Paper #132

EXPERIMENTAL FLIGHT TEST EVALUATION OF THE EFFECTS OF ROTOR STATE MEASUREMENTS AND FEEDBACK CONTROL ON VARIABLE STABILITY HELICOPTERS

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Abstract

The National Research Council of Canada Flight Research Laboratory (NRC-FRL) has been experimenting with high-order rotorcraft state measurements based on main rotor hub mounted sensor systems installed on the NRC Bell 412 Advanced Systems Research Aircraft (ASRA). Utilizing the NRC Bell 205A Airborne Simulator (AS), a model following flight test investigation of the effects of rotor state measurements and feedback on flying, handling and ride qualities was performed. Using an eight degree-of-freedom mathematical model of the Bell 412 ASRA that included rotor flapping dynamics, several control system designs were developed. Desktop simulation was used to investigate controllers designed using Root Locus Method (RLM), Classical Multivariable Control (CMC), and Eigenstructure Assignment Control (EAC) algorithms featuring rigid-body and rotor state dynamics and feedback. The research concluded that rotor state feedback of longitudinal and lateral disc tilt dynamics significantly improves inter-axis decoupling, disturbance rejection characteristics, rotor response dynamics, command tracking accuracy, and rigid-body bandwidth performance.

NOMENCLATURE

a_1, b_1	Disc Tilt (Longitudinal, Lateral) Displacement
p, q, r	Attitude Rates - Roll, Pitch, Yaw (degs./sec.)
u, v, w	Translational Velocities (For., Lat., Vert.) (ft./sec.)
x, y	Axis Direction - Longitudinal, Lateral
A_1, B_1	Harmonics of Blade Feathering, (Longitudinal, Lateral) Cyclic Pitch
G_{TF}, G_{SS}	Closed loop (transfer functions, state space)
H(s)	Compensator Gain
Ixx, Iyy	Mass Moment of Inertia, Lon., Lat. (lb-in^2)
Kb1s, Ka1s	…Spring Constant, Rotor Flapping (Lat., Long.)
K, K_{FF}	Gain (Feedback, Feedforward)
L, M	Moment Derivative (Roll, Pitch)
L1, L2, L3	ADS-33 Criteria (Level 1, Level 2, Level 3)
Lb1s	Roll Flapping Spring
Ma1s	Pitch Flapping Spring
δ_{COM}, δ_{METS}, δ_N	Models (Command, Turb., Decoupling)
δ_{LAT}, δ_{LON}	Cyclic Control (Lateral, Longitudinal)
ω_0, ω_N	Frequency - Undamped, Natural, (rads./sec.)
η_{GUST}, η_G	Turbulence (Gust Response, Gust Rotor Axis)
θ, ϕ, ψ	Euler Angles (pitch-, roll-, yaw-axes)
Ω, γ	Rotor (Rotational Speed, Lock Number)
ζ, ζ_{RF}	Damping Ratio (Nominal, Rotating Frame)
τ_{a1s}, τ_{b1s}	Time constants (Long., Lat. (Disc tilt)),
τ_e ; τ_p; τ_F	Delay (Time; Phase; Fuselage)
ABC	Advancing Blade Concept
AS	Airborne Simulator
ASRA	Advanced Systems Research Aircraft
CLC, CMC	Control (Classical, Classical Multivariable)
EAC	Eigenstructure Assignment Control
FCDE	Flight Control Development Environment
HES	Hall Effect Sensor
HMMS	Hybrid Mathematical Model Structure
HPF	High Pass Filter
METS	Mixer Equivalent Turbulence Simulation
MFCA	Model Following Control Architecture
MMLE	Maximum Likelihood Estimation
RLM	Root Locus Method
RSF	Rotor State Feedback
RSCM	Rotor State Computer Module
RSMS	Rotor State (Measurement System

1. INTRODUCTION

Interactions between the rotor and flight control systems in high bandwidth helicopters have been investigated from many perspectives. Overall, these interactions impact the vehicle's structural durability, handling qualities and ride characteristics, as well as limit the ability to predict dynamics and performance. Historically, rotor state feedback (RSF) has been applied mechanically in the rotor system design, electronically in digital flight control architectures, and actively through concepts such as active rotor control. Examples of mechanical systems for altering rotor-vehicle control and stability include delta-3, stabilizer bars, and rotor degree-of-freedom couplings. These systems were designed either auxiliary to or as integral parts of the control loop[1]. Significant improvements of helicopter attitude and control instability by rotor based stabilization devices occurred in the 1940's by Young, Stuart III, Miller and Kaman [2, 3, 4]. In the 1970's systems applying rotor and fuselage state feedback specific to hingeless rotor helicopters were applied to the Westland Lynx, Bolkow/Vertol Bo105, Bell Model 609, Lockheed AH-56 Cheyenne and Sikorsky ABC Coaxial concept[1]. The introduction of electronic and digital flight control was a catalyst for producing electromechanical equivalents of rotor mechanical feedback systems. The past 6 decades of rotor state feedback research shows reliance on classical transfer function, mode placement, and modern multivariable strategies wherein classical context (Root Locus Method, Sequential Loop Closure, Proportional-Integral-Derivative) and modern context (Linear Quadratic Regulation, H-Infinity, Eigenstructure Assignment) [5, 6, 7, 8, 9, 10, 11, 12] are applied. The control structures were primarily observer (state estimate) form with some applications of full-state feedback[13]. Based on these strategies, research in flight control law design applying estimated and/or measured rotor states has demonstrated the ability to optimize rotorcraft dynamics and flight performance.

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Ingle et al. and Howitt et al. [8], demonstrated reduced control activity as well as attenuated rotor dynamics responses that can be catalysts in coupled rotor-body interactions with studies of the UH-60 and the DERA/Agusta-Westland hingeless rotor rig, respectively[14]. RSF has been applied for reduction of rotor sensitivity to gusts, as well as control-actuation sensitivity to sensor noise. Briczinski et al., Chen, Takahashi, and Diftler illustrated these findings, based on studies of CH-53 and UH-60 flight dynamics [4, 6, 9, 12]. A large body of research illustrated that RSF allowed heightened closed loop bandwidths, controller robustness to model uncertainty and feedback gain variation, inter-axis decoupling, and control law design process insight.

It has also been shown that control laws designed without rotor dynamics often over-predict feedback gain limits for rotor mode stability. Further, mathematical models without this high frequency content do not represent key dynamics of concern leading to false performance prediction, poorly mapped stability margins, or ineffective control law designs. Research by Ellis, Hall and Bryson, Chen and Hindson, Miller and White, Tischler and Curtiss, and Mullen and Brinson represent 6 decades of research on effects of modeling errors (uncertainty such as neglected rotor dynamics) on high bandwidth flight control law design and performance[13, 4, 3, 14, 11].

Mathematical model structures for incorporating rotor dynamics have been synthesized by many researchers. Important contributions to high order modelling were extended equations of rotor dynamics and model structures with eight or more degrees-of-freedom (DOF) appending these rotor dynamics to base 6-DOF formulations. Talbot et al. and Padfield et al [15, 16] developed extended rotor system equations (i.e.; 2 rotor degrees of freedom). Model structures having more than 8-DOF were developed by researchers such as Mullen et. al., Kaletka et al., Hansen, Blackwell, Talbot and Chen, and Tischler et al. Hui developed an 8-DOF model of the NRC Bell412 ASRA applying Talbot and Chen coupled rotor-body equations [11, 17, 18, 19, 14].

Variable stability helicopters such as the NRC-FRL Bell 412 ASRA and the Bell 205A AS have played key roles in the advancement of modern rotorcraft technology, design requirements, flying/handling qualities, and standards of airworthiness and flight safety[20]. These vehicles enable tailoring of response characteristics over broad frequency ranges to simulate aircraft, flight conditions, and missions. They provide ideal platforms to test and validate rotor state modelling, feedback control, and performance.

The objective of this investigation was to evaluate the impact of measured NRC Bell 412 rotor states and their feedback on multi-variable helicopter control, as well as flying and handling qualities. This paper will provide a scientific overview of the systems, modelling, simulation, and flight test project phases.

2. RESEARCH METHODOLOGY

This applied investigation involved aircraft systems development and integration, modelling, simulation, and flight testing. To investigate rotor state feedback, a rotor state measurement system (RSMS) was developed and integrated into the NRC Bell 412. Prior to testing, a simulation-based study was undertaken to substantiate the impact of rotor state feedback (RSF) on helicopter dynamics, control, and flying/handling qualities. The first phase of the study was the identification of a high-order mathematical model of the NRC Bell 412. Time domain-based system identification synthesized an 8-DOF hybrid model incorporating rigid-body and measured rotor states. The next phase involved a simulation study of rotor state feedback using Classical, Root-Locus, and Eigenstructure Assignment control laws in the Matlab/Simulink environment. Finally, a model-following flight test trial was conducted utilizing ADS-33E-PRF and Cooper Harper handling qualities evaluation metrics.

3. DESCRIPTION OF THE TEST VEHICLES

For this investigation, two variable stability fly-by-wire (FBW) research helicopters were applied in testing. The NRC Bell 412 ASRA was utilized to collect data for aircraft model development, and was the focus of the controller design and desktop simulation exercise. The Bell 205A Airborne Simulator (AS) was utilized to perform in-flight testing of the rotor state feedback concept through model following[20].

