

EXPLORATORY EVALUATION OF SIDE-STICK FLIGHT SCIENCES ON VARIABLE STABILITY RESEARCH AIRCRAFT: A STUDY OF INCEPTOR THROW AND FORCE GRADIENT

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Abstract

There is increasing evidence of the benefits of active side-stick inceptors in rotorcraft in areas such as pilot comfort, handling qualities, safety, limit protection, and cockpit design. In-flight evaluations of an active force-sensing (large-displacement, position-output) side-stick inceptor were conducted on the NRC Bell 412 Advanced Systems Research Aircraft. The aircraft was configured with a Rate Damped control response type in pitch and roll axes. A number of qualitative and quantitative results due to side-stick setting preferences were gathered. For a survey of modified ADS-33E-PRF Depart-Abort and Lateral-Reposition mission task elements in good cueing conditions, static setting preferences included average longitudinal and lateral force-gradients of 0.43 N/mm and 0.32 N/mm, respectively. The associated longitudinal and lateral throw limits were 19.3 mm and 25.8 mm, respectively. Dynamic setting preferences included maximum longitudinal and lateral natural frequencies of 16 rad/sec and 15 rad/sec, respectively, combined with average damping ratios of 0.65. In a high bandwidth variable stability helicopter application, this study exposed both benefits (rapid tailoring, comfort) and limiting conditions (physical static and dynamic constraints) of active side-stick technology.

NOMENCLATURE

F	Force (N; lbf.)
F_B	Breakout Force (N; lbf.)
I	Inertia (kg; lb)
J	Optimization Cost Function
k_{FG}	Force Gradient (N/mm; lb/in.)
p, q, r	Attitude Rates - Roll, Pitch, Yaw (degs./sec.)
u, v, w	Translational Velocities (Forward, Lateral, Vertical) (ft./sec.)
x, y	Axis Direction - Longitudinal, Lateral
S_F	Control Force Sensitivity (N/degs./sec.)
S_δ	Control Displacement Sensitivity (mm/degs./sec.)
ζ	Damping
ω_N	Natural Frequency (rads./sec.)
δ	Displacement (mm; degs.)
τ_{eff}	Effective Time Delay (sec.)

1. INTRODUCTION

Research in the area of rotorcraft side-stick inceptor design is a multi-disciplinary challenge involving handling qualities (flight dynamics, mission tasks, cueing), human factors (biomechanics, ergonomics), and control (augmentation, feel system statics and dynamics). Advancements have benefited from theoretical and simulation studies, as well as significant results from fixed-wing research programs^[1]. Helicopter in-flight investigations for development of side-stick technology and application criteria are uncommon. Due to incorporation of adaptable fly-by-wire control and pilot force feel systems, a significant body of research associates with international variable stability aircraft.

Between 1960 and 1970, two Boeing programs demonstrated side-stick technologies. The CH-47 based Tactical Aircraft Guidance^[1] (TAGS with 3-axis side-stick configuration) and the Heavy Lift

Helicopter^[1] (HLH with 4-axis load-control crew side-stick) programs demonstrated flight safety and workload reduction improvements.

Between 1980 and 1990, the NRC investigated side-stick inceptor technology using the NRC Bell 205 Airborne Simulator. Morgan et. al researched side-stick characteristics, designed integration systems and configurations, investigated handling qualities, and supported industrial feasibility studies^[2]. In the 1980's, the US Army Advanced Digital/Optical Control Systems (ADOCS) program investigated the implications of side-stick technology in high bandwidth applications^[1]. All of these flight research efforts contributed to the development of side-stick design criteria for the Light Attack Helicopter (LHX) program and eventually, side-stick technology implemented into the RAH-66 Comanche^[1].

In the last decade, variable stability helicopters have been used to investigate side-stick implementation for increasing availability, flight safety, optimizing handling qualities, and demonstrating technology feasibility. NRC performed industrial flight testing on the NRC Bell 412 Advanced Systems Research Aircraft (ASRA) to support the advancement of technology readiness levels^[3]. Several programs applied side-stick inceptors which influenced aircraft development programs such as the Sikorsky CH-53K and Bell 525. DLR performed developmental testing to evaluate a suite of pilot assistance technologies (vision systems, haptic cueing, etc.) for improving mission task effectiveness^[4]. Further, DLR and the US Army have applied DLR EC-135 and US Army UH-60 research aircraft in investigations of handling qualities criteria for side-stick inceptors^[5]. In Future Vertical Lift programs^[6], advancements in cockpit technologies are critical in the development of next generation aircraft. Many programs highlight the application of active inceptors as key technology for effective pilot interfacing.

2. RESEARCH METHODOLOGY

This paper will summarize exploratory findings on pilot evaluations of a large displacement side-stick integrated into the variable-stability flight control system of the NRC Bell 412 Advanced Systems Research Aircraft (ASRA). In the following sections, overviews of the study scope, analytical method, description of aircraft and side-stick technology, and results from the system identification are provided.

2.1. Research Scope

The objective of this investigation was to evaluate the impact of side-stick force gradient and throw on aspects of helicopter handling qualities in a flight environment. Handling qualities characteristics of concern included control response, aircraft response, and mission task performance. Flight evaluations of the side-stick configuration were performed in the NRC-FRL low speed test range (Ottawa, Canada) using two ADS-33^[7] course references as depicted in **Figure 1**. Data encompassed sorties involving test pilot school training, functional integration testing, and mission task evaluations. The data set was comprised of a set of 100 mission tasks performed by 6 pilots. The two mission tasks included Depart-Abort and Lateral-Reposition.

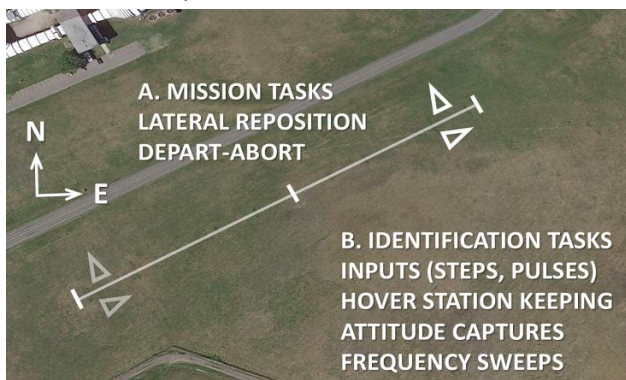


Figure 1: NRC Low Speed Test Area (Ottawa)

2.2. Analytical Method

As depicted in **Figure 2**, the analytical methodology applied in this research involved two steps. The first step was System Identification with sub-tasks involving Hangar Evaluation and Flight Evaluations. The second step involved Flight Data Assessment with sub-tasks involving Flight Data Gathering and associated Data Analysis.

