HANDLING QUALITIES STUDIES INTO THE INTERACTION BETWEEN ACTIVE SIDESTICK PARAMETERS AND HELICOPTER RESPONSE TYPES

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Abstract

Active inceptors offer great potential for improving the handling qualities of fly-by-wire rotorcraft. In a cooperative research, effort the DLR Institute of Flight Systems in Germany and the U.S. Army Aeroflightdynamics Directorate (AFDD) conducted several in-flight experiments to study the influence of the dynamic characteristics (natural frequency and damping) of the cyclic stick on the overall handling qualities of a rotorcraft. Experiments were performed looking at sidestick (DLR) and centerstick (AFDD) inceptors for Rate and Attitude Command response types. The results of two different experiments are presented in this paper. The first experiment evaluated the roll handling in forward flight and was only performed with a sidestick inceptor. The task used in this experiment was designed during exercises of the Empire Test Pilots' School (ETPS) on DLR's Flying Helicopter Simulator EC135 ACT/FHS. ETPS also contributed to the optimization of the static sidestick characteristics that were used for the testing. The second, more comprehensive experiment, evaluating ADS-33 Hover and Slalom Mission Taks Elements, was performed both with a sidestick and a centerstick allowing a direct comparison of both types of inceptors. Regression analyses are performed on the collected pilot ratings to gain a systematic insight into the preferred stick characteristics for the different inceptor and response types. The test results consistently suggest that the preferred characteristics are best described by first order response model.

NOTATION

D	damping ratio (–)
k	force gradient (N/%)
m	equivalent stick inertia (kg)
s	LAPLACE variable (rad/sec)
T	time constant (sec)
δ_x	control displacement (%)
δ_F	control force (N)
τ	equivalent time delay (sec)
ω_n	natural frequency (rad/sec)
AC	Attitude Command
ACT/FHS	Advanced Control Technology/ Flying Helicopter Simulator
ADOCS	Advanced Digital/Optical Control System
ADS	Aeronautical Design Standard
AFDD	U.S. Army Aeroflightdynamics Directorate
DLR	Deutsches Zentrum für Luft- und Raumfahrt

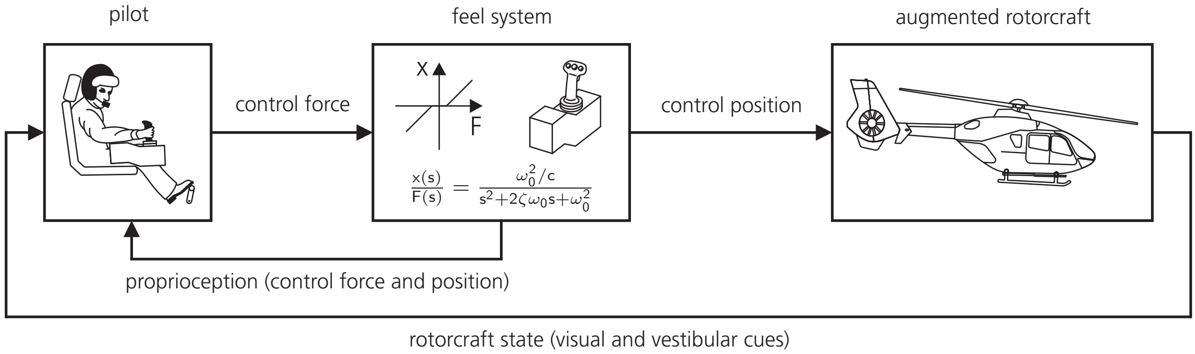


Figure 1: Pilot-inceptor-aircraft loop

ETPS	Empire Test Pilots School
FTE	flight test engineer
HQR	Handling Qualities Rating
LOES	low order equivalent system
MTE	Mission Task Element
PIO	pilot induced oscillation
RASCAL	Rotorcraft Aircrew Systems Concepts Airborne Laboratory
RC	Rate Command
RCHH	Rate Command/Height Hold
RPC	rotorcraft pilot coupling
RMS	root mean square
TP	test pilot
WTD	Bundeswehr Technical and Airworthiness Center for Aircraft

1. INTRODUCTION

As helicopter missions become more and more demanding, full authority fly-by-wire control systems will be increasingly used in new helicopters to provide good handling qualities. Besides granting significant design freedom regarding the flight control laws, fly-by-wire systems offer the chance to redesign the primary human-machine-interfaces in the cockpit. Compact, laterally positioned inceptors, so-called sidesticks, can be used instead of conventional inceptors to improve ergonomics, comfort and crash safety. Due to the lack of mechanical linkages, active inceptors, where the control forces are electromechanically generated, can be used.

Active inceptors can easily and dynamically change their force-displacement characteristics. Tactile cueing (Ref. 1) and tailoring of the force-displacement characteristics to specific response types become possible. This has significant potential for improving the rotorcraft's handling qualities because the pilot controls the aircraft through the inceptors as can be seen from the overall control loop depicted in Figure 1.

Only very little formal guidance exists on the design of inceptor characteristics for helicopters. The military handling qualities standard ADS-33E (Ref. 2) provides some limits for the static characteristics of conventional controllers. However, it includes no requirements for the dynamic characteristics, as damping or inertia, and especially no requirements for short-pole sidestick inceptors. Paragraph 3.6.2 (Sidestick Controllers) of the specification is even explicitly "reserved for future requirements".

Under Task X, Handling Qualities for Actively Controlled Rotorcraft of the U.S. German Memorandum of Understanding on Helicopter Aeromechanics, the DLR Institute of Flight Systems in Germany and the U.S. Army Aeroflightdynamics Directorate (AFDD) conduct cooperative research efforts to study the influence of the inceptor force-displacement characteristics on the overall handling qualities of helicopters. In Germany, DLR uses the Advanced Control Technology/Flying Helicopter Simulator EC135 ACT/FHS with active sidestick inceptors (Figure 2), and in the U.S., AFDD uses the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) JUH-60A in-flight simulator with an active centerstick.

1.1. Overview of previous research activities

A number of studies have been conducted to assess the impact of controller force-displacement characteristics on the handling qualities of high performance fixed wing fly-by-wire aircraft, primarily directed towards minimizing pilot induced oscillations and roll ratcheting (Refs. 3, 4). There has been much less research into the effects of force-feel characteristics on rotorcraft handling qualities.

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 (Ref. 5). A simulation study looked at a range of force displacement gradients from stiff (40 lb/deg)

(a) EC135 ACT/FHS **(b)** Right and left hand sidesticks

Figure 2: In-flight simulator EC135 ACT/FHS with active sidestick inceptors

to soft (0.6 lb/deg) with functionality ranging from 4-axis (lateral, longitudinal, directional and vertical) to 2-axis (lateral and longitudinal only) sidesticks with pedals and left hand collective. This study provided especially valuable insight into the number of axes controlled by the side-stick controller of the ADOCS demonstrator aircraft.

Some studies have also been conducted to assess the effects of cyclic force-feel characteristics in flight. A study conducted on the NASA/Army CH-47B variable-stability helicopter looked at the influence of the dynamic characteristics of a centerstick inceptor on handling qualities (Ref. 6). A Rate Command/Attitude Hold response type was provided for this study. The cyclic damping and the natural frequency was varied by manipulating 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 (Refs. 3, 4).

The Canadian Institute for Aerospace Research conducted a similar study using their variable-stability Bell 205A helicopter (Ref. 7). 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.

A requirement integrating both above-mentioned helicopter studies was proposed in Reference 8. According to this study, a minimal damping ratio of 0.3 and a natural frequency of 10 rad/s is required to provide acceptable dynamic characteristics.

