Handling Qualities Evaluations of Active Inceptors with Varying Force-Feel Characteristics

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ABSTRACT

Active Inceptors in fly-by-wire aircraft offer new possibilities for control law reconfigurability, haptic cueing and system redundancies. Based on recent active inceptor research, new requirements for force-feel characteristics are proposed. Results are obtained from a simulation campaign investigating the influence of dynamic force-feel characteristics on the overall air-vehicle handling qualities (HQs). For this study, a rate-command type controller is evaluated in a pilot-in-the-loop simulation facility. Five mission task elements (MTEs) are flown with a range of force-feel characteristics (stick damping and stick natural frequency). Pilot comments on the active inceptors indicate clear differences and preferences between inceptor configurations. Generally, inceptor configurations with lower damping and higher natural frequency are preferred. Some minor differences, with respect to the MTEs flown, were noted and these may be explored in more detail in future research.

INTRODUCTION

The use of Active Inceptors can improve rotorcraft handling qualities (HQs) to reflect specific operating conditions or specific operational modes. Active Inceptors replace mechanically linked pilot/co-pilot controls, to allow variations in force-feel parameters during real-time operations. Active inceptors offer additional benefits, such as electronic control axis de-coupling and haptic feedback. Previous research has shown various benefits of active inceptors, through both simulation and flight test campaigns [1], [2], [3] [4]. This paper presents results from a new simulation campaign to determine changes in HQ ratings due to active inceptor sidestick force-feel parameters. The study includes a range of mission tasks and flight speeds. The flight conditions flown, the inceptor configurations tested, the tasks selected, and the results are discussed.

A number of studies have investigated the optimal settings for both static and dynamic force-feel settings using active inceptors. Efforts by researchers at the U.S. Army Capabilities Development Command (DEVCOM) Aviation & Missile Center (AvMC) [1] and the German Aerospace Center (DLR) [5] are notable. The former conducted tests using an active center stick, the latter using an active inceptor sidestick. From these studies, boundaries have been drawn for the dynamic force-feel characteristics of active inceptors, including rate command and attitude command flight control strategies. These boundaries, which define the damping and natural frequency of the inceptor force-feel system, are contained in proposed revisions to Aeronautical Design Standard – 33E [6] and are shown below. Figure 1 shows the boundaries for attitude command systems, while Figure 2 shows rate command boundaries of primary interest for this investigation. These boundaries have been drawn predominantly from tests conducted using the center stick active inceptor. Comparing Figure 1 and Figure 2, the Level 1 region is most stringent, requiring the narrowest range of damping and natural frequency, for the rate command system. Generally, as the damping and natural frequency increase, the

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HQs improve. For both rate and attitude command systems, cases with high natural frequency and low damping are considered Level 3. This is due to biodynamic feedback effects which may occur for this configuration. Typically, all cases greater than HQL 2 are critically damped or overdamped. From studies conducted at DLR using active inceptor sidesticks, it appears that the natural damping of the pilot's arm may lead to a reduction in damping required for Level 1 HQ, with respect to the boundaries shown in Figure 2 [5].

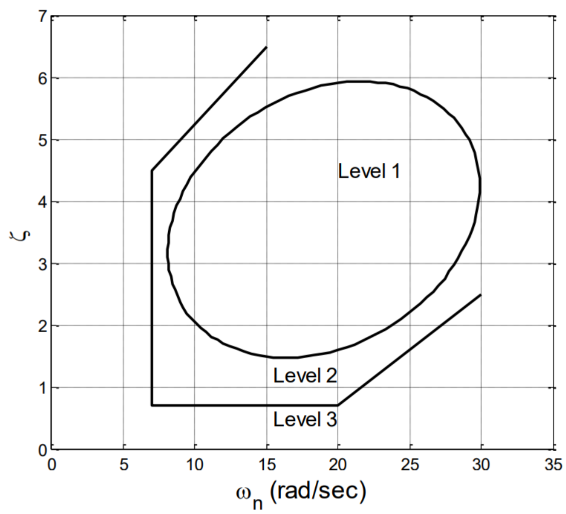


Figure 1: Proposed Boundaries for Active Inceptors, Attitude Command Response

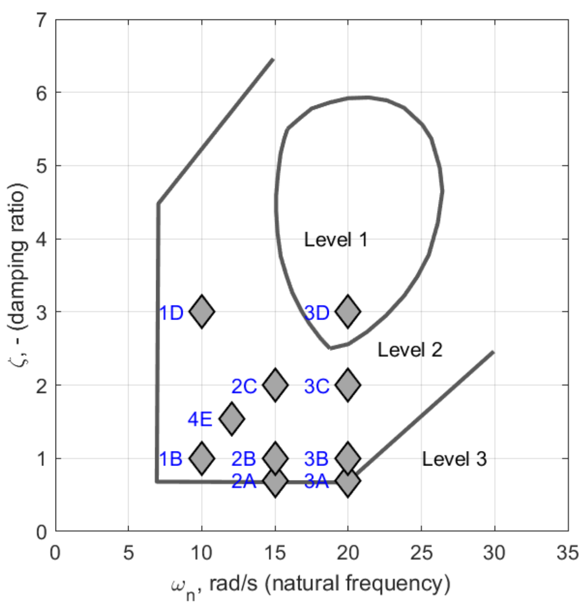


Figure 2: Proposed Boundaries for Active Inceptors, Rate Command Response, and Test Points

TEST CAMPAIGN SET-UP

Over a two-week period, formal force-feel inceptor evaluations were conducted using a fixed-base simulation facility at Bell Textron Inc., Fort Worth, TX. Three test pilots participated in conducting approximately 20-25 hours of simulation testing. Throughout the test campaign, changes to the sidestick force-feel characteristics were the only changes made. The vehicle model and control system parameters were left unchanged, so as to not introduce additional variables.

Experimental Setup

The inceptor force-feel evaluations were conducted in is a fixed-based simulator. It featured a single pilot station with a multi-functional display, a right-hand sidestick, a left-hand collective, and pedals. The simulation graphics were projected onto a 3D high-resolution domed display that provided a +180 deg field-of-view. The simulation featured multiple environments and included the virtual courses required for conducting the various selected evaluation tasks.

For the experiment, both left- and right-hand sidesticks were initially evaluated. The left-hand sidestick was configured to have functionality similar to a traditional collective control inceptor, as done in previous investigations (e.g., DLR research). The right-hand sidestick was configured to control longitudinal and lateral motion. Due to the selected mission task elements (MTEs) and the availability of upper-modes (i.e., height-hold), the pilot was rarely required to perform corrections for height deviation and therefore, the left-hand sidestick was not a factor in the investigation. Thus, for purposed of this evaluation, all changes were made purely in the right-hand inceptor.

Figure 3 shows the static force-feel characteristics used for the investigation. These characteristics were fixed during the investigation to limit the variables while allowing the focus to be on dynamic characteristics. Figure 3 shows a slight difference in positive and negative static friction to account for the pilot's arm position.

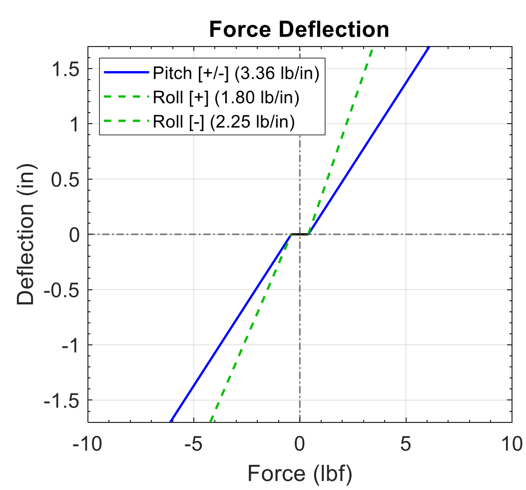


Figure 3: Force-Feel Static Inceptor Characteristics

To investigate the control law configurations with more stringent requirements, a baseline rate command control system was used to select the control inceptor damping/natural frequency boundaries. It is anticipated that a rate command type of controller would be most affected by changes to dynamic force-feel configurations.

A design space containing 10 possible right-hand control inceptor dynamic configurations, was developed to account for configurations with damping values up to 3 and natural frequencies to 20 rad/s. The natural frequency was limited by the available range of the hardware at the time of the experiment. All configurations considered are shown in Figure 2.

Referring to Figure 2, two underdamped cases were selected in the Level 3 region. In previous DLR investigations, results showed lower damping requirements for sidestick inceptors due to the armrest and inceptor position [5]. Therefore, the underdamped cases were tested to see whether these may be suitable for sidestick inceptors. Prior to the investigation it was noted that these configurations may be susceptible to biodynamic feedback, particularly in the real aircraft, where aircraft accelerations and vibration are at play. Bio-dynamic feedback was found to impact certain results in previous studies, particularly with higher natural frequency cases.