System identification of side-stick characteristics was performed to evaluate side-stick characteristics both independent from and integrated into the test aircraft. In this phase, evaluations were performed with the side-stick hardware integrated into the NRC Bell 412 Flight Control Loop, (Flight Control Laws Disengaged) to evaluate Flight Control Mechanical Characteristics (such as the displacement and force envelopes, the static/dynamic characteristics, ergonomics, etc.).

Flight evaluations were performed to identify Closed Loop Control Characteristics with a Rate Damped control response type.

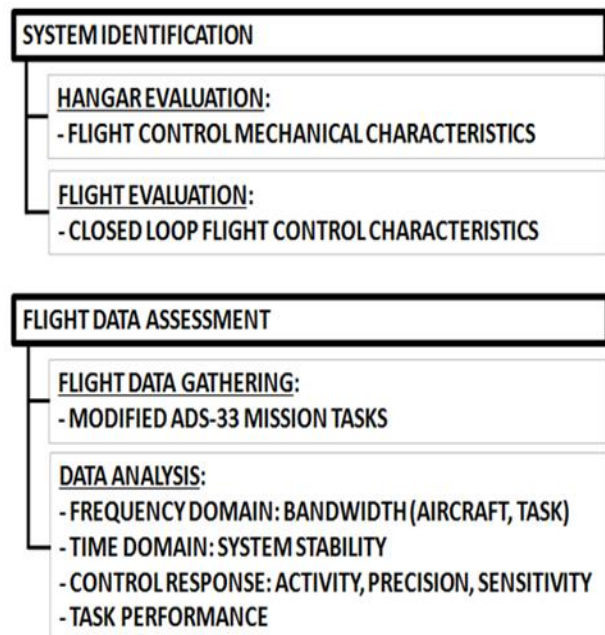


Figure 2: Analysis Methodology

Flight test data was analyzed using time and frequency domain techniques to explore implications on control activity, mission task performance, handling qualities (such as cutoff frequency and bandwidth), and control issues (such as biodynamic interactions, unfavorable control activity, etc.).

Applicable handling qualities metrics applied in this study are summarized as follows:

- a. **Cutoff Frequency^[8]:** A measure of the pilot's control input frequency.
- b. **Task Bandwidth^[8]:** A measure of the minimum control activity required to perform a mission task.
- c. **Aircraft Bandwidth:** A measure of the maximum frequency at which a pilot using pure gain may apply in control without causing aircraft destabilization.
- d. **Compensation:** A measure of additional pilot effort and attention required to maintain levels of performance relative to deficient control characteristics.
- e. **Control Activity:** Measures of control input dynamics in quantities such as stick displacement as a function of time.
- f. **Control Precision:** A measure of the pilot's ability to perform control inputs or to achieve a desired flight condition. 'Predictability' may be used to define this measure qualitatively.
- g. **Task Performance:** Measures of performance of a given mission task in quantities such as aircraft referenced velocity, distance, and time.

2.3. Facilities Description: Test Aircraft and Side-Stick Integration

The NRC Bell 412 ASRA depicted in **Figure 3** is an airborne simulator^[9] derived from the Bell 412HP helicopter. This medium, twin-engine aircraft has a gross take-off weight of 11,900 pounds. Featuring a 4-bladed soft-in-plane rotor system, the aircraft was powered by Pratt & Whitney PT6T-3BE turboshaft engines at the time of testing.

An experimental simplex fly-by-wire control system was integrated. Its simplex architecture consists of a single set of fly-by-wire actuators, one non-redundant flight control computer (FCC), a single set of aircraft state sensors, and a single set of flight control software. Nominal aircraft crewing includes a safety pilot, evaluation pilot, and a flight test engineer.

The NRC Bell 412 ASRA side-stick is an active force-sensing, large-displacement, position-output inceptor manufactured by Stirling Dynamics Incorporated. This electrically-driven and actively-controlled pitch and roll axis inceptor features programmable force-feel characteristics. The device features an ergonomic hand grip with an integrated index finger activated trigger switch, as well as thumb activated multi-axis hat and push button switches. Control is based on the device's position and force feedback as well as motor-driven servo control.

The side-stick is integrated into the NRC Bell 412 ASRA fly-by-wire flight control architecture providing the evaluation pilot full control authority over aircraft response while providing the safety pilot back driven control feedback. The side-stick is mounted in 2+1+1 format whereby it provides the evaluation pilot with an alternate center-cyclic inceptor configuration for commanding longitudinal and lateral inputs.

Classic collective and pedals command heave and yaw inputs, respectively, based on the ASRA's Force Feel System (FFS). The side-stick system hardware consists of servo and control modules. The servo module houses the side-stick and creates the pilot's armrest. The unit contains *active* electromechanical drive components necessary for side-stick motion. The control module contains signal processing, motor drive, and analog circuitry. For ease of integration, the control unit, mounted separately from the servo module, has been located in the aircraft's aft cabin.

Located on the evaluation pilot's right side, the servo-module with the integrated side-stick is mounted to the evaluation pilot seat. The installation provides vertical and lateral adjustment relative to the seat. Once the side-stick position is set, its location remains fixed relative to longitudinal and vertical adjustments of the pilot seat. Location of the servo-module is restricted on the right (by the cockpit center console), to the left (by the pilot's right leg), and forward (by the cockpit instrument panel). These restrictions do not impede side-stick operation within normal ranges of adjustment or displacement described in this experiment.

The side-stick operating software was hosted on the aircraft's fly-by-wire flight control computer. NRC Bell 412 ASRA experimental aircrew interface dials and function switches located either in the cockpit (center console) and in the cabin (flight test engineer station) were configured to enable side-stick function selections. For this study, the aircraft configuration emulated a cargo utility operations category helicopter. The flight control law implemented in testing was a Rate Damped response type in Pitch, Roll, and Yaw axes with the heave axis remaining un-augmented.



Figure 3: NRC-FRL Bell 412 ASRA Evaluation Pilot Seat (Left/Right - Side-Stick Integration)

2.4. Ground Test System Identification: Identification of Side-Stick Static and Dynamic Characteristics

Prior to flight investigations, the author performed ground testing to identify side-stick Flight Control Mechanical Characteristics (FCMC) and determine the setting envelope. For this study, primary characteristics analyzed were stick displacement (throw) and stick force which provided force feel trending (force gradient). Stick displacement throw and force were tunable via cockpit dials and had a maximum deflection of +/- 25 degrees (6.6 cm) and maximum force of +/-150N. Displacement and force asymmetry in the stick longitudinal and lateral axes was provided to account for pilot bio-mechanics. Lateral stops were set 30% greater than those of the longitudinal axis. The lateral force-gradient was set at 70% that of the longitudinal axis. Frequency sweeps were performed to provide data for system identification of the side-stick inceptor system characteristics throughout the force and displacement envelopes. The identification applied CIFER^[8] utilities enabling design of transfer functions for side-stick characteristics. Typical transfer function models identified were of second order form:

$$\frac{\delta}{F} = \frac{K(e^{-\tau})}{s[\zeta, \omega_N]}$$

In this format, damping ratio and natural frequency $[\zeta, \omega_N]$, implies $s^2 + 2\zeta\omega_N s + \omega_N^2$ and K is a gain composed of side-stick gearing, natural frequency, and side stick variable force. τ represents time delay for lumping higher-order dynamics such as side-stick electro-mechanics. Using the CIFER NAVFIT^[8] optimization utility, it was determined that the classic 2nd order response transfer function enabled low order fitting of the response in the range of 0.1 to 15 rad/sec with cost function magnitudes of approximately $J = 50$ to 100. Further optimization of the fit ($J < 50$) added parameters that could be associated with side-stick input trim offsets, axis cross-coupling, pedestal motion, and neuromuscular effects.