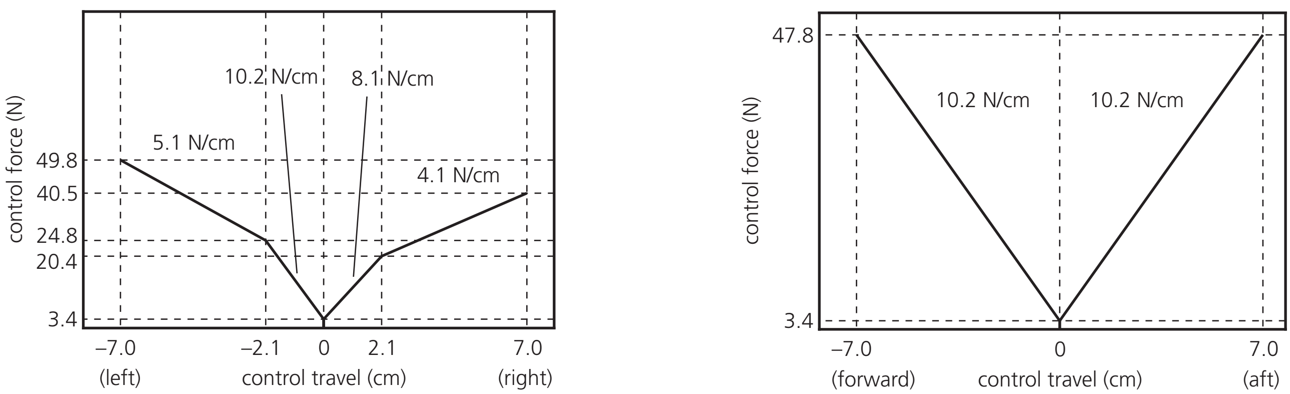
More recently, Sikorsky Aircraft performed a simulation study to gather data in support of the development of handling qualities specifications for sidestick force-displacement characteristics (Ref. 9). This study looked at variations of stick travel, breakout forces, damping and force gradient (with 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 response types. Due to the experimental setup (generally only a single factor was varied at a time), the study provides some valuable insight into different trends, but allows no integrated, quantitative analysis of the data.

1.2. Coverage of the paper

This paper presents and discusses results of different in-flight handling qualities experiments conducted under Task X, Handling Qualities for Actively Controlled Rotorcraft of the U.S. German Memorandum of Understanding on Helicopter Aeromechanics. The focus of this paper is on the testing conducted with the EC135 ACT/FHS. Selected results of experiments flown with the JUH-60A RASCAL are presented to allow comparisons between sidestick and centerstick inceptors. Reference 10 provides a more comprehensive documentation of the flight testing conducted with the RASCAL helicopter.

The flight control laws and the static force-displacement characteristics used for the testing on the ACT/FHS were opimized over several years during exercises flown on this helicopter by Empire Test Pilots' School (ETPS) students.

Based on a handling qualities tasks designed by ETPS student teams a first experiment was conducted to evaluate the dynamic characteristics of the sidestick's lateral control axis for a Rate Command (RC) and Attitude Command (AC) response type.



(a) Lateral control axis

(b) Longitudinal control axis

Figure 3: Static force-displacement characteristics

A much more comprehensive study was performed in cooperation with the Bundeswehr Technical Airworthiness Center (WTD 61) in Manching. Ground referenced ADS-33 Mission Task Elements were evaluated in this flight test campaign. The test matrix and the sub-experiments in this campaign were a replication of tests flown earlier on the U.S. Army's RASCAL with an active long-pole centerstick (Ref. 10).

A discussion of the overall results is given with special respect to comparisons between Rate and Attitude Command response types as well as centerstick and sidestick inceptors. Finally a new approach of describing the dynamic stick characteristics is presented.

2. INITIAL FEEL SYSTEM OPTIMIZATION

The dynamic characteristics of active inceptors are generally modeled as simple second order dynamics based on the natural frequency ω_n and the damping ratio D:

$$(1) \quad \frac{\delta_x}{\delta_F} = \frac{\omega_n^2/k}{s^2 + 2D\omega_n s + \omega_n^2}$$

The static force displacement characteristics include a breakout force and may be nonlinear (Fig. 3). Thus, the force gradient k is only defined locally. For a fixed gradient, variations of the natural frequency are equivalent to variations of the stick inertia ($m = k/\omega_n^2$).

The right hand sidestick parameters for pitch and roll control were optimized by ETPS student test pilot (TP) and flight test engineer (FTE) teams during an exercise at DLR Braunschweig over a two week period in autumn 2009. Throughout the optimization process the flight control system (FCS) was configured as Attitude Command Attitude Hold (ACAH) in pitch and roll. The FCS feedback and command path gains were implemented in accordance with results from a previous ETPS student exercise at DLR in 2008. The yaw and heave axes were controlled by conventional pedals and collective, again with FCS gains set in accordance with results from the 2008 exercise. The flight regime of interest during the 2008 and 2009 exercises was 'forward flight'. Further assessments were made with the optimized sidestick by ETPS staff TPs during hover and low speed testing in 2010 and during testing at increased forward flight speeds by ETPS students and staff in 2011.

In 2009 after an introduction to the effect of varying the sidestick damping ratio over a wide range of values from 0.2 to 1.5 in the DLR fixed base simulator, an initial set of five sidestick configurations covering the hardware limits of the stick was agreed with DLR staff. This set was made available for evaluation in the simulator and during initial 30 minute demonstration and familiarization flights in the EC135 ACT/FHS for each student. The damping ratios in pitch and roll were matched and varied from 0.6 to 1.4 with the natural frequency held constant at 3.2 Hz. The sidestick force-displacement gradients and breakout characteristics remained matched and constant in both axes.

Following the simulator and demonstration flight qualitative assessments in which no HQR (Handling Qualities Rating) data were assigned, the initial set of five sidestick configurations was judged by the team of two student TPs as unsatisfactory. Control harmony between pitch and roll axes was poor and the force gradients were excessive, particularly when maintaining sustained stick displacements from trim in the roll axis. Additionally, the excessive force gradients were more apparent in displacements to the right than to the left. Accordingly, the TP/FTE team developed a second set of five sidestick configurations in the fixed base simulator. In this set, the damping ratio and natural frequency were maintained constant at 0.8 and 3.2 Hz respectively for four configurations with the damping ratio increased to 1.3 for the fifth. The first two configurations introduced reduced force-displacement gradients in roll compared with pitch and then asymmetric gradients in roll with reduced gradient to the right compared to the left. The third and fourth configurations maintained asymmetric gradients in the roll axis and introduced reductions in these gradients as displacement from trim increased beyond 15%. The fifth configuration differed from the fourth only in an increased damping ratio from 0.8 to 1.3. The optimized static force-displacement characteristics for the cyclic inceptor are illustrated in Figure 3.

The 2009 ETPS exercise objectives required HQR data to be used in flight testing of the sidestick performance following the familiarization flights. The student team designed seven straightforward handling tasks for this purpose. These involved assessments of speed acquisition, speed maintenance, target acquisition, heading maintenance, bank angle capture, bank angle maintenance and heading capture. Additionally, a slightly modified ADS-33E slalom maneuver was designed as part of the handling assessments. Task completion was assessed in the simulator and during three 1 hour flights flown by two student TPs and one staff TP. The outcome from these evaluations was that the fifth configuration yielded the best set of assigned HQRs. However these were a mixture of Level 2 and Level 1 ratings and refinement of the sidestick parameters was required by a second team of ETPS students during the 2009 exercise.

Further simulator and flight evaluations of ten additional sidestick configurations were planned. A constraint on configuration changes was that only one parameter was to be varied on each change. Small increases in damping ratio—from 1.3 to 1.5—in the pitch and roll axes were introduced followed by small adjustments to the force-displacement characteristics and natural frequency of the roll axis inceptor. The same handling tasks were used to assign HQRs with the configurations assessed during simulator and flight testing. Three one hour flights were completed in this second week by two student TPs and one staff TP. The two final flight evaluations resulted in Level 1 HQRs utilizing the 'ETPS optimized' sidestick configuration.

This configuration was assessed again by ETPS teams in 2010 during hover/low speed testing and then in 2011 at increased forward flight speeds. Comments were made during these later in-flight evaluations about the sidestick influence on HQRs, particularly with regard to the trim and control strategy of the evaluating pilot when using the stick in the hover and low speed environment. However the focus of the 2010 and 2011 exercises was not on further development of the sidestick and the optimal ETPS configuration remains that established in 2009.

