In Flight Evaluation of Active Inceptor Force-Feel Characteristics and Handling Qualities

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Abstract

The effect of inceptor feel-system characteristics on piloted handling qualities has been a research topic of interest for many years. Most of the research efforts have focused on advanced fly-by-wire fixed-wing aircraft with only a few studies investigating the effects on rotorcraft. Consequently, only limited guidance is available on how cyclic force-feel characteristics should be set to obtain optimal handling qualities for rotorcraft. To study this effect, the U.S. Army Aeroflightdynamics Directorate working with the DLR Institute of Flight Systems in Germany under Task X of the U.S. German Memorandum of Understanding have been conducting flight test evaluations. In the U.S., five experimental test pilots have completed evaluations of two Mission Task Elements (MTEs) from ADS-33E-PRF and two command/response types for a matrix of center-stick cyclic force-feel characteristics at Moffett Field. In Germany, three experimental test Pilots have conducted initial evaluations of the two MTEs with two command/response types for a parallel matrix of side-stick cyclic force-feel characteristics at WTD-61 in Manching. The resulting data set is used to correlate the effect of changes in natural frequency and damping ratio of the cyclic inceptor on the piloted handling qualities. Existing criteria in ADS-33E and a proposed Handling Qualities Sensitivity Function that includes the effects of the cyclic force-feel characteristics are also evaluated against the data set and discussed.

Introduction

For most helicopters, the force-feel system characteristics of the cyclic inceptors are set based on the characteristics of the mechanical components in the control system (mass, springs, friction dampers, etc.). For these helicopters, the force-feel characteristics typically remain constant over the entire flight envelope, with perhaps a trim release to minimize control forces while maneuvering. With the advent of fly-by-wire control systems and active inceptors in helicopters, the force-feel characteristics are now determined by the closed-loop response of the active inceptor itself as defined by the inertia, force/displacement gradient, damping, breakout force and detent shape configuration parameters in the inceptor control laws. These systems give the flexibility to dynamically prescribe different feel characteristics for different control modes or flight conditions, and the ability to provide tactile cueing to the pilot through the actively controlled side-stick or center-stick cyclic inceptor. A number of studies have been conducted to assess the impact of controller force-feel characteristics on the pilot-vehicle flying qualities in high performance fixed wing fly-by-wire aircraft, primarily directed toward minimizing

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pilot induced oscillations and roll ratcheting [1][2]. There has been much less research into the effects of force-feel characteristics on rotorcraft handling qualities. A brief overview of a few of these studies is given in the following paragraphs.

One of the major elements studied by Boeing Vertol under the Army's Advanced Digital/Optical Control System (ADOCS) program was the pilot's integrated side-stick controller [3]. This simulation study looked at a range of force displacement gradients from stiff (40 lb/deg) to large deflection (0.6 lb/deg) with functionality ranging from 4-axis (lateral, longitudinal, directional and vertical) to 2-axis (lateral and longitudinal only) side sticks with pedals and left hand collective. This study provided valuable insight into force-deflection characteristics and the number of axes controlled by the side-stick controller for the ADOCS demonstrator aircraft. However, the study recommended provisions for evaluations of multiple controller configurations in the flight demonstration aircraft due to differences between simulation and flight.

More recently, Sikorsky Aircraft working on a Technical Area of Joint Interest (TAJI) funded under the National Rotorcraft Technology Center (NRTC) performed a simulation study to gather data in support of the development of handling qualities specifications for side-stick feel characteristics [4]. This study looked at variations of stick travel, breakout forces, damping and force gradient (with fixed stick inertia) in Sikorsky's motion base simulator. The simulation model was based on early CH-53K control laws with both rate command attitude hold, and attitude command velocity hold control modes. This study provided valuable insight into the effects of changes in control travel and force gradient, but cautioned that the results should be validated and refined in flight test before being incorporated into a future update of ADS-33E [5].

Studies have been conducted to assess the effects of cyclic force-feel characteristics in flight, two of which are discussed herein. The first study was conducted on the NASA/Army CH-47B variable-stability helicopter [6]. The aircraft was equipped with a programmable active center stick and rate command, attitude hold response types. The cyclic damping was varied, and the lateral natural frequency was varied by varying the stick inertia while keeping the stick gradient constant. The maneuver performed by the evaluation pilot was a roll attitude regulation task while the copilot flew the longitudinal cyclic, pedals and collective. Due to the safety monitors on the aircraft, the acceleration, rate and attitude capabilities were limited necessitating the use of a relatively benign sum-of-sines input compared to the input used in other studies [1][2]. Although not in the published paper, the presentation by Watson and Schroeder showed a proposed requirement on the feel system characteristics. The requirement set boundaries based on the cyclic natural frequency and inertia, with the stipulation of a lower damping limit of 0.3. An updated version of the requirement is published in [7].

The second study was conducted by the Canadian Institute for Aerospace Research using their variable-stability Bell 205A helicopter [8]. This study evaluated isometric sticks and variations in damping ratio and natural frequency of displacement sticks. The pilots evaluated both a sum-of-sines tracking task and various low-speed maneuvering tasks. One of the outcomes of this research was a suggested boundary for stick dynamics based on natural frequency and damping ratio. While these two studies produced boundaries for acceptable/unacceptable stick dynamics for rotorcraft, they were not able to provide guidance on how variations of the stick dynamics in the acceptable region impact handling qualities.

Under Task X, Handling Qualities for Active Controlled Rotorcraft of the U.S. German Memorandum of Understanding for cooperative research on helicopter aeromechanics, the U.S. Army Aeroflightdynamics Directorate (AFDD) and the DLR Institute of Flight Systems Germany are conducting an active inceptor characteristics flight test study. In the U.S., AFDD is utilizing the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) JUH-60A in-flight simulator with an active center stick, and in Germany DLR is utilizing their Active Control Technology/Flying Helicopter Simulator (ACT/FHS) with an active side stick. Evaluations of the ADS-33E Hover Mission Task Element (MTE) and Slalom MTE are being performed on both aircraft with a common matrix of inceptor natural frequencies and damping ratios with both attitude command and rate command response types. In the U.S., evaluations have been completed on the RASCAL by four U.S. Army experimental test pilots (XPs) and one German military XP at Moffett Field California. In Germany, preliminary flight tests have been conducted on the ACT/FHS at WTD-61 in Manching Germany by two German military XPs and one U.S. Army XP.

Coverage of paper

This paper presents the results of a flight test study conducted to collect data to investigate how changes in cyclic inceptor force-feel characteristics effect piloted handling qualities, to evaluate existing handling qualities criteria, and to provide a basis for developing new criteria that account for the cyclic inceptor force-feel characteristics. A description of the RASCAL and ACT/FHS as configured for these tests is presented, followed by an overview of the matrix of cyclic force-feel characteristics evaluated with both Attitude Command (AC) and Rate Command (RC) response types. Results include handling qualities ratings, a set of quantitative ratings designed to augment the HQR scale, and pilot comments.

The current ADS-33E short term response (bandwidth) requirements as applied to response due to both displacement and force input is presented for the RASCAL center-stick configurations to assess the applicability of the current criteria when using cyclic force as the input. A comparison of results of the center stick evaluations of the Slalom maneuver against predicted handling qualities levels from the Handling Qualities Sensitivity Function (HQSF) proposed in [9] is also presented to investigate the viability of the HQSF as a predictive tool.

Conduct of Test

Two Mission Task Elements (MTEs) from ADS-33E were chosen as evaluation maneuvers for this testing to study the effects of force-feel characteristics on handling qualities, the Hover MTE for low-speed maneuvering using small precise inputs, and the Slalom MTE for high-speed maneuvering when making large inputs. To the extent possible, the testing always began with a baseline cyclic force-feel configuration. The pilot then performed as many practice runs as desired to become familiar with the task using the baseline configuration. The pilot then performed a minimum of three evaluation runs "for the record" and provided feedback. The remaining configurations were evaluated "blind", in a random order and rated by the pilot using the same procedure. At the end of the evaluations the pilot was allowed to go back and look at any of the configurations and update their evaluation if desired. The pilot then ranked their order of preference of the inceptor configurations for the MTE and response type being evaluated. Not all pilots were able to evaluate all configurations.

The pilot comments collected at the end of each configuration evaluation included the assignment of a Cooper-Harper handling qualities rating (HQR) and answers to a structured questionnaire about task performance, aircraft characteristics and demands on the pilot. In addition, the pilots were asked to assign a numerical score from one to nine rating the level of precision obtainable, their ability to be aggressive, and on ride quality where higher numerical scores were considered to be the best. The pilots were also asked to assign numerical scores for characteristics of the cyclic inceptor feel, forces, and response sensitivity where five was considered to be optimal. This choice of quantities to be rated and the adjectives used to describe the quantities was based on recurring adjectives recorded during numerous other flight tests conducted by AFDD. The application of a numerical rating scale based on common adjectives allowed for quantitative analysis of the otherwise qualitative comments.