As depicted in **Table 1**, increasing longitudinal displacement range to full-throw for low stick forces (Limits A and B) coincided with reduced gradient, inertia, natural frequency, and damping respectively. Increasing longitudinal forces to force-limits for low-throw stick (Limits A and D) significantly increased force-gradient and inertia, natural frequency and damping. Comparatively, increasing lateral displacement range to full-throw for low stick forces (Limits A and B) coincided with reduced gradient, inertia, natural frequency, and damping. Increasing lateral forces to force-limits for low-throw stick forces (Limits A and D) significantly increased force-gradient, inertia, natural frequency. The damping ratio depicted minor variations in magnitude overall for these limiting conditions.

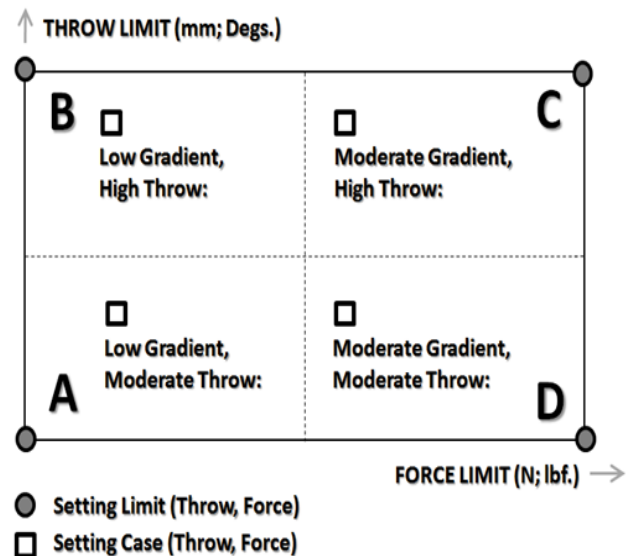


Figure 4: Side-stick Setting Envelope

These parameters enabled definition of envelope setting limits and cases of the side-stick configuration (**Figure 4**) to which pilots were exposed in evaluations. Based on these exposures, pilots were then provided an opportunity to tune the side-stick inceptor to their particular preferences. Limiting setting conditions are summarized in **Table 1**.

Side-stick Envelope Location	δ , mm (Deg)		F , N (lbf)		k_{FG} , N/mm (lb/in)		I , kg (lbm)		ω_N , rads./s. (Hz)		ζ	
	x	y	x	y	x	y	x	y	x	y	x	y
Limit, A	10 (3.8)	13.3 (5.1)	0.08 (0.02)	0.08 (0.02)	0.01 (0.06)	0.01 (0.06)	0.06 (0.13)	0.04 (0.09)	10.8 (1.72)	11.69 (1.86)	0.62	0.62
Limit, B	40 (15.2)	53 (20.1)	0.08 (0.02)	0.08 (0.02)	0.002 (0.01)	0.001 (0.01)	0.02 (0.04)	0.01 (0.02)	10.4 (1.66)	9.9 (1.58)	0.5	0.62
Limit, C	40 (15.2)	53 (20.1)	37.5 (8.43)	37.5 (8.43)	0.9 (5.14)	0.71 (4.05)	3.34 (7.36)	2.9 (6.39)	16.8 (2.67)	15.6 (2.48)	0.74	0.71
Limit, D	10 (3.8)	13.3 (5.1)	37.5 (8.43)	37.5 (8.43)	3.77 (21.53)	2.83 (16.16)	16.53 (36.44)	13.45 (29.65)	15.1 (2.40)	14.5 (2.31)	0.7	0.62

NOTES: Breakout Forces: $F_{Bx} = 5$ N (1.12 lbf), $F_{By} = 3$ N (0.67 lbf)

Table 1: NRC-FRL Bell 412 ASRA Identified Inceptor Characteristics, Side-stick Envelope Limits

2.5. Flight Test System Identification: Identification of Aircraft and Side-Stick Dynamics in Closed Loop

A preliminary flight test was performed by NRC pilots to determine handling qualities and control characteristics of the NRC Bell 412. The data provided reference information for configuration and assessment of the side-stick. Maneuvers performed included frequency sweeps, attitude captures, step inputs, and impulses.

NRC pilots selected three side-stick setting cases within the setting limits defined in the preceding section. Defined previously as Low Gradient/Moderate Throw (A), Low Gradient/High Throw (B), and Moderate Gradient/Moderate Throw (D), the force gradient and throw for each of these cases is provided in **Table 2**. Using these settings, an evaluation of ADS-33^[7] Bandwidth, Attitude Quickness, and Cross Coupling was performed.

Side-stick Envelope Location	δ , mm (Deg)		k_{FG} , N/mm, (lb/in)	
	x	y	x	y
Case, A	18.71 (7.05)	24.94 (9.4)	0.52 (2.98)	0.4 (2.2)
Case, B	35.81 (13.5)	47.75 (18)	0.21 (1.2)	0.16 (0.9)
Case, D	17.9 (6.75)	23.87 (9)	1.46 (8.37)	1.1 (6.3)

Table 2: NRC Bell 412 Test Case Static Settings

Requirements for small-amplitude pitch and roll attitude changes in hover and low speed were assessed for all other mission task elements (UCE=1 and Fully Attended operations). The pitch and roll bandwidth for the aircraft is depicted in **Figure 5**.

