AN EXPLORATION OF ROTOR SYSTEM COMPONENT LOADS OF THE NRC BELL412 ADVANCED SYSTEMS RESEARCH AIRCRAFT DUE TO VARIATIONS IN FLIGHT CONTROL AUGMENTATION

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Abstract

Supporting military rotorcraft life cycle research, the National Research Council of Canada - Flight Research Laboratory integrated a flight loads measurement suite (FLMS) into the NRC-FRL Bell412 Advanced Systems Research Aircraft (ASRA). In the rotor system's rotating frame, main rotor blade, pitch link, and swashplate link loads were captured. In the rotor control system's non-rotating frame, swashplate support, gimbal ring, and boost tube cylinder loads were captured. To examine inter-relationships between control augmentation and rotor system loading, the aircraft was configured with variations of six rate and attitude - based inner-loop control response types spanning Level 1 to 2 ADS-33 handling qualities. Data was analyzed from 3 Hz limited roll-axis frequency sweep tests performed in hover and forward flight. Results highlighted coherence between piloted inputs, fly-by-wire actuation, rotor control component loading, rotor hub dynamics, and vehicular rates. Component load frequency spectra due to rate, attitude, and hold-based responses differed in modal content. Rate- and attitude-based response types associated with the highest and lowest rotor system loading, respectively. Attitude command and -hold (attitude, velocity), response types associated with the greatest change in maximum oscillatory loads between hover and forward flight. Results project critical requirements for ongoing higher-order rotor state measurement research as next generation unconventional, agile, augmented, and pilot-optional vertical lift vehicles are developed.

1. NOTATION

BS-Lag	Blade Spindle Lead-Lag Displacement
FLMS	Flight Loads Measurement System
GR	Gimbal Ring
HES	Hall Effect Sensor
NORM.	Normalized, Loads Data (Also NRM.)
PL	Pitch Link
RBL.S36	Blade Lead-Lag Inboard Station, S36
RBL.S132	Blade Lead-Lag Outboard Station, S132
RSCM	Rotor State Computer Module
RSMS	Rotor State Measurement System
RY-Flap	Rotor Hub Yoke Flap Displacement
SL	Swashplate Link
SS	Swashplate Support

2. INTRODUCTION

Flight loads measurement technologies have played key roles in validating vehicle design theory, substantiating production vehicle certification methods, and enabling experimental flight research.

Loads measurements are critical in developing and validating comprehensive rotorcraft mathematical models. Applied in vehicle analyses such as aeromechanics and performance, these models incorporate rotor, airframe, flight control, and propulsion systems. For over a decade the UH-60 Air-loads Program (**Ref. 1**) a flight loads survey featuring extensive instrumentation, has been central in many rotorcraft code validation studies. Further, loads data has enabled research into the relationship between control characteristics and structural response in high bandwidth helicopters.

Rozak et al. (**Ref. 2**) showed that component fatigue life in rotorcraft was highly sensitive to controller bandwidth, especially in the pitch and yaw axes. To address this type of interaction, researchers investigated carefree techniques designed to limit loads. Industry applications of these techniques in fly-by-wire (FBW) rotorcraft include Bell-Boeing V-22 load alleviation (**Ref. 3**) and Sikorsky load alleviation control (**Ref. 4**) or S-92F, UH-60M, and CH-53K.

In the rotorcraft structural life cycle domain, loads measurement and recorded data are critically applied at the certification stage. Data provides a basis for specification validation and component integrity analysis during qualification. Furthermore, manufacturers utilize data to derive component fatigue life. Usage monitoring techniques enabled evaluations of helicopter component life. Two methods are Flight Condition Monitoring (which addresses evaluation of maneuver severity) and Flight Loads Monitoring (which addresses measurement of component loads). For example, Sikorsky utilized FAR/JAR 29.71 Flaw Tolerant Safe Life principles to calculate component retirement times for the S-92 and its fly-by-wire helicopter derivatives (S-92F, H-92/CH-148, (**Ref. 5**)). Further, Bell Helicopter developed techniques and technologies for condition-based maintenance for application to its rotorcraft production line (**Ref. 6**). Applications include structural health monitoring, diagnostics, and prognostics. Regulatory strategies for achieving airworthiness approval for health and usage monitoring technology in view of FAR/JAR Advisory Circular 29 focus on installation, credit validation, and continued airworthiness (**Ref. 6**).