Figure 1: NRC-FRL Bell 412 ASRA

The Bell 412 ASRA, as depicted in **Figure 1**, is an airborne research simulator derived from the Bell 412HP helicopter. This aircraft has a soft-inplane main rotor hub featuring high control power and low response time delays. This main rotor consists of a four-bladed fiberglass rotor, two soft-inplane flex-beam yokes, and two elastomeric bearings per blade. Installed in the ASRA is an experimental, single string fly-by-wire control system used for research purposes only. ASRA instrumentation consists of non-rotating (Fuselage) and rotating (Rotor) state measurement systems [20]. As depicted in **Figure 2**, the rotor state measurement system (RSMS) incorporated a rotor-mounted transmitter and a fuselage-mounted receiver linking the rotor and airframe via a radio frequency connection[21].

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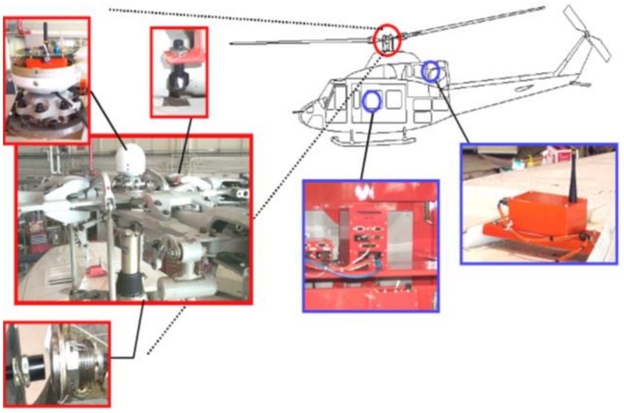


RSMS Weight	20 lbs
Signal to Noise Ratio	30 dB
Sampling Rate	311 Hz
Data Latency	3 ms
RPM Accuracy	1 RPM
Flap Resolution	0.1 mm
Azimuth Accuracy	+/- 0.5 deg
Bandwidth Capability	15 Hz Rotor Dynamics, Flight Control

Figure 2: NRC Rotor State Measurement System

The Flapwise Hall Effect Sensor (HES) is located on the inboard surfaces of the main rotor hub yoke. For Lead-Lag HES installations, the main rotor blade spindle forms key reference and attachment points. A dedicated HES enables measurement of rotor speed and blade azimuth data. A dedicated rotor state computer module (RSCM) performs computation and monitoring tasks. Sample RSMS power spectrum data (**Figure 3)** indicates rotor yoke flap displacement content out to 4 per rev (21.6 Hz) frequencies.

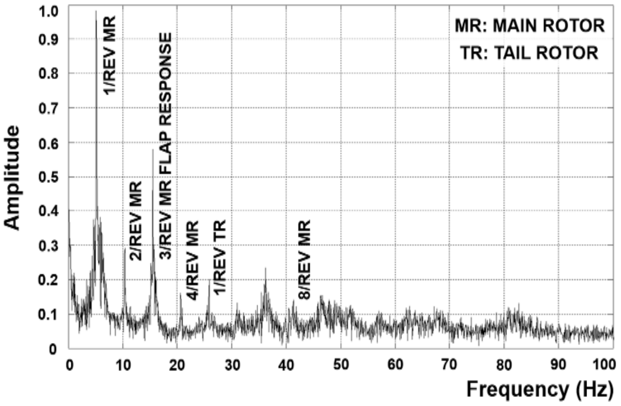


Figure 3: Power Spectrum, Rotor Hub Yoke Flap

The Bell 205A AS (**Figure 4**) teetering rotor hub results in lower bandwidth capability when compared to the hingeless rotor Bell 412 ASRA. Longitudinal and lateral response bandwidth extension is provided by removal of the main rotor stabilizer bar.

Both aircraft possess full-authority simplex FBW systems with electro-hydraulic actuation. The system enables mechanical flight control (by an safety pilot), and electrical control through flight control computer (FCC) processing (by an evaluation pilot)[20].

Figure 4: NRC-FRL Bell 205 AS

4. TIME DOMAIN SYSTEM IDENTIFICATION

A linearly parameterized mathematical model of the Bell 412 ASRA was needed for desk-top and inflight simulation; synthesis requirements [24, 25] included:

1. Range of Validity: Modes of concern for high bandwidth flight control included classical attitude response and regressing rotor modes.
2. Order: Rigid body and rotor state representation was to capture explicit rotor dynamics equations, rotor control response, and angular rate response.
3. Accuracy: Quantification of parameter accuracy in the representation of on- and off-axis response.
4. Fidelity: Time and frequency domain helicopter physics were to be captured.
5. Robustness: Robustness was required for real-time applications that included design point variations (airspeed, turbulence, weight, center-of-gravity, etc.) and digital non-linearities.

4.1. Rotor State Model Synthesis Methodology

Time domain system identification of rotor hub yoke flap dynamics was accomplished by incorporating Bell 412 ASRA flight data in the optimization procedure of the NRC modified version of NASA's Modified Maximum Likelihood Estimation (MMLE3) code[26]. This routine calculates stability and control derivatives by maximizing probable values or a likelihood ratio. Offline MMLE3 iteration validates model structure, data, rotor state equations, and resulting response.

For inflight simulation, coupled rotor/body flap and lead-lag dynamics are necessary for tight command tracking, robustness to disturbances and variations in flight conditions, as well as precise/agile maneuver tracking. These high frequency dynamics occurring out to 30 rad/s (e.g.; for hingeless rotor Bo105 and Bell412) are unattainable by 6-DOF models. These formulations account for rotor dynamics by time delays and absorbing steady state rotor flapping effects into rigid body stability derivatives.

For this project NRC developed an 8-DOF Hybrid Mathematical Model (HMMS) structure (**Figure 5**) to capture attitude modes (Short Period, Dutch Roll, Phugoid, Spiral), coupled rotor/body behaviors (rotor/control, angular rate, rotor to body lead dynamics), and second-order rotor flap dynamics.

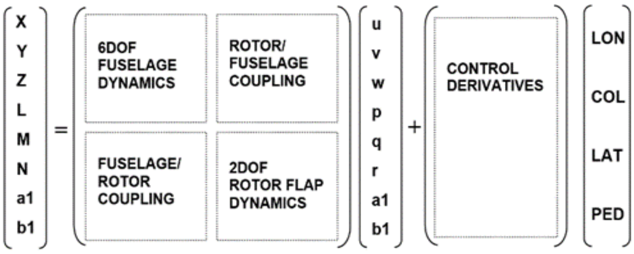


Figure 5: NRC Hybrid Math Model Structure, HMMS

The model was synthesized with NRC's explicit rotor state measurements parameterizing a differential equation defining coupled rotor/ body response. This second-order linearized representation of rotor flap to body attitude-rate dynamics was derived by Chen and Talbot. Research by Kaletka, Von Grunhagen, Tischler and Hui validated these rotor flapping dynamics for the soft-inplane hingeless Bo105 and Bell412 helicopters[17, 14, 18, 16] where the first-order representation is provided by;

$$\begin{bmatrix} \dot{a}_1 \\ \dot{b}_1 \end{bmatrix} + \frac{\Omega}{\frac{\gamma^2}{64}+4} \begin{bmatrix} \frac{\gamma}{4} & \frac{\gamma^2}{64} \\ -\frac{\gamma^2}{64} & \frac{\gamma}{4} \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} - \frac{\Omega}{\frac{\gamma^2}{64}+4} \begin{bmatrix} \frac{\gamma^2}{64} A_1 - \frac{\gamma}{4} B_1 \\ \frac{\gamma}{4} A_1 + \frac{\gamma^2}{64} B_1 \end{bmatrix} + \begin{bmatrix} q \\ p \end{bmatrix} = 0$$

Some key mathematical model inaccuracies and non-linearities to be accounted for in the NRC rotor state feedback flight control law design process include:

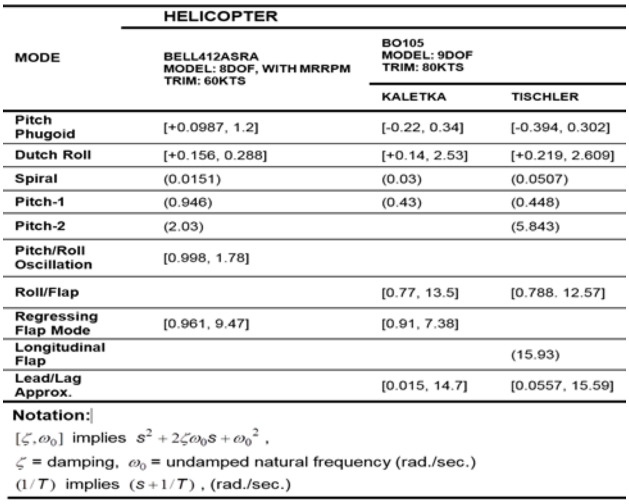
- Neglected dynamics (higher order dynamics such as lead-lag, torsion, engine, and airmass)
- Absent and correlated model derivatives
- Single point and off-blade rotor state sensing
- Linear assumptions in rigid offset hinge modeling
- Single flight condition identification

These aspects predict poor model fidelity in off-axis response and poor robustness to off-design conditions. NRC would apply modern multivariable flight control methods to mitigate poor performance.

4.2. System Identification Results

System identification flight tests were performed in smooth air conditions, at target speed and altitudes of 60 knots and 2500 feet, respectively. Time domain testing by piloted 2-3-1-1 and step inputs were executed in each control axis. Piloted frequency sweeps executed over 0.1 to 3 Hz enabled identification of coupled rotor/body response of the hingeless rotor and high bandwidth actuator system.

MMLE3 optimizations resulted in a 64-stability and 32-control derivative (8-DOF) solution. Modal placements depicted in **Table 1** were compared with published data soft-inplane hingeless rotor data for trend verification[1, 24]. The roll flapping spring derivative, Lb1s, sets the frequency of the hingeless rotor 2nd order coupled roll/flapping mode and the 6-DOF upper limit bandwidth model such that $\zeta_{RF} = \sqrt{Lb1s}$. In the case of the Bell 412 ASRA model, this derivative indicates a limit of some 9.91 rad./sec.



