gain (1.5) still returned to and oscillated about the capture attitude at about the same time in the capture and the lower command gain (0.5) still achieved the desired attitude by about five seconds into the capture. The increase in overshoot and undershoot values across the different breakpoint cases were on the order of 1° or less. The 0.35 breakpoint case had the largest difference between the lower command gains (0.5) undershoot and the higher command gains (1.5) overshoot, ~2°.

For both the fixed breakpoint with varying command gain and fixed command gain with varying breakpoint cases, the peak amplitude of the stick inputs remained essentially unchanged and any differences noticed were on the order of half a degree or less. With a fixed breakpoint value, the stick inputs tended to roll off faster at the higher command gain values. For a fixed gain value, though, the stick inputs were present for similar durations across all breakpoint values; the only distinction was in how much stick input was being used at a given time. As the breakpoint increased, the amplitude of the stick input increased for the lower command gain (0.5) case. Specifically, the amplitude of the small oscillation after the initial capture command increased as breakpoint increased for the higher command gain (1.5) case.

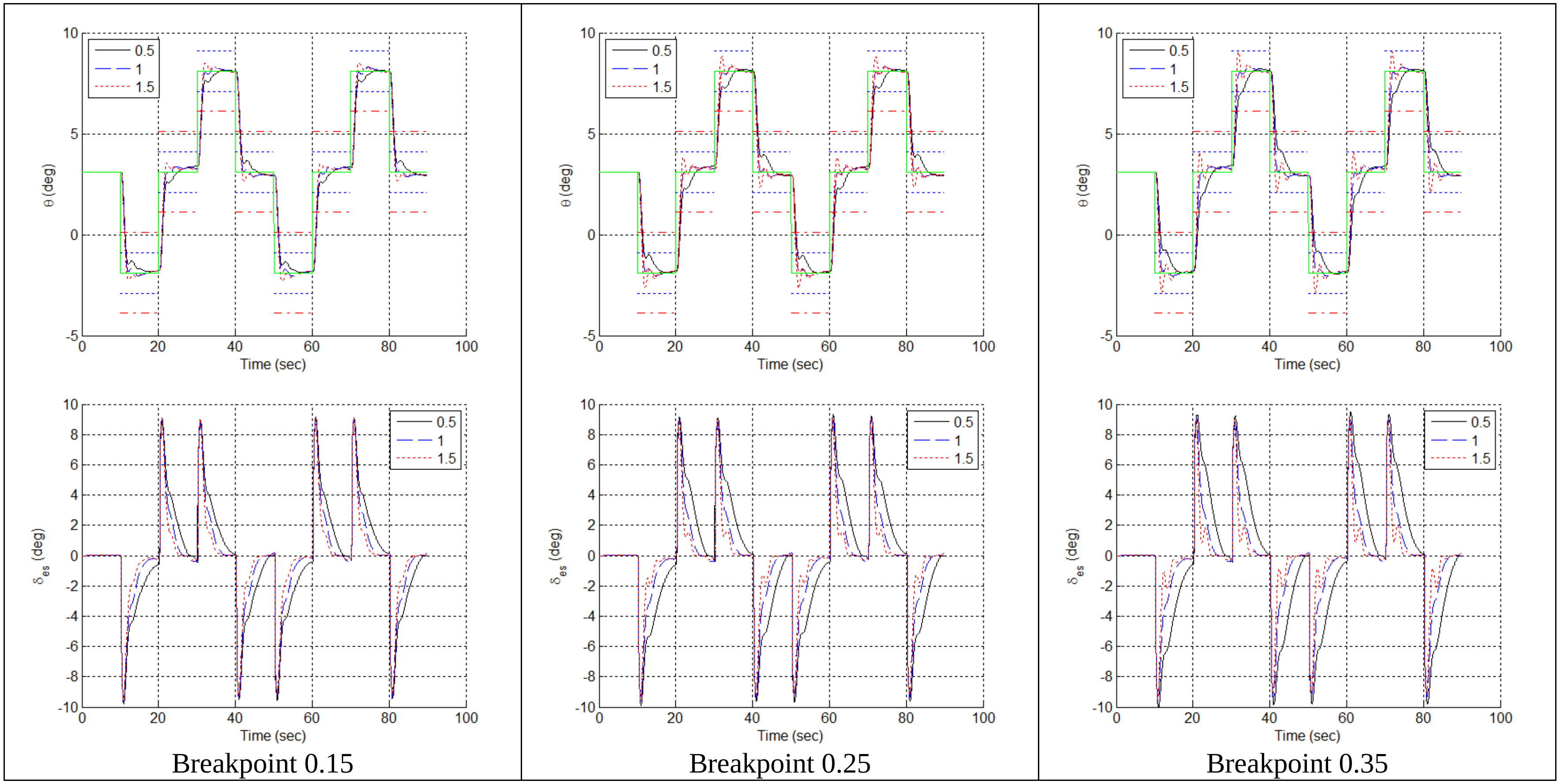


Figure 121. Fixed breakpoint (5° captures)

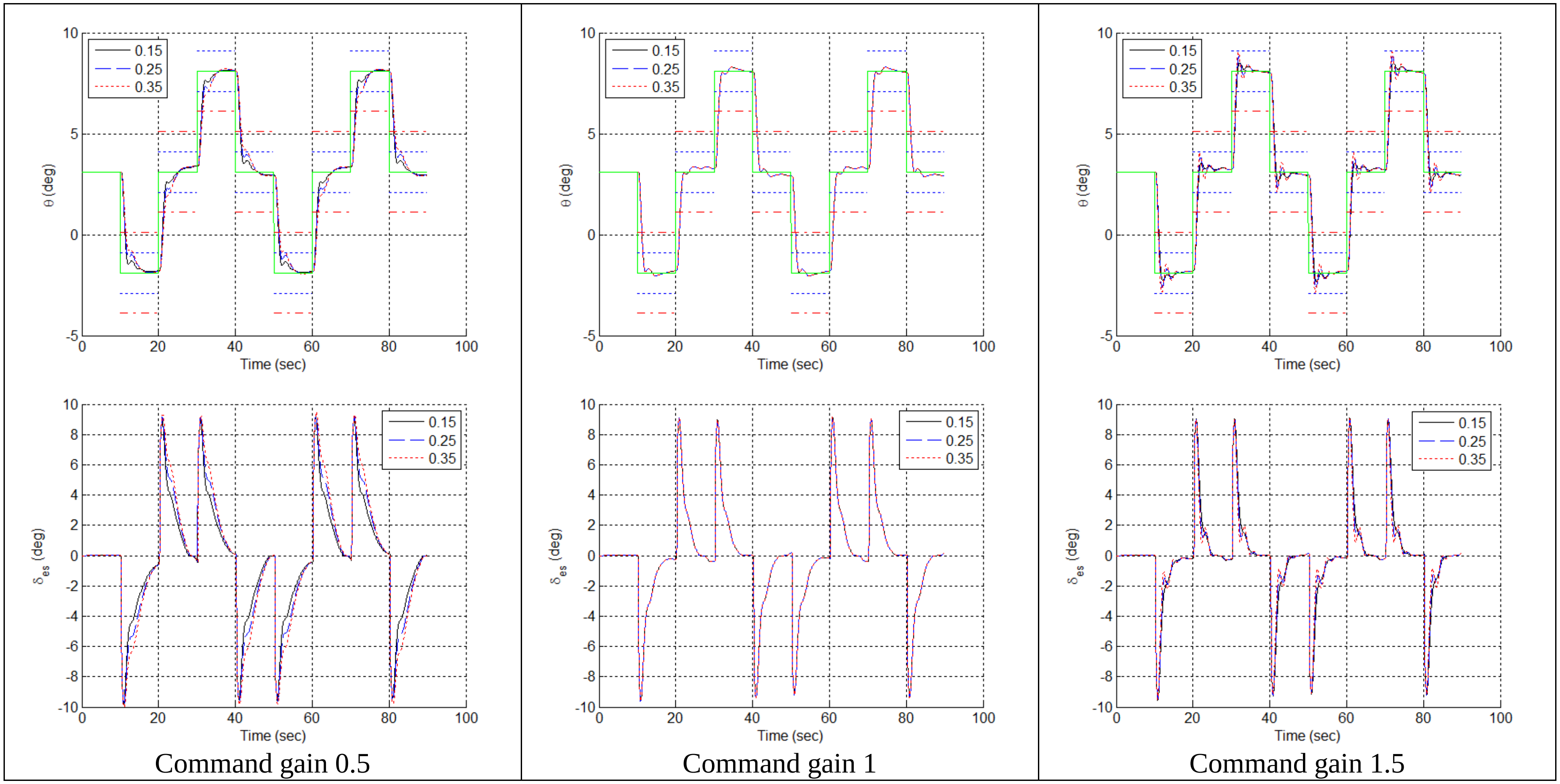


Figure 122. Fixed gain (5° captures)

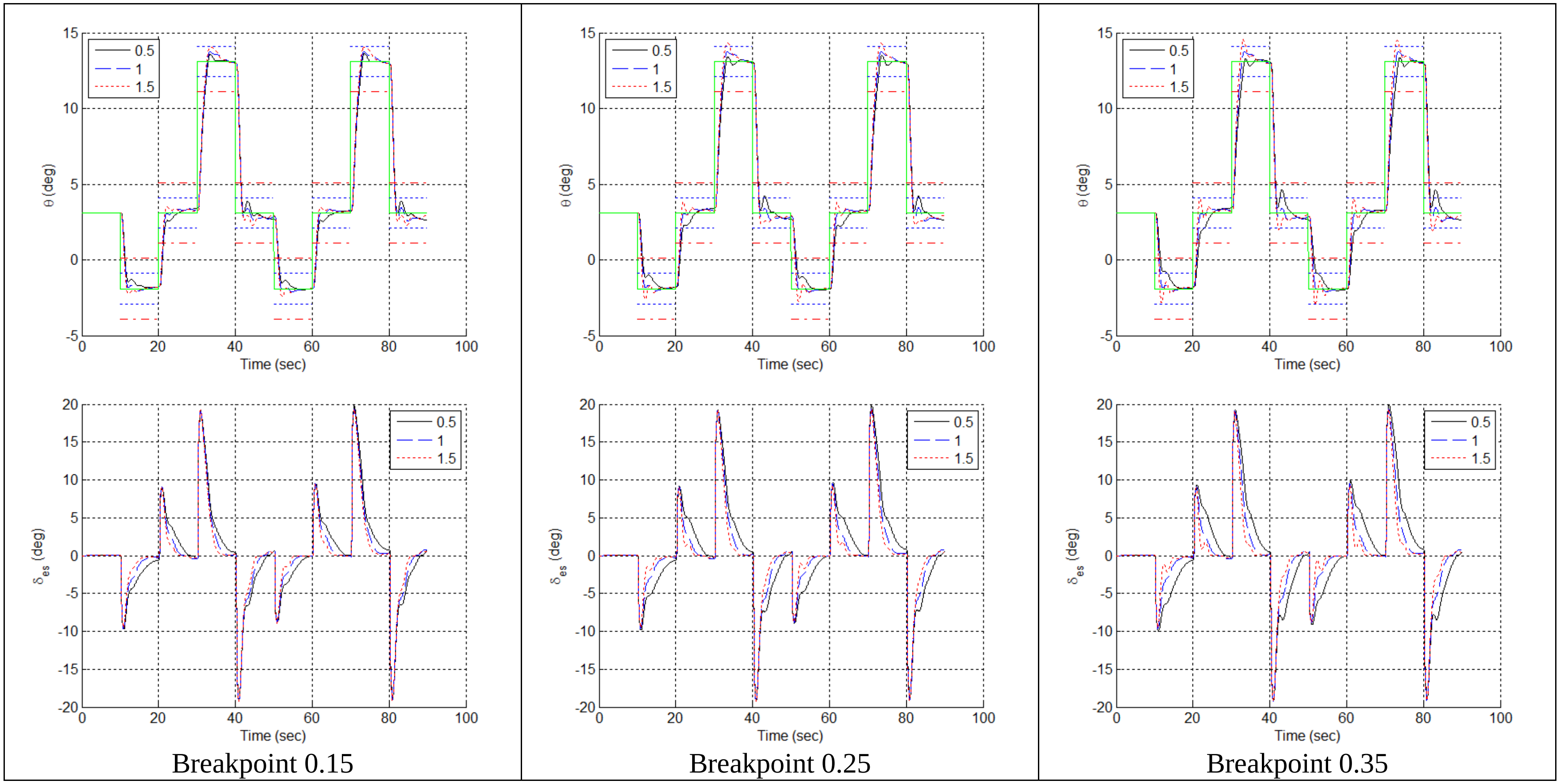


Figure 123: Fixed breakpoint (10° captures)

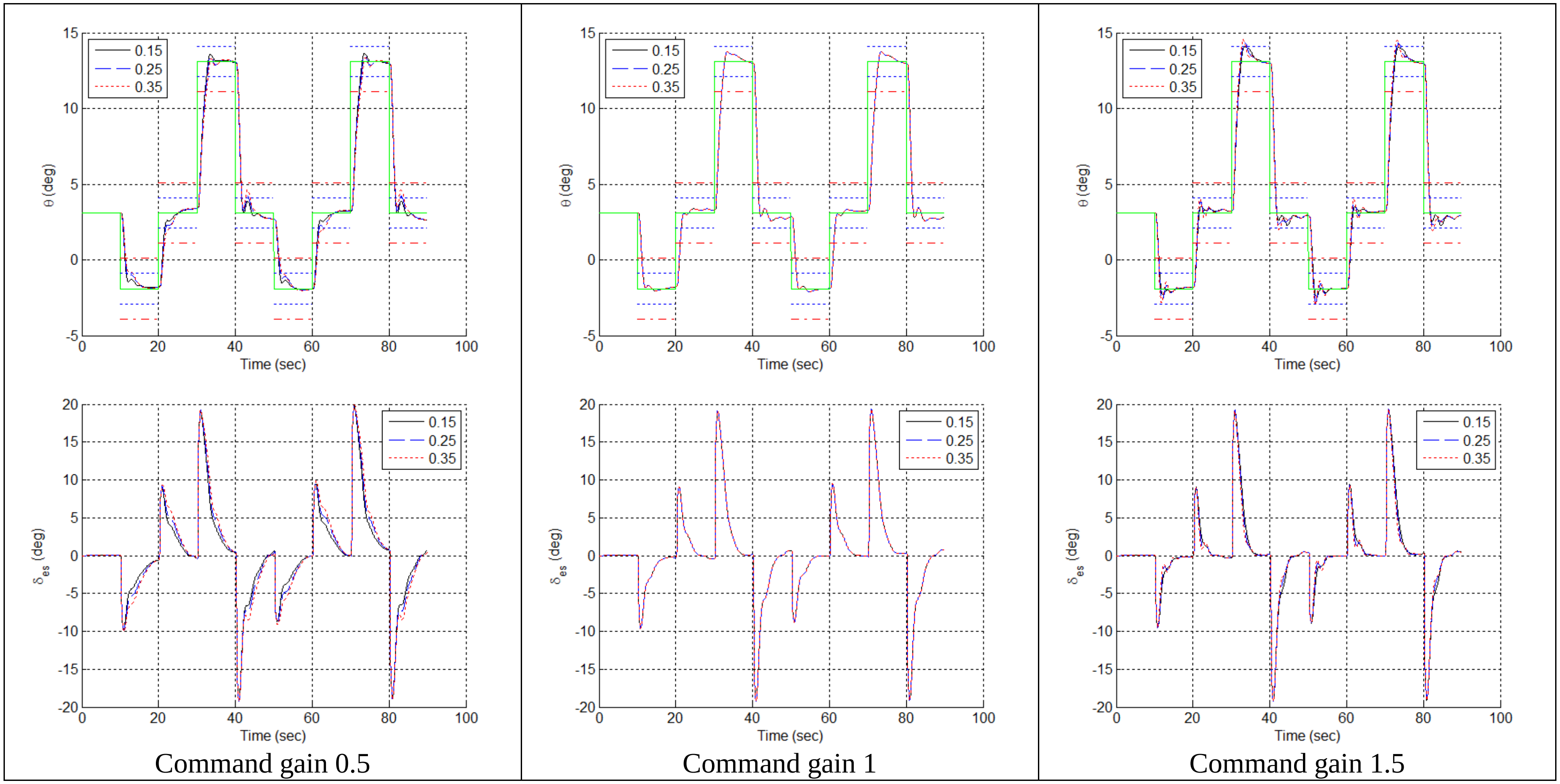
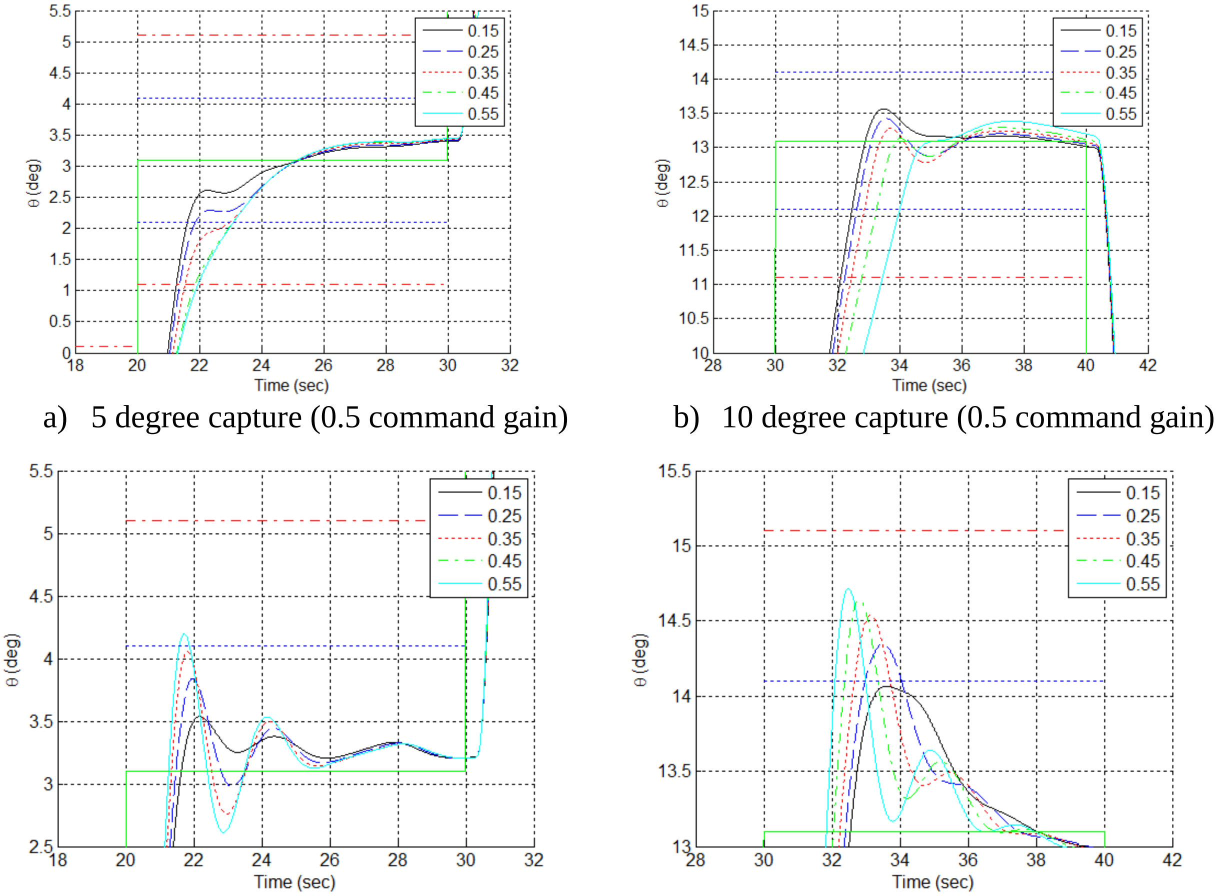


Figure 124. Fixed gain (10° captures)



a) 5 degree capture (0.5 command gain)

b) 10 degree capture (0.5 command gain)

c) 5 degree capture (1.5 command gain)

d) 10 degree capture (1.5 command gain)

Figure 125. Breakpoint trend

<u>10.4.1.5.2 10° Captures</u>

When capturing the 5° attitudes for the fixed breakpoint cases (required to correct back to trim from the -5° captures), similar trends were seen as those noted for the 5° capture sequence described above. The neutral command gain (1) setting met and settled on the desired attitude quickly across all breakpoints. The undershoot that was noted for the 5° attitude captures was not present in the 10° captures.

For a fixed breakpoint value, increasing command gain increased the amplitude of the initial response with a difference on the order of ~1° or less. None of the command gain and breakpoint combinations had any undershoot present for the 10° captures and only the higher command gain (1.5) case overshot the capture attitude by more than 1°, but this exceedance was very minor.

For a fixed gain, there is little distinction at the 10° capture attitudes between the various breakpoints. The lower command gain (0.5) case had a slightly higher initial overshoot value for the 0.15 breakpoint location when compared against the 0.25/0.35 cases; the 0.25 and 0.35 cases were essentially the same. For the higher gain case (1.5), the higher breakpoint values were associated with higher initial overshoot values, but these again are small, on the order of less than 1°.

For the stick inputs, the trends noted for the 5° captures are similar to those seen for the 10° captures. The 10° captures had some small differences in stick input usage for the higher command gain (1.5) with varying breakpoints, but it was very minimal.

10.4.1.6 Breakpoint Survey

As a part of the above evaluations, a survey was made for both the 5° and 10° attitude capture performance over a range of breakpoint values at a fixed gain (0.5 and 1.5). The results are presented in figure 125.

For the lower command gain (0.5) case, it can clearly be seen that the 5° captures have a slight undershoot, but still remain at or close to desired performance for the initial capture before meeting and holding the desired attitude. The 10° capture case for the lower command gain (0.5) achieved and held the desired attitude from the very beginning of the capture. The lower breakpoint cases reached the attitude faster, an expected trend given that less time is spent in the initial low-gain region of the stick input command.

For the higher command gain (1.5) case, both the 5° and 10° captures show an increasing initial amplitude response as the breakpoint is increased; for the 5° capture, the 0.45 and 0.55 breakpoint cases overlay one another.

10.4.1.7 Offline Analysis Observations and Conclusions

This follow-on task is intended to be conducted as part of a piloted simulation that fixes the breakpoint at a single value and varies the command gain between runs. In support of this piloted simulation, a survey was performed of the gain and breakpoint trends in order to better understand the effect of each and also to assist in the selection of a final breakpoint value to be used for the piloted simulation. Examination of the above results suggests that a breakpoint of 0.35 would be a reasonable starting point for the piloted evaluations. For the lower command gain cases, it offers good performance and a relatively large variation in pitch amplitude between the low and high command-gain cases and as evidenced by the fixed-gain comparisons shown herein. The 0.35 breakpoint also had the greatest difference in required stick input when evaluating different command-gain values, a trend that may assist the pilot in discerning differences in the performance and required stick activity for the different command gains.

For the three considered breakpoint values (0.15, 0.25, and 0.35) for the attitude capture analysis, it was noted that increasing the breakpoint tended to exacerbate the tendencies of the pitch attitude response, be that over- or undershooting the command attitude. Increasing the command gain tended to increase the amplitude of the pitch response and reduced the duration of the stick input command. The peak amplitude of the stick input commands varied little, if at all, between both variations in command gain and breakpoint.

10.4.2 Piloted Evaluations

10.4.2.1 PA Flight Condition

10.4.2.1.1 Principal Outcomes

The baseline command gain configuration was constant through the whole stick deflection. The command sensitivity was varied by scaling the gain for low stick deflection amplitude in the range command sensitivity longitudinal (CSLON) = [0.3, 1.4]. The range varied slightly throughout the different pilots, based on the comments provided by each one of them during the evaluation, with the widest range for pilot 3 CSLON = [0.3, 1.3]. Figure 126 represents the HQ and PIO tendency ratings (HQR, PIOR) assigned by the different pilots on the basis of the ground simulations. Figure 127 contains the plots of the individual HQR and PIORs for each pilot, as a function of gain scaling. More than one simulation for each pilot was performed of the baseline configuration, leading to no negligible scatter in the ratings. This is due to the fact that baseline was evaluated with a pure discrete capture task and with the standard discrete + SoS disturbance. The different sequence in which the same configuration was tested by the given pilot potentially affects the ratings as well.

The reason for evaluating the baseline through the two different tasks was to ensure that the baseline configuration was satisfactory without improvement when evaluated with a pure discrete task. The impact of the disturbance could also be quantified in terms of HQ degradation.

From the analysis of the pilots' ratings and simulation data, the following indications can be derived for the specific pitch attitude capture task with SoS disturbance:

1. SoS disturbance produces a slight HQ degradation of the baseline configuration, corresponding to an HQR increment of 1. This has no negligible impact on pilot 3's ratings, as HQ transition from level 1 to level 2. For the other pilots, this increment is within the ratings scatter and does not indicate a definite impact of the disturbance on HQ. Overall, baseline configuration is rated HQ level 1, marginal level 2.

2. The scaling factor has a minor impact on the HQR in this configuration, comparable to the overall scatter of the baseline configuration for all pilots, except pilot 3. No definite tendency to HQ degradation is evident with the increase of the scaling factor. Reduction of the factor leads to a slight HQR degradation, with worst rating HQR = 6 for CSLON = 0.3 for pilot 3. Pilot 3's ratings demonstrate a higher dependency on the command gain scaling with respect to the other pilots.

3. PIORs are not significantly affected by the command gain scaling factor variation. Different, constant PIORs are assigned by the different pilots. No PIO tendency is assessed (see figure 127).

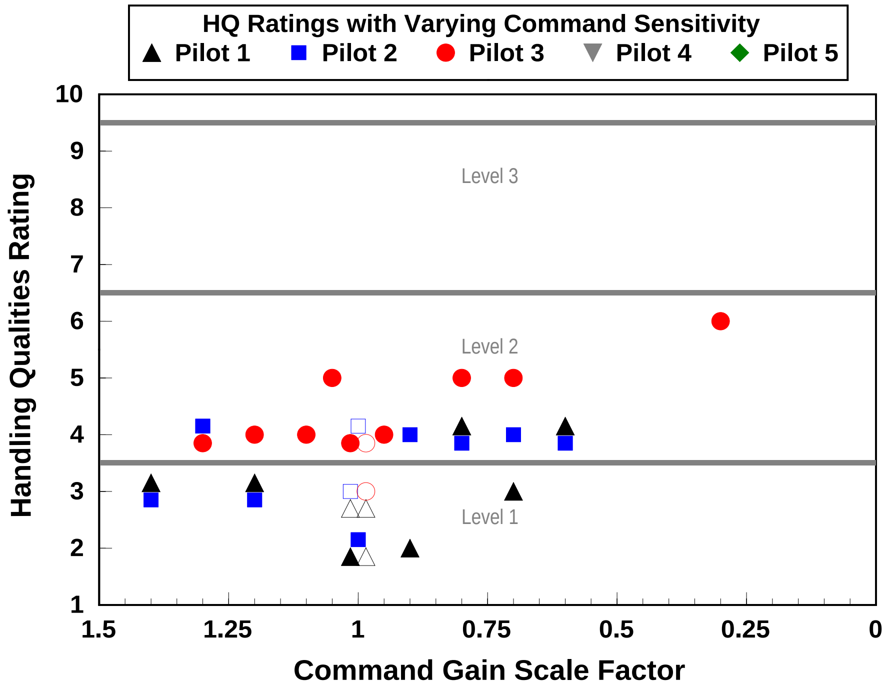
4. Piloting technique is characterized by open-loop inputs for the gross acquisition task and closed-loop, higher frequency inputs for the fine tracking. The amplitude of the low-frequency inputs increases when command gain-scaling factor is decreased for all pilots.

Dependency of higher frequency inputs on gain scaling factor is lower—for pilot 3 in particular.

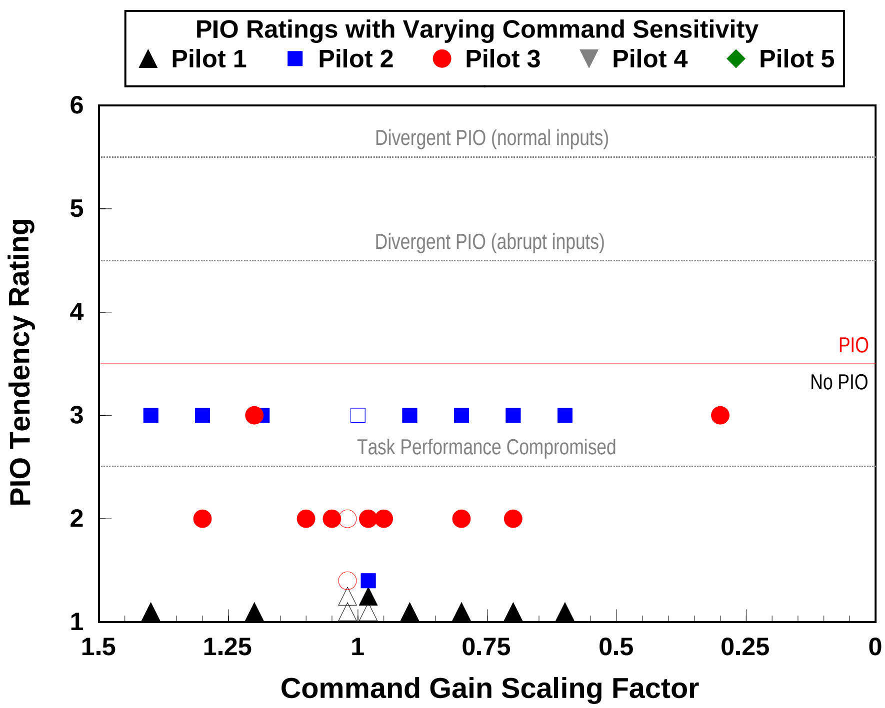
5. There is no direct correlation between scoring, HQR, and PIORs. A slight degradation of continuous task scoring for HQR ≥ 4 was detected in pilot 3's runs.

It is derived that the overall impact of reducing the command gain in the low-amplitude stick-deflection range slightly degrades the HQ in PA. This has been associated by pilots 1 and 3 to a higher heaviness, physical demand. Pilot 2 reported a more noticeable gain breakpoint with lower gain scaling factor. No significant impact due to gain increase is evident, even if a tendency to lighter forces is reported.

Figures 128–130 show the PSD of pilots 1, 2, and 3.

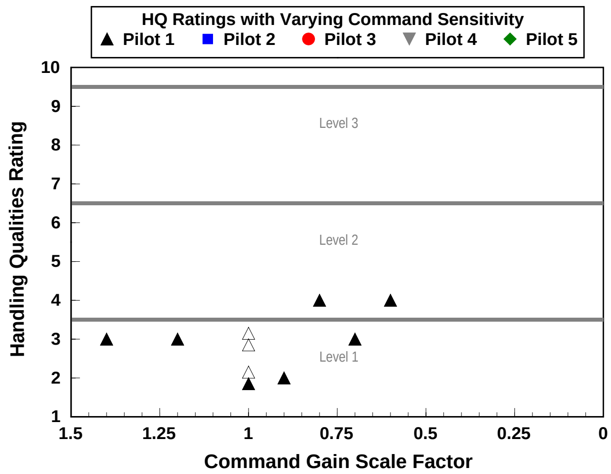


a) Handling Qualities

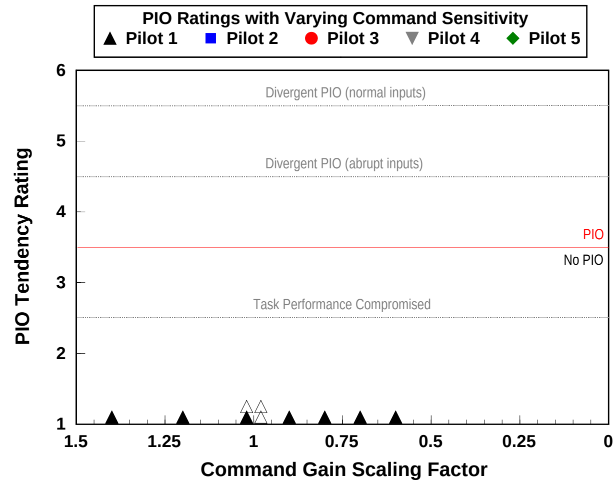


b) PIO Tendency

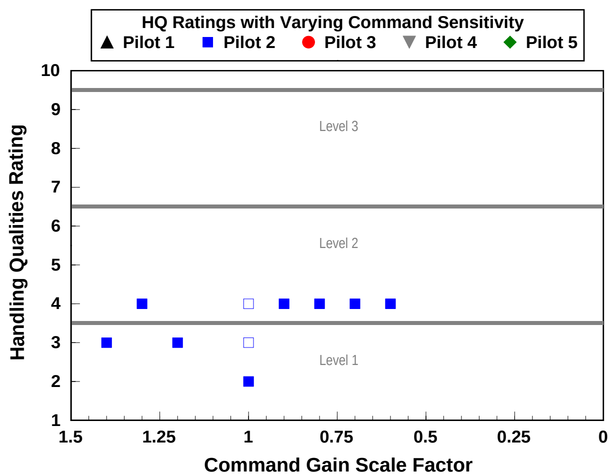
Figure 126. PIORs summary, all pilots, pitch PA command sensitivity (passive) evaluations



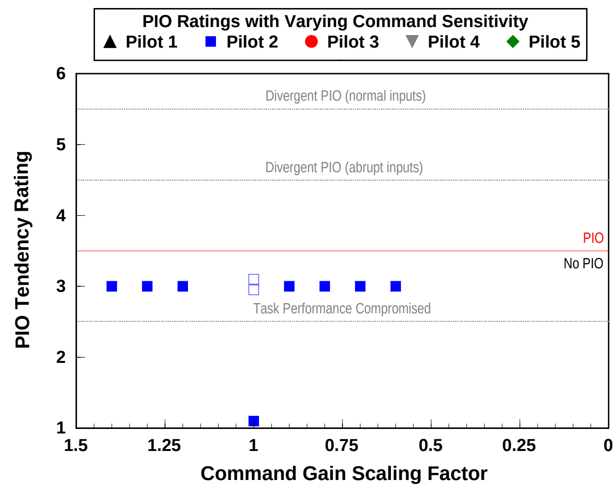
a) Handling Qualities – Pilot 1



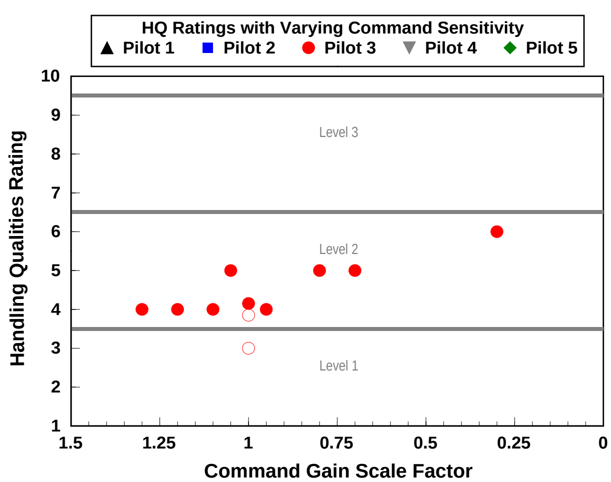
b) PIO Tendency – Pilot 1



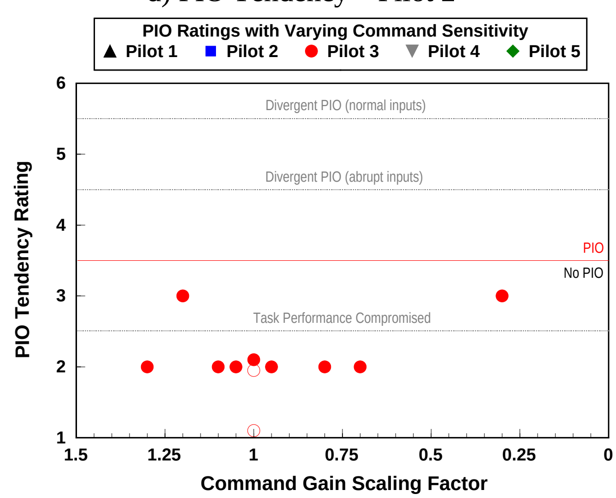
c) Handling Qualities – Pilot 2



d) PIO Tendency – Pilot 2



e) Handling Qualities – Pilot 3



f) PIO Tendency – Pilot 3

Figure 127. Individual pilot ratings, pitch PA command sensitivity (passive) evaluations

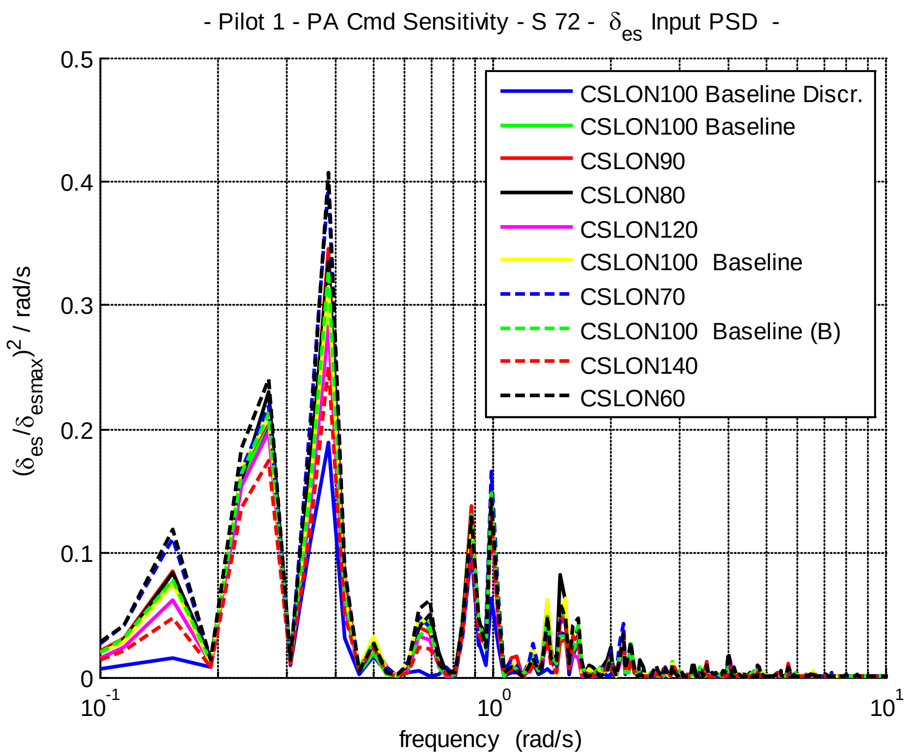


Figure 128. PSD of pilot 1's δ_{es} input—command sensitivity passive — PA

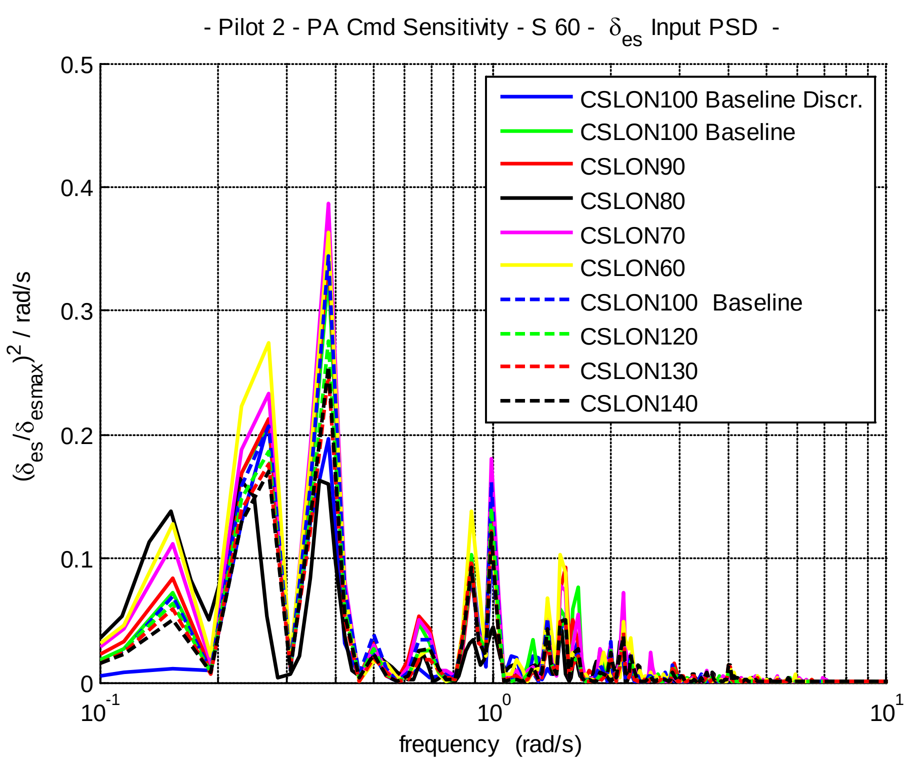


Figure 129. PSD of pilot 2's δ_{es} input—command sensitivity passive — PA

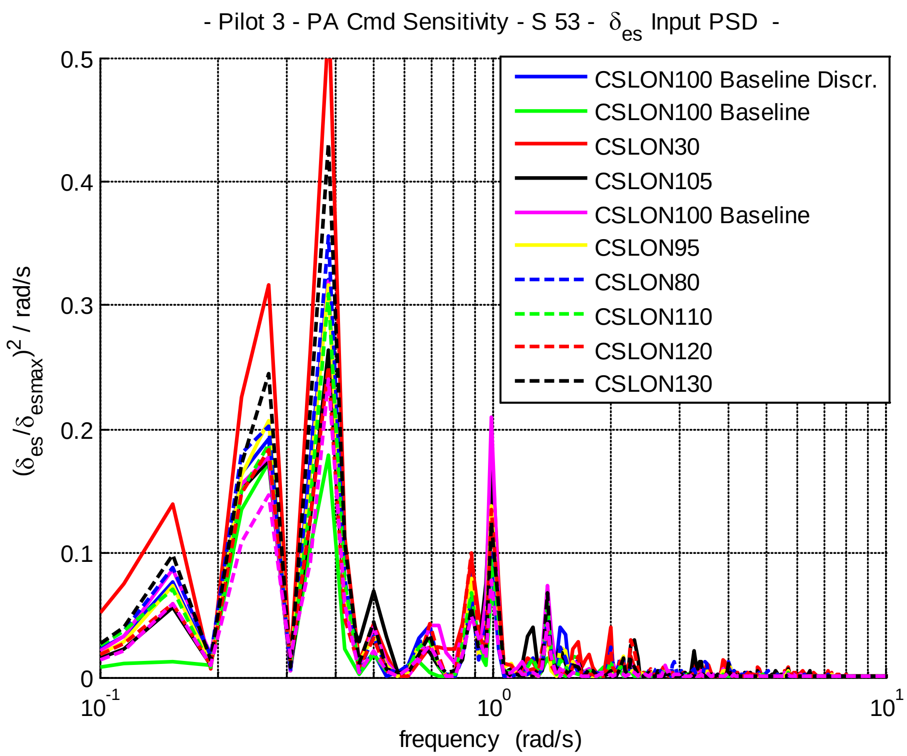


Figure 130. PSD of pilot 3's δ_{es} input—command sensitivity passive — PA

10.4.2.1.2 Pilot Ratings, Comments, and Task Scoring

10.4.2.1.2.1 Pilot 1

Pilot Ratings and Comments — Baseline is HQ level 1 (HQR = 2, 3). Reduction of the command gain scaling factor is occasionally associated with higher forces and heaviness. A slight trend to HQ worsening is detected because of it. Higher scaling factor is reported to correspond to lower accuracy in the gross acquisition task: "Fine tracking no problem. Gross acquisition harder to acquire" for CSLON = 1.4. Overall ratings variation is HQR = 2 to 4. A slight trend to HQ worsening due to gain scaling decrease is detected, see figure 127(a). No PIO proneness is reported: PIOR = 1 for all configurations. The sensitivity variation is perceived with significant accuracy by pilot 1, who relates the command gain variation with a varying effective stick gradient. The comment for the configuration with CSLON = 0.8 is: "Seems heavier than last. Fine tracking good. Heavier forces than I would like. Forward stop 2 times." That for CSLON = 1.2 is: "Lighter than the previous one. Similar to the baseline, maybe lighter. I can do the job fine." This indicates how a change of the low stick deflection amplitude command gain can be perceived by the pilot accurately and consistently with a passive stick as a sensitivity variation. The overall effect is limited with the ratings range of variation being HQR = [2, 4].

Task Scoring — Average scoring is desired = 78% and adequate = 92% for the discrete captures, while it is desired = 61% and adequate = 70% for the continuous tracking. Minimal variation is present for the continuous tracking scoring across the different configurations. Significant scatter exists for the discrete captures, with minimum desired = 50% for the baseline configuration. No correlation between HQR and scoring is present.

Piloting Technique and Time Histories — Figure 128 shows that stick activity has significant peaks in a relatively broad frequency range. The low-frequency content is comparable with all other evaluations because it is associated to the discrete captures task. There is no negligible activity at very low angular frequency ($\omega = 0.15\ \frac{\text{rad}}{\text{s}}$). It is noticeable that low-frequency activity is inversely proportional to the gain-scaling factor, even if the major impact of the gain scaling on the commanded surface deflection is at small stick inputs. The maximum frequency at which there is a significant pilot input energy content is $\omega = 1.5\ \frac{\text{rad}}{\text{s}}$, with slightly higher values for the configurations with a lower gain scaling factor. The stick input energy distribution indicates a combination of open and different frequencies closed loop piloting technique, which is displayed in the time history of figure 131.

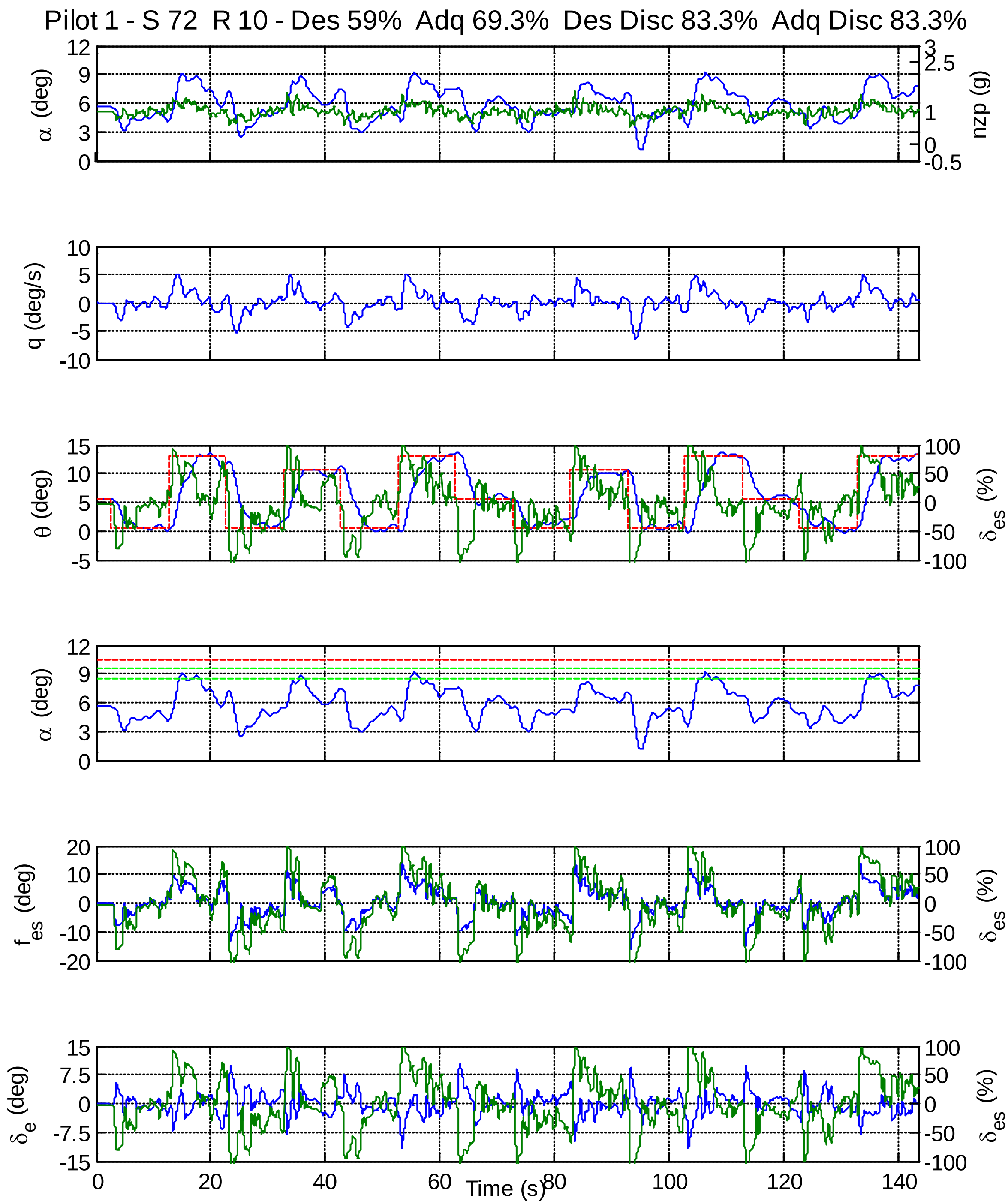


Figure 131. Pilot 1 CSLON = 0.7 captures time history plot — PA

10.4.2.1.2.2 Pilot 2

Pilot Ratings and Comments — The variation due to command gain scaling is comparable to the scatter of the baseline HQR (HQR = 2 to 4). Low-gain scaling factors are associated to higher command nonlinearity and to the reduction of pitch authority, particularly in NU for CSLON = 0.9: “There is some nonlinearity from gross acquisition to fine tracking when NU. ND is not as noticeable. When I came off the input, the pitch rate stagnated, more compensation," and for CSLON = 0.8: "Have to modulate in NU. Sometimes NU stagnation from gross acquisition. ND not as much." This demand for more compensation corresponds to a reduction of HQ level for the configurations with CSLON < 1.0 (HQR = 4). All other configurations are rated HQR = 3. The PIOR is degraded by the SoS disturbance with respect to pure discrete capture task. No impact of command gain scaling variation on the PIORs of the discrete + SoS tasks: PIOR = 3 for all configurations.

Task Scoring — Average task scoring is desired = 85 % and adequate = 91% for discrete captures; desired = 63% and adequate = 71% for continuous scoring. Continuous scoring is correlated to HQR, with a maximum desired = 65% for HQR = 2 and minimum desired = 56% for HQR = 4.

Piloting Technique and Time Histories — Frequency content of pilot 2 stick activity is coincident with that of pilot 1, as it can be derived from comparison of the pilot's inputs PSD displayed in figures 128 and 129. It is a combination of open loop and closed loop piloting technique. The impact of the command gain scaling is an increase of stick inputs amplitude with decreasing of the CSLON value, throughout the whole frequency range.

10.4.2.1.2.3 Pilot 3

Pilot Ratings and Comments — Pilot 3 assigned a larger variation of HQR across the tested configurations, with a discrete + SoS tracking task (HQR = 4 to 6). There is a tendency of HQR degradation caused by the reduction of gain scaling factor. This is due to larger stick motions, higher physical demand, and lower sensitivity, as reported by pilot 3. For CSLON = 0.8: "Larger motions again, my wrist is tired. Less sensitive, more sluggish. Large motions of my hand. Not as good performance in terms of tracking." Higher gains scaling is reported to provide higher precision in gross acquisition. For CSLON = 1.3: "More sensitive. No fast oscillations. Better precision at AoA = 9.5 deg." This increased precision does not lead to significant HQR improvement, which are HQR = 4, like baseline, for CSLON $\geq$ 1.0, except for a single occurrence of HQR = 4. No PIO tendency is assessed for any configuration, with PIORs = 2 to 3.

Task Scoring — Average task scoring is desired = 76% and average = 91% for discrete captures; desired = 51% and adequate = 63% for continuous regulation. The minimum discrete captures scoring is desired = 50%, which indicates a significant variation across the configurations, with no definite trend with HQR. A slight trend can be identified between continuous regulation scoring and HQR: Seven configurations from the total of 10 with HQR $\geq$ 4 correspond to a desired < 50% scoring (see table 60).

Table 60. Command sensitivity continuous task scoring — pilot 3 — PA

Command Sensitivity PA Continuous Regulation Scoring and HQR			
Run Number	HQR	Desired (%)	Adequate (%)
1	4	55.4	64.1
2	3	56.4	63.0
3	6	46.3	61.2
4	5	47.0	59.2
5	4	47.0	60.6
6	4	52.2	64.5
7	5	44.9	61.2
8	4	52.4	60.8
9	4	47.9	60.6
10	5	46.1	59.7
11	4	46.8	59.7

Piloting Technique and Time Histories — Pilot 3's piloting technique is comparable with that of pilots 1 and 2: a combination of large amplitude inputs to accomplish the discrete part of the captures task and a closed loop technique for fine tracking. Amplitude of low frequency stick activity inputs is broadly inversely proportional to command gain scaling. Amplitude of higher frequency inputs is not significantly affected by the command gain scaling. There is a significant stick input shaping also in the gross acquisition phase of the task. Figure 132 displays the time history of record 7 of the configuration with CSLON = 0.8. A significant amount of input shaping with local large amplitude is evident, with consequent small pitch oscillations, as demonstrated by the pitch rate time history. This also confirms the comment reported above regarding higher physical demand for this configuration.

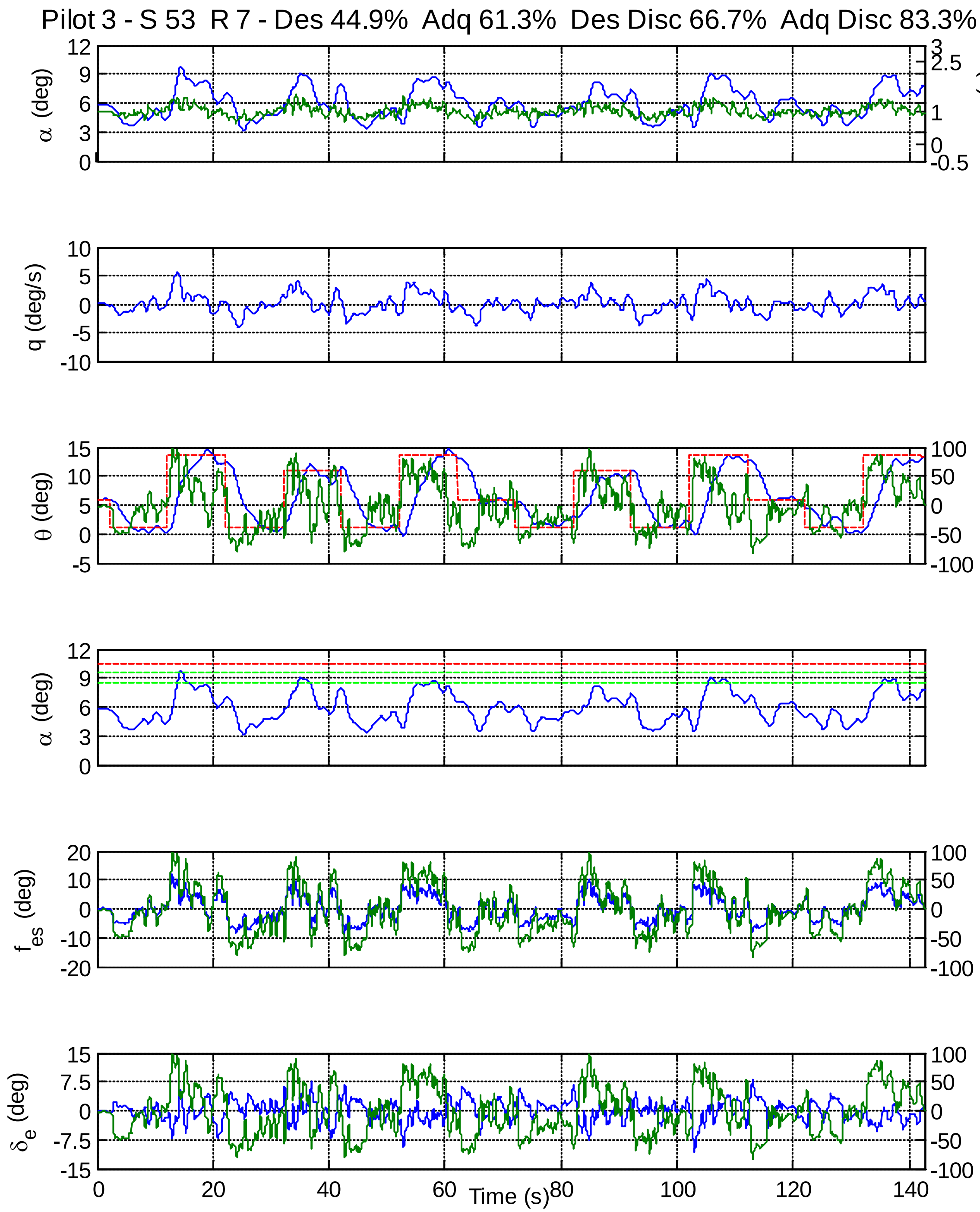
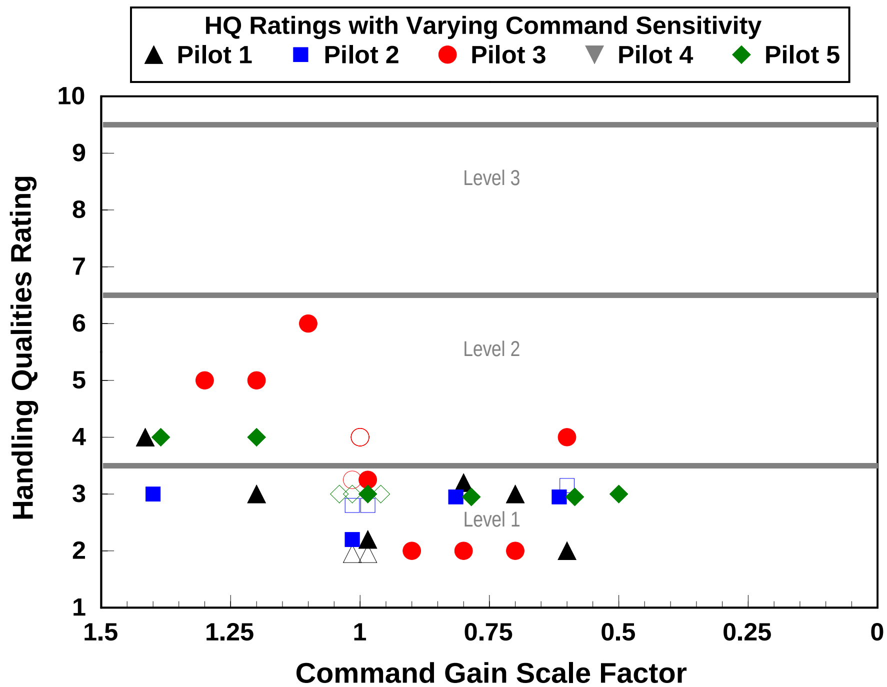


Figure 132. Pilot 3 CSLON = 0.8 captures time history plot — PA

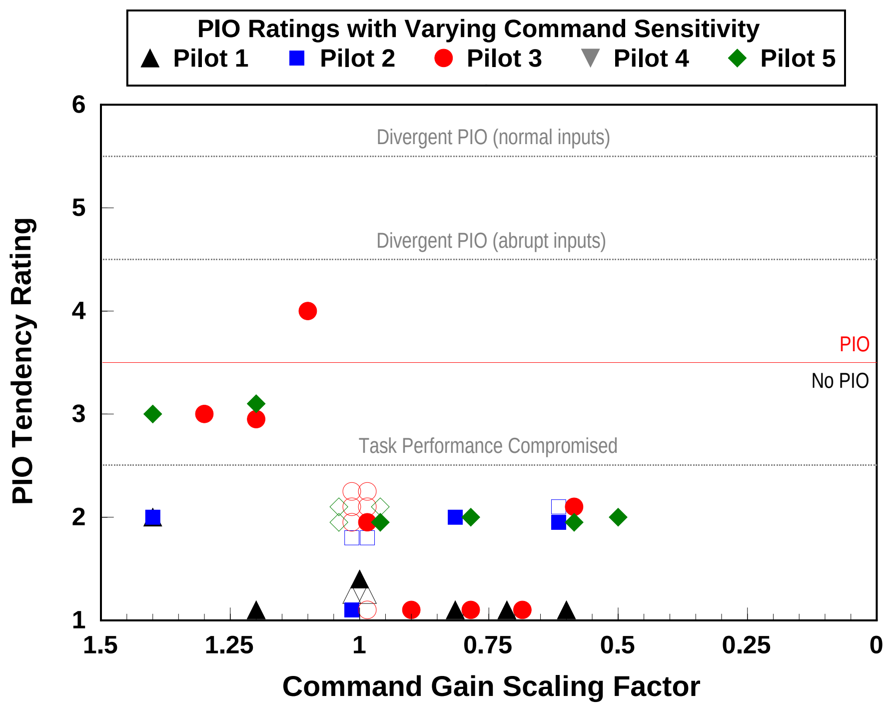
10.4.2.2 V_C Flight Condition

10.4.2.2.1 Principal Outcomes

The baseline command gain configuration was constant throughout the entire stick deflection. The command sensitivity was varied by scaling the gain for low stick deflection amplitude in the range CSLON = [0.5, 1.6]. Based on the comments provided by each one of the pilots during the evaluation, the range varied slightly among them. Figure 133 displays the HQ and PIO tendency ratings (HQR, PIOR) assigned by the different pilots on the basis of the ground simulations. Figure 134 contains the plots of PIOR versus HQR for each pilot. More than one simulation for each pilot was performed for some configurations, leading to limited scatter in the ratings; this was potentially due to the sequence in which the same configuration was tested by that pilot.

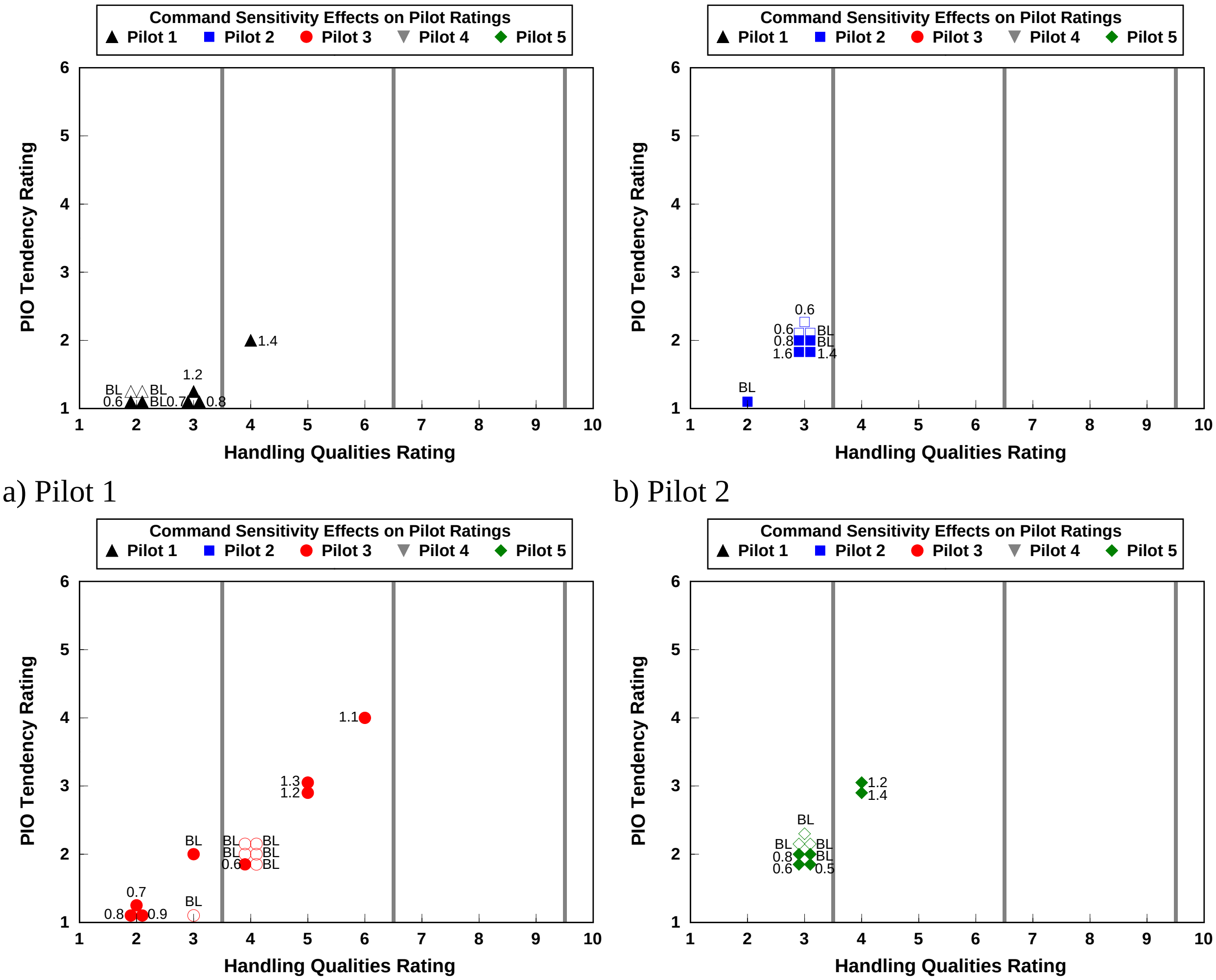


a) Handling Qualities



b) PIO Tendency

Figure 133. The HQR and PIORs summary, all pilots, pitch V_C command sensitivity (passive) evaluations



a) Pilot 1 b) Pilot 2

c) Pilot 3 d) Pilot 5

Figure 134. Ratings summary, all pilots, pitch V_C command sensitivity (passive) evaluations

From the analysis of the pilots' ratings and piloting technique, the following indications can be derived for the specific pitch attitude capture task with SoS disturbance:

- Command sensitivity moderately affects HQR within the same pilot, with a tendency for worsening of the ratings to increase the command gain in the small stick deflection range (higher gain scaling factor). Pilot 3 demonstrates a higher sensitivity to command gain variation, with slightly different trend with respect to the other pilots, leading to HQ low level 2 and a higher scatter for scaling factors higher than unity. For pilot 3, local worsening of the HQR is also produced in correspondence of the minimum tested value of the gain scaling factor. This trend is common, with lower dependency on gain scaling factor values, to pilots 5 and 1.

- The PIOR is slightly affected by command sensitivity variation, with a tendency for degradation comparable to that of HQR. As for HQR, pilot 3 demonstrates higher susceptibility to sensitivity variation for command gain scaling higher than unity in particular. One occurrence in the PIO prone range (PIOR = 4) is present.

- Limited scatter is present for the ratings of the baseline configuration.
- There is higher correlation between PIORs and HQR for pilot 3, which is potentially due to the higher sensitivity and consequent higher range of ratings variation.
- No particular correlation between task scoring and ratings could be identified across all pilots.

From numbers 1 and 2 in the previous list, it is derived that the higher sensitivity produced by a higher command gain in the range of small stick deflections leads to a higher level of pilot compensation, independent from the piloting technique.

A tendency for bobbling with higher gains is reported in particular by pilots 3 and 5. Reduction of the initial command gain slope occasionally led the pilots to maneuver for gross acquisition significantly beyond the gain breakpoint, with consequent higher local sensitivity. This is considered a potential source of scatter in the ratings, as derived through occasional, slightly unexpected, comments.

The overall effect of command sensitivity variation on HQ levels is moderate. It leads to HQ level 2 for gain scaling higher than unity and PIO proneness in a single case throughout all performed evaluations (figures 135–138).

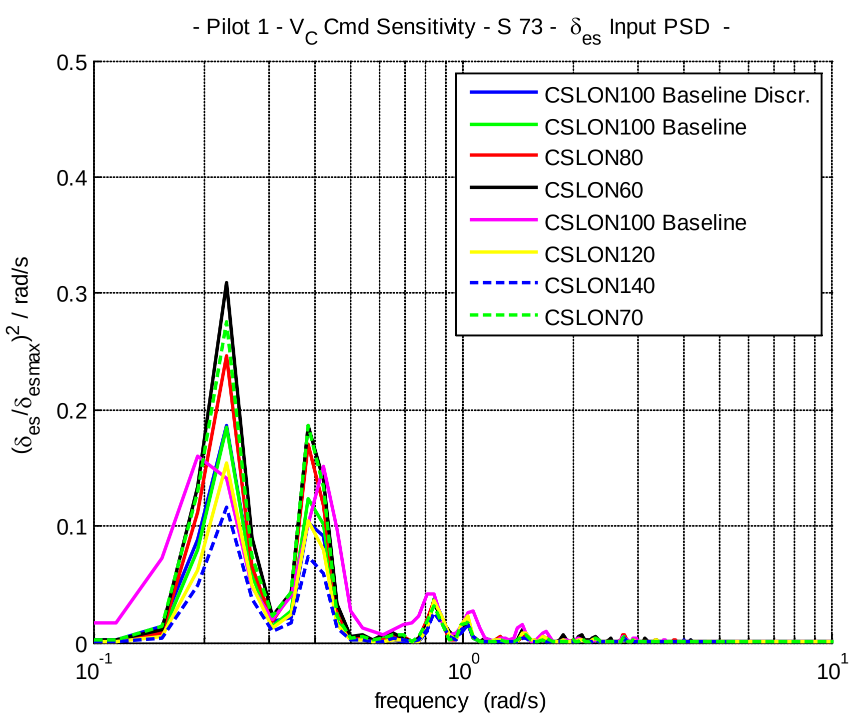


Figure 135. The PSD of pilot 1's δ_{es} input — command sensitivity passive — V_C

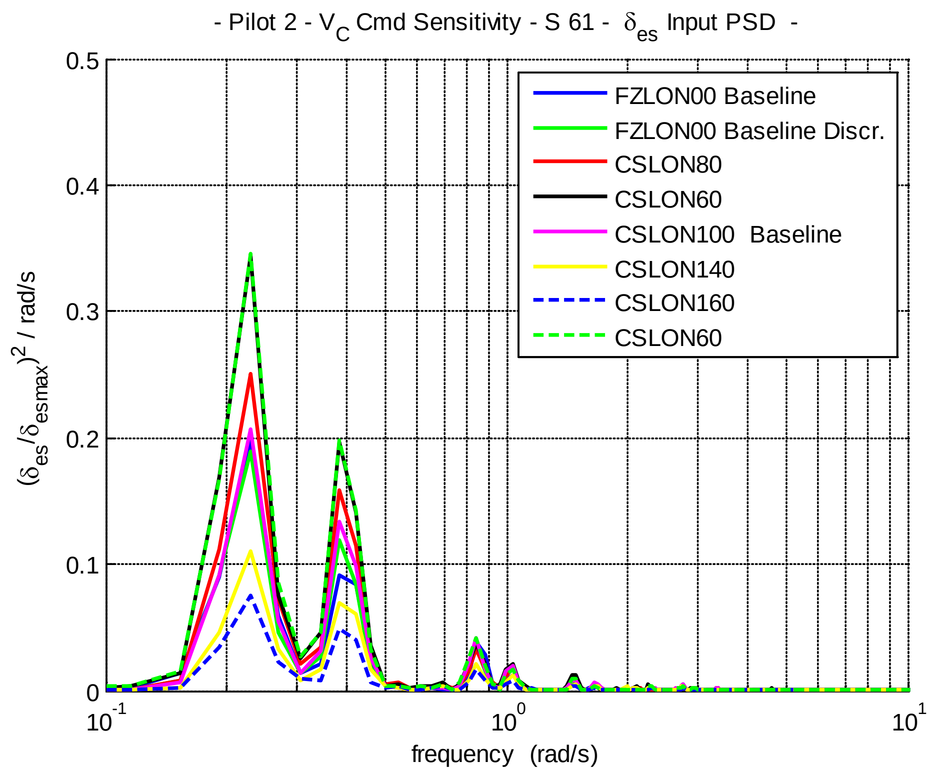


Figure 136. The PSD of pilot 2's $\boldsymbol{\delta_{es}}$ input — command sensitivity passive — $\mathbf{V_C}$

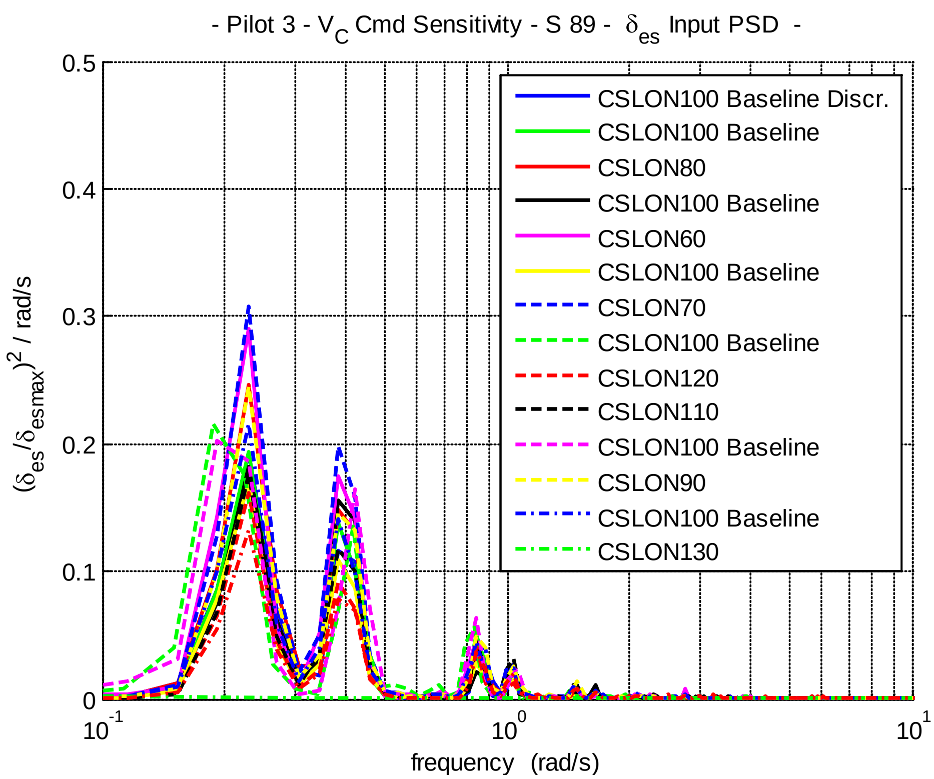


Figure 137. The PSD of pilot 3's $\boldsymbol{\delta_{es}}$ input — command sensitivity passive — $\mathbf{V_C}$

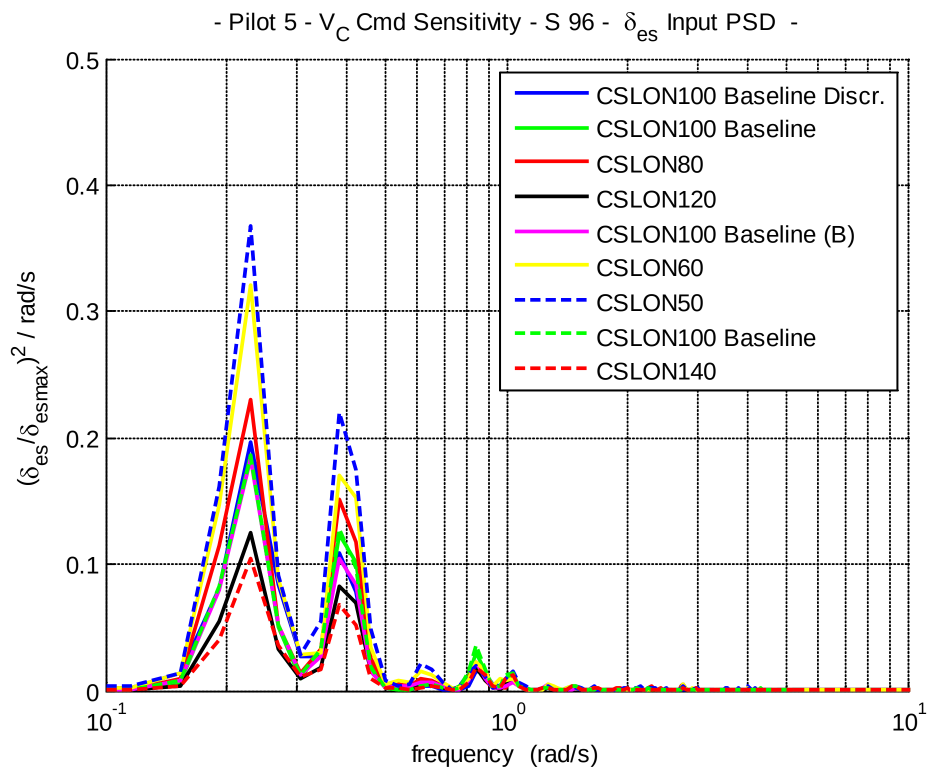


Figure 138. The PSD of pilot 5's δ_{es} input — command sensitivity passive —V_C

10.4.2.2.2 Pilot Ratings, Comments, and Task Scoring

10.4.2.2.2.1 Pilot 1

Pilot Ratings and Comments — The pilot preferred the baseline or configurations with gain scaling factor less than unity (HQR = 2, 3). The corresponding higher heaviness deriving from lower sensitivity was preferred to the higher sensitivity for the fine tracking phase of the task. The CSLON = 0.6 configuration has the best HQR (HQR = 2). The relative comment is: "Very similar to the previous, heavier than the baseline. I can get the g I want. No fine tracking problem. A little lighter than the previous." Worst HQR and PIORs (HQR = 4, PIOR = 2) were assigned to CSLON = 1.4 for the oscillatory tendency: "More sensitivity for fine tracking. Bobbling and overshooting. It is easy to adapt to." These comments confirm the trend described above. A slight tendency to a minimal worsening of the HQR with increasing sensitivity is visible in figure 133 (a). A slight correlation between HQR and PIORs is identifiable. See figure 134 (a), showing a higher PIOR for the configuration with the highest CSLON and HQR.

Task Scoring — Average discrete task scoring is desired ≡ adequate = 91%, while continuous scoring is averagely discrete = 72%, adequate = 78%. The high average values demonstrate a relatively low number of exceedances and time to acquire the target. There is no correlation between scoring and HQR: scatter is limited, with a maximum of 20% for discrete and 10% for desired continuous scoring.

Piloting Technique and Time Histories — Low-stick activity is present, as displayed in figure 135, in the frequency range outside that of the discrete captures. Higher frequency closed loop inputs are of small amplitude, and input shaping is present in the gross acquisition phase of the task. The low-frequency inputs amplitude is broadly inversely proportional to the value of the gain-scaling factor.

10.4.2.2.2.2 Pilot 2

Pilot Ratings and Comments — The HQR variation is negligible throughout all configurations. The baseline configuration is the preferred one. No tendency to HQ level degradation and PIO proneness was reported, even for the configuration with the highest gain-scaling factor (CSLON160; CSLON = 1.6). No specific issues were revealed by PIORs. Pilot 2 stresses the two phases of the task, composed of gross acquisition and fine tracking. Relevance is given to the transition between the first and the second phase: "I was looking at the g meter more, so the release was not quite right."

Task Scoring — Average discrete task scoring is desired ≡ adequate = 95%, continuous scoring is average discrete = 69%, adequate = 75%, with no correlation with HQR and maximum scatter equal to 7% for the desired scoring.

Piloting Technique and Time Histories — As for pilot 1, stick activity at relatively higher frequency is low; small-amplitude closed-loop inputs are present in the regulation part of the task. Low-frequency inputs modulation is present for the configurations with higher command-gain scaling. Figure 139 displays the time history of the CSLON160 case (CSLON = 1.6).

10.4.2.2.2.3 Pilot 3

Pilot Ratings and Comments — HQR were mostly based on the tendency to overshoot in the fine-tracking phase of the task. Comments reflect the tendency to prefer lower gain scaling than unity, but not as low as to reduce sensitivity significantly (HQR = 4 for CSLON = 0.6). Higher stick activity and PIO proneness are associated with the higher CSLONs. Unpredictability is reported for CSLON = 1.3. Pilot 3 identified a preferable gain scaling range: CSLON = [0.7, 1.0], outside of which HQ degradation occurs, as displayed in figure 133 (c). Configurations with gain scaling factor below the lower limit are associated with insufficient sensitivity: "Larger motions for fine tracking, a little on the flat side. A little insensitive. Would want more sensitivity on the pull." Higher degradation of the HQ occurs with a gain scaling factor higher than unity, with respect to reduced gain.

It is noticeable that the trend of HQR and PIORs as a function of CSLON is similar. As a consequence, HQR and PIORs are strictly correlated, as displayed in figure 134 (c). This confirms the dependency of HQR from the tendency to pitch oscillations in the fine-tracking part of the task. This trend is potentially dependent on the augmented aircraft pitch response, which is characterized by a relatively high-pitch-rate overshoot, $\Delta G(q) = 8.24$ dB (section 2.4.1.2). The same trend with CSLON is not as evident in PA flight condition, for CSLON > 1.0 in particular, as the augmented aircraft pitch rate overshoot is lower: $\Delta G(q) = 1.21$ dB. This confirms the validity of the FQ criteria used to assess the predicted FQs

and the effectiveness of the simulator in exposing the closed-loop pilot-vehicle HQ characteristics accurately.
Task Scoring – Average discrete scoring is desired ≡ adequate = 84%, average continuous scoring is discrete = 71%, adequate = 77%. No correlation with HQR is present. Minimum continuous scoring is desired = 65% and adequate = 71%.

Piloting Technique and Time Histories – Piloting technique is similar to that of the other pilots. Low-frequency stick activity is inversely proportional to the gain scaling factor. Relatively higher frequency content is not negligible at the two frequencies $= 0.75; 0.85\ \frac{\text{rad}}{\text{s}}$.

10.4.2.2.2.4 Pilot 5

Pilot Ratings and Comments – Baseline configuration is HQR = 3 in all four repeated evaluations, no scatter. Pilot 5 confirms the tendency of HQ level 1 for configurations with gain-scaling factors lower than unity. Higher sensitivity (CSLON > 1.0) is associated with tendency to overshoot and requirement for backing out of the loop, transitioning to an open loop piloting technique. Compensation is required for the transition. This is reported in the comment to CSLON 140 (CSLON = 1.40): "Sensitive fine tracking, have to dampen/control inputs. Balancing act. More sensitive; have to back out of control loop and pulse the stick." Configurations with CSLON < 1.0 are reported to have better fine-tracking HQ and are rated HQ level 1. The comment for CSLON 60 describes this trend accurately: "Sluggish gross acquisition same as others; a little larger forces needed. A little better fine tracking, more manageable. Initial overshoot ± 1 degree."

Pilot 5 indicates a definite split between the gross acquisition and the fine-tracking phase of the task. Ratings, as for pilot 3, principally depend on the fine-tracking phase. Gross acquisition is judged overall sluggish in all configurations. Similar correlation to pilot 3 is present between command gain, PIORs, and HQR within a smaller range of ratings variation (figure 134 (d)). Lower proneness to PIO (PIOR = 3) is rated for the worst HQ configurations (CSLON 120; CSLON 140 - CSLON = 1.20; 1.40) with respect to pilot 3.

Task Scoring – Average discrete scoring is desired ≡ adequate = 94%, average continuous scoring is discrete = 64%, adequate = 71%. No correlation with HQR is present. Minimum continuous scoring is desired = 58% and adequate = 68%.

Piloting Technique and Time Histories – The high discrete and relatively low continuous scoring is an indication of relatively low aggressiveness in performing the captures task. The higher-frequency stick activity is low and the trend common to all pilots of adapting the gross-acquisition stick amplitude to the command-gain scaling is confirmed, with amplitude inversely proportional to the scaling factor. Through the comparison of the time histories in figure 140 (CSLON = 0.6) with those in figure 141 (CSLON = 1.4), it is possible to see more gradual gross acquisition inputs for the second configuration, with comparable closed-loop activity and input shaping between the two configurations. The pilot did not significantly change the closed-loop technique as confirmed by the inputs PSD. The time to acquire the target for the lower sensitivity configuration is higher, with larger margins with respect to the pilot station normal load factor (n_{zp}) margins leading to higher discrete captures scoring. This is the potential reason for the higher pitch-rate oscillations present in the second configuration and the higher tendency for pitch bobbling reported by the pilot.

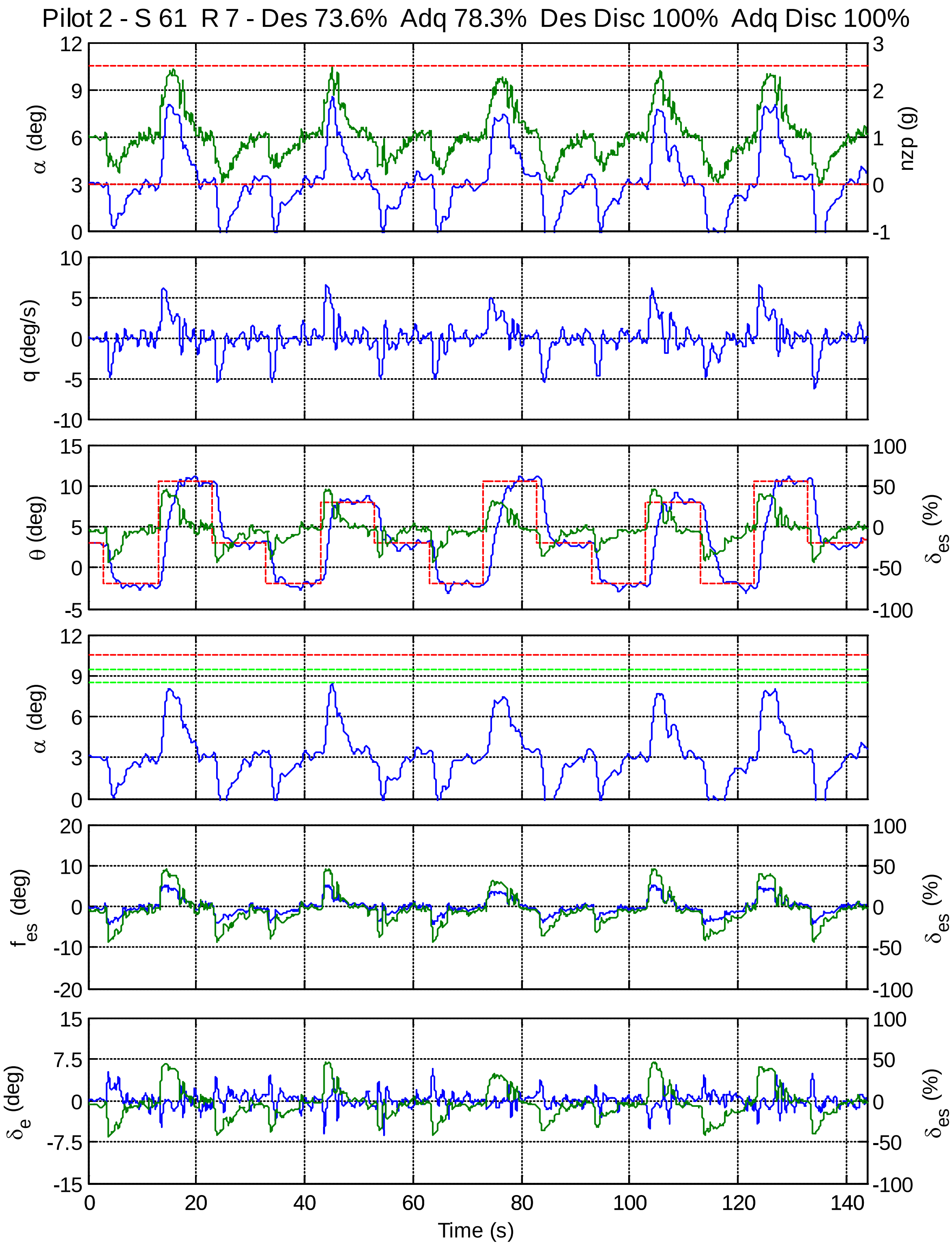


Figure 139. Pilot 2 CSLON = 1.60° captures time history plot — V_C

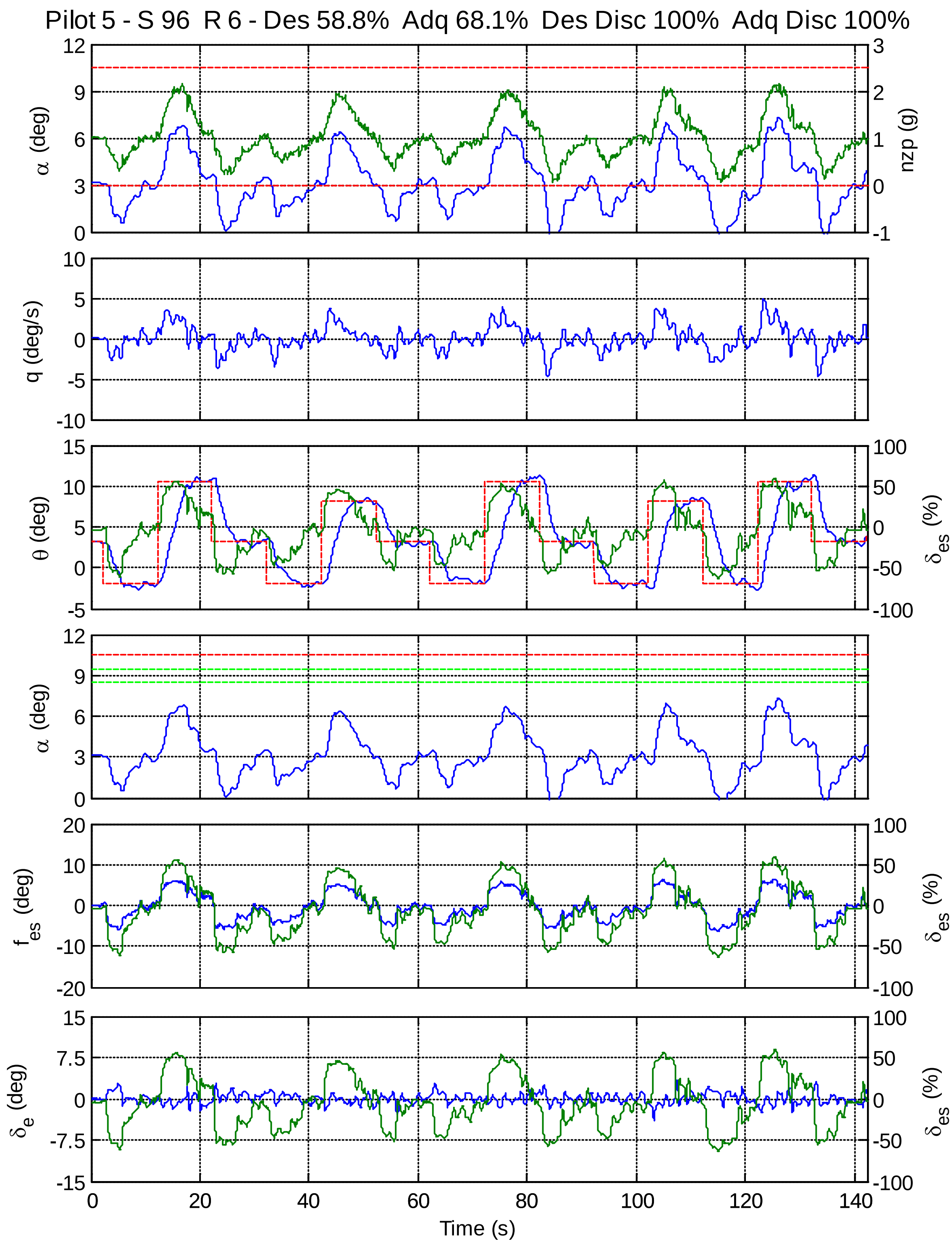


Figure 140. Pilot 5 CSLON = 0.6° captures time history plot — V_C

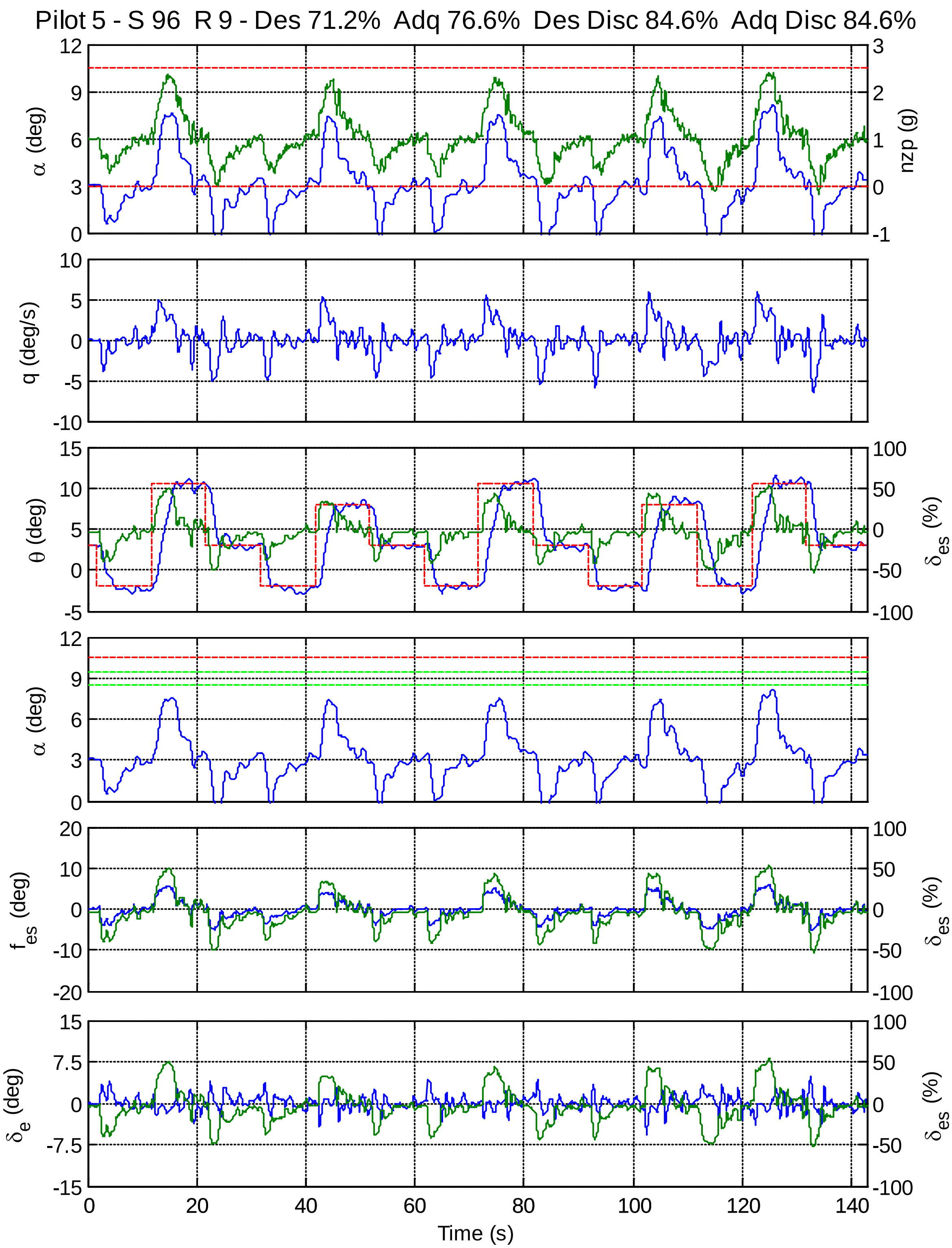


Figure 141. Pilot 5 CSLON = 1.4° captures time history plot — V_C

10.4.2.3 Pilot Evaluations, Observations, and Conclusions

From the analysis and comparison of the results and comments of the evaluations of the command gain sensitivity, the following conclusions can be drawn:

- The recommended values of low amplitude command gain scaling is 0.7 < CSLON in PA and 0.7 < CSLON < 1.0 in V_C.

- The impact of the command sensitivity variation is different depending on the flight conditions and augmented open-loop aircraft response.

- In the PA flight condition, values of the gain-scaling factor lower than unity lead to worsening of the HQ because of higher physical workload and heaviness perceived by the pilots. This is more evident for pilots with higher closed-loop stick activity. The opposite effect is evident in the V_C flight condition, in which a reduction of the command sensitivity leads to a slight HQ improvement. As for PA, this is partly affected by piloting technique and partly by the augmented aircraft response.

- An open-loop (vehicle only), augmented response characterized by higher values of pitch rate overshoot is more sensitive to command sensitivity variation. Increase of sensitivity leads to degraded HQ for the higher proneness to pitch oscillations when operated in closed loop (pilot + vehicle). This is the reason for the dependency on the flight condition, as in these evaluations the augmented aircraft in PA has a low pitch rate overshoot compared to that in the V_C flight condition.

- Design and development of command-gain scheduling with stick deflection and flight condition is expected to be implemented at production-level standards with low criticalities. Guidance can be derived from offline FQ criteria to identify potential issues with the pilot in the loop.

- An adequate level of robustness to command sensitivity variation is particularly demonstrated by the evaluations in the V_C flight condition. This is expected to allow for consistent in-flight evaluation and refinement of the design through dedicated test campaigns.

10.5 ACTIVE INCEPTOR COMMAND SENSITIVITY

10.5.1 PA Flight Condition

10.5.1.1 Principal Outcomes

All sessions began with the stick shaker deactivated. Pilots first evaluated the shaker off baseline both with and without the SoS disturbance to ensure level 1 HQ. The shaker amplitude and frequency was held constant throughout testing; only the AoA at which the shaker activated was varied. Onset AoA in the range AoA = [8.5° 10°]. Note that at 10°, the shaker does not activate until the maximum AoA of 9.5° for desired performance is exceeded. Figure 142 represents the

HQR assigned by the different pilots on the basis of the ground simulations. Figures 143–145 contain the plots of the individual HQR and PIORs for each pilot.

From the analysis of the pilots' ratings and simulation data, the following conclusions can be drawn regarding the specific pitch attitude capture task with SoS disturbance:

1. The shaker onset AoA has no impact on pilot HQR and PIORs. A PIOR of 1 was given for every run. HQR of only 2 and 3 were given, with no noticeable trend based on shaker onset AoA.

2. The shaker onset AoA had a negligible impact on task performance. Pilot 2's scores were consistent and unaffected by the presence or absence of the shaker. Pilot 1's scores were slightly reduced by the addition of the shaker at higher AoA.

3. Based on pilot comments, it is most important to ensure that the shaker onset is at an appropriate AoA relative to the limit. If the shaker onset is too high, it will not adequately protect the aircraft and allow the pilot to achieve desired performance. This was witnessed with pilot 1, who flew the shaker and often exceeded 9.5° AoA when the shaker activated at this value or above. If the shaker onset is too low, it becomes a nuisance and the pilot tends to ignore it. Pilot 1 commented that he had to switch to using the AoA gauge to obtain limit information when the shaker onset was too early (8.5°) because the information that the shaker provided was not only unhelpful but also detrimental.

There is no significant impact of the shaker onset on pilot ratings or task performance. However, for the shaker to be useful, the onset must be appropriate relative to the aircraft limits. For this specific test, a shaker onset of 9° AoA was found to be best at allowing the pilots to achieve desired performance and preclude exceedance of the AoA limit.

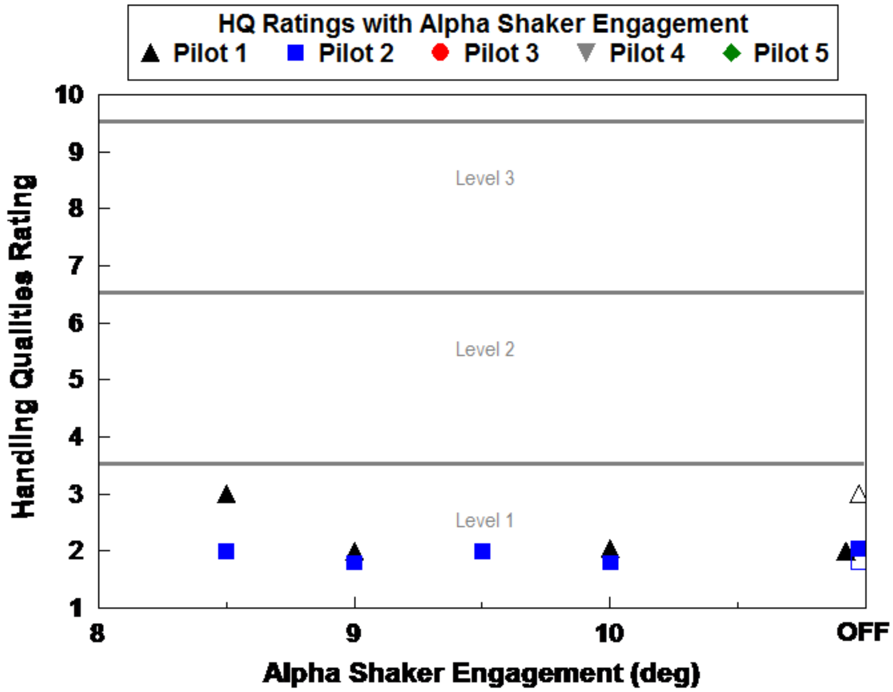
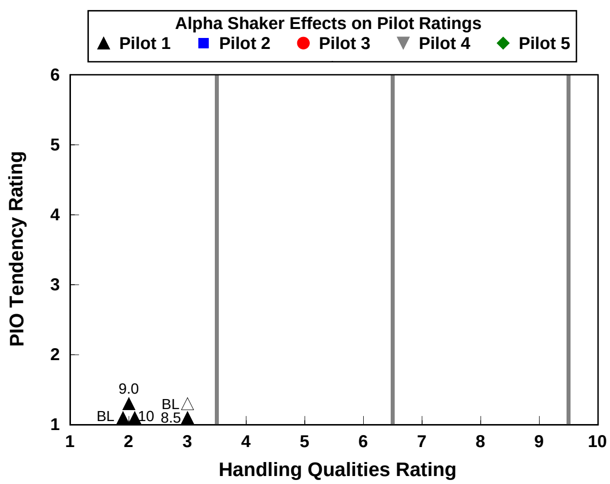
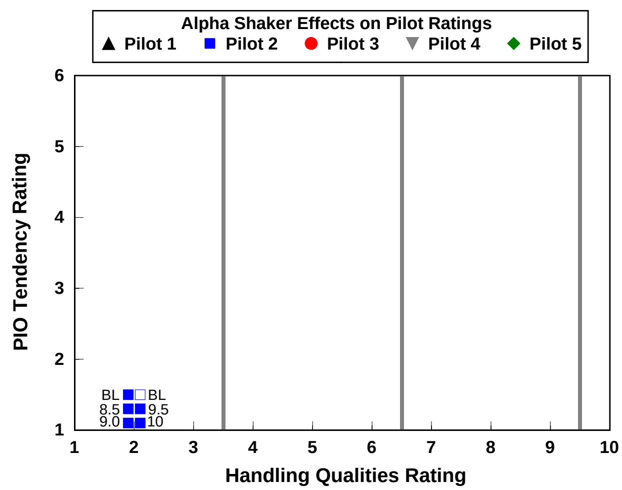


Figure 142. All pilot ratings, pitch PA command sensitivity (active) evaluations



a) Pilot 1



b) Pilot 2

Figure 143. Individual pilot ratings, pitch PA command sensitivity (active) evaluations

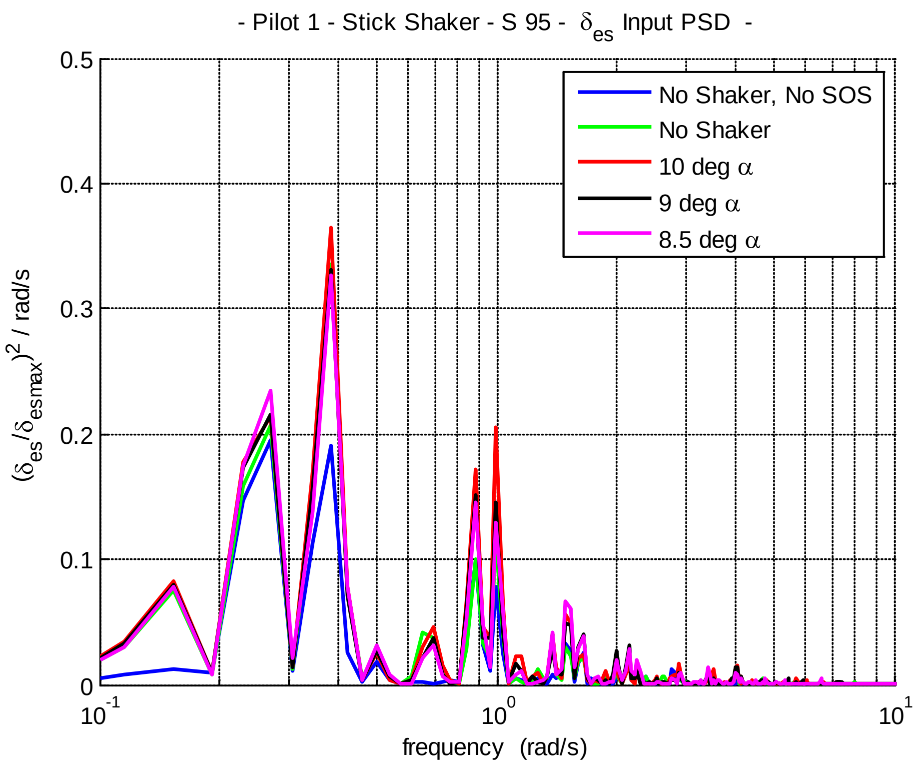


Figure 144. The PSD of pilot 1's δ_{es} input — command sensitivity active — PA

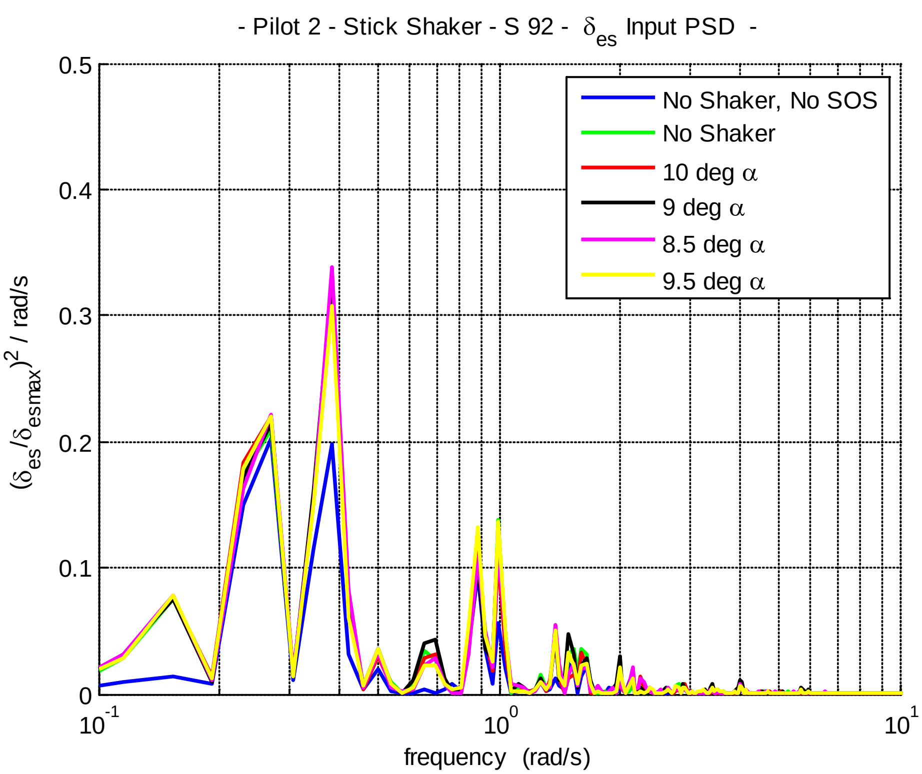


Figure 145. The PSD of pilot 2's δ_{es} input — command sensitivity active — PA

10.5.1.2 Pilot Ratings, Comments, and Task Scoring

10.5.1.2.1 Pilot 1

Pilot Ratings and Comments — The baseline (no shaker) is HQ level 1 (HQR = 2, 3). The addition of the SoS disturbance made the task more difficult, but there were no over-control tendencies. The addition of the shaker always resulted in retaining HQ level 1. The pilot intentionally went a little higher to ensure that the shaker was encountered. According to the pilot, the cue was nice, not overwhelming, came on quietly, and let you know when you were reaching the alpha limits. When comparing shaker activation at 9° and 10° AoA, the pilot could not detect much of a difference. It didn't matter to the pilot where the shaker was set, as long as it was set to the appropriate limit; he just backed off whenever it came on. However, when the shaker activated at 8.5°, the pilot felt that the cue came on too early. The pilot had to rely on the gauge to really know how far away from the limit he was. No PIO tendencies were noted as PIOR ratings of 1 were given for every gain setting.

Task Scoring — Average scoring is desired = 50% and adequate = 83% for the discrete captures, while it is desired = 61% and adequate = 70% for the continuous tracking. Minimal variation is present for the continuous tracking scoring across the different configurations. Generally, discrete scores were better without the shaker present because exceedances of the AoA limit were only achieved on runs with the shaker activation at 9° and 10°. This was potentially due to the fact that the pilot was pulling more to ensure the shaker was encountered so that it could be evaluated. Encountering the shaker at 10° AoA required the pilot to sacrifice desired performance. When the shaker came on earlier (8.5°), there were no AoA exceedances and the discrete score was equivalent to the scores obtained with no shaker. There was no scoring trend with HQR or PIOR.

Piloting Technique and Time Histories — Figure 128 shows that stick activity has significant peaks in a relatively broad frequency range. The only noticeable difference between the runs is that there is less activity in the lower frequency range for the first run, which is where the SoS disturbance is not being used. This corresponds to the lack of the continuous compensatory activity required to alleviate the disturbance. There is no obvious difference in pilot inputs for different shaker variations. The time history of figure 131 shows the AoA exceedances resulting from the shaker activating at 10°.

10.5.1.2.2 Pilot 2

Pilot Ratings and Comments — Ratings of HQR = 2 and PIOR = 1 were given for every shaker configuration tested. The baseline aircraft was found to be predictable and without PIO tendencies. There was a tendency to overshoot or coast beyond the desired stopping point, but it generally tracked as the pilot wanted it to. For shaker activations of 9.5° and 10° AoA, the shaker was never encountered and the pilot noticed no difference between these configurations and the baseline. At 9°, the pilot felt the shaker was a good cue not to exceed the limit and that it did not change the way he performed the task. At 8.5°, the pilot found the shaker to be distracting because it fired in the middle of the target.

Task Scoring — Average task scoring is desired = 86 % and adequate = 97% for discrete captures, it is desired = 58%, adequate = 66% for continuous scoring. Scores were consistent for every run, so there were no scoring trends with shaker setting or pilot ratings.

Piloting Technique and Time Histories — Frequency content of pilot 2 stick activity is coincident with that of pilot 1, as it can be derived from comparison of the pilot's inputs PSD displayed in figures 146 and 147. It is a combination of open-loop and closed-loop piloting technique. Again, the only noticeable difference between the runs is the lack of lower frequency activity for the baseline run with the SoS task off. All time history plots for pilot 2 look essentially the same, regardless of the shaker setting, which illustrates the lack of effect the shaker had on pilot technique and performance. A typical time history is shown in figure 132.

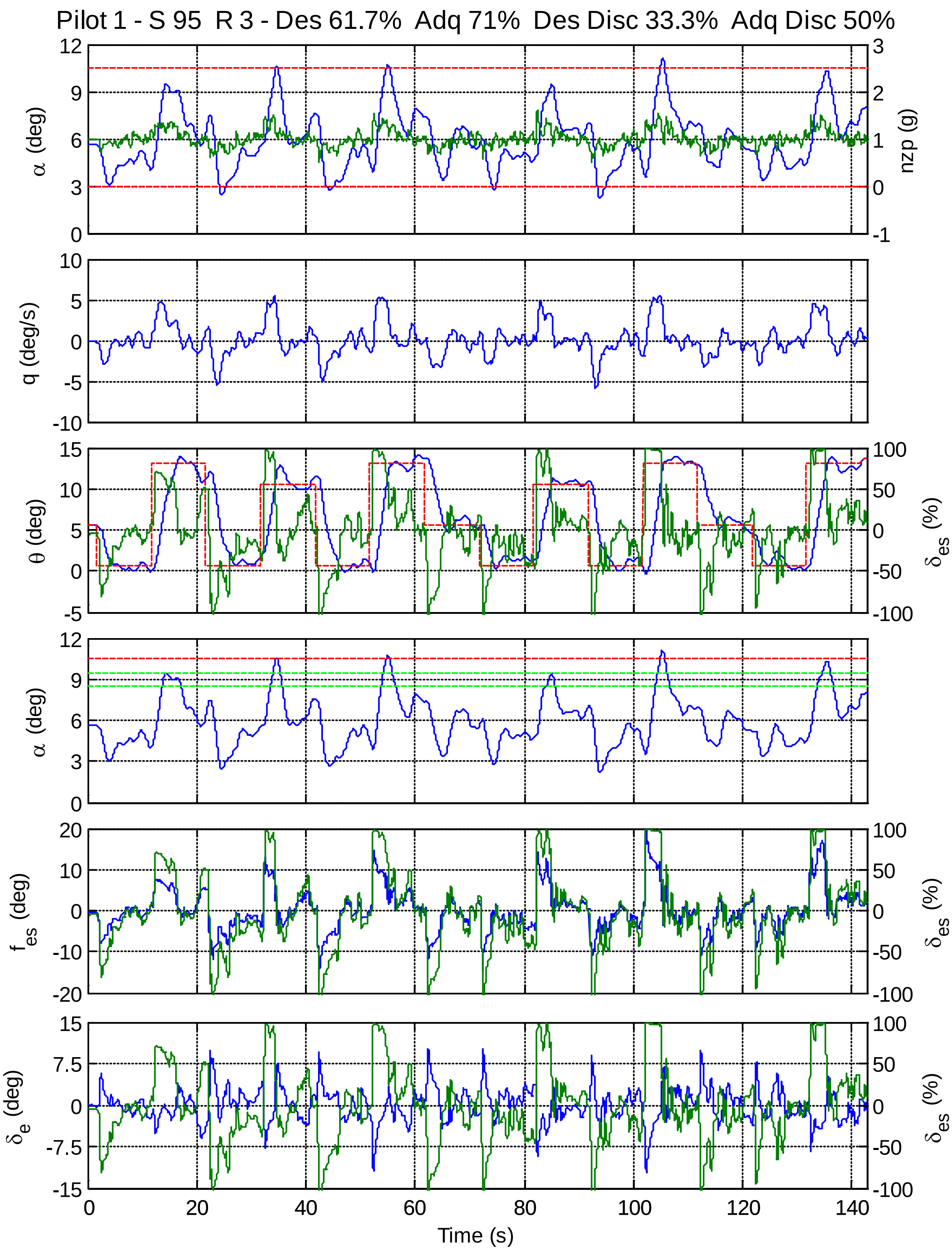


Figure 146. Pilot 1 shaker 10° AoA — captures time history plot

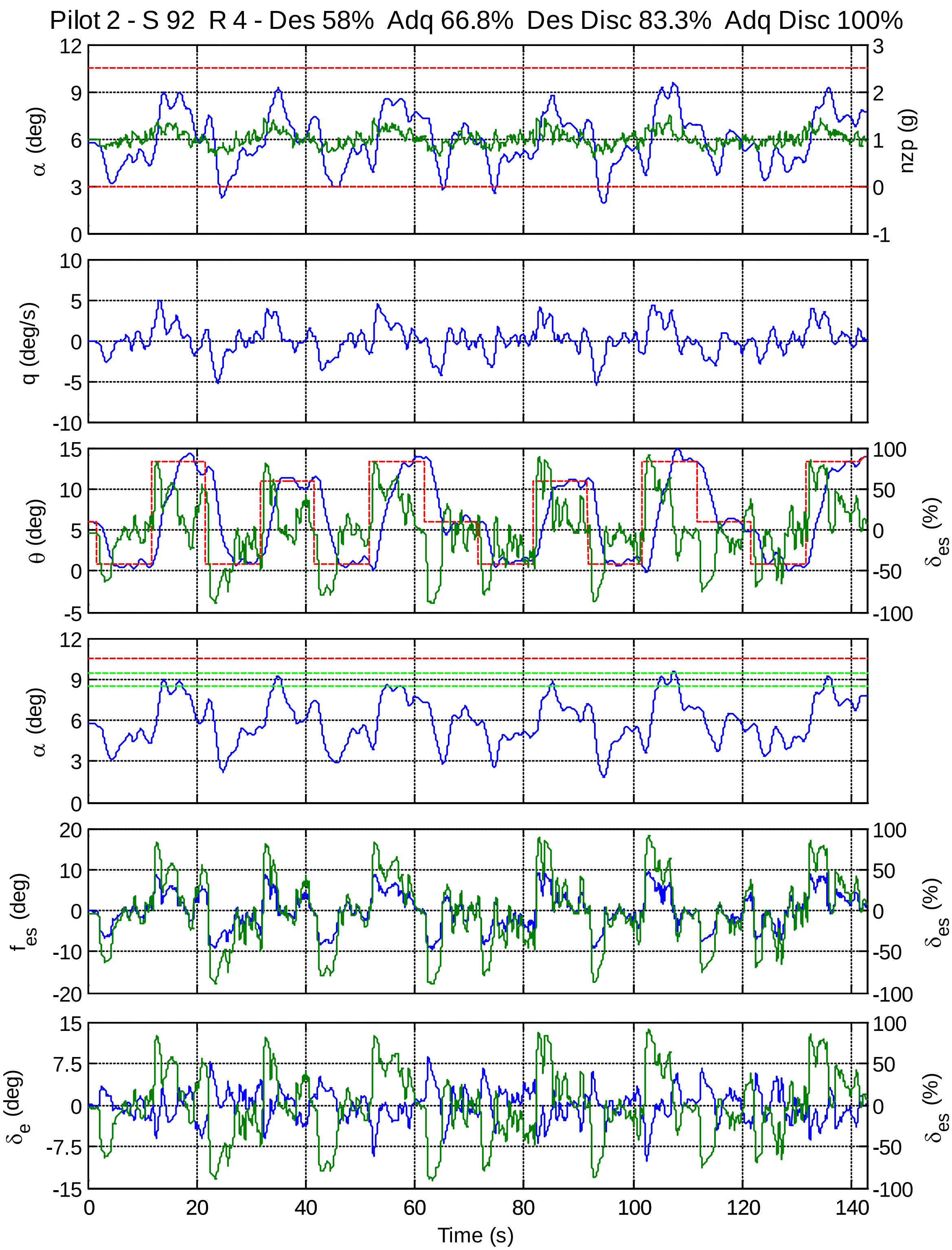


Figure 147. Pilot 2 shaker 9° AoA — captures time history plot

10.5.2 V_C Flight Condition

10.5.2.1 Principal Outcomes

This test evaluated the effect of and active stick gradient change on n_z envelope protection. Testing started in the baseline configuration with a gradient scale of 2 and a stick rate threshold of 0, with the n_z onset of 0.5 and 2 g. Pilots evaluated the baseline configuration with the SoS task both enabled and disabled to provide a reference point throughout the testing. The gradient scale was first varied from 2 to 4 while holding the stick-rate threshold and n_z onset at the baseline values. Next, the gradient scale was held fixed and the pilot's preferred value while the stick rate threshold was varied over the range [0–5]. Finally, while holding the first two varied parameters constant, the n_z onset limits were varied in the ranges $n_{z_{min}}$ = [0.25–0.5] and $n_{z_{max}}$ = [1.25–5]. Figure 148 depicts the variation of HQR with gradient scale. The variation of HQR with stick-rate threshold is shown in figure 149. Individual HQR and PIOR for each pilot are summarized in figures 150–153.

From the analysis of the pilots' ratings and piloting technique, the following indications can be derived for the specific pitch attitude capture task, with SoS disturbance:

- Pilots felt that the active stick implementation cue was not helpful and that it was actually objectionable. The cue was nonlinear and felt like the stick was fighting the pilot.

- Increasing the gradient scale factor resulted in poorer HQR and more critical pilot comments. The larger the scale factor, the more nonlinear the resulting gradient becomes and the higher forces the pilot encounters. Pilots felt that this made the aircraft less predictable and that the cue was a detriment rather than an aid.

- There was minimal measurable effect of the stick rate threshold on pilot ratings and comments. For large subsequent changes in the threshold, pilot 2 noted that the bumps in the cue onset could be slightly reduced but not eliminated with an increased stick rate threshold but that the increase was not large enough to warrant an improvement in HQR.

- Decreasing the n_z onset resulted in poorer HQR and less favorable pilot comments. Earlier onset of the higher gradient results in higher stick forces required to pull past 2 g, which pilots found to be objectionable. Although the pilots didn't like the early onset, the increased forces actually helped to prevent G-exceedances.

- A PIOR of 1 was given for every parameter variation, indicating that the active gradient does not result in PIO tendencies.

- Active gradient parameter variations had no effect on the continuous scoring component for this task.

- The active gradient scale and stick rate threshold variations had no effect on the discrete scoring component for this task. For pilot 1, a lower n_z onset did help to increase the discrete scoring by preventing G-exceedances. There was no effect of n_z onset on the discrete scoring for pilot 2.

Comments for this active stick implementation were almost universally negative; pilots did not like it. There were no combinations of its parameters discovered in testing that pilots found to be favorable. The only slight benefit seen was that for one pilot, the resulting increase in forces helped to prevent G-exceedances. A potentially better and simpler solution to this active stick implementation may be to use a constant gradient with higher forces than the baseline. This has the benefit of the higher forces making it harder to over g the aircraft without the negative effects of introducing nonlinearities.

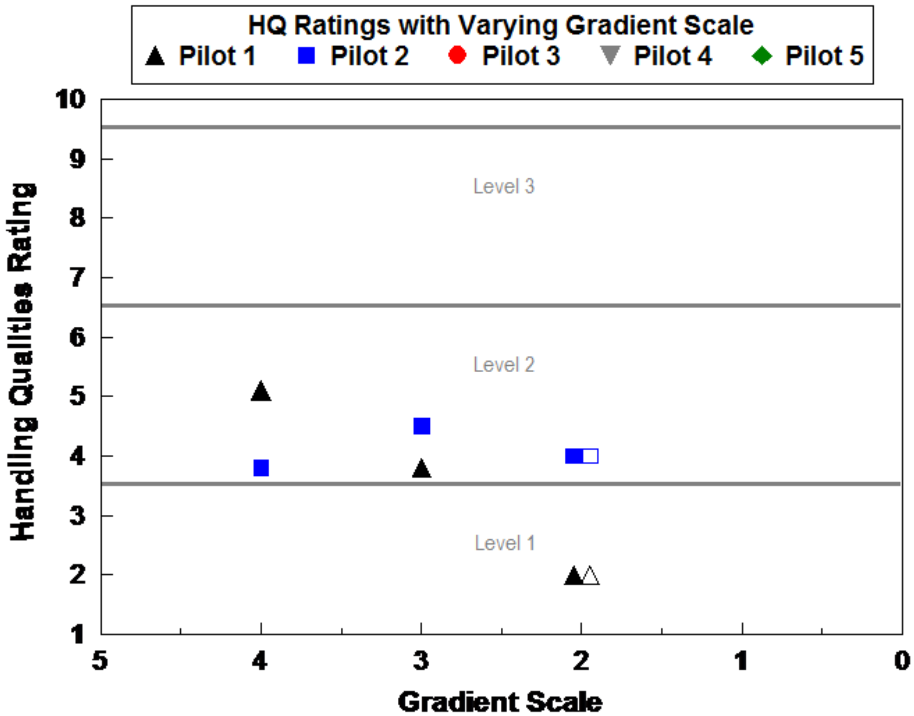


Figure 148. All pilot ratings, pitch PA command sensitivity (active) — gradient scale evaluations

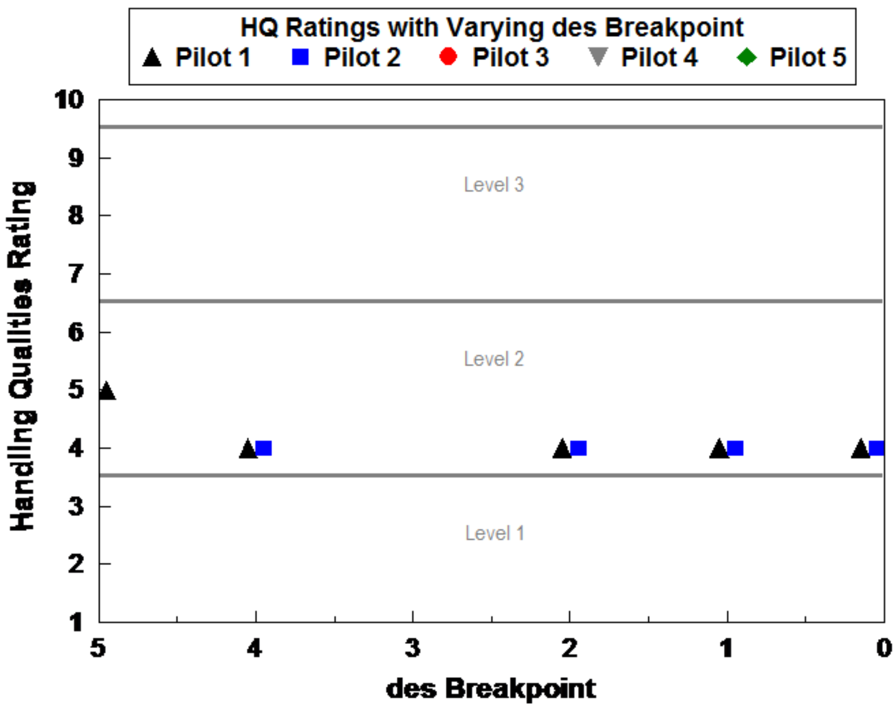


Figure 149. All pilot ratings, pitch PA command sensitivity (active) — stick rate threshold evaluations

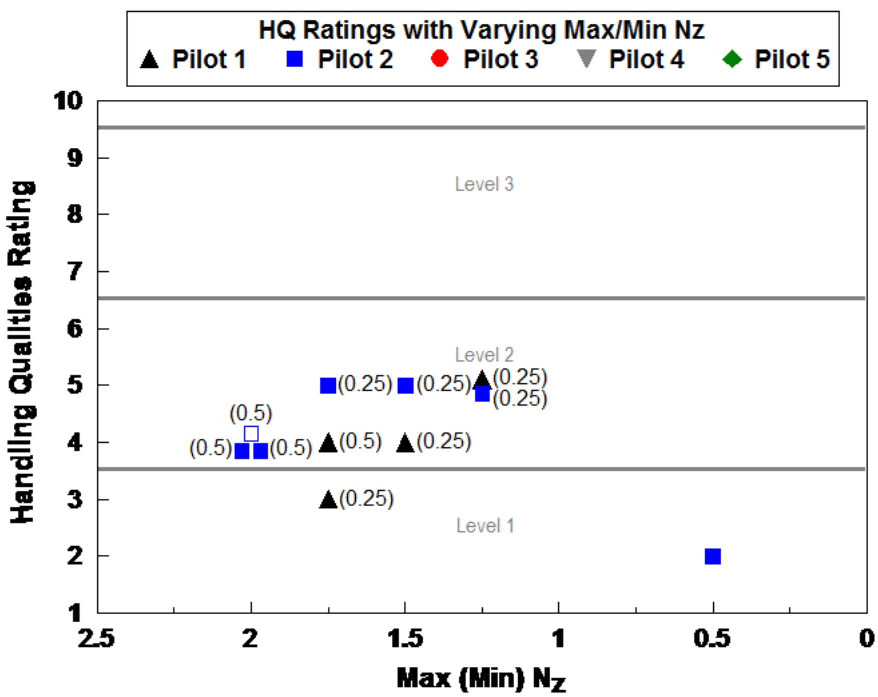
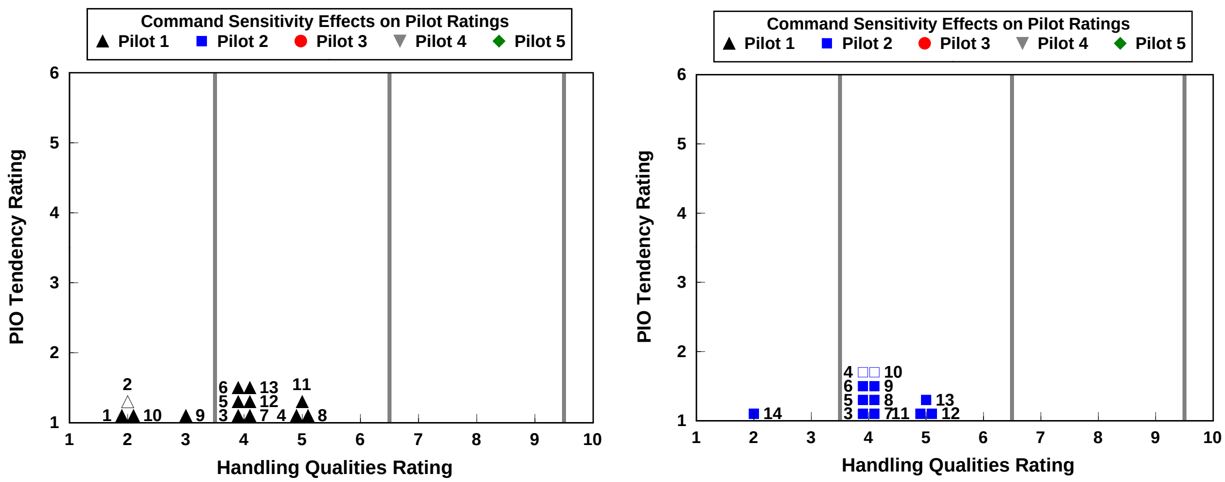


Figure 150. All pilot ratings, pitch PA command sensitivity (active) — n_z limit evaluations



a) Pilot 1　　b) Pilot 2

Figure 151. Ratings summary, all pilots, pitch V_c command sensitivity (active) evaluations

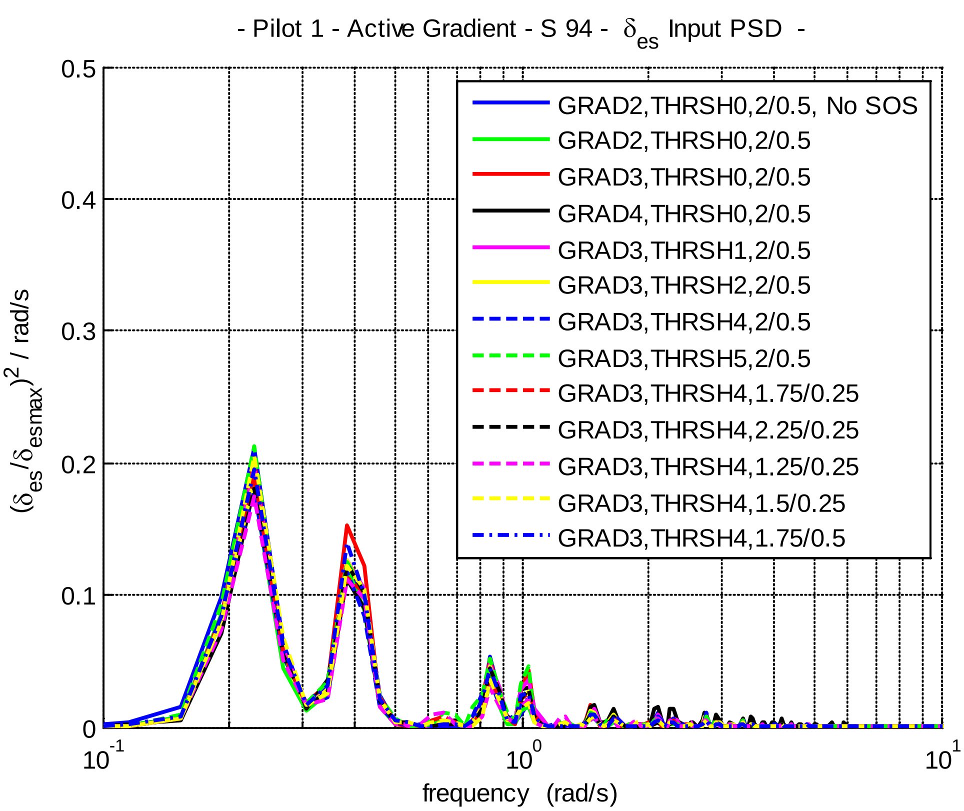


Figure 152. PSD of pilot 1's δ_{es} input — command sensitivity active — V_C

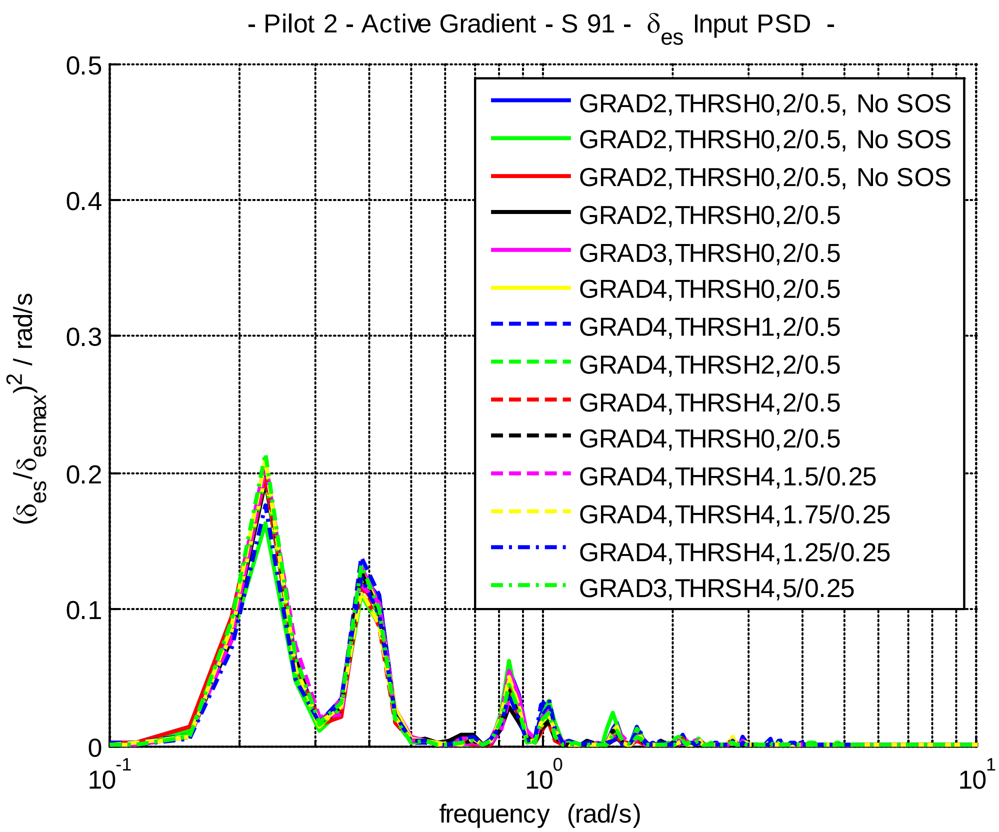


Figure 153. PSD of pilot 2's δ_{es} input — command sensitivity active — V$_C$

10.5.2.2 Pilot Ratings, Comments, and Task Scoring

10.5.2.2.1 Pilot 1

Pilot Ratings and Comments – The baseline aircraft was felt to be easy, although the addition of the SoS task made things a bit harder. As the gradient scale was increased from 2 to 4, there was a clear trend with degrading HQR of 2 to 5. The pilot felt like the stick was pushing back on him and that it was very nonlinear. When the gradient scale was increased to 4, the pilot felt that it was more objectionable, that it felt like a soft stop, and that it felt like it was fighting back at him. HQR ratings were consistently level 2 (HQR = 4, 5) throughout all variations of the stick rate threshold. Comments were similar for each value in that the pilot still felt that the stick was bucking, nonlinear, and that it felt like an "electric stop." As the n_z limit was moved in from 2 g to 1.25 g, the HQR ratings worsened from a 3 to a 5. At lower n_z onset, the primary complaint was that the forces were too high. This was due to more displacement on the increased force gradient. No PIO tendencies were noted for any of the configurations as a PIOR of 1 was given for every run.

Task Scoring – Average discrete task scoring is desired ≡ adequate = 70%, while continuous scoring is averagely desired = 74%, adequate = 80%. The high average values demonstrate a relatively low number of exceedances and time to acquire the target. There was minimal variation in continuous scoring throughout all parameter variations. Generally, all runs with higher gradient scales received poorer discrete scores. Although the pilot disliked the heavy forces resulting from the low onset n_z, these heavy forces improved the task performance by making it harder for the pilot to over g the aircraft.

Piloting Technique and Time Histories – As evidenced by figure 135, none of the active stick variations has any effect on the pilot input frequency content, indicating that the variations did not affect the pilot's technique. Figure 139 is a time history depicting the highest amount of stick activity for any of the runs in this session. This record was the active gradient scale of 4, which the pilot felt to be most objectionable and nonlinear. The nonlinearity and lack of predictability result in large stick and n_z oscillations.

10.5.2.2.2 Pilot 2

Pilot Ratings and Comments – The pilot did not like the baseline configuration and felt that the transition to the active gradient was objectionable. However, he felt that this did not affect his ability to fly the task. All variations of gradient scale received an HQR 4. The pilot felt that the gradient did not help him, that he could not maneuver carefree, and that the cue was a nuisance. The pilot still had to rely on the G-meter for limit awareness. All variations of the stick-rate threshold also received an HQR 4. The pilot complained about the notchiness in the stick at all values of the threshold, although he indicated that the resulting bumps were a little bit smaller when the threshold was increased. Decreasing the onset n_z below the baseline value of 2 always resulted in HQR of 5. The aircraft seemed to be more nonlinear and the "G was more bouncy." The pilot felt that it was difficult to determine how much force to use. The pilot felt that 1.25 g was the worse one yet because the cue came on too soon, the force release was dramatic, and it was very unpredictable. However, he felt that the high forces may prevent an over-g condition. The best rating (HQR = 2) was achieved when the max g was set to 5 so that effectively the cue did not activate during a pull. No PIO tendencies were noted for any of the configurations, as a PIOR of 1 was given for every run.

Task Scoring — Average discrete task scoring is desired ≡ adequate = 85%, continuous scoring is average desired = 72.5%, and adequate = 77.5%. There was very little scatter in both the discrete and continuous scores and there were no observable trends with scores and parameter values.

Piloting Technique and Time Histories — Figures 154 and 155 indicate that there are no noticeable changes in pilot technique from any of the parameter variations. Pilots 1 and 2 both provided similar type inputs. Figure 140 illustrates a run in which the pilot felt the force release was dramatic, as indicated by the large stick motions.