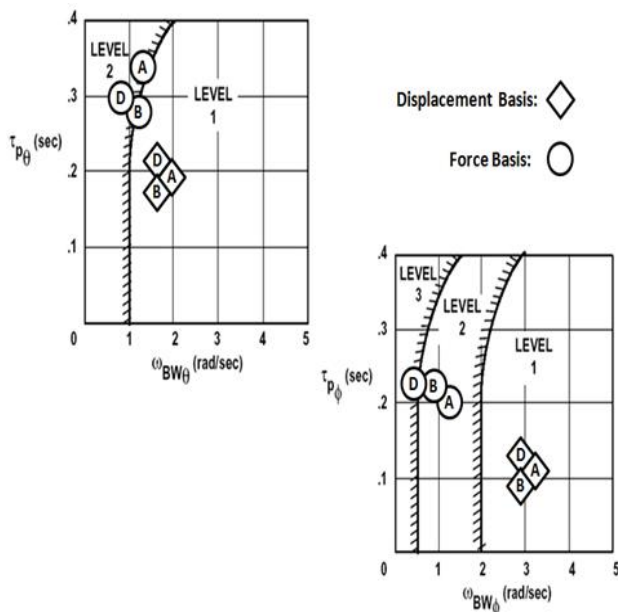


Figure 5: ADS-33 Bandwidth Criteria^[7]

The gain limited Rate Damped response of the aircraft was assessed to be Level 1 in both pitch and roll axes on a side-stick displacement basis. On a force basis, the response was evaluated to be Level 2 in both the pitch and roll axes. Stick settings explored did not significantly alter bandwidth response.

Requirements for moderate-amplitude pitch and roll attitude changes in hover and low speed were assessed for all other mission task elements (UCE=1 and Fully Attended operations).

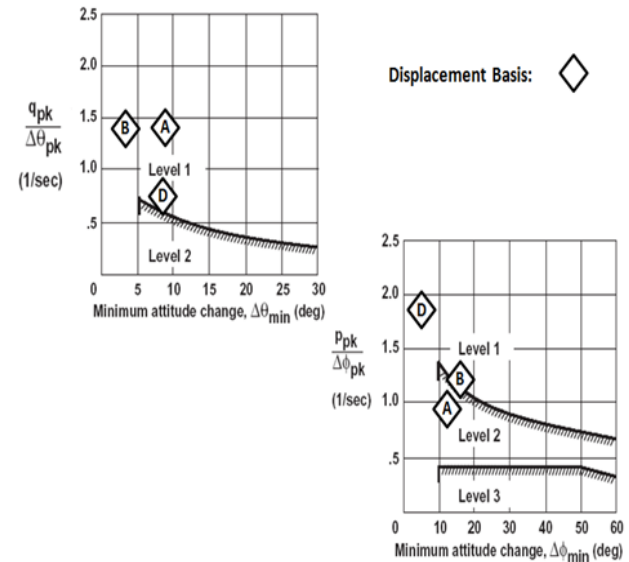


Figure 6: ADS-33 Attitude Quickness Criteria^[7]

The pitch and roll attitude quickness for the aircraft for target acquisition and all other mission tasks is depicted in **Figure 6**. The gain-limited rate-damped response of the aircraft was assessed to be Level 1 in the pitch axis, while Level 1 and 2 responses were seen in the roll axis.

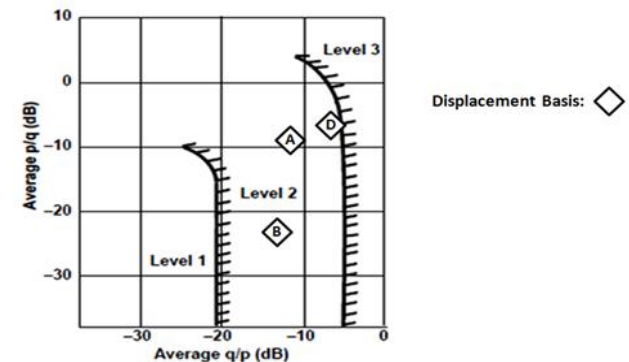


Figure 7: ADS-33 Cross Coupling Criteria^[7]

Aircraft requirements for pitch due to roll and roll due to pitch coupling for aggressive agility are depicted in **Figure 7**. The aircraft was assessed to show coupling mid-Level 2 to borderline Level 3 based on the setting of the side-stick.

The modification of attitude capture and axis coupling were key findings illustrating the impact of side-stick configuration on handling qualities.

3. RESEARCH RESULTS

Following the identification of side-stick characteristics and performance of flight training sorties which exposed pilots to both favorable and unfavorable settings, the flight test data was analyzed. Assessments were based on analyses of exploratory inputs (step, pulses), modified ADS-33 mission tasks, and stationary hovering. Two mission tasks including the Depart-Abort and the Lateral-Reposition are the focus of the research results. Assembling tasks with similar levels of aggression and to similar levels of performance, data was analyzed to:

- Evaluate effects of force gradient on stick dynamic behavior
- Evaluate the effects of force gradient on controllability during mission tasks
- Evaluate effects of force gradient on mission task performance

3.1. Depart-Abort Mission Task Analysis

The Depart-Abort mission task was performed over varying distance from 600 to 800 feet but was performed using the same pilot control strategy. The control strategy consisted of longitudinal side-stick input to capture 30 knots ground speed. A pitch up attitude greater than 20 degrees was typically used to arrest forward motion to bring the helicopter to a stable hover. Phases are highlighted in **Figure 8**.

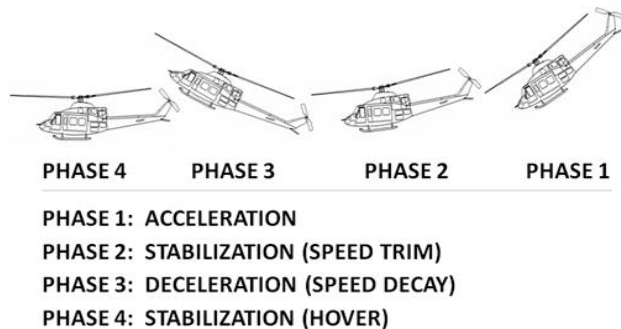


Figure 8: Depart-Abort Task Overview

Six pilots performed the Depart-Abort mission task using a variety of force and throw (force gradient) stick settings. A series of 15 Depart-Abort tasks were filtered based on pilot input auto-spectrum cutoff frequency. As depicted in **Figure 9**, task cutoff frequencies ranged from 0.5 to 2.75 rads/sec. The aircraft pitch axis rate command configuration bandwidth was 1.8 rads/sec. The task bandwidth is approximately 1 rads/sec. As aircraft bandwidth is greater than Depart-Abort task bandwidth, pilot cutoff frequency may be used to estimate task bandwidth. At low longitudinal force gradients, pilot cutoff frequencies were greater than 2.5 rads/sec. This condition left little margin between task and aircraft bandwidth. This led to degraded handling qualities due to levels of compensation for pitch rate and attitude control using excessive side-stick longitudinal

throw. Further, in higher gain phases of the Depart-Abort oscillatory control response could occur. At high force gradients, pilot cutoff frequencies were well below the aircraft bandwidth providing a margin of 2.5 rads/sec to achieve desirable handling qualities. However, compensation associated with high stick inertia caused control sluggishness and pilot fatigue which degraded reported handling qualities.