MODE	HELICOPTER		
	BELL412ASRA MODEL: 8DOF, WITH MRRPM TRIM: 60KTS	BO105 MODEL: 9DOF TRIM: 80KTS	
		KALETKA	TISCHLER
Pitch Phugoid	[+0.0987, 1.2]	[-0.22, 0.34]	[-0.394, 0.302]
Dutch Roll	[+0.156, 0.288]	[+0.14, 2.53]	[+0.219, 2.609]
Spiral	(0.0151)	(0.03)	(0.0507)
Pitch-1	(0.946)	(0.43)	(0.448)
Pitch-2	(2.03)		(5.843)
Pitch/Roll Oscillation	[0.998, 1.78]		
Roll/Flap		[0.77, 13.5]	[0.788. 12.57]
Regressing Flap Mode	[0.961, 9.47]	[0.91, 7.38]	
Longitudinal Flap			(15.93)
Lead/Lag Approx.		[0.015, 14.7]	[0.0557, 15.59]

Notation:

$[\zeta, \omega_0]$ implies $s^2 + 2\zeta\omega_0 s + \omega_0{}^2$,

ζ = damping, ω_0 = undamped natural frequency (rad./sec.)

$(1/T)$ implies $(s + 1/T)$, (rad./sec.)

Table 1: Soft-Inplane Hingeless Modal Comparisons, NRC Bell412 8-DOF and Bo105 9-DOF

Time constants indicate rotor to rigid body time frame response due to pilot control. During model development, the longitudinal flap time constant was τ_{a1s} = 0.04s. The roll-flap damping ratio was 134.9% by the roll damping and the rotor flap time constant by $\zeta_{RF} = \sqrt{-(1/(4L_p\tau_F))}$. Overall, in magnitude, this indicates highly damped rotor flap dynamics of the Bell 412 ASRA at the 60knot design point. The roll and pitch flapping spring ratio, which determines the helicopter's ratio of pitch and roll moment of inertia, is 1.2345 given by |Lb1s/Mb1s|. The pitch response couplings, |Mp/Mq| and |Mp/Lp|, and roll response couplings, |Lq/Mq| and |Lq/Lp|, which are typically large for helicopters, have null values for the Bell 412 ASRA as defined by the HMMS model where the Lq, Mp, and Mq derivatives are absent. Their effects are incorporated explicitly by rotor flap dynamics equations and measurements. The pitch spring constant to roll spring constant defines the ratio of the helicopter's pitch to roll inertia, which is typically on the order of 3.0. Inertias for the Bell 412 ASRA are I_{xx}=15,027,800 lbin^2 and I_{yy}=67,080,400 lbin^2 at an aircraft weight of 7428.4lb giving a ratio of 4.464. Further then, the pitch spring constant Ma1s should be 1/3 of the roll spring Lb1s; for the Bell 412 ASRA however, this ratio is 0.81. The lateral flapping spring constant Kb1s, is 0.001844 by |LδLat/Lb1s|. The off-axis control responses in roll, |LδLon/LδLat|, and pitch, |MδLon/MδLat|, are both significant (1.1562, 0.8086), indicating highly coupled, high workload, bare-airframe flying characteristics. The pitch control to collective and longitudinal stick control couple, |MδCol/MδLon|, is moderate (0.4926), indicating high collective to longitudinal cyclic coupling.

In summary, these trends are valid for hingeless rotor dynamics and therefore the HMMS had its fidelity band-limited to 2Hz (12.6 rad/sec.), just beyond the rotor flap regressive mode. The 8-DOF model was cleared for flight control design and inflight testing of rotor state feedback based on flapping dynamics.

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5. FLIGHT CONTROL DESIGN PROCESS

The flight control law design process featured both classical and modern multivariable methods. Use of the 8-DOF model described in previous section allowed for designs incorporating rotor state feedback to be readily tested using desktop simulation.

5.1. Control Law Design Requirements

A subset of ADS-33-E-PRF[22] and ADS-33C[23] forward flight requirements for Target Acquisition and Tracking (TA+T) were used as performance specifications for flight control laws. The design point was a 60-knot forward flight condition with an Attitude Command Attitude Hold (ACAH) response type. ACAH response develops a vehicle attitude proportional to cyclic control deflection force. This allows the pilot to manage flight path of the aircraft without having to also provide attitude stabilization.

Using vehicle rate and attitude gyro sensors, ACAH is useful in Instrument Flight Rules (IFR) flight conditions where useable environmental cues are low. The system frequency is selected based on the desired vehicle output response. The set of flight control design requirements included [22, 23, 24, 25]:

i. Fidelity-Robustness: To evaluate the model fidelity and robustness to the flight control effort. Minimal changes should be required to implement controllers in flight test and feedback should effect designed control action with good model following over an off-design margin.

ii. Disturbance Rejection: To evaluate rotor state feedback in rejection of gust induced attitude-rate and signal noise induced control-actuation dynamics.

iii. Mode Placement: To ensure stable mode location, trajectory, and interactions as applied to both rigid-body and rotor state modes. (Specs. Rigid-Body 3.3.2; ADS33C)

iv. Attitude Bandwidth and Phase Delay: To ensure input control response over closed loop system bandwidth with moderate input frequencies, bandwidths, and phase delays are bound. This is defined for pitch, roll, and yaw attitude response. (Specs. 3.4.1.1, 3.4.6.1, 3.4.8.1; ADS33EPRF)

v. Control Power: To attain required attitude rates and vertical axis response for TA+T task maneuverability and agility. Requirements are based on large amplitude attitude change, vertical axis velocity, and rotor disc tilt due to longitudinal control response.

vi. Axis Decoupling: To ensure pitch, roll yaw, and heave dynamics afford low pilot workload. This is defined for forward flight pitch-to-roll and roll-to-pitch coupling, and hover/low-speed yaw response to collective. (Specs. 3.3.9.1, 3.4.5.4; ADS33EPRF)

5.2. Mathematical and Simulation Modeling

State space, transfer function, and linear and non-linear simulation models were used throughout this investigation to predict helicopter performance due to rotor state feedback applied in real-time. The 8-DOF HMMS mathematical model used as the baseline for flight control law design represents the Bell 412 ASRA at a forward flight (60 knot) and constant rotor speed (Ω=324RPM) condition. The fuselage is modeled as a rigid body with attitude-rates (q, p, r) and attitude-angles (θ, ϕ, ψ) used for fuselage state feedback. The parameters used for rotor state feedback are longitudinal (a1) and lateral (b1) disc-tilt dynamics, describing the tip-path-plane. The rotor state measurement system was calibrated to compute longitudinal and lateral disc tilt using data from Hall Effect Sensors (HES) mounted on the ASRA hub main rotor hub yoke flexures. At the time of the experiment, these quantities were calibrated in millimeters (mm). of deflection at the measurement point. Although this quantity is proportional to disk tilt angle, the exact relationship had not yet been determined. As such, the model was identified so that the disk tilt quantities were also in millimeters. Torsional and lead-lag rotor dynamics, as well as rotor inflow were not modeled. In order to retain model non-singularity, no poles or perfect integrators could be present, thus eliminating the heading state. In this research, experimentation with a heading hold system with turn coordination was performed in desk-top simulation studies only.

NRC Bell 412 ASRA actuation system modeling is unconventional in that its variable stability fly-by-wire (FBW) installation includes both the standard Bell412HP mechanical servos and the ASRA FBW actuators. These dynamics are modeled by a servo-actuator system consisting of eight, second-order transfer functions. ASRA flight dynamics were simulated in a nonlinear simulation. Actuator subsystem, state-feedback control loop, trim settings, disturbance injection subsystem, and non-linearity dynamics were integrated in a Matlab/Simulink based flight control development environment (FCDE).

5.3. Classical Single-Input/Single Output Control Study of Rotor State Dynamics: Root Locus Method (RLM)

The benefits of incorporating rotor states in mathematical models and feeding back measured rotor states in control laws were investigated by both reduced order and closed loop control simulations. With respect to rotor state feedback, theoretical studies as shown in **Figure 6** suggested that for constant rigid-body attitude-rate to attitude gain ratio (e.g.; K_q/K_θ = 0.5), increasing rotor state feedback gain increases the ability to attain cross-over frequency and bandwidth. This applied within bounds of stability and given phase delay (τ_e) accrued in implementation of the flight control system.

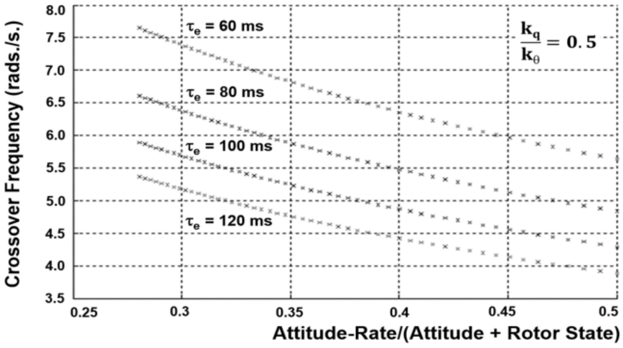


Figure 6: Cross-Over Frequency Variation due to Combined Rigid-Body/Rotor State Gain Ratio

With respect to understanding the effects of the presence of rotor state dynamics in model structures, single-input/single output root locus method (RLM) control theory was used[27]. This methodology analyzed response of closed loop characteristic transfer functions, **$G_{TF}(s)$**, due to rigid body gain variation (i.e. compensator gain – **H(s)**) in the presence of measured rotor states. RLM determines stability by investigating whether the return difference, **$1+G_{TF}(s)H(s)$**, of a feedback loop becomes zero for any value of s in the positive s-plane. The RLM closed loop feedback control structure is shown in **Figure 7**.