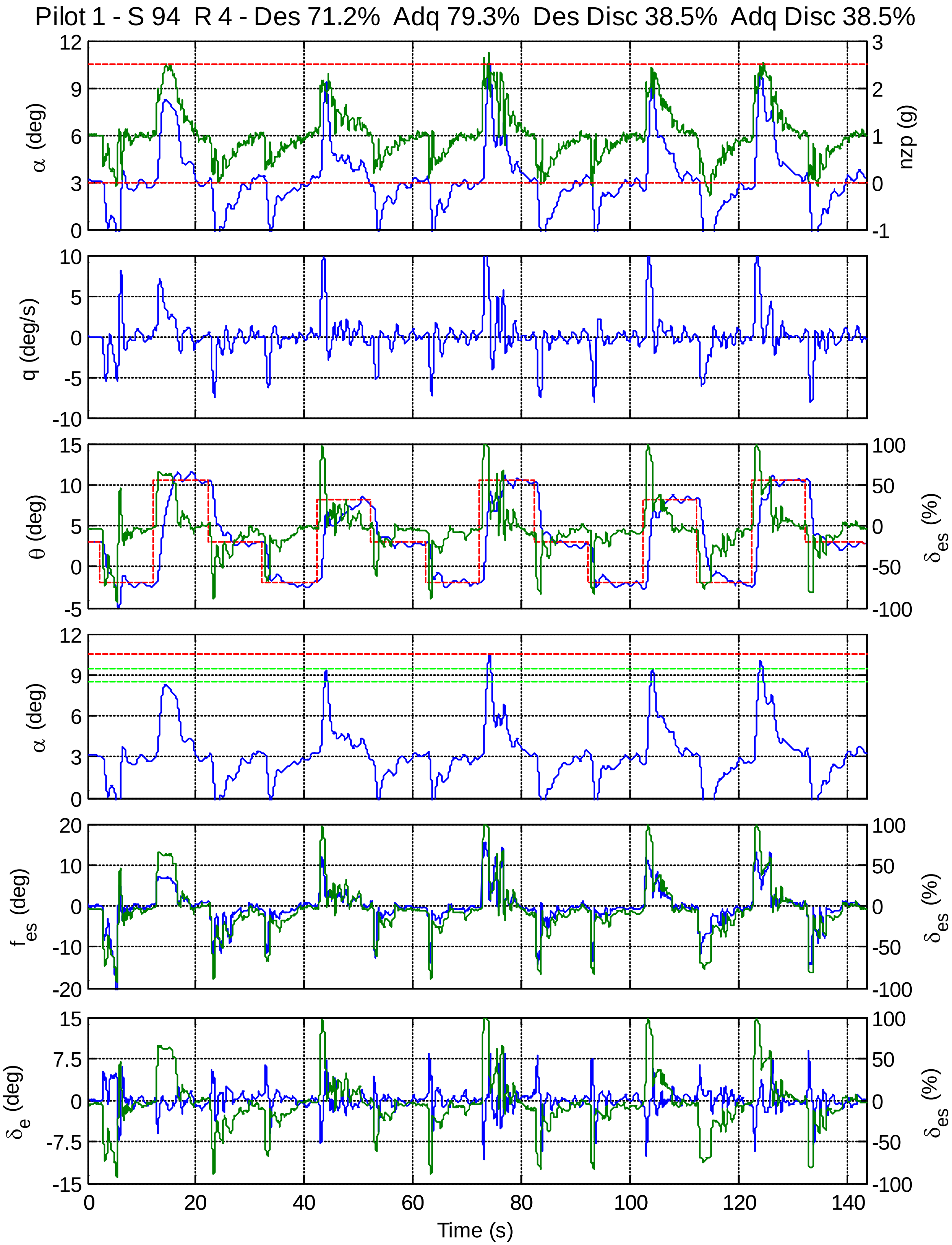


Figure 154. Pilot 1 gradient scale 4 captures time history plot — V_C

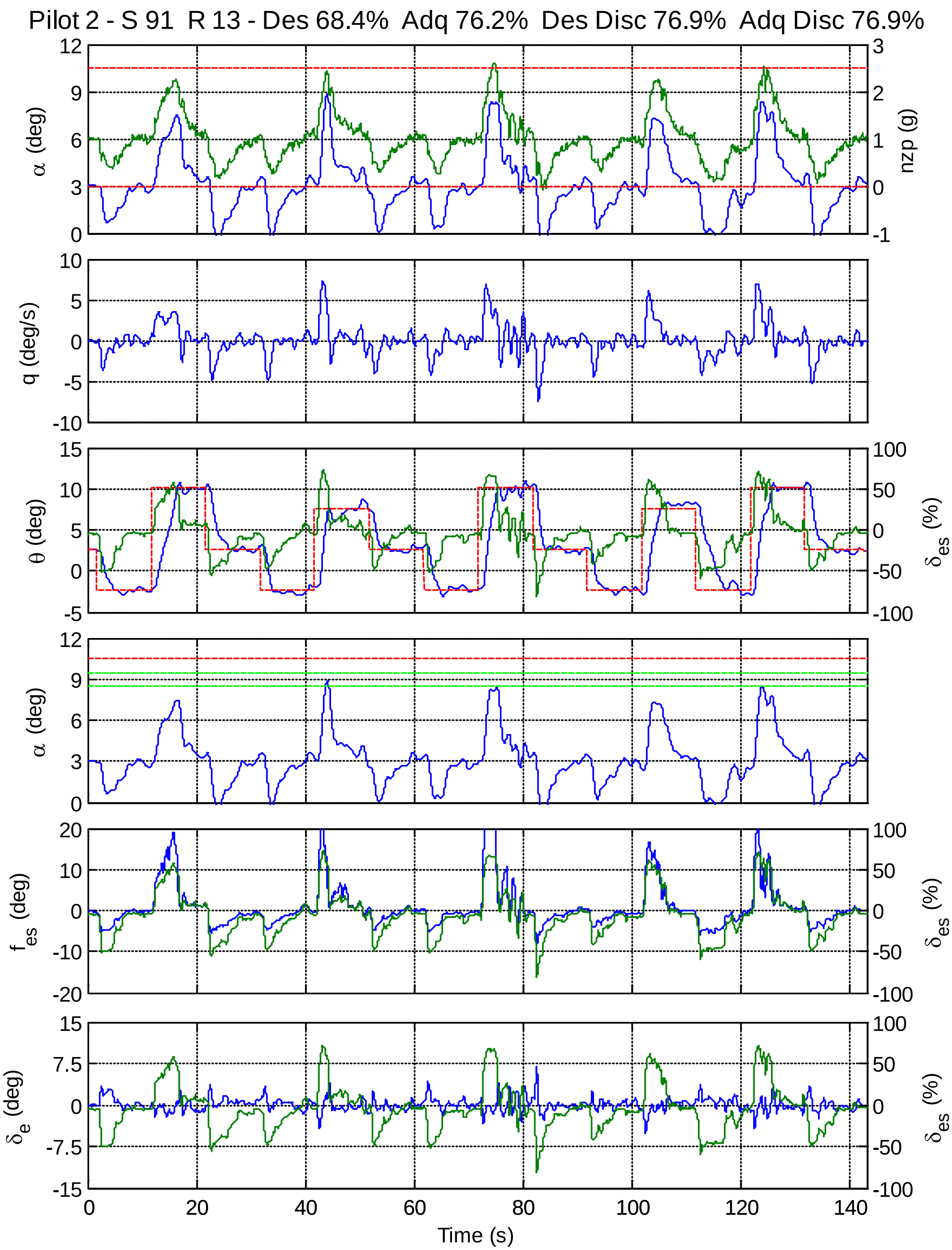


Figure 155. Pilot 2 n_z onset 1.25 g captures time history plot — V_C

10.5.3 Observations and Conclusions

A direct comparison between the PA and V_C configurations is difficult because these conditions lend themselves to very different cues to prevent envelope exceedances. A stick shaker is appropriate for PA to prevent an AoA exceedance, whereas a variable stick gradient was utilized to attempt to prevent G-exceedances at V_C. One overarching conclusion is that the value that the cue is activated, relative to the limit it is meant to protect against, is critical. There is no protection gained if the cue is activated too late. The cue may be objectionable and ignored if it is activated too soon because the pilot may be forced to fly in the cue during normal non-limited operations.

10.6 PASSIVE INCEPTOR NATURAL FREQUENCY

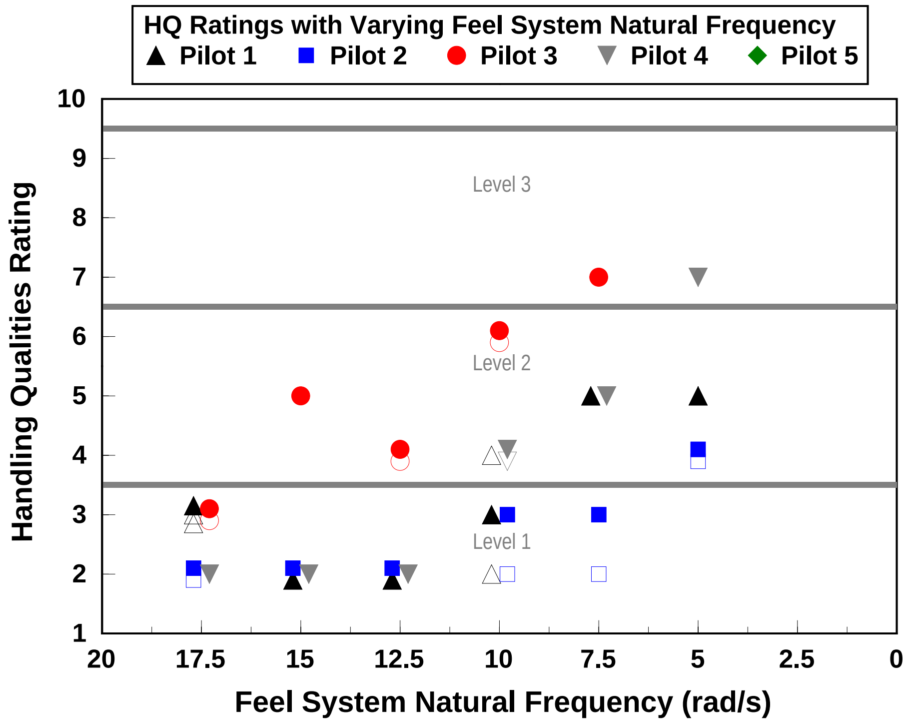
10.6.1 Introduction

This section presents an analysis of the fixed-base simulation evaluations of the effects of pitch feel system natural frequency on longitudinal axis HQ. Four pilots participated in the pitch feel system natural frequency evaluations [14]. The evaluations were SoS tracking tasks in PA configuration with a bare airframe SM of SM = 5% ($\bar{c}$). The HQ and PIO tendency ratings were recorded after each evaluation run and task scoring data was recorded for offline analysis. Stick natural frequency was varied from 17.5 rad/s (baseline) to 5 rad/s.

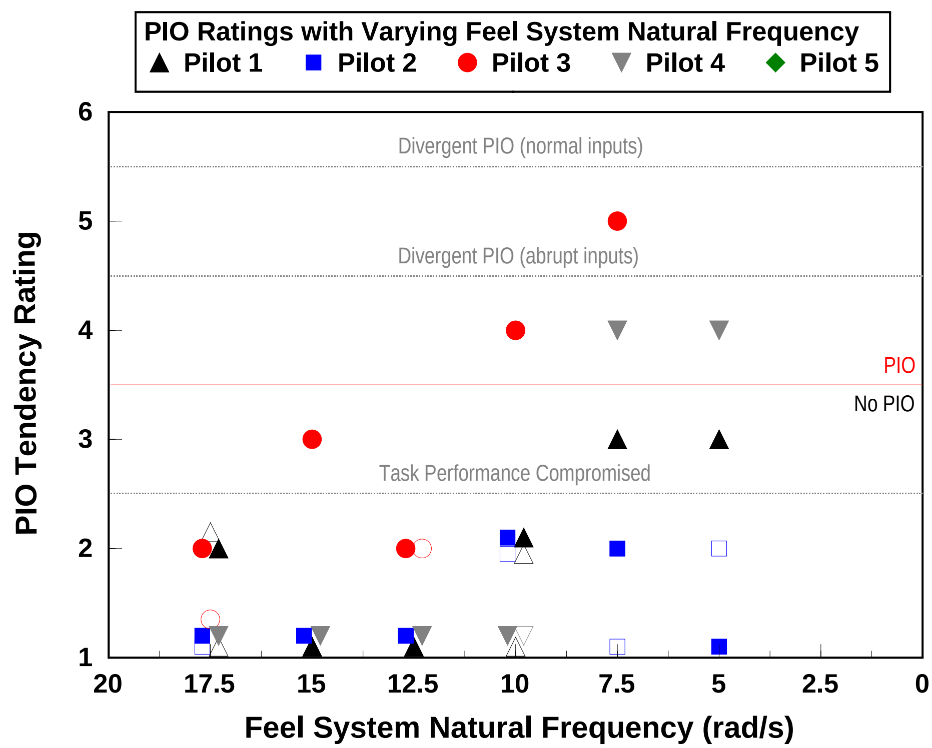
10.6.2 Analysis Summary

Figure 156 gives a summary of the HQ and PIO tendency ratings for the four pilots that participated in the pitch-feel system natural frequency evaluations.

A distinct trend emerges from the pilot ratings shown in figure 156. The HQ and PIO tendency ratings given in figure 156 show a distinct drop for all pilots at 10 rad/s. This is directly correlated to the piloted frequency range upper limit for this task, as demonstrated in figure 46. Above 10 rad/s, feel system dynamics do not heavily impact task performance or ratings, while lowering stick natural frequency below 10 rad/s has a significant effect on the pilot’s ability to perform the task and the amount of compensation required to achieve desired performance. Based on the results of this study, feel system natural frequencies should be required to be at least 10 rad/s, with recommendations of 12.5 rad/s or higher to avoid possible HQ and PIO tendency issues.



a) Handling Qualities



b) PIO Tendency

Figure 156. Pilot ratings, all pilots, pitch feel system natural frequency variations (a) handling qualities and (b) PIO tendency

As illustrated in table 61 and figure 157, task performance was not significantly impacted by feel system natural frequency for pilots 1 and 2, and desired performance is easily achieved. Pilots 3 and 4 saw a dramatic drop in achieved performance for cases below 10 rad/s. As will be shown herein, this indicates that a change in feel system dynamics impacts more aggressive pilots much more than less-aggressive pilots, such as pilots 1 and 2. Because pilot behavior can vary dramatically, the feel system natural frequency should be designed above the threshold where aggressive pilots see a drop in performance and HQ.

Symbol annotations in figure 156 give HQR for each run.

Table 61. Task performance summary, all pilots, pitch feel system natural frequency variations

Stick Frequency (rad/s)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
17.5	91.17	99.02	98.52	98.88
15.0	100	100	99.42	99.07
12.5	93.70	99.23	93.78	94.37
10.0	94.95	99.08	91.32	98.88
7.5	91.77	94.28	71.07	90.68
5.0	87.67	98.00	–	77.25

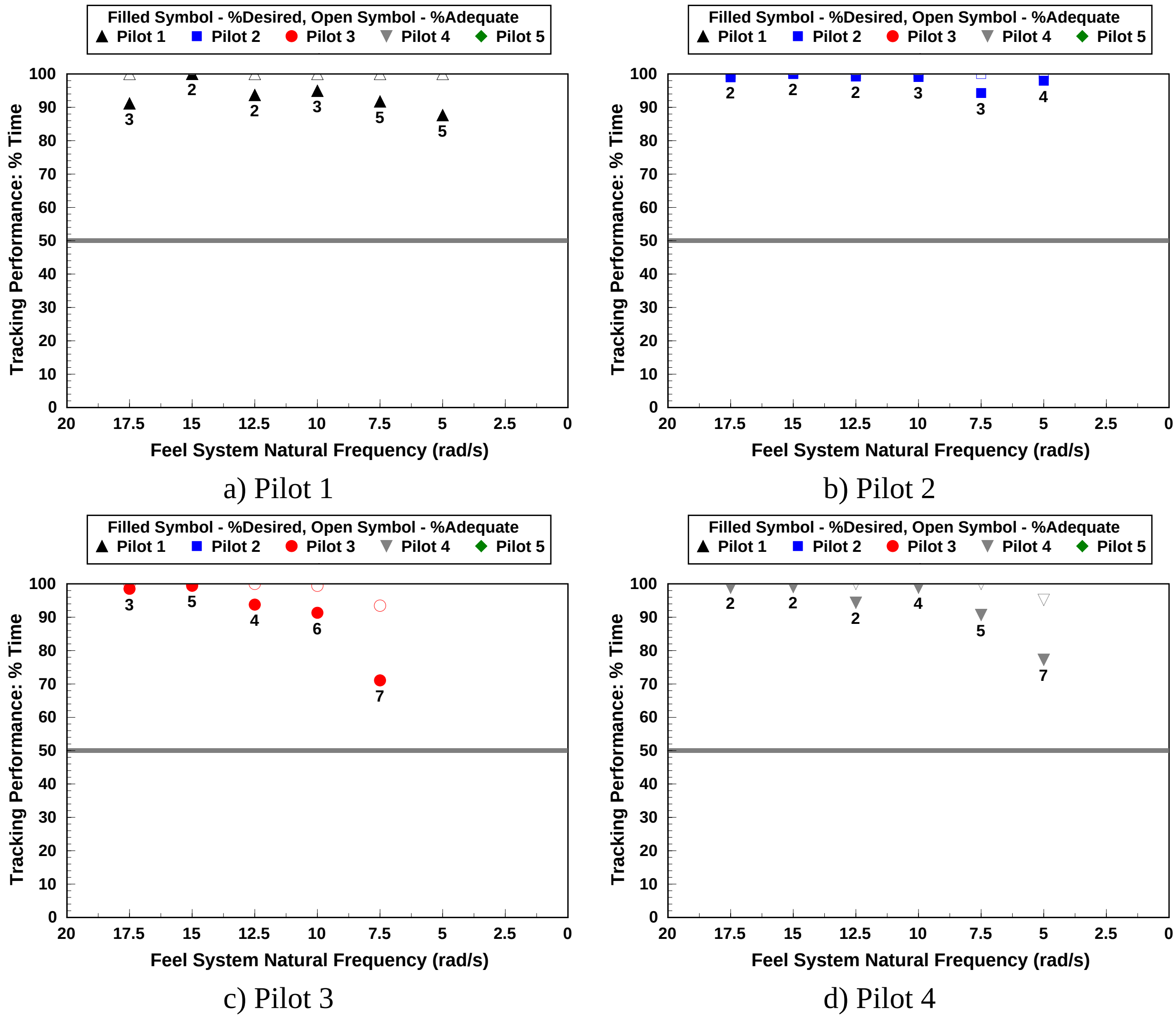


Figure 157. Tracking task performance, pitch feel system natural frequency variations

10.6.3 Detailed Analysis of Selected Cases

10.6.3.1 Introductory Notes

Variations among multiple runs by the same pilot can provide insight into the effects of feel system natural frequency variations on pilot behavior and the level of compensation necessary to perform the task. Correlations between degraded ratings for lower stick frequencies and increased pilot compensation or changes in pilot behavior further emphasize the impact of the feel system natural frequency on the ability to perform the task.

The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which may be inadequate to accurately predict the impact of feel-system parameter changes in real aircraft due to a lack of motion cueing.

10.6.3.2 Pilot 3 – Session 12 Evaluations

Pilot 3 participated in pitch stick frequency evaluations on June 19, 2012. The data were collected during Session 12 of the Year 2 Follow-on evaluations. Nine total runs were completed in the pitch axis, with one unrated warmup run in the baseline configuration and eight scored runs, which were rated. The baseline configuration was scored twice during the session, first known and then blind to the pilot. A full listing of the configurations flown and ratings given by pilot 3 are shown in table 62 and figure 158.

Table 62. Pilot ratings and comments, pilot 3/session 12

Session	Run	Configuration	HQR	PIOR	Comments
12	1	FLON175 (baseline)	–	–	–
12	2	FLON175 (baseline)	3	2	Not-too-difficult stick motion. Not too many large excursions. Tiny PIO. Quick stick motions.
12	3	FLON150	5	3	First impression: heavier forces and more resistant stick. More physical and mental effort required. Tends to oscillate more. Probably more time delay in the loop. Not as good ability to command the stick.
12	4	FLON100	6	4	Very objectionable. Oscillations. A lot of physical workload. Large excursions. Not for precise tasks. Would not like to fly that for hours.
12	5	FLON125	4	2	Much better than last one. More spongy than baseline and a little more resistant.
12	6	FLON175 (baseline-blind)	3	1	Pretty decent performance. Very close to the baseline. Not too many unintended oscillations. Wrist not tired.
12	7	FLON100	6	4	Oscillations back. Did not feel as bad as (4). Natural frequency close to my natural frequency.
12	8	FLON075	7	5	Not acceptable. Does not seem right. For ground simulator = 7, but not airborne.
12	9	FLON125	4	2	Better. Chance of doing a good job.

FLON = frequency longitudinal (feel system)

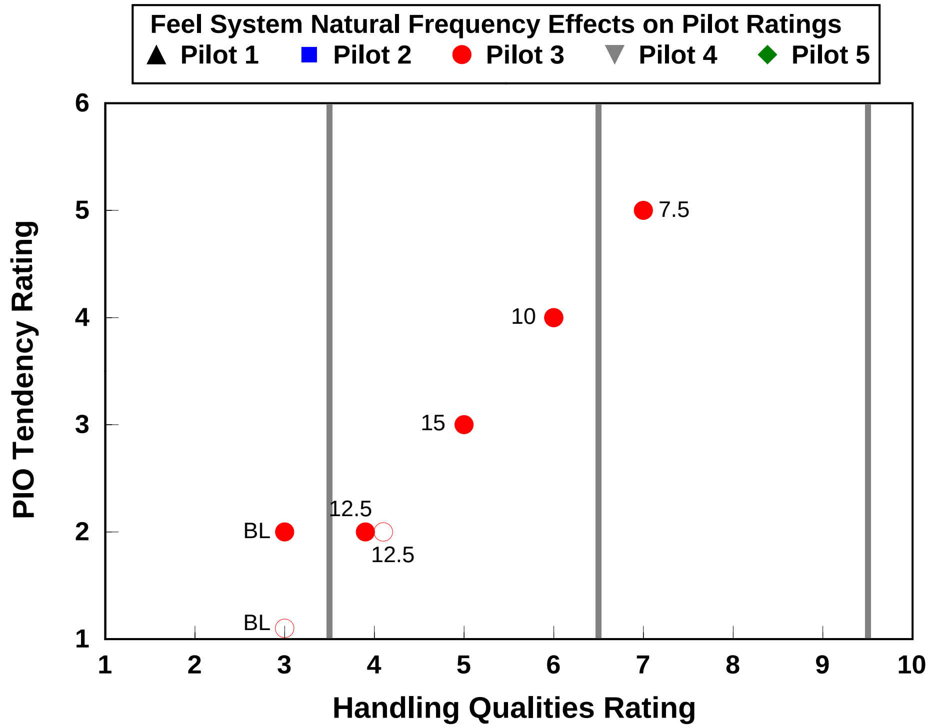


Figure 158. Ratings summary, pitch feel system natural frequency variations, pilot 3/session 12

The following analysis will focus on runs 4, 5, and 6 to highlight the differences in how pilot 3 flew the lower natural frequency case and ratings improved as feel system natural frequency was increased to baseline.

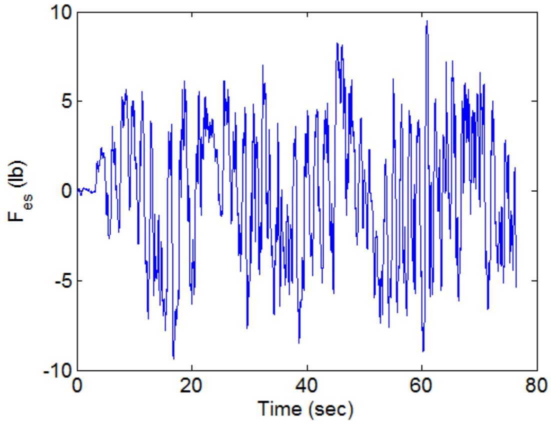
<u>10.6.3.3 Task Analysis</u>

In figure 156, a predictable trend in pilot ratings is seen for the pitch feel system natural frequency evaluations for pilot 3. With the exception of the 15 rad/s case, which was evaluated immediately after the baseline, ratings predictably degraded as feel system natural frequency was lowered, until it was firmly in the level 3 region with a divergent PIO risk for the 7.5 rad/s case. Pilot 3 did not participate in a 5 rad/s evaluation, but it is a reasonable assumption based on these results that poor HQ and a substantial PIO risk similar to or worse than the 7.5 rad/s case would be observed.

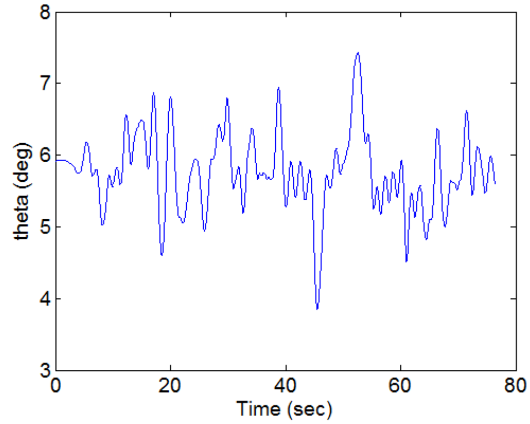
Figure 159 gives time histories for runs 4, 5, and 6 of session 12. These runs represent the 10, 12.5, and 17.5 rad/s cases, respectively, and were given progressively better ratings. From the time histories, the 10 rad/s case featured large amplitude inputs at high frequency (figure 159 (a)) and the vehicle response exhibited oscillatory behavior (figure 159 (b)). This is reflected in the pilot comments, as pilot 3 stated the configuration was "very objectionable" and required "a lot of physical workload" because of the oscillations present.

Run 5 was a 12.5 rad/s case, a configuration that featured a feel system natural frequency further from the piloted frequency range. Though the pilot did note the configuration felt “more spongy than baseline and a little more resistant,” the inputs to the stick were of lower amplitude and frequency (figure 159 (c)) and the resulting vehicle motion was much less oscillatory (figure 159 (d)).

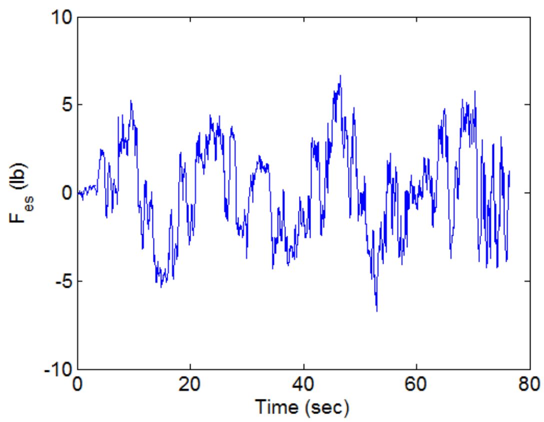
Run 6 was a blind baseline and a similarity is seen to the HQR 4/PIOR 2 run shown for the 12.5 rad/s case in figures 159 (c) and (d). This is reflected in the ratings, as the blind baseline received ratings of HQR 3/PIOR 1.



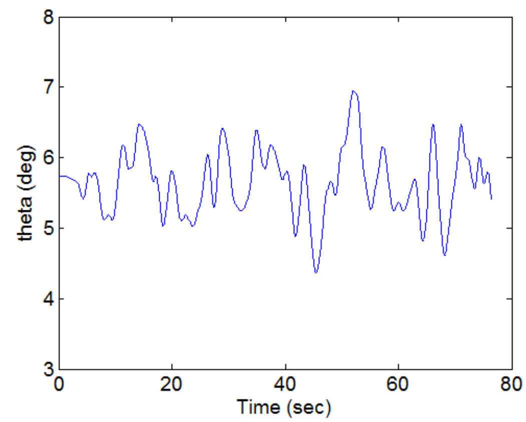
a) Stick Force – Pilot 3 S12/R4
(HQR 6/PIOR 4)



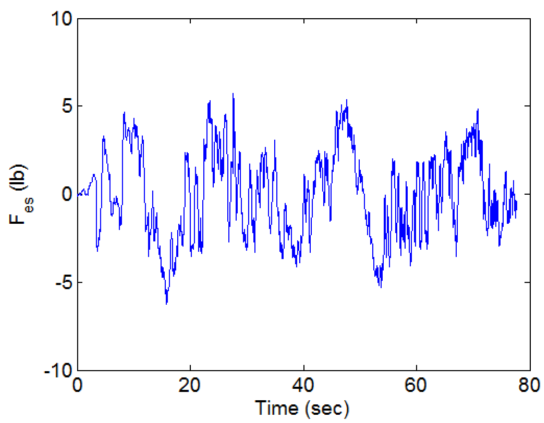
b) Pitch Attitude – Pilot 3 S12/R4
(HQR 6/PIOR 4)



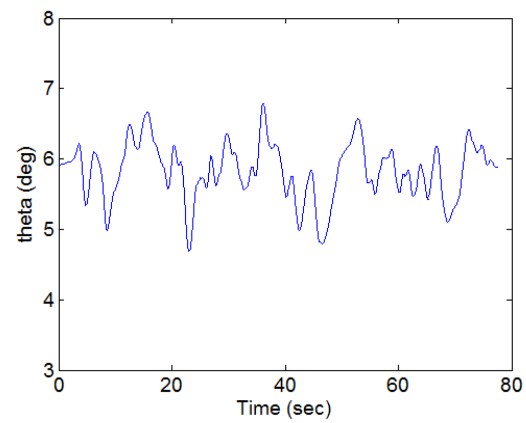
c) Stick Force – Pilot 3 S12/R5
(HQR 4/PIOR 2)



d) Pitch Attitude – Pilot 3 S12/R5
(HQR 4/PIOR 2)



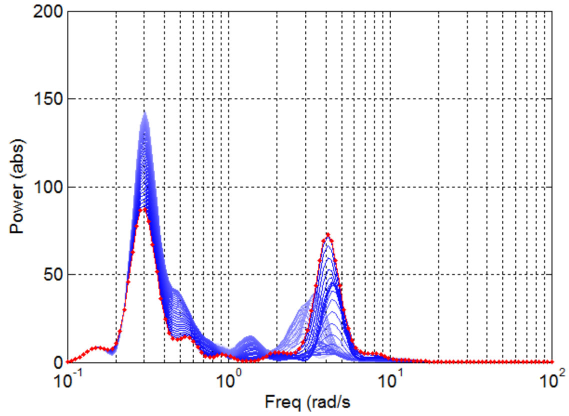
e) Stick Force – Pilot 3 S12/R6
(HQR 3/PIOR 1)



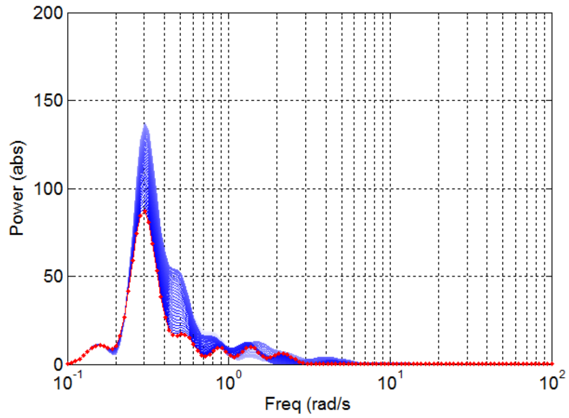
f) Pitch Attitude – Pilot 3 S12/R6
(HQR 3/PIOR 1)

Figure 159. Feel system analysis, varying pitch feel system natural frequency

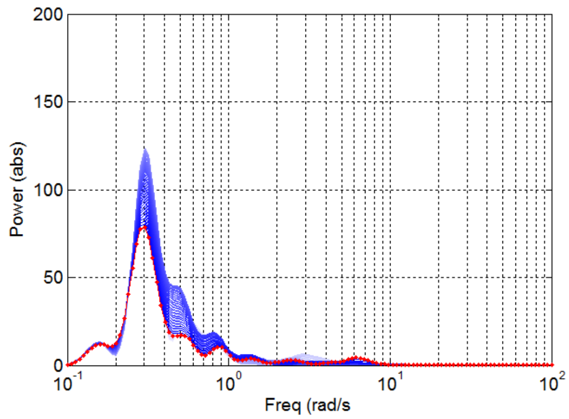
These observations are furthered by the scalograms [17] shown in figure 160. Scalograms provide a means to investigate how the PSD of the signal varies in time. The red dotted line in the figure shows the selected time slice from the run, while the blue lines indicate time slices moving back in time from dark blue to light blue. Though low frequency behavior is largely similar for the three runs, the poorly rated run 4 features a distinct spike in power at higher frequency that is absent from the other two runs. This correlates to the observations made in figure 159 (a) for the stick force time history and demonstrates an adverse interaction with the slower feel system dynamics for this run.



a) Pilot 3 S12/R4 (HQR 6/PIOR 4)



b) Pilot 3 S12/R5 (HQR 4/PIOR 2)



c) Pilot 3 S12/R6 (HQR 3/PIOR 1)

Figure 160. Longitudinal stick force scalograms

10.6.4 Piloted Evaluations Observations and Conclusions

- Based on the results of the limited fixed-base simulation study, pitch axis feel system natural frequencies greater than 10 rad/s are recommended for sidestick inceptor configurations, as HQ and task performance may be compromised for configurations with lower natural frequency.

- PIO tendency becomes a significant issue for stick frequencies lower than 10 rad/s because of the interaction with pilot input frequencies. Task performance also degrades sharply for some pilots with aggressive or high-frequency lead-compensation techniques.

- Stick dynamics must maintain adequate separation from task frequencies or adverse interactions between pilot inputs and stick dynamics will result in degraded HQ, increased PIO tendency, and poor task performance.

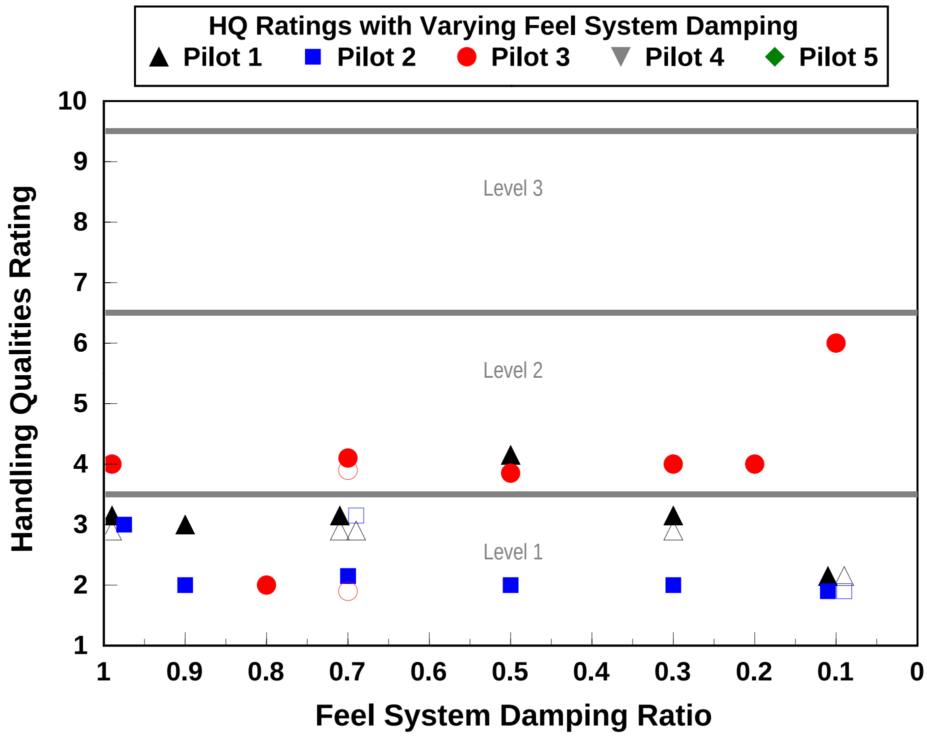
10.7 PASSIVE INCEPTOR DAMPING RATIO

10.7.1 Introduction

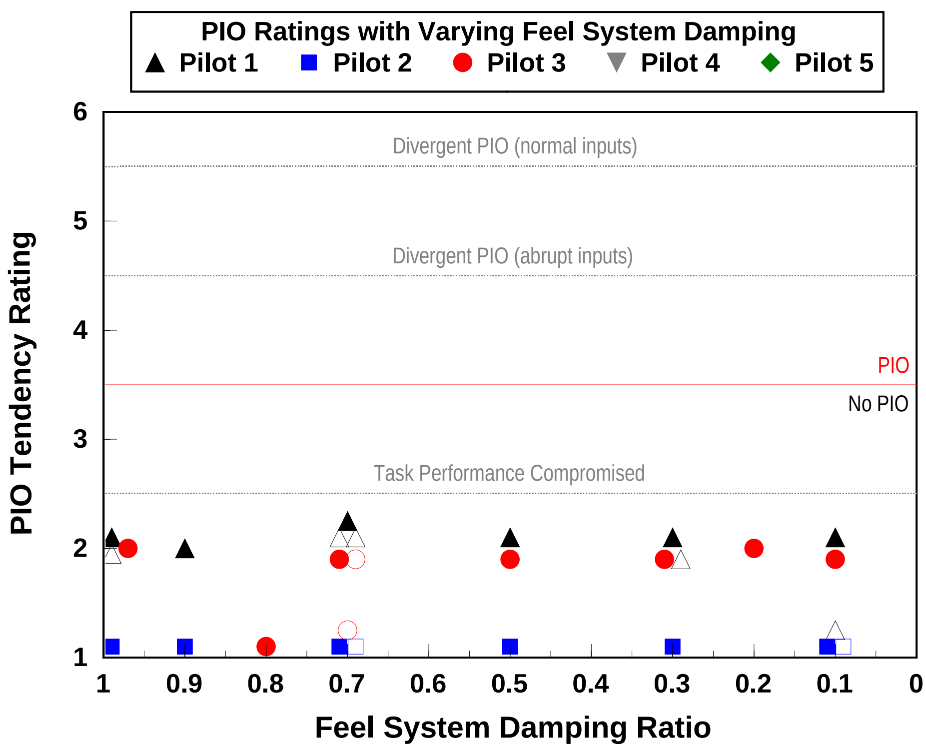
This section presents an analysis of the effects of pitch-feel-system damping on longitudinal axis HQ. Three pilots participated in the pitch-feel system damping evaluations, described in detail in section 4 and [14]. The evaluations were ACH tasks in PA configuration with a bare airframe SM of SM = 5% ($\bar{c}$). The HQ and PIO tendency ratings were recorded after each evaluation run, and task performance data was recorded for offline analysis. Stick-damping ratio was varied from 0.1–1.0, with a baseline damping configuration of 0.7.

10.7.2 Analysis Summary

Figures 161 and 162 provide summaries of the HQ and PIO tendency ratings for the three pilots who participated in the pitch feel system damping evaluations. No distinct trend emerges from the pilot ratings shown in figures 161 and 162. The HQ and PIO tendency ratings given in the figures show that all pilots rate the baseline case level 1, with the exception of pilot 3 who rated two of the three runs in the baseline configuration slightly into level 2. The pilots showed very little sensitivity to stick damping, with pilot 3 showing slight sensitivity to heavily damped-feel system dynamics and acute sensitivity to very lightly damped dynamics. Pilot 1 preferred the feel system with lower damping (less than 0.5), while pilot 3 showed degraded ratings for the most lightly damped (0.1) case. From these results, it would appear that feel-system damping only minimally affects piloted HQ and, though care should be taken to avoid very lightly damped stick dynamics, a fairly wide range of damping settings can be used without negatively impacting HQ or PIO ratings for discrete capture and hold tasks.

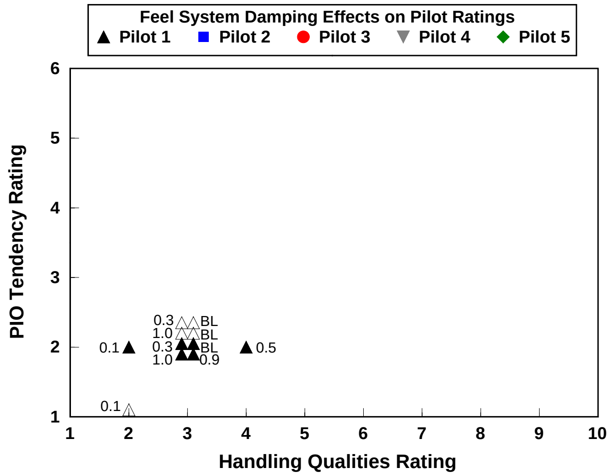


a) HQ

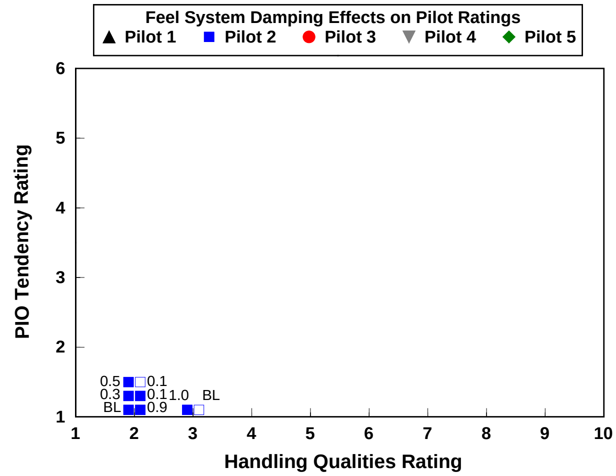


b) PIO Tendency

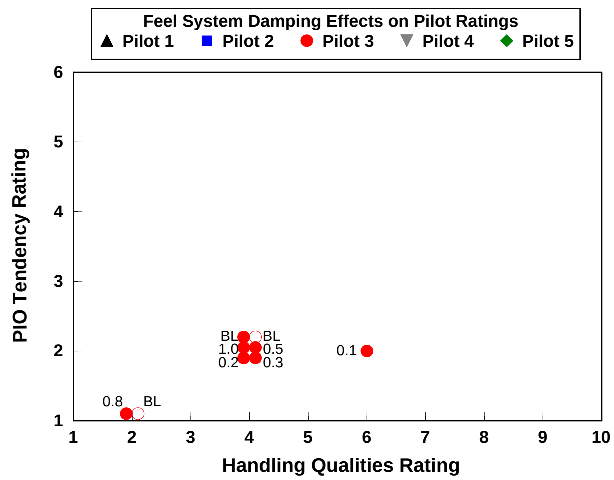
Figure 161. Ratings summary, pitch feel system damping variations



a) Pilot 1



b) Pilot 2



c) Pilot 3

Figure 162. Pilot ratings, pitch feel system damping variations

10.7.3 Detailed Analysis of Selected Cases

10.7.3.1 Introductory Notes

Variations among multiple runs by the same pilot can provide insight into the effects of feel system damping variations on pilot behavior and the level of compensation necessary to perform the task. Correlations between degraded ratings and increased pilot compensation, poor task performance, or changes in pilot behavior further emphasize the impact of the feel system damping variations on the ability of the pilot to perform the task.

The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which is potentially not fully adequate to accurately predict the impact of feel-system parameter changes in real aircraft due to a lack of motion cueing.

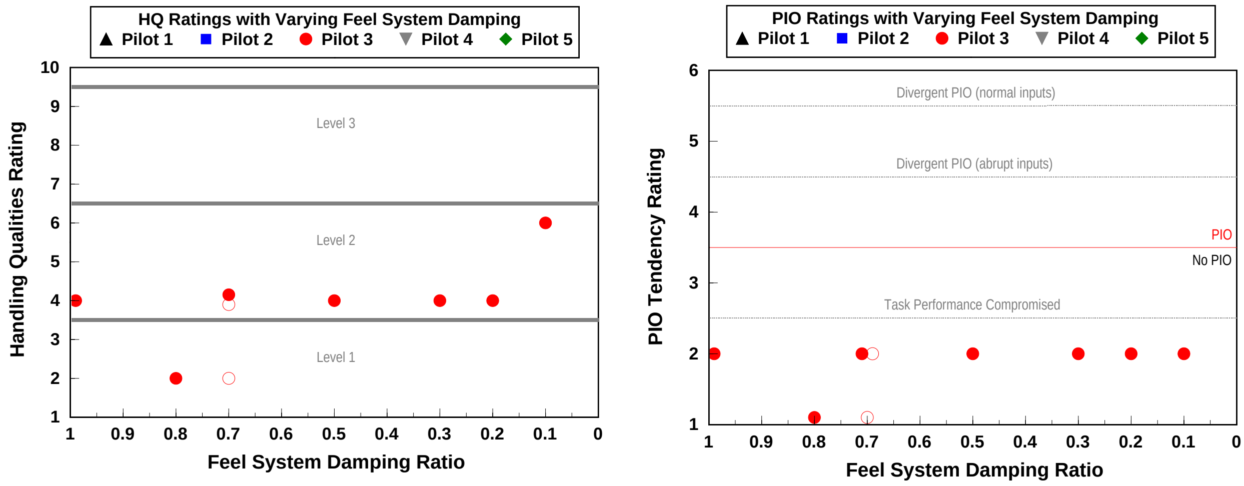
10.7.3.2 Pilot 3 – Session 14 Evaluations

Pilot 3 participated in pitch-feel system-damping evaluations on June 19, 2012. The data were collected during session 14 of the Year 2 Follow-on evaluations. A total of nine runs were completed in the pitch axis, with nine scored runs rated, including three runs in the baseline configuration. The baseline configurations were scored blind to the pilot. A full listing of the configurations flown and ratings given by pilot 3 are shown in table 63 and figure 163.

Table 63. Pilot ratings and comments, pilot 3/session 14

Session	Run	Configuration	HQR	PIOR	Comments
14	1	DLON07 (baseline)	4	2	A little bit of oscillation around the end, close to level 1. Compensation is more than minimal; 3 oscillations. Overshoots and undershoots.
14	2	DLON05	4	2	Last two captures pretty nice. I am not seeing any marked change. Oscillations a little more persistent.
14	3	DLON07 (baseline)	4	2	Can’t tell the difference.
14	4	DLON03	4	2	Stick is easier to move to a new position. Stick not over-driving me. Stick was not a factor.
14	5	DLON01	6	2	Now something is different. The stick is wiggling at the end of the stroke. Tiring over the long run. Performance a little worse.
14	6	DLON02	4	2	2–3 residual oscillations. Stick moves pretty quickly. Small frequency.
14	7	DLON07 (baseline)	2	1	The stick does not bounce around this time. Clearly better.
14	8	DLON10	4	2	This feels heavier. It is resisting me.
14	9	DLON08	2	1	A little overshoot. The stick does not bother me. Not as heavy as the last one.

DLON = damping longitudinal (feel system)



e) Handling Qualities

f) PIO Tendency

Figure 163. Pilot 3 ratings, pitch feel system damping variations

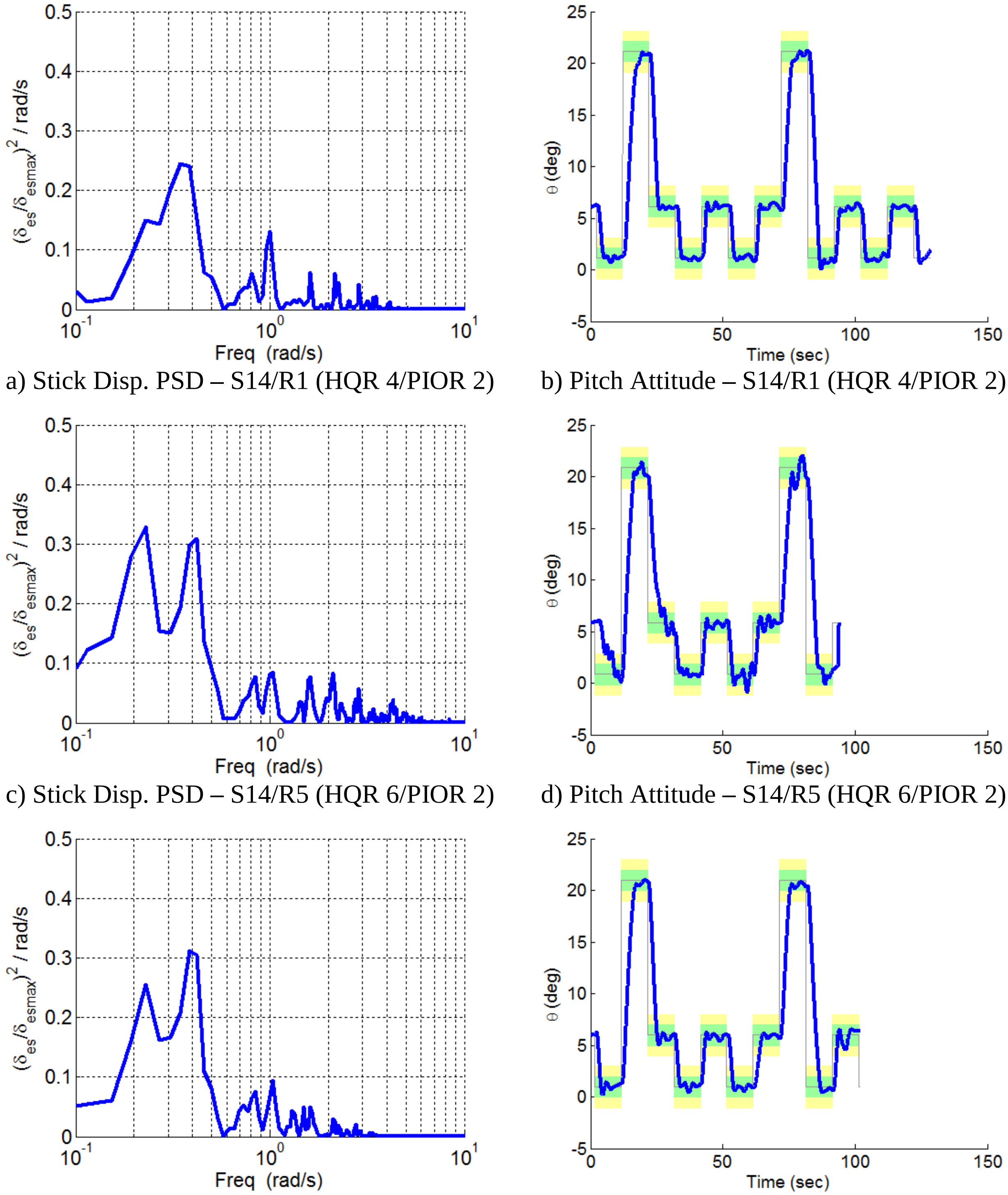
The following analysis will focus on runs 1, 5, and 7 to highlight the differences in ratings when the baseline case follows a series of lightly damped runs.

<u>10.7.3.3 Task Analysis</u>

In figure 163, pilot ratings for the pitch-feel system damping ratio evaluations show a lack of variance for most damping ratio settings. With the exception of the very lightly damped (0.1) case, all configurations are given borderline level 1/2 HQ with minimal undesirable oscillations. For run 7, however, the baseline configuration is given an HQR 2/PIOR 1, a much better rating than the HQR 4/PIOR 2 rating it received in the initial run of the session.

Figure 164 gives time histories and stick displacement power spectral densities (PSDs) for runs 1, 5, and 7 of session 14. The green and yellow regions of the time history plots signify desired and adequate performance regions. These runs represent the baseline and 0.1 damping cases, respectively. From the time histories, it can be seen that the lightly damped case (figure 232 (d)) is much more oscillatory in its response, with the amplitude of the oscillations large enough to break out of the desired hold region for some of the large amplitude NU captures. The pilot notes this oscillation along with the corresponding drop in task performance and also notes an increased workload (“tiring over the long run”), all of which contribute to the degraded ratings for this run.

Looking at the left column of figure 164, we see a distinct difference in the input frequency for runs 5 and 7 from the baseline (run 1). Rather than one distinct spike in input power near 0.35 rad/s, we see two spikes at 0.2 and 0.5 rad/s. Though the vehicle response is only slightly different for the baseline case evaluated in run 7 (figure 164 (f)), the pilot is flying similarly to the lightly damped cases that were flown prior to the baseline. Because the pilot is able to fly in a similar manner and get a large improvement in the vehicle response, the ratings are correspondingly high when compared to the original baseline run in which the pilot was flying with moderate aggressiveness.



a) Stick Disp. PSD – S14/R1 (HQR 4/PIOR 2)

b) Pitch Attitude – S14/R1 (HQR 4/PIOR 2)

c) Stick Disp. PSD – S14/R5 (HQR 6/PIOR 2)

d) Pitch Attitude – S14/R5 (HQR 6/PIOR 2)

e) Stick Disp. PSD – S14/R7 (HQR 2/PIOR 1)

f) Pitch Attitude – S14/R7 (HQR 2/PIOR 1)

Figure 164. Task analysis, varying pitch feel system damping ratio

Pilot 3 is able to achieve desired performance for both baseline runs and adequate performance for the most lightly damped case evaluated. Task performance did degrade for this pilot as the damping ratio was lowered below 0.3, but the pilot was still able to perform the task with only slightly degraded ratings due to increased workload and pilot annoyance with the dynamics of the stick.

10.7.4 Piloted Evaluations, Observations, and Conclusions

Based on the results of the limited fixed-base simulation study with a baseline level 1 aircraft configuration, pitch axis feel system damping ratio is not a critical parameter when kept above 0.3. Variations in HQ are minimal between pilots and consistent for damping ratios between 0.3 and 1.0.

PIO tendency is not a significant risk, even for very lightly damped configurations with damping ratios less than 0.3.

Though task performance degrades slightly for pilots sensitive to lightly damped feel-system dynamics, loss of control is not an issue and adequate performance can still be achieved.

10.8 PASSIVE INCEPTOR SCHEDULED COMMAND SENSITIVITY

10.8.1 Principal Outcomes

The elevator command gain of the baseline configuration is constant throughout all flight conditions and is not a function of stick deflection. Its value is defined not to exceed the positive (NU) load factor limit ($n_{z_{max}}$ = 2.5) with an FBS input in V_A flight condition. The scheduled command gain was implemented as a function of dynamic pressure, not to exceed the positive and the negative load factor limit ($n_{z_{min}}$ = 0), with an FBS and a full forward stick (FFS) input, respectively, in the airspeed range delimited by V_A and V_C. The scope of this implementation was to provide the pilot with a control system that allows broadly carefree maneuvering in pitch. Additional information is provided in section 4.10. The intent was a reduction of the pilot's workload/compensation for the inherent envelope protection with respect to g exceedances provided by the CLAWS.

The label "Baseline" in figure 165 refers to the baseline configuration evaluated with respect to the baseline task: pitch attitude captures + SoS disturbance.

From the analysis of the pilots' ratings, comments, and the time histories (figures 165 and 166 and table 63), the following outcomes can be identified:

1. No significant impact on HQ derives from the implementation of a variable command gain, which automatically prevents load-factor exceedance. There is a slight degradation of the HQR with respect to the baseline, for pilot 1: from HQR = 2 to HQR = 3.

2. The main effect on piloting technique is an increase of stick deflection/activity at all frequencies. This is associated to higher forces, as a passive stick with constant force

gradient is used. A reduction of the control precision is also reported, with a higher tendency to oscillate in pitch.

3. Pilot 1 reported, “The only advantage is that it helps control the amount to pull back.” This indicates that the intended carefree type of piloting technique can be achieved with this design element.

4. The different piloting technique allowed by the g self-limited configuration is not considered an advantage. No significant effect on the piloting technique is due to the SoS disturbance.

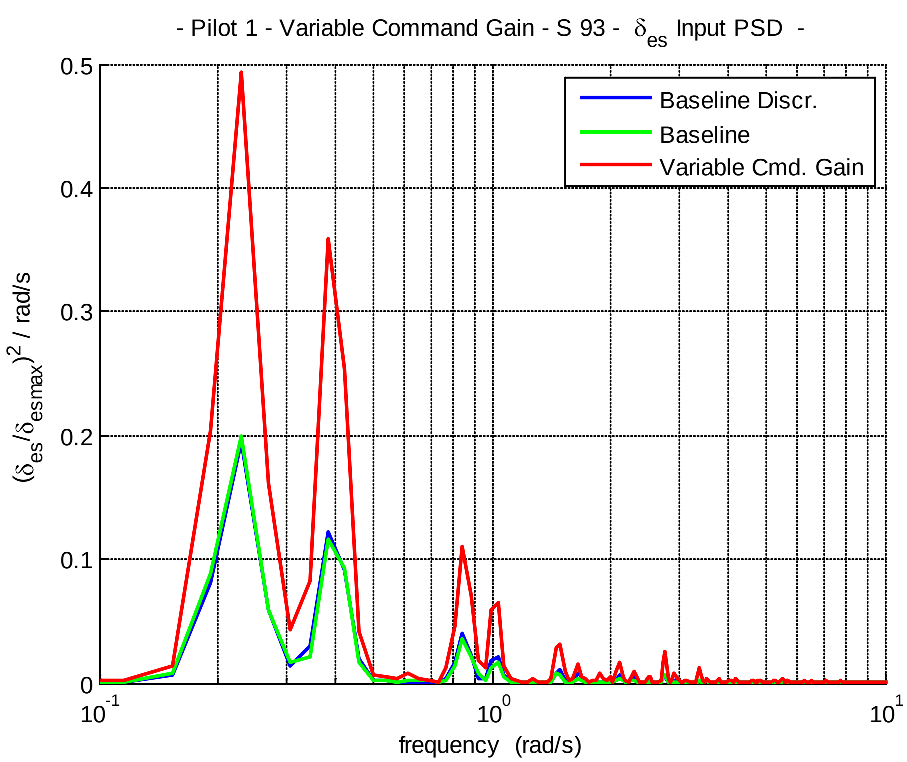


Figure 165. PSD of pilot 1’s δ_{es} input — scheduled command sensitivity passive — V_C

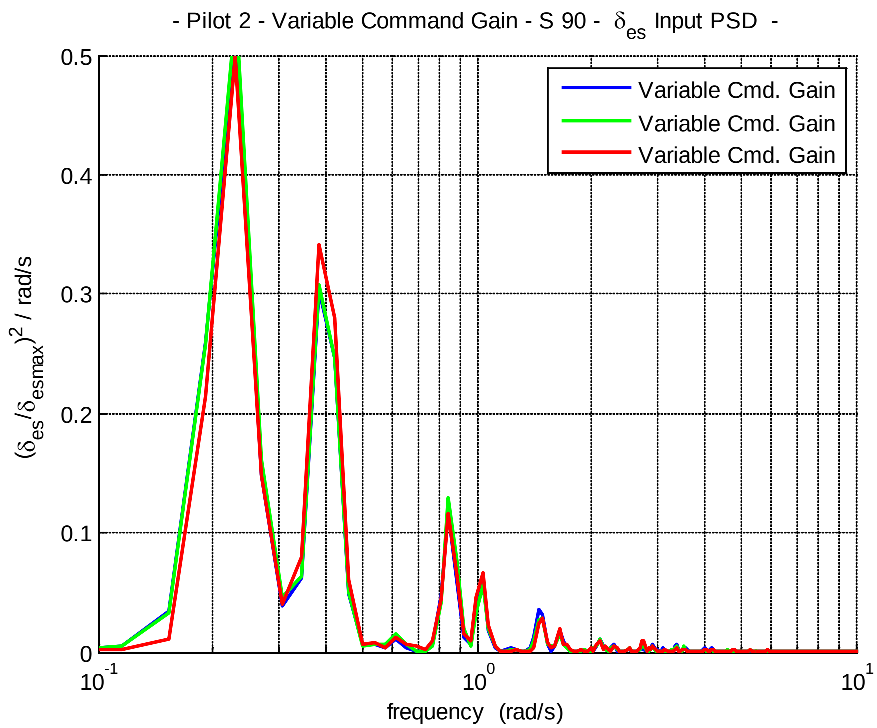


Figure 166. PSD of pilot 2's δ_{es} input — scheduled command sensitivity passive — V_C

<u>10.8.2 Pilot Ratings, Comments, and Task Scoring</u>

<u>10.8.2.1 Pilot 1</u>

Pilot ratings and comments – A limited number of evaluations were conducted in V_C flight condition. Two were run of the baseline and one of the scheduled command-gain configuration. No significant impact of the scheduling was identified on HQ, which is level 1, with a slight degradation of HQR: from HQR = 2 to HQR = 3. PIOR is not affected by the new CLAWS setup: PIOR = 1 in all evaluations. The overall impact with respect to the baseline configuration was assessed by the pilot as an increase of the stick forces. This is due to the fact that the passive stick has constant gradient and that in V_C flight condition, a reduction of the command gain with respect to the baseline is required so as not to exceed the g limits. This requires larger stick deflections and larger forces as a consequence. One advantage was reported to be the support to control of the positive stick deflection (in the gross acquisition phase), as expected. Table 64 contains pilot 1's ratings and comments.

Table 64. Pilot 1 scheduled command sensitivity ratings — comments

Evaluation: Gain Scheduling – Pilot: 1 – Date: 07/19/12							
Session	Run	Axis	Unaugmented S.M. (cbar)	Configuration	HQR	PIOR	Comments
Vc							
93	1	Pitch	5%	Baseline pure discrete	2	1	Easy to do fine tracking. Monitoring the g during the gross acquisition. Forces are light enough.
93	2	Pitch	5%	Baseline discrete and SoS	2	1	Same task. Just a little more annoying with a wandering bar. Still easy to do.
93	3	Pitch	5%	Gain Scheduling Switch ON	3	1	Forces are heavier. Have to use a different technique. Only advantage is that it helps control the amount to pull back. No big advantages and just made the forces heavier.

Task scoring – Comparison of the task scoring between the two configurations demonstrates a nominal reduction of the discrete captures scoring for the scheduled gain configuration. With the discrete + SoS task: desired ≡ adequate = 92% for the baseline, desired ≡ adequate = 69% for the scheduled gain configuration. The continuous scoring is close between the two configurations. For the baseline, it is: desired = 71%, adequate = 77%, while for the scheduled gain configuration it is: desired = 70%, adequate = 78%.

Piloting technique and time histories – The apparent discrete task higher scoring for the baseline configuration was achieved by the pilot maintaining a non-negligible margin with respect to the *nzp* limits during the baseline evaluation, with non-negligible minimum margin Δnzp_{min} = 0.2 (g) with respect to *nzp* = 2.5 (g). When in the scheduled gain configuration, the aircraft was flown at the limits of the envelope in each capture. The exceedances are nominal and correspond to a maximum value $|\Delta nzp_{max}|$ = 0.08 (g) mostly due to local spikes. This significantly different piloting technique is displayed in figures 167 and 168, showing the baseline and the scheduled gain captures, respectively. It can be noted that there is minimal input shaping in the gross acquisition phase for the scheduled gain configuration. The pilot acquired the target with FBS or FFS inputs and abruptly transitioned to a closed-loop technique for the fine-tracking phase. The PSD of the stick inputs displayed in figure 167 shows the significantly higher stick activity for the scheduled gain configuration, with respect to the baseline, in the whole frequency range. The peaks of the stick activity occur at the same frequencies, confirming that the main impact is an increased stick deflection. Minor stick activity increase is evident at high frequency: $\omega = 2.8\ \frac{\text{rad}}{\text{s}}$.

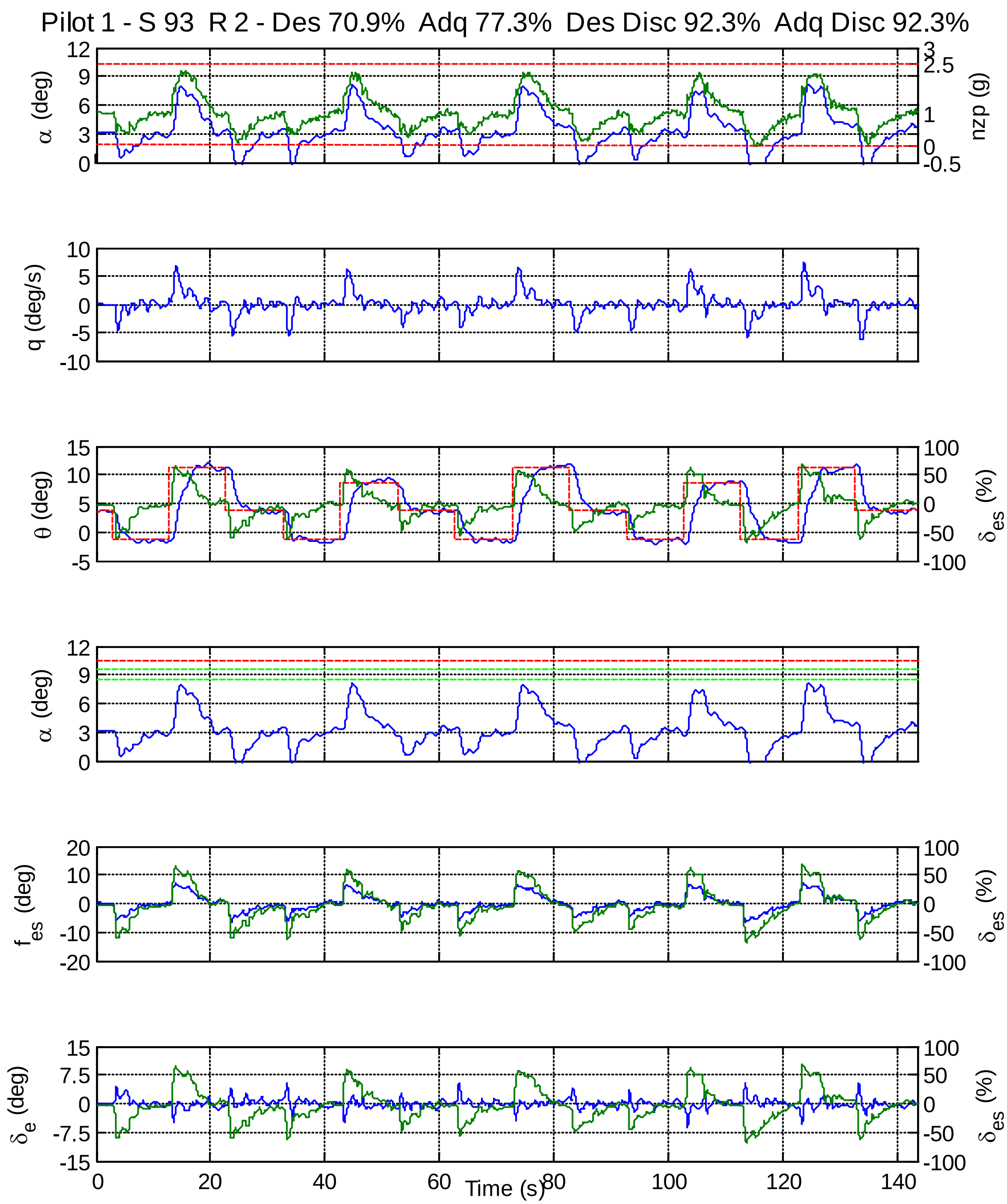


Figure 167. Pilot 1 baseline configuration captures time history plot — V_C

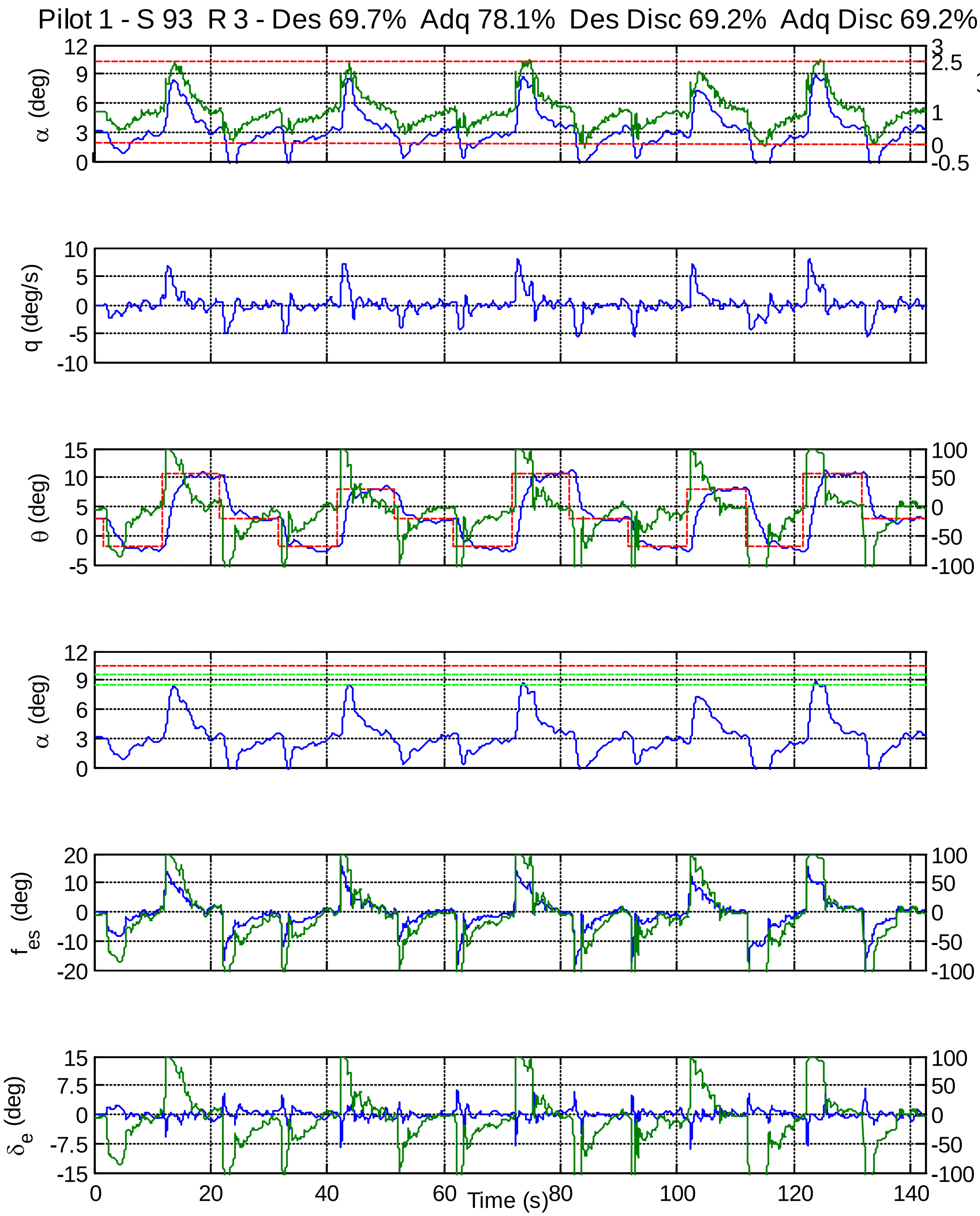


Figure 168. Pilot 1 scheduled gain configuration captures time history plot — V_C

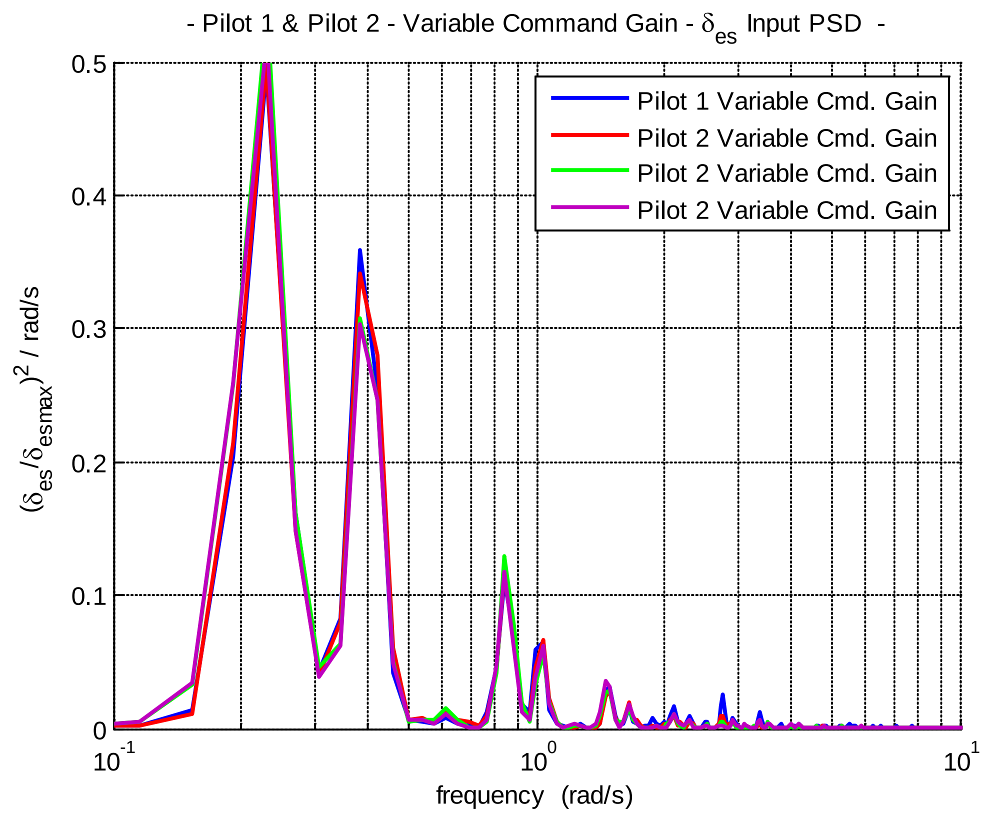


Figure 169. PSD of pilots 1 and 2's $\boldsymbol{\delta_{es}}$ input — scheduled command sensitivity passive — $\mathbf{V_C}$

10.8.2.2 Pilot 2

Pilot ratings and comments — Pilot 2 evaluations are of the scheduled command gain configuration only. The pure discrete and the discrete + SoS tasks were used in the evaluations. HQ is level 1 for all the evaluations (HQR = 3). Pilot reported a tendency to bobble, typical of this flight condition, with and without SoS disturbance. Unpredictability and low precision are reported, not sufficient to degrade the HQR below HQ level 1. As for pilot 1, PIOR is constant through the different evaluations (PIOR = 2), denoting no proneness to PIO. Table 65 contains the comments and ratings of pilot 2.

Table 65. Pilot 2 scheduled command sensitivity ratings — comments

Evaluation: Gain Scheduling – Pilot: 2 – Date: 07/19/12							
Session	Run	Axis	Unaugmented S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
90	1	Pitch	5%	Pure discrete			Initial response as expected, then seems to slow down. I can deal with it. Bobble tendency on target. When aggressive, stagnates before I want to stop.
90	2	Pitch	5%	Pure discrete	3	2	Bounces back when I try to stop it. It does not stop precisely on target. Oscillations when I go to capture. Compensation to capture the target.
90	3	Pitch	5%	Discrete and SoS	3	2	A bit of oscillation, same as before. It is hard for me to predict the rate. Bobbles on target. Minor oscillations with SoS.

Task scoring – Average discrete tasks scoring is desired ≡ adequate = 77%, continuous scoring is averagely desired = 73%, adequate = 78%. As for pilot 1, *nzp* exceedances are nominal in the scheduled gain configuration, as can be seen in figure 170.

Piloting technique and time histories – The piloting technique of pilot 2 is technically coincident with that of pilot 1, characterized by FBS and FFS inputs for gross acquisition and fast transition to smaller amplitude closed-loop inputs. This is evident from figure 167, in which the PSDs of the two pilots' inputs for the scheduled gain configuration are compared. Frequency content is comparable, with minimal differences in the frequency range $\omega = [2, 3]\ \frac{\text{rad}}{\text{s}}$. Piloting technique is displayed in figure 170. No significant input shaping in the gross acquisition phase is visible.

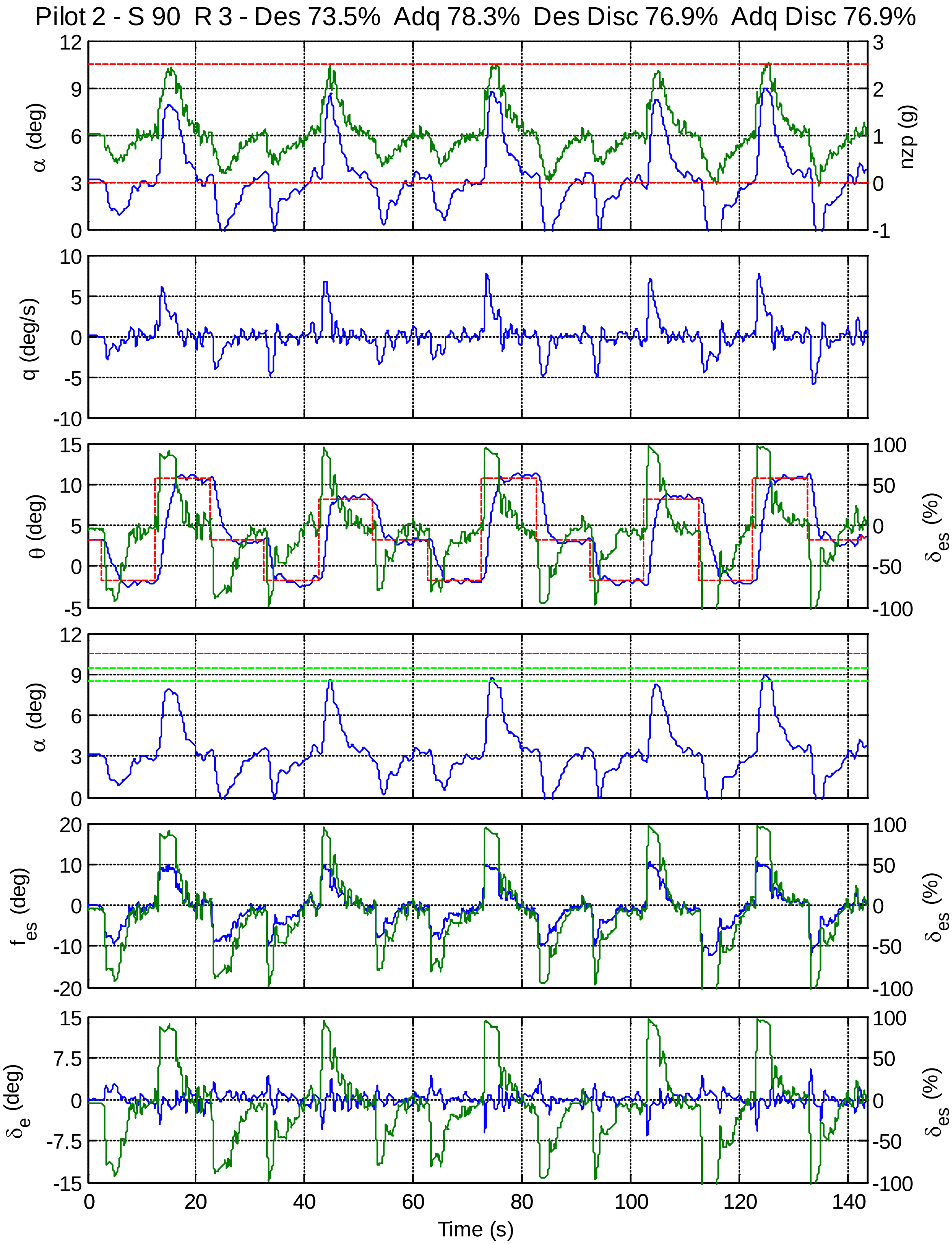


Figure 170. Pilot 2 scheduled gain configuration captures time history plot — V_C

10.9 ACTUATOR NATURAL FREQUENCY

10.9.1 Introduction

The first part of this section documents the results of a longitudinal axis study investigating the effects of varying actuator natural frequency and damping with and without a command path dead zone. The actuator natural frequency and damping were first varied with no additional dead zone to examine their effects separately. The same parameters were then varied with a 1° command path dead zone present to study the effects of reduced actuator damping and lower natural frequency on HQ and tracking task performance.

The flight condition used for this analysis is the maneuvering speed cruise configuration defined as Hp = 38,000 ft pressure altitude with zero flaps at knots calibrated airspeed (KCAS) = 234. The aircraft is in its SM = 5% ($\bar{c}$) bare airframe SM configuration. A pilot model that employs unit gain and an effective delay of 250 msec is utilized throughout the piloted task performance analysis.

Actuator natural frequencies of 75, 50, and 20 rad/s and damping ratios of 0.7, 0.4, and 0.2 were examined in this study. The 75 rad/s case with 0.7 damping is considered the baseline actuator configuration.

Offline analysis focuses on the airplane bandwidth/phase delay criteria and an SoS disturbance regulation tracking task. A detailed description of the nature of the task and its implementation is given in section 4.4, while the signal used for this analysis is shown in figure 171. Desired and adequate bounds were once again set as ±1° and ±2° of error from trim (figure 172). In the figure, only desired bounds are shown because the adequate bounds were never exceeded in the analysis.

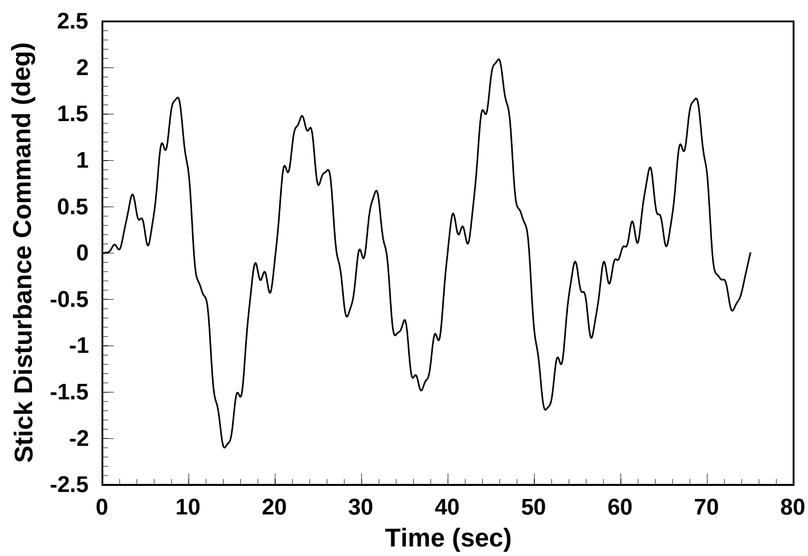


Figure 171. Fibonacci series-based lower frequency SoS input forcing function time history

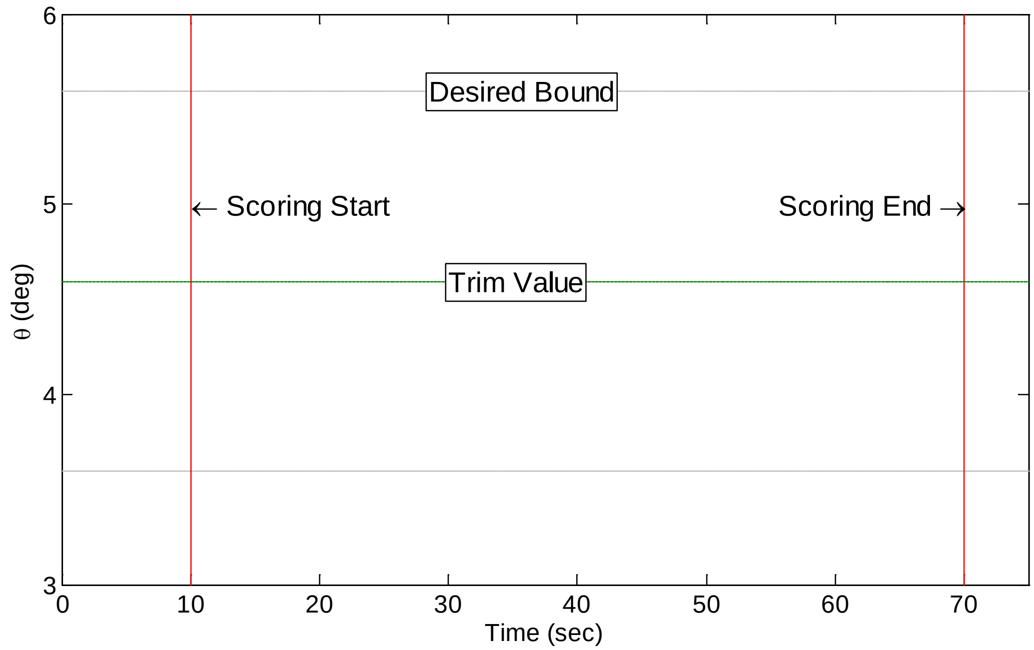


Figure 172. Task performance time history plot annotations

The second part of this section presents an analysis of the fixed-base simulation evaluations investigating the effects of pitch (elevator) actuator natural-frequency on longitudinal axis HQ. Three pilots participated in the pitch actuator natural-frequency evaluations [14]. The evaluations featured an SoS tracking task in PA and cruise maneuver speed (V_A) configuration with a bare airframe SM of SM = 5, 2.5, and 0% ($\bar{c}$). The aircraft FCS was designed to provide the same HQ for all SM configurations with the baseline actuator natural frequency. The HQ and PIO tendency ratings were recorded after each evaluation run and task performance data were recorded for offline analysis. Actuator natural frequency was varied from 75 rad/s (baseline) to 5 rad/s.

10.9.2 Offline System Analysis

10.9.2.1 Closed-Loop Aircraft

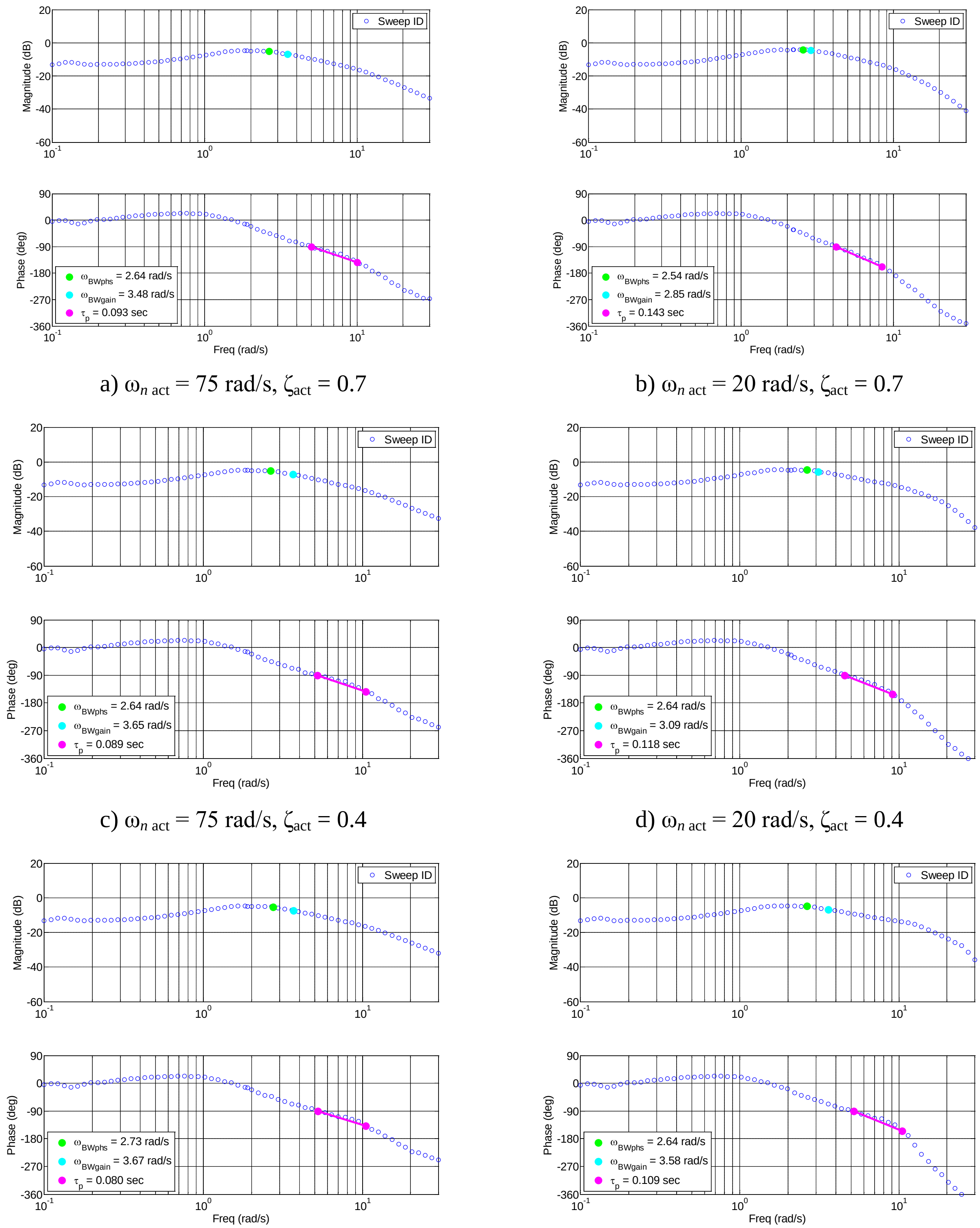
The objective of this analysis was to determine the effects of changing actuator dynamics on task performance and pilot behavior with and without a command path dead zone present. The analysis first examines the effects of reduced damping and studies the effects of lower natural frequency. The analysis is then repeated with a command path dead zone of 1°.

The controlled element Y_c refers to the closed-loop augmented aircraft that includes the CLAWS, feel system, and vehicle dynamics. The command path dead zone is also considered part of the controlled element for this analysis when present.

10.9.2.2 Nominal Command Path

Figure 173 shows the identified vehicle responses for various actuator damping ratios at the baseline natural frequency of 75 rad/s and a lower natural frequency of 20 rad/s. Note that for both natural frequencies, phase delay improves as damping is reduced. Reduced damping with a fixed natural frequency adds phase lead in the region where the bandwidth and phase delay are calculated so that there is a net reduction in phase delay. This is not, however, a recommended method for achieving such gains because the added overshoot that accompanies the reduced damping will negatively impact actuator performance.

The reduced damping for the 75 rad/s case has minimal effect on phase at low frequencies, which is expected as the actuator dynamics are much higher in frequency than the 1–10 rad/s frequency range typically associated with piloted control. The presence of actuator dynamics at 20 rad/s has a profound effect on the phase and causes phase delay to degrade by 50% when compared to the baseline frequency for the 0.7 damping case.



a) $\omega_{n\ \mathrm{act}}$ = 75 rad/s, ζ_{act} = 0.7

b) $\omega_{n\ \mathrm{act}}$ = 20 rad/s, ζ_{act} = 0.7

c) $\omega_{n\ \mathrm{act}}$ = 75 rad/s, ζ_{act} = 0.4

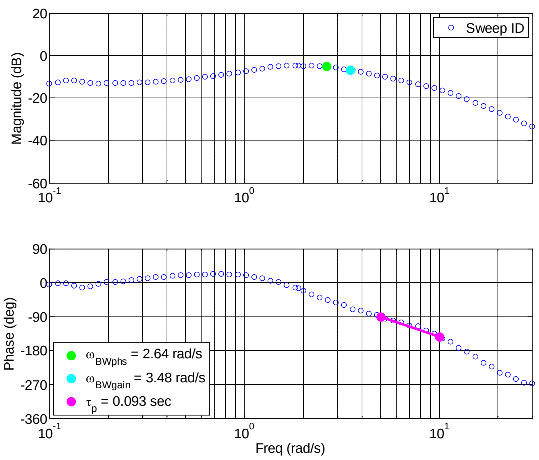
d) $\omega_{n\ \mathrm{act}}$ = 20 rad/s, ζ_{act} = 0.4

e) $\omega_{n\ \mathrm{act}}$ = 75 rad/s, ζ_{act} = 0.2

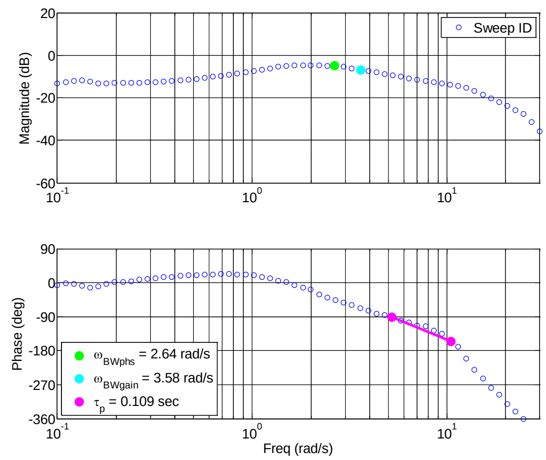
f) $\omega_{n\ \mathrm{act}}$ = 20 rad/s, ζ_{act} = 0.2

Figure 173. Aircraft plus feel system identified frequency responses and FQ metrics

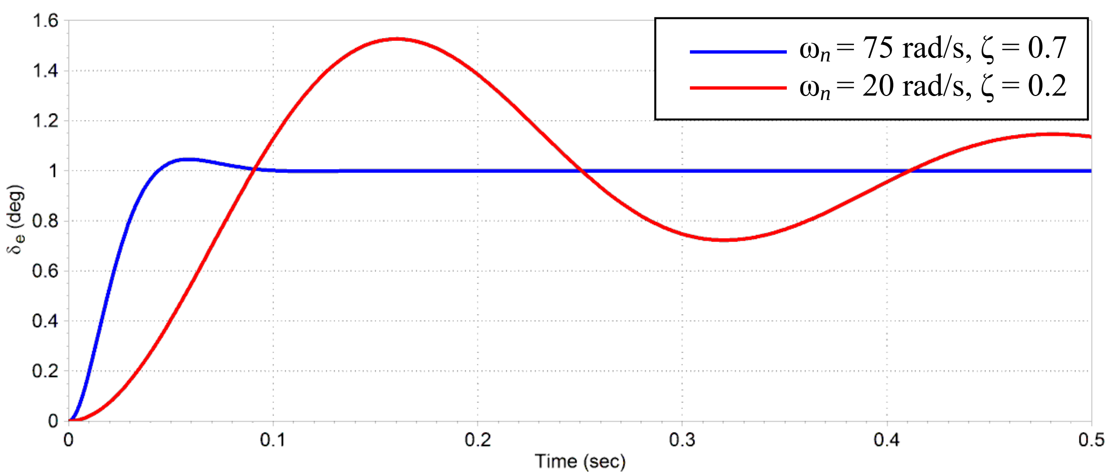
Reducing the damping for the 20 rad/s case minimizes the phase loss due to the lower natural frequency as it flattens out the phase curve in the frequency region just before the actuator. In this case, because the ω_{-180} and $2\omega_{-180}$ frequencies are in the 5–10 rad/s range, reduced damping allows the phase-delay parameters to recover much of what is lost with the lower frequency actuator. Figure 174 shows a comparison of the complete vehicle response with baseline actuator (figure 174 (a)) and 20 rad/s actuator with reduced damping (figure 174 (b)), which demonstrates that the bandwidth and phase delay are similar to the baseline despite the actuator natural frequency being only slightly above the piloted control frequency range. As mentioned previously, the reduced damping will negatively impact actuator performance (figure 174 (c)), so there is a trade-off between gains in airplane bandwidth parameters and tolerable actuator overshoots.



a) $\omega_{n\ act} = 75$ rad/s, $\zeta_{act} = 0.7$



b) $\omega_{n\ act} = 20$ rad/s, $\zeta_{act} = 0.2$



c) Unit Step Response Comparison

Figure 174. Comparison of baseline and lightly damped reduced frequency actuators

The predicted HQ shown in figure 175 indicate a lack of variance in pitch attitude bandwidth. Only for the lightly damped/baseline frequency case and the nominally damped/low actuator frequency cases did the bandwidth vary from its baseline values of 2.64 rad/s. This variance was also very small, on the order of 4%. For the 75 rad/s and 50 rad/s actuator natural frequency cases, phase delay was slightly improved with reduced damping, though this improvement was minimal. For the 20 rad/s case, the baseline damping of 0.7 created a PIO risk for configurations with flight path bandwidth less than 0.7 rad/s (table 66). Reduced damping for this case, although not desirable because of excessive overshoot and oscillatory behavior, brought phase delay to within tolerable PIO bounds, though the aircraft is still level 2.

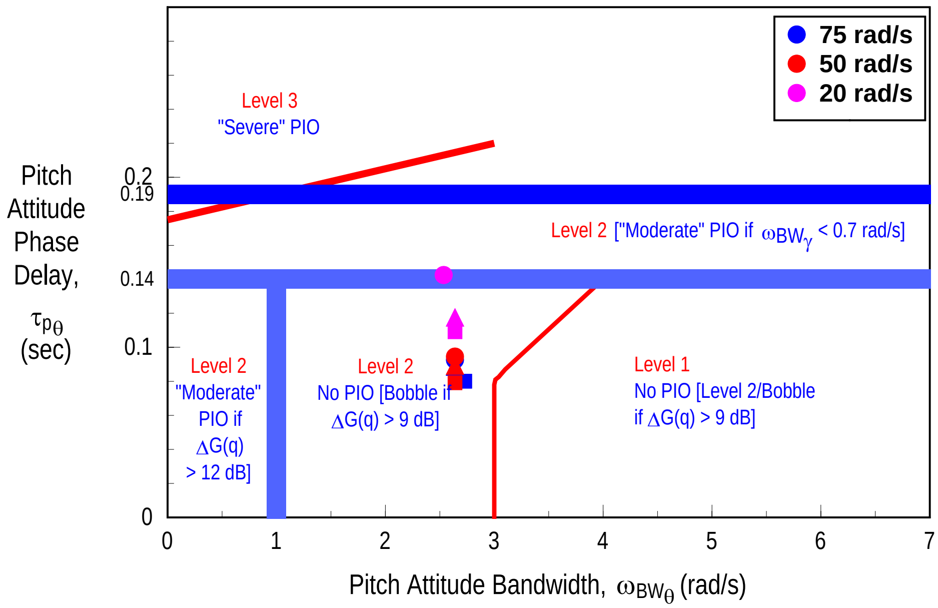
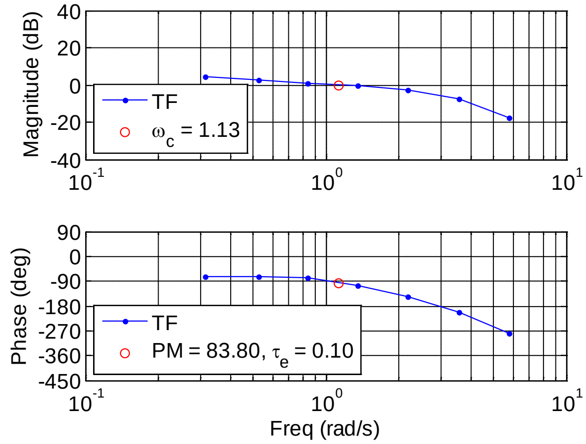


Figure 175. Pitch handling qualities for 0.7 (circle), 0.4 (triangle), and 0.2 (square) damping cases [13]

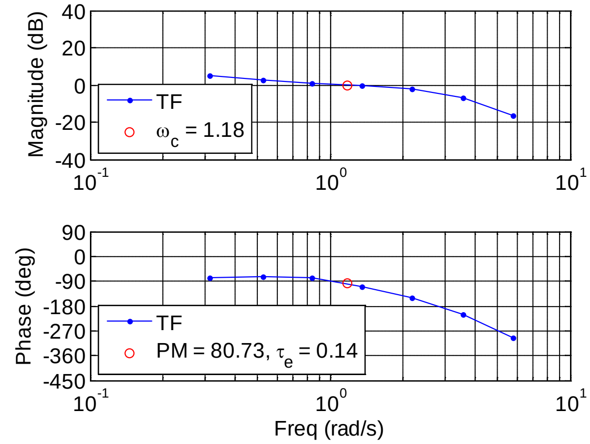
Table 66. Summary of closed-loop aircraft bandwidth/phase delay

$\omega_{n\ act}$ (rad/s)	$\zeta = 0.7$	$\zeta = 0.4$	$\zeta = 0.2$
75	2.6394 r/s / 0.0926 s	2.6394 r/s / 0.0886 s	2.7286 r/s / 0.0801 s
50	2.6394 r/s / 0.0945 s	2.6394 r/s / 0.0892 s	2.6394 r/s / 0.0792 s
20	2.5358 r/s / 0.1425 s	2.6394 r/s / 0.1176 s	2.6394 r/s / 0.1092 s

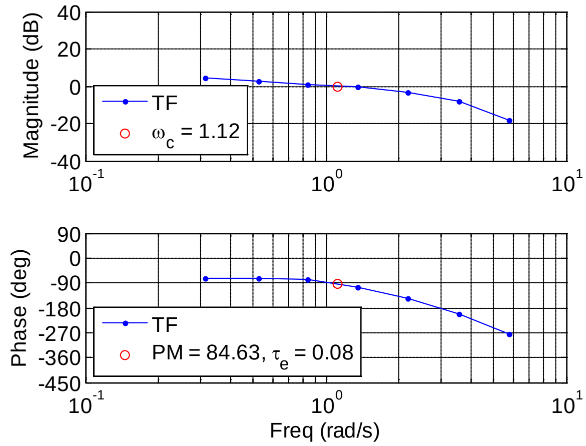
Analysis of the PVS reveals that lower actuator natural frequency and reduced damping have minimal effect on system crossover frequency or piloted task performance for the cases studied herein. The PVS crossover remains the same regardless of the changes in the actuator that occur at higher frequencies. For the disturbance regulation task used in this analysis, even a reduction of actuator natural frequency to 20 rad/s did not affect PVS crossover significantly and, though the reduced damping cases did achieve improved PVS phase margin and effective delay, no significant difference was observed (figure 176).



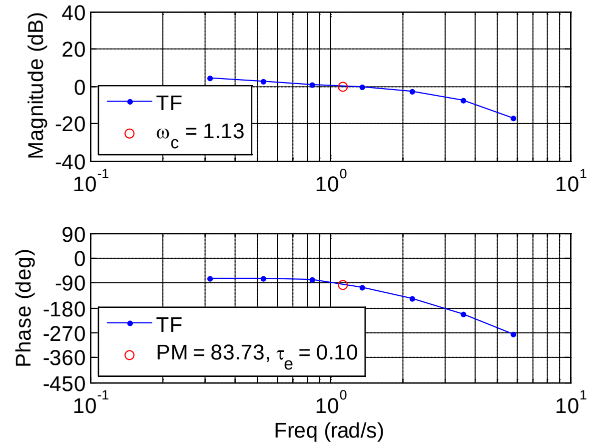
a) $\omega_{n\ act}$ = 75 rad/s, ζ_{act} = 0.7



b) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7



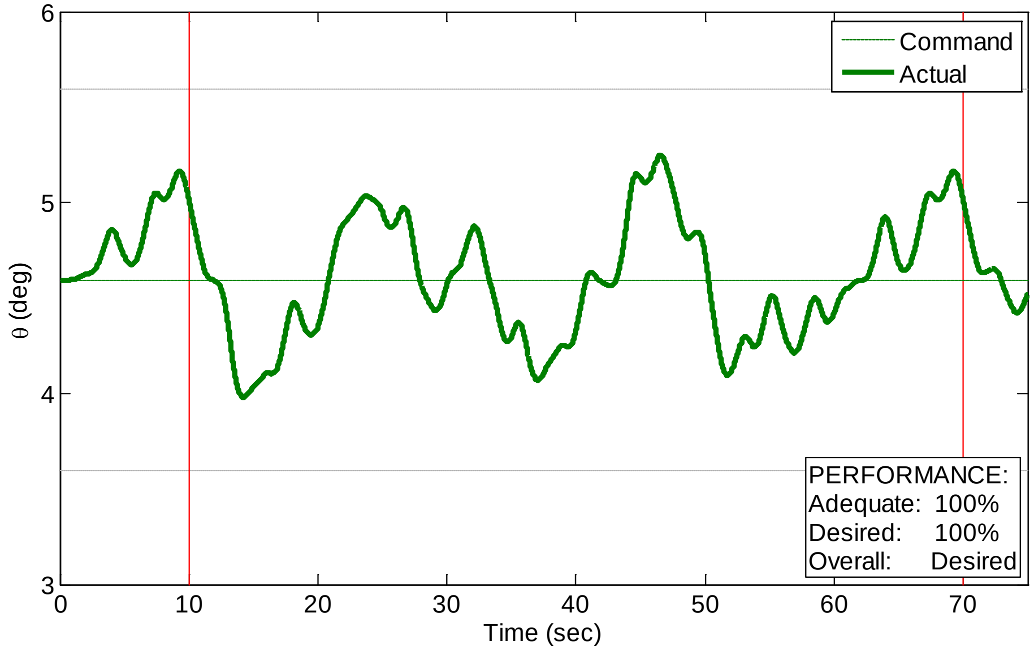
c) $\omega_{n\ act}$ = 75 rad/s, ζ_{act} = 0.2



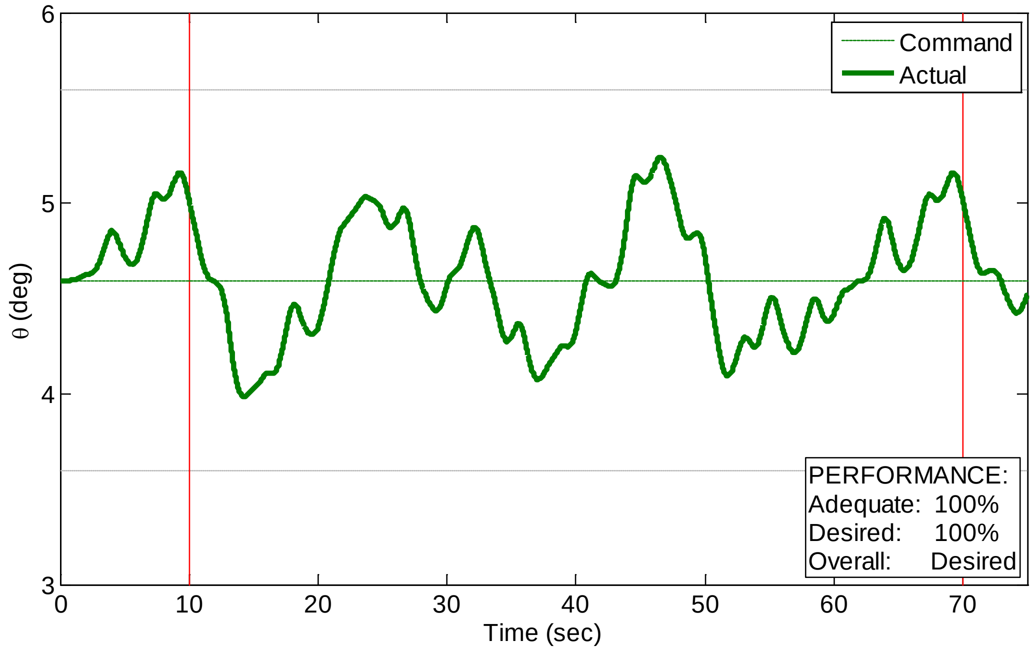
d) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.2

Figure 176. Pilot-vehicle describing functions with crossover frequency and phase margin/effective delay

There was no change in task performance because of the easily attainable desired bounds for the task studied with a paper pilot model. Figures 177 and 178 show task performance for the 75 rad/s and 20 rad/s cases with baseline and lightly damped actuators. Although small differences exist, they are negligible. This reiterates the results shown in figure 176, which indicate almost identical PVS for the longitudinal axis.

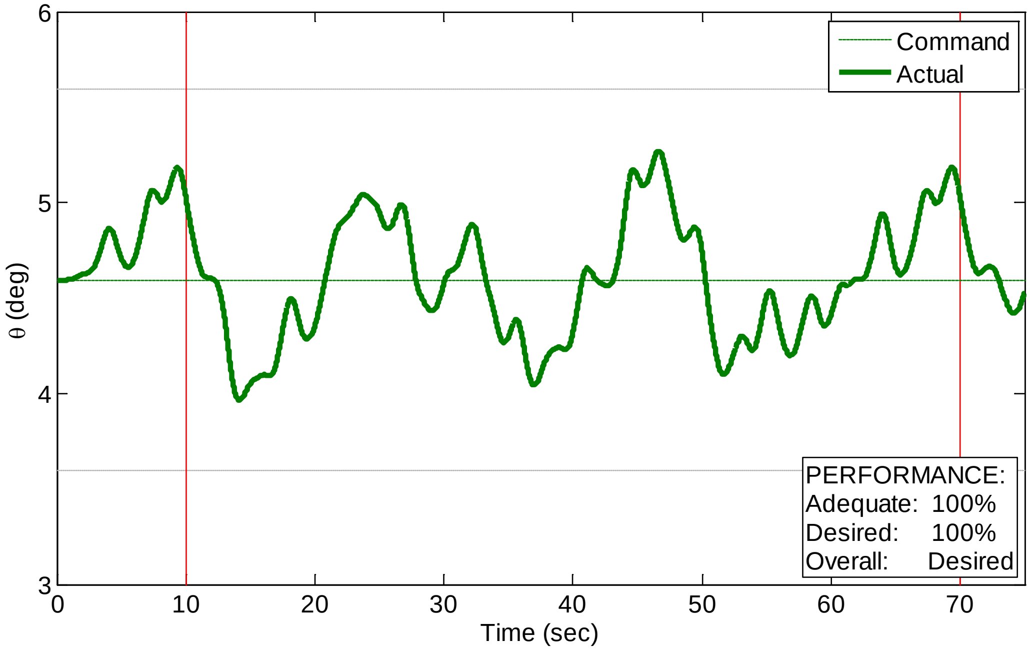


a) $\omega_{n\ act}$ = 75 rad/s, ζ_{act} = 0.7

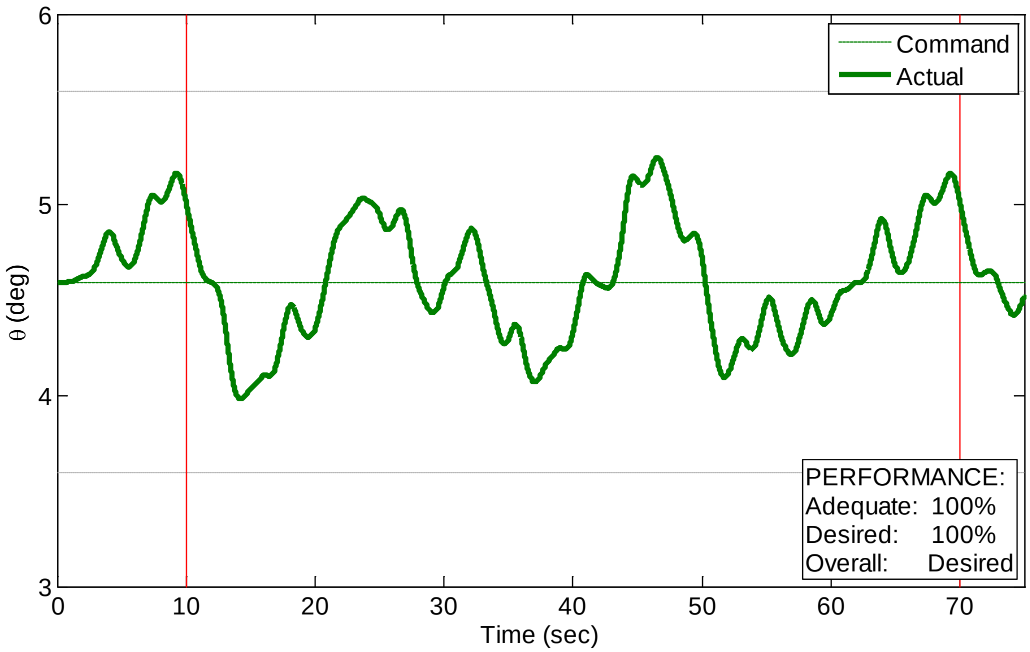


b) $\omega_{n\ act}$ = 75 rad/s, ζ_{act} = 0.2

Figure 177. Task performance time histories (75 rad/s)



a) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7



b) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.2

Figure 178. Task performance time histories (20 rad/s)

10.9.2.3 Effects of Command Path Dead Zone

Figure 179 and table 67 give the HQ parameters for the vehicle with a 1° command-path dead zone. In contrast to the roll results [18], which showed an improvement in bandwidth and slightly degraded phase delay, phase delay is slightly improved for the longitudinal case while airplane bandwidth is made slightly worse by the introduction of a 1° command-path dead zone. The phase delay for the 0.7 damping ratio case at 20 rad/s is still level 2 with a moderate PIO risk, though reduced damping cases improve the phase delay to restore it to that of the baseline case.

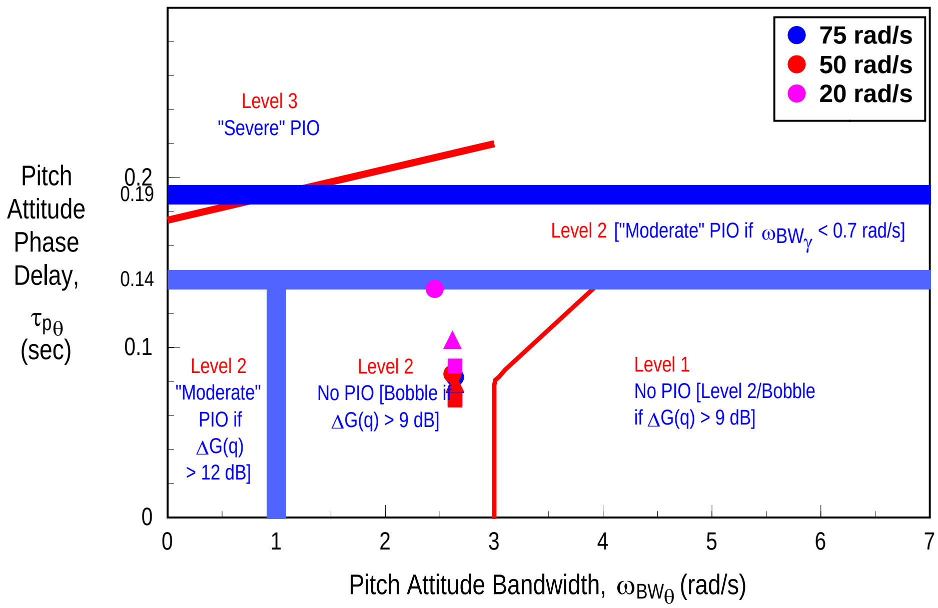
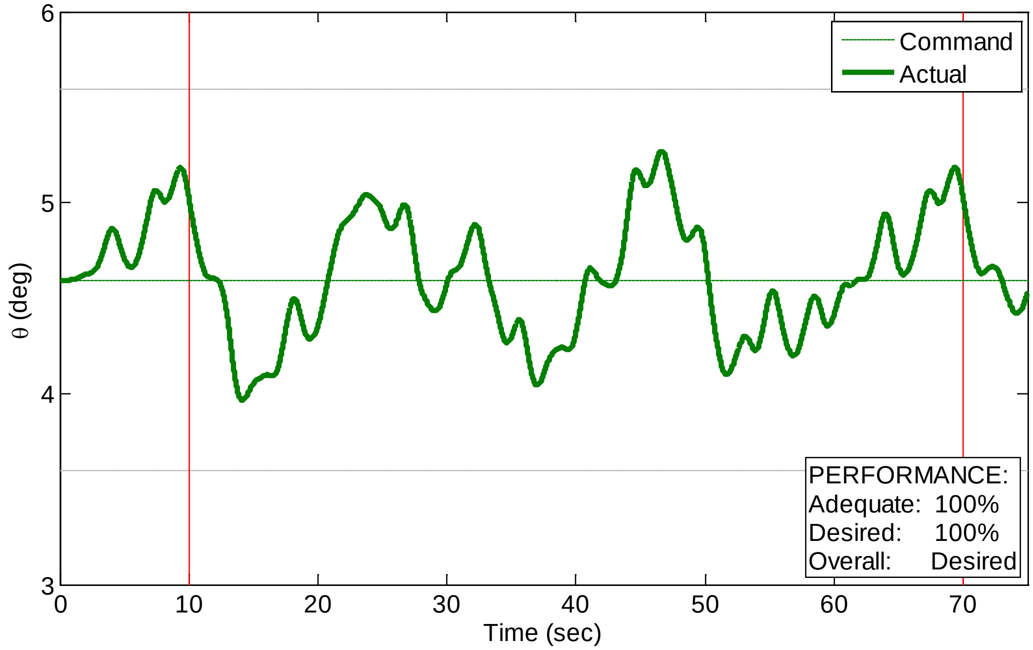


Figure 179. Pitch handling qualities with 1° command-path dead zone for 0.7 (circle), 0.4 (triangle), and 0.2 (square) damping cases [13]

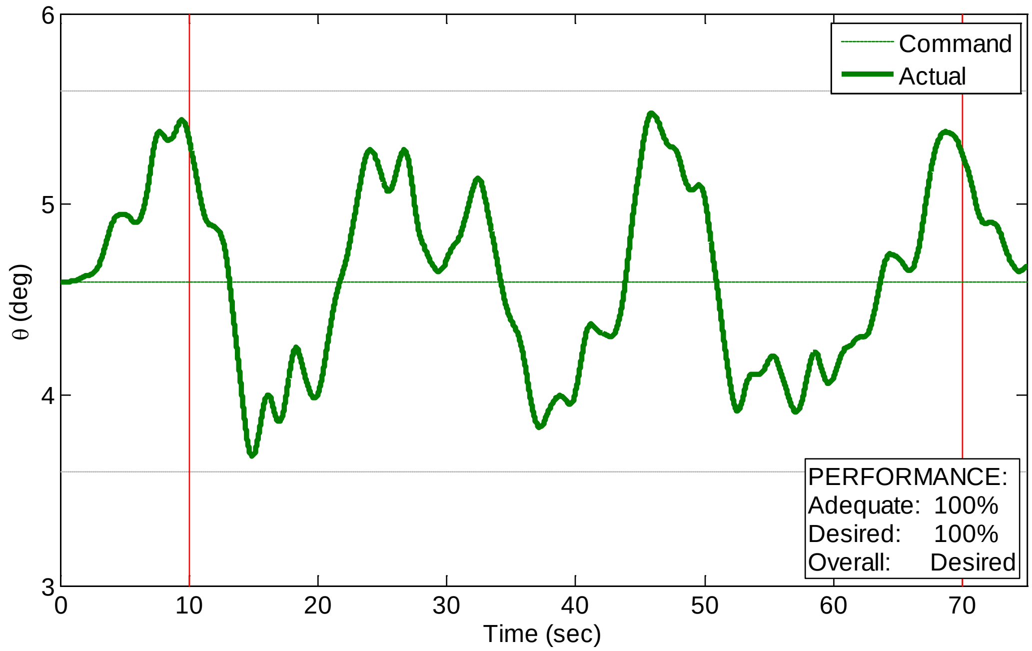
Table 67. Summary of closed-loop aircraft bandwidth/phase delay with command-path dead zone

$\omega_{n\ act}$ (rad/s)	$\zeta = 0.7$	$\zeta = 0.4$	$\zeta = 0.2$
75	2.6394 r/s / 0.0826 s	2.6394 r/s / 0.0786 s	2.6394 r/s / 0.0701 s
50	2.6156 r/s / 0.0845 s	2.6394 r/s / 0.0792 s	2.6394 r/s / 0.0692 s
20	2.4531 r/s / 0.1345 s	2.6156 r/s / 0.1045 s	2.6394 r/s / 0.0892 s

Though the phase-delay parameters slightly improve with the introduction of the dead zone, this is not seen in task performance for the reduced damping cases. Figure 180 shows the results of the simulated task performance with the dead zone for the 20 rad/s case—and though desired performance percentages do not change, the amplitude of the aircraft's divergence from trim caused by the disturbance is much larger. This is because of the reduced precision of the aircraft response due to the pilot's commands being negated by the presence of the dead zone. Varying of the actuator damping (figure 181) does not significantly affect the results.

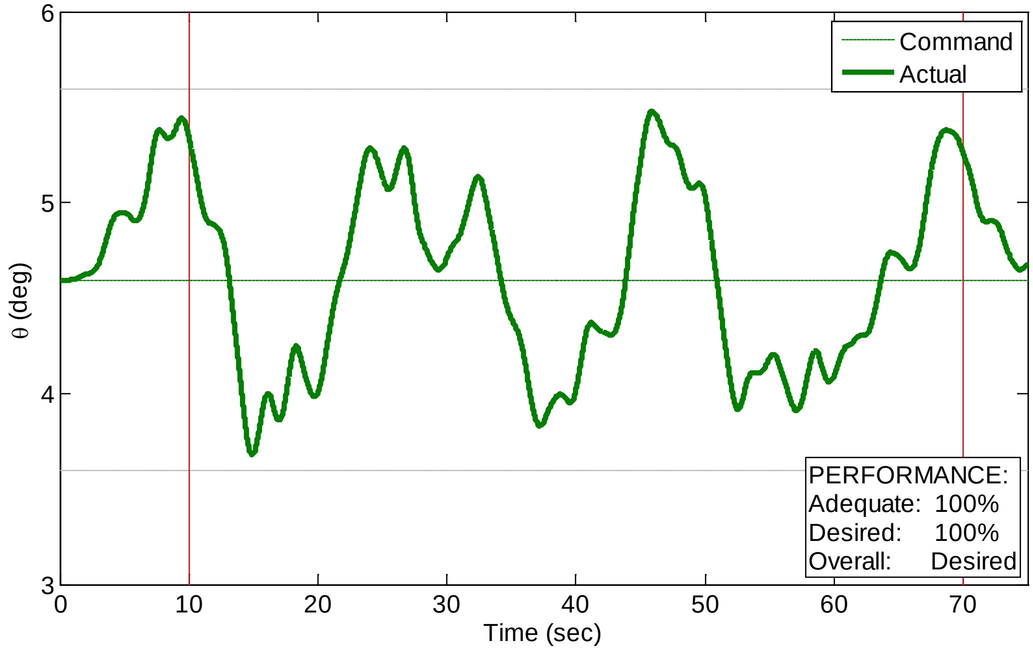


a) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7, no dead zone present.

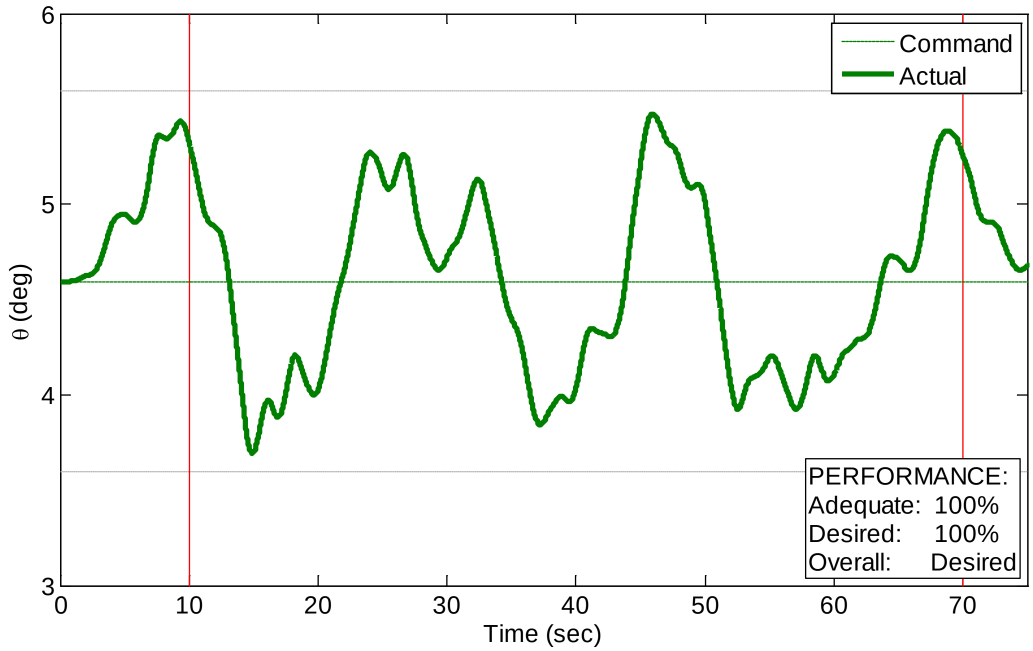


b) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7, 1 degree command path dead zone.

Figure 180. Task performance time histories with and without a command path dead zone



a) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7



b) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.2

Figure 181. Task performance time histories with varying actuator damping ratio (1° dead zone)

10.9.3 Offline Analysis Observations and Conclusions

- Because the actuator dynamics are modeled similarly for both the aileron and elevator control surfaces, the results of the pitch axis actuator analysis, for the most part, parallel those of the roll axis (section 11.5.2).

- In the pitch axis, lower actuator natural frequency and reduced damping do not affect PVS crossover or task performance.

- Reduced damping greatly influences actuator performance in terms of increased overshoot. This change may more significantly impact larger amplitude maneuvering associated with terminal flight operations.

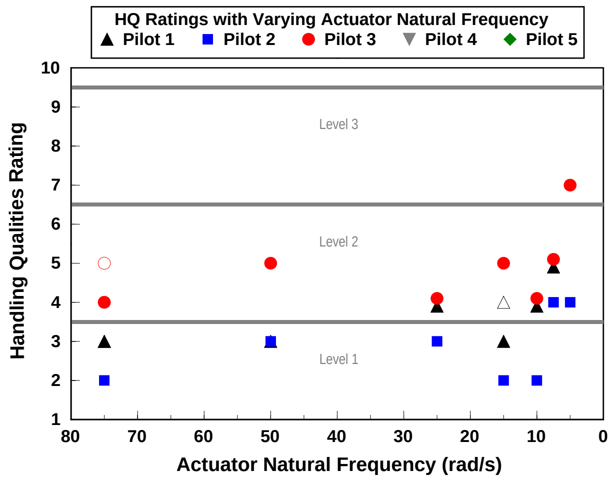
- The introduction of a 1° command-path dead zone slightly improves HQ parameters, but an improvement in task performance was not seen in the simulation results and the amplitude of the divergence from trim due to the disturbance input is much larger.

- This limited analysis reveals a large design space for control-surface actuator bandwidth and natural frequency. Optimum values for a given aircraft design will be dependent on the control allocation required for stability, maneuvering, gust load alleviation, failure modes, etc.

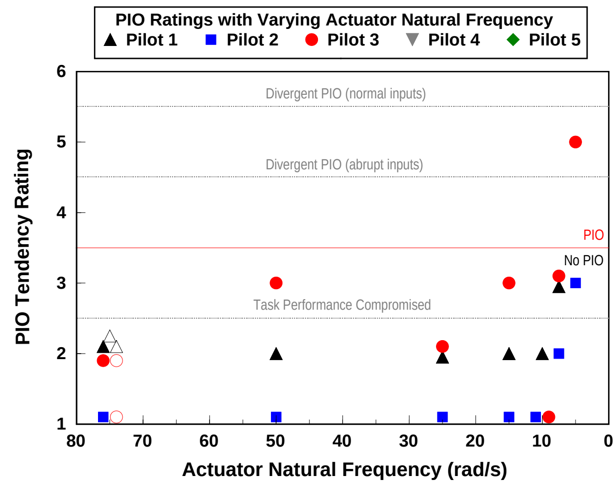
10.9.4 Piloted Evaluations Analysis Summary

Figures 182 and 183 give a summary of the HQ and PIO tendency ratings for the three pilots who participated in the pitch actuator natural frequency evaluations. Results for PA and V_A flight conditions are shown.

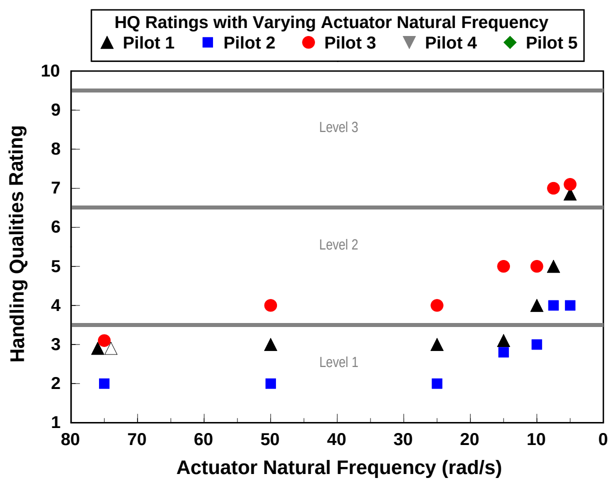
Figures 182 and 183 give the HQ and PIO tendency ratings for the PA and V_A flight conditions, respectively. Results for the longitudinal axis parallel those for the lateral axis, with both HQ and PIO tendency ratings degrading significantly for actuator natural frequencies below 15 rad/s. This degradation in ratings is seen for all three pilots, both of the flight conditions, and all of the SM configurations evaluated in this study. The results showed little variation with SM. Configurations with actuator natural frequencies 10 rad/s and below were given especially poor ratings, with one pilot giving HQR of 9 and 10 for these configurations, indicating loss of control of the aircraft. It is therefore recommended that actuator requirements be set above 15 rad/s to avoid issues with poor HQ and an increased risk of PIO.



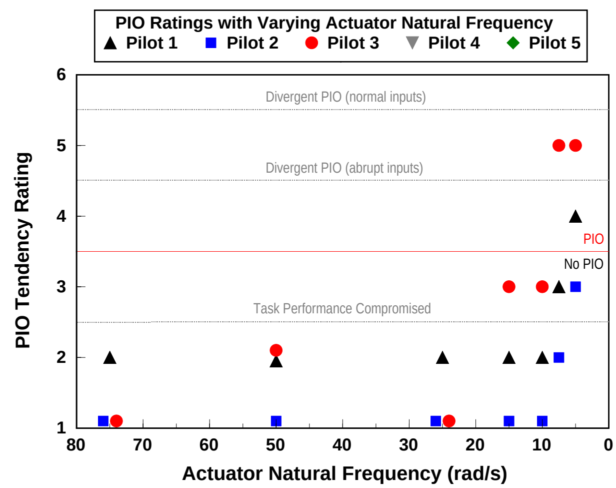
a) Handling Qualities – 5% Static Margin



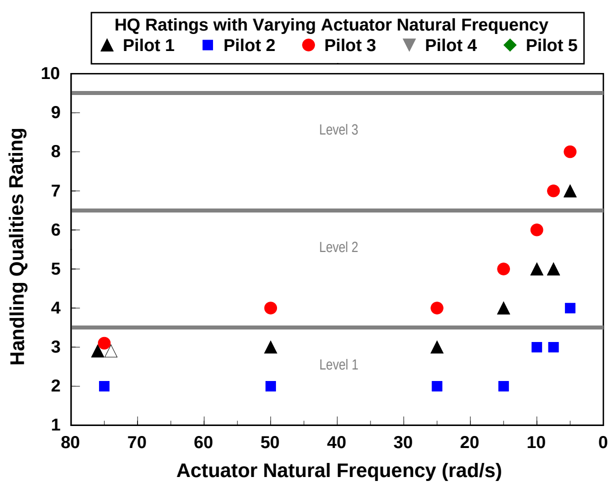
b) PIO Tendency – 5% Static Margin



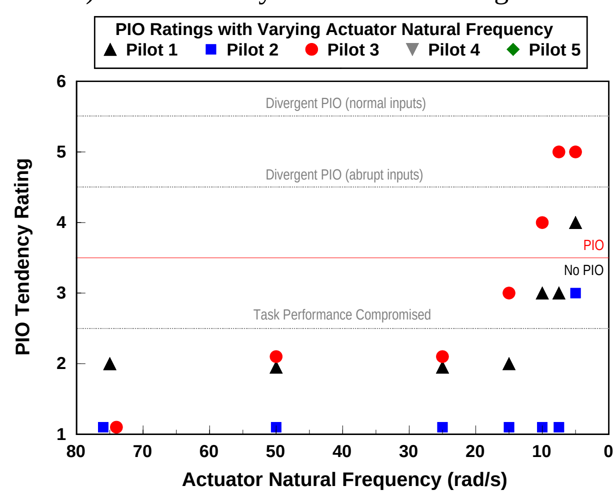
c) Handling Qualities – 2.5% Static Margin



d) PIO Tendency – 2.5% Static Margin

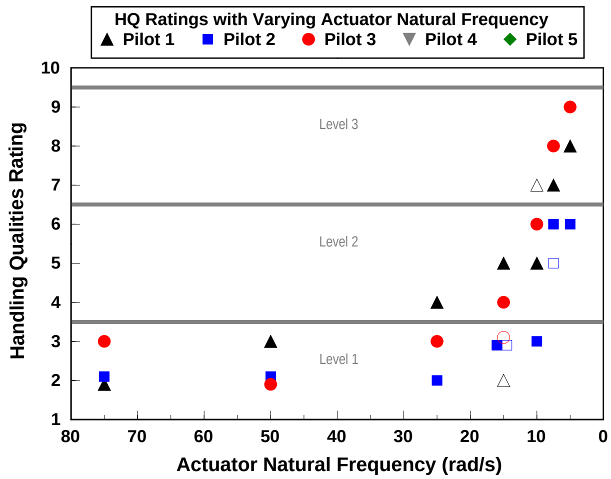


e) Handling Qualities – 0% Static Margin

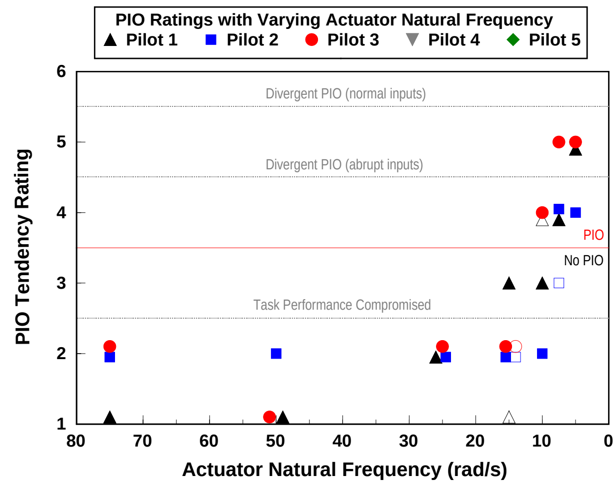


f) PIO Tendency – 0% Static Margin

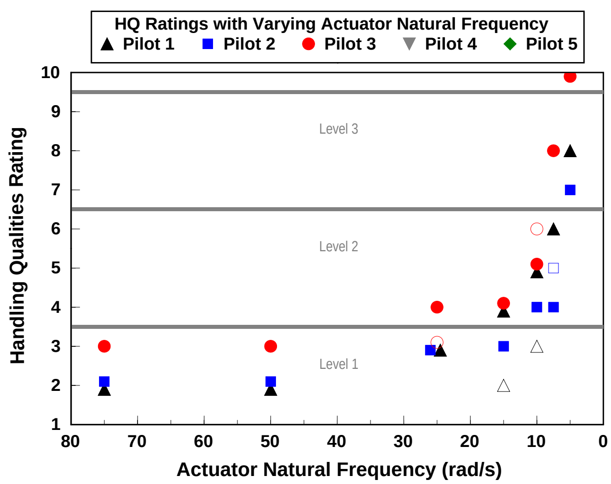
Figure 182. Pilot ratings, PA flight condition, pitch actuator natural frequency variations



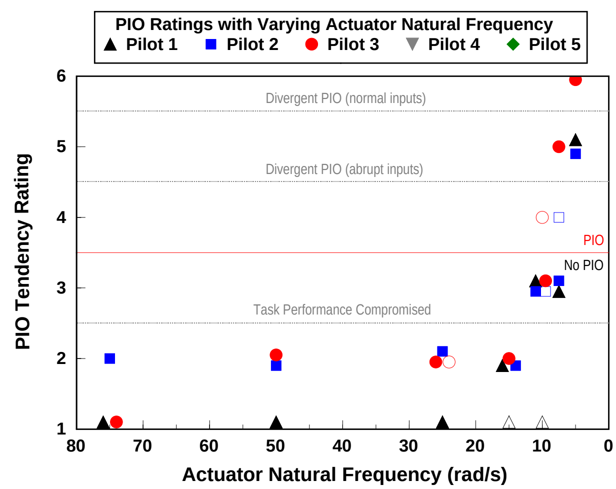
a) Handling Qualities – 5% Static Margin



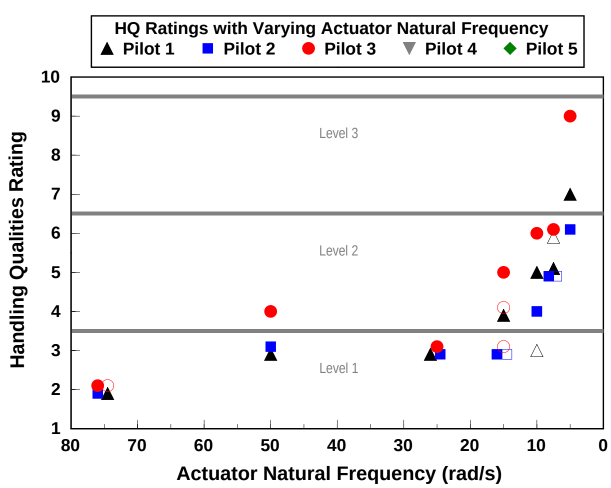
b) PIO Tendency – 5% Static Margin



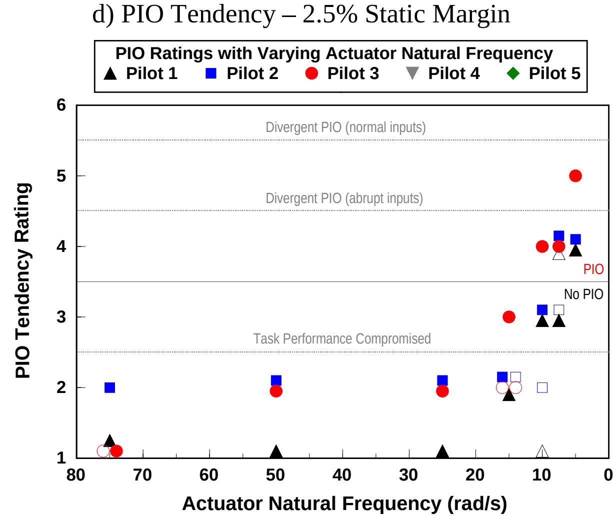
c) Handling Qualities – 2.5% Static Margin



d) PIO Tendency – 2.5% Static Margin



e) Handling Qualities – 0% Static Margin



f) PIO Tendency – 0% Static Margin

Figure 183. Pilot ratings, V_A flight condition, pitch actuator natural frequency variations

As illustrated in tables 68 and 69, there is a dropoff in task performance corresponding to the degraded ratings seen above for configurations below 15 rad/s. All pilots see degradation in performance due to the more sluggish actuators below this threshold for both flight conditions analyzed. Pilots 2 and 3 see the most significant drop for actuator frequencies below 10 rad/s in PA. All three pilots see poor performance for these cases for the V_A flight condition. Pilot 3 was more sensitive to actuator changes for the V_A flight condition, with ratings and task performance worse for the same actuator and SM configurations in V_A when compared to PA.

This further supports the conclusion that the lower threshold for actuator natural frequencies in the longitudinal axis should be set at 15 rad/s to avoid poor performance in pilot-in-the-loop tasks for both approach and up-and-away configurations. Variations among SM cases were minimal.

Symbol annotations give HQR for each run.

Table 68. Task performance summary, pitch actuator natural frequency variations, PA flight condition

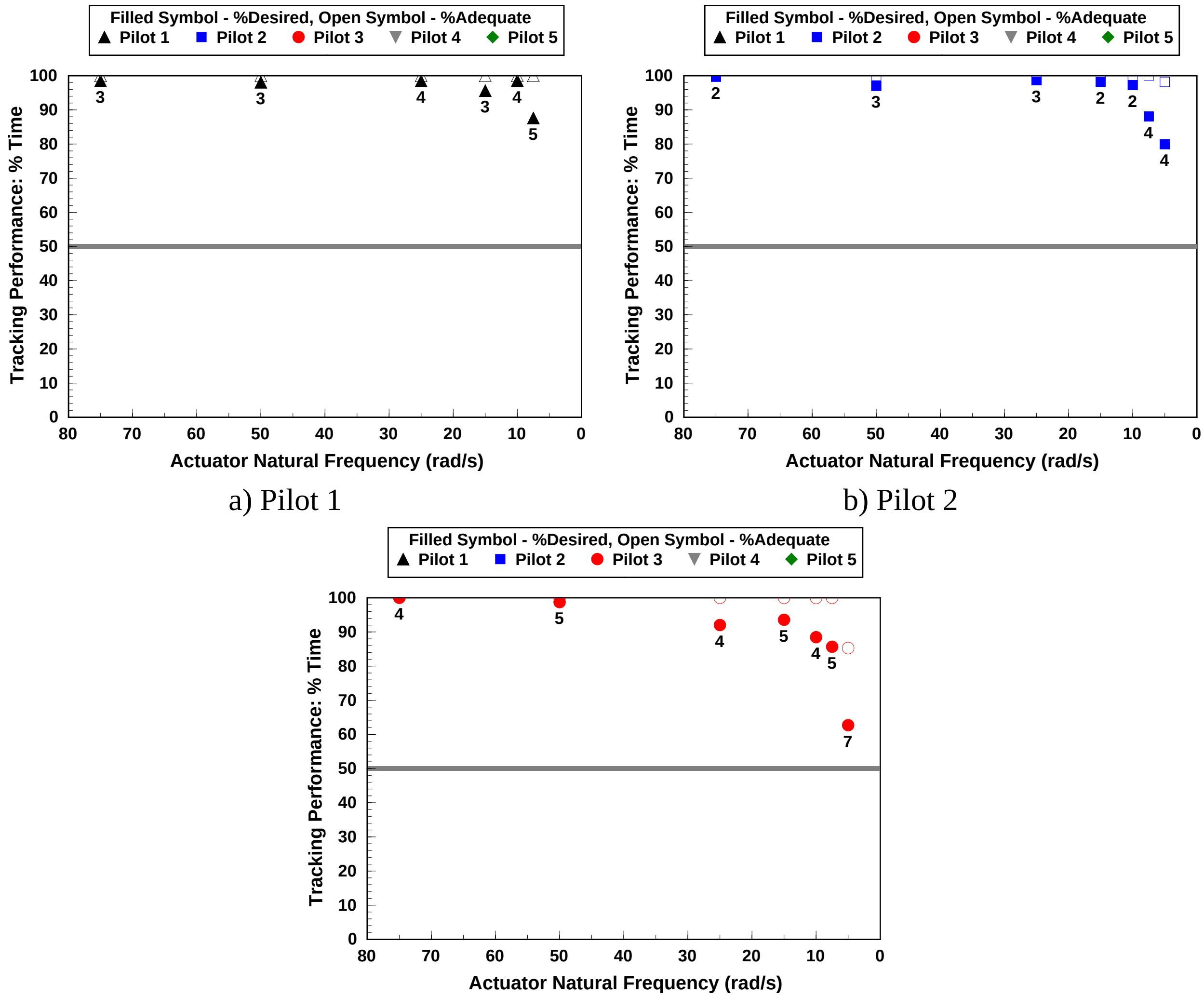
Actuator Frequency (rad/s)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
75.0	98.48 (5%) 100.00 (2.5%) 99.23 (0%)	99.70 (5%) 100.00 (2.5%) 100.00 (0%)	100.00 (5%) 95.90 (2.5%) 94.10 (0%)	–
50.0	98.08 (5%) 100.00 (2.5%) 99.30 (0%)	97.03 (5%) 100.00 (2.5%) 100.00 (0%)	98.73 (5%) 93.08 (2.5%) 96.75 (0%)	–
25.0	98.45 (5%) 96.72 (2.5%) 100.00 (0%)	98.67 (5%) 98.77 (2.5%) 99.02 (0%)	92.02 (5%) 95.72 (2.5%) 96.30 (0%)	–
15.0	95.62 (5%) 97.62 (2.5%) 98.27 (0%)	98.17 (5%) - (2.5%) 97.67 (0%)	93.57 (5%) 83.62 (2.5%) 96.48 (0%)	–
10.0	98.57 (5%) 93.98 (2.5%) 95.53 (0%)	97.25 (5%) 98.53 (2.5%) 97.45 (0%)	88.47 (5%) 93.57 (2.5%) 89.08 (0%)	–
7.5	87.63 (5%) 92.15 (2.5%) 95.63 (0%)	88.08 (5%) 91.80 (2.5%) 90.58 (0%)	85.67 (5%) 74.02 (2.5%) 70.85 (0%)	–
5.0	- (5%) 74.98 (2.5%) 80.90 (0%)	79.95 (5%) 82.78 (2.5%) 78.93 (0%)	62.70 (5%) 66.93 (2.5%) 57.92 (0%)	–

Table 69. Task performance summary, pitch actuator natural frequency variations, V_A flight condition

Actuator Frequency (rad/s)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
75.0	97.25 (5%) 95.87 (2.5%) 96.53 (0%)	96.32 (5%) 99.13 (2.5%) 98.52 (0%)	92.67 (5%) 81.67 (2.5%) 79.78 (0%)	–
50.0	95.95 (5%) 96.07 (2.5%) 97.58 (0%)	98.90 (5%) 98.50 (2.5%) 100.00 (0%)	94.47 (5%) 93.42 (2.5%) 94.25 (0%)	–
25.0	95.37 (5%) 93.65 (2.5%) 92.33 (0%)	98.00 (5%) 97.40 (2.5%) 98.85 (0%)	91.98 (5%) 89.02 (2.5%) 88.30 (0%)	–
15.0	95.73 (5%) 92.00 (2.5%) 97.48 (0%)	95.20 (5%) 95.13 (2.5%) 94.85 (0%)	89.87 (5%) 89.59 (2.5%) 88.82 (0%)	–
10.0	85.27 (5%) 91.62 (2.5%) 86.72 (0%)	87.62 (5%) 85.70 (2.5%) 92.53 (0%)	82.38 (5%) 82.78 (2.5%) 83.03 (0%)	–
7.5	84.45 (5%) 80.88 (2.5%) 82.00 (0%)	73.97 (5%) 87.67 (2.5%) 81.82 (0%)	79.13 (5%) 77.50 (2.5%) 72.47 (0%)	–
5.0	53.37 (5%) 49.85 (2.5%) 66.42 (0%)	53.07 (5%) 48.27 (2.5%) 61.48 (0%)	54.85 (5%) 47.25 (2.5%) 52.82 (0%)	–

Figures 184–186 show the tracking performance for 3 pilots at 3 different PA SM.