The three pilots who participated in the campaign (Pilots A, B, C) were all experimental test pilots, familiar with the HQ rating scales and approach used in the campaign. Pilot C had significant experience flying the physical aircraft being modeled.

Test Matrix

Test evaluations included Pilot feedback consisting of general comments, questionnaires, and formal qualitative ratings. The Cooper-Harper scale (HQRs) [7] served as the basis for handling qualities ratings. Additional feedback regarding workload and PIO tendencies were collected using the Bedford Workload Rating scale (BWL) [8] and the Pilot-Induced Oscillation Tendency Rating scale (PIOR) [10] respectively. Pilots were also asked to complete the questionnaire shown in the Appendix.

Five mission task elements (MTEs) were selected to evaluate both hover and forward-flight conditions. Two of these MTEs (Hover and Slalom) were taken directly from ADS-33E-PRF [9] and used the Scout/Attack tolerances. These two MTEs were selected on the basis that they had previously been used in many of the active inceptor studies undertaken by the US Army and DLR.

An additional Roll Step MTE was selected as an alternative to the Slalom MTE. An issue with the Slalom MTE is its lack of tight, high gain, closed-loop control. The Roll Step MTE was proposed by Meyer and Padfield in Ref [11] because this MTE incorporates both large changes in roll attitude and tracking elements. The task aggression is driven by the flight speed. The course position remains fixed for different flight speeds and therefore the required roll attitudes and time allowed to complete runway transitions become larger and shorter respectively as forward flight speed increases. For this investigation, the Roll Step MTE was flown at 120kts. This was found to exhibit an appropriate level of aggression for the vehicle tested. Figure 4 shows the Roll Step course used during this investigation. Figure 5 a) shows the whisker symbology provided to the pilot display for the Sum-of-Sines tracking task. The objective for each commanded attitude is to maintain the orange dot capture and hold within the green circles for pitch. Simultaneously, the pilot captures and holds the green line within the diagonal whisker bounds for roll. Figure 5 b) shows a command signal for the Sum-of-Sines tracking task with the scoring time limited to a 60 second window.

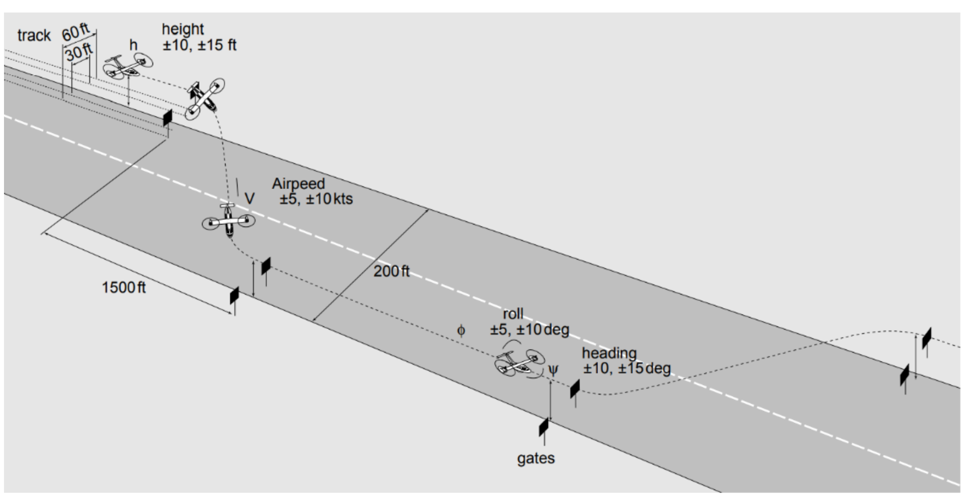


Figure 4: Suggested Course for the Roll Step (Reproduced from Reference [11])

In addition, both independent roll and pitch sum-of-sines tracking tasks were used as single axis tasks, predominantly to determine the pilot characteristics. These tasks were developed during Vertical Lift Consortium (VLC) simulation campaigns [12]. Piloting tasks and target forward flight speeds are shown in Table 1, additional targets and tolerances can be required, specific by MTE. Task performance was assessed by pilot feedback and associated discussion and included qualitative evaluation of performance during the completion of test points. The assessment also included objective qualitative performance analysis from the recorded flight data. Due to time constraints, not all inceptor configurations were flown for all MTEs. The inceptor force-feel configurations selected for each MTE are shown in Table 2, indicating that the majority of configurations were well represented.

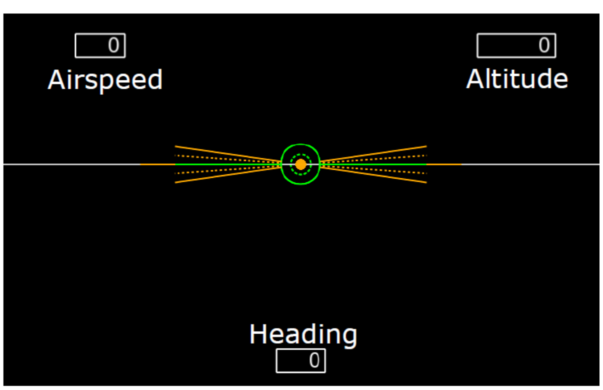
Table **3** shows the performance tolerance for the Sum-of-Sines task used during the evaluations. More details can be found in Reference [12].

Table 1: Selected MTE Tasks and Associated Forward Flight Speed

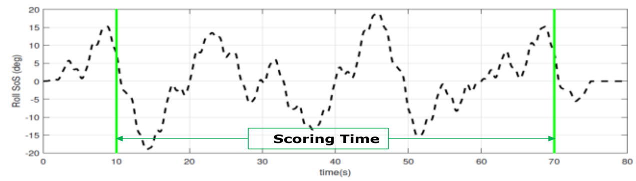
	Target Airspeed (KTAS)		
Task	0-10	20-60	120-150
Hover MTE	X		
Slalom MTE		60	
SoS Tracking Roll			120
SoS Tracking Pitch			120
Roll Step MTE			120

Table 2: Inceptor Configurations Flown with Respect to MTE

MTE	**Force-Feel Configurations**
Hover	1B, 1D, 2A, 2C, 3B, 3D, 4E
Roll Step	1B, 1D, 2A, 2C, 3B, 3D, 4E
Slalom	1B, 1D, 2A, 2C, 3A, 3B, 3C, 3D, 4E
SoS Pitch	1B, 1D, 2A, 2B, 2C, 3B, 3C, 3D, 4E
SoS Roll	1B, 1D, 2A, 2C, 3B, 3D, 4E



a) Cockpit Display During Sum-of-Sines Task



b) Sum-of-Sines Command Signal

Figure 5: Sum-of-Sines Task References [12]

Table 3: Performance Tolerances for Roll and Pitch Tracking

	Desired	Adequate
Pitch: at least X% of the scoring time within pitch attitude error tolerance:	50% ±1°	75% ±2°
Roll: at least X% of the scoring time within roll attitude error tolerance:	50% ±5°	75% ±10°
PIO Considerations:	No PIO tendencies	No divergent PIO tendencies
Inter-axis coupling shall not be	Undesirable	Objectionable

RESULTS

This section shows selected results obtained during the investigation. All ratings obtained during the investigation are given in the Appendix.

Subjective Results for the Evaluation of Sidestick Control Inceptors

Pilots flew the identified inceptor configurations over the course of several days, during which the pilots flew predetermined MTEs with configurations preset. After a brief series of practice runs, to gain familiarity with each MTE/feel-system configuration, the pilots performed several scoring runs. Following these runs, the pilots gave a formal rating using the questionnaire and HQ, BWL, and PIO rating scales. Overall, the pilots awarded HQRs within the Level 1 and Level 2 regions. Overall, the Sum-of-sines pitch tracking task was found to exhibit lower HQ ratings but remained at Level 2 throughout.

A good example of the HQR results (with respect to various MTEs) is shown in Figure 6 and Figure 7 where the respective HQ and Bedford workload ratings are shown for the 4E configuration. The numbers in the plot (n#) identify the number of times a rating was awarded. As shown, some of the cases were only flown twice. The Sum of Sines pitch task shows a large spread in the rating, particularly regarding the Bedford Workload Rating results.