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Loads measurement systems have also played key roles in enabling flight research. The NRC Flight Research Laboratory operates two experimental fly-by-wire (FBW) variable stability rotorcraft; the Bell205A Airborne Simulator (AS) and Bell412 Advanced Systems Research Aircraft (ASRA). Integration of specialized state measurement technology into these platforms was required for safety monitoring as well as research. To this end, NRC-FRL integrated Rotor State Measurement Systems (RSMS). In the NRC Bell205A, rotor flapping technology was developed to monitor teetering rotor hub flap limits to prevent aircraft contacts during FBW engagements. In the Bell412 ASRA, an RSMS was a vital technology to extend research capabilities. NRC-FRL integrated sensors for measuring hingeless rotor hub yoke and blade root displacement dynamics using Hall Effect Sensors (HES, (**Ref. 7**)). Research areas included system identification and high bandwidth control.

Later, NRC-FRL would embark on a rotorcraft life cycle management investigation for the Canadian Forces supporting objectives to apply life extension strategies to its aging helicopter fleets. Here, NRC-FRL integrated a flight loads measurement suite (FLMS) into the Bell412 ASRA consisting of existing RSMS technologies as well as instrumented components on loan from the Canadian Forces Aerospace Engineering Test Establishment (AETE). The FLMS monitored both rotating and non-rotating frame component loads.

The purpose of this paper is to describe technology, processes, and results from evaluations of loading conditions propagating through the NRC Bell412 ASRA rotor and control system. The aircraft, FLMS hardware components, and associated instrumentation will be described. Loading theory and analysis methodology will be presented. Finally, results from frequency sweep excitation trials in hover and forward flight will be discussed in context of the interrelationship between flight control response types and rotorcraft structural loads.

3. TEST AIRCRAFT DESCRIPTION

The NRC Bell412 Advanced Systems Research Aircraft is an airborne simulator derived from the Bell 412HP, a medium size, twin-engine helicopter with a gross take-off weight of 11,900 lbs. The aircraft features a 4-bladed soft-inplane hingeless rotor system which generates high control power and low response time delays. NRC's platform is powered by a Pratt & Whitney PT6T-9 Twin-Pac turboshaft engine rated at 1800 SHP for improved flight stability and features a glass cockpit for enhanced crew interfacing. NRC integrated an experimental simplex single-string fly-by-wire control system comprised of a single set of FBW actuators, one non-redundant flight control computer (FCC), a single set of aircraft state sensors, and a single set of flight software.

Integrated FLMS technologies have provided measurements of inflight structural loads of the rotor and flight control systems. Its sensors were installed on main rotor and control components as well as interfaced with the aircraft's research data acquisition systems. The Bell412 ASRA, FBW control architecture, hingeless rotor hub, and rotor control system are depicted in **Figures 1** and **2.**

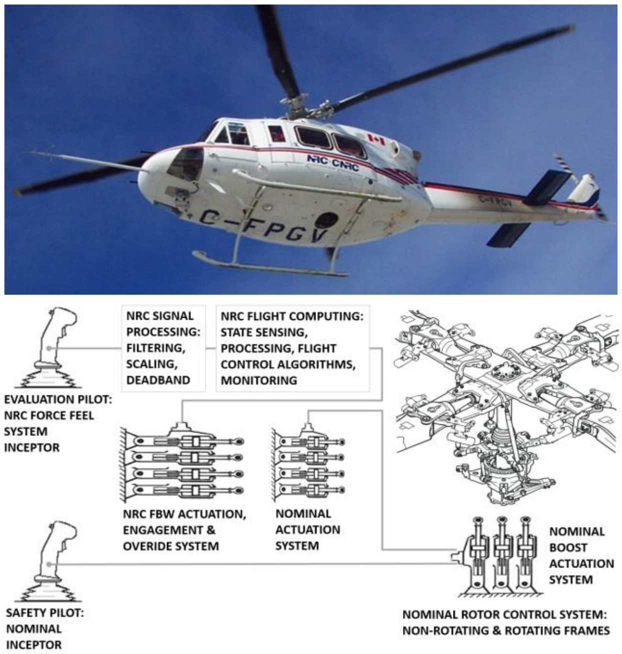

Figure 1: NRC-FRL Bell412 ASRA, Fly-By-Wire Flight Control Actuation System Diagram.

The Bell412 main rotor control system consists of rotating (pitch links, rephasing levers, drive links and hub, swashplate links and outer ring) and non-rotating (inner ring, swashplate support, gimbal ring, collective sleeve and levers, and boost tube cylinders) components. Pilot cyclic and collective control inputs are transmitted to hydraulic actuators attached to the collective lever and inner ring arms. The inputs are transferred through the collective sleeve and swashplate to alter the main rotor blade angle of attack. The rotor blade resultant induced loads are transmitted by the pitch links through the rotating system, and reacted by boost tube cylinders in the non-rotating control system (**Ref. 8**).