Figures 187–189 show the tracking performance for 3 pilots at 3 different V_A SM.

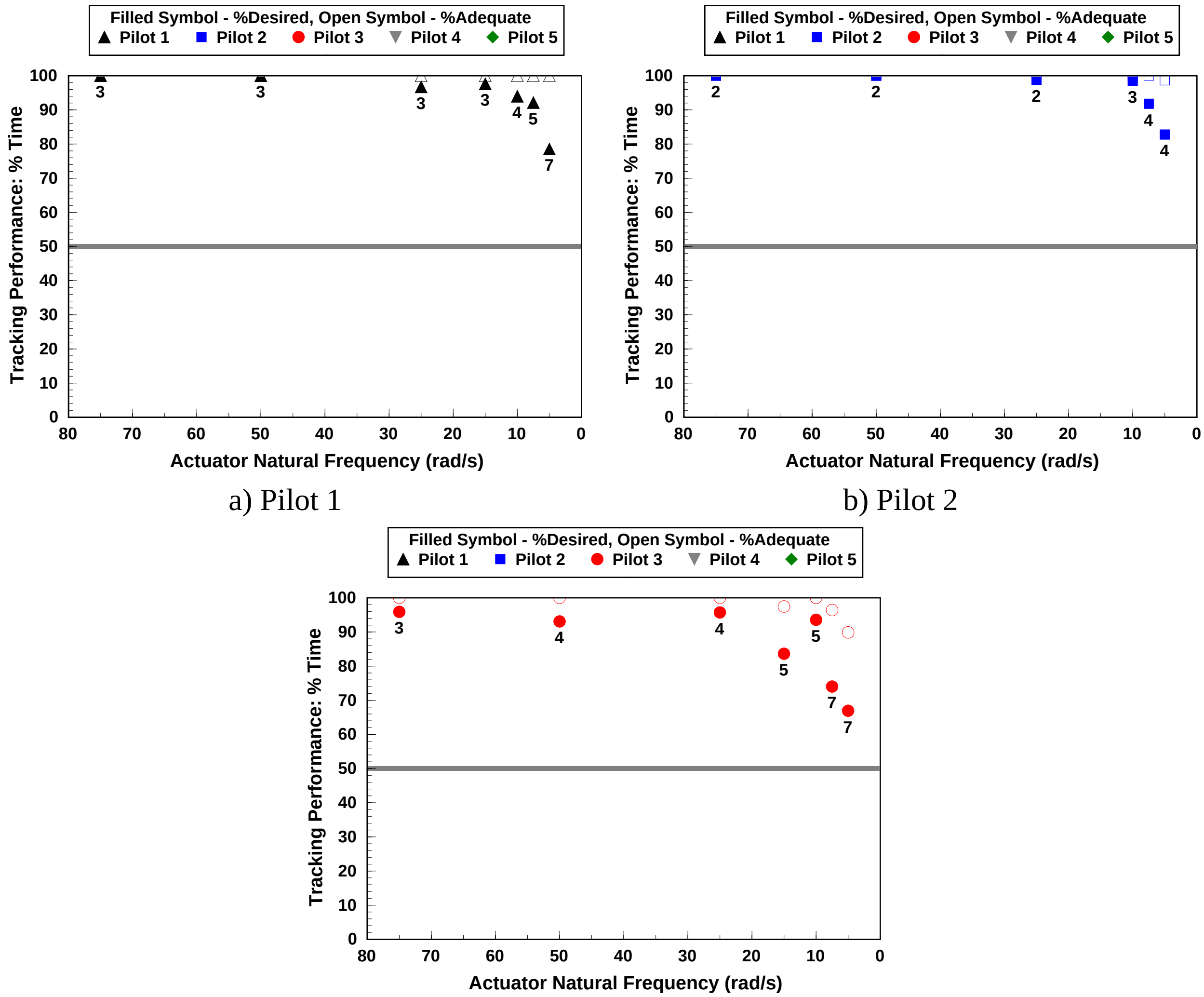


a) Pilot 1

b) Pilot 2

c) Pilot 3

Figure 184. Tracking task performance, pitch actuator natural frequency variations, PA/5% static margin

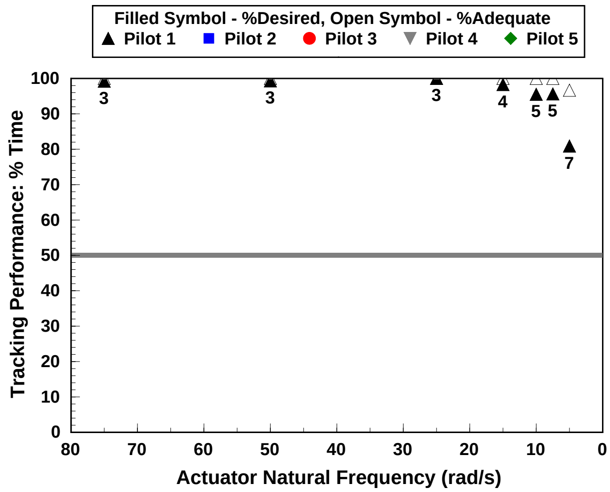


a) Pilot 1

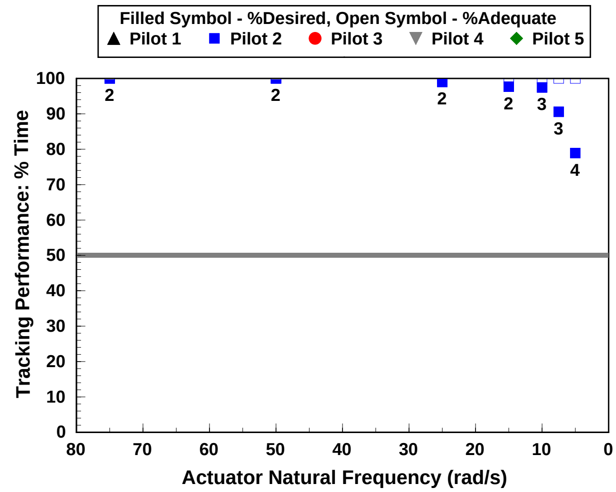
b) Pilot 2

c) Pilot 3

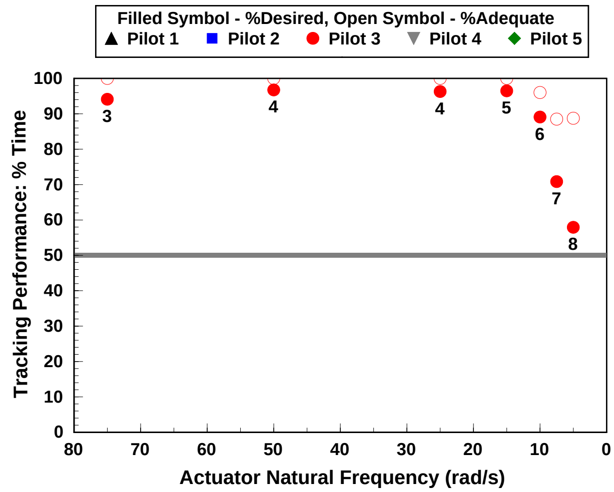
Figure 185. Tracking task performance, pitch actuator natural frequency variations, PA/2.5% static margin



a) Pilot 1



b) Pilot 2



c) Pilot 3

Figure 186. Tracking task performance, pitch actuator natural frequency variations, PA/0% static margin

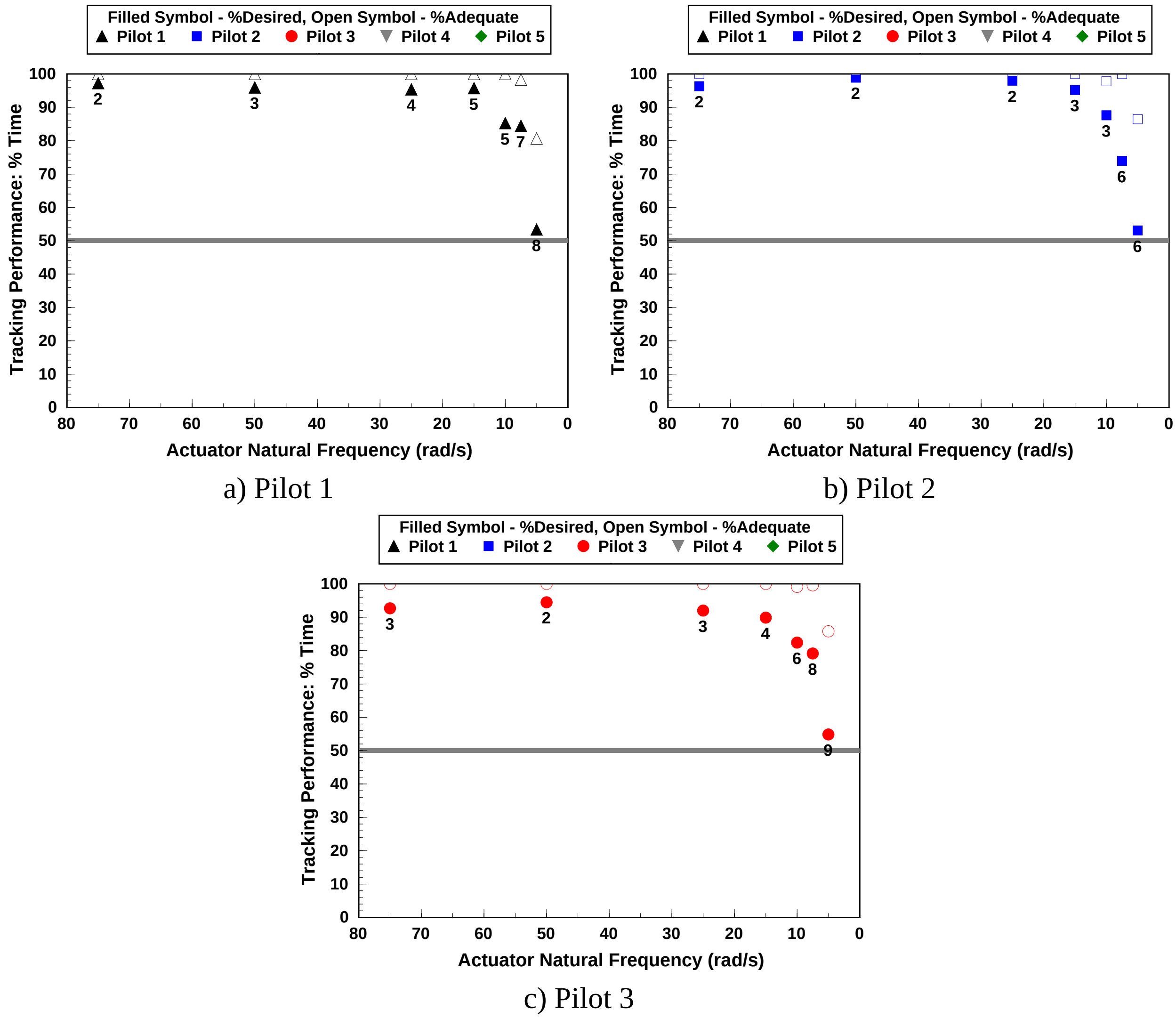
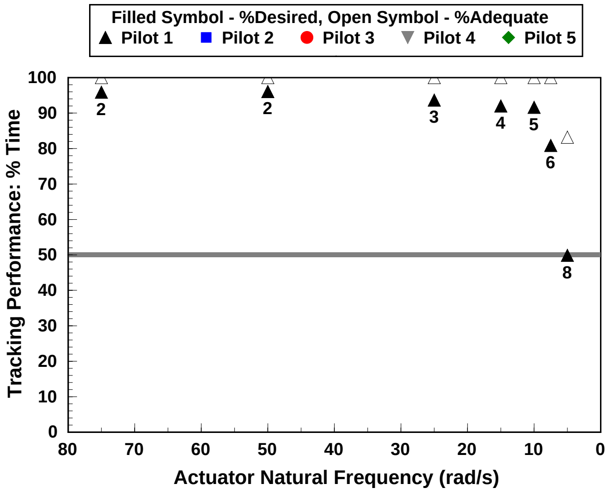
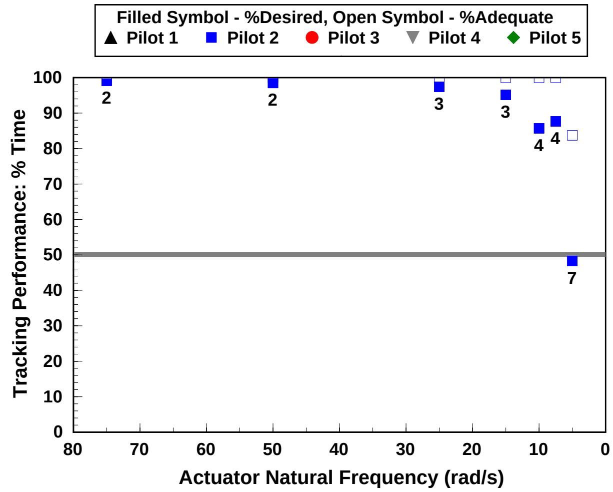


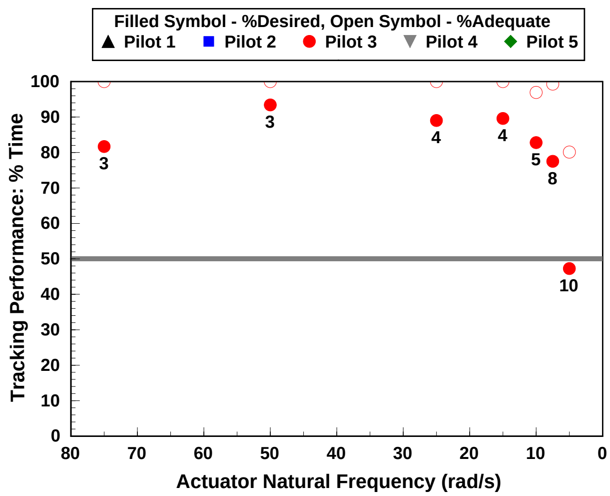
Figure 187. Tracking task performance, pitch actuator natural frequency variations, V_A/5% static margin



a) Pilot 1

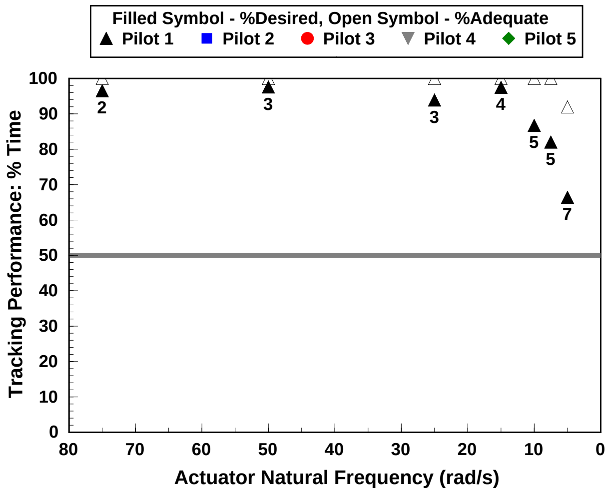


b) Pilot 2

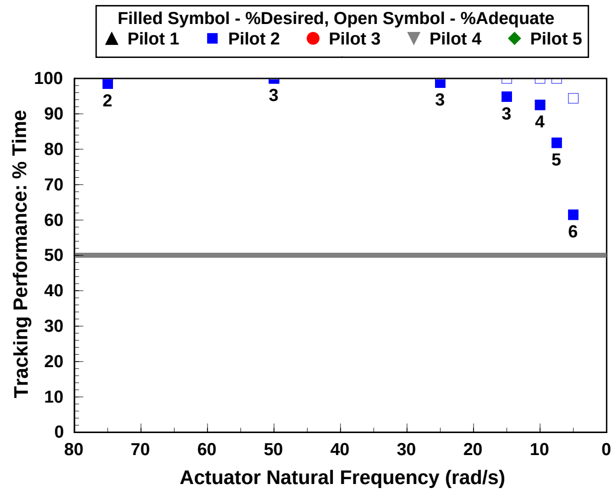


c) Pilot 3

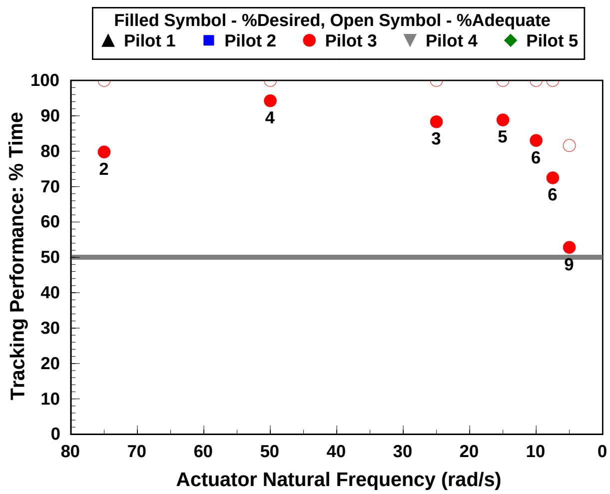
Figure 188. Tracking task performance, pitch actuator natural frequency variations, V_A/2.5% static margin



a) Pilot 1



b) Pilot 2



c) Pilot 3

Figure 189. Tracking task performance, pitch actuator natural frequency variations, V_A/0% static margin

10.9.5 Detailed Analysis of Selected Cases

10.9.5.1 Introductory Notes

Reviewing variations among pilots or multiple runs by the same pilot can provide insight into the effects of actuator natural frequency variations on pilot behavior and the level of compensation necessary to perform the task. Correlations between degraded ratings for lower frequency actuator dynamics and increased pilot compensation or changes in pilot behavior further emphasize the impact of the feel system natural frequency on the ability to perform the task.

The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which may be inadequate to accurately predict the impact of feel system parameter changes in real aircraft due to a lack of motion cueing.

10.9.5.2 Pilot 1 – Sessions 15 and 67 Evaluations

Pilot 1 participated in pitch actuator frequency evaluations on June 20, 2012. The data were collected during sessions 15 and 67 of the Year 2 Follow-on evaluations. A total of nine runs were completed for both the PA and maneuver speed configurations, with a SM of 5% for these sessions. One run in the baseline configuration and eight additional runs were completed for the V_A flight condition, while three baseline runs and six additional runs were completed for the PA flight condition. Runs varied from baseline (75 rad/s) to the most sluggish configuration of 5 rad/s. Note that the 5 rad/s case was not run for the PA flight condition.

A full listing of the configurations flown and ratings given by pilot 1 are given in tables 70 and 71.

Table 70. Pilot ratings and comments, pilot 1/session 15 (PA flight condition)

Session	Run	Configuration	HQR	PIOR	Comments
15	1	BWLON75 (baseline)	3	2	Sluggish pitch response. Tendency to over-control and need compensation.
15	2	BWLON50	3	2	Don't feel any difference. A little more lag to the response compared to baseline. Not significantly.
15	3	BWLON25	4	2	More lag than previous one. Still good performance.
15	4	BWLON15	3	2	All very small differences. Not as bad as the previous one. Similar to the baseline.
15	5	BWLON75 (blind)	3	2	Very similar to the baseline, if not baseline.
15	6	BWLON75 (baseline)	3	2	Same, all very close.
15	7	BWLON15	4	2	This is different. It is easier to overcontrol. Errors bigger, but still desired. Compensation is the issue, not PIO.
15	8	BWLON10	4	2	Similar to last one. Error bigger than baseline. Less compensation than before.
15	9	BWLON7.5	5	3	This has the most lag. Worst one I have seen. Errors bigger.

Table 71. Pilot ratings and comments, pilot 1/session 67 (V_A flight condition)

Session	Run	Configuration	HQR	PIOR	Comments
67	1	BWLON75 (baseline)	2	1	Easy. No control issues. Able to eliminate the error.
67	2	BWLON25	4	2	Not quite as easy as the previous one. Tendency to overcontrol. Errors still in desired.
67	3	BWLON50	3	1	Initially I thought it was worse. Then, not much different from baseline. Not the same tendency to overcontrol as the previous.
67	4	BWLON15	5	3	Not as predictable. More PIO tendency. Errors just as good. More tendency to overcontrol. Phase lag feeling.
67	5	BWLON10	5	3	Like the previous but worse. Overcontrol tendency but not enough to be a 6.
67	6	BWLON7.5	7	4	Same overcontrol problem as the previous. Entering PIO in tight control. +/- 2 deg PIO.
67	7	BWLON10	7	4	Overcontrol and PIO issue. Slightly better than previous. Not as much phase lag.
67	8	BWLON05	8	5	The worst so far. I enter PIO without tight control. Negative damped oscillations. Dynamically unstable aircraft.
67	9	BWLON15	2	1	Need to back out. Almost the baseline.

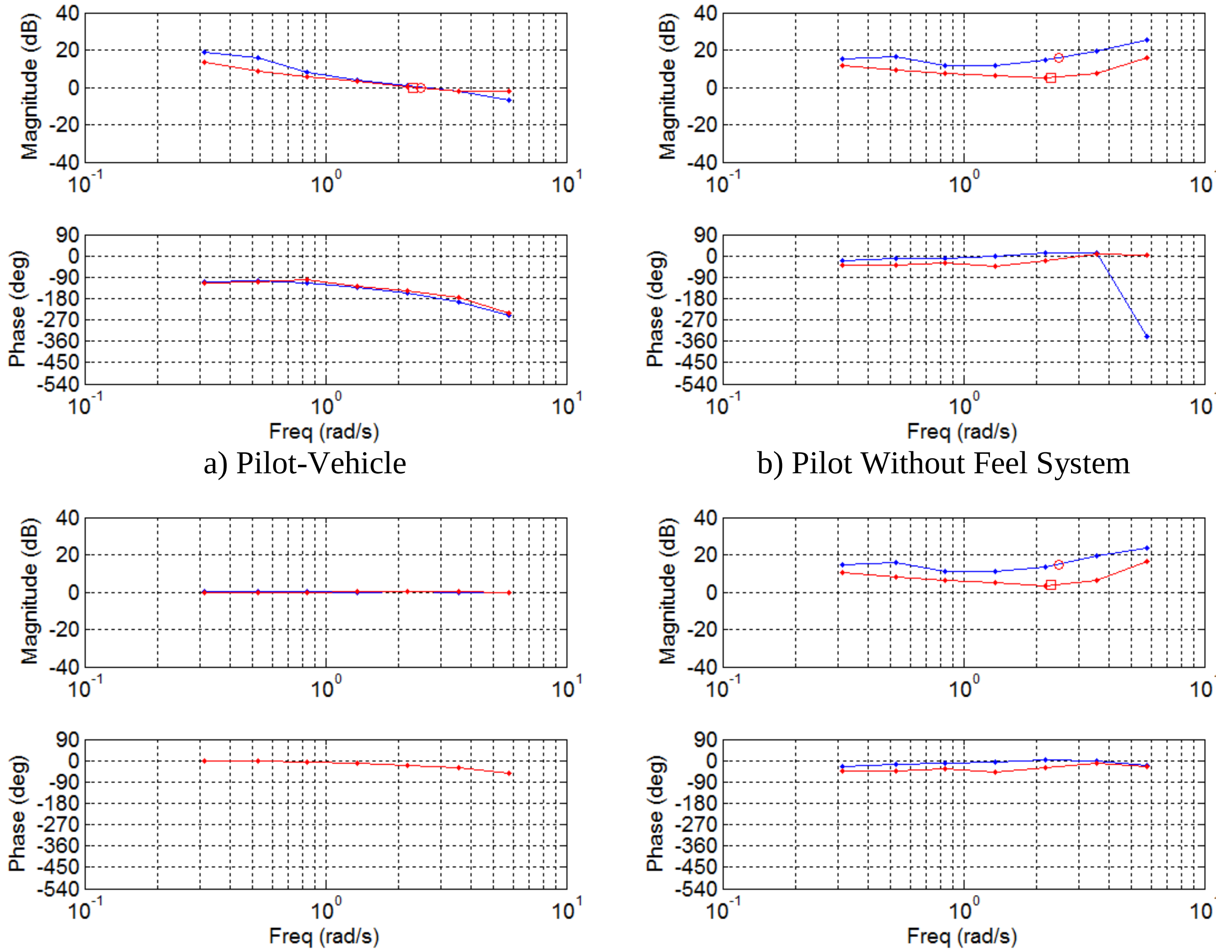
The following analysis will focus on run 7, from session 67, and run 8, from session 15, to highlight the differences regarding how pilot 1 flew the 10 rad/s control surface actuator natural frequency case.

10.9.5.3 The PVS Analysis

Figure 190 gives describing functions for the 10 rad/s runs for both PA and V_A flight conditions. First note that the elevator describing functions in figure 190 (c) are the same for both runs, confirming the consistency of the configurations.

For the PA run (S15/R8) shown in blue, a k/s-like PVS response (figure 190 (a)) is seen with a crossover of 2.5 rad/s. This is considered aggressive, with the pilot providing substantially more gain across the frequency range and additional lead compensation at frequencies above 1 rad/s (figure 190 (b) and (c)). The pilot was able to achieve the desired k/s-like behavior at crossover and rated the configuration slightly level 2 with an HQR 4/PIOR 2.

For the V_A run (S67/R7) shown in red, a distinct difference in the pilot compensation is observed (figures 190 (b) and (c)). In this example, the pilot is unable to add lead except at higher frequencies because of an “over-control and PIO issue” that required the pilot to back out of the loop to restore phase margin. The differing aircraft dynamics for this flight condition prevent the same control strategy and the resulting PVS (figure 190 (a)) shows differences in low-frequency gain that translate directly to tracking performance. As a result, the V_A flight condition run was rated an HQR 7/PIOR 4.



a) Pilot-Vehicle

b) Pilot Without Feel System

c) Elevator

d) Pilot w/Feel System and Nonlinearities

Figure 190. Identified describing functions, overlay (session 15/run 8 – blue, session 67/run 7 – red)

<u>10.9.6 Piloted Evaluations Observations and Conclusions</u>

- Based on the results of the limited, fixed-base simulation study, pitch actuator natural frequencies greater than 15 rad/s are recommended, as HQ and task performance may be compromised for configurations with lower natural frequencies.

- PIO tendency becomes a significant issue for actuator frequencies lower than 25 rad/s because of the additional phase lag incurred.

- SM did not have a significant impact on ratings or task performance, as actuator natural frequency was varied.

- Task performance was consistent for natural frequencies above 10 rad/s, although slight degradations were seen for actuator natural frequencies below 15 rad/s. Pilots 2 and 3 saw the worst degradation in task performance for actuator natural frequencies below 10 rad/s.

- The change in aircraft dynamics between the PA and V_A flight conditions caused one pilot to drastically alter his control strategy, negatively impacting HQ and task performance.

11. RESULTS OF ROLL AXIS TESTING

11.1 BASELINE AIRCRAFT

11.1.1 Introduction

This working paper presents an overview of the fixed-base simulation evaluations of the lateral/directional baseline configuration. Five pilots participated in the evaluations [14]. The evaluations were SoS and ACH tasks in PA, V_C, and V_A configurations. The bare airframe SM was SM = 5% ($\bar{c}$) in all evaluations. HQ and PIO tendency ratings were recorded after each evaluation run.

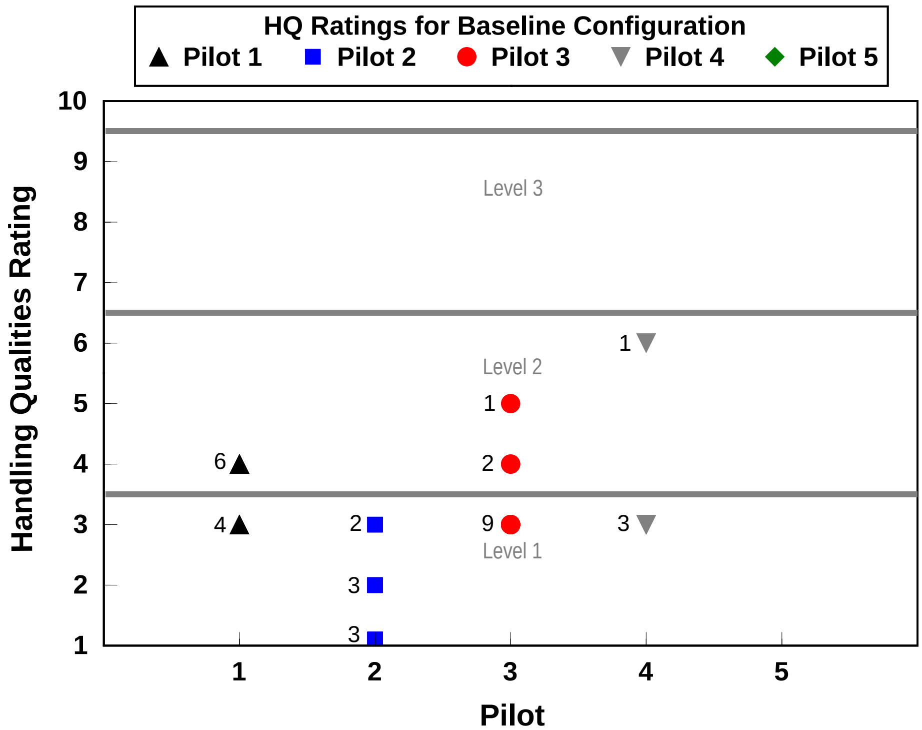
11.1.2 Analysis Summary

Figures 191 and 192 show a summary of the HQ and PIO tendency ratings for the five pilots who participated in the evaluations. Repeated configurations are shown as open symbols unless otherwise noted. In figures 191 and 192, the text annotations denote the number of times the baseline run was given that rating.

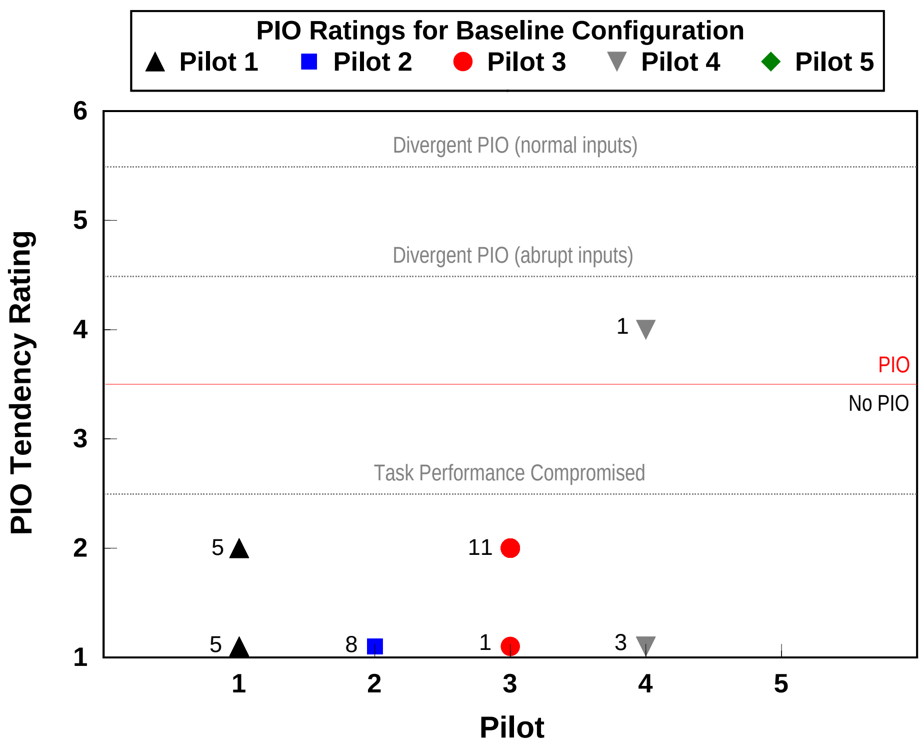
Each pilot flew the baseline configuration to begin each session and often repeated the baseline configuration, both known and blind, during each session for ratings through the duration of the experiment. Pilot 1 evaluated the baseline 10 times; pilot 2, eight times; pilot 3, twelve times; and pilot 4, four times.

Figures 191 and 192 show that pilots generally rated the baseline level 1, with pilots 1 and 3 giving borderline level 1/2 ratings. The aircraft model used in the evaluation was designed to be HQR 3 at all flight conditions and the ratings shown in figures 191 and 192 are consistent with the design objectives.

PIO tendency is not an issue for the baseline configuration, with only one PIO rating worse than PIOR 2 given for all of the evaluation runs. The results in figure 192 show that each pilot rated the configuration favorably, with only a few outlier ratings for each pilot, which are likely because of blind runs following poor configurations. This led to pilots altering control schemes and perceiving the baseline differently than when originally evaluated. Overall, the baseline configuration in the pitch axis is level 1 with minimal PIO tendency.



a) Handling Qualities



b) PIO Tendency

Figure 191. Ratings summary, roll baseline configuration

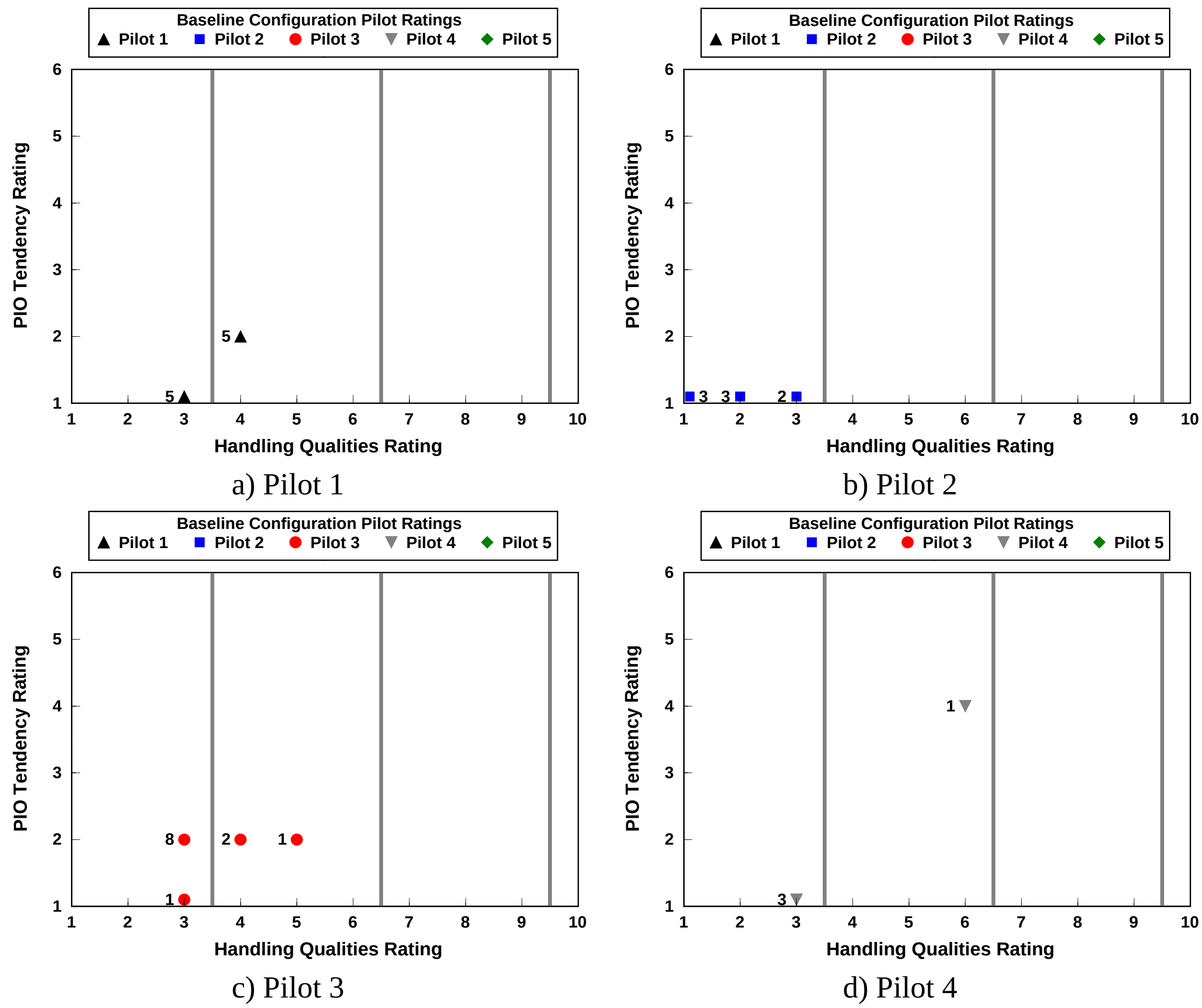


Figure 192. Pilot ratings, roll baseline configuration

<u>11.1.3 Piloted Evaluations, Observations, and Conclusions</u>

- The baseline configuration in the roll axis was flown a total of 96 times by five pilots. Pilots 1, 2, and 3 participated in the majority of the evaluations while Pilots 4 and 5 only participated in a limited amount.
- HQR are mostly Level 1, with Pilot 1 and 3 rating the configuration borderline Level 1/2.
- PIO tendency is not an issue with only one of the lateral baseline runs rated a PIOR 4.
- Outlier ratings are most likely due to blind evaluations following a poorly performing configuration.

11.2 COMMAND PATH DEAD ZONE

11.2.1 Introduction

This section details the roll axis offline and piloted evaluations analysis. Included in this analysis are an assessment of the closed-loop vehicle dynamics, a study of the effects of command path dead zones, and the effect that these dead zones have on vehicle response and task performance.

The flight condition selected for analysis is the maneuvering speed of KCAS = 234 at Hp = 38,000 ft pressure altitude. The aircraft is in cruise configuration with 0° flap deflection and bare airframe SM = 5% ($\bar{c}$) SM.

The disturbance signal used for the regulation task was described in section 4.4, with a gain of 5 applied to the amplitude to make it appropriate for the roll axis. The disturbance signal is shown in figure 193.

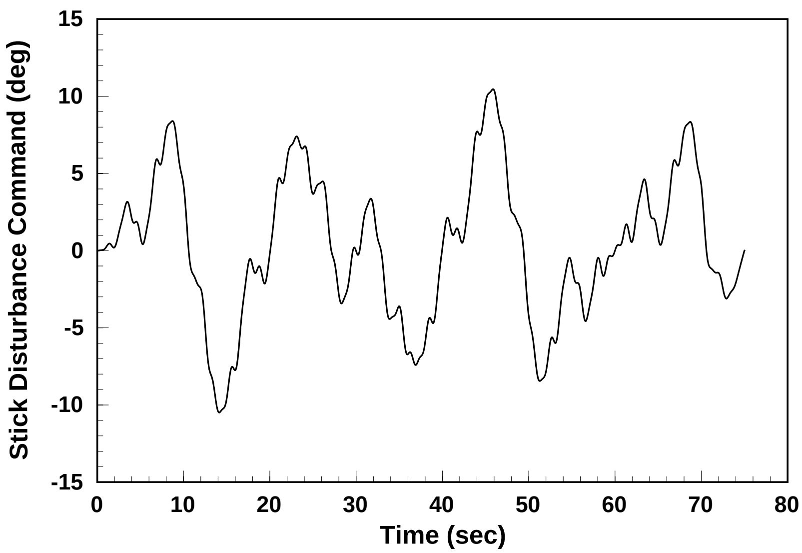


Figure 193. Fibonacci series-based lower frequency SoS input forcing function time history

The objective of the disturbance regulation task is to maintain trim bank angle in the presence of a SoS disturbance (i.e., to negate any deviation from trim). Desired bounds were set as ±3° of error from trim and adequate bounds were set as ±6° (figure 194).

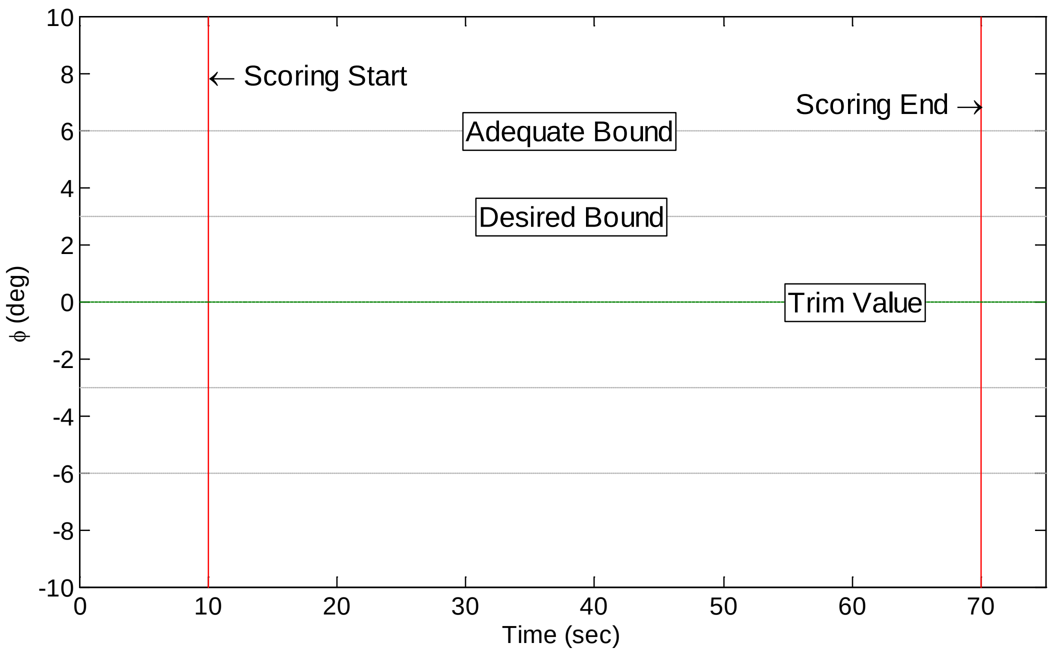


Figure 194. Task performance time history plot annotations

The second part of this section presents an analysis of the fixed-base simulation evaluations investigating the effects of roll feel system dead zones on lateral-axis HQ. Four pilots participated in the roll dead zone evaluations [14]. The evaluations were made using an SoS tracking task in PA configuration with an SM = 5% ($\bar{c}$). The HQR and PIO tendency ratings were recorded after each evaluation run and task performance data were recorded for offline analysis. Dead zones were varied from not present (baseline) to ±2.5°, which represents 25% of total stick travel.

11.2.2 Offline Analysis

11.2.2.1 Closed-Loop Aircraft

The objective of this analysis is to determine the effects of command-path dead zone on task performance and pilot behavior. The baseline pilot model is used, which is determined by using frequency sweep identifications of the baseline aircraft at maneuvering speed. The command-path dead zone was then varied from 0–2° to determine the effects on the system frequency response and task performance. This analysis mirrors the one performed in section 10.2.2 for the longitudinal axis.

The controlled element Y_c refers to the closed-loop augmented aircraft that includes the CLAWS, feel system, and vehicle dynamics. The command-path dead zone is also considered part of the controlled element for this analysis.

Because the analysis is based on identified responses from frequency sweep inputs, the roll rate response of the aircraft is used. The rate output signal contains much more power in the frequency domain than the attitude signal, so it is easier to identify. Although the airplane bandwidth criteria are defined for stick-to-attitude frequency responses, equivalent HQ metrics can be derived by using phase points that are offset by the 90° typical of a rate-to-attitude integration. Frequency responses provided in this report show the equivalent rate response phase points used to determine HQ parameters.

The roll rate frequency response for the maneuvering speed flight condition with no dead zone present is shown in figure 195, in which the identified nonlinear system is overlaid with identified airplane bandwidth frequencies and related parameters shown as colored dots.

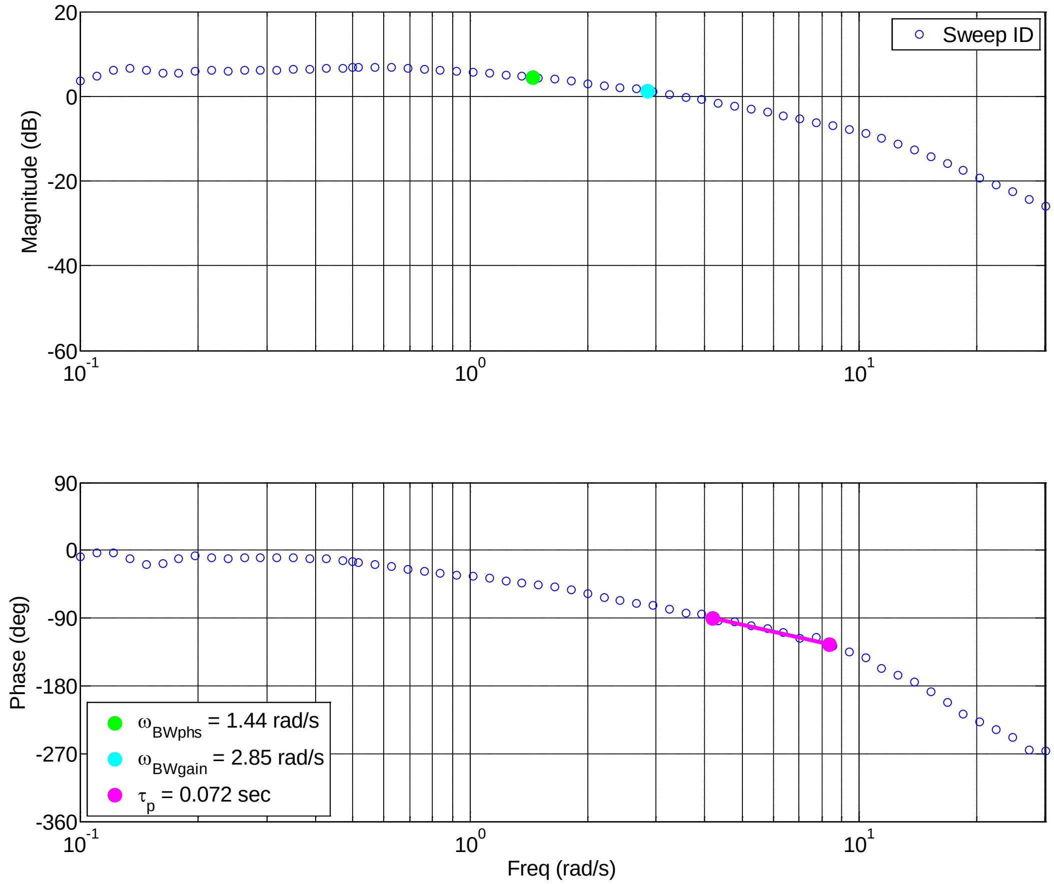
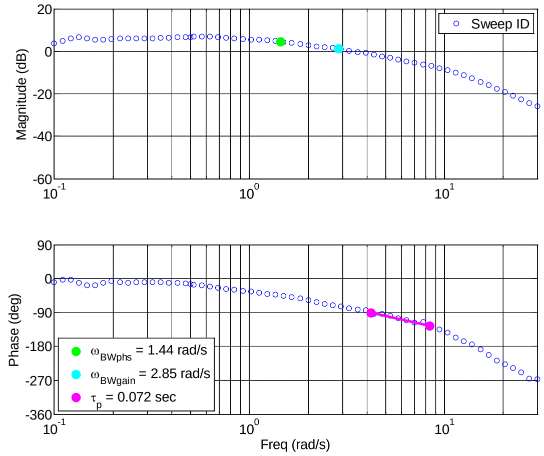


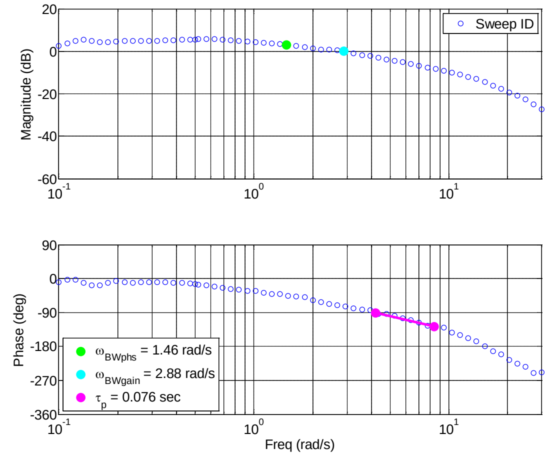
Figure 195. Baseline closed-loop aircraft identified frequency response and handling qualities parameters

A well-damped vehicle response with an airplane bandwidth of 1.44 rad/s indicates a responsive vehicle in roll. Note that the ω_{-180} frequency is shown as -90° for the equivalent rate response in figure 195.

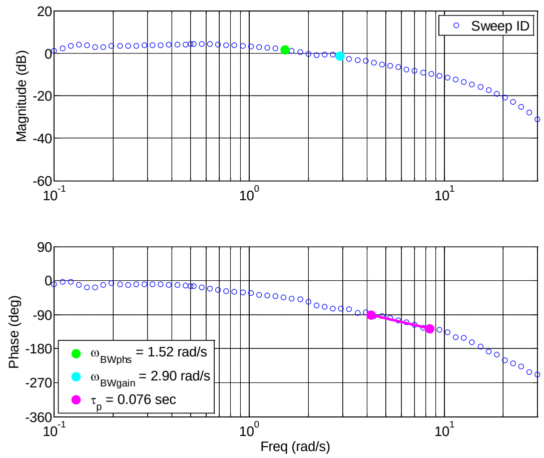
As dead zone is increased, there is a corresponding gain loss that was also seen in the longitudinal axis. There is also a slight flattening of the phase response in the region of -45°, which causes the phase bandwidth to increase with increasing dead zone (figure 196). This would indicate a tendency of command-path dead zone to improve vehicle responsiveness, though care should be taken to draw definitive conclusions because identification of a nonlinear system using linear identification methods can lead to unpredictable results.



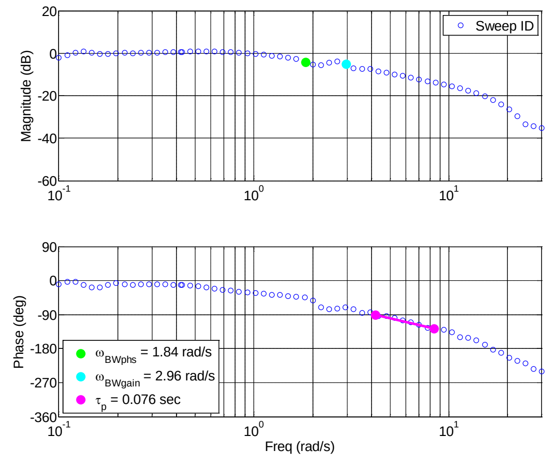
a) DZ = 0°



b) DZ = 0.5°



c) DZ = 1.0°



d) DZ = 2.0°

Figure 196. Aircraft plus feel system identified frequency responses and handling qualities parameters

An assessment of the HQ and PIO tendency for the closed-loop aircraft is shown in figure 197 and summarized in table 72. (For the lateral axis in cruise, there are no defined bandwidth requirements for transport aircraft because of a lack of research test data in this flight regime.) Using the terminal flight condition boundaries, level 1 HQ are predicted, with no significant PIO risk shown for the current configuration. Phase delay is well below the level 2 PIO boundary, with no significant increase as dead zone increases.

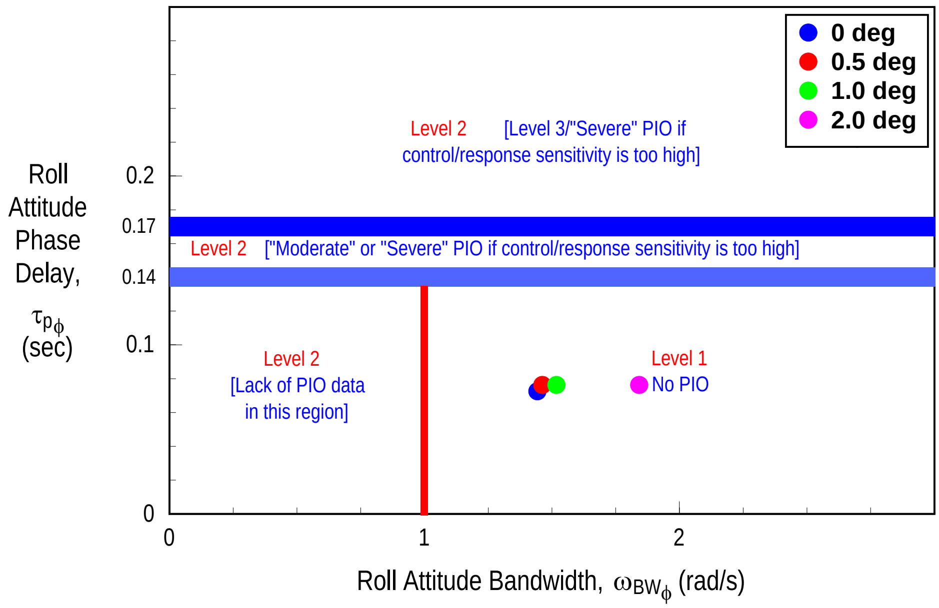


Figure 197. Roll attitude bandwidth/PIO summary, cruise configuration/maneuver speed [13]

Table 72. Summary of closed-loop aircraft handling qualities

Dead Zone (deg)	Bandwidth (rad/s)	Phase Delay (msec)
0	1.4429	72.492
0.5	1.4625	76.331
1.0	1.5180	76.331
2.0	1.8424	76.331

11.2.2.2 The PVS

The pilot model is introduced as a regulator acting on bank-angle error. Bank-angle error is calculated as the disturbance from trim bank angle, which, for the maneuver speed flight condition used for this analysis, was 0° (i.e., wings level).

11.2.2.3 Describing Function Analysis

A unit gain pilot was used because it provided adequate PVS crossover for the specified task for all dead zone cases. A summary of the achieved PVS crossover with a pure gain pilot employing unit gain and a 250 msec delay is given in table 73.

Table 73. Summary of identified PVS crossover frequencies

Dead Zone (deg)	Crossover (rad/s)
0	1.66
0.5	1.61
1.0	1.57
2.0	1.47

The pilot vehicle describing functions shown in figure 198 give systems that are largely similar, despite a fairly large dead zone, which represents 10% of total stick travel (figure 198 (d)). Though a gain loss is present, causing crossover frequency to decrease slightly, there is a slight lead effect in the region of crossover that improves phase margin. This can also be seen in the pilot describing functions in figure 199.

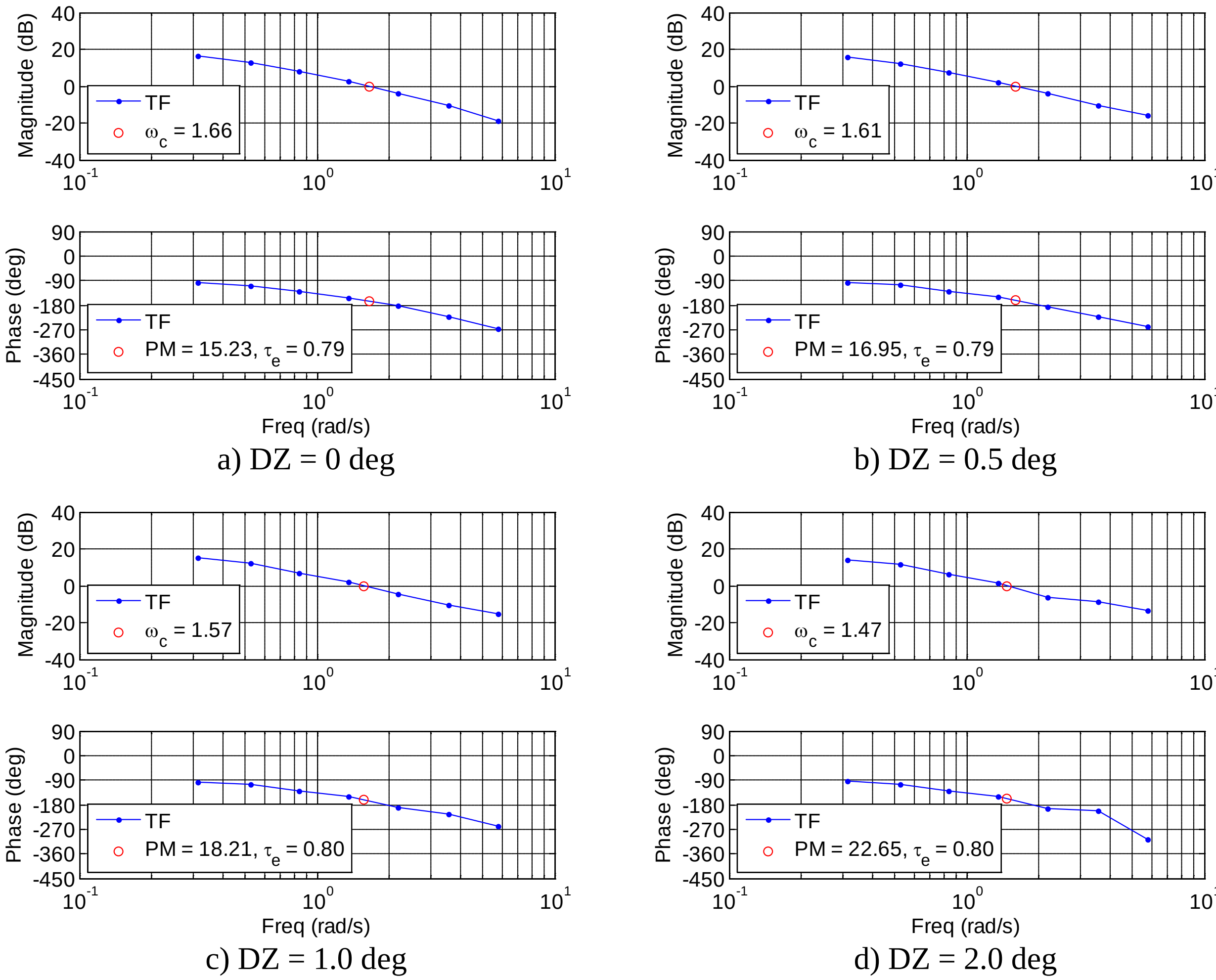
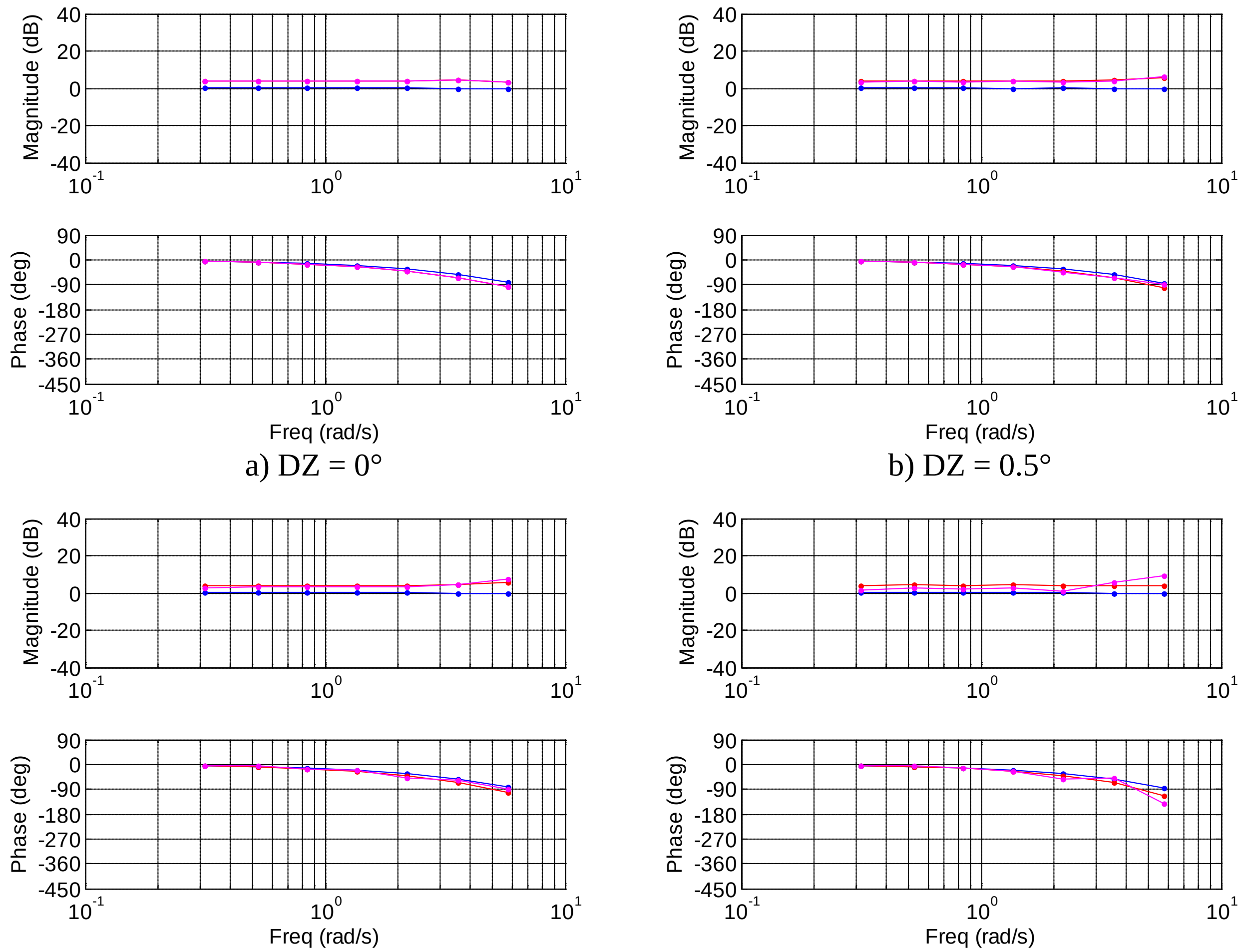


Figure 198. Pilot-vehicle describing functions with crossover frequency and phase margin/effective delay

Examining the pilot describing functions with both the feel system and command-path dead zones included, there is a distinct contrast for the roll axis that was not present for pitch. In the pitch axis, there was a slight loss of gain across the feel system due to the BO force. Though the same BO force of 0.25 lb. is employed in the roll axis, there is a gain increase across the feel system even with no dead zone present (figure 199 (a)). The inclusion of increasing dead zones applies the same gain loss seen in pitch, though the effects are much less pronounced for the roll cases, as evidenced by the similar PVS crossovers shown in table 72. The dead zone gain and phase-loss effects are not as significant for the roll cases, so they have a lesser impact on feel-system gain and PVS crossover. This indicates that effects on pilot workload and task performance are less significant as well.



a) DZ = 0°

b) DZ = 0.5°

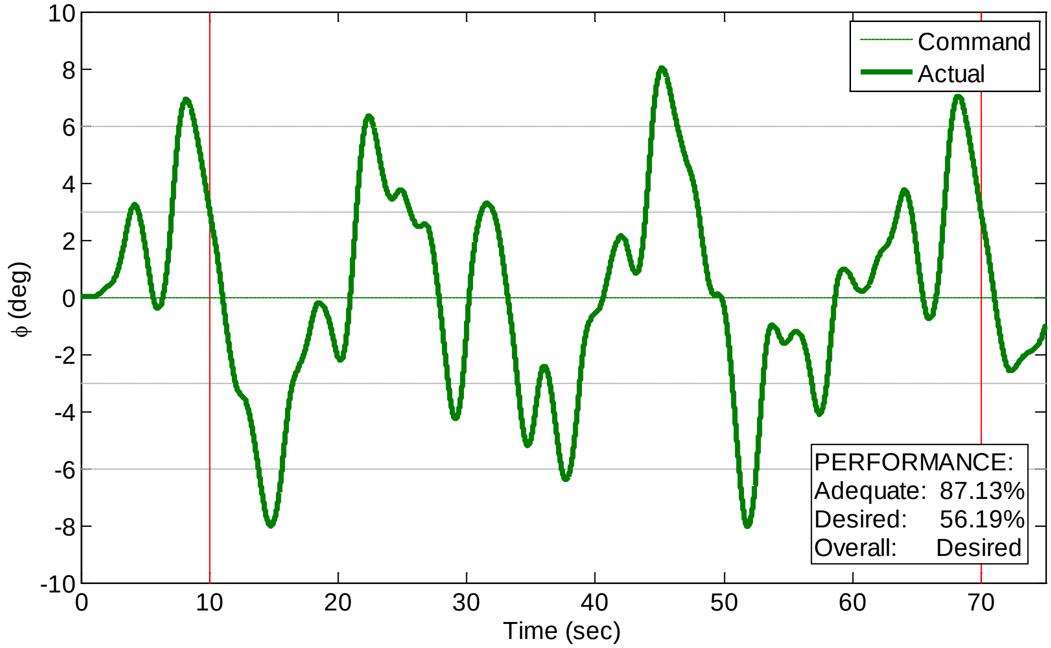
c) DZ = 1.0°

d) DZ = 2.0°

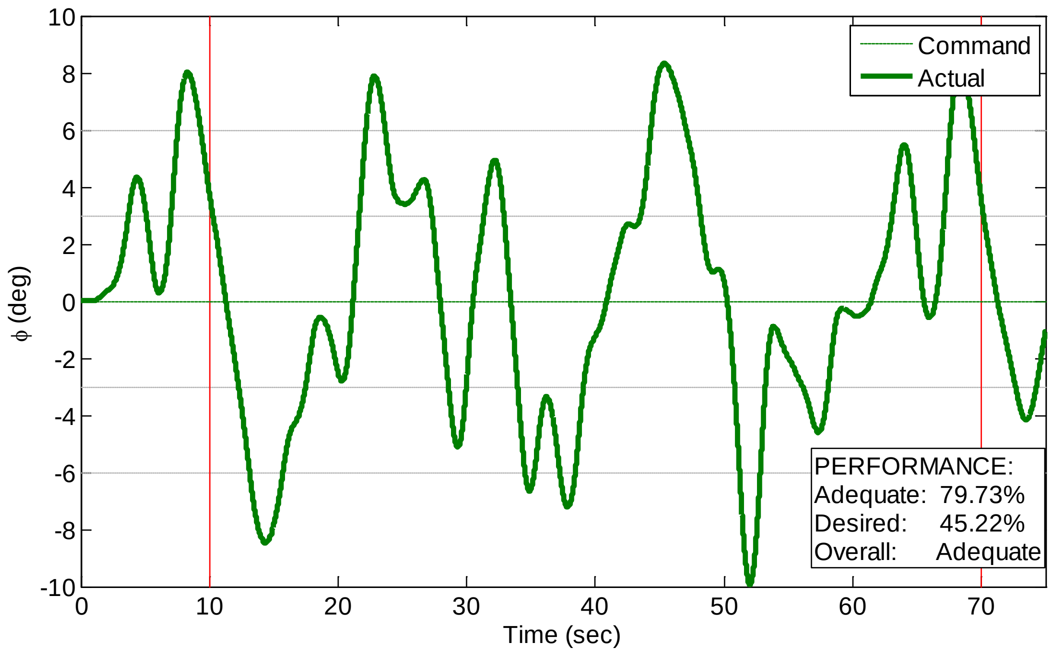
Figure 199. Pilot describing functions — pilot model (blue) with feel system (red) and dead zone (magenta) effects

11.2.2.4 Task Performance

The results of the describing function analysis indicate that task performance is very similar for all of the dead zone cases, with slight differences caused by the gain loss and/or lead induced by the dead zone (figure 200). Examination of the regulation task time histories, however, shows that as the dead zone increases, there is a significant impact on the high-frequency vehicle response, allowing the vehicle to depart from the trim condition. This increased error from trim causes performance to degrade from desired for the 2° dead zone case. The 0°, 0.5°, and 1.0° dead zone cases all achieve desired performance but degrade with increasing dead zone (table 74).



a) DZ = 0.5°



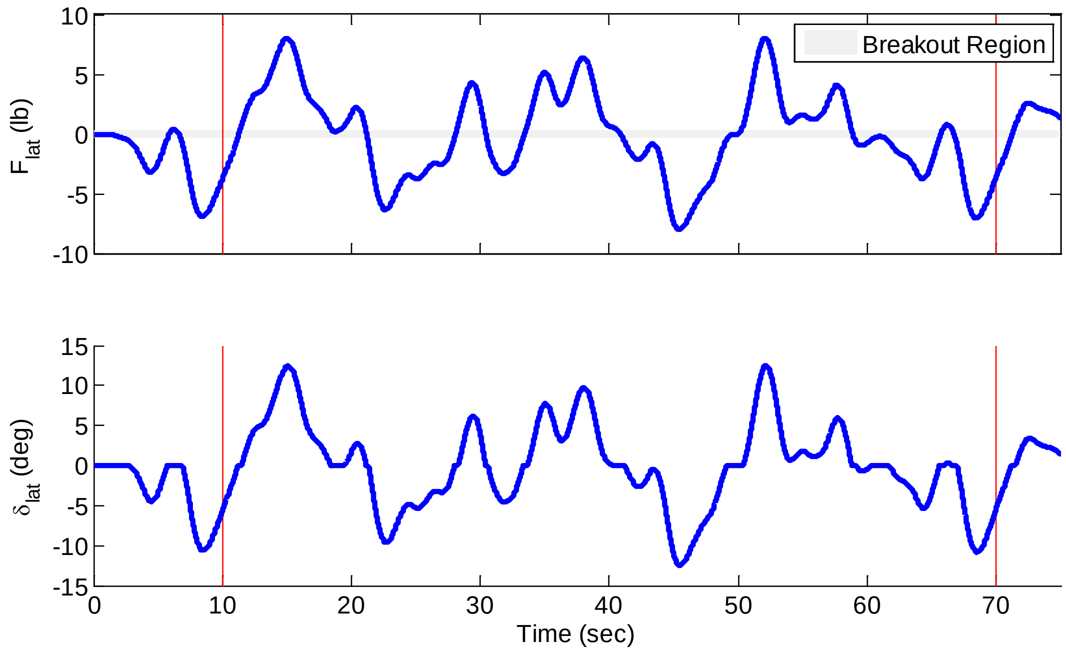
b) DZ = 2.0°

Figure 200. Task performance time histories

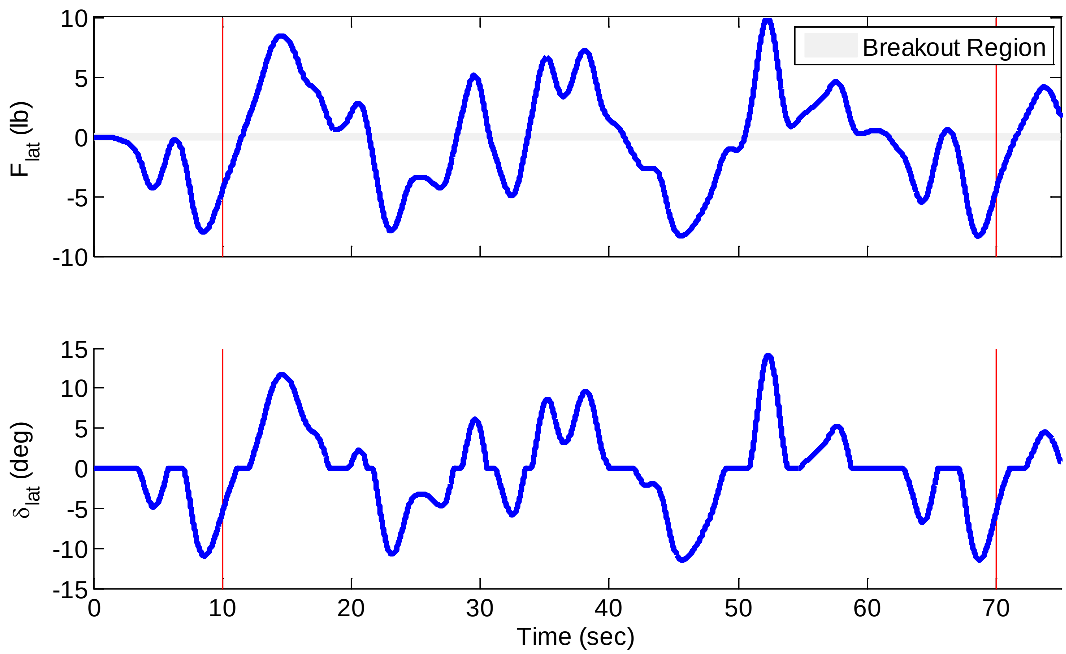
Table 74. Comparison of piloted task performance

Dead Zone (deg)	% Adequate	% Desired
0	90.58	59.91
0.5	87.13	56.19
1.0	84.68	51.33
2.0	79.73	45.22

The corresponding stick activity in figure 201 shows the effects of the dead zone on task performance. For the 2° case, the paper pilot is controlling with much more stick input (force) in response to tracking error, but the dead zone does not allow any deflection input to the aircraft. Though the general control traces appear to be similar, the necessity to use large inputs to overcome the larger error, which accumulated while the stick was in a dead zone region, does not allow for the use of higher frequency inputs that keep the aircraft within desired and adequate performance bounds.



a) DZ = 0.5°



b) DZ = 2.0°

Figure 201. Stick activity time histories

11.2.3 Offline Analysis, Observations, and Conclusions

- There is a net gain increase across the feel system that was not seen for the pitch axis. This is due to the different gradient that results in larger deflections for equal stick force in the roll axis.

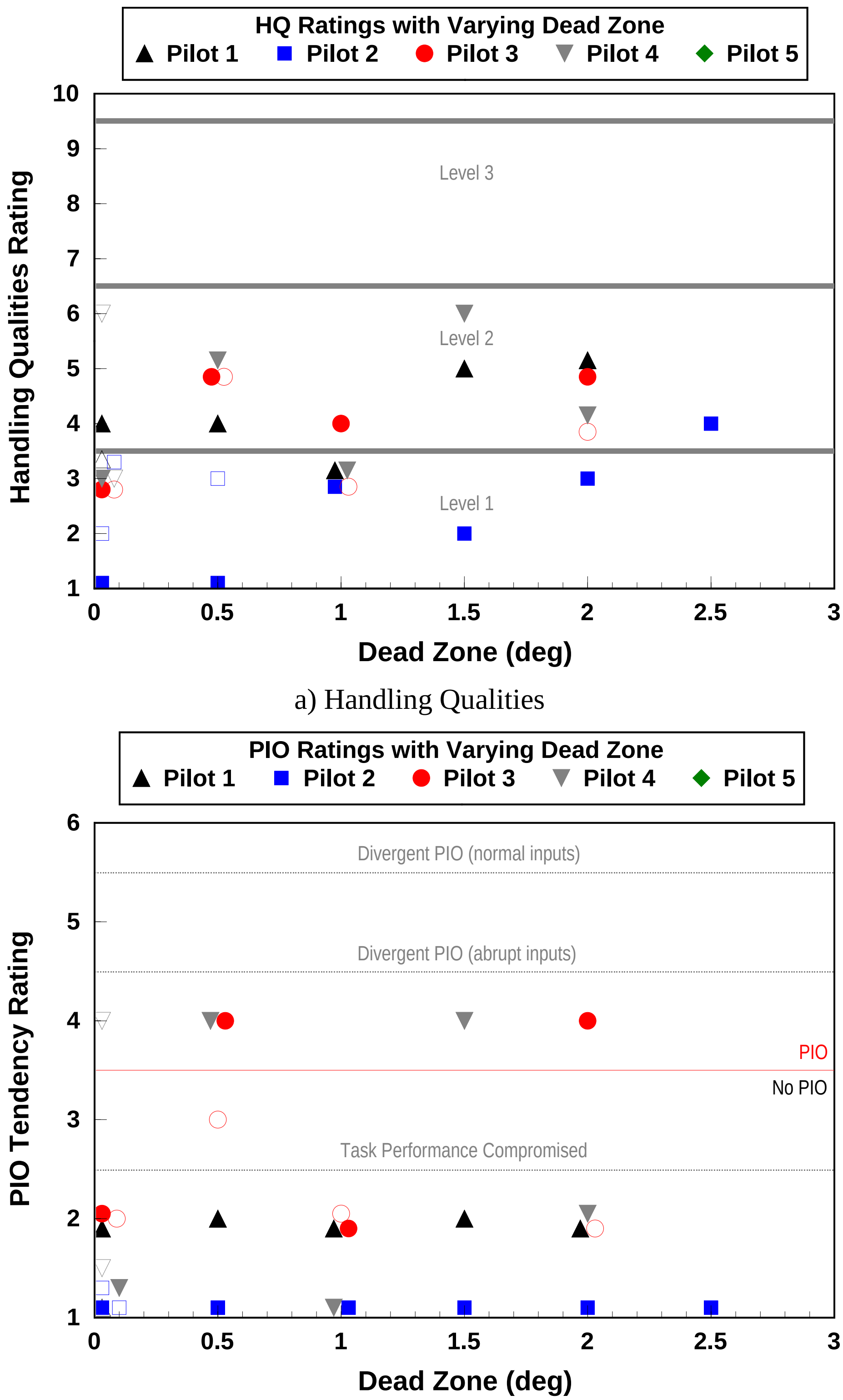
- The inclusion of a command path dead zone results in a gain loss across the feel system and slight phase-lead effect. The result of this gain loss is decreased crossover while the phase lead contributes a small amount of phase margin to the PVS.

- Dead zones in the roll axis command path cause performance to degrade and, with bounds of ±3 and ±6 degrees for desired and adequate performance, cause piloted task performance to drop out of desired for dead zones above 1° for the cases simulated herein with a simple pilot model.

11.2.4 Piloted Evaluations Analysis Summary

Figure 202 gives a summary of the HQR and PIO tendency ratings for the four pilots that participated in the roll dead zone evaluations.

No distinct trend emerges from the pilot ratings shown in figure 202. For the HQR shown in figure 202 (a), no distinct trend emerges because pilots 3 and 4 do not follow any noticeable trend in their ratings. Pilots 1 and 2 show a degradation in ratings for dead zones above 1°, but the lack of a discernible trend across the four pilots indicates that the pilots were much more sensitive to dead zone in the lateral axis than was seen for the longitudinal axis evaluations. This would lead to the conclusion that dead zone in the lateral axis should be minimized if possible, but definitely limited to no more than 1°. Similarly, in figure 202 (b), pilots 1 and 2 did not note any changes in PIO tendency with increasing dead zone, while pilots 3 and 4 scored the various dead zone runs erratically.



a) Handling Qualities

b) PIO Tendency

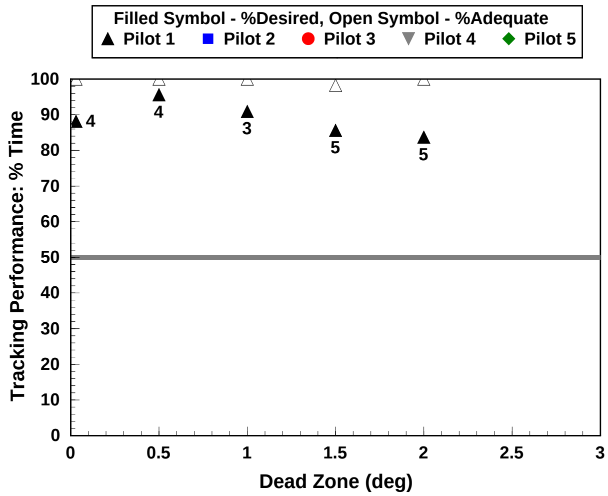
Figure 202. Pilot ratings, all pilots, roll dead zone variations

As illustrated in table 75 and figure 203, task performance is not significantly impacted by dead zone for pilots 3 and 4, although desired performance is much lower for roll dead zone cases than for the pitch cases because of the significantly larger amplitude of the roll task. This is in contrast to the ratings seen in figure 202 because performance was relatively constant for all dead zones, with slight degradation for large dead zone cases. This would indicate that the degraded ratings are a result of increased pilot workload as the pilot was forced to use more compensation to achieve the same performance.

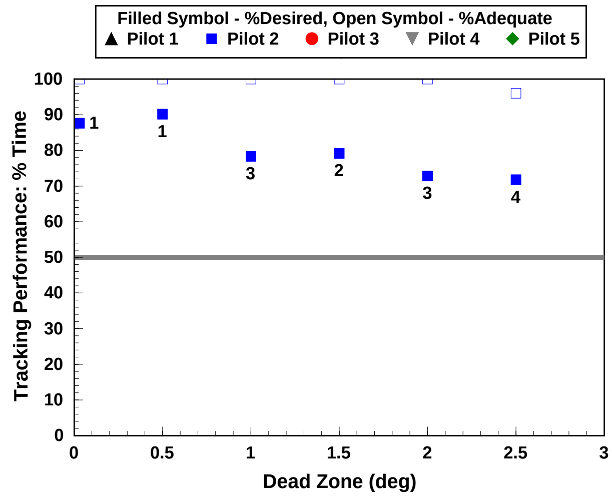
Symbol annotations in figure 202 show HQR for each run.

Table 75. Task performance summary, all pilots, roll dead zone variations

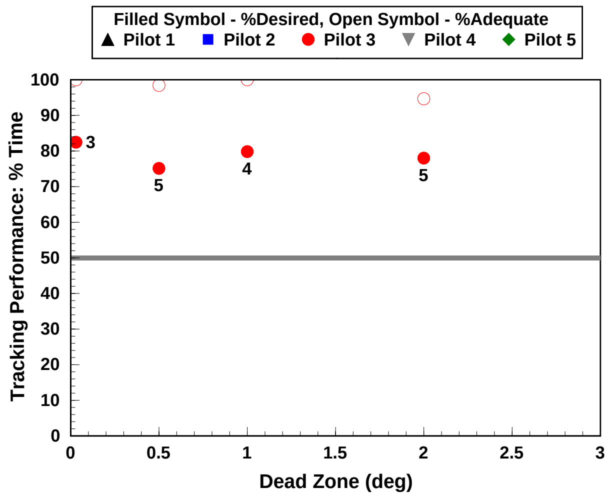
Dead Zone (deg)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
0.0	88.15	87.63	82.45	88.50
0.5	95.60	90.17	75.12	86.87
1.0	90.92	78.35	79.82	81.73
1.5	85.60	79.15	–	76.03
2.0	83.70	72.82	78.00	82.77
2.5	–	71.78	–	–



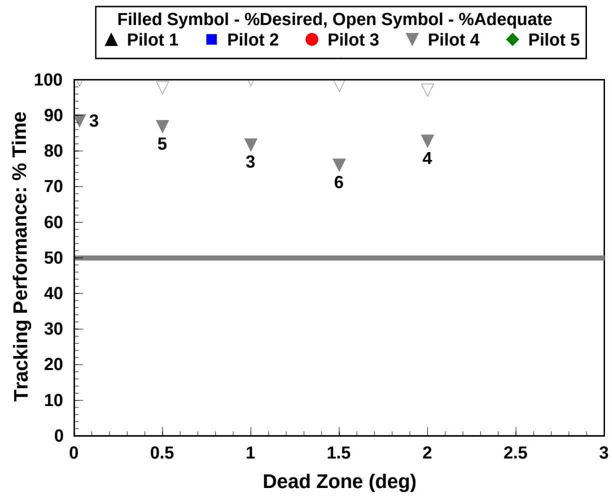
a) Pilot 1



b) Pilot 2



c) Pilot 3



d) Pilot 4

Figure 203. Tracking task performance, roll dead zone variations

11.2.5 Detailed Analysis of Selected Cases

Variations among pilots or for multiple runs by the same pilot can provide insight into the effects of dead zone on pilot behavior and the level of compensation necessary to perform the task. Correlations between degraded ratings for larger dead zones and increased pilot compensation or changes in pilot behavior further emphasize the impact of the dead zone on the ability to perform the given task.

The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which may be inadequate to accurately predict the impact of feel-system parameter changes in real aircraft due to a lack of motion cueing.

11.2.5.1 Baseline Evaluations – Pilots 1 and 4

Pilot 1 participated in roll dead zone evaluations on June 18, 2012. The data were collected during Session 4 of the Year 2 Follow-on evaluations. A total of 11 runs were completed in the roll axis, with one unrated blind run in the baseline configuration and seven scored runs, which were rated by the pilot. The baseline configuration was scored twice during the session — first a known repeat and then blind to the pilot. A full list of the configurations flown and ratings given by pilot 1 is presented in table 76 and shown in figure 231.

Table 76. Pilot ratings and comments: pilot 1, session 4

Session	Run	Configuration	HQR	PIOR	Comments
4	16	DZLAT00 (baseline)	4	2	Roll forces are heavy. Mild PIO tendency ±1 degree.
4	17	DZLAT05	4	2	A little harder to get the error correction started. Force/deflection bigger than baseline. Forces are higher. Less PIO prone. The initial force is the annoying factor.
4	19	DZLAT10	3	2	Undesirable motions are there. Do not need to back off as much to avoid PIO oscillations. Less sustained than baseline. Hit the stops one time.
4	21	DZLAT00 (baseline-blind)	3	1	Minor PIO again. Lighter forces than last couple. Did not chase as much. Very similar to baseline.
4	23	DZLAT05	4	2	I have to hold the input to eliminate the error. Not heavy initially; it looks like a delay. Bigger errors.
4	24	DZLAT20	5	2	Like the last one, but more significant. Responds well once it starts. Less than PIO problem. The issue is the delay. Hit left stop twice.
4	25	DZLAT15	5	2	Hard time seeing a difference. Heavy forces. Left stop once.

DZLAT = lateral dead zone

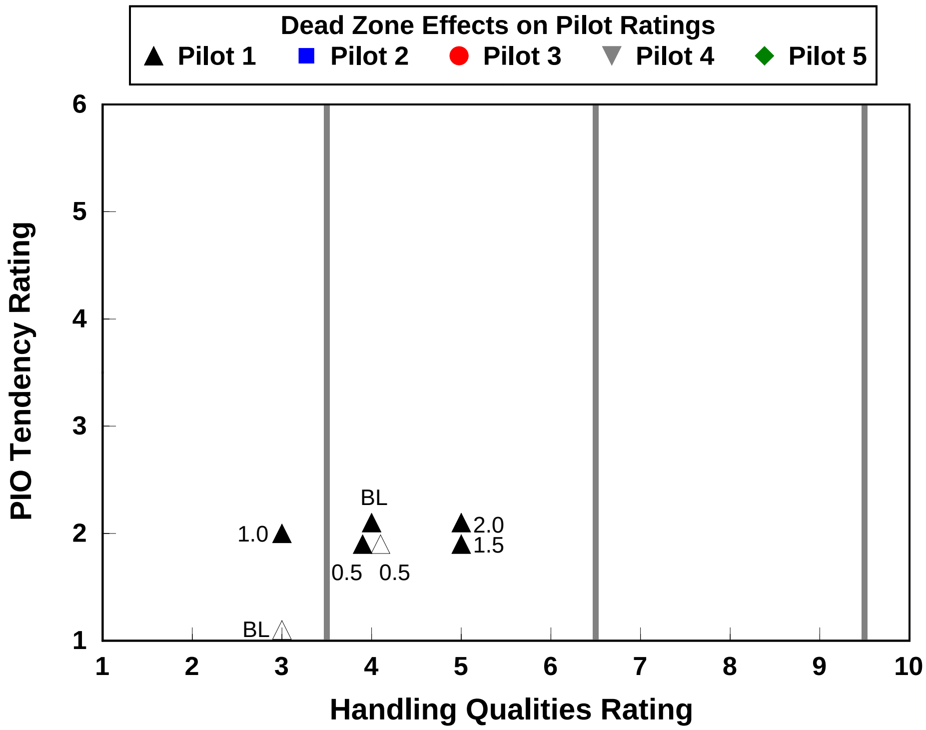


Figure 204. Ratings summary, roll dead zone variations: pilot 1, session 4

Pilot 4 participated in roll dead zone evaluations on June 20, 2012. The data were collected during Session 21 of the Year 2 Follow-on evaluations. A total of eight runs were completed in the roll axis, with one unrated blind run in the baseline configuration and seven scored runs, which were rated. The baseline configuration was scored twice during the session, once blind and once known to the pilot. A full list of the configurations flown and ratings given by pilot 4 is presented in table 77 and shown in figure 205.

Table 77. Pilot ratings and comments, pilot 4, session 21

Session	Run	Configuration	HQR	PIOR	Comments
21	1	DZLAT00 (baseline)	3	1	I find myself focusing on just one end of the bar. A little slow time constant. I have to lead.
21	2	DZLAT05	5	4	A little bit more sluggish. Overshooting. If I was normally working this hard I would not have achieved desired. Stops.
21	4	DZLAT00 (baseline-blind)	6	4	Kind of like the last one. Very easy to overshoot. This one still bad. Worse than previous one.
21	5	DZLAT10	3	1	More predictable than last one. A lot easier. Did touch the stop. I don't feel behind the airplane. More like the baseline.
21	6	DZLAT00 (baseline)	3	1	Feels similar to the last one. A little bit of motion. Touched the stops.
21	7	DZLAT15	6	4	This is not responding. Just banging it to go where I want. I don't like this. I have to back out of the loop.
21	8	DZLAT20	4	2	Not as bad as the last one but not as good as the baseline. Overshoots.

DZLAT = lateral dead zone

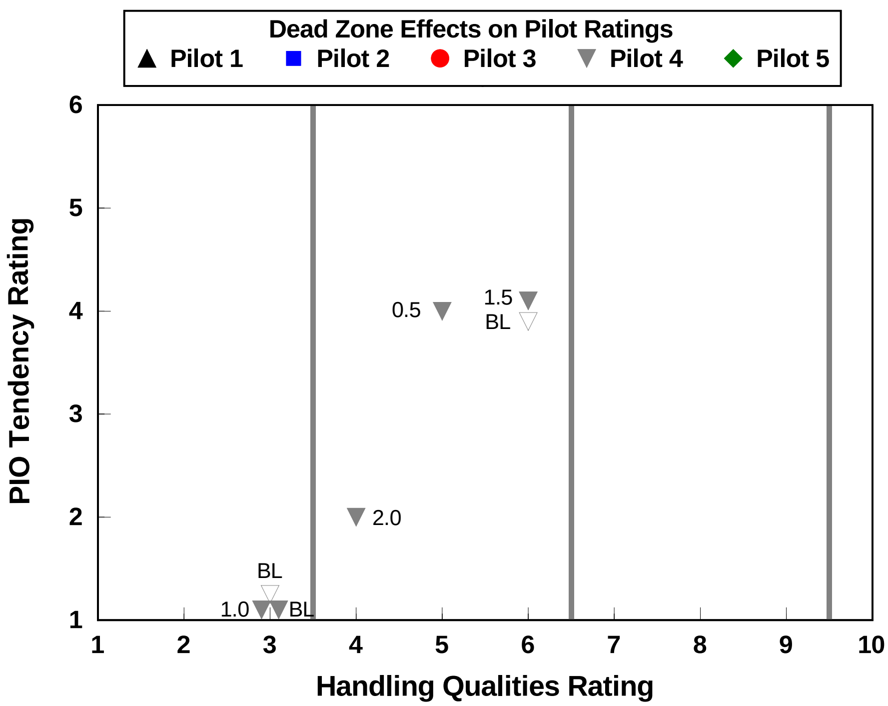


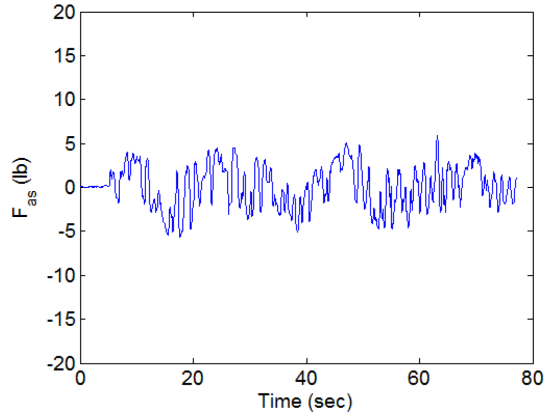
Figure 205. Ratings summary, roll dead zone variations: pilot 4, session 21

The analysis focuses on differences between pilot 1 and pilot 4 when evaluating the baseline runs, both known (run 16 for pilot 1 and run 1 for pilot 4) and blind (run 21 for pilot 1 and run 4 for pilot 4) to the pilot. Differences in how each pilot flew the blind baseline case when compared to the known baseline were analyzed as well as differences between the pilots for each baseline case.

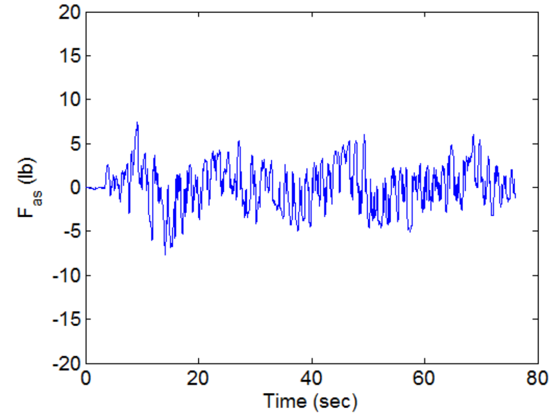
11.2.5.2 Feel System Analysis

Note again that figure 205 shows a much larger spread in ratings for the baseline cases for pilot 4. Pilot 1 rated the blind baseline case slightly better than the known case with level 1 HQ and no PIO tendency, while pilot 4 gave a poor level 2 HQ rating of 6 and noted a divergent PIO tendency for abrupt inputs by giving a PIO rating of 4. Both pilots flew identical aircraft configurations, so an analysis of PVS behavior is necessary to determine the cause of the degraded ratings.

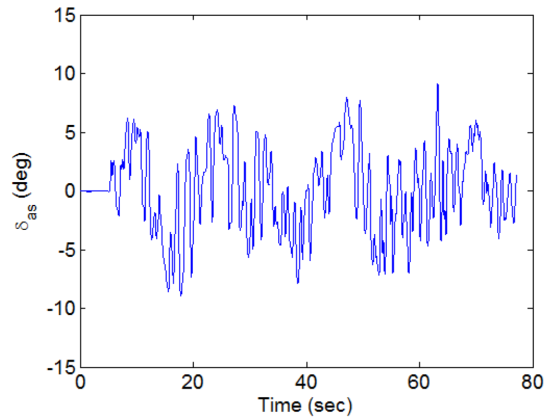
Figure 206 shows the feel system time histories and describing functions for both pilots flying the known baseline configuration. Note that both pilots use similar gain (figure 206 (a) and (b)) when imparting control inputs into the stick, which results in similar stick displacements and, thus, similar inputs into the FCS command path (figure 206 (c) and (d)). Though pilot 4 would appear to be controlling with higher frequency inputs, the feel system describing functions (δ_{es}/F_{es}) shown in figures 206 (e) and (f) are nearly identical, indicating that nonlinearity in the stick was not an issue. For these runs, both pilots rated the configuration similarly, with pilot 1 giving slightly degraded ratings due to heavy stick forces and a slight PIO tendency for fine tracking.



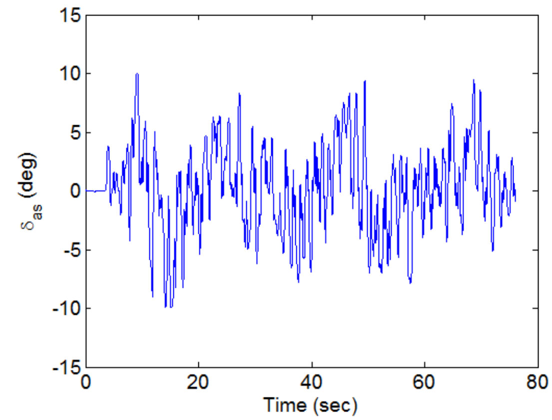
a) Stick Force – Pilot 1 S4/R16
(HQR 4/PIOR 2)



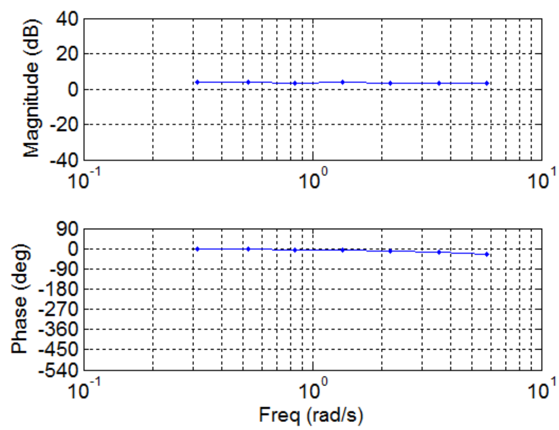
b) Stick Force – Pilot 4 S21/R1
(HQR 3/PIOR 1)



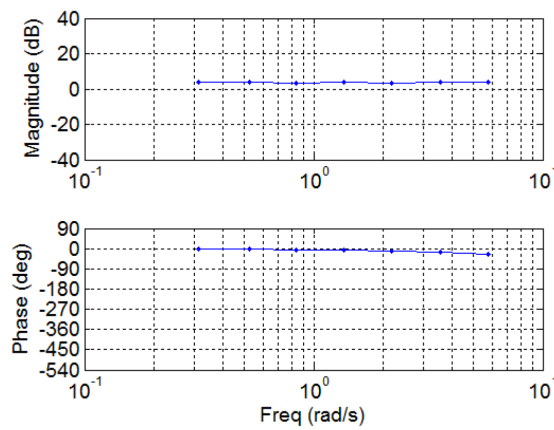
c) Stick Disp. – Pilot 1 S4/R16
(HQR 4/PIOR 2)



d) Stick Disp. – Pilot 4 S21/R1
(HQR 3/PIOR 1)



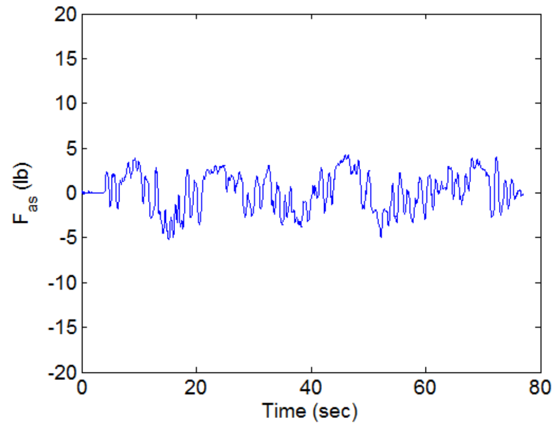
e) Feel System Describing Function – Pilot 1 S4/R16 (HQR 4/PIOR 2)



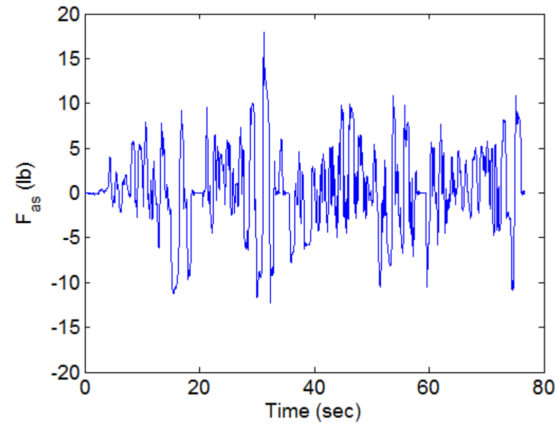
f) Feel System Describing Function – Pilot 4 S21/R1 (HQR 3/PIOR 1)

Figure 206. Feel system analysis, known baseline runs

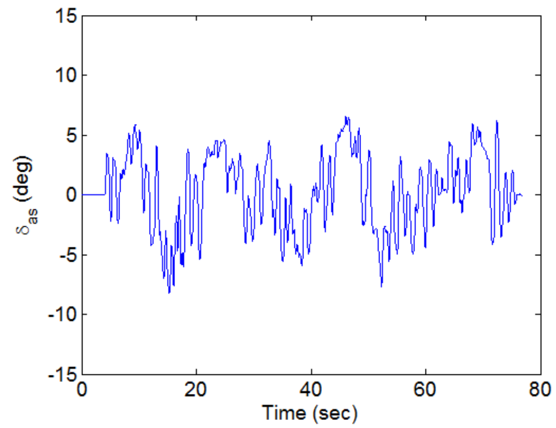
There is a distinct difference in the way each pilot flew the blind baseline runs. Pilot 1 flew the blind case almost identically to the known case, and the feel system describing function was also nearly identical. Pilot 4, however, flew the blind case much more aggressively than both pilot 1 and his own known baseline case, with significantly larger stick forces (figure 207 (b)). This resulted in encounters with both the left and right travel limits (figure 207 (d)) and contributed to the nonlinear behavior of the stick shown in figure 207 (e). Further analysis of the blind baseline runs for both pilots are presented in the following section.



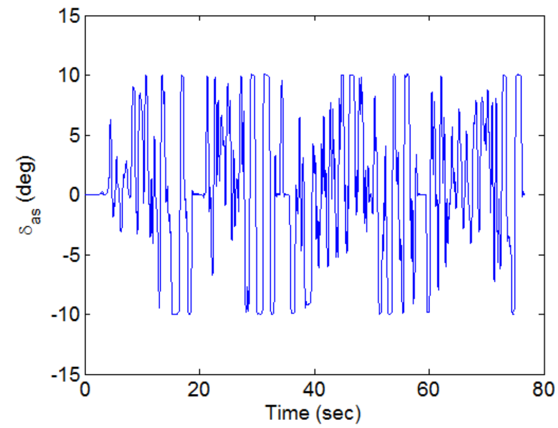
a) Stick Force – Pilot 1 S4/R21 (HQR 3/PIOR 1)



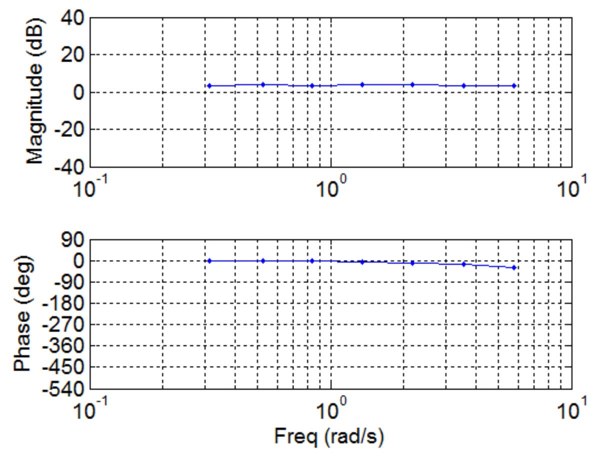
b) Stick Force – Pilot 4 S21/R4 (HQR 6/PIOR 4)



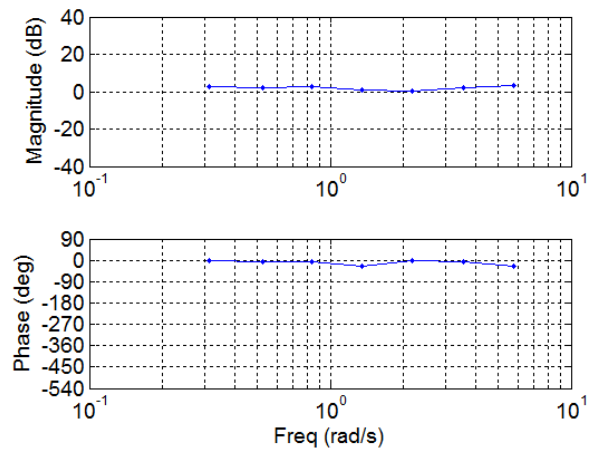
c) Stick Disp. – Pilot 1 S4/R21 (HQR 3/PIOR 1)



d) Stick Disp. – Pilot 4 S21/R4 (HQR 6/PIOR 4)



e) Feel System Describing Function – Pilot 1 S4/R21 (HQR 3/PIOR 1)



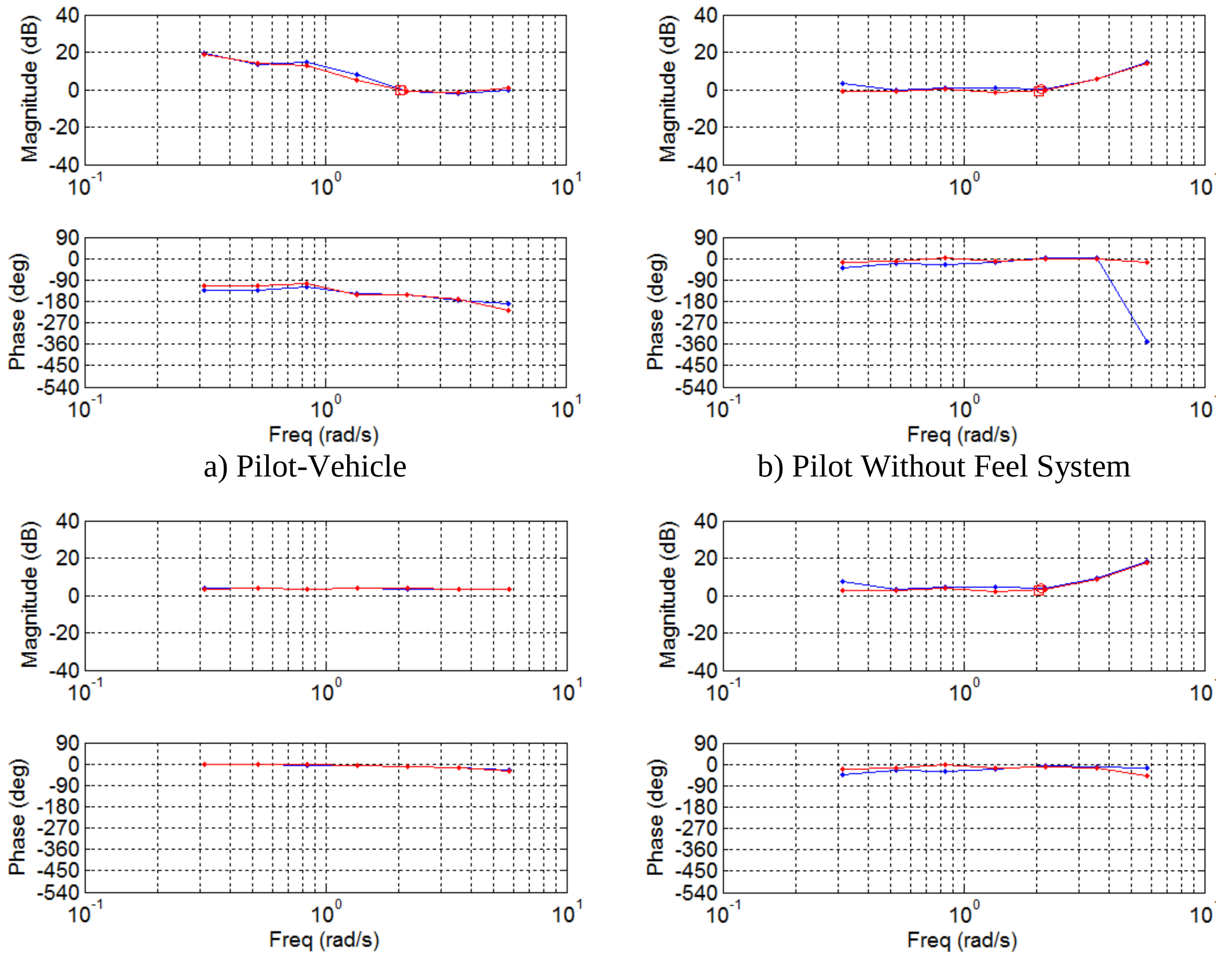
f) Feel System Describing Function – Pilot 4 S21/R4 (HQR 6/PIOR 4)

Figure 207. Feel system analysis, blind baseline runs

11.2.5.3 The PVS Analysis

To further investigate the effects of pilot 4's aggressive behavior when evaluating the blind baseline configuration, we've examined describing function overlays for each pilot in comparison to the known baseline runs, which were shown to be very similar.

Figure 208 shows the describing functions for pilot 1. We note almost identical pilot behavior in figure 208 (b) for the known and blind baseline runs, which was observed in the time histories shown in the previous section. The feel system (figure 208 (c)) is also identical, indicating that no additional nonlinearity is introduced into the stick for the blind baseline run. Figure 208 (d) also follows this pattern, as the pilot behavior when coupled with the feel system in the absence of nonlinearity is shown to be the same, except for a small gain difference due to feel system gearing. The resulting PVS shows a nearly identical response with a very similar crossover frequency, correlating to the similar ratings for these two runs.



a) Pilot-Vehicle

b) Pilot Without Feel System

c) Feel System

d) Pilot With Feel System & Nonlinearities

Figure 208. Describing function overlay, known (blue) and blind (red) baseline runs, pilot 1

Although the PVS response and crossover (figure 209 (a)) are similar for the two baseline runs, pilot 4 is controlling with considerably more high frequency lead (figure 209 (b)) and is suffering from gain loss across the feel system (figure 209 (c)). The resulting pilot-plus-command path describing function (figure 209 (d)) shows a marked difference between the way the pilot flew the blind baseline run when compared to the known baseline. Pilot 4 gave the blind baseline run ratings of HQR 6/PIOR 4 because of the additional compensation required to perform the task, PIO tendency, and nonlinearity experienced because of the encounters with the stick travel limits.

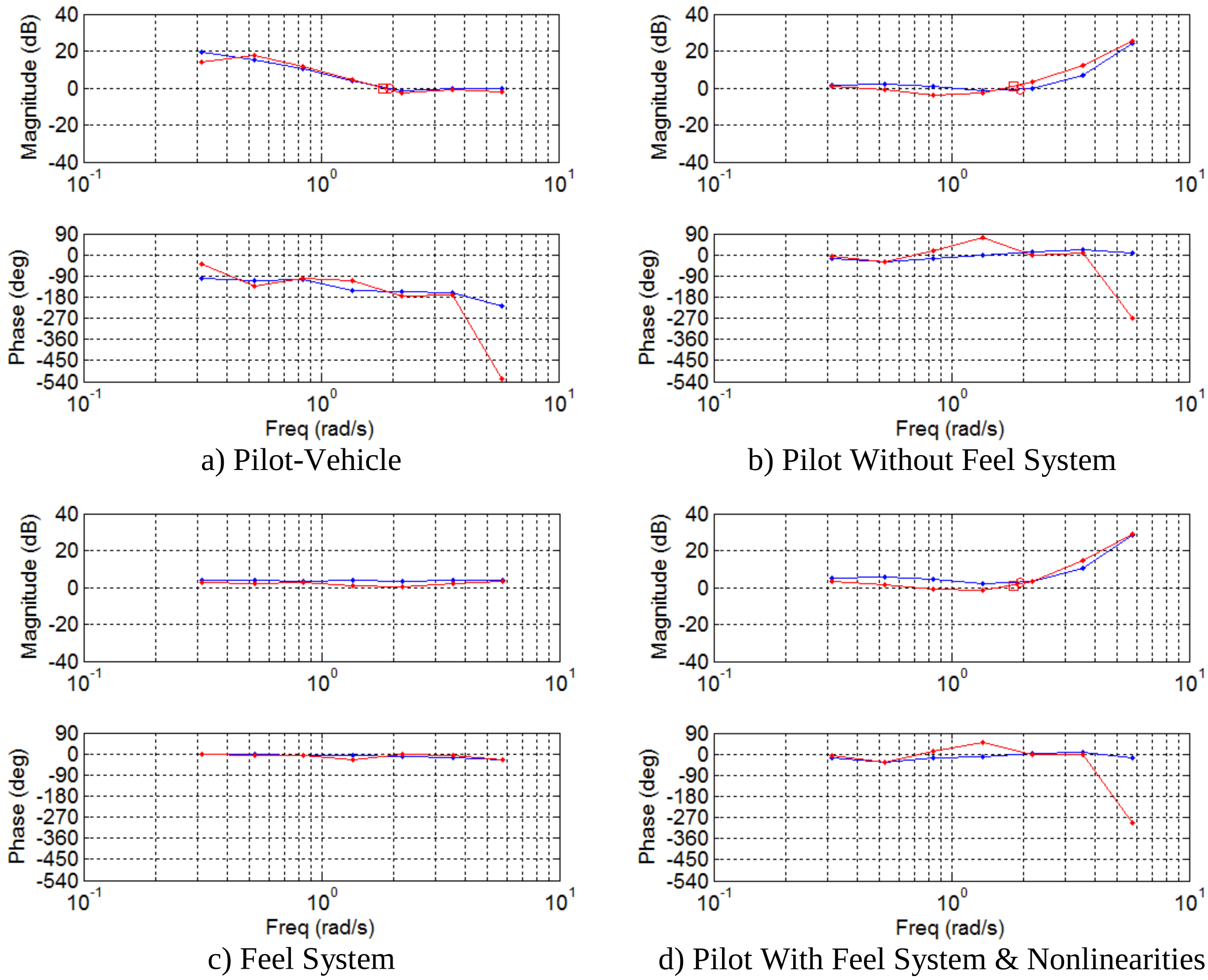


Figure 209. Describing function overlay, known (blue) and blind (red) baseline runs, pilot 4

11.2.5.4 Dead Zone Comments

Though the analyses presented herein are an examination of baseline cases, which do not have dead zones present, the causes of the degraded ratings shown are relevant to the results of the dead zone study. It was shown that one of the causes of the degraded ratings for pilot 4 was consistent encounters with the stops due to large amplitude pilot inputs, a phenomenon which is known to degrade further for dead zone cases in which control gain is attenuated. Indeed, it is noted in many of the pilot's comments that stops were encountered for dead zone runs that were rated poorly. Because reaching stick-travel limits is of high concern and it has been demonstrated to be a problem in the lateral axis for moderate-high pilot aggressiveness, even in the absence of dead zone, it is not recommended that dead zones larger than 1° be included, as they can lead to significant HQ and PIO issues.

11.2.6 Piloted Evaluations, Observations, and Conclusions

- Based on the results of the limited fixed-base simulation study, dead zone in the lateral axis is considered undesirable, so it is not recommended that dead zones greater than 1° be used for sidestick inceptor configurations, as HQ and task performance may be compromised.

- PIO tendency is not a significant issue for large dead zones because of the command attenuation effect. PIO susceptibility is inherently tied to large input amplitudes and dead zone increases generally negate these larger inputs.

- Task performance was degraded only slightly with increasing dead zone, likely due to increased pilot compensation to offset the negative effects of the dead zone. This increased workload resulted in degraded ratings despite similar task performance.

- Pilot technique can significantly impact ratings in the lateral axis, even in the absence of a dead zone, specifically the nonlinearity introduced by encounters with the left and right travel limits of the stick. Inclusion of dead zones can only serve to amplify this effect, as they attenuate command gain and should be kept to a minimum to avoid HQ and PIO issues.

11.3 PASSIVE INCEPTOR NATURAL FREQUENCY

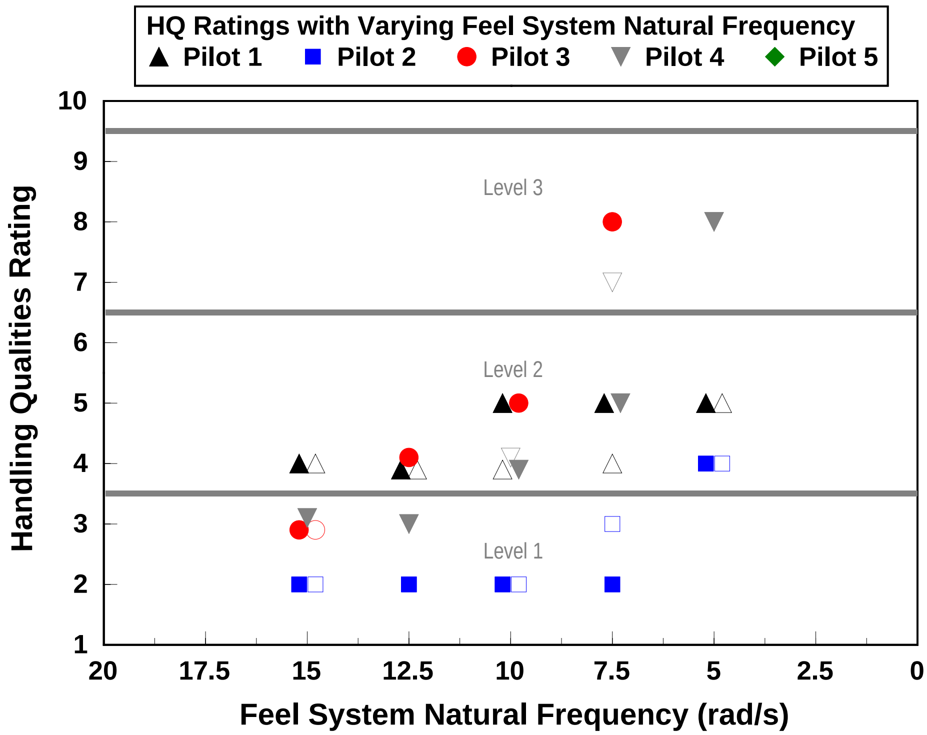
11.3.1 Introduction

This report presents an analysis of the fixed-base simulation evaluations investigating the effects of roll-feel-system natural frequency on lateral axis HQ. Four pilots participated in the roll-feel-system natural frequency evaluations [14]. The evaluations were SoS tracking tasks (section 4.4) in PA configuration with a bare airframe SM = 5% ($\bar{c}$). The HQ and PIO tendency ratings were recorded after each evaluation run, and task performance data were recorded for offline analysis. Stick natural frequency was varied from 15 rad/s (baseline) to 5 rad/s.

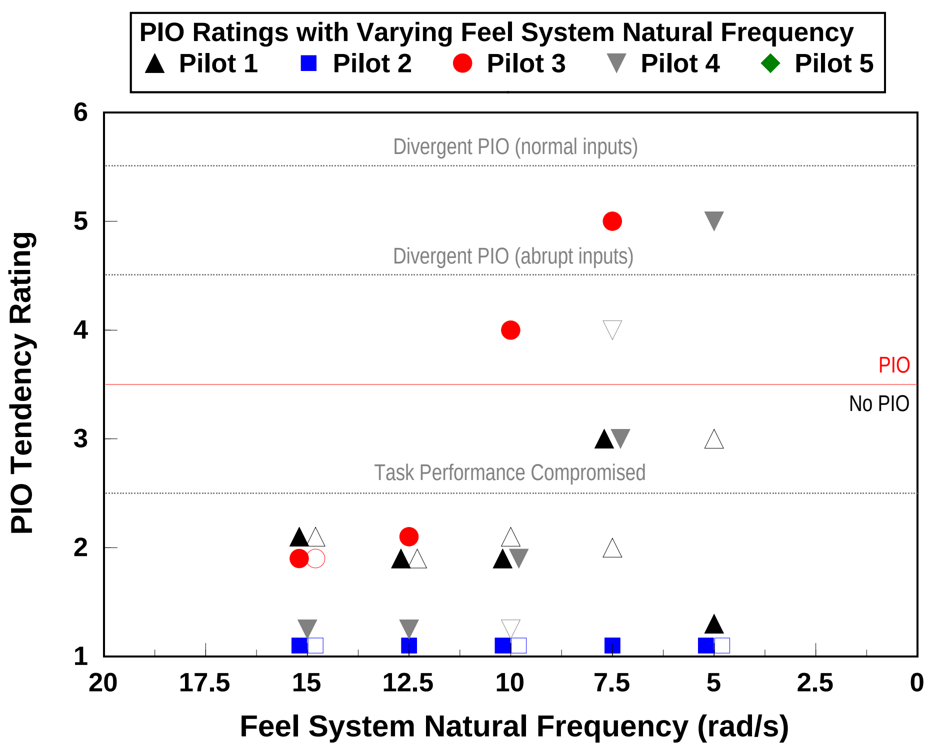
11.3.2 Analysis Summary

Figure 210 gives a summary of the HQ and PIO tendency ratings for the four pilots who participated in the roll-feel-system natural-frequency evaluations.

A trend similar to that seen for the pitch-axis feel-system natural-frequency evaluations emerges from the pilot ratings shown in figure 210. The HQ and PIO tendency ratings given in figure 210 show a distinct increase among all pilots for stick frequencies at 10 rad/s, with pilot 2 slightly less sensitive to the 10 rad/s case than the other three pilots. Unlike the other pilots, pilot 2 found no PIO sensitivity due to changes in the stick dynamics. Above 10 rad/s, feel system dynamics do not heavily impact task performance or ratings, while lowering stick natural frequency below 10 rad/s has a significant effect on the pilot's ability to perform the task and the amount of compensation required to achieve desired performance. Based on the results of this study, feel-system natural frequencies in the lateral axis should be required to be at least 12.5 rad/s, with recommendations of 15 rad/s or higher to avoid possible HQ and PIO tendency issues.



a) Handling Qualities



b) PIO Tendency

Figure 210. Pilot ratings, all pilots, roll feel system natural frequency variations

As illustrated in table 78 and figure 211, task performance is significantly impacted by feel-system natural frequency for all pilots, although desired performance is still achievable. Unlike the pitch axis stick natural frequency evaluations — in which two pilots showed minimal impact on task performance with decreasing stick natural frequency — all pilots saw a dramatic drop in achieved roll tracking performance for cases with natural frequencies lower than the baseline. This indicates that sensitivity to feel-system natural frequency has greater impact on lateral axis tasks when compared to those in the longitudinal axis.

Symbol annotations in figure 210 give HQR for each run.

Table 78. Task performance summary, all pilots, roll feel system natural frequency variations

Stick Frequency (rad/s)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
15.0	82.55	72.28	89.57	–
12.5	85.68	84.17	80.87	74.00
10.0	74.48	74.52	83.58	81.23
7.5	67.67	69.55	63.92	67.80
5.0	50.65	59.70	–	58.42

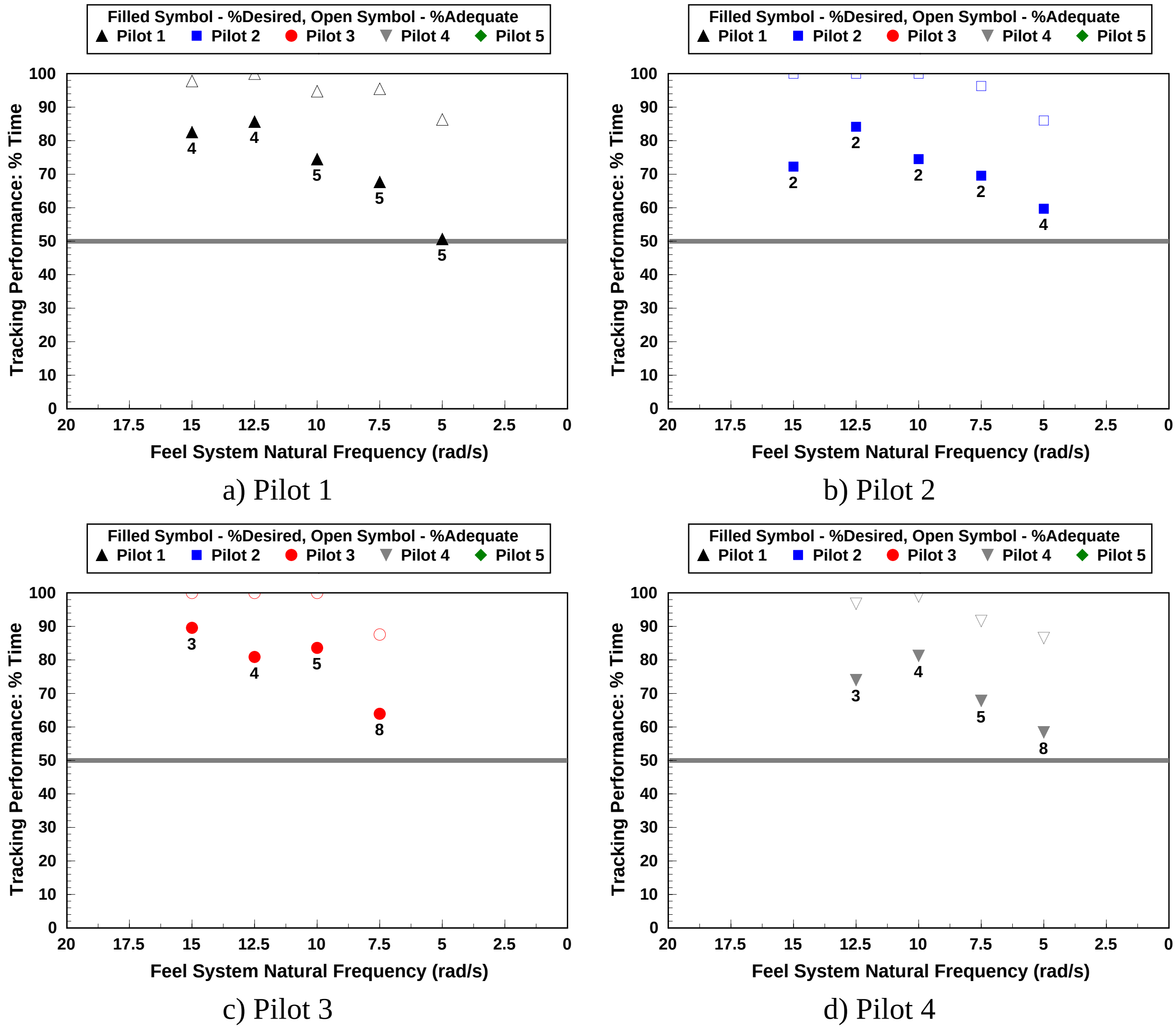


Figure 211. Tracking task performance, roll feel system natural frequency variations

11.3.3 Detailed Analysis of Selected Cases

11.3.3.1 Introductory Notes

Review of performance variations among pilots or multiple runs by the same pilot can provide insight into the effects of feel-system natural frequency variations on pilot behavior and the level of compensation necessary to perform the task. The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which may be inadequate to accurately predict the impact of feel-system parameter changes in real aircraft due to a lack of motion cueing.

11.3.3.2 Pilot 3 – Session 13 Evaluations

Pilot 3 participated in pitch stick frequency evaluations on June 19, 2012. The data were collected during Session 13 of the Year 2 Follow-on evaluations. A total of five runs were completed in the roll axis, with one run with the baseline configuration and four additional rated and scored runs. The baseline configuration was scored twice during the session, both known to the pilot. The lowest natural frequency configuration of 5 rad/s was not flown by pilot 3 in the roll axis.

A full list of the configurations flown and ratings given by pilot 3 are presented in table 79 and figure 212.

Table 79. Pilot ratings and comments: pilot 3, session 13

Session	Run	Configuration	HQR	PIOR	Comments
13	1	FLAT150 (baseline)	3	2	Hit stops two times. Large stick deflections. Pretty good performance.
13	2	FLAT100	5	4	Persistent oscillations. Heavy stick. Considerable pilot compensation. Stick continues after you take the force off.
13	3	FLAT075	8	5	Compensation requirement increased. No ability to control rates. Cannot control/maneuver wings.
13	4	FLON150 (baseline)	3	2	Much easier. Don't have to think about the stick. Inputs easier.
13	5	FLAT125	4	2	Requires mental activity. Not the worst. Too easy to couple with the airplane. Easier to have oscillations than the baseline.

FLAT = Frequency Lateral (feel system); FLON = Frequency Longitudinal (feel system)

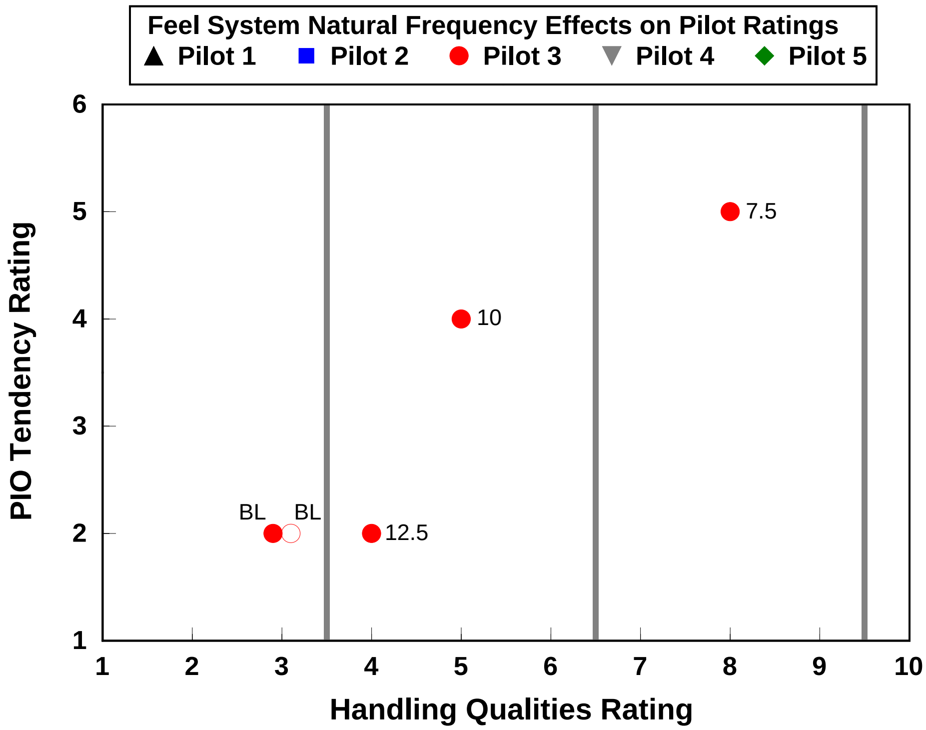
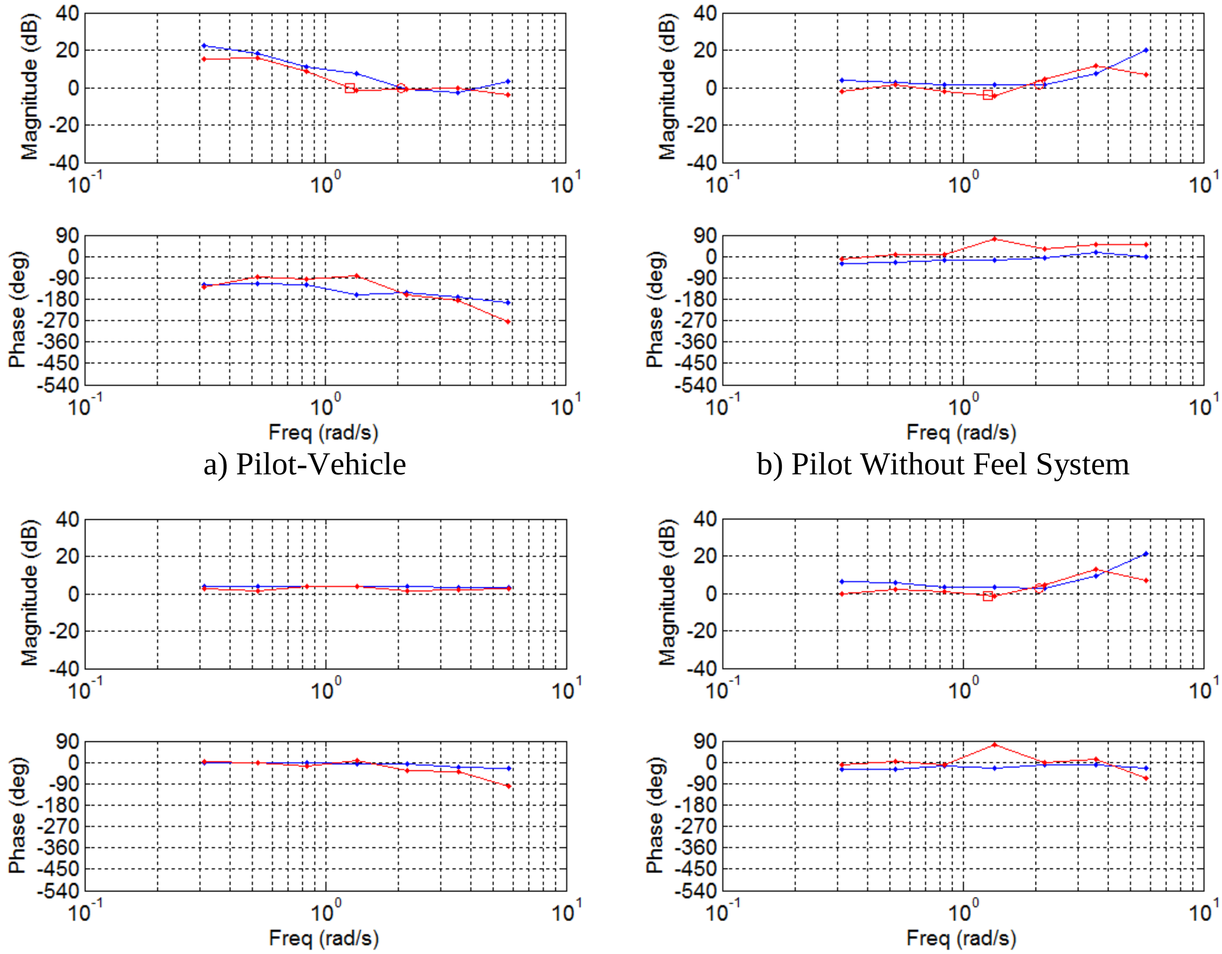


Figure 212. Ratings summary, pitch feel system natural frequency variations: pilot 3, session 12

The following analysis will focus on runs 1 and 3 to highlight the differences in how pilot 3 flew the lower frequency case when compared with the baseline and why ratings degraded as feel-system natural frequency was decreased to well within the piloted frequency range.

11.3.3.3 Comparison of Baseline and 7.5 rad/s Feel System Cases

Pilot 3 gave the baseline case ratings of HQR 3/PIOR 2 and noted “pretty good performance” for the configuration. This run, shown in blue in figure 213, featured a PVS crossover frequency of 2.07 rad/s. Figure 213 (b) shows the pilot controlling with gain and lead compensation at high frequencies, contributing to the observed crossover. For the 7.5 rad/s case shown in red, the additional phase lag in the feel system (figure 213 (c)) causes the pilot to impart lead compensation at a much lower frequency when compared to the baseline, as well as a reduced gain at lower frequencies. The result is a lower crossover frequency of 1.27 rad/s, as the pilot is forced to back out of the control loop in the presence of the more sluggish feel-system dynamics.



a) Pilot-Vehicle

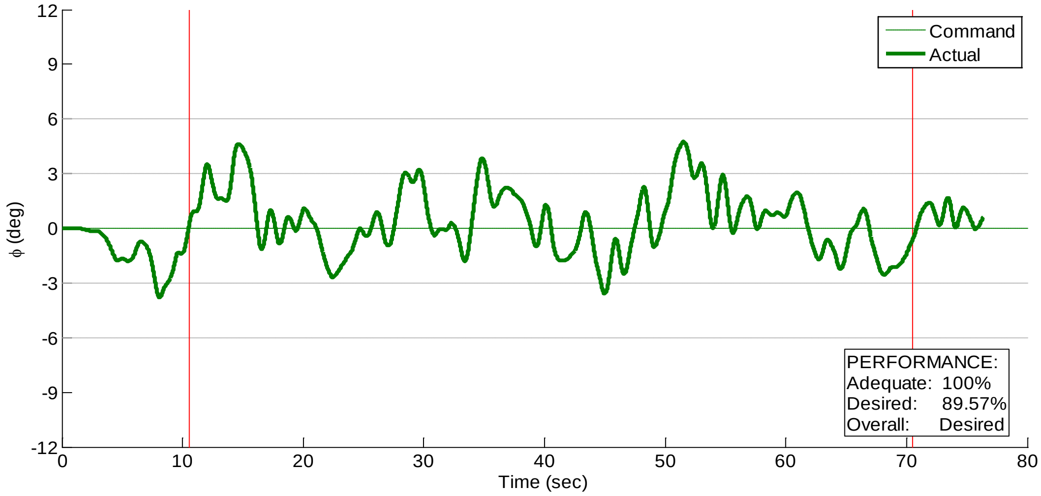
b) Pilot Without Feel System

c) Feel System

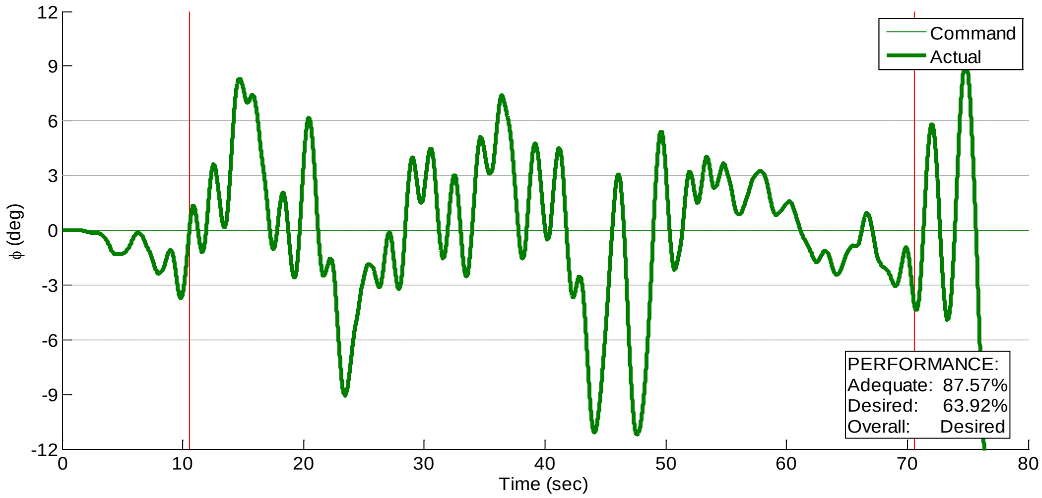
d) Pilot w/Feel System & Nonlinearities

Figure 213. Identified describing functions, session 13 overlay (run 1 – blue, run 3 – red)

The impact on task performance is seen in figure 214. In figure 214 (a), the well-behaved PVS stays within desired bounds almost 90% of the scored task time. In figure 214 (b), on the other hand, there is much more oscillatory behavior and large-amplitude excursions from the trim-bank angle with the 7.5 rad/s case, leading the pilot to comment, “cannot control or maneuver the wings.” Desired performance drops to just 64% for this case, with several examples of 10° errors.



a) Run 1 – Baseline (HQR 3/PIOR 2)



b) Run 3 – 7.5 rad/s (HQR 8/PIOR 5)

Figure 214. Task performance, session 13

11.3.4 Piloted Evaluations, Observations, and Conclusions

- Based on the results of the limited fixed-base simulation study, lateral-axis feel system natural frequencies greater than 12.5 rad/s are recommended for sidestick inceptor configurations, as HQ and task performance may be compromised for configurations with lower natural frequencies.