Hover MTE

The Hover MTE is a multi-axis maneuver that is initiated at a ground speed between 6 and 10 knots and at an altitude less than 20 ft. The target hover point is oriented approximately 45 degrees relative to the initial heading of the rotorcraft. The target hover point is a repeatable, ground-referenced point from which rotorcraft deviations are measured. The ground track should be such that the rotorcraft will arrive over the target hover point.

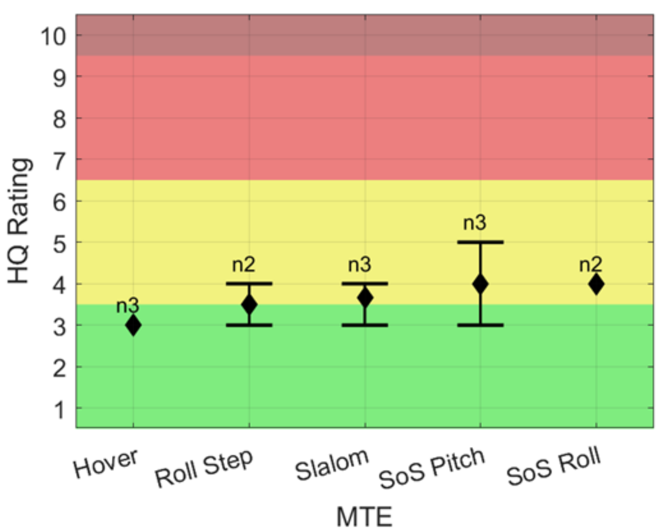


Figure 6: Summary of HQRs Obtained, Configuration: 4E

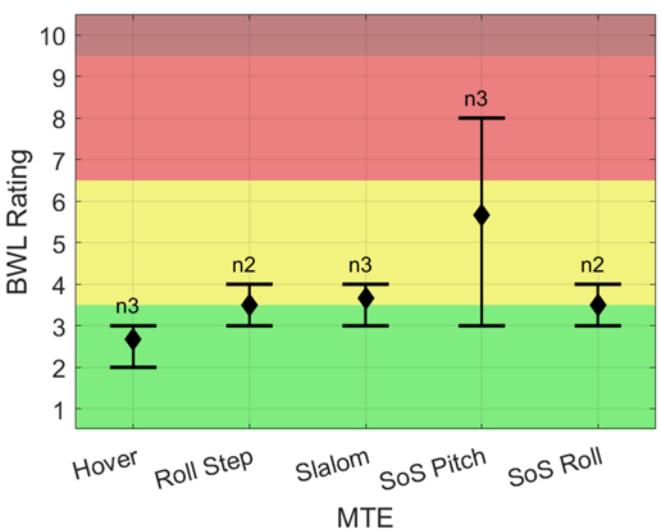


Figure 7: Summary of BWRs Obtained, Configuration: 4E

Figure 8 shows the Bedford Workload ratings awarded during the Hover MTE with respect to each inceptor force feel configuration. As shown, case 1D received BWRs within Level 2. All other configurations were generally awarded Level 1 HQs. For the Hover MTE, all pilots generally felt that configuration 1D was not suitable for the task. This was reflected in ratings awarded and through the quantitative performance. For example, regarding configuration 1D, Pilot A was not able to remain within the adequate tolerances (drifting outside) and had trouble correcting both lateral and longitudinal drift. All three pilots disagreed (or strongly disagreed) that the pitch breakout force was desirable for the given MTE. All three pilots also made comments that the stick (inceptor) felt "too heavy" or "sluggish." Some general comments from the pilots included disharmony, sluggish, heavy. These deficiencies led to a decrease in task performance.

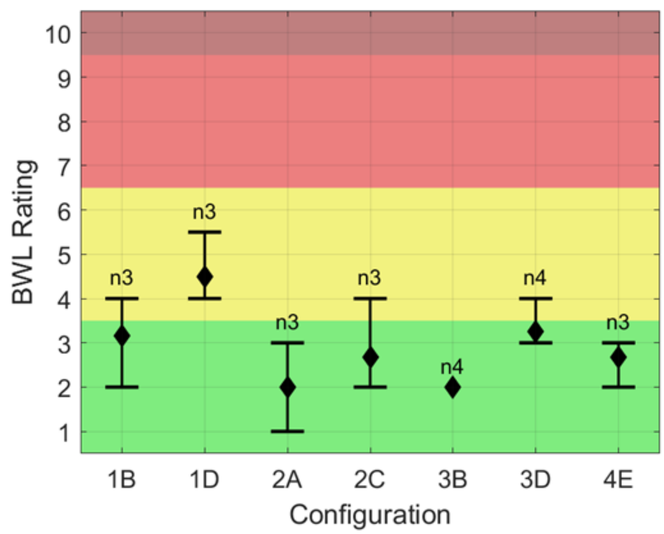


Figure 8: Bedford Workload Ratings, Hover

Configuration 3B, (critically damped, high natural frequency), was found to have some of the most favorable characteristics for the Hover MTE. Based on Pilot comments, the much lighter stick feel resulted in the expected improved performance over configuration 1D. Configuration 2A was also found to be generally favorable by all pilots, receiving a HQR 1 from one of the pilots.

For configuration 1B, large differences in pilot opinion were found. Pilot C reacted positively to this configuration awarding HQR 1. The other pilots awarded ratings in the Level 2 region. The pilot-to-pilot discrepancy is believed to be due to the strategy employed by Pilot C during the Hover. Due to the HQs of the vehicle with the given feel-system configurations, and lack of disturbances, Pilot C could achieve the desired performance with minimal control inputs. Therefore, despite this configuration being labelled 'heavy', Pilot C did not experience discomfort during completion of the task.

Scalograms allow for the visualization of pilot activity when using the control inceptor and provide rapid insight into the "peaks" in pilot activity. As depicted in Figure 9, scalograms show the power in the inceptor input signal with respect to time and frequency. Scalograms have been shown to be a useful tool in differentiating run-to-run and pilot-to-pilot characteristics regarding pilot-vehicle system behavior [13]. The time varying Scalogram technique is described by Thompson *et.al.* in Reference [14], and Mallet in Reference [15].

Scalogram analysis further demonstrates the difference in performance between two of the inceptor force feel configuration cases; 1D and 3B. Figure 9 and Figure 10 show the lateral inceptor input for the Hover MTE flown by Pilot A for cases 1D and 3B respectively. The only variable between the cases is the force-feel setting. As shown for 1D (Figure 9), strong peaks between 1-10 rad/s were observed throughout the MTE (approximately 60 seconds). These peaks increase in magnitude during the stabilization and hover element of the task (after 30 seconds). In contrast, case 3B (Figure 10), shows very low inceptor control activity and no peaks at higher frequency. This correlates with pilot feedback, that he was very light on the controls, applying small corrective inputs for the 3B configuration.

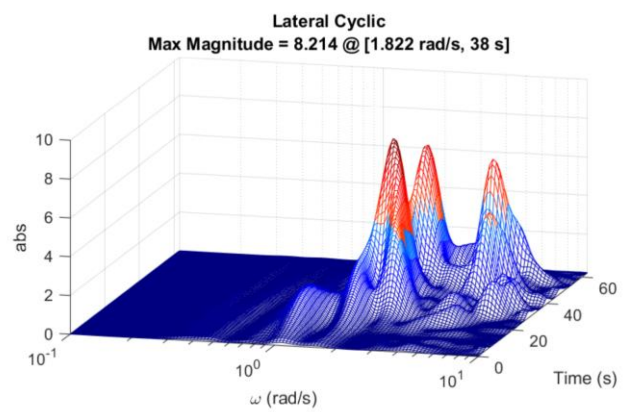


Figure 9: Scalogram, Hover, Control Inceptor Input, Lateral, Configuration 1D, HQR 5, BWL 5.5, PIOR 2

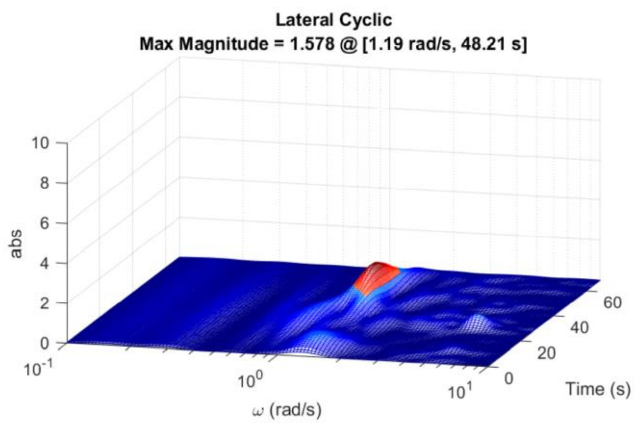


Figure 10: Scalogram, Hover, Control Inceptor Input, Lateral, Configuration 3B, HQR 2, BWL 2, PIOR 2

Roll Step MTE

The Roll Step MTE is a lateral maneuver that requires the pilot to initiate the maneuver in level unaccelerated flight at the centerline between two gates. The pilot must then perform a turn to traverse laterally 200 ft, stabilize, then perform the turn in the opposite direction. The maneuver is completed at a given height and flight speed. The maneuver is completed when the aircraft successfully travels through all gates. The flight speed can be used to modify the task aggression.