Table 1: Sub-experiments of Experiment 1

Task	Response Type
ETPS Roll Handling Task	*RC*
ETPS Roll Handling Task	*AC*

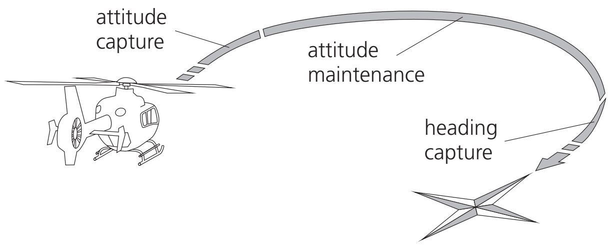


Figure 4: ETPS Roll Handling Task

3. EXPERIMENT 1: ROLL HANDLING TASK

Due to the unavailability of ADS-33 MTE test courses at DLR's Braunschweig test facility a subset of the ETPS maneuvers (requiring no ground references) designed for the ETPS exercises was used to systematically investigate the influence of the sidestick's dynamic roll axis characteristics on the handling qualities. A primary focus of this experiment was to look at the differences between Rate and Attitude Command response types. Therefore, two different sub-experiments were performed as defined in Table 1. This experiment was only performed on the ACT/FHS with an active sidestick inceptor for cyclic control in an early stage of the research. No corresponding experiment was conducted with the RASCAL and centerstick inceptor.

3.1. Setup and test procedure

The ETPS Roll Handling Task is illustrated in Figure 4. The task is comprised of three sub-tasks (bank angle capture, bank angle maintenance and heading capture). The standards for desired and adequate performance are given in Table 2.

The approach to optimizing the stick characteristics during the ETPS exercises as described in the previous section was an iterative one. For this experiment, a factorial design was used to gain a systematic understanding of the underlying mechanisms leading to different perceptions of the handling qualities. The design matrix is shown in Figure 5. The center point that is included in the design represents the dynamic default setting of the sidestick.

Table 2: ETPS Roll Handling Task

Performance Requirement	Desired	Adequate
Capture 30 deg bank angle within ±X deg	4 deg	8 deg
Capture 30 deg bank angle within ±X seconds	5 sec	10 sec
Maintain 30 deg bank angle within ±X deg	3 deg	6 deg
Maintain 30 deg bank angle for at least ±X seconds	30 sec	30 sec
Capture assigned heading within ±X deg	3 deg	6 deg
Capture assigned heading within ±X seconds	5 sec	10 sec

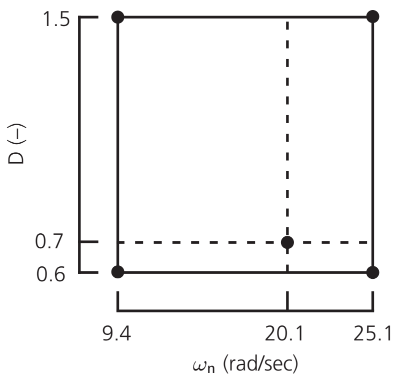


Figure 5: Experimental design for the roll handling task

The ACT/FHS Rate and Attitude Command control laws as optimized during the ETPS exercises to provide Level 1 handling qualities were used for this experiment. Two DLR pilots evaluated the test matrix for both Rate and Attitude Command response types in August 2010. A Handling Qualities Rating (HQR) based on the COOPER-HARPER-Scale (Ref. 11) was assigned for each subtask. A special display for monitoring the task performance was used to give online feedback to the pilots prior to assigning the ratings.

3.2. Results

Figure 6 shows the time histories of the bank angle and the roll control input for representative Rate Command and Attitude Command test runs. The target bank angle and the trimmed stick position are indicated by the thin dotted lines. The different control strategies required to perform the task with different response types can be clearly distinguished: While only short inputs are required for the Rate Command response type, a steady deflection is necessary to maintain the bank angle with an Attitude Command response type.

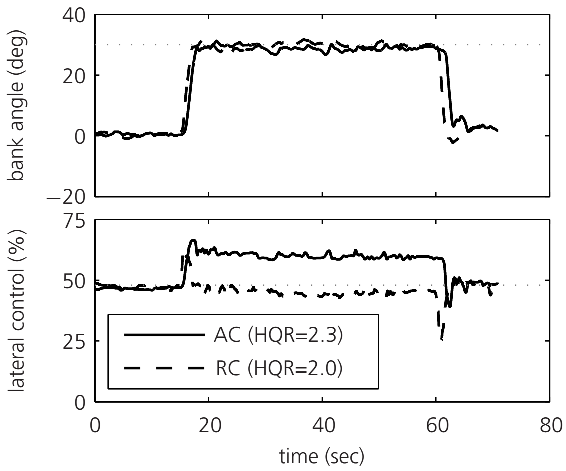


Figure 6: Bank angle and control time histories for the Roll Handling Task

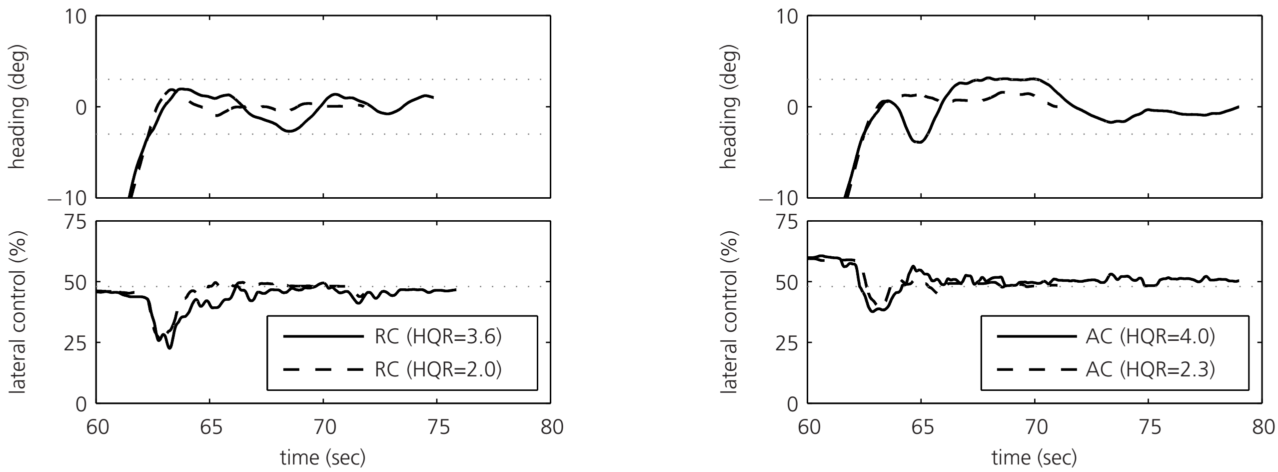
3.2.1. Task performance

There is an obvious correlation between the task performance and the assigned HQRs, although desired performance was met for all test configurations. Figure 7 shows the heading and lateral control time histories for the heading capture subtask. The desired performance limits and the trimmed stick position are indicated by the thin dotted lines. The same effect can be observed for both the Rate and Attitude Command response type: Relatively smooth transitions can be observed for the configurations that are rated as Level 1. However, a tendency to PIOs is visible for the configurations that receive Level 2 ratings.

3.2.2. Analysis of the HQRs

Although the COOPER-HARPER rating scale is ordinal, regression analyses can support the interpretation of the results. Contour plots of linear regression models fit to the HQR data are shown in Figure 8. In these plots, the numbers on the individual contour lines designate the corresponding HQR. The arrows point into the direction of greatest improvement (steepest descent). The plots are restricted to the parameter ranges covered by the experimental design. An extrapolation beyond the tested factor ranges is generally not valid for this kind of empirical reponse surface models.