- PIO tendency becomes a significant issue for feel system natural frequencies lower than 10 rad/s. Task performance also degrades sharply for some pilots with aggressive or high-frequency lead-compensation techniques.

- In comparison to the pitch-axis evaluations, there is increased sensitivity to feel-system natural-frequency variations in the lateral axis.

- To yield best HQ results, the feel system natural frequency should maintain adequate separation from the operating frequencies of the PVS; otherwise, adverse interactions between pilot inputs and stick dynamics can result in degraded HQ, increased PIO tendency, and poor task performance. Results for pilot 3 showed level 3 HQ and a significant PIO risk in addition to a 25% drop in desired performance when the feel system dynamics fell in this frequency range.

11.4 PASSIVE INCEPTOR DAMPING RATIO

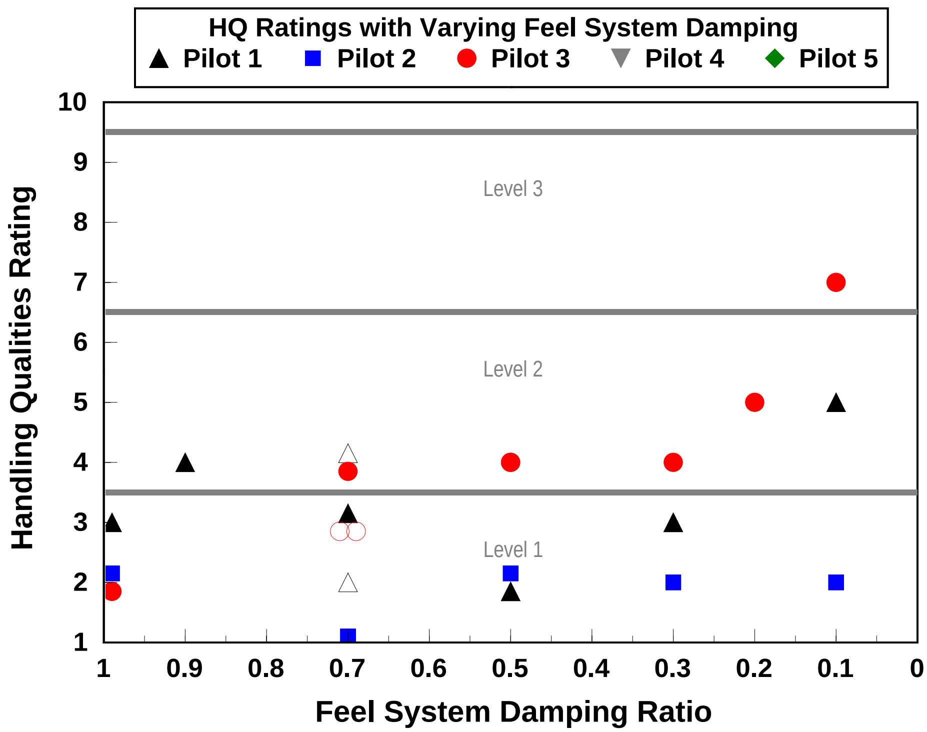
11.4.1 Introduction

This section presents an analysis of the fixed-base simulation evaluations of the effects of roll-feel system damping on lateral-axis HQ. Three pilots participated in the roll-feel system damping evaluations [14]. The evaluations were discrete ACH tasks in PA configuration with a bare airframe SM = 5% ($\bar{c}$) (Cfg 1). The HQ and PIO tendency ratings were recorded after each evaluation run and task performance data was recorded for offline analysis. Stick damping ratio was varied from 0.1–1.0, with a baseline damping-ratio configuration of 0.7.

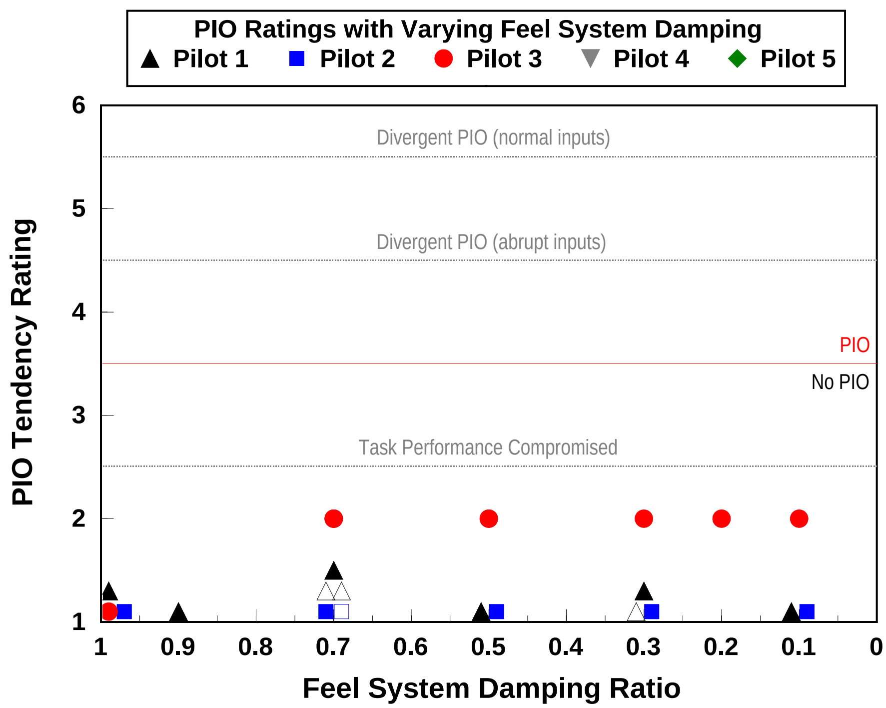
11.4.2 Analysis Summary

Figures 215 and 216 provide summaries of the HQ and PIO tendency ratings for the three pilots who participated in the roll-feel system-damping evaluations.

A distinct trend emerges from the pilot ratings shown in figures 215 and 216. The HQ and PIO tendency ratings presented in the figures show that all pilots rate the baseline case level 1, with the exception of pilot 3, who rated the original of the three runs in the baseline configuration slightly into level 2 (HQR = 4). Similar to the pitch-axis feel-system damping-ratio evaluations, the pilots showed little sensitivity to stick damping for cases above 0.3. Unlike the pitch-axis evaluations, however, pilot 1 showed a sensitivity to very light feel-system damping in the lateral axis. Although slight improvement was seen for a small decrease in damping to 0.5, in general, pilot 2 saw degraded ratings as damping ratio was lowered. From these ratings, it would appear that feel-system damping in the lateral axis, though more significant than in the longitudinal axis, only minimally affects piloted HQ. Care should once again be taken to avoid very lightly damped stick dynamics to avoid problems, such as increased workload, to achieve task performance.



a) Handling Qualities



b) PIO Tendency

Figure 215. Ratings summary, roll feel system damping variations

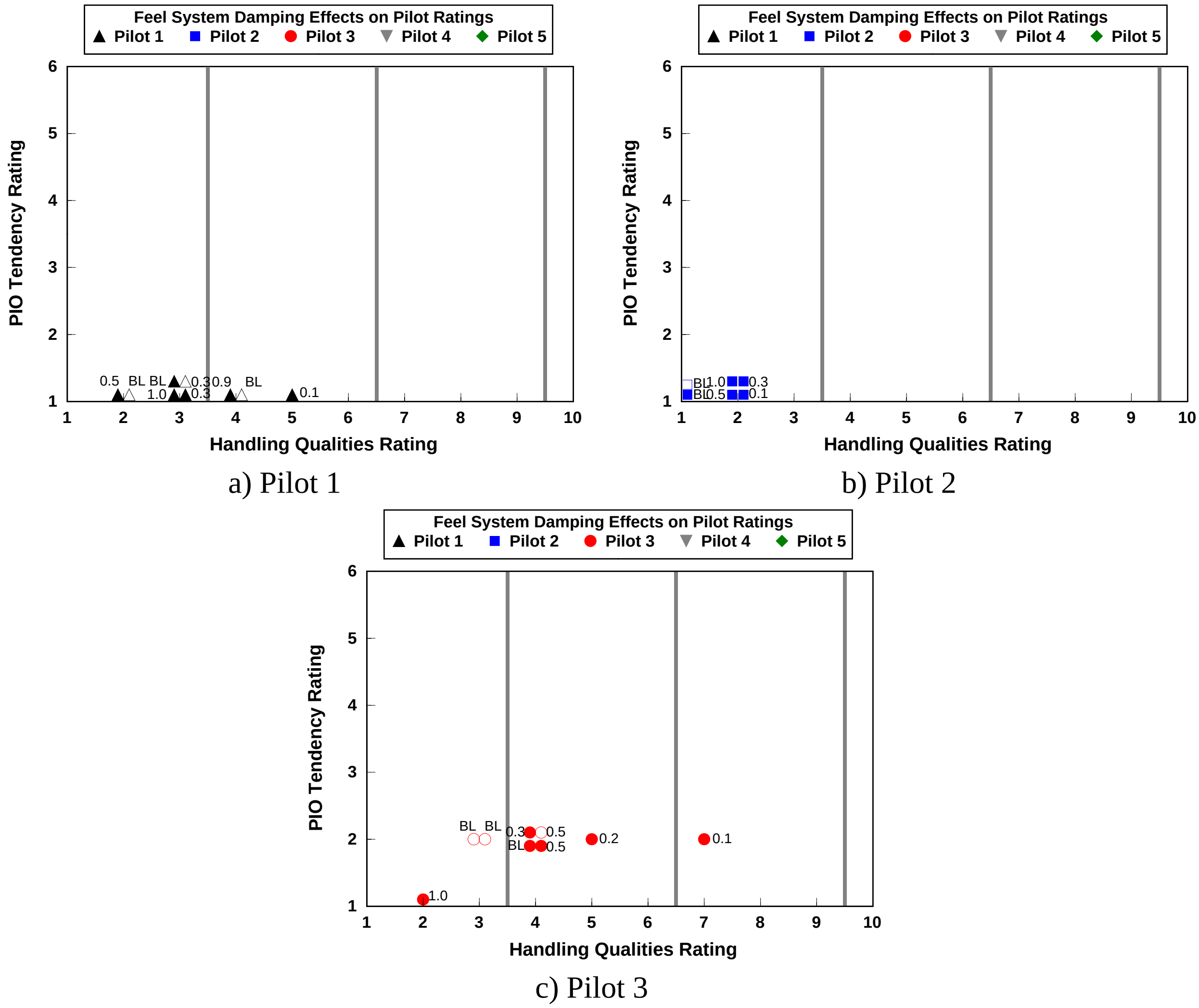


Figure 216. Pilot ratings, roll-feel system damping variations

11.4.3 Detailed Analysis of Selected Cases

11.4.3.1 Introductory Notes

Variations among multiple runs by the same pilot can provide insight into the effects of feel-system damping variations on pilot behavior and the level of compensation necessary to perform the task. Correlations between degraded ratings and increased pilot compensation, poor task performance, or changes in pilot behavior further emphasize the impact of the feel-system damping variations on the ability of the pilot to perform the task.

The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which may be inadequate to accurately predict the impact of feel-system parameter changes in real aircraft due to a lack of motion cueing.

11.4.3.2 Pilot 1 – Session 9 Evaluations

Pilot 1 participated in roll-feel-system damping evaluations on June 19, 2012. The data were collected during session 9 of the Year 2 Follow-on evaluations. A total of nine runs were completed in the roll axis, with nine scored runs that were rated, including two runs in the baseline configuration. The baseline configurations were first scored known, then blind, to the pilot. A full list of the configurations flown and ratings given by pilot 1 are provided in table 80 and figure 217.

Table 80. Pilot ratings and comments: pilot 1, session 9

Session	Run	Configuration	HQR	PIOR	Comments
9	1	DLAT07 (baseline)	3	1	Heavy force. Large acquisition on the stops.
9	2	DLAT05	2	1	No difference in performance. Fine corrections at the end. Feels a little lighter in forces. 1–2 fine corrections.
9	3	DLAT03	3	1	More trouble to get a very exact fine correction, a little less precise. Takes another input to capture. A little looser.
9	4	DLAT01	5	1	I can feel the stick moving in my hand. Annoying oscillations. Ringing. 5 corrections.
9	5	DLAT07 (baseline-blind)	4	1	Heavier, better than the previous one. Not hitting the stops as much.
9	6	DLAT09	4	1	Heavier stick. Not hitting the stops. Low natural frequency feel system. Very viscous feel in my hand.
9	7	DLAT07	2	1	Lighter stick. Good accuracy. Hitting stops at big changes. Fine corrections.
9	8	DLAT10	3	1	Not much different from the baseline. Slightly heavier. Good tracking.
9	9	DLAT03	3	1	Lighter stick, vibrating a little. Slight ringing. Stop twice.

DLAT = Damping Lateral (feel system)

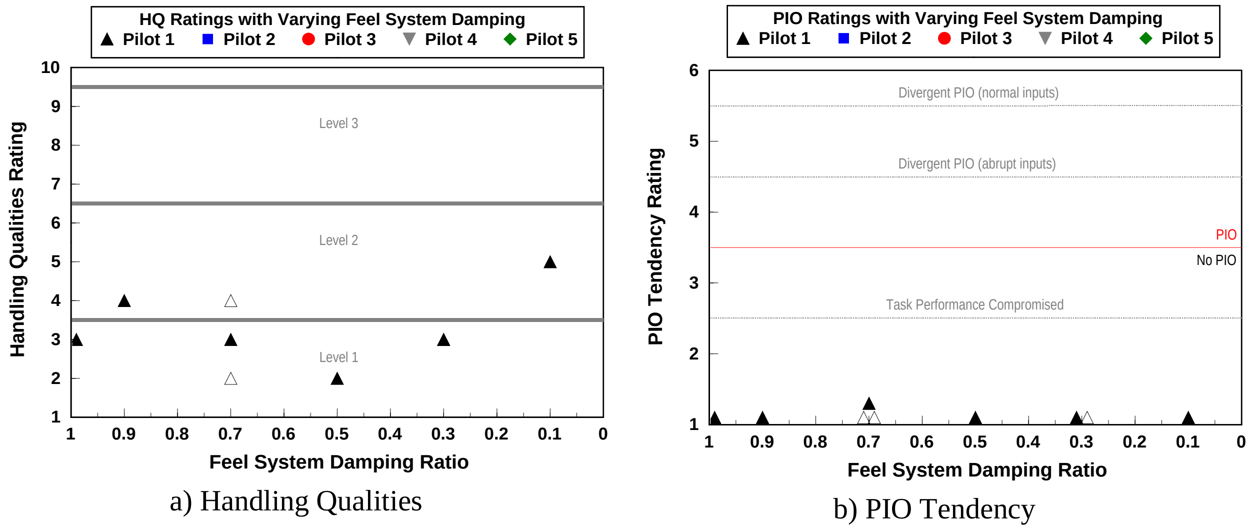


Figure 217. Pilot 1 ratings, roll-feel system damping variations

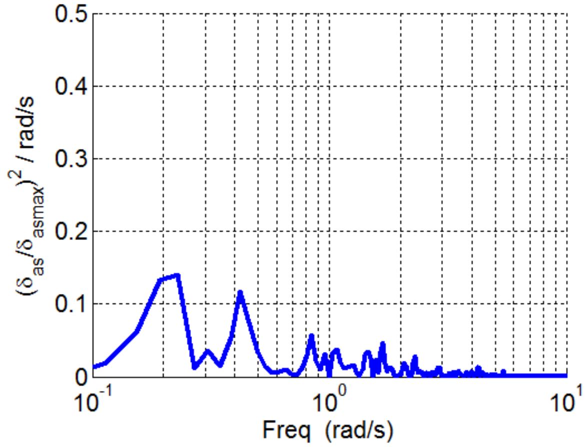
The following analysis will focus on runs 2 and 4 to highlight the differences between the very lightly damped 0.1 case and the more damped 0.5 case that received favorable ratings.

<u>11.4.3.3 Task Analysis</u>

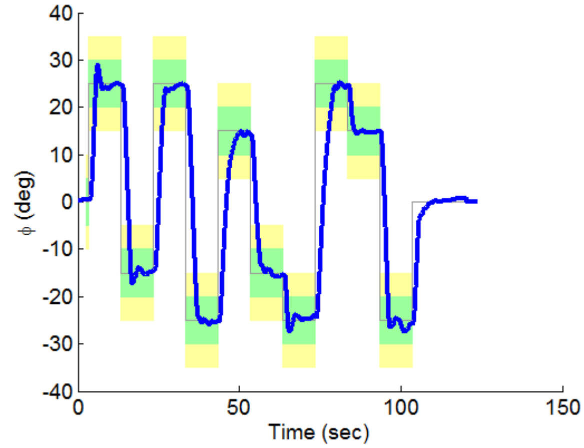
In figure 215, pilot ratings for the roll feel-system damping-ratio evaluations show a slight variation for most damping-ratio settings. All configurations are given borderline level 1/2 HQ with no undesirable oscillations, but other than a slight improvement in ratings for a slightly less damped feel system, ratings degrade for damping ratios below 0.5. For run 4, however, the lightly damped damping lateral (DLAT) 01 configuration is given an HQR 5, a stark contrast to the HQR 2 the DLAT05 configuration received for run 2.

Figure 218 gives time histories and stick displacement PSDs for runs 2 and 4 of session 9. The green and yellow regions of the time history plots signify desired and adequate performance regions. These runs represent the slightly lower-than-baseline 0.5 and very lightly damped 0.1 cases, respectively. From the time histories, we see that the lightly damped case (figure 218 (d)) is much more oscillatory in its response, although desired performance is still achievable. The pilot notes this oscillation as "annoying" and also notes an increased number of corrections required to capture the desired bank angle, contributing to the degraded ratings for this run.

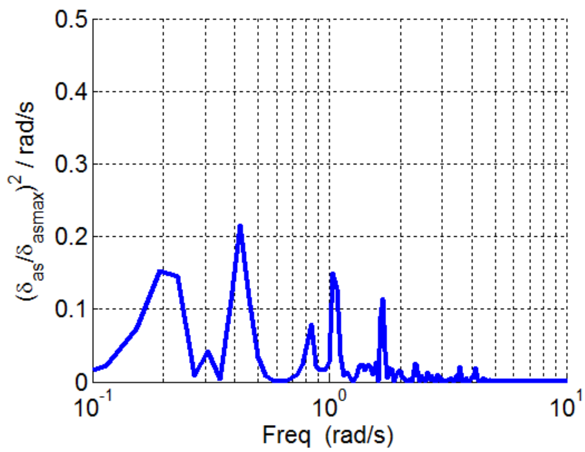
Looking at the left column of figure 218, we see a distinct difference in the input frequency for runs 2 and 4. Other than the similar spike in input power near 0.2 rad/s, we see higher amplitude spikes at higher frequencies, most notably near 0.5 rad/s, where the input power is double for the lightly damped case. Similarly, spikes at frequencies between 1 and 2 rad/s are also of higher amplitude, showing the pilot's increased workload in attempting to complete the task with desired performance.



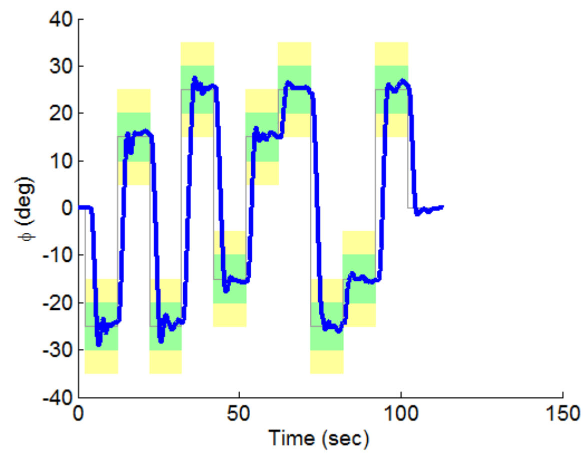
a) Stick Disp. PSD – S9/R2 (HQR 2/PIOR 1)



b) Pitch Attitude – S9/R2 (HQR 2/PIOR 1)



c) Stick Disp. PSD – S9/R4 (HQR 5/PIOR 1)



d) Pitch Attitude – S9/R4 (HQR 5/PIOR 1)

Figure 218. Task analysis, varying pitch-feel system damping ratio

Pilot 3 is able to achieve desired performance for both baseline runs and adequate performance for the most lightly damped case tested. Task performance did degrade for this pilot as damping ratio was lowered below 0.3, but the pilot was still able to perform the task with only slightly degraded ratings due to increased workload and pilot annoyance with the dynamics of the stick.

11.4.4 Piloted Evaluations, Observations, and Conclusions

- Based on the results of the limited fixed-base simulation study with a level 1 baseline aircraft configuration, feel-system damping ratio is not a critical parameter when kept above 0.3, although pilot sensitivity to changes in lateral axis feel-system damping appears to be increased when compared with the longitudinal axis results.
- PIO tendency is not a significant risk, even for very lightly damped configurations with damping ratios of less than 0.3.
- Although task performance degrades slightly for pilots sensitive to lightly damped feel-system dynamics, loss of control is not an issue and desired performance can still be achieved.

11.5 ACTUATOR NATURAL FREQUENCY

11.5.1 Introduction

The first part of this section documents the results of a roll axis study investigating the effects of varying actuator natural frequency and damping with and without a command path dead zone. The actuator natural frequency and damping were first varied with no additional dead zone to examine their effects separately. The same parameters were then varied with a 1° command path dead zone present to study the effects of lighter actuator damping and lower natural frequency on HQ and task performance.

The flight condition used for this analysis is the maneuvering speed cruise configuration defined as Hp = 38,000 ft pressure altitude with zero flaps at KCAS = 234. The aircraft is in its SM = 5% ($\bar{c}$) bare airframe SM configuration. A pilot model that employs unit gain and a reaction delay of 250 msec is utilized throughout the piloted task performance analysis.

Actuator natural frequencies of 75, 50, and 20 rad/s and damping ratios of 0.7, 0.4, and 0.2 were examined in this study. The 75 rad/s case with 0.7 damping is considered the baseline actuator configuration.

Analysis focuses on the bandwidth/phase delay criterion and an SoS disturbance regulation tracking task. A detailed description of the nature of the task and its implementation is given [19], while the signal used for this analysis is shown in figure 219. Desired and adequate bounds were once again set as ±3 and ±6 degrees of error from trim (figure 220).

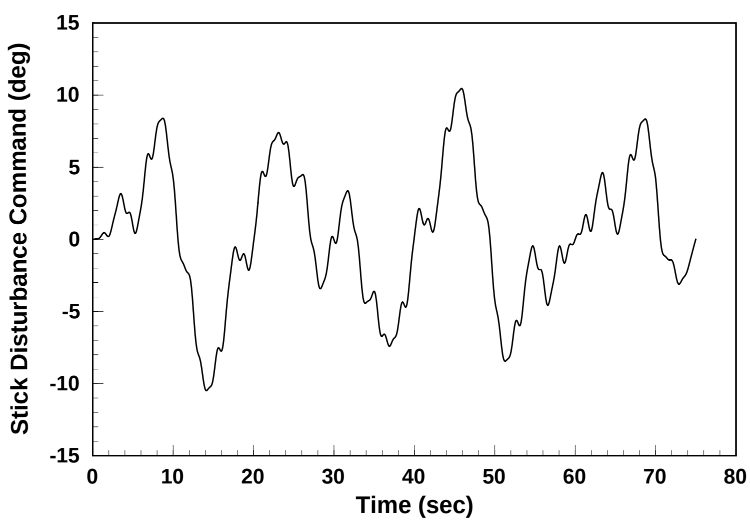


Figure 219. Fibonacci series-based lower frequency SoS input forcing function time history

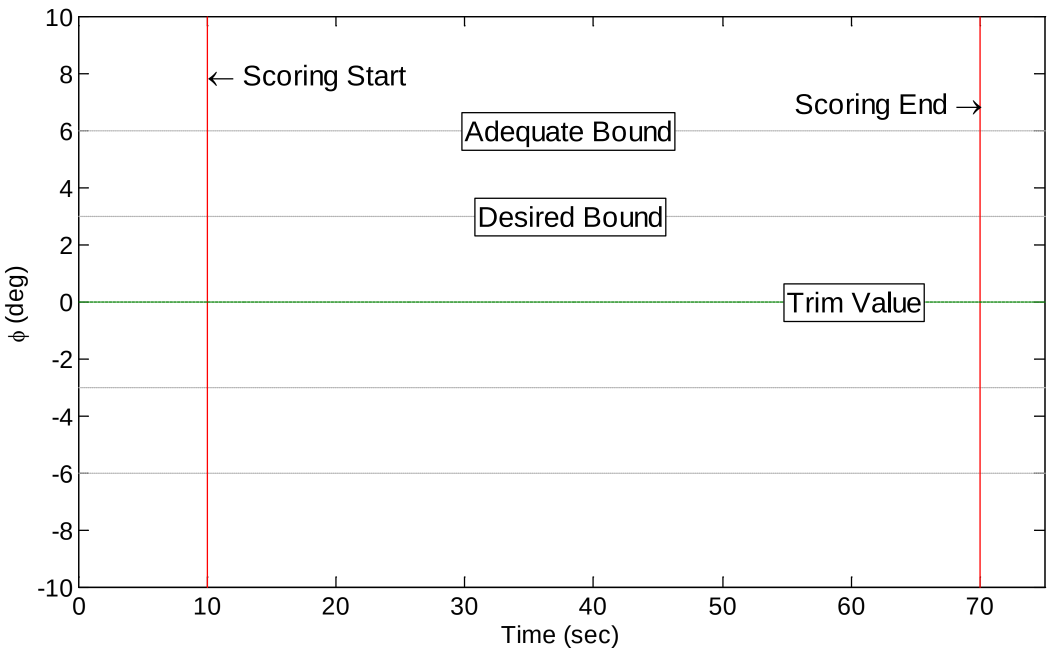


Figure 220. Task performance time history plot annotations

The second part of this section presents an analysis of the fixed-base simulation evaluations investigating the effects of aileron control surface actuator natural frequency on lateral axis HQ. Three pilots participated in the roll actuator natural frequency evaluations [14]. The evaluations were SoS tracking tasks (section 4.4) in (PA) and cruise maneuver speed (V_A) configurations with a SM of 5%. The HQ and PIO tendency ratings were recorded after each evaluation run and task performance data was recorded for offline analysis. Actuator natural frequency was varied from 75 rad/s (baseline) to 5 rad/s.

11.5.2 Offline Closed-Loop Aircraft Analysis

11.5.2.1 Introductory Notes

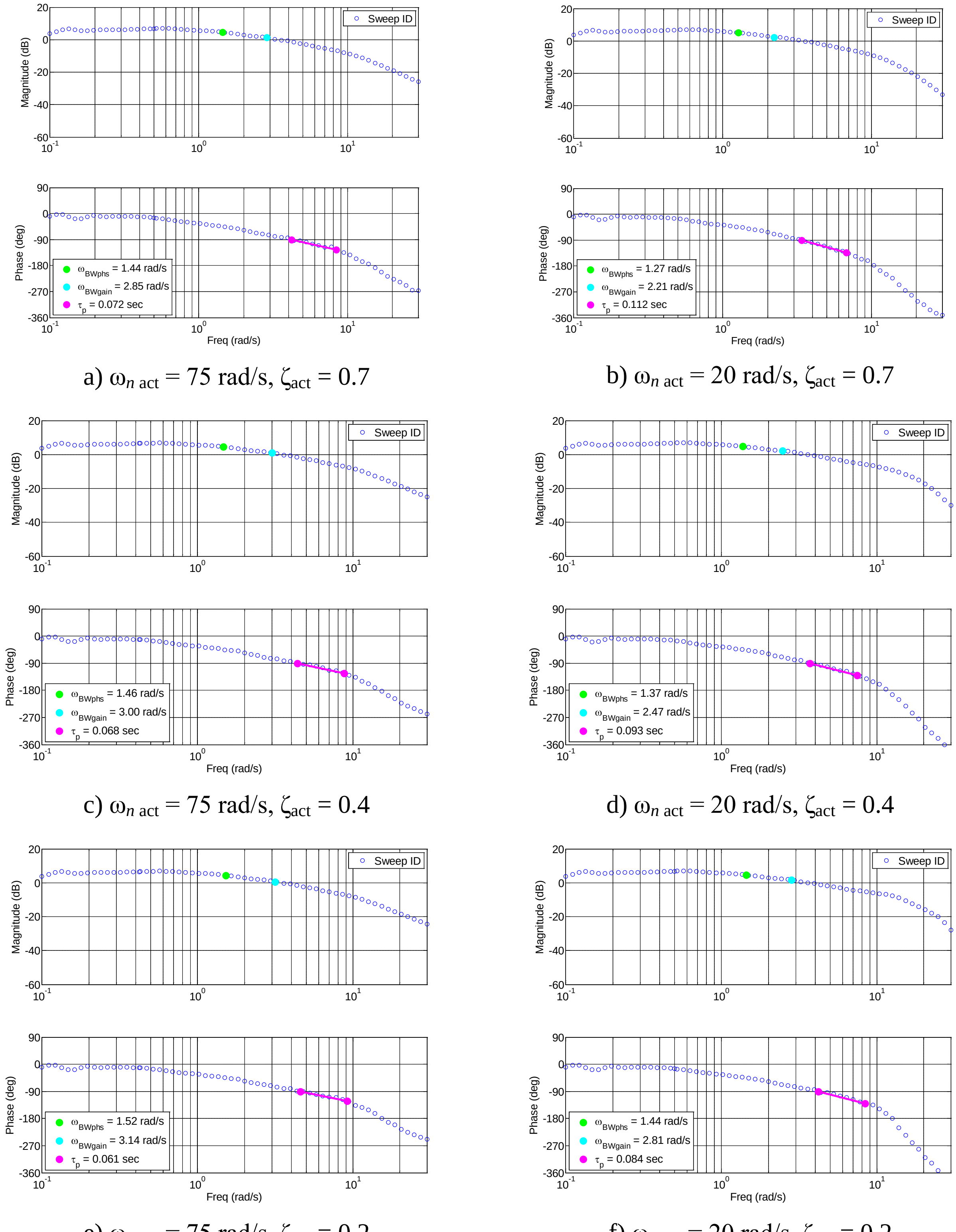
The objective of this analysis is to determine the effects of changing actuator dynamics on task performance and pilot behavior with and without a command path dead zone present. The analysis first examines the effects of reduced damping and studies the effects of lower natural frequency. The analysis is then repeated with a command path dead zone of 1°.

The controlled element Y_c refers to the closed-loop augmented aircraft that includes the CLAWS, feel system, and vehicle dynamics. The command path dead zone is also considered part of the controlled element for this analysis when present.

11.5.2.2 Nominal Command Path

Figure 221 shows the identified vehicle responses for various actuator damping ratios at the baseline natural frequency of 75 rad/s and a lower natural frequency of 20 rad/s. Note that for both natural frequencies, bandwidth and phase delay are improved with lighter damping. The presence of the actuator dynamics at a much lower frequency for the 20 rad/s cases causes a phase rolloff that impacts bandwidth. Reduced damping with a fixed natural frequency adds phase lead in the region where the bandwidth and phase delay are calculated so that there is a net improvement in the HQ parameters. This is not, however, a recommended method for achieving such gains because the added overshoot will negatively impact actuator performance.

The reduced damping for the 75 rad/s case has minimal effect on phase at low frequencies, which is expected because the actuator dynamics are much higher in frequency than the 1–10 rad/s frequency range typically associated with piloted control. The presence of actuator dynamics at 20 rad/s has a profound effect on the phase and causes phase delay to degrade by 50% for the baseline damping case.



a) $\omega_{n\ act}$ = 75 rad/s, ζ_{act} = 0.7

b) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7

c) $\omega_{n\ act}$ = 75 rad/s, ζ_{act} = 0.4

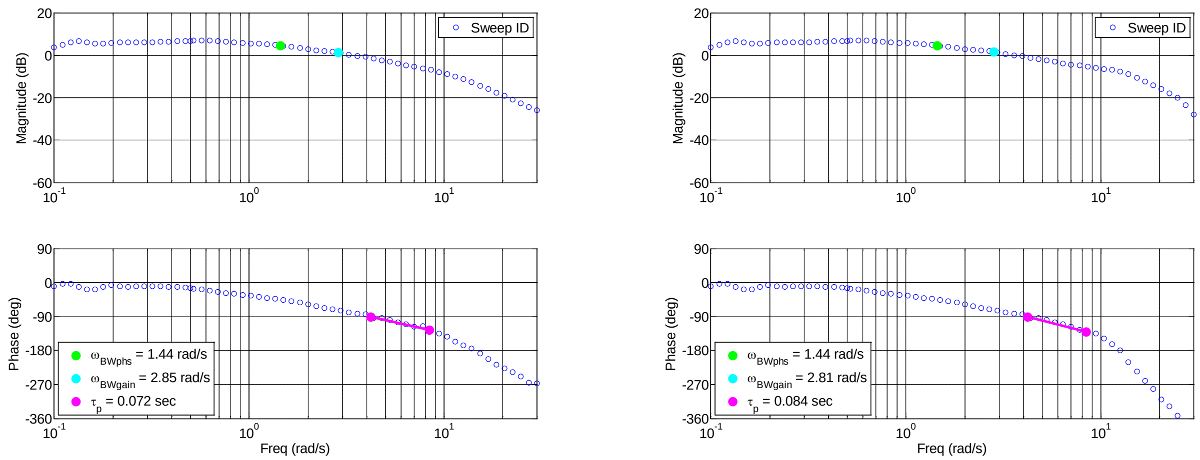
d) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.4

e) $\omega_{n\ act}$ = 75 rad/s, ζ_{act} = 0.2

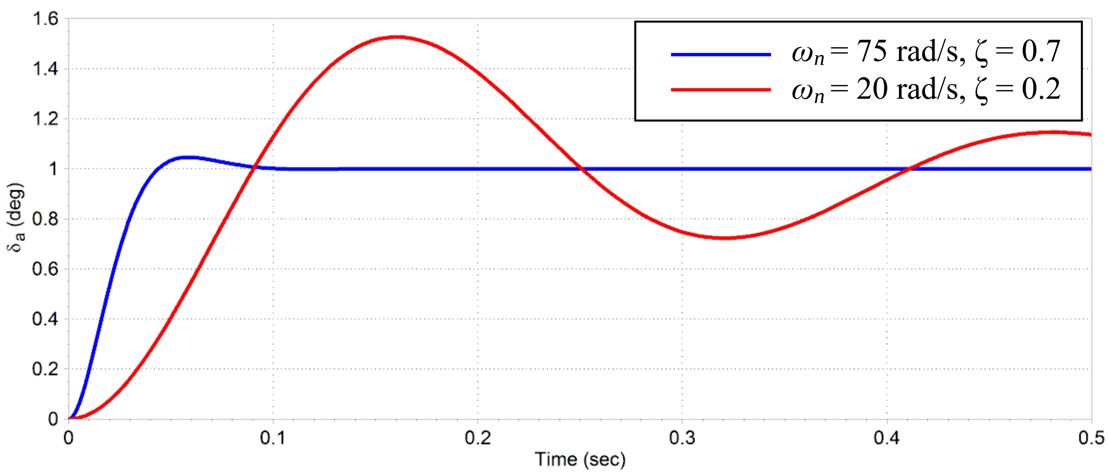
f) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.2

Figure 221. Aircraft plus feel system identified frequency responses and FQ metrics

Reducing the damping for the 20 rad/s case minimizes the phase loss due to the lower natural frequency as it flattens out the phase curve in the frequency region just before the actuator. In this case, because the ω_{-180} and $2\omega_{-180}$ frequencies are in the 5–10 rad/s range, reduced damping allows the vehicle metrics to recover much of what is lost with the lower frequency actuator. Figure 222 shows a comparison of the vehicle with baseline actuator (figure 222 (a)) and 20 rad/s actuator with reduced damping (figure 222 (b)), which demonstrates that the bandwidth and phase delay are similar to the baseline despite the actuator natural frequency being only slightly above the piloted control frequency range. As mentioned previously, the reduced damping will negatively impact actuator performance (figure 222 (c)), so there is a trade-off between improvements in airplane bandwidth parameters and tolerable actuator overshoots as well as rapidity of the initial response (figure 223 and table 81).



a) $\omega_{n\ act} = 75$ rad/s, $\zeta_{act} = 0.7$ b) $\omega_{n\ act} = 20$ rad/s, $\zeta_{act} = 0.2$



c) Unit Step Response Comparison

Figure 222. Comparison of baseline and lightly damped reduced frequency actuators

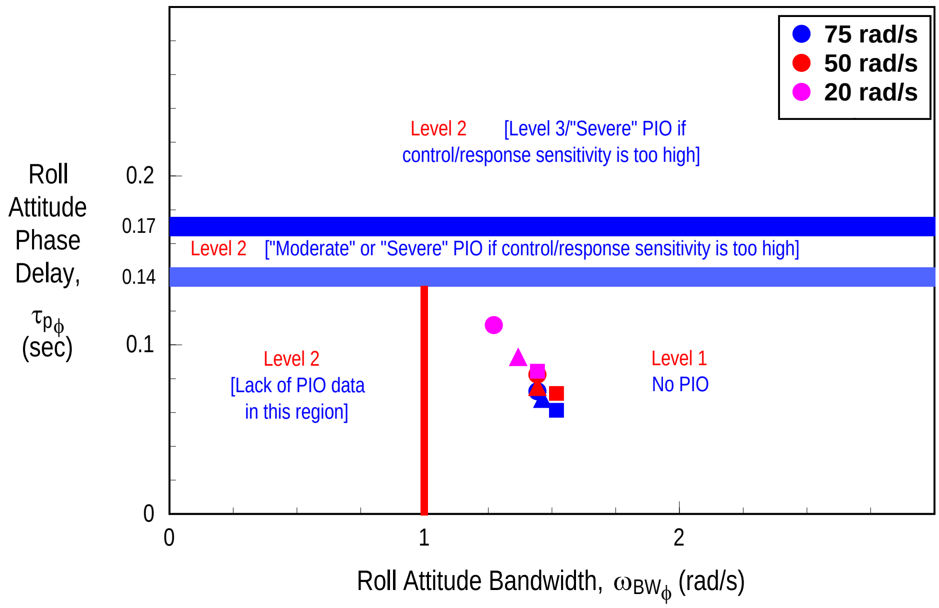
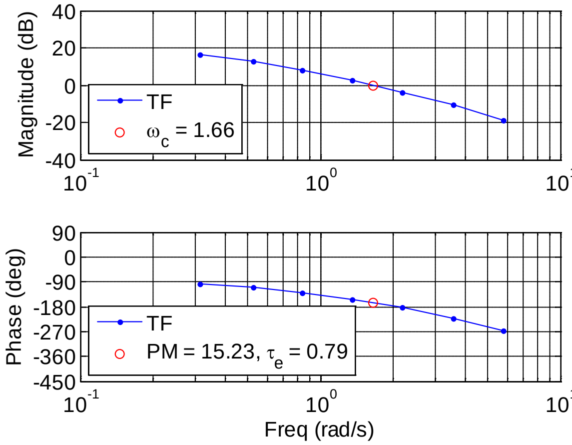


Figure 223. Roll attitude bandwidth/PIO summary for 0.7 (circle), 0.4 (triangle), and 0.2 (square) damping cases [13]

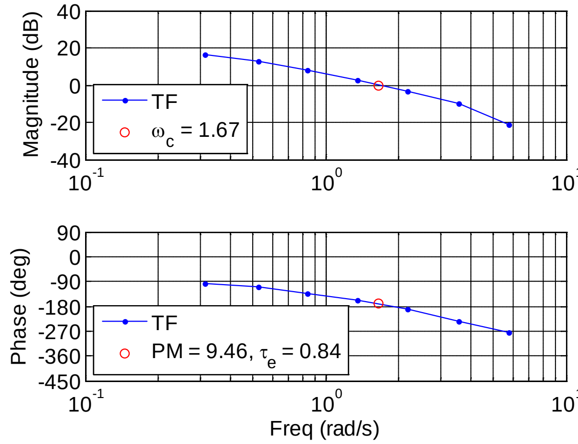
Table 81. Summary of closed-loop aircraft bandwidth/phase delay

$\omega_{n\ act}$ (rad/s)	$\zeta = 0.7$	$\zeta = 0.4$	$\zeta = 0.2$
75	1.4429 r/s / 0.0725s	1.4625 r/s / 0.0681 s	1.5180 r/s / 0.0613 s
50	1.4429 r/s / 0.0824 s	1.4429 r/s / 0.0752 s	1.5180 r/s / 0.0713 s
20	1.2719 r/s / 0.1117 s	1.3677 r/s / 0.0929 s	1.4429 r/s / 0.0844 s

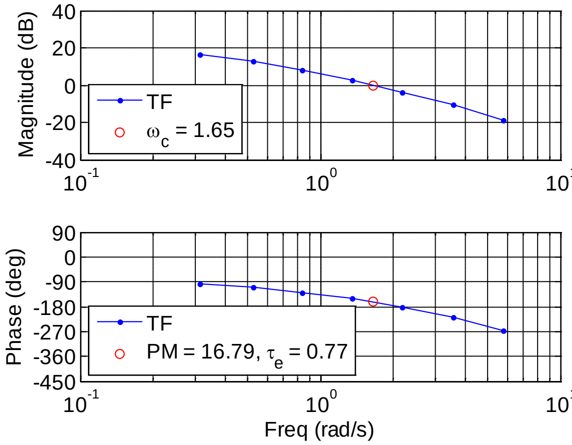
Analysis of the PVS reveals that lower actuator natural frequency and reduced damping have minimal effect on system crossover frequency or piloted task performance for the cases studied herein. The PVS crossover remains the same regardless of the changes in the actuator that occur at higher frequencies. For the disturbance regulation task used in this analysis, even a degradation of actuator natural frequency to 20 rad/s did not affect PVS crossover and, although the reduced damping cases did achieve improved PVS phase margin and effective delay, no significant difference was observed (figure 224).



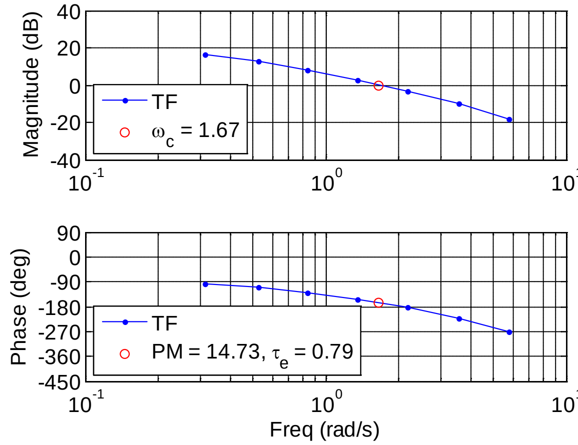
a) $\omega_{n\ \mathrm{act}}$ = 75 rad/s, ζ_{act} = 0.7



b) $\omega_{n\ \mathrm{act}}$ = 20 rad/s, ζ_{act} = 0.7



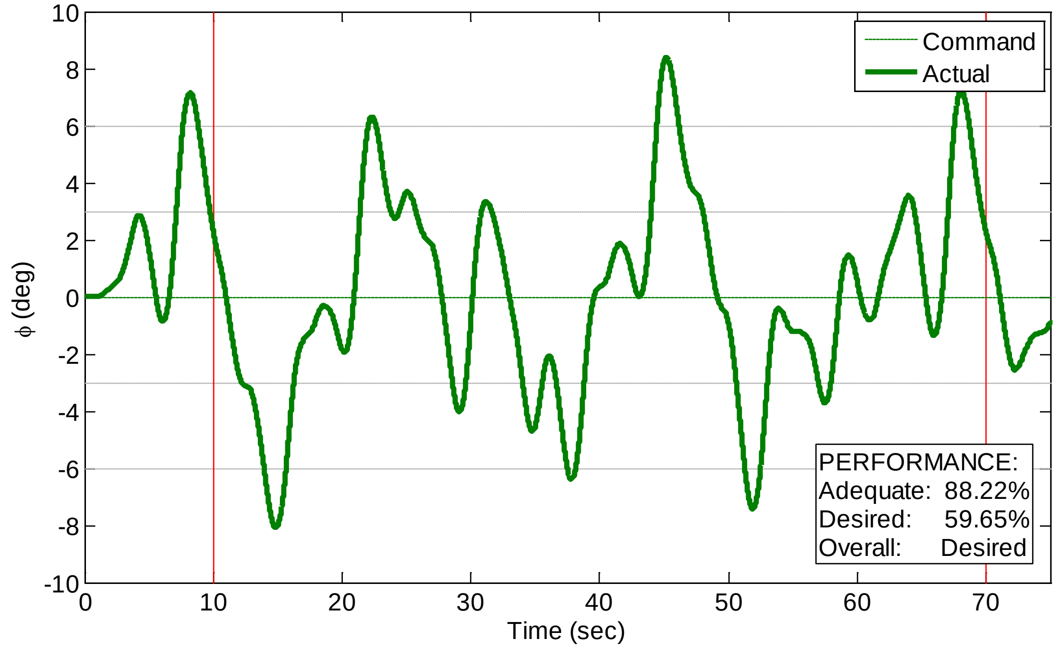
c) $\omega_{n\ \mathrm{act}}$ = 75 rad/s, ζ_{act} = 0.2



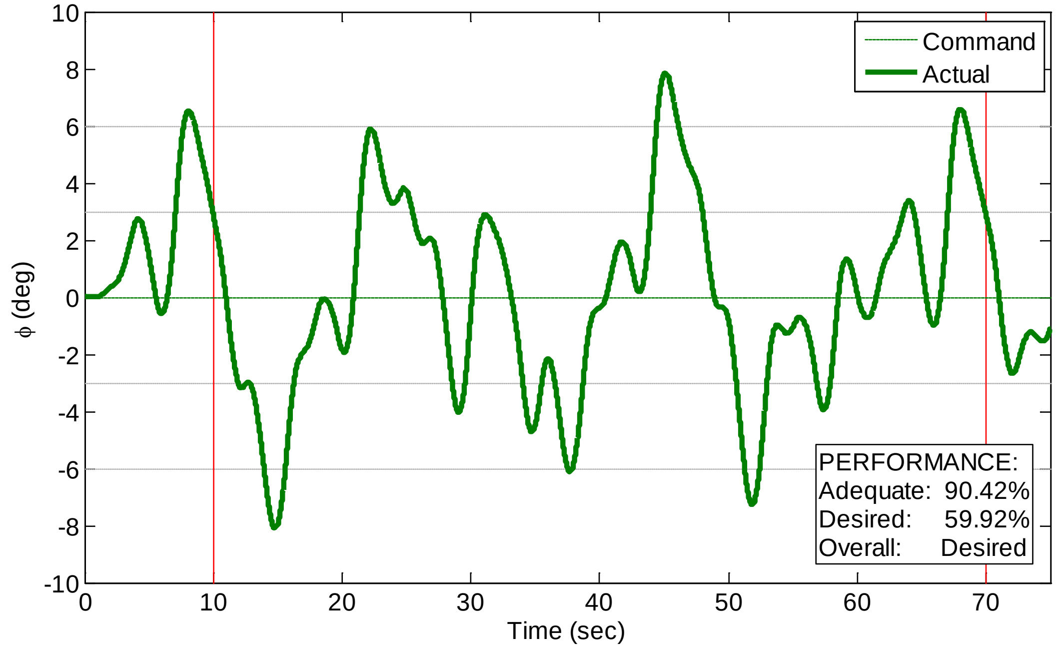
d) $\omega_{n\ \mathrm{act}}$ = 20 rad/s, ζ_{act} = 0.2

Figure 224. Pilot-vehicle describing functions with crossover frequency and phase margin/effective delay

There was, however, a slight improvement in task performance because of the improved effective delay. This improvement was minimal but demonstrated the effect of reduced damping for lower actuator natural frequencies. Performance drops and a small amount of effective delay found their way into the system as the actuator dynamics affected the piloted control frequency range. Less damping allowed the vehicle to respond slightly more quickly, allowing the pilot to keep the bank angle slightly more within performance bounds, but, as shown earlier, the added overshoot impacted precision of control for larger amplitude maneuvering that may be associated with terminal flight operations (figure 225).



a) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7



b) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.2

Figure 225. Task performance time histories

11.5.2.3 Effects of Command Path Dead Zone

Figure 226 and table 82 provide the HQ parameters for the vehicle with a 1° command path dead zone. In general, airplane bandwidth is slightly improved while phase delay is made slightly worse by the introduction of a 1° command path dead zone. The phase delay for the 0.7 damping ratio case at 20 rad/s is approaching level 2 with a PIO risk, though lighter damping cases improve the phase delay to restore it to that of the baseline case.

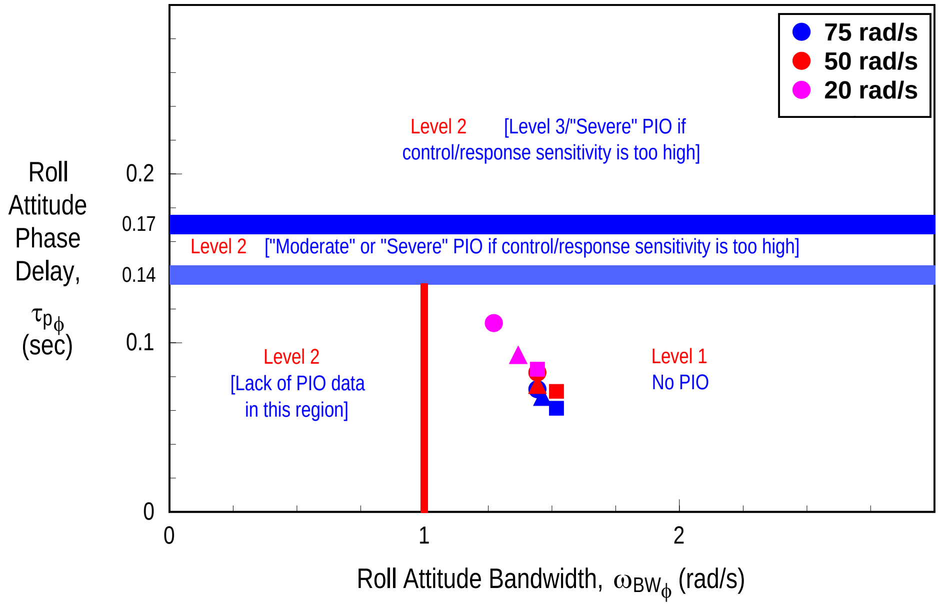
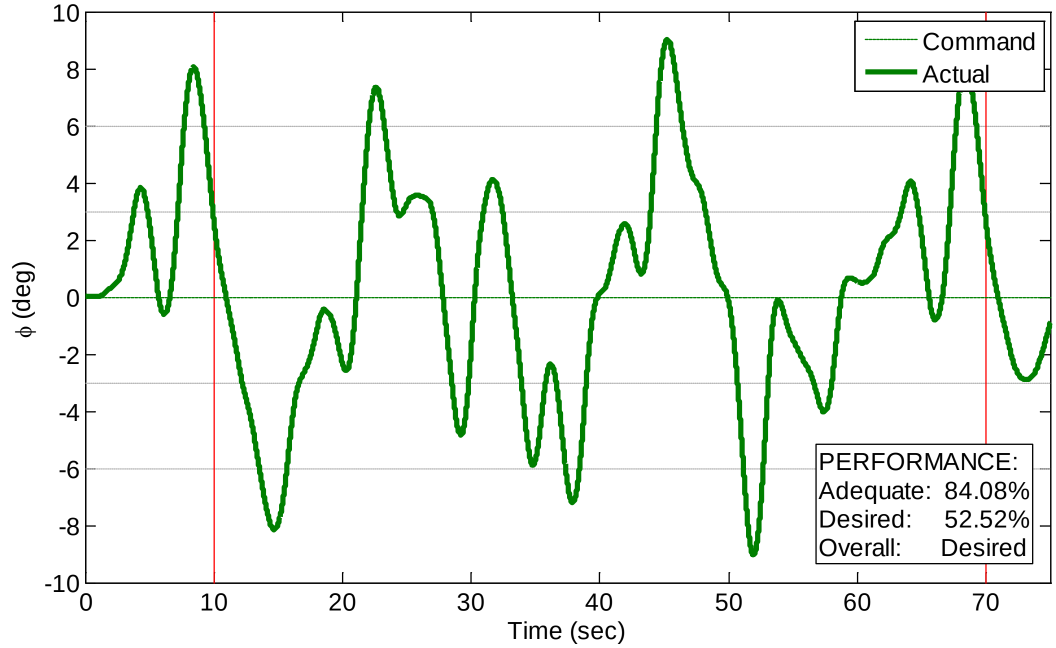


Figure 226. Roll attitude bandwidth/PIO summary for 0.7 (circle), 0.4 (triangle), and 0.2 (square) damping cases with command path dead zone [13]

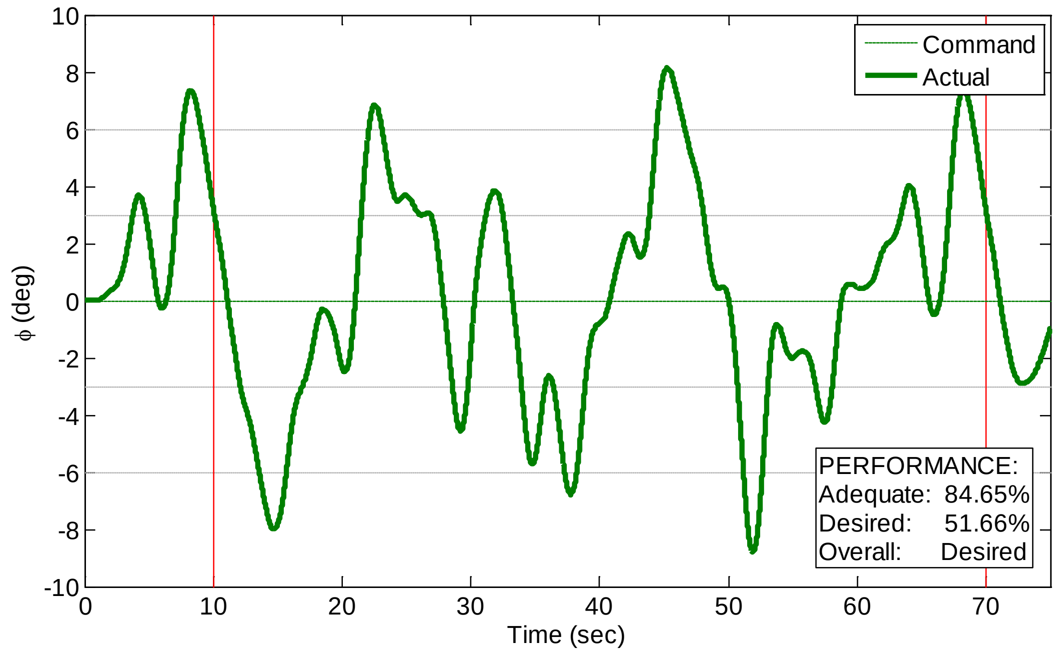
Table 82. Summary of closed-loop aircraft bandwidth/phase delay with command path dead zone

$\omega_{n\ act}$ (rad/s)	$\zeta = 0.7$	$\zeta = 0.4$	$\zeta = 0.2$
75	1.5180 r/s / 0.0763 s	1.6253 r/s / 0.0681 s	1.6253 r/s / 0.0638 s
50	1.5180 r/s / 0.0824 s	1.5180 r/s / 0.0752 s	1.6253 r/s / 0.0713 s
20	1.3651 r/s / 0.1155 s	1.4429 r/s / 0.0929 s	1.5180 r/s / 0.0824 s

Though the airplane bandwidth parameters see a slight improvement with the introduction of the dead zone, this same slight improvement is not seen in task performance for the reduced damping cases, as was seen with no dead zone present. Figure 227 shows the results of the simulated task performance with the dead zone for the 20 rad/s case and, though there are some slight differences in vehicle behavior during the task, the desired and adequate performance percentages do not change.



a) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.7



b) $\omega_{n\ act}$ = 20 rad/s, ζ_{act} = 0.2

Figure 227. Task performance time histories with command path dead zone

11.5.3 Offline Analysis, Observations, and Conclusions

- A sufficiently high frequency of actuator dynamics keeps changes in damping from affecting piloted control in tasks like disturbance regulation. Reduced damping does, however, greatly influence actuator performance in terms of increased overshoot. This change may more significantly impact larger amplitude maneuvering associated with terminal flight operations. Furthermore, the lower natural frequency impacts the rapidity of the initial actuator response.

- When actuator natural frequency is lowered to just above the piloted control frequency range, aircraft HQ and task performance are compromised. These effects can be partially negated with lighter actuator damping, but because of the significant added overshoot in the actuator response, this is not a recommended approach.

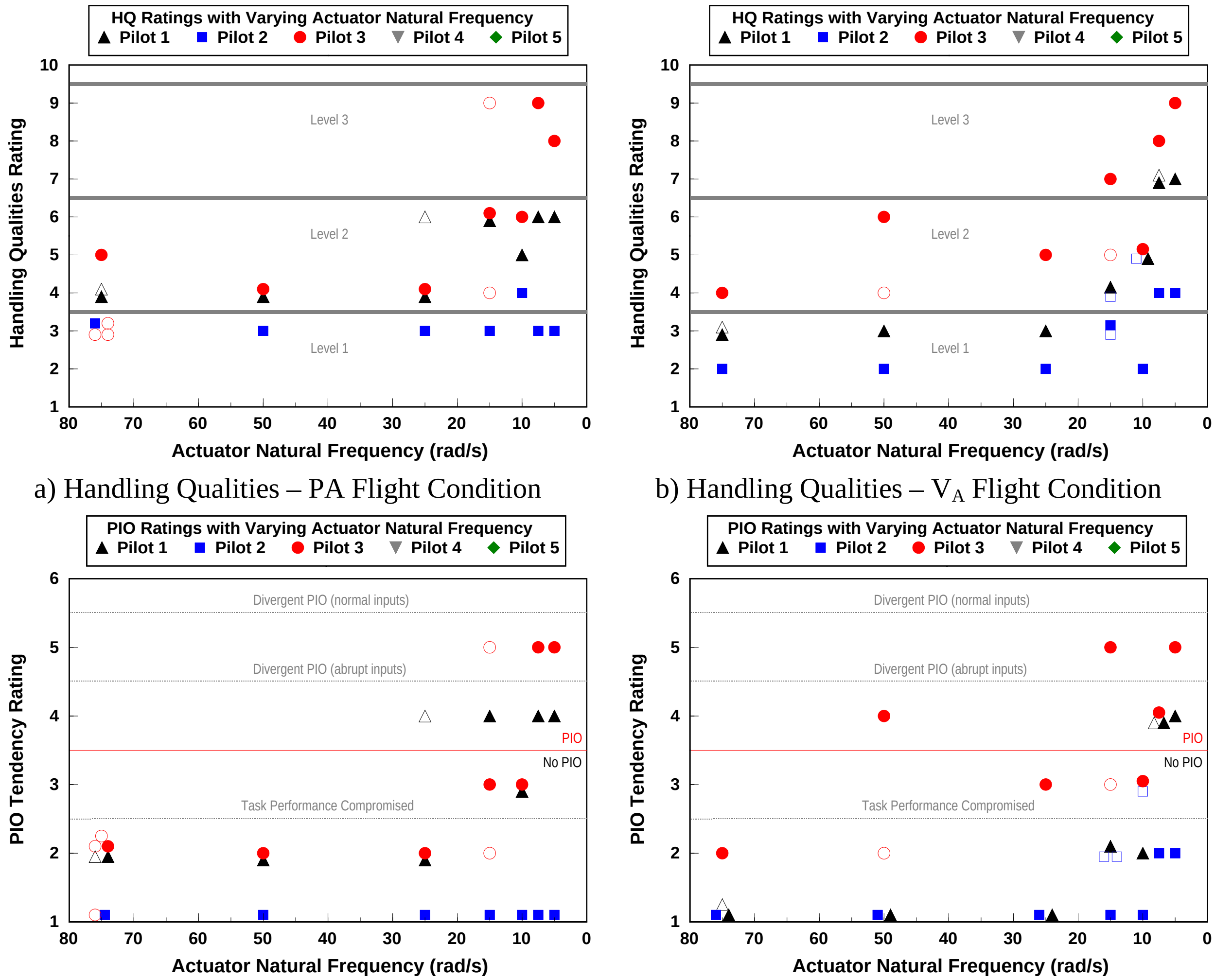
- The introduction of a 1° command path dead zone slightly improves airplane bandwidth parameters, but the same improvement in task performance in cases without a command path dead zone was not seen in the simulation results.

11.5.4 Piloted Evaluations Analysis Summary

Figure 182 presents a summary of the HQ and PIO tendency ratings for the three pilots that participated in the roll actuator natural frequency evaluations. Results for both PA and V_A flight conditions are shown.

Figure 228 gives the HQ and PIO tendency ratings for the PA and V_A flight conditions. Both HQ and PIO tendency ratings degrade significantly for actuator natural frequencies below 25 rad/s. This degradation in ratings is seen for all three pilots who participated in this study for both of the flight conditions evaluated in this study. Configurations with actuator natural frequencies 15 rad/s and under were given especially poor ratings, with one pilot giving HQR of 9 for these configurations, indicating that intense pilot control was required to maintain control of the aircraft. It is therefore recommended that actuator requirements be set above 25 rad/s to avoid issues with poor HQ and an increased risk of PIO.

As shown in tables 83 and 84, and figures 228–230, there is a drop-off in task performance corresponding to the degraded ratings seen above for configurations below 25 rad/s. All pilots noted degradations in performance because of the more sluggish actuator natural frequency. Symbol annotations show HQR for each run.



a) Handling Qualities – PA Flight Condition

b) Handling Qualities – V_A Flight Condition

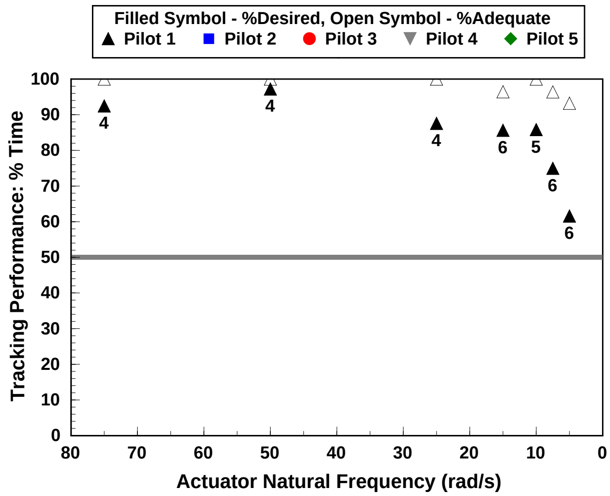
c) PIO Tendency – PA Flight Condition

d) PIO Tendency – V_A Flight Condition

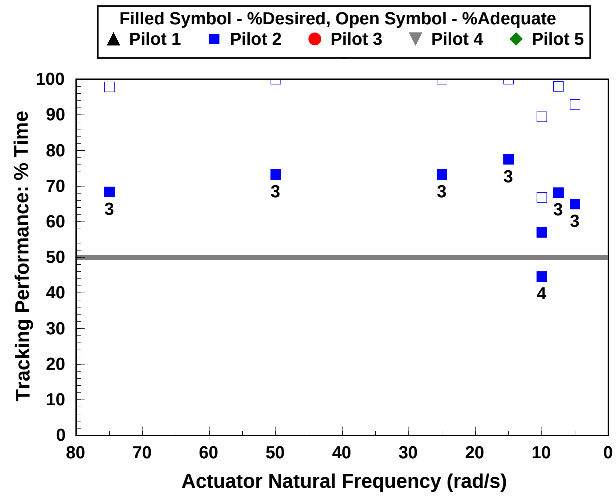
Figure 228. Pilot ratings, all pilots, roll actuator natural frequency variations

Table 83. Task performance summary, roll actuator natural frequency variations, PA flight condition

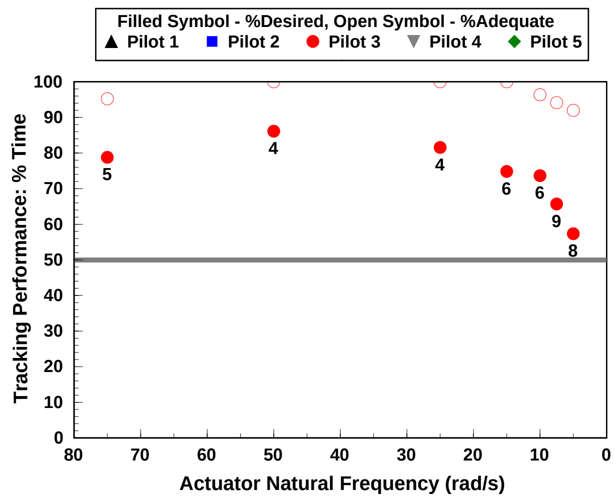
Actuator Frequency (rad/s)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
75.0	92.48	68.38	78.77	–
50.0	97.22	73.27	86.12	–
25.0	87.58	73.28	81.55	–
15.0	85.63	77.55	74.82	–
10.0	85.82	44.60	73.63	–
7.5	74.97	68.15	65.68	–
5.0	61.58	64.95	57.33	–



a) Pilot 1



b) Pilot 2

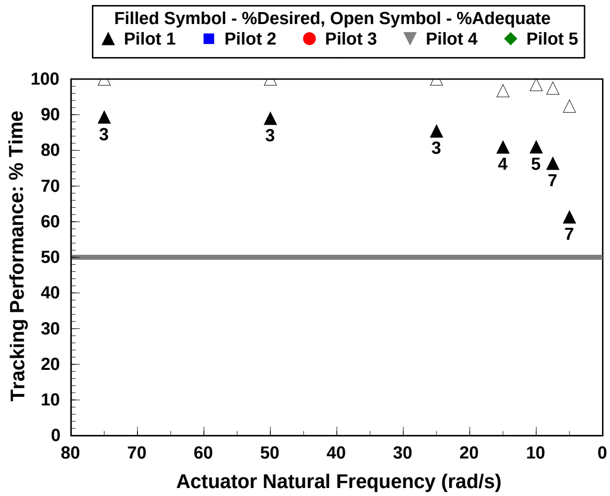


c) Pilot 3

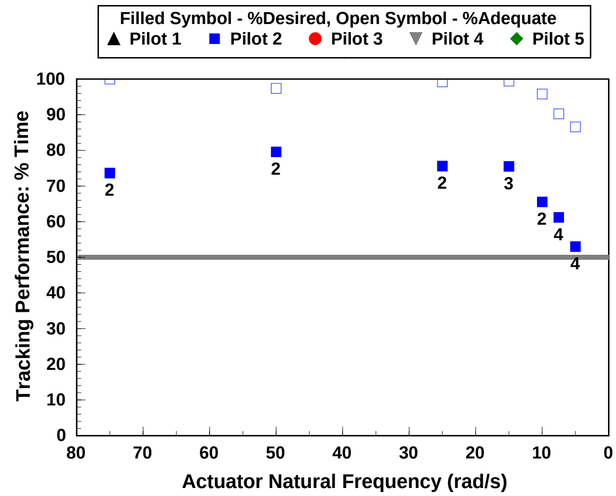
Figure 229. Tracking task performance, roll actuator natural frequency variations, PA flight condition

Table 84. Task performance summary, roll actuator natural frequency variations, V_A flight condition

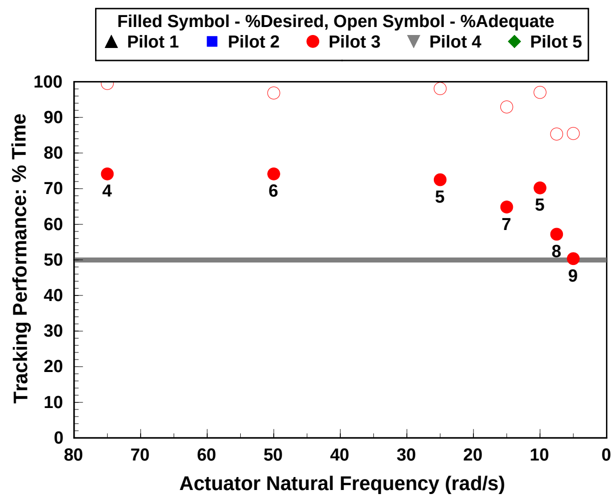
Actuator Frequency (rad/s)	Task Performance (% desired)			
	Pilot 1	Pilot 2	Pilot 3	Pilot 4
75.0	89.33	73.63	74.12	-
50.0	88.98	79.60	74.13	-
25.0	85.42	75.60	72.50	-
15.0	80.93	75.53	64.83	-
10.0	80.98	65.57	70.20	-
7.5	76.37	61.22	57.20	-
5.0	61.32	53.02	50.33	-



a) Pilot 1



b) Pilot 2



c) Pilot 3

Figure 230. Tracking task performance, roll actuator natural frequency variations, V_A flight condition

11.5.5 Detailed Analysis of Selected Cases

11.5.5.1 Introductory Notes

Reviewing variations among pilots or multiple runs by the same pilot can provide insight into the effects of actuator natural frequency variations on pilot behavior and the level of compensation necessary to perform the task. Correlations between degraded ratings for lower frequency actuator dynamics and increased pilot compensation or changes in pilot behavior further emphasize the impact of the feel system natural frequency on the ability to perform the task.

The analysis summarized in this section is presented with the caveat that the data were collected using fixed-base simulation, which may be inadequate to accurately predict the impact of feel system parameter changes in real aircraft because of a lack of motion cueing.

11.5.5.2 Pilot 2 – Session 47 Evaluations

Pilot 2 participated in roll actuator frequency evaluations on June 27, 2012. The data were collected during Session 47 of the Year 2 Follow-on evaluations. A total of eight runs were completed in the roll axis in PA configuration, with one run in the baseline configuration and seven additional runs. Runs varied from baseline (75 rad/s) to the most sluggish configuration of 5 rad/s. One 10 rad/s run was not rated and has been omitted from the results presented.

A full list of the configurations flown and ratings provided by pilot 2 are listed in table 85 and shown in figure 231. Though there is not much variance in the HQR, the one case that was rated higher than the rest (BWLAT10 or 10 rad/s) did not achieve desired performance and provides insight into the effects of lower actuator bandwidth on piloted control.

Table 85. Pilot ratings and comments, pilot 2/session 47

Session	Run	Configuration	HQR	PIOR	Comments
47	1	BWLAT75 (baseline)	3	1	Variable amount of force. Unpredictable. No PIO tendency.
47	2	BWLAT50	3	1	–
47	3	BWLAT25	3	1	Varying amount of input to get result that I want. Very close to before.
47	5	BWLAT10	4	1	A few large oscillations. Predictable. Not always desired. Kind of out of phase.
47	6	BWLAT15	3	1	Smaller amplitude deviations. Unpredictable. Stops very precisely. No PIO tendencies.
47	7	BWLAT05	3	1	Somewhat larger deviations.
47	8	BWLAT7.5	3	1	Small deviations. No PIO.

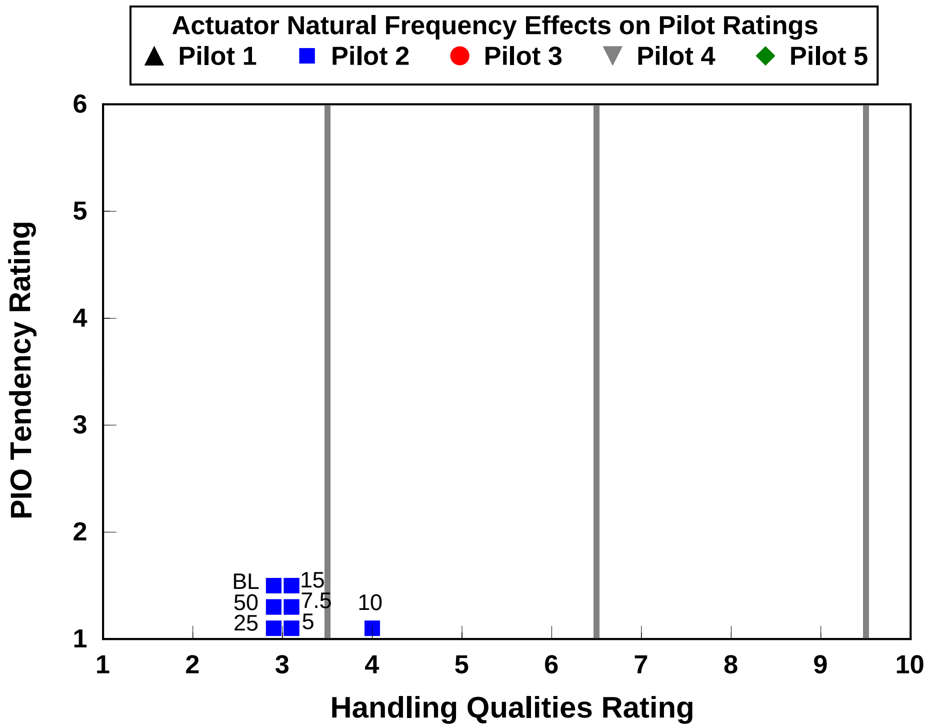
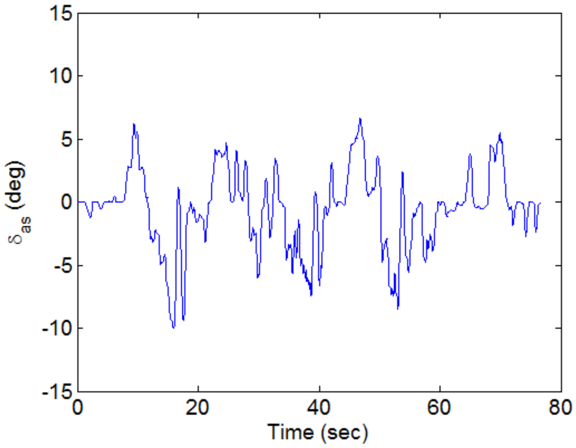


Figure 231. Ratings summary, pitch feel system natural frequency variations, pilot 2/session 47

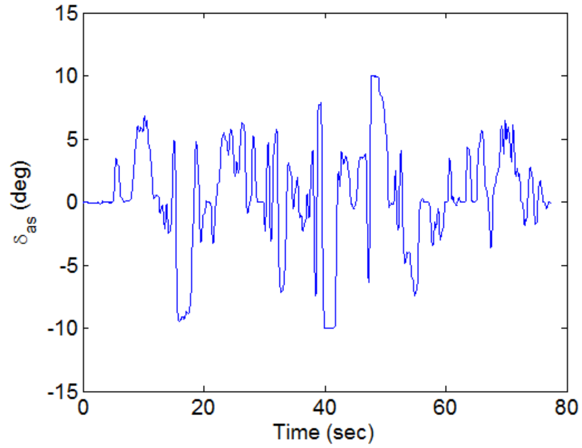
The following analysis will focus on runs 1 and 5 to highlight the differences in how pilot 2 flew the lower frequency case when compared with the baseline and why task performance degraded as actuator natural frequency was decreased.

11.5.5.3 Task Analysis

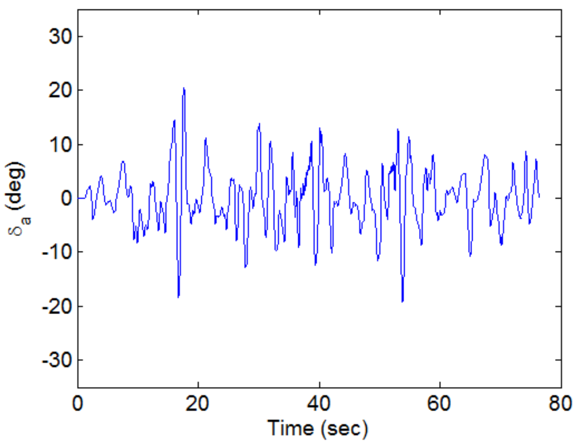
Figure 232 gives time histories for the baseline and 10 rad/s runs evaluated by pilot 2. In figure 232 (b), the pilot encountered the travel limits for the stick at several points in the run. These encounters with the stops correspond to large amplitude control activity (figure 232 (d)) and are most likely due to the pilot's attempts to compensate for the lower frequency actuator. As a result, much larger errors are seen in the bank angle time history (figure 232 (f)), and desired performance cannot be achieved for this run.



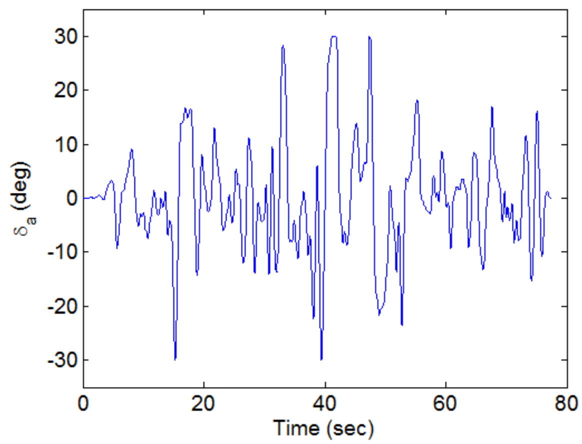
a) Stick Displacement – Run 1 (baseline)



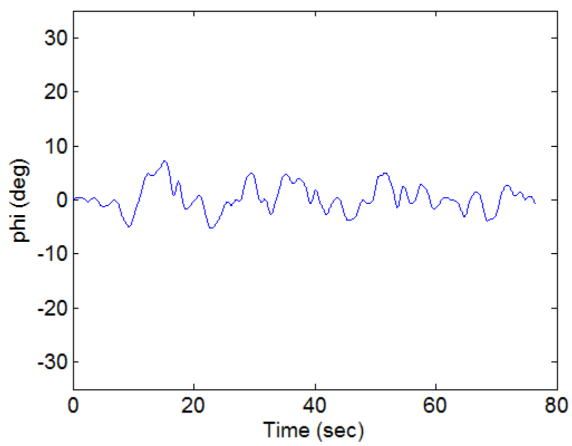
b) Stick Displacement – Run 5



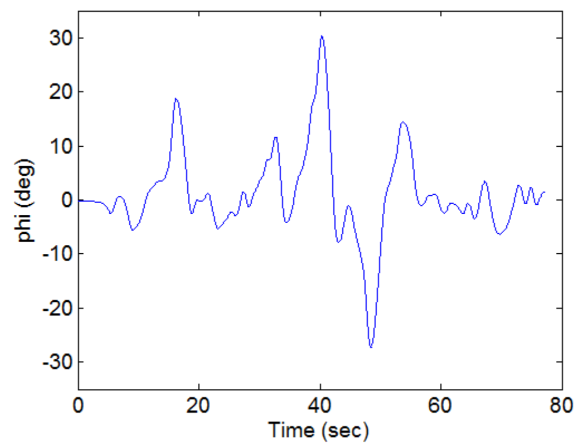
c) Actuator Activity – Run 1 (baseline)



d) Actuator Activity – Run 5



e) Bank Angle – Run 1 (baseline)



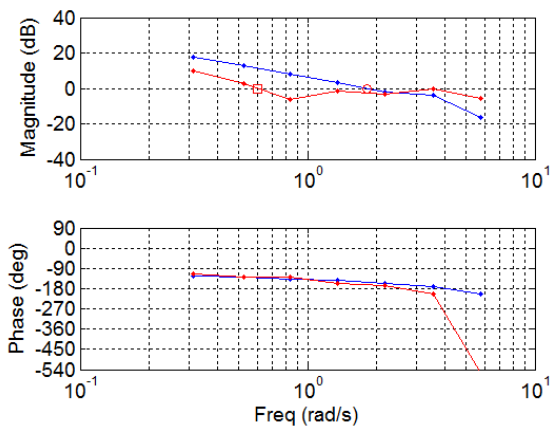
f) Bank Angle – Run 5

Figure 232. Time histories, pilot 2, session 47

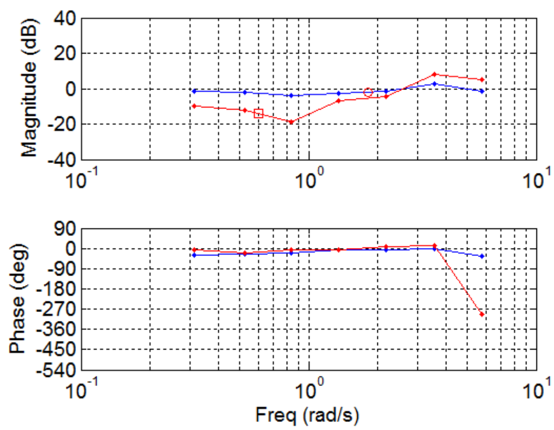
11.5.5.4 The PVS Analysis

Pilot 2 commented that run 5 felt “out of phase” with his inputs, which can be seen in the describing function plots shown in figure 233. First note that the vehicle response (figure 233 (c)) includes the actuator dynamics and shows a rolloff in phase for frequencies above 1 rad/s when compared with the baseline. The “out of phase” comment made by the pilot is because this additional phase lag results from the lower frequency actuator when attempting close loop control above 1 rad/s.

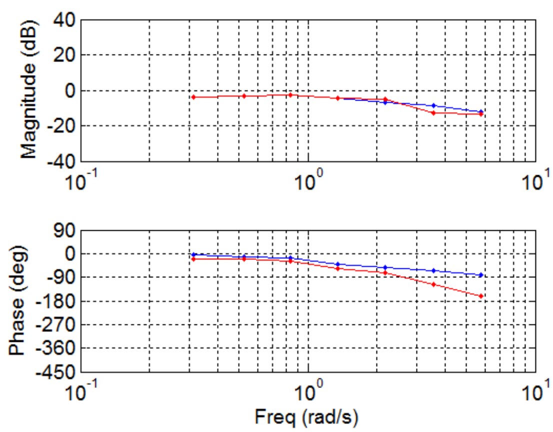
The same result is noted in the pilot-vehicle describing function shown in figure 233 (a). The pilot uses a reduced low-frequency gain and backs out of the loop to avoid reduced stability associated with the added phase lag, resulting in a crossover frequency of 0.60 rad/s, much lower than the 1.82 rad/s for the baseline case. There is also a considerable amount of lead compensation observed in the pilot describing function for frequencies above 1 rad/s (figure 233 (b)) that are not present with the baseline case. This indicates the pilot had to utilize an alternate control approach to perform the task that resulted in reduced task performance and slightly degraded ratings.



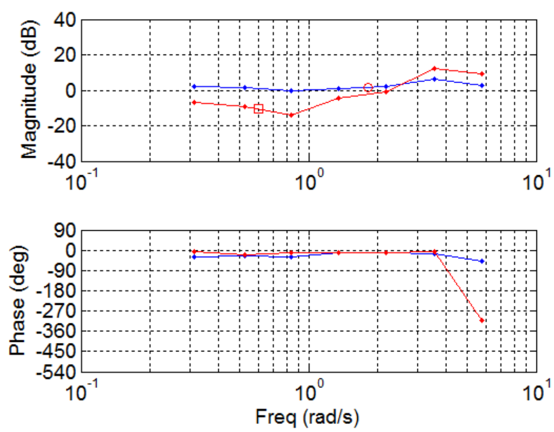
a) Pilot-Vehicle



b) Pilot Without Feel System



c) Vehicle



d) Pilot w/Feel System and Nonlinearities

Figure 233. Identified describing functions, overlay (run 1 – blue, run 5 – red)

11.5.6 Piloted Evaluations, Observations, and Conclusions

- Based on the results of the limited fixed-base simulation study, roll actuator natural frequencies greater than 25 rad/s are recommended as HQ and task performance may be compromised for configurations with lower natural frequencies.

- Control surface actuator natural frequencies below 25 rad/s negatively impact task performance and ratings. The PIO tendency becomes a significant issue for actuator frequencies lower than 25 rad/s because of the additional phase lag incurred.

12. AFI-FCS AUGMENTED AIRCRAFT OFFLINE ANALYSIS

12.1 BACKGROUND INFORMATION

A model of the AFI-FCS was provided by the FAA as a general example of a full envelope protection aircraft control system, operating with a passive inceptor. This design includes the characteristics listed in the following excerpt, in bulleted form, provided by the FAA [1]):

- An energy based thrust control function, which is normally engaged, but can be disengaged.
- A vertical FPA Rate Command/FPA Hold augmented manual control algorithm, intended for “Direct FPA control.”
- A continuously adapting parabolic schedule for the Nz_{cmd} versus inceptor deflection relationship, such that a full ND deflection always commands a delta Nz = -1 g (relative to equilibrium flight condition), zero deflection always commands a delta Nz = 0 g, while a full NU deflection always commands the maximum aerodynamically achievable Nz (reduced by a .1 g safety margin) or the structural limit Nz. The resulting Nz_{cmd} is converted to an FPA rate command and integrated to develop the reference FPA command.
- Augmented manual Roll Rate Command/Roll Attitude Hold control/Beta command mode. For this control algorithm, the roll control inceptor deflection commands a proportional roll rate. With the roll control inceptor at neutral, the bank angle is maintained if it is less than 30 degrees (neutral spiral stability). When the bank angles is greater than 30 degrees and the roll control inceptor is returned to neutral, the bank angle will decrease smoothly to 30 degrees and hold there (strong spiral stability). The roll inceptor output is normalized to +1/-1 at full deflection and interpreted to command a proportional roll rate. The roll rate command is integrated to provide the reference roll angle command. Currently, the bank angle limit is set at 60 degrees. This limit can only be attained and maintained by a full lateral stick/wheel deflection. The rudder pedal deflection commands a proportional sideslip angle, as well as a coordinated bank angle, to maintain zero cross track acceleration—thus allowing for a de-crab without drifting sideways at the design condition.
- Automatic FPA control mode
- Altitude Acquisition/Hold modes
- Automatic IAS mode (requiring auto thrust to be engaged)
- Automatic Heading Angle control mode
- Automatic Track Angle control mode
- Vmin/Vmax control, covering all automatic and augmented manual control mode operations. The automatic modes use speed priority control on the elevator to continue to maintain the

commanded speed after the thrust control reaches its limits (T_{max} or T_{min}) due to vertical mode maneuvering. The speed command selected by the pilot is limited to Vmin on the low side and V_{max} on the high side. The Vmax is defined by Flap Placard , landing gear position, and V_{mo}. V_{min} is based on a dynamic V_{stall} computation, using airplane weight and Cl_{max} (which is a function airplane configuration), and then corrected for bank angle. Airplane weight is estimated based on the lift coefficient as defined by AOA, airplane configuration, dynamic pressure, and Normal Load Factor. Alternatively, weight can be entered as a fixed value. For the automatic modes and for the augmented manual mode when the pitch control inceptor is at neutral, the V_{min} = 1.2 Vstallbank and when the pitch control inceptor is full NU the Vmin effectively equals 1.05 Vstallbank.

- When the autothrust function is engaged and after thrust reaches its upper limit, the airspeed is allowed to drop off relative to the IAS control mode command in proportion to inceptor deflection, so that for continued full NU deflection, the airspeed will settle at 1.05 Vstallbank, thereby in effect providing Static/Speed Stability. Similarly, for a ND inceptor defection and after thrust reached the idle limit, the speed is allowed to increase relative to the IAS control mode command in proportion to inceptor deflection, so that for continued full ND deflection the airspeed will settle at Vmo or other selected Vmax. The selected IAS command on the Mode Control Panel is used as the “Reference Trim Speed,” so that when the inceptor is returned to the neutral position, the speed will return to the selected IAS command.
- When the autothrust is disengaged, the vertical maneuvering induced normalized longitudinal acceleration (vdot/g) at constant thrust is approximately equal to and opposite in sign to the change in vertical FPA. Therefore, in order to keep the airspeed constant, the pilot must manually adjust the thrust in proportion to the change in FPA, using the acceleration cue on the PFD. A change in FPA without changing thrust can only be sustained until the speed margin to Vmin or Vmax becomes depleted, at which time the speed protection control will engage to stabilize the airspeed at Vmin or Vmax. The reference speed for Vmin control is Vmin = Vstallbank (1.2- .15*δ_{stick}) and the reference speed for Vmax control is Vmax = Vmo-K_{vmo}*δ_{stick} . So, with the control inceptor at neutral and no active thrust control, the speed will settle at 1.2 Vstallbank or Vmo, and for a continued full nose deflection the airspeed will settle at 1.05*Vstallbank—at which time all of the available kinetic energy has been converted to altitude. Similarly, and for a continued full down inceptor deflection the airspeed will settle at Vmo -K_{vmo}*δ_{stick}. Thus, when the autothrust function is disengaged, static/speed stability is provided with 1.2 Vstallbank as the “Reference Trim Speed” on the low side of the speed range and Vmo on the high speed side of the speed range.

12.2 AUGMENTED AIRCRAFT DYNAMICS

12.2.1 Introduction

This section describes the data generation procedure and presents an example analysis of the simulation model supplied by the FAA for the FBW and active stick research effort. A matrix of 14 cruise and 12 approach flight conditions was selected for system identification and FQ analysis. In the pitch axis, additional flight conditions were analyzed at 20,000 ft.

Frequency sweep data were generated and analyzed using the Systems Technology Incorporated (STI) proprietary Rapid Analysis Parameter Identification Software (RAPIDS) software suite. System identification was performed with the FREDA and Narrowband Signature (NBS) identification routines. The aircraft model did not allow for frequency sweep inputs in its original state, so modifications were made in order to generate the necessary input-output data for analysis.

In addition to end-to-end system identification results, this section briefly reviews the bare airframe dynamics and examines the actuator identification to check for a linear actuator response to the input used to generate the end-to-end identification data. Though a full analysis of the airframe and actuator dynamics is not included, an example is shown for each configuration.

An FQ summary is also shown with PIO susceptibility analysis and a bandwidth/phase delay study that investigates the characteristics of the closed-loop aircraft in the pitch and roll axes.

12.2.2 Data Generation

12.2.2.1 Flight Conditions and Weight Configuration

A total of 26 flight conditions were analyzed; three airspeeds at four altitudes for the approach case and four airspeeds at four altitudes for the cruise case. The 350 knots (kts) case, at 10,000 and 15,000 ft, could not be trimmed and were excluded from the analysis. Cases were selected to represent realistic trim conditions for the aircraft and configurations being modeled (figure 234 and tables 86 and 87).

The approach configuration was defined as flaps down with landing gear extended. The cruise configuration was “clean” with flaps and landing gear retracted. All cases were for the same configuration with a weight of 120,000 lb. and c.g. and aerodynamic center location of 25% MAC (zero bare airframe SM).

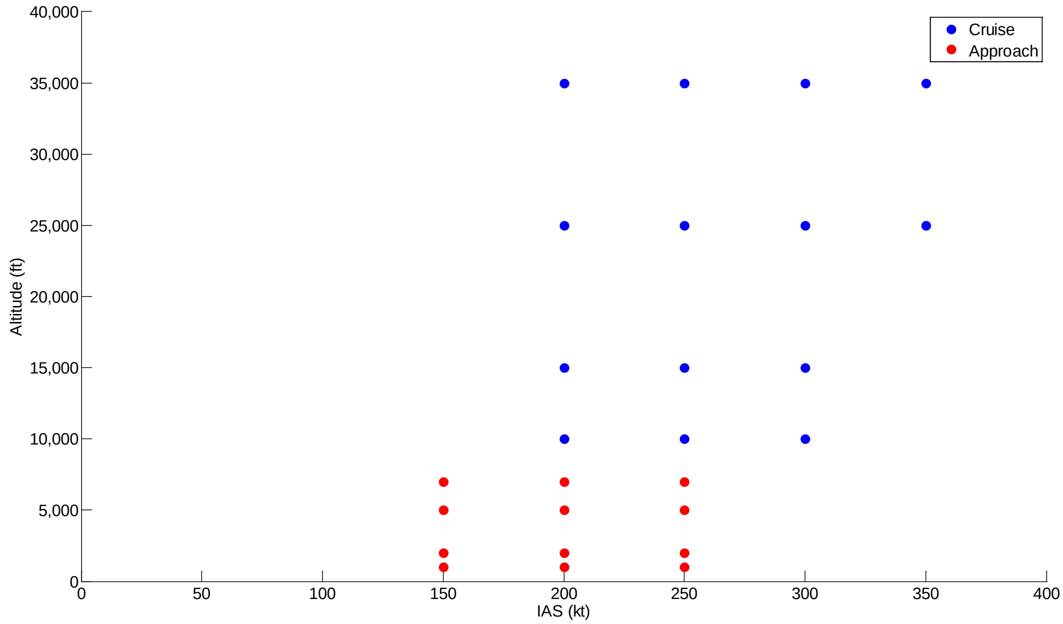


Figure 234. Flight condition analysis matrix

Table 86. Flight conditions used for analysis — cruise configuration

IAS (kt)	Altitude (ft)
200	10,000
200	15,000
200	25,000
200	35,000
250	10,000
250	15,000
250	25,000
250	35,000
300	10,000
300	15,000
300	25,000
300	35,000
350	25,000
350	35,000

Table 87. Flight conditions used for analysis — approach configuration

IAS (kt)	Altitude (ft)
150	1,000
150	2,000
150	5,000
150	7,000
200	1,000
200	2,000
200	5,000
200	7,000
250	1,000
250	2,000
250	5,000
250	7,000

12.2.2.2 Frequency Sweep Inputs

Time history data were generated using frequency sweep inputs that varied in frequency from 0.05–30 rad/s. The duration of the frequency sweep was 100 seconds, with 15 seconds of zero padding to allow the aircraft to fully trim at the selected flight condition. The total time history length for each run was 115 seconds. An example frequency sweep is shown in figure 235.

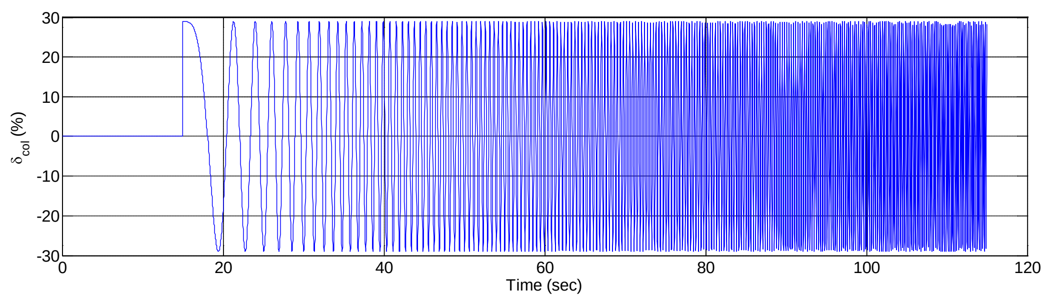


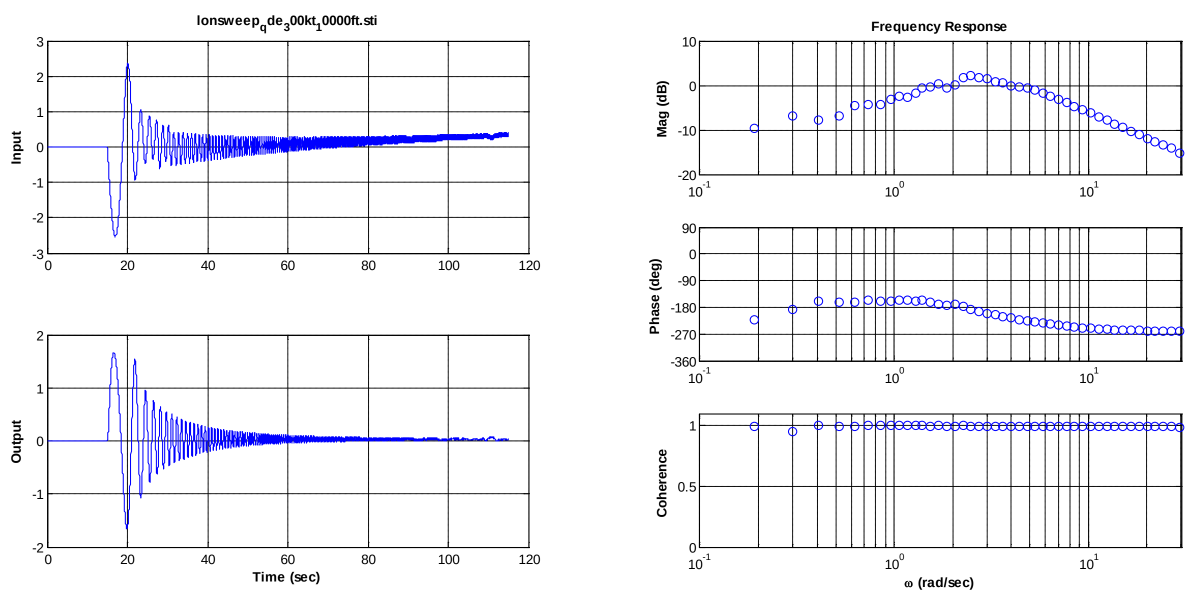
Figure 235. Example longitudinal axis frequency sweep input

12.2.2.3 System Identification

The frequency sweep data were analyzed using the RAPIDS software suite, which was developed by STI as a system identification and analysis tool with novel identification algorithms aimed at improving the results obtained from both traditional frequency sweep and shorter duration pulse and doublet inputs.

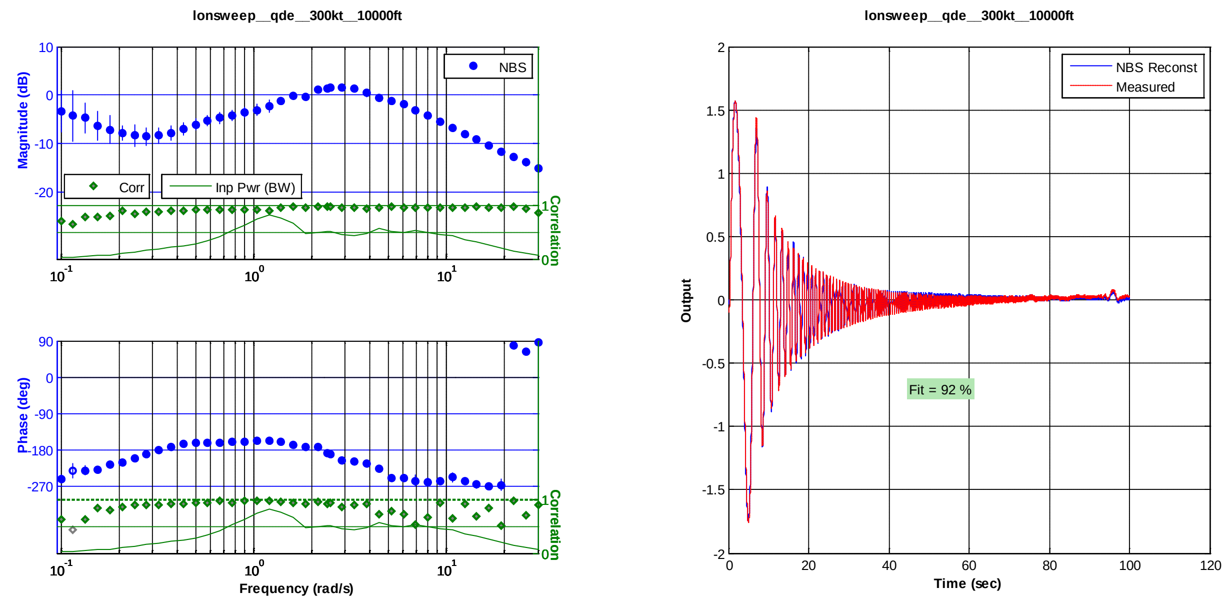
RAPIDS software uses two algorithms to perform its system identification. The first is FREDA, a traditional fast Fourier transform (FFT) routine developed by STI. Additional analysis can be performed using the NBS identification algorithm developed specifically for use in RAPIDS. This method, while maintaining the quality of the frequency response identification from sweep inputs typically seen with traditional FFT methods, greatly improves the identification results when using shorter duration inputs. For this analysis, however, only frequency sweep inputs were used so that any method of identification can be called upon if the analysis needs to be repeated. The RAPIDS software suite and NBS identification method are described in more detail in [20].

Example results for both methods follow. Note that the time history used for the identification is shown in figure 236 (a) and is the same for the results in figures 236 and 237.



a) Time History b) Identified Frequency Response

Figure 236. Example FREDA identification results



a) Identified Frequency Response b) Time Series Reconstruction

Figure 237. Example NBS identification results

<u>12.2.3 Actuator Model Analysis</u>

The simulation model uses a linear actuator representation with an undamped natural frequency of 30 rad/s and a damping ratio of 0.7. The purpose of this analysis is to check the linear behavior of the actuator in the presence of the 25 deg/s elevator rate limit and examine the response of the ailerons to an aileron deflection command.

Figure 238 shows the results of the actuator identification. To perform this analysis, the actuator deflection command is selected as the input and the actual deflection is selected as the output. A frequency sweep is then injected into the column command signal for frequencies of 1–10 Hz (6.28–62.8 rad/s). The resulting identified system is the response of the actuator to commands and allows one to determine how linearly the actuator is behaving for the column sweep input used.

It is noted that the identified response shown in figure 238 shows nonlinear behavior that does not match the actuator model for frequencies above 10 rad/s. Though the phase response overlays with the model for frequencies up to our 62.8 rad/s limit, the magnitude response shows a significant rolloff for frequencies above 10 rad/s. Upon further investigation, figure 239 shows an expanded view of the output time history for the 5-second interval between t = 97 and 102 seconds. In this interval, about 15–20 seconds from the end of the run, the input frequency is nearing the upper limit of 62.8 rad/s. This high-frequency region is where the gain mismatch is observed and we note the jagged response typical of nonlinearity. Although it is possible this is because of the higher frequency inputs causing the elevator to encounter the rate limit, it is also possible that there is some form of calculation or sampling issue causing the data to appear sparse at higher frequencies. This would cause the input-output correlation to be suspect and the identification algorithms to incorrectly identify the system at these frequencies.

The same behavior can be seen in the aileron response shown in figure 240. Though the jagged response is not as severe for the lateral case, it is still significant and possibly the cause of the high-frequency phase loss exhibited by the identified response shown in figure 241.

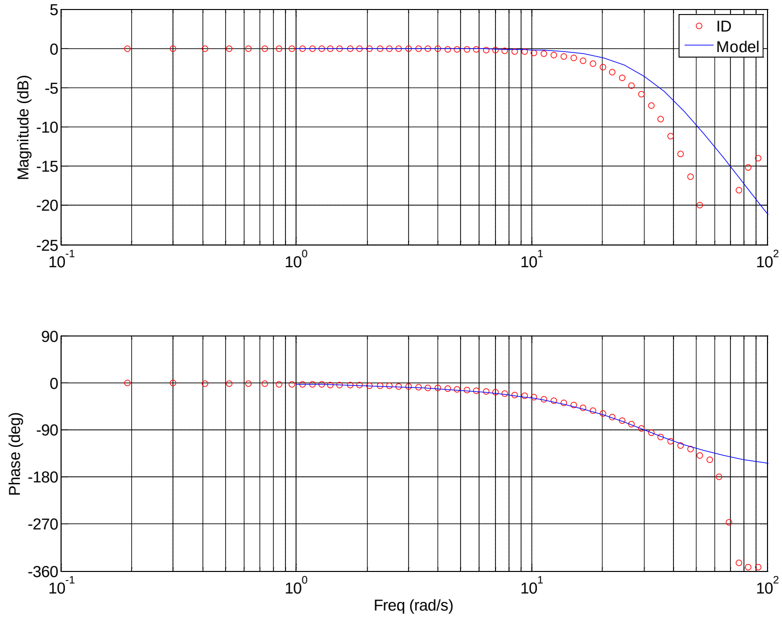


Figure 238. Comparison of linear and identified elevator actuator frequency responses

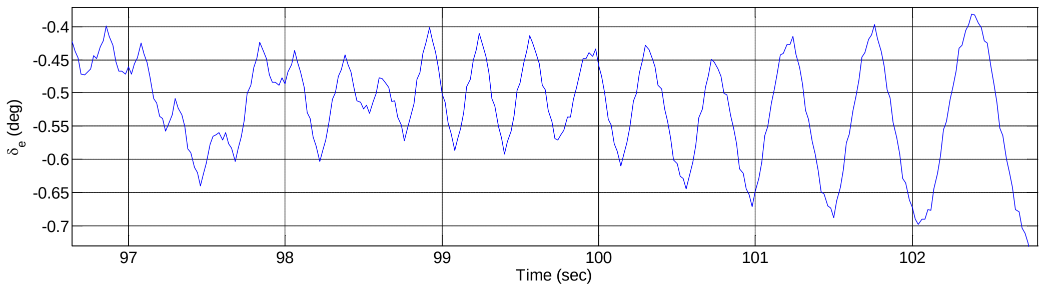


Figure 239. High-frequency elevator response

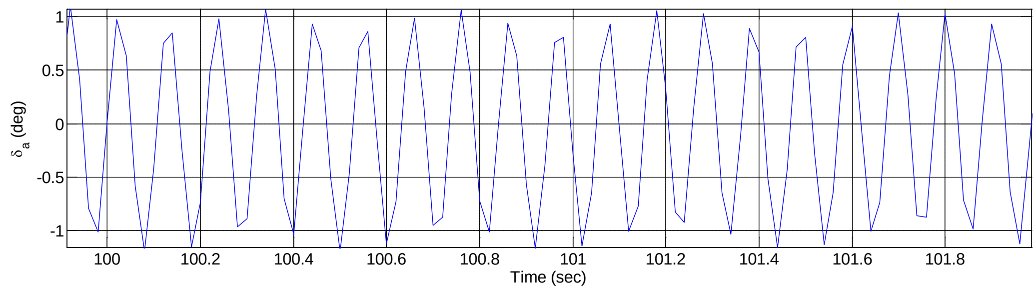


Figure 240. High frequency aileron response

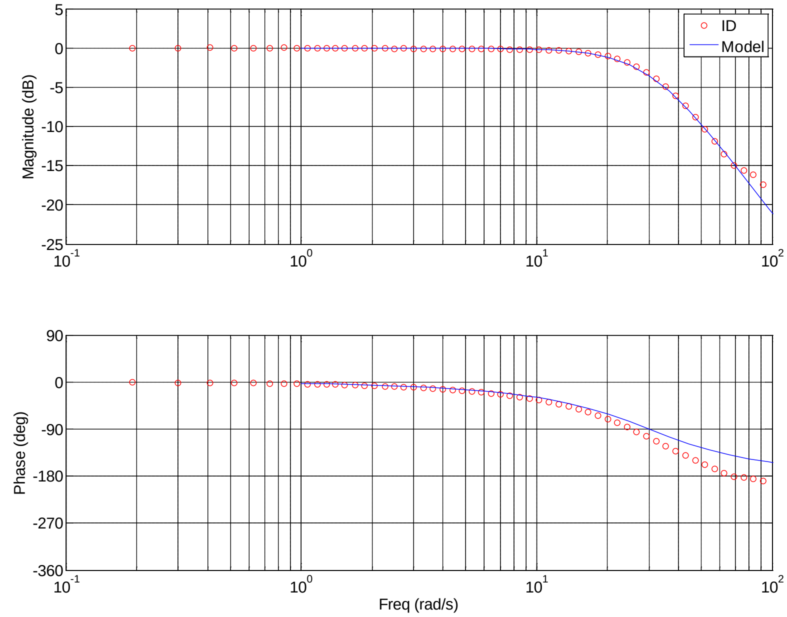


Figure 241. Comparison of linear and identified aileron actuator frequency responses

Decreasing the sample time from 0.02 seconds (50 Hz) to 0.01 seconds (100 Hz) confirms that a large part of the nonlinearity shown in the identification is due to sample time errors. At this faster sample time, the jagged response is much smoother (figure 242) and the corresponding identification (figure 243) matches the linear model much more closely.

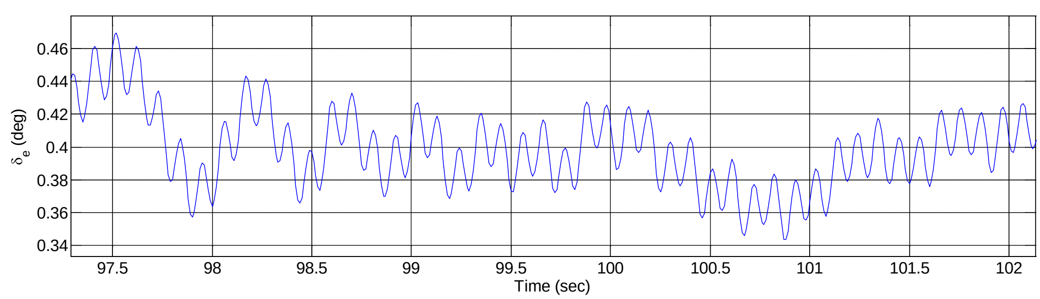


Figure 242. High-frequency elevator response with 100 Hz sample rate

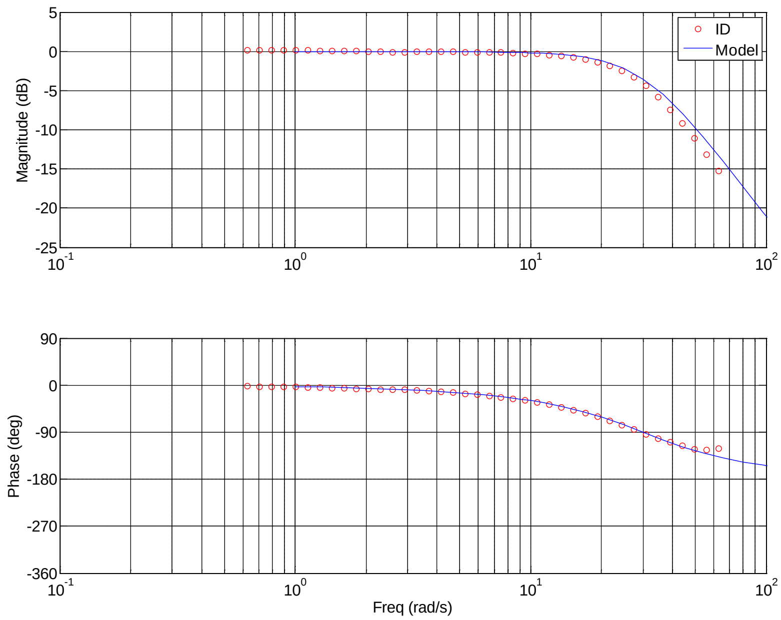
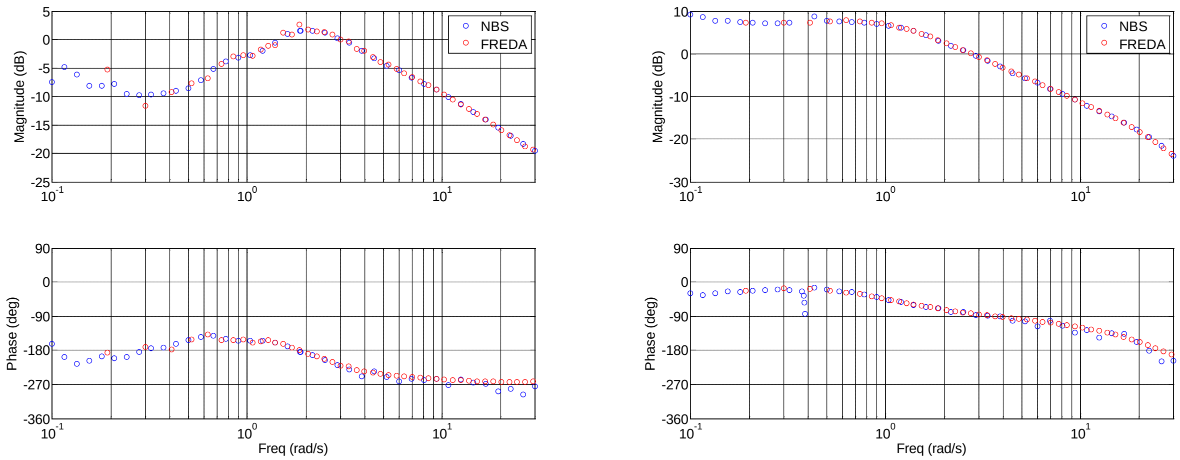


Figure 243. Identified elevator actuator with 100 Hz sample rate

12.3 UNAUGMENTED AIRCRAFT DYNAMICS

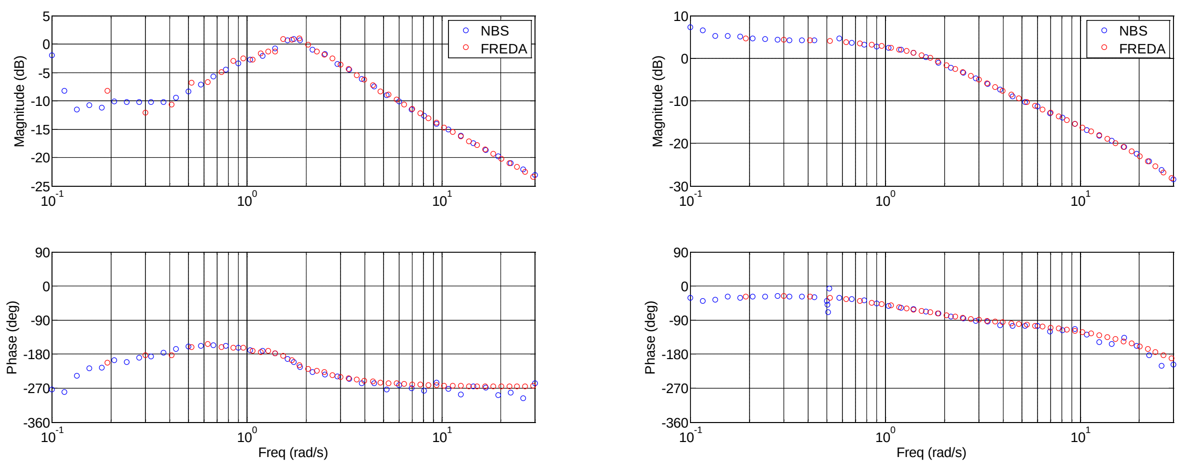
The dynamics of the airframe can be identified in a manner similar to the method used to identify the actuators in the previous section. A single column/wheel sweep can be used with an input signal scoped at various locations in the feedback loop architecture to identify frequency responses for the various components of the model.

To identify the airframe, the longitudinal and lateral body rate responses were selected as outputs to control surface deflection inputs. Using the rate signal typically yields more output power than attitude responses. Example identification results in both axes are shown for the cruise and approach configurations in figures 244 and 245.



a) Longitudinal b) Lateral

Figure 244. Identified airframe dynamics in cruise configuration — 250 kt., 25,000 ft



a) Longitudinal b) Lateral

Figure 245. Identified airframe dynamics in approach configuration — 150 kt., 2,000 ft

12.4 LONGITUDINAL MODEL FITS

In the longitudinal axis, it is important to understand the characteristics of the short-period mode of motion because it will determine the short-term response of the aircraft to pilot inputs and has the most significant effect on HQ. A transfer function fitting routine was used to fit the identified data with a second-order transfer function meant to represent the short-period dynamics. Though this method is not exact, the results can be used to expose trends and give insight into the behavior of the aircraft and the effects of flight condition and configuration changes on the modes.

An example mode fit is shown in figure 246. We see the identified bare airframe for the 250 kt. cruise case at 25,000 ft. There is a distinct peak in the response at a frequency that is typical of the short-period dynamics of an airplane of this size and configuration. Using the STIFIT fitting routine that is included in RAPIDS, a transfer function fit determines the mode to be at approximately 2.1 rad/s with a damping of about 0.65.

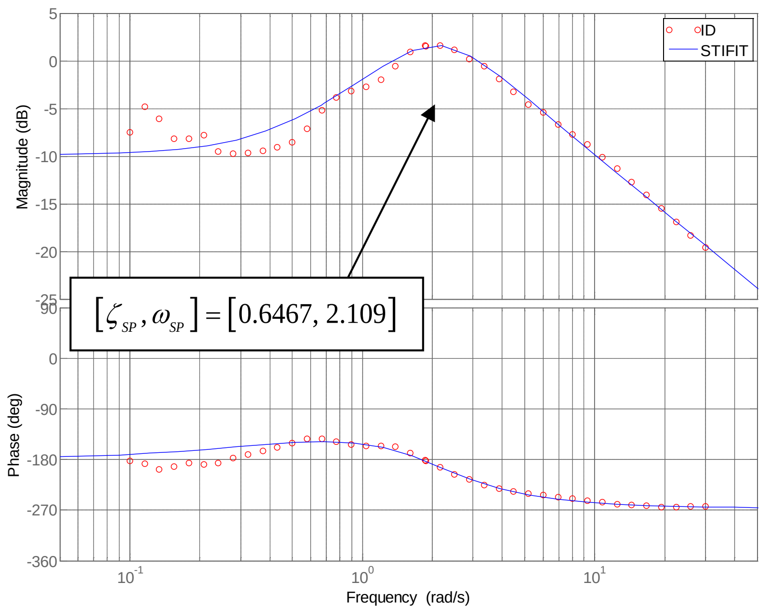


Figure 246. Example mode fit to determine short-period characteristics in cruise, 250 kt., 25,000 ft

The full results of the analysis are shown in tables 88 and 89. We observe that for cruise, both damping and natural frequency generally decrease with altitude, but increase with airspeed, and the airframe generally exhibits a fairly well-damped SP for all flight conditions considered. The approach cases follow the same trend, with the lowest natural frequencies and highest damping ratios at the low and slow ends of the analysis matrix.

Table 88. Short-period mode determined by fit, cruise configuration

IAS (kt)	Altitude (ft)	[ζ_{SP}, ω_{nSP}]
200	10,000	[0.5828, 1.669]
200	15,000	[0.5722, 1.656]
200	20,000	[0.5632, 1.634]
200	25,000	[0.5538, 1.583]
200	35,000	[0.5893, 1.486]
250	10,000	[0.7230, 2.167]
250	15,000	[0.7117, 2.142]
250	20,000	Indeterminate
250	25,000	[0.6467, 2.109]
250	35,000	[0.6412, 1.785]
300	10,000	[0.7855, 2.786]
300	15,000	[0.7619, 2.739]
300	20,000	[0.6952, 2.763]
300	25,000	[0.6624, 2.667]
300	35,000	[0.7323, 2.412]
350	25,000	[0.7246, 3.183]
350	35,000	[0.7651, 2.955]

Table 89. Short-period mode determined by fit, approach configuration

IAS (kt)	Altitude (ft)	[ζ_{SP}, ω_{nSP}]
150	1,000	[0.5603, 1.573]
150	2,000	[0.5503, 1.603]
150	5,000	[0.5331, 1.626]
150	7,000	[0.5302, 1.623]
200	1,000	[0.6133, 1.637]
200	2,000	[0.6100, 1.640]
200	5,000	[0.6002, 1.653]
200	7,000	[0.5977, 1.637]
250	1,000	[0.6693, 2.354]
250	2,000	[0.7192, 2.193]
250	5,000	[0.6560, 2.420]
250	7,000	[0.6170, 2.354]

Figure 247 shows a case for which a fit could not be determined. For the 26 total cases analyzed, this was the only flight condition that was indeterminate. A fit could not be found because of the odd phase behavior, which can be seen when comparing the phase response in figure 247 to that of the adjacent flight condition, shown in figure 246. While the phase response in figure 246 starts at -180 degrees and rolls off to -270 degrees at higher frequencies, the phase response in figure 247 starts near 0 and rolls off continuously near the mode. As a result, the routine fails to fit a second order mode to the data.

The NBS identification could be a possible reason for this issue. For this analysis, only the NBS identification data were used as they provide more points in the frequency range of interest and are generally smoother in nature when compared to the results from FREDA. The NBS identification supplies two phase responses—one a raw response, the other a response that has been magnitude correlated. The magnitude-correlated response is also smoother than the raw NBS phase, so it was used to avoid errors in the fitting routine due to erratic phase data. This worked well for most of the cases analyzed, but the magnitude-correlated phase for the 250 kt. case at 20,000 ft. was inconsistent.

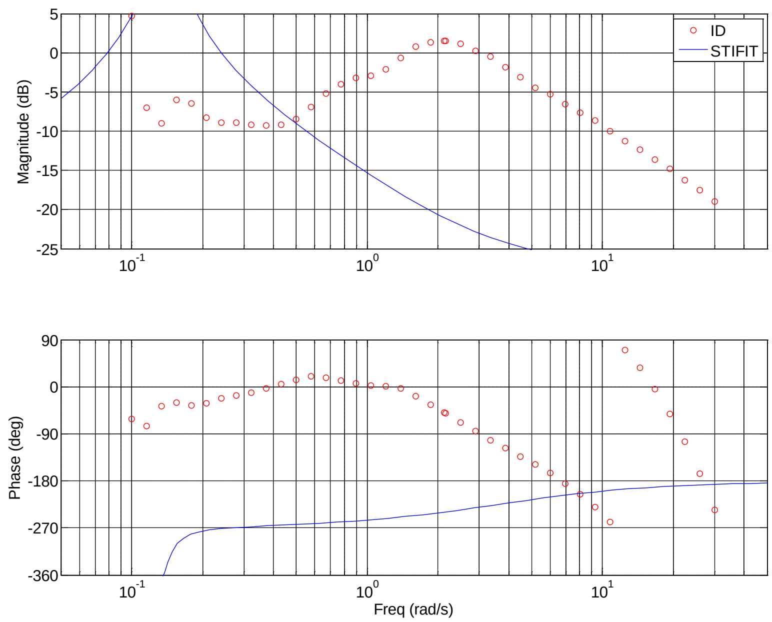


Figure 247. Indeterminate short-period mode fit for cruise configuration, 250 kt., 20,000 ft

Using the raw NBS identification data allowed for a fit to be determined, shown below in figure 248. The mode is found to have a damping of 0.58 and a natural frequency of 2.24 rad/s, which is higher than the other flight conditions in this area of the envelope, shown in tables 87 and 88. Repeating the analysis for the other flight conditions shows that, in general, the identified mode is of slightly higher frequency when using the raw NBS response as opposed to the magnitude-correlated identification data.

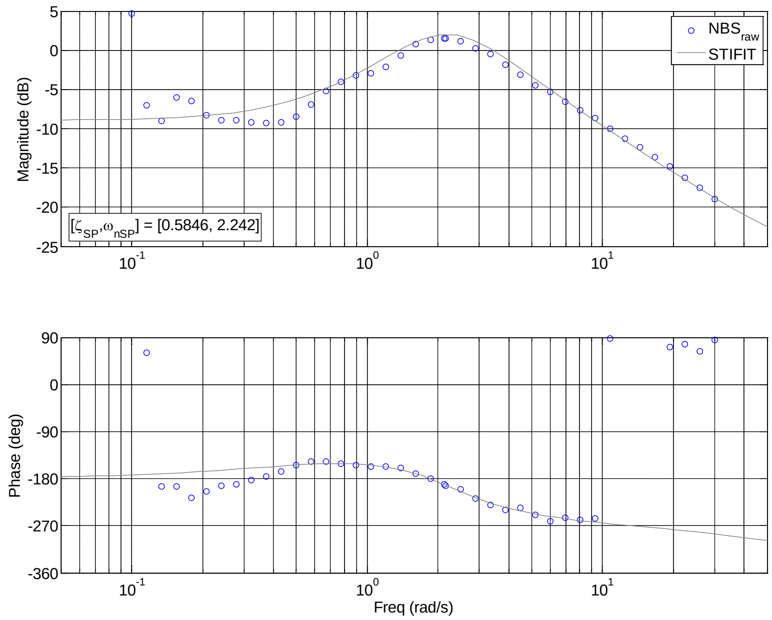
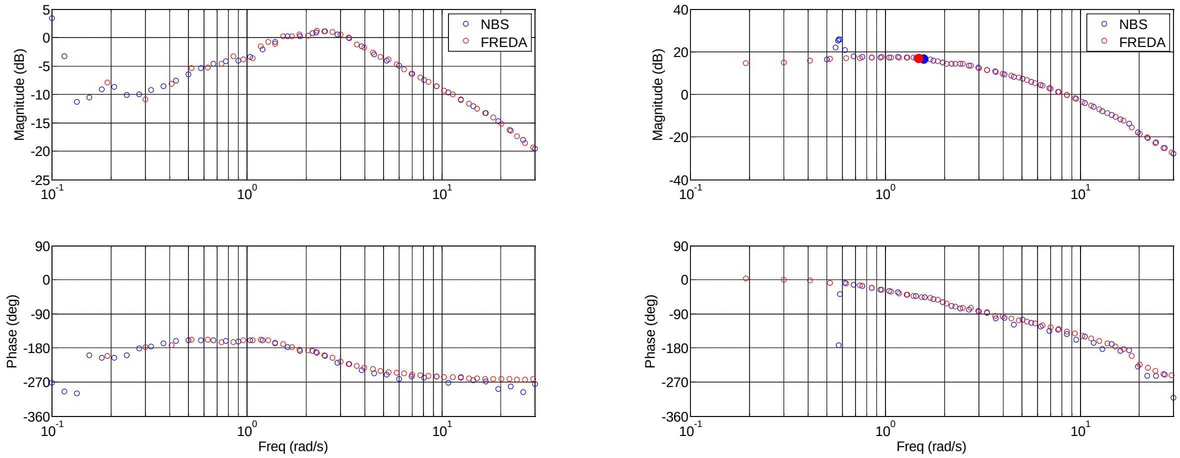


Figure 248. Short-period mode fit using NBS raw-phase identification

12.5 CLOSED-LOOP SYSTEM IDENTIFICATION

To perform an HQ assessment, the end-to-end closed-loop system was identified and analyzed. The same column/wheel frequency sweep inputs were used to generate input-output data for pilot input to aircraft rate response. This data was then identified to determine the effects of the FCS on the closed-loop frequency response of the system. For the purpose of brevity and because the roll closed-loop responses are not significantly altered by the FCS architecture, only the pitch axis will be presented.

Below are the identification results for the open- and closed-loop systems. The analysis shows that the closed-loop system eliminates the second-order nature of the SP and attempts to provide a first-order response to pilot inputs. This is done through static inversion, as described in [21]. The goal of the FCS is to give consistent HQ for all cases at all flight conditions, and an examination of the bandwidth criteria in the next section details the success of this system in providing consistent predicted HQ.



a) Bare Airframe b) Closed Loop

Figure 249. Comparison of longitudinal responses, approach configuration — 250 kt, 5,000 ft

12.6 HANDLING QUALITIES ANALYSIS

12.6.1 Introductory Notes

The closed-loop identifications will be used to determine bandwidth/phase delay in the pitch and roll axes as a means of assessing the HQ of the simulation model. A PIO assessment can also be performed to determine the tendency of the model to encounter PIO for the cases and configurations considered. A brief review of the criteria background followed by a summary of the results of this study are presented below.

12.6.2 Criteria Background

12.6.2.1 Pitch Criteria

For general HQ purposes, the criteria input parameters are pitch attitude bandwidth ($\omega_{BW\theta}$) and pitch attitude phase delay ($\tau_{P\theta}$). An auxiliary input parameter is flight path bandwidth ($\omega_{BW\gamma}$).

In figure 250, the pitch axis HQ criteria can be found. Along the horizontal axis is the airplane pitch attitude bandwidth frequency in rad/s. Airplane bandwidth is a measure of the highest frequency at which the pilot can operate the control system without threatening stability. Along the vertical scale is the phase delay parameter in seconds. Phase delay is another important parameter for closed-loop tracking tasks. It measures the "rate-of-change" of phase loss if the pilot has to increase frequency to control the aircraft at or beyond the bandwidth frequency. Together, bandwidth and phase delay have been shown to be effective predictive measures of aircraft HQ for closed-loop tasks. The thin-lined red boundaries mark levels of HQ based upon bandwidth and phase delay. Regardless of task or aircraft class, HQ degrade as the plot line moves from the lower right of the graph to the upper left. Currently, there is no upper limit on bandwidth frequency.

Along with general pitch axis HQ, bandwidth and phase delay are also strongly related to the prediction of PIO tendencies. The high-frequency dynamics of the aircraft and control system, characterized by phase delay, are the primary drivers of the wide blue boundaries found in figure 250. Only transport-applicable requirements are shown.

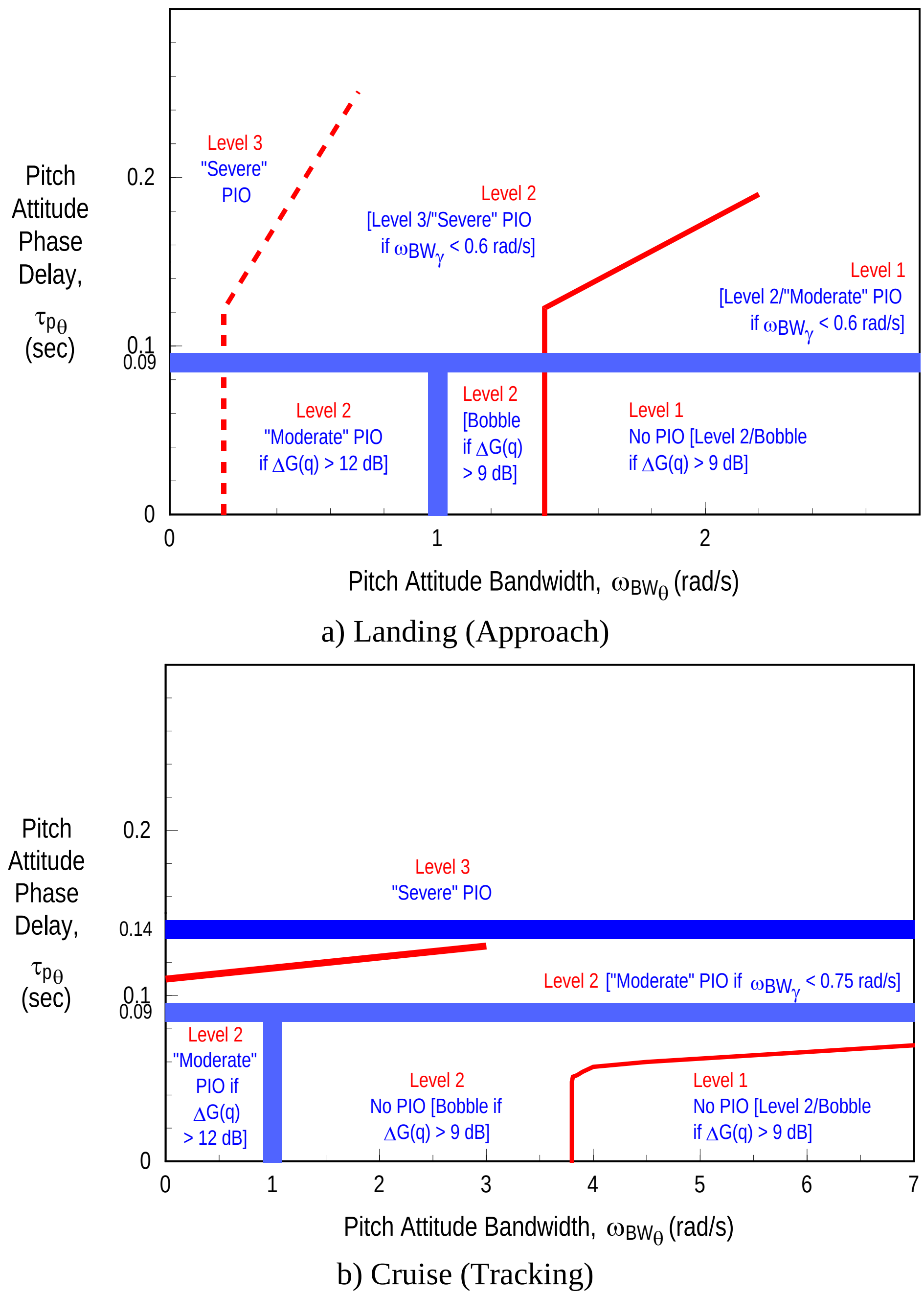


Figure 250. Pitch axis HQ criteria [13]

12.6.2.2 Flight Path Requirements

Another HQ concern in the longitudinal axis is the control and handling of flight path. As stated in [22], a consonance between flight-path and pitch-attitude dynamics should exist to meet pilot expectations. When the flight path control is far more abrupt or more sluggish than the attitude response, attempts by the pilot to control flight path in a precise manner may be problematic or lead to the possibility of PIO. Research has shown a strong interdependence between the flight path and attitude response, as shown in figure 251.

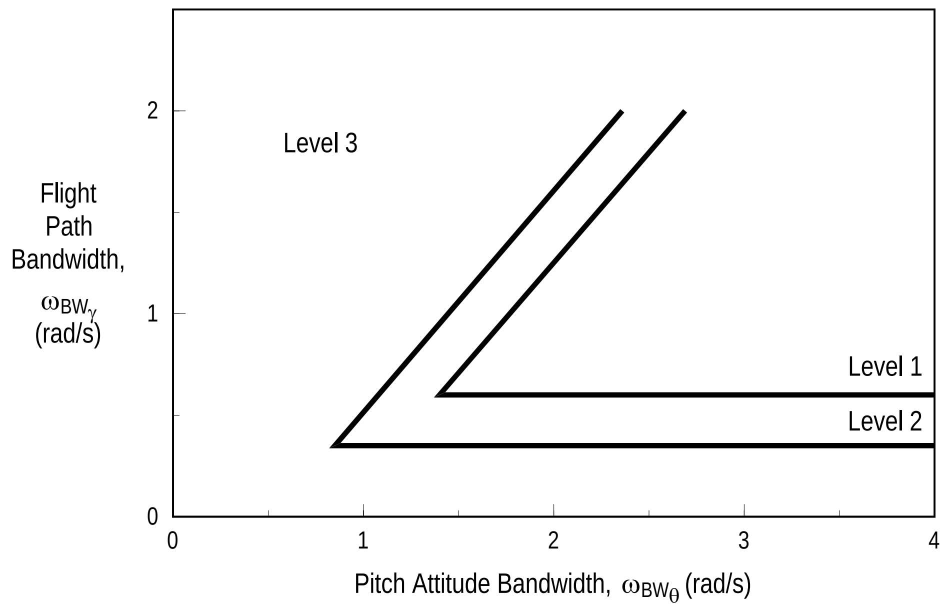


Figure 251. Flight path/attitude consonance HQ requirements [13]

Along the vertical scales is the flight path bandwidth ($\omega_{BW\gamma}$). Flight path bandwidth is measured as the frequency at which there is 45 degrees of phase margin left in the response of flight path to inceptor force input (measured in an identical fashion as the phase margin portion of pitch attitude bandwidth above). The requirement is applicable to a wide variety of aircraft performing a multitude of tasks. Transports are class III; typically, the closed-loop compensation made by the pilots is in the form of gradual control inputs to capture and maintain flight path.

12.6.2.3 Roll Criteria

Unlike the longitudinal axis, there has been little attempt to develop exotic response dynamics for lateral-directional motions. Thus, the modal criteria generally work well. It is still possible, however, to design advanced CLAWS that do not fit the classical response characteristics described by modal parameters. In this case, nonmodal criteria are needed. There has been some work on a set of "lateral-directional Neal-Smith" requirements that have not been widely adopted, and on lateral attitude bandwidth criteria. Both of these suffer from the same basic problem: a severe shortage of data, especially for transports. Other than the NASA HSR program, there is virtually no systematic database for development of lateral-directional criteria for transports. Revised HQR/PIO boundaries from [13] are provided in figure 252.

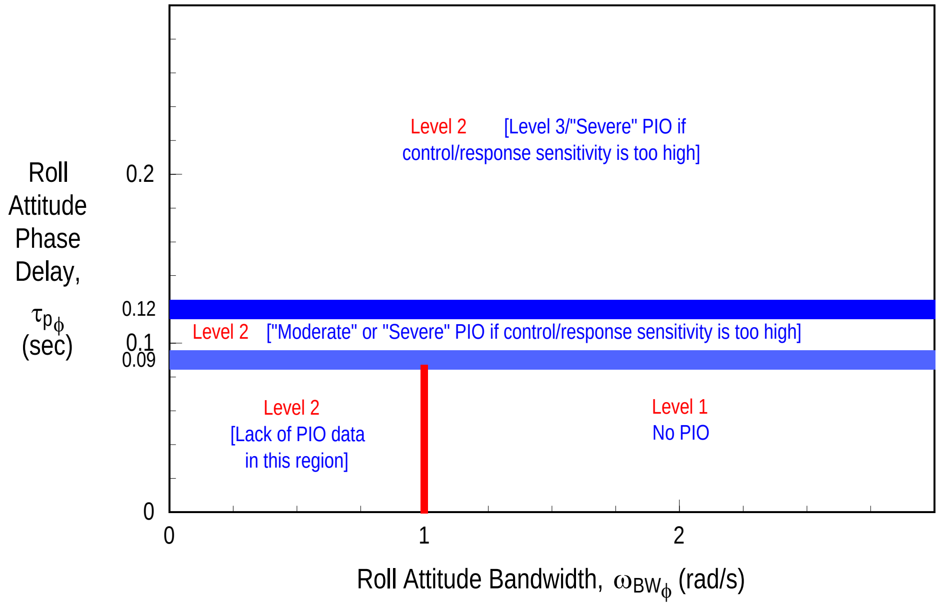
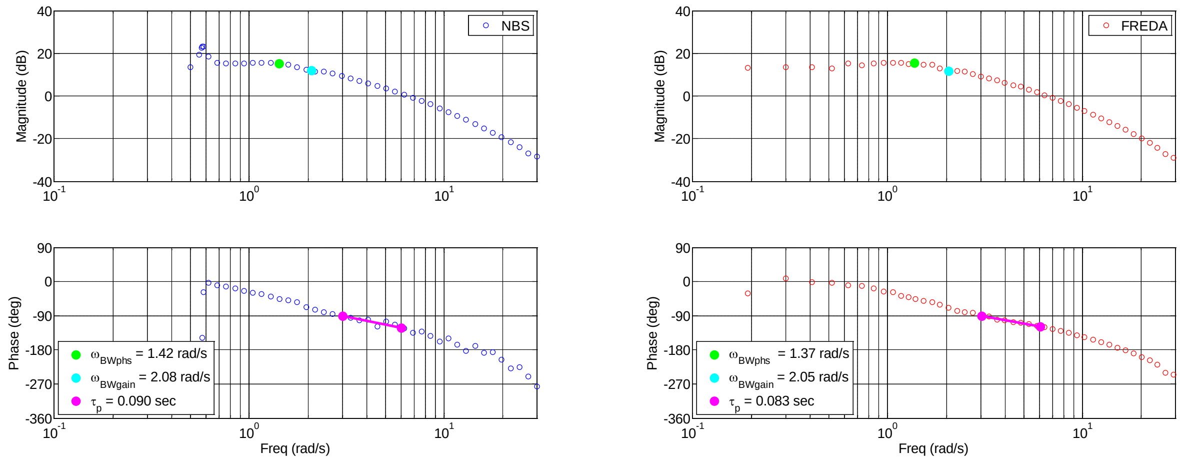


Figure 252. Revised HQR/PIO boundaries for all flight conditions

12.6.3 Pitch Attitude Bandwidth

The pitch attitude bandwidth was determined to assess the HQ and PIO tendency of the aircraft. Figure 253 provides an example of the calculations, with both phase and gain bandwidths shown on the plots as well as the two points used to calculate the phase delay. For this analysis, the raw NBS phase identification is used to avoid issues caused by miscalculations in the magnitude-correlated phase data.



a) NBS b) FREDA

Figure 253. Example bandwidth/phase delay calculation, cruise configuration — 300 kt, 15,000 ft

Repeating the calculations for all of the cruise cases, we find that the bandwidth remains fairly consistent in the 1.3–1.7 rad/s range for the entire envelope. Phase delay was also fairly consistent, with values of 80–90 msec for the lower airspeeds considered. At higher altitudes and higher airspeeds, however, the phase delay increases dramatically and for some flight conditions is nearing 120 msec. This indicates that for higher indicated airspeeds not considered for this analysis, phase delay could pose a problem for both HQ and PIO. Table 90 summarizes the pitch attitude bandwidth calculation, with both FREDA and NBS results listed.