Center-Stick Cyclic Testing

The flight testing on the RASCAL with an active center stick cyclic was conducted by AFDD on the ADS-33 course at Moffett Field [10]. The RASCAL has a full-authority, fly-by-wire research flight control system for the right seat evaluation pilot, while maintaining the standard UH-60 mechanical controls for the safety pilot in the left seat [11]. The control laws used for the evaluations were model following control laws with both RC and AC response types for the lateral and longitudinal axes and are described in detail in [12] [13]. The gains for these control laws were optimized to provide Level 1 handling qualities; the optimization did not consider the cyclic force-feel characteristics. The control laws featured height hold in the vertical axis, heading hold at hover/low speeds and zero side-slip hold at high speeds in the directional axes. This allowed the pilots to fly the Hover and Slalom MTEs using only the cyclic. For the Slalom MTE, velocity hold was enabled in the pitch axis which allowed the pilot to use only the lateral cyclic to conduct the evaluations. Position hold was disabled for all evaluations.

The characteristics of the cyclic inceptor dynamics are defined by the inertia and the force displacement features shown in Figure 1. The inceptor displacement due to force input can be modeled as a simple second order system:

$$\frac{\delta_{disp}}{\delta_{force}} = \frac{\omega_n^2 / k}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

where the k is the force gradient shown in Figure 1 and $\omega_n = \sqrt{k/Mass}$. A matrix of two undamped natural frequencies (ω_n = 7 and 23 rad/sec) and two damping ratios (ζ = 0.7 and 1.5) were selected that defined the boundaries of the test space to be evaluated. Within this

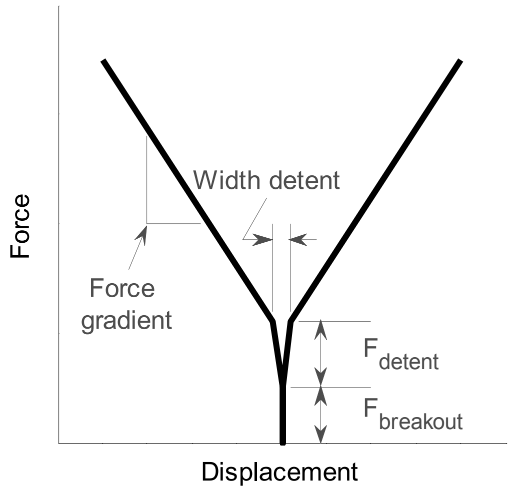

Figure 1. Cyclic force displacement diagram

test space, an additional interior point (ω_n = 9 rad/sec, ζ = 0.9) that had been used for the testing in [13] was selected as the baseline configuration. The force-displacement gradient was set to 0.75 lb/in for all configurations and the inertia was adjusted to change the undamped natural frequency. For evaluations with AC, the breakout force was set to 0.1 lb and the detent was set to 1 lb with a width of 0.14 inches. When the AC breakout and detent settings were evaluated with RC the detent was found to be objectionable, so the detent was removed and the breakout was set at 1 lb. The lateral and longitudinal cyclic force-feel characteristics were constrained to be equal for each configuration. The five cyclic configurations used for the evaluations are shown in Table 1, plotted against the boundaries from [6] [7] in Figure 2, and plotted against the boundaries from [8] in Figure 3. None of the center-stick configurations fall in the degraded regions of either figure.

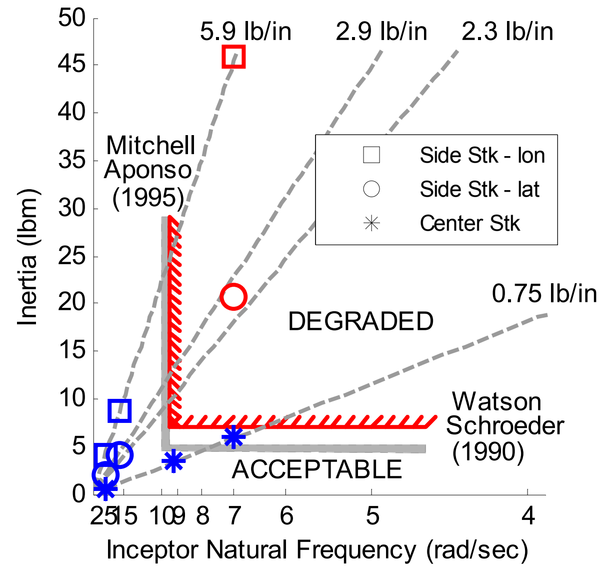

Figure 2. Boundaries on inceptor inertia and natural frequency from [5] and [6]

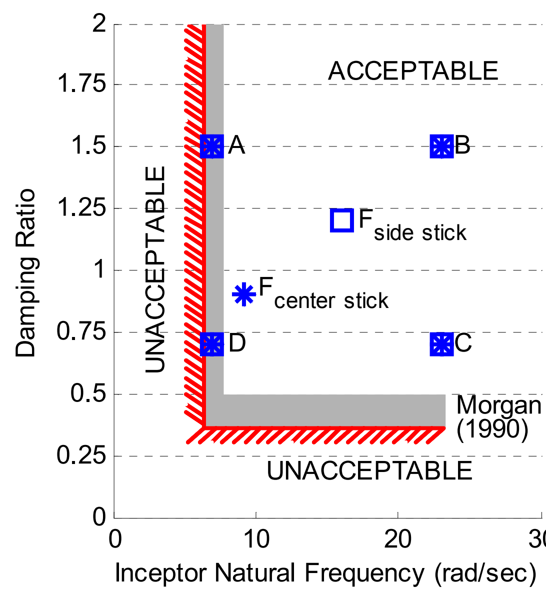

Figure 3. Boundaries on inceptor damping ratio and natural frequency from [7]

Table 1. RASCAL center-stick cyclic configurations

Config.	Inertia[a] (lbm)	ω_n (rad/sec)	ζ	Breakout (lb)		Detent (lb, in)	
				AC	RC	AC	RC
A	5.9	7.0	1.5	0.1	1.0	1.0, 0.14	0, 0
B	0.6	23.0	1.5	0.1	1.0	1.0, 0.14	0, 0
C	0.6	23.0	0.7	0.1	1.0	1.0, 0.14	0, 0
D	5.9	7.0	0.7	0.1	1.0	1.0, 0.14	0, 0
F	3.4	9.2	0.9	0.1	1.0	1.0, 0.14	0, 0

[a] Inertia (lbm) is listed to be consistent with the criteria of Figure 2

Side-Stick Cyclic Testing

Flight test evaluations with an active side-stick were conducted by DLR at the Technical and Airworthiness Center for Aircraft (WTD 61) in Manching Germany on the ACT/FHS [14][15][16]. The test aircraft research system features a full authority, four times redundant (quadruplex) fly-by-light primary flight control system that incorporates a simplex experimental flight control computer. The control laws used for the evaluations were developed at DLR, and were also used during an Empire Test Pilot School rotorcraft exercise on the ACT/FHS, to give the trainees the opportunity to tune their own control laws. The control laws were AC in pitch and roll, with a selectable RC in the roll axis. Rate command was not selected in the pitch axis to reduce the need for compensation inputs to maintain velocity during maneuvers with large bank angles changes. The AC control laws and the mixed RC roll, AC pitch control laws were predicted to provide Level 1 handling qualities.

Altitude hold performance was dependant on setting the collective trim position in the detent at the initiation of each evaluation, and occasionally required small corrections by the pilot to maintain altitude. Heading hold was not available for these tests so the pilot had to manually maintain heading during the evaluations.

The side-stick force-feel configurations that were tested on the ACT/FHS are tabulated in Table 2. The side-stick longitudinal characteristics were symmetric about trim; the lateral characteristics were set differently from the longitudinal characteristics and were not symmetric about trim. The natural frequency of the lateral side stick reported in Table 2 and plotted in the following figures is based on the average of the left and right natural frequencies. The difference in longitudinal and lateral, and left and right force-feel characteristics are to account for different capabilities of the human arm and wrist. The intent was to provided the pilot with a side stick that felt qualitatively the same laterally and longitudinally, and symmetric about trim. The undamped natural frequencies and damping of configurations A through D were selected to be approximately the same as the configurations evaluated with the center stick on the RASCAL, but the gradient and breakout were set to values more appropriate for a side stick. For testing of the side stick, configuration F was selected to be in the center of the test space. As a result, the damping and natural frequency of this configuration differs from configuration F that was evaluated with the center stick on RASCAL (Figure 3). The test procedure with the side stick was similar to the procedure used for testing with the center stick described in the previous section. A different pilot questionnaire was used for testing of the side stick, which contained only a subset of the questions from the center stick testing.

Results

The results of the testing with the center stick and side stick are presented in the following sections. As stated earlier, the results with the side stick are preliminary results so only the HQRs are presented herein. A more in depth analysis of the results from the testing on the ACT/FHS will be published in [17].

Both the RASCAL and the ACT/FHS have safety monitoring systems that disengage the research flight control systems when limits on command input magnitude or rate are encountered. During evaluations of the Slalom task the presence of these monitors forced the pilots to constrain their technique to prevent trips of the safety monitors. This was more of a factor on the RASCAL than on the ACT/FHS.