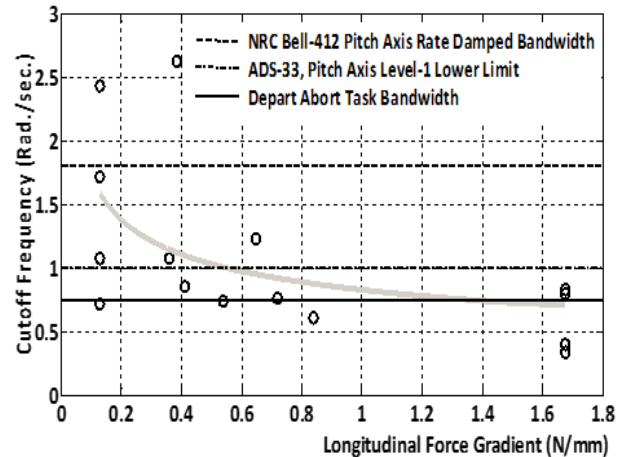


Figure 9: Task Discrimination: Longitudinal Axis Cutoff Frequencies, Depart-Abort

Qualitative observations associated with these limiting conditions and their influence on longitudinal response characteristics of the Depart-Abort mission task are summarized in **Table 3**.

Low (Inertia, Force Gradient), High Travel: "Sensitive"	
PHASE 1: ACCELERATION	Pitch axis over-control with pitch axis; issues with predictability
PHASE 2: SPEED TRIM	High pitch rate variations with difficulty in acquiring trim speed
PHASE 3: DECELERATION	Over-Control tendency with excessive pitch axis attitudes
PHASE 4: HOVER	Decreased time to achieve hover; tendency to arrest hover too early
High (Inertia, Force Gradient), Low Travel: "Sluggish"	
PHASE 1: ACCELERATION	Over-Control tendency in pitch axis
PHASE 2: SPEED TRIM	Able to acquire trim speed; high compensation
PHASE 3: DECELERATION	Under-Control tendency with excessive pitch axis attitudes
PHASE 4: HOVER	Increased time for hover stabilization; tendency to overshoot hover position

Table 3: Depart Abort - Qualitative Observations

In the time domain, implications of the unfavorable longitudinal stick settings on control strategy and aircraft response are depicted in **Figure 10** for limits of low and high gradient cases.

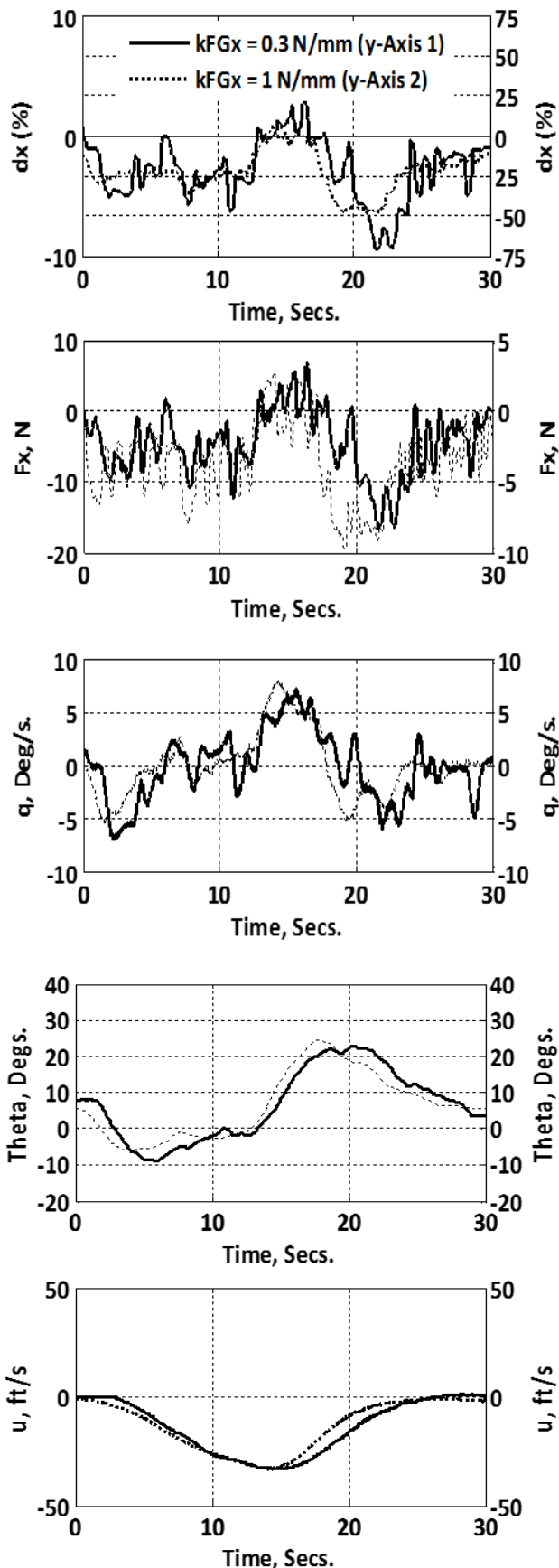


Figure 10: Task Performance: Longitudinal Axis, Depart-Abort

The above mentioned effects may degrade pilot controllability during initiation, speed trim, and stabilization phases which overall may decrease task precision. High longitudinal displacement and low longitudinal force (low force gradient) side-stick settings resulted in excessive control activity for the Depart-Abort mission task. In terms of task performance, pitch attitude and forward velocity profiles were matched. As depicted in **Figure 10**, in high force gradient setting (1 N/mm) the pilot applied 8 deg/sec (20 degrees nose up attitude) rate response in the final phases of the Depart-Abort. Comparatively, the same pilot applied 6 deg/sec (20 degrees nose up attitude) in low force gradient (0.3 N/mm) setting to arrest helicopter forward motion for attaining a stable hover. The latter case depicts heightened stick activity due to combined effects of gradient to friction ratio and low inertia translating into increased pitch rate variations and low ride qualities. Pilot preferences for the Depart-Abort were associated with side-stick setting Case A (low gradient/moderate throw) of the envelope. Force gradients between 0.2 N/mm and 0.5 N/mm and throws between 18 mm and 25 mm provided favorable control and aircraft response. The effects of their preferences are summarized in **Figure 11** for the hover stabilization phase covering the final pitch up to the arresting of forward speed to attain hover.