Figure 11 shows the HQRs awarded with respect to the configuration. Similar to the Hover MTE, the majority of HQRs awarded were Level 1. For the Roll Step MTE, configuration 3B was found to be the most favorable. For cases 1B, 1D, and 4E HQ ratings did not discern a difference between the cases. However, further feedback from the pilot questionnaire indicated that case 1D was the least suitable for the Roll Step MTE, as was the case for the 1D Hover MTE.

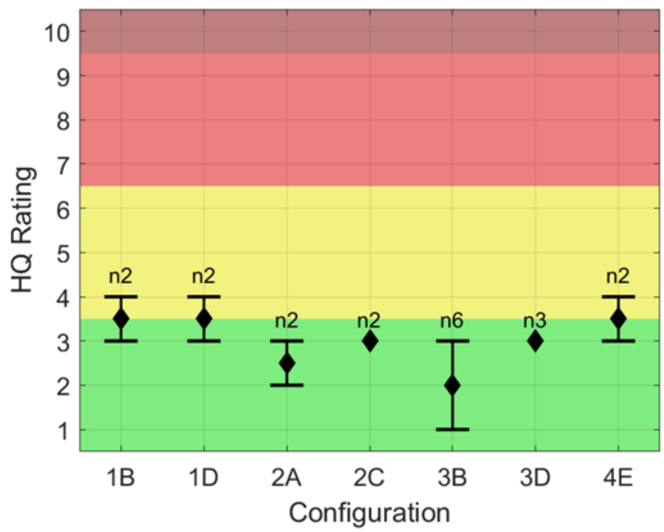


Figure 11: HQRs, Roll Step MTE

The Roll Step MTE successfully exposed differences between the inceptor force feel configurations. For the Roll Step MTE, the pilots preferred a lighter stick feel than configuration 1D. Pilot C stated that it took more movement to displace the stick in case 1D and rated the Roll Step task with a HQR 3 and BWL 4. Pilot A stated that the 1D configuration response was slow, "laggy", and heavy. The pilot also stated that he found it challenging to maintain the centerline. Pilot A also stated that in configuration 1D, the aircraft "flies like a bomber," awarding HQR 4 for the Roll Step task. For configuration 1D, the questionnaire results indicated that pitch and roll sensitivity were not desirable, that there was disharmony between the axes, and that the aircraft response lagged the control input.

In contrast, case 3B had favorable comments. The pilot stated that the harmony felt nice, predictable, and that the aircraft responded well. Pilot A stated that configuration 3B was their favorite, also mentioned multiple times that it felt "snappy." However, both pilots stated that the pitch axis felt heavy. Pilot

A also stated that case 3B had heavy stick breakout force but agreed that 3B was a generally desirable inceptor configuration for completing the Roll Step task. For the Roll Step task, HQR 2-3 and BWL 2-3 and PIOR 1 were assessed across the pilots.

For case 2A Pilot C stated the configuration was "more comfortable" than case 3B, stating the aircraft was "fast through the gates." Pilot A felt that there was free-play in the lateral axes but said that the system had a snappy response and was able to perform the task correctly, with level-wing through the target gates.

Figure 12 and Figure 13 show the lateral cyclic scalograms for configuration 1D and 3B, while Figure 14 shows the scalogram for the longitudinal cyclic of configuration 1D. Cases 1D and 3B represent the least favorable inceptor configurations for the roll axis. For all three pilots, the Roll Step task is dominated by the lateral cyclic response with two unique frequencies dominating the lateral response. As seen in Figure 12 and Figure 13, the lower frequency peak is likely associated with the Roll-Step's acquisition of an initial new lateral position, while the second slightly higher frequency peak appears to be associated with the precision capture of the new position. This was apparent for all pilots, regardless of feel system configuration.

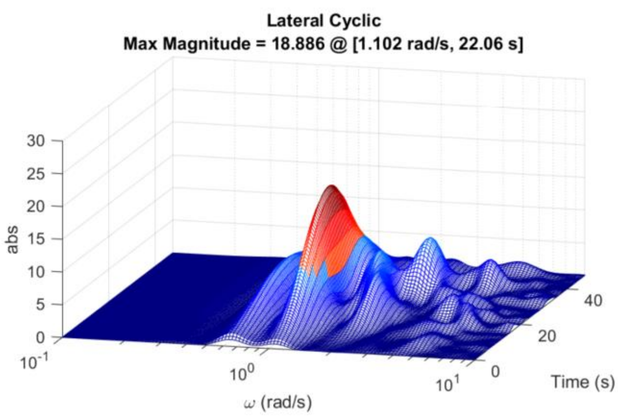


Figure 12: Lateral Cyclic, Roll Step, Configuration 1D, HQR 4, BWL 4, PIOR 2

The Slalom MTE is as maneuver that is initiated in level unaccelerated flight with the front of the aircraft lined up with the centerline of the test course. The pilot must perform a series of smooth turns at 500-ft intervals (at least twice to each side of the course). The turns are 50 ft from the centerline, with a maximum allowed lateral error of 50 ft. The maneuver is accomplished below a given reference altitude.

Referring to Figure 15, the Slalom MTE (like the previous Hover and Roll Step maneuver tasks), achieved HQRs in the Level 1 region, but with several cases awarded Level 2 ratings. All pilots generally agreed that configuration 1D was not suitable for the Slalom task. In particular, Pilot B strongly indicated that configuration 1D was unsuitable, awarding an HQR 5 for that case. In general, pilot feedback was positive for inceptor force-feel configuration 3B. However, during the initial 3B evaluation of the Slalom MTE, Pilot B felt there was insufficient stick travel to complete the MTE. When the pilot repeated the task, ratings were positive. For this reason, a large spread of HQRs was found for configuration 3B, as seen in Figure 15.

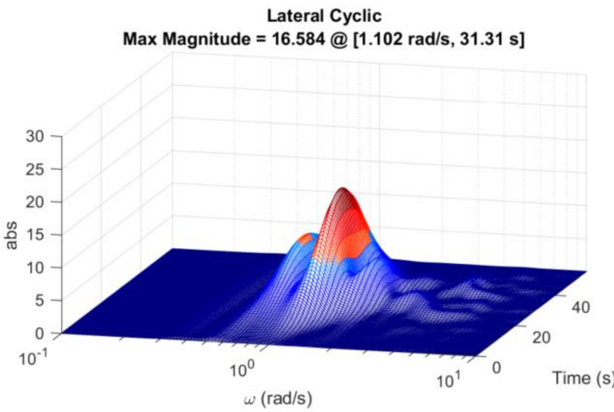


Figure 13: Lateral Cyclic, Roll Step, Configuration 3B, BWL 3, PIO 1

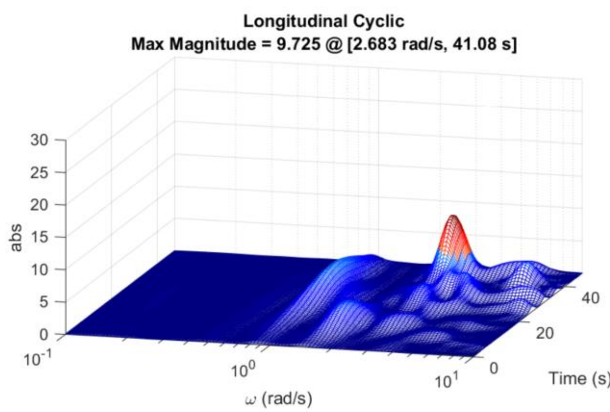


Figure 14**: Longitudinal Cyclic, Roll Step, Configuration 1D, HQR 4, BWL 4, PIOR 2Slalom MTE**

The Slalom MTE indicated the system had sufficient bandwidth to complete the required task. The performance plots (Figure 15) showed no major deficiencies for any of the inceptor configurations. Unlike the Hover and Roll Step MTEs, (see Table 2) two additional inceptor configurations (3A and 3C) were flown for the Slalom MTE. For the Slalom MTE, inceptor configuration 3C was found to be suitable, which may be of interest for future evaluations. Overall, during testing, the pilots preferred evaluating the Roll Step MTE compared to the Slalom MTE. The Roll Step MTE included both low-frequency translational inputs and higher frequency stabilization and tracking, which was not generally the case for the Slalom. For the Slalom MTE, only low frequency inputs could be used to achieve the desired performance.