Table 90. Pitch attitude bandwidth/phase delay, cruise configuration

IAS (kt)	Altitude (ft)	Bandwidth (rad/s) (FREDA/NBS)	Phase Delay (msec) (FREDA/NBS)
200	10,000	1.498/1.634	81.7/86.6
200	15,000	1.529/1.634	81.0/86.6
200	20,000	1.579/1.634	80.5/86.6
200	25,000	1.635/1.784	81.7/86.6
200	35,000	1.566/1.560	85.8/98.4
250	10,000	1.467/1.508	86.4/99.6
250	15,000	1.511/1.612	87.5/99.6
250	20,000	1.529/1.634	88.4/99.6
250	25,000	1.662/1.634	90.1/99.6
250	35,000	1.725/1.766	113.4/111.2
300	10,000	1.338/1.353	83.2/100.2
300	15,000	1.372/1.420	82.5/90.4
300	20,000	1.387/1.423	84.9/90.4
300	25,000	1.501/1.561	118.7/129.1
300	35,000	1.595/1.634	102.4/111.5
350	25,000	1.349/1.353	112.0/88.2
350	35,000	1.444/1.476	89.2/99.5

When plotting the data onto the bandwidth/PIO criteria for cruise tracking, most of the cases lie near or past the border that predicts moderate PIO for cases in which flight path bandwidth is less than 0.75 rad/s. Flight path bandwidth is analyzed in a later section, but the results show that for all of the cases plotted in figure 254, flight path bandwidth is less than 0.75 rad/s, indicating a risk for moderate PIO for all cruise configurations when pitch tracking is required.

Assessing HQ, the cruise tracking criteria show that the aircraft is well into the level 2 HQ region with several cases approaching the level 3 boundary. The NBS identification for the KCAS = 300 case at Hp = 25,000 ft is shown as level 3 and the FREDA results for the same case are on the boundary. This observation, combined with the low flight-path bandwidth, indicates an aircraft with poor responsiveness and PIO tendencies.

The bandwidth plots shown in this section (such as the one shown in figure 254) use solid symbols for FREDA results and open symbols for NBS results. The PIO boundaries are for feel system excluded for all bandwidth/PIO plots as well.

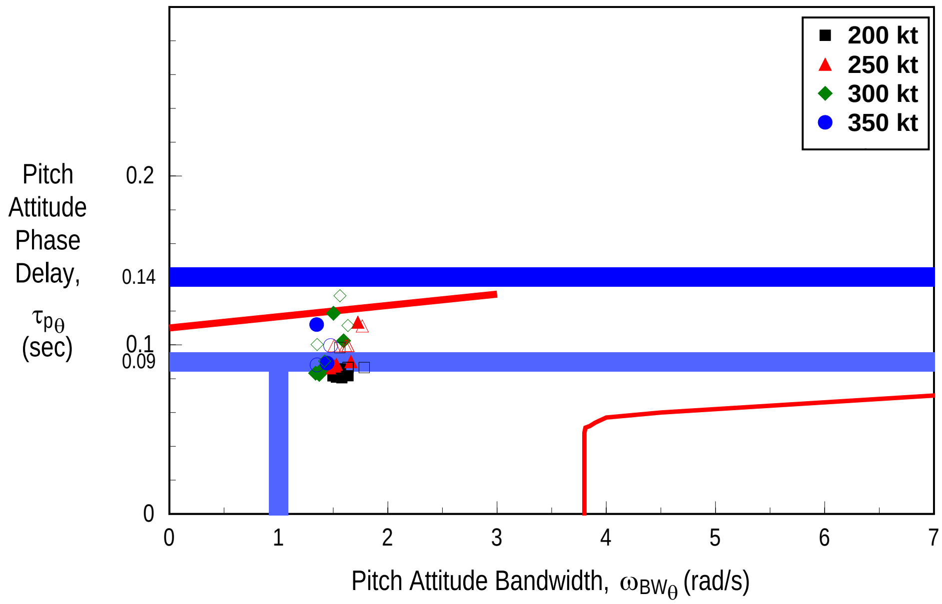


Figure 254. Pitch attitude bandwidth/PIO summary, cruise configuration

In the approach configuration, results are very similar to those observed for cruise. Bandwidths are generally in the 1.4–1.6 rad/s range, with the phase delay range being between 85–100 msec. NBS once again generally predicts slightly higher bandwidths and more phase delay than FREDA (table 91).

Table 91. Pitch attitude bandwidth/phase delay, approach configuration

IAS (kt)	Altitude (ft)	Bandwidth (rad/s) (FREDA/NBS)	Phase Delay (msec) (FREDA/NBS)
150	1,000	1.460/1.508	95.2/100.1
150	2,000	1.459/1.508	95.0/100.1
150	5,000	1.482/1.508	94.1/100.1
150	7,000	1.498/1.634	93.5/100.1
200	1,000	1.477/1.508	85.8/100.1
200	2,000	1.486/1.508	85.7/100.1
200	5,000	1.510/1.634	85.3/100.1
200	7,000	1.527/1.634	85.0/100.1
250	1,000	1.381/1.508	86.3/99.6
250	2,000	1.479/1.508	86.3/99.6
250	5,000	1.475/1.561	86.7/112.0
250	7,000	1.510/1.612	87.6/99.6

The relaxed landing boundaries give better predicted HQ for the approach configuration. Except for the highest IAS at 1,000 ft. considered with flaps down and gear extended, all of the flight conditions produce level 1 HQ, though most cases are above the 90 msec PIO risk boundary. Flight path bandwidth is once again below the threshold of 0.6 rad/s for most of the cases considered in this configuration, which is predicted to result in moderate PIO [13].

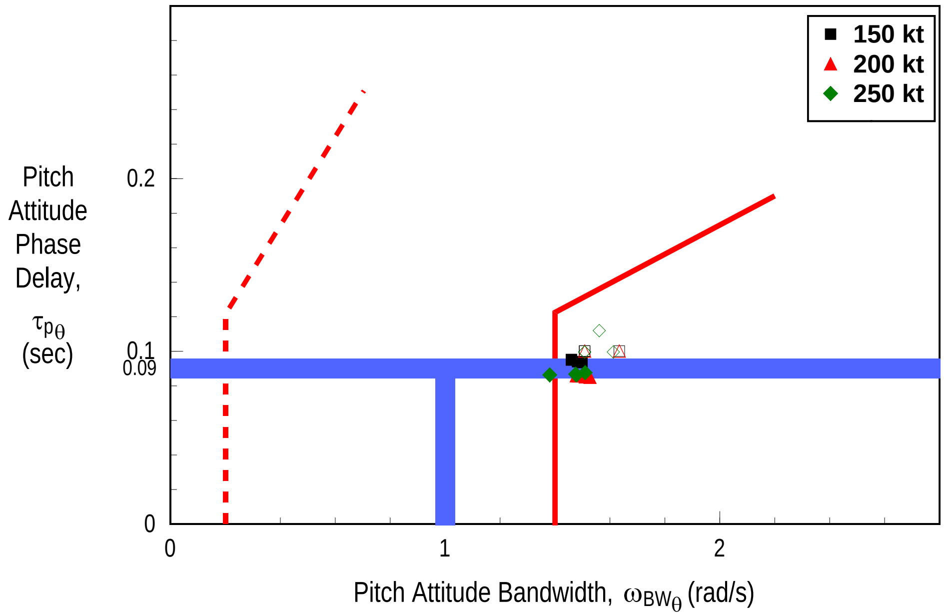


Figure 255. Pitch attitude bandwidth/PIO summary, approach configuration

12.6.4 The FPA Bandwidth

Flight path bandwidth is calculated in the same manner as the pitch attitude bandwidth, with the identified FPA response to a pilot control input the selected input-output pair. The criteria use this value, in combination with pitch attitude bandwidth, to predict HQ and help assess PIO susceptibility, as described in the previous sections.

Results are shown only for the NBS identification. Solid symbols in flight-path bandwidth plots are for NBS results; FREDA results are not included. Table 92 summarizes the flight path and pitch attitude bandwidths for the cruise configuration.

Table 92. The FPA bandwidth, cruise configuration

IAS (kt)	Altitude (ft)	$\omega_{BW\gamma}$ (rad/s)	$\omega_{BW\theta}$ (rad/s)
200	10,000	0.531	1.634
200	15,000	0.525	1.634
200	20,000	0.634	1.634
200	25,000	0.736	1.784
200	35,000	0.785	1.560
250	10,000	0.573	1.508
250	15,000	0.634	1.612
250	20,000	0.639	1.634
250	25,000	0.700	1.634
250	35,000	0.714	1.766
300	10,000	0.573	1.353
300	15,000	0.556	1.420
300	20,000	0.634	1.423
300	25,000	0.634	1.561
300	35,000	0.668	1.634
350	25,000	0.602	1.353
350	35,000	0.639	1.476

The results show that many of the cruise configurations suffer from degraded HQ because of low flight-path bandwidth. As airspeed increases, HQ appears to degrade as the desired corresponding increase in flight path bandwidth is not present. This is due to the dynamics of the closed-loop aircraft because the numerator zero, which governs the flight path consonance, results in the path lag.

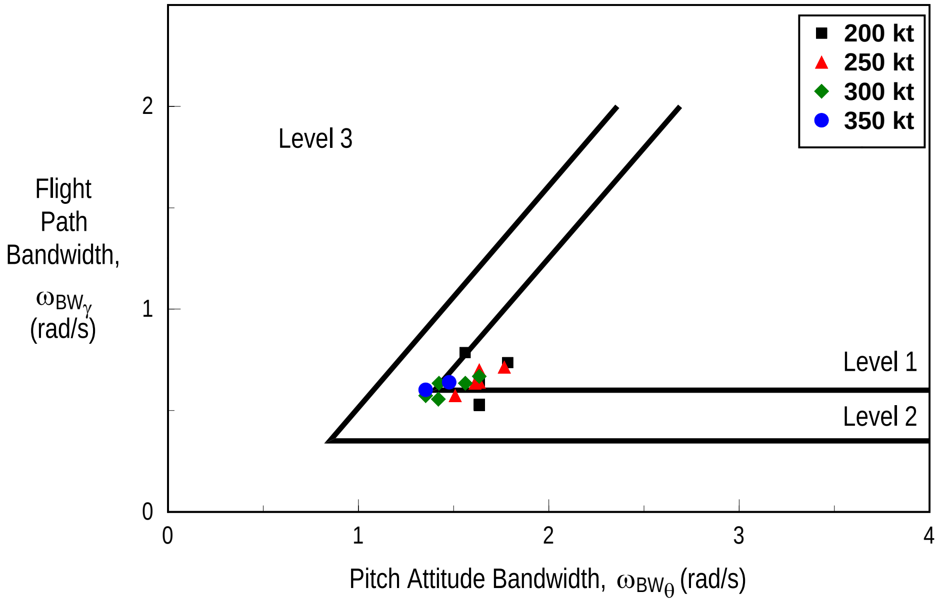


Figure 256. Flight-path bandwidth summary, cruise configuration

The approach configuration appears to be the opposite, with higher airspeeds giving better HQ, while the lower airspeeds have deficient flight-path bandwidth, resulting in degraded HQ. The 250 kts cases have adequate flight path bandwidth and satisfactory pitch attitude bandwidth, but the 150 and 200 kts cases have low flight-path bandwidth, which pushes the results into the level 2 region (table 93).

Table 93. Flight path angle bandwidth, approach configuration

IAS (kt)	Altitude (ft)	$\omega_{BW\gamma}$ (rad/s)	$\omega_{BW\theta}$ (rad/s)
150	1,000	0.525	1.508
150	2,000	0.525	1.508
150	5,000	0.525	1.508
150	7,000	0.525	1.634
200	1,000	0.547	1.508
200	2,000	0.547	1.508
200	5,000	0.531	1.634
200	7,000	0.531	1.634
250	1,000	0.634	1.508
250	2,000	0.634	1.508
250	5,000	0.668	1.561
250	7,000	0.668	1.612

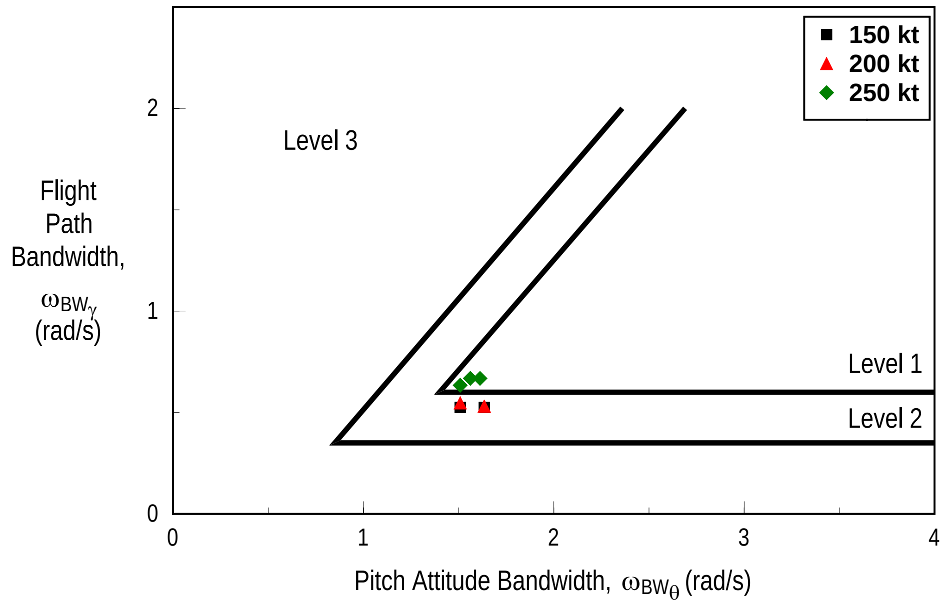


Figure 257. Flight-path bandwidth summary, approach configuration

<u>12.6.5 Roll Attitude Bandwidth</u>

The analysis was repeated for the lateral axis, with the lateral boundaries used to predict PIO tendency and to give some insight into HQ in the roll axis. Again, there are no defined HQ boundaries for the roll axis, so these results are highly qualitative and are primarily focused on PIO risk in the lateral axis.

Table 94 provides a summary of the lateral axis results. Bandwidth and phase delay are consistent for all cases and fall within the 1.0–1.1 rad/s range with phase delay of about 50–60 msec. Unlike the pitch axis which saw some variation between airspeeds and altitudes, the roll axis varies little as flight condition changes.

Table 94. Roll attitude bandwidth/phase delay, cruise configuration

IAS (kt)	Altitude (ft)	Bandwidth (rad/s) (FREDA/NBS)	Phase Delay (msec) (FREDA/NBS)
200	10,000	1.095/1.044	50.6/56.9
200	15,000	1.092/1.042	50.6/57.0
200	25,000	1.087/1.037	50.7/57.3
200	35,000	1.083/1.033	50.8/57.6
250	10,000	1.059/1.015	50.2/57.3
250	15,000	1.056/1.013	50.2/57.4
250	25,000	1.051/1.013	50.2/56.2
250	35,000	1.047/1.010	50.3/56.6
300	10,000	1.033/1.002	50.1/56.8
300	15,000	1.030/1.000	50.1/56.9
300	25,000	1.026/0.997	50.2/57.3
300	35,000	1.023/0.994	50.2/57.7
350	25,000	1.009/0.991	50.1/55.6
350	35,000	1.007/0.989	50.2/56.2

The summary plot shows all of the cases clustered just outside of the lower bandwidth boundary. The NBS and FREDA results are also in better agreement for the roll axis, as both solid and outlined symbols overlay for these cases. All cases are well below the 90 msec PIO risk boundary, where control sensitivity could lead to a PIO risk for this configuration.

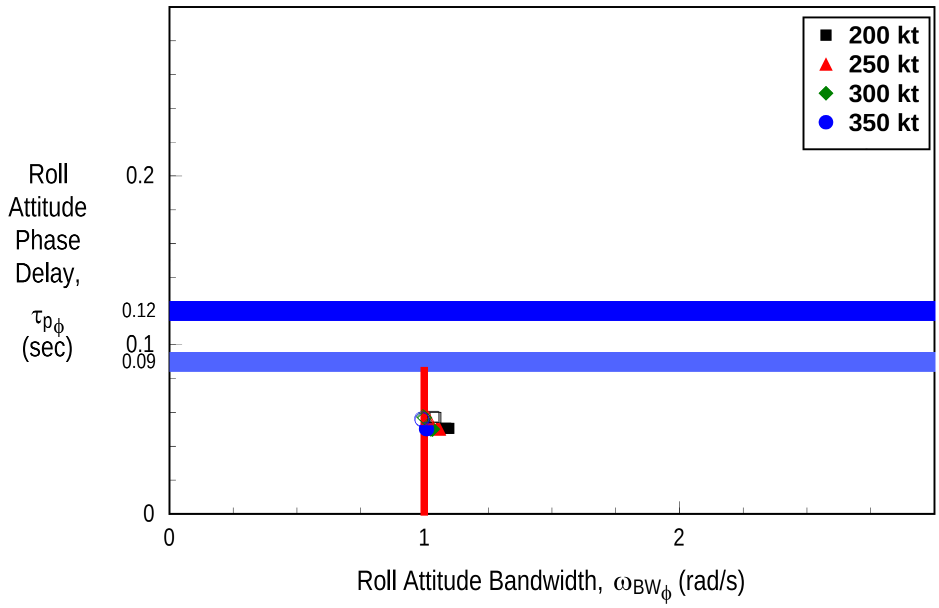


Figure 258. Roll attitude bandwidth/PIO summary, cruise configuration

In the approach configuration, the bandwidth frequencies are slightly higher, while phase delay is consistent with what was seen in cruise. The roll axis closed-loop dynamics do not change with altitude or airspeed and the extension of landing gear or flaps does not seem to have a significant effect on the responsiveness or equivalent delay in this axis (table 95).

Table 95. Roll attitude bandwidth/phase delay, approach configuration

IAS (kt)	Altitude (ft)	Bandwidth (rad/s) (FREDA/NBS)	Phase Delay (msec) (FREDA/NBS)
150	1,000	1.118/1.062	50.8/56.5
150	2,000	1.117/1.061	50.8/56.5
150	5,000	1.114/1.059	50.8/56.5
150	7,000	1.112/1.058	50.8/56.5
200	1,000	1.096/1.046	50.6/56.5
200	2,000	1.095/1.045	50.6/56.5
200	5,000	1.093/1.043	50.6/56.6
200	7,000	1.092/1.042	50.6/56.6
250	1,000	1.061/1.017	50.2/57.0
250	2,000	1.060/1.016	50.2/57.0
250	5,000	1.058/1.015	50.2/57.1
250	7,000	1.056/1.014	50.2/57.1

The bandwidth/phase delay summary for the approach configuration (figure 259) is very similar to that seen in figure 258 for cruise. All cases have very similar bandwidth and phase-delay values and all are within level 1 boundaries.

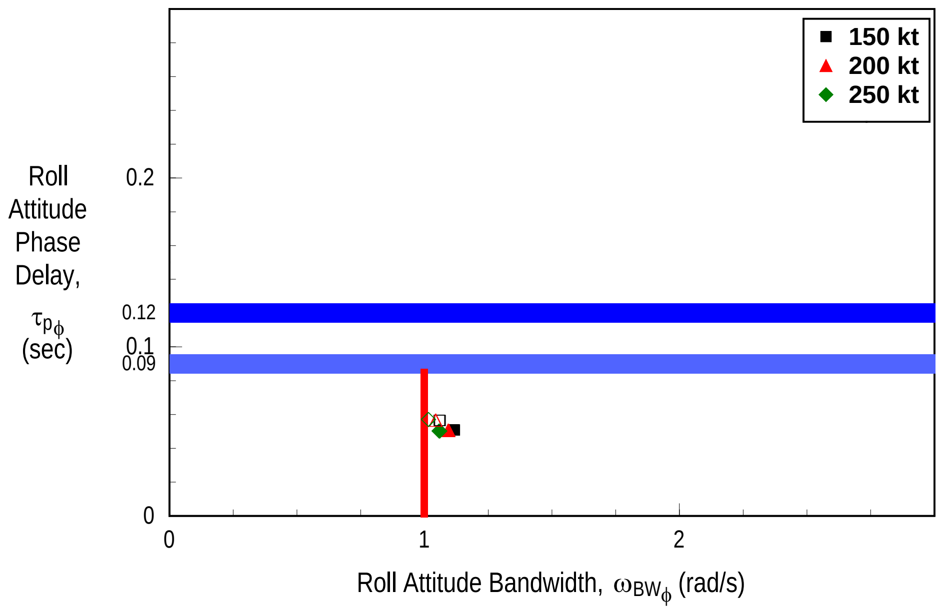


Figure 259. Roll attitude bandwidth/PIO summary, approach configuration

12.6.6 Summary

System identification techniques were used to perform a basic airframe assessment and HQ analysis of the FAA simulation model. A flight envelope representative of typical cruise and approach flight conditions was selected and bandwidth/phase delay criteria used to determine the predicted HQ and PIO tendency of the aircraft. Some nonlinear actuator behavior was uncovered and investigated and the dominant longitudinal airframe dynamics were analyzed so that the effects of the FCS loop closures could be determined. The nonlinear actuator behavior was attributed to low sample rate and the model has been modified to avoid future issues with high-frequency inputs. It was found that the pitch axis exhibits a substantial HQ deficiency and PIO risk for cruise tracking and a possible issue for all configurations because of low flight-path bandwidth. The roll axis closed-loop response varies little with flight condition or configuration and no PIO risk was observed.

12.6.7 AFI-FCS HQ Observations and Conclusions

- A sample time issue caused data corruption at higher frequencies for the actuator identification. Increasing the simulation sample rate from 50 to 100 Hz brought the identified actuator into better agreement with the linear model.

- Short-period mode frequency and damping decrease with altitude, but increase with airspeed.

- Bandwidth and phase delay are fairly consistent for all flight conditions in each configuration. Generally, HQ are just inside the level 1 border.

- NBS predicts higher bandwidth frequencies and phase delay values than FREDA. Qualitative examination of the differences in the identification data shows that actual differences are minimal and that the discrepancies are likely due to the way the parameters are calculated from the interpolated phase and magnitude points.

- Pitch attitude bandwidth and phase delay indicate that there is a significant HQ deficiency for most of the flight envelope and a PIO risk. Flight path bandwidth results confirm a risk for moderate PIO.

- Flight path bandwidth is slightly deficient and results lie in the level 2 region for most of the flight envelope for both cruise and approach configurations.

- Roll closed-loop dynamics vary little over the flight envelope and bandwidth/phase delay values are within the level 1 boundary for all cases and configurations. Neither of the configurations approach the PIO boundary for any flight condition.

13. AFI-FCS DESIGN ELEMENTS OFFLINE ANALYSIS

13.1 INTRODUCTION

An offline analysis was conducted of the AFI-FCS augmented aircraft. The impact on the response of the design elements variations evaluated during the pilot in the loop simulations of the Calspan/STI aircraft was assessed. A set of the most representative elements was considered, both in support of the Year 2 Follow-on task analysis and to understand/describe the characteristics of the AFI-FCS augmentation system. The results of this investigation are thought to be relevant to the project, considering the significant differences between the augmentation algorithm of the Calspan/STI and the AFI-FCS aircraft. Every subsection reports the results of one design element analysis.

13.2 PASSIVE INCEPTOR COMMAND SENSITIVITY

13.2.1 Introductory Notes

In support of the Year 2 Follow-On task “Harmony between the passive control inceptor feel force and the control maneuver command sensitivity,” a survey has been conducted of the control maneuver command sensitivity scheduling using the MATLAB/Simulink model of the AFI-FCS augmented aircraft provided by the FAA. This model is intended to be representative of a midsize, medium-range transport aircraft with a FPA Rate Command and Hold (FPARC/FPAH) control system [21]. More details on the unaugmented and augmented aircraft are provided in sections 12.2 and 12.3. The following analysis sought to understand the effect of variations in pressure altitude, airspeed, and aircraft configuration (PA with flaps and landing gear extended or cruise) on the Δn_z command, pilot-stick command, thrust-level command, and task performance when the maneuver commands are scheduled as functions of both deflection and airspeed (V^2/V^2_{stall}). Scheduling the command sensitivity in this manner results in a parabolic gradient with no discontinuity at zero inceptor deflection. This scheduling should result in a full stick input commanding the limiting value of Δn_z at higher speeds, while at low speed for a full pull-up deflection, the maximum available safe Δn_z command should be used [1].

This scheduling seeks to achieve the maximum possible Δn_z command at the aircraft's current airspeed.

A simple pilot model was implemented to assess the PACH task performance at the defined flight conditions. Configurations and the time history results of the pertinent signals are reported and discussed.

13.2.2 Evaluation Tasks

The PACH task is intended to investigate three aspects:

- The ability of the aircraft to pitch and capture a defined attitude
- Maneuverability limitations
- The PIO tendencies

Pitch attitude captures of -5, 0, and 5 degrees about the trim attitude have been defined. This task was also repeated using pitch attitude captures of -5, 0, and 10 degrees about the trim attitude. A sample PACH task is presented in figure 260. The first 10 seconds of the task are reserved for the model to trim, after which the PACH task begins. Each capture attitude is commanded for 10 seconds, allowing time for the PVS to achieve the designated attitude and maintain it for at least five seconds. For adequate and desired performance, the pilot must achieve and maintain an attitude within ± 2 degrees and ± 1 degree, respectively, of the commanded attitude.

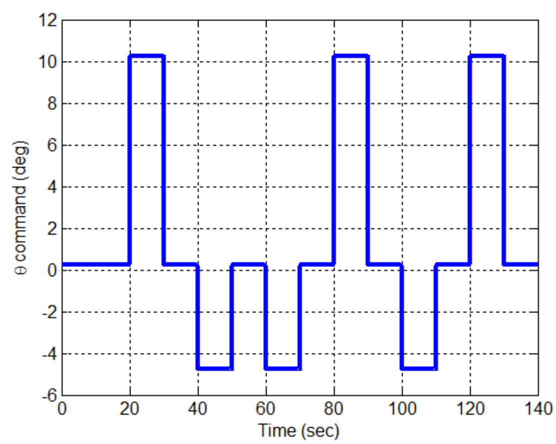


Figure 260. Example PACH command signal

13.2.3 Flight Conditions

As mentioned previously, both approach and cruise configurations have been examined. These configurations are distinguished from one another by their flap setting, landing gear status (extended or retracted), and aircraft weight and are summarized in table 96. The altitude and speed combinations examined for each configuration are presented in tables 97 and 98. All of the flight conditions have the bare airframe aerodynamic center at 25% MAC (zero SM).

Each analysis run was conducted at a fixed aircraft configuration and speed while the altitude was adjusted. Given that each combination has a slightly different trim attitude, to compare the task performance directly across the different altitudes, the resulting pitch attitude signal was adjusted to some standard trim value. To meet this requirement, the lowest altitude considered for each aircraft configuration and speed was treated as having the reference trim value to which all other cases (i.e., different altitudes) were adjusted. The removal of this trim bias was done only for comparison and evaluation purposes after the simulation was complete and in no way affects the performance of the system.

Table 96. Flight condition characteristics

	Approach	Cruise
Flap settings (deg.)	30	0
Landing gear extended	Yes	No
Weight (lb)	100,000	120,000

Table 97. Approach flight conditions

Speed (kts)	Altitude (feet)
125	0
125	5,000
125	10,000
150	0
150	5,000
150	10,000
175	0
175	5,000
175	10,000
200	0
200	5,000
200	10,000

Table 98. Cruise flight conditions

Speed (kts)	Altitude (feet)
200	10000
200	20000
200	30000
250	10000
250	20000
250	30000
300	10000
300	20000
300	30000

13.2.4 Pilot Model

A simple pure-gain pilot model was used as the controller for this evaluation task. An effective delay of 250 msec was included to represent a pilot's typical reaction time. A pilot gain was selected for the evaluations from the 225 kt, 10 kft cruise configuration. With the selected gain, the 10° pitch attitude captures achieved adequate performance, while the trim and -5° pitch attitude capture consistently achieved desired performance. Pilot gain values lower than the one used negatively impacted the ability of the PVS to achieve even adequate performance when capturing the 10° pitch attitude; values higher than the one used here improved the performance of the 10° capture, but at the cost of having oscillations about the trim and -5° attitude captures.

13.2.5 System Analysis

The settings used for the approach and cruise conditions are shown in table 97 and the evaluated speeds and altitudes are shown in tables 98 and 99, respectively. The Δn_z command, pilot stick input, task performance, and throttle command time histories are reported here for both the 5° and 10° pitch attitude capture tasks. The time histories for the approach cases are shown in figures 262–269 and, for the cruise cases, figures 271–276. Each of the following sections details the trends and activity of the signal specified. There are a few things to note when examining these figures.

- For the task performance figure, the blue dotted lines above and below each capture attitude represent the desired boundaries of ±1 degree and the red dash-dot lines above and below each capture attitude represent the adequate boundaries of ±2 degrees.

- The stick input in the FAA model is the normalized stick deflection bounded at -1 and 1. When looking at the pilot stick command, these same limits apply, so although the pilot may be attempting to command more than 1 (i.e., more than full deflection), the stick command that is actually registered remains limited to 1.

- The Δn_z command is limited to -1 g and +1.5 g.

- The model includes an autothrottle that is engaged for the entire run. No alterations have been made to its settings or mechanisms.

13.2.6 Powered Approach Flight Condition

13.2.6.1 Δn_z Command

- [-5, 0, 5] degree captures:

  The Δn_z command required to perform the pitch attitude captures increased with the speed, from 125 to 175 kts, seen in figures 262–264. The values of Δn_z essentially did not change as the velocity increased from 175 to 200 kts. There was also little change in Δn_z command required as altitude varied. Two exceptions to this trend were observed, however: 1) the Δn_z command required to hold the 5-° pitch attitude captures increased as altitude increased, with the largest amplitudes occurring at the higher speeds and 2) the correction to trim from the 5° pitch attitude capture generally required less Δn_z at 30 kft and
  175 and 200 kts, seen in figures 264 and 265.

- [-5, 0, 10] degree captures:

  As with the [-5, 0, 5] degree capture sequence, the Δn_z command required to perform the attitude captures increased as the speed increased. One exception to this trend was noticed for the 0 kft and 5 kft cases: the Δn_z required to correct to trim from the 10° capture was always at the negative limiting value for Δn_z and held at ~ 90–93% of the negative Δn_z limit for the same correction at the 10 kft altitude. This held true at all airspeeds. In addition, aside from the variation in Δn_z just described and the Δn_z required to maintain the positive attitude capture, there was no variation in Δn_z commanded across the different altitudes. This trend is valid over all considered airspeeds. It was also noticed that the Δn_z commands used to maintain the 10° attitude captures grew in amplitude as altitude and speed increased. These commands increased in frequency between the 125 and 175 kts, 10 kft altitude cases.

13.2.6.2 Pilot Stick Input

- [-5, 0, 5] degree captures:

  The pilot stick command varied little among the different altitudes. Any variations occurred at the same location as those seen in the Δn_z command signal: maintaining the 5° captures and returning to trim after the 5° captures. In addition, with the exception of these two cases, the magnitude of the pilot stick command showed little if any difference between the various speeds and the actual command never exceeded ~60% of the maximum stick travel in either direction.

- [-5, 0, 10] degree captures:

  As was observed with the [-5, 0, 5] degree amplitude capture sequence, the pilot stick command varied little between cases as altitude changed. Any variations occurred at the same location as variations seen in the Δn_z command signal: maintaining the 10° captures and returning to trim after the 10° captures. In addition, with the exception of these two locations, the magnitude of the pilot stick command changed little if any between the various speeds. It was also noticed that the pilot was attempting to command more than the full stick deflection when capturing the 10° attitude and either full or near-full stick deflection when returning to trim from the 10° capture; this was true at all altitudes and speeds.

13.2.6.3 Task Performance

- [-5, 0, 5] degree captures:

  The time histories of pitch attitude show that there was no issue for the PVS in meeting and maintaining desired performance at the trim and -5° attitudes at any altitude or speed. In addition, the system at 0 kft and 5 kft altitudes had no issue meeting the 5° pitch attitude capture at any speed. The 10 kft case began to show some small oscillations at 150 kts when performing the 5° pitch attitude capture. These oscillations grew slightly between the 150 and 175 kts cases and lost some amplitude, no longer meeting desired performance and instead holding adequate performance only, as shown in figures 263 and 264, respectively.

- [-5, 0, 10] degree captures:

  The time histories of pitch attitude show that there was no issue for the pilot in meeting and maintaining desired performance at the trim and -5° attitudes at any altitude or speed. The only minor exception to this was for the corrections back to trim from the 10° captures; the 125 and 150 kts cases seen in figures 266 and 267 had one overshoot into the adequate region for each initial correction before settling into the desired region. The variations in performance due to altitude are most visible in the 10° captures, with only the 0 kft case meeting and maintaining desired performance across all speeds. The 5 kft case was able to maintain adequate performance throughout the 10° capture at all speeds with the occasional dip into either the desired or failed regions. The 10 kft case was unable to meet even adequate performance when attempting to capture the 10° attitude. It was also noticed that for the 175 and 200 kts cases shown in figures 268 and 269, the captures of 10° were more oscillatory than those performed at the lower speeds or at any of the other attitudes. This was true of all altitudes, although the amplitude of these oscillations tended to be higher for the 10 k foot altitude case.

13.2.6.4 Throttle

- [-5, 0, 5] degree captures:

The throttle command for the approach conditions increased in value both as the altitude and the speed increased. It was also noted that the throttle settings have significant variations in amplitude over the course of the run and that the throttle adjustments were made very rapidly. These variations could amount to an almost 60% change in commanded throttle over the course of just a few seconds. In addition, with the exception of the 125 kt case shown in figure 262, the 30 kft altitude case at all other speeds requires maximum throttle input when performing the 5° pitch attitude captures. To better ascertain if these characteristics were unique to this task, an additional task was performed at the same condition. The SoS tracking task command signal is presented in figure 261, along with the resulting throttle commands. As is evident here, similar dramatic variations are noticed in the commanded throttle percentage, including a need to command 100% throttle for a period of time.

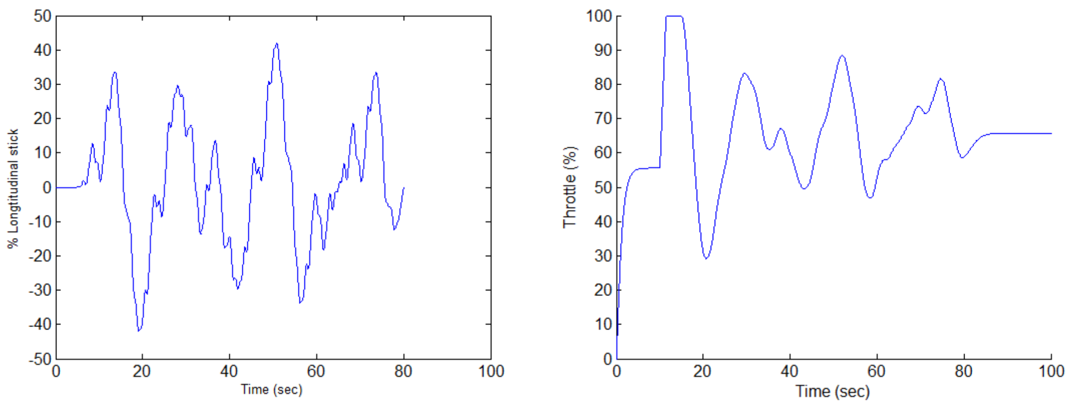


Figure 261. Approach 150 knots 5 kft — SoS task

- [-5, 0, 10] degree captures:

The general trends described for the [-5, 0, 5] degree capture sequence apply to the 10° capture runs as well. The amplitude of some of the % throttle command variations were larger and existed for longer portions of the run, likely because of the increased amplitude being required for the pitch attitude capture.

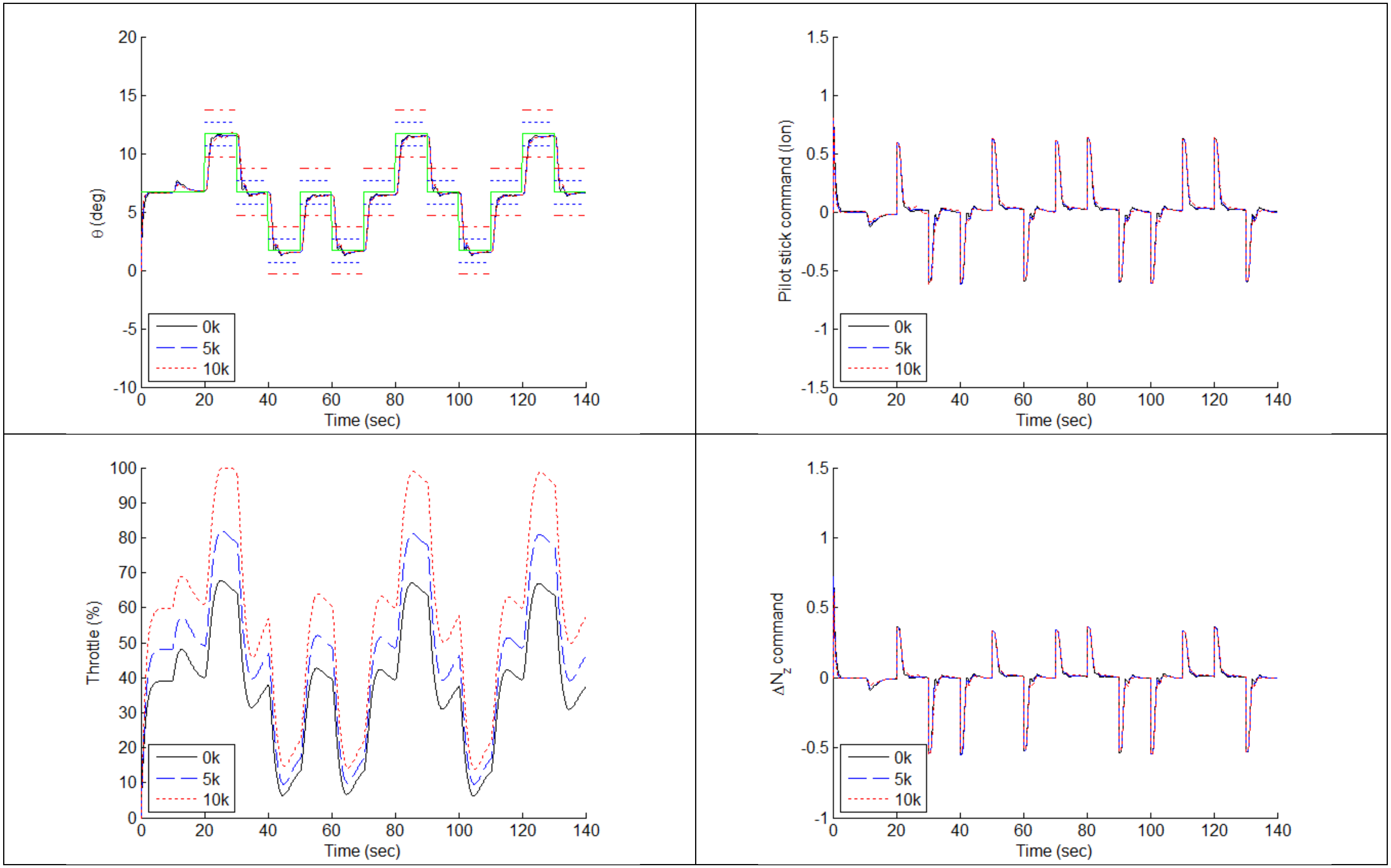


Figure 262. 125 knots — approach (5°capture)

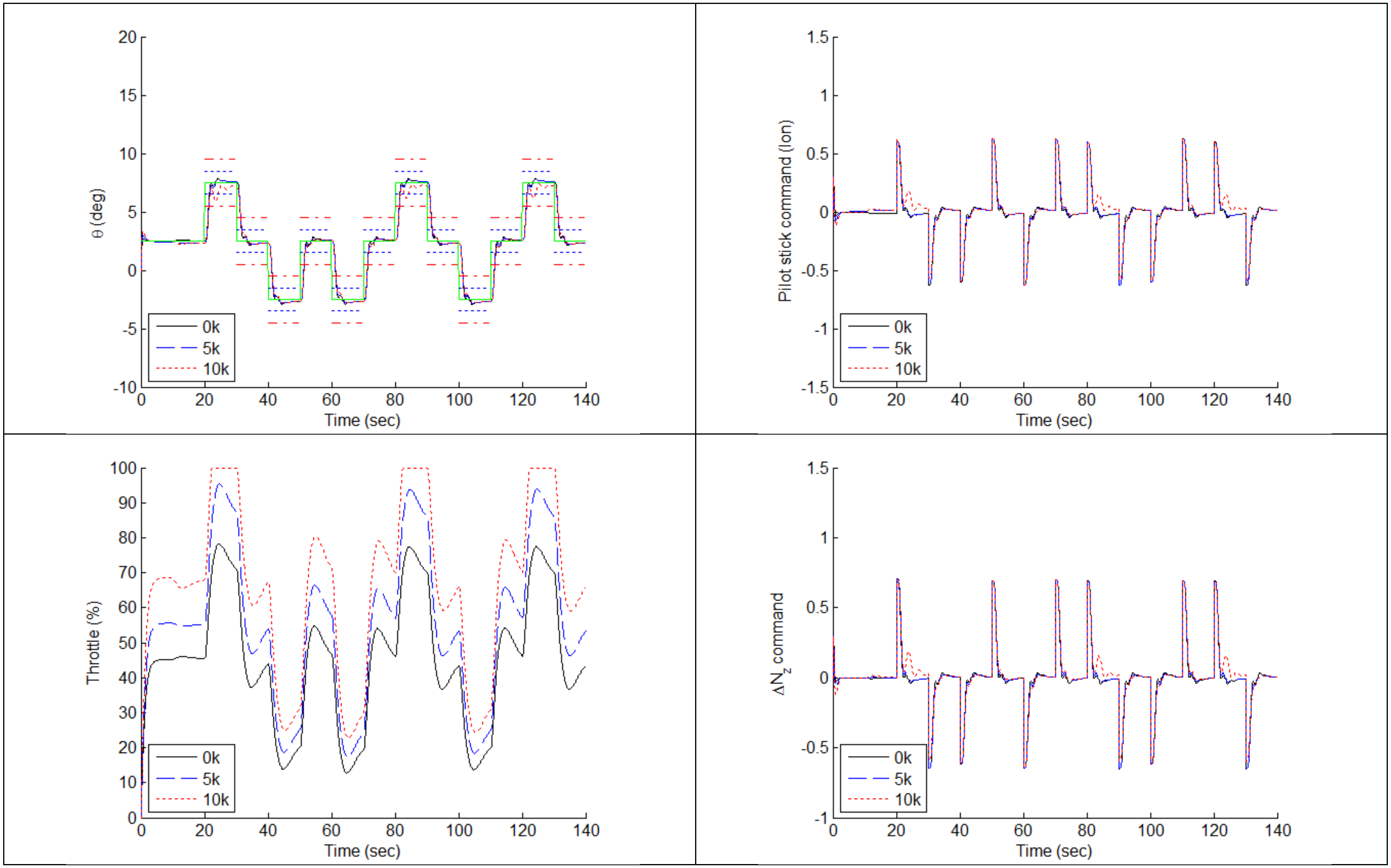


Figure 263. 150 knots — approach (5° capture)

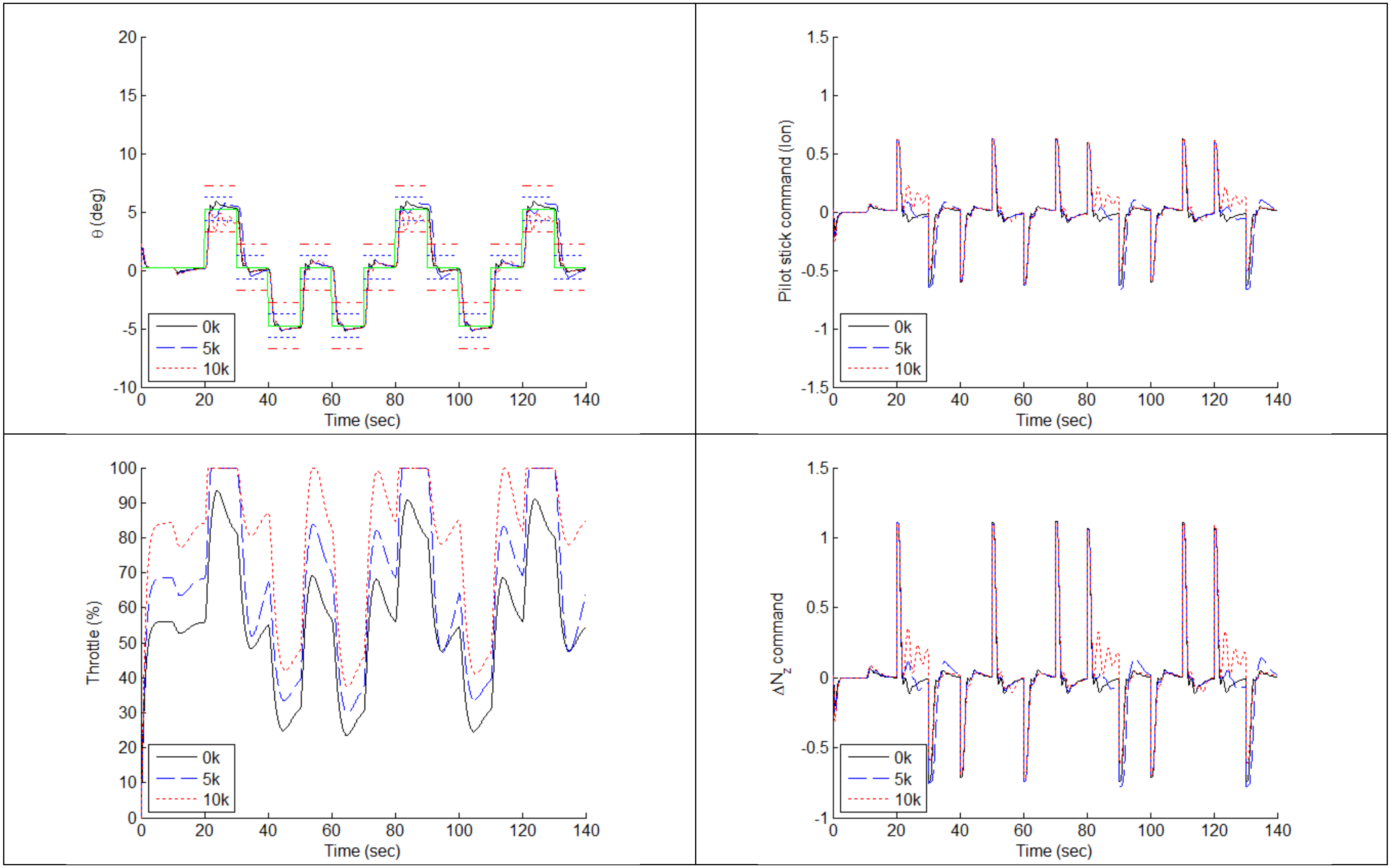


Figure 264. 175 knots — approach (5° capture)

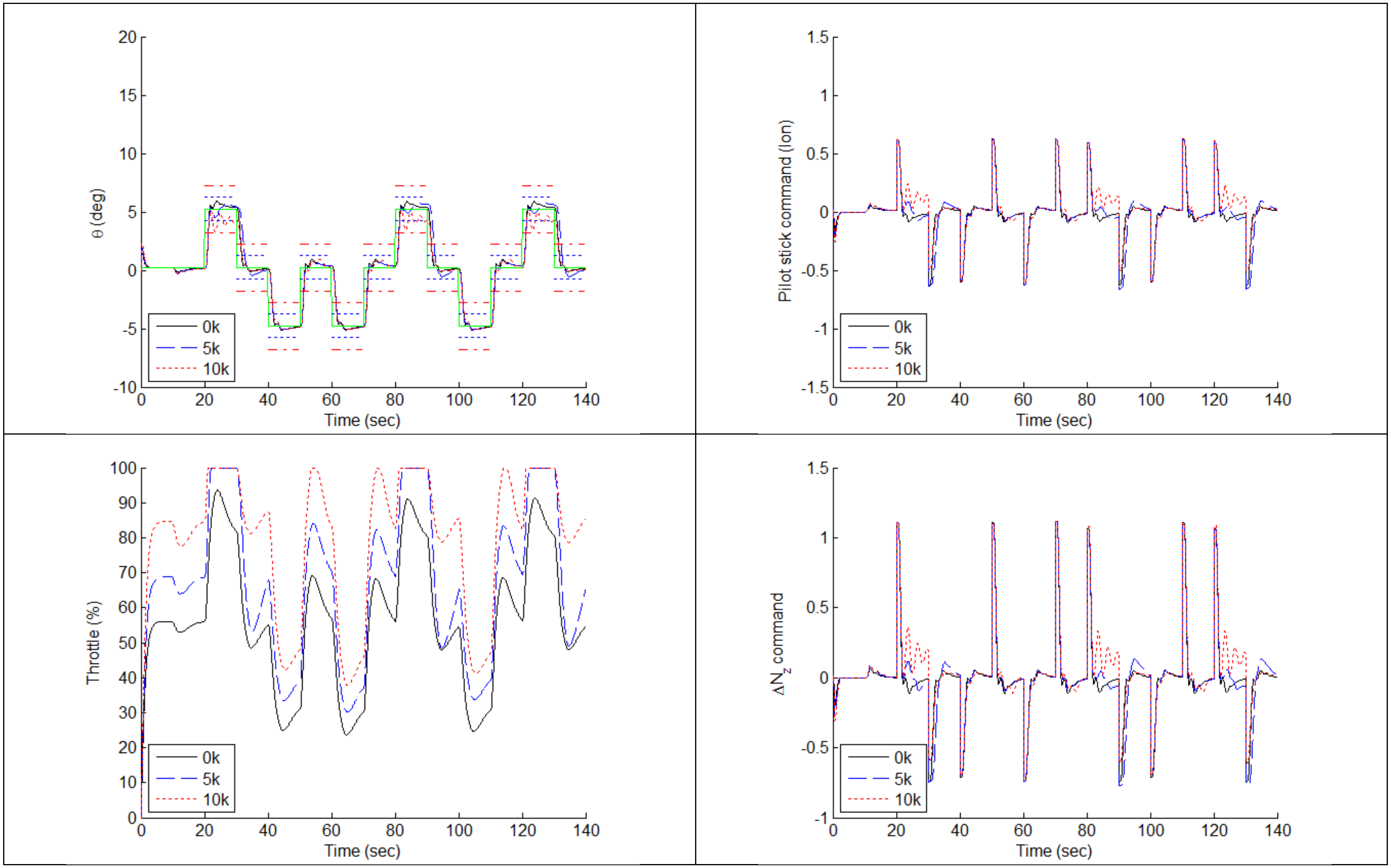


Figure 265. 200 knots — approach (5° capture)

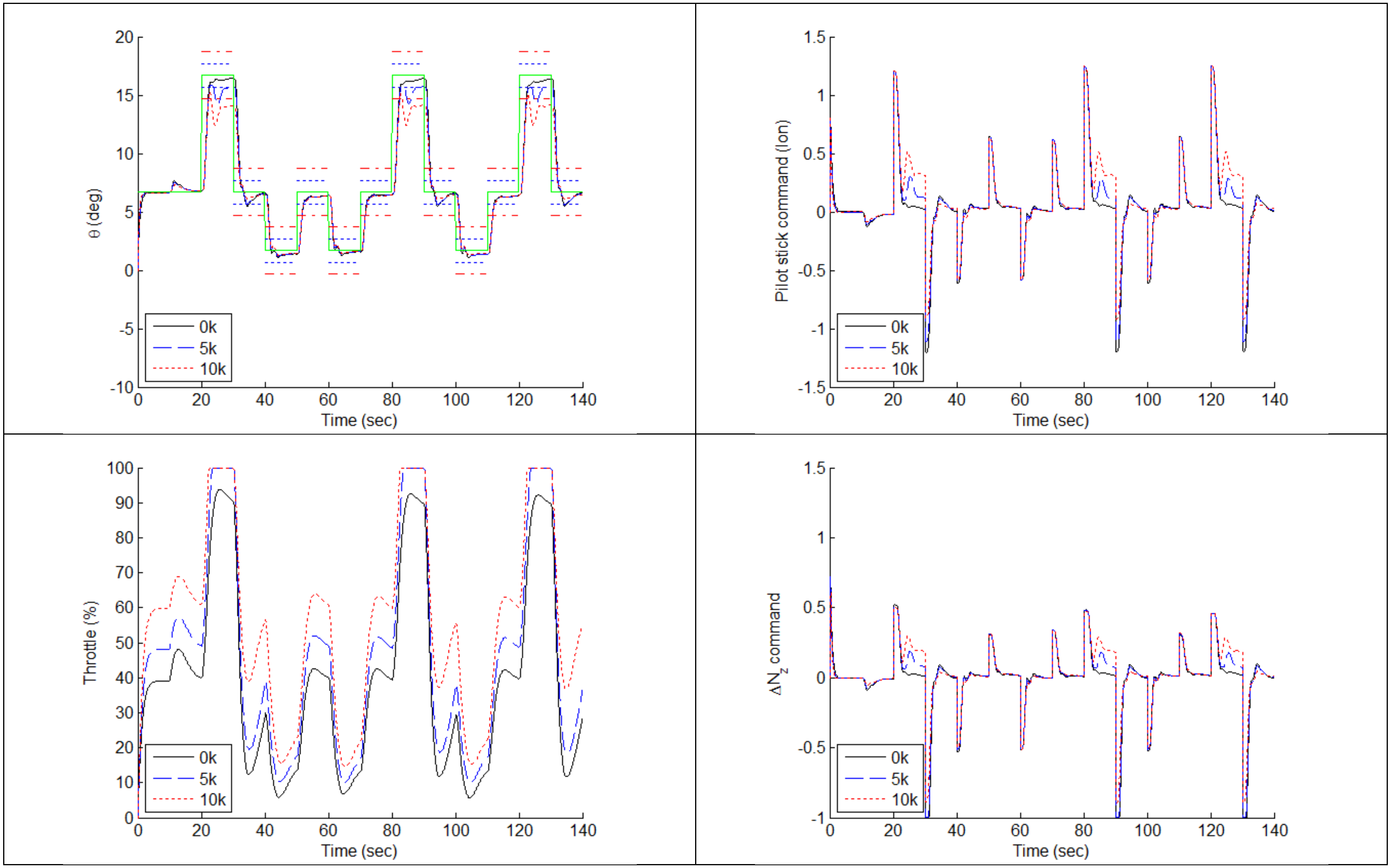


Figure 266. 125 knots — approach (10° capture)

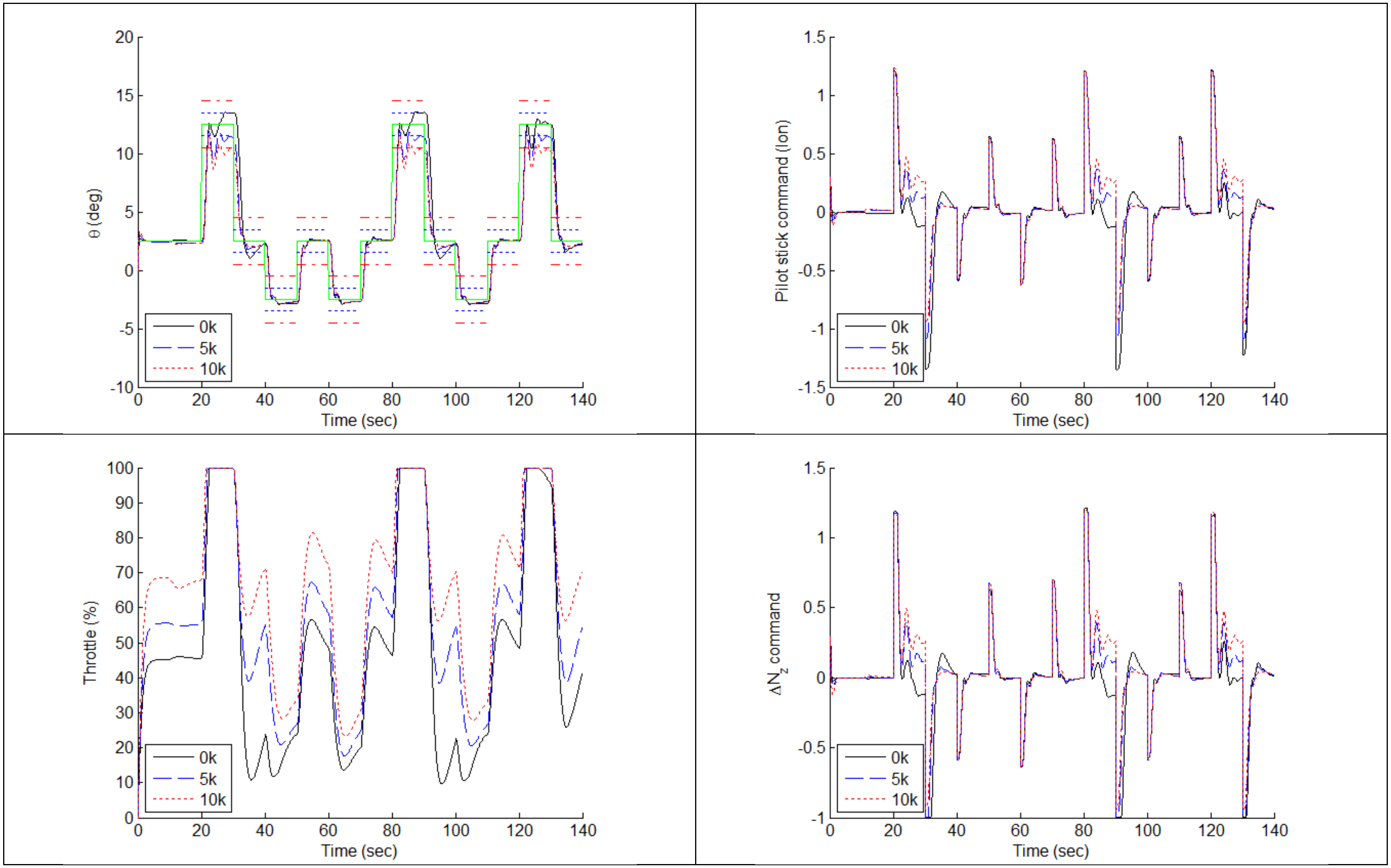


Figure 267. 150 knots — approach (10° capture)

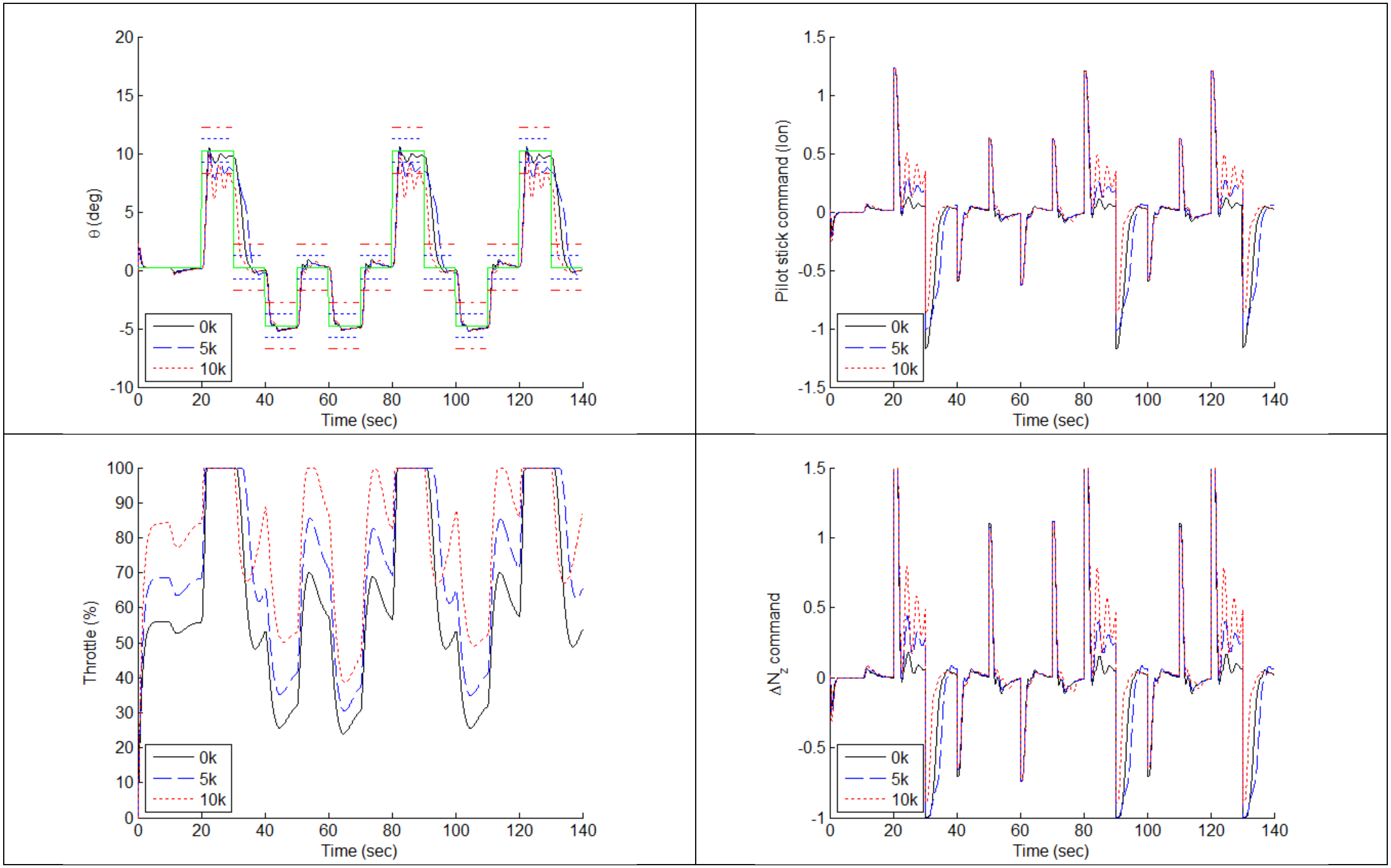


Figure 268. 175 knots — approach (10° capture)

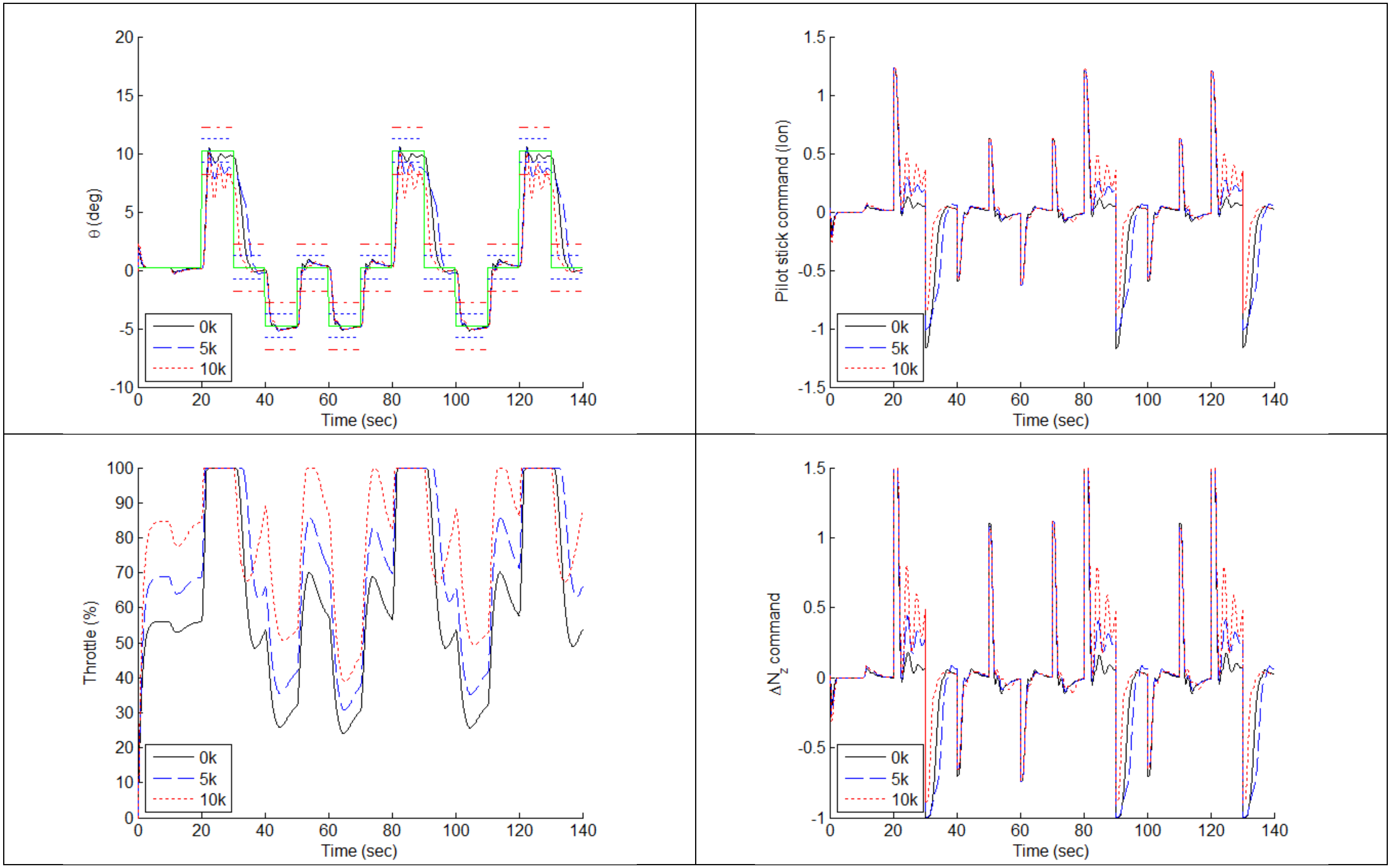


Figure 269. 200 knots — approach (10° capture)

13.2.7 Cruise Flight Condition

13.2.7.1 Δn_z Command

- [-5, 0, 5] degree captures:

  As with the approach configurations, it was noted that as the speed increased, the Δn_z command required to perform the attitude captures increased as well. In addition, there were oscillations similar to those seen in the approach configuration in the Δn_z command when attempting to hold the 5° pitch attitude capture. The amplitude of these oscillations tended to increase as speed increased and was always largest for the 30 kft altitude case. There were also some variations in the Δn_z command required at the different altitudes, but these were seen only for the 5° pitch attitude captures or the command used to return to trim from that attitude. The 10- and 20-kft cases tended to be very similar, with the variation again being seen primarily in the 30 kft case. The 200 and 250 kts 30 kft cruise cases in figures 271 and 272 saw reduced Δn_z command required to correct back to trim after the 5° pitch attitude capture; this difference was greatest for the 200 kt case. The 300 kt case shown in figure 273 saw slightly increased amounts of Δn_z command required, relative to that needed for the 10- and 20-kft cases, to correct back to trim for some captures at 30 kft.

- [-5, 0, 10] degree captures:

  For these captures, it was noted that as the speed increased, so did the Δn_z command required to perform the attitude captures. The exception to this trend was again found when performing the correction to trim from the 10° captures; while the negative limiting Δn_z command value was used at all altitudes for the 250 and 300 kts cases seen in figures 275 and 276, respectively, the 200 kt case showed some difference in the Δn_z commanded at the considered altitudes (figure 274). The Δn_z required for the captures of 10° and trim from either attitude showed a tendency to decrease as altitude increased. The Δn_z command required the 10° captures to experience a dramatic increase between the 200 and 250 kts cases and the 300 kt case commanded the maximum allowable positive Δn_z value, 1.5 g. The 200 and 250 kts case also differed from the other cases examined in both the approach and cruise configurations because the commanded Δn_z for the 10° captures was not uniform among the various altitudes and actually required lesser amounts of Δn_z for the higher altitudes. As with the approach conditions, the Δn_z required maintenance of the 10° captures at a fixed speed, increased as altitude increased, and was higher in amplitude across all considered speeds as speed increased.

13.2.7.2 Pilot Stick Input

- [-5, 0, 5] degree captures:

  For the cruise configuration, the pilot stick command varied little among the different altitude values and variations across altitudes. These occurred at the same locations seen in the Δn_z command signal: maintaining and then returning to trim from the 5° captures. In addition, with the exception of these two cases, the magnitude of the pilot stick command changed little, if any, between the various speeds and never exceeded ~60% of the maximum stick travel in either direction.

- [-5, 0, 10] degree captures:

  For the cruise configuration, the pilot stick command again varied little between the different altitude values and when there were variations across altitudes, they occurred at the same locations seen in the Δn_z command signal: maintaining and then returning to trim from the 10° captures. The 300-knot, 30 kft case also had some additional oscillations when correcting back to trim from the -5° attitude captures, something that was not seen in any other configuration, altitude, or speed. As with the approach case, the pilot would attempt to command more than full stick deflections when making the 10° captures and near-to-full stick deflections when correcting back to trim from the 10° captures. There were only a few select instances for which full stick was not being commanded when returning to trim from the 10° captures; these commands occurred only for the 20- and 30-kft altitudes at 200 kts (figure 274).

13.2.7.3 Task Performance

- [-5, 0, 5] degree captures:

  The 10- and 20-kft altitude cases either reached desired performance or fell on the border of desired/adequate for all captures and trim conditions at all speeds. The 30-kft case met all -5° pitch attitude captures and trim conditions without difficulty, but never achieved desired performance for the 5° pitch attitude capture. The performance for this altitude did improve as the speed increased, but started borderline adequate/failed at 200 kts and improved to solidly adequate by 300 kts, as shown in figures 271 and 273, respectively.

- [-5, 0, 10] degree captures:

  As with the approach condition, the captures of trim and -5° were always within desired range with two exceptions: the capture of trim from the -5° attitude had two instances in which the 300 kt case at 30 kft fell into the adequate region instead of desired (figure 276). For the 10° captures, task performance tended to degrade as the altitude increased, a trend more noticeable at lower speeds than high, at which there was little, if any, difference. Across all speeds, the 30-kft case always failed to capture 10°. In addition, the amplitude of the oscillations, when attempting to maintain the 10° capture for all altitudes, increased as the speed increased.

13.2.7.4 Throttle

- [-5, 0, 5] degree captures:

The same comments that were made for the approach condition apply to cruise as well. The cruise cases have larger amplitude variations between throttle commands for the capture task, in some instances experiencing a 100% difference in commanded throttle values over the course of a few seconds. These trends are also repeated for the same SoS task as was used for the approach case (figure 270). Also shown is the true airspeed time history. Once the trim speed is reached, there is little variation observed — never more than ±2.5 ft/s about trim. While the throttle varies drastically and rapidly over the course of a run, the speed is held steady at its desired value.

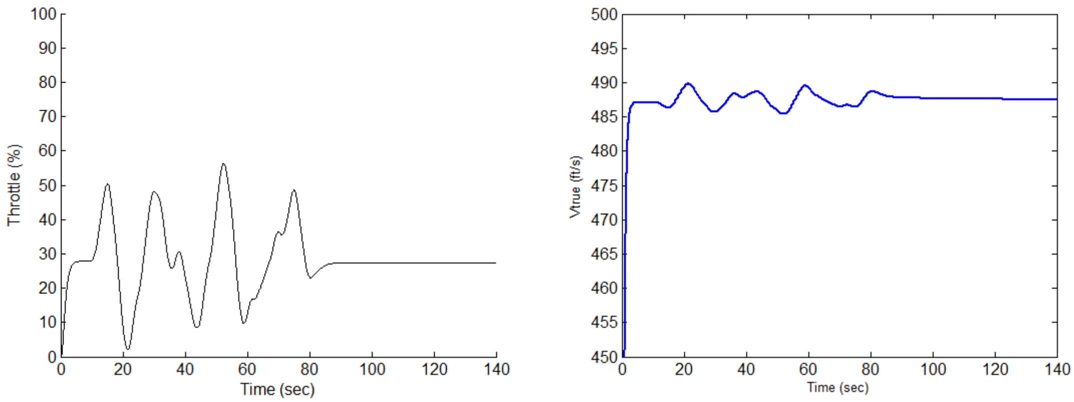


Figure 270. 250 kts at 10 kft

- [-5, 0, 10] degree captures:

As with the approach cases, the throttle trends for this capture attitude mimic and exaggerate those seen for the [-5, 0, 5] degree pitch attitude capture sequence.

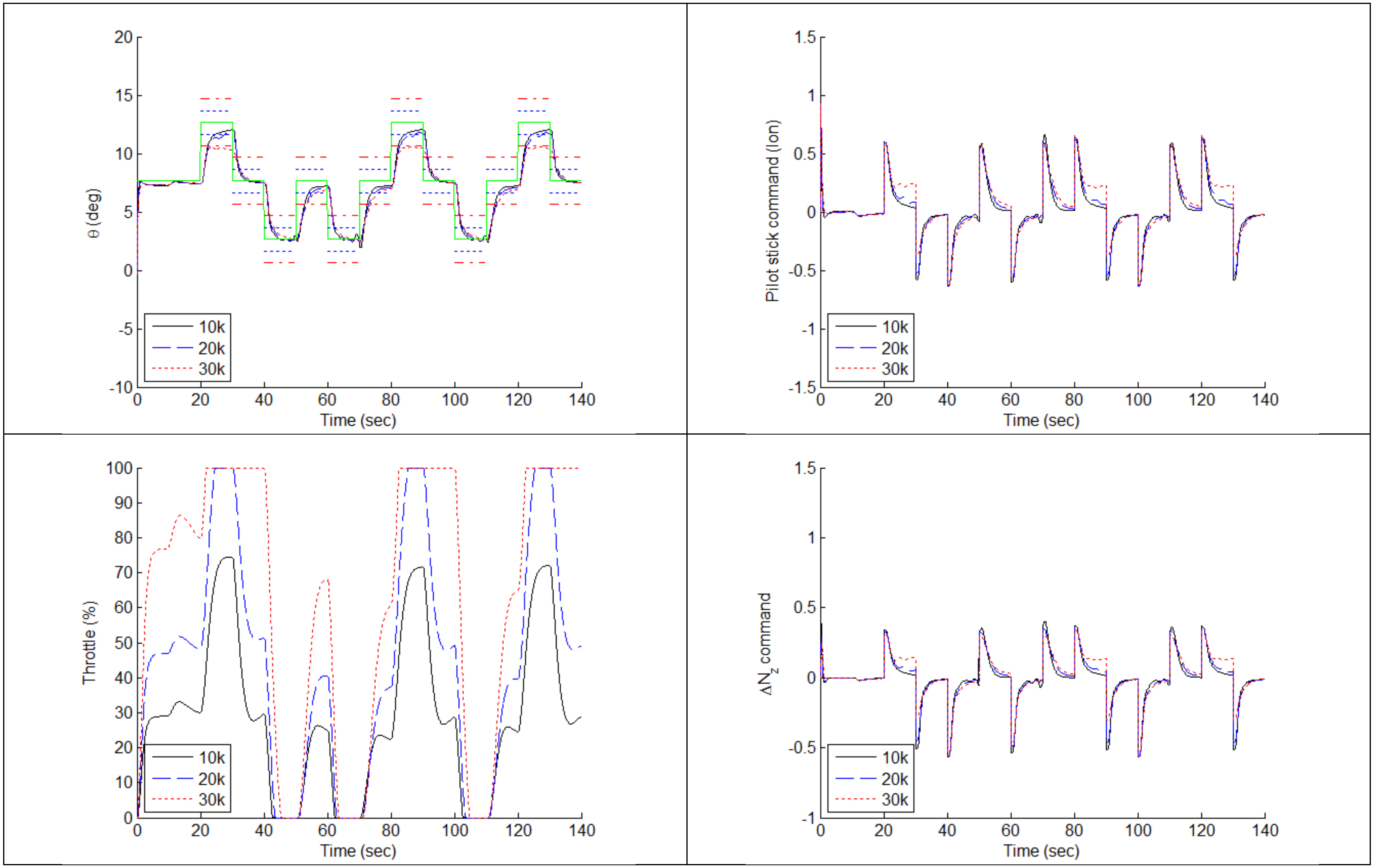


Figure 271. 200 knots — cruise (5° capture)

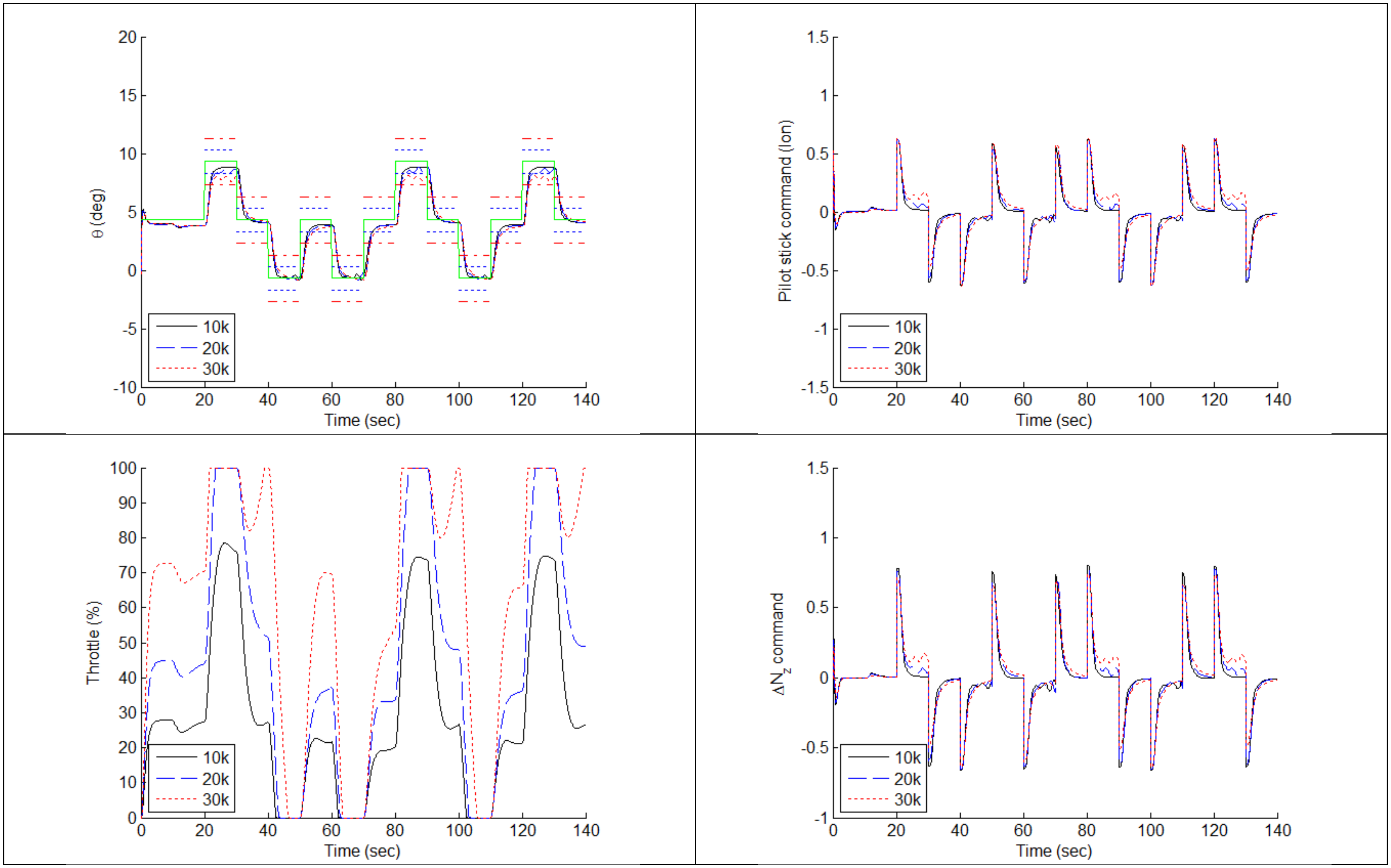


Figure 272. 250 knots — cruise (5°capture)

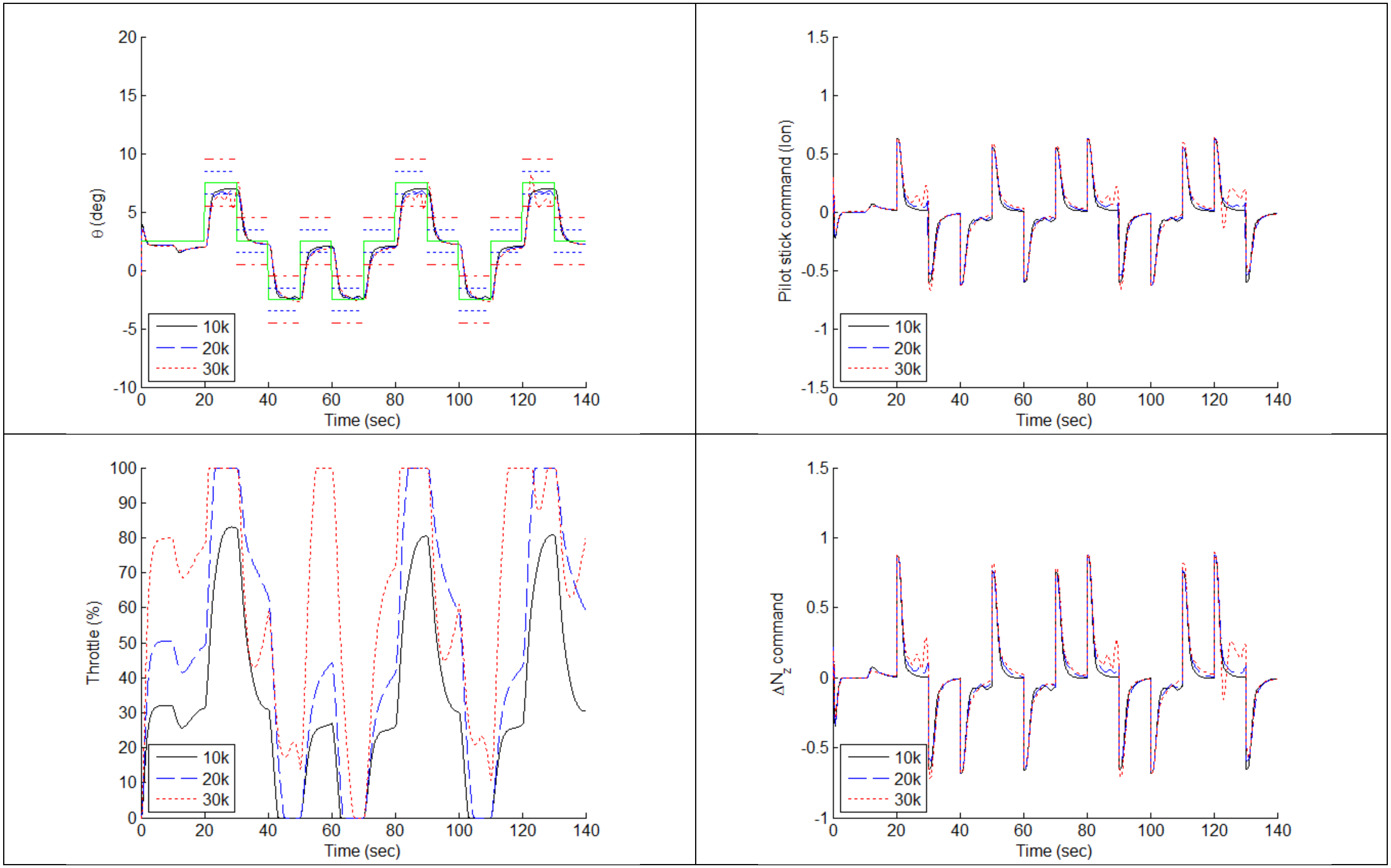


Figure 273. 300 knots — cruise (5° capture)

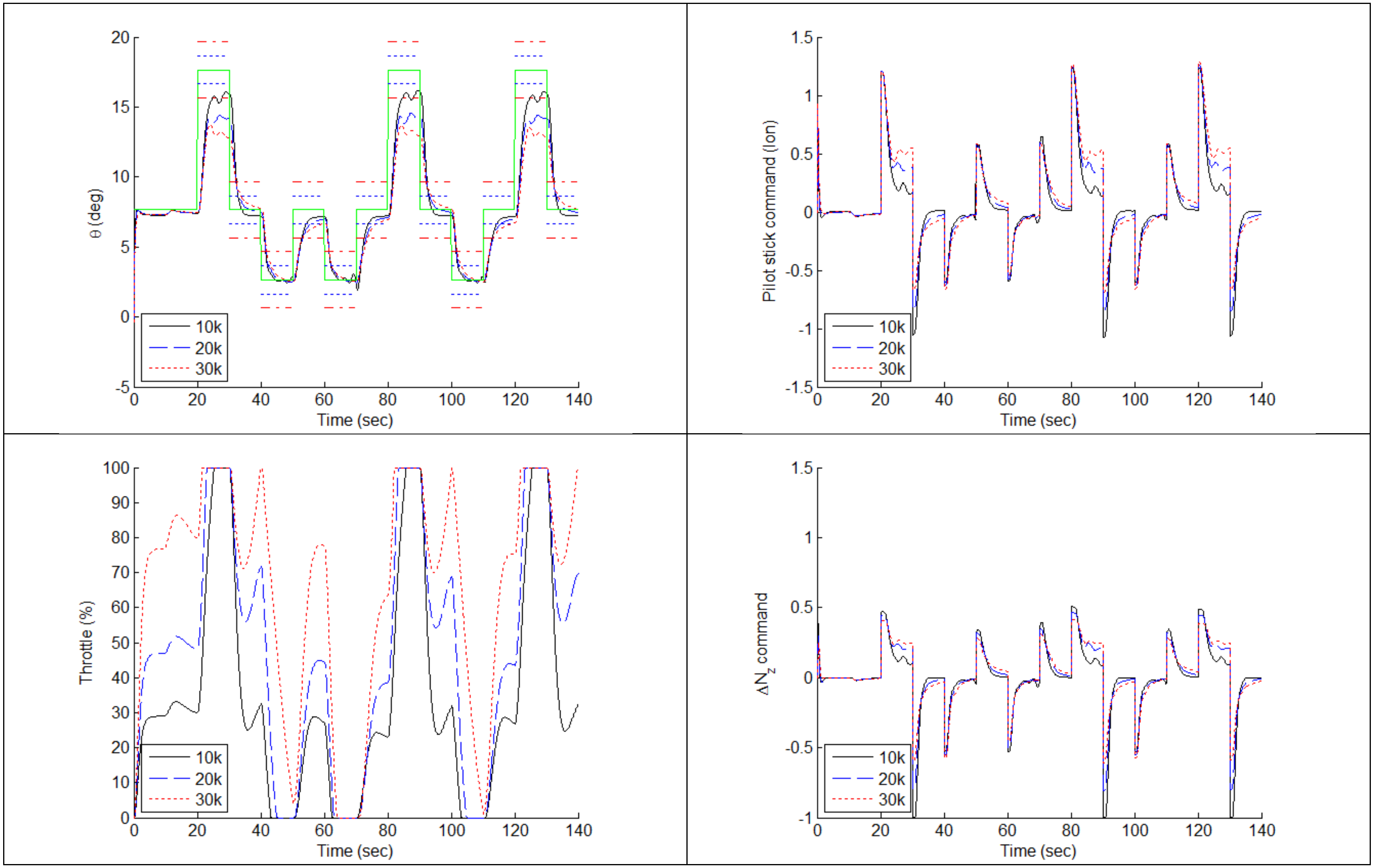


Figure 274. 200 knots — cruise (10° capture)

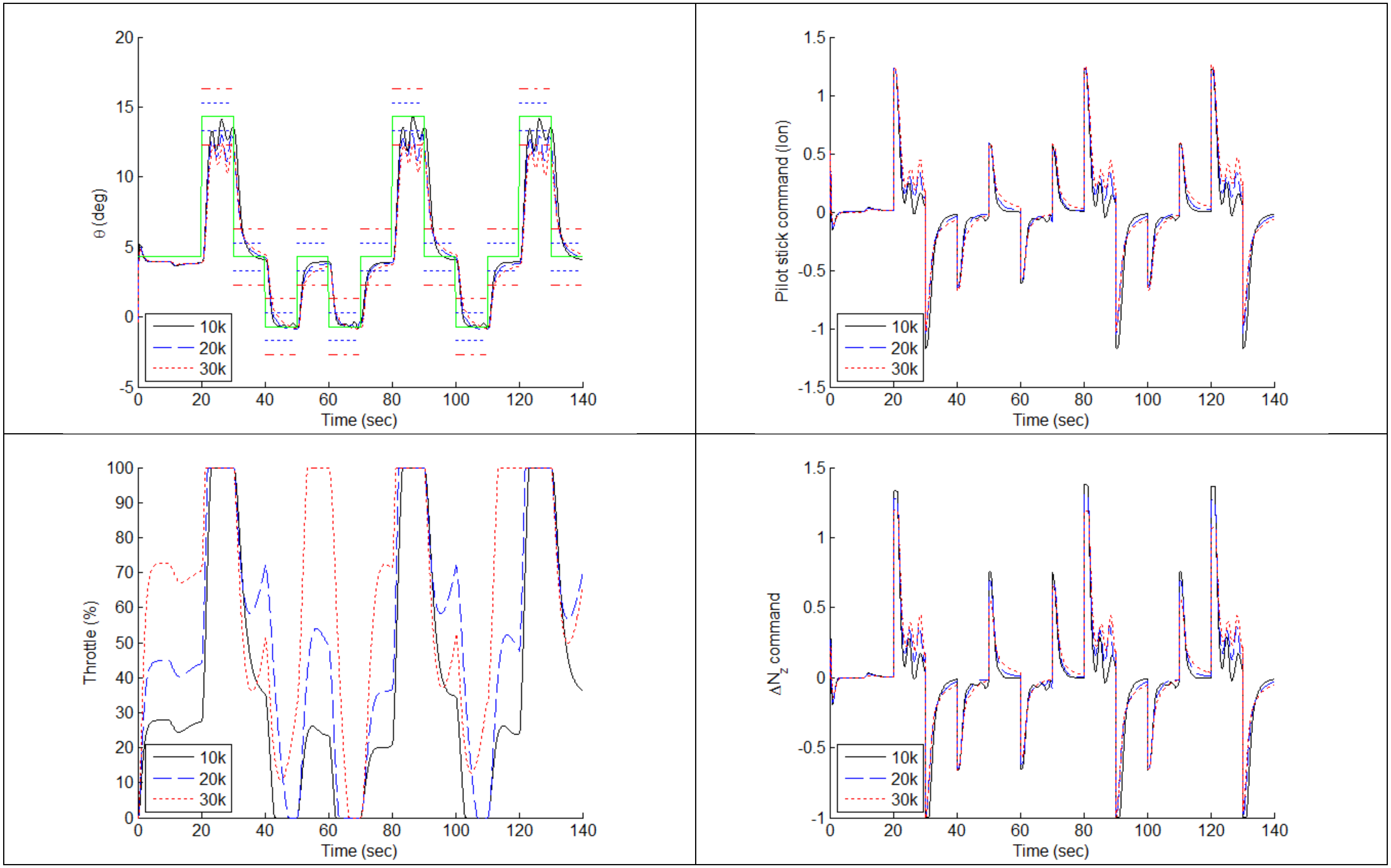


Figure 275. 250 knots — cruise (10° capture)

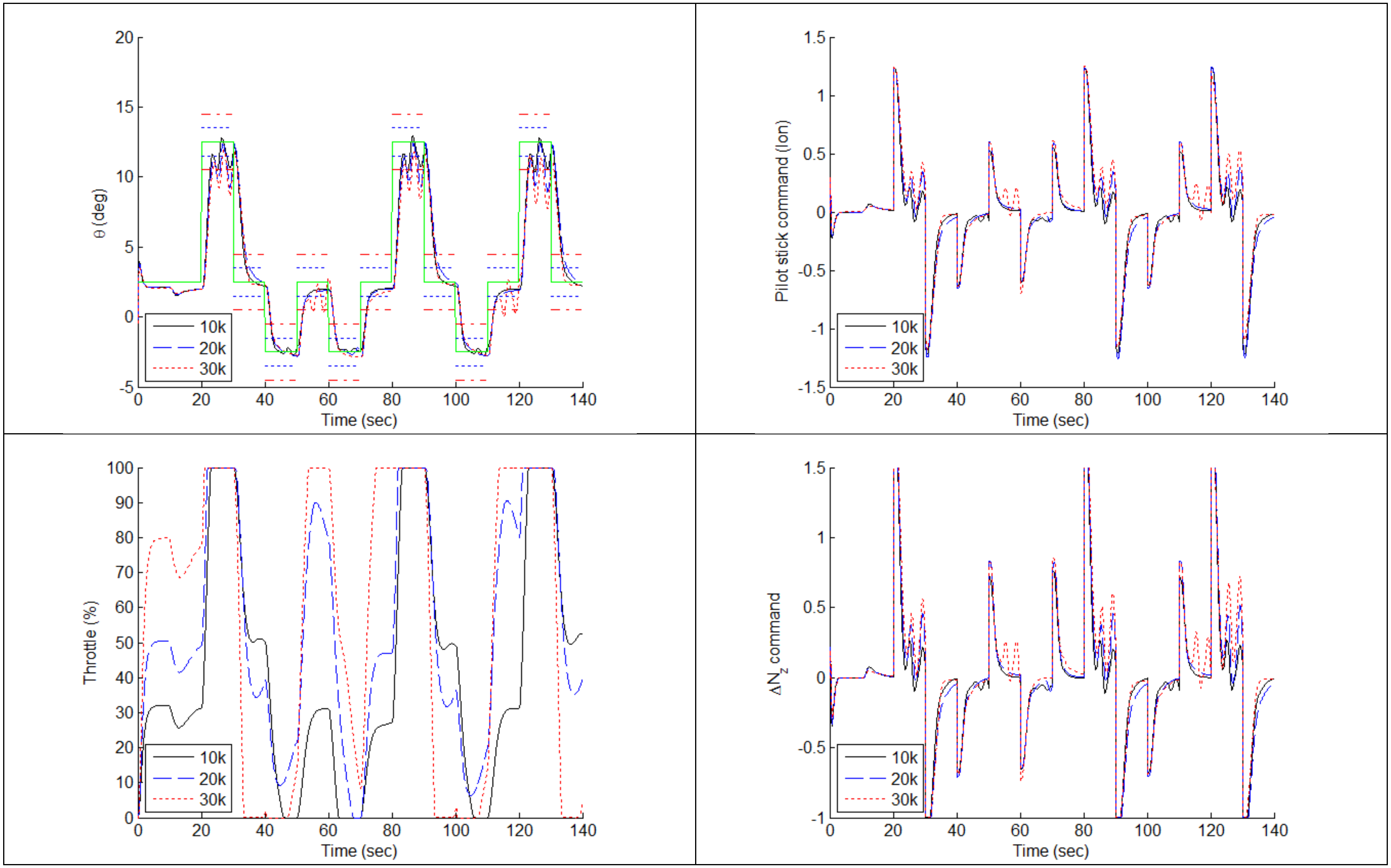


Figure 276. 300 knots — cruise (10° capture)

13.2.8 AFI-FCS Design Elements Observations and Conclusions

The inceptor command sensitivity is scheduled with speed and stick position using a parabolic gradient determined from the inceptor travel limiting values and the inceptor null position. The sensitivity and scheduling is done in such a way that a full stick input will command the limiting value of Δn_z at high speeds and the maximum available safe Δn_z command at low speeds.

For those cases that had commands using near full or FFS (i.e., to recapture trim or the -5° pitch attitudes), it was noted that the Δn_z value commanded was either near or at the negative limiting value. This trend appears to be consistent with the design intent of the command sensitivity scheduling. These commands were seen in the 10° captures sequences for approach and cruise at all speeds. The 5° captures did not command FFS or any limiting value of Δn_z, but the Δn_z commanded did tend to increase in amplitude as speed increased for similar levels of stick input, as was expected.

A number of cases also had full aft-stick commands, primarily for the 10° captures in both approach and cruise configurations. The commanded Δn_z value tended to increase as speed increased before hitting and holding its maximum value at the 175 and 200 kts cases for approach. No other cases ever commanded full aft stick, but they did show increasing Δn_z values for similar stick commands as speed increased, which was in line with the expected trends of stick command and Δn_z values.

In addition, a number of similarities were noticed between the approach and cruise configurations for the examined signals. A summary follows. Unless otherwise noted, these comments pertain to both the 5° and 10° capture sequences.

- With the few exceptions that were already noted above, the Δn_z values generally increased as the speed increased.
- The Δn_z required to maintain the positive pitch attitude captures at a fixed speed increased as altitude increased and the oscillations in general had a higher amplitude as speed increased.
- The Δn_z values commanded to return to trim from the 10° captures tended to be very close to or at the limiting value of -1 g. The notable exception was for the 200 kt cruise case at the 20k and 30k foot altitudes.
- The commanded Δn_z tended not to vary with altitude, with the two notable exceptions previously mentioned: the Δn_z required to maintain the positive pitch attitude captures and the Δn_z required to correct back to trim from this attitude.
- The positive attitude captures were uniformly the most difficult of all the capture attitudes to reach and maintain; of the two attitudes examined, the 10° capture was the most difficult.

- As speed increased, the 10° captures experienced higher frequency oscillations than lower speed cases and the amplitude of these oscillations tended to increase as altitude increased. Similar trends were noted in the pilot stick command and Δn_z time histories.

- Both the approach and cruise configurations showed degradation in their task performance as altitude increased when attempting to capture the positive pitch attitudes.

- With the few exceptions already noted, there was no issue reaching and maintaining desired performance for the trim and -5° captures.

- The pilot stick command varied little between altitude for both the approach and cruise configurations with the two exceptions already described: while trying to maintain the positive pitch attitude captures and returning to trim from these same attitudes.

- The pilot stick command exceeded the stick travel limit for all initial captures of 10°.

- The pilot stick command routinely came close to or exceeded the stick travel limit for the capture of trim after having captured 10°.

- The pilot stick command changed very little at the different speeds within the different configurations.

- Oscillations were noted when attempting to capture and maintain the positive pitch attitudes. The oscillations tended to grow in amplitude as speed increased.

The throttle settings experienced large swings in value that occurred in very short periods of time; this was true of all speeds, altitudes, flight conditions, and tasks.

14. AFI-FCS PILOTED EVALUATIONS TEST PLAN

14.1 BACKGROUND INFORMATION

The simulations were aimed at evaluating the HQ and the effectiveness of the envelope protection algorithm. They are based on different discrete captures tasks, to require the pilot to fly the aircraft progressively at the boundaries of the flight envelope, and to verify the effectiveness of the AFI-FCS in protecting from envelope exceedances. Discrete captures of different amplitudes are used to reach the limits with different rates and to provide a structured frame, common to all of the pilots, for the evaluations.

Additional discrete captures tasks are used for the HQ assessment. For the nature and the scope of the evaluations, the same level of priority is assigned to the assessment of the envelope protection system effectiveness and HQ.

No variations with respect to the nominal AFI-FCS settings and algorithm implementation are required to be evaluated. The main objectives are the investigation and assessment of two envelope protection modes:

- Speed protection (V_{min}/V_{max} mode)
- AoA protection (AoA_{prot} mode)

Based on the augmented aircraft dynamics reported in section 12.3, different flight conditions are identified for the AFI-FCS evaluations. They are selected in order for the AFI-FCS augmented aircraft dynamics to be comparable to those of the standard augmentation Calspan/STI aircraft. Considering the generic type of aircraft modeled and the inherent bare airframe differences, this allows for consistent comparison of the results between the two augmented aircraft. The selected flight conditions are reported in table 99.

Table 99. AFI-FCS aircraft evaluation flight conditions

Flight Condition	Hp (kft)	KCAS	TAS (ft/s)	Mach
Powered Approach (PA)	1	150	256	0.23
Maneuvering Speed (V_A)	15	250	524	0.50
Design Cruise Speed (V_C)	15	300	626	0.59

14.2 INTRODUCTORY NOTES

The AFI-FCS control system contains a vertical FPA Rate Command/FPA Hold augmented manual control algorithm, intended for “Direct FPA control.” FPA and pitch attitude captures are used for HQ evaluations. This is intended to require the pilot to use different cues and piloting techniques. The evaluations are of the nominal baseline configuration, with no variations.

Three different evaluation sessions are performed, varying tasks and display configurations:

- Standard pitch attitude captures with standard display in PA, $V_{A,}$ and V_C flight conditions

- Alternate positive/negative FPA captures of different amplitudes: $FPA = \pm 3.5°; \pm 5°$ with dedicated display, with and without FPA command marker

- Alternate positive/negative pitch attitude captures of different amplitudes: $\theta = \pm 3.5°; \pm 5°$ with dedicated display, with and without FPA command marker.

The standard capture tasks allow direct comparison of the HQ assessment between the AFI-FCS and the standard augmentation Calspan/STI aircraft. The other two tasks are specific to the AFI-FCS to allow the pilot to evaluate the FPARCH control algorithm versus FPA captures, which are expected to maximize its performances. The pitch attitude captures require standard technique, based on the pilot flying with pitch attitude as principal cue. The cues to the pilot are thought to be an important component of the evaluations for this highly augmented aircraft, from which the choice of performing the tasks with and without FPA command markers derives.

14.2.1 Envelope Protection Effectiveness Evaluation

This test is meant to assess the effectiveness of the AFI-FCS in protecting from envelope exceedances. Two types of tasks are dedicated to this evaluation:

- Progressive increase/decrease of FPA with steps of amplitude $|\Delta\gamma| = 1°; 2°; 3$
- Progressive increase/decrease of pitch attitude with steps of amplitude $|\Delta\theta| = 1°; 2°; 3$

An HQ assessment can be derived from these tasks as well when considered valid by the pilot.

14.2.2 Handling Qualities Tasks Description

The two standard Year 2 Follow-on pitch attitude captures profiles are used (PA and V_A flight conditions), together with additional FPA captures profiles of different maximum amplitude, displayed in figure 277. The task execution, scoring logics, and error requirements with respect to the target are identical to those described in section 4.3 for the discrete captures. No specific requirements are applied to the AoA to be achieved during the captures. An SoS disturbance is added to these tasks. These tasks are executed with and without the FPA command marker displayed on the HDD screen (section 14.2.4).

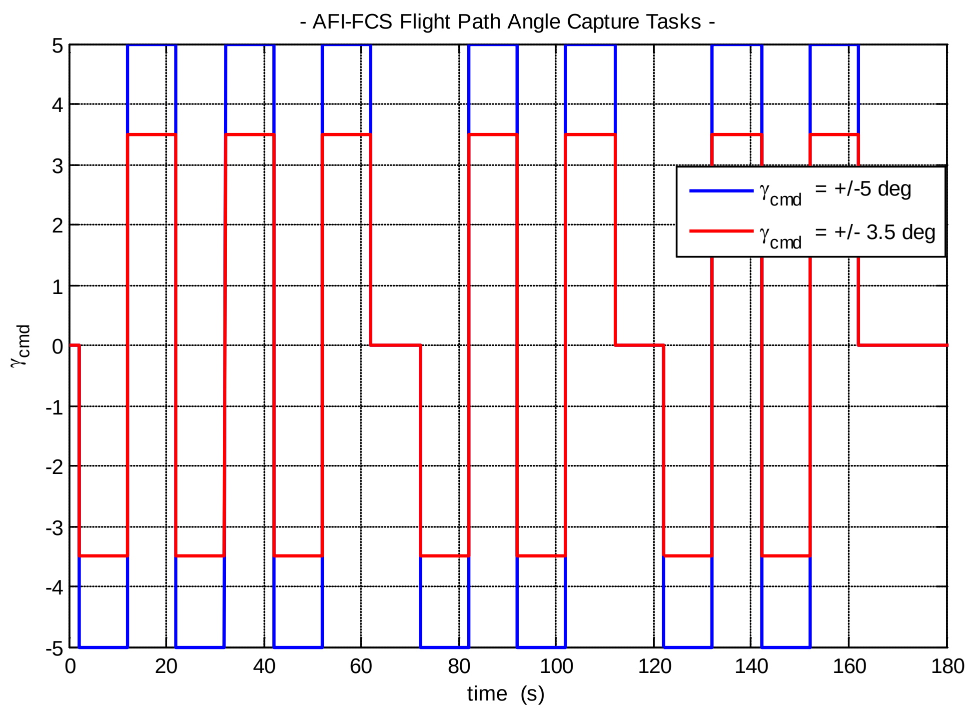


Figure 277. AFI-FCS γ command HQ tasks

14.2.3 Envelope Protection Tasks Description

Series of positive and negative pitch attitude and FPA increasing amplitude steps ($\Delta\theta$; $\Delta\gamma$) are used for the envelope protection system evaluation. An example of the target profile used for both pitch attitude and FPA positive captures is displayed in figure 278 (the actual task starts when $\gamma\ or\ \theta = 0$ is commanded). The steps amplitude is varied from $\Delta\theta;\ \Delta\gamma = 1$ deg to 3 deg, progressively, depending on the appropriate amplitude for the given flight condition.

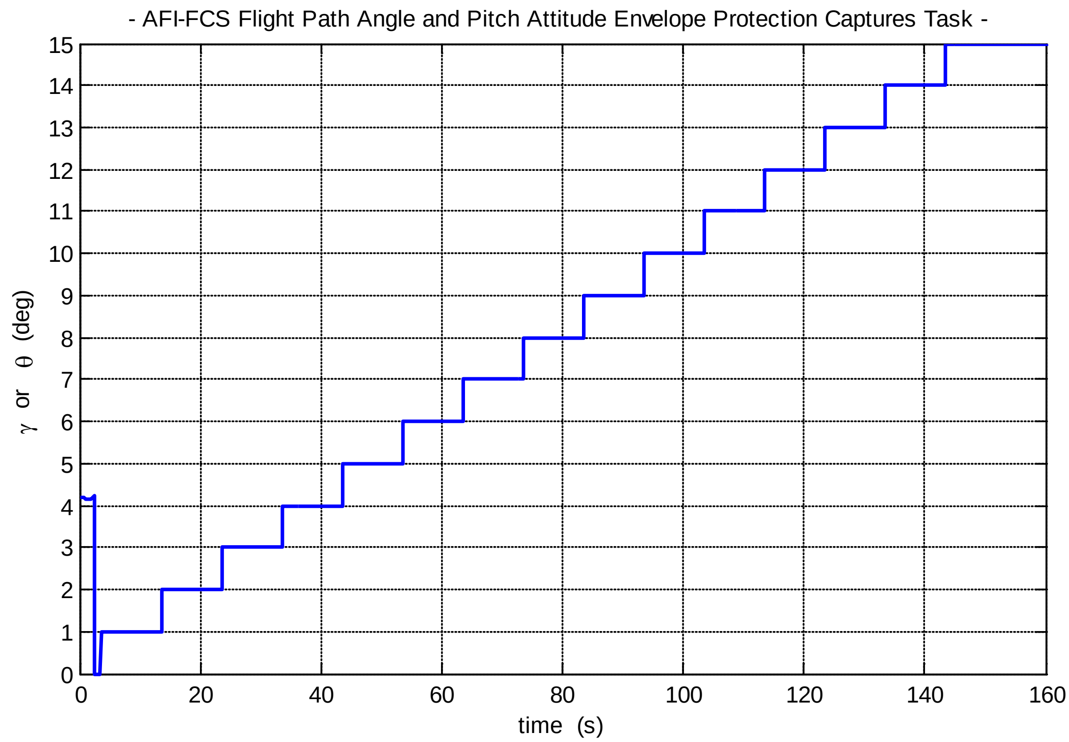


Figure 278. AFI-FCS γ and θ command envelope protection tasks

14.2.4 Aircraft Displays

Figures 279 and 280 illustrate the aircraft displays used to accomplish the pitch tasks, with and without the FPA command marker, respectively. The AFI-FCS aircraft is controlled by a vertical FPA Rate Command/FPA Hold augmented manual control algorithm, intended for "Direct FPA control." For this reason, both displays include an FPA marker, noted in the figures. The second display includes an FPA command marker, which is intended to support the pilot in the captures task, allowing him to use a different piloting technique with respect to the previous standard technique, with pitch attitude as the principal cue. The AoA references have been changed to match the AFI-FCS aircraft characteristics.

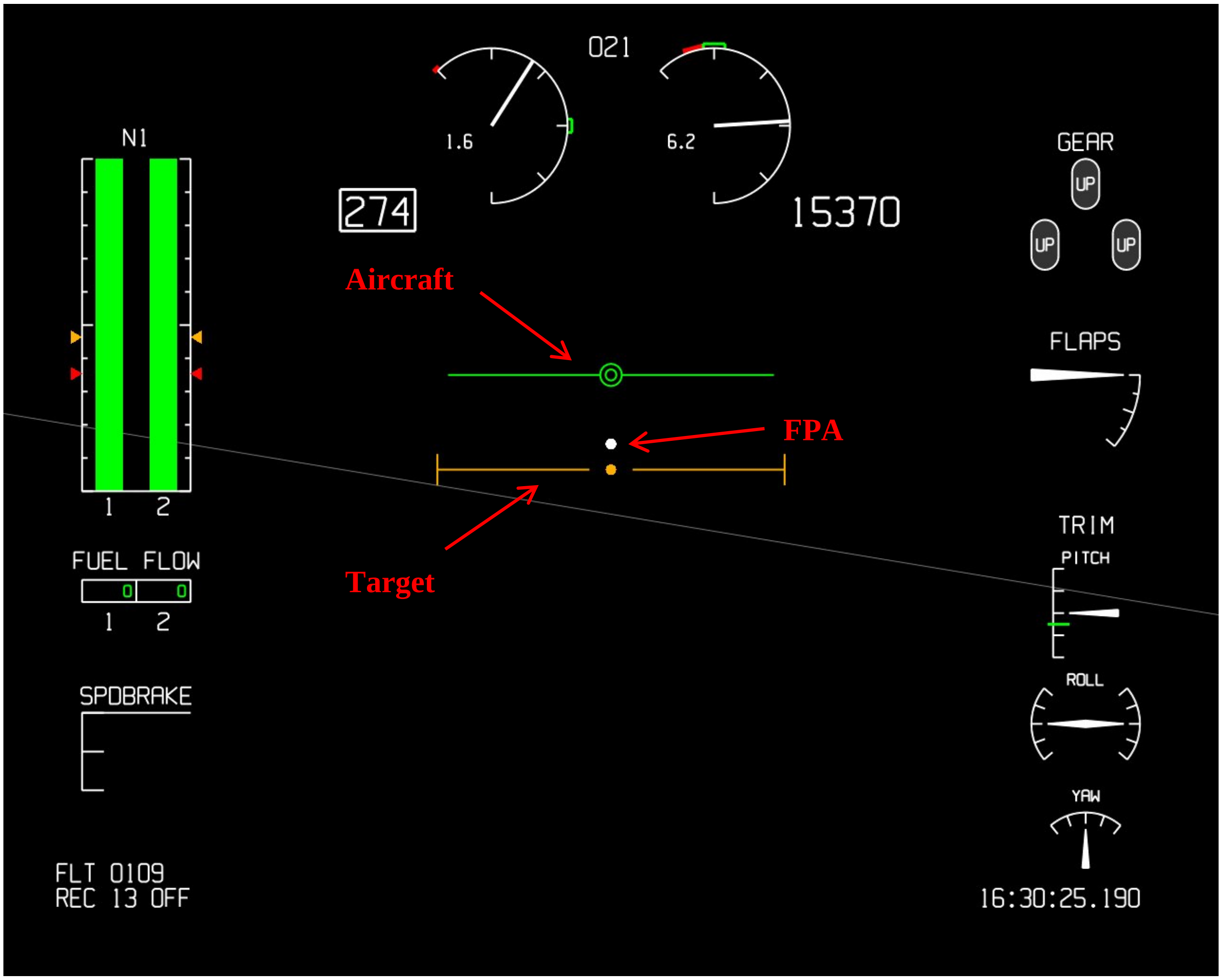


Figure 279. The HDD pitch task representation — FPA marker

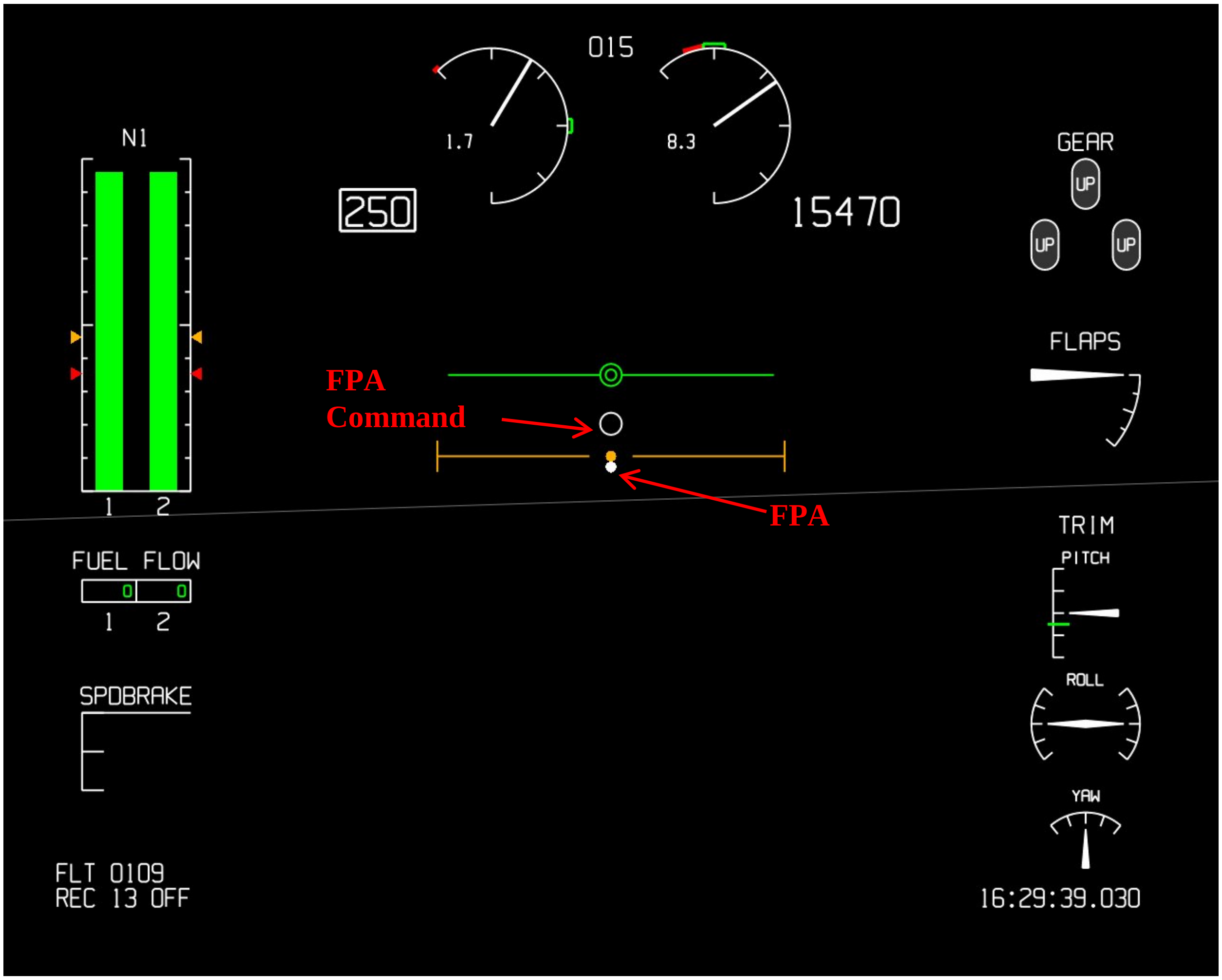


Figure 280. The HDD pitch task representation — FPA marker and FPA command marker

<u>14.2.5 Evaluation Questionnaire</u>

A dedicated questionnaire is used to synthesize the pilot's evaluation and provide a quantitative metric to assess the effectiveness of the envelope protection system. This is required for the nature of the evaluations, which are subject to different requirements and criteria with respect to standard HQR. The questionnaire is displayed in figure 281. When applicable, the standard HQR will also be provided by the pilot.

Pilot: ________________ Evaluation of: _______________ Axis: _______________ Date: _____________

Flight #: ____________ Record #s: ________________

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 281. AFI-FCS evaluation questionnaire

15. RESULTS OF AFI-FCS HANDLING QUALITIES EVALUATIONS

15.1 INTRODUCTION

Pitch attitude and FPA captures were flown, with and without SoS disturbance, replicating the same sequence of the tasks used for the Year 2 Follow-on HQ evaluations. The pure pitch attitude SoS task was also flown by some pilots. A minimum of two evaluations were conducted, which were rated separately or with a single rating for both—depending on the pilot's judgment. No variations were done of the baseline fully operational system, which was rated as the baseline configuration. The discrete captures scoring is not applicable in these evaluations for the different aircraft to be evaluated and relative task requirements.

15.2 PA FLIGHT CONDITION

15.2.1 Principal Outcomes

The aircraft HQ were evaluated by four pilots with respect to several tasks and with different HDD configurations, with the intent of exposing the most relevant characteristics of the augmented aircraft. This led to scatter in the ratings across the different pilots and within the evaluations of the same pilot. This is an important result, considering that pilots were aware of testing the nominal configuration and that no changes were made to it. It indicates a tendency for the HQ to depend on the piloting technique and task.

From the analysis of the pilots' ratings and piloting techniques, the following indications can be derived for the specific pitch attitude capture task, with SoS disturbance:

1. The aircraft is HQ level 1, marginal level 2, as predicted by the Pitch Bandwidth Criterion, with occasional ratings in the HQ low level 2 range (HQR = 7).

2. The low flight-path angle bandwidth and relatively high pitch-attitude phase delay, analyzed and reported in section 12.6, are consistently perceived by the pilots as low responsiveness and lagging of the pitch response during pitch attitude and large amplitude FPA captures, in particular.

3. The response characteristic described above produced a non-negligible scatter in the ratings and a sensitivity of the HQ to the piloting technique. The same pilot provided HQR = 2 (two occurrences) and HQR = 5 with respect to the pitch attitude captures task.

4. The HQR significantly depend on the visual cues to the pilot which are provided by the HDD. The tasks were usually flown with the FCS FPA command marker visible in the HDD (figure 280). Flying the same tasks without the marker produced a significant degradation of the HQ, for pilot 3 in particular, from HQR = 4 to HQR = 7. Pilot 2 reported a higher PIO proneness with this second HDD configuration, PIOR = 3. The risk for moderate PIO was predicted by offline analyses on the basis of the flight path bandwidth values presented in section 12.6.

5. Piloting technique affects HQ and the perceived performance by the pilot. Better HQR were assigned when the pilot used an open-loop technique, in particular when gross

acquisition was performed with gradual, low-amplitude inputs with negligible higher frequency stick activity (pilot 5). After attempt to control the aircraft with a closed loop technique, pilots occasionally opted for an open-loop technique based on the aircraft response. Pilot 2 commented: “Easier to overshoot—need less aggressive inputs and to come off earlier. Difficult to modulate the correct back stick pressure/force for NU. Not quite as much PIO, even though it was still evident.”

6. The FCS suppresses external disturbances very effectively, requiring a lower pilot workload with respect to the standard Calspan/STI augmentation. This is reported by all the pilots as a positive characteristic, which allows focus to be on target gross acquisition, with a limited subsequent requirement for fine tracking and CCC.

From the points described above, it is determined that the aircraft response is mostly appropriate for open-loop piloting technique with gradual large-amplitude inputs and a low-level of high-frequency stick activity. This is consistent with the operatively relevant requirements for aircraft of this class. Dedicated, more demanding tasks expose potential HQ deficiencies when the aircraft is controlled with higher priority to the task performance/scoring.

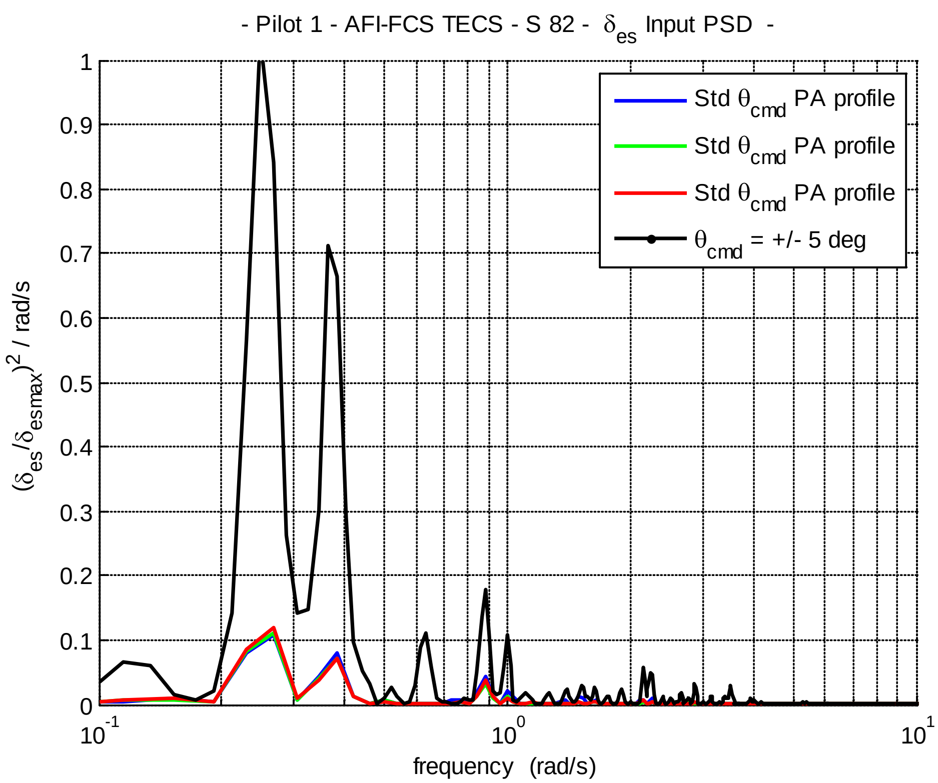


Figure 282. PSD of pilot 1’s δ_{es} input — AFI-FCS pitch attitude captures

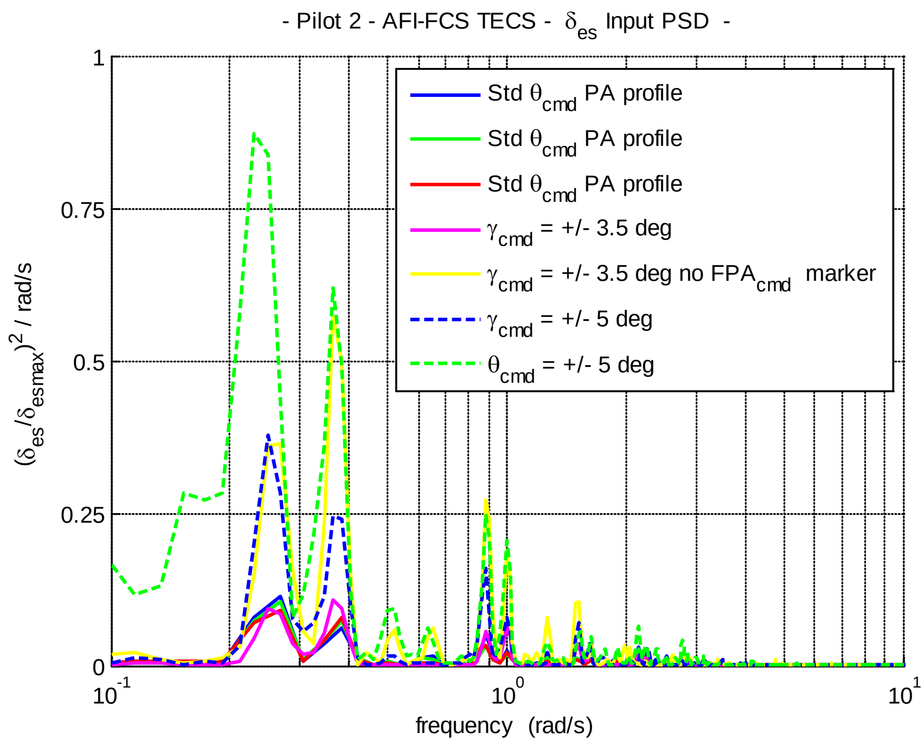


Figure 283. PSD of pilot 2's δ_{es} input — AFI-FCS pitch attitude — FPA captures

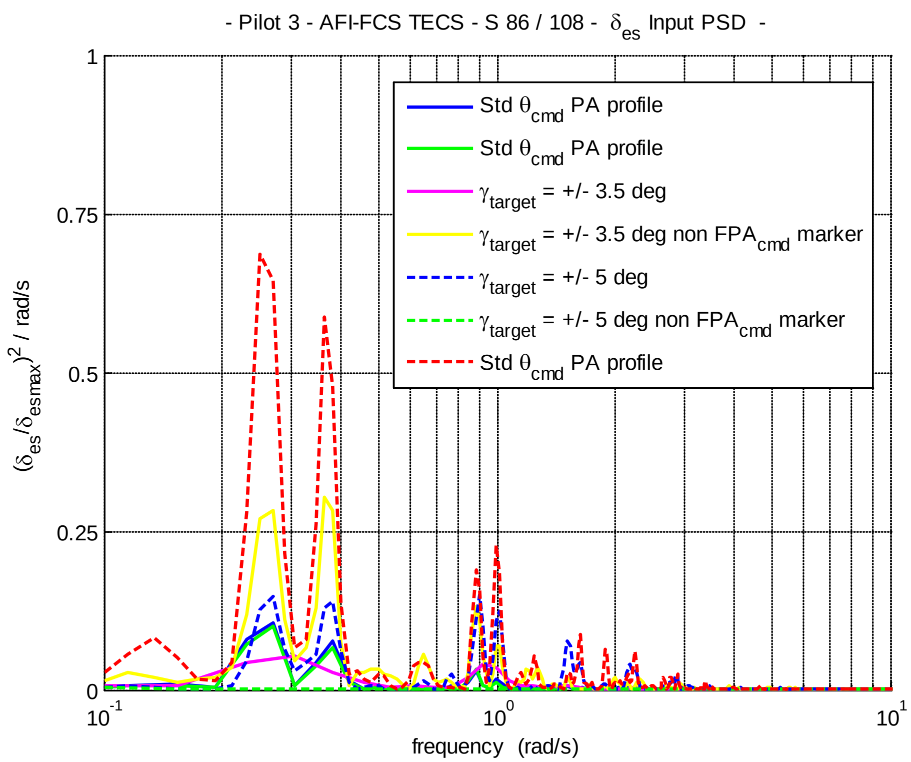


Figure 284. PSD of pilot 3's δ_{es} input — AFI-FCS pitch attitude — FPA captures

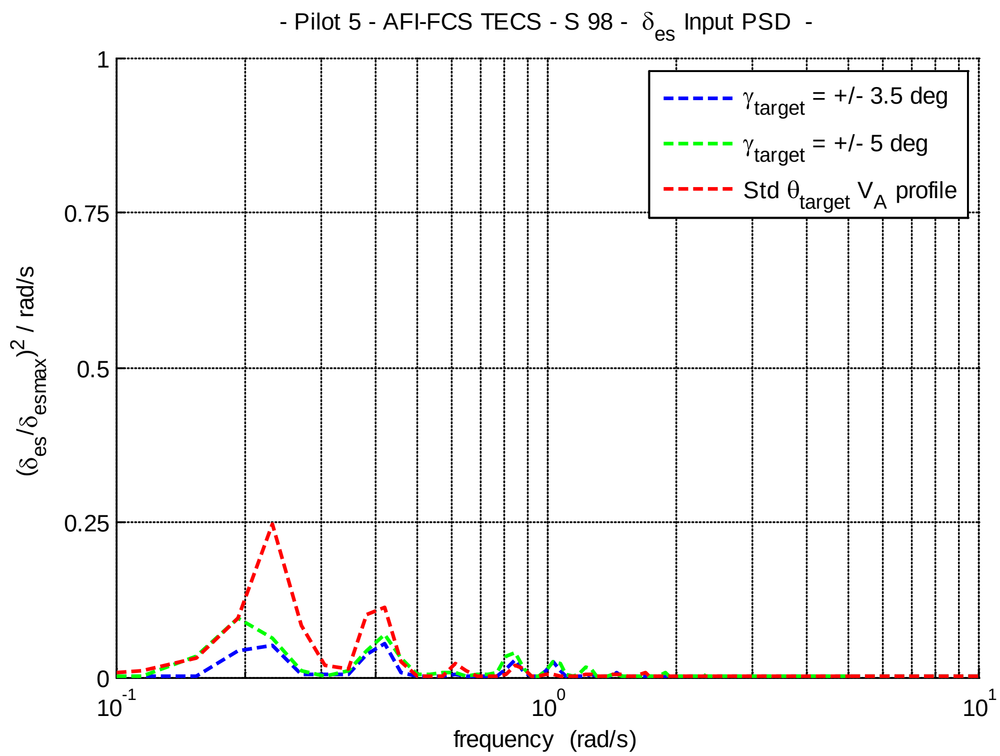


Figure 285. PSD of pilot 5's δ_{es} input — AFI-FCS pitch attitude — FPA captures

15.2.2 Pilot Ratings, Comments, and Task Scoring

15.2.2.1 Pilot 1

- Pilot ratings and comments – With respect to the standard pitch attitude task, the aircraft is rated HQ solid level 1, with minimal differences between HQR: two HQR = 2 and one HQR = 1 occurrences. A slight tendency to bobbling was reported in the first evaluation. This was not reported in the other evaluations, potentially due to learning of the task: "Getting better at the task." No tendency to PIO is evident. The effectiveness of the disturbance suppression capabilities of the system is considered one important factor for good handling qualities: "Easy because of the mostly blocked SoS (disturbance)." No correlation between task scoring and HQR was present (see table 100).

Table 100. Pilot 1 AFI-FCS HQ ratings and comments — pitch attitude captures

Evaluation: FAA Model - Discrete & SoS - Pilot: 1 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
82	1	Pitch	baseline	2	1	A couple overshoots to steady. Some bobble. Easy to acquire alpha. Forces lighter. Tracking is fine.
82	2	Pitch	baseline	2	1	Getting better at the task.
82	3	Pitch	baseline	1	1	Easy because of the mostly blocked SoS.

With respect to the $\theta_{target} = +/-5°$ discrete task, the aircraft is rated HQ level 2 (HQR = 5) with tendency to be PIO prone (PIOR = 3). This is a single evaluation, indicating a potential dependency of HQR on the task to be executed. Quantitative scoring is comparable across all performed evaluations and all tasks. A different piloting technique is the reason for this different rating. More details on this aspect are contained in the "Piloting Technique and Time Histories" subparagraph.

With respect to FPA captures, the aircraft is consistently rated HQ level 2 (HQR = 4) and PIOR = 2, indicating a tendency to develop uncommanded motions with no impact on the capability to achieve desired performance. Pilot reported too much lag in the response, with the requirement for him to ignore the FPA command marker and refer to the FPA marker: "I am controlling the actual FPA marker instead of the hollow circle (too 'squirrely,' too much lag). New technique – overshoot to capture faster and beat the lag. Can get desired this way but is more workload. I can get rid of my command when the FPA command reverses." Figures 286 and 287 display the time history of one FPA discrete capture for which the initial large amplitude inputs are clear.

Overall, the aircraft is HQ level 1, marginal level 2. A dependency of the ratings on the task and on the piloting technique is present.

- Task scoring – The average continuous scoring with the standard (Year 2 Follow-on) PA pitch attitude capture task profile is desired = 63% and adequate = 68% with minimal variations across the different evaluations. The scoring of the evaluation with the $\theta_{target} = +/-5°$ task is desired = 61% and adequate = 67%, comparable to the other evaluations.

  These values are slightly lower than the average scoring of the standard Calspan/STI aircraft baseline configuration.

  The continuous scoring with the FPA captures is desired = 45%, adequate = 57%.

Piloting technique and time histories – Pilot 1 used a very different piloting technique between the first three consecutive evaluations and the others, which occurred several days later. In the first three evaluations, the gross acquisition was performed with relatively small amplitude inputs, with no significant input shaping overall. In the fourth evaluation, the gross acquisition was performed with a large amplitude initial input (FBS or FFS) and subsequent significant input shaping. The PSD of the longitudinal stick inputs in figure 282 and the time histories of figures 286 and 287 demonstrate these different piloting techniques, which are not expected to depend on the capture amplitude.

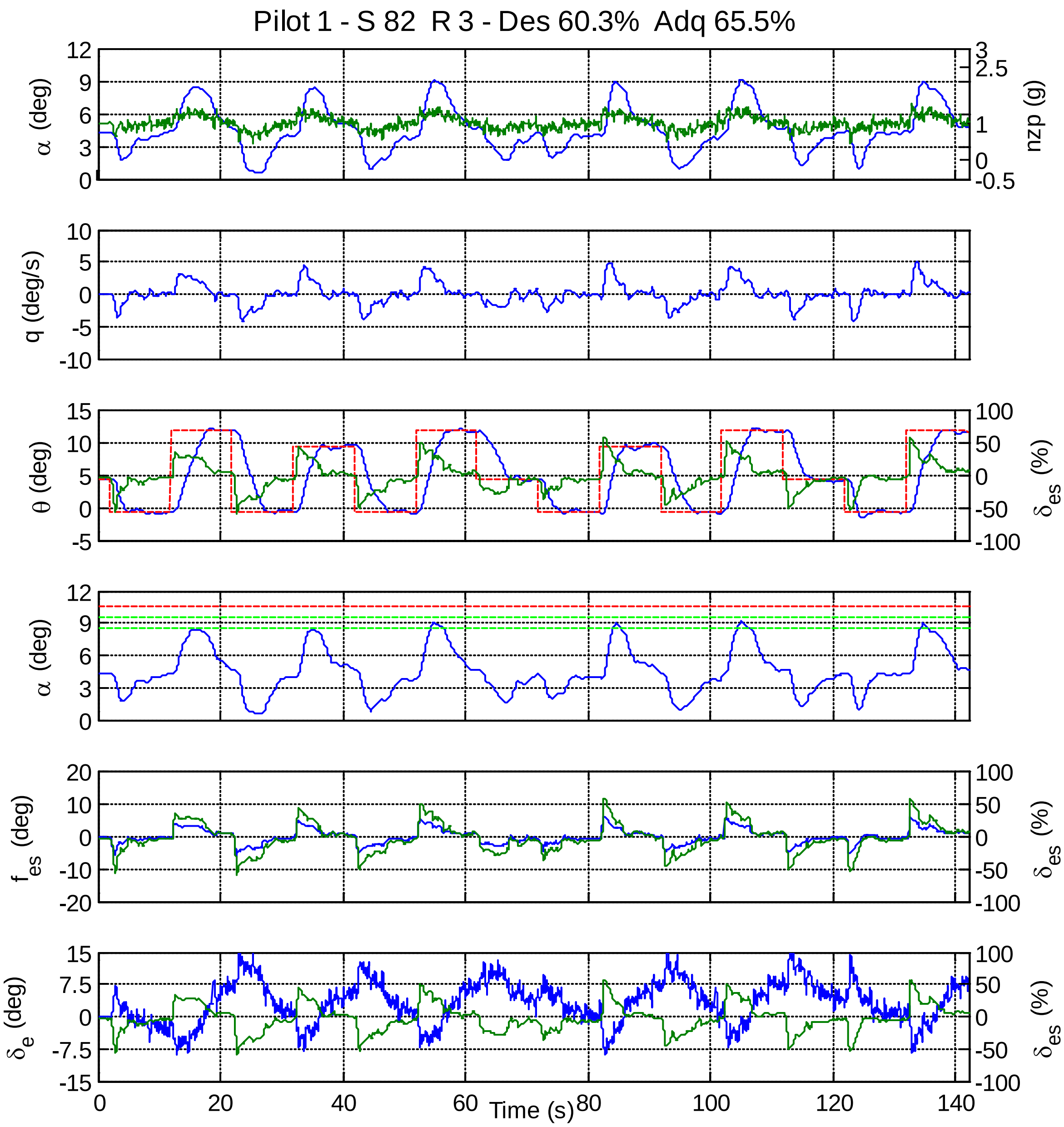


Figure 286. Pilot 1 AFI-FCS pitch attitude captures time history — plot S82 run 3 — PA

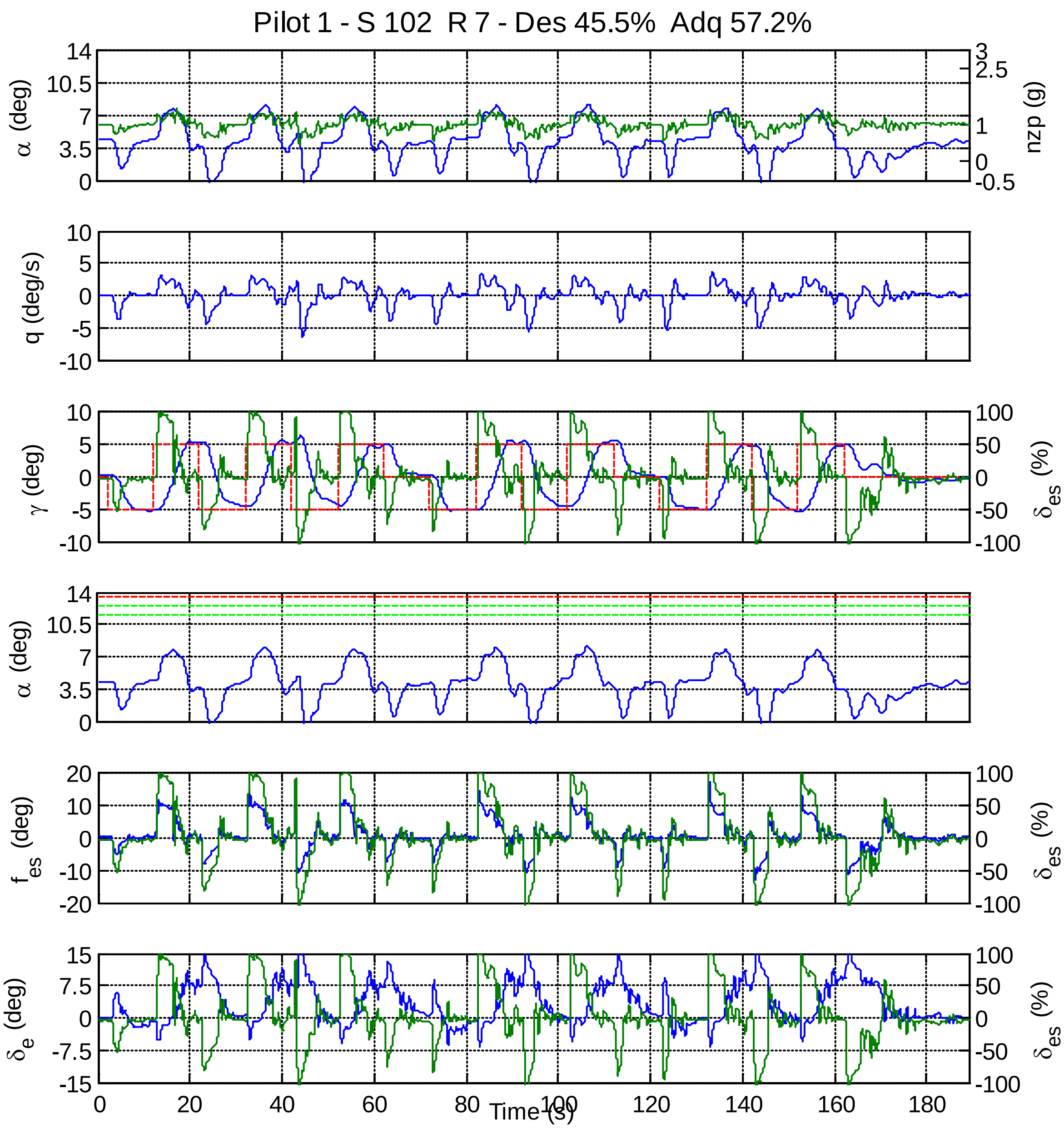


Figure 287. Pilot 1 AFI-FCS FPA captures time history — plot S102 run 7 — PA

15.2.2.2 Pilot 2

- Pilot ratings and comments – With respect to the standard PA pitch attitude task profile, the aircraft is rated HQ level 2, with a high degree of consistency among the ratings: HQR = 4; PIOR = 2 for all three evaluations and among the comments regarding the aircraft dynamics. In all these evaluations, no FPA command marker was displayed on the HDD. The recurrent indication from the pilot is the occurrence of pitch oscillations when a closed loop technique is used, which requires the pilot to change to an open loop technique. The relevant ratings and comments are reported in table 101. As in the case of pilot 1, different ratings were given by pilot 2 in a fourth evaluation. The aircraft was rated HQ level 1 and oscillations were reported, with no tendency to PIO (HQR = 3; PIOR = 2) when the pilot used a different piloting technique with larger initial inputs.

Table 101. AFI-FCS pilot 2 HQ ratings and comments

Evaluation: FAA Model - Discrete & SoS - Pilot: 2 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
81	1	Pitch	baseline	4	2	Easier to overshoot—need less aggressive inputs and to come off earlier. Difficult to modulate the correct back stick pressure/force for NU. Not quite as much PIO even though it was still evident.
81	2	Pitch	baseline	4	2	Being aggressive causes PIO. Works better in open loop.
81	3	Pitch	baseline	4	2	Rate slows down and it takes longer in NU, concentrate more on alpha. ND rate is quick and then oscillates.