All of the evaluations of the Hover MTE were performed

Table 2. ACT/FHS side-stick cyclic configurations

Config.	Inertia[a] (lbm)		Gradient (lb/in)			ω_n[b] (rad/sec)	ζ	Breakout (lb)		Detent (lb, in)		
	lat	lon	lat		lon			lat	lon	lat		lon
			left	right						left	right	
A	20.7	45.9	2.9	2.3	5.8	6.3	1.5	0.76	0.76	4.8, 1.7	3.8, 1.7	0, 0
B	1.9	4.2	2.9	2.3	5.8	25.1	1.5	0.76	0.76	4.8, 1.7	3.8, 1.7	0, 0
C	1.9	4.2	2.9	2.3	5.8	25.1	0.7	0.76	0.76	4.8, 1.7	3.8, 1.7	0, 0
D	20.7	45.9	2.9	2.3	5.8	6.3	0.7	0.76	0.76	4.8, 1.7	3.8, 1.7	0, 0
F	4.0	8.8	2.9	2.3	5.8	15.7	1.1	0.76	0.76	4.8, 1.7	3.8, 1.7	0, 0

[a] Inertia (lbm) is listed to be consistent with the criteria of Figure 2

[b] lateral natural frequency is average of left and right natural frequencies

in the day (GVE) when the winds were 10 kt or less, and evaluations of the Slalom MTE were conducted when the winds were 15 kt or less. During the pilot debriefings conducted at the end of each flight, none of the pilots considered winds to be a factor during any of the evaluations. In addition to HQRs, when available the numerical ratings for ability to be precise, limitations on ability to be aggressive, and ride quality collected for each configuration were fit to a regression plane model. A two-way Analysis of Variance (ANOVA) was also performed on the data to test the statistical significance of the influences of damping and natural frequency, and the interaction effect of the two. Results with a p-level of less than 0.05 were considered statistically significant, and with levels between 0.05 and 0.1 to be marginally significant. When available, pilot ratings of the stick feel, forces and sensitivity were averaged and plotted with 95 percent confidence intervals.

Hover MTE Evaluation, Center Stick (RASCAL)

The results of the regression plane fits of the HQRs from evaluations of the Hover MTE for the five cyclic inceptor configurations with AC are shown in Figure 4, and with RC in Figure 5. The lines of constant HQR are plotted with the numerical rating, and the arrow shows the direction of improvement. The figures show that configuration B produced the best average HQR (Level 1), and that configuration D produced the worst average HQR (Level 2) for both AC and RC. The ANOVA showed that the influence of damping (ζ) was significant, the influence of natural frequency (ω_n) was marginally significant for AC, and that the interaction effect of the two (ζ and ω_n) was not significant. The figures also show that for all cyclic configurations there is almost one HQR improvement for AC compared to RC.

These results are consistent with the results reported in [13] which utilized configuration F. The main difference between the two tests is that position hold was enabled for the results of [13] where position hold was disabled for this test, forcing the pilot to maintain position using the cyclic during the entire 30 seconds of the Hover MTE.

The pilots also rated their level of precision obtainable on a nine point scale (one = low precision, and nine = high precision), limitations on their ability to be aggressive (one = limited, nine = unlimited), and ride quality (one = jerky, nine = smooth). The regression fit of the scores from the precision rating for the Hover MTE with AC is shown in Figure 6, and with RC in Figure 7. For this

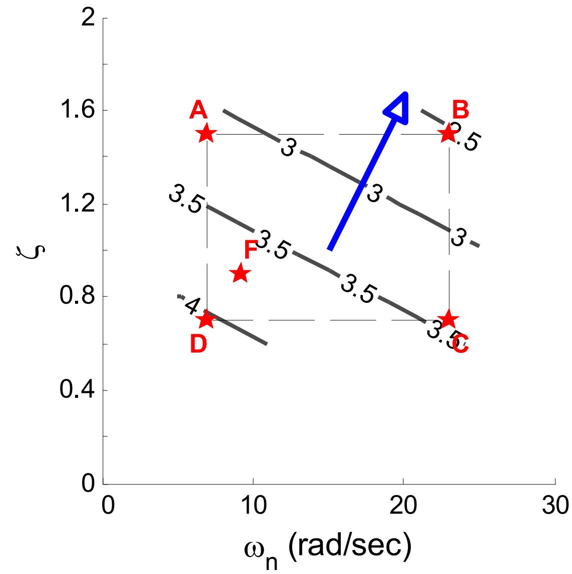

Figure 4. Regression fit of HQRs for Hover, AC, center stick

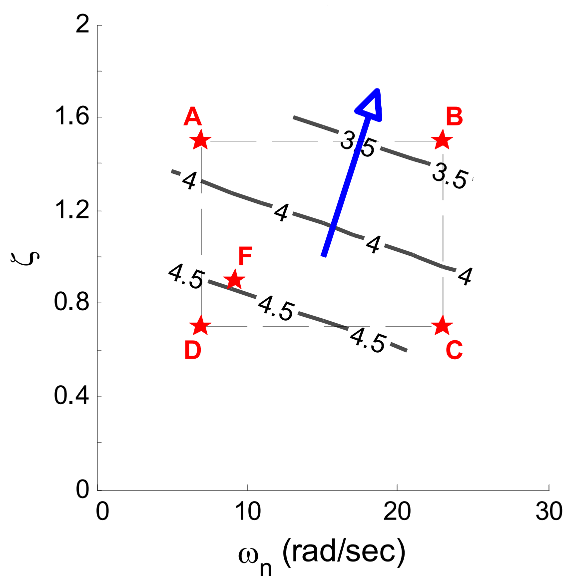

Figure 5. Regression fit of HQRs for Hover, RC, center stick

rating, a higher numerical value is better, and the direction of improvement is indicated by the arrow.

The results show that the pilot's perceived ability to be precise was the best for configuration B, and worst for configuration D. The results of the ANOVA showed that the influences of damping and natural frequency were significant for AC, but were not significant for RC. Interaction effects were not significant for either AC or RC. The figures also show that configuration D has about the same precision rating for both AC and RC. While the

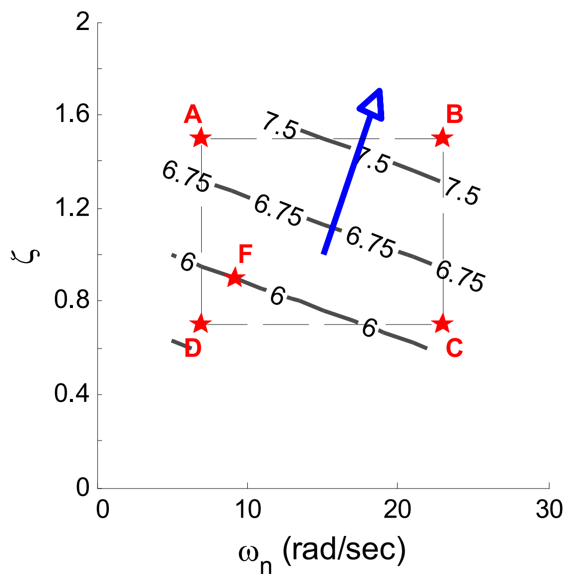

Figure 6. Regression fit of precision rating, Hover, AC, center stick

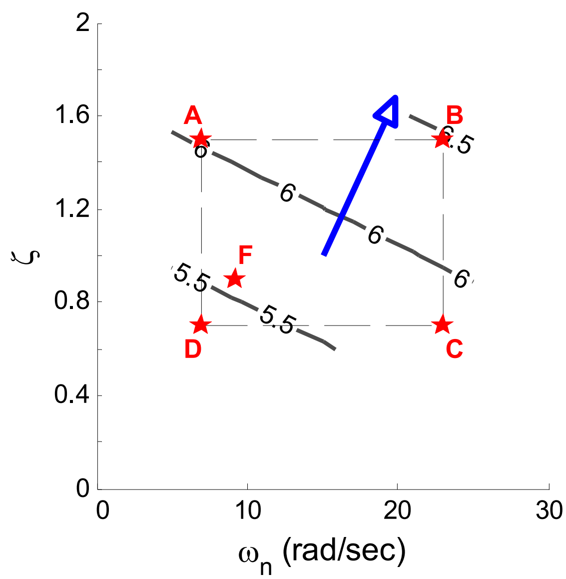

Figure 7. Regression fit of precision rating, Hover, RC, center stick

regression plane fit for RC (Figure 7) shows only a small change in numerical scores between D and B (relatively flat slope), the fit for AC (Figure 6) shows a much larger change in the numerical scores (steeper slope) toward high precision for configuration B when performing the Hover MTE.