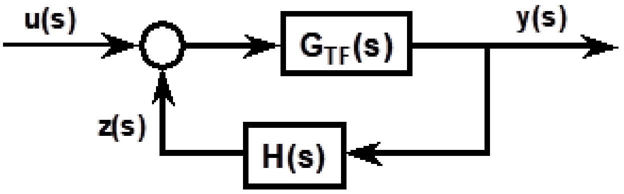


Figure 7: RLM Feedback Control Structure

Trajectory of the locus of the each of the roots of the return difference function (pole trajectory) was used to evaluate stability margins.

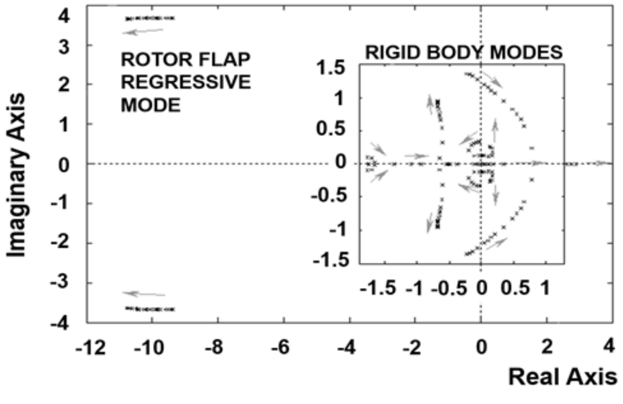


Figure 8: RLM Root Locus Pole Trajectories

Applying pitch and roll axis feedback gains, with and without rotor states in the characteristic transfer functions, produced bandwidth ranges and ADS33E-PRF compliances. A sample lateral axis root locus is presented in **Figure 8** based on a 10th order transfer function defining open loop rigid body and rotor lateral disc tilt dynamics.

Positive roll rate feedback stabilizes rotor flap regressive mode (with Dutch Roll as a limiting mode) while negative feedback destabilizes the flap regressive mode (with Phugoid and Spiral as limiting modes). Several important conclusions were drawn from this design exercise:

i. RLM control did not address implications of phase delay and latency induced in control actuation. Compliance results also indicate overly aggressive gains such that several bandwidths would be unattainable by the Bell 412 ASRA.
ii. At specific gain ratios, either solely based on rigid body dynamics or incorporating rotor state dynamics, limits were placed on attainable crossover frequency and bandwidth.
iii. The existence of response correlation between rotor disc tilt and rigid body dynamics in both on- and off-axis forms provide significant influences of rigid-body attitude rate feedback on off-axis rotor flap mode dynamics.
iv. Alteration of gain may allow attainment of bandwidth-frequency requirements, however, system stability is not assured.

5.4. Classical Multivariable Control Study of Rotor State Dynamics and Feedback (CMC)

For more accurate analyses, classical multivariable control (CMC) theory[28] was used to investigate coupled rotor-body response by combined rotor and rigid body feedback. Here, control laws were synthesized in the non-linear FCDE with requirements for attaining the second order ACAH response type. The ACAH response was achieved by relating open and closed loop crossover frequency, phase margin, effective vehicular time delay and gain values using design methodologies by Tischler and NRC-FRL Rotary-Wing Flight Controls Group[24,25]. Referencing ADS-33E-PRF criterion the desired pitch, roll, and yaw bandwidths are 2 - 4 rad./sec, 2.5 - 6 rad./sec., and 3.5 - 6 rad./sec. respectively[22]. The stabilization crossover frequency and characteristic bandwidth for ACAH are typically based on 3 - 6 rad./s. and 2 - 4 rad./s., respectively. Once a baseline controller was developed, rotor state gains were tuned to evaluate benefits such as bandwidth attainment, attitude capture accuracy, axis decoupling, and disturbance rejection. The CMC control structure as depicted in **Figure 9**, includes the command model – **δ_{COM}**, vehicular state space – **$G_{SS}(s)$**, and rigid-body and rotor state gains – **K_{CMC}**.

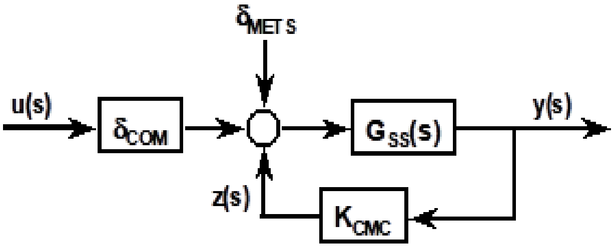


Figure 9: CMC Feedback Control Structure

Emulation of signal noise in the form of a turbulence model developed by Tischler et al. was introduced to assess the effects of rotor state feedback on disturbance rejection[29]. The parameters of the Mixer Equivalent Turbulence Simulation (METS) model were applied to the Bell 412 ASRA actuation control block. This model (δ_{METS}) was injected at the control actuators (mixer or swashplate).

Overall, the CMC methodology tended to produce non-optimal controllers. **Figure 10** illustrates CMC controller compliance with ADS-33E-PRF. The effects of longitudinal and lateral disc tilt feedbacks were to drive vehicle response to the Level 3 region. This was due to the controller's heightened phase delay and lack of translational velocity components in the gain structure leading to poor control of rotor-body mode interactions.

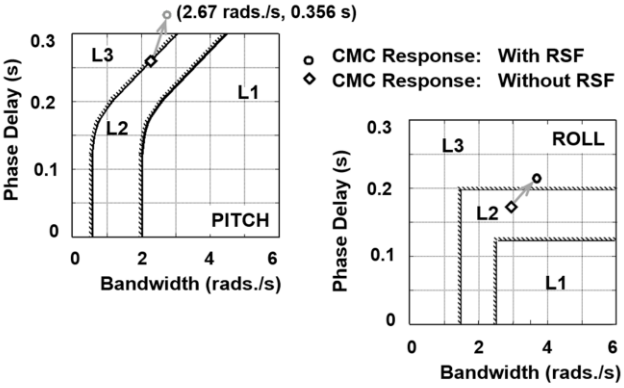


Figure 10: ADS33EPRF Compliance:
CMC Controller with and without RSF

As well as Level 3 handing qualities compliances demonstrated, the CMC controllers demonstrated poor turbulence rejection with instances of response magnification, lack improvement in attitude capture tasks, and mode alterations causing undesirable on- and off-axis coupled rotor-body response.

In summary, CMC was not effective helicopter modal control as well as lacked tuning and design insight.

5.5. Modern Multivariable Control Studies of Rotor State Dynamics and Feedback

Eigenstructure Assignment Control (EAC) theory [11] was applied in the development of a flight control system for the Bell 412 ASRA. This direct (non-iterative) procedure computed the state feedback controller, achieved eigenvalue vector, and the eigenvector matrix, for a system given a desired unitary eigenvector matrix. The initial desired eigenstructures were derived from ADS-33 specifications for the TA+T mission, as originally developed by Ingle[30]. First order system estimates of desired pole locations for pitch, roll, and yaw were set equivalent to the specification bandwidth. The Level 1 boundaries of ADS-33EPRF specifications set roll, pitch, yaw, and heave bounds at 4.0, 4.0, 5.0, and 3.5 rads./sec., respectively. The forward and lateral velocity poles remained at their fixed open loop values to assist in forward-lateral velocity as well as roll-pitch dynamics correlation. Optimization of the response and application of rotor state feedback from this design point was achieved by manual pole migration (including those of rotor states) and application of rotor state gains. The EAC control structure as depicted in **Figure 11**, includes the command model – δ_{COM}, disturbance model – δ_{METS}, vehicular state space – **$G_{SS}(s)$**, and rigid-body and rotor state gain – **K_{EAC}**. The full state feedback structure eliminated requirement for the decoupling matrix – δ_N, and by application of explicit rotor state measurements, the state estimator – **$L(s)$**.

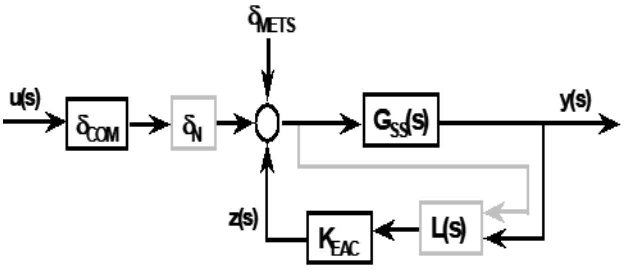


Figure 11: EAC Control Structure

Overall, the EAC methodology produced optimal controllers. This method clearly demonstrated that modal control is an important feature required to meet modern design requirements of coupled rotor-body stability and performance in the presence of rotor states and their feedback.

5.5.1. Bandwidth Attainment

To investigate the effects of an EAC controller with rotor state feedback on rigid-body bandwidth performance, an EAC controller applying single-axis rotor state feedback was synthesized. Rotor state feedback gains are calibrated in inches of control to millimeters of disc tilt (in./mm.). For this simulation, pitch bandwidth was improved by 42.5% while the roll by 54.4 %. As depicted in **Figure 12**, the effects of rotor state feedback increased bandwidth and thus drove the rigid-body dynamics into Level 1, TA+T ADS-33 mission compliance for pitch and roll axes. Overall, EAC control design was intuitive and produced compliances that remained in Level 1 bounds.