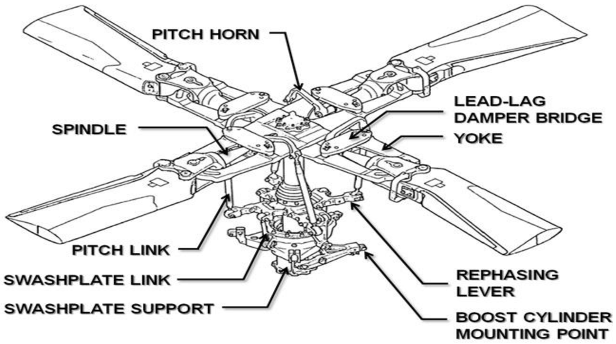

Figure 2: NRC-FRL Bell412 ASRA, Hingeless Rotor Hub and Rotor System Controls (**Ref. 8**)

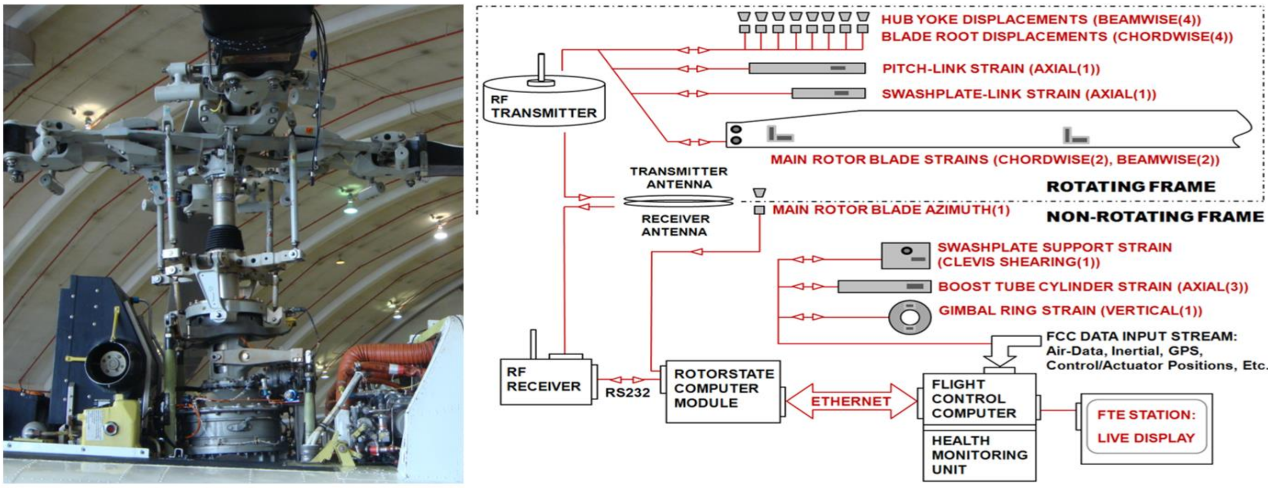

Figure 3: NRC Bell412 ASRA Flight Loads Measurement Suite (FLMS) Architecture

3.1 Instrumentation Description

The FLMS (**Figure 3** and **Table 1**) is an airworthy system enabling sensing and recording of rotor and flight control systems structural response of rotating and non-rotating frame loads (axial, vertical, shearing) and moments (bending). The FLMS utilized the ASRA rotor state measurement system (RSMS) functionalities. First, measured strain gauge signals were processed (i.e.; digitally conditioned). Second, the RSMS wirelessly transmitted data from the rotor rotating frame to the fuselage non-rotating frame. The RSMS transmitter and receiver were based on the KMT CT-16 Rotate™ measurement system. As depicted in **Figure 3**, major FLMS elements include the RSMS architecture, rotating and non-rotating frame instrumentation, rotor state computing, and the aircraft's information network.

The primary processing device in the rotor rotating frame was the KMT CT-16. It captured data in analog format, performed analog-to-digital conversion, and performed radio frequency data transmission. The device collected 14 data channels consisting of strains (blade strains, pitch link strains, swashplate link strains) and displacements (hub yoke flapping and blade root spindle lead-lag). The CT-16 supported both voltage and strain signals. Displacement sensing via Hall Effect Sensors (HES) were processed by voltage channels. Loads measurements emanating from strain gauges were processed by strain channels. The rotating and non-rotating frames of the RSMS were linked via transmitter and receiver modules. A single board computer known as the rotor state computer module (RSCM) processed RSMS data and transmitted it to the ASRA flight control computer. The RSCM acquired raw flapping and lead-lag data as well as applied calibrations. A HES-based azimuth sensor enabled the transformation of RSMS data to the non-rotating frame via Kalman filtering for real-time estimation of flapping, lead-lag, tilt, coning, RPM, and azimuth rotor states.