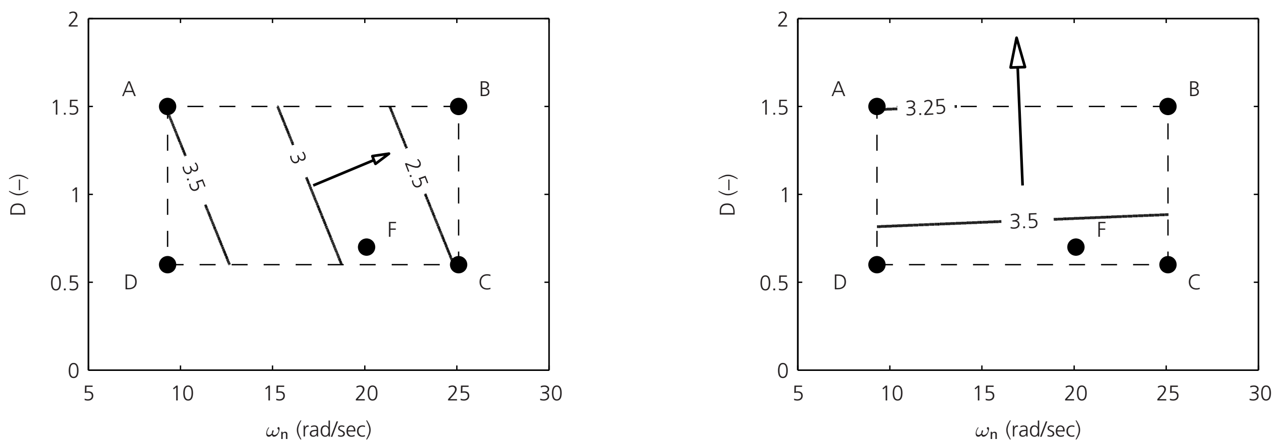
For both Rate and Attitude Command response types, a tendency towards higher damping values can be seen. A difference can be observed regarding the natural frequency. For a Rate Command system improvement is obtained from increasing the natural frequency (lower mass) while for an Attitude Command system a lower natural frequency (higher mass) is preferred. The latter trend is not very strong, though.



(a) Rate Command

(b) Attitude Command

Figure 7: Heading Capture



(a) Rate Command

(b) Attitude Command

Figure 8: Contour plots for the roll handling task

Table 3: Sub-experiments of Experiment 2

Task	Response Type
ADS-33 Hover MTE	*RC*+RCHH
ADS-33 Hover MTE	*AC*+RCHH
ADS-33 Slalom MTE	*RC*+RCHH
ADS-33 Slalom MTE	*AC*+RCHH

The high frequency inputs needed to control a Rate Command response type obviously require an agile, but sufficiently damped stick to allow for precise control of the inceptor position. The relatively slow response of the helicopter for an Attitude Command response type requires a stick that prevents the pilots from applying pulse-like inputs. Otherwise PIO and roll ratcheting problems occur because the attitude does not follow the stick input and the pilot has difficulties stabilizing the helicopter at the targeted attitude especially in maneuvering flight.

4. EXPERIMENT 2: HOVER AND SLALOM MTES

In order to verify the results of the first experiment and expand the study to the hover flight regime, a second experiment was devised. This was designed together with AFDD to generate results based on a common test setup for different types of inceptors (sidestick and centerstick). Two ADS-33 MTEs (Hover and Slalom) evaluted to the Cargo/Utility performance standards in the Good Visual Environment were used for the testing. Both MTEs were evaluated for a Rate Command and an Attitude Command response type resulting in four sub-experiments defined in Table 3. Results for the Rate Command response type, however, will not be presented and discussed in this paper because the test course used for the Hover MTE had to be modified halfway into the testing. The initial course setup could not convey sufficient cueing to the pilot regarding the longitudinal hover position.

4.1. Setup and test procedure

For this experiment, a test matrix similar to that used on the RASCAL was used to allow for a comparison of the results between sidestick and centerstick. The full factorial design with center point used for the testing is shown in Figure 9.

The factor ranges covered by the test matrix are adjusted to cover both the unacceptable and acceptable regions for the stick dynamics defined in Reference 8

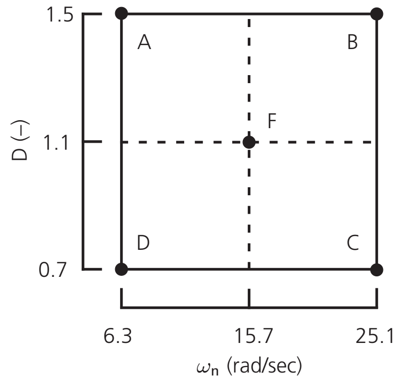


Figure 9: Factorial design for two factors

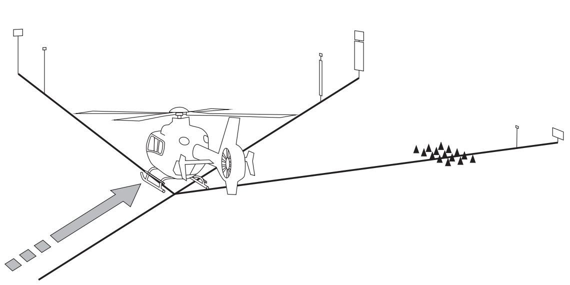
where the Level 1 boundary was by a minimal damping ratio of 0.3 and a minimal natural frequency of 7 rad/sec. Regarding the damping ratio however, only values greater than 0.6 were considered in this experiment. Settings with lower damping values were not tested in flight because excessive bob-weight effects were observed during the test preparations that appeared to be unacceptable to the pilots. The maximum values of damping and natural frequency correspond to the limits of the sidestick as does the lowest natural frequency in the test matrix.

The two ADS-33 MTEs used in the experiment are illustrated in Figure 10. While the Hover MTE requires high frequency, small amplitude control, the Slalom MTE is characterized by low frequency, large amplitude control inputs. A wide range of pilot control strategies is therefore covered with these two MTEs. To monitor the task performance and to be able to give objective feedback to the pilot special Task Performance Displays were used (Fig. 11).

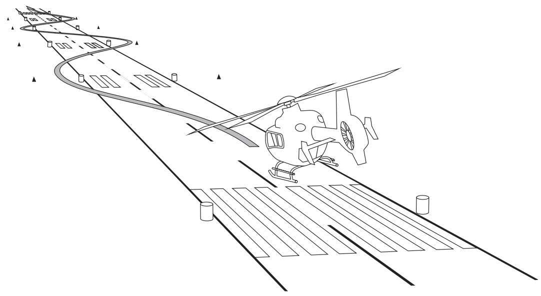
The ACT/FHS control laws were again configured to provide Level 1 Rate and Attitude Command response types. Additionally, a Rate Command/Height Hold (RCHH) response type was used in the vertical control axis.

The experiment was evaluated in a comprehensive flight test campaign in October 2011 in cooperation with the Technical and Airworthiness Center for Aircraft (WTD 61) of the German Armed Forces in Manching, Germany. The test site at WTD 61 provided test courses for the ADS-33 MTEs which have been used previously for handling qualities evaluations of the CH-53G (Ref. 12). Using WTD 61 telemetry infrastructure allowed online monitoring of the tests via the MTE task performance displays.

Three test pilots (two from WTD 61 and one from the U.S. Army) participated in the testing. Randomized run orders are used to suppress any influence of uncontrollable externalities on the test results. A pilot questionnaire was used to collect comments from the pilots for

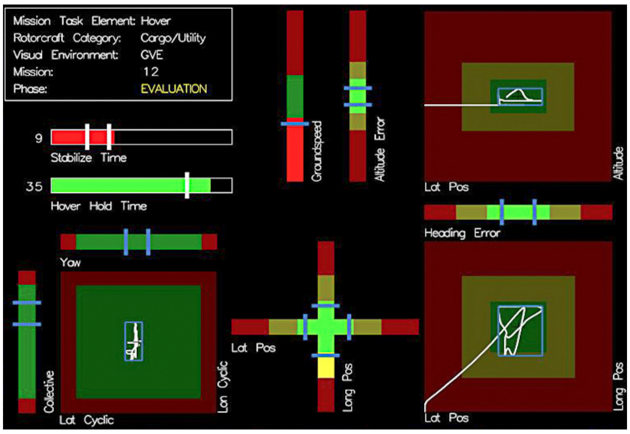


(a) ADS-33 Hover MTE

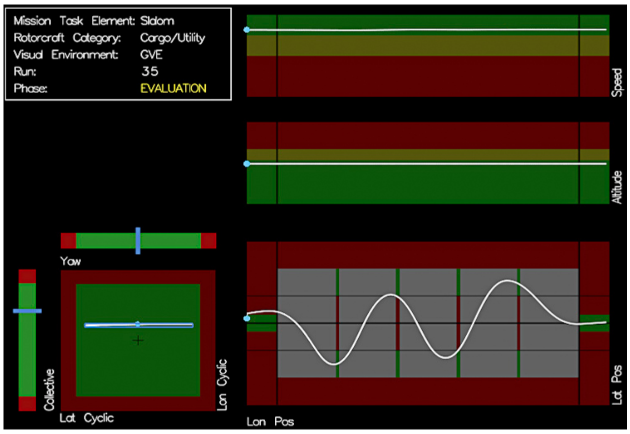


(b) ADS-33 Slalom MTE

Figure 10: MTE test courses



(a) ADS-33 Hover MTE



(b) ADS-33 Slalom MTE

Figure 11: Task performance displays

each test point. Additionally, different numerical ratings are collected. These include the HQR, a PIO-rating, ratings for precision and aggressiveness as well as ratings concerning the perception of different stick characteristics.