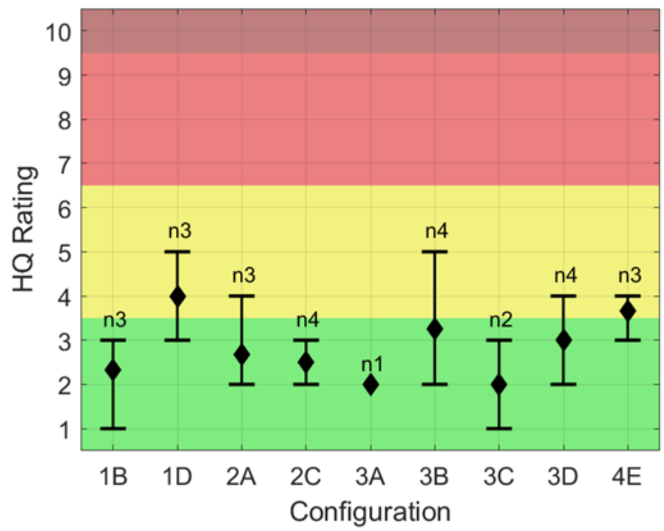


Figure 15: HQRs, Slalom MTE

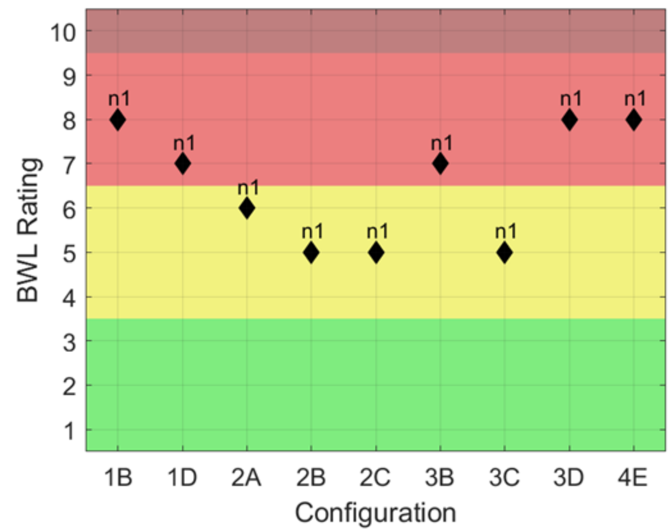


Figure 16: Bedford Workload Ratings Awarded for SoS Pitch Tracking, Pilot B.

Sum-of-Sines (SoS) Pitch Tracking MTE

The Sum-of-Sines Pitch MTE asks the pilot to aggressively track the displayed signal in pitch attitude while keeping the aircraft wings level and while attempting to keep tracking errors within the specified tolerances. This task is driven by an automated command signal selected by the flight test engineer.

The Sum-of-Sines Pitch tracking MTE was successful in exposing differences between the inceptor configurations. In several instances, inceptor differences, regarding MTE performance, was apparent. From all the MTEs attempted, the SoS was found to have the poorest ratings, both in terms of HQR and BWR awarded. With particular regard to the BWRs, several ratings were found at Level 3. Pilot B gave the poorest BWRs for the SoS MTE. The ratings awarded, with respect to inceptor force-feel configuration, are shown in Figure 16. The pilot stated that high concentration was required to complete the task and performance was difficult to achieve. Pilots generally achieved desired (or adequate) task performance, thus the high (poor) BWRs were not consistent with task performance. Evidently the high task workload was the main factor in the BWR score and not task performance requirements. For this reason, a larger spread was found in the BWRs compared to the HQRs for the same (SoS) MTE. Generally, HQRs for the SoS task were within the Level 2 region.

Based on the SoS MTE feedback from the pilot questionnaires, it appears that the perceived ‘breakout force’ was too large for the inceptor force-feel configurations, which may have been a factor that led to high workload with this configuration. The generally high workload was also due to high levels of concentration required to complete the task and maintain tracking performance for over 60 seconds. Some of the general comments from the pilots included “too much force, exhausting, and heavy”. The pilots stated that they were working harder, which led to poorer tracking.

The SoS MTE tracking performance evaluation runs for two of the pilots, Pilot A and Pilot C, are shown in Figure 17-Figure 20. These evaluations represent inceptor configuration 1D (Figure 17 and Figure 18) and inceptor configuration 3D (Figure 19 and Figure 20).

For the SoS Pitch and Roll Tracking tasks, a ‘score’ (or ‘performance’) can be calculated based on the overall time that the pilot maintains adequate and/or desired performance. The adequate score is the percentage of time for which the pilot maintained the pitch (or roll) attitude within the adequate boundaries. For inceptor configuration 1D, Pilot A (Figure 17) was able to achieve a relatively high adequate performance of greater than 90%, while Pilot C (Figure 18) preformed much worse reaching only 67.24% adequate performance throughout the maneuver duration. As shown in Figure 18, large oscillations are present throughout. These appear to be pilot-induced oscillations (PIO), even though these were not identified by the pilot (PIOR 1). There are clear oscillations throughout and desired performance cannot be sustained. These oscillations were noted by the test team during the evaluations.

Figure 19 and Figure 20 show generally improved SoS Pitch tracking results for the inceptor force feel case 3B, where Pilot A and C both improved desired performance, and Pilot C also improved adequate performance. For this case, some of the pilot comments included “predictable” and “more responsive”. Configuration 3B was one of the preferred cases for Pilot A, receiving the best (lowest) HQR. However, Pilot A generally felt the ‘breakout forces’ were too high, and that the inceptor control configuration generally did not have a light quick response. For Pilot C, oscillations appear to be present in the maneuver (as with the configuration 1D case) however these oscillations appear to be smaller for inceptor configuration 3B compared to the inceptor 1D case. For this reason, the inceptor 3B configuration's adequate performance is better than the configuration 1D performance.

For the SoS MTE, the questionnaire feedback (from all pilots) indicates that the perceived 'breakout force' for inceptor configurations 1D and 3D was too large and did not favor the high workload SoS task. The break-out force may have been a factor that led to high workload, alongside the generally high level of concentration required to complete the task and maintain tracking for over 60 seconds. Some of the general comments from the pilots included too much force, exhausting, and heavy. The pilots stated that they were working harder, which led to poorer tracking.