FLMS rotating component strains were associated with an instrumented main rotor blade as well as rotor control pitch and swashplate links. FLMS non-rotating component strains were associated with the lower swashplate assembly, and its gimbal ring and swashplate support. Additionally, the Bell412 ASRA swashplate boost tube cylinders were instrumented for monitoring non-rotating control system loads.

Table 1: NRC Bell412 FLMS Measurements

Component	Measure	Location
Main Rotor Blade	Chordwise & Beamwise Bend	Chord & Beam Stations (S36, S132)
Hub Yoke	Displacement	Yoke Flapping
Blade Root Spindle	Displacement	Spindle Lead-Lag
Pitch Link	Axial Strain	Central Load
Swashplate Link	Axial Strain	Central Load
Gimbal Ring	Axial Strain	Vertical Load
Swashplate Support	Axial Strain	Clevis Shear

In terms of access, the non-rotating and rotating frame data was captured and transmitted via Ethernet to the FCC at 400 Hz. Data recording occurred on the RSCM Flash™ Drive (typically for RSMS system maintenance), as well as on either of the aircraft's permanent or removable hard-drives. This network also enabled FLMS live data access on any of the aircraft's research displays.

In NRC-FRL's studies (**Ref. 7, 9**) of RSMS and FLMS technologies, it is clear that ongoing utilization by industry and government will be beneficial to life cycle extension, control and accident mitigation. Methods for embedding sensors as well as rotor state estimation are critical future requirements. Detailed descriptions instrumented components, calibrations, and system software may be found in supporting publications (**Ref. 7, 9**), with general information provided next for research clarity.

Main Rotor Blade Instrumentation: The Bell412 four-bladed hingeless rotor hub is formed by stacking two identical titanium yokes (see **Figure 2, 3**). The instrumented main rotor blade was mounted on the upper yoke stack. This rotor blade (**Figure 4**) was integrated with four standard strain gauge bridges for measurement of flap (beamwise) and lead-lag (chordwise) bending moments at inboard (station S36) and outboard (station S132) locations.

Figure 4: B412 Instrumented Main Rotor Blade

The strain gauges were bonded to the upper and lower blade surfaces. At the inboard station, standard bridge configurations were implemented with gauge pairings on upper and lower blade root surfaces. Beamwise and chordwise strain gauges (four per bridge) were applied in a symmetrical pattern about the blade's twist centerline.

At the outboard blade station, similar standard bridge configurations were implemented. To correct for built-in blade twist developing in outboard blade stations, upper and lower gauging was located relative to structural property changes and to determine bending mode shapes. As shown in **Figure 5**, for the upper and lower surface beamwise measurements, gauges were located ahead of the blade's twist centerline. In chordwise measurement, upper and lower surface gauges were located towards the blade's leading and trailing edges.

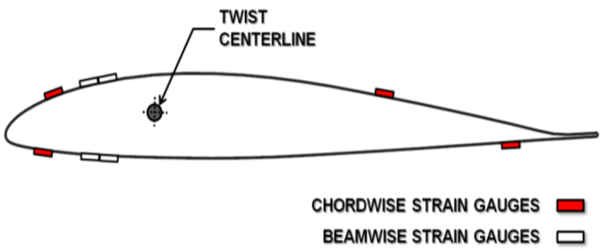

Figure 5: B412 Instrumented Blade, Station S132

Pitch Link Instrumentation: The pitch link (**Figure 6**) was instrumented with a single standard strain gauge bridge for measurement of link axial load. This link mounts between the rephasing lever and the rotor blade pitch horn. The pitch link load path includes rotor pitching moment induced axial loads transferred to boost cylinders, and axial loads from control system cyclic and collective blade pitch commands.