The regression fit of the aggressiveness rating for the Hover MTE with AC is shown in Figure 8, and with RC in Figure 9. The figures show that configuration B received the highest average aggressiveness rating and

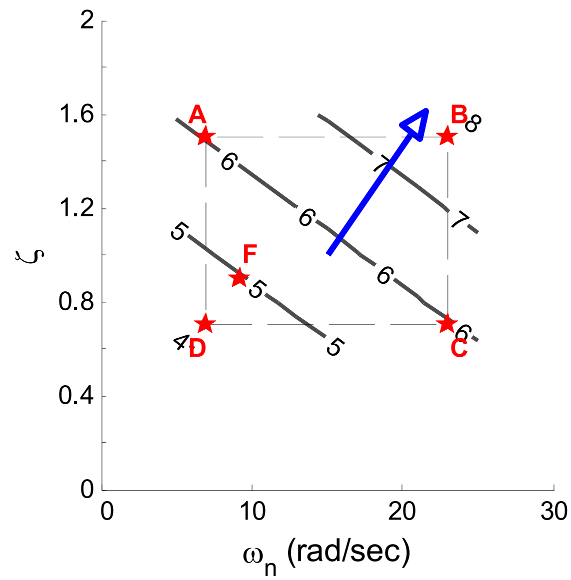

Figure 8. Regression fit of aggressiveness rating, Hover, AC, center stick

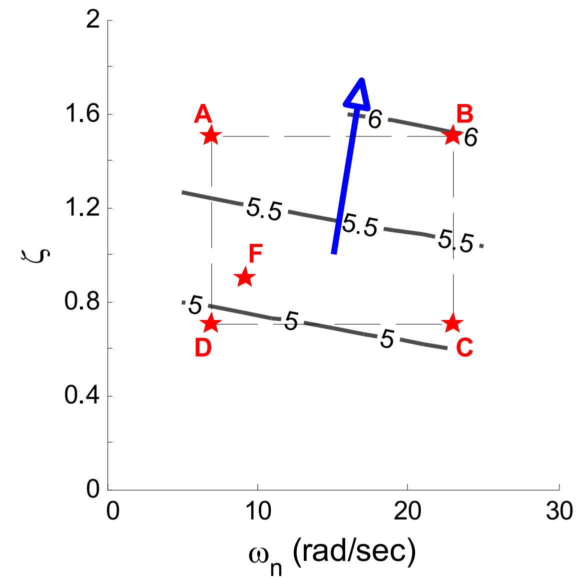

Figure 9. Regression fit of aggressiveness rating, Hover, RC, center stick

configuration D the lowest for both AC and RC. The results of the ANOVA showed that interaction effects were not significant, that the influences of damping and the influence of natural frequency were significant for AC, but were not significant for RC. Again this is consistent with the relatively steep slope of the plane for AC, and the relatively flat slope of the plane for RC. It is interesting to note that the ratings for both precision and aggressiveness for the best configuration (B) are rated much higher for AC than for RC.

The regression fit of the ride quality rating for the Hover MTE with AC is shown in Figure 10, and with RC in Figure 11. The figures show that the pilots were able to perceive an improvement in ride quality with increasing damping of the cyclic. For AC, the ANOVA results did not show that the influence of damping, natural frequency, or the interaction effect were significant. For RC, the ANOVA results showed that the influence of damping on ride quality was marginally significant, and that the influence of natural frequency and the interaction effect were not significant. A summary of the ANOVA p-levels from evaluations of the Hover MTE with a center stick are presented in Table 3. Statistically significant results are in bold, and the marginally significant results are shaded.

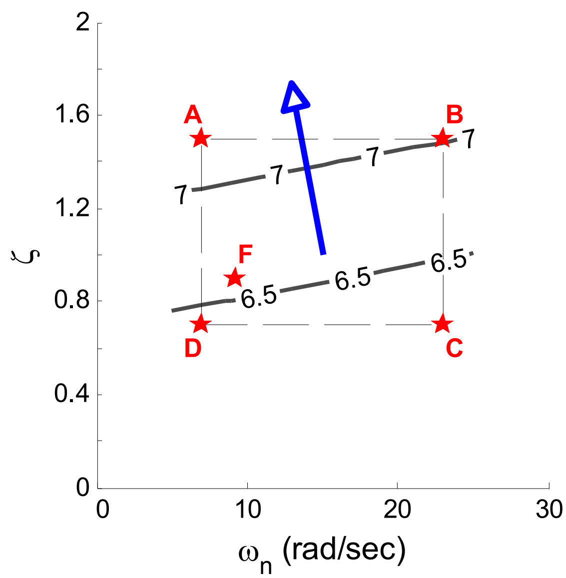

Figure 10. Regression fit of ride quality rating, Hover, AC, center stick

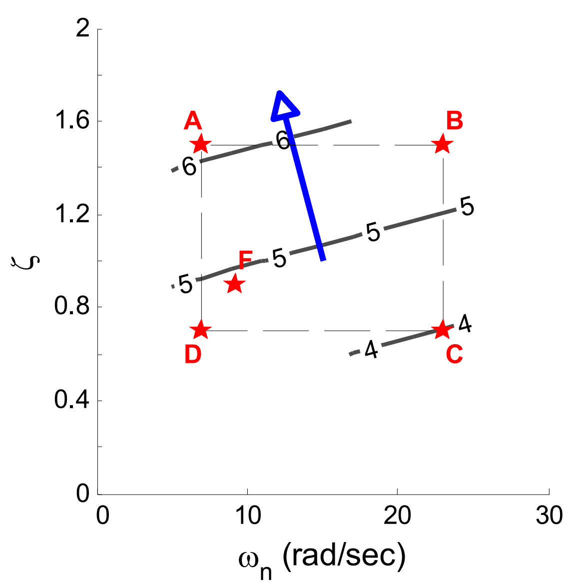

Figure 11. Regression fit of ride quality rating, Hover, RC, center stick

Table 3. Summary of ANOVA p-levels, Hover, center stick

Response type	Rating scale	Main effect ζ	Main effect ω_n	Interaction $\zeta \times \omega_n$
AC	HQR	**0.016**	0.057	1.00
	Precision	**0.001**	**0.014**	0.177
	Aggressiveness	**0.032**	**0.032**	0.558
	Ride quality	0.356	0.576	0.356
RC	HQR	**0.012**	0.124	0.518
	Precision	0.432	0.563	0.495
	Aggressiveness	0.165	0.407	0.407
	Ride quality	0.067	0.156	0.257

Slalom MTE Evaluation, Center Stick (RASCAL)

The regression plane fits of the HQRs for the Slalom MTE for AC are shown in Figure 12, and for RC in Figure 13. Both figures indicate that there is a slight improvement in handling qualities with increasing damping. However the results of the ANOVA showed that neither the influence of damping, natural frequency, nor the interaction effect were statistically significant for both AC and RC. The same is true for the precision ratings, and the aggressiveness ratings for both AC and RC. The improvement in ride quality rating with increasing damping was the only parameter for the Slalom that did show a statistically significant effect for AC and marginally significant effect for RC.

The reasons for the difference in the effect of the configurations on handling qualities between the Slalom and Hover MTEs lie in the requirements of the maneuver, which drive the character of the pilot inputs. Two metrics that can be used to characterize the pilot inputs are the RMS and cutoff frequency (ω_{co}) of the cyclic input time histories. The cutoff frequency is calculated from the autospectra of the pilot control time history, and is defined as the upper end of the frequency range that encompasses one half of the total area under the curve. This parameter is a direct measure of the pilot's operating frequency and has been shown to be a good estimate of the piloted crossover frequency [18] [19].

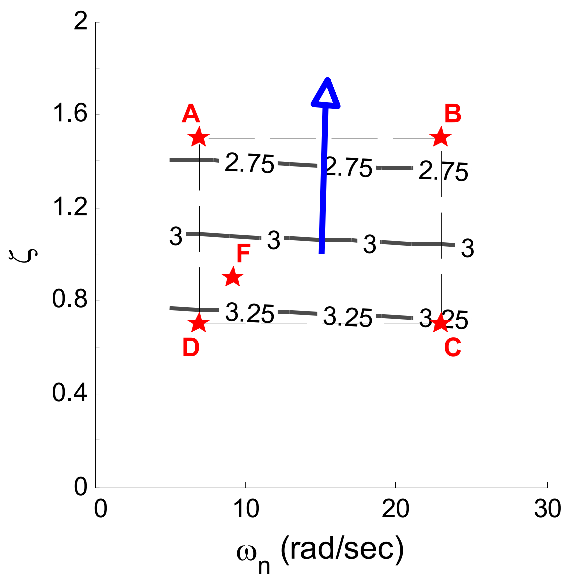

Figure 12. Regression fit of HQRs, Slalom, AC, center stick

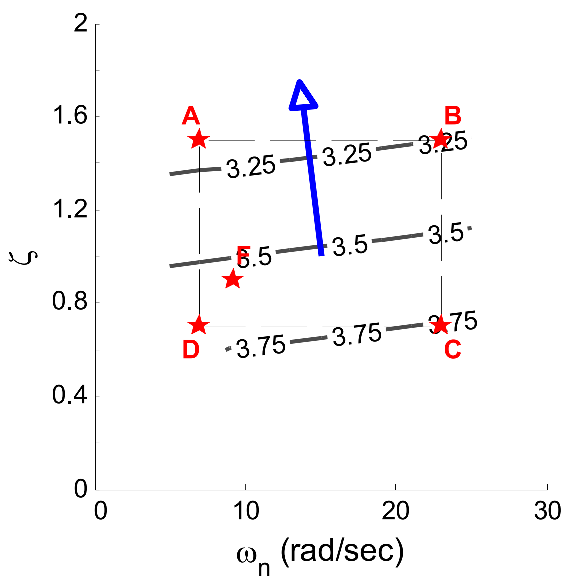

Figure 13. Regression fit of HQRs, Slalom, RC, center stick

The mean lateral cyclic cutoff frequencies are plotted in Figure 14 and the mean RMS are plotted in Figure 15 along with the 95 percent confidence intervals for all the evaluations of the Hover and Slalom MTEs. Figure 14 and Figure 15 show quantitatively that the pilots adopted a high frequency/small amplitude control strategy for the Hover MTE, and a low frequency/high amplitude control strategy for the Slalom MTE.