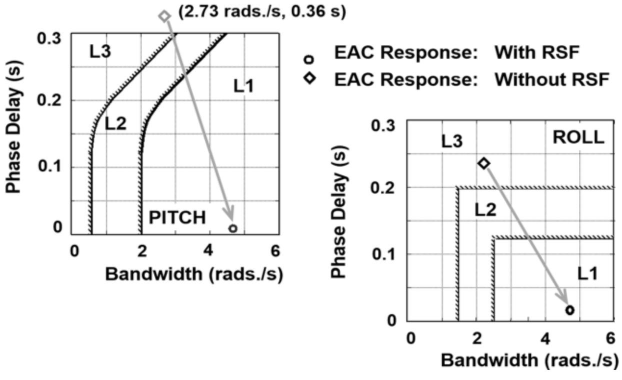


Figure 12: ADS33EPRF Compliance (Pitch, Roll):
EAC Controller with and without RSF

5.5.2. Attitude Capture Accuracy

High bandwidth variable stability research requires control systems capable of tightly tracking pilot or flight control computer generated commands. EAC control tracking of a 5 degree pitch attitude hold design objective is depicted in **Figure 13**. Here, a first order command model as well as longitudinal and lateral disc tilt feedbacks resulted in excellent tracking. Multiple objective benefits of rotor state feedback are evident in tracking performance including more optimal control usage, reduced rotor disc displacement, and reduced axis coupling.

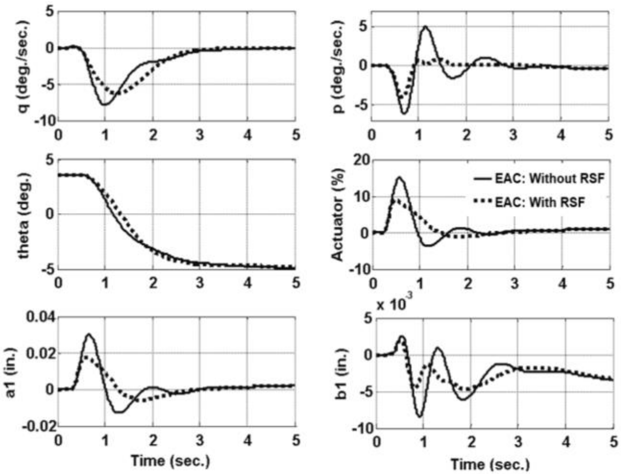


Figure 13: EAC Feedback - Attitude Capture Task

5.5.3. Axis Decoupling

The reduction of pilot workload by axis decoupling is one method of improving helicopter handling qualities for attainment of mission tasks. The application of measured on-axis longitudinal and lateral disc tilt feedback was effective in decoupling both the pitch due to lateral cyclic and roll due to longitudinal cyclic interaction as shown in **Figure 14.**

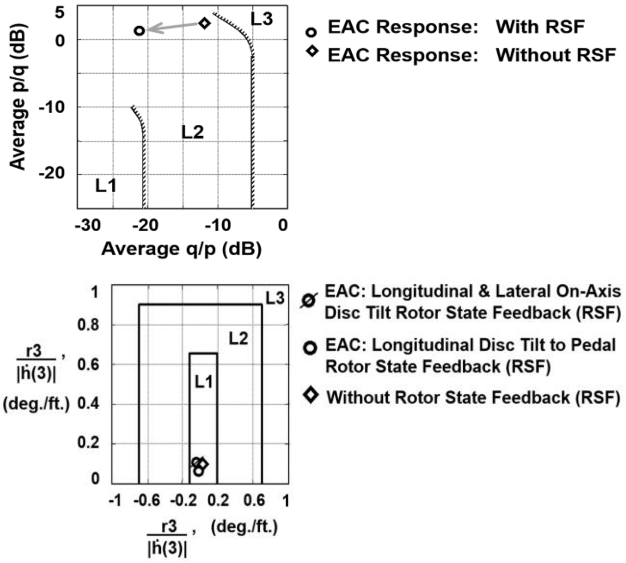


Figure 14: ADS33EPRF Compliance – EAC Controller Response, Pitch-Roll and Roll-Pitch Coupling (Top); Yaw to Collective Coupling (Bottom)

5.5.4. Disturbance Rejection

The longitudinal control axis component of the METS disturbance model was injected into the simulation with pilot controls trimmed. As depicted in **Figure 15**, the presence of rotor state feedback promoted peak-to-peak attenuation of the disturbances in all axes in both vehicle and actuator activity. The rotor states applied in this case were an on-axis longitudinal disc tilt gain and on-axis lateral disc tilt gain.

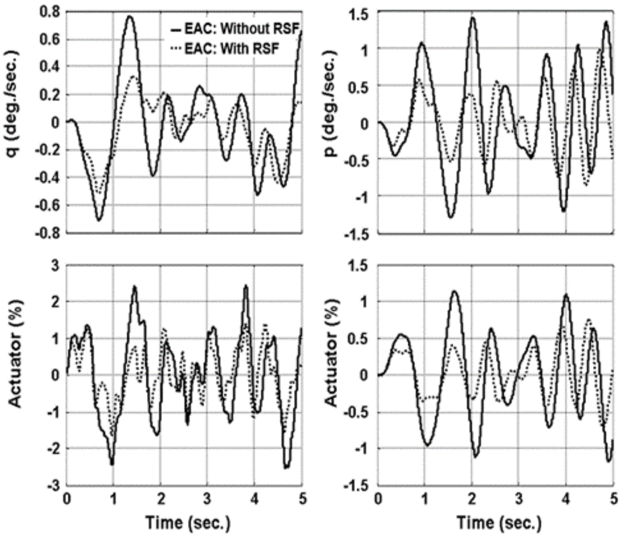


Figure 15: EAC Signal Noise Rejection due to Rotor State Feedback, (Rigid-Body, Actuation)

The analysis resulted in reductions of 47%, 49%, and 40%, in pitch, roll, and yaw rates, respectively. Reductions in actuator activity are shown to be 52%, 63%, and 22% for the same respective axes. This attenuation extends to rotor hub yoke activity as shown in **Figure 16** that correlates to the reduction in rotor flap displacement. The reductions demonstrated are 58% and 52% in longitudinal and lateral disc tilt response, respectively.

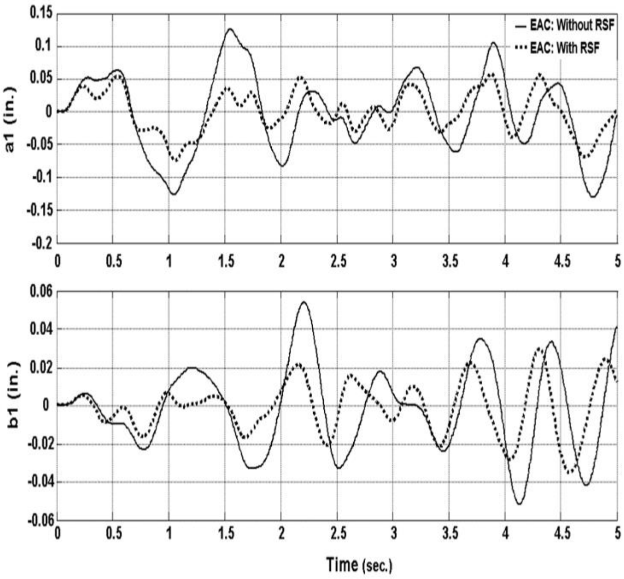


Figure 16: EAC Signal Noise Rejection due to Rotor State Feedback, (Rotor Dynamics)

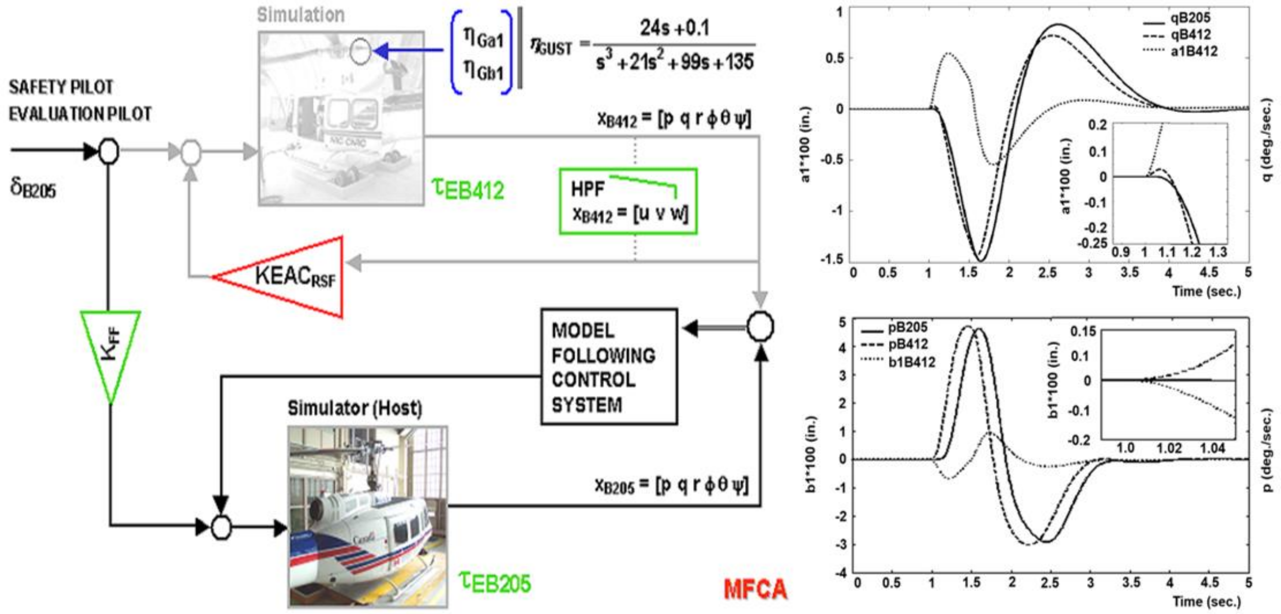


Figure 17: Model Following Control Architecture (MFCA) with EAC Controller, (Right: Coupled Rotor-Body Responses without RSF; (Top) Due to a Longitudinal Pulse, (Bottom) Due to a Lateral Pulse))

6. FLIGHT TEST EVALUATIONS OF ROTOR STATE FEEDBACK

The purpose of the flight evaluation was to test the effectiveness of rotor state feedback (RSF) in the attainment of handling qualities, performance, and disturbance rejection objectives in a realistic flight environment. Due to delays in the development of FBW systems and RSMS technologies on the Bell 412 Advanced Systems Research Aircraft (ASRA) at the time, it was decided to implement the controller on the Bell 205A Airborne Simulator (AS). This model following concept required the host Bell 205A AS to emulate the dynamics of the Bell 412 ASRA in flight based on the rigid body dynamics resulting from the feedback of rotor states. The flight test program consisted of airworthiness trials (ground testing; flight clearance) and 4 flight hours of RSF control law investigation.