Figure 6: B412 Instrumented Main Rotor Pitch Link2

Swashplate Assembly Instrumentation: The swashplate assembly shown in **Figure 7** was central to a number of instrumented components. The swashplate support is tubular with two diametrically opposed clevises at the upper end for attachment of the gimbal ring. The support has loading paths from collective boost tube cylinders (axial), gimbal ring (vertical), and hub and rotor system (shearing). The swashplate link was instrumented with a single standard strain gauge bridge for measurement of link axial load. This link mounts between the swashplate assembly's rephasing lever and rotating ring components. The gimbal ring was instrumented with a single standard strain gauge bridge for capturing ring vertical load. The swashplate support was instrumented with a single standard strain gauge bridge for measuring gimbal ring attachment clevis lateral shearing load.

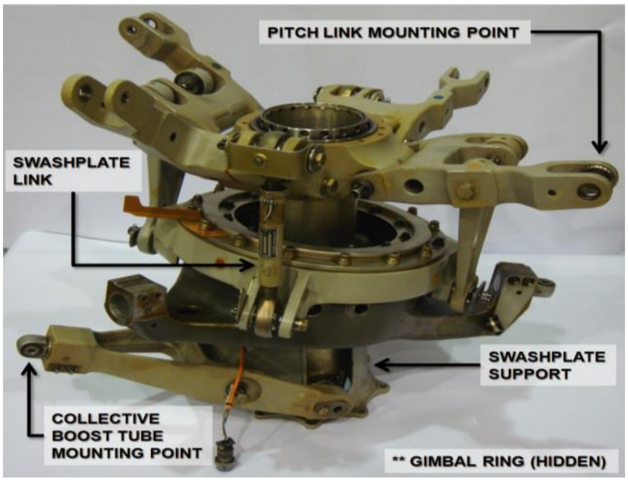

Figure 7: B412 Instrumented Swashplate Assembly

3.2 Control Response Type Implementation

For this investigation, the NRC Bell412 ASRA was utilized to emulate inner-loop vehicle response types characteristic of military FBW helicopters. Control response types shown in **Table 2** were programmed into the aircraft's flight control computer providing selectable control modes and bandwidths. In **Figure 8**, a summary of associated bandwidths, phase delays, and crossover frequencies are plotted on ADS-33 Military Rotorcraft Handing Qualities specifications for Pitch and Roll Axes (**Ref. 10**).

Table 2: NRC B412 ASRA Control Response Types

Cueing	Primary Control Axes (Roll, Pitch)[c,d]
GVE[a]	Direct Drive (Open Loop)
GVE	Rate Damped
GVE	Rate Command Attitude Hold
GVE	Attitude Command Velocity Hold
DVE[b]	Attitude Command Attitude Hold
DVE	Translational Rate Command

[a] **Good Visual Environment (GVE)**
[b] **Degraded Visual Environment (DVE)**
[c] **Yaw Response: Rate Damped (RD)**
[d] **Heave Response: Open-Loop, Damped, Height-Hold (HTH)**

NRC Rate-Based control response types utilized in this research included Direct Drive, Rate Damped, Translational Rate Command, and Rate Command Attitude Hold; these provide Level-1 and Level-2 handling qualities. **NRC Direct Drive (DDRV)** response is utilized in variable stability operations to emulate Bell412 open-loop (un-augmented) flying qualities. The **Rate Damped (RD)** response type is implemented such that rate damping or feedback is applied to lower pilot workload. Here, the aircraft rate response is generally proportional to pilot inceptor displacement (or applied force) activity. This response type is utilized for aggressive maneuvering. Both low (RTD1) and high (RTD2) bandwidth cases of this response type are provided. **Translational Rate Command (TRC)** response is implemented such that aircraft translational velocity (rate) longitudinally or laterally is proportional to inceptor displacement (or applied force) relative to its center neutral position. The **Rate Command Attitude Hold (RCAH)** response type provides the pilot with responsiveness during mission tasks and operations where maneuverability is required. In this system, aircraft rate response is generally proportional to pilot inceptor displacement (or applied force) activity. Upon the inceptor's return to center neutral position (or release of applied force) a new attitude reference is acquired and an attitude hold response engaged.

NRC Attitude-Based control response types utilized in this research include Attitude Command Attitude Hold and Attitude Command Velocity Hold; these provide Level-1 and Level-2 handling qualities.

Attitude Command response is required by ADS-33 to provide reduced workload in degraded visual environments (DVE). The Attitude Command Attitude Hold (ACAH) response type is implemented such that pitch or roll attitude of the aircraft is proportional to pilot inceptor displacement (or applied force) relative to its center neutral position. Upon the inceptor's return to center neutral position (or release of applied force), the control system commands a null or zero attitude reference. The **Attitude Command Velocity Hold (ACVH)** response type appends a velocity reference to nominal ACAH response. Here, when the cyclic is returned to center neutral position, the control system acquires a new velocity reference and engages a velocity hold response.