4.2. Results

Since this experiment was not only conducted on the ACT/FHS but also on the RASCAL results of both test campaigns are presented in the following paragraphs. This allows a comparison of sidestick and centerstick test results. The centerstick results are taken from Reference 10.

4.2.1. Control activity

From the control activity (control displacement) the RMS value and the pilot cut-off frequency was calculated. The RMS value provides a metric to quantify the effective magnitude of the control inputs. The pilot cut-off frequency is a good approximation of the pilot crossover frequency which determines the primary frequency of the pilot's control activity (Ref. 13). 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.

The RMS values are plotted in Figure 12 for all test points and both sidestick and centerstick along with the 95 percent confidence intervals. Figure 13 shows the cut-off frequencies. Both figures 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. The reasons for the difference between the two MTEs lie in the requirements of the respective maneuver, which drive the character of the pilot inputs.

Figures 12 to 13 show very consistent results for RMS and cut-off frequency values for all considered response and inceptor types (sidestick or centerstick). The good agreement of the RMS and cut-off frequency values generally demonstrates the identical task setup for the ACT/FHS and RASCAL experiments. Furthermore, the close agreement of the RMS values shows that the control gearing in both helicopters is nearly identical assuming that the same attitudes are used in the maneuvers with both helicopters.

4.2.2. Bandwidth and phase delay

The attitude bandwidth and phase delay metrics as defined in ADS-33E were calculated for the roll axis for the side-stick configurations evaluated on the ACT/FHS and on the center-stick configurations evaluated on the RASCAL. The bandwidth/phase delay requirement states that the attitude response to the controller position inputs shall meet the specified limits. It also states that it is desirable to also meet the limits for controller force inputs.

Figure 14 shows the resulting bandwidth/phase delay values for the Rate Command response type and Figure 15 for the Attitude Command response type. The numbers in parentheses are the average HQRs for the respective test point for all evaluations flown with the respective stick characteristic. These numbers are indicated to support the argument given below.

In case of the sidestick bandwidth values (Rate Command), it is important to note that the displacement referenced bandwidth and also the force referenced bandwidth values (except for configuration A) are gain limited. The bandwidth values for the centerstick are all phase limited. This explains the different structure of the distribution of the test points for the Rate Command response type. For the Attitude Command response type a good agreement of the relative location of the different test points can be seen.

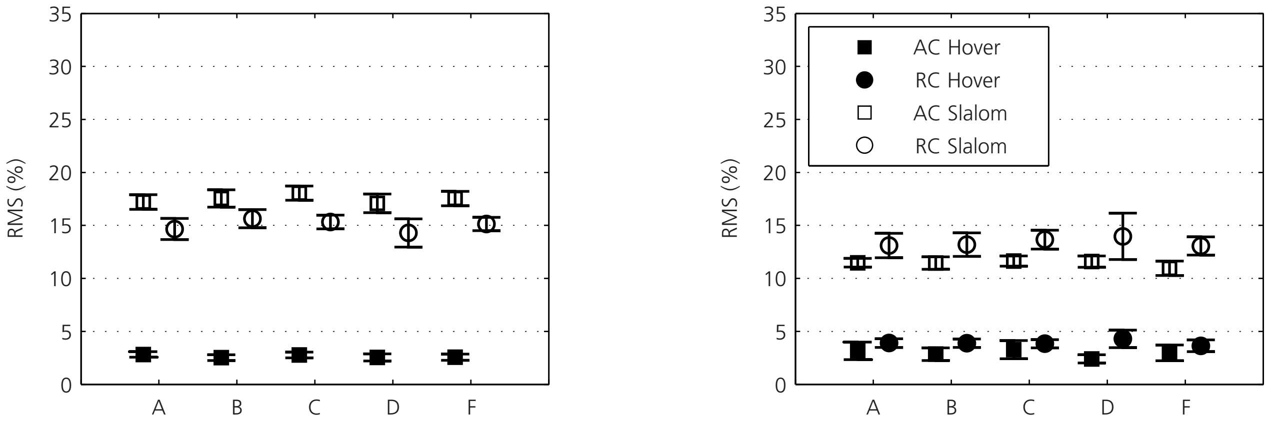
All displacement referenced bandwidth values are in the Level 1 region. For the ACT/FHS Rate Command response type the bandwidth is gain limited which explains the significantly reduced bandwidth compared to the Attitude Command response type.

Although the force referenced test points lie both in the Level 1 and Level 2 region of the diagram for the Rate Command response type (ACT/FHS and RASCAL), there is no correlation between the predicted Level and the assigned Ratings. For the Attitude Command response type, all test points (rated Level 1 and Level 2) lie within the Level 1 region of the diagram. Also for this response type no correlation between bandwidth and rating can be observed.

A comparison of HQRs for the corresponding test points on the bandwidth/phase delay diagrams shows that meeting the Level 1 boundary did not always result in Level 1 handling qualities ratings and even Level 1 ratings can be found in the Level 2 region. These results indicate that the bandwidth/phase delay criteria should be evaluated using displacement inputs, and the force-feel characteristics should be considered separately.

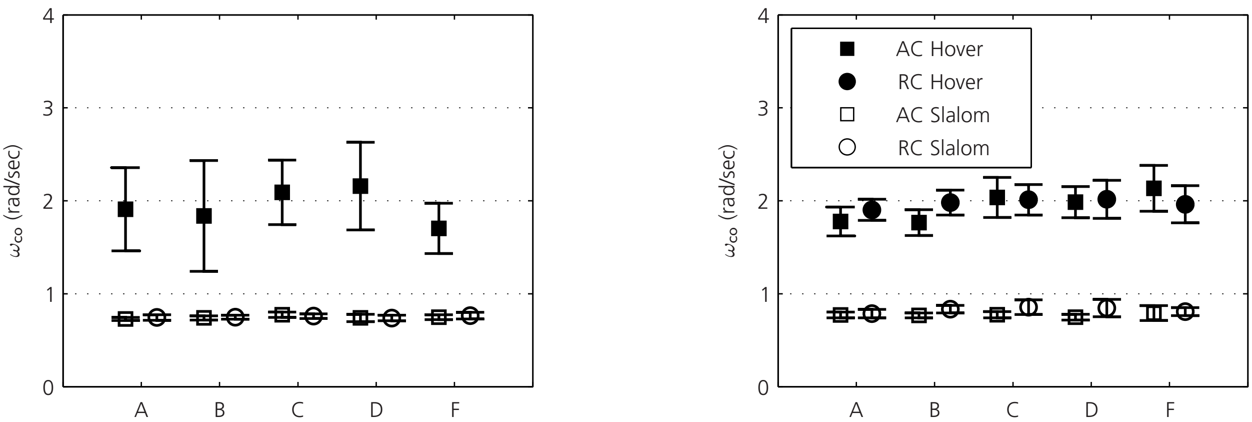
4.2.3. Analysis of the HQRs

As for the Roll Handling Task, an impression of the overall information contained in the HQRs can again be gained form contour plots of linear regression models