With respect to the $\gamma_{target} = +/-3.5°; +/-5°$ captures task with FPA command marker displayed on the HDD, the aircraft is rated HQ level 1 (HQR = 2 and 3, respectively) and tendency to induce uncommanded motions was reported in one case (PIOR = 1; 2).

For the smaller amplitude FPA captures, pilot comment was: "Task is not the same as before. Easy to put in circle, FPA follows and catches up. Being aggressive and there is no PIO. Good HQ. No time restraint." The HQ degradation for the larger amplitude captures is due to a reported lag in capturing the target: "Takes a long time to coast up. So, put the predictor beyond the target." This is a similar technique to that used by pilot 1.

With the same task performed without the FPA command marker on the HDD, the aircraft is rated HQ level 2 (HQR = 5), with reported PIO proneness (PIOR = 3): "A lot of lagging. It is an open-loop guessing game. Hard to be aggressive; there is too much lag between command and gamma response. Can be very PIO sensitive." The lack of the command marker leads to unpredictability, which causes HQ degradation.

Overall, the aircraft is rated HQ level 1, marginal level 2. The dependency of HQR on the type of task is noticeable.

- Task scoring – With respect to the standard PA pitch attitude captures profile, average scoring is desired = 64%, adequate = 70%, with negligible variations across the three evaluations.

Average scoring of the FPA captures with visible FPA command marker is desired = 48%, adequate = 59%. The only FPA captures evaluation without FPA command marker has a scoring of desired = 46%, adequate = 66%. Scoring is not correlated to HQR and PIORs; a slight dependency on task can be identified, with lower scoring for FPA captures. The FPA command marker improves both scoring and HQ with respect to the same task without marker.

- Piloting technique and time histories – Piloting technique demonstrates differences across all evaluations, with three distinct types:

1. Low stick activity across the whole frequency range, with higher frequency input shaping, used for the standard pitch attitude captures PA profile.

2. Significant amplitude low-frequency inputs, with closed-loop, higher frequency stick activity, on a wider frequency range, used for FPA captures.

3. A technique similar to the previous one (#2 above) for the higher frequency content, with much higher low-frequency inputs, used for small amplitude pitch attitude captures.

The correspondence between tasks and technique is reported and considered valid specifically for these tests. Piloting technique affects the HQR, as verified by pilot 1.

Figure 288 displays the third piloting technique of the list above: initial large inputs, with subsequent higher frequency content inputs to refine the capture visible from the traces.

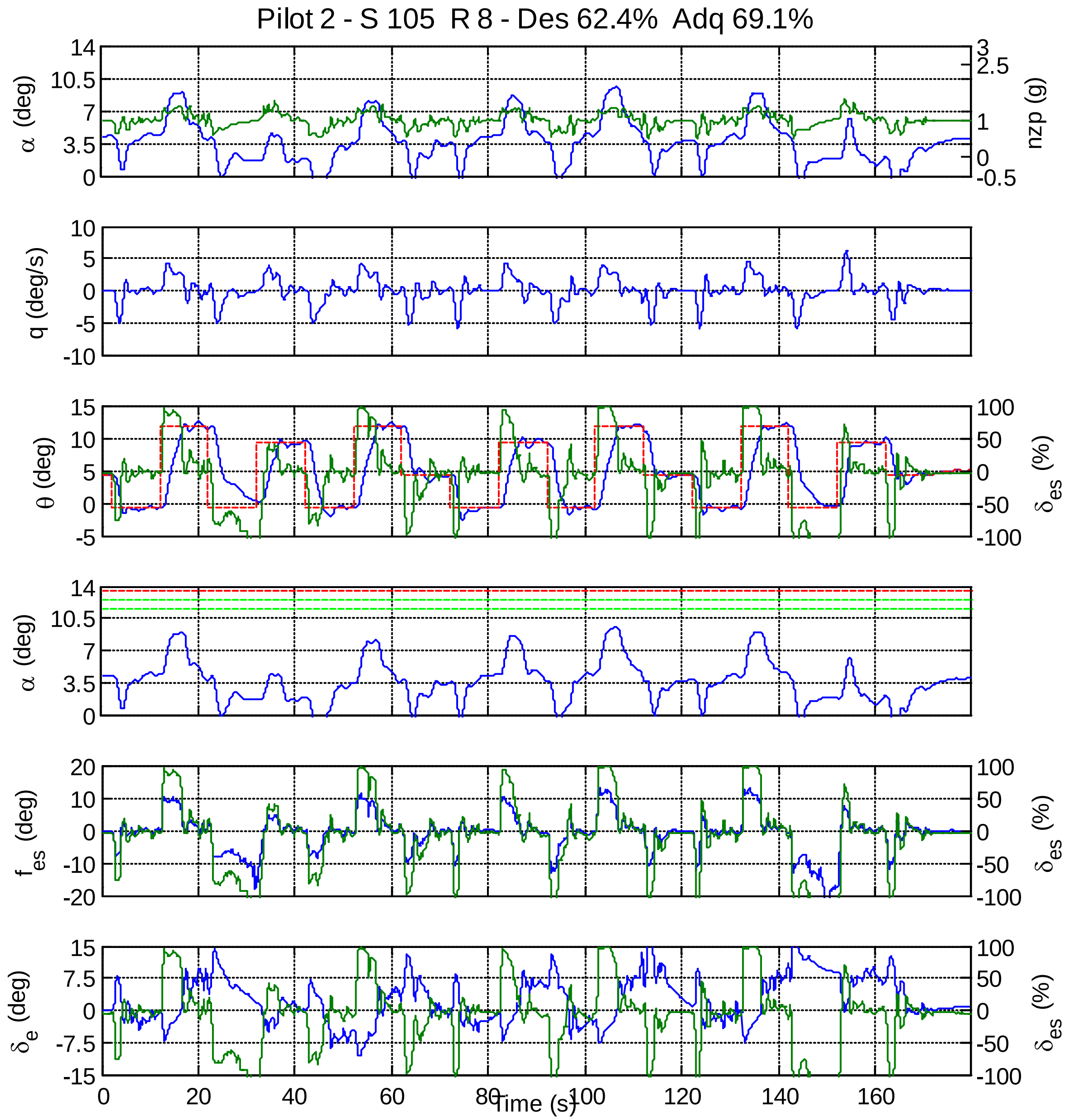


Figure 288. Pilot 2 AFI-FCS FPA captures time history — plot S105 run 8 — PA

15.2.2.3 Pilot 3

- Pilot ratings and comments – With respect to the standard pitch attitude task in PA, the aircraft is rated HQ level 1 (HQR = 2; 3). The first two evaluations, which correspond to solid HQ level 1 (HQR = 2), were performed before, without the FPA command marker. The third was performed within a broader assessment of the envelope protection effectiveness and included the HDD FPA command marker. Pilot 3 stressed the very effective disturbance suppression provided by the FCS. He also compared the response with that of the Calspan/STI standard augmentation, noting a lower tendency to uncommanded motions for the AFI-FCS aircraft, even if occasional alpha overshoots were reported.

Degraded HQ were rated when evaluations were conducted with the FPA command marker on. The pilot was qualitatively aware of the control system status by observing the marker and there was a tendency to use larger initial stick inputs for gross acquisition. The information derived from the marker potentially affected the pilot's evaluations. Because of the aircraft's state at the time of system engagement, the pitch attitude captures target of session 108, run 9, had a positive bias of $\theta_{target_{bias}} = 3°$, which potentially affected the evaluations. Table 102 contains the pilot's comments and ratings.

Table 102. Pilot 3 AFI-FCS HQ ratings and comments — pitch attitude captures

Evaluation: FAA Model - Discrete & SoS - Pilot: 3						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
86	1	Pitch	Baseline-pure discrete	2	1	Alpha seems to respond less quickly to the stick input=alpha overshoot. Less oscillatory than Calspan standard augmentation with exception of alpha overshoot.
86	2	Pitch	Baseline	2	1	Overshoot alpha again. Easy to keep in desired. SoS does not degrade performance as much as standard with SoS. Does a pretty good job canceling the disturbance.
108	9	Pitch	Baseline Theta Captures PA	3/4	2	Big changes are worrying. Can see the mode change from the FPA cmd movement, but it shouldn't be jumping around like that.

With respect to the FPA captures task, the aircraft is rated HQ level 2. Significant impact on HQ is due to the lack of the FPA command marker in the HDD. Both evaluations, which included the marker, were HQR = 4 and PIOR = 2. The evaluations without the marker were HQR = 7 and PIOR = 5, denoting a significant degradation of the HQ and PIO tendency to the point that the pilot "may abandon the task." The pilot appreciated the precision of the capture, which requires a low workload, reporting delay in the aircraft response, which affects the time to capture. The time delay perceived by the pilot is considered a relevant factor of the ratings: "When I use the big circle for small captures, it is ok. For bigger captures, the response is too slow." The delay is considered a determinant factor of HQ degradation in the captures without the FPA command marker: “A huge amount of lead is required. The nose is moving around in a non-natural way when trying to quicken up the FPA.” Table 103 reports the pilot’s ratings and comments.

Table 103. Pilot 3 AFI-FCS HQ ratings and comments — FPA captures

Evaluation: FAA Model - Discrete & SoS - Pilot: 3						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
108	5	Pitch	FPA Captures 3.5°	4	2	When I use the big circle for small captures, it is ok. For bigger captures, the response is too slow. The FPA cmd circle is quite easier to follow than just the FPA, which tends to overshoot. I can learn to go a little bit long. It makes FPA quicker. Undesirable motions.
108	6	Pitch	FPA Captures 3.5° no cmd circle	7	4	A huge amount of lead is required. The nose is moving around in a non-natural way when trying to quicken up the FPA. For this task there is a non-tolerable workload. It is not possible to keep it in desired. This would be unsafe with disturbance.
108	7	Pitch	FPA Captures 5°	4	2	It takes a long time for FPA to get in the FPA cmd. Not seeing anything that should drive any protection.
108	8	Pitch	FPA Captures 5° no cmd circle	7	4	Same as before. Feels unnatural like I am not flying a plane.

- Task scoring — With respect to the standard PA pitch attitude captures profile, average scoring is desired = 59%, adequate = 66%, with maximum scoring deviation equal to 10%. Scorings of other captures are not available from the recorded data.

- Piloting technique and time histories — Pilot 3 used different piloting techniques among the pitch attitude captures runs, the FPA captures, and between pitch attitude and FPA captures. This is displayed in the pilot’s inputs PSD of figure 284. The third pitch attitude captures run is characterized by a significantly higher input amplitude in the gross acquisition part of the task and higher stick activity at relatively high frequency

($\omega = 0.9; 1\ \mathrm{rad/s}$). These large differences do not produce significantly different HQR: The aircraft is rated consistently HQ level 1. FPA captures were executed with and without the displayed FPA command marker. The impact on the piloting technique was that larger inputs for gross acquisition were used when flying the airplane without the FPA command marker. As described in the previous subparagraph, this different required piloting technique produced an HQ degradation.

15.2.2.4 Pilot 5

- Pilot ratings and comments – Pilot 5 rated the AFI-FCS aircraft HQ with respect to both FPA and pitch attitude captures. All tasks were performed with the FPA command marker visible in the HDD. The aircraft is rated HQ solid level 1 (HQR = 2), with no tendency to PIO (PIOR = 1) in all three evaluations. As with the other pilots, pilot 5 reports lag in the response for pitch attitude captures: “Not as responsive as I want it to be, but doing pretty good. Very stable. Excellent.” This does not affect the ratings (see table 104).

Table 104. AFI-FCS pilot 5 HQ ratings and comments

Evaluation: Alpha Limitor - Pilot: 5 - Date: 08/03/2012						
Session	Run	Axis	Task	HQR	PIOR	Comments
PA mode=0						
98	7	Pitch	FPA captures 3.5°	2	1	Very nice and stable. Excellent acquisition and tracking. Solid airplane.
98	8	Pitch	FPA captures 5°	2	1	Very well behaved, very nice.
98	9	Pitch	Theta captures	2	1	Not as responsive as I want it to be, but doing pretty good. Very stable. Excellent.

- Task scoring – Discrete captures continuous task scoring is reported in table 105. The relatively low scoring of the FPA captures is an indication of low aggressiveness in performing the task. It is noticeable that the pitch attitude captures have the highest scoring, with desired level overall, even if the pilot reported a not completely satisfactory responsiveness in pitch.

Table 105. AFI-FCS pilot 5 task scoring discrete pitch captures

AFI-FCS Pilot 5 Task Scoring Discrete Pitch Captures				
Session	Run	Task	Desired (%)	Adequate (%)
98	7	FPA captures 3.5°	45	55
98	8	FPA captures 5°	33	41
98	9	Theta captures PA	56	62

- Piloting technique and time histories – Pilot 5 uses a different, less aggressive piloting technique with respect to all the other pilots. This is evident from the PSD of the pilot's stick inputs in figure 285 and from the captures time histories in figures 289 and 290. Stick activity is limited, also in the low-frequency input range, which corresponds to the gross acquisition phase of the task. Minor higher frequency stick activity ($\omega = 0.9; 1\ rad/s$) is present for all the captures, slightly higher for FPA captures. A noticeable difference is visible for the pitch attitude captures technique, which is characterized by higher low-frequency stick activity. This is partly due to the different pitch transient demand of the two tasks, but it also denotes a higher aggressiveness in the execution of the task, as it can be seen also from the time histories. A long time to acquire the target is accepted by the pilot, in the FPA captures task in particular, to the point that many captures were completed at the end of the $\Delta t = 10\ s$ of the individual capture duration. In this case, stick inputs are mostly open loop, with minimal shaping. Figure 290 shows definitely larger gross acquisition inputs for pitch attitude captures, with a mainly open-loop technique and slightly higher input shaping than for the FPA captures.

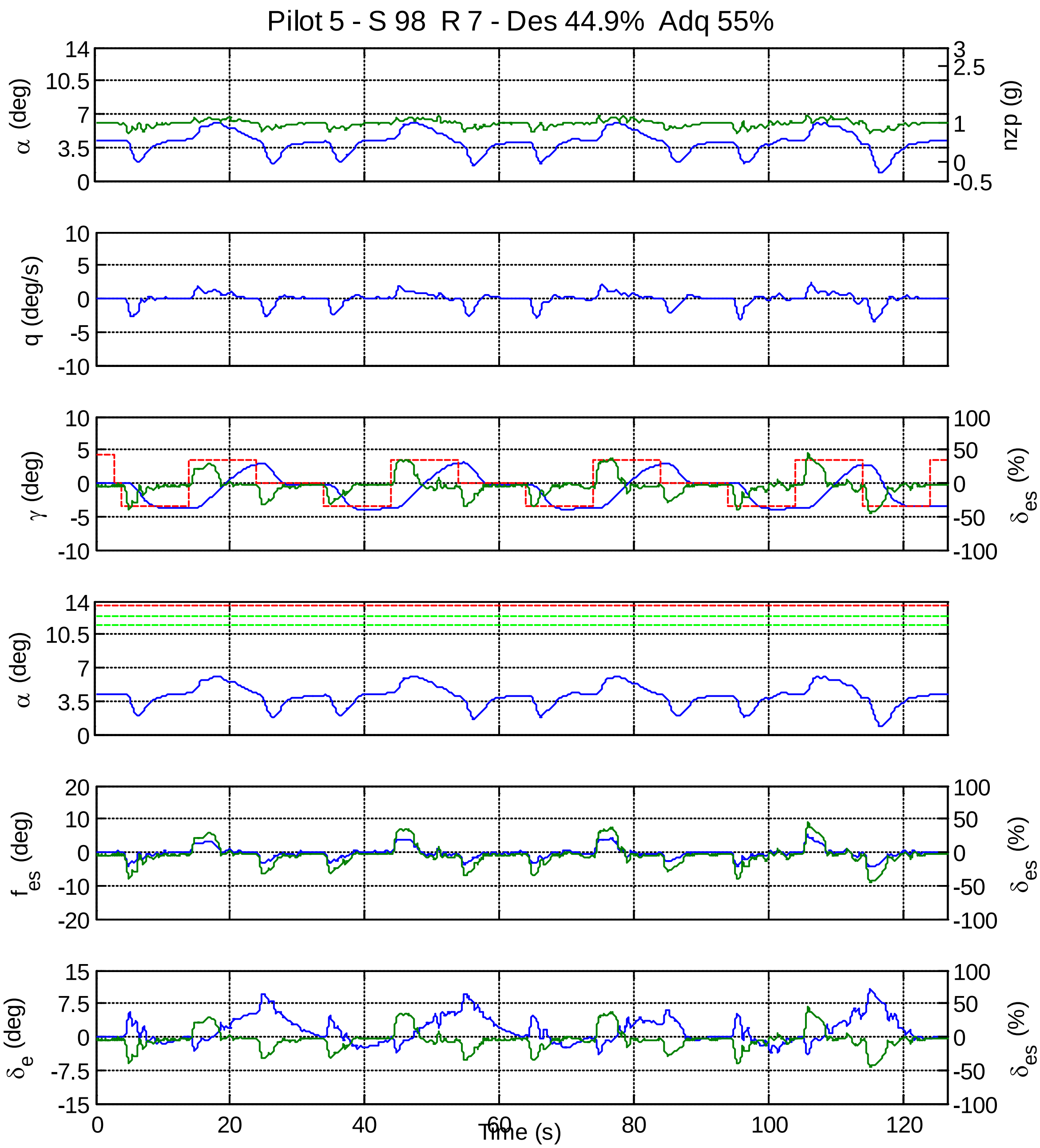


Figure 289. Pilot 5 AFI-FCS FPA captures time history — plot S98 run 7 — PA

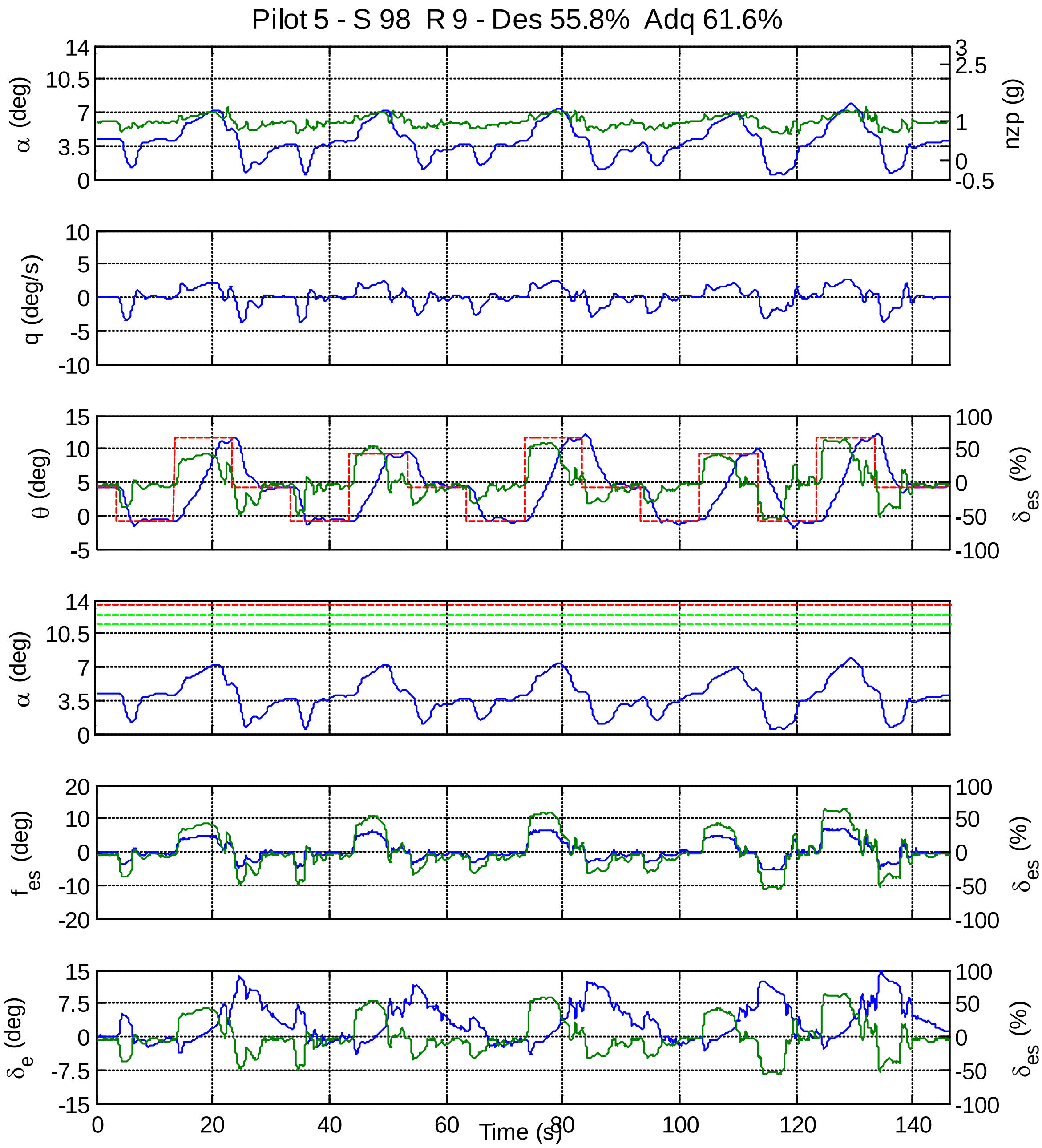


Figure 290. Pilot 5 AFI-FCS pitch attitude captures time history — plot S98 run 9 — PA

15.3 V_A FLIGHT CONDITION

15.3.1 Principal Outcomes

The baseline AFI-FCS aircraft configuration was evaluated in V_A flight condition with respect to both pitch attitude and FPA captures tasks. Based on the analysis of the data and the pilot's comments, the following results were identified.

1. The aircraft is HQ level 2, marginal level 1, as predicted by the offline analyses of section 10.6. This is mainly due to the reported lag in the pitch response perceived by the pilot. The lag was more evident in the pitch attitude task — potentially due to the generally low FPA bandwidth compared to the pitch attitude bandwidth.

2. The flight control and envelope protection system is very effective in protecting the aircraft from envelope exceedances. This was occasionally reported by the pilots as a positive characteristic for good HQ, but not significant to improve the HQ level.

3. All pilots indicated that an open-loop technique is required to avoid pitch attitude oscillations. An example of this approach is the comment from pilot 2: "Aggressive capture causes oscillations. Open loop inputs make it better, learning how to compensate. Fine gross acquisition."

4. Better HQR were assigned by pilots with an open-loop piloting technique and a more gradual transition between the gross acquisition phase and fine tracking. In this case, the ratings scatter was smaller and no significant oscillations were reported.

5. Pitch attitude oscillations reported by the pilots when in tight control were potentially due to the pitch attitude dynamics commanded by the FCS to achieve the commanded FPA.

6. Visual cues affect HQ: When the aircraft is flown without the FPA marker on the HDD, the pilot has to lead compensate given the inherently low bandwidth of the FPA response controlled by the aircraft FCS. This requires higher workload and compensation, which degrade the HQ. This tendency depends on the capture amplitude: The degradation is greater with higher amplitudes.

7. Pilots are resistant to changing the piloting technique, which they usually adopt to perform the tasks used in these evaluations. They clearly recognize the importance of an open-loop technique, which they broadly consider an HQ limitation instead of a specific characteristic of the aircraft.

8. The ND and NU pitch responses are reported to be different. This potentially depends on the command gain parabolic interpolation between the two limiting conditions as a function of stick deflection and dynamic pressure.

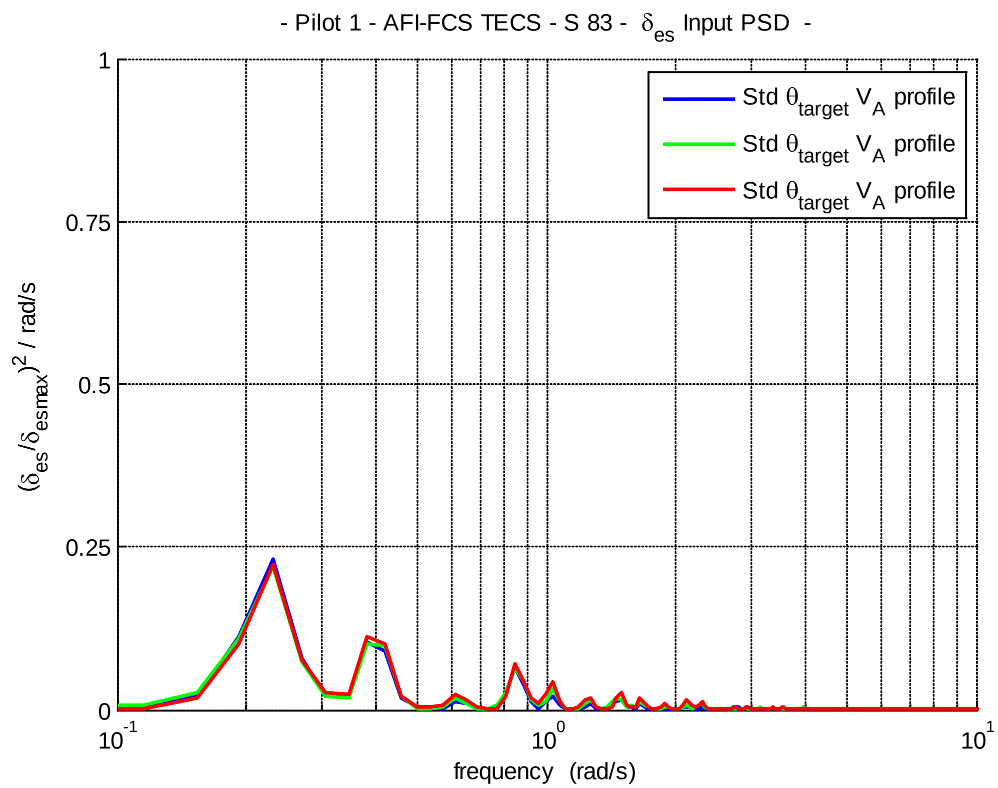


Figure 291. The PSD of pilot 1's δ_{es} input — AFI-FCS pitch attitude captures — V_A

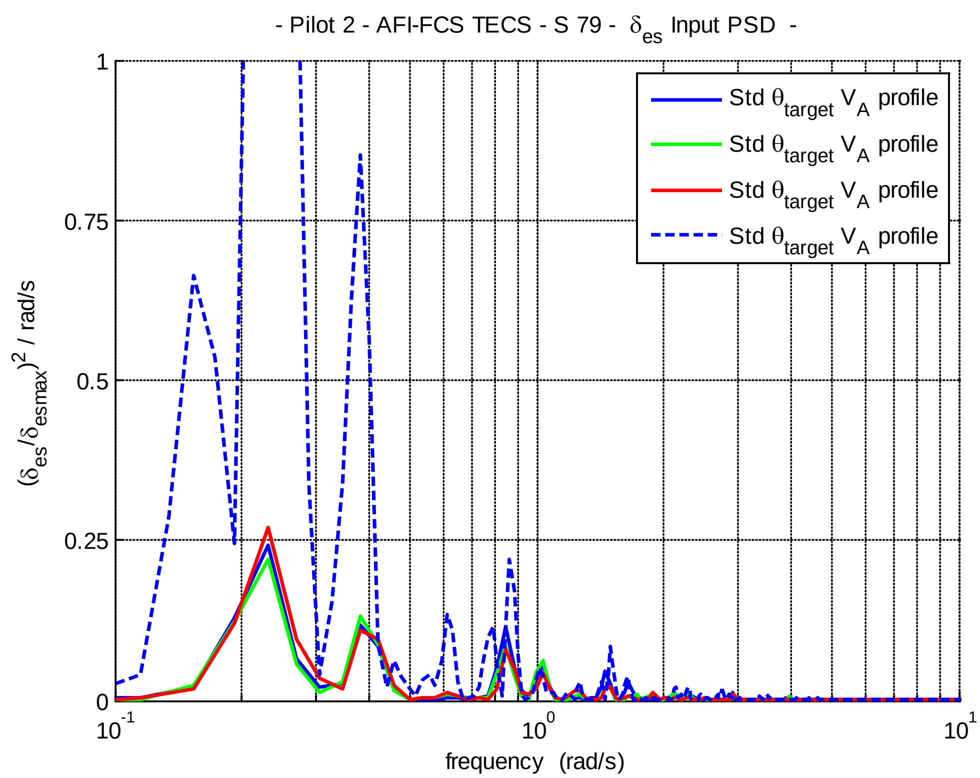


Figure 292. The PSD of pilot 2's δ_{es} input — AFI-FCS pitch attitude captures — V_A

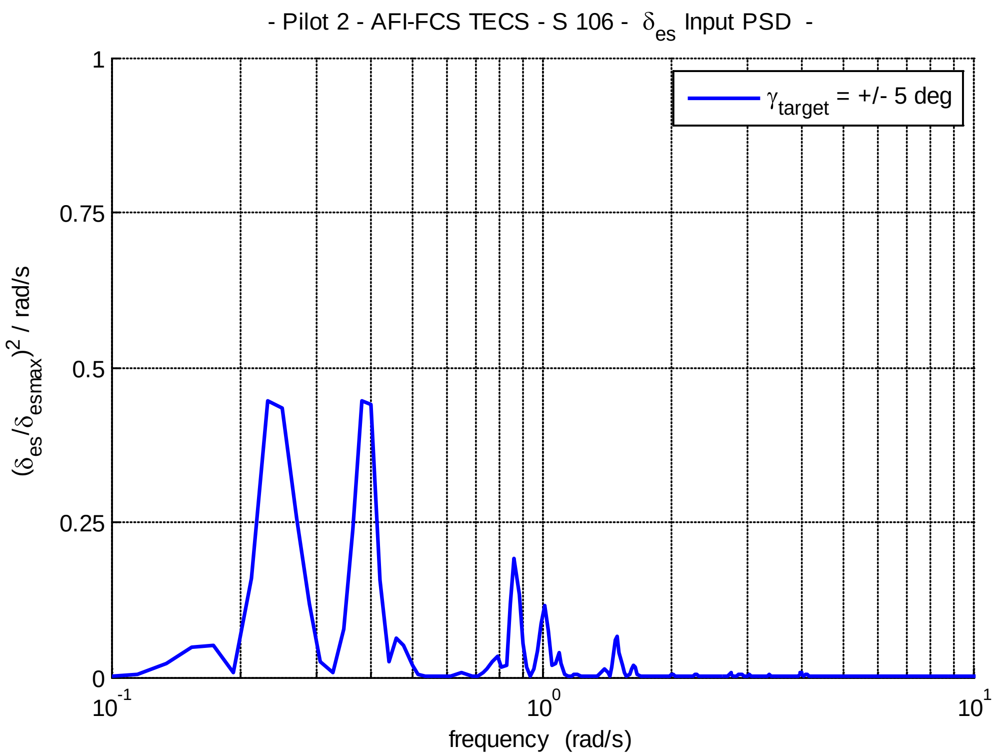


Figure 293. The PSD of pilot 2's $\boldsymbol{\delta_{es}}$ input — AFI-FCS FPA captures — V_A

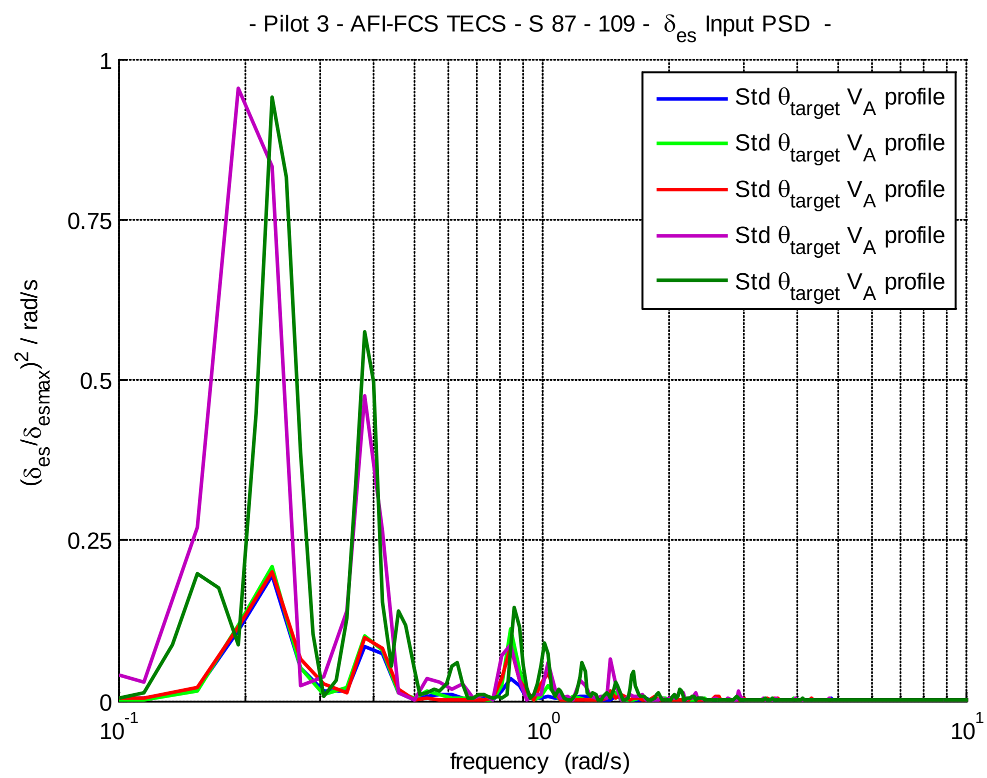


Figure 294. The PSD of pilot 3's $\boldsymbol{\delta_{es}}$ input — AFI-FCS pitch attitude captures — V_A

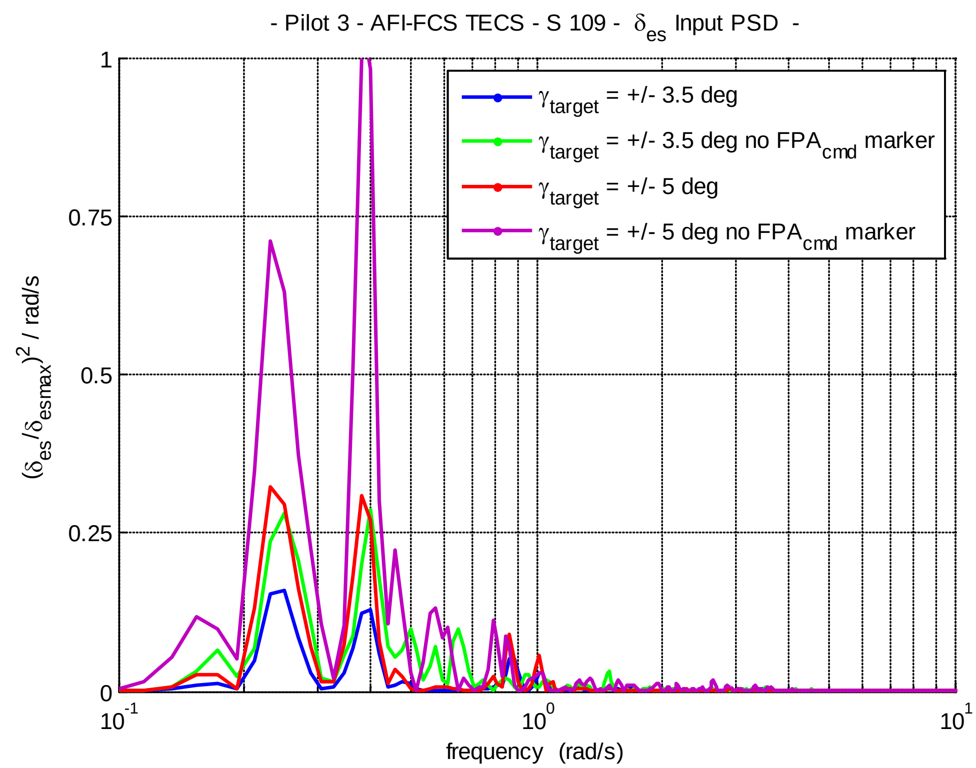


Figure 295. The PSD of pilot 3's δ_{es} input — AFI-FCS FPA captures — V_A

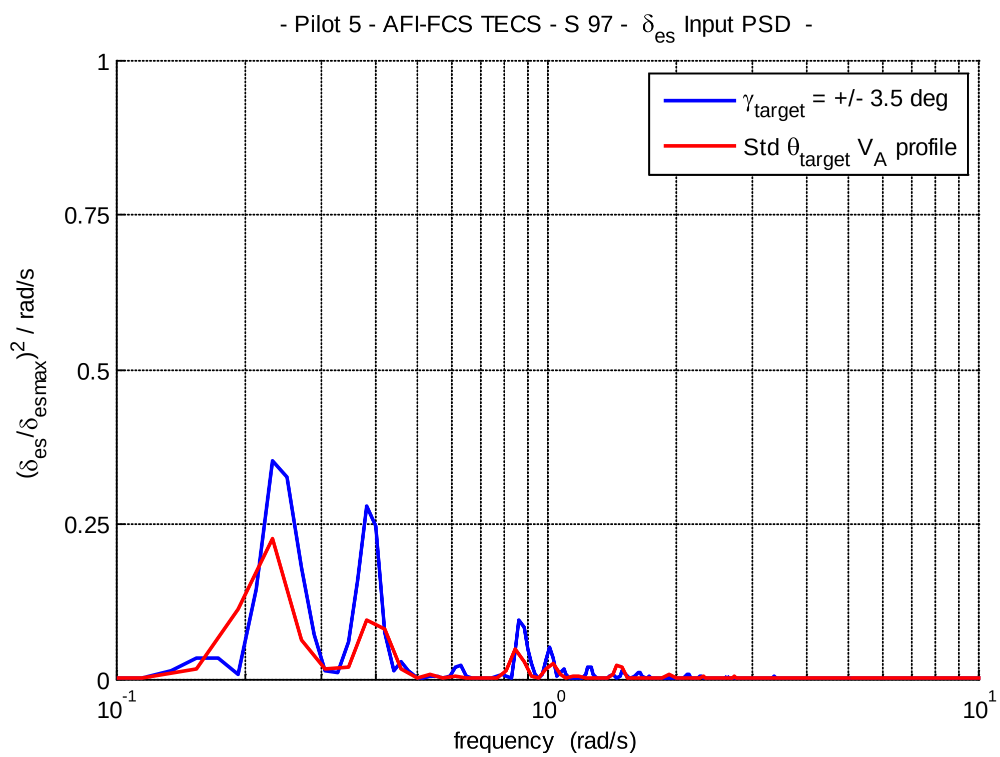


Figure 296. The PSD of pilot 5's δ_{es} input — AFI-FCS pitch attitude and FPA captures — V_A

15.3.2 Pilot Ratings, Comments, and Task Scoring

15.3.2.1 Pilot 1

- Pilot Ratings and Comments—The aircraft was evaluated with respect to the standard pitch attitude captures profile + SoS task and the continuous regulation task with pure SoS disturbance. The FPA command marker was not displayed on the HDD.

  The aircraft was rated HQ level 1 with respect to the discrete captures task, with two HQR = 3 and one HQR = 2 occurrences. No definite PIO tendency was rated, with one PIOR = 1 and two PIOR = 2 occurrences, denoting the presence of uncommanded motions. A proneness to pitch oscillations when controlling the aircraft with a closed loop piloting technique can be identified from the pilot's comments: "3–4 times back and forth during ND, some from disturbance. Does not happen going up. Open loop and release: no issues." It is clear from this comment that this tendency is not present when adopting an open loop technique.

  With respect to the CCC task, the aircraft is consistently HQ level 2 (HQR = 4) and a tendency to uncommanded oscillations is rated, with PIOR = 2 in all evaluations. This tendency can be clearly derived from the pilot's comment: "Getting desired but harder task. Moderate compensation due to avoiding overcontrol by smoothing inputs" (table 106).

Table 106. Pilot 1 AFI-FCS HQ ratings and comments — pitch attitude captures — V_A

Evaluation: FAA Model - Discrete & SoS - Pilot: 1 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A						
83	1	Pitch	V_A baseline	2	1	Great forces. No PIO tendency. Easy tracking. Very little overshoot. Good accuracy.
83	2	Pitch	V_A baseline	3	2	Some tendency to bounce around target. About 2 corrections when fine tracking. ND sensitivity a little too high.
83	3	Pitch	V_A baseline	3	2	3–4 times back and forth during ND, some from disturbance. Does not happen going up. Open loop and release: no issues.
Pure SoS						
85	2	Pitch	V_A baseline			Tendency to bobble. Sensitivity issue.
85	3	Pitch	V_A baseline	4	2	Getting desired but harder task. Moderate compensation due to avoiding overcontrol by smoothing inputs.
85	4	Pitch	V_A baseline	4	2	Quickly trying to correct errors leads to a bobble.

- Task Scoring — The average scoring is desired = 63% and adequate = 68%, with respect to the standard pitch attitude captures task in V_A. The normal load factor did not exceed the structural limits ($0 <= n_z =< 2.5$) in any of the discrete captures.

  It is average desired = 94% and adequate = 100% with respect to the standard CCC task with SoS disturbance. The very high scoring of the second task demonstrates a very effective disturbance suppression provided by the FCS.

- Piloting Technique and Time Histories — Pilot 1 adopted a mainly open-loop piloting technique, with small input shaping after a relatively large initial input, whose amplitude is lower on average than that used with the Calspan/STI aircraft for the same task. Higher frequency stick activity occurs at $\omega = 0.9; 1\ rad/s$. This is of a significantly lower level with respect to the low-frequency one.

  The SoS task piloting technique is characterized by minimal stick displacement throughout the whole frequency range, mainly due to the small amplitude of the disturbances. Figure 297 displays the time history of a pitch attitude capture sequence.

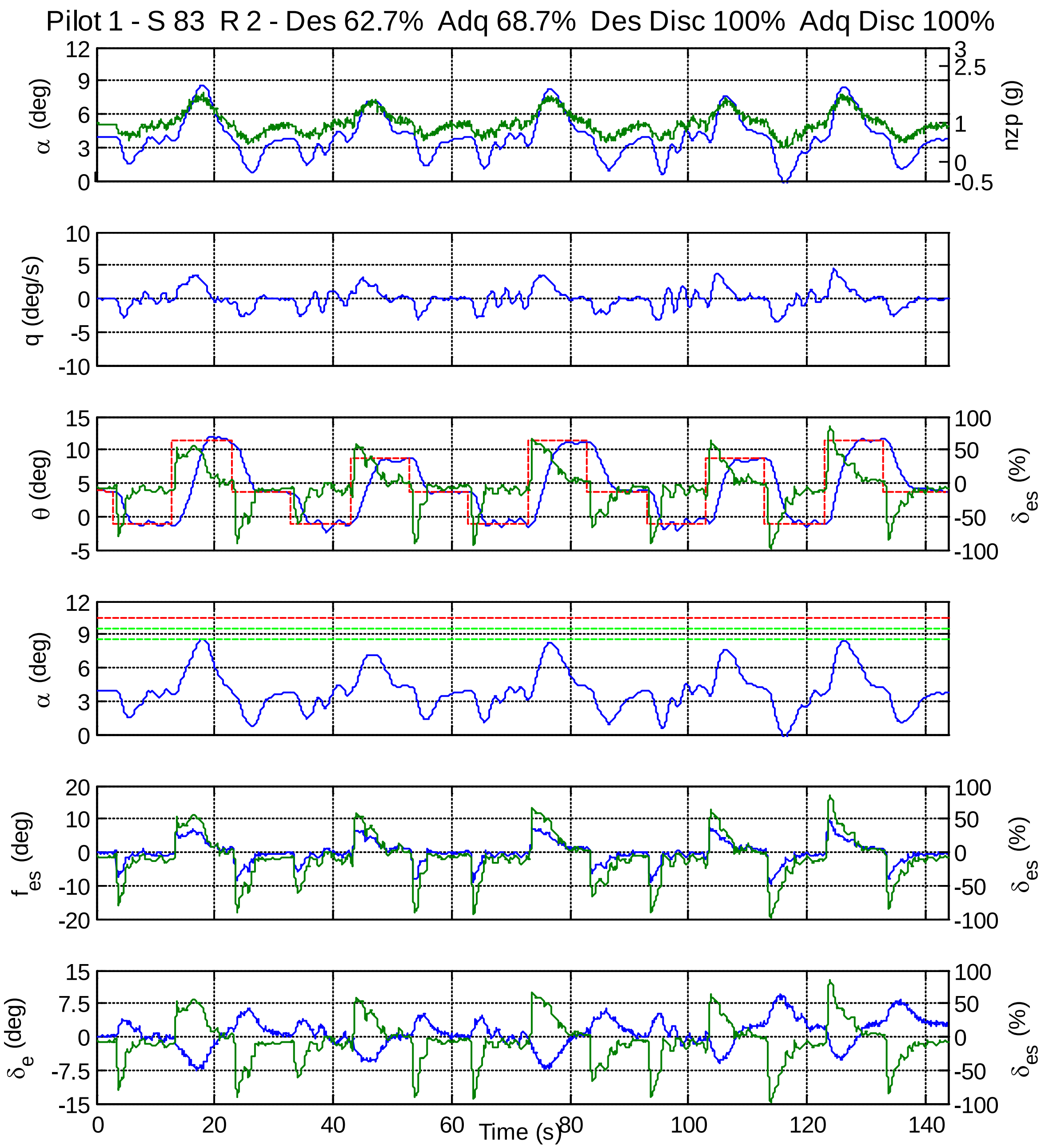


Figure 297. Pilot 1 AFI-FCS pitch attitude captures time history plot S83 run 2 — V_A

15.3.2.2 Pilot 2

- Pilot Ratings and Comments — Four standard pitch attitude captures were evaluated. The aircraft was rated three times HQR = 4 and PIOR = 2, corresponding to HQ level 2 and no PIO proneness, with the presence of uncommanded oscillations. In the fourth evaluation, in which large amplitude inputs were used for gross acquisition, it is rated HQR = 2 and PIOR = 1, corresponding to HQ solid level 1. Pilot 2 confirms the tendency for HQ to depend on the piloting technique. Pilot reports a different response between NU and ND maneuvers. Most of the comments report the preference of an open-loop piloting technique, which causes less oscillations in the pitch attitude capture task: “Aggressive capture causes oscillations. Open loop inputs make it better, learning how to compensate. Fine gross acquisition.” This is common to more evaluations.

With respect to the FPA capture task, the aircraft is rated HQ solid level 1 (HQR = 2, PIOR = 1). A slight degradation occurs when the task is performed without the FPA command marker: HQR = 3 and PIOR = 2. This is due to a reduced predictability and difficultly understanding the effect of the controller on the aircraft response. The pilot reports that HQ are better than in PA flight condition. Table 107 contains ratings and comments of pilot 2 HQ evaluations.

- Task Scoring — With respect to the first three standard pitch attitude captures tasks, the average scoring is desired = 64% and adequate = 71%. In the fourth evaluation, with respect to the same task, the scoring is desired = 38% and adequate = 43%, which is significantly lower than the average of the first three. This demonstrates the dependency of scoring with respect to piloting technique. The normal load factor did not exceed the structural limits ($0 \leq n_z \leq 2.5\ (g)$) in any of the discrete captures.

  Scoring is desired = 48% and adequate = 56% with respect to the discrete $\gamma_{target} = +/-5$ deg captures, which is overall adequate, marginally desired.

- Piloting Technique and Time Histories — Pilot 2 intentionally used two distinct piloting techniques for the standard pitch attitude captures profile. The first three evaluations were performed with relatively low stick activity at low frequency and closed-loop type of inputs near $0.9\ rad/s$. In the fourth evaluation, prolonged FBS inputs were used for the gross acquisition, with significant activity at the very low frequency $\omega = 0.15\ rad/s$ and frequencies $\omega = [0.6; 0.8; 0.9; 1.5]\ rad/s$, which indicate a not-negligible input shaping. In this case, the pilot successfully relied on the control system to avoid envelope exceedances.

  The second technique produced low scoring; however, the pilot rated the aircraft HQ level 1, demonstrating independency of the scoring from the actual performance used by the pilot for the HQ assessment. Figures 298 and 299 represent the two distinct piloting techniques described above.

  In the FPA captures, gross-acquisition inputs were of short duration compared to the time to acquire the target. They were followed by lower amplitude, higher frequency input shaping. The correspondent PSD and time history are displayed in figures 293 and 300, respectively.

Table 107. Pilot 2 AFI-FCS HQ ratings and comments — pitch attitude and FPA captures — V_A

Evaluation: FAA Model - Discrete & SoS - Pilot: 2 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A						
79	1	Pitch	Baseline	4	2	NU and ND tasks are different. NU–have to control the value of alpha. ND–Concentrate on the target. PIO tendencies in fine tracking, 2–3 oscillations. More coupling with the roll axis.
79	2	Pitch	Baseline	4	2	Aggressive capture causes oscillations. Open loop inputs make it better, learning how to compensate. Fine gross acquisition.
79	3	Pitch	Baseline	4	2	The small SoS could be causing the oscillations. Oscillations more noticeable now than run 2.
106	4	Pitch	FPA captures 3.5°	2	1	FPA does not seem to lag as much as before. It goes down faster than up. Easier to predict than in PA. Disconcerting behavior at 230.
106	5	Pitch	FPA captures 3.5° No Cmd Circle	3	2	Harder to predict. I do not understand the control and/or they are not consistent.
106	6	Pitch	FPA captures 5°	2	1	Predictable. I do not like the limits when the predictor drops down–it forces me to change technique.
106	7	Pitch	Theta captures	2	1	Why is it dropping off now? I am not on the target yet. I like the g-limit portion, not the other parts. I do not know what it is doing. At times I am not flying the airplane.

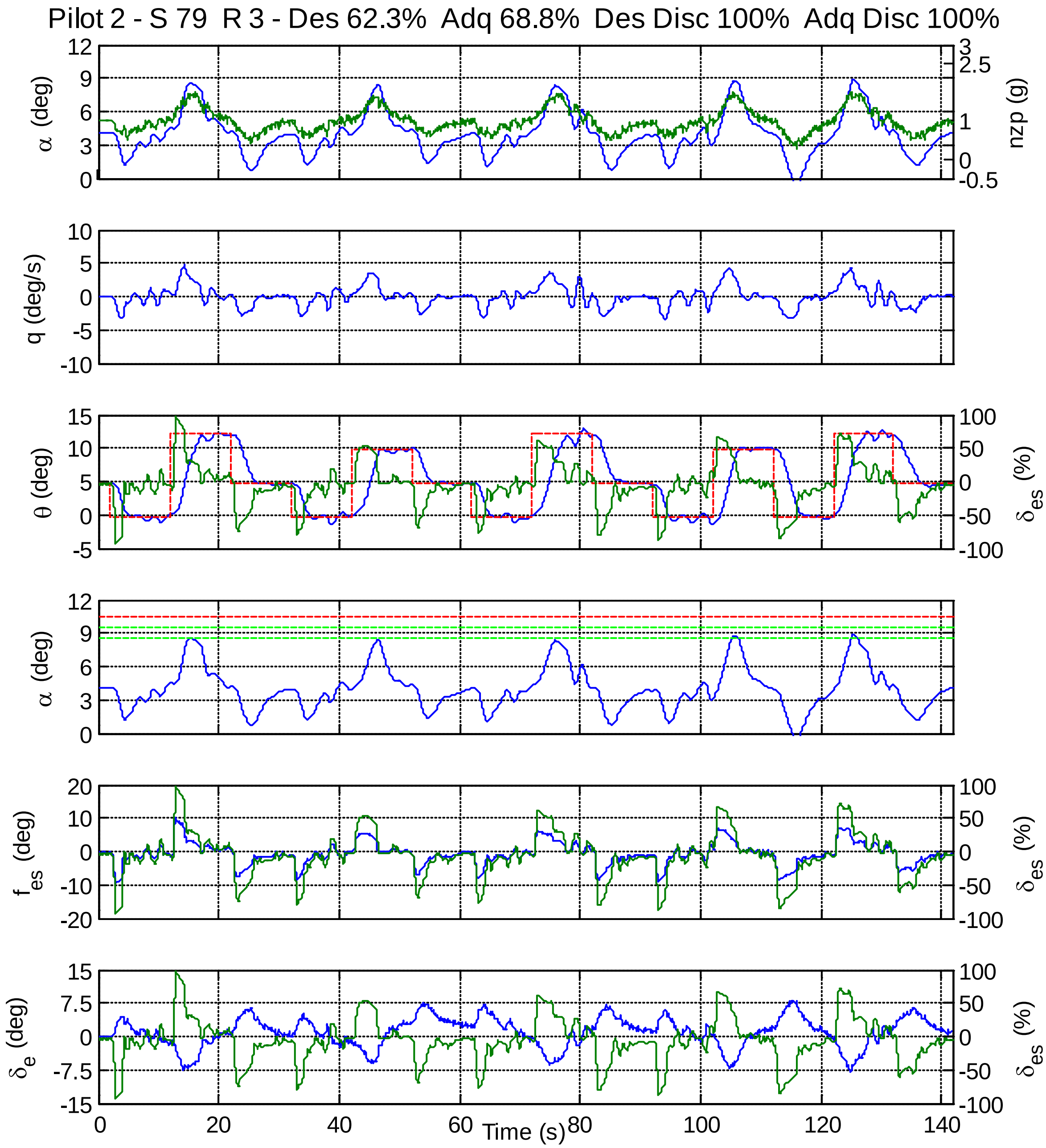


Figure 298. Pilot 2 AFI-FCS pitch attitude captures time history plot S79 run 3 — V_A

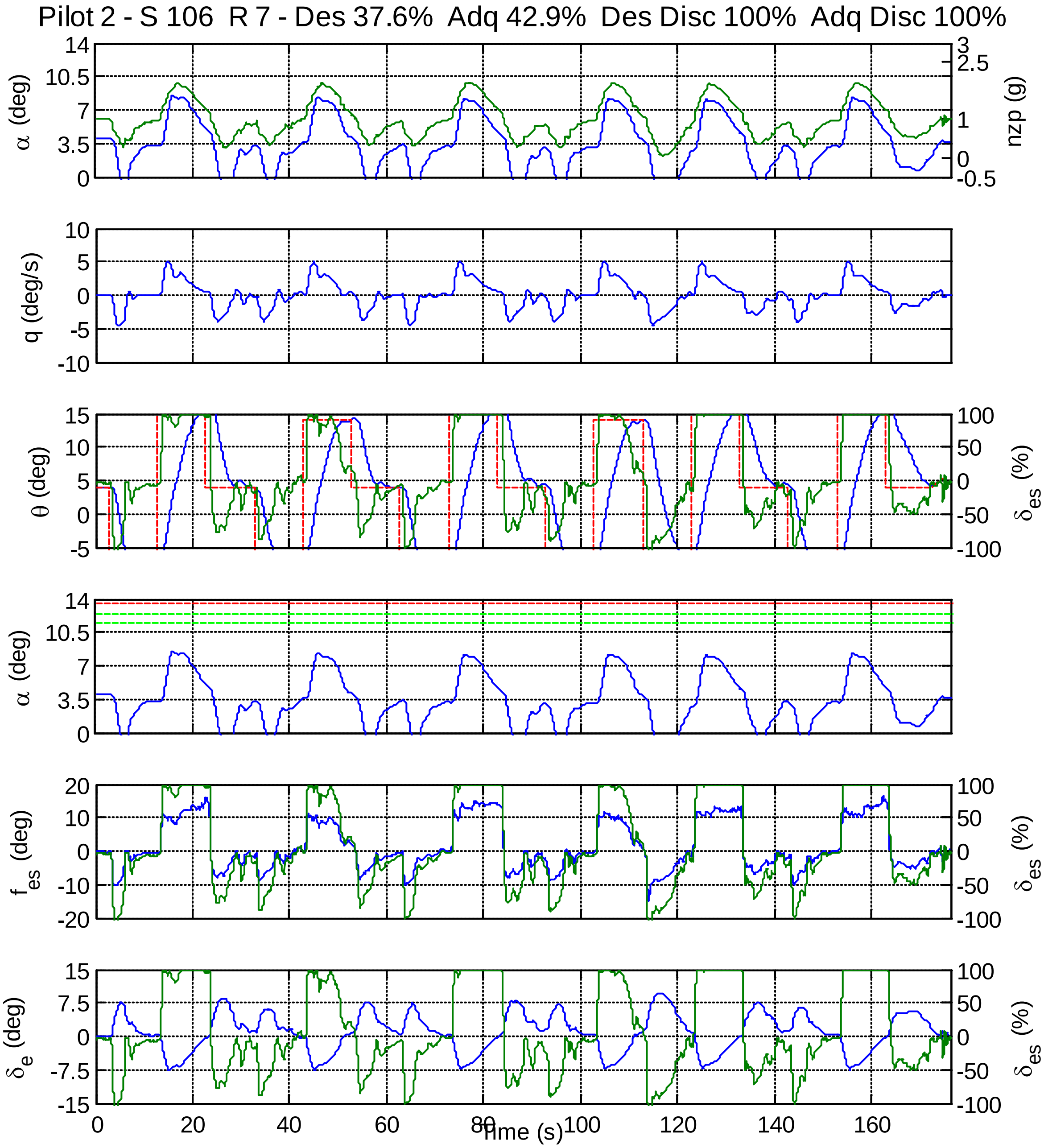


Figure 299. Pilot 2 AFI-FCS pitch attitude captures time history plot S106 run 7 — V_A

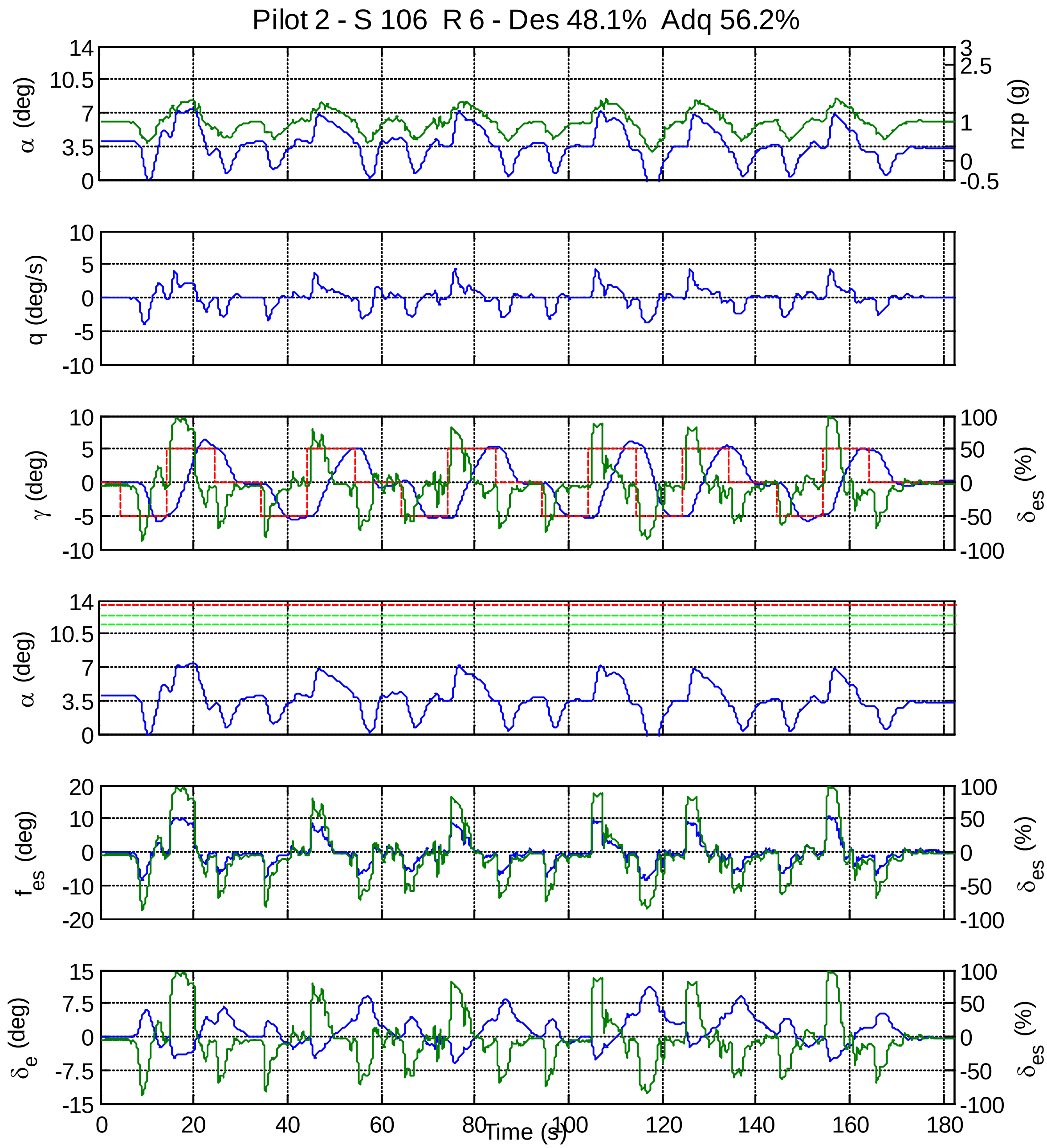


Figure 300. Pilot 2 AFI-FCS FPA captures time history plot S106 run 6 — V_A

15.3.2.3 Pilot 3

- Pilot Ratings and Comments — Pilot 3 rated the aircraft performing three evaluations with the standard pitch attitude capture profile. Subsequently, he performed FPA captures of different amplitude and repeated the pitch attitude captures with a different piloting technique.

With respect to all the pitch attitude captures, the aircraft is consistently HQ level 2: three HQR = 5 and one HQR = 4 occurrences. The HQR = 4 is relative to the pure discrete task, without SoS disturbance. The PIOR = 2 for the pure discrete task and for the piloting technique with FBS gross acquisition inputs, PIOR = 3 for the discrete + SoS task. The PIOR = 3 denotes PIO proneness, which is described also in the pilot's comments: "Increase my workload to see if I can avoid those things. Have to work hard to keep desired. Too much ping-pong. Feels like an unpredictable low-frequency airplane."

Comments also related to the time delay in the response, as reported by the other pilots: "More bouncy. Large time delay. Tends to overshoot. Not enough time to capture. Feels like disturbance even though there is none. If you go slower, it is better, but not with tight control. Uncommanded motions do occur." This also confirms that an open-loop piloting technique is the most appropriate to accomplish the required task with this aircraft.

With respect to the FPA captures with FPA command marker, the aircraft is rated HQ level 2 (HQR = 4) with uncommanded motions, but no PIO proneness (PIOR = 2). The same task performed without the marker produces a significant HQ degradation (HQR = 7) and significant overshoots or oscillations initiated by the pilot when in tight control (PIOR = 5). This tendency is common to the other pilots. Pilot 3's comment: "A mind of its own! Not adequate performance. Too much work-tiring. Have to lead a lot during nose oscillations and they are bad for the passengers." These oscillations are potentially due to the pitch attitude dynamics required to achieve the commanded FPA. This reported tendency to oscillate in pitch is identified in the offline analyses of the augmented aircraft HQ in section 12.6. Table 108 contains ratings and comments of pilot 3.

Table 108. Pilot 3 AFI-FCS HQ ratings and comments — pitch attitude and FPA captures — V_A

Evaluation: FAA Model - Discrete & SoS - Pilot: 3 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A						
87	1	Pitch	Baseline-pure discrete	4	2	More bouncy. Large time delay. Tends to overshoot. Not enough time to capture. Feels like disturbance even though there is none. If you go slower it is better, but not with tight control. Uncommanded motions do occur.
87	2	Pitch	Baseline discrete + SoS	5	3	Hard to push it down. Adequate but not desired. More workload and worse performance. Significant increase in workload – considerable compensation.
87	3	Pitch	Baseline discrete + SoS	5	3	Increase my workload to see if I can avoid those things. Have to work hard to keep desired. Too much ping-pong. Feels like an unpredictable low-frequency airplane.
109	8	Pitch	FPA captures 3.5°	4	2	A little overshoot – is it me or the flight control system? So far desired performance. The ball wanders around often and it is annoying. Too much uncommanded motion.
109	9	Pitch	FPA captures 3.5° no cmd circle	7	5	A mind of its own! Not adequate performance. Too much work-tiring. Have to lead a lot during nose oscillations and they are bad for the passengers.
109	10	Pitch	FPA captures 5°	4	2	Takes a while to get there. Desired performance not taking much compensation.
109	11	Pitch	FPA captures 5° no cmd circle	7	5	High throttle activity. I am well within limits but I can still feel the protection. The workload is constraining.
109	12	Pitch	Theta captures			–
109	13	Pitch	Theta captures	5	2	No longer a linear airplane response. I am FBS multiple times and cannot capture. No PIO problem. It seems like someone is taking something away from me.

- Task Scoring — With respect to the first three standard pitch attitude captures task, the average scoring is desired = 57% and adequate = 66%. In the other two evaluations, using a different piloting technique with the same target, the average scoring is desired = 55% and adequate = 61%. This is an indication of consistency of the quantitative part of the performance and at the same time of the relatively low impact of piloting technique on the time to acquire and fine tracking. The normal load factor did not exceed the structural limits ($0 \leq n_z \leq 2.5\ (g)$) in any of the discrete captures.

  With respect to the discrete $\gamma_{target} = +/-3.5; 5\ deg$ captures, scoring is desired = 34% and adequate = 55%, which is overall adequate. These scorings are comparable with those achieved by the other pilots.

  The average scoring of the two evaluations with the FPA command marker displayed is desired = 46%, adequate = 56%. Average scoring is desired = 37%, adequate = 54% without the marker. The lack of the marker negatively impacts the scoring—desired scoring in particular—which potentially indicates a lower fine-tracking precision.

- Piloting Technique and Time Histories — With respect to the pitch attitude captures, pilot 3 used two different piloting techniques. The pilot used gradual gross acquisition inputs and low-to-moderate high-frequency stick activity in the first three evaluations. The pilot also used large gross acquisition inputs and higher inputs shaping in the frequency range $\omega = [0.9, 1.8]\ rad/s$ in the other two evaluations (figure 294).

  Piloting technique of the FPA captures is affected by the availability of the FPA command marker on the HDD. Evaluations without the marker are characterized by larger initial inputs for gross acquisition and significantly higher input shaping. This can be seen from the inputs PSD of figure 295 and time histories of FPA captures with and without the FPA command marker, displayed, respectively, in figures 301 and 302. This impact on the piloting technique is noticeably higher for the larger amplitude captures.

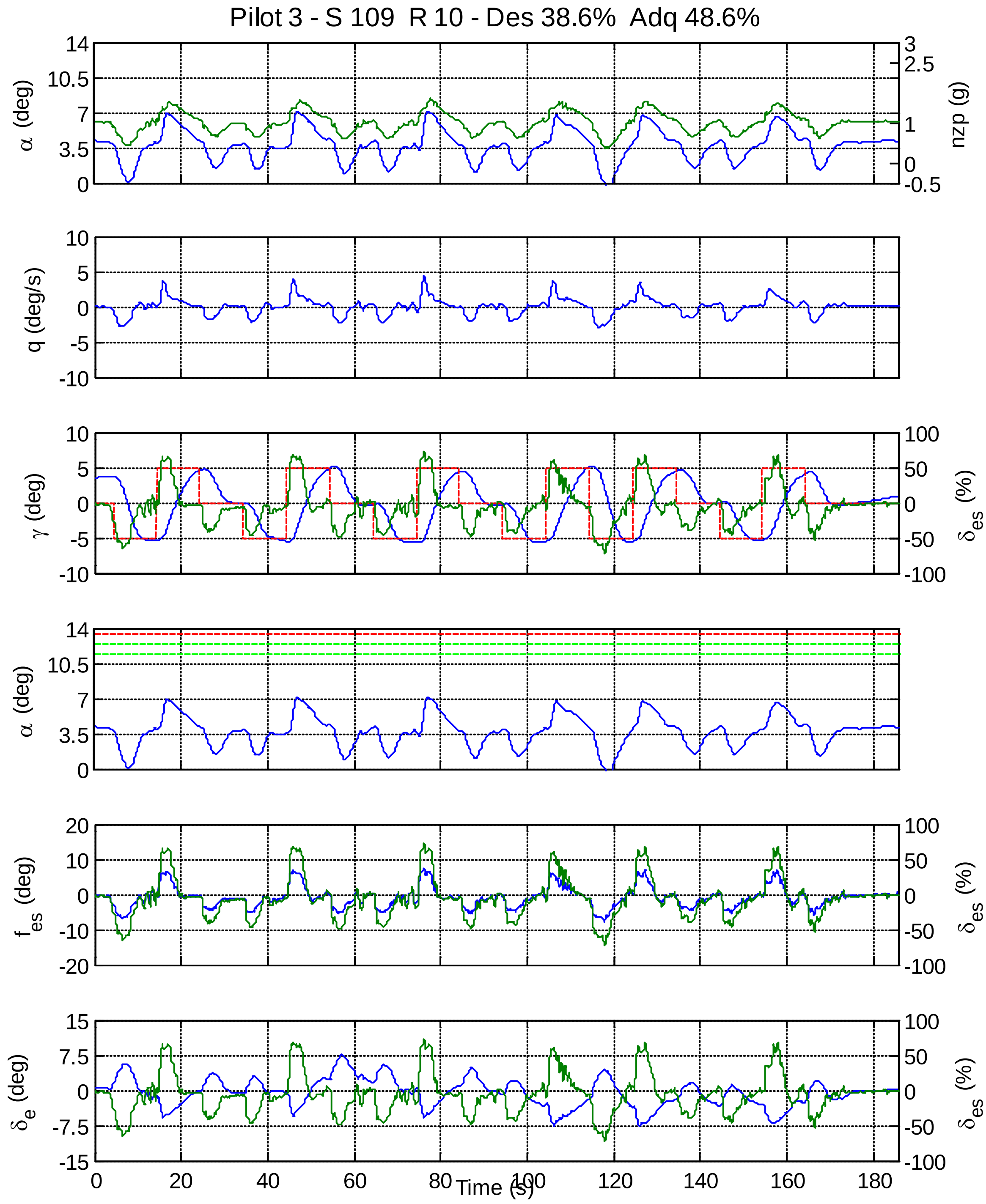


Figure 301. Pilot 3 AFI-FCS FPA captures time history plot S109 run 10 — V_A — with FPA command marker

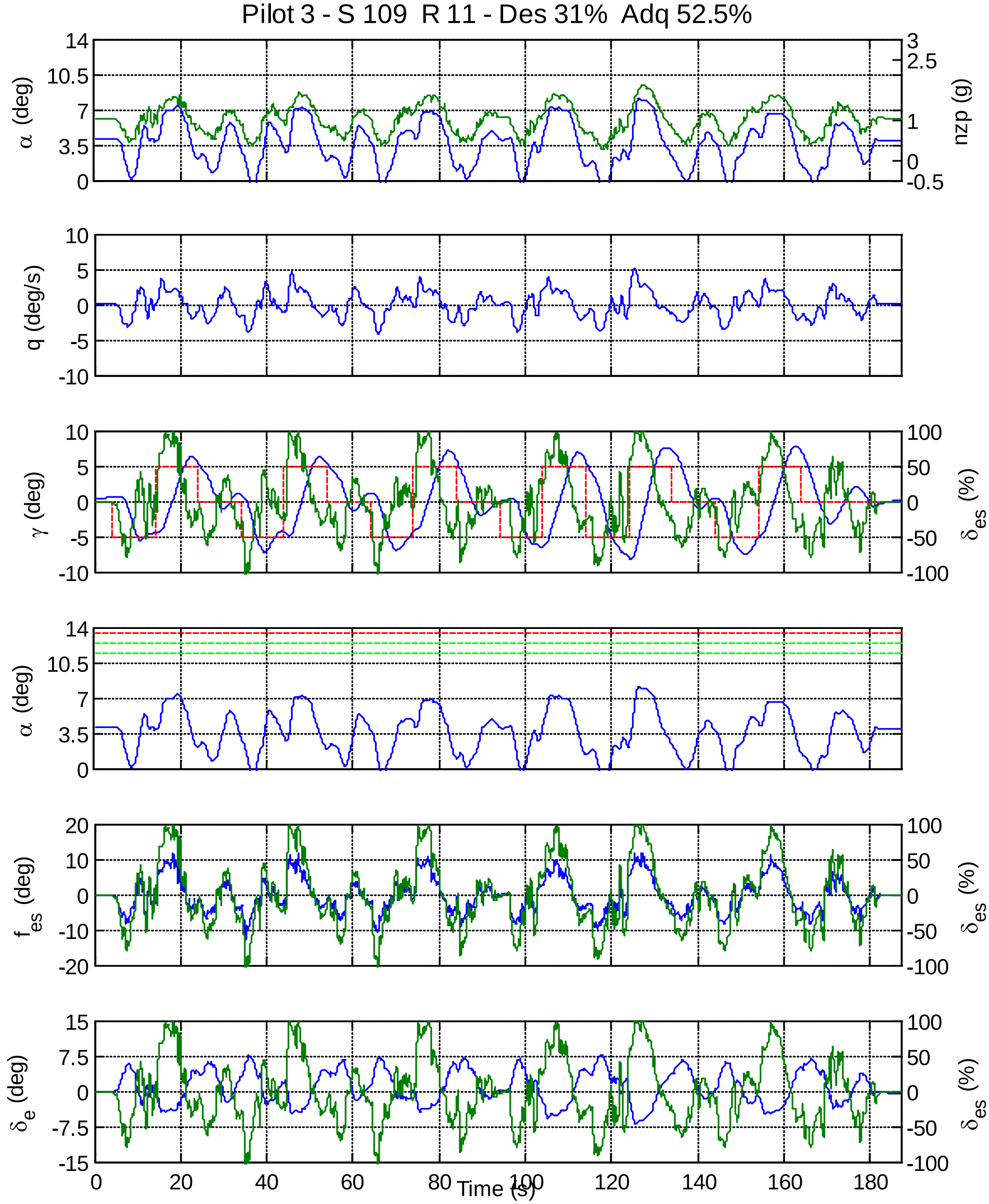


Figure 302. Pilot 3 AFI-FCS FPA captures time history plot S109 run 10 — V_A — without FPA command marker

15.3.2.4 Pilot 5

- Pilot Ratings and Comments — Pilot 5 conducted three HQ evaluations: two FPA captures and one pitch attitude capture. The aircraft was rated HQ solid level 1: HQR = 2, PIOR = 1 in all evaluations. Pilot stressed the good HQ in the fine tracking phase and for the FPA captures in particular: "Good and predictable captures, slight compensation involved, super nice. Good aircraft characteristics. No oscillatory tendency in the fine tracking, excellent fine tracking." He reported slight bobbles in the pitch attitude captures (table 109).

Table 109. Pilot 3 AFI-FCS HQ ratings and comments — pitch attitude and FPA captures — V_A

Evaluation: Velocity Limitor - Pilot: 5 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A mode=2						
97	3	Pitch	FPA captures 3.5°	2	1	Nice tracking. Aircraft is not approaching any limits. Good handling qualities. Speed is good as long as stay within envelope.
97	4	Pitch	FPA captures 5°	2	1	Good and predictable captures, slight compensation involved, super nice. Good aircraft characteristics. No oscillatory tendency in the fine tracking, excellent fine tracking.
97	7	Pitch	Theta captures	2	1	Very slight pitch bobble, but tracking nicely.

- Task Scoring — Scoring is desired = 50% and adequate = 59% for the $\gamma_{target} = +/-5°$ captures task, it is desired = 65% and adequate = 71% for the pitch attitude captures.

- Piloting Technique and Time Histories — Piloting technique is comparable to that used by all the pilots to perform these tasks. There is a minor stick activity at the two frequencies $\omega = [0.9; 1]\ rad/s$, denoting closed loop inputs, as it can be seen in the time history of the pitch attitude captures displayed in figure 303. The pitch oscillations reported by the pilot are clearly visible. As in the other evaluations, pilot's comments match offline predictions.

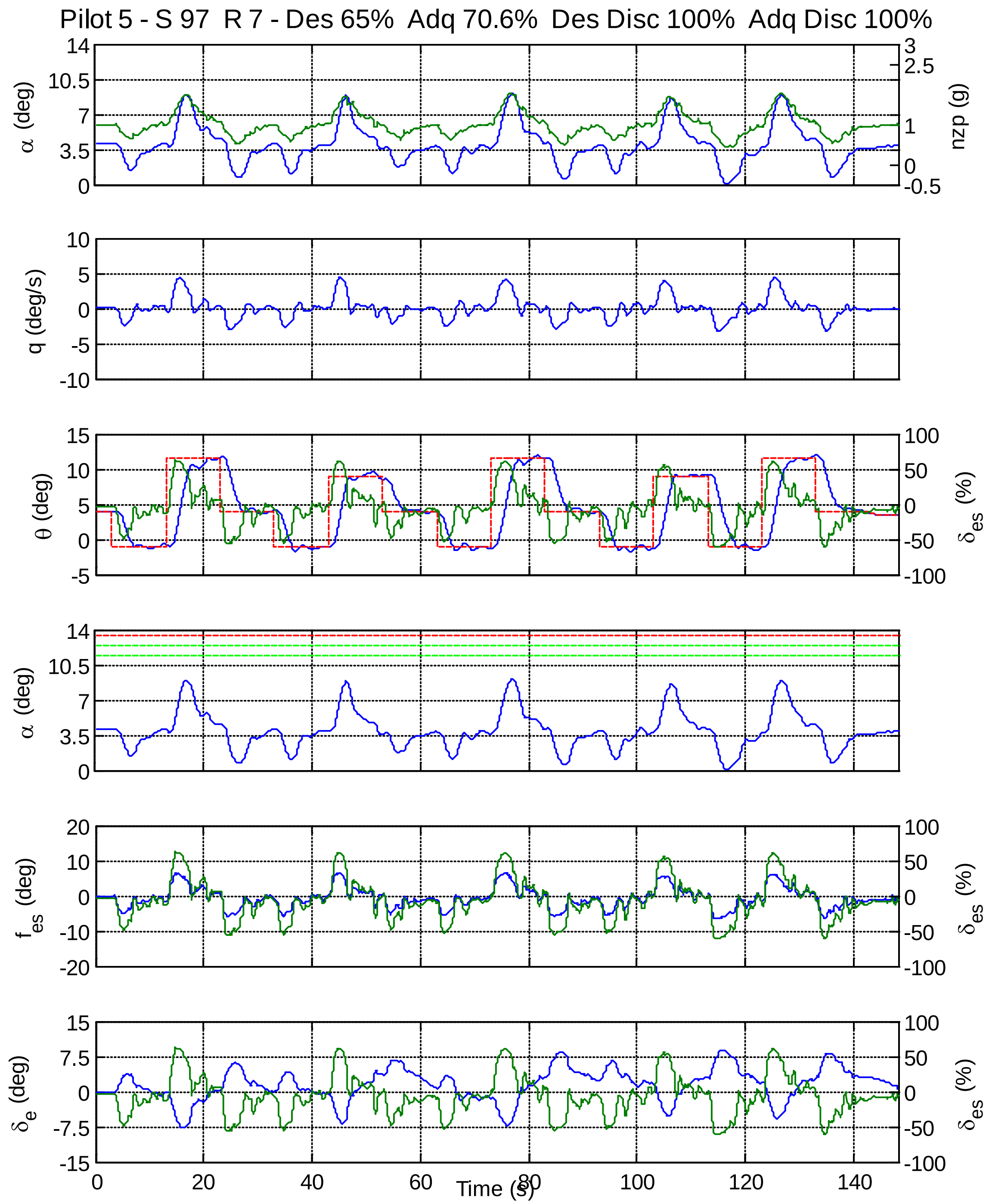


Figure 303. Pilot 3 AFI-FCS pitch attitude captures time history plot S97 run 7 — V_A

15.3.3 Principal Outcomes

The HQ task of these evaluations was the standard pitch attitude capture task used to evaluate the Calspan/STI aircraft in V_C flight condition. The main results of the evaluations are listed below:

1. The aircraft is HQ level 1, marginal level 2. Minimal scatter is present among the ratings of all the pilots: HQR = 3 to HQR = 4.

2. The PIOR = 2 consistently across all evaluations performed. No PIO proneness is rated, with uncommanded motions occurring, which still permit desired performance to be achieved.

3. Piloting technique was comparable among the three pilots, with pilot 2 having, on average, a higher stick activity.

4. All pilots reported the requirement to adopt an open-loop piloting technique to minimize the occurrence of uncommanded motions.

5. Scoring is not strictly correlated to HQR and performance perceived by the pilots.

6. A relevant comment, which is specific to this tested flight control/augmentation system, is the different response of the aircraft to positive (NU) and negative (ND) stick inputs. Pilot 1, in particular, reported oscillations when controlling through neutral stick position, leading to minor unpredictability. This is expected to depend on the parabolic shaping of the command gain, produced by second degree polynomial interpolation between the normalized extremes of stick deflection.

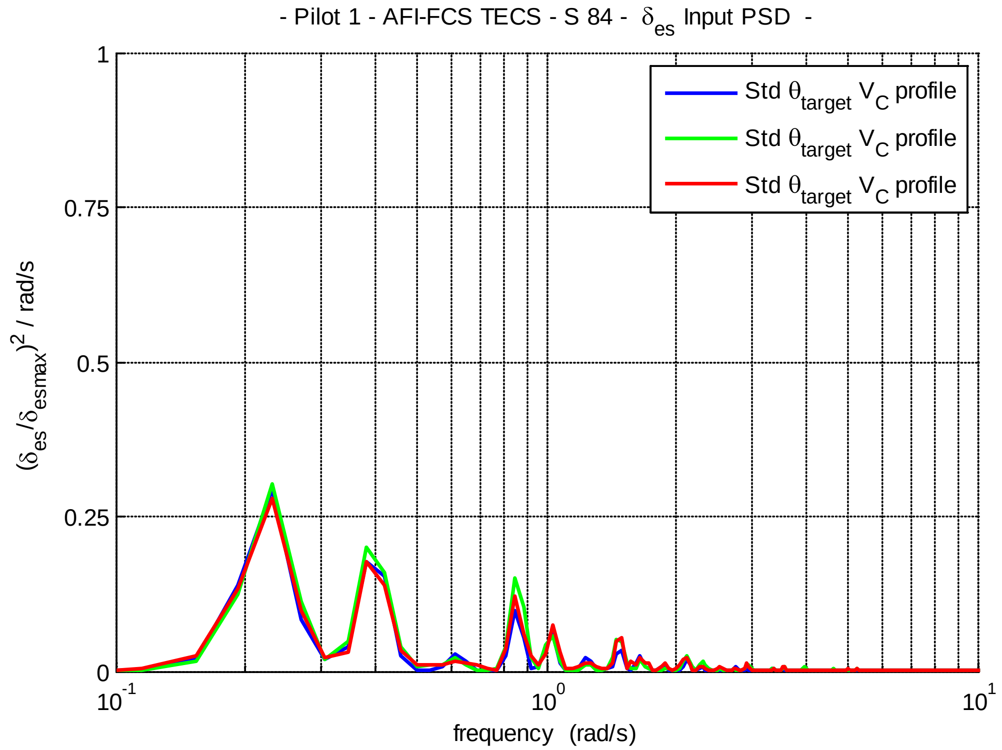


Figure 304. The PSD of pilot 1's δ_{es} input — AFI-FCS pitch attitude captures — V_C

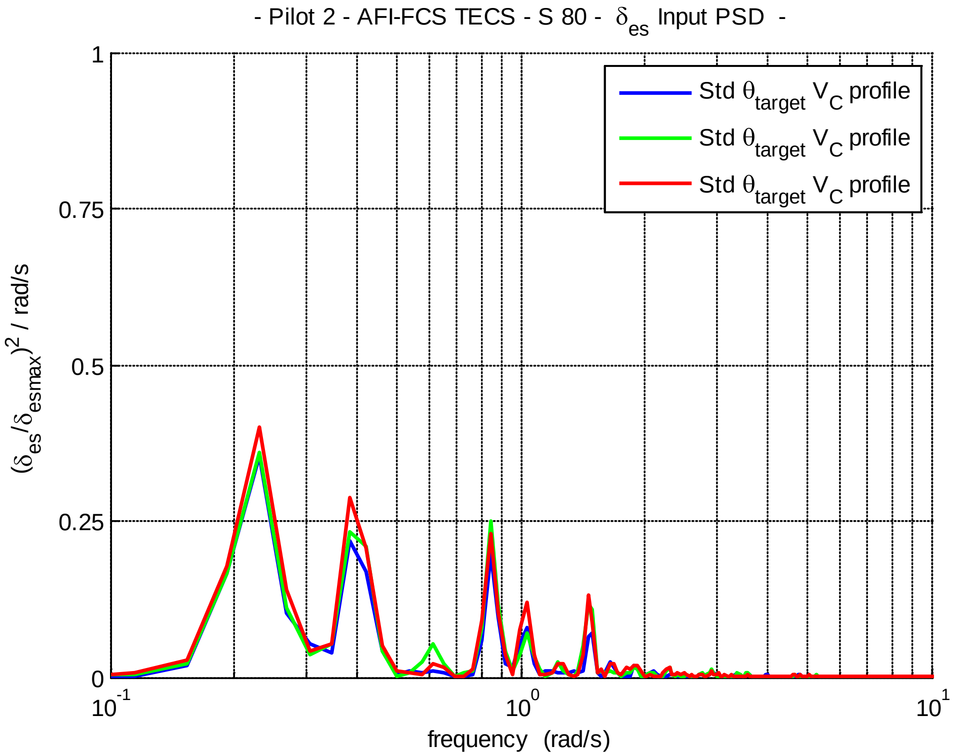


Figure 305. The PSD of pilot 2's δ_{es} input — AFI-FCS pitch attitude captures — V_C

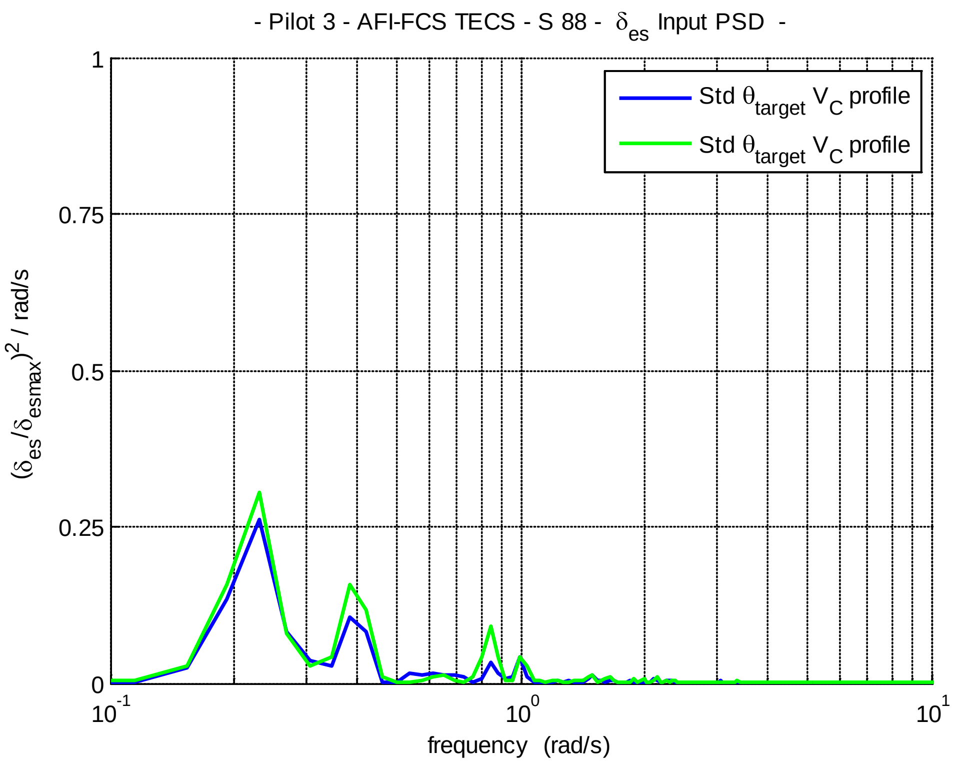


Figure 306. The PSD of pilot 3's δ_{es} input — AFI-FCS pitch attitude captures — V_C

15.3.4 Pilot Ratings, Comments, and Task Scoring

15.3.4.1 Pilot 1

- Pilot Ratings and Comments — The aircraft was rated with respect to the standard pitch attitude captures task. It was consistently HQ level 1: HQR = 3 and PIOR = 2 in all evaluations. The PIOR = 2 signals the occurrence of pitch oscillations, with no impact on desired performance. The oscillatory tendency is more evident with ND inputs with respect to NU, in particular, when passing through the stick neutral position. This is repeatedly stated by the pilot: "Only when I correct through neutral do I have oscillations. Same ND phenomenon—doesn't happen every time, only through neutral control. Do not compensate through neutral, slowly release the force when close to target to avoid oscillations. Stick neutral–ND: oscillations" (table 110).

Table 110. Pilot 1 AFI-FCS HQ ratings and comments — pitch attitude captures — V_C

Evaluation: FAA Model - Discrete & SoS - Pilot: 1 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_C						
84	1	Pitch	Baseline	3	2	Only when I correct through neutral do I have oscillations. Same ND phenomenon–doesn't happen every time, only through neutral control. Do not compensate through neutral, slowly release the force when close to target to avoid oscillations. Stick neutral–ND: oscillations.
84	2	Pitch	Baseline	3	2	Noticed a little bubble on NU but not as easy to get into as ND.
84	3	Pitch	Baseline	3	2	Trying more aggressive.

- Task Scoring — Average task scoring is desired = 64%, adequate = 70%, with minimal scatter among the three evaluations.

- Piloting Technique and Time Histories — Piloting technique is consistent with that used across all evaluations, with relatively large initial inputs for gross acquisition and higher frequency input shaping at the frequencies $\omega = [0.9; 1; 1.5]\ rad/s$. The low-frequency stick activity is at $\omega = [0.25; 0.4]\ rad/s$ (figure 303). Negligible differences in the technique are present between the three evaluations.

15.3.4.2 Pilot 2

- Pilot Ratings and Comments — The aircraft was rated with respect to the standard pitch attitude captures task. It is consistently HQ upper level 2: HQR = 4 and PIOR = 2 in all evaluations. Pilot 2 stresses that the aircraft has a different response depending on the sign of the stick input: NU or ND. The relevant comment is: "NU task easier, not exceeding limits. More cross inputs to roll axis." Oscillations are also reported during fine tracking. Table 111 contains all pilot 2 comments and ratings.

Table 111. Pilot 2 AFI-FCS HQ ratings and comments — pitch attitude captures — V_C

Evaluation: FAA Model - Discrete & SoS - Pilot: 2 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_C						
80	1	Pitch	baseline	4	2	Gross acquisition fine. Still oscillations around target during fine tracking. Invert the command to capture, which produces overshoots.
80	2	Pitch	baseline	4	2	NU task easier, not exceeding limits. More cross inputs to roll axis.
80	3	Pitch	baseline	4	2	No difference.

- Task Scoring — Scoring is desired = 64%, adequate = 71%. A single (nominal) load factor overshoot was detected with respect to 14 captures.

- Piloting Technique and Time Histories — The PSD of pilot's inputs in figure 305 demonstrates higher stick activity on average compared to pilot 1 in the whole frequency range. Pilot 2 has a significantly higher stick activity at the two distinct frequencies $= [0.85; 1.5]\ rad/s$, which indicates a more closed-loop technique, as seen in figure 307. This is a potential reason for an HQR = 4, HQ level 2, lower than pilot 1 rating. As it was reported in all preceding evaluations, a closed-loop piloting technique produces uncommanded oscillations. This is the expected reason for the HQ degradation, with no impact on task performance, which leads to PIOR = 2.

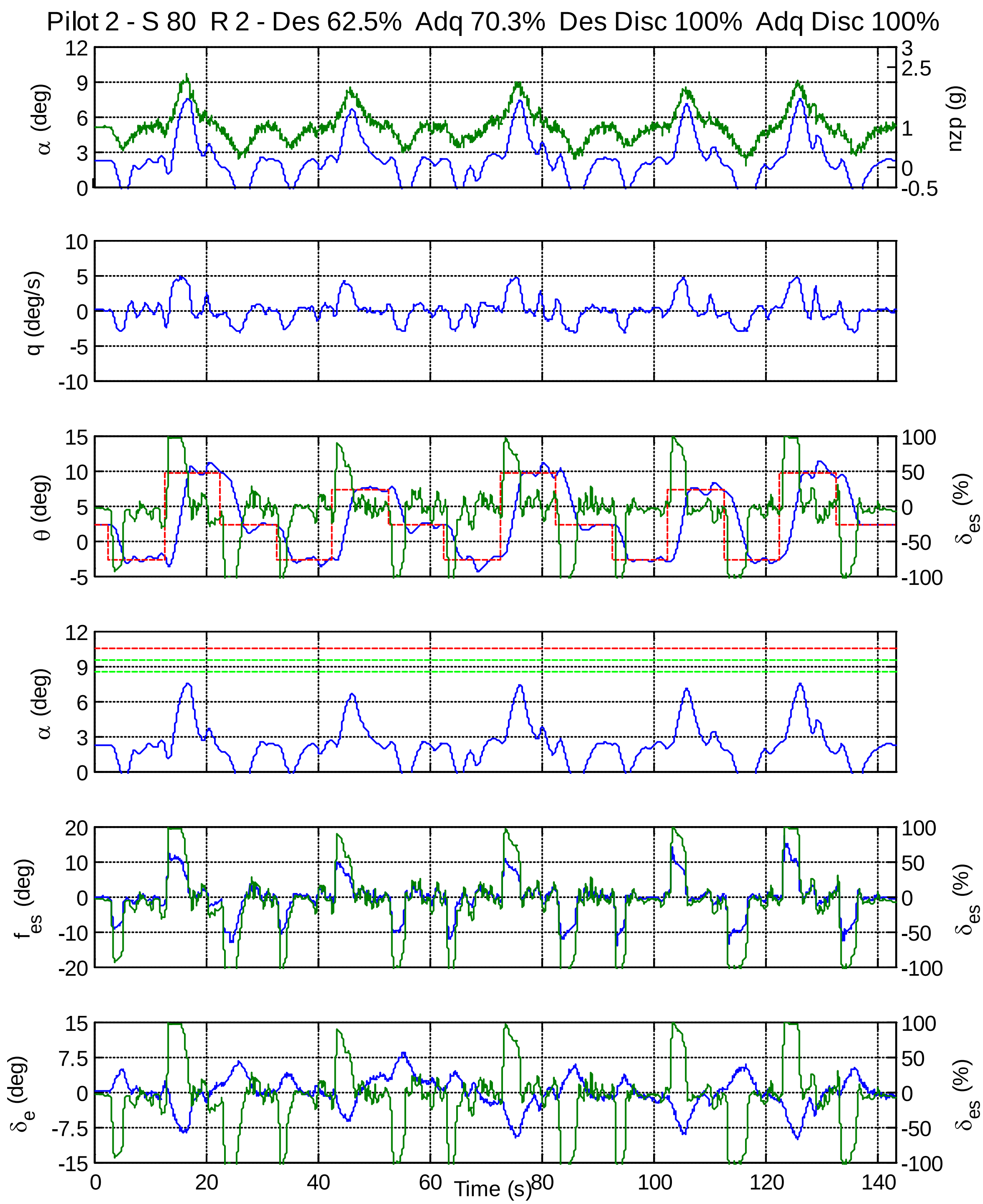


Figure 307. Pilot 2 AFI-FCS pitch attitude captures time history plot S80 run 2 — V_C

15.3.4.3 Pilot 3

- Pilot Ratings and Comments — The aircraft is rated with respect to discrete pitch attitude captures, with and without SoS disturbance. The SoS disturbance degrades the HQ, from

HQ level 1 (HQR = 3) to HQ level 2 (HQR = 4), due to increased workload. Pilot 3 reports higher forces than desired. Uncommanded motions are reported and no PIO proneness is rated, with PIOR = 2 in both evaluations. Pilot also reports a learning curve effect regarding his capability to perform the task. Table 112 contains pilot 3 ratings and comments.

Table 112. Pilot 3 AFI-FCS HQ ratings and comments — pitch attitude captures — V_C

Evaluation: FAA Model - Discrete & SoS - Pilot: 3 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_C						
88	1	Pitch	baseline-pure discrete	3	2	Not much different from V_A. A lot of force needed to get it going. Similar problem of capturing the target and then sliding through. Not as much trouble anymore–learned.
88	2	Pitch	baseline	4	2	Compensation level has not gone up a lot, but there is a little more workload. The delayed action is annoying. A little bit of oscillations.

- Task Scoring — Scoring is desired = 49%, adequate = 60% for run 1, it is desired = 59%, adequate = 65% for run 2, demonstrating to be uncorrelated with HQR.

- Piloting Technique and Time Histories — Piloting technique is comparable to that used by the other pilots. The inputs PSD of figure 306 indicates a lower closed-loop activity than pilot 1 and pilot 2. It is important to notice the consistency of the comment on the increased compensation required when an SoS disturbance was injected, with the measured higher stick activity for the same run, as displayed in figure 306. Pilot 3 could detect a small workload increase, even though the control system is capable of suppressing disturbances with high effectiveness.

15.4 AFI-FCS HANDLING QUALITIES, PILOTED EVALUATIONS, OBSERVATIONS, AND CONCLUSIONS

- With respect to both pitch attitude and FPA captures tasks, the aircraft is HQ level 2, marginal level 1. This is mainly due to the reported lag in the pitch response perceived by the pilot. The lag is more evident in the pitch attitude task.

- The low FPA bandwidth and relatively high pitch attitude phase delay, which were analyzed and reported in section 12.6, are consistently perceived by the pilots as having low responsiveness and lag.

- The rated HQ level tends to be higher versus the FPA captures with respect to the pitch attitude captures. The scatter in the ratings is reduced with increasing airspeed.

- Piloting technique affects HQ. All pilots reported the necessity to adopt an open-loop piloting technique to avoid pitch attitude oscillations. This requirement diminishes increasing airspeed. Better HQR were assigned when the pilot used an open-loop technique, in particular when gross acquisition was performed with gradual, low amplitude inputs with negligible higher frequency stick activity (pilot 5).

- HQR depend on the visual cues available to the pilot through the HDD. Flying without the marker produced a significant degradation of the HQ, for pilot 3 in particular, from HQR = 4 to HQR = 7. The pilot has to lead compensate given the inherently low bandwidth of the FPA response controlled by the aircraft FCS. This tendency depends on the capture amplitude: the degradation is greater with higher amplitudes.

- Pilots are resistant to change the piloting technique, which they usually adopt for the tasks performed in these evaluations. They recognized the necessity of an open-loop technique, which they broadly considered an HQ limitation, instead of a specific characteristic of the aircraft.

- The flight control and envelope protection system is very effective in protecting the aircraft from envelope exceedances. This was occasionally reported by the pilots as a positive characteristic for good HQ.

- The FCS suppresses external disturbances very effectively, requiring a lower additional pilot workload with respect to the standard Calspan/STI augmentation. This is reported by all the pilots as a positive characteristic which allows them to focus on target gross acquisition with a limited subsequent requirement for fine tracking and CCC.

- A recurrent comment is the different response of the aircraft to positive (NU) and negative (ND) stick inputs. Pilot 1, in particular, reported oscillations when controlling through neutral stick position, leading to minor unpredictability. This is expected to depend partially on the parabolic shaping of the command gain, produced by second-degree polynomial interpolation between the normalized extremes of stick deflection.

16. RESULTS OF AFI-FCS ENVELOPE PROTECTION EVALUATIONS

16.1 BACKGROUND INFORMATION ON AFI-FCS ENVELOPE PROTECTION EFFECTIVENESS EVALUATIONS

Evaluations of the effectiveness of the envelope protection algorithm, which makes use of the AFI-FCS, were conducted. Two modes were tested in two different flight conditions:

- Alpha protection in PA
- V_{min}/V_{max} in V_A

The evaluation tasks are described in section 13. They were aimed at requiring the pilot to enter the envelope protection mode/flight condition gradually, with slightly different piloting techniques. The same tasks were used for both modes/flight conditions. The evaluations were applied to different types of exceedances when in a given mode; they were not limited to the principal function for which the given mode was designed. For the nature of the task and of the assessment of the system to be performed, an evaluation questionnaire was used to synthesize pilot's evaluations in a quantitative way (section 13). The HQR was assigned when the pilot considered it applicable. Dedicated additional visual cues were added to the HDD for appropriate pilot awareness of the aircraft's FCS operation and status.

16.2 ALPHA PROTECTION MODE IN PA

16.2.1 Principal Outcomes

This section reports the results of the effectiveness evaluations of the Alpha Protection mode. Different plots of the evaluation grades are provided for each pilot. More than one evaluation was performed and scatter is present among the evaluation grades. The empty symbols are relative to the NU maneuvering and have priority with respect to those relative to the ND maneuvering. When a single grade was assigned to a given evaluation element, the open symbol is used in the figures. From an analysis of the grades and comments, the following conclusions were drawn:

1. Aircraft response predictability and aircraft dynamics at mode switch are the two main components of the evaluation. Final grades on the suggested use of the tested envelope protection system mainly depend on the overall predictability of the combined aircraft/system functioning at envelope protection engagement.

2. Except for pilot 5, there is no indication from the pilots of a possible/suggested use of the current combined avionics/envelope protection system in production mode.

3. All pilots reported that in order to improve the use of the Alpha Protection system in production mode, a detailed description of its functionality and an understanding of the control algorithm's basic principles are required. Pilot 2 illustrated the importance of the systems knowledge in terms of safety of flight with the comment: "For example, when I centered the stick at the end of the ND runs, the pitch and power responses were not clearly understood. This will result in the pilots being unsure what the automation will do and thus [lead them to not trust it]. Additionally, the difference between what the pilot expects and what the system does leads to a high potential for incidents/accidents."

4. Accurate design of the avionics and of the visual cues to the pilot, consistent with the envelope protection functions, can significantly improve the effectiveness of the system. Pilot 2 indicated that back-driven throttles are an important cue of the engine controls status.

5. A recurrent comment from all the pilots is the preference of control authority to carefree piloting technique. This is common with all of the evaluations performed, including those for HQ assessment. This important component of the pilot's approach to the use of new

systems has to be taken into account in the conceptual design of the envelope protection algorithm.

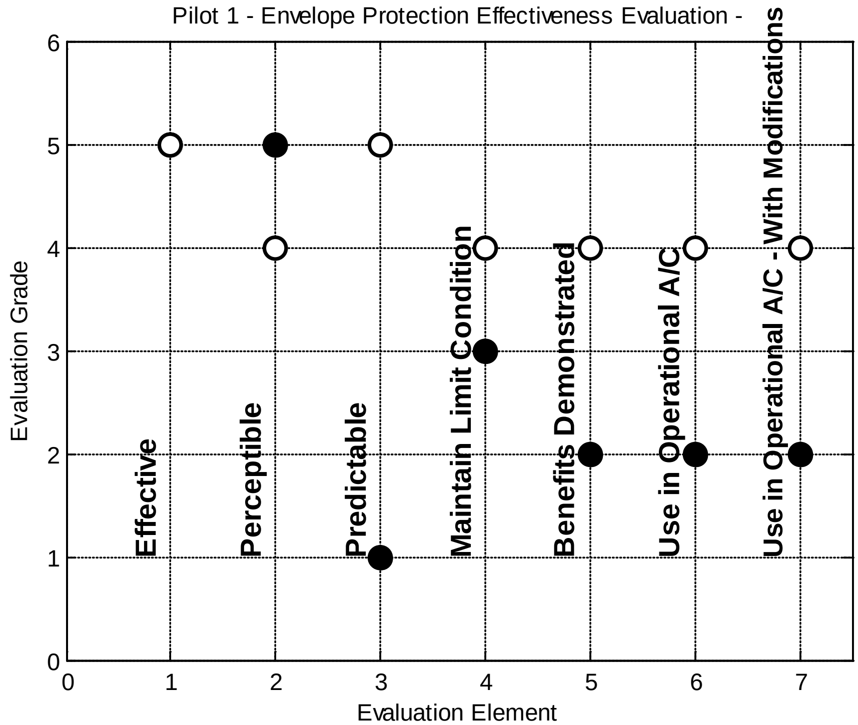


Figure 308. Pilot 1 AFI-FCS alpha protection evaluation grades

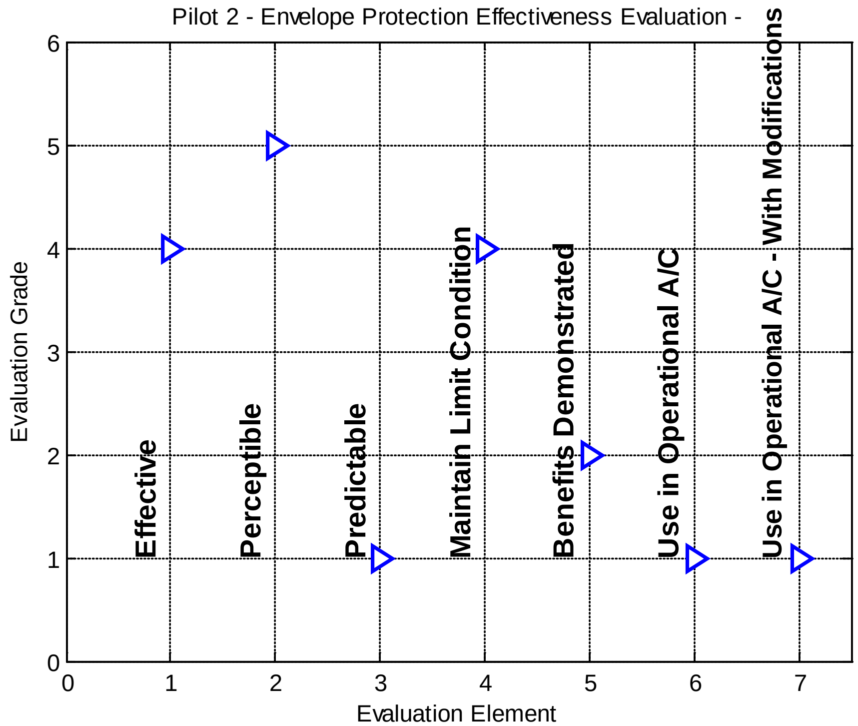


Figure 309. Pilot 2 AFI-FCS alpha protection evaluation grades

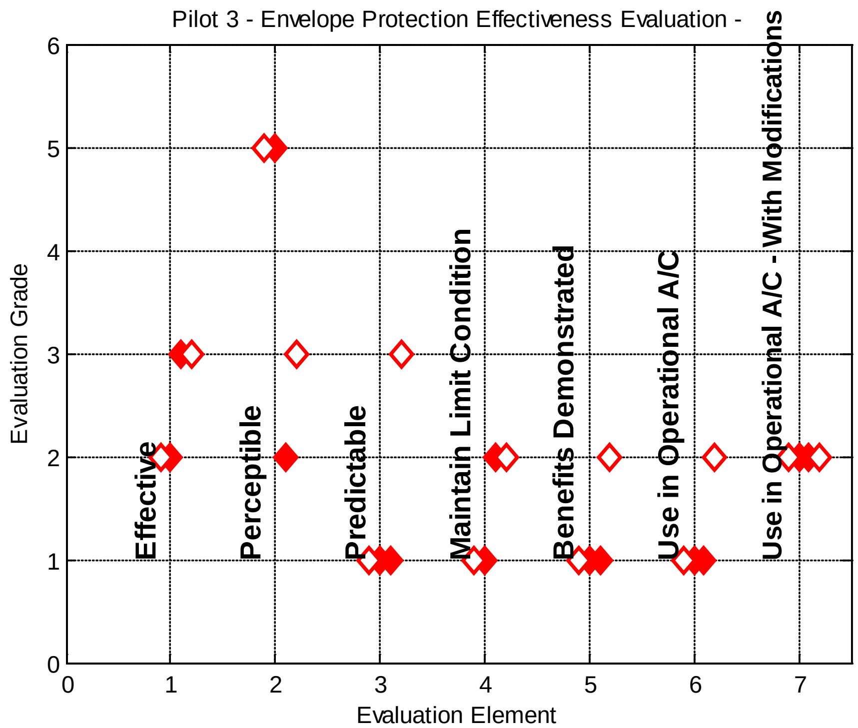


Figure 310. Pilot 3 AFI-FCS alpha protection evaluation grades

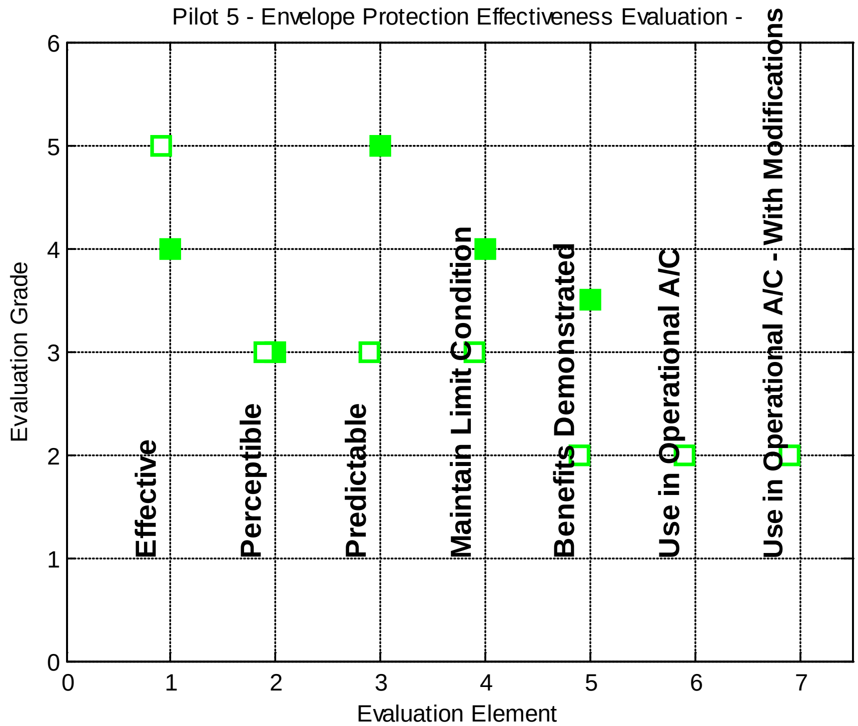


Figure 311. Pilot 5 AFI-FCS alpha protection evaluation grades

16.2.2 Pilot Grades and Comments

16.2.2.1 Pilot 1

Pilot 1 evaluated the alpha mode of the envelope protection function as very effective (Grade = 5). The highest concern was the predictability of the aircraft response while in protection mode, which was graded completely "not predictable" (grade = 1). The switch to the protection mode was considered "very perceptible," with the comment relative to the ND protection following: "A couple of problems: got kicks and 'squirrelly' behavior as I approached limits. The attitude bounced around. Then, when at the limit, I pulled up to level airplane and it took forever to level aircraft. Then I got into a PIO with the throttle going full up then back."

The NU protection is graded positively overall and the pilot would suggest its use in a production aircraft. The pilot stressed the highly perceptible mode change, which is not considered a positive characteristic. ND protection would not be suggested in a production aircraft, with or without modifications. Table 113 contains the pilot's comments for each evaluation run, while table 114 reports grades and additional comments.

Table 113. Pilot 1 AFI-FCS envelope protection comments — alpha protection

Evaluation: Alpha Limitor - Pilot: 1 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
102	1	Pitch	FPA Steps Up 1°			I got a kick down. I did not like it. I can't get there anymore.
102	2	Pitch	Theta Steps Up 2°			I do not like the kick. Stop at alpha=13.9°, KCAS = 111
102	3	Pitch	FPA Steps Down -1°			There is a kick. I cannot pull the nose up from maximum speed condition. Stop at KCAS = 200.
102	4	Pitch	Theta Steps Down -3°			Start to feel limit at KCAS = 175; it is harder to push the nose down. I got the kick. PIO between throttle and FPA.

Table 114. Pilot 1 AFI-FCS envelope protection grades — alpha protection

Session:102 Records:1-2	
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:	Didn't like the kicks that preceeded the actual limit. When I reached the limit it was evident because there was no more command authority.
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 flight 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:	

Session:102 Records: 1-4	
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:	A couple problems: got kicks & "squirelly" behavior as I approached limits. The attitude bounced around. Then when at the limit I pulled up to level airplane and it took forever to level aircraft. Then I got into a PIO with the throttle going full up then back.
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the limit flight 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:	

16.2.2.2 Pilot 2

Pilot 2's evaluation results relate that the envelope protection system is very effective in preventing exceedances and limit condition is maintained accurately: grade = 4 and grade = 5, respectively. The benefits of the alpha protection were not considered to be completely and clearly demonstrated. The fact that the mode transition is very perceptible and aircraft response is not predictable prevents the mode from being recommended for production aircraft. Pilot 2 does not recommend the implementation of this system in an operational commercial aircraft. From the comments, it is clear that the system is capable of effectively protecting the aircraft from envelope exceedances. The comments highlight the requirement for the pilot to be aware of the system functioning: "Throttles at idle at 150 [KCAS]. Tracking is okay. Need to start using force at 180 [KCAS]. Not sure what the system is trying to do, pilots need to know."

The two main concerns of pilot 2 are aircraft response predictability and control system status awareness. These are the reasons for the system not being recommended by the pilot for commercial/production use. The following comments, contained in table 117, detail pilot 2's specific concerns: "For example, when I centered the stick at the end of the ND runs, the pitch and power responses were not clearly understood. This will result in the pilots being unsure what the automation will do and thus [leave them] not trusting. Additionally, [the] difference between what the pilot expects and what the system does leads to a high potential for incidents/accidents." This comment indicates the requirement for a more complete set of information available to the pilot and provides a useful synthesis of the overall pilot approach to highly augmented control systems. This is relevant information, as it can be considered one of the principal issues involving the safe commercial development of highly augmented airplanes/systems.

Pilot 2 provided a single grade for the combined evaluation of all four runs/tasks. Table 115 contains the pilot's comments for each evaluation run; table 116 reports grades and additional comments.

Table 115. Pilot 2 AFI-FCS envelope protection comments — alpha protection

Evaluation: Alpha Limitor - Pilot: 2 - Date: 08/07/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
Alpha Protection PA						
105	1	Pitch	FPA Steps Up 1°	–	–	I just move the predictor circle and wait for the actual gamma to catch up. Full back and I cannot do the task at 120, 10.9°. Throttle position is an important tactile cue.
105	2	Pitch	Theta Steps Up 1°	–	–	Not difficult but pitch attitude seems to move on its own and I have to hold back pressure at 120, 11.1°. I cannot capture, track or control the airplane.
105	3	Pitch	FPA Steps Down -1°	–	–	Airspeed is slowly increasing while altitude is decreasing. Auto throttles maintaining speed at 150. Big burble, I have lost the capability to control. Throttles on idle. Started feeling pressure at 170. Full forward stick at 190 and the speed stays at 200. Two transients.
105	4	Pitch	Theta Steps Down -3°	–	–	Throttles at idle at 150. Tracking is okay. Need to start using force at 180. Not sure what the system is trying to do, pilots need to know.

Table 116. Pilot 2 AFI-FCS envelope protection grades — alpha protection

Session:105							
Effectiveness of Envelope Protection Design Element							What the system was trying to do was not completely clear. I understand that it was trying to prevent maximum alpha and min/max airspeed, but otherwise the aircraft responses were not clear. For example, when I centered the stick at the end of the nose down runs, the pitch and power responses were not clearly understood. This will result in the pilots being unsure what the automation will do and thus not trusting. Additionally, a difference between what the pilot expects and what the system does leads to a high potential for incidents/accidents. On the nose down exercises, there was a definite and objectionable pitch transient that appeared to occur when the system lost the ability to control airspeed with power. I was not always sure what the engines were doing or trying to do. Back-driven throttles would significantly improve the awareness of the pilot to thrust changes.
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 flight 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:							

16.2.2.3 Pilot 3

Pilot 3 graded all four runs/tasks individually and a limited scatter is present among the grades. The NU tasks, which are those for which this protection mode was principally designed, were graded higher overall than the ND tasks (figure 310). As for the other pilots, mode switch perceptibility and predictability of the response in envelope protection mode, which received, respectively, grade = 2 to 5 and grade = 1 to 3, are the main concerns of pilot 3. Use of the system in production mode is moderately recommended. The modifications that can improve the system toward a standard production operation are a more gradual mode switch and additional information being made available to the pilot regarding the status of the control system. Table 117 contains the pilot's comments for each evaluation run, while tables 118 and 119 report grades and additional comments.

Table 117. Pilot 3 AFI-FCS envelope protection comments — alpha protection

Evaluation: Alpha Limitor - Pilot: 3 - Date: 08/09/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
mode=2 - outside/in lims						
108	1	Pitch	FPA Steps Up 1°	–	–	The mode change was not good. I could not go to alpha = 14°, so I was limited when I should not have been. FBS at KCAS = 113, alpha = 12° and still climbing in altitude. It should tell me when in protection mode–a red light or something.
108	2	Pitch	Theta Steps Up 1°	–	–	What is it saving me from? Protection at alpha = 5° is ridiculous.
108	3	Pitch	FPA Steps Down -1 °	–	–	Keeping speed at KCAS = 150 with active throttle. When throttles idle, speed maxed at KCAS = 200.
108	4	Pitch	Theta Steps Down -3°	–	–	Full stick at KCAS = 180. Idle throttles until max KCAS = 200.

Table 118. Pilot 3 AFI-FCS envelope protection grades — alpha protection — 1

Session:108 Records:1	
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 flight 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:	
Session:108 Records: 2	
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 flight 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:	

Table 119. Pilot 3 AFI-FCS envelope protection grades — alpha protection — 2

Session:108 Records:3	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope protection	Started at too low airspeed.
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 flight condition was maintained:	Started at too low airspeed.
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:	

Session: 108 Records: 4	
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 flight 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:	

16.2.2.4 Pilot 5

Pilot 5 graded the NU tasks separately from the ND ones. The operative aspects of the system (effectiveness, predictability, capability to maintain limit condition, and demonstrated benefits) received high-level grades for the ND tasks: grade = 3.5 to 5. This is an overall positive evaluation of the system's operational effectiveness in providing envelope protection from airspeed exceedance. Grades of the same elements for the NU tasks were lower, on average, with respect to predictability and demonstrated benefits in particular. The pilot's comments stress the capability of the system to maintain the limit flight conditions and the requirement of more pilot authority when approaching the limits. These are potentially conflicting requirements, which slightly affect the grades and the utility of the envelope protection perceived by the pilot. The relevant comment is: "Stable, could finish task. Feel forces at KCAS = 145. Small degree of pitch authority at KCAS = 210. Alpha = 14.4°. Release and recapture attempt, can't capture. Expected more authority."

The approach of pilot 5 to the envelope protection mode switch is similar to that of the other pilots: "Started to come in, but was not as definable [a] condition, grey area. Initially predictable in the subsequent recapture attempts. Don't know why/how protection is implemented. What flight condition? Recapture attempts aborted in behavior not fully understood. I have a question on recapture logic." These comments indicate the requirement for a more complete explanation to the pilot of the envelope protection logics and algorithm together with additional visual cues on the current status of the system.

The pilot adapted to the aircraft characteristics during the evaluation, which allowed him to increase his understanding of the system functionalities, mainly in ND tasks. Table 120 contains the pilot's comments for each evaluation run, while table 121 reports grades and additional comments.

Table 120. Pilot 5 AFI-FCS envelope protection comments — alpha protection

Evaluation: Alpha Limitor - Pilot: 5 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA - mode=0						
98	1	Pitch	FPA steps up 1°	–	–	Very good acquisition. Excellent tracking. Very stable. Can feel the protection come in at KCAS = 135. Full aft stick and velocity slowing at KCAS = 125; unable to capture. Alpha stayed at 14.6 deg.
98	2	Pitch	Theta steps up 1°	–	–	Very stable tracking. Definitely level 1. Feel forces at KCAS = 135; never got to the limit during the task.
98	3	Pitch	Theta steps up 2°	–	–	Stable; could finish task. Feel forces at KCAS = 145. Small degree of pitch authority at KCAS = 210. Alpha=14.4 deg. Release and recapture attempt; can't capture. Expected more authority.
98	4	Pitch	FPA steps down -1°	–	–	Good characteristics and captures. Forward pressure at KCAS = 160. Hitting stop at KCAS = 190. Max speed at KCAS = 200.
98	5	Pitch	Theta steps down -1°	–	–	Very nice and stable. Very slight forward force to hold condition.
98	6	Pitch	Theta steps down -2°	–	–	A bit of bobbles when getting to limit conditions. Full forward stick at KCAS = 160. Relax and recapture gives a lot of pitch authority. Do not feel the limit.

Table 121. Pilot 5 AFI-FCS envelope protection grades — alpha protection

Session: 98 Record:1,2,3	
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 flight 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:	
Started to come in, but was not as definible condition, grey area. Initially predictable, in the subsequent recapture attempts. Don't know why/how protection implemented. What flight condition? Recapture attempts aborted in behavior not fully understood. I have a question on recapture logic.	
Session: 98 Record 4,5,6	
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 flight 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:	
Transition point not fully apparent.	

16.3 V_{min}/V_{max} MODE IN V_A

16.3.1 Principal Outcomes

The same tasks used for the assessment of the alpha protection mode were used, with small variations in the amplitude, when requested by the pilot. The V_{min}/V_{max} envelope protection mode was tested in V_A flight condition. Pilot 1, who evaluated the alpha protection mode, did not take part in these tests. The empty symbols in figure 311 are relative to the NU maneuvering and have priority with respect to those relative to the ND maneuvering. When a single grade was assigned to a given evaluation element, the open symbol is used in the figures.

From analysis of the grades and comments, the following principal outcomes can be derived:

1. The envelope protection mode was graded overall positively by the three EPs, with high grades for the protection effectiveness: Grade = 3 to 5.

2. Grades to the predictability of the aircraft response when in protection mode were characterized by significant scatter: Grade = 1 for all runs of pilot 3, Grade = 3 to 5 for the other pilots, with the highest values for pilot 5. This indicates a potential dependency on the piloting technique and on the pilot exposure to this type of system. One example of this second reason is pilot 5, who flies aircraft with different levels of hard envelope protections more frequently.

3. The V_{max} limitation was graded higher overall because of the reported lower impact on piloting technique of the neutral speed stability.

4. The importance of the pilot awareness of the control system status was stressed by every pilot. Grades are expected to be affected by the test limitations and the limited adaptation of the HDD configuration to the specific characteristics of the tested system.

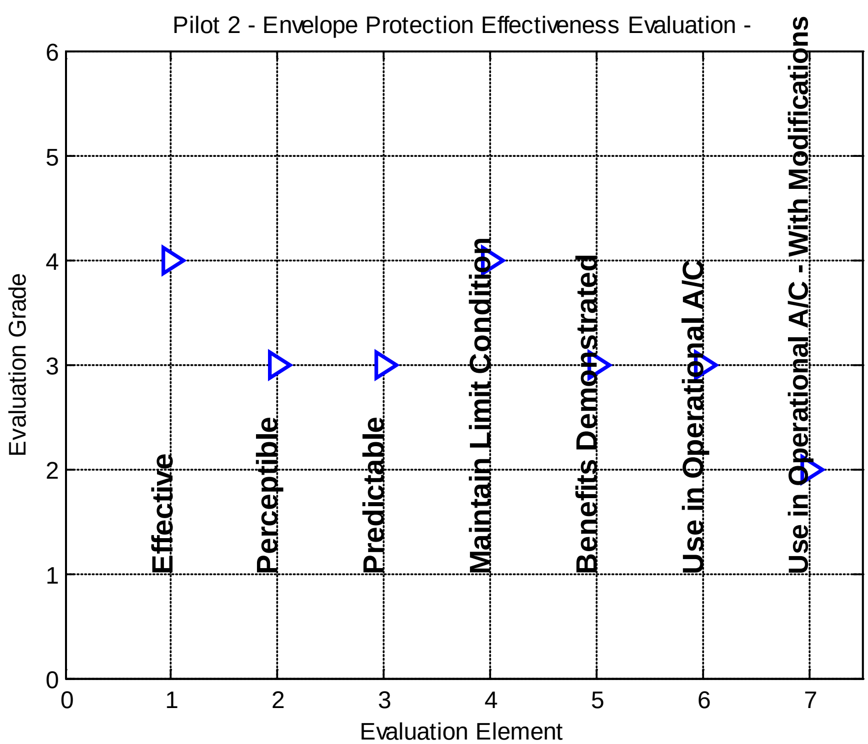


Figure 312. Pilot 2 AFI-FCS V_{min}/V_{max} protection evaluation grades

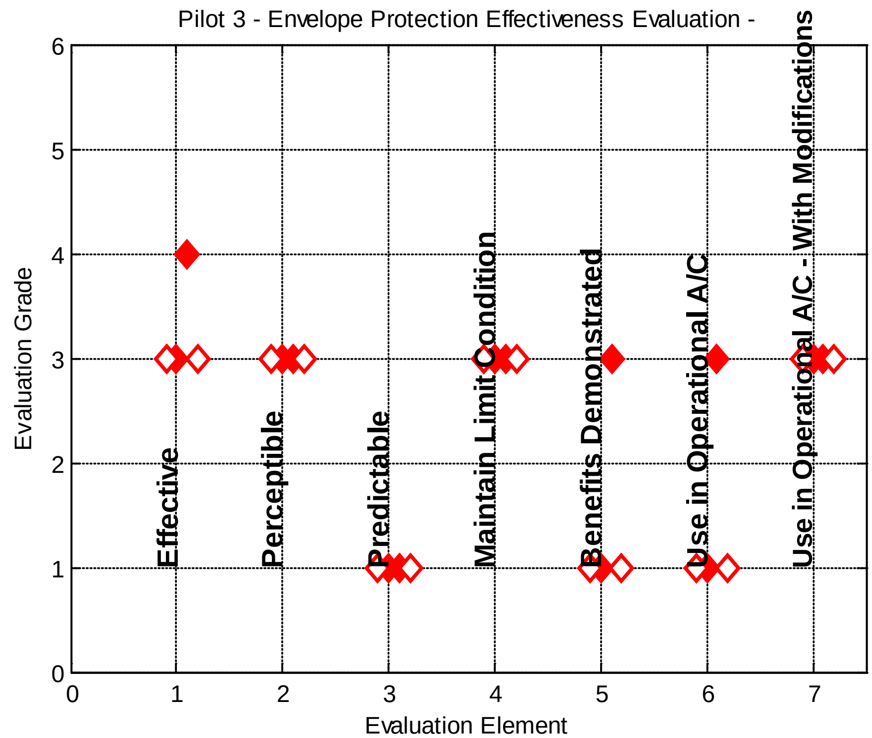


Figure 313. Pilot 3 AFI-FCS V_{min}/V_{max} protection evaluation grades

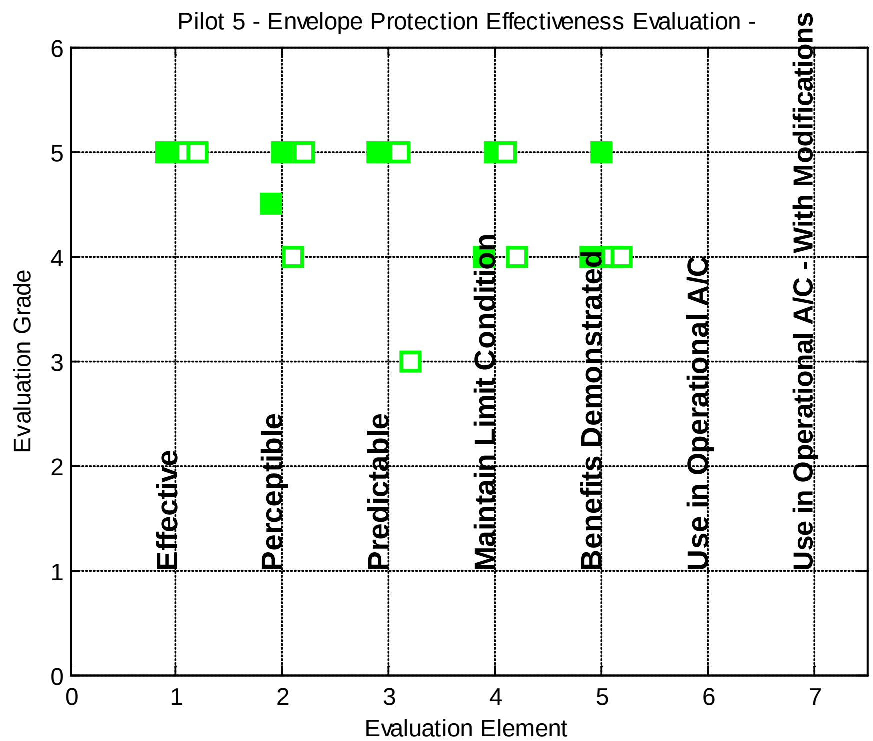


Figure 314. Pilot 5 AFI-FCS V_{min}/V_{max} protection evaluation grades

16.3.2 Pilot Grades and Comments

16.3.2.1 Pilot 2

Pilot 2 provided a single set of grades for both NU and ND tasks. The average grade is slightly higher than grade = 3, with high grades for envelope protection system effectiveness and capability to maintain the limit condition (grade = 4). All other evaluation parameters are grade = 3 and no modifications are suggested for use in an operational aircraft. This is, overall, a significantly positive evaluation of the envelope protection system. Predictability of aircraft response and relatively low perception of the mode switch (pitch bobble) are considered determinant factors for the broad appreciation of the system. The capability to maintain the limit condition was highlighted in the comment: "Full forward stick KCAS = 400, idle throttle. Did not stop at KCAS = 375 when released."

Pilot 2 did not provide specific comments pertaining to the limitations of a pilot's authority, which is usually one of the main concerns of highly augmented aircraft and of the other protection modes/design elements evaluated throughout the whole project. However, as a background comment, he does allude to the requirement for higher awareness of the system status. Table 123 contains the pilot's comments for each evaluation run while table 124 reports grades and additional comments.

Table 122. Pilot 2 AFI-FCS envelope protection comments — V_{min}/V_{max} protection

Evaluation: Velocity Limitor - Pilot: 2 - Date: 08/07/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A						
106	1	Pitch	FPA Steps Up 1°	–	–	–
106	2	Pitch	Theta Steps Up 1°	–	–	Back force at KCAS = 200, alpha = 6.8°. Full stick soon after, speed decreasing to KCAS = 165, alpha = 12°. Pitch transient when the airspeed started to drop off.
106	3	Pitch	FPA Steps Down -1°	–	–	Full forward stick KCAS = 400, idle throttle. Did not stop at KCAS = 375 when released.
106		Pitch	Theta Steps Down -2°	–	–	Power at idle when KCAS = 250. Force needed at KCAS = 385. Very suddenly full forward and unable to capture. Max speed at KCAS = 400.

Table 123. Pilot 2 AFI-FCS envelope protection grades — V_{min}/V_{max} protection

Session:106	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope protection	
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	
protection was:	Only perceptible on one nose-up run (theta tracking I think)-a pitch bobble that was very noticeable.
Not Predictable 1 2 **3** 4 5 Very Predictable	
With active envelope protection, the flight 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	
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:	
Uncertainty still exists as to what the system will do after the limit has been reached and then the pilot releases the stick. Lack of back-driven throttles decreases awareness of engine status.	

16.3.2.2 Pilot 3

Pilot 3 assigned relatively high grades to the envelope protection system effectiveness and to the capability to maintain limit conditions: grade = 3 for all runs, with exception of grade = 4 for the negative steps pitch attitude captures. Low predictability (grade = 1) and relatively high perceptibility of mode switch (grade = 3) indicate issues with the current implementation and visual cues and information regarding the system status available to the pilots. Demonstrated benefits of the implementation were assigned grade = 1, with the exception of the negative steps pitch attitude captures, which received grade = 3. Pilot 3 suggests the implementation of the system in operational aircraft after modifications (grade = 3). This is an overall positive result, considering the test limitations due to the use of a fixed base simulator and the restricted number of visual cues available pertaining to the status of the system. The grades and comments indicate higher acceptability of the V_{max} limitation with respect to V_{min}, mostly because of the neutral speed stability affecting the piloting technique. This is indicated by the comment: "I have to lead a lot then I overshoot. The neutral speed stability is a problem. I do not like that the neutral speed stability requires the protection. Adding more force to keep the nose going down seems more natural than the pull up conditions."

Table 124 contains the pilot's comments for each evaluation run, while tables 125 and 126 report grades and additional comments.

Table 124. Pilot 3 AFI-FCS envelope protection comments — V_{min}/V_{max} protection

Evaluation: Velocity Limitor - Pilot: 3 - Date: 08/10/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A						
109	1	Pitch	FPA steps up 1°	–	–	Kind of weird because in the protection mode there is a big dead spot in the command path. I can't adjust the airspeed and I feel disconnected. In mode at speed of 215, not a huge transition. When I go to the new step my natural tendency is to put the gamma marker on the target, not the gamma command. I have no idea what the limit is.
109	2	Pitch	Theta steps up 1°	–	–	Tendency to overshoot. Full thrust at 250 then losing speed. FBS at 185, 8.5°. The airplane pitches down and I would not know why.
109	3	Pitch	FPA steps down -1°	–	–	FFS at 400 max.
109	4	Pitch	Theta steps up 1°	–	–	–
109	5	Pitch	Theta steps up 1°	–	–	The transition is ridiculous and scary. Totally unacceptable. What is this airplane doing? Disconnected from the plane.
109	6	Pitch	Theta steps down -3°	–	–	–
109	7	Pitch	Theta steps down -3°	–	–	I have to lead a lot, then I overshoot. The neutral speed stability is a problem. I do not like that the neutral speed stability requires the protection. Adding more force to keep the nose going down seems more natural than the pull-up conditions.

Table 125. Pilot 3 AFI-FCS envelope protection grades — V_{min}/V_{max} protection — 1

Session:109 Records:1	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight 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	
Disagree **1** 2 3 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	
Session:109 Records: 2	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight 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	
Disagree **1** 2 3 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	

Table 126. Pilot 3 AFI-FCS envelope protection grades — V_{min}/V_{max} protection — 2

Session:109 Records:3	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight 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	
Disagree **1** 2 3 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	
Session: 109 Records:6,7	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight condition was maintained:	
Poorly 1 2 **3** 4 5 Very Accurately	
Summary:	
The benefits of the envelope protection were clearly demonstrated:	If have to have no speed stability.
Disagree 1 2 **3** 4 5 Agree	
I would encourage the use of an envelope protection such as this in	
Disagree 1 2 **3** 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	
Speed stability poor. The increase of forward stick force to hold altitude seemed more natual than for the nose high case.	

16.3.2.3 Pilot 5

Pilot 5 assigned overall high grades to this envelope protection mode (grade = 4 to 5), for the ND tasks in particular. Predictability received grade = 3 for the positive FPA steps captures (V_{min} protection). Pilot stressed the requirement for a better understanding of the system functioning, as indicated by the following comments:

- “Don’t know; need to better understand the concepts. Envelope protection obvious when triggered. Definite lower limit. Beyond that, don’t yet know enough.”

- “Most modern planes have this protection, but need tools to make pilot aware of these changes.”

This is a common approach revealed in all of the pilots’ evaluations. Benefits of the envelope protection mode were clearly demonstrated, as reported in the comment, “The envelope is apparent and effective.” Pilot 5 did not grade the suggested use of this system in operational aircraft. Table 127 contains the pilot’s comments for each evaluation run while tables 128 and 129 report grades and additional comments.

Table 127. Pilot 5 AFI-FCS envelope protection comments — V_{min}/V_{max} protection

Evaluation: Velocity Limitor - Pilot: 5 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A						
97	1	Pitch	FPA steps up 1°	–	–	Very nice stable tracking. It is just a matter of pulling. Speed is slowing but airplane tracks well. Full aft cannot get capture at KCAS = 200. Stabilizes at KCAS = 165. Some protection that prevented completion of task. Protection is obvious when triggered and active. Neutral apparent speed stability at KCAS = 200.
97	2	Pitch	FPA steps down 1°	–	–	Very benign tracking. Speed starting to pick up and is still good at KCAS = 325. Slowing down at KCAS = 345. KCAS = 375. Full aft could not do tracking task. Neutral apparent speed stability up to KCAS = 375. The protection starts to feed in ranges of speeds. Most modern planes have this protection but need tools to make pilot aware of these changes.
97	5	Pitch	Theta steps up 1°	–	–	Slight bobble in the pitch. Can still pull at KCAS = 200 but at KCAS = 175 full aft and cannot accomplish task.
97	6	Pitch	Theta steps down 1°	–	–	Very good tracking. Increase in the column force at KCAS = 270. At KCAS = 380, unable to do the task at forward stick. Upper Limit of KCAS = 401. Let go-power at idol and 1 g until it returns to KCAS = 250 and the thrust comes back up. The envelope is apparent and effective.

Table 128. Pilot 5 AFI-FCS envelope protection grades — V_{min}/V_{max} protection — 1

Session:97 Record:1	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 **3** 4 5 Very Predictable	
With active envelope protection, the flight 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	
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:	
Don' t know, need to better understand the concepts. (AoA limiter is employed by Boeing as well). Envelope protection obvious when triggered. Definite lower limit. Beyond that, don't yet know enough.	
Session:97 Record:2	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 3 4 **5** Very Predictable	
With active envelope protection, the flight 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	
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:	
Need to better understand. Apparent when envelope protection triggered. Definite upper limit (402 KCAS).	

Table 129. Pilot 5 AFI-FCS envelope protection grades — V_{min}/V_{max} protection — 2

Session:97 Record:5	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 3 4 **5** Very Predictable	
With active envelope protection, the flight 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	
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:	
Session:97 Record:6	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 3 4 **5** Very Predictable	
With active envelope protection, the flight 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	
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:	

16.4 AFI-FCS ENVELOPE PROTECTION EVALUATIONS, OBSERVATIONS, AND CONCLUSIONS

From the previous evaluations of the AFI-FCS envelope protection effectiveness in alpha protection and V_{min}/V_{max} modes, the following observations and conclusions can be derived:

- The evaluations demonstrated the capability of the envelope protection system to prevent envelope exceedances in the longitudinal axis. Combined longitudinal and lateral/directional maneuvers were not tested intentionally.

- Aircraft response predictability and aircraft dynamics at mode switch are the two main components of the evaluation and acceptance of the protection system from the pilots. In the alpha protection mode, aircraft response predictability was occasionally considered very poor, with moderate scatter in the grades provided by the same pilot or across all pilots.

- Implementation of the alpha protection mode is potentially more critical than the V_{min}/V_{max} mode. Within the V_{min}/V_{max} mode, the protection from overspeed is preferred by the pilots, with respect to the V_{min} protection. This confirms the criticalities of the design in the low-airspeed range of the flight envelope.

  During the evaluations, pilots repeated their intention to override the limits occasionally, when the margins related to the expected limits were considered excessive. Pilots prefer control authority to carefree piloting technique.

- Pilot awareness of the system functioning and of the basic principles of the control algorithm is fundamental for piloting technique, HQ, and safety. Pilot 2 illustrated this aspect in the comment: "For example, when I centered the stick at the end of the ND runs, the pitch and power responses were not clearly understood. This will result in the pilots being unsure what the automation will do and thus [leave them] not trusting. Additionally, a difference between what the pilot expects and what the system does leads to a high potential for incidents/accidents."

- Accurate design of the avionics and visual cues to the pilot, consistent with the envelope protection functions, are expected to improve the effectiveness of the system significantly by inherently guiding the most appropriate piloting technique. Pilot 2 also indicated that back-driven throttles are an important cue of the engine's controls status.

- Pilots with large transport aircraft background tend to more positively grade the authority limitations inherent in a full envelope protection system.

Overall, the envelope protection system was highly effective in preventing exceedances, occasionally limiting the aircraft with significant margins with respect to the limit expected by the pilot. Pilots required more knowledge of the system in order to consider it acceptable. Margins of improvements have been identified in the mode switch transient dynamics and design of the avionics. This last component is expected to improve the use of the envelope protection significantly, as the HDD used in the evaluations contained a limited set of signals providing information on the status of the system.

17. TEST LIMITATIONS

The results of this test are affected by the fidelity of the simulator. Even though a g-meter was available in the HDD, the pilots had partial awareness of the accelerations of the aircraft while performing the tasks because of the lack of motion cueing. They reported the necessity to split their peripheral view between the g-meter and capture target depending on the task phase (i.e., gross acquisition or fine tracking). The limited direct cues slightly increased the workload and required extrapolation from the pilots when assigning ratings that are supposed to be valid, given a more comprehensive set of cues. It is believed that, had these configurations been tested in flight, overall ratings of the aircraft may have been higher and with a lower scatter. Although the absolute value of the ratings may differ between simulator and flight testing, the trends of the ratings as parameters are varied and are expected to remain the same. The meaningful outcome of this experiment is the trend information from these simulations.