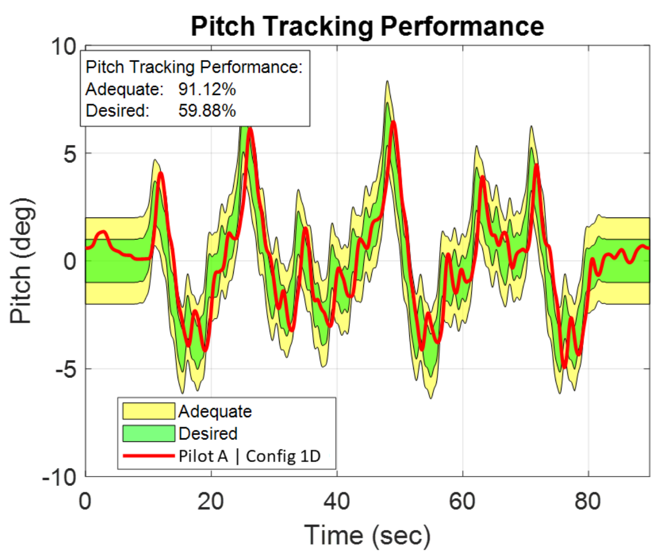


Figure 17: Example of Pitch Tracking Performance, Pilot A, Configuration 1D

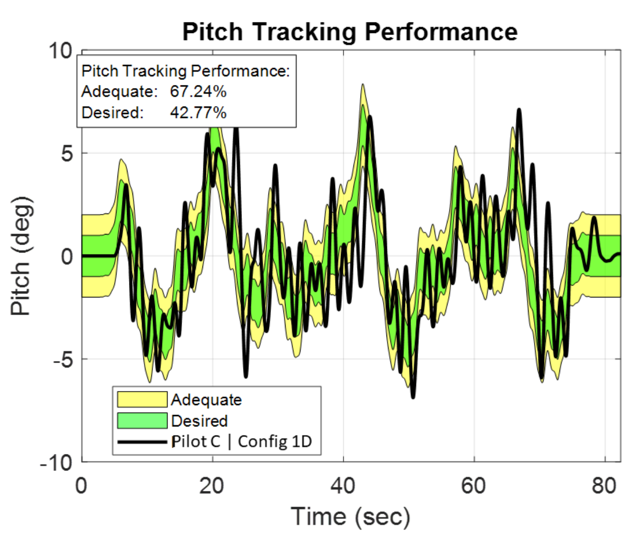


Figure 18: Example of Pitch Tracking Performance, Pilot C, Configuration 1D

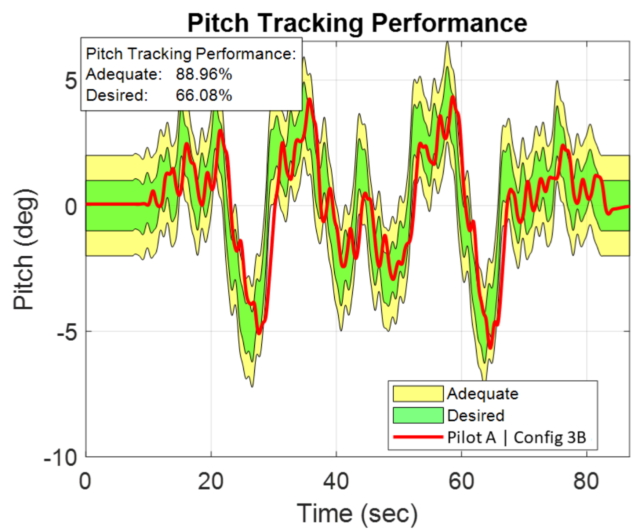


Figure 19: Example of Pitch Tracking Performance, Pilot A, Configuration 3B

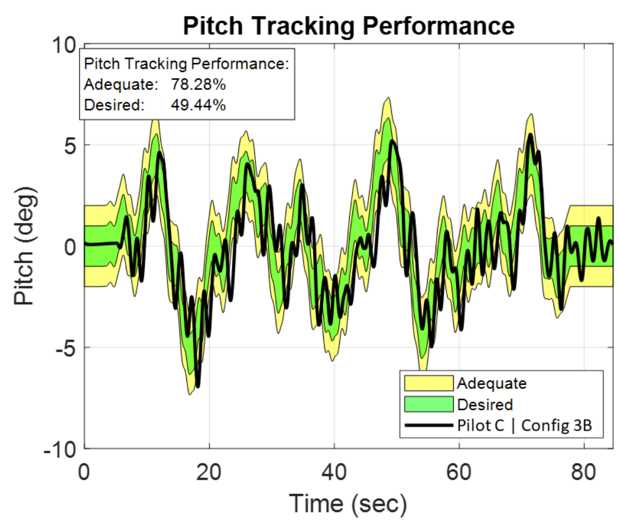


Figure 20: Example of Pitch Tracking Performance, Pilot C, Configuration 3B

Overall, pilots preferred the cases with lighter stick (inceptor) forces, a factor that was generally found to significantly reduce workload. This result is also supported with evidence that the inceptor oscillations observed in Pilot C tracking were reduced with the lighter forces.

Sum-of-Sines (SoS) Roll Tracking MTE

The Sum-of-Sines Roll MTE asks the pilot to aggressively track the displayed signal in roll attitude while keeping the aircraft at a constant pitch angle and while attempting to keep tracking errors within the specified tolerances. This task is driven by an automated command signal selected by the flight test engineer.

While still informative, the Sum-of-Sines Roll tracking MTE was less successful in exposing key differences between inceptor force feel configurations (compared to Sum-of-Sines Pitch tracking MTE). Figure 21 shows the SoS Roll MTE BWRs with respect to inceptor force feel configuration, for all three pilots. As shown, the best HQ was obtained for the case 3B, which also had the highest spread (and was flown the greatest number of times). Configuration 2A was also found to exhibit low workload, however some oscillations were apparent. The inceptor force-feel configuration 4E was found to exhibit harmony issues.

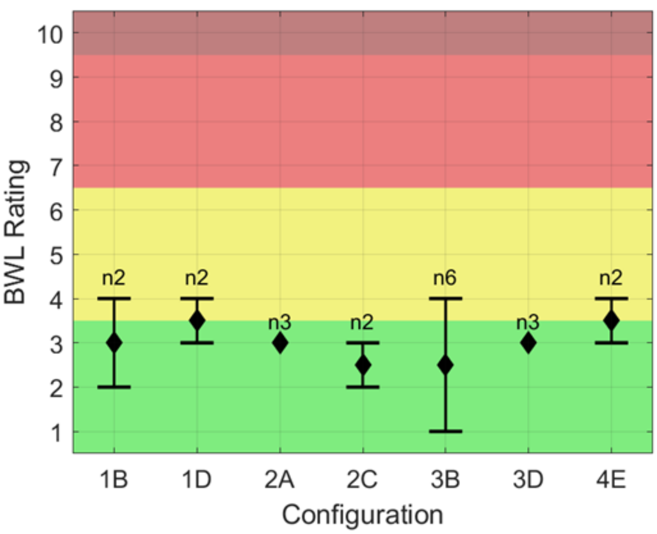


Figure 21: Overall BWRs obtained from the SoS Roll Tracking MTE

DISCUSSION

Based on the overall results, the Hover and Sum-of-Sines MTEs were the most successful tasks for highlighting the impact of the different inceptor force-feel configurations. Pilot-induced oscillations were observed in the Sum-of-Sines task for both pitch and roll axes, while the Hover task highlighted force-feel configurations where control system lag was more noticeable by the pilots. Lag or noticeable delay in the Hover task resulted in increased drift, requiring more compensation from pilots (more frequent/aggressive pilot corrections). The Slalom and Roll Step were useful for comparing inceptor force-feel configurations and offered pilot comments on the agility of the aircraft.

Bandwidth and phase delay [9] represent additional measures that can be used to characterize the speed of aircraft response with respect to pilot stick input. Bandwidth is usually calculated on the basis of the inceptor position but can be computed using the inceptor force signal to shows the effect of the different inceptor force-feel settings. Phase delay and bandwidth results, based on inceptor force, are shown in Figure 22 (for the SoS Pitch MTE) and Figure 23 (for the SoS roll MTE). Inceptor force-feel configurations 2A and 3B are located within the Level 2 region, near the Level 1 boundary (for both pitch and roll axes). These inceptor configurations are associated with a less sluggish response and reduced latency compared to the other tested inceptor force-feel configurations. In contrast, configurations 1D, 4E, and 1B are located within the Level 3 region or near its boundary and are associated with a more sluggish response and higher latency. This result is in-line with the performance seen during the SoS MTE tasks and the pilot comments obtained during debriefing. Overall, the phase delay/bandwidth results illustrate a trend, which is that inceptor force-feel configurations with a lower damping ratio and higher natural frequency tend to bring the system closer to Level 1 HQ ratings. In contrast, configurations with a higher damping ration and lower natural frequency result in a more sluggish response and higher latency.

Considering the aircraft state time histories, Pilot C frequently experienced pilot-induced oscillations. These were most noticeable during the Sum-of-Sines maneuvers but are also evident some of the other MTEs. Nevertheless, pilot C did not typically indicate the presence of the PIOs in his ratings. It is not uncommon for PIO to go unrecognized by pilots when flying in a fixed-base simulator. In some cases, such as SoS Pitch (inceptor force-feel configuration 1D) the, PIO was quite severe given the tracking performance, but the pilot rated it with a PIOR 1. The pilot did give the 1D inceptor configuration a higher BWLR and HWR indicating the pilot was aware of the extra difficultly in completing the task but did not attribute this to PIO.

Pilot B often gave consistently higher ratings for all the configurations compared to pilots A and C. This was especially true during the scoring of the sum-of-sines pitch tracking MTE. This may have been due to the fact that pilot B is the “lower gain” or “lower bandwidth” pilot, when compared to the other two, hence the tasks that demand more continuous compensation result in higher ratings for Pilot B.

Overall, the most favorable ratings were awarded for configuration 3B. This configuration corresponds to an inceptor with high natural frequency and low damping ratio. The favored configuration (3B) has a natural frequency of 20 rad/s and a damping ratio of 1. The test results indicate that a slightly lower natural frequency (i.e., 15 rad/s) was also acceptable in most tasks. High damping increases the pilot’s response lag and results in a correspondingly worse rating for the associated HQR, BWL, and PIO. The three pilots generally agreed that configuration 1D felt too heavy across all tasks, and thus received the worst average Handling Qualities and Bedford Workload ratings. Based on the overall results, configurations with a frequency between 15-20 rad/s and a damping ratio between 1-2 were found to be acceptable, for the rate command response. This corresponds to a Level 2 (bordering on Level 3 for the favored configuration 3B) in the originally proposed boundaries seen in Figure 2.