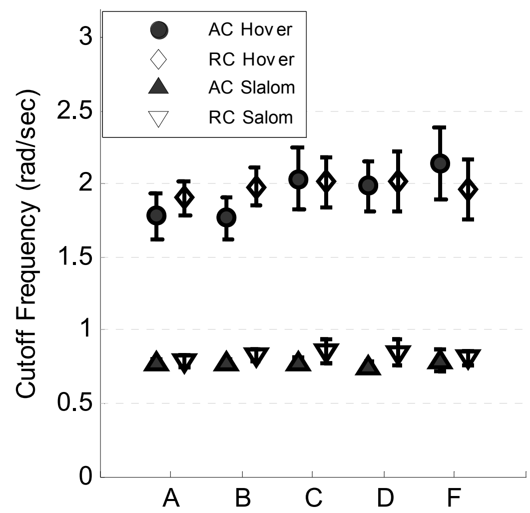

Figure 14. Pilot lateral cyclic cutoff frequencies with 95% confidence interval, center stick

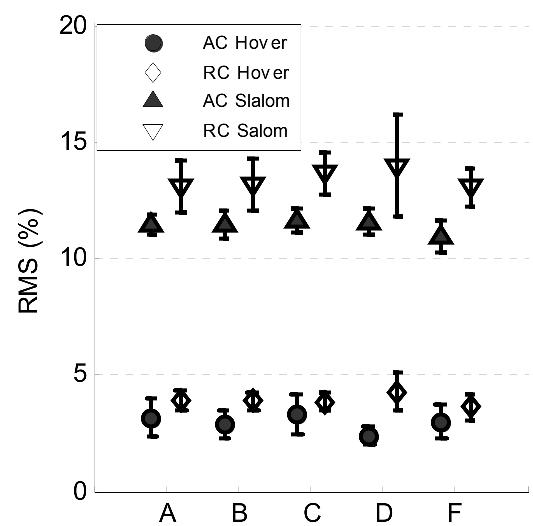

Figure 15. Pilot lateral cyclic RMS with 95% confidence interval, center stick

This indicates that the lower operating frequency and larger magnitude of the pilot inputs associated with the Slalom MTE did not expose any significant benefit, or deficiency of any inceptor configuration with respect to task performance. However, the improvement in ride quality with increased damping of the inceptor is an important result that can impact pilot fatigue and overall mission performance. A summary of the ANOVA p-levels from evaluations of the Slalom MTE with a center stick are presented in Table 4.

Table 4. Summary of ANOVA p-levels, Slalom, center stick

Response type	Rating scale	Main effect ζ	Main effect ω_n	Interaction $\zeta \times \omega_n$
AC	HQR	0.218	0.909	0.427
	Precision	0.164	0.279	0.279
	Aggressiveness	0.683	0.435	0.875
	Ride quality	**0.007**	0.752	0.964
RC	HQR	0.574	0.574	0.198
	Precision	0.737	0.666	0.149
	Aggressiveness	0.804	0.804	0.172
	Ride quality	0.081	0.496	0.649

Additional Pilot Ratings, Center Stick (RASCAL)

In addition to the ratings presented above, the pilots were asked to provide ratings of three qualitative parameters on a nine point scale, with five being optimal. The parameters were the feel of the cyclic (1=too slow, 9=too fast), the cyclic forces (1=too low, 9=too high), and the sensitivity (1 = too small of a response for a given input, 9 = too large of a response for a given input) with five corresponding to optimal. The intent of these questions was to expose objectionable characteristics (e.g. sluggish dynamics, excessive force gradients or response sensitivity gains) so they could be corrected early in the testing.

Figure 16 shows the average ratings from the combined evaluations of Hover and Slalom MTEs with AC. The error bars on the plots correspond to the 95% confidence intervals of the mean values. The figure shows that configurations A and D with the lowest natural frequency were rated slightly slower than the other configurations. Configuration F was rated as fast as configurations B and C, even though the natural frequency of configuration F is close to configuration D. The figure shows that in general the force-deflection gradient was rated near optimal for AC. It is interesting to note that configuration D was perceived to have slightly lower than optimal forces and sensitivity even though the force-displacement gradient and sensitivity did not change between configurations.

The average qualitative ratings for RC are shown in Figure 17. For RC, there appears to be more variation in the pilot ratings than there were for AC, in particular for configuration D. The feel ratings for RC follow a similar trend to the trend observed for AC. In general for both

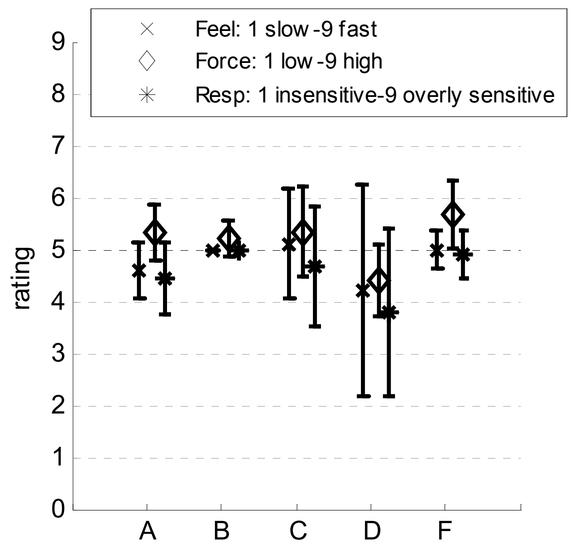

Figure 16. Average cyclic qualitative ratings with 95% confidence interval, AC, center stick

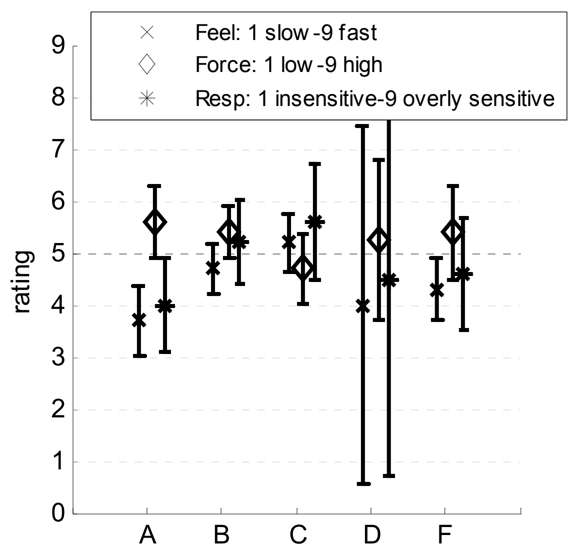

Figure 17. Average cyclic qualitative ratings with 95% confidence intervals, RC, center stick

AC and RC, these results show that the feel rating tracked the inceptor natural frequency, and that the force-displacement gradient and stick sensitivities were satisfactory for the experiment.

Hover MTE Handling Qualities Ratings, Side Stick (ACT/FHS)

The regression plane fit of the HQRs for the Hover MTE conducted on the ACT/FHS with AC is shown in Figure 18. Once again, configuration B received the best overall average HQR. In contrast to the results from the center

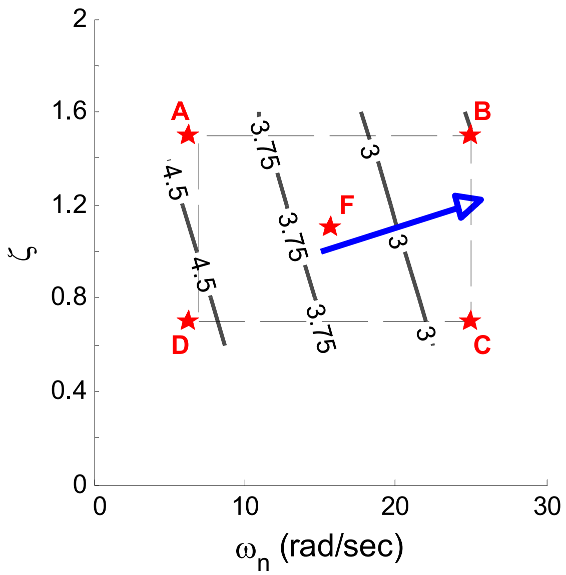

Figure 18. Regression fit of HQRs, Hover, AC, side stick

stick, the slope of the regression plane for the side stick shows the greatest improvement in handling qualities with increasing natural frequency. This observation is confirmed by the ANOVA analysis which showed that the influence of natural frequency was significant, but that neither the influence of damping, nor the interaction effect was significant. Results are not presented here from the evaluations of the Hover MTE with RC due to the mixed mode and the limited number of pilots evaluations currently available.

The reduction of the influence of damping for the side stick as compared to the center stick may be related to the presence of the arm rest for the side stick [16], which would tend to stabilize the pilot's arm. The increased influence of natural frequency for the side stick may be attributable to the use of wrist motion for the side sticks versus arm motion for center sticks. In addition, the inertia of the different stick configurations could also be a factor. For the center stick, all of the configurations fall in the acceptable region of Figure 2. For the side stick, configurations B, C and F are in the acceptable region of Figure 2, while configurations A and D are in the degraded region due to the large mass required to obtain a natural frequency of 6.3 rad/sec for these two configurations.