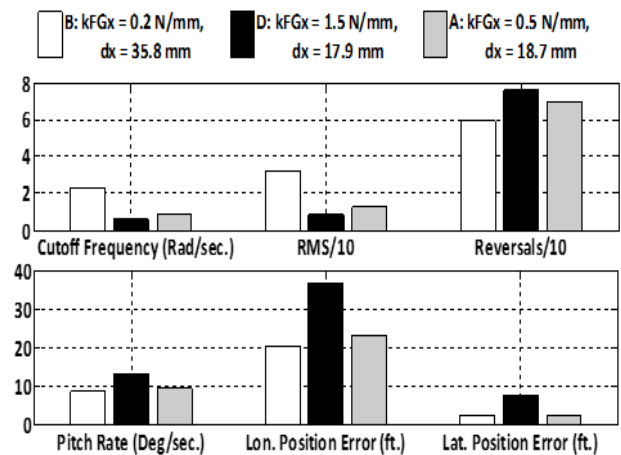


Figure 11: Task Control Activity and Performance: Depart-Abort, Longitudinal Axis, Hover Stabilization.

In terms of control response, at cutoff frequencies greater than 2 rad/sec., side-stick RMS was greater in side-stick setting Case B due to higher throw limits than in Case D where cutoff frequencies were 0.75 rad/sec. Lower throw limits in Case D led to the highest reversal counts of both cases. In terms of aircraft response, pitch rate and longitudinal position errors were greater in Cases D than B. Side-stick Case A (low gradient/moderate throw) provided the most favorable compromise between control activity and position error (typically within one main rotor diameter) while providing margin for pilots to increase gain to achieve desired handling qualities.

3.2. Lateral Reposition Mission Task Analysis

The evaluations were performed on the NRC ADS-33 course with task modifications typically associated with the length of the maneuver from acceleration to final hover. Again, this altered attained ground speed, roll attitude attained, and duration of the mission task element. As depicted in **Figure 12**, Lateral-Reposition mission task objectives involved evaluation of the ability perform Mission Task Element (MTE) phases including laterally dependent acceleration, controllability at steady trim speed, deceleration, and re-establishment of hover.

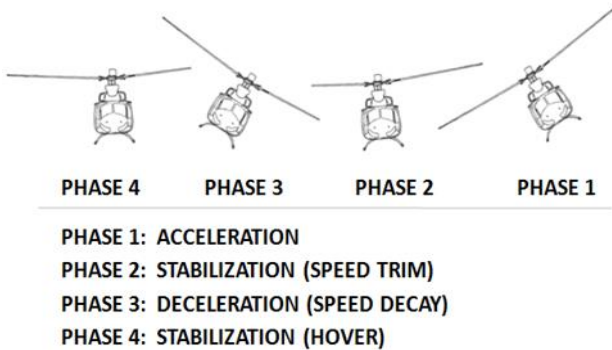


Figure 12: Lateral-Reposition Task Overview

Six pilots performed the Lateral-Reposition mission task using a variety of force and throw (force gradient) stick settings. The MTE was performed over varying distances from 400 to 600 feet but was performed using the same pilot control strategy. This strategy consisted of lateral side-stick input to capture 30 knots ground speed. A roll attitude greater than 20 degrees was typically used to arrest sideward motion to achieve a stable hover.

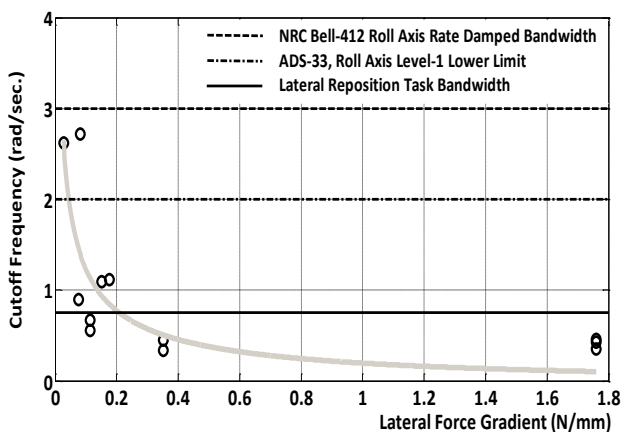


Figure 13: Task Discrimination - Cutoff Frequency, Lateral-Reposition

As depicted in **Figure 13**, in the frequency domain, cutoff frequencies for the Lateral-Reposition mission task ranged from 0.3 to 2.75 rad/sec. Task bandwidth was estimated to be 0.75 rad/sec. Data points at high cutoff frequencies (High Throw, Low Gradient) predict poor handling qualities as little margin exists between task and aircraft bandwidth.

Data points at low cutoff frequencies (Low Throw, High Gradient) predict good handling qualities. However, combined heaviness and stiffness of the side-stick leads to Pilot Induced Oscillation (PIO) tendencies. Impacts of these unfavorable settings are summarized qualitatively in **Table 4**, relative to mission task phase. These effects are substantiated by examination of time domain responses.

Low (Force Gradient, Inertia), High Throw: "Sensitive"	
PHASE 1: ACCELERATION	Over-Control tendency roll axis control system limit excursion
PHASE 2: SPEED TRIM	Able to acquire trim speed; high compensation, low predictability
PHASE 3: DECELERATION	Lack of precision in attaining appropriate roll attitude
PHASE 4: HOVER	Decreased time to achieve hover; tendency to arrest hover too early
High (Force Gradient, Inertia), Low Throw: "Sluggish"	
PHASE 1: ACCELERATION	Roll axis over-control with evidence of (pitch-roll coupling)
PHASE 2: SPEED TRIM	High roll rate variations, difficulty in acquiring trim speed
PHASE 3: DECELERATION	Lack of precision in attaining roll attitude: pitch-roll coupling: ratchety
PHASE 4: HOVER	Increased time for hover stabilization; tendency to overshoot hover position

Table 4: Lateral-Reposition - Qualitative Observations

Implications of the unfavorable lateral stick settings on control strategy and aircraft response are depicted in **Figure 14**. For low throw and high gradient (2 N/mm), pilots adopted a low frequency and low amplitude input strategy. As the stick setting provided a significant margin between the cutoff frequencies and the aircraft roll axis bandwidth (3 rad/sec), the pilots can provide gain input to satisfactorily perform the mission task. The task bandwidth is below the ADS-33 Level 1 lower limit providing the ability to achieve Level 1 handling qualities. The level of compensation to achieve satisfactory handling qualities was high in all phases of the mission task.

At the limits of low throw, unpredictable roll control inputs and roll rate response was exhibited. The high gradient may have resulted in improved side-stick centering and sensitivity. However, the stick configuration had a poor gradient to breakout ratio with friction causing 'ratchety' response. A roll PIO is exhibited in the hover stabilization phase that may be due to neuromuscular mode excitation^[10]. This caused significant roll rate variations and decreased ride qualities.