To further augment test pilot task performance in low-speed testing, height hold was provided. **Height hold (HTH)** enables maintenance of height above ground lowering altitude control workload.

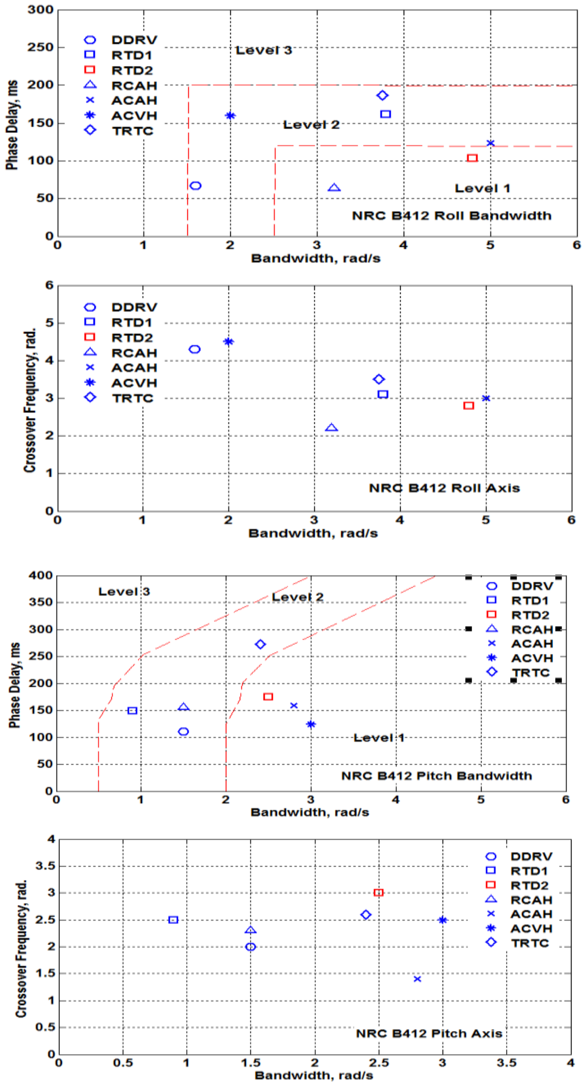

Figure 8: NRC Bell412 ASRA Inner-Loop Control Response and Parameters (Bandwidth, Phase Delay, Crossover)

4. RESEARCH EXECUTION: METHODOLOGY AND DATA PREPARATION

The objective of this investigation is to present case study observations critically examining flight loads propagating through the NRC Bell412 non-rotating and rotating rotor control system as depicted in **Figure 9**. Low-speed hover and high-speed forward flight are selected as test cases. For each speed, manually executed frequency sweeps are processed through control response types to excite or stimulate aircraft dynamics and loading conditions. Coupled vehicle roll-axis and rotor lead-lag aeromechanics are the focus of analyses.

4.1 Methodology and Constraints

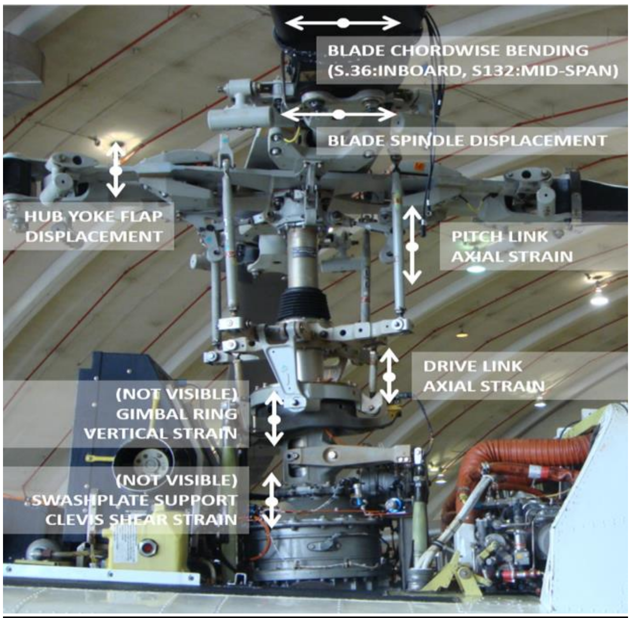

Figure 9: NRC Bell412 ASRA, Main Rotor Control System, Strain and Displacement Measurements