Slalom MTE Handling Qualities Ratings, Side Stick (ACT/FHS)

The regression plane fits of the HQRs for the Slalom with AC is shown in Figure 19, and with RC in Figure 20. The ANOVA did not show that either of the influences of damping or natural frequency, nor the interaction effect were statistically significant for the evaluations with AC. For the evaluations with RC, only the influence of natural frequency was statistically significant. Again, this may be a characteristic of side sticks that is attributable to the action of the wrist (versus the arm for center sticks), and could be influenced by the large inertia required to obtain the desired natural frequency for configurations A and D.

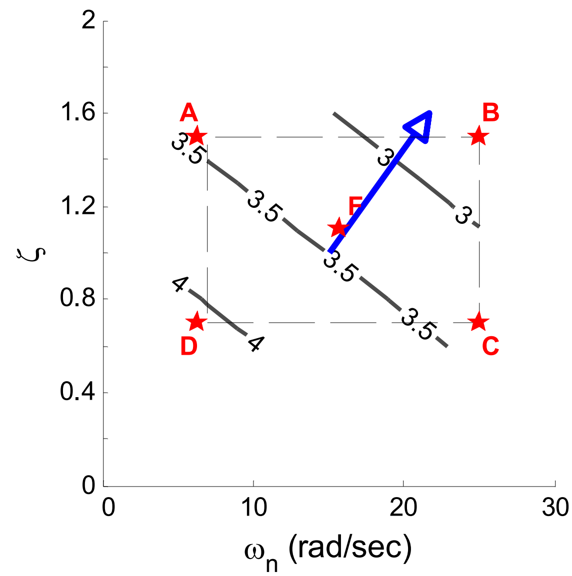

Figure 19. Regression fit of HQRs, Slalom, AC, side stick

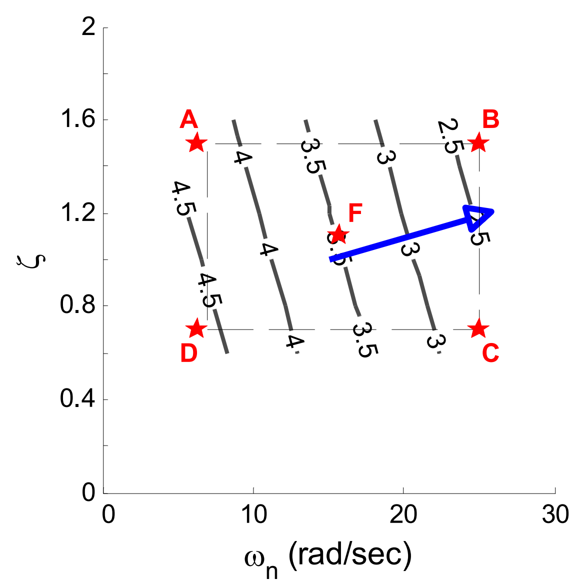

Figure 20. Regression fit of HQRs, Slalom, RC, side stick

Pilot Comments, Center Stick and Side Stick

The two ADS-33E maneuvers flown were well suited for revealing differences since they required different control techniques: quick, small, precise inputs for stabilizing and maintaining the aircraft in a hover, and large, moderate to highly aggressive inputs for the slalom course. For the Hover MTE, the following inceptor characteristics were generally found desirable:

- A light, quick feel
- Well damped to allow precise small inputs around trim
- Little to no perceived delay in aircraft response to control input

There seemed to be benefits on increased damping such that greater levels of precision were achieved resulting in the lowest workload. While the force gradient and sensitivity of the inceptor remained unchanged between the different configurations, the pilots' perception was that inceptor configurations with lower natural frequencies presented a heavier feel, and were less sensitive making the workload to capture and maintain a hover more difficult. An inceptor with the combination of a heavy feel and low damping (configurations D) provided the least precision, felt wobbly when making small rapid inputs, and was the most prone to over-controlling the aircraft.

For the Slalom MTE, desirable characteristics were:

- An inceptor that tracked well with the aircraft movement (especially for AC)
- Little to no perceived delay in aircraft response to control input
- Well damped to prevent over-controlling resulting in a jerky ride quality
- No susceptibility to bio-feedback

Pilot preference varied somewhat between the configurations when flying the slalom task but the dominant factor that affected pilot perception was how precisely the aircraft tracked or responded to control inputs. Bio-feedback (aircraft vibrations being fed back through the pilot's arm into the inceptor) and its effect was more noticeable in the attitude command configuration since the lateral cyclic inputs had to remain displaced and held from the detent in order to hold the desired aircraft attitudes. The lighter, less-damped configurations (configurations C) proved to be the most susceptible to bio-feedback interference with the slalom task. It should be noted that when flying the slalom task in the AFDD JUH-60A RASCAL the evaluation pilot control inputs had to be slightly restrained to avoid tripping the aircraft's internal lateral rate safety monitors on the Research Flight Control System (RFCS) which would result in the RFCS disengaging. Because of this, some pilots felt that they could have been more aggressive with their inputs in several of the stick configurations.

Qualitatively, for flight maneuvers requiring larger, sustained stick displacements, such as the slalom when flown in AC, the side stick configuration was preferred since the force required to hold the stick out of detent was less objectionable than with the center stick. Additionally the effects of bio-feedback were less perceptible with the side arm controller due in part to the integrated arm rest providing a more stable platform for the pilot's arm. The asymmetrical lateral force characteristics of the side stick felt symmetrical in all but configuration B (low inertia, high damping) when flying high gain maneuvers.

Pilot Ranking of Configurations

As part of the questionnaire, the pilots were asked to rank the configurations from best to worst for each command type (AC and RC) and each MTE (Hover and Slalom). Generally, the pilots' rankings correlated well with their HQRs. For the center stick, configuration B was rated as best by most pilots, and as second best by the remaining pilots. This was the case for both response types and both MTEs. Configuration D was generally rated at or near the bottom. The exception was for the Slalom where one pilot rated configuration D as best for RC and AC (B was the pilot's second choice) and another pilot rated it second best for AC (behind B).

For the side stick evaluations of both response types and MTEs, configuration B was again rated as best by most pilots and second best by all but one of the remaining pilots. This pilot rated configuration B as the third best for Hover, RC. Again, configuration D was rated consistently near the bottom (4^{th} or 5^{th}), with the best rating of third best by one pilot for Slalom, RC.

Predictive Criteria

Assessment of ADS-33 Criteria

The attitude bandwidths for pitch and roll as defined in ADS-33E section 3.3.2, small-amplitude pitch and roll attitude changes, were calculated for the center-stick configurations evaluated on the RASCAL. This requirement states that pitch (roll) response to the longitudinal (lateral) cyclic control position inputs shall meet the specified limits. It also states that it is desirable to also meet the criteria for controller force inputs. The roll bandwidths for AC are plotted in Figure 21, and the pitch bandwidths for AC are plotted in Figure 22 with the specified limits for UCE = 1 and fully attended operations. The roll bandwidths for RC are plotted in Figure 23, and the pitch bandwidths for RC are plotted in Figure 24 with the same limits. The numbers in brackets are the average HQRs from the Hover MTE for each center-stick configuration. The differences between the two displacement points on the plots are due to the location of the control position measurement. The displacement inputs for the CLAW are at the input to the control laws, where the inceptor inputs are the unfiltered outputs of the cyclic inceptor rotary potentiometers. The differences between the two are primarily due to anti-alias filters on the inceptor signals.

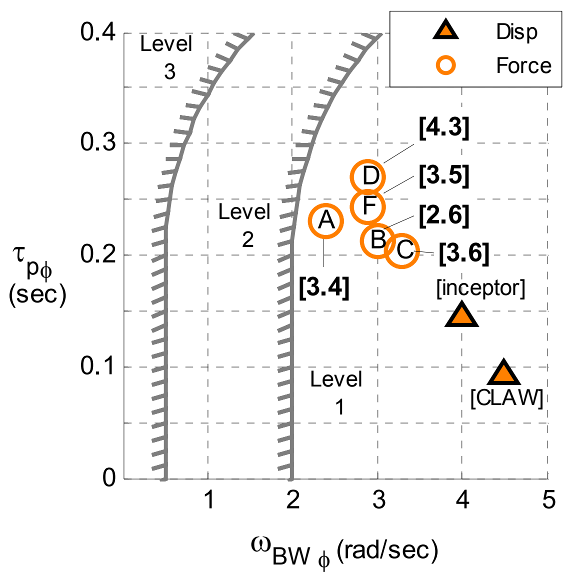

Figure 21. Roll bandwidth from displacement input and from force inputs, AC, center stick