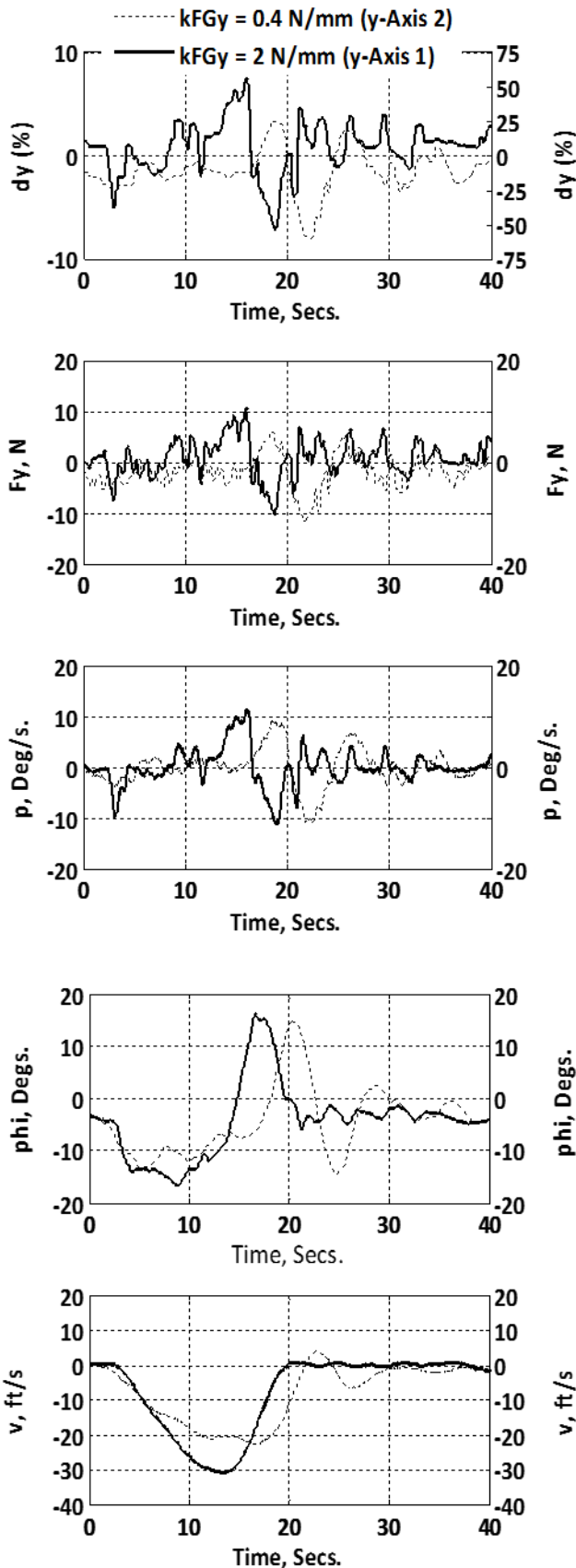


Figure 14: Task Performance: Lateral Axis, Lateral-Reposition

For high throw and low gradient settings (0.4 N/mm), pilots adopted a high frequency and high amplitude input strategy. As the stick setting placed the cutoff frequencies near the aircraft roll axis bandwidth (3 rad/sec), the pilots increased their level of compensation. This equated to degraded handling qualities due to an increase in workload in speed trim and hover stabilization phases of the lateral reposition. The high throw created predictable roll control inputs and roll rate responses. The low gradient may have resulted in decreased side-stick roll sensitivity.

The limit of high throw resulted in requirements for ergonomic adjustments (i.e.; hand and arm shifting), an unfavorable gradient to breakout ratio which created a dampening effect on the side-stick response, and poor centering characteristics. In **Figure 14**, an overshoot is observed during initiation of the hover stabilization phase. Oscillatory response is further indicated as the pilot attempts to arrest the helicopter's forward motion by increasing input lead. As indicated earlier, the poor aircraft handling in this case is associated with high compensation attributed to excessive side-stick throw. Further, in this setting, there is no margin between the aircraft bandwidth and pilot cutoff frequency. As indicated in **Figure 15**, the combination of throw and gradient caused a shift in control strategy.

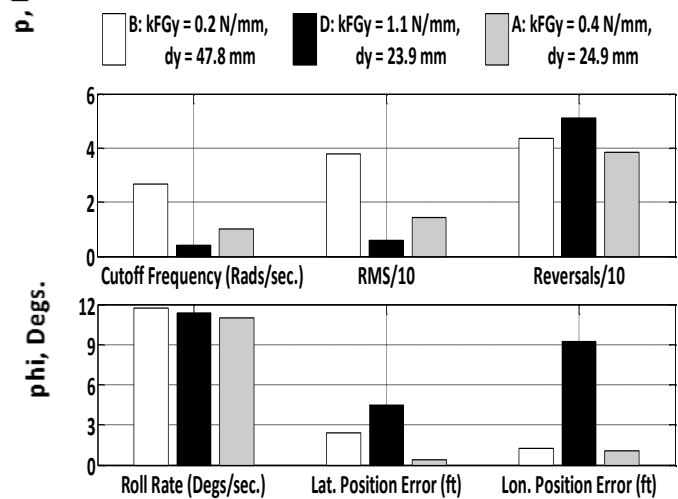


Figure 15: Task Control Activity and Performance: Lateral Axis, Lateral-Reposition, Hover Stabilization.

High throw/low gradient resulted in high amplitude high frequency control activity while low throw/high gradient resulted in low amplitude/low frequency control activity. In terms of overall Lateral-Reposition task performance, Case A (moderate throw and low gradient) produced the least position error in both lateral and longitudinal aircraft response. Force gradients between 0.2 N/mm and 0.4 N/mm and throws between 20 mm and 30 mm provided favorable control and aircraft response.

4. DISCUSSION



Figure 16: NRC Bell 412 ASRA – Side-Stick Testing

Pilot preferences from the test campaign (**Figure 16**) were evaluated and tabulated following the performance of mission tasks. Pilots were exposed to unfavorable side-stick response and then provided the opportunity to independently tune gradient and throw to their preference. A sample of the preferences from nine pilots was analyzed providing the side-stick static and dynamic data. The side-stick characteristics were analyzed using basic descriptive statistics to convey data distribution in terms of central tendency and data spread.

x-axis	F	δ	k_{FG}	S_{δ}	S_F
AVG	7.96	19.34	0.43	1.29	0.53
MIN	6.75	13.92	0.27	0.93	0.45
MAX	11.2	27.85	0.63	1.86	0.75
STD	1.45	4.59	0.12	0.31	0.1
y-axis	F	δ	k_{FG}	S_{δ}	S_F
AVG	7.96	25.79	0.32	1.03	0.32
MIN	6.75	18.57	0.2	0.7	0.27
MAX	11.2	37.14	0.47	1.49	0.45
STD	1.45	6.12	0.09	0.25	0.06

NOTES:

- a. $F_{BX} = 5N, F_{BY} = 3N$
- b. **Units;** $k_{FG} = N/mm$; $S_{\delta} = mm/(Deg/s)$; $S_F = N/(Deg/s)$

Table 5: Side-stick Preferences, Static Characteristics

The preferred static characteristics are presented in **Table 5**. Maximum desired side-stick forces of 11 N were the same in the longitudinal and lateral axes. The preferred longitudinal and lateral throws were 19 mm and 26 mm, respectively. The ratio of longitudinal to lateral throw limit was 0.75. The preferred forces and throws indicated significant deviation in the preferences of pilots across the sample group.