The two augmented aircraft evaluated, the Calspan/STI standard augmentation and the AFI-FCS provided by the FAA, both had a nonlinear lift curve slope. This exposed the pilots to partial nonlinear effects in the aircraft response and was considered a relevant factor in the evaluations, with the envelope protection being particularly affected by the presence of the partial dynamic nonlinearities. The implementation of more nonlinear aerodynamic effects typical of large transport aircraft could have revealed specific issues of the envelope protection algorithms, adding more components to the evaluation. The current level of fidelity of the aircraft representation was accepted because it was considered adequate for the scopes and width of the present investigation.

Longitudinal and lateral/directional kinematics were coupled, requiring pitch inputs to maintain a level turn and consequent amount of pilot compensation in the roll task. This also affected the purely pitch axis tasks for which high workload/compensation qualitatively corresponded to a higher degree of input coupling. Pilots referred to the pitch/roll inputs and motion coupling as an additional HQ metric for their evaluations. This required the direct implementation of a 1° amplitude dead zone in the roll command path when performing longitudinal tasks, demonstrating the operative validity of the design elements under investigation.

The different types of tasks, in the longitudinal axis in particular, exposed different aspects of the aircraft HQ components. The task execution criteria and capture amplitudes were refined with extensive pilot-in-the-loop evaluations, which also involved modifications to the HDD to improve pilot awareness of the aircraft state. These evaluations were conducted using the same process as the formal evaluations and the data recorded for post-processing and analysis. The objective was to provide the test team with a consistent frame of reference and combined simulator/testing procedure tool, which could provide reliable, high-fidelity repeatable results compatibly within the limits of the simulation and of the cues available to the pilots.

Because of budgetary constraints and the inherent physical limitations of a fixed-base simulator, one design element and the impact of some atmospheric disturbances on HQ could not be evaluated. This is not believed to have affected the overall effectiveness of the work in investigating the principal objectives of the project.

The overall results were not affected by these limitations, as general trends were derived from the evaluations. The number of pilots involved in the simulation activities, and their different backgrounds and approaches, supports the validity of the trends found and provides an adequate level of generalization.

18. SUMMARY OF FINDINGS

18.1 BACKGROUND INFORMATION

The outcome of the quantitative analysis of the simulations performed and the related pilot ratings and feedback are summarized in this section. The degree of generalization corresponds to the limitations reported above.

Different categories, based on the objective of their implementation, can be defined for the evaluated design elements. They are as follows:

- Feel system characteristics: frequency and damping.
- Command path/command augmentation elements: dead zones, small-amplitude variable command sensitivity.
- Primary control surface actuator bandwidth.
- Envelope protection elements: flat zones, scheduled command sensitivity, stick shaker, variable command sensitivity active stick, AFI-FCS envelope protection algorithm.

18.2 FEEL SYSTEM CHARACTERISTICS

Feel system characteristics have a moderate impact on HQ. Stick natural frequency affects HQ and task performance and leads to a tendency to PIO when reduced below threshold values. These threshold values have been identified in the current experiment as 10 rad/s for the longitudinal axis and 15 rad/s for lateral. The overlying requirement is that adequate separation from the operating frequencies of the PVS is required, typically in the 0.5–10 rad/s frequency range. Damping ratio demonstrated a significantly lower impact on both HQ and PIO tendency. Controllability is never in question and the system exhibits resistance to induced oscillations, even at $\zeta < 0.3$, for both the longitudinal and lateral axis.

18.3 COMMAND PATH/COMMAND AUGMENTATION ELEMENTS

Command path dead zones have a non-negligible effect on HQ in both the longitudinal and lateral axes. There is a consistent degradation of HQR for increasing DZLON amplitudes, with a maximum value of 1.5 degrees (corresponding to 15% of pitch authority) recommended for the tested side-stick configuration. Higher values produce an increase in pilot workload and occasional full travel stick inputs that negatively impact task performance and can lead to PIO or loss of control. The increased workload and compensation are not directly associated with decreased task scoring. Though potentially due to relaxed task requirements, this is nonetheless an indication of a lower perceived performance by the pilots. Evaluation of a blind baseline run after a run with a large dead zone led to modified pilot behavior, which resulted in degraded HQ and an increased PIO tendency rating for pilot 2. Repetition of a known baseline run resulted in the same ratings as the first baseline run. In general, dead zones did not increase the pilot's tendency to encounter PIO.

The impact of lateral dead zones (DZLATs) on HQ is higher than that seen in the longitudinal axis, with a maximum recommended amplitude of 1 degree. The pilot's compensation increases with increasing dead zone amplitude, while task scoring is not significantly affected by the introduction of the command path nonlinearity. The HQR are chiefly dependent on piloting technique, in particular on the command nonlinearity introduced by occasional full travel stick inputs. The presence of DZLATs, even if not impacting the ability of the pilot to accomplish the task with the desired scoring, reduces the command authority. This induces the pilot to command more frequent full stick travel inputs, increasing the nonlinear nature of the control and consequently degrading the HQ. Additionally, the lower authority affects a pilot's control technique as he performs the task and the increase in pilot workload can lead to PVS stability issues for select circumstances. No corresponding increase in PIO proneness has been directly identified for the configurations evaluated in this experiment.

The impact of the passive inceptor command sensitivity configurations varies with flight condition, augmented open-loop aircraft response, and piloting technique. For the PA flight condition, values of gain scaling factor lower than unity lead to worsening of the HQ due to a higher physical workload and perceived heaviness in the feel system as reported by the pilots. This is more evident for pilots with higher closed-loop stick activity. The opposite effect is noted for the V_C flight condition, where a reduction of the command sensitivity leads to a slight HQ improvement. The PA flight condition is minimally affected by piloting technique and augmented aircraft response. An open-loop (vehicle only) augmented response characterized by higher pitch rate overshoot is more sensitive to command sensitivity variation. An increase of the sensitivity leads to degraded HQ because of the higher proneness to pitch oscillations when operated as a closed-loop (pilot-vehicle). In these evaluations, the augmented aircraft has a low pitch rate overshoot in PA when compared to a much higher pitch rate overshoot in the V_C flight condition.

This correlation indicates that effective design guidance can be derived from offline FQ criteria in the identification of pilot-in-the-loop response issues related to varying command gain. No significant impact of varying command sensitivity on PIO and task scoring is identified.

An adequate level of robustness to command sensitivity variation is demonstrated by the evaluations, in the V_C flight condition in particular. This is expected to allow for consistent in-flight evaluation and refinement of the design through dedicated test campaigns.

18.4 PRIMARY CONTROL SURFACE ACTUATOR BANDWIDTH

Pitch actuator natural frequency has a noticeable impact on HQR, PIO tendency, and task scoring. The PIO tendency becomes a significant issue for actuator natural frequencies lower than 25 rad/s because of the additional phase lag incurred. Natural frequencies greater than 15 rad/s are recommended to avoid compromised HQ and task performance. For the standard augmentation of the tested aircraft, SM did not have a significant impact on ratings or task scoring as actuator natural frequency was varied.

Task performance was consistent with HQR for natural frequencies above 10 rad/s, though slight degradations were seen for actuator natural frequencies below 15 rad/s. The change in aircraft dynamics between the PA and V_A flight conditions caused one pilot to drastically alter his control strategy, negatively impacting HQ and affecting his task performance.

Roll actuator natural frequencies greater than 25 rad/s are also recommended because HQ and task performance may be compromised for configurations with lower natural frequencies. Control surface actuator natural frequencies below 25 rad/s negatively impacts task performance and HQR. The PIO tendency becomes a significant issue for actuator frequencies lower than 25 rad/s because of the additional phase lag incurred.

The results from both the pitch and roll axis actuator natural frequency evaluations showed similar results. Low actuator natural frequencies caused additional phase lag near piloted control frequencies, resulting in higher workload, a less responsive aircraft making desired performance harder to achieve, and larger amplitude inputs. These factors all contributed to degraded ratings and increased the tendency to induce oscillations.

18.5 ENVELOPE PROTECTION ELEMENTS

Flat zones degrade HQ in both the PA and V_C flight condition, independently from the open-loop augmented aircraft dynamics, which differ significantly between the two flight conditions.

The principal effect on aircraft response perceived by the pilot is the pitch authority limitation and unpredictability due to the implementation of the flat zones.

Piloting technique affects HQR, with lower correlation between HQR and flat zone amplitude for the pilots, with more gradual inputs in the gross acquisition portion of the task (i.e., discrete capture). This is likely due to the input amplitude being mostly lower than the flat zone breakpoint.

There is a large scatter between HQR assigned to the same flat zone configuration by the same pilot and across different pilots' ratings. This is an indication of a potentially critical implementation of this design element in a control system that is considered production standard. The implication is that significant difficulties are expected in the definition of a centralized value/design, which provides an adequate degree of flat zone robustness.

Additional visual and acceleration cues in the tests would have improved the pilots' awareness of the aircraft condition related to task limits and the predictability of the response with respect to pilot inputs. In this regard, pilots noted that real-world acceleration cues would have allowed the correlation of a given load factor value at a given flight condition with incipient saturation of the pitch control. This would have potentially reduced the nonlinear nature of the control perceived by the pilot, thus providing a predictable reference for the amplitude of the flat zone. It is also expected that the flat zone would have protected the aircraft from envelope exceedances.

No significant impact on HQ is derived from the implementation, which prevents load factor exceedances by varying the maximum commanded elevator deflection. To achieve this result, the linear command gain was reduced as a function of dynamic pressure at airspeeds higher than maneuvering speed. There is a slight degradation of HQR with respect to the baseline for pilot 1: from HQR 2 to HQR 3.

The main effect on piloting technique is an increase in stick deflection/activity at all input frequencies. This is attributed to higher stick forces, as the reduction of command gain with a constant force gradient effectively increases stick force per g. A reduction of control precision is also reported, with a higher tendency to oscillate in pitch. This effect is potentially magnified by the high pitch rate overshoot in V_C flight conditions.

No significant effect on piloting technique is produced by the SoS disturbance when compared with the discrete task. Pilot 1 reported that the "only advantage is that it helps control the amount to pull back." This indicates that the intended "carefree" type of piloting technique can be achieved with proper design and implementation of this design element. While the ability of this self-limited configuration to provide significant HQ improvement has not been assessed in this study, the result can be considered a positive outcome from a design standpoint. A minor HQ degradation, which can be minimized by a properly designed force gradient, can be considered acceptable within the scope of protecting the aircraft from unintentional g exceedances. This design was not thought to be applicable at low-airspeed flight conditions to protect the aircraft from exceeding the maximum aerodynamic performance capabilities of the airplane.

Active stick implementations in PA and V_C flight conditions were tested, with different respective solutions: stick shaker in PA and a variable force gradient as a function of g in V_C. The stick shaker onset AoA has no impact on pilot HQR and PIORs; a PIOR of 1 was given for every run. The HQR of 2 and 3 were given, with no noticeable trend based on shaker onset AoA. The shaker onset AoA had a negligible impact on task-scoring and performance. Pilot 2's scores were consistent and unaffected by the presence or absence of the shaker. Pilot 1's scores were slightly reduced by the addition of the shaker at higher AoA. It is most important to ensure that the shaker onset is at an appropriate AoA relative to the limit. If the shaker onset is too high, it will not adequately protect the aircraft and will allow the pilot to achieve desired performance. This was noted by pilot 1, who flew the shaker and often exceeded 9.5 degrees AoA when the shaker activated at this value or above. If the shaker onset was too low, it became a nuisance and the pilot tended to ignore it. This had an impact on piloting technique: Pilot 1 commented that he had to switch to using the AoA gauge to obtain limit information when the shaker onset was too early (8.5 degrees) because the information that the shaker provided was not only unhelpful but detrimental.

In V_C flight condition, pilots felt that the tested active-stick implementation cue was not helpful and that it was actually objectionable. The cue was nonlinear and it felt as though the stick was fighting the pilot. Increasing the gradient scale factor resulted in poorer HQR and more critical pilot comments. The larger the scale factor, the more nonlinear the resulting gradient became and the higher the forces the pilot encountered. Pilots felt that this made the aircraft less predictable and that the cue was a detriment rather than an aid.

There was minimal measurable effect of the stick-rate threshold for high-gradient disengagement on pilot ratings and comments. For large subsequent changes in the threshold, pilot 2 noted that the bumps in the cue onset could be slightly reduced, but not eliminated, with an increased stick-rate threshold and that the increase was not large enough to warrant an improvement in HQR.

Decreasing the n_z of higher gradient onset resulted in poorer HQR and less favorable pilot comments. Earlier onset of the higher gradient results in higher stick forces required a pull past 2 g, which pilots found to be objectionable. Although the pilots didn't like the early onset, the increased forces actually helped to prevent g-exceedances. A PIOR of 1 was given for every parameter variation, indicating that the active gradient does not result in PIO tendencies.

Active gradient parameter variations had no effect on the continuous-scoring component for this task, as expected, given the relatively low stick deflections required for fine tracking.

The active gradient scale and stick-rate threshold variations had no effect on the discrete scoring component for this task. For pilot 1, a lower n_z onset did help to increase the discrete scoring by preventing g-exceedances. There was no effect of n_z onset on the discrete scoring for pilot 2. Under a feel system design standpoint, the tests confirm that a background knowledge of the aircraft aerodynamics and a dedicated flight-test campaign allow for the development of a well-tuned stick shaker. Active stick design for high airspeeds g-exceedances protection requires a relatively more extensive design and testing process. The results obtained with pilot 1, in particular, demonstrate that a simple conceptual design — like the one tested in this evaluation — provides a non-negligible degree of protection from excessive g.

19. FBW DESIGN SAFETY REQUIREMENTS AND BEST PRACTICE GUIDANCE MATERIAL

19.1 INTRODUCTION

The research effort in this report was focused on the use of a conventional sidestick as the longitudinal and lateral axes inceptor for all simulation and analysis activities. All safe design tolerances shown below are based on the evaluations of baseline level 1 aircraft conducted with the fixed-base simulator described in appendix C of this report. The results presented in this report should be regarded as preliminary and verified by piloted flight evaluation.

Evaluations of the standard augmentation Calspan/STI and of the AFI-FCS augmented aircraft provided by the FAA were conducted. This section reports the results of both evaluations.

19.2 STANDARD AUGMENTATION CALSPAN/STI AIRCRAFT

19.2.1 Longitudinal Inceptor Natural Frequency

The recommended longitudinal inceptor natural frequency is frequency longitudinal ≥ 10 rad/s.

Pitch-axis feel-system natural frequencies greater than 10 rad/s do not compromise HQ and task performance. The PIO tendency becomes a significant issue for stick frequencies lower than 10 rad/s because of the interaction with pilot input frequencies. Stick dynamics must maintain adequate separation from task frequencies or adverse interactions between pilot inputs and stick dynamics will result in degraded HQ, increased PIO tendency, and poor task performance.

19.2.2 Longitudinal Inceptor Damping Ratio

The recommended longitudinal inceptor damping ratio is damping longitudinal (DLON) ≥ 0.3.

The pitch-axis feel-system damping ratio is not a critical parameter when kept above 0.3. Variations in HQ are minimal between pilots and consistent for damping ratios between 0.3–1.0. The damping ratio does not affect PIO tendency, which is not a significant risk, even with damping ratios less than 0.3. Though task performance degrades slightly for pilots sensitive to lightly damped feel-system dynamics, loss of control is not an issue and adequate performance can still be achieved.

19.2.3 Lateral Inceptor Natural Frequency

The recommended lateral inceptor natural frequency is frequency lateral ≥ 12.5 rad/s.

Lateral-axis feel-system natural frequencies greater than 12.5 rad/s do not compromise HQ and task performance. There is a margin with respect to PIO tendencies, which becomes a significant issue for feel-system natural frequencies lower than 10 rad/s. To yield best HQ results, the feel-system natural frequency should maintain adequate separation from the operating frequencies of the PVS; otherwise, adverse interactions between pilot inputs and stick dynamics can result in degraded HQ, increased PIO tendency, and poor task performance. Pilots demonstrated to be more sensitive to the variation of lateral feel-system natural frequency with respect to longitudinal.

19.2.4 Lateral Inceptor Damping Ratio

The recommended longitudinal inceptor damping ratio is DLAT ≥ 0.3.

The lateral feel-system damping ratio is not a critical parameter when kept above the value of 0.3. Pilot sensitivity to changes in lateral-axis feel-system damping is higher when compared to the longitudinal axis results. The PIO tendency is not a significant risk, even for very lightly damped configurations with damping ratios less than 0.3. Though task performance degrades slightly for pilots sensitive to lightly damped feel-system dynamics, loss of control is not an issue and desired performance can still be achieved.

19.2.5 Longitudinal Command Path Dead Zone

The recommended DZLON amplitude is DZLON ≤ 15% pitch authority

It is recommended that DZLONs smaller than 15% of pitch authority (1.5 degrees for the tested configuration) be used for sidestick inceptor configurations because HQ may be compromised by larger amplitudes. The PIO tendency is not a significant issue for large dead zones because of the command attenuation effect. The introduction of dead zones of 20% authority (2.0 degrees) or higher shows a degradation in HQR due to increased pilot workload and occasional FBS or FFS inputs. This saturation of the pilot's inputs, in fact, leads to a nonlinear nature of the control.

19.2.6 Lateral Command Path Dead Zone

The recommended DZLAT amplitude is DZLAT ≤ 10% roll authority

Dead zone in the lateral axis is considered undesirable. It is recommended that dead zones smaller than 1 degree be used for sidestick inceptor configurations because HQ and task performance may be compromised. As for the longitudinal case, PIO tendency is not a significant issue for large dead zones because of the command attenuation effect. Inclusion of dead zones amplifies the nonlinear effect of FLS pilot inputs, which is more often present overall than in the longitudinal plane. DZLAT amplitude should be kept to a minimum to avoid HQ and PIO issues.

19.2.7 Longitudinal Variable Command Sensitivity

The recommended low-amplitude longitudinal command gain scaling factors are:

- CSLON ≥ 0.7 in the PA flight condition
- 0.7 ≤ CSLON ≤ 1.0 in the V_C flight condition

In PA flight condition, values of the gain-scaling factor significantly lower than unity lead to worsening of the HQ. The opposite effect is evident in the V_C flight condition, in which a reduction of the command sensitivity leads to a slight HQ improvement. This is partly affected by piloting technique, the augmented aircraft response, and the higher physical workload and heaviness perceived by the pilots with a low command gain in PA.

Higher values of the open loop (vehicle only) augmented response pitch rate overshoot make the response more sensitive to command sensitivity increases, with degradation of the HQ, for the higher proneness to pitch oscillations when operated in a closed loop (pilot + vehicle). The design and development of command-gain scheduling with stick deflection and flight condition is expected to be implemented at production-level standards with low criticalities. Guidance can be derived from offline FQ criteria to identify potential issues of the pilot in the loop response.

An adequate level of robustness to command sensitivity variation is demonstrated by the evaluations, in the V_C flight condition in particular. This is expected to allow for consistent in-flight evaluation and refinement of the design through dedicated test campaigns.

19.2.8 Primary Control Surface Actuator Bandwidth

The evaluations of the primary control surface actuator bandwidth were conducted by varying the actuator natural frequency and maintaining a damping ratio of $\zeta = 0.7$. In the evaluations, the natural frequency is considered equivalent to the actual bandwidth.

The recommended longitudinal and lateral control surface actuator bandwidth is:

- BWLON/BWLAT ≥ 25 rad/s

In the longitudinal plane, PIO tendency becomes a significant issue for longitudinal actuator frequencies lower than 25 rad/s because of the additional phase lag incurred. The HQ and task performance may be compromised for configurations with bandwidth BWLON < 10 rad/s. The HQ and task performance can be affected by the open-loop augmented aircraft dynamics, which can cause the pilot to alter his control strategy. Lower sensitivity is demonstrated with respect to the bare aircraft SM. This bandwidth requirement is not expected to be critical in normal operation. Potential issues, particularly related to PIO, are to be considered in aircraft degraded/failure modes.

In the lateral/directional plane, PIO tendency becomes a significant issue for actuator bandwidth lower than 25 rad/s because of the additional phase lag incurred. The HQ and task performance may also be compromised. This abrupt cliff of the response degradation requires a significant margin with respect to the value recommended above during normal operation. Hydraulic system failures can result in a significant reduction of the aircraft HQ level.

19.2.9 Longitudinal Command Path Flat Zone

The recommended command path flat zone amplitudes are:

- FZLON ≤ 50% positive pitch authority in the PA flight condition
- FZLON ≤ 40% positive pitch authority in the V_C flight condition
- FZLON ≤ 60% negative pitch authority in the V_C flight condition

These recommendations are relative to the full-stick authority for generalization of the results. The maximum values are provided, as no minimum limitations apply. Flat zones generally degrade HQ in both the PA and V_C flight condition because of the pitch authority limitation and the nonlinearity introduced by the command saturation, which produces response unpredictability. A trade-off between HQ degradation and envelope protection effectiveness has to be conducted. The recommended values correspond to the configurations, which are rated HQ level 1, marginal level 2, in presence of the flat zone. The large scatter between HQR of the same flat zone configuration for the same pilot and across different pilots indicates the potential for a critical implementation of this design element. Significant difficulties are expected in the definition of a centralized value/design, which provides an adequate degree of robustness of flat zones in production mode.

19.2.10 Scheduled Command Sensitivity

No significant HQ advantages are derived from the implementation of a piecewise command gain allowing for commanding limit load factor with FBS or FFS pilot's inputs in the $V > V_A$ envelope region.

The main effect on piloting technique is an increase of stick deflection/activity at all frequencies. This is associated with higher forces and a reduction of the control precision, with a higher tendency to oscillate in pitch. The intended carefree type of piloting technique can be achieved with this design element.

A trade-off is potentially to be conducted for the implementation in normal-operation mode. The two contrasting effects of operational advantages deriving from the envelope protection effectiveness versus HQ degradation are the main factors. Relaxation of the achievable load factor and of the gain scheduling with dynamic pressure can be used to maintain higher command gain values, reducing the stick forces and increasing control precision.

19.2.11 Stick Shaker Implementation in PA

It is recommended for the stick shaker onset AoA to be 1 degree lower than the limit AoA.

This was found to be best for allowing the pilots to achieve desired performance and preclude exceedance of the AoA limit. The stick shaker onset AoA has no impact on HQ and PIO proneness. Evaluations demonstrate that it is most important to ensure that the shaker onset is at an appropriate AoA relative to the limit. If the margin between limit AoA and shaker onset AoA is too small, the shaker will not adequately protect the aircraft and allow the pilot to achieve desired performance. This depends also on piloting technique, in particular for pilots who tend to "fly the shaker." With a margin that is too large, the shaker becomes a nuisance and the pilot tends to ignore it.

19.2.12 Variable Command Sensitivity Active Stick in V_C

The active stick implementation with an increase of the force gradient for load factor values above a given threshold is moderately helpful in preventing envelope exceedances. The impact on HQ is negative.

The force cue is nonlinear and feels like the stick fighting the pilot. Increasing the scaling factor between the increased gradient and the baseline one reduces the aircraft response predictability because of the higher, nonlinear nature of the control. A transition to the baseline gradient can be made dependent on the stick release angular rate to reduce the nonlinearity.

A low-onset value of the load factor helped to prevent g exceedances because of the increased forces, although the pilots didn't like the early onset.

A potentially better and simpler solution to this active stick implementation may be to use a constant gradient with a force-positive bias when exceeding the load factor onset value. This has the benefit of the higher forces making it harder to over g the aircraft without the negative effects of introducing nonlinearities.

19.3 AFI-FCS AUGMENTED AIRCRAFT

19.3.1 HQ

With respect to both pitch attitude and FPA captures tasks, the aircraft is HQ level 2, marginal level 1. This is mainly due to the reported lag in the pitch response perceived by the pilot. The lag was more evident in the pitch attitude task.

Small amplitude FPA captures/commands are the most appropriate piloting technique for the evaluated augmented aircraft, aircraft response predictability, and low pilot compensation. An open-loop technique, with gradual, low-amplitude inputs, allows avoidance of pitch attitude oscillations. The requirement for this piloting technique diminishes increasing airspeed.

Visual cues available to the pilot on the status of the system are fundamental for good HQ because they increase the pilot's awareness and overall aircraft response predictability.

Based on the previously provided description, the successful implementation of the AFI-FCS in normal mode operation depends also on the pilot's adaptation to changing his usual piloting technique when necessary to obtain desired performance with minimal pilot compensation.

The FCS is very effective in suppressing external disturbances, such as the SoS disturbance injected during the evaluations. The disturbance suppression allows for a lower additional pilot workload with respect to a standard augmentation aircraft. This is reported by all the pilots as a positive characteristic, which permits the pilot to focus on targeting gross acquisition with a limited subsequent requirement for fine tracking and CCC.

The parabolic shaping of the pitch command gain, obtained with second-degree polynomial interpolation between the normalized extremes of stick deflection, is required for envelope protection and gradual variation of the command sensitivity. On the other side, it produces a nonlinear nature of the control, which is occasionally reported to be not completely satisfactory for a predictable pitch aircraft response around the inceptor null position.

19.3.2 Envelope Protection System

The envelope protection system is highly effective in preventing exceedances, occasionally limiting the aircraft with significant margins relating to the limit expected by the pilot. There is a non-negligible mismatch between the functioning of the FCS expected by the pilots and the actual aircraft response at the limits of the envelope. This mismatch can be reduced, providing the pilots with extensive background knowledge of the control system and, by means of a dedicated design of the avionics, including real-time information on the current status of the system. This additional information can support the pilot in flying the aircraft with the most appropriate piloting technique, increasing the perceived degree of authority required by the pilots in normal operation of the aircraft.

As a consequence of limited awareness of the envelope protection logics, pilots repeated their intention to override the limits during the evaluations when margins related to the expected envelope limits were considered excessive.

Improvements can also be achieved by increasing the predictability of the aircraft response at mode switch. Pilots reported pitch attitude oscillations when entering protection mode, which affected their capability to control the aircraft for a limited time span.

The system envelope protection functions are rated more positively by pilots with backgrounds flying highly augmented large-transport aircraft. This is expected to depend on their familiarity with the authority limitations inherent in a full envelope protection system.

20. THE FBW DESIGN VALIDATION CHECKLIST

The FBW design checklist reported in this section is based on the results from the FBW Research Task 2 Follow-on and Year 3 work conducted by Calspan and STI. It is based on the fixed-based simulations described in this report and on the analysis of the test data from these simulations.

The design validation checklist uses a tabular format (table 130). It is presented as the design validation item, the design safety requirements values based on this report, and traceability to Title 14 Code of Federal Regulations Part 25 requirements. To maintain an adequate level of generalization of the results, values specific to the test inceptor configuration were reported as a control authority percentage. The outcome of the simulations is valid in accordance with the test limitations reported in section 17.

Table 130. Design validation checklist recommendations

FBW Design Item	FBW Design Safety Requirement	FBW Design Verification Method	Traceability
Inceptor Design (Sidestick) Recommendations			
Longitudinal inceptor natural frequency	Control inceptor natural frequency $\geq$ 10 rad/s	FBS or MBS, GT, FT	25.143, 25.671(a)
Lateral inceptor natural frequency	Control inceptor natural frequency $\geq$ 12.5 rad/s	FBS or MBS, GT, FT	25.143, 25.671(a)
Longitudinal inceptor damping ratio	Control inceptor damping ratio $\geq$ 0.3	FBS or MBS, GT, FT	25.143, 25.671(a)
Lateral inceptor damping ratio	Control inceptor damping ratio $\geq$ 0.3	FBS or MBS, GT, FT	25.143, 25.671(a)
Active inceptor for envelope protection (PA)	Stick shaker onset AoA = (AoA_{lim} – 1 deg)	FBS or MBS, FT	25.143, 25.671(a)
Active inceptor for envelope protection (V_C)	Protection force gradient scaling factor* = 2	FBS or MBS, FT	25.143, 25.671(a)
Command Path Augmentation Recommendations			
Longitudinal command path dead zone	Longitudinal dead zone $\leq$ 15% pitch authority	OLAn, FBS or MBS, FT	25.143, 25.671(a)
Lateral command path dead zone	Lateral dead zone $\leq$ 10% roll authority	OLAn, FBS or MBS, FT	25.143, 25.671(a)
Longitudinal variable command sensitivity	Longitudinal command gain scaling factor CSLON $\geq$ 0.7 in PA 0.7 $\leq$ CSLON $\leq$ 1.0 in V_C	OLAn, FBS or MBS, FT	25.143, 25.671(a), 25.331
Longitudinal command path flat zone	Longitudinal flat zone FZLON $\leq$ 50% Positive pitch Authority in PA FZLON $\leq$ 40% Positive pitch Authority in V_C FZLON $\leq$ 60% Negative pitch Authority in V_C	FBS or MBS, FT	25.143, 25.671(a), 25.331
Control Effector Bandwidth			
Longitudinal actuator bandwidth	Actuator bandwidth $\geq$ 25 rad/s	OLAn, FBS or MBS, GT	25.143, 25.671(a), (c)
Lateral actuator bandwidth	Actuator bandwidth $\geq$ 25 rad/s	OLAn, FBS or MBS, GT	25.143, 25.671(a), (c)

OLAn = offline analysis, FBS = fixed base simulator, MBS = moving based simulator, GT = ground test, FT = flight test.
* The active stick implementation is described in section 4.8.2. The force-gradient scaling factor reported in the table is the factor applied to the baseline gradient beyond the normal load-factor threshold.

21. SUGGESTED FURTHER DEVELOPMENT

Because of the limitations of the ground-based simulator used to obtain the results in this report, the quantitative design tolerances quoted herein may not be completely representative of a real flight environment. It is recommended that these results be confirmed by using the recommendations of this document as guidance for the identification of a subset of tests to be repeated in flight using an inflight simulator. The addition of real-world visual and motion cues will provide more reliable results and allow for a more complete set of evaluation tasks than was possible with the ground-based simulation described herein.

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APPENDIX A — CALSPAN/STI AIRCRAFT MODEL

A.1 AIRCRAFT MODEL OVERVIEW

This appendix reports data and information on the standard augmentation Calspan/STI aircraft model. The model is initialized by means of the initialization file "Init_FAA_FBW_model_Task3.m." For offline simulations, the pilot's force inputs or inceptor displacements are specified by the user in the same initialization file in the format of time histories of longitudinal stick/column, lateral stick/wheel, and pedal force. The output of each offline simulation is organized in MATLAB structures with time and is saved in a simulation file for post-processing. A real-time version of the same model runs in the fixed-base simulator used for the manned evaluations. The subsystems that compose the aircraft model are described in detail in the following sections.

A.2 AIRFRAME MODEL

The subsystem AIRCRAFT contains the bare aircraft nonlinear aerodynamic and mass properties model and six degrees of freedom equations of motion subsystems.

The aircraft model characteristics (aerodynamic derivatives, mass properties, flight conditions) are derived from those of a twin-aisle medium-size transport aircraft. The aircraft's main characteristics are:

- Maneuvering equivalent airspeed is V_{EA} = 207.5 kts, corresponding to KCAS = 234.0 at Hp = 38 kft.
- Cruise Mach number is $Mach_{CR}$ = 0.875 at Hp = 38 kft.
- Cruise equivalent airspeed is V_{EC} = 261.7 kts, corresponding to KCAS = 280.6 at Hp = 38 kft.

Equations of motion are solved in the body axes system. The kinematic is nonlinear and coupling exists between the two planes of the aircraft dynamics. The coefficients of aerodynamic moments are reduced to the moment reference point (mrp) mrp = [25, 0, 0] $(\%\bar{c})$ and transposed to the current CG within the 6 degrees of freedom model.

Different values of the body axes moments of inertia are used for PA and up-and-away configurations. It is considered adequate approximation for the scopes of the simulations/analysis that the aircraft moments of inertia do not vary as a function of CG position.

The lift coefficient versus angle of attack (AoA, alpha, α) $C_L(\alpha)$ is nonlinear. No compressibility effect is modeled in the aerodynamics data and the $C_L(\alpha)$ relationships are notional, considered representative of this class of aircraft (figure A-1).

Aerodynamic drag is calculated according to the standard quadratic polar. The value of C_{D_0} for the up-and-away, Hp = 38 kft flight conditions has been increased from the baseline value in order to have a significant airspeed margin with respect to the minimum of the required thrust versus airspeed curve $(T_n(V))$. This allows for positive speed stability throughout the testing envelope. The value of the coefficient of induced drag (K_i) of the quadratic polar is representative of an aircraft of this class. Figure A-2 represents the drag polars of both aircraft configurations.

Linear extrapolation of the aerodynamic data is allowed for simulations beyond the current limits of the aerodynamic model. The scope of a simplified model is to minimize the requirement for gain scheduling and maintain the results within an adequate degree of generalization. All evaluations are carried out without configuration transition. This is also consistent with the approach followed by the FAA for the development of different aircraft models.

A range of longitudinal SM of the bare aircraft is considered. Table A-1 reports the *x* CG location, in construction axes reference, as a function of bare aircraft SM and the respective configuration code. The range of bare airframe SM is aimed at requiring different demands on the augmentation system. For a more detailed and complete description of SM, see [4].

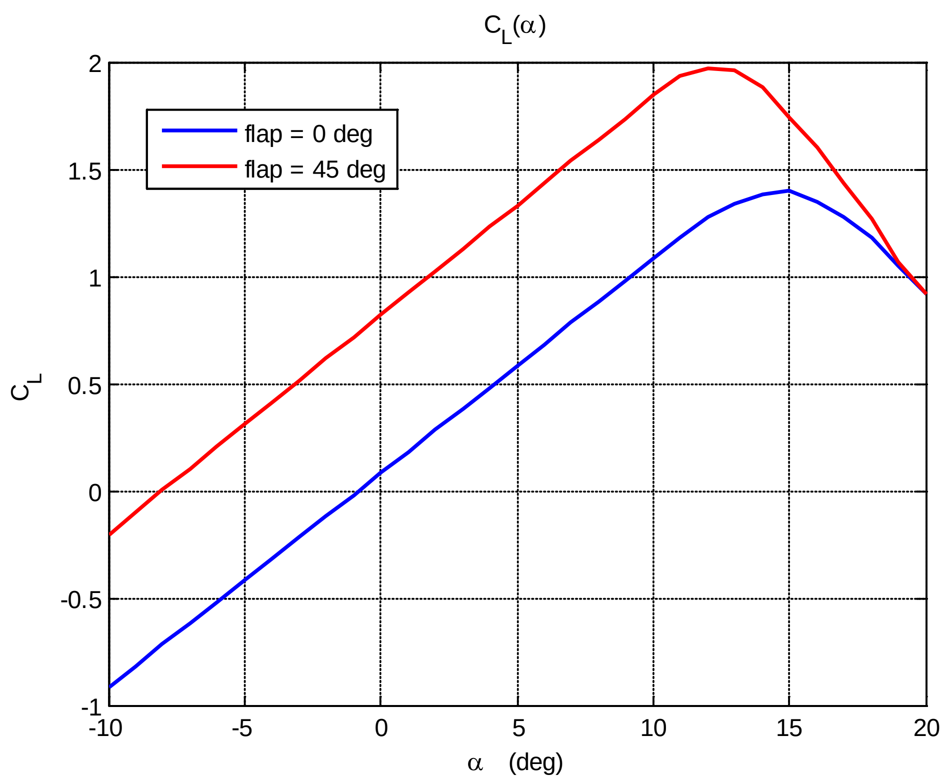

Figure A-1. Basic CL as a function of alpha, for flap = 0 and flap = 45 degrees

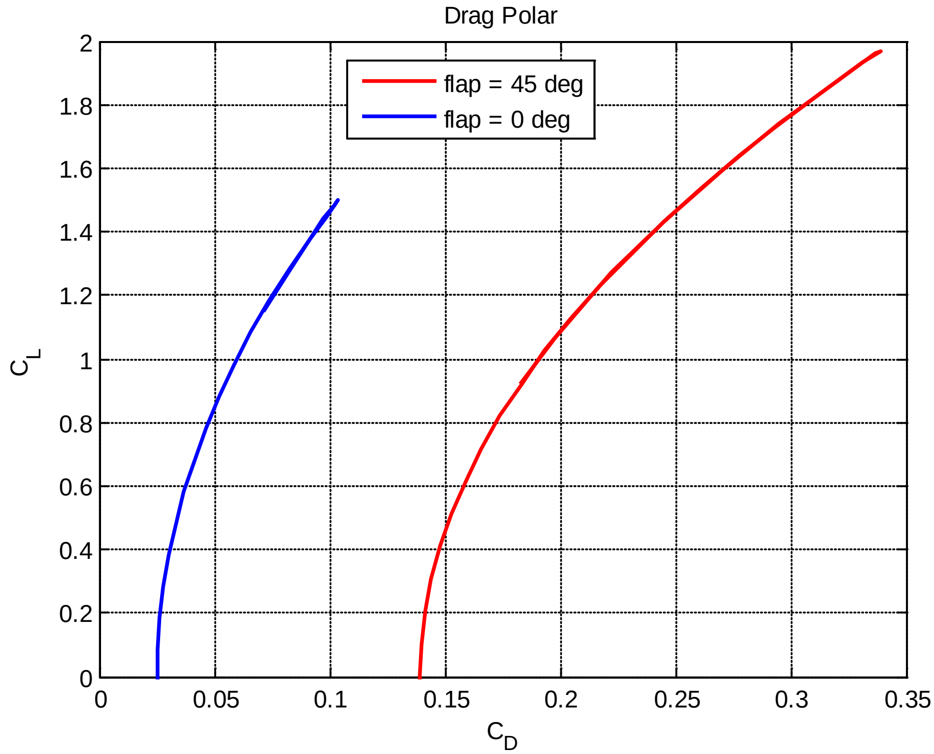

Figure A-2. Drag polar, for flap = 0 and flap = 45 degrees

Table A-1. Aircraft longitudinal SM and X CG locations

Configuration Code	Bare Aircraft SM (% $\bar{c}$)	X CG (% $\bar{c}$) Hp = 38 kft Flap = 0 deg	X CG (% $\bar{c}$) Hp = 0 kft Flap = 45 deg
Cfg 1	5	35	23.2
Cfg 2	2.5	37.5	25.7
Cfg 3	0	40	28.2

The simulation's initial conditions are contained in the trim files, which are loaded before launching the simulations. Each file contains the file name identifier and the MATLAB data structure "acfbw," with the aircraft configuration and flight conditions reference data. Tables A-2 through A-4 report the values of the parameters contained in the structure "acfbw" in the three flight conditions. Multiple values in the same cell correspond to different *x* CG configurations — cfg 1 to cfg 3, from top to bottom. The values indicated as "hardwired" are constant.

The internal structure of the subsystem AIRCRAFT is displayed in figure A-3; the aerodynamic model is contained in the Simulink block with the light-blue background.

Table A-2. Parameters of the trim initialization MATLAB structure “acfbw” for PA flight condition/configuration

Structure fieldname	Default Value	Units	Definition	Type
mass.ZFW	300000	lbs	Aircraft Zero Fuel Weight	
mass.w_fuel	0	lbs	Fuel Weight	
mass.weight	300000	lbs	Aircraft Weight	
mass.Ixx	3.5196e+006	$slug \cdot ft^2$	Moment of Inertia About *x* Body Axis	
mass.Iyy	12500000	$slug \cdot ft^2$	Moment of Inertia About *y* Body Axis	
mass.Izz	1.5680e+007	$slug \cdot ft^2$	Moment of Inertia About *z* Body Axis	
mass.Ixz	4.8921e+005	$slug \cdot ft^2$	*xz* Product of Inertia	
mass.cg_ref	0.232 0.257 0.282	$\bar{c}$	CG Position	User-defined (depending on loaded trim file)
mass.neu_pt	0.282	$\bar{c}$	Neutral Point Position	Hardwired
mass.mrp:	0.2500	$\bar{c}$	Moment Reference Point	
geom.S	3460	ft^2	Wing Reference Surface Area	
geom.cbar	24	ft	Wing Mean Aerodynamic Chord	
geom.b	155	ft	Wing Span	
airdata.Vc	136.2700	kts	Calibrated Air Speed	
airdata.Ve	136.2700	kts	Equivalent Air Speed	
airdata.Vt	230	ft/s	True Airspeed	
airdata.h	0	ft	Pressure Altitude	
airdata.Pstat	2.1162e+003	psf	Static Pressure	
airdata.rho	0.0024	$slug/ft^3$	Air Density	
airdata.Ta	288.1000	°K	Outer Air Temperature	
airdata.q_c	63.5300	psi	Impact Pressure	
airdata.qbar	62.8700	psi	Dynamic Pressure	
airdata.Mach	0.2060	a	Mach Number	
attitude.theta	5.7048 5.5675 5.4302	deg	Pitch Attitude	
attitude.phi	0	deg	Roll Angle	

Table A-2. Parameters of the trim initialization MATLAB structure "acfbw" for PA flight condition/configuration (continued)

Structure fieldname	Default Value	Units	Definition	Type
attitude.alpha	5.7048 5.5675 5.4302	deg	Angle of Attack	
attitude.beta	0	deg	Angle of Sideslip	
attitude.gamma	0	deg	Flight Path Angle	
attitude.nx	0.0994 0.0970 0.0946	g	Axial Load Factor (Body Axes)	
attitude.nz	-0.9950 -0.9953 -0.9955	g	Normal Load Factor (Body Axes)	
control.de	0	deg	Elevator Deflection	
control.da	0	deg	Aileron Deflection	
control.dr	0	deg	Rudder Deflection	
control.dx	51143 51148 51153	lbs	Thrust Required	
control.ds	-8.8286 -6.2110 -3.5922	deg	Horizontal Stabilizer Deflection	
control.dsp	0	deg	Spoiler Deflection	
control.df	45	deg	TE Flap deflection	
control.gear	down	–	Landing Gear Status	

Table A-3. Parameters of the trim initialization MATLAB structure "acfbw" for V^A flight condition/configuration

Structure fieldname	Default Value	Units	Definition	Type
mass. ZFW	300000	lbs	Aircraft Zero Fuel Weight	
mass.w_fuel	0	lbs	Fuel Weight	
mass.Ixx	3.5196e+006	$slug \cdot ft^2$	Moment of Inertia about *x* Body Axis	
mass.Iyy	12500000	$slug \cdot ft^2$	Moment of Inertia about *y* Body Axis	
mass.Izz	1.5680e+007	$slug \cdot ft^2$	Moment of Inertia about *z* Body Axis	
mass.Ixz	4.8921e+005	$slug \cdot ft^2$	*xz* Product of Inertia	
mass.cg_ref	0.3500 0.3750 0.4000	$\bar{c}$	CG Position	User-defined (depending on loaded trim file)
mass.neu_pt	0.4000	$\bar{c}$	Neutral Point Position	Hardwired
geom.S	3460	ft^2	Wing Reference Surface Area	
geom.cbar	24	ft	Wing Mean Aerodynamic Chord	
geom.b	155	ft	Wing Span	
airdata.Vc	234.0	kts	Calibrated Air Speed	
airdata.Ve	221.3	kts	Equivalent Air Speed	
airdata.Vt	716.4	ft/s	True Airspeed	
airdata.h	38000	ft	Pressure Altitude	
airdata.Pstat	431.1460	psf	Static Pressure	
airdata.rho	$6.46 \cdot 10^{-4}$	$slug/ft^3$	Air Density	
airdata.Ta	216.66	°K	Outer Air Temperature	
airdata.q_c	199.778	psi	Impact Pressure	
airdata.qbar	165.773	psi	Dynamic Pressure	
airdata.Mach	0.74	a	Mach Number	
attitude.theta	4.5941 4.5269 4.4597	deg	Pitch Attitude	
attitude.phi	0	deg	Roll Angle	

Table A-3. Parameters of the trim initialization MATLAB structure "acfbw" for V^A flight condition/configuration (continued)

Structure fieldname	Default Value	Units	Definition	Type
attitude.alpha	4.5941 4.5269 4.4597	deg	Angle of Attack	
attitude.beta	0	deg	Angle of Sideslip	
attitude.gamma	0	deg	Flight Path Angle	
attitude.nx	0.08010 0.07809 0.07780	g	Axial Load Factor (body axes)	
attitude.nz	-0.9968 -0.9969 -0.9970	g	Normal Load Factor (body axes)	
control.de	0	deg	Elevator Deflection	
control.da	0	deg	Aileron Deflection	
control.dr	0	deg	Rudder Deflection	
control.dx	19961 19960 19959	lbs	Thrust Required	
control.ds	-1.1980 -0.9152 -0.6323	deg	Horizontal Stabilizer Deflection	
control.dsp	0	deg	Spoiler Deflection	
control.df	0	deg	TE Flap deflection	
control.gear	up	–	Landing Gear Status	

Table A-4. Parameters of the trim initialization MATLAB structure "acfbw" for V^C flight condition/configuration

Structure Fieldname	Default Value	Units	Definition	Type
mass. ZFW	300000	lbs	Aircraft Zero Fuel Weight	
mass.w_fuel	0	lbs	Fuel Weight	
mass.Ixx	3.5196e+006	$\text{slug} \cdot \text{ft}^2$	Moment of Inertia About *x* Body Axis	
mass.Iyy	12500000	$\text{slug} \cdot \text{ft}^2$	Moment of Inertia About *y* Body Axis	
mass.Izz	1.5680e+007	$\text{slug} \cdot \text{ft}^2$	Moment of Inertia About *z* Body Axis	
mass.Ixz	4.8921e+005	$\text{slug} \cdot \text{ft}^2$	*xz* Product of Inertia	
mass.cg_ref	0.3500 0.3750 0.4000	$\bar{c}$	CG Position	User-defined (depending on loaded trim file)
mass.neu_pt	0.4000	$\bar{c}$	Neutral Point Position	Hardwired
geom.S	3460	ft^2	Wing Reference Surface Area	
geom.cbar	24	ft	Wing Mean Aerodynamic Chord	
geom.b	155	ft	Wing Span	
airdata.Vc	280.6386	kts	Calibrated Airspeed	
airdata.Ve	261.7	kts	Equivalent Airspeed	
airdata.Vt	847.7	ft/s	True Airspeed	
airdata.h	38000	ft	Pressure Altitude	
airdata.Pstat	431.1460	psf	Static Pressure	
airdata.rho	$6.46 \cdot 10^{-4}$	slug/ft^3	Air Density	
airdata.Ta	216.66	°K	Outer Air Temperature	
airdata.q_c	278.7451	psi	Impact Pressure	
airdata.qbar	231.8615	psi	Dynamic Pressure	
airdata.Mach	0.875	a	Mach Number	
attitude.theta	3.0983 3.0501 3.0019	deg	Pitch Attitude	
attitude.phi	0	deg	Roll Angle	

Table A-4. Parameters of the trim initialization MATLAB structure “acfbw” for V^C flight condition/configuration (continued)

Structure Fieldname	Default Value	Units	Definition	Type
attitude.alpha	3.0983 3.0501 3.0019	deg	Angle of Attack	
attitude.beta	0	deg	Angle of Sideslip	
attitude.gamma	0	deg	Flight Path Angle	
attitude.nx	0.0540 0.0532 0.0524	g	Axial Load Factor (body axes)	
attitude.nz	-0.9985 -0.9986 -0.9986	g	Normal Load Factor (body axes)	
control.de	0	deg	Elevator Deflection	
control.da	0	deg	Aileron Deflection	
control.dr	0	deg	Rudder Deflection	
control.dx	24200 24200 24199	lbs	Thrust Required	
control.ds	-1.0376 -0.8350 -0.6323	deg	Horizontal Stabilizer Deflection	
control.dsp	0	deg	Spoiler Deflection	
control.df	0	deg	TE Flap deflection	
control.gear	up	–	Landing Gear Status	

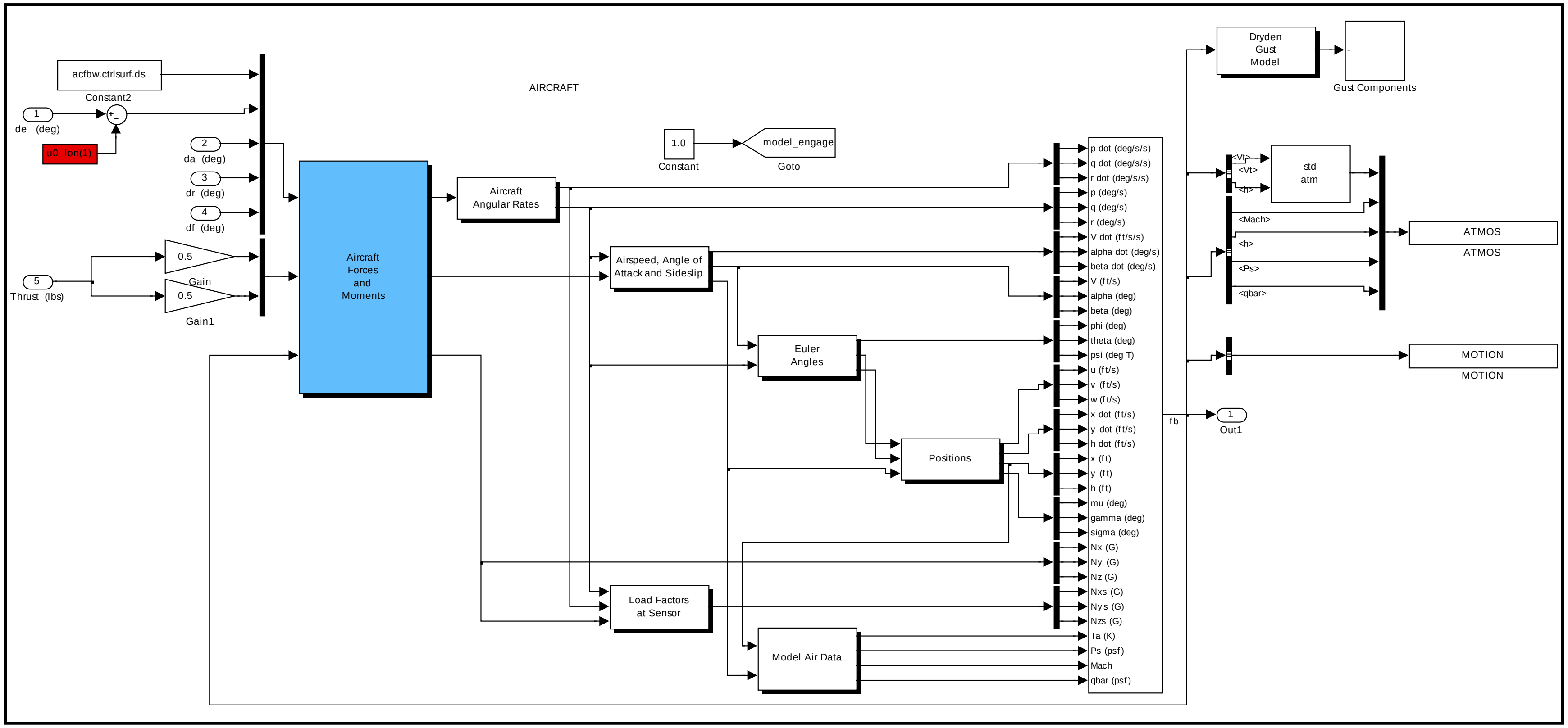

Figure A-3. Aircraft subsystem structure

Tables A-5 through A-7 report the inputs, states, and output signals, respectively, for the AIRCRAFT simulation subsystem.

Table A-5. Aircraft subsystem inputs

Input Name	Units	Description	From Subsystem
de	deg	Elevator deflection	ACTUATORS
da	deg	Aileron deflection	
dr	deg	Rudder deflection	
dthrustc	lbs	Commanded delta thrust	ENGINE
engage	boolean	System engage status	–

Table A-6. Aircraft subsystem states

Longitudinal		Lateral/Directional	
q	Pitch Rate	p	Roll Rate
alpha	Angle of Attack	r	Yaw Rate
V	True Airspeed	beta	Angle of Sideslip
theta	Pitch Attitude	phi	Roll Attitude
h	Altitude	psi	Yaw Attitude

Table A-7. Aircraft subsystem outputs

Output Name	Units	Description	To Subsystem
Vc_kts	kts	Calibrated Airspeed	
Mach	a	Mach Number	
q	deg/s	Pitch Rate	CLAWS
alpha	deg	Angle of Attack	CLAWS
Vt	ft/s	True Airspeed	
theta	deg	Pitch Attitude	PILOT
h	ft	Altitude	
q_dot	deg/s	Pitch Acceleration	
alpha_dot	deg/s	Angle of Attack Rate	
Vt_dot	$\mathrm{ft/s^2}$	True Airspeed Derivative with Time	
h_dot	$\mathrm{ft/s^2}$	Altitude Derivative with Time	
gamma	deg	Flight Path Angle	
nx	g	Axial Load Factor	
nz	g	Normal Load Factor	
p	deg/s	Roll Rate	
r	deg/s	Yaw Rate	CLAWS
beta	deg	Angle of Sideslip	PILOT
phi	deg	Roll Attitude	PILOT
psi	deg	Yaw Attitude	
p_dot	deg/s	Roll Acceleration	
r_dot	deg/s	Yaw Acceleration	
beta_dot	deg/s	Angle of Sideslip Rate	
sigma	deg	Flight Path Angle	
ny	g	Side Force Load Factor	

A.3 ACTUATORS MODEL

The ACTUATORS subsystem contains the simulation model of the three linear control surface hydraulic actuators. Each actuator is modeled by the same linear dynamic model of the position controlled servo. The bandwidth of the actuator alone is: $\omega_{act} = 75\ \frac{rad}{s}$.

Each system contains a second-order model of the surface dynamics with nonlinearities that computes surface positions from surface commands. Trim surface positions are then added to the output of the actuator model so that the aerodynamic model remains trimmed. The system-engage signal is used to reset the model integrators for use inside of the Learjet.

Each actuator model is second order with nonlinearities of the form shown in figure A-4. The parameters for each model are listed in table A-8. Each surface uses actuators with the same parameters. The model is essentially a linear second-order system with selectable natural frequency and damping ratios. Both integrators can be saturated to implement rate and position limits. The output of the system is passed through a time-delay block. Position limits were selected to be representative of the motion available on transport aircraft. The natural frequencies, damping ratios, and rate limits were selected to provide high performance so the actuator dynamics would not influence the pilot's ability to perform tasks. Average actuators usually have lower bandwidths and maximum rates; however, these values have been selected to discriminate between the impact on HQ of the programmed nonlinearities and the inherent aircraft hardware characteristics. Time delays of one computer cycle (200 Hz) were implemented to model the lag associated with digital control of the surface and prevent an algebraic loop within Simulink.

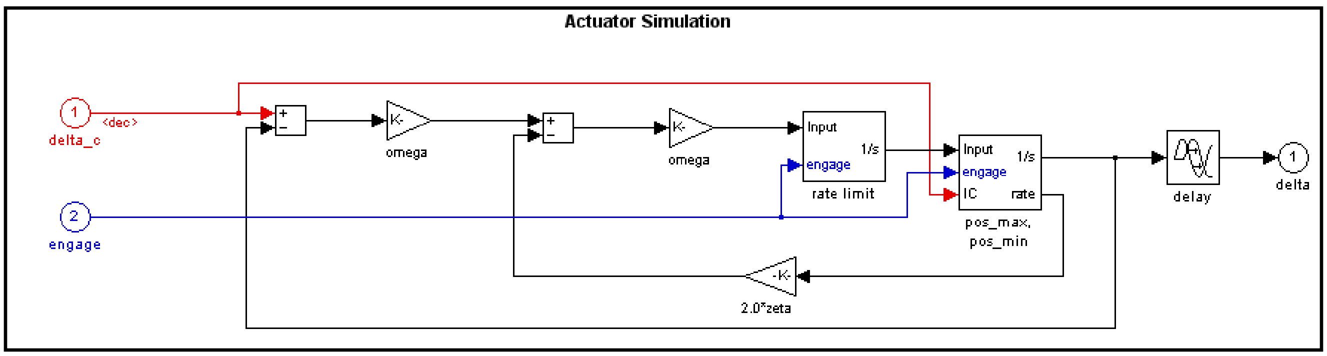

Figure A-4. Block diagram of second order actuator model

Table A-8. Actuator system initialized parameters

Parameter Name	Default Value	Units	Description	Type
de_wn	75	rad/s	Elevator Natural Frequency	Hardwired
de_zeta	0.7	–	Elevator Damping Ratio	
de_max	30	deg	Maximum Elevator Position	
de_min	-30	deg	Minimum Elevator Position	
de_rl	100	deg/s	Elevator Rate Limit	
de_delay	0.005 s	–	Elevator Time Delay	
da_wn	75	rad/s	Aileron Natural Frequency	
da_zeta	0.7	–	Aileron Damping Ratio	
da_max	30	deg	Maximum Aileron Position	
da_min	-30	deg	Minimum Aileron Position	
da_rl	100	deg/s	Aileron Rate Limit	
da_delay	0.005	s	Aileron Time Delay	
dr_wn	75	rad/s	Rudder Natural Frequency	
dr_zeta	0.7	–	Rudder Damping Ratio	
dr_max	30	deg	Maximum Rudder Position	
dr_min	-30	deg	Minimum Rudder Position	
dr_rl	100	deg/s	Rudder Rate Limit	
dr_delay	0.005	s	Rudder Time Delay	

A.4 CONTROL LAWS MODEL

The model contains three different subsystems, collectively named control laws (CLAWS), containing the CLAWS simulation model. Each of the systems corresponds to a different envelope protection level: no protection, soft protection, and hard protection. The no protection subsystem is considered for the Year 2 Follow-on evaluations. This section describes the simulation system dedicated to stability augmentation.

Software rate-limiting of the actuator command is available in this simulation subsystem for each commanded control surface deflection. The corresponding rate-limit values can be set in the model initialization file by the user for each surface independently. The block diagrams of figures 18 and 19 illustrate, respectively, the longitudinal and lateral/directional CLAWS conceptual feedback structure.

Table A-9 reports the names, default values, and description of the initialized parameters as contained in the initialization file. The CLAWS system is defined by the values indicated as hardwired, which remain unchanged throughout all offline and manned simulations.

The full deflection values in both directions of all three control inceptors are reported in table A-10.

Table A-9. Claws subsystem initialized parameters

Parameter Name	Parameter Symbol	Default Value PA	V_A	V_C	Units	Description	Type
dec_per_des	$K_{\delta e_c\_\delta_{es}}$	−1.00	-1.4		deg/deg	Elevator command gain	Hardwired
dac_per_daw	$K_{\delta a_c\_\delta_{aw}}$	−3.0			deg/deg	Aileron command gain	
drc_per_drp	$K_{\delta r_c\_\delta_p}$	−15.0			deg/in	Rudder command gain	
alpha_fdbk_gain	K_α	0.67	1.15		deg/deg	AoA feedback gain	
q_fdbk_gain	$K_{\dot\theta}$	1	0.82		deg/deg/s	Pitch attitude rate feedback gain	
vt_fdbk_gain	K_{Vt_P}	1.5	0.5		deg/(ft/s)	Proportional TAS error feedback gain	
vt_fdbk_gain_int	K_{Vt_I}	0	0.005		deg/ft	Integral TAS error feedback gain	
r_fdbk_gain	K_r	0	0.8		deg/deg/s	Yaw rate feedback gain	
K_ARI	K_{ARI}	0.4	0.2*	0.1*	deg/deg	ARI gain	
rate_lim_dec	–	40			deg/s	Commanded elevator rate limit	
rate_lim_dac	–	60			deg/s	Commanded aileron rate limit	
rate_lim_drc	–	60			deg/s	Commanded rudder rate limit	

* Values at intermediate flight conditions are calculated with linear interpolation.

Table A-10. Feel_system subsystem initialized parameters

Parameter Name	Default Value	Units	Description	Type
des_wn	17.5	rad/s	Column Natural Frequency	User's defined
des_zeta	0.7	–	Column Damping Ratio	
des_breakpoint	10	deg	Column Gradient Breakpoint	
des_grad1	1.0	lb/deg	First Segment Column Gradient	
des_grad2	1.0	lb/deg	Second Segment Column Gradient	
des_preload	0.25	lb	Column Preload	
des_pgrad	100	lb/deg	Column Preload Gradient	
des_friction	0	lb	Column Friction	
des_max	10	deg	Column Aft Stop	
des_min	-10	deg	Column Forward Stop	
daw_wn	15	rad/s	Wheel Natural Frequency	
daw_zeta	0.7	–	Wheel Damping Ratio	
daw_grad	0.6	lb/deg	Wheel Gradient	
daw_preload	0.25	lb	Wheel Preload	
daw_pgrad	100	lb/deg	Wheel Preload Gradient	
daw_friction	0	lb	Wheel Friction	
daw_max	10	deg	Wheel Right Stop	
daw_min	-10	deg	Wheel Left Stop	
drp_wn	16	rad/s	Pedal Natural Frequency	
drp_zeta	0.7	–	Pedal Damping Ratio	
drp_grad	40	lb/in	Pedal Gradient	
drp_preload	5	lb	Pedal Preload	
drp_pgrad	200	lb/in	Pedal Preload Gradient	
drp_friction	0		Pedal Friction	
drp_max	2	in	Right Pedal Stop	
drp_min	-2	in	Left Pedal Stop	

A.5 FEEL SYSTEM

The FEEL_SYSTEM subsystem contains models of the dynamics of the side-stick and pedals. Each inceptor's model is second order with nonlinearities of the form shown in figure A-5. The inceptor positions are computed as a function of the applied pilot force and the feel system parameters listed in table A-10. Each second-order model contains a selectable natural frequency and damping ratio. The hard-stop compensators force the rate and acceleration signals to zero when the position stops are encountered, preventing the inceptor from moving past the limit while allowing the inceptor to be moved back toward the center position. A linear spring gradient is used for the longitudinal and lateral side-stick spring and pedals. The longitudinal side-stick gradient is shown in figure 38 of the main report. The lateral side-stick gradient is pictured in figure 39 of the main report.

The preload force is used to provide additional centering of the inceptors when close to the center position. Preload is implemented as a spring with a steep but finite gradient and a maximum output force corresponding to the preload value. Static and dynamic friction forces are optionally available. The static friction force will prevent motion of the inceptor until the pilot applies enough force to overcome the friction force. The dynamic friction force is a constant magnitude force that opposes the direction of inceptor motion whenever the inceptor has a perceptible velocity.

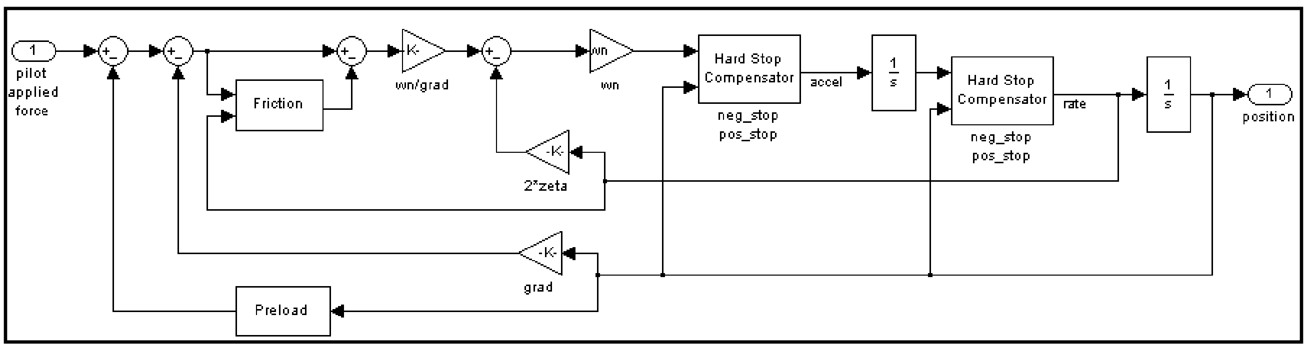

Figure A-5. Block diagram of second-order feel model

A.6 ENGINE MODEL

The aircraft is provided with an auto-throttle system. In order for the level of fidelity of the system to be consistent with the scope of the simulations, a simplified engine model was developed. It is contained in the subsystem ENGINE.

It is assumed that:

1. The aircraft maximum thrust is:

$$\mathrm{T}_{\mathrm{max}_{\mathrm{MSL}}} = 122{,}000 \text{ (lbs) at MSL} \tag{A-1}$$

$$\mathrm{T}_{\mathrm{max}_{38\ \mathrm{kft}}} = 0.6 \cdot \mathrm{T}_{\mathrm{max}_{\mathrm{MSL}}} = 73{,}200 \text{ (lbs) at Hp = 38 kft} \tag{A-2}$$

2. The average spool time constant of the engines is:

$$\mathrm{T}_{\mathrm{es}} = 2 \text{ (s)} \tag{A-3}$$

3. The TLA variation from approach thrust setting to maximum thrust is:

$$\Delta TLA_{MSL} = 60 \text{ (deg) at MSL} \tag{A-4}$$

$$\Delta TLA_{38kft} = 50 \text{ (deg) at Hp = 38 kft} \tag{A-5}$$

4. The dynamic of the engine is that of a first order lag.

5. The throttle servo dynamic is neglected.

The collective TLA to engine thrust gain K_{TLA} is calculated taking into account the thrust required at trim.

$$K_{TLA} = \frac{T_{\max} - T_{trim}}{\Delta TLA} \tag{A-6}$$

The final combined throttle and engine transfer function is:

$$\frac{\delta_T}{\delta_{TLA}} = K_{TLA} \cdot \frac{1/T_{es}}{(s+1/T_{es})} = K_{TLA} \cdot \frac{0.2}{s+0.2} \tag{A-7}$$

The simulation model is formed by a single Simulink transfer function block. The diagram is intentionally omitted.

APPENDIX B — CALSPAN/STI AIRCRAFT RESPONSE TIME HISTORIES

B.1 UNAUGMENTED AIRCRAFT

Figures B-1 through B-21 contain the time histories of the unaugmented aircraft response to longitudinal and lateral pilots' inputs. These figures complement the information provided in previous sections.

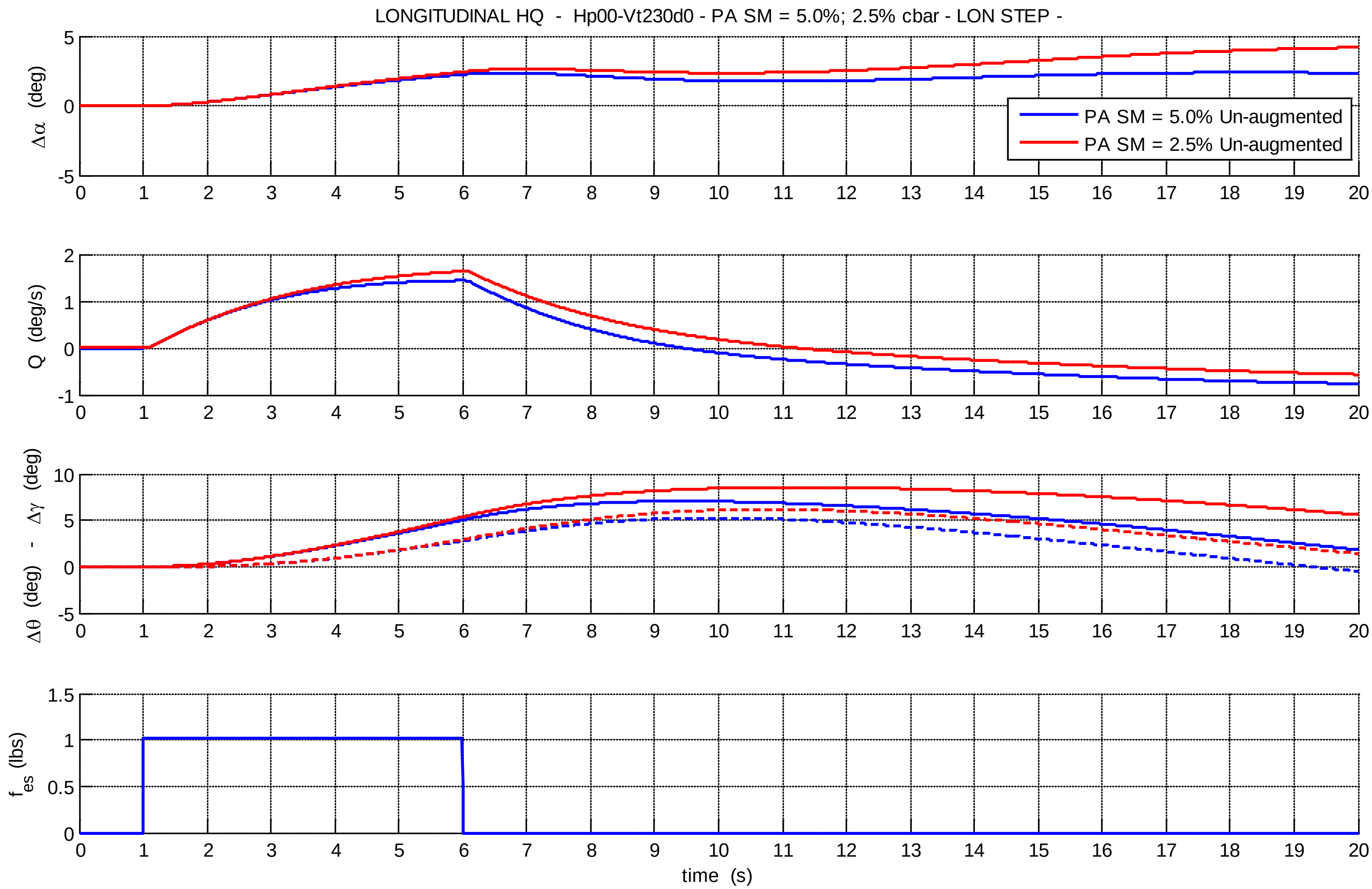

Figure B-1. PA SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history

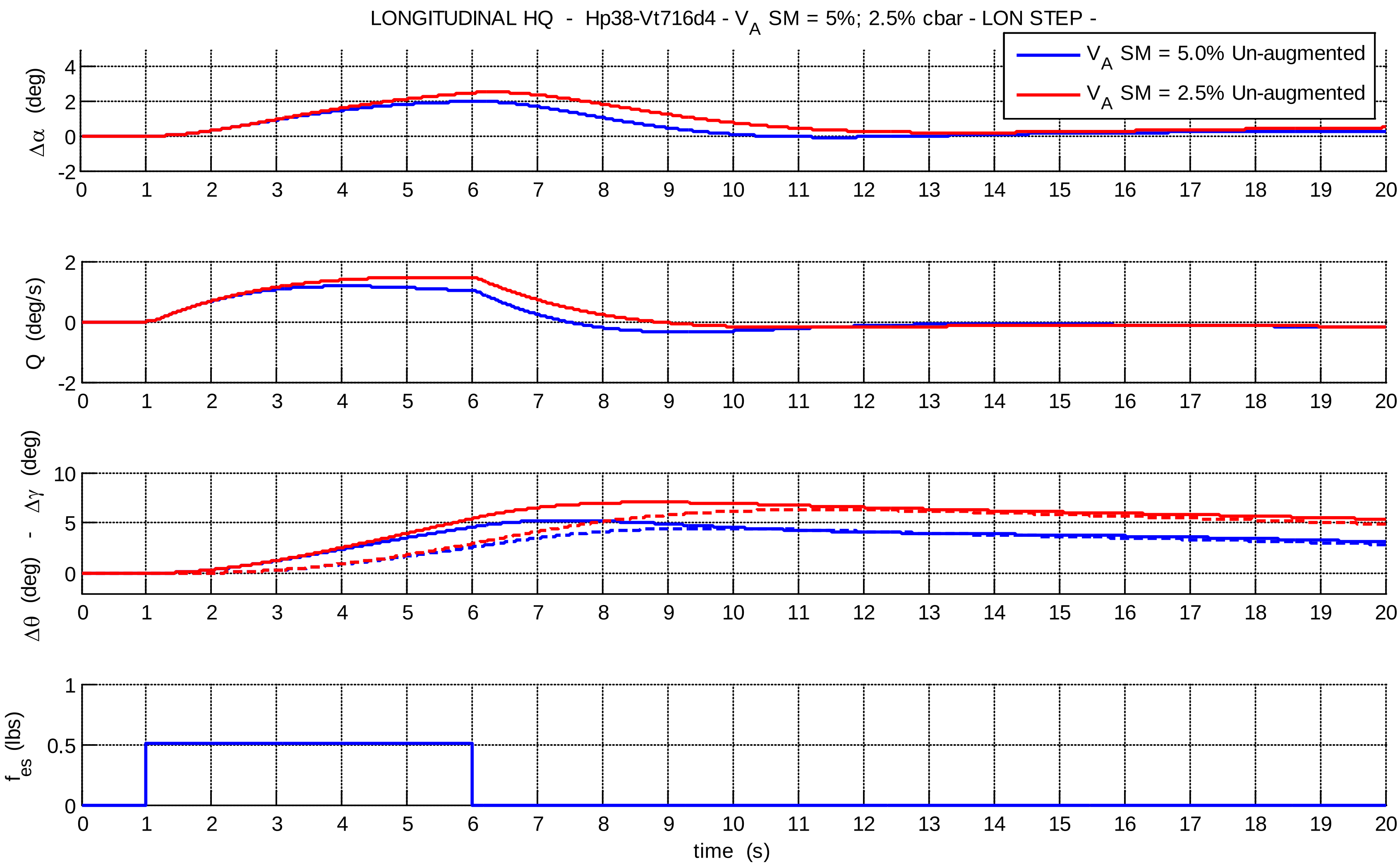

Figure B-2. VA SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history

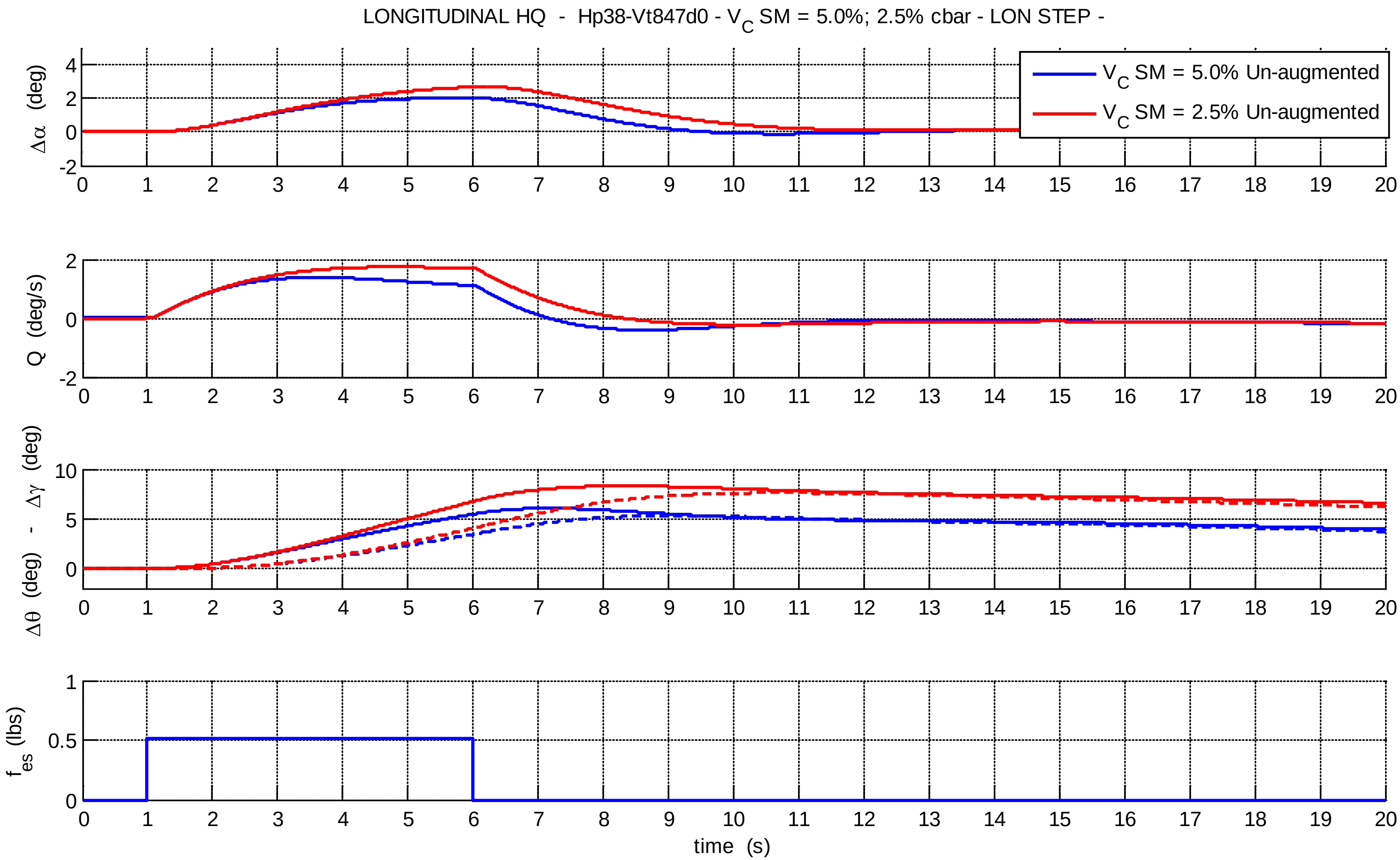

Figure B-3. VC SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history

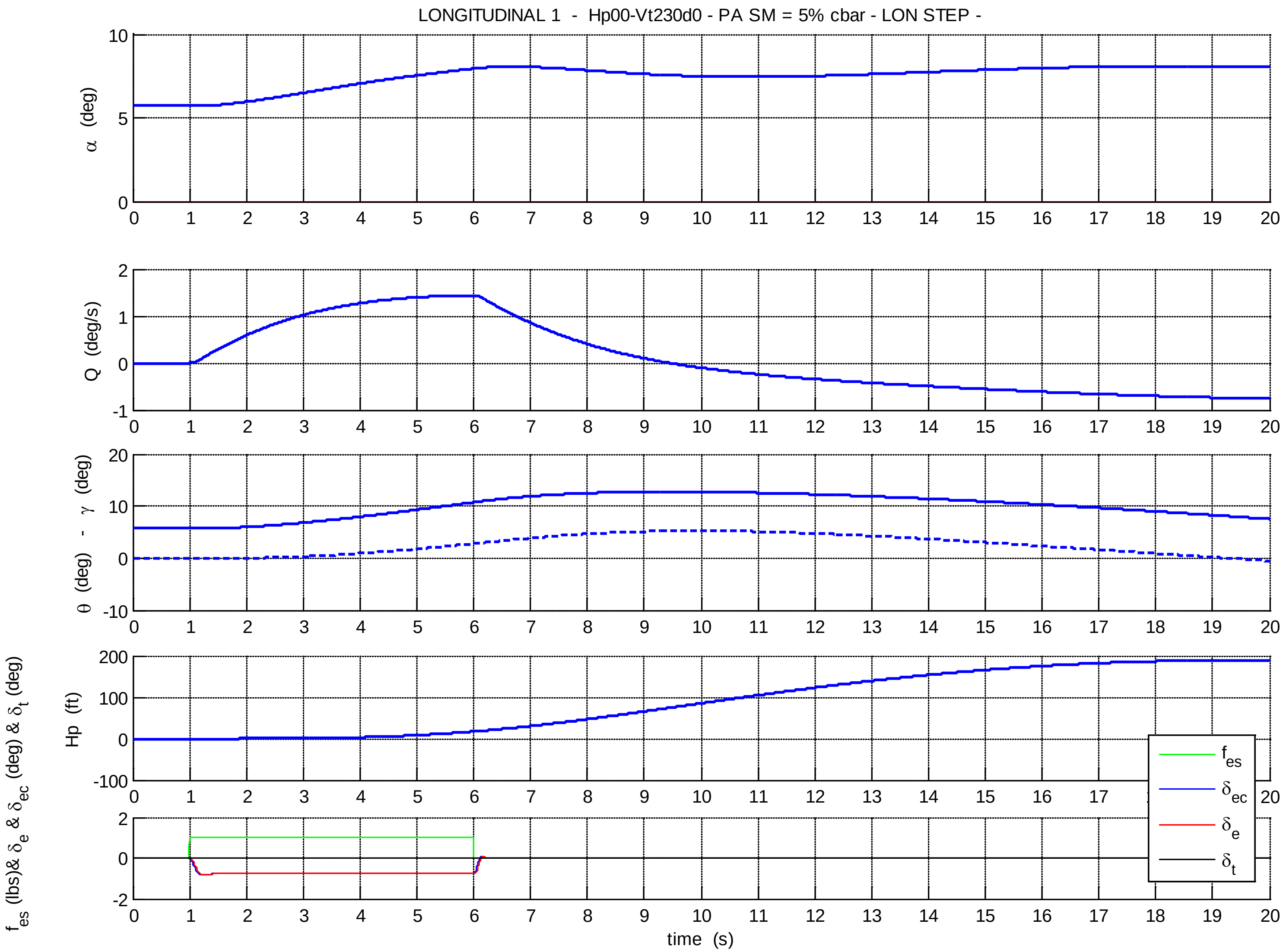

Figure B-4. PA SM = 5% — longitudinal step input unaugmented response time history 1 of 2

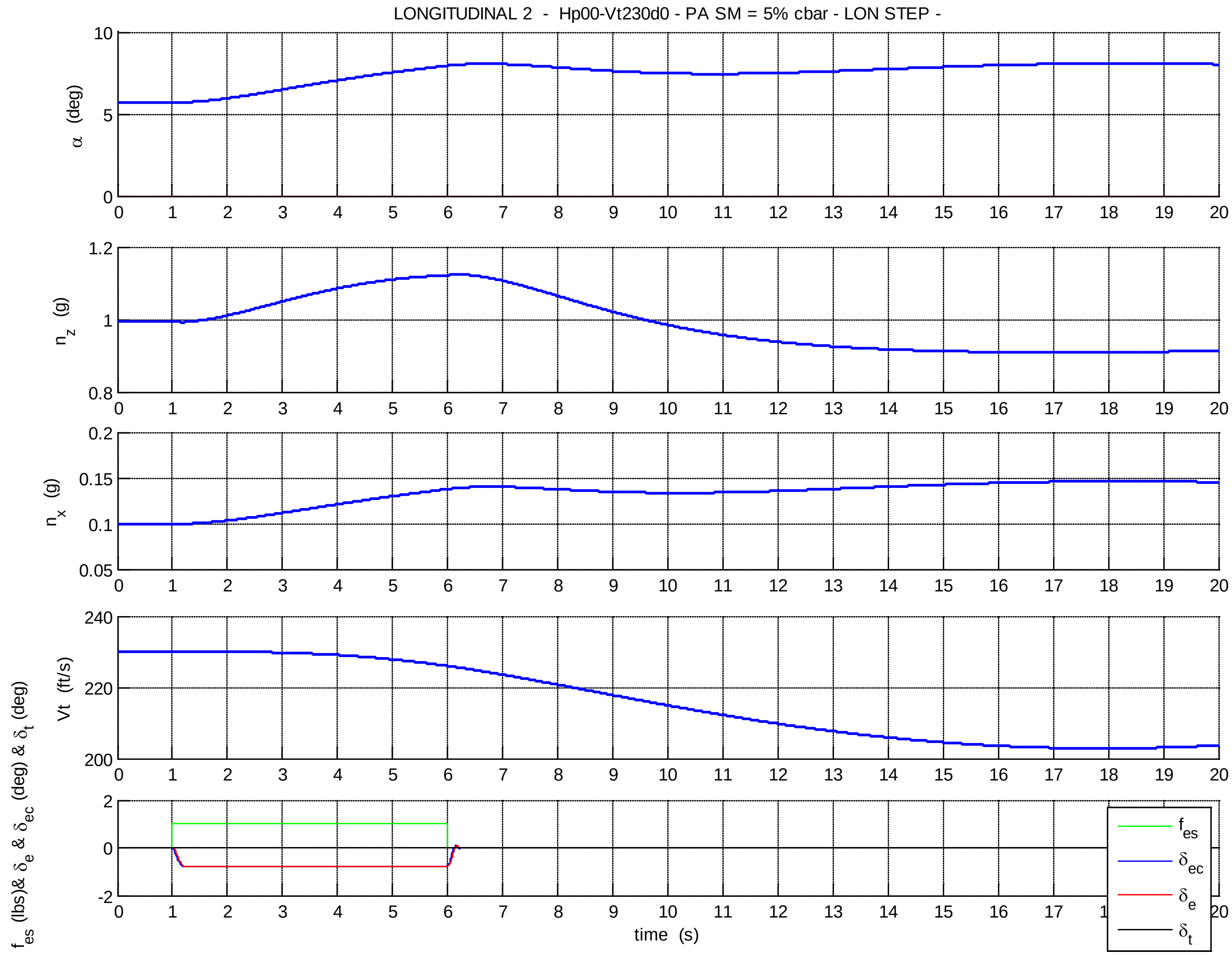

Figure B-5. PA SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history 2 of 2

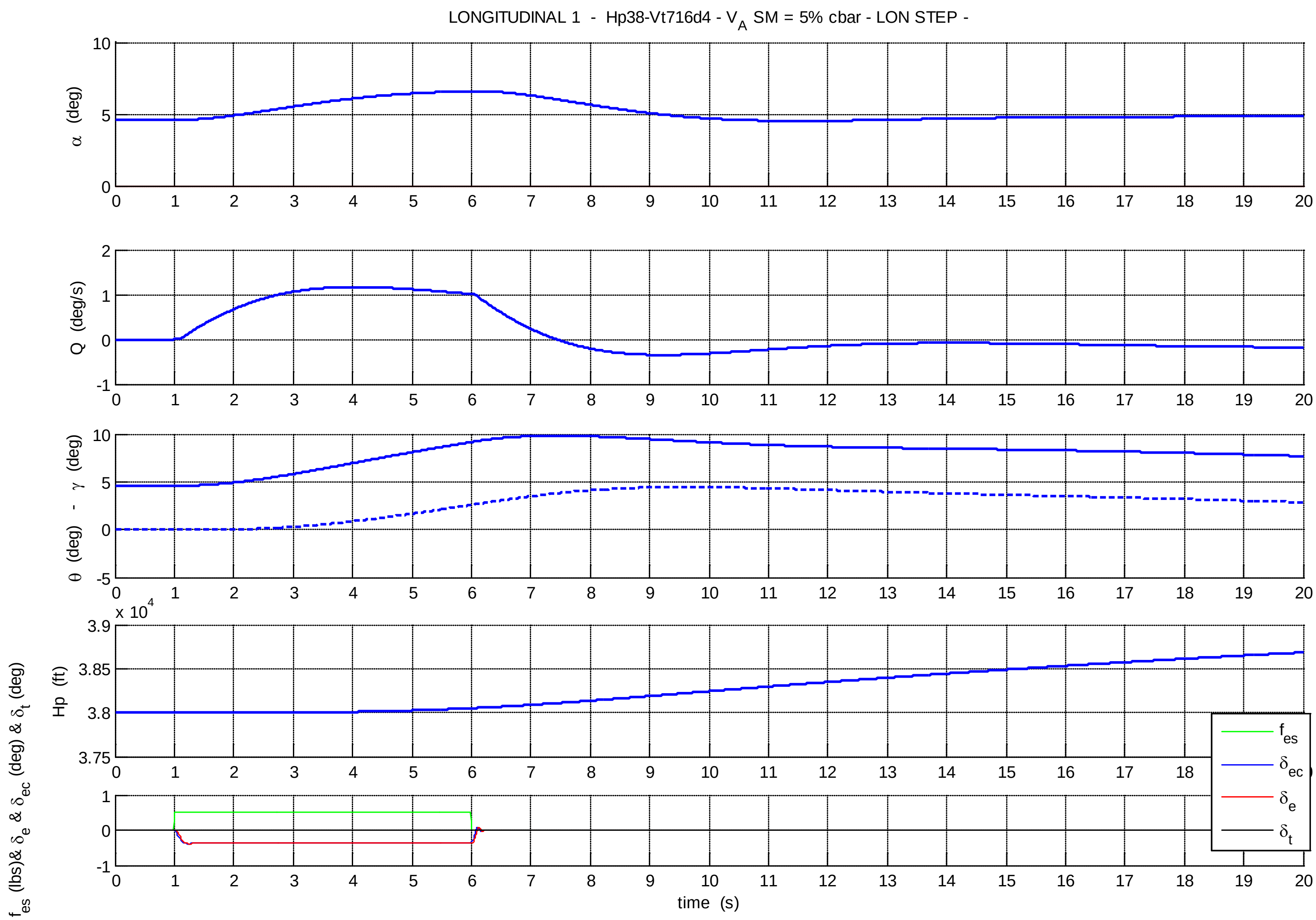

Figure B-6. VA SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history 1 of 2

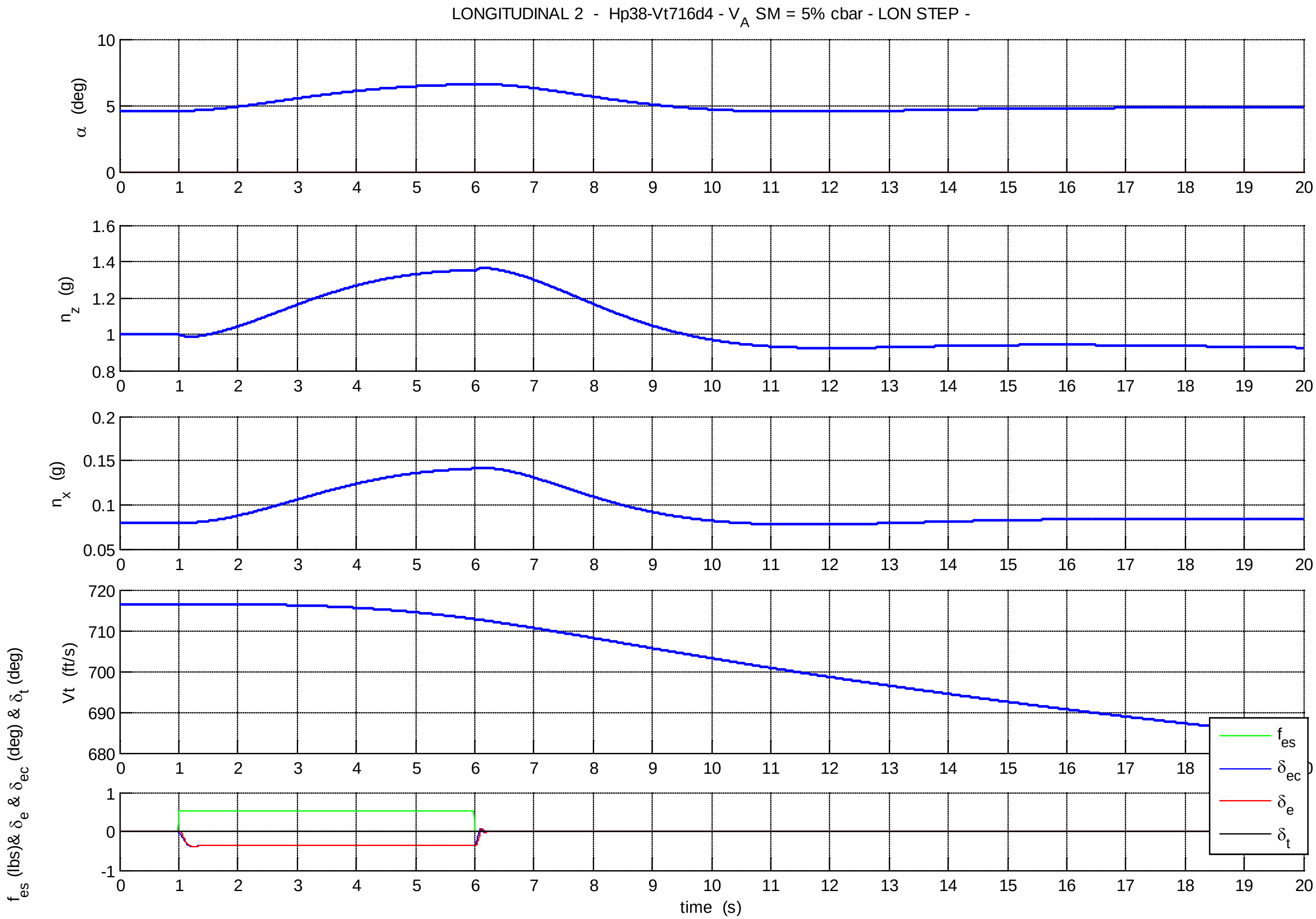

Figure B-7. VA SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history 2 of 2

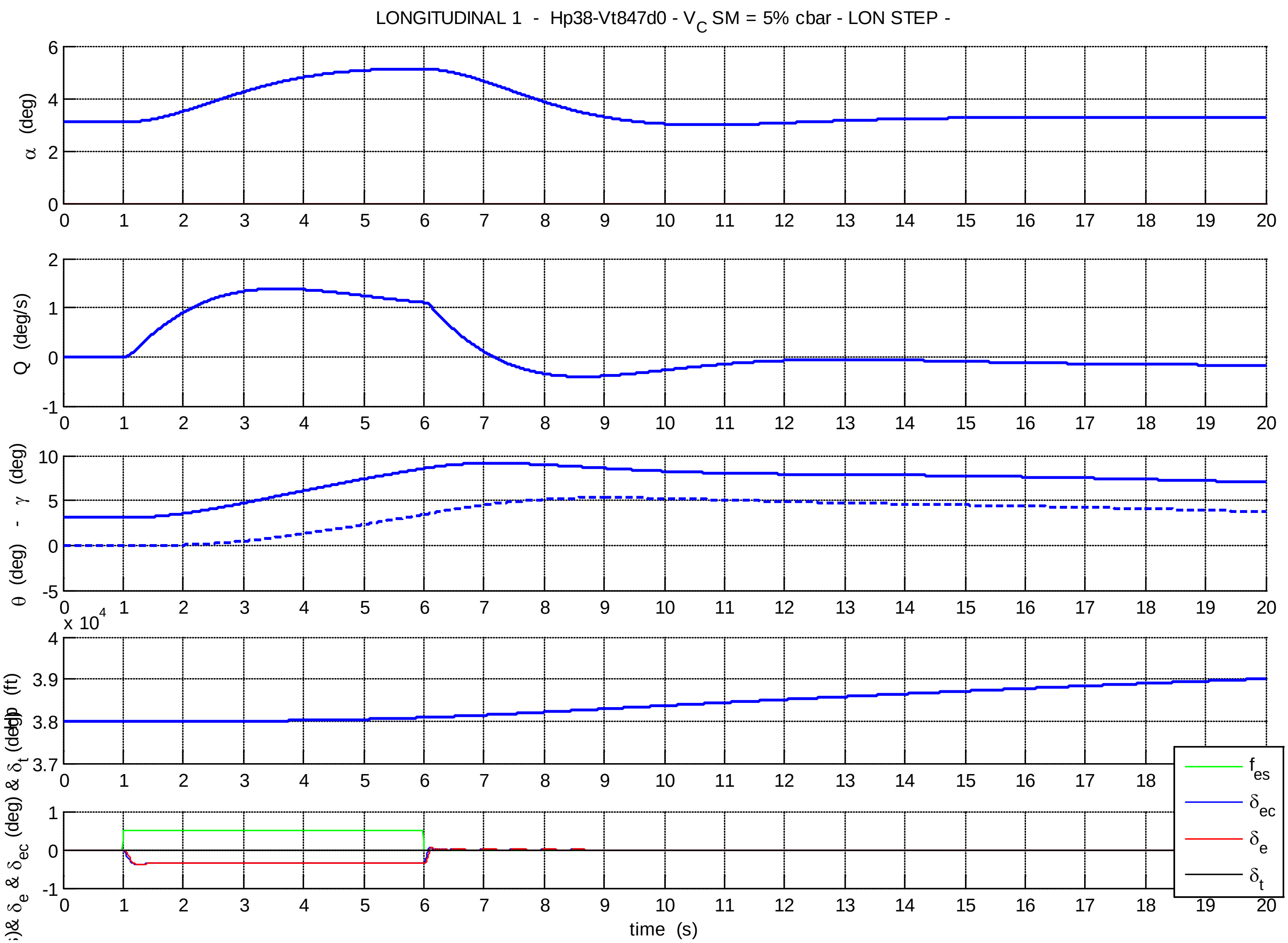

Figure B-8. VC SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history 1 of 2

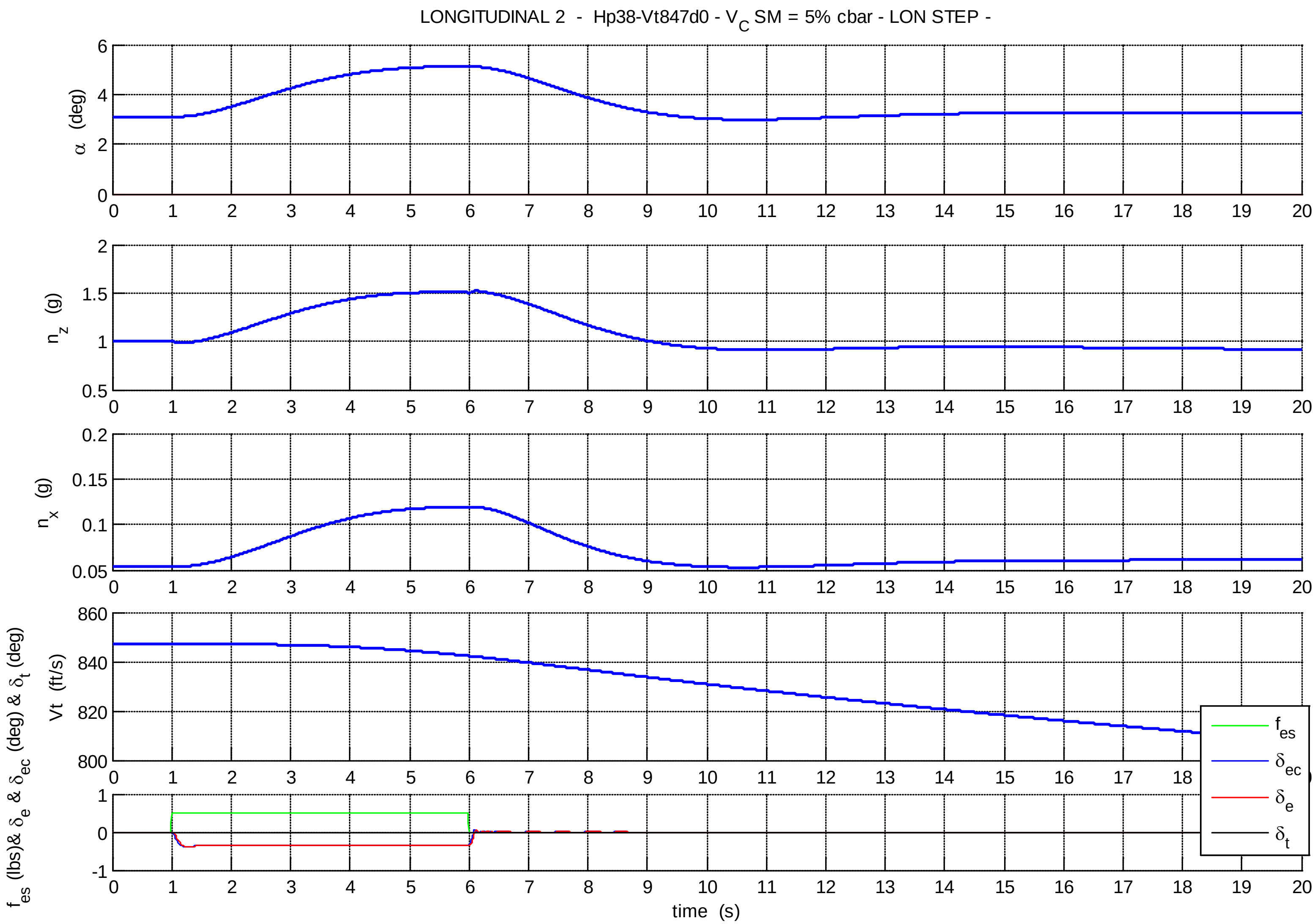

Figure B-9. VC SM = 5% $\bar{c}$ — longitudinal step input unaugmented response time history 2 of 2

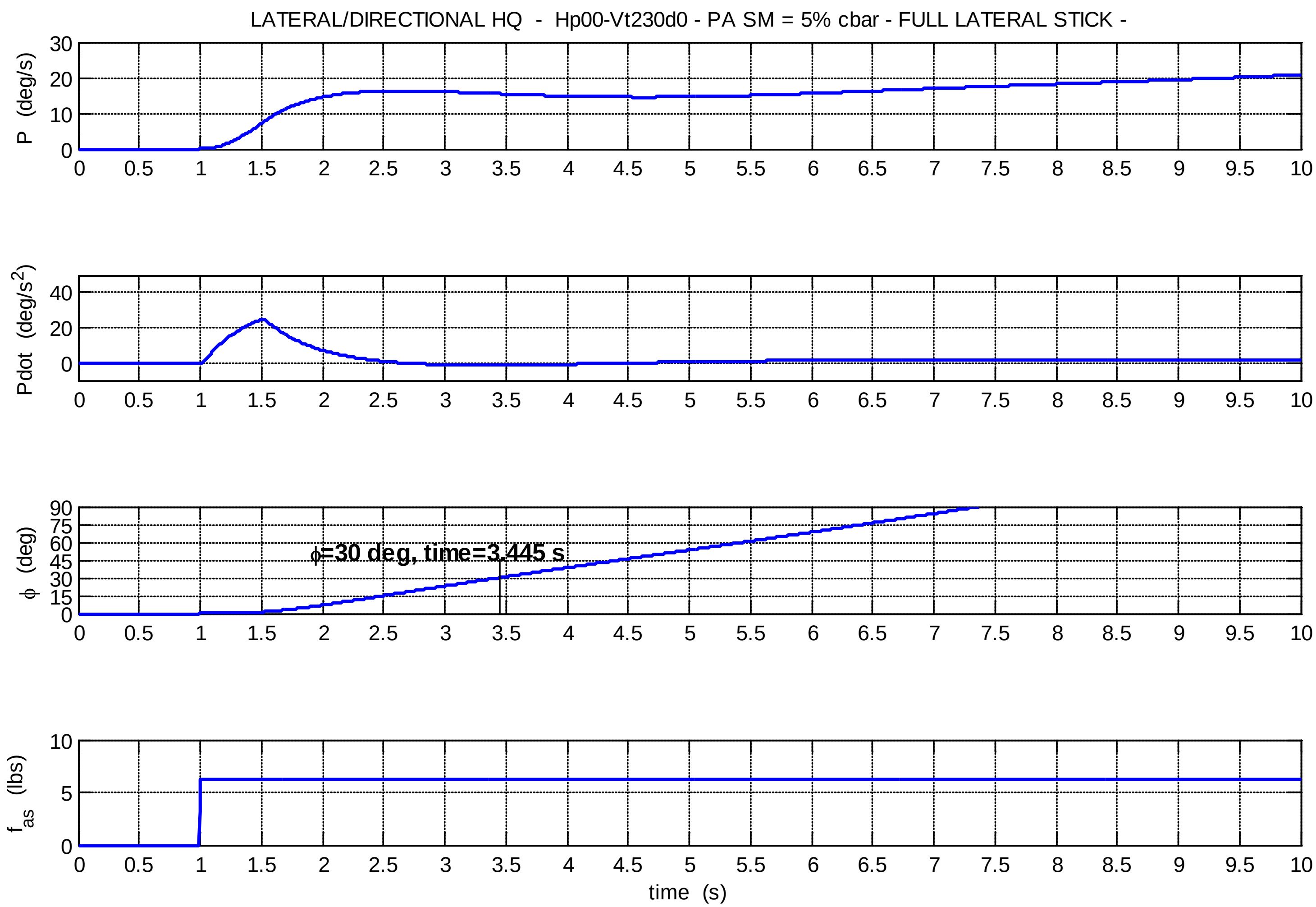

Figure B-10. PA SM = 5% $\bar{c}$ — full lateral stick input unaugmented response time history

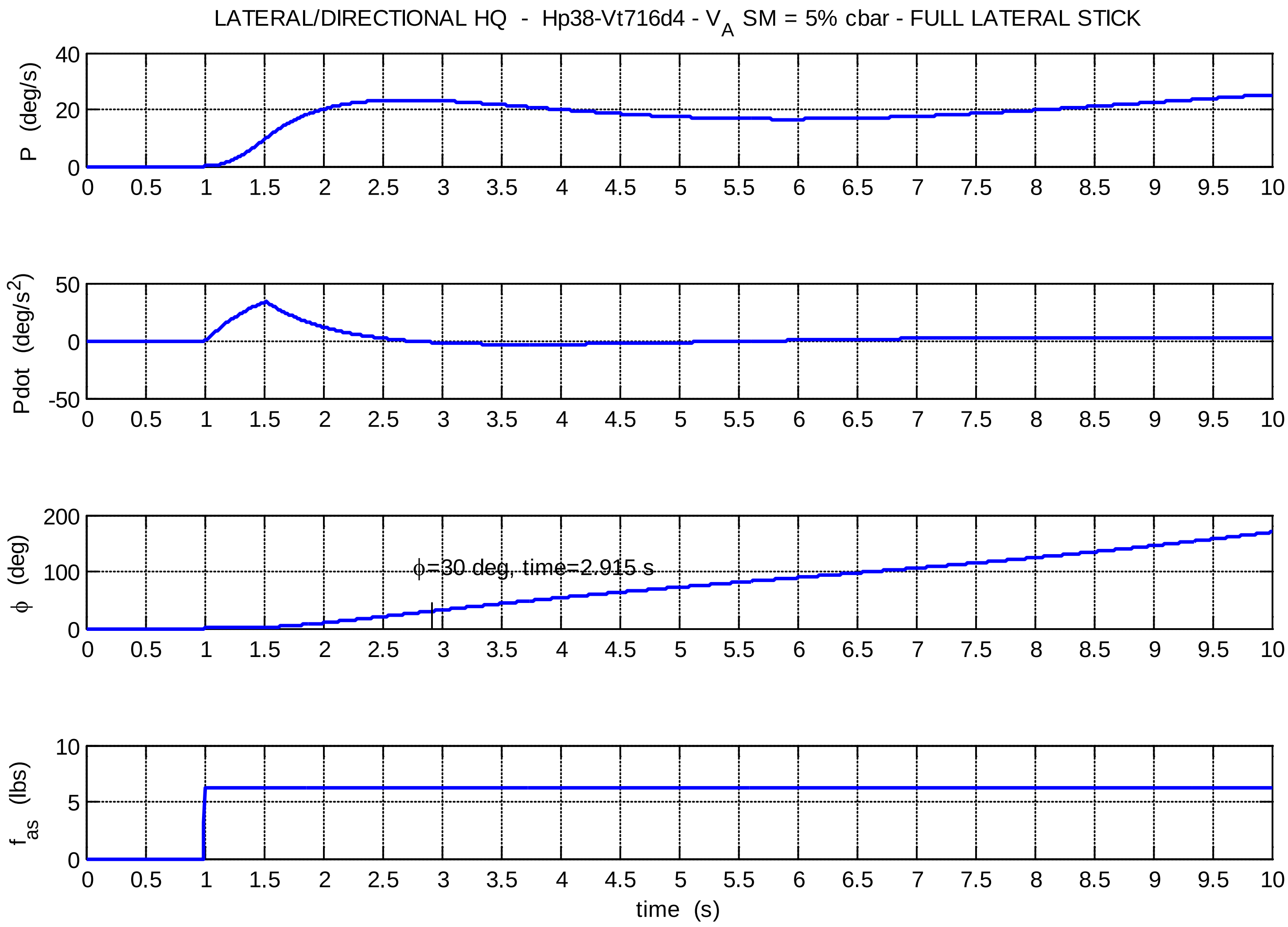

Figure B-11. VA SM = 5% $\bar{c}$ — full lateral stick input unaugmented response time history

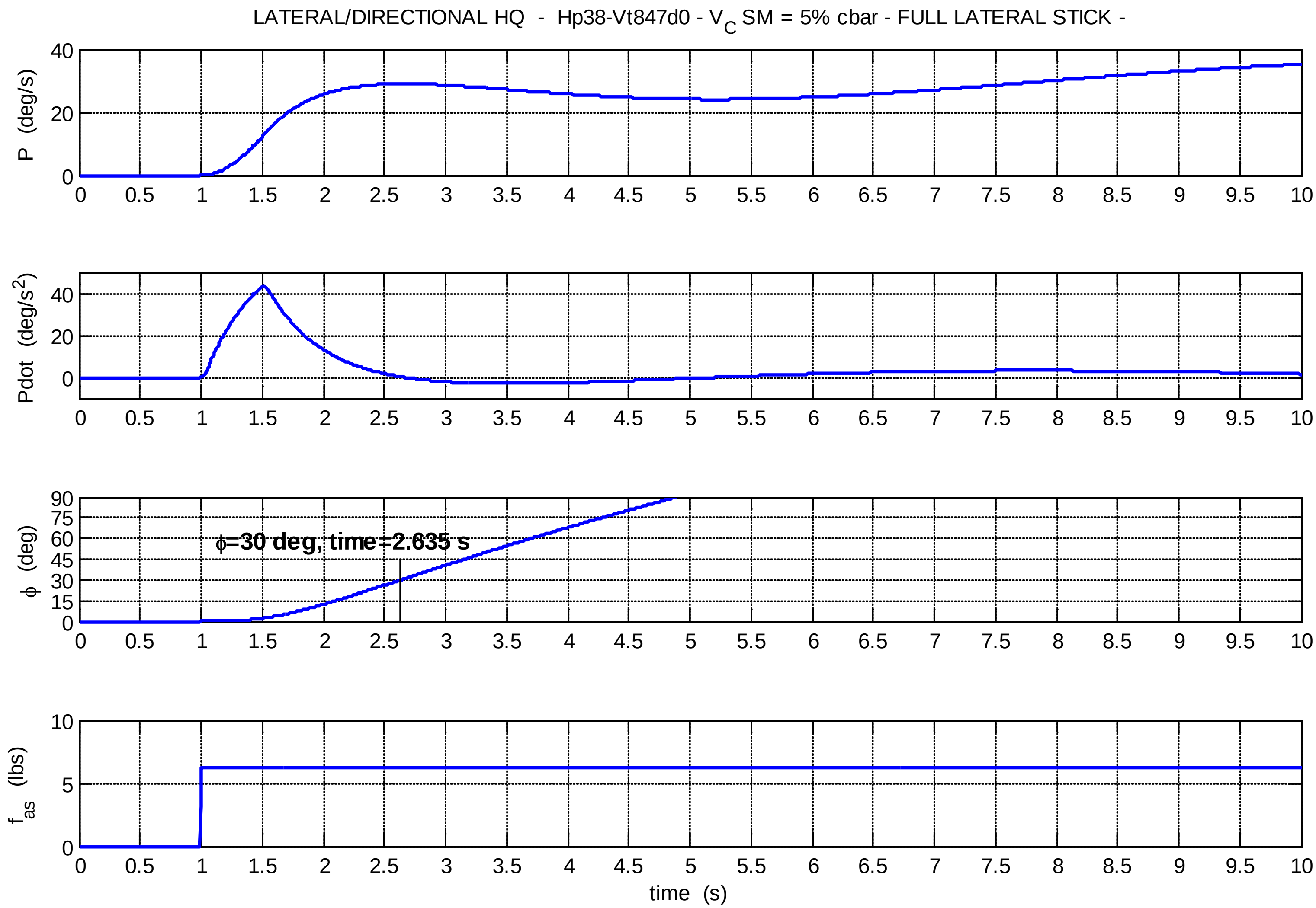

Figure B-12. VC SM = 5% $\bar{c}$ — full lateral stick input unaugmented response time history

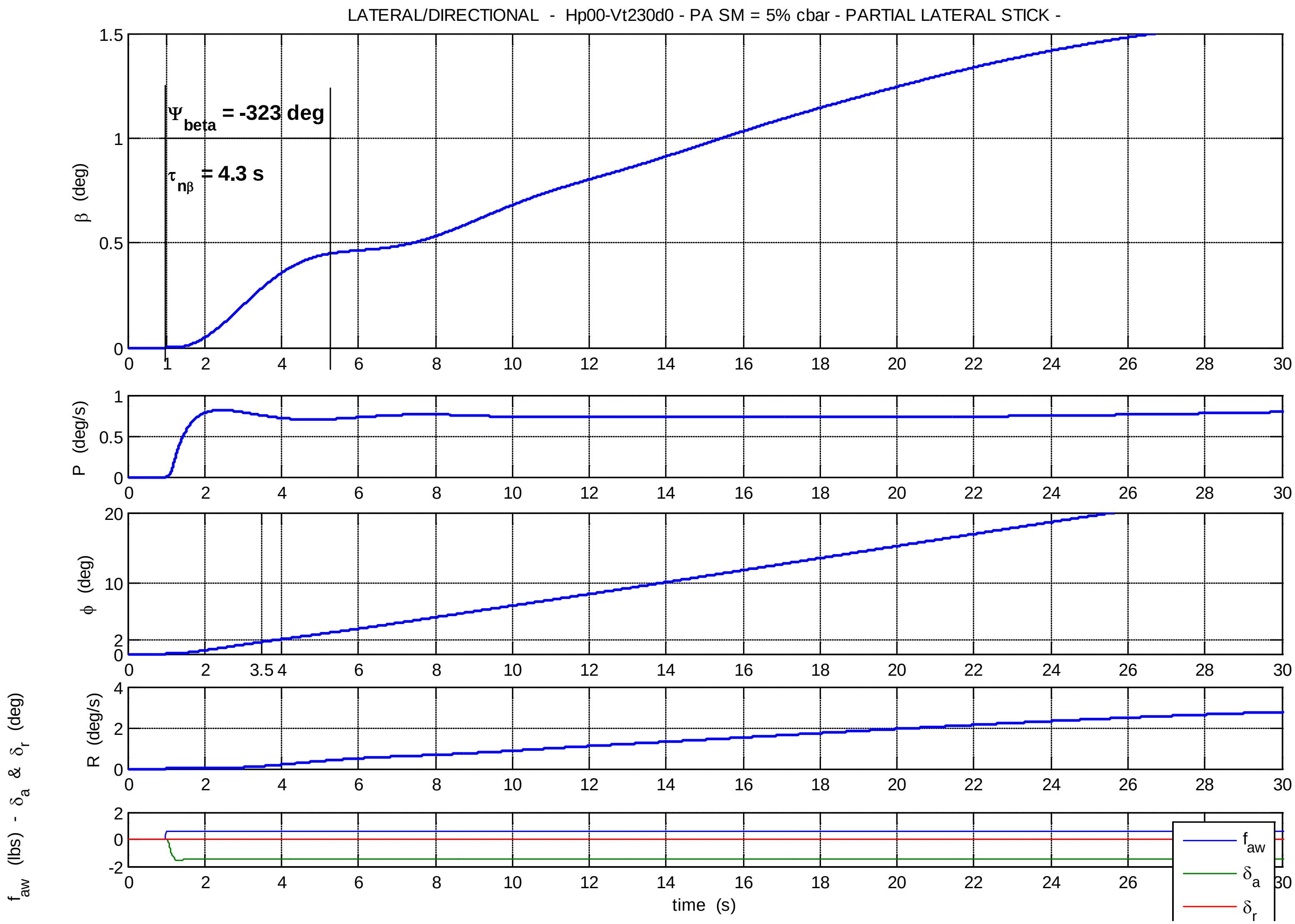

Figure B-13. PA SM = 5% $\bar{c}$ — partial lateral stick input unaugmented response time history

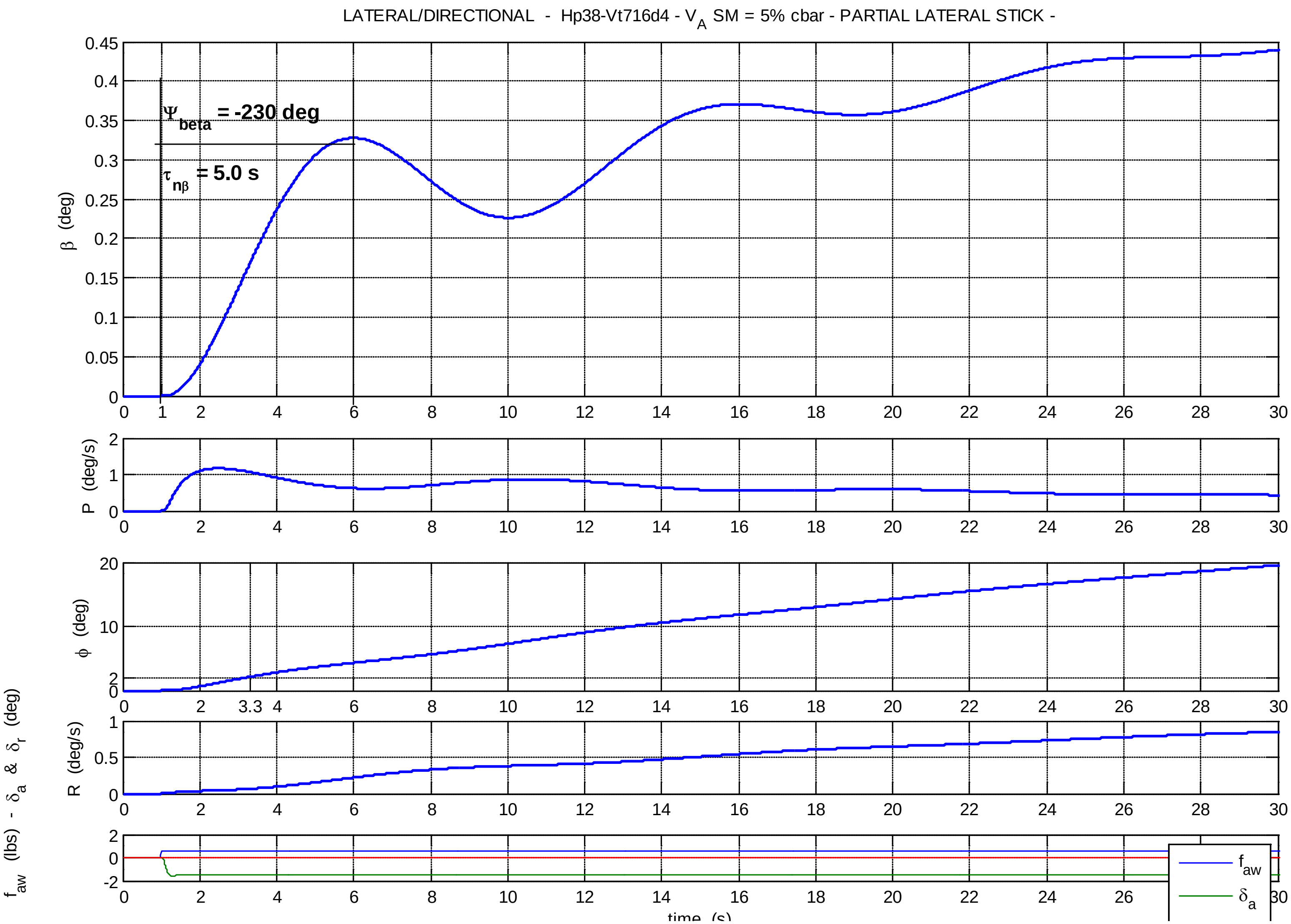

Figure B-14. VA SM = 5% $\bar{c}$ — partial lateral stick input unaugmented response time history

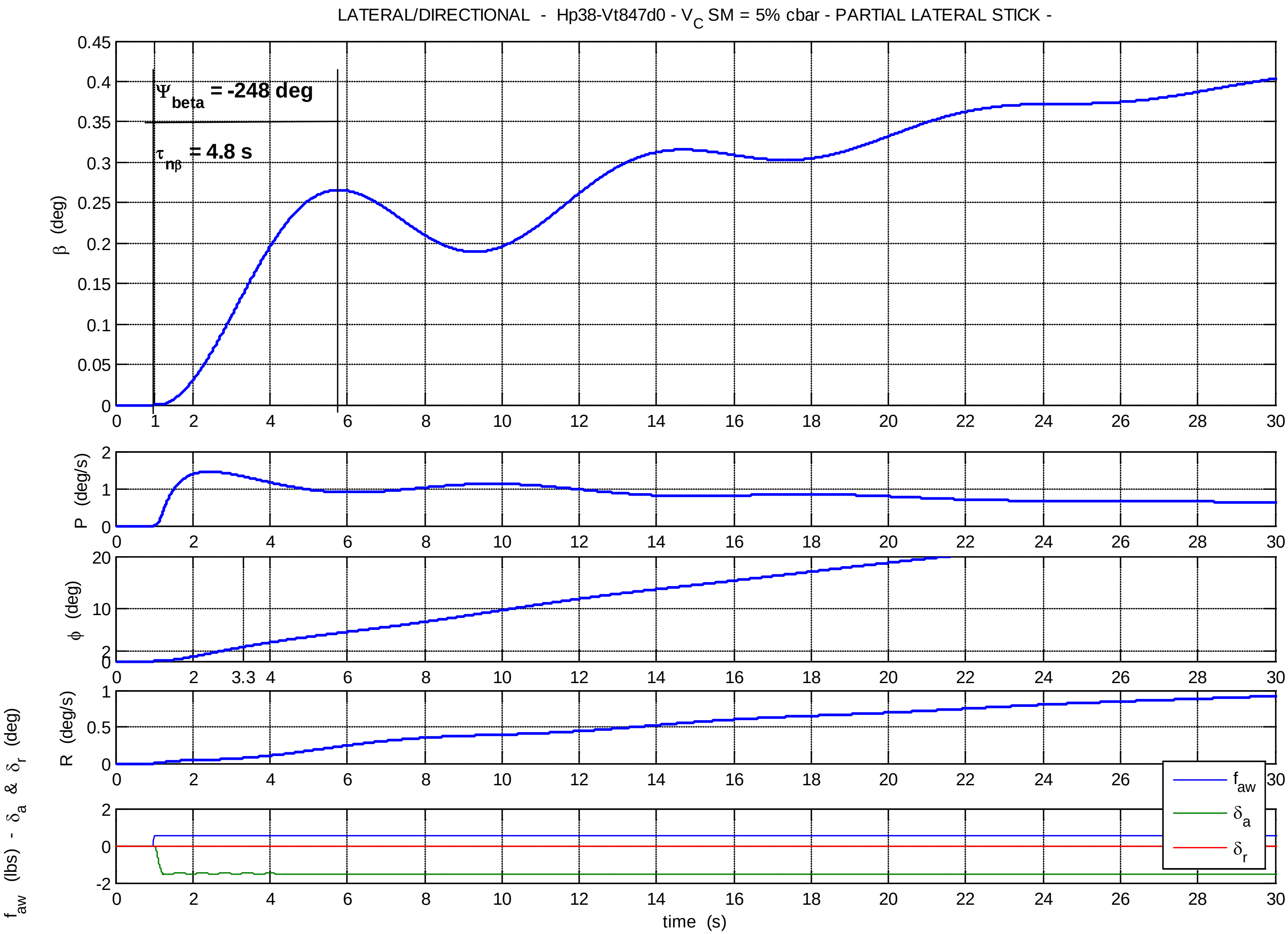

Figure B-15. VC SM = 5% $\bar{c}$ — partial lateral stick input unaugmented response time history

B.2 AUGMENTED AIRCRAFT

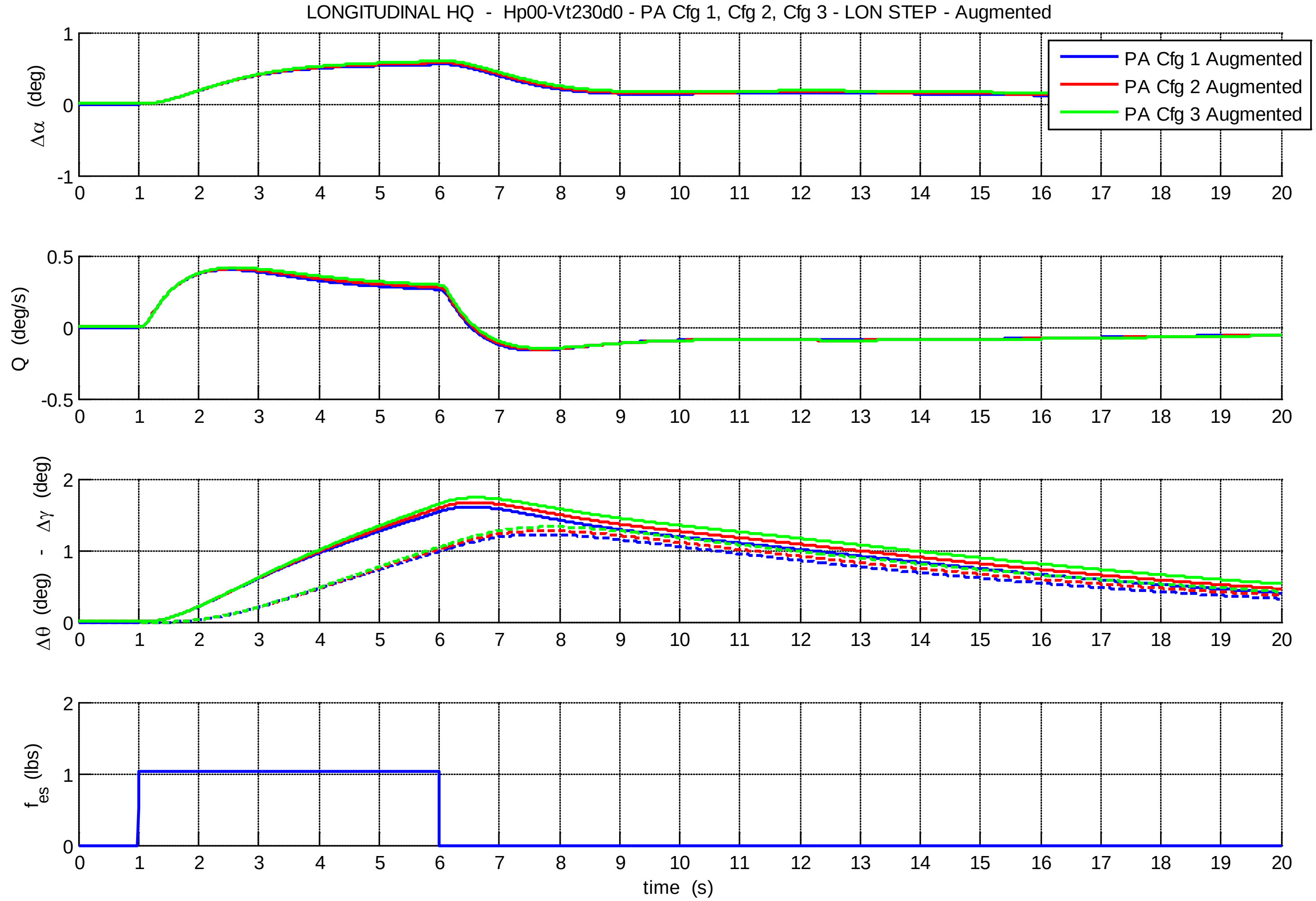

Figure B-16. PA — longitudinal step input augmented response time history

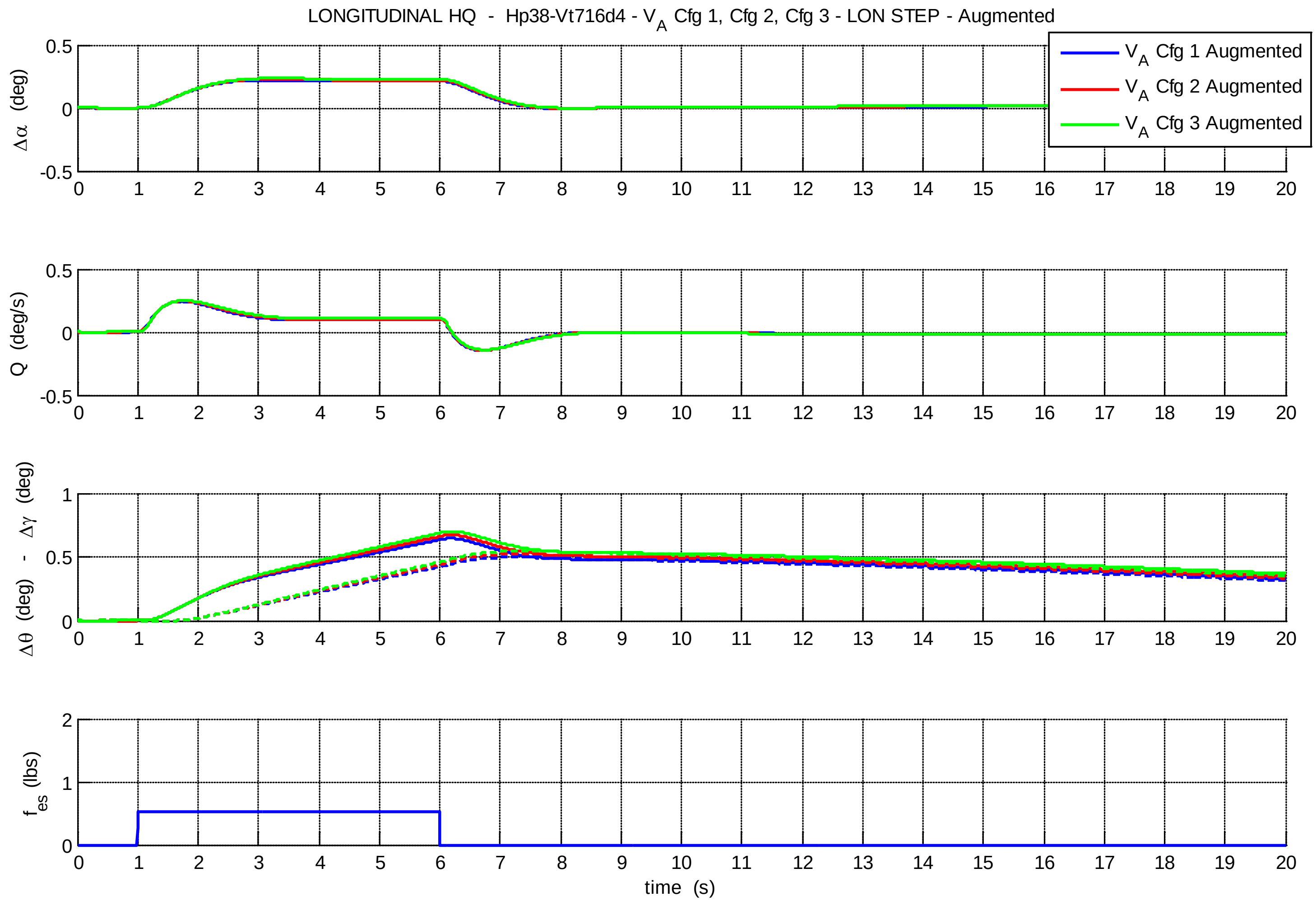

Figure B-17. VA — longitudinal step input augmented response time history

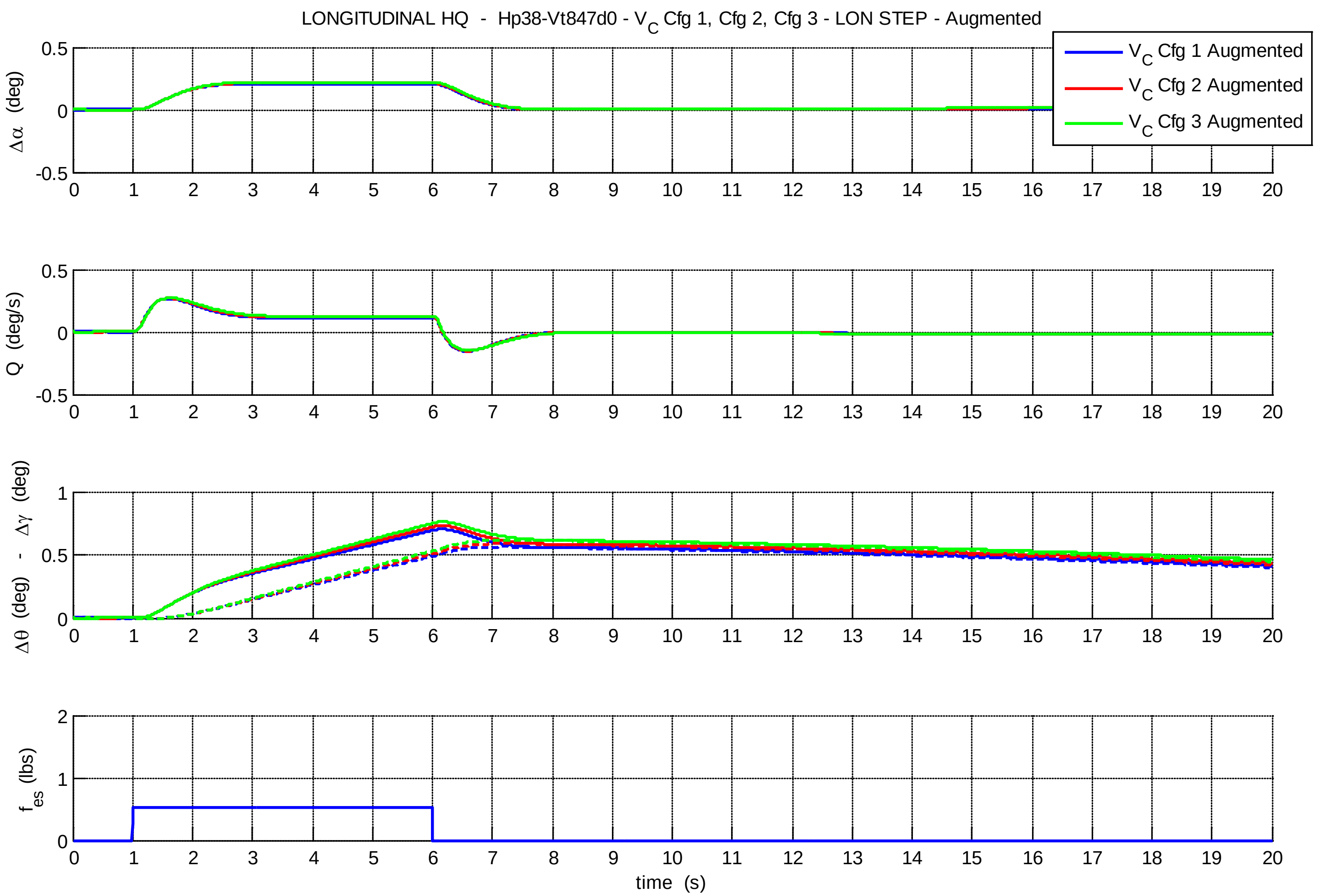

Figure B-18. VC — longitudinal step input augmented response time history

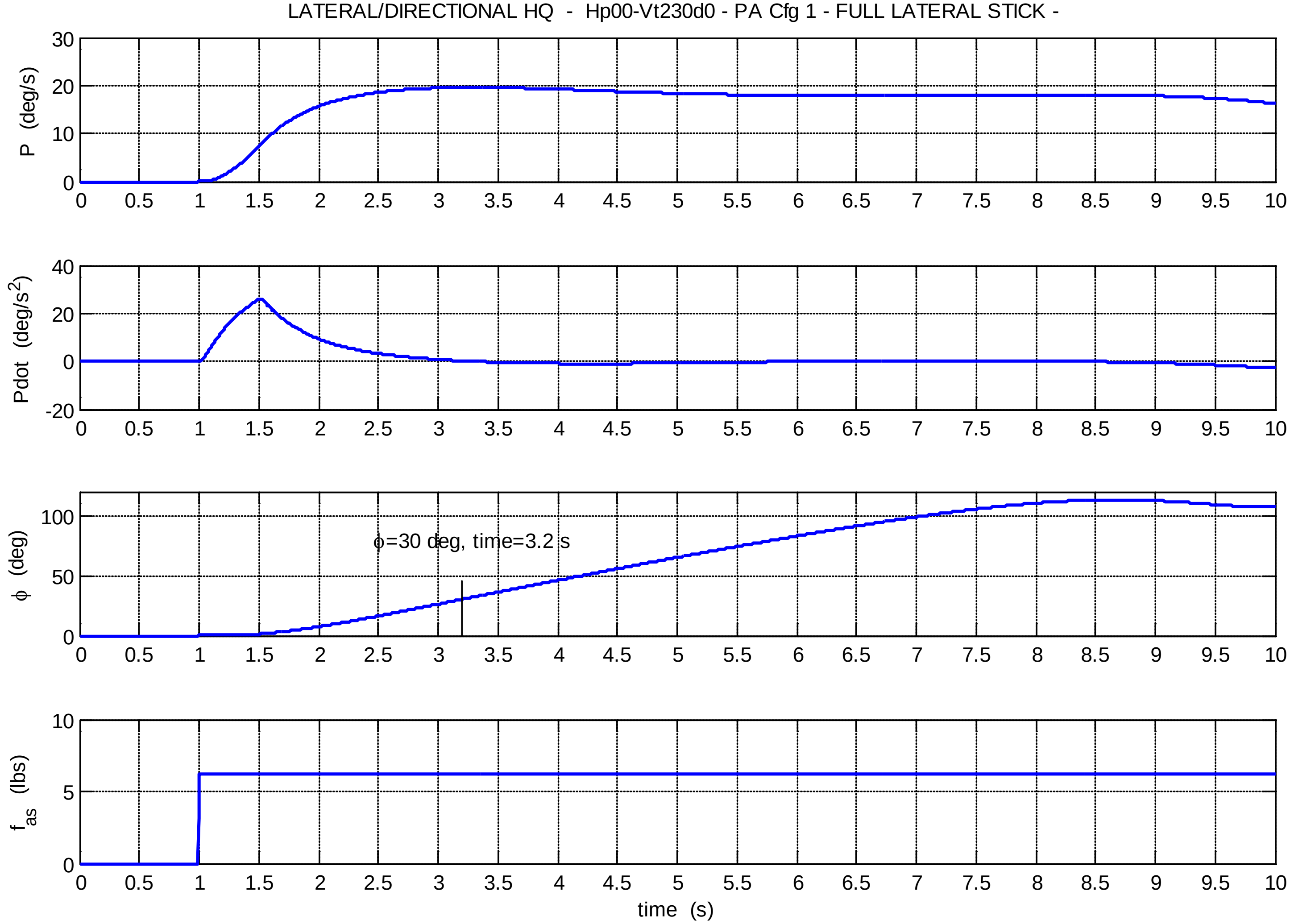

Figure B-19. PA — lateral step input augmented response time history

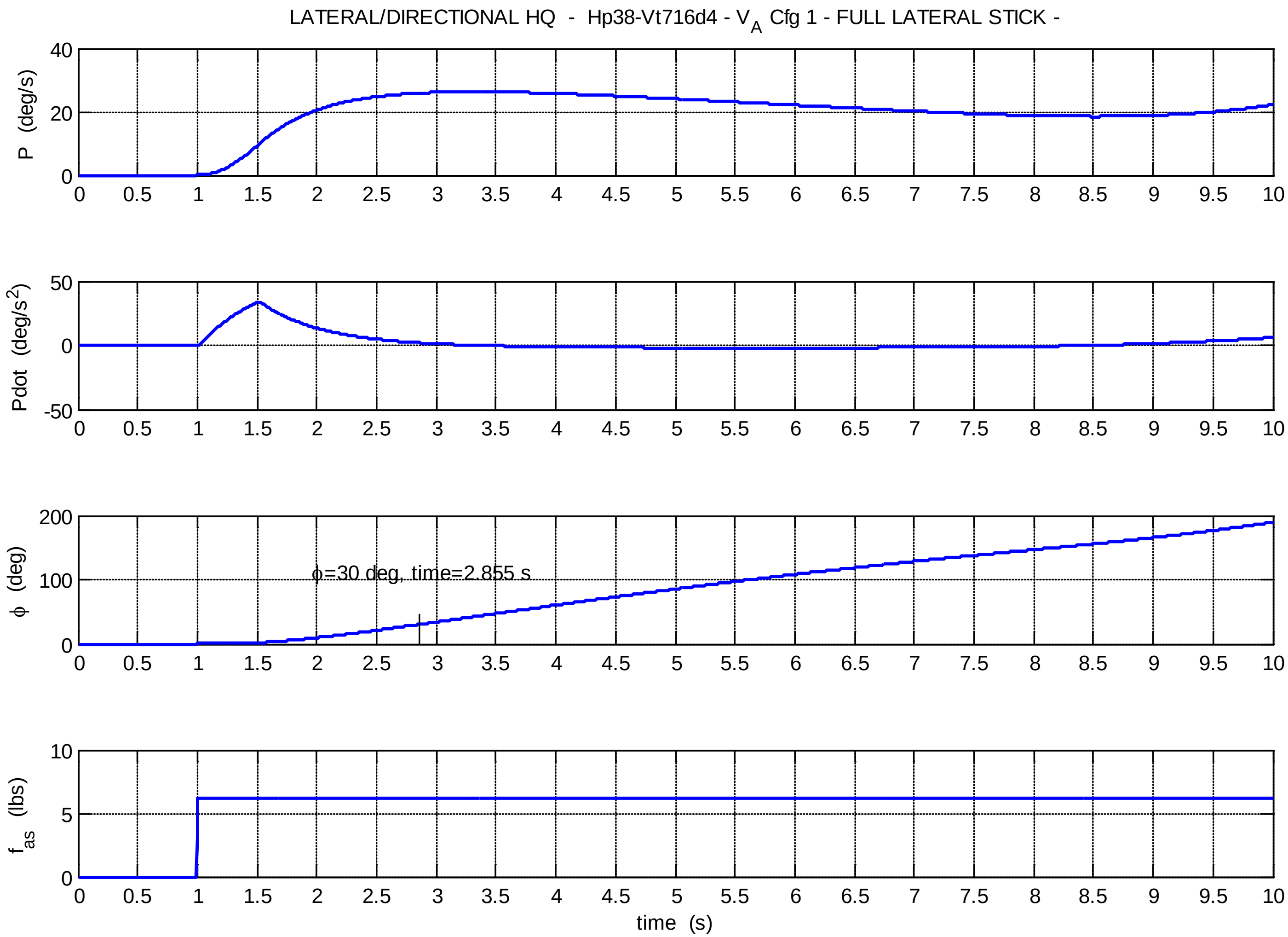

Figure B-20. VA — lateral step input augmented response time history

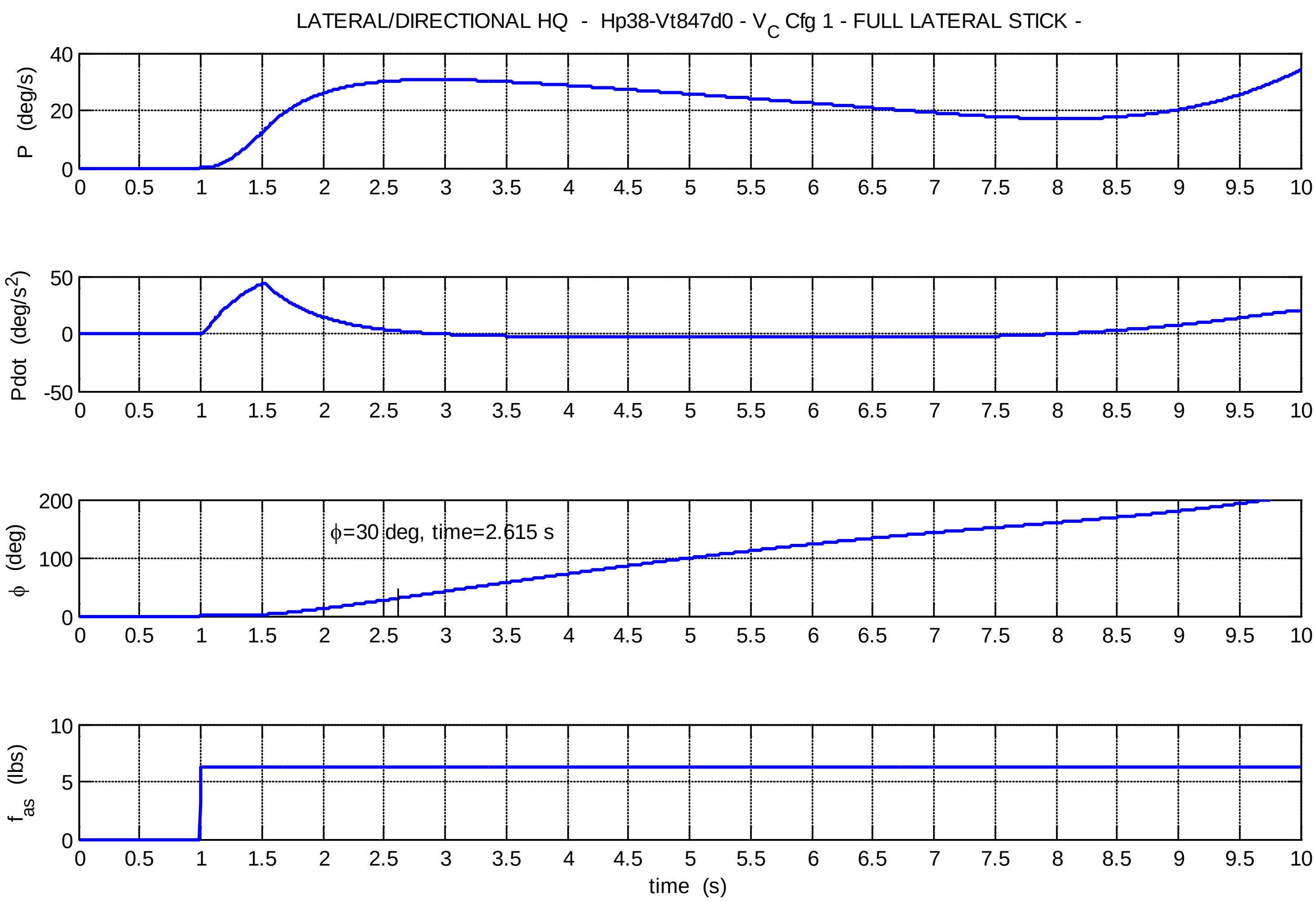

Figure B-21. VC — lateral step input augmented response time history

APPENDIX C — GROUND SIMULATOR

C.1 SIMULATOR DESCRIPTION

The simulator used for this evaluation was a fixed-base, programmable flight simulator developed by Calspan (figure C-1). The simulator included programmable, variable-feel side stick and rudder pedals that allowed simulation and evaluation of a wide range of characteristics.