6.1. Description of the Real-Time Flight Control Architecture

The model following flight control architecture (MFCA) as shown in **Figure 17** comprises:

i. Helicopter State Dynamics: Bell412 ASRA (8DOF), Bell 205A AS (6-DOF)

ii. Feedback System Dynamics: Bell205A AS Mixed Rate Signal, Rotor State Feedback Control Gains

iii. Feed-forward System Dynamics: Input and Actuation Dynamics

iv. Nonlinearities: Turbulence Model, Filters, Latencies, etc.

The functionality of the MFCA utilized control inputs from the evaluation pilot to provide feed forward commands for the RSF control law. Using the control input and feedback response from the Bell 412 ASRA model, the MFCA computed model following states. These states were subtracted from measured Bell 205A AS states to create actuator commands. Bell 412 ASRA model states that were not model followed were high-pass filtered to prevent their divergence (i.e.; conflicts, divergences, disengagements) of the in-flight simulation.

A turbulence model was implemented by application of an analytical identification of power spectrum (PSD) data from a 1990 study by Baillie and Morgan[31]. This study of Bell 205A AS atmospheric disturbance and bandwidth research resulted in identified third order transfer functions. Implemented in the Bell 205A AS and shown in **Figure 17**, these functions emulate a band pass filter with a peak frequency at –11.6 dB and 2.89 rad./sec. Applying this transfer function to the Bell 412 ASRA simulation resulted in the development of theoretical pitch and roll disturbance dynamics that would be used to evaluate RSF in gust rejection, ride qualities, and handling qualities tasks. The developmental assumptions of the turbulence model were based on the equivalent size of the Bell 412 ASRA and Bell 205A AS, that RSF by longitudinal and lateral disc tilt feedbacks required primarily pitch and roll turbulence emulation, and that this turbulence coincided with response correlation between rigid-body and rotor disc tilt dynamics.

Other parameters such as control system gearing or sensitivity, force-feel stick characteristics, the filtering type, and model following gains were coded into the Bell 205 A AS pilot interfaces for in-flight tuning. With this flight control configuration, the evaluation pilot had the opportunity to evaluate the controllers with and without rotor state feedback, with and without active turbulence, and the raw Bell 412 ASRA simulation in a single flight.

6.2. Description of Test Facilities

Flight testing was performed at NRC-FRL Facilities in Ottawa, Ontario (Canada). As depicted in Figure 18, two test sites including NRC-FRL Low Speed Test Area and McDonald Cartier International Airport (CYOW) Runway 25.

Figure 18: RSF Test Sites (a. CYOW Runway 25, b. NRC Low Speed Test Area)

The Eigenstructure Assignment Control (EAC) law was selected for RSF flight trials. No anomalies were detected during airworthiness ground tests, which ensured that the control laws were correctly coded and implemented. Airworthiness flight tests did not indicates technical issues and validated that the model following control laws were stable. During this phase, pilots set baseline gain levels, sensitivities, and force-feel inceptor characteristics. RSF flight engagements were graded by quantitative (ADS-33E-PRF) and qualitative (Copper Harper Rating Scale) metrics. Target Acquisition and Tracking (TA+T) Slalom and Roll Attitude Capture mission task elements were selected for the trials with flight test conditions summarized in **Table 2**.

Aircrew	**Pilots :** Carignan; Leslie **FTE :** Ellis; Gubbels
Mission Task Elements (ADS-33EPRF)	1. Slalom 2. Roll Attitude Capture
Weather, Useable Cueing Environment	- Light winds, - No turbulence, - UCE (Visibility 15 statute mi.)
Off-Design Points	Speed (±20 knots), Altitude (+4000 feet)
Control Law	MFCA with EAC-based RSF

Table 2: Summary, Flight Test Evaluation Conditions

The flight test evaluation of rotor state feedback control (RSF) successfully demonstrated the attainment of multiple mission enhancing helicopter performance objectives as presented in the following discussions.

6.3. Initial Response Correlation

The objective of the MFCA flight evaluation was to have the Bell 205A AS emulate rigid body rates and attitudes of the Bell412 ASRA due to its simulated rotor state feedback. As depicted in **Figure 17** with rotor response scaled by a factor of 100, due to longitudinal and lateral pulses, the ASRA's rotor state responses correctly lead rigid-body responses. In the roll axis, the rotor disc reacts in a similar time frame as the rigid body dynamics. In flight test, the lower bandwidth teetering rotor is evident in the comparison of lagged attitude-rate peaks as shown in **Figure 19**.

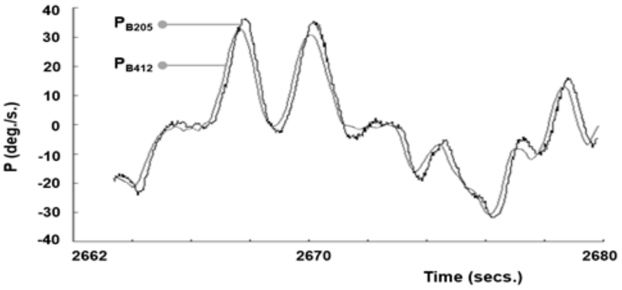


Figure 19: Roll Rate Response – Slalom Event, With Turbulence & Rotor State Feedback

Here teetering rotor response to roll rate peaks are more than that required for the hingeless rotor Bell 412. The hingeless rotor flap response is similar in magnitude to the teetering hub, however the latter does not produce a hub moment and can accelerate rigid-body dynamics faster than teetering designs. Bell 205 rigid-body response matches the ASRA's maximum roll rate with an elevated time constant.

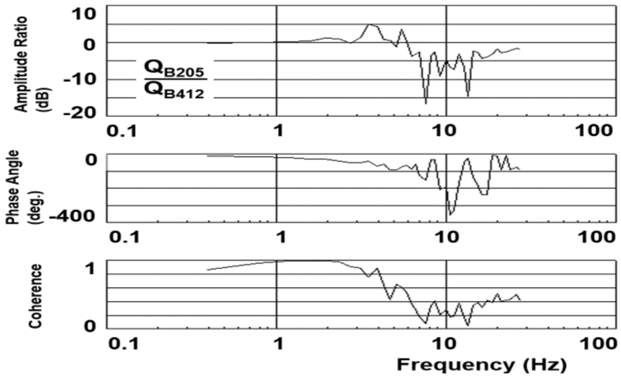


Figure 20: Bell 205A AS Model Following Limits Pitch-Axis, With Rotor State Feedback

Model following bandwidth limits without rotor state feedback are illustrated by resonant peaks in frequency magnitudes and phase roll-off under frequency responses with good signal coherence. Typically, coherences of greater than 0.8 are used in system identification and controls research to establish signal quality. Without rotor state feedback the limits identified in flight were 4.0 rad./sec. and 3.5 rad./sec. in pitch and roll, respectively. In the presence of rotor state feedback, only limits in pitch were curtailed to 3.6 rad./sec (**Figure 25**). These results validate the MFCA control architecture.

Comparing MFCA prediction to flight test results (**Figure 21**), the bandwidths of Bell 412 ASRA RSF_OFF cases were higher than RSF_ON cases for either the pitch or roll axes; the same trend held for the host aircraft, the Bell 205A AS. Some large deviations in prediction to flight test results were found without rotor state feedback. In the roll axis the Bell 205A AS flight test points in Level 2 and Level 3 bounds suggested poor control law tuning. This was confirmed by pilots who reported minor deficiencies in handling qualities with or without rotor state feedback engaged.

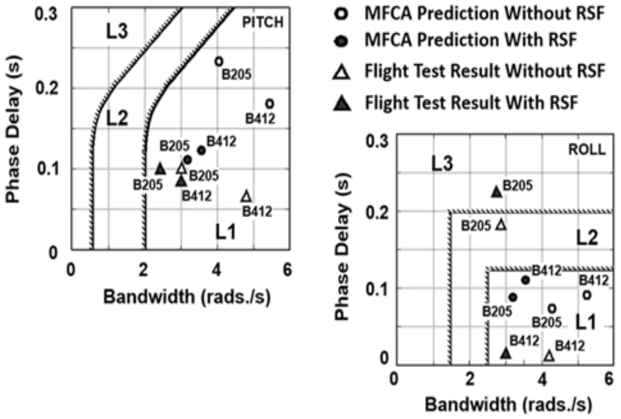


Figure 21: ADS33EPRF Compliance (TA+T Short Term Response) – Validation of MFCA Bell205 AS and Bell412 ASRA Desk-Top and Flight Test Results

From these results it was judged that the quality of the model following was suitable for handling qualities assessment of the rotor state feedback controllers.