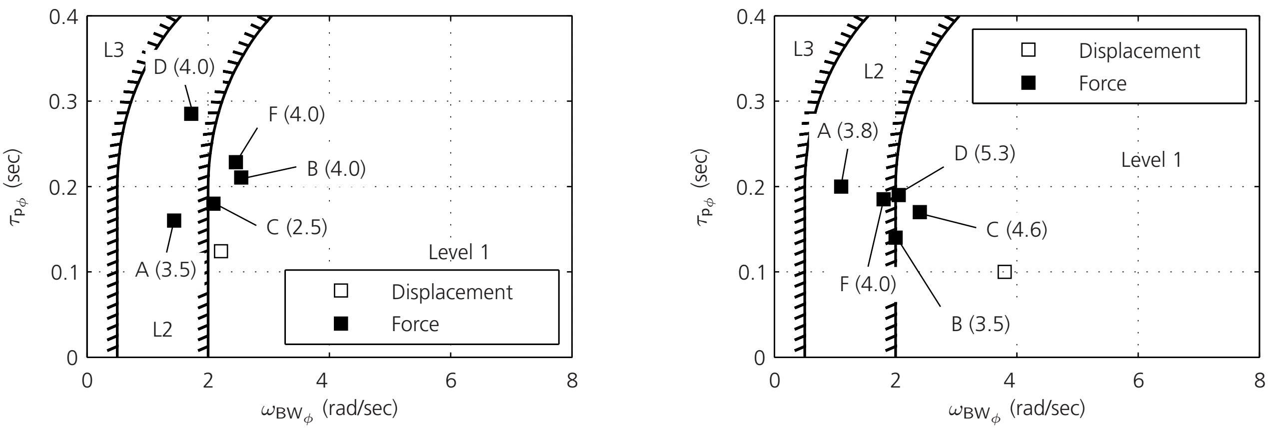
(a) Sidestick **(b)** Centerstick

Figure 12: Control Activity (RMS values)



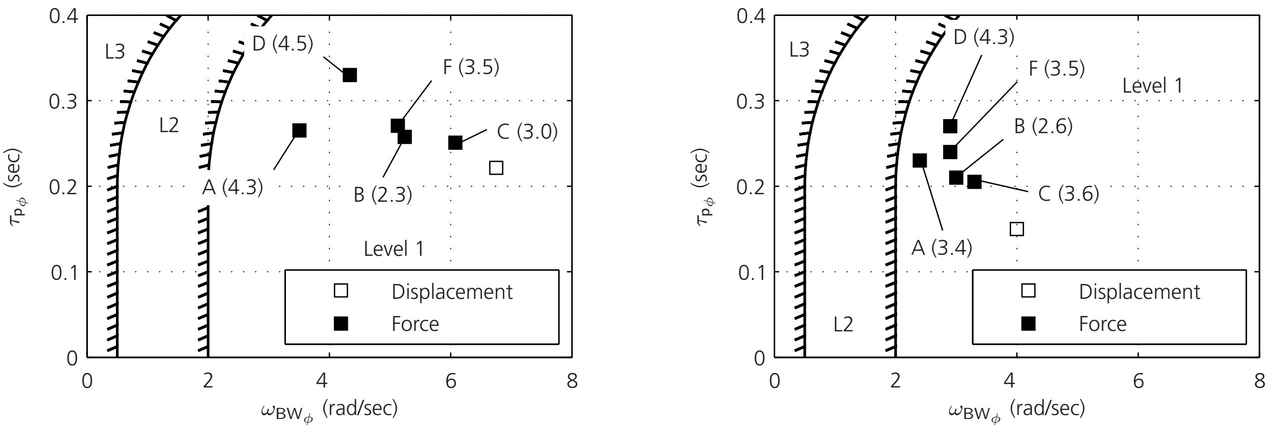
(a) Sidestick **(b)** Centerstick

Figure 13: Control Activity (cutoff frequencies)



(a) Sidestick **(b)** Centerstick

Figure 14: Bandwidth/Phase Delay (Slalom MTE in Rate Command)



(a) Sidestick

(b) Centerstick

Figure 15: Bandwidth/Phase Delay (Slalom MTE in Attitude Command)

fit to the HQR data (Fig. 8). In these plots, the numbers on the individual contour lines designate the corresponding HQR. The arrows point into the direction of greatest improvement (steepest descent).

The contour plots for the Hover MTE with AC are shown in Figure 16 for sidestick and centerstick. Configuration B consistently received the best average HQRs (Level 1) and configuration D the worst average HQR (Level 2) for both inceptor types. For the centerstick, the direction of greatest improvment points to higher damping to frequency ratios than for the sidestick.

The contour plots for the Slalom MTE with RC are shown in Figure 17 for sidestick and centerstick. For the sidestick, a significant improvement of the handling qualities can be observed for increasing the natural frequency. The contour lines for the centerstick indicate a slight improvement of the handling qualities for an increased damping ratio.

The contour plots for the Slalom MTE with AC are shown in Figure 18 for sidestick and centerstick. For the sidestick, the handling qualities show an improvement with both increased natural frequency and damping ratio. For the centerstick, there is a slight improvement of the handling qualities only due to increased damping.

4.2.4. Pilot Comments

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 of the aircraft response to control inputs

Generally, there seems to be a benefit of increased damping ratios which improve the precision and reduce the pilot workload.

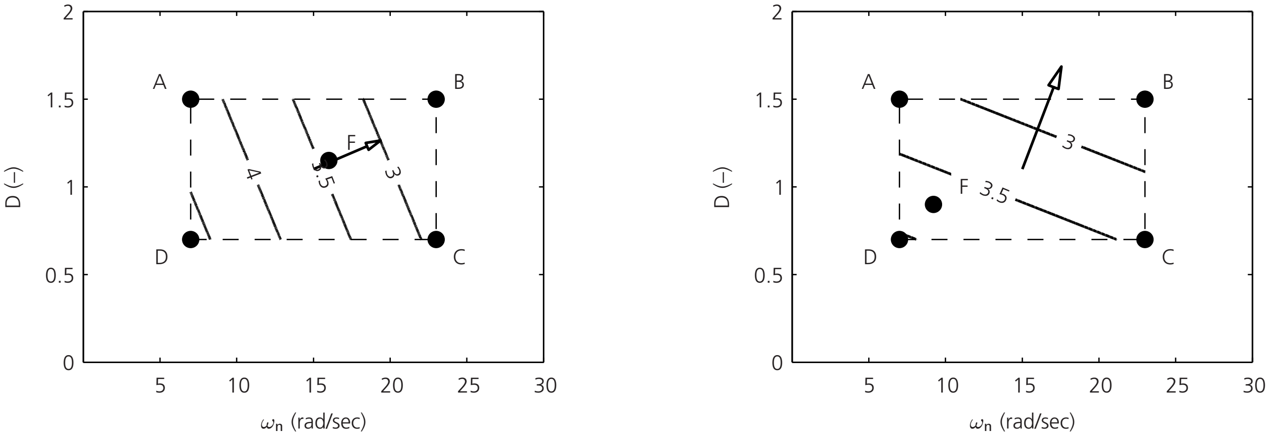
While the force gradient and control sensitivities remained unchanged through the experiment, the pilots' perception was that inceptor configurations with lower natural frequencies presented a heavier feel and were less sensitive increasing the workload to capture and maintain the hover.

A sidestick with a low natural frequency and low damping (configuration D) leads to undesirable motions of the stick which compromises the task performance. A centerstick with a low natural frequency and low damping ratio (configuration D) has low precision, feels wobbly when making small rapid inputs, and is prone to over-controlling the aircraft.

For the Slalom MTE, the following inceptor characteristics were generally found desirable:

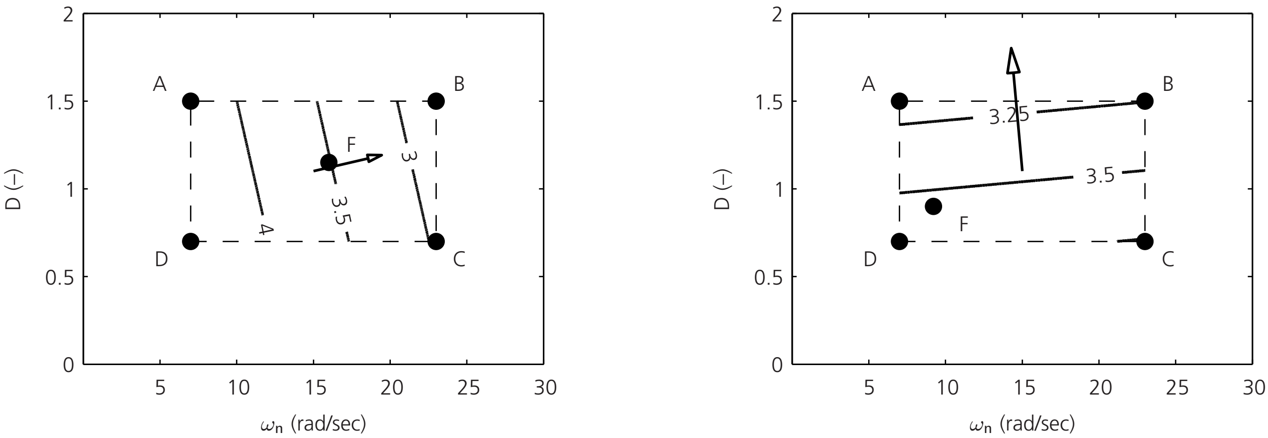
- An inceptor tracking well with the aircraft response (especially for AC)
- Little to no perceived delay of the aircraft response to control input
- Well damped to prevent over-controlling
- No susceptibility to feedback of the aircraft motion to the controller via the pilot's arm (bio-feedback)