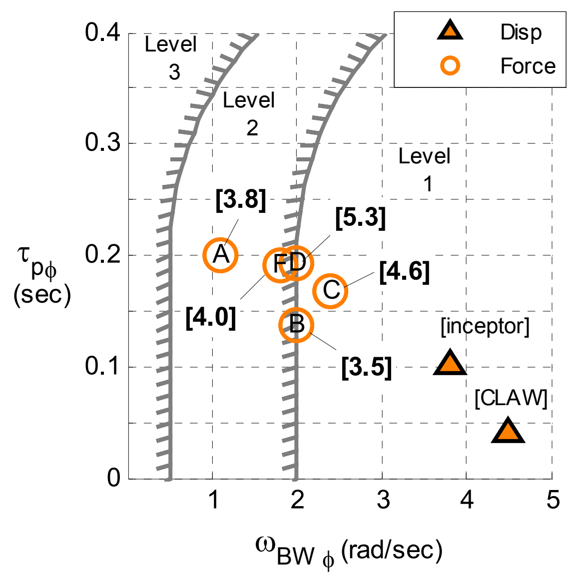

Figure 23. Roll bandwidths from displacement and force inputs, RC, center stick

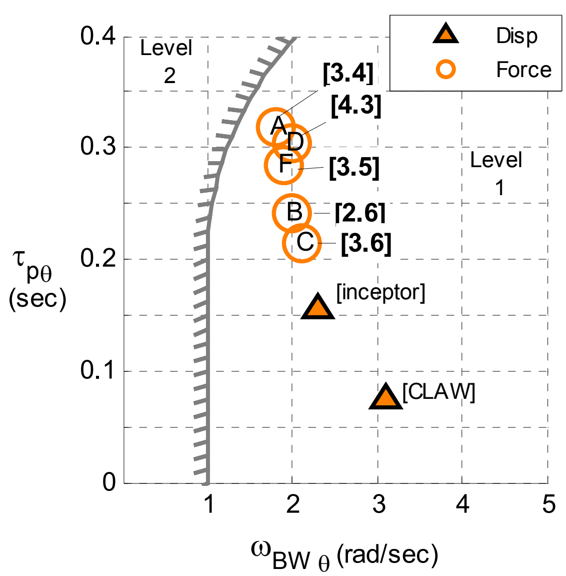

Figure 22. Pitch bandwidth from displacement input and from force inputs, AC, center stick

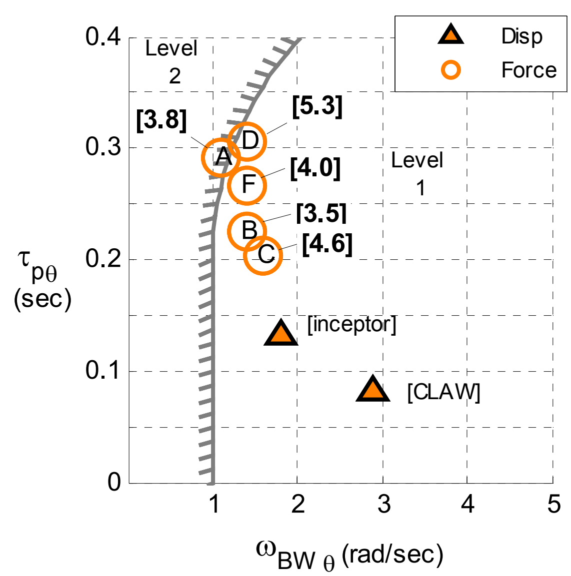

Figure 24. Pitch bandwidths from displacement input and force inputs, RC, center stick

All of the bandwidths and phase delays from the position inputs are solidly in the Level 1 regions of the criteria, although there is a significant loss of bandwidth and increase in phase delay due to the anti-alias filters. All of the plots suggest that configuration C would confer the best ratings as the C inceptor characteristics impart the least reduction in the bandwidth, and the least amount of additional delay. This prediction does not agree with the HQRs from the Hover MTE which show that configuration B confers the best HQRs. These results show that all of the force points that fall in the Level 2 region received Level 2 HQRs, however all the force points in the Level 1 region did not receive Level 1 HQRs. This result indicate that the bandwidth/phase delay criteria should be evaluated using displacement inputs, and the force-feel characteristics should be considered seperatly.

Handling Qualities Sensitivity Function Criteria

An alternative method of predicting the handling qualities of the closed-loop system that includes the inceptor characteristics is the Handling Qualities Sensitivity Function (HQSF) proposed by Hess [9]. The block diagram shown in Figure 25 illustrates a mathematical representation of the feedback structure employed by a pilot flying a compensatory lateral position tracking task from [9]. This compensatory pilot-aircraft model is seen to rely on a structural pilot model for inner-loop attitude (roll) compensation. Sub-components for the structural pilot include neuromuscular dynamics (Y_{NM}), proprioceptive and vestibular feedback (Y_{PF} and $sK_{\dot{m}}$ respectively), and the visual error compensation (Y_e). A key feature of this approach is the modeling of proprioceptive feedback, which accounts for the ability of the pilot to make corrections to his control inputs based on the perception of stick displacement. This allows for the modeling of the inceptor dynamic response to pilot force inputs (Y_{FS}).

The use of the structural pilot model for handling qualities prediction is predicated on the value of the Handling Qualities Sensitivity Function (HQSF)

$$HQSF = \left| \frac{U_M}{\phi_{com}}(j\omega) \cdot \frac{1}{K_e} \right|$$

being contained within a prescribed set of boundaries (Figure 26) over the typical frequency range of pilot control, i.e., 1–10 rad/sec. Here U_M is the pilot compensation in response to proprioceptive and vestibular feedback, and K_e is the proportional component of the visual compensation strategy. At its core the fundamental concept of the HQSF is to quantify the compensation required from proprioceptive and vestibular feedback, in response to a desired attitude command. Handling qualities predictions from this model approach can be tailored to be task dependent. This is achieved by specifying the pilot crossover frequency, which

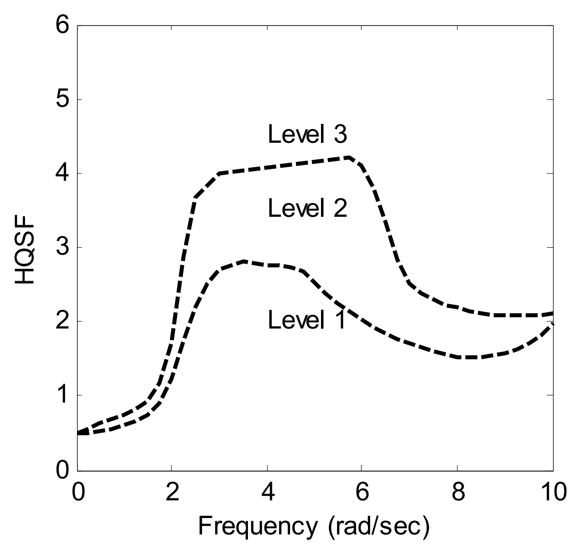

Figure 26. Handling qualities prediction boundaries

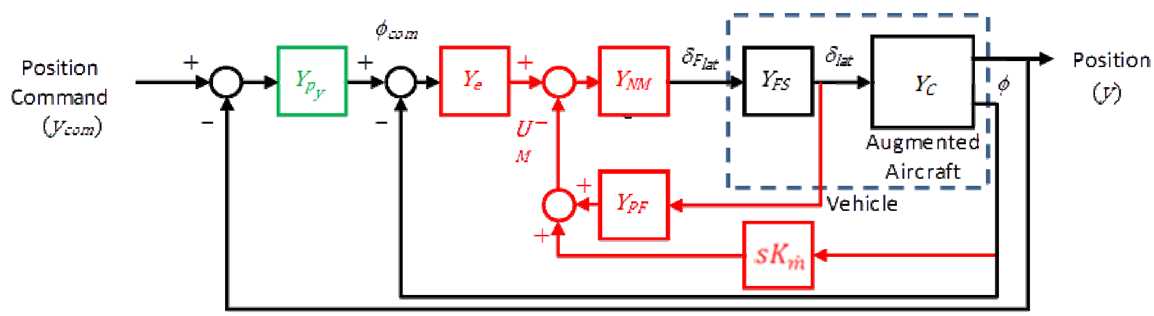

Figure 25. Compensatory feedback pilot model

fundamentally serves as an independent tuning parameter to the model. This assumes an a priori estimate of the crossover frequency for a given task is available. Herein this was achieved a posteriori, from estimates of the crossover frequency based on the spectral analysis computation of the pilot control input cutoff frequency (Figure 14) to validate the methodology.

As a starting point, selection of the pilot model sub-component parameters was done to match the literature [9]. Lower Order Equivalent System (LOES) models of the RASCAL RC and AC control modes were used for this analysis. The implementation of the proprioceptive loop is critical to the success of the HQ analyses, and the method is sensitive to selection of the proprioceptive feedback model, i.e., $K(s+a)$, K or $K/(s+a)$. At the experimental cut off frequencies, aircraft dynamics for AC indicate a transition between Ks and K.

Results for AC shown below are based on the selection of Ks (i.e., a = 0) as the best approximation at the nominal cut-off frequencies. Selection of the proprioceptive feedback model for RC was quite straightforward with K representing a perfect fit of the aircraft dynamics over a wide range of frequencies. Selection of pilot low frequency integral compensation can also have an impact on the analytical handling qualities prediction. Results below assume zero integral compensation. Also, because validation of the handling qualities boundaries had been achieved from fixed-base simulation [9], the vestibular feedback was assumed to be zero, which may not be appropriate for the current flight test activity.

Handling Qualities Sensitivity Function Predictions

Comparisons against flight data showed that the proposed compensatory tracking model could adequately represent pilot inceptor input activity amplitude and general qualitative character for the slalom maneuver with a center stick. These results were encouraging and provided increased confidence in the values selected for the structural model parameters.