The side-stick longitudinal and lateral sensitivities were normalized using maximum attitude rates (15 deg/sec and 25 deg/sec pitch and roll rates, respectively) based on control power at maximum side-stick deflection. The preferred longitudinal and lateral displacement sensitivities were 1.3 mm/deg/s and 1.03 mm/deg/s respectively. The preferred longitudinal and lateral force sensitivities were 0.53 N/deg/s and 0.32 N/deg/s respectively. This provided preferred longitudinal and lateral force gradients of 0.43 N/mm and 0.32 N/mm, respectively. The ratio of longitudinal to force gradient was 1.34. The preferred force gradients indicated limited deviation in preferences across the pilot sample group.

Average breakout forces between 3N and 5N provided tactile cueing for the unique trim configuration of the side-stick. This provided a gradient to breakout ratio of 0.17 and 0.22 for longitudinal and lateral axes respectively.

x-axis	ζ	ω_N	I	τ_{eff}
AVG	0.650	15.50	1.81	0.08
MIN	--	14.50	1.21	0.08
MAX	--	16.00	2.56	0.09
STD	--	0.75	0.55	0.004
y-axis	ζ	ω_N	I	τ_{eff}
AVG	0.65	14.00	1.71	0.09
MIN	--	12.00	1.03	0.09
MAX	--	15.00	2.81	0.11
STD	--	1.50	0.64	0.01

NOTES:

- a. $\omega_N = \text{rads/sec.}$
- b. $I = \text{kg}$
- c. $\tau_{eff} = \text{secs.}$

Table 6: Side-stick Preferences, Dynamic Characteristics

The preferred dynamic characteristics are presented in **Table 6**. The ratio of longitudinal to lateral natural frequency was 1.11. Maximum longitudinal and lateral natural frequencies of 16 rad/sec and 15 rad/sec, respectively, combined with 0.65 average damping ratios were preferred. This combination provided stick agility (encompassing cross-over, attitude rate response, and regressive flap mode frequencies) and precision (limiting over-shoots). The effective time delay for the preferred side-stick characteristics was approximately 100 ms.

The preference of relatively high side-stick inertias is indicative of the current NRC Bell 412 ASRA side-stick systems integration. Preferred average longitudinal and lateral side-stick inertias were 1.81 kg and 1.71 kg, respectively. A number of factors could be associated with this choice. The Rate Damped control response type provides the pilot with a capacity to achieve high agility whereby little augmentation exists and high filter breakpoints provide high control activity.

In the current side-stick architecture, no bandpass filtering was implemented for the side-stick, thus bio-inertial feedback could be induced in the force gradient setting ranges occurring in this study. The preferred side-stick inertia balanced system architecture, physical workload, cueing (trim, rotor response), dynamic sensitivity, and bio-inertial feedback mitigation. Given that Rate Damped response type was integrated into a high bandwidth control system on a helicopter with a hingeless rotor system, elevated stick inertia provided pilots with a sense of side-stick dampening.

5. CONCLUSIONS

Depart-Abort and Lateral-reposition mission tasks were analyzed to evaluate the implications of side-stick parameter settings on flight control and handling requirements. Though this investigation was exploratory in nature, findings on side-stick setting preference were derived which provide both substantiation of beneficial and cautionary implications for application of the technology in high bandwidth helicopters. Side-stick setting parameters influenced handling qualities, control response, and mission task performance.

Vehicle cross-axis coupling response was affected by two factors. The first factor was the stick setting relationship between pitch and roll axis parameters including gradient, throw, and inertia. The second factor was associated with the limits of pilot bio-mechanics and force asymmetry relative to the side-stick's physical mounting configuration.

In terms of static setting preferences, for a Rate Damped control architecture, longitudinal gradients between 0.27 N/mm and 0.63 N/mm were selected by the pilots. Longitudinal Throw limits between 14 mm and 27 mm were preferred. Lateral gradients between 0.2 N/mm and 48 N/mm were selected by the pilots to be preferable. Lateral Throw limits between 19 mm and 40 mm were preferred. These settings resulted in preferred longitudinal displacement and force sensitivities of 1.29 mm/deg/sec and 0.53 N/deg/sec., respectively. Preferred lateral displacement and force sensitivities were 1.03 mm/deg/sec and 0.32 N/deg/sec., respectively.

In terms of dynamic setting preferences, maximum longitudinal and lateral natural frequencies of 16 rad/sec and 15 rad/sec, respectively, combined with average damping ratios of 0.65 were preferred. Finally, the preferred average longitudinal and lateral side-stick inertias were 1.81 kg and 1.71 kg, respectively.

The flight test environment exposed aspects such as the inter-relationships between side-stick settings factors such as system architecture, physical workload, cueing (trim, rotor response), sensitivity, and bio-inertial feedback mitigation.

6. ACKNOWLEDGEMENTS

This publication is dedicated to the inspiration provided by a former colleague, Stephan Carignan. Contributions made by NRC Flight Research Laboratory staff and test aircrew of the 'Ecole du personnel navigant d'essais et de réception (EPNER; Istres, France)' test pilot school program are gratefully acknowledged.

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Stephan Carignan, a dedicated husband, father, and test pilot passed away September 14, 2014. He had a successful 20 year career at the National Research Council of Canada Flight Research Laboratory (NRC-FRL) in Ottawa, Ontario. He obtained a military education through the Royal Canadian Air Force (RCAF) that included a Mechanical Engineering degree, Helicopter Flight Training, and Test Pilot Training ('École du personnel Navigant d'essais et de reception', France). Operationally, he was assigned to RCAF 423 Maritime Helicopter Squadron (Shearwater, Nova Scotia) and RCAF Aerospace Engineering Test Establishment (Cold Lake, Alberta). Starting his career at NRC-FRL in 1996, he spent 18 years accumulating almost 6700 hours of flying time on 45 aircraft types. He performed flight research in areas such as vision systems, control, and handling qualities, as well as development of the NRC Bell 412 Advanced Systems Research Aircraft. Stephan's contributions to aeronautics garnered him many prestigious awards including NRC Achievement, American Helicopter Society Leonardo (Gruppo Augusta) International Fellowship, and Multiple Technical Cooperation Program Achievement. Perhaps his most significant career achievements are those of Royal Aeronautical Society Bronze and Alan Marsh Medal Medals.