Pilot preference varied somewhat between the configurations when flying the Slalom MTE but the dominant factor that affected pilot perception was how precisely the aircraft tracked or responded to control inputs. Biofeedback was less perceptible with the sidestick controller due in part to the integrated arm rest providing



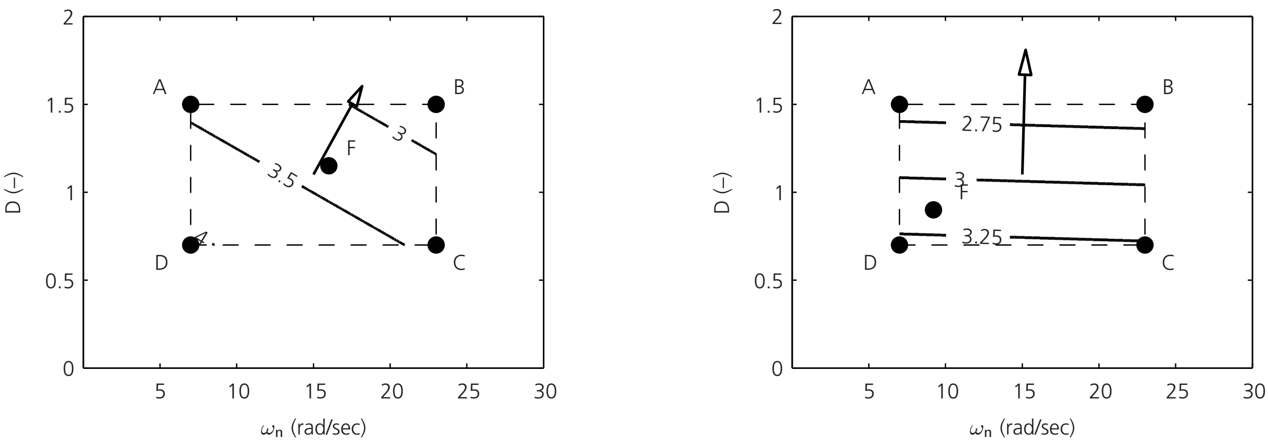
(a) Sidestick **(b)** Centerstick

Figure 16: Contour plots (Hover MTE in Attitude Command)



(a) Sidestick **(b)** Centerstick

Figure 17: Contour plots (Slalom MTE in Rate Command)



(a) Sidestick **(b)** Centerstick

Figure 18: Contour plots (Slalom MTE in Attitude Command)

a more stable platform for the pilot's arm. The effect of aircraft vibrations being fed back through the pilot's arm into the centerstick was more noticeable in the attitude command configuration since the lateral cyclic control deflection had to be maintained out of the detent in order to hold the desired aircraft attitudes. The lighter, less-damped configurations (configurations C and D) proved to be the most susceptible to bio-feedback interference with the Slalom MTE.

It should be noted that when flying the Slalom MTE with the 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. The same was true for the ACT/FHS were a bank angle limit of 45 degress was imposed which was monitored by the safety pilot. Some pilots felt that they could have been more aggressive with certain stick characteristics without these restrictions.

Qualitatively, for flight maneuvers requiring larger, sustained stick displacements, such as the Slalom MTE when flown in AC, the sidestick configuration was preferred since the force required to hold the stick out of detent was less objectionable than with the centerstick. The asymmetrical lateral force characteristics of the sidestick felt well balanced in all but configuration B (low inertia, high damping) when flying high gain maneuvers.

5. DISCUSSION

The results of different handling qualities experiments were presented in this paper. Two different experiments were conducted to study the influence of the dynamic sidestick characteristics on handling qualities. One of these experiments was identical to one performed with the JUH-60A RASCAL by the AFDD and an active centerstick inceptor. A discussion of differences and similarities of the test results with respect to the different experiments and inceptors types is given below. Additionally, an alternative mathematical description of the dynamic stick characteristics is presented that may better capture the preferred stick characteristics observed in the experiments.

5.1. Comparison of experiments

Generally, there is a good agreement of the results gained from both experiments (Roll Handling Task and Slalom MTE), although the setup of the Roll Handling Task is much simpler and needs no ground references. Both tasks require large pilot inputs for maneuvering. In addition, the Roll Handling Tasks includes an extended tracking phase where the pilot has to make small corrections. For the Attitude Command response type these corrections must be made about a large static deflection.

The sidestick results for the Roll Handling Task in Rate Command (Fig. 8a) and Slalom MTE in Rate Command (Fig. 17a) show a good agreement. In both cases an improvement of 1.5 HQR points can be observed from maximizing the natural frequency within the limits of the tested factor range. The influence of the damping ratio is also nearly identical.

The results for the Roll Handling Task in Attitude Command (Fig. 8b) and the Slalom MTE in Attitude Command (Fig. 18a) show both an improvement directed more towards higher damping ratios. By maximizing the damping ratio within the test limits, an improvment of 0.4 HQR points can be achieved for the Roll Handling Task and of 1.5 points for the Slalom MTE. The independence of the rating from the natural frequency for the Roll Handling Task can also be observed for the centerstick for the Slalom MTE in AC (Fig. 18b).

5.2. Comparison of sidestick and centerstick

The Hover and Slalom MTEs were evaluted both with sidestick and centerstick inceptors. This allows a direct comparison of both inceptor types.

For the Hover MTE (AC only) an increase in damping and natural frequency resulted in improved handling qualities for both sidestick and centerstick. The sensitivity of the HQR with respect to the natural frequency is higher for the sidestick than for the centerstick and with respect to the damping ratio lower for the sidestick than for the centerstick.

For the Slalom MTE in RC the HQR improves for an increased natural frequency in case of the sidestick and an increased damping ratio in case of the centerstick. The damping ratio has nearly no influence on the rating for the sidestick, whereas the rating for the centerstick shows no significant dependeny on the natural frequency.

For the Slalom MTE in AC the situation is unchanged for the centerstick. For the sidestick, however, an increased damping ratio is now also the primary driver for improved handling qualities, while there is still definite trend towards higher natural frequencies.

The generally reduced influcence of the natural frequency compared to the Hover MTE may be explained by the task itself. The pilots is required to make large amplitude inputs at relatively low frequencies reducing the benefits of a fast (high natural frequency) inceptor.

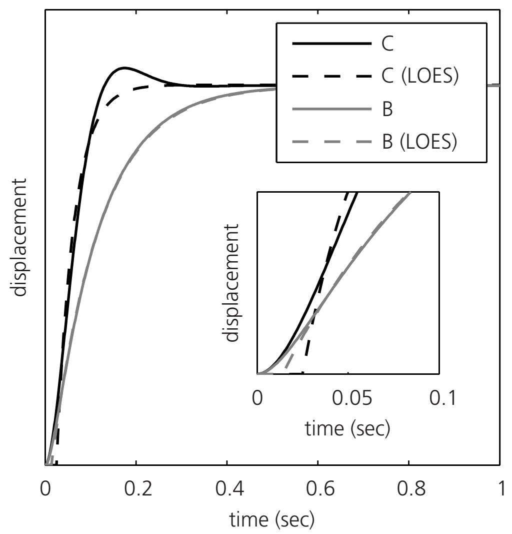


Figure 19: Low order approximation of stick dynamics

The fact that the sidestick generally requires lower damping ratios may be attributable to the wrist action necessary for controlling the sidestick as opposed to the arm action for controlling a centerstick.

5.3. Optimal stick characteristics

At least for attitude command systems all optimal configurations are over-critically damped ($D > 1$). These over-critically damped second order systems can also be considered as two first order systems. The first order system with the smaller time constant can be reduced to the effect of a pure time delay. The same decomposition can be achieved for under-critically damped systems by fitting an equivalent low order system (LOES). In Figure 19 the step responses for the second order system and the equivalant first oder system with time delay are compared for the test cases B and C. The detail view in Figure 19 shows the initial reaction, highlighting the equivalence of the effects of inertia and time delay for systems with sufficiently high natural frequencies.