Table 5 and Table 6 summarize the results obtained for the slalom task, with AC and RC control modes with a center stick. It is noted that, based on the cutoff frequency approximations obtained from flight test data, the structural pilot model predicts Level 1 handling qualities for all five active inceptor configurations in AC (Table 5). Table 6 indicates discrepancies between the predicted and experimental handling qualities in the RC evaluations for two configurations in particular: configurations A and C. Configuration A received a Level 1 rating, whereas the structural pilot model HQ sensitivity function predicted Level 2 handling qualities. Conversely, configuration C, which was predicted to be Level 1, was assigned convincing Level 2 ratings.

Figure 27 illustrates the qualitative differences between the two configurations in question. The discrepancy with configuration A is actually seen to not be that significant. Assigned ratings were in actuality reflective of borderline Level 1-2 handling qualities. The Level 2 prediction for configuration A is based on the HQSF breaching the Level 1-2 boundary. This breach is, however, weak and far removed from the actual operating frequency of the pilot. The HQSF for configuration C, interestingly, is the farthest away from the boundary, and presumably should have provided the best handling qualities. It is noted that evaluation pilots indicated a tendency for this configuration to be prone to biodynamic feedback in response to the motion of the aircraft. The particular setup of the structural model does not include the effect of vestibular feedback, which could contribute to this discrepancy.

Table 5. Comparison of assigned and predicted handling qualities levels, Slalom, AC, center stick

	Experimental Average Cooper-Harper rating	Analytical
Config. A	2.8 (Level 1) (4 pilots)	Level 1
Config. B	2.5 (Level 1) (4 pilots)	Level 1
Config. C	3.4 (Level 1) (4 pilots)	Level 1
Config. D	3.0 (Level 1) (3 pilots)	Level 1
Config. F	3.2 (Level 1) (4 pilots)	Level 1

Table 6. Comparison of experimental and analytical handling qualities levels, Slalom, RC, center stick

	Experimental Average Cooper-Harper rating	Analytical
Config. A	3.4 (Level 1) (3 pilots)	Level 2
Config. B	3.0 (Level 1) (3 pilots)	Level 1
Config. C	3.8 (Level 2) (3 pilots)	Level 1
Config. D	3.0 (Level 1) (2 pilots)	Level 1
Config. F	3.5 (Level 1) (3 pilots)	Level 1

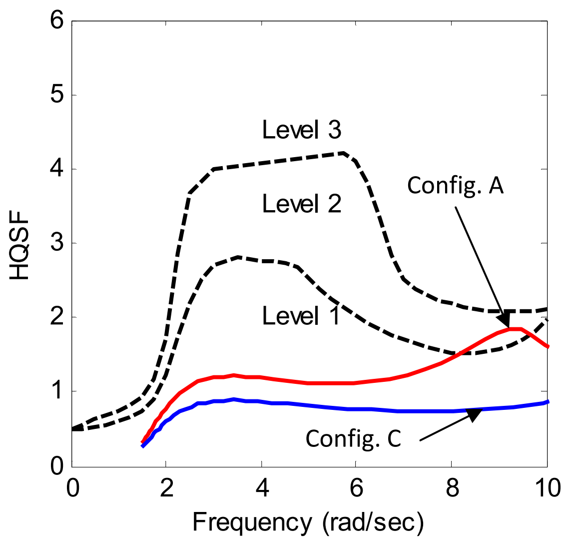

Figure 27. HQSF for configurations A and C, Slalom, RC, center stick

Discussion

A flight test evaluation of the interaction between cyclic inceptor force-feel characteristics and handling qualities has been conducted with a center stick cyclic on the RASCAL JUH-60A, and initiated with a side stick on the ACT/FHS EC-135. In addition to collecting HQRs, a set of numerical ratings of how changes in inceptor characteristics affect the pilots ability to perform the task were collected. The intent being to develop a set of ratings to complement the Cooper-Harper scale in cases where the pilots have a strong preference for a one configuration over another, yet the HQRs assigned to the two configurations are nearly the same. The results presented in this paper support the criteria published in [6] [7] for cyclic inertia and damping, and in [8] for cyclic damping and natural frequency in defining regions where the cyclic force-feel system will degrade handling qualities.

The results of the testing show that for center sticks AC provided almost one full HQR improvement over RC for corresponding cyclic configurations, which is consistent with the results presented in [13]. From evaluations of the Hover MTE with a center stick, the following results were observed:

- increasing the damping of the cyclic resulted in a statistically significant improvement in HQRs for both AC and RC
- increasing natural frequency resulted in a nearly statistically significant improvement in HQR for AC (P=0.057), but not for RC
- precision and aggressiveness ratings showed improvement with increasing damping and increasing natural frequency. Only the results for AC proved to be statistically significant
- ride quality improved with increasing damping and reduced natural frequency for both AC and RC, but the improvements were not shown to be statistically significant
- no statistically significant interaction effect of damping and natural frequency were observed

While results for evaluations of the Slalom MTE with a center stick showed similar trends, the results were not as significant. This is likely due to the task requirements of the Slalom MTE which require the pilots to make larger amplitude inputs at a lower frequency than for the Hover MTE, reducing the benefits of a fast inceptor with high damping. The one result from the Slalom MTE that did show a statistically significant effect was the improvement in ride quality rating with increased cyclic damping for AC; the improvement for RC was marginally significant. This could be an important consideration that would not normally be exposed through the use of the Cooper-Harper scale alone.

In contrast to the center stick results, the side stick results showed a tendency for improved HQRs with increasing natural frequency for both the Hover MTE (AC) and the Slalom (AC and RC). This could be attributable to the wrist action when controlling the side stick as opposed to arm action when controlling a center stick. This result may also be influenced by the fact that the two configurations with the lowest natural frequency are located in the degraded region of Figure 2.

For evaluations of the Hover MTE with a side stick, only results from AC were presented herein. Analysis of HQRs resulted in the following observations:

- increasing natural frequency resulted in a statistically significant improvement in HQRs
- the influence of damping was not strong and did not prove to be statistically significant

For evaluations of the Slalom MTE with both AC and RC, similar trends were observed. The only statistically significant result was the improvement in HQRs with increasing natural frequency. A more in-depth analysis of the results of evaluations of the side-stick on the ACT/FHS will be presented in [17].

The bandwidth and phase delay from force inputs were calculated for each center stick inceptor configuration and plotted against the hover/low-speed short-term response to control inputs requirement from ADS-33E. A comparison of HQRs from the Hover MTE for the corresponding points on the plot showed that meeting the Level 1 boundary did not always result in Level 1 handling qualities ratings. These results indicate that the current guidance in ADS-33E is appropriate; the bandwidth/phase delay criteria should be assessed using displacement as the input, and checked using force input. To reliably include the important effects of cyclic force-feel characteristics on predicted handling qualities of rotorcraft, other approaches need to be investigated.

To this end, an analytical closed-loop pilot-vehicle methodology [9] for predicting helicopter handling qualities was evaluated against data collected during evaluations of the Slalom MTE with a center-stick cyclic. The helicopter control laws (altitude hold, velocity hold and turn coordination) made this a lateral cyclic only task. This consideration made the maneuver ideal for analysis through this method. The HQSF approach, based on the structural model of pilot-vehicle coupling, was chosen because it encompasses some of the key physical elements of the proprioceptive feedback loop which is absent from other analytical approaches: nominal neuromuscular dynamics and simplified inceptor dynamics (including inertia, damping and force gradient). Generally good agreement between the analytical predictions and the flight test results was achieved, particularly for the AC configurations. Discrepancies in the results for the RC configurations could be attributed to the absence of vestibular feedback in the model setup.

However, other questions regarding the feedback model setup remain to be addressed. Validity of the HQ Level boundaries in the literature could also be questioned, for example. These proposed boundaries have been predicated on the use of very specific set of parameter values for the structural pilot model. Deviation from any of these parameters would render the HQ predictions invalid based on these boundaries. An example of one such parameter would be the pilot low frequency integral compensation mentioned above. Selection of this parameter was arbitrary; however, it can have a direct impact on the analytical handling qualities prediction. Further analysis will be required to specifically isolate appropriate values for this and other configuration parameters.

Conclusions

Based on the results of these tests, the following conclusions are made:

1) The effect of cyclic force-feel characteristics have been shown to have a significant impact on the handling qualities of rotorcraft.
2) For tasks that require high precision such as the Hover MTE, Attitude Command was preferred over Rate Command in the good visual environment with a center stick.
3) The damping of the center stick cyclic inceptor can have an impact on the pilot's perception of the aircraft ride quality.
4) Meeting the current ADS-33E Level 1 bandwidth requirements from force inputs is necessary, but not sufficient to ensure Level 1 handling qualities. Therefore, bandwidth requirements should be assessed using displacement as the input.

Future Plans

Additional flight testing on the ACT/FHS with a side-stick inceptor is anticipated along with publication of a detailed analysis of the results. In the U.S., a simulation study is planned in the NASA Ames Vertical Motion Simulator which will expand the current matrix of inceptor configurations and allow for evaluations of both a center-stick and a side-stick inceptor. The study will also explore the use of tactile cueing to provide the pilot feedback when approaching the actuator command and rate limits of the RASCAL safety monitors.

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