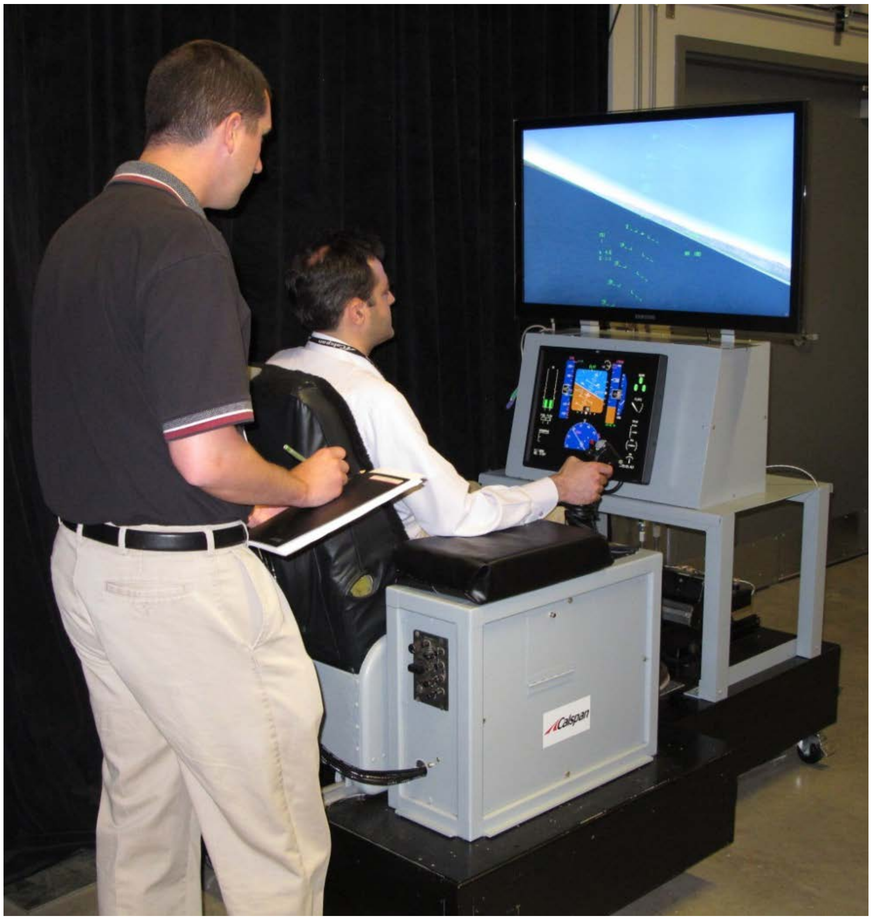

Figure C-1. Ground simulator

Each inceptor axis (pitch stick, roll stick, and pedals) is moved using a hydraulically actuated servo. Strain gages are located on each inceptor that measure the pilot-applied force. This force is input to the mathematical feel system model described in appendix A, section A.5, which runs in real-time in the simulator computer. A proprietary model-following technique is used to cancel out the dynamics of the servo (and the real mass of the inceptor) so that the actual inceptor position matches the model inceptor position for a given pilot-applied force. Any number of feel system characteristics (friction, natural frequency, BO, etc.) can be programmed into the model, which will then be followed by the real inceptor.

The out-the-window (OTW) scenery is generated using FlightGear, a popular public-domain flight simulation package released under the GNU General Public License (GPL). The scenery is generated from public Department of Defense digital elevation maps of the entire world as well as public FAA and international airport data. Detailed information on FlightGear and the GPL may be found at www.flightgear.org and www.gnu.org, respectively. A head-up display (HUD) may be superimposed on the OTW display, as shown in figure C-2. The HUD symbology is based on MIL-STD-1787B, "Aircraft Display Symbology." The head-down display consists of a B777-style primary flight display surrounded by generic engine, gear, flap, speedbrake, and trim indicators. The default HDD is shown in figure C-3.

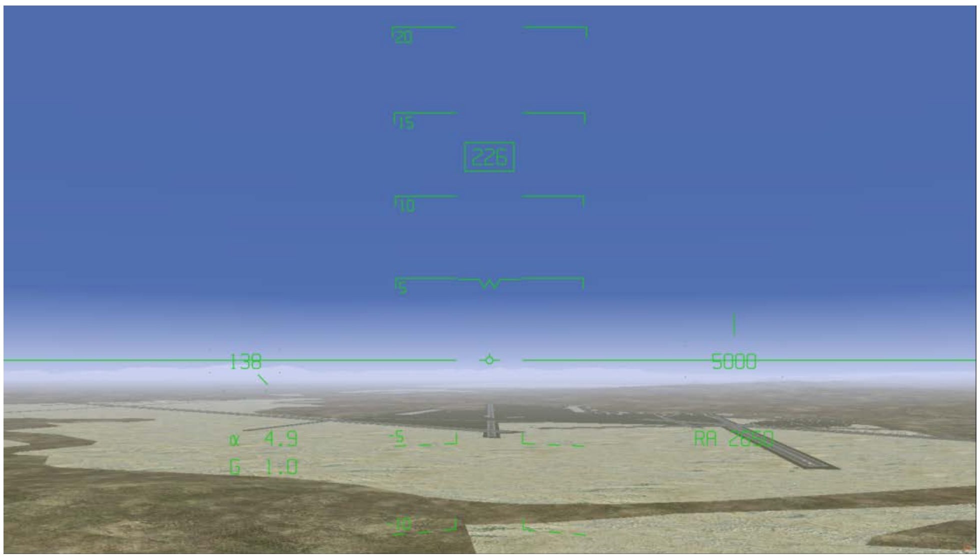

Figure C-2. The OTW display with superimposed head-up display

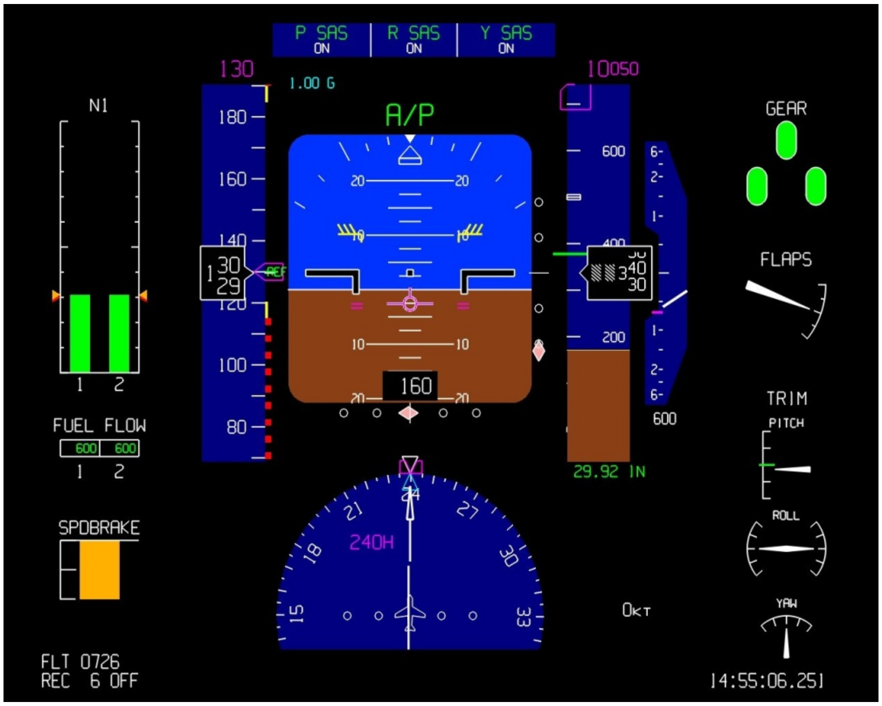

Figure C-3. The head-down display

Data acquisition in the simulator is controlled by a PC host computer interface at the test engineer console. Selected parameters may be directed to the test engineer's computer displays for real-time monitoring.

The simulator selected for this project was a Calspan-developed simulator that was available within the budget constraints of this project. It uses control inceptor hardware and display software that is similar to the Learjet in-flight simulator that was used for the flight simulation efforts for the task 2 study. The fixed-base simulator was chosen over the Learjet for the task 2 follow-on effort because of the greater schedule availability and flexibility that ultimately led to more simulation sessions and runs than would have been possible using the Learjet. However, the advantage of the Learjet over the fixed-base simulator is that it is a real aircraft cockpit, which provides a more realistic environment for the simulation. Both simulators lack motion cues (i.e., when Learjet is used as a ground simulator) and have limited visual cues. These limitations force the pilots to extrapolate their comments to link the simulation results to real-world tasks and operations. Despite these disadvantages, the consistency of the results reflects a low impact on the quality of the conclusions.

C.2 SIMULATOR MECHANIZATION

The control laws, actuators, engine, and aircraft subsystems from the desktop simulation model in figure 1 of the main report were pasted into the simulator's Simulink model. This model was then auto-coded using MATLAB's Real-Time Workshop so that the aircraft model could be integrated into the simulator computer and run in real-time. The aircraft model was then connected to the simulator side stick, pedals, and displays, which provided the evaluation pilot with the ability to fly the aircraft model. The software that models the dynamics for the electrohydraulic side stick uses the same parameters and has a similar structure to that which was implemented for the desktop feel-system model. Therefore, the feel-system model in figure 1 of the main report was not explicitly integrated into the simulator because software that provides the equivalent functionality is already part of the system.

Frequency sweeps were taken in the simulator to ensure the proper implementation of the side stick feel system. Because of limitations in the feel-system servo performance, the requested stick frequency (bandwidth) was not always achieved, especially at higher frequencies. Figures C-4 and C-5 illustrate the relationship between the desired frequency entered into the computer and that which was actually achieved. The frequencies matched at lower values while the discrepancies increased as the requested frequency was increased. Tables C-1 and C-2 provide the corrected (nominal) value that must be entered into the simulator to get the actual desired frequency. Figure C-6 shows the fast Fourier transform (FFT) results of the pitch stick force (F_{es}) to pitch stick position (D_{es}) frequency sweep run. Figure C-7 shows the FFT results of the roll stick force (F_{as}) to roll stick position (D_{as}) frequency sweep run. The red markers denote the bin averaged points for the same FFT data.

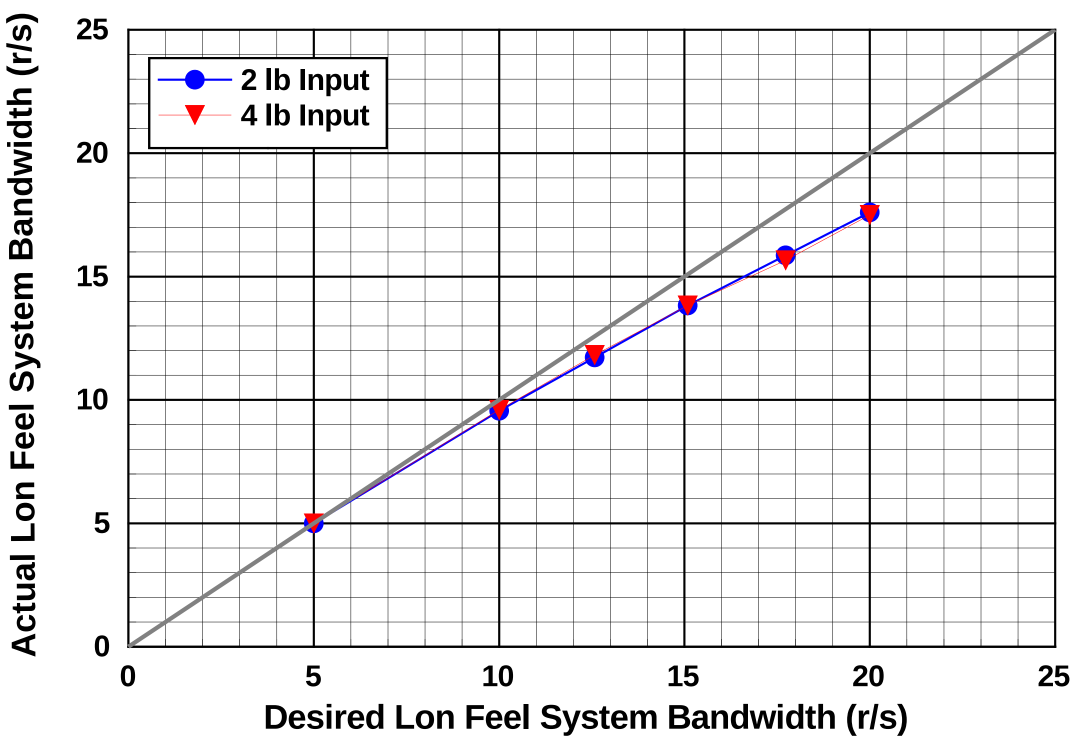

Figure C-4. Desired vs. actual pitch feel system bandwidth

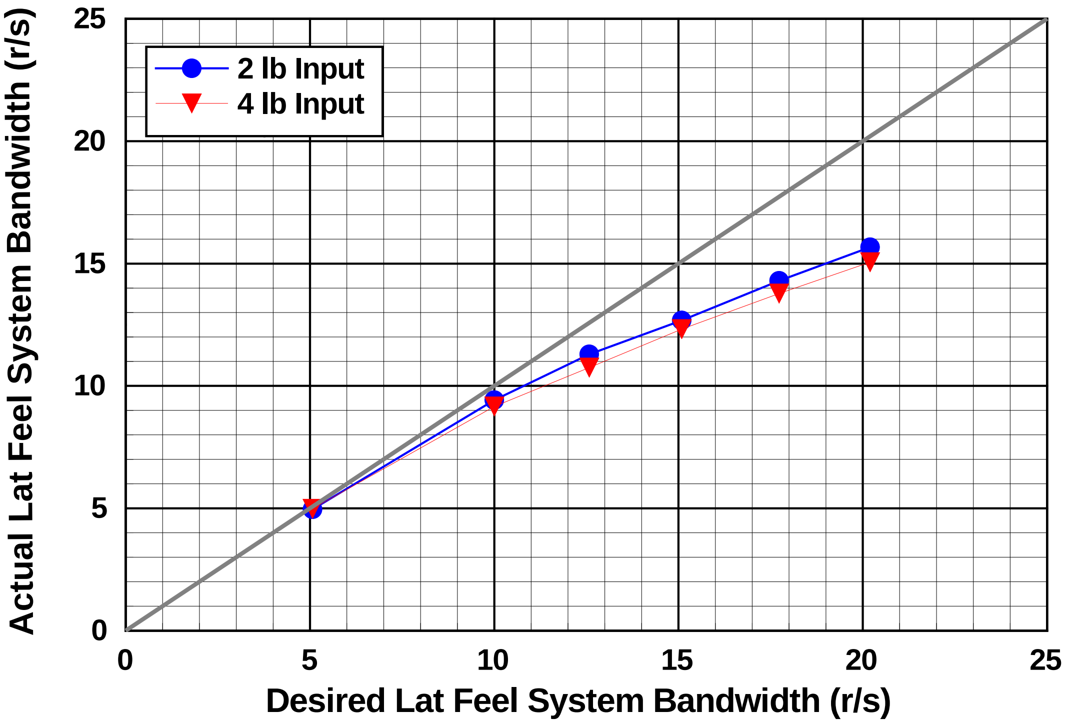

Figure C-5. Desired vs. actual roll feel system bandwidth

Table C-1. Nominal settings for actual pitch feel bandwidth

Longitudinal Feel System Bandwidth (rad/s)	
Actual	Nominal
5.0	5.0
7.5	7.7
10	10.5
12.5	13.5
15	16.6
17.5	20.0

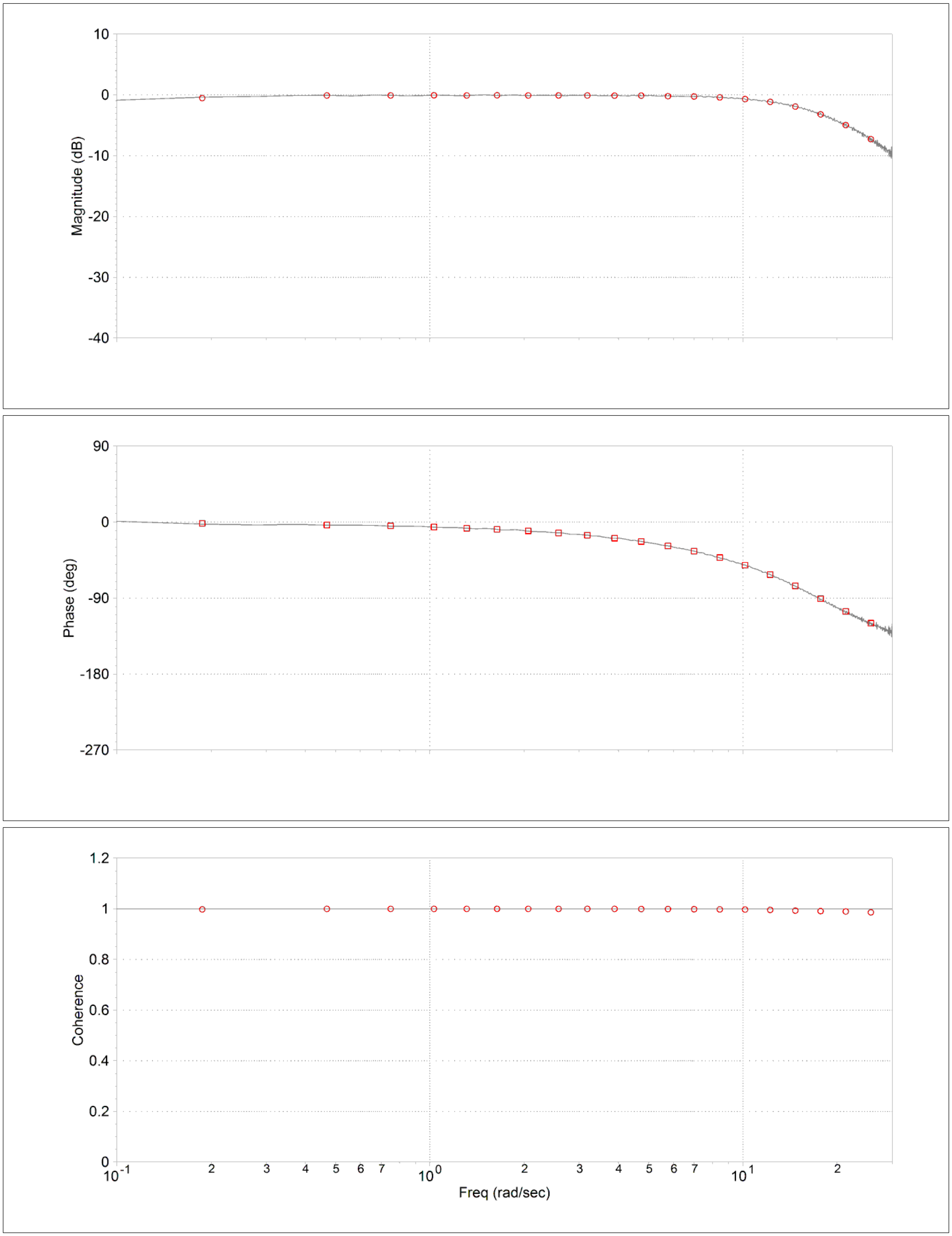

Figure C-6. DES/F_{es} 20 RAD/s feel, 4 lb-pitch sweep

Table C-2. Nominal settings for actual roll feel bandwidth

Lateral Feel System Bandwidth (rad/s)	
Actual	Nominal
5.0	5.0
7.5	8.0
10	11.4
12.5	15.3
15	20.2
17.5	27.8

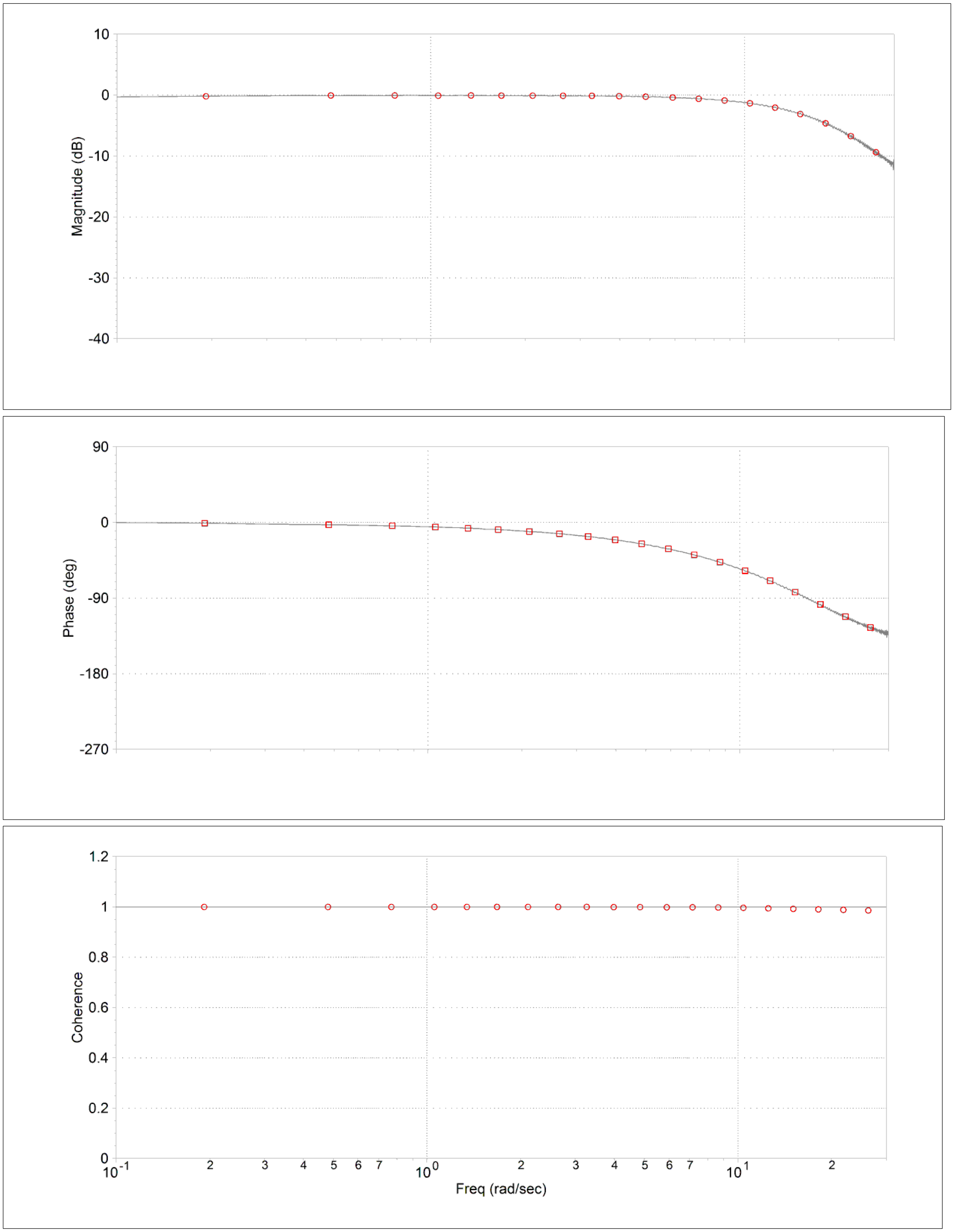

Figure C-7. D_{as}/F_{as} 20 RAD/s feel, 4-lb roll sweep

APPENDIX D — DETAILED RUN LOGS FROM TESTING

D.1 COMMAND PATH DEAD ZONES

Table D-1. Pilot 1 command path dead zones ratings — comments

Evaluation: Dead Zone (degrees) - Pilot: 1 - Date: 06/18/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
4	1	Pitch	5%	DZLON00 (baseline)			–
4	2	Pitch	5%	DZLON00 (baseline)	3	2	On the sluggish side. Tendency to lag compensate.
4	3	Pitch	5%	DZLON05			–
4	4	Pitch	5%	DZLON05	4	2	More sluggish. Harder to minimize error. More lag compensation. Bigger initial input. Subtle difference.
4	5	Pitch	5%	DZLON15	4	2	Similar characteristics but a little more so. Bigger inputs to get it going. Smooth compensation.
4	6	Pitch	5%	DZLON20			–
4	7	Pitch	5%	DZLON20	5	2	Errors are bigger. Harder to get going. Harder to eliminate the error than lag compensation. Initial command harder.
4	8	Pitch	5%	DZLON00 (baseline-blind)	3	2	More sensitive. Smaller inputs to get it going. Better errors. The best one since the baseline. Counter correction is critical. Not predictable.
4	9	Pitch	5%	DZLON10			–
4	10	Pitch	5%	DZLON10	4	1	Higher forces than previous one. Bigger errors. Not as hard as the middle one but not as easy as the one before. Less PIO tendency.
4	11	Pitch	5.0%	DZLON25			–

Table D-1. Pilot 1 command path dead zones ratings — comments (continued)

Evaluation: Dead Zone (degrees) - Pilot: 1 - Date: 06/18/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
4	12	Pitch	5.0%	DZLON25	5	2	I do not like this as much as the previous one. More like the middle ones (6 &7). Bigger errors. Input in and nothing happens. The worst. Hit the forward stop once.
4	13	Pitch	5.0%	DZLON05			–
4	14	Pitch	5.0%	DZLON05	4	3	More like the baseline. Overcontrol tendency is the issue. Initial response is easier than previous but worse than baseline. Response more predictable. Counter correction is critical. Over compensation.
4	15	Roll	5.0%	DZLON00 (baseline)			–
4	16	Roll	5%	DZLON00 (baseline)	4	2	Roll forces are heavy. Mild PIO tendency +/- 1 degree.
4	17	Roll	5%	DZLAT05	4	2	A little harder to get the error correction started. Force/deflection bigger than baseline. Forces are higher. Less PIO prone. The initial force is the annoying factor.
4	18	Roll	5%	DZLAT10			–
4	19	Roll	5%	DZLAT10	3	2	Undesirable motions are there. Do not need to back off as much to avoid PIO oscillations. Less sustained than baseline. Hit the stops one time.
4	20	Roll	5%	DZLAT00 (baseline-blind)			–
4	21	Roll	5%	DZLAT00 (baseline-blind)	3	1	Minor PIO again. Lighter forces than last couple. Did not chase as much. Very similar to baseline.
4	22	Roll	5%	DZLAT05			–

Table D-1. Pilot 1 command path dead zones ratings — comments (continued)

Evaluation: Dead Zone (degrees) - Pilot: 1 - Date: 06/18/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
4	23	Roll	5%	DZLAT05	4	2	I have to hold the input to eliminate the error. Not heavy initially; it looks like a delay. Bigger errors.
4	24	Roll	5%	DZLAT20	5	2	Like the last one but more significant. Responds well once it starts. Less than PIO problem. The issue is the delay. Hit left stop twice.
4	25	Roll	5%	DZLAT15	5	2	Hard time seeing difference. Heavy forces. Left stop once.

Table D-2. Pilot 2 command path dead zones ratings — comments

Evaluation: Dead Zone (degrees) - Pilot: 2 - Date: 06/15/12 - Lateral Dead Zone = 1 deg							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
2	1	pitch	5%	DZLON00 (baseline)			–
2	2	pitch	5%	DZLON00 (baseline)			–
2	3	pitch	5%	DZLON00 (baseline)	2	1	A bit more difficult task
2	4	pitch	5%	DZLON15	3	1	Very similar but a bit more difficult than before, very close. Workload higher.
2	5	pitch	5%	DZLON05	3	1	That one seemed different. The task looked different. Not too different configuration. Two big inputs
2	6	pitch	5%	DZLON20	4	1	Larger amplitude inputs. Disconcerting to be on the stop one time. Larger inputs to track
2	7	pitch	5%	DZLON00 (baseline-blind)	4	2	More PIO tendency. Easier to track than the last. More fighting for target
2	8	pitch	5%	DZLON25	4	1	Larger amplitude inputs. Task seems inconsistent. Similar to (6).

Table D-2. Pilot 2 command path dead zones ratings — comments (continued)

Evaluation: Dead Zone (degrees) - Pilot: 2 - Date: 06/15/12 - Lateral Dead Zone = 1 deg							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
2	9	pitch	5%	DZLON00 (baseline)	2	1	Similar to baseline before.
2	10	pitch	5%	DZLON15	4	1	Larger inputs than baseline. Not too bad. Hit stop one time. He is at least 50% less on target.
2	11	pitch	5%	DZLON05	3	1	Somewhere between. Better than the last one. Tracks pretty well.
2	12	Roll	5%	DZLAT00 (baseline)			–
2	13	Roll	5%	DZLAT00 (baseline)	1	1	Very Easy. Fairly good input. I tried to keep right on.
2	14	Roll	5%	DZLAT05	1	1	A little bit more difficult. More pitch input. Not too different from the last one.
2	15	Roll	5%	DZLAT20	2	1	Taking larger inputs and effort. No PIO tendency, more pitch variation. More difficult.
2	16	Roll	5%	DZLAT15	2	1	Not very difficult.
2	17	Roll	5%	DZLAT00 (baseline-blind)	2	1	Not very different.
2	18	Roll	5%	DZLAT20	2	1	Larger amplitude inputs. More pitch attitude disturbance. Worse than last one.
2	19	Roll	5%	DZLAT10	2	1	Pretty good. Not too large inputs.
2	20	Roll	5%	DZLAT00 (baseline)	1	1	Very Responsive.
2	21	Roll	5%	DZLAT15	2	1	Higher pitch attitude variations. Larger inputs to maintain the target.
2	22	Roll	5%	DZLAT00 (baseline)- Roll task gain of 8			Better
2	23	Roll	5%	DZLAT00 (baseline)-Roll task gain of 10			–
Roll Task Gain = 8							
2	24	Roll	5%	DZLAT00 (baseline)	1	1	–

Table D-2. Pilot 2 command path dead zones ratings — comments (continued)

Evaluation: Dead Zone (degrees) - Pilot: 2 - Date: 06/15/12 - Lateral Dead Zone = 1 deg							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
2	25	Roll	5%	DZLAT05	1	1	No big differences. A little bit more amplitude.
2	26	Roll	5%	DZLAT15	2	1	A little bit higher workload. More pitch attitude distribution. Larger inputs.
2	27	Roll	5%	DZLAT25	4	1	Against the stops. Larger inputs. More pitch attitude variation. Detached from the real world.
2	28	Roll	5%	DZLAT10	3	1	Higher workload. More pitch disturbance. Better than last one. Tracked mostly nicely. Some oscillations.
2	29	Roll	5%	DZLAT00 (baseline-blind)	3	1	More workload. Task more difficult. Not hitting stops. A little better than last one.
2	30	Roll	5%	DZLAT00 (baseline)	2	1	–
2	31	Roll	5%	DZLAT20	3	1	Stops. Larger inputs. Not as bad as (27). Not consistent.
2	32	Roll	5%	DZLAT05	3	1	Sustained moderate amplitude inputs. Better than last one.

Table D-3. Pilot 3 command path dead zones ratings — comments

Evaluation: Dead Zone (degrees) - Pilot: 3 - Date: 06/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
10	1	Pitch	5%	DZLON00 (baseline)	4	2	Minor but annoying bandwidth deficiencies in the jabbing of the inputs. Some undesirable motions but does not affect performance much.
10	2	Pitch	5%	DZLON05	4	3	Similar performance but more workload. Oscillations more insistent. Not as good as previous one but not working at maximum tolerance level.

Table D-3. Pilot 3 command path dead zones ratings — comments (continued)

Evaluation: Dead Zone (degrees) - Pilot: 2 - Date: 06/15/12 - Lateral Dead Zone = 1 deg							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
10	3	Pitch	5%	DZLON15	4	2	Larger motions but performance not terribly bad. Wrist action larger than previous. Bandwidth unnecessarily low.
10	4	Pitch	5%	DZLON20	4	2	Motions seem smaller this time. Higher frequency oscillations. Apparent quickness gives undesirable motions.
10	5	Pitch	5%	DZLON25	5	3	Larger motions. Hit stops several times.
10	6	Pitch	5%	DZLON00 (baseline)	3	2	Smaller motions than before. Responds quicker. Higher bandwidth than before.
10	7	Pitch	5%	DZLON10	4	2	Roll interferes–loss of concentration. Slightly larger motions than before. Can hardly tell the difference.
10	8	Pitch	5%	DZLON20	6	4	Hitting the stops harder than before. Back to the larger motions. POI=4 due to significant overshoots.
11	1	Roll	5%	DZLAT00 (baseline)	3	2	Oscillations. Not so sluggish as the pitch is. Less jabbiness to the desired performance. Overshoots.
11	2	Roll	5%	DZLAT10	4	2	Having to fight more than previous one. Larger stick motions. Hit the stop once. Harder to stop wings. Nature of oscillations different.
11	3	Roll	5%	DZLAT20	5	4	Hit stops 2 times. Almost rate limiting circumstances. Not good. Harder than other one. Oscillations-dutch roll.
11	4	Roll	5%	DZLAT00 (baseline)			–

Table D-3. Pilot 3 command path dead zones ratings — comments (continued)

Evaluation: Dead Zone (degrees) - Pilot: 2 - Date: 06/15/12 - Lateral Dead Zone = 1 deg							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
11	5	Roll	5%	DZLAT00 (baseline)	3	2	Higher bandwidth. Higher frequency oscillations. Less workload and less frustrating. Smaller inputs.
11	6	Roll	5%	DZLAT05	5	4	Hit the stop. Large oscillations. Feels like the bandwidth is lower. More PIO.
11	7	Roll	5%	DZLAT20	4	2	Higher bandwidth than last one. Jabby. Haven't touched the stops. Similar to baseline.
11	8	Roll	5%	DZLAT10	3	2	Hit the stop once. Performance pretty good. Smaller motions. Bandwidth good.
11	9	Roll	5%	DZLAT05	5	3	Performance pretty good. Small motions. Unexpected oscillations. Overshoot/PIO 3 times.

Table D-4. Pilot 4 command path dead zones ratings — comments

Evaluation: Dead Zone - Pilot: 4 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
20	1	Pitch	5%	DZLON00 (baseline)	3	1	Desired performance. Lead requirement for compensation. A bit slow.
20	2	Pitch	5%	DZLON05	3	1	Not too different. A little bit more lead than before.
20	3	Pitch	5%	DZLON10	3	1	This one is harder. Small little motions I am making do not seem to have much effect. Not much difference.
20	4	Pitch	5%	DZLON20	4	2	Forward stop. Feels a little bit different. Larger inputs. Less authority. Full stick to the stop several times.
20	5	Pitch	5%	DZLON00 (baseline-blind)	3	1	More like the baseline. Not close to the stops.
20	6	Pitch	5%	DZLON25	4	2	This one I need more stick. On the stops. I need to lead. Lack of motion.
21	1	Roll	5%	DZLAT00 (baseline)	3	1	I find myself focusing on just one end of the bar. A little slow time constant. I have to lead.
21	2	Roll	5%	DZLAT05	5	4	A little bit more sluggish. Overshooting. If I was normally working this hard I would not have achieved desired. Stops.
21	3	Roll	5%	DZLAT00 (baseline-blind)			–
21	4	Roll	5%	DZLAT00 (baseline-blind)	6	4	Kind of like the last one. Very easy to overshoot. This one still bad. Worse than previous one.
21	5	Roll	5%	DZLAT10	3	1	More predictable than last one. A lot easier. Did touch the stop. I don’t feel behind the airplane. More like the baseline.

Table D-4. Pilot 4 command path dead zones ratings — comments (continued)

Evaluation: Dead Zone - Pilot: 4 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
21	6	Roll	5%	DZLAT00 (baseline)	3	1	Feels similar to the last one. A little bit of motion. Touched the stops.
21	7	Roll	5%	DZLAT15	6	4	This is not responding. Just banging it to go where I want. I don't like this. I have to back out of the loop.
21	8	Roll	5%	DZLAT20	4	2	Not as bad as the last one but not as good as the baseline. Overshoots.

D.2 COMMAND PATH FLAT ZONES

Table D-5. Pilot 1 command path flat zones ratings — comments

Evaluation: Flat Zone - Pilot: 1 - Date: 06/29/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
48	1	Pitch	5%	FZLON00 (baseline) discrete	2	2	Nose down different than nose up. Nose up: Look at the green gauge to establish the rate. Nose down: I do not have a reference, a bit of overcontrol.
48	2	Pitch	5%	FZLON00 (baseline) discrete+SoS			–
48	3	Pitch	5%	FZLON00 (baseline) discrete+SoS	3	2	Harder task. Have to divide attention between the two tasks.
48	4	Pitch	5%	FZLON20	3	2	No difference. I can tend to accept whatever rate to capture as long as it is not too heavy.
48	5	Pitch	5%	FZLON50	7	2	Slower response in nose up. Can't get to maximum alpha: this is a problem.

Table D-5. Pilot 1 command path flat zones ratings — comments (continued)

Evaluation: Flat Zone - Pilot: 1 - Date: 06/29/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
48	6	Pitch	5%	FZLON40	4	2	I can get in the alpha target in a reasonable period of time. Slower than the baseline but more acceptable. Enough authority to do the job. Limiting at times.
48	7	Pitch	5%	FZLON20	3	2	Not limited so far. Like the baseline.
48	8	Pitch	5%	FZLON30	4	2	A little heavier. Less control authority than the previous but can get into the green.
48	9	Pitch	5%	FZLON60	7	2	Can't get there. Too limited. Unacceptable.
V_C							
70	1	Pitch	5%	FZLON00 (baseline) discrete	2	1	Easy to capture. No overshoots. Desired pretty good. Two part task: gross acquisition then command bars for fine tracking.
70	2	Pitch	5%	FZLON00 (baseline)	2	1	Harder task. Moves when trying to fine tune. Responds to commands well.
70	3	Pitch	5%	FZLON40	2	1	Still getting the Gs I want. No difference. Couldn't sense a rate change.
70	4	Pitch	5%	FZLON50	4	1	Harder to get Gs in desired range but can still get there. Too heavy in pull. Hit the stop once. Same fine tracking.
70	5	Pitch	5%	FZLON60	7	1	Cannot get there even with full back stick. Cannot do the task. Performance issue. Fine tracking okay.
70	6	Pitch	5%	FZLON50/-50	4	1	Enough nose up authority but heavier than baseline. Nose down is adequate to do the job. Full back stop at 2.2 Gs. I want more nose up authority.

Table D-5. Pilot 1 command path flat zones ratings — comments (continued)

Evaluation: Flat Zone - Pilot: 1 - Date: 06/29/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
70	7	Pitch	5%	FZLON40/-60	3	1	Better than the last. More command authority. Similar to baseline. ND a little heavier than baseline.
70	8	Pitch	5%	FZLON40/-70	7	1	Too heavy ND. Very slowly moving. Not enough command authority. NU is okay.
70	9	Pitch	5%	FZLON40/-50	3	1	Can get in the G-range and track fine without overcontrol (for both). ND a little heavy.

Table D-6. Pilot 2 command path flat zones ratings — comments

Evaluation: Flat Zone - Pilot: 2 - Date: 07/02/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
57	1	Pitch	5%	FZLON00 (baseline) pure discrete	2	1	Slight oscillations when trying to stop quickly.
57	2	Pitch	5%	FZLON00 (baseline)	3	1	More effort to keep target center. Hard to divert attention to two different tasks.
57	3	Pitch	5%	FZLON30	3	1	NU: alpha attention. Stagnate on occasion. ND: attention on target.
57	4	Pitch	5%	FZLON50	5	2	ND the same. NU: Different authority. Changing rate. Unpredictable. Pitch rate changing is unacceptable.
57	5	Pitch	5%	FZLON40	5	2	Small oscillations when fine tracking. NU predictability not as bad. Slightly better than last time.
57	6	Pitch	5%	FZLON20	3	1	Closer to the baseline. Not quite the same since hit stop. Have to modulate input from going past green.
V_C							
59	1	Pitch	5%	FZLON00 (baseline)	2	3	Bobbling. The gross acquisition is good. Bobbling for fine tracking. Predictable for large tracking.

Table D-6. Pilot 2 command path flat zones ratings — comments (continued)

Evaluation: Flat Zone - Pilot: 2 - Date: 07/02/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
59	2	Pitch	5%	FZLON00 (baseline) pure discrete	2	1	Less PIO tendency for fine tracking. Nose down not as predictable as nose up. A split task for gross acquisition. Initial attention to the G, then start to decrease the pull angle to refine the tracking and capture.
59	3	Pitch	5%	FZLON40	3	2	Small pitch changes required. Stagnation of the pitch rate. Spend more time on the G meter.
59	4	Pitch	5%	FZLON50	3	2	Hesitation in ND pitch rate. Inconsistent negative pitch rate. Aggressive maneuvering. More than usual for a transport.
59	5	Pitch	5%	FZLON60	3	2	Inconsistent ND pitch rate. ND pitch rate slows down faster than expected. Large inputs. Noticeable flat zone, no impact on the task but on the performance.
59	6	Pitch	5%	FZLON50/-30	3	2	The positive NU is limited as well. No significant limitations in ND.
59	7	Pitch	5%	FZLON50/-40	3	2	I do not like the NU limitations. Inconsistent itch rate. PIO tendencies with fine tracking. No limitation in ND.

Table D-6. Pilot 2 command path flat zones ratings — comments (continued)

Evaluation: Flat Zone - Pilot: 2 - Date: 07/02/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
59	8	Pitch	5%	FZLON50/-50	3	2	Pitch rate inconsistencies. Not fully predictable. Slight oscillations for fine tracking. Have to look at the G meter for ND. Divide attention in gross acquisition.
59	9	Pitch	5%	FZLON50/-60	3	2	I do not like to be limited to 2 Gs. 2.2 Gs NU. Have to compensate.
59	10	Pitch	5%	FZLON40/-50	3	2	2.4 Gs capable. NU not as limited as before. Have to learn and change technique every time.

Table D-7. Pilot 3 command path flat zones ratings — comments

Evaluation: Flat Zone - Pilot: 3 - Date: 06/29/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
50	1	Pitch	5%	FZLON00 (baseline) discrete	3	2	Medium aggressiveness is sufficient to achieve the target alpha. Small oscillations. 1–2 overshoots. Compensation level not high.
50	2	Pitch	5%	FZLON00 (baseline) discrete+SoS	4	2	Task harder. Increased compensation. Larger and easier to start oscillations. Some heavy resistance. Stronger PIO.
50	3	Pitch	5%	FZLON40	5	3	Stick full back holding at stop–just barely touched desired. Higher compensation due to trouble commanding to desired alpha. Not as fast as I would like. Not as good performance.
50	4	Pitch	5%	FZLON30	5	3	Better than the last. Not on the stop as much. Still hard to do the task.
50	5	Pitch	5%	FZLON20	5	3	The rate is as I would like. One case of no control. Oscillations keeping from desired.
50	6	Pitch	5%	FZLON50	7	3	Full back stick, on the stops–still doesn't get there for a while. Extensive compensation. Much less alpha and G than target.
V_C							
65	1	Pitch	5%	FZLON00 (baseline) pure discrete	3	1	Achieving desired with some compensation.

Table D-7. Pilot 3 command path flat zones ratings — comments (continued)

Evaluation: Flat Zone - Pilot: 3 - Date: 06/29/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
65	2	Pitch	5%	FZLON00 (baseline)	3	2	Harder to get desired. The workload is a little more associated with SoS. I don't know if the compensation is greatly increased. Mildly pleasant deficiencies.
65	3	Pitch	5%	FZLON40	7	2	Hit the stop and can't get to 2.5 Gs, only 2.3. Target tracking similar to before. Transition is hard and heavier.
65	4	Pitch	5%	FZLON00 (baseline)	3	2	Linear movement between stick and G much better.
65	5	Pitch	5%	FZLON30	4	2	More trouble settling down. Can get to 2.5 Gs. It seems linear. Felt the flatness in the end. I learned to open loop.
65	6	Pitch	5%	FZLON00 (baseline)	3	2	Around 2 overshoots because of attention to gross acquisition. Not as adapted due to the break.
65	7	Pitch	5%	FZLON50	5	1	A little less aggressive. Full aft and still cannot get to desired G. Uncommanded motions less this time. Considerable compensation.
65	8	Pitch	5%	FZLON00 (baseline)	3	1	Solid task. More PIO than previous. Minimal compensation.
65	9	Pitch	5%	FZLON40	4	2	Can get closer to the desired G, around 2.4. Tracking is the same as the others. Better than the last.

Table D-7. Pilot 3 command path flat zones ratings — comments (continued)

Evaluation: Flat Zone - Pilot: 3 - Date: 06/29/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
65	10	Pitch	5%	FZLON00 (baseline)	3	2	Same as baselines before. The full back stick does a pretty good job of preventing me from over G-ing.
65	11	Pitch	5%	FZLON40/-50	4	2	Full aft stick. Not much time to modulate and then settle in. Pretty well protected on both ends.
65	12	Pitch	5%	FZLON40/-60	5	2	Bang-bang control, chaos. Full sticks and job focus changes when hit flat spot.
65	13	Pitch	5%	FZLON40/-40	6	2	Closer to G. In between case. Do not like how you have to be careful and not assume it is limited. Undependable.

Table D-8. Pilot 4 command path flat zones ratings — comments

Evaluation: Flat Zone - Pilot: 4 - Date: 06/27/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA Discrete & SoS							
38	1	Pitch	5%	FZLON00 (baseline)			
38	2	Pitch	5%	FZLON00 (baseline)	5	3	Easy to pull too far. I have to concentrate on the angle of attack. I have to predict where it is going to stop. I need low gain. I have to lead.
38	3	Pitch	5%	FZLON50	7	2	Not a lot of difference. Full stick and I do not get what I want. I do not like that.
38	4	Pitch	5%	FZLON25	5	3	I feel I have a little bit more authority. Easier. I might be learning. Overshoots. Not as bad as the previous one. Not too different from the baseline.

Table D-8. Pilot 4 command path flat zones ratings — comments (continued)

Evaluation: Flat Zone - Pilot: 4 - Date: 06/27/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA Discrete & SoS							
38	5	Pitch	5%	FZLON50	7	2	Problem to get into the green close to the baseline.
38	6	Pitch	5%	FZLON15	5	4	The steady state response is back to the baseline. I do not like the initial response.
38	7	Pitch	5%	FZLON05	5	4	About the same
V_C Discrete + SoS							
40	1	Pitch	5%	Baseline	5	4	The G response is quick, easy, lagging inputs. Easy to exceed the limits.
40	2	Pitch	5%	FZLON50	5	4	No big differences. I do not feel any limitation. I do not want to use a lot of stick to avoid over G.
40	3	Pitch	5%	FZLON70	6	4	PIO prone. Not feeling a lot of difference. Last two captures: a little bit of limiting.
40	4	Pitch	5%	FZLON60	5	3	More like (2). I am afraid of doing what I am used to. Not as bad as the last one. I have seen some limiting.
40	5	Pitch	5%	FZLON80	5	3	Like the first one. Same as baseline. Tough airplane, very twitchy.
40	6	Pitch	5%	Baseline	5	3	Similar to the last one.

D.3 STICK NATURAL FREQUENCY

Table D-9. Pilot 1 stick natural frequency ratings — comments

Evaluation: Stick Natural Frequency (rad/s) - Pilot: 1 - Date: 06/18/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
4	26	Pitch	5%	FLON175 (baseline)	3	2	Sluggish. Tendency to overcontrol.
4	27	Pitch	5%	FLON100	3	2	A little different in my hands. I can feel a bit of ringing. The same error correction. Barely perceptible change in stick dynamics.
4	28	Pitch	5%	FLON150			–
4	29	Pitch	5%	FLON150	2	1	Don't feel anything in my hand. A little quicker A/C response. Same error elimination. Just like baseline if not quicker, easier inputs.
4	30	Pitch	5%	FLON175 (baseline-blind)	3	1	Stick a little heavier. Very similar to baseline.
4	31	Pitch	5%	FLON125	2	1	Harder to get the inputs in but not degrading. A slower stick than the previous one. Very good error. Slightly heavier forces.
4	32	Pitch	5%	FLON100	4	2	Tendency to over-control. More sluggish. Bigger errors.
4	33		5%				–
4	34	Pitch	5%	FLON075	5	3	Stick feels lighter again. Stick moving in hand. Faster stick but tendency to PIO.
4	35	Pitch	5%	FLON050	5	3	Hard to fly. Sluggish stick, low damping. Annoying feel to stick.
4	36	Pitch	5%	FLON175 (baseline)	3	2	A little sluggish. Lighter forces than the previous one. Tendency to over-control.

Table D-9. Pilot 1 stick natural frequency ratings — comments (continued)

Evaluation: Stick Natural Frequency (rad/s) - Pilot: 1 - Date: 06/18/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
4	37	Pitch	5%	FLON100			–
4	38	Pitch	5%	FLON100	2	1	Forces on the lighter side. Errors pretty good. A little better than the baseline.
	39		5%	FLON125			–
5	40	Pitch	5%	FLON125	2	1	Worse than previous one. Pretty good stick. Not fighting anything. A little lower frequency.
5	1	Roll	5%	FLAT150(baseline)	4	2	Roll oscillations are annoying.
5	2	Roll	5%	FLAT100	5	2	Heavier. Less PIO tendency. Higher errors. Errors eliminated over a longer period of time.
5	3	Roll	5%	FLAT125	4	2	Inputs go in quicker. Not as good as baseline. PIO tendency back.
5	4	Roll	5%	FLAT075	5	3	Harder to get inputs in. Stick feels sluggish in my hand. Ringing.
5	5	Roll	5%	FLAT050	5	1	Stick feels lighter but for some reason my errors are higher. Slow stick, resisting my inputs. I do not like the feel.
5	6	Roll	5%	FLAT150 (baseline)	4	2	Stick feels quicker. Tendency to over-control.
5	7	Roll	5%	FLAT125	4	2	Feel system very close to the baseline.
5	8	Roll	5%	FLAT100	4	2	A little harder to get the corrections. Not as precise.
5	9	Roll	5%	FLAT075	4	2	Light forces, easier to control. Not getting the initial rate going.
5	10	Roll	5%	FLAT050	5	3	Stick is heavier and slower in my hand. Sluggish.

Table D-10. Pilot 2 stick natural frequency ratings — comments

Evaluation: Stick Natural Frequency (rad/s) - Pilot: 2 - Date: 06/15/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
6	1	Pitch	5%	FLON175 (baseline)			–
6	2	Pitch	5%	FLON175 (baseline)	2	1	A little bit of PIO when I get into the loop. Not as stable as the other day's baseline.
6	3	Pitch	5%	FLON150	2	1	Very similar to baseline. Tracks very close to what I command. Might have been more active.
6	4	Pitch	5%	FLON100	3	2	More active stick in my hand. Performance not as good. Small undesirable motions.
6	5	Pitch	5%	FLON075	3	2	Stick feels sluggish. Large movements.
6	6	Pitch	5%	FLON050	4	1	Stick feels heavy and slow. Still can track it but there is feedback from stick. Less PIO.
6	7	Pitch	5%	FLON175 (baseline)	2	1	Stick feels tighter in my hand. No big changes except for how the stick feels. A couple of intentional large inputs.
6	8	Pitch	5%	FLON125	2	1	Pretty good again. Responds well No significant PIO tendencies. Not much different from baseline.
6	9	Pitch	5%	FLON100	2	2	Not much different from previous. More PIO.
6	10	Pitch	5%	FLON050	4	2	Can feel the stick moving around again. PIO tendency. Feel stick fighting a little. Some oscillations.
6	11	Pitch	5%	FLON075	2	1	Not fighting back as much. No PIO tendencies.

Table D-10. Pilot 2 stick natural frequency ratings — comments (continued)

Evaluation: Stick Natural Frequency (rad/s) - Pilot: 2 - Date: 06/15/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
7	1	Roll	5%	FLAT150 (baseline)	2	1	A lot more motion than pitch axis. Hit the stops a couple times (3).
7	2	Roll	5%	FLAT100	2	1	Predictable and crisp. No PIO tendencies.
7	3	Roll	5%	FLAT075	2	1	Bigger and longer inputs to get the response I want. Predictable. Tracking well. Not much different but not as precise.
7	4	Roll	5%	FLAT050	4	1	Stick Definitely feels more sluggish than before. Does not feel precise. Wanders around when I make an input. Hit stop once.
7	5	Roll	5%	FLAT125	2	1	More crisp in my hand than the last one. Responsiveness is good. Closer to the baseline.
7	6	Roll	5%	FLAT150 (baseline-blind)	2	1	Responsive again. Hit the stop once.
7	7	Roll	5%	FLAT075	3	1	Sluggish, fighting my input a little bit. Controls are heavier. Oscillations. Hit stop once.
7	8	Roll	5%	FLAT100			–
7	9	Roll	5%	FLAT100	2	1	No stick dynamics. A bit heavier forces. Not too bad. Fairly crisp.
7	10	Roll	5%	FLAT050	4	1	Stick feel sluggish now. A lot of input to get things going. Hit the stops a couple of times (twice).

Table D-11. Pilot 3 stick natural frequency ratings — comments

Evaluation: Stick Natural Frequency (rad/s) - Pilot: 3 - Date: 06/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
12	1	Pitch	5%	FLON175 (baseline)			–
12	2	Pitch	5%	FLON175 (baseline)	3	2	Not too difficult stick motion. Not too many large excursions. Tiny PIO. Quick stick motions.
12	3	Pitch	5%	FLON150	5	3	First impression–heavier forces and more resistant stick. More physical and mental effort required. Tends to oscillate more. Probably more time delay in the loop. Not as good ability to command the stick.
12	4	Pitch	5%	FLON100	6	4	Very objectionable. Oscillations. A lot of physical workload. Large excursions. Not for precise tasks. Would not like to fly that for hours.
12	5	Pitch	5%	FLON125	4	2	Much better than last one. More spongy than baseline and a little more resistant.
12	6	Pitch	5%	FLON175(baseline-blind)	3	1	Pretty decent performance. Very close to the baseline. Not too many unintended oscillations. Wrist not tired.
12	7	Pitch	5%	FLON100	6	4	Oscillations back. Did not feel as bad as (4). Natural frequency close to my natural frequency.
12	8	Pitch	5%	FLON075	7	5	Not acceptable. Does not seem right. For ground simulator = 7 but not airborne.
12	9	Pitch	5%	FLON125	4	2	Better. Chance of doing a good job.

Table D-11. Pilot 3 stick natural frequency ratings — comments (continued)

Evaluation: Stick Natural Frequency (rad/s) - Pilot: 3 - Date: 06/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
13	1	Roll	5%	FLAT150 (baseline)	3	2	Hit stops two times. Large stick deflections. Pretty good performance.
13	2	Roll	5%	FLAT100	5	4	Persistent oscillations. Heavy stick. Considerable pilot compensation. Stick continues after you take the force off.
13	3	Roll	5%	FLAT075	8	5	Compensation requirement increased. No ability to control rates. Cannot control/maneuver wings.
13	4	Roll	5%	FLAT150 (baseline)	3	2	Much easier. Don't have to think about the stick. Inputs easier.
13	5	Roll	5%	FLAT125	4	2	Requires mental activity. Not the worst. Too easy to couple with the airplane. Easier to have oscillations than the baseline.

Table D-12. Pilot 4 stick natural frequency ratings — comments

Evaluation: Stick Natural Frequency - Pilot: 4 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
22	1	Pitch	5%	FLON175 (baseline)	2	1	Fairly predictable. Initial response a little sluggish. Learning curve.
22	2	Pitch	5%	FLON150	2	1	Still sampling technique. Not much difference. I do not feel the stick resisting me. Moving the stick very fast.
22	3	Pitch	5%	FLON100	4	1	The stick is heavier this time, like a large mechanical control system. When I sample, I feel resistance that is not desirable but easy to handle. No PIO.

Table D-12. Pilot 4 stick natural frequency ratings — comments (continued)

Evaluation: Stick Natural Frequency - Pilot: 4 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
22	4	Pitch	5%	FLON125	2	1	Not a lot of difference. Not as bad as the last one, less mass.
22	5	Pitch	5%	FLON075	5	4	Feels like a very large mass slowing me down. Natural freq of airplane is about the natural freq of the stick. Hard. I do not like it. PIO tendency.
22	6	Pitch	5%	FLON100	4	1	More predictable. Lighter mass. Not resisting me. Performance looks pretty good. Fighting me a little bit more than the baseline.
22	7	Pitch		FLON050	7	4	This is the worst one yet. It really fights me. I am coupling. Too much resistance.
23	1	Roll	5%	FLAT150 (baseline)	3	1	A little slow initial response. Not terrible.
23	2	Roll	5%	FLAT100	4	2	This is fighting me a little bit. Quick inputs in particular. Lead prediction/compensation. A little more difficult.
23	3	Roll	5%	FLAT125	3	1	Not too bad. Not the same resistance to motion. Close to the baseline.
23	4	Roll	5%	FLAT075	5	3	This one I feel the stick is fighting a little bit. Changing the frequency of the stick to avoid coupling. PIO frequency.
23	5	Roll	5%	FLAT100	4	1	Not as bad as the last one, not as good as the baseline. I do not couple with it as much. I can predict.

Table D-12. Pilot 4 stick natural frequency ratings — comments (continued)

Evaluation: Stick Natural Frequency - Pilot: 4 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
23	6	Roll	5%	FLAT050	8	5	This is terrible. Just sticks. Worst one yet in roll. Very PIO prone. Reducing the size of the input to avoid PIO.
23	7	Roll	5%	FLAT075	7	4	Much better but not perfect. Definitely extra weight. Almost like the one I was coupling with my inputs. PIO prone.

D.4 STICK DAMPING RATIO

Table D-13. Pilot 1 stick damping ratio ratings — comments

Evaluation: Stick Damping Ratio - Pilot: 1 - Date: 06/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
8	4	Pitch	5%	DLON07 (baseline)	3	2	Full control power used. 2–3 counter corrections.
8	5	Pitch	5%	DLON09	3	2	Feels like baseline, maybe a hair heavier.
8	6	Pitch	5%	DLON10	3	2	Maybe a little slower. Heavier feel. 1–2 corrections.
8	7	Pitch	5%	DLON05	4	2	Harder to do fine corrections. Less precise. 4–5 corrections.
8	8	Pitch	5%	DLON03	3	2	Like the previous, but more of it, 2 oscillations more. Like the baseline.
8	9	Pitch	5%	DLON01	2	2	Like the previous one, like the baseline. 1–2 oscillations.
8	10	Pitch	5%	DLON07 (baseline-blind)	3	2	Slightly more imprecise. Countercorrection overcontrol. Lead compensation.
8	11	Pitch	5%	DLON07 (baseline)	3	2	Two sets of gains: gross acquisition, low gain and lower, depending on performance.

Table D-13. Pilot 1 stick damping ratio ratings — comments (continued)

Evaluation: Stick Damping Ratio - Pilot: 1 - Date: 06/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
8	12	Pitch	5%	DLON03	3	2	A little looser, more oscillations. Not quite as precise.
8	13	Pitch	5%	DLON01	2	1	Initial reaction feels heavier. Slightly smaller oscillations. Heavier in gross acquisition. More precise in tracking.
8	14	Pitch	5%	DLON10	3	2	Slightly greater oscillations. More like baseline.
9	1	Roll	5%	DLAT07 (baseline)	3	1	Heavy force. Large acquisition on the stops.
9	2	Roll	5%	DLAT05	2	1	No difference in performance. Fine corrections at the end. Feels a little lighter in forces. 1–2 fine corrections.
9	3	Roll	5%	DLAT03	3	1	More trouble to get a very exact fine correction, a little less precise. Takes another input to capture. A little looser.
9	4	Roll	5%	DLAT01	5	1	I can feel the stick moving in my hand. Annoying oscillations. Ringing. 5 corrections.
9	5	Roll	5%	DLAT07 (baseline-blind)	4	1	Heavier, better than the previous one. Not hitting the stops as much.
9	6	Roll	5%	DLAT09	4	1	Heavier stick. Not hitting the stops. Low natural frequency feel system. Very viscous feel in my hand.
9	7	Roll	5%	DLAT07	2	1	Lighter stick. Good accuracy. Hitting stops at big changes. Fine corrections.
9	8	Roll	5%	DLAT10	3	1	Not much different from the baseline. Slightly heavier. Good tracking.
9	9	Roll	5%	DLAT03	3	1	Lighter stick, vibrating a little. Slight ringing. Stop twice.

Table D-14. Pilot 2 stick damping ratio ratings — comments

Evaluation: Stick Damping Ratio - Pilot: 2 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
33	1	Pitch	5%	DLON07 (baseline)	2	1	Large displacement inputs—open loop. Not much overshoot.
33	2	Pitch	5%	DLON09	2	1	Pitch rate decreases as approaching. One overshoot per attempt. Not much difference.
33	3	Pitch	5%	DLON05	2	1	No significant difference. Slightly more oscillations.
33	4	Pitch	5%	DLON03	2	1	A little more oscillation.
33	5	Pitch	5%	DLON01	2	1	More oscillation.
33	6	Pitch	5%	DLON10	3	1	More movement and oscillation.
33	7	Pitch	5%	DLON07 (baseline-blind)	3	1	More oscillations but still very predictable.
33	8	Pitch	5%	DLON01	2	1	Oscillation within desired. Felt a slight fight from the stick.
43	1	Roll	5%	DLAT07 (baseline)	1	1	Very responsive and predictable. A little overshoot due to aggressiveness. Few oscillations.
43	2	Roll	5%	DLAT10	2	1	Does not seem as crisp and responsive. Anyway fairly good. Slower to get there. Very similar to the last one.
43	3	Roll	5%	DLAT05	2	1	Very similar to the last one. Predictable. No PIO tendencies.
43	4	Roll	5%	DLAT03	2	1	One overshoot due to large input. More sluggish than baseline.
43	5	Roll	5%	DLAT07 (baseline)	1	1	Not as crisp as I remember.
43	6	Roll	5%	DLAT01	2	1	Seems to be handling about the same. Sometimes the stick feels different.

Table D-15. Pilot 3 stick damping ratio ratings — comments

Evaluation: Stick Damping Ratio - Pilot: 3 - Date: 06/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
14	1	Pitch	5%	DLON07 (baseline)	4	2	A little bit of oscillation around the end, close to level 1. Compensation is more than minimal. 3 oscillations. Overshots and undershots.
14	2	Pitch	5%	DLON05	4	2	Last two captures pretty nice. I am not seeing any marked change. Oscillations a little more persistent.
14	3	Pitch	5%	DLON07 (baseline)	4	2	Can't tell the difference.
14	4	Pitch	5%	DLON03	4	2	Stick is easier to move to a new position. Stick not over-driving me. Stick was not a factor.
14	5	Pitch	5%	DLON01	6	2	Now something is different. The stick is wiggling at the end of the stroke. Tiring over the long run. Performance a little worse.
14	6	Pitch	5%	DLON02	4	2	2–3 residual oscillations. Stick moves pretty quickly. Small frequency.
14	7	Pitch	5%	DLON07 (baseline)	2	1	The stick does not bounce around this time. Clearly better.
14	8	Pitch	5%	DLON10	4	2	This feels heavier. It is resisting me.
14	9	Pitch	5%	DLON08	2	1	A little overshoot. The stick does not bother me. Not as heavy as the last one.
19	1	Roll	5%	DLAT07 (baseline)	4	2	Some oscillation in the stick. Tendency to go full stick and rest at the stop. Desired performance.
19	2	Roll	5%	DLAT05	4	2	Didn't hit the stop as much. Heavier stick and less oscillation. Felt less damped towards the end. Not as much coupling. Did I learn the task?

Table D-15. Pilot 3 stick damping ratio ratings — comments (continued)

Evaluation: Stick Damping Ratio - Pilot: 3 - Date: 06/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
19	3	Roll	5%	DLAT07 (baseline)	3	2	Closed loop. Roll stick less damped than baseline pitch. No real performance difference.
19	4	Roll	5%	DLAT05	4	2	Some ping-pong action that can be avoided if paid attention to.
19	5	Roll	5%	DLAT03	4	2	Hard to tell the difference. No ping-pong. A little wiggling. Easy to make couple.
19	6	Roll	5%	DLAT01	7	2	Immediately aggravating. Oscillations at the end of everything. A lot of concentration needed. Not adequate.
19	7	Roll	5%	DLAT02	5	2	Initially much better than last. When increased aggressiveness it got worst but still better than the previous.
19	8	Roll	5%	DLAT07 (baseline)	3	2	Oscillations are more damped but less damped than in pitch. I like my ability to move the stick to some determined place.
19	9	Roll	5%	DLAT10	2	1	Oscillations less than baseline. Can be more aggressive. Forces feel heavier. Less overshoot. Best one of the group.

D.5 ACTUATOR NATURAL FREQUENCY

Table D-16. Pilot 1 actuator natural frequency ratings — comments

Evaluation: Actuator Natural Frequency(rad/s) - Pilot: 1 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
15	1	Pitch	5%	BWLON75 (baseline)	3	2	Sluggish pitch response. Tendency to over-control and need compensation.
15	2	Pitch	5%	BWLON50	3	2	Don't feel any difference. A little more lag to the response compared to baseline. Not significantly.
15	3	Pitch	5%	BWLON25	4	2	More lag than previous one. Still good performance.
15	4	Pitch	5%	BWLON15	3	2	All very small differences. Not as bad as the previous one. Similar to the baseline.
15	5	Pitch	5%	BWLON75 (baseline-blind)	3	2	Very similar to the baseline if not baseline.
15	6	Pitch	5%	BWLON75 (baseline)	3	2	Same, all very close.
15	7	Pitch	5%	BWLON15	4	2	This is different. It is easier to over-control. Errors bigger but still desired. Compensation is the issue, not PIO.
15	8	Pitch	5%	BWLON10	4	2	Similar to last one. Error bigger than baseline. Less compensation than before.
15	9	Pitch	5%	BWLON7.5	5	3	This has the most lag. Worst one I have seen. Errors bigger.
16	1	Pitch	2.5%	BWLON75 (baseline)	3	2	Easier to over-control than other baseline. A little more sluggish.
16	2	Pitch	2.5%	BWLON50	3	2	I cannot tell the difference. Same tracking error.
16	3	Pitch	2.5%	BWLON25	3	2	Tracking accuracy was better. The aircraft did not feel more laggy than the previous.
16	4	Pitch	2.5%	BWLON15	3	2	I can't tell any difference.

Table D-16. Pilot 1 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency(rad/s) - Pilot: 1 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
16	5	Pitch	2.5%	BWLON75	3	2	–
16	6	Pitch	2.5%	BWLON10	4	2	Tend to overcontrol more. A little more lag.
16	7	Pitch	2.5%	BWLON7.5	5	3	Another with lag. Worse than previous one.
16	8	Pitch	2.5%	BWLON05			–
16	9	Pitch	2.5%	BWLON05	7	4	Most lag I have seen. PIO prone. Difficult to back off my gains.
17	1	Pitch	0%	BWLON75 (baseline)	3	2	Feels the same as the first (5%) baseline.
17	2	Pitch	0%	BWLON50	3	2	Not quite as easy as the baseline. Pretty close, slightly noticeable. A little more laggy.
17	3	Pitch	0%	BWLON25	3	2	Errors are bigger than the previous. Less predictable. Better at the end.
17	4	Pitch	0%	BWLON15	4	2	Less predictable than baseline. Compensation issue. No PIO.
17	5	Pitch	0%	BWLON10	5	3	More over-control. Cautious about getting in the loop tightly.
17	6	Pitch	0%	BWLON75 (baseline-blind)	3	2	Better again. Similar to if not baseline.
17	7	Pitch	0%	BWLON7.5	5	3	More laggy again. Errors with oscillations more sustained.
17	8	Pitch	0%	BWLON05	7	4	Worst one. Sustained PIO with tight control.
18	1	Roll	5%	BWLAT75 (baseline)	4	2	Heavy forces. Sluggish.
18	2	Roll	5%	BWLAT50	4	2	Just like baseline.
18	3	Roll	5%	BWLAT25	4	2	Hit the stop once. A hair laggier, a little behind command bar.

Table D-16. Pilot 1 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency(rad/s) - Pilot: 1 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
18	4	Roll	5%	BWLAT15	6	4	More lag than previous one. Back and forth 2–3 times. PIO tendency starting.
18	5	Roll	5%	BWLAT25	6	4	Hit the stops. Oscillating. Very easy to excite oscillations. Similar to previous.
18	6	Roll	5%	BWLAT75 (baseline)	4	2	I have to smooth my inputs, but I don't go back and forth. No sustained oscillations.
18	7	Roll	5%	BWLAT10	5	3	Not as good as baseline, but not as bad as others. Have to compensate more than baseline.
18	8	Roll	5%	BWLAT05	6	4	Hit the stops. Easy to PIO. No longer precise.
18	9	Roll	5%	BWLAT7.5	6	4	Hit the stops. Have to back out.
V_A							
67	1	Pitch	5%	BWLON75 (baseline)	2	1	Easy. No control issues. Able to eliminate the error.
67	2	Pitch	5%	BWLON25	4	2	Not quite as easy as the previous one. Tendency to over-control. Errors still in desired.
67	3	Pitch	5%	BWLON50	3	1	Initially I thought it was worse. Then, not much different from baseline. Not the same tendency to over-control as the previous.
67	4	Pitch	5%	BWLON15	5	3	Not as predictable. More PIO tendency. Errors just as good. More tendency to overcontrol. Phase lag feeling.
67	5	Pitch	5%	BWLON10	5	3	Like the previous but worse. Overcontrol tendency but not enough to be a 6.

Table D-16. Pilot 1 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency(rad/s) - Pilot: 1 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
67	6	Pitch	5%	BWLON7.5	7	4	Same overcontrol problem as the previous. Entering PIO in tight control. +/- 2 deg PIO.
67	7	Pitch	5%	BWLON10	7	4	Overcontrol and PIO issue. Slightly better than previous. Not as much phase lag.
67	8	Pitch	5%	BWLON05	8	5	The worst so far. I enter PIO without tight control. Negative damped oscillations. Dynamically unstable aircraft.
67	9	Pitch	5%	BWLON15	2	1	Low need to back out. Almost the baseline.
68	1	Pitch	2.5%	BWLON75 (baseline)	2	1	Easy. No difference with the other baseline configuration.
68	2	Pitch	2.5%	BWLON50	2	1	Hard pressed to tell the difference. Subtle difference.
68	3	Pitch	2.5%	BWLON25	3	1	Pretty good. A bit of phase lag. I have to lag compensate to avoid over control.
68	4	Pitch	2.5%	BWLON15	4	2	Performance still desired. 2–3 oscillations.
68	5	Pitch	2.5%	BWLON10	5	3	More phase lag. Oscillating around the error. Difficult to eliminate the error.
68	6	Pitch	2.5%	BWLON7.5	6	3	Some PIO tendency. More phase lag. Entered a divergent PIO. 2–3 overshoots.
68	7	Pitch	2.5%	BWLON05	8	5	Have to abandon the task many times to avoid PIO.
68	8	Pitch	2.5%	BWLON10	3	1	Back to very little phase lag. Not as good as the baseline.
68	9	Pitch	2.5%	BWLON15	2	1	Better than the previous one. Like the baseline.

Table D-16. Pilot 1 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency(rad/s) - Pilot: 1 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
69	1	Pitch	0%	BWLON75 (baseline)	2	1	No tendency to over-control. No bobble. Like other config baselines.
69	2	Pitch	0%	BWLON50	3	1	A little feeling of disconnect. Errors still good. Subtle difference.
69	3	Pitch	0%	BWLON15	4	2	3 oscillations to eliminate error. Tighter in the loop is more difficult.
69	4	Pitch	0%	BWLON25			–
69	5	Pitch	0%	BWLON25	3	1	At first thought it was worse. Then not. Like previous. Some slight over control. Not oscillating.
69	6	Pitch	0%	BWLON10	5	3	Over-control tendency. Not really bad yet.
69	7	Pitch	0%	BWLON05	7	4	A lot of phase lag. Tight control-continuous oscillation. Have to back off but not abandon the task.
69	8	Pitch	0%	BWLON7.5	5	3	Better than the last. Still PIO. 2–3 overshoots to settle.
69	9	Pitch	0%	BWLON10	3	1	Better. Some phase lag but no continuous overshoots. Not the best but I can do my job.
69	10	Pitch	0%	BWLON7.5	6	4	More phase lag and PIO. 2–3 oscillations. Sometimes have to back out to stop the oscillations.
71	1	Roll	5%	BWLAT75 (baseline)	3	1	Harder SoS task than pitch: higher forces. Desired most of the time. No PIO. Mildly unpleasant deficiencies are the high forces.
71	2	Roll	5%	BWLAT25	3	1	Very similar to the baseline. Same issue with the forces.
71	3	Roll	5%	BWLAT50	3	1	Could not feel any difference.

Table D-16. Pilot 1 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency(rad/s) - Pilot: 1 - Date: 06/20/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
71	4	Roll	5%	BWLAT10	5	2	Does not seem quite as connected.
71	5	Roll	5%	BWLAT75 (baseline)	3	1	Really hard to separate what I am inducing from the disturbance. Still heavy forces. No more oscillations when task is finished.
71	6	Roll	5%	BWLAT15	4	2	Not quite as good as the baseline. Distraction led to hitting the left stop. Slight phase lag.
71	7	Roll	5%	BWLAT7.5	7	4	A lot of phase lag. Too much sluggishness. Easy to over-control. I do not like the PIO tendency.
71	8	Roll	5%	BWLAT05	7	4	Also has phase lag. Hard to tell which is worse, this or the previous. Easy to get out of phase. Similar in nature to the previous.
71	9	Roll	5%	BWLAT7.5	7	4	This one is worst. Easy to get out of phase. I can do the task but I have to reduce my gain.

Table D-17. Pilot 2 actuator natural frequency ratings — comments

Evaluation: Actuator Natural Frequency - Pilot: 2 - Date: 06/27/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
44	1	Pitch	5%	BWLON75 (baseline)	2	1	Nothing significantly bad. Predictable.
44	2	Pitch	5%	BWLON50	3	1	A little more difficult to track. Harder workload and more compensation.
44	3	Pitch	5%	BWLON25	3	1	Similar to the last one. More workload.
44	4	Pitch	5%	BWLON15	2	1	That one was a bit more difficult than the baseline.
44	5	Pitch	5%	BWLON7.5	4	2	More oscillations. Harder to track. Larger amplitude errors trying to track.
44	6	Pitch	5%	BWLON10	2	1	Errors are smaller. Easier to track. Not much workload.
44	7	Pitch	5%	BWLON05	4	3	Worse than last one. Larger motions. More PIO tendencies. Back out of the loop. More difficult to track.
45	1	Pitch	2.5%	BWLON75 (baseline)	2	1	Easy to track. No PIO tendencies. Deviations are small.
45	2	Pitch	2.5%	BWLON50	2	1	Easy to track. Predictable. No PIO tendencies. No oscillations.
45	3	Pitch	2.5%	BWLON25	2	1	Deviations seem to be small. Tracking is predictable. No oscillation tendencies. Easy to track.
45	4	Pitch	2.5%	BWLON10	3	1	Still tracking okay. Deviations seem to be larger than before. Compensation required.
45	5	Pitch	2.5%	BWLON15	3	1	Same motion as the last. Easier than the last.
45	6	Pitch	2.5%	BWLON7.5	4	2	Oscillations. Larger errors.

Table D-17. Pilot 2 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 2 - Date: 06/27/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
45	7	Pitch	2.5%	BWLON05	4	3	More PIO tendency. More oscillations. Easier to go out of phase. A lot more motion.
46	1	Pitch	0%	BWLON75 (baseline)	2	1	Predictable. Tendency to stop where I want it to.
46	2	Pitch	0%	BWLON50	2	1	No oscillations. Easy to track. Not different. Small errors.
46	3	Pitch	0%	BWLON25	2	1	Larger errors initially. Not significantly different.
46	4	Pitch	0%	BWLON10	3	1	More oscillations, larger. I can stop it where I want it. A bit more workload, not much.
46	5	Pitch	0%	BWLON05	4	3	More tendency to oscillate. More workload to track. More PIO tendency.
46	6	Pitch	0%	BWON7.5	3	1	Smaller amplitude disturbances. No tendency to oscillate. No real PIO tendencies. More workload than HQR 2.
46	7	Pitch	0%	BWLON15	2	1	Small amplitude errors. Tracks really well. Easier than the last one.
47	1	Roll	5%	BWLAT75 (baseline)	3	1	Variable amount of force. Unpredictable. No PIO tendency.
47	2	Roll	5%	BWLAT50	3	1	–
47	3	Roll	5%	BWLAT25	3	1	Varying amount of input to get result that I want. Very close to before.
47	4	Roll	5%	BWLAT10			–
47	5	Roll	5%	BWLAT10	4	1	A few large oscillations. Predictable. Not always desired. Kind of out of phase.

Table D-17. Pilot 2 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 2 - Date: 06/27/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
47	6	Roll	5%	BWLAT15	3	1	Smaller amplitude deviations. Unpredictable. Stops very precisely. No PIO tendencies.
47	7	Roll	5%	BWLAT05	3	1	Somewhat larger deviations.
47	8	Roll	5%	BWLAT7.5	3	1	Small deviations. No PIO.
V_A							
62	1	Pitch	5%	BWLON75 (baseline)	2	2	Some oscillations. Predictable.
62	2	Pitch	5%	BWLON50	2	2	Not much different.
62	3	Pitch	5%	BWLON25	2	2	A little different. More oscillations.
62	4	Pitch	5%	BWLON15	3	2	Bigger pitch changes to capture further from target.
62	5	Pitch	5%	BWLON7.5	6	4	Many oscillations. Easy to get out of phase.
62	6	Pitch	5%	BWLON10	3	2	Not as bad as previous. Easier to track. More oscillations than the baseline.
62	7	Pitch	5%	BWLON15	3	2	Oscillations not bad.
62	8	Pitch	5%	BWLON05	6	4	A lot more oscillations. Tighter control needed. Very PIO prone.
62	9	Pitch	5%	BWLON7.5	5	3	PIO prone.
63	1	Pitch	2.5%	BWLON75 (baseline)	2	2	Fair tracking. Some uncommanded motions.
63	2	Pitch	2.5%	BWLON50	2	2	Similar to last.
63	3	Pitch	2.5%	BWLON25	3	2	A little more difficult. Larger deviations and more effort.
63	4	Pitch	2.5%	BWLON10	4	3	More motion.
63	5	Pitch	2.5%	BWLON15	3	2	Close to 2 for HQR.
63	6	Pitch	2.5%	BWLON7.5	4	3	More movement. More PIO tendency.
63	7	Pitch	2.5%	BWLON05	7	5	A lot of PIO. Have to work to lower oscillations.

Table D-17. Pilot 2 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 2 - Date: 06/27/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_A							
63	8	Pitch	2.5%	BWLON7.5	5	4	Long periods of no deviations.
63	9	Pitch	2.5%	BWLON10	4	3	Some oscillations.
64	1	Pitch	0%	BWLON75 (baseline)	2	2	Tracks inputs well. Some oscillations.
64	2	Pitch	0%	BWLON50	3	2	A little more difficult to track target without too much workload. Same PIO. Some oscillations.
64	3	Pitch	0%	BWLON25	3	2	More PIO prone. Then settled.
64	4	Pitch	0%	BWLON10	4	3	More difficult. More oscillations. More work.
64	5	Pitch	0%	BWLON15	3	2	Easier than before. Not as much PIO.
64	6	Pitch	0%	BWLON7.5	5	4	PIO tendencies.
64	7	Pitch	0%	BWLON10	4	2	–
64	8	Pitch	0%	BWLON05	6	4	More PIO and oscillations.
64	9	Pitch	0%	BWLON7.5	5	3	A little PIO.
64	10	Pitch	0%	BWLON15	3	2	A little more difficult than baseline.
66	1	Roll	5%	BWLAT75 (baseline)	2	1	A lot of input to get the response I need. Took more force in all of them. Lateral gradient is bigger than I would expect.
66	2	Roll	5%	BWLAT25	2	1	Larger inputs than expected. Responding to my inputs appropriately. More difficult task, target more active.
66	3	Roll	5%	BWLAT50	2	1	A little difference. I have to hold the inputs longer.
66	4	Roll	5%	BWLAT10	2	1	Not much more difference. Some more overshoots.

Table D-17. Pilot 2 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 2 - Date: 06/27/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
66	5	Roll	5%	BWLAT15	3	1	A little more overshoot. I do not notice them with small changes. With a small amplitude task, they all look similar.
66	6	Roll	5%	BWLAT7.5	4	2	More PIO prone. Tendency to overshoot entering the loop.
66	7	Roll	5%	BWLAT05	4	2	Larger inputs needed than I expected. Similar to the last one in terms of PIO. I feel out of phase.
66	8	Roll	5%	BWLAT15	4	2	I did not notice any huge problems, but there are problems. Often on the stops.
66	9	Roll	5%	BWLAT10	5	3	Definitely out of phase more than the last one. Almost continuous oscillations.
66	10	Roll	5%	BWLAT15	3	2	Not as bad as the last one. Tracks precisely.

Table D-18. Pilot 3 actuator natural frequency ratings — comments

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
27	1	Pitch	5%	BWLON75 (baseline)	4	2	Noticed changes due to the tracking technique. Different concentrating on the dots or the wing. The response is not quite as crisp. Less predictability than I like.

Table D-18. Pilot 3 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
27	2	Pitch	5%	BWLON50	5	3	Feels a little harder. In the adequate zone significantly more than before. Lower predictability. Times with extensive compensation.
27	3	Pitch	5%	BWLON25	4	2	Predictability seems to be better. Much less undesirable motions. Can hardly tell the difference with the baseline. Over-shooting a bit.
27	4	Pitch	5%	BWLON75 (baseline-blind)	5	2	A little worse than the last one. Predictability is becoming more of an issue.
27	5	Pitch	5%	BWLON75 (baseline)	4	1	Better than the last one. Less brain work. Minimal compensation. Predictability is much better.
27	6	Pitch	5%	BWLON15	5	3	Predictability issue. Hard to take care of roll. More oscillatory than before. Predictability affects the way I put the nose.
27	7	Pitch	5%	BWLON10	4	1	Easier so far. Better bank control. Better airplane. Predictable.
27	8	Pitch	5%	BWLON7.5	5	3	Not as good as the baseline. Some self-induced oscillations. Try to do little compensation outside adequate for two seconds.
27	9	Pitch	5%	BWLON05	7	5	This is the cliff. Predictability quite bad. Continuously oscillating. Not an adequate airplane.
28	1	Pitch	2.5%	BWLON07 (baseline)	3	1	When I try to excite pitch PIO, I cannot really make it happen.
28	2	Pitch	2.5%	BWLON50	4	2	Predictability has gone down a little bit. Not on the cliff yet.

Table D-18. Pilot 3 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
28	3	Pitch	2.5%	BWLON25	4	1	Felt better than the previous. I did not think it was a 3, but at times I thought it could be close to minimal.
28	4	Pitch	2.5%	BWLON15	5	3	3 oscillations. Predictability has gone down. Commanded peaks.
28	5	Pitch	2.5%	BWLON10	5	3	Similar to the last one. A little bouncy.
28	6	Pitch	2.5%	BWLON7.5	7	5	A lot more anticipation required. Easy to have big oscillations. Bad predictability. Coupling with large excursions.
28	7	Pitch	2.5%	BWLON05	7	5	Trouble similar to the last one. Poor predictability. Not acceptable.
29	1	Pitch	0%	BWLON07 (baseline)	3	1	Minimal compensation. I feel I do not quite have enough authority for correcting large errors.
29	2	Pitch	0%	BWLON50	4	2	I get behind. Still minimal compensation. A little less predictable than baseline. More oscillations.
29	3	Pitch	0%	BWLON25	4	2	Seems better than the last. Definitely less annoying.
29	4	Pitch	0%	BWLON15	5	3	Oscillation at the end.
29	5	Pitch	0%	BWLON10	6	4	Predictability not as good. Much easier to get oscillations. The worst one yet.
29	6	Pitch	0%	BWLON7.5	7	5	Not adequate. It is very easy to initiate abrupt maneuver in tight control. Task is not achievable.
29	7	Pitch	0%	BWLON05	8	5	This seems worse. Predictability is a problem. Close to the place of impossible to enter the loop.
77	1	Roll	5%	BWLAT75 (baseline)	5	2	Requires large motions to get there. Once there, seems sensitive and oscillatory.

Table D-18. Pilot 3 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
77	2	Roll	5%	BWLAT75 (baseline)			Feels like there is sideslip working against me and like there is adverse yaw.
77	3	Roll	5%	BWLAT75 (baseline)	3	2	Majority of the time in desired. Moderate workload. Minimal compensation.
77	4	Roll	5%	BWLAT25	4	2	Hit the stops. A little more difficult. More undesirable motions. Desired performance.
77	5	Roll	5%	BWLAT50	4	2	I don't notice much difference between this and the last one. Maybe a little more oscillatory.
77	6	Roll	5%	BWLAT75 (baseline)	3	1	Easier than the last one–more linear feel. Less time delay. No PIO.
77	7	Roll	5%	BWLAT15	6	3	Harder than the baseline. Not linear roll response. Extensive compensation. It is mixed. Sometimes the performance is not too bad, but if you leave the input a bit longer you can over-control.
77	8	Roll	5%	BWLAT10	6	3	A couple of bigger excursions. I have to try and check the roll.
77	9	Roll	5%	BWLAT75 (baseline)	3	2	Things feel more linear. Not as jabby in the input.
77	10	Roll	5%	BWLAT15	9	5	Harder to settle on the target. Feel dutch roll at the end of the task.
77	11	Roll	5%	BWLAT7.5	9	5	Had to back out of loop. Large time delay.
77	12	Roll	5%	BWLAT05	8	5	Unacceptable. Large oscillations. Have to really anticipate. Not as bad as the last one. Was able to back out enough.

Table D-18. Pilot 3 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
77	13	Roll	5%	BWLAT15	4	2	Easier than the last few but not as good as the baseline.
V_A							
74	1	Pitch	5%	BWLON75 (baseline)	3	2	Can keep in desired more than 50% of the time. Can notice the breakout in the stick. Small undesired motion when I quickly and aggressively bring it back in. Mildly unpleasant deficiencies.
74	2	Pitch	5%	BWLON25	3	2	Still in desired. Can't see much difference, not enough to pinpoint.
74	3	Pitch	5%	BWLON15	4	2	Larger excursion. Feel a little more tendency to oscillate around the target. 3–4 ping pong oscillations. Moderate compensation. PIO still 2 because still in desired.
74	4	Pitch	5%	BLON50	2	1	Performance is better than before. Like the baseline. No ping-pong or PIO.
74	5	Pitch	5%	BWLON10	6	4	Not as good. Ping-ponging. Several bouncy oscillations. Big workload. Adequate performance.
74	6	Pitch	5%	BWLON7.5	8	5	Bouncing around a little. Have to be careful, too easy to PIO. Harder than the previous one. Big workload, might not be tolerated in the long run.
74	7	Pitch	5%	BWLON15	3	2	A little oscillation but not as much as the others. Closer to the baseline.
74	8	Pitch	5%	BWLON05	9	5	Harder again. Extensive compensation. Not adequate. Clearly not a 7.
75	1	Pitch	2.5%	BWLON75 (baseline)	3	1	–

Table D-18. Pilot 3 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
77	13	Roll	5%	BWLAT15	4	2	Easier than the last few but not as good as the baseline.
75	2	Pitch	2.5%	BWLON50	3	2	Not quite as good. More oscillatory. Easily maintaining desired. 2 uncommanded motions. Moderate workload.
75	3	Pitch	2.5%	BWLON15	4	2	Ping-pong once. Slightly more difficult. More attention needed to stay in desired.
75	4	Pitch	2.5%	BWLON25	4	2	About the same mental and physical activity.
75	5	Pitch	2.5%	BWLON10	5	3	More bouncy feeling if I don't pay attention to stay out of the loop.
75	6	Pitch	2.5%	BWLON25	3	2	Mostly desired. Better than the last one.
75	7	Pitch	2.5%	BWLON10	6	4	Worse again. I can stay in desired for a while. More PIO prone.
75	8	Pitch	2.5%	BWLON7.5	8	5	Much larger uncommanded motions. Not acceptable. I can get to a place where no matter how hard I work, I can't get out of trouble.
75	9	Pitch	2.5%	BWLON05	10	6	Nearly the case where entering the loop causes PIO. Easy to fall into divergent PIO.
76	1	Pitch	0%	BWLON75 (baseline)	2	1	Just like the other baselines. Small workload. Compensation not a factor.
76	2	Pitch	0%	BWLON25	3	2	More undesired motions and PIO.
76	3	Pitch	0%	BWLON15	5	3	More difficult. Bigger uncommanded motions. Need more concentration. Ping-ponging. G excursions.
76	4	Pitch	0%	BWLON50	4	2	So far, better than last. Desired. Compensation down. Not quite satisfactory.

Table D-18. Pilot 3 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
77	13	Roll	5%	BWLAT15	4	2	Easier than the last few but not as good as the baseline.
76	5	Pitch	0%	BWLON10	6	4	Larger uncommanded motions. Have to be careful. Generally speaking, I can keep it in adequate.
76	6	Pitch	0%	BWLON15	3	2	A little tamer than the last one. Mostly in desired. Little bounces.
76	7	Pitch	0%	BWLON75 (baseline)	2	1	Not much workload.
76	8	Pitch	0%	BWLON7.5	6	4	Much easier to PIO.
76	9	Pitch	0%	BWLON15	4	2	Able to get desired still. Oscillatory but not too bad.
76	10	Pitch	0%	BWLON05	9	5	Not acceptable. Not adequate performance. Barely controllable. Extensive compensation.
78	1	Roll	5%	BWLAT75 (baseline)	4	2	It was a hard time. It should be easier than that.
78	2	Roll	5%	BWLAT25	5	3	Touched the stops. Did well until the end .
78	4	Roll	5%	BWLAT50	6	4	More and bigger oscillations. Easy to get out of phase. PIO. Extensive compensation.
78	6	Roll	5%	BWLAT15	7	5	Almost unacceptable. Controllability not an issue until the last two seconds, deep oscillations.
78	7	Roll	5%	BWLAT10	5	3	Better than the last one.
78	8	Roll	5%	BWLAT7.5	8	4	Worse than the last one. Easy to get in a PIO. Not acceptable or adequate.
78	9	Roll	5%	BWLAT15	5	3	Less anticipation, more linear. Oscillations but easier than the previous one. Borderline desired.

Table D-18. Pilot 3 actuator natural frequency ratings — comments (continued)

Evaluation: Actuator Natural Frequency - Pilot: 3 - Date: 06/22/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
78	10	Roll	5%	BWLAT50	4	2	Desired performance. Not a lot of workload. Small ping-pong action. A lot like the baseline.
78	11	Roll	5%	BWLAT05	9	5	Have to back out of the loop to keep control. Hard touched the stops. Oscillations due to time delay. High workload. Not an acceptable airplane.

D.6 PASSIVE INCEPTOR VARIABLE COMMAND SENSITIVITY

Table D-19. Pilot 1 passive inceptor command sensitivity ratings — comments

Evaluation: Command Sensitivity Passive Stick - Pilot: 1 - Date: 07/09/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
72	1	Pitch	5%	CSLON100 (baseline) pure discrete	2	1	Easy. Good airplane. Gross acquisition and fine tracking easy to do.
72	2	Pitch	5%	CSLON100 (baseline)	3	1	Harder task. Forward stop once.
72	3	Pitch	5%	CSLON90	2	1	Lighter forces in both directions. Get used to it after a while. Not overly sensitive. Easier to track to green.
72	4	Pitch	5%	CSLON80	4	1	Seems heavier than last. Fine tracking good. Heavier forces than I would like. Forward stop 2 times.
72	5	Pitch	5%	CSLON120	3	1	Lighter than the previous one. Similar to the baseline, maybe lighter. I can do the job fine.

Table D-19. Pilot 1 passive inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Passive Stick - Pilot: 1 - Date: 07/09/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
72	6	Pitch	5%	CSLON100 (baseline)	3	1	I really can't tell the difference from the previous. Maybe a hair heavier. Forward stop 2 times. Back stop one time.
72	7	Pitch	5%	CSLON70	3	1	Similar to the baseline, maybe slighter lighter forces. All very similar. Hard to tell differences. Hand is tired at the end.
72	8	Pitch	5%	CSLON100 (baseline-blind)	2	1	Lighter than the previous one. I am mostly seeing the difference in gross acquisition. Easier to get to the green.
72	9	Pitch	5%	CSLON140	3	1	Maybe a little heavier than the previous one. Fine tracking no problem. Gross acquisition harder to acquire.
72	10	Pitch	5%	CSLON60	4	1	Heavier than the previous one. I can get the job done. Wish I had more control. Fine tracking is easy.
V_C							
73	1	Pitch	5%	CSLON100 (baseline) pure discrete	2	1	Easy. No PIO. Little compensation.
73	2	Pitch	5%	CSLON100 (baseline)	2	1	Compensation not an issue. No problems.
73	3	Pitch	5%	CSLON80	3	1	Very similar to the baseline. Initial reaction: heavier but small differences. Different force requirement, forces are too heavy and I prefer lighter. No PIO tendency.
73	4	Pitch	5%	CSLON60	2	1	Very similar to the previous. Heavier than the baseline. I can get the G I want. No fine tracking problem. A little lighter than the previous.

Table D-19. Pilot 1 passive inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Passive Stick - Pilot: 1 - Date: 07/09/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
73	5	Pitch	5%	CSLON100 (baseline)	2	1	Very close to the last one. Easy. Hard to tell the difference.
73	6	Pitch	5%	CSLON120	3	1	A little more sensitive than the baseline. Easier to overshoot Gs.
73	7	Pitch	5%	CSLON140	4	2	More sensitivity for fine tracking. Bobbling and overshooting. It is easy to adapt to.
73	8	Pitch	5%	CSLON70	3	1	Clearly heavier. Good tracking accuracy, better than the last. Gross acquisition is annoying.

Table D-20. Pilot 2 passive inceptor command sensitivity ratings — comments

Evaluation: Command Sensitivity Passive Stick - Pilot: 2 - Date: 07/03/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
60	1	Pitch	5%	CSLON100 (baseline) pure discrete	2	1	–
60	2	Pitch	5%	CSLON100 (baseline)	3	3	For NU must monitor AoA. Modulating and keeping the AoA needle in the green is the most difficult part of the task. Task performance a little bit compromised.

Table D-20. Pilot 2 passive inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Passive Stick - Pilot: 2 - Date: 07/03/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
60	3	Pitch	5%	CSLON90	4	3	There is some linearity from gross acquisition to fine tracking when NU. ND is not as noticeable. When I came off the input the pitch rate stagnated, more compensation.
60	4	Pitch	5%	CSLON80	4	3	Have to modulate in NU. Sometimes NU stagnation from gross acquisition. ND not as much. Tight control-undesirable motions.
60	5	Pitch	5%	CSLON70	4	3	A lot has to do with the transition point. ND I go full forward stick until I get close, no modulation. Transition to the capture is the issue.
60	6	Pitch	5%	CSLON60	4	3	Stagnated pitch rate in ND. There is a breakpoint. Hard to modulate.
60	7	Pitch	5%	CSLON100 (baseline)	4	3	A lot of oscillations that I do not like.
60	8	Pitch	5%	CSLON120	3	3	Dramatically increase then decrease. Better than last time.
60	9	Pitch	5%	CSLON130	4	3	Not very predictable, especially in the transition from gross acquisition to tracking task.
60	10	Pitch	5%	CSLON140	3	3	Not as many unpredictable pitch rate changes.

Table D-20. Pilot 2 passive inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Passive Stick - Pilot: 2 - Date: 07/03/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
61	1	Pitch	5%	CSLON100 (baseline) pure discrete	2	1	Very predictable. Linear change of pitch rate. Divide the task in two portions: G meter and the fine tracking.
61	2	Pitch	5%	CSLON100 (baseline)	3	2	More oscillations. A little bit of a PIO tendency. Same division of attention of the task. No difficult gross acquisition. Fine tracking more difficult.
61	3	Pitch	5%	CSLON80	3	2	Some oscillations when I transition from the G meter to the transition [point]. HD not as bad.
61	4	Pitch	5%	CSLON60	3	2	I was looking at the G meter more, so the release was not quite right.
61	5	Pitch	5%	CSLON100 (baseline)	3	2	–
61	6	Pitch	5%	CSLON140	3	2	–
61	7	Pitch	5%	CSLON160	3	2	Oscillations.
61	8	Pitch	5%	CSLON60	3	2	Oscillations. Slowed down as well.

Table D-21. Pilot 3 passive inceptor command sensitivity ratings — comments

Evaluation: Command Sensitivity Passive Stick - Pilot: 3 - Date: 07/02/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
PA							
53	1	Pitch	5%	CSLON100 (baseline)	4	2	Not more than minimal compensation for desired. Not too difficult to get to the AoA. The increment of compensation due to SoS is higher than it should be.
53	2	Pitch	5%	CSLON100 (baseline) pure discrete	3	1	Much easier: level 1. Easy to get desired AoA.
53	3	Pitch	5%	CSLON30	6	3	I feel I am using larger stick motions. Physically more demanding. More sluggish. Not as good performance. Much more concentration needed. Delay to the response.
53	4	Pitch	5%	CSLON105	5	2	More responsive than last one. More oscillations. Ping pong. Not as easy to stop at AoA = 9.5. More sensitive. Smaller inputs to move the play. Smaller, higher frequency oscillations.
53	5	Pitch	5%	CSLON100 (baseline)	4	2	Some oscillations around the target. Better than the last one. Not as bouncy as the last one. If I lower the gain, not hard.
53	6	Pitch	5%	CSLON95	4	2	Not much to complain about this. The sensitivity feels like the baseline, slightly worse. Not enough more difficult to give a 5.
53	7	Pitch	5%	CSLON80	5	2	Larger motions again, my wrist is tired. Less sensitive, more sluggish. Large motions of my hand. Not as good performance in terms of tracking.

Table D-21. Pilot 3 passive inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Passive Stick - Pilot: 3 - Date: 07/02/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
53	8	Pitch	5%	CSLON110	4	2	Better performance and smaller workload. More in control. More like the baseline. The target is a little more difficult than the baseline.
53	9	Pitch	5%	CSLON120	4	3	Feels heavier. I do not feel as confident. Larger motions. Changing technique to adapt to the slowness of the response.
53	10	Pitch	5%	CSLON70	5	2	More confident. I have no idea. Initially feeling better with a large input. Frustration.
53	11	Pitch	5%	CSLON130	4	2	More sensitive. No fast oscillations. Better precision at AoA 9.5.
V_C							
89	1	Pitch	5%	CSLON100 (baseline) pure discrete	3	2	Oscillations cause there to be an extra workload making HQR = 3. There could be a better airplane.
89	2	Pitch	5%	CSLON100 (baseline)	4	2	Larger and more persistent uncommanded motions. Still in desired. Compensation increased.
89	3	Pitch	5%	CSLON80	2	1	Seems easier, can still get to 2.5 and 0 Gs. The wrist action is lighter. Looks like baseline pure discrete or better. Very little uncommanded motions.
89	4	Pitch	5%	CSLON100 (baseline)	4	2	More activity to hold it at the center of desired. More workload and compensation. Minor but annoying oscillations and ping-pong.
89	5	Pitch	5%	CSLON60	4	2	Larger motions for fine tracking, a little on the flat side. A little insensitive. Would want more sensitivity on the pull.

Table D-21. Pilot 3 passive inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Passive Stick - Pilot: 3 - Date: 07/02/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
89	6	Pitch	5%	CSLON100 (baseline)	4	2	The previous was slightly more aggravating than the baseline, similar though. Sizes of motion feel different.
89	7	Pitch	5%	CSLON70	2	1	Easier to track than the baseline. Quite good. Easier than the pure discrete baseline. Less excursion. Less nervous.
89	8	Pitch	5%	CSLON100 (baseline)	4	2	G bobbling around more than last.
89	9	Pitch	5%	CSLON120	5	3	Worse than the baseline. PIO is downgrading, I don't want to bobble around the sky like this.
89	10	Pitch	5%	CSLON110	6	4	Worse than the last. I have the impression that the slope getting to G is flatter, insensitive. Arm is getting tired. Extensive compensation at the high end.
89	11	Pitch	5%	CSLON100 (baseline)	4	2	Easier than the last. More uniform displacement. Smaller oscillations.
89	12	Pitch	5%	CSLON90	2	1	Easier than the baseline. Some undesired motions. Satisfactory without improvement.
89	13	Pitch	5%	CSLON100 (baseline)	3	1	Not as far apart from the previous. Hard time telling the difference. I must have learned.
89	15	Pitch	5%	CSLON130	5	3	Bouncier than the baseline. Easier to couple. PIO. More sensitive initial response. Easy to overshoot, unpredictable nature. It looks like higher bandwidth with the pilot in the loop.

Table D-22. Pilot 5 passive inceptor command sensitivity ratings — comments

Evaluation: Command Sensitivity Passive Stick - Pilot: 5 - Date: 08/01/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
96	1	Pitch	5%	CSLON100 (baseline) pure discrete	3	2	Slow and sluggish. Slight bobble. About +/- 1 degree oscillations/overshoots on fine tracking. Harder for large steps. 2-element task: gross acquisition then tracking. Have to back out of control.
96	2	Pitch	5%	CSLON100 (baseline)	3	2	Only saw tolerance exceeded once. Same comments as previous. Doable.
96	3	Pitch	5%	CSLON80	3	2	Still sluggish in large capture, gross acquisition the same. Not much difference from previous one. A little more sensitive in fine tracking than the previous. Have to back out of the loop.
96	4	Pitch	5%	CSLON120	4	3	Gross acquisition similar. Fine tracking more sensitive for small deflections causing overshoots and more compensation. Moderate compensation.
96	5	Pitch	5%	CSLON100 (baseline) blind	3	2	Large deviation gross acquisition is sluggish, no different than previous. Oscillations may be less than the previous. Some oscillations in fine tracking. If I modify the control strategy, I can reduce them. Using small gentle inputs. Some compensation backing out of the loop.
96	6	Pitch	5%	CSLON60	3	2	Sluggish gross acquisition same as others, a little larger forces needed. A little better fine tracking, more manageable. Initial overshoot +/- 1 degree.

Table D-22. Pilot 5 passive inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Passive Stick - Pilot: 5 - Date: 08/01/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
96	7	Pitch	5%	CSLON50	3	2	Similar gross acquisition and fine tracking. 1–2 cycles to track, maybe a touch more oscillation. Back out of the loop.
96	8	Pitch	5%	CSLON100 (baseline)	3	2	About 2 overshoots. Slight oscillation tendency.
96	9	Pitch	5%	CSLON140	4	3	Sensitive fine tracking, have to dampen/control inputs. Balancing act. More sensitive, have to back out of control loop and pulse the stick.

D.7 ACTIVE INCEPTOR COMMAND SENSITIVITY

Table D-23. Pilot 1 active inceptor command sensitivity ratings — comments

Evaluation: Command Sensitivity Active Stick - Pilot: 1 - Date: 07/19/12									
Session	Run	Axis	Configuration				HQR	PIOR	Comments
			Task	Gradient Scale	Des Breakpoint	Max/Min n_z			
V_C									
94	1	Pitch	Pure Discrete	2	0	2/.5	2	1	Easy. Easy forces. No problem.
94	2	Pitch	Discrete & SoS	2	0	2/.5	2	1	SoS makes it a little harder.
94	3	Pitch	Discrete & SoS	3	0	2/.5	4	1	Stick is pushing back at me then releases when I'm close. I am not sure I like it. Disconcerting push back. Nonlinear feel.
94	4	Pitch	Discrete & SoS	4	0	2/.5	5	1	I do not like that, really fighting back on me. Quicker push back in ND, a little bit in NU causing some PIO. Pilots like predictability. Different in character from before, like a soft stop.
94	5	Pitch	Discrete & SoS	3	1	2/.5	4	1	More like first active stick, still increases force then releases in ND. The stick is "bucking" at me.
94	6	Pitch	Discrete & SoS	3	2	2/.5	4	1	Still bucking. Pushing back then releasing in ND. I do not feel much difference from the last one. Heaviness in NU but is still linear.
94	7	Pitch	Discrete & SoS	3	4	2/.5	4	1	Non-linear changes in ND. High forces against me. I still don't like it. Maybe not as sharp-edged. A bit softer transition.

Table D-23. Pilot 1 active inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Active Stick - Pilot: 1 - Date: 07/19/12									
Session	Run	Axis	Configuration				HQR	PIOR	Comments
			Task	Gradient Scale	Des Breakpoint	Max/Min n_z			
94	8	Pitch	Discrete & SoS	3	5	2/.5	5	1	NU is getting to be too heavy. It has an electronic stop feel. ND is still bucking and is also a little heavier.
94	9	Pitch	Discrete & SoS	3	4	1.75/.25	3	1	Just a little nonlinearity. Better. Closer to the baseline. Lighter than the previous one.
94	10	Pitch	Discrete & SoS	3	4	2.25/.25	2	1	Heavier than the baseline. Fairly linear. As good as the baseline. Forces are a little heavier.
94	11	Pitch	Discrete & SoS	3	4	1.25/.25	5	1	This is too heavy. I can't get to the G in NU gross acquisition. Non-linear feel in ND.
94	12	Pitch	Discrete & SoS	3	4	1.5/.25	4	1	Too heavy NU. Worse than in ND due to the forces. Bucking felt slightly rounded, softer edged. The main issue is the heaviness.
94	13	Pitch	Discrete & SoS	3	4	1.75/.5	4	1	Lighter forces but not linear. Softer on NU bucks.
PA				Stick Shaker					
95	1	Pitch	Pure Discrete				2	1	No problems doing task. Pretty easy.
95	2	Pitch	Discrete & SoS				3	1	Not as easy. Harder task. No over-control tendencies.

Table D-23. Pilot 1 active inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Active Stick - Pilot: 1 - Date: 07/19/12									
Session	Run	Axis	Configuration				HQR	PIOR	Comments
			Task	Gradient Scale	Des Breakpoint	Max/Min n_z			
95	3	Pitch	Discrete & SoS-Shaker ON	10			2	1	Just like the previous one. I am intentionally going a little higher. It is a very nice cue, not overwhelming. It tells you when you are reaching alpha limits. I just go FBS and close on fine tracking. Substitute a scan to alpha for the shaker during gross acquisition. Initially gross acquisition was made two parts. The shaker comes on very quietly. It simplified my scan-5.
95	4	Pitch	Discrete & SoS-Shaker ON	9			2	1	I could not tell much difference. Inconsequential difference wherever alpha shaker is set, it has to be at the optimal alpha. I Just back off when it comes on.-5
95	5	Pitch	Discrete & SoS-Shaker ON	8.5			3	1	If it comes on too early, the pilot uses the gauge more. The pilot sees that it is early and has to look up more to know how much more to go. It is not the optimal place for me.-3

Table D-24. Pilot 2 active inceptor command sensitivity ratings — comments

Evaluation: Command Sensitivity Active Stick - Pilot: 2 - Date: 07/19/12									
Session	Run	Axis	Configuration				HQR	PIOR	Comments
		V_C	Task	Gradient Scale	Des Breakpoint	Max/Min n_z			
91	1	Pitch	Pure Discrete	2	0	2/.5			I don’t like it. Objectionable in the transition. Forces heavy then breaks. I feel disconnected from the vehicle. Does not affect the possibility to do the task.
91	2	Pitch	Pure Discrete	2	0	2/.5			Notchiness in the stick. Getting more used to it but do not like it. I did not feel the bumps.
91	3	Pitch	Pure Discrete	2	0	2/.5	4	1	I feel the bump more in ND than NU. Compensation not bad. The cue did not help me. I do not like it for HQR. Not much PIO. Desired performance > 50%
91	4	Pitch	Discrete & SoS	2	0	2/.5	4	1	Notch in the fine tracking. Don’t feel change in gradient.
91	5	Pitch	Discrete & SoS	3	0	2/.5	4	1	The active gradient does not help me in NU. A bit of help in ND. I cannot maneuver care-free. ND I can feel it activating.

Table D-24. Pilot 2 active inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Active Stick - Pilot: 2 - Date: 07/19/12									
Session	Run	Axis	Configuration				HQR	PIOR	Comments
		V_C	Task	Gradient Scale	Des Breakpoint	Max/Min n_z			
91	6	Pitch	Discrete & SoS	4	0	2/.5	4	1	I still have to look at the G meter. As soon as I start the input I can feel the gradient change: a nuisance.
91	7	Pitch	Discrete & SoS	4	1	2/.5	4	1	Notchiness in the final portion of the capture task. It is not preventing me from over G-ing.
91	8	Pitch	Discrete & SoS	4	2	2/.5	4	1	I just notice the bump at the end of the capture sometimes, more on ND. Less bumps than before.
91	9	Pitch	Discrete & SoS	4	4	2/.5	4	1	Notching back and forth in ND when changing position. The abrupt task does not help.
91	10	Pitch	Discrete & SoS	4	0	2/.5	4	1	Notchiness may be more noticeable. Not more frequently but larger bumps in ND. A little more distinct.

Table D-24. Pilot 2 active inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Active Stick - Pilot: 2 - Date: 07/19/12									
Session	Run	Axis	Configuration				HQR	PIOR	Comments
		V_C	Task	Gradient Scale	Des Breakpoint	Max/Min n_z			
91	11	Pitch	Discrete & SoS	4	4	1.5/.25	5	1	NU is definitely different now. I do not like it. It is very non-linear, a lot of notchiness. ND is not bad.
91	12	Pitch	Discrete & SoS	4	4	1.75/.25	5	1	ND is pretty good. In NU it seems to release and come back, not predictable. It is fighting me. The G seems to be more bouncy. I don't know how much force to use.
91	13	Pitch	Discrete & SoS	4	4	1.25/.25	5	1	Seems to come on very soon. This might prevent from over G-ing. Force release is dramatic. Very unpredictable in NU. Worst one yet. ND is fine.
91	14	Pitch	Discrete & SoS	4	4	5/.25	2	1	No bumps or gradient changes felt. Tracked like commanded.
		PA		Alpha Shaker					
92	1	Pitch	Pure Discrete	off			2	1	Predictable. No PIO tendencies. Sometimes coasts beyond the point where I wanted to stop. Not much compensation.

Table D-24. Pilot 2 active inceptor command sensitivity ratings — comments (continued)

Evaluation: Command Sensitivity Active Stick - Pilot: 2 - Date: 07/19/12									
Session	Run	Axis	Configuration				HQR	PIOR	Comments
		V_C	Task	Gradient Scale	Des Breakpoint	Max/Min n_z			
92	2	Pitch	Discrete & SoS	off			2	1	Overshoot tendency more than before. Tracking like I want it to.
92	3	Pitch	Discrete & SoS	10			2	1	No differences. Not getting close to red (ade) at all.
92	4	Pitch	Discrete & SoS	9			2	1	Shaker at mid-green felt activation. Doesn't change HQ. Good cue to not exceed. Does not change how I do the task.
92	5	Pitch	Discrete & SoS	8.5			2	1	Activates at the beginning of the green. Distracting while trying to track because it is firing in the middle of the target.
92	6	Pitch	Discrete & SoS	9.5			2	1	Have not felt it at all. I am on the low side of alpha and always have.

D.8 PASSIVE INCEPTOR SCHEDULED COMMAND SENSITIVITY

Table D-25. Pilot 1 scheduled command sensitivity ratings — comments

Evaluation: Gain Scheduling - Pilot: 1 - Date: 07/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
93	1	Pitch	5%	baseline pure discrete	2	1	Easy to do fine tracking. Monitoring the G during the gross acquisition. Forces are light enough.
93	2	Pitch	5%	baseline discrete & SoS	2	1	Same task. Just a little more annoying with a wandering bar. Still easy to do.
93	3	Pitch	5%	Gain Sched Switch ON	3	1	Forces are heavier. Have to use a different technique. Only advantage is that it helps control the amount to pull back. No big advantages and just made the forces heavier.

Table D-26. Pilot 2 scheduled command sensitivity ratings — comments

Evaluation: Gain Scheduling - Pilot: 2 - Date: 07/19/12							
Session	Run	Axis	S.M. (cbar)	Configuration	HQR	PIOR	Comments
V_C							
90	1	Pitch	5%	pure discrete			Initial response as expected, then seems to slow down. I can deal with it. Bobble tendency on target. When aggressive, stagnates before I want to stop.
90	2	Pitch	5%	pure discrete	3	2	Bounces back when I try to stop it. It does not stop precisely on target. Oscillations when I go to capture. Compensation to capture the target.
90	3	Pitch	5%	discrete & SoS	3	2	A bit of oscillation, same as before. It is hard for me to predict the rate. Bobbles on target. Minor oscillations with SoS.

D.9 AFI-FCS AUGMENTED AIRCRAFT HANDLING QUALITIES

Table D-27. Pilot 1 AFI-FCS augmented aircraft ratings — comments

Evaluation: FAA Model - Discrete & SoS - Pilot: 1 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
82	1	Pitch	baseline	2	1	A couple overshoots to steady. Some bobble. Easy to acquire alpha. Forces lighter. Tracking is fine.
82	2	Pitch	baseline	2	1	Getting better at the task.
82	3	Pitch	baseline	1	1	Easy because of the mostly blocked SoS.
V_A						
83	1	Pitch	baseline	2	1	Great forces. No PIO tendency. Easy tracking. Very little overshoot. Good accuracy.
83	2	Pitch	baseline	3	2	Some tendency to bounce around target. About 2 corrections when fine tracking. ND sensitivity a little too high.
83	3	Pitch	baseline	3	2	3–4 times back and forth during ND, some from disturbance. Does not happen going up. Open loop and release: no issues.
V_C						
84	1	Pitch	baseline	3	2	Only when I correct through neutral I have oscillations. Same ND phenomenon-doesn’t happen every time, only through neutral control. Do not compensate through neutral, slowly release the force when close to target to avoid oscillations. Stick neutral - ND: oscillations.
84	2	Pitch	baseline	3	2	Noticed a little bubble on NU but not as easy to get into as ND.
84	3	Pitch	baseline	3	2	Trying more aggressive.
Pure SoS						
85	1	Pitch	PA baseline	2		Very easy. Does not seem like I am working very hard.

Table D-27. Pilot 1 AFI-FCS augmented aircraft ratings — comments (continued)

Evaluation: FAA Model - Discrete & SoS - Pilot: 1 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
85	2	Pitch	Va baseline			Tendency to bobble. Sensitivity issue.
85	3	Pitch	Va baseline	4	2	Getting desired but harder task. Moderate compensation due to avoiding over-control by smoothing inputs.
85	4	Pitch	Va baseline	4	2	Quickly trying to correct errors leads to a bobble.

Table D-28. Pilot 2 AFI-FCS augmented aircraft ratings — comments

Evaluation: FAA Model - Discrete & SoS - Pilot: 2 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
81	1	Pitch	baseline	4	2	Easier to overshoot, need less-aggressive inputs and to come off earlier. Difficult to modulate the correct back stick pressure/force for NU. Not quite as much PIO even though it was still evident.
81	2	Pitch	baseline	4	2	Being aggressive causes PIO. Works better in open loop.
81	3	Pitch	baseline	4	2	Rate slows down and it takes longer in NU, concentrate more on alpha. ND rate is quick and then oscillates.
V_A						
79	1	Pitch	baseline	4	2	NU and ND tasks are different. NU–have to control the value of alpha. ND–concentrate on the target. PIO tendencies in fine tracking, 2–3 oscillations. More coupling with the roll axis.
79	2	Pitch	baseline	4	2	Aggressive capture causes oscillations. Open loop inputs make it better, learning how to compensate. Fine gross acquisition.
79	3	Pitch	baseline	4	2	The small SoS could be causing the oscillations. Oscillations more noticeable now than run 2.

Table D-28. Pilot 2 AFI-FCS augmented aircraft ratings — comments (continued)

Evaluation: FAA Model - Discrete & SoS - Pilot: 2 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_C						
80	1	Pitch	baseline	4	2	Gross acquisition fine. Still oscillations around target during fine tracking. Invert the command to capture, which produces overshoots.
80	2	Pitch	baseline	4	2	NU task easier, not exceeding limits. More cross inputs to roll axis.
80	3	Pitch	baseline	4	2	No difference.

Table D-29. Pilot 3 AFI-FCS augmented aircraft ratings — comments

Evaluation: FAA Model - Discrete & SoS - Pilot: 3 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
86	1	Pitch	baseline-pure discrete	2	1	Alpha seems to respond less quickly to the stick input = alpha overshoot. Less oscillatory than Calspan standard augmentation with exception of alpha overshoot.
86	2	Pitch	baseline	2	1	Overshoot alpha again. Easy to keep in desired. SoS does not degrade performance as much as standard with SoS. Does a pretty good job canceling the disturbance.
V_A						
87	1	Pitch	baseline-pure discrete	4	2	More bouncy. Large time delay. Tends to overshoot. Not enough time to capture. Feels like disturbance even though there is none. If you go slower it is better, but not with tight control. Uncommanded motions do occur.
87	2	Pitch	baseline	5	3	Hard to push it down. Adequate but not desired. More workload and worse performance. Significant increase in workload–considerable compensation.
87	3	Pitch	baseline	5	3	Increase my workload to see if I can avoid those things. Have to work hard to keep desired. Too much ping-pong. Feels like an unpredictable low-frequency airplane.

Table D-29. Pilot 3 AFI-FCS augmented aircraft ratings — comments (continued)

Evaluation: FAA Model - Discrete & SoS - Pilot: 3 - Date: 07/12/12						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_C						
88	1	Pitch	baseline-pure discrete	3	2	Not much different from V_A. A lot of force needed to get it going. Similar problem of capturing the target and then sliding through. Not as much trouble anymore–learned.
88	2	Pitch	baseline	4	2	Compensation level has not gone up a lot but there is a little more workload. The delayed action is annoying. A little bit of oscillations.

D.10 AFI-FCS AUGMENTED AIRCRAFT ENVELOPE PROTECTION

Table D-30. Pilot 1 AFI-FCS augmented aircraft envelope protection — comments

Evaluation: Alpha Limitor - Pilot: 1 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
PA						
102	1	Pitch	FPA Steps Up 1°			I got a kick down, I did not like it. I can't get there anymore.
102	2	Pitch	Theta Steps Up 2°			I do not like the kick. Stop at alpha=13.9°, v=111
102	3	Pitch	FPA Steps Down -1°			There is a kick. I cannot pull the nose up from maximum speed condition. Stop at v=200.
102	4	Pitch	Theta Steps Down -3°			Start to feel limit at v=175, it is harder to push the nose down. I got the kick. PIO between throttle and FPA.
102	5	Pitch	FPA Captures 3.5°			More lead to the FPA cmd to capture more quickly. I will ignore the FPA next time. It is different nose down–easier than nose up.

Table D-30. Pilot 1 AFI-FCS augmented aircraft envelope protection — comments (continued)

Evaluation: Alpha Limitor - Pilot: 1 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
102	6	Pitch	FPA Captures 3.5°	4	2	I am controlling the actual FPA marker instead of the hollow circle (too "squirrely," too much lag). New technique–overshoot to capture faster and beat the lag. Can get desired this way but is more workload. I can get rid of my command when the FPA command reverses.
102	7	Pitch	FPA Captures 5°	4	2	Capture takes a long time. Overcontrol a little. The response depends on the stick rate. Hallow circle reverses quickly. The FPA command reverses two times in the ND: disturbance.
102	8	Pitch	Theta Captures	5	3	Non-linear response, less predictable. 2–3 overshoots in fine tracking. Workload getting higher throughout. Not as easy.

Table D-31. Pilot 1 AFI-FCS augmented aircraft envelope protection — comments

Session:102 Records:1-2	
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:	Didn't like the kicks that preceeded the actual limit. When I reached the limit it was evident because there was no more command authority.
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 flight 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:	

Session:102 Records: 1-4	
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:	A couple problems: got kicks & "squirelly" behavior as I approached limits. The attitude bounced around. Then when at the limit I pulled up to level airplane and it took forever to level aircraft. Then I got into a PIO with the throttle going full up then back.
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the limit flight 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:	

Table D-32. Pilot 2 AFI-FCS augmented aircraft envelope protection — comments

Evaluation: Alpha Limitor - Pilot: 2 - Date: 08/07/2012						
Session	**Run**	**Axis**	**Configuration**	**HQR**	**PIOR**	**Comments**
105	1	Pitch	FPA Steps Up 1 °			I just move the predictor circle and wait for the actual gamma to catch up. Full back and I cannot do the task at 120, 10.9°. Throttle Position is an important tactal cue.
105	2	Pitch	Theta Steps Up 1			Not difficult but pitch attitude seems to move on its own and I have to hold back pressure at 120, 11.1°. I cannot capture, track or control the airplane.
105	3	Pitch	PA Steps Down -			Airspeed is slowly increasing while altitude is decreasing. Auto throttles maintaining speed at 150. Big burble, I have lost the capability to control. Throttles on idle. Started feeling pressure at 170. Full Forwards stick at 190 and the speed stays at 200. Two transients.
105	4	Pitch	eta Steps Down			Throttles at idle at 150. Tracking is okay. Need to start using force at 180. Not sure what the system is trying to do, pilots need to know.
105	5	Pitch	FPA Captures 3.5	2	1	Task is not the same as before. Easy to put in circle, FPA follows and catches up. Being aggressive and there is no PIO. Good handling qualities . No time restraint.
105	6	Pitch	ptures 3.5° no cm	5	1/3	A lot of lagging. It is an open-loop guessing game. Hard to be aggressive , there is too much lag between command and gamma response. Can be very PIO sensitive.
105	7	Pitch	FPA Captures 5°	3	2	Takes a long time to coast up. So, put the predictor beyond the target.
105	8	Pitch	eta Captures gai	3	2	More oscillatory ND. ND stop at 175 then couldn't get any further. Not doing what I want on occasions. Protecting but not letting me do the task.

Session:105

Effectiveness of Envelope Protection Design Element							Comments
For the task required/flight phase under consideration, the envelope protection was:							What the system was trying to do was not completely clear. I understand that it was trying to prevent maximum alpha and min/max airspeed, but otherwise the aircraft responses were not clear. For example, when I centered the stick at the end of the nose down runs, the pitch and power responses were not clearly understood. This will result in the pilots being unsure what the automation will do and thus not trusting. Additionally, a difference between what the pilot expects and what the system does leads to a high potential for incidents/accidents. On the nose down exercises, there was a definite and objectionable pitch transient that appeared to occur when the system lost the ability to control airspeed with power. I was not always sure what the engines were doing or trying to do. Back-driven throttles would significantly improve the awareness of the pilot to thrust changes.
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 flight 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:							

Table D-33. Pilot 3 AFI-FCS augmented aircraft envelope protection — comments

Evaluation: Alpha Limitor - Pilot:3 - Date: 08/09/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
			Mode = 2	outside/in lims		
108	1	Pitch	FPA Steps Up 1°			The mode change was not good. I could not go to 14°, so I was limited when I should not have been. FBS at 113, 12° and still climbing in altitude. It should tell me when in protection mode–a red light or something.
108	2	Pitch	Theta Steps Up 1°			What is it saving me from? Protection at 5° is ridiculous.
108	3	Pitch	FPA Steps Down -1 °			Keeping speed at 150 with active throttle. When throttle is idle, speed maxed at 200.
108	4	Pitch	Theta Steps Down -3°			Full stick at 180. Idle throttles until max 200.
108	5	Pitch	FPA Captures 3.5°	4	2	When I use the big circle for small captures it is ok. For bigger captures the response is too slow. The FPA cmd circle is quite easier to follow than just the FPA which tends to overshoot. I can learn to go a little bit long–it makes FPA quicker. Undesirable motions.
108	6	Pitch	FPA Captures 3.5° no cmd circle	7	4	A huge amount of lead is required. The nose is moving around in a non-natural way when trying to quicken up the FPA. For this task there is a non-tolerable workload. It is not possible to keep it in desired. This would be unsafe with disturbance.
108	7	Pitch	FPA Captures 5°	4	2	It takes a long time for FPA to get in the FPA cmd. Not seeing anything that should drive any protection.
108	8	Pitch	FPA Captures 5° no cmd circle	7	4	Same as before. Feels unnatural like I am not flying a plane.
108	9	Pitch	Theta Captures	3/4	2	Big changes are worrying. Can see the mode change from the FPA cmd movement, but it shouldn’t be jumping around like that.

Table D-34. Pilot 3 AFI-FCS augmented aircraft envelope protection — comments

Session:108 Records:1	
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 flight 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:	
Session:108 Records: 2	
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 flight 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:	

Table D-35. Pilot 3 AFI-FCS augmented aircraft envelope protection — comments

Session:108 Records:3	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope protection	Started at too low airspeed.
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 flight condition was maintained:	Started at too low airspeed.
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:	
Session: 108 Records: 4	
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 flight 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:	

Table D-36. Pilot 5 AFI-FCS augmented aircraft envelope protection — comments

Evaluation: Alpha Limitor - Pilot: 5 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
			PA	mode=0		
98	1	Pitch	FPA Steps up 1°			Very good acquisition. Excellent tracking. Very stable. Can feel the protection come in at 135. Full aft stick and velocity slowing at 125, unable to capture. Alpha stayed at 14.6.
98	2	Pitch	Theta Steps up 1°			Very stable tracking. Definitely level 1. Feel forces at 135, never got to the limit during the task.
98	3	Pitch	Theta Steps up 2°			Stable, could finish task. Feel forces at 145. Small degree of pitch authority at 210. Alpha=14.4. Release and recapture attempt, can't capture. Expected more authority.
98	4	Pitch	FPA Steps down -1°			Good characteristics and captures. Forward pressure at 160. Hitting stop at 190. Max speed at 200.
98	5	Pitch	Theta Steps down -1°			Very nice and stable. Very slight forward force to hold condition.
98	6	Pitch	Theta Steps down -2°			A bit of bobbles when getting to limit conditions. Full forward stick at 160. Relay and recapture gives a lot of pitch authority. Do not feel the limit.
98	7	Pitch	FPA captures 3.5°	2	1	Very nice and stable. Excellent acquisition and tracking. Solid airplane.
98	8	Pitch	FPA captures 5°	2	1	Very well behaved, very nice.
98	9	Pitch	Theta captures	2	1	Not as responsive as I want it to be, but doing pretty good. Very stable. Excellent.

Table D-37. Pilot 5 AFI-FCS augmented aircraft envelope protection — comments

Session: 98 Record:1,2,3						
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 flight 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:						
Started to come in, but was not as definible condition, grey area. Initially predictable, in the subsequent recapture attempts. Don't know why/how protection implemented. What flight condition? Recapture attempts aborted in behavior not fully understood. I have a question on recapture logic.						
Session: 98 Record 4,5,6						
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 flight 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:						
Transition point not fully apparent.						
Evaluation: Soft Alpha Limitor - Pilot: 5 - Date: 08/03/2012						
Session	**Run**	**Axis**	**Configuration**	**HQR**	**PIOR**	**Comments**
101	1	Pitch	FPA Steps up 1°			Speed stability. Low frequency shaker. Speed Stability provided cue of the change in speed.
101	2	Pitch	Theta Steps up 1°			Tracking still good. Shaker obvious. Speed and stability well behaved.
101	3	Pitch	FAA model FPA Steps up 1°			Definite uncommanded pulse in the system

Table D-38. Pilot 2 AFI-FCS augmented aircraft envelope protection — comments

Evaluation: Velocity Limitor - Pilot: 2 - Date: 08/07/2012						
Session	**Run**	**Axis**	**Configuration**	**HQR**	**PIOR**	**Comments**
			Va	mode=0		
106	1	Pitch	FPA Steps Up 1°			
106	2	Pitch	Theta Steps Up 1°			Back force at KCAS = 200, alpha = 6.8°. Full stick soon after, speed decreasing to KCAS = 165, alpha = 12°. Pitch transient when the airspeed started to drop off.
106	3	Pitch	FPA Steps Down -1°			Full forward stick KCAS = 400, idle throttle. Did not stop at KCAS = 375 when released.
106		Pitch	Theta Steps Down -2°			Power at idle when KCAS = 250. Force needed at KCAS = 385. Very suddenly Full forward and unable to capture. Max speed at KCAS = 400.
106	4	Pitch	FPA Captures 3.5°	2	1	FPA does not seem to lag as much as before. It goes down faster than up. Easier to predict than in PA. Disconcerning behavior at KCAS = 230.
106	5	Pitch	FPA Captures 3.5° No Cmd Circle	3	2	Harder to predict. I do not understand the control and/or they are not consistent.
106	6	Pitch	FPA Captures 5°	2	1	Predictable. I do not like the limits when the predictor drops down-it forces me to change technique.
106	7	Pitch	Theta Captures	2	1	Why is it dropping off now? I am not on the target yet. I like the G limit portion, not the other parts. I do not know what it is doing. At times I am not flying the airplane.

Session:106	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope protection	
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	
protection was:	Only perceptible on one nose-up run (theta tracking I think)-a pitch bobble that was very noticeable.
Not Predictable 1 2 **3** 4 5 Very Predictable	
With active envelope protection, the flight 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	
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:	
Uncertainty still exists as to what the system will do after the limit has been reached and then the pilot releases the stick. Lack of back-driven throttles decreases awareness of engine status.	

Table D-39. Pilot 3 AFI-FCS augmented aircraft envelope protection — comments

Evaluation: Velocity Limitor - Pilot: 3 - Date: 08/10/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
			V_A			
109	1	Pitch	FPA Steps Up 1°			Kind of weird because in the protection mode there is a big dead spot in the command path. I can't adjust the airspeed and I feel disconnected. In mode at speed of 215, not a huge transition. When I go to the new step my natural tendency is to put the gamma marker on the target, not the gamma command. I have no idea what the limit is.
109	2	Pitch	Theta Steps Up 1°			Tendency to overshoot. Full thrust at 250 then losing speed. FBS at 185, 8.5°. The airplane pitches down and I would not know why.
109	3	Pitch	FPA Steps Down -1°			FFS at 400 max.
109	4	Pitch	Theta Steps Up 1°			–
109	5	Pitch	Theta Steps Up 1°			The transition is ridiculous and scary. Totally unacceptable. What is this airplane doing? Disconnected from the plane.
109	6	Pitch	Theta Steps Down -3°			–
109	7	Pitch	Theta Steps Down -3°			I have to lead a lot then I overshoot. The neutral speed stability is a problem. I do not like that the neutral speed stability requires the protection. Adding more force to keep the nose going down seems more natural than the pull up conditions.
109	8	Pitch	FPA Captures 3.5°	4	2	A little overshoot–is it me or the flight control system? So far desired performance. The ball wanders around often and it is annoying. Too much uncommanded motion.

Table D-39. Pilot 3 AFI-FCS augmented aircraft envelope protection — comments (continued)

Evaluation: Velocity Limitor - Pilot: 3 - Date: 08/10/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
109	9	Pitch	FPA Captures 3.5° no cmd circle	7	5	A mind of its own! Not adequate performance. Too much work–tiring. Have to lead a lot during nose oscillations and they are bad for the passengers.
109	10	Pitch	FPA Captures 5°	4	2	Takes a while to get there. Desired performance not taking much compensation.
109	11	Pitch	FPA Captures 5° no cmd circle	7	5	High throttle activity. I am well within limits but I can still feel the protection. The workload is constraining.
109	12	Pitch	Theta Captures			–
109	13	Pitch	Theta Captures	5	2	No longer a linear airplane response. Am FBS multiple times and cannot capture. No PIO problem. It seems like someone is taking something away from me.

Table D-40. Pilot 3 AFI-FCS augmented aircraft envelope protection — comments

Session:109 Records:1	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight 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	
Disagree **1** 2 3 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	
Session:109 Records: 2	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight 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	
Disagree **1** 2 3 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	

Table D-41. Pilot 3 AFI-FCS augmented aircraft envelope protection — comments

Session:109 Records:3	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight 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	
Disagree **1** 2 3 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	
Session: 109 Records:6,7	
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	
Not Predictable **1** 2 3 4 5 Very Predictable	
With active envelope protection, the flight condition was maintained:	
Poorly 1 2 **3** 4 5 Very Accurately	
Summary:	
The benefits of the envelope protection were clearly demonstrated:	If have to have no speed stability.
Disagree 1 2 **3** 4 5 Agree	
I would encourage the use of an envelope protection such as this in	
Disagree 1 2 **3** 4 5 Agree	
If modifications are made, I would encourage the use of an envelope	
Disagree 1 2 **3** 4 5 Agree	
Additional Comments:	
Speed stability poor. The increase of forward stick force to hold altitude seemed more natual than for the nose high case.	

Table D-42. Pilot 5 AFI-FCS augmented aircraft envelope protection — comments

Evaluation: Velocity Limitor - Pilot: 5 - Date: 08/03/2012						
Session	Run	Axis	Configuration	HQR	PIOR	Comments
V_A mode=2						
97	1	Pitch	FPA Steps Up 1°			Very nice stable tracking. It is just a matter of pulling. Speed is slowing but airplane tracks well. Full aft cannot get capture at KCAS = 200 . Stabilizes at KCAS = 165. Some protection that prevented completion of task. Protection is obvious when triggered and active. Neutral apparent speed stability at KCAS = 200.
97	2	Pitch	FPA Steps Down 1°			Very benign tracking. Speed starting to pick up and is still good at KCAS = 325. Slowing down at KCAS = 345. KCAS = 375 full aft could not do tracking task. Neutral apparent speed stability up to KCAS = 375. The protection starts to feed in ranges of speeds. Most modern planes have this protection but need tools to make pilot aware of these changes.
97	3	Pitch	FPA Captures 3.5°	2	1	Nice tracking. Aircraft is not approaching any limits. Good handling qualities. Speed is good as long as stay within envelope.
97	4	Pitch	FPA Captures 5°	2	1	Good and predictable captures, slight compensation involved, super nice. Good aircraft characteristics. No oscillatory tendency in the fine tracking, excellent fine tracking.
97	5	Pitch	Theta Steps Up 1°			Slight bobble in the pitch. Can still pull at KCAS = 200 but at KCAS = 175 full aft and cannot accomplish task.
97	6	Pitch	Theta Steps Down 1°			Very good tracking. Increase in the column force at KCAS = 270. At KCAS = 380, unable to do the task at forward stick. Upper Limit of KCAS = 401. Let go–power at idol and 1 G until it returns to KCAS = 250 and the thrust comes back up. The envelope is apparent and effective.
97	7	Pitch	Theta Captures	2	1	Very slight pitch bobble, but tracking nicely.

Table D-43. Pilot 5 AFI-FCS augmented aircraft envelope protection — comments

Session:97 Record:1	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 **3** 4 5 Very Predictable	
With active envelope protection, the flight 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	
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:	
Don' t know, need to better understand the concepts. (AoA limiter is employed by Boeing as well). Envelope protection obvious when triggered. Definite lower limit. Beyond that, don't yet know enough.	
Session:97 Record:2	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 3 4 **5** Very Predictable	
With active envelope protection, the flight 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	
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:	
Need to better understand. Apparent when envelope protection triggered. Definite upper limit (402 KCAS).	

Table D-44. Pilot 5 AFI-FCS augmented aircraft envelope protection — comments

Session:97 Record:5	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 3 4 **5** Very Predictable	
With active envelope protection, the flight 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	
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:	
Session:97 Record:6	
Effectiveness of Envelope Protection Design Element	
For the task required/flight phase under consideration, the envelope	
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	
Not Predictable 1 2 3 4 **5** Very Predictable	
With active envelope protection, the flight 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	
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:	