In terms of Bell412 rotor system rotating and non-rotating frame loading, pilot cyclic and collective control inputs propagate to actuators attached to the collective lever and inner ring arms, then through the collective sleeve and swashplate to effect changes in rotor blade angle of attack. The main rotor blade rotor induced loads propagate via pitch links through the rotating system and are reacted by boost cylinders in the fixed control system. Swashplate linkages transfer direct oscillatory loads from the main rotor blades and their torsion dynamics. Pitch link loads are reactions from blade aerodynamic and dynamic pitching moments. Alternating pitch link loads show rapid increase in magnitude at blade stall or when severe compressibility occurs. These loads indicate stall, flutter, and maneuvering characteristics. Bell412 swashplate support and gimbal ring loads indicate propagation through the lower swashplate system. Boost tube actuators and cylinders are critical measures of design limit loads associated with severe control inputs and vehicle maneuvers (**Ref. 11, 12**).

The methodology for data analysis involved six phases of study. Generally, parameters such as loading (magnitude) and control (bandwidth, phase delay, and crossover frequency) were reference parameters. The data analysis phases included;

A. **Data Management**: Research preparation including flight axis (Roll-axis vehicle dynamics, rotor lead-lag response) and data analysis (quality assessment, assembly, and identification of a suitable working data set).

B. **Test Case Selection**: For this investigation roll-axis frequency sweeps (i.e.; 6 response types under hover and forward flight conditions) defined the test case. Sweeps were constrained to NRC and Bell defined 3.0 Hz limits.

C. **Coherence Assessment**: Perform a hover coherence assessment relating structural components loading to actuation and vehicle attitude-rate. Coherence frequency range and magnitude were assessed as actual thresholds for structural failure are unknown.

D. **Frequency Response Assessment**: Perform spectrographic analyses to assess the nature of loading conditions.

E. **Correlation Assessment**: Perform loads-to-response-type correlation for low- and high-speed flight.

F. **Variability Assessment**: Compare low- and high-speed loading conditions.

Due to data collection constraints, results from analyses provided herein are not statistically representative or validated. The key constraints impacting analytical rigor associated with this investigation are as follows:

1. **Structural Information**: Engineering data (damage thresholds, fatigue limits, etc.) for instrumented components were unknowns.
2. **Instrumentation**: The instrumentation system is a unique research system. There is no validation or baseline for this system.
3. **Data Record**: Flight data was collected in both research (dedicated trials) as well as normal operations (best available collection) contexts. The data is also limited in scope (i.e.; limited maneuver archive) and parameters (i.e.; rotor loads data does not include blade air-loads and strain data is limited in spanwise distribution)
4. **Subjects**: The flight testing was performed with a single qualified NRC Test Pilot.
5. **Test Aircraft**: The NRC facility is a uniquely modified utility tactical helicopter without data validations or vehicle comparisons.

As such, for this investigation, results provided represent research **test case observations** and **not guidance or advice subjects associated with on rotorcraft life cycle management**.