6.4. Bandwidth Attainment

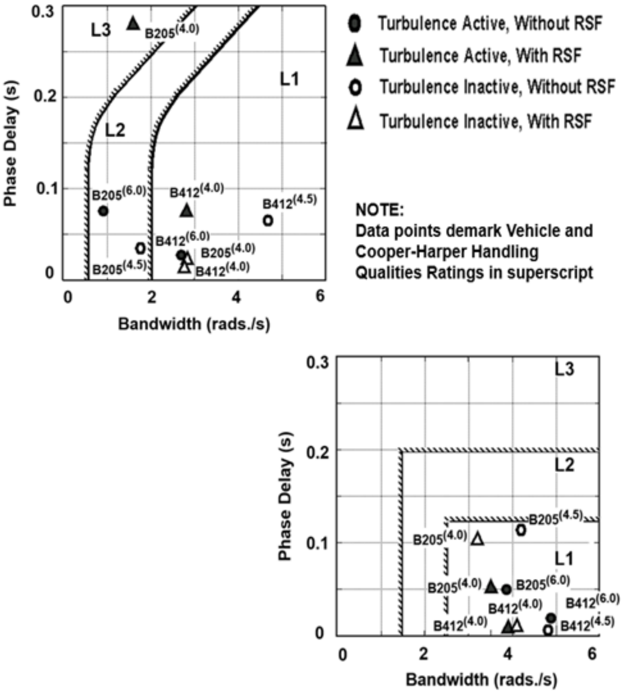
The handling qualities flight test evaluation of rotor state feedback subject to turbulence (slalom mission task) is presented in **Table 3** and in **Figure 22**.

AXIS	ACHIEVED BANDWIDTH (BW) PERFORMANCE FLIGHT TEST POINT: SLALOM HANDLING QUALITIES ASSESSMENT							
	CASE: WITHOUT TURBULENCE ENGAGED							
	BELL205 BW$_{NRSF}$ (rad./sec.)	RATING	BELL412 BW$_{NRSF}$ (rad./sec.)	RATING	BELL205 BW$_{RSF}$ (rad./sec.)	RATING	BELL412 BW$_{RSF}$ (rad./sec.)	RATING
PITCH	1.8	L3	4.6	L1	2.9	L1	2.8	L1
ROLL	4.1	L1	4.9	L1	3.2	L1	4.0	L1
	CASE: WITH TURBULENCE ENGAGED							
AXIS	BELL205 BW$_{NRSF}$ (rad./sec.)	RATING	BELL412 BW$_{NRSF}$ (rad./sec.)	RATING	BELL205 BW$_{RSF}$ (rad./sec.)	RATING	BELL412 BW$_{RSF}$ (rad./sec.)	RATING
PITCH	0.98	L2	2.8	L1	1.7	L2	2.9	L1
ROLL	3.9	L1	4.9	L1	3.5	L1	4.0	L1

Notation:
NRSF = **Without** Rotor State Feedback
RSF = **With** Rotor State Feedback
L1, L2, L3 = Level 1, Level 2, Level 3, with respect to ADS-33EPRF Compliance

Table 3: Summary of EAC Flight Test Bandwidth Performance – Slalom Handling Qualities Task

Assessments of Slalom and Target Acquisition and Tracking (TA+T) maneuvers do not correlate in terms of piloted flight dynamics mainly due to level of accuracy and aggression applied. Also, the interpretation of bandwidth in the presence of turbulence is clouded by low control-response coherence. However, the analysis is performed such that qualitative pilot Handling Qualities Ratings (HQR) are assessments of Aircraft Performance and of Workload Required to achieve Mission Tasks.



NOTE:
Data points demark Vehicle and Cooper-Harper Handling Qualities Ratings in superscript

Figure 22: ADS33EPRF Compliance (TA+T Short Term Response) – Bell205 AS and Bell412 ASRA Pitch and Roll Compliances due to Combined RSF and Turbulence

The depicted pitch and roll compliances were generally very good with the exception of several out-lying points again associated with the Bell 205A AS. Results indicate that in roll, the pilot evaluated the Bell 205A AS with better handling qualities for lower bandwidth configurations whether RSF_ON with TURBULENCE_ON or RSF_OFF with TURBULENCE_OFF cases. The best ratings were assessed for the RSF_ON with or without turbulence. The worst rating was assessed for the TURBULENCE_ON case without rotor state feedback. The pitch axis results show that the host aircraft was assessed to have better handling qualities at higher bandwidths. The best HQR applied to the RSF_ON case without turbulence and the worst to RSF_OFF with turbulence.

Overall the results suggest that pilots were very sensitive to changes in phase delay associated with EAC rotor state feedback. In pitch, increases in phase delay were associated with higher HQR's and lower handling qualities levels; in roll the opposite trend was evaluated for increases in phase delay.

6.5. Attitude Capture

For a roll-attitude capture task, the evaluation pilot reported that the RSF_OFF case provided improved attitude capture (with ±3° roll- and ±1° pitch-attitude excursion) than the RSF_ON case (with ±5° roll- and ±1° pitch-attitude excursion). This was due to some instability caused by the controller when engaged. This contradicts simulation results where both attitude capture on- and off-axis performances were substantially improved over baseline control. The instability as shown in **Figure 23** is characterized by on- and off-axis attitude oscillation.

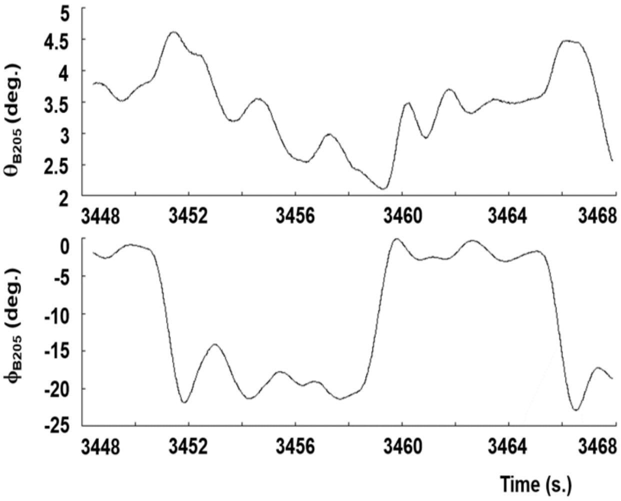


Figure 23: Bell205A AS Attitude Capture – Case: RSF_ON without turbulence

The instability is believed to correlate with a mode interaction. The decaying nature of oscillation points to an excessive bandwidth condition, a coupled-rotor-body response, or a biodynamic instability.

This latter point is important since the pilots were under high workload (i.e.; low level flight in an active airport traffic pattern), using position-sensing inceptors, and adjusting control sensitivities to perform experimental mission tasks.

6.6. Axis Decoupling

The evaluation pilot reported no pitch-roll coupling events in either RSF_ON or RSF_OFF modes, for all turbulence and maneuver conditions. Several important findings with respect to rotor state feedback and axis decoupling in the presence of atmospheric turbulence are supported by results in **Figure 24**.

Turbulence produces lower coherence between pilot input and vehicle response. In terms of phase response the RSF_ON with turbulence case in **Figure 24**, illustrates how RSF in roll-to-pitch maintains phase correlation with controlled dynamics.

Further, in terms of response coherence, it is also illustrated that RSF develops substantially lower response coherence between control and rigid-body while maintaining this phase information in the presence of turbulence.

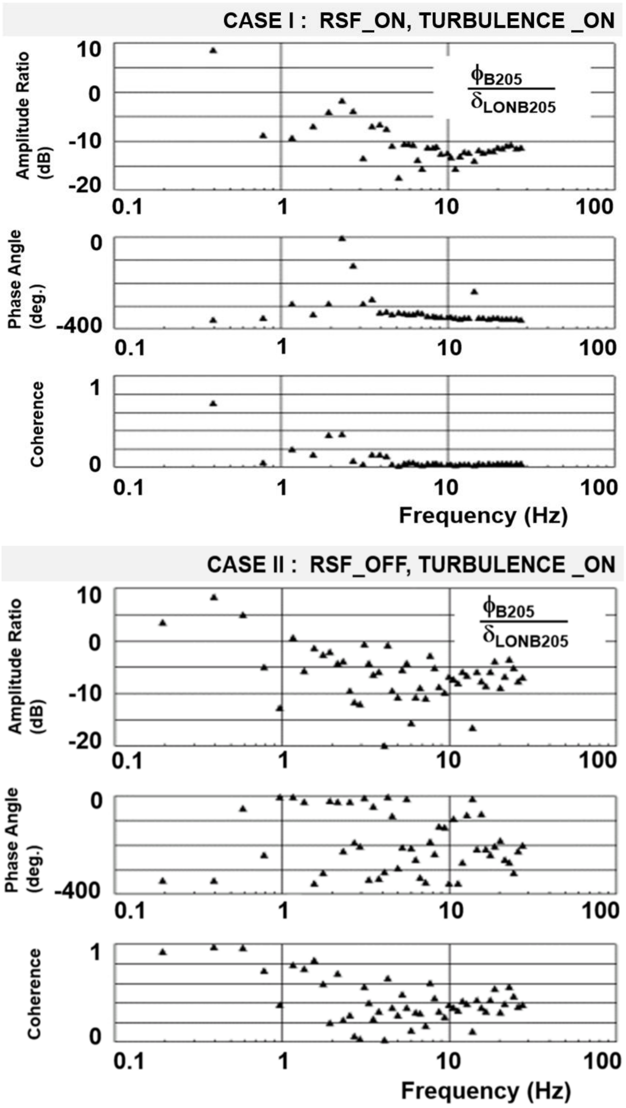


Figure 24: Bell205A AS Response Couplings – Roll to Longitudinal Cyclic – Cases: RSF_ON, RSF_OFF with turbulence

This combined decoupling and disturbance rejection effect by rotor state feedback control is of critical importance for mission task performance for several reasons. Firstly, the host Bell 205A AS was emulating a more coupled hingeless rotor helicopter. And secondly, axis coupling would have rendered mission tasks unattainable given the pilots' level of divided attention and flight control workload due to turbulence.