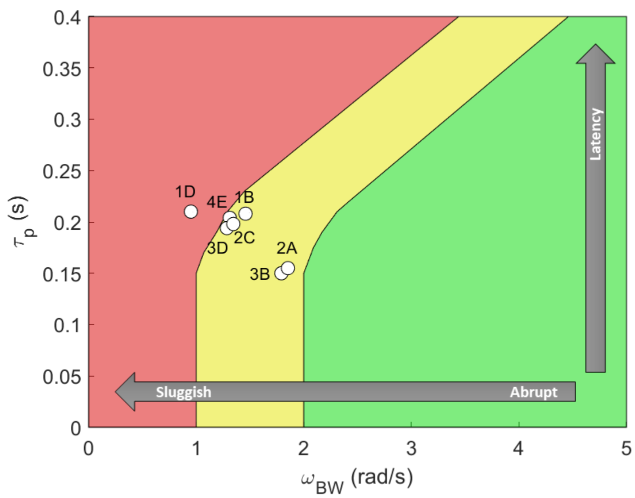


Figure 22: Pitch Axis Bandwidth/Phase Delay

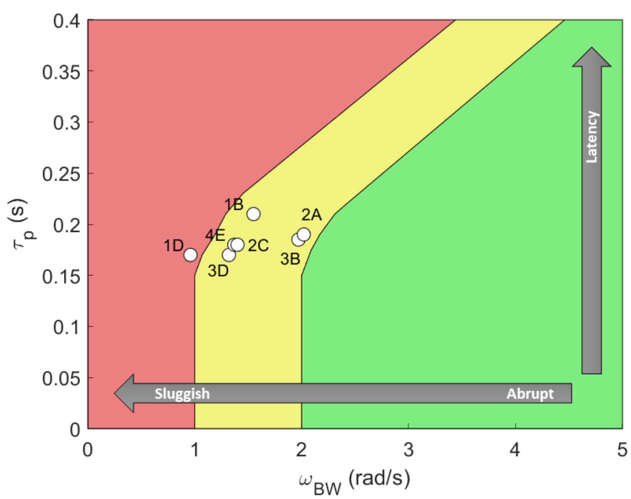


Figure 23: Roll Axis Bandwidth/Phase Delay

Configuration 3D was a test point that fell inside of the originally proposed Level 1 region. Configuration 1D consistently lead to poorer aircraft tracking performance, when compared to the so called "Level 2" configurations. Additionally, 1D was the only configuration that was Level 3 for both roll and pitch axis in bandwidth/phase delay. Based on the evaluations and analyses performed in this study, it is recommended the boundaries be revisited in further studies to investigate the applicability for different control response types and for sidestick inceptors.

CONCLUSIONS

The test campaign described in this paper was designed to investigate the influence of inceptor force-feel characteristics, for one flight control response type, tested in a number of mission task elements (MTEs). Key conclusions from this study are as follows:

- Inceptor force-feel configurations with lower damping and higher natural frequency resulted in lower latency and a less "sluggish" aircraft response. Overall maneuver task performance was improved for inceptor force-feel configurations with a natural frequency range of 15-20 rad/s, and damping ratios of 1-2.
- The multi-axis nature and the three distinct elements of the Hover MTE allowed for a rich exploration of the pilot inputs as inceptor force-feel characteristics were varied. Inceptor trends could be observed with consistency among the pilots.

For the Slalom MTE, the lateral cyclic scalograms for all three pilots were similar in frequency and amplitude as the nature of the task dictates the required pilot inputs.

Generally, results from this study reflect those from previous campaigns and results available in the literature. A trend was found towards improved Handling Qualities with increasing natural frequency and damping of the force-feel characteristics. The natural damping due to the pilot's arm position for the sidestick inceptors appeared to reduce the requirements for damping in the force-feel system. Results obtained strongly reflected those from DLR studies, where points with high natural frequency and low damping were found to be acceptable. It is important to note that all tests reported here were with a fixed-motion base simulator. The preferred configurations with respect to damping ratio are expected to increase once motion is introduced into the flight simulator. Thus, the recommendation is to consider damping ratios not only at the preferred level (found in this study with case 3B), but also slightly higher values, that is, damping ratios between 1 and 2.

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APPENDIX

Table 4: Pilot Debrief Questionnaire

Question	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
Q1. The cyclic control pitch/roll harmony was desirable for the selected MTE.	○	○	○	○	○
The cyclic characteristics identified below were desirable for the selected MTE:					
• **Q2.** Pitch sensitivity (gradient)	○	○	○	○	○
• **Q3.** Roll sensitivity (gradient)	○	○	○	○	○
• **Q4.** Pitch breakout force	○	○	○	○	○
• **Q5.** Roll breakout force	○	○	○	○	○
Q6. The damping of the cyclic response in pitch was ideal for the selected MTE.	○	○	○	○	○
Q7. The damping of the cyclic response in roll was ideal for the selected MTE.	○	○	○	○	○
Q8. The cyclic inceptor in pitch had a light, quick response	○	○	○	○	○
Q9. The cyclic inceptor in roll had a light, quick response.	○	○	○	○	○
Q10. There was little or no perceived delay in the aircraft response to control input.	○	○	○	○	○
Q11. The stick travel in the pitch and roll axes was sufficient to perform the selected MTE	○	○	○	○	○

Table 5: Hover MTE Pilot Ratings

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Hover	1B	A	4	3.5	2	0	1	1	1	1	1	-1	-1	-1	1	1
Hover	1B	B	5	4	3	1	-1	-1	0	0	0	0	0	0	1	2
Hover	1B	C	1	2	2	1	1	1	1	1	1	1	1	1	1	1
Hover	1D	A	5	5.5	2	-1	1	1	-1	-1	-1	-1	-1	-1	1	1
Hover	1D	B	5	4	2	-1	0	0	-2	-2	1	1	-2	-2	1	1
Hover	1D	C	5	4	3	1	-1	-1	-1	-1	0	0	0	0	-1	1
Hover	2A	A	2	2	2	1	1	1	1	1	1	1	0	0	0	1
Hover	2A	B	3	3	2	1	1	1	1	1	1	1	1	1	0	1
Hover	2A	C	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hover	2C	A	3	2	2	1	1	0	1	1	1	1	1	1	0	1
Hover	2C	B	5	4	2	0	0	1	1	1	1	0	1	1	0	1
Hover	2C	C	2	2	1	1	1	1	1	1	0	0	1	1	1	1
Hover	3B	A	2	2	2	1	1	1	1	1	1	1	1	1	1	1
Hover	3B	A	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Hover	3B	B	2	2	2	2	2	2	2	1	2	2	2	2	1	2

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Hover	3B	C	3	2	2	2	1	1	1	1	0	0	1	1	1	2
Hover	3D	A	5	4	2	0	1	1	0	1	-1	-1	-1	1	-1	1
Hover	3D	B	3	3	2	1	1	0	1	1	1	0	0	0	0	2
Hover	3D	B	3	3	2	2	1	1	-1	-1	1	1	-1	-1	1	1
Hover	3D	C	4	3	2	1	0	0	0	0	0	0	0	-1	-1	1
Hover	4E	A	3	3	2	1	1	1	1	0	0	1	-1	1	1	1
Hover	4E	B	3	3	2	1	1	1	1	1	1	0	0	0	2	2
Hover	4E	C	3	2	2	1	2	0	1	0	1	1	1	1	1	2

Table 6: Roll Step MTE Pilot Ratings

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Roll Step	1B	A	4	3.5	2	-1	-1	-1	-1	1	-1	0	1	0	0	1
Roll Step	1D	A	4	4	2	-1	-1	-1	0	0	-1	0	-1	-1	-1	1
Roll Step	1D	C	3	4	1	1	1	1	1	0	0	0	0	0	0	1
Roll Step	2A	A	3	3	2	1	1	1	1	1	1	1	-1	1	1	1
Roll Step	2A	C	2	3	1	1	1	1	0	0	1	1	0	0	0	1
Roll Step	2C	A	3	3	2	-1	-1	1	-1	0	-1	-1	-1	1	0	1
Roll Step	2C	C	3	3	1	1	1	1	0	1	0	1	0	0	0	1
Roll Step	3B	A	3	3	1	1	1	1	1	1	1	1	1	1	1	0
Roll Step	3B	A	2	2	1	1	1	1	1	1	1	1	0	0	1	1
Roll Step	3B	C	2	3	1	1	1	1	1	1	0	0	0	1	0	1
Roll Step	3B	C	2	2	1	1.5	1.5	1.5	1.5	1	1	1	1	1	1	1
Roll Step	3B	C	2	3	1	1	1	1.5	1.5	1	1	1	1	1	1	1
Roll Step	3D	A	3	3	1	0	1	1	1	1	0	0	1	1	1	1
Roll Step	3D	A	3	3	1	-1	-1	0	-1	-1	-1	1	1	0	1	1
Roll Step	3D	C	3	3	1	1.5	1	1.5	1	1	1	1	1	1	1	1
Roll Step	4E	A	3	3	1	1	1	0	1	1	1	0	0	0	0	1
Roll Step	4E	C	4	4	1	1	0	0	0	0	0	0	1	1	0	1
Roll Step	1B	C	3	4	1	1	1	1	1	1	1	1	1	1	1	1
Roll Step	3B	C	1	2	1	1.5	1.5	1.5	1.5	1.5	1	1.5	1	1	1.5	1