The mapping of the factors from damping and natural frequency to equivalent time constants (resp. time constant and time delay) distorts the original factor space as illustrated in Figure 20. This figure shows in the plane of time constant T and equivalent time delay τ the lines of constant damping, starting for $D = 1$ to $D = 3$ in intervals of 0.1 for natural frequencies from 6.3 to 21.5 rad/sec. It can be seen that starting from test point B an increased damping produces slower systems (higher time constant) and smaller time delays. From test point A to B (increase of the natural frequency) the system becomes quicker (lower time constant) with a significant reduction of the equivalent time delay.

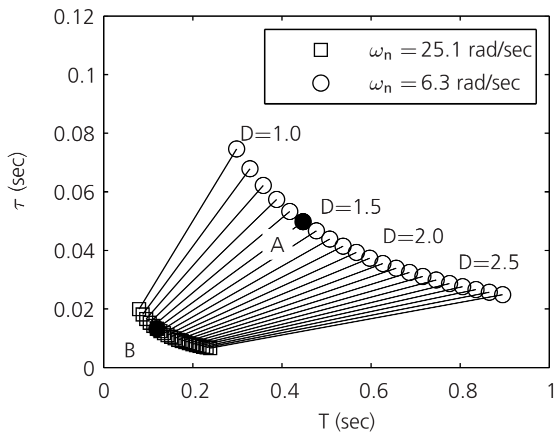


Figure 20: Factor Mapping

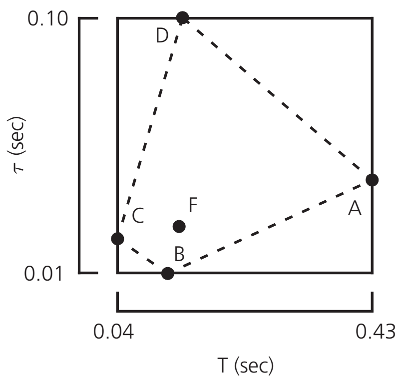
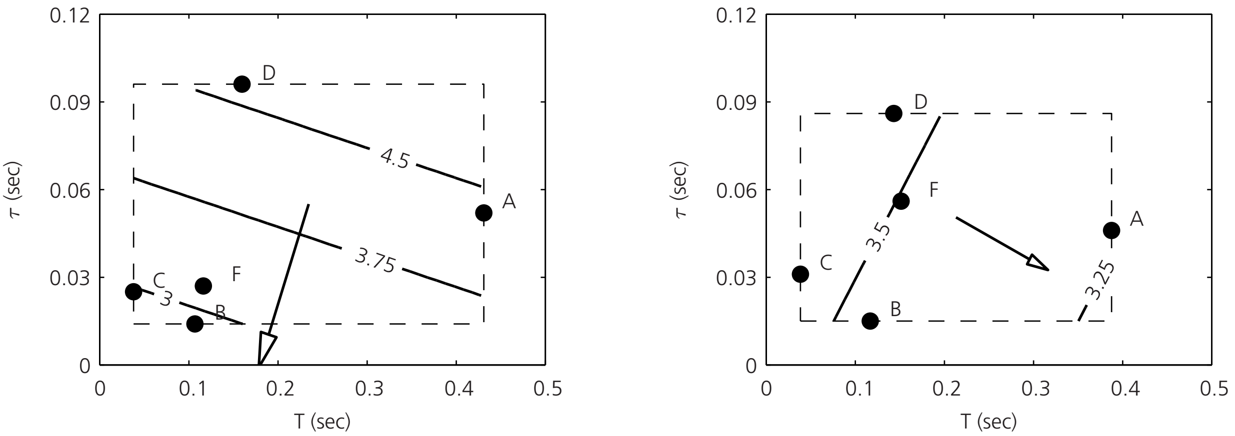


Figure 21: Distorted design matrix

The effect of this distortion on the five test points of the original factorial design is highlighted in Figure 21 for the sidestick test matrix. Although the test matrix is ill-conditioned in this factor space, the linear regression is applied to the HQR ratings (Slalom MTE only) producing the contour plots depicted in Figures 22 and 23.

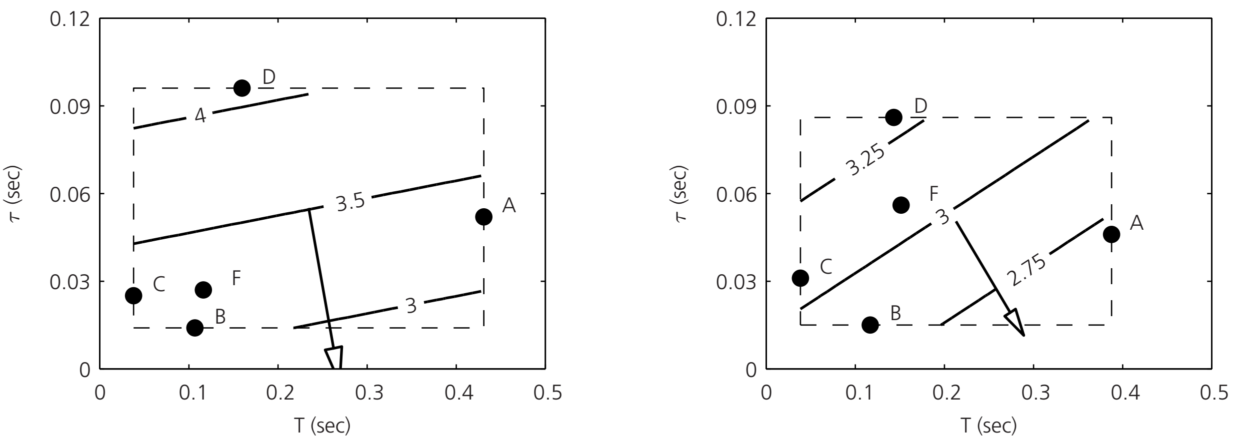
The trend for improved handling qualities points towards a minimal time delay for both inceptor and response types. With a Rate Command response type an agile stick (low time constant) is preferred, while for a centerstick a significantly slower stick (high time constant) is preferred. With an Attitude Command response type a slower stick is preferred for both types of inceptors.

In all cases the preferred dynamic force-displacement characteristics have a minimal time delay, i.e. a quick and immediate response. This is exactly what constitutes a pure first order response. So one question remains to be answered by follow-up investigations: *Is the optimal dynamic stick characteristic a first order response?* If yes, only one stick parameter (the time constant) would have to be adjusted to be in harmony with the dynamic response of the augmented rotorcraft.



(a) Sidestick **(b)** Centerstick

Figure 22: Contour plot for factor mapping (Slalom MTE in Rate Command)



(a) Sidestick **(b)** Centerstick

Figure 23: Contour plot for factor mapping (Slalom MTE in Attitude Command)

6. CONCLUSIONS

Flight test evaluations of the interaction between cyclic inceptor force-feel characteristics and rotorcraft handling qualities has been performed with a centerstick on the JUH-60A RASCAL, and with a sidestick on the EC 135 ACT/FHS. Based on the results of these test, the following conclusions are drawn:

1. The cyclic force-feel characteristics have a significant impact on the handling qualities of rotorcraft.
2. In forward flight, different test maneuvers (Roll Handling Task and Slalom MTE) show comparable results.
3. While the sidestick shows differences between Rate and Attitude Command, there is no significant difference for the centerstick.
4. For the Attitude Command response type, the improvement for the centerstick points to higher damping to frequency ratios than for the sidestick. This means the sidestick should be more agile than the centerstick for the AC reponse type.
5. For the Rate Command response type, the difference between centerstick and sidestick is even more pronounced. So an even more agile stick characteristic is preferred for the sidestick.
6. An in-depth analysis of RPC effects (with special regard to bio-feedback) may explain the trend to lower damping for sidesticks as a consequence of different arm rest positions compared to centersticks and its effect on pilot control dynamics.
7. Meeting the current ADS-33E Level 1 bandwidth requirements from force inputs is not sufficient to ensure Level 1 handling qualities for both inceptor types.

7. ACKNOWLEDGEMENTS

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