6.7. Vehicular Disturbance Rejection

The disturbance rejection results were compelling in demonstration of the effects of RSF in both attenuation of rigid-body excursions in the host Bell 205A AS and rotor response excursions in the simulated Bell 412 ASRA due to as disturbances induced by the MFCA. As shown in **Figure 25**, in transient response, the simulated turbulence through lateral disc tilt response is introduced at 920 seconds of the event by the pilot.

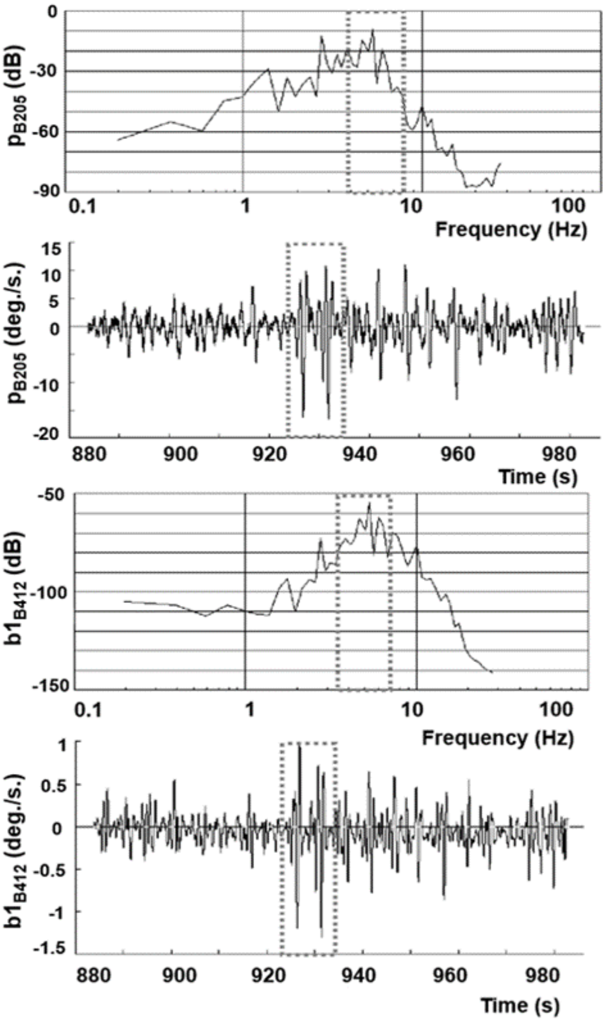
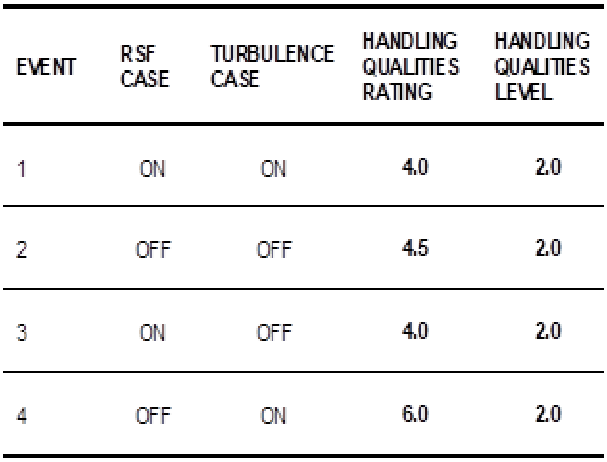


Figure 25: NRC Bell 205A AS and Bell 412 ASRA Turbulence Characterization, Roll Axis

The turbulence peaks highlighted in **Figure 25** correlate between Bell 412 ASRA rotor response and Bell 205A AS rigid body response. Comparatively, the Bell 412 lateral rotor hub yoke response and Bell 205 rigid-body roll attitude-rate excitations appear at 5.5 rads./sec. In transient response, these excitations produce peak-to-peak lateral rotor hub yoke displacements of 1.7 mm. and roll attitude-rate excursions of 22 degs./sec.

During flight engagements with slalom maneuvers the pilots commented that there was significant reduction in disturbance activity felt during the execution of the mission task when rotor state feedback was engaged. The evaluation pilot reported this attenuation as a striking 5:1 reduction in vehicular rigid-body response while in aggressive maneuvering. As summarized in **Table 4**, for RSF_ON and TURBULENCE_OFF the handling qualities rating (HQR) degraded from 4.5 to.4.0 with a Level 2 placement as represented in the Cooper-Harper ratings scale. The same trend held true with RSF_ON and TURBULENCE_ON.



EVENT	RSF CASE	TURBULENCE CASE	HANDLING QUALITIES RATING	HANDLING QUALITIES LEVEL
1	ON	ON	4.0	2.0
2	OFF	OFF	4.5	2.0
3	ON	OFF	4.0	2.0
4	OFF	ON	6.0	2.0

Table 4: Slalom Mission Task Rating Summary

This indicated that the EAC controller with rotor state feedback attenuated the effects of turbulence, or allowed the pilot to perform the mission task element more compliantly. Another trend shows the beneficial performance of this controller. With TURBULENCE_ON for both RSF_OFF and RSF_ON cases, the pilot rated the mission task element performance as 6.0 and 4.0, respectively. This illustrates that the EAC controller with rotor state feedback improved task performance in the presence of the simulated turbulence.

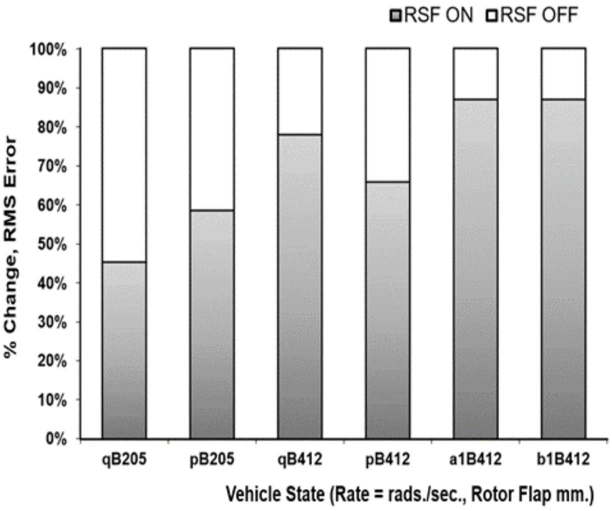


Figure 26: Percent Change RMS (Root Mean Square) State Errors due to Rotor State Feedback with Turbulence

The disturbance rejection capability of the EAC rotor state feedback controller in-flight is decisive as shown by **Figure 26** which depicts the reductions in Root Mean Square (RMS) state error for the host, Bell205A AS and the Bell 412 ASRA in in-flight simulation. For the host, the reductions are 54.7% and 41.5% in pitch- and roll-rate RMS, while for the Bell 412 ASRA the reductions are 22.1%, 34.2%, 13.8%, and 13.1% reductions in pitch- and roll-rate, and longitudinal- and lateral-rotor disc tilt RMS state activity errors.

7. CONCLUSIONS

This research endeavor resulted in significant contributions to NRC-FRL rotorcraft flight control and rotor state measurement programs. Major conclusions include:

- Validation of wireless rotor state measurement system (RSMS) technology for system identification and flight control law development in the handling and ride qualities bandwidths. The RSMS has limited fidelity in aeromechanical and aeroservoelastic contexts due to single-point and off-blade sensing.
- Validation of the 8-DOF mathematical model of Bell 412 ASRA coupled rotor-body dynamics. This model captured by explicit rotor equations and rotor state measurements second-order rotor flap response, correlation of attitude-rate and rotor flap dynamics, and response lead of rotor flap over rigid body dynamics. The model was robust in both desk-top and real-time flight test applications. However, response was deficient in off-axis prediction due to neglected dynamics.
- Analyses by Root Locus Methods (RLM) suggest that rotor states in Single Input / Single Output (SISO) models limit attainable bandwidth. In feedback, attitude-rate feedback is dominant in effecting mode trajectories and coupled rotor-body interactions.
- Analyses by Classical Control Methods (CLC, CMC) produced non-optimal control with rotor state feedback. This method was ineffective in modal control (due to lack of translational velocity gains) and did not provide control law design process insight.
- Model following flight-testing of an Eigenstructure Assignment based rotor state feedback control algorithm (EAC) produced Level-1 ADS-33E-PRF and Level-4 Cooper Harper handling qualities. In the presence of high model uncertainty, the EAC algorithm provided robust control action in off-design conditions such as elevated pilot workload/ and divided-attention environments, parameter offsets (including altitude, weight/balance, and airspeed), and inclement weather test points. EAC provided insightful understanding of rigid-rotor helicopter modal dynamics for real-time high bandwidth flight control applications in the area of rotor state feedback control.

8. ACKNOWLEDGEMENTS

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10. BIBLIOGRAPHY

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