Table 7: Slalom MTE Pilot Ratings

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Slalom	1B	A	3	3	1	0	-1	1	1	1	-1	1	1	1	1	1
Slalom	1B	B	3	3	1	1	1	1	1	1	1	1	1	1	1	0
Slalom	1B	C	1	1	1	2	2	2	2	2	2	2	1	1	1	2
Slalom	1D	A	4	3	1	-1	-1	1	0	0	-1	1	-1	0	-1	1
Slalom	1D	B	5	6	1	0	-2	-2	-2	-2	-1	-1	-1	-2	-1	-2
Slalom	1D	C	3	4	1	0	0	0	0	0	0	0	-1	-1	-1	1
Slalom	2A	A	2	2	1	1	1	1	1	1	1	1	0	0	1	1
Slalom	2A	B	4	4	1	0	-1	-1	1	2	0	-1	1	1	0	-1
Slalom	2A	C	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Slalom	2C	A	2	2	-	1	1	1	1	1	0	1	1	1	1	1
Slalom	2C	B	3	4	1	0	1	1	1	1	1	1	1	1	0	-1
Slalom	2C	C	3	4	1	1	0	0	0	0	0	0	1	1	0	1
Slalom	2C	C	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Slalom	3A	C	2	2	1	1	1.5	1.5	1.5	1.5	1	1	2	2	2	1

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Slalom	3B	A	3	2.5	1	0	1	1	1	1	0	0	-1	1	1	-1
Slalom	3B	B	5	6	1	-1	0	-1	0	0	-2	-2	-2	-2	-2	-2
Slalom	3B	B	3	2	1	1	1	2	1	1	1	2	1	1	1	0
Slalom	3B	C	2	2	1	1	1	1	1	1	1	1	1	1	1	1
Slalom	3C	A	3	3	1	0	0	0	1	1	-1	1	0	1	1	-1
Slalom	3C	C	1	1	1	2	2	2	2	2	1.5	1.5	1	1	1	1.5
Slalom	3D	A	2	2	1	-1	1	1	1	1	-1	1	-1	1	1	1
Slalom	3D	B	4	4	1	0	0	0	-1	-1	0	-1	-1	-1	-1	-2
Slalom	3D	C	3	3	1	1	1	1	1	1	1	1	0	0	0	1
Slalom	3D	C	3	2	1	1	0	0	0	0	0	0	-1	-1	0	1
Slalom	4E	A	3	3	1	1	1	-1	1	1	1	-1	0	0	1	1
Slalom	4E	B	4	4	1	0	-2	1	0	0	1	1	-1	-1	0	1
Slalom	4E	C	4	4	1	1	0	0	0	0	1	1	0	-1	0	1

Table 8: SoS Pitch MTE Pilot Ratings

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
SoS Pitch	1B	A	3	2	2	1	1	-	1	-	-1	-	1	-	1	1
SoS Pitch	1B	B	5	8	2	0	-1	-	0	-	-1	-	-1	-	-1	0
SoS Pitch	1B	C	4	4	1	1	1	-	0	-	0	-	1	-	1	1
SoS Pitch	1D	A	3	3	2	0	-1	-	-1	-	1	-	-1	-	0	1
SoS Pitch	1D	B	4	7	1	0	0	-	-2	-	1	-	-2	-	0	0
SoS Pitch	1D	C	6	6	1	-	-1	-	-2	-	-1	-	-1	-	-1	0
SoS Pitch	2A	A	4	4	2	1	1	-	1	-	-1	-	1	-	1	1
SoS Pitch	2A	B	4	6	2	0	-1	-	2	-	1	-	0	-	0	0
SoS Pitch	2A	C	4	4	1	0	1	-	0	-	0	-	1	-	1	1
SoS Pitch	2B	B	4	5	1	0	1	-	1	-	1	-	1	-	1	0
SoS Pitch	2B	C	4	4	1	1	1	-	1	-	1	-	1	-	0	1
SoS Pitch	2C	A	4	4	2	0	1	-	1	-	-1	-	1	-	1	1
SoS Pitch	2C	B	4	5	1	0	0	-	-1	-	1	-	-1	-	0	0
SoS Pitch	2C	C	4	4	1	1	1	-	-1	-	0	-	1	-	0	1
SoS Pitch	3B	A	2	2	2	1	1	-	1	-	-1	-	1	-	1	1
SoS Pitch	3B	A	3	3	2	1	0	-	1	-	-1	-	0	-	0	1
SoS Pitch	3B	B	4	7	2	0	0	-	-1	-	-1	-	0	-	-1	0
SoS Pitch	3B	C	5	5	1	0	-1	-	0	-	-1	-	0	-	0	0
SoS Pitch	3C	A	4	4	2	1	0	-	0	-	-1	-	-1	-	-1	1
SoS Pitch	3C	B	4	5	1	0	1	-	1	-	1	-	1	-	1	0
SoS Pitch	3C	C	5	5	1	-	0	-	0	-	0	-	0	-	0	1
SoS Pitch	3D	A	2	2	2	1	1	-	1	-	0	-	0	-	1	1
SoS Pitch	3D	A	2	2	2	1	1	-	1	-	1	-	0	-	1	1
SoS Pitch	3D	B	5	8	1	0	-1	-	-2	-	0	-	-2	-	-1	0
SoS Pitch	3D	C	5	5	1	0	0	-	-1	-	-1	-	0	-	0	0
SoS Pitch	4E	A	3	3	2	1	1	-	1	-	0	-	0	-	1	1
SoS Pitch	4E	B	4	8	2	0	-1	-	-1	-	-1	-	-1	-	-1	1
SoS Pitch	4E	C	5	6	1	0	0	-	-1	-	-1	-	-1	-	-1	0

Table 9: SoS Roll MTE Pilot Ratings

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Roll Step	1B	A	4	3.5	2	-1	-1	-1	-1	1	-1	0	1	0	0	1

MTE	Config	Pilot	HQR	BWL	PIOR	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
Roll Step	1B	C	3	4	1	1	1	1	1	1	1	1	1	1	1	1
Roll Step	1D	A	4	4	2	-1	-1	-1	0	0	-1	0	-1	-1	-1	1
Roll Step	1D	C	3	4	1	1	1	1	1	0	0	0	0	0	0	1
Roll Step	2A	A	3	3	2	1	1	1	1	1	1	1	-1	1	1	1
Roll Step	2A	C	2	3	1	1	1	1	0	0	1	1	0	0	0	1
Roll Step	2C	A	3	3	2	-1	-1	1	-1	0	-1	-1	-1	1	0	1
Roll Step	2C	C	3	3	1	1	1	1	0	1	0	1	0	0	0	1
Roll Step	3B	A	3	3	1	1	1	1	1	1	1	1	1	1	1	0
Roll Step	3B	A	2	2	1	1	1	1	1	1	1	1	0	0	1	1
Roll Step	3B	C	2	3	1	1	1	1	1	1	0	0	0	1	0	1
Roll Step	3B	C	2	2	1	1.5	1.5	1.5	1.5	1	1	1	1	1	1	1
Roll Step	3B	C	1	2	1	1.5	1.5	1.5	1.5	1.5	1	1.5	1	1	1.5	1
Roll Step	3B	C	2	3	1	1	1	1.5	1.5	1	1	1	1	1	1	1
Roll Step	3D	A	3	3	1	0	1	1	1	1	0	0	1	1	1	1
Roll Step	3D	A	3	3	1	-1	-1	0	-1	-1	-1	1	1	0	1	1
Roll Step	3D	C	3	3	1	1.5	1	1.5	1	1	1	1	1	1	1	1
Roll Step	4E	A	3	3	1	1	1	0	1	1	1	0	0	0	0	1
Roll Step	4E	C	4	4	1	1	0	0	0	0	0	0	1	1	0	1

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