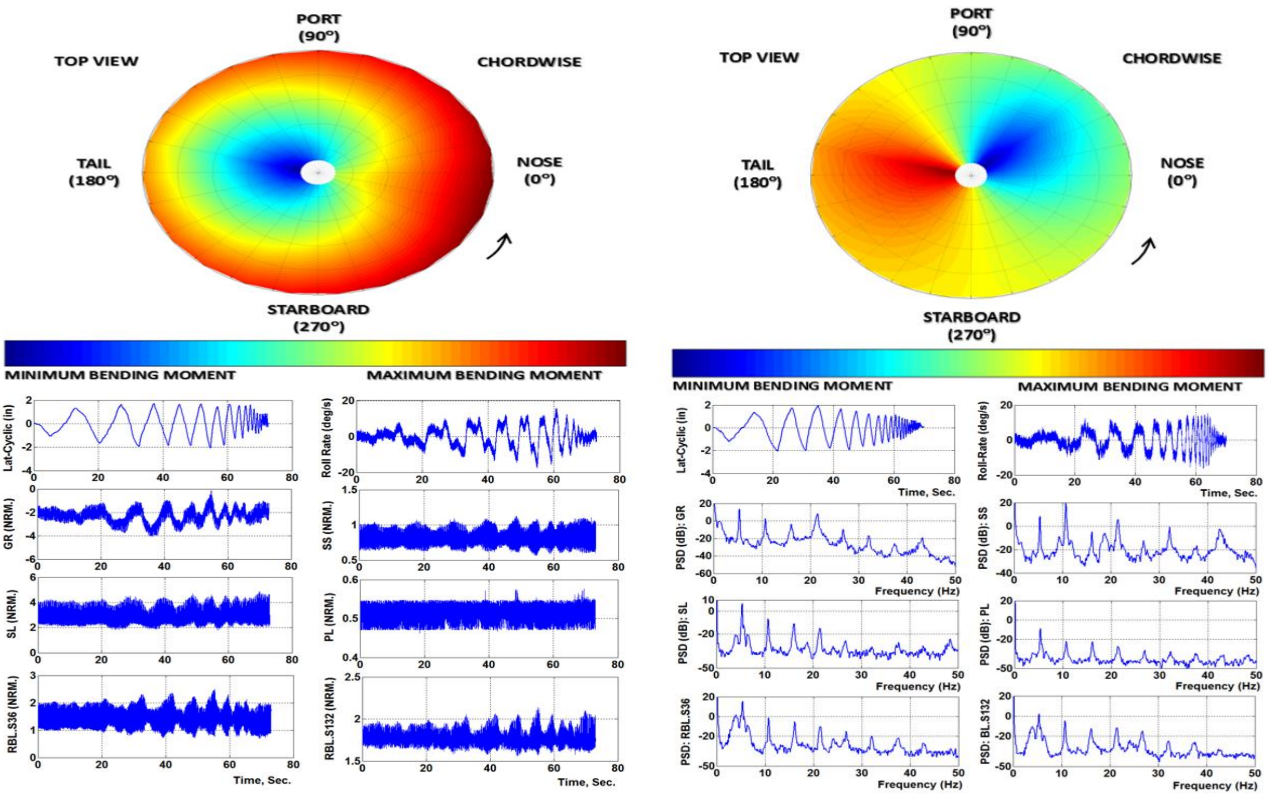

Figure 10: NRC Bell412 FLMS Roll-Axis Frequency Sweep Data Set Sample,
(Left) Attitude Command Velocity Hold (ACVH) Response Type, Hovering Flight Temporal History,
(Right) Attitude Command Attitude Hold (ACAH) Response Type, Hovering Flight Frequency Spectrum,

4.2 Data Set Preparation

FLMS data validation ensured proper time/frequency response, magnitude/trend activity with vehicle states, and internal/external response consistency. Signal-to-noise-ratio was 35dB with a frequency spectrum ranging out to 100 Hz. Lateral response (vehicular; rotor lead-lag dynamics/loads) was selected for research herein. The data set consisted of manually executed (conventional pilot inceptors) frequency sweeps for hover and forward flight; aircraft configurations are provided in **Table 3**.

Table 3: Test Conditions, Hover and Forward Flight

Parameters	**Hover Sortie**	**Flight Sortie**
	Parameter Ranges	
Start Weight (lbs)	9774	9975
End Weight (lbs)	9702	9880
CG Variation (in)	Lon(0.1);Lat(0)	Ln(0.13);Lat(0)
Weight Coefficient	[0.05, 0.06]	[0.055, 0.059]
G-Loading	[2.1, -0.3]	[-1.91, -0.06]
Advance Ratio	[0.0013, 0.023]	[0.0013,0.023]
MR Rotor RPM	[318.7, 324.5]	[323.7, 328.1]
Max. Speed (kts)	10	105.5
Altitude (ft)	[0, 80]	[0, 1011]
Winds (deg., kts)	(280, 10)	(300, 8)
Pitch Rate(deg./s)	[8, -8.5]	[8.27, -9.96]
Roll Rate (deg./s)	[17.4, -24.4]	[20.77, -26.95]
Yaw Rate (deg./s)	[7.5, -12]	[8.97, -11.76]
Record Time (s.)	388	515

NOTES: Crew (2 Pilots/Conv. Pilot Inceptors, 1 FTE); FBW (On); Stability Augment.(Off); Height Hold(Off)

Six sweeps were recorded per sortie for each response type (i.e.; DDRV, RD1, RD2, RCAH, ACAH, and ACVH). TRC data was collected during hover trials. Sample time history and frequency spectrum data from low-speed ACAH and ACVH sweeps are provided in **Figure 10**. Parameter labels include Gimbal Ring (GR), Swashplate Support (SS), Pitch Link (PL), Swashplate Link (SL), and Blade Chordwise Lead-Lag at Stations 36 and 132. (RBL-36 and RBL-132). Data illustrate the input (70 sec.; 3 Hz cut-off limit; inches), roll attitude-rates (degs./s.), and rotor system component loading (normalized). The ACAH blade chordwise polar plot (i.e.; 8 s. duration for 43 blade revolutions) indicates inboard blade section load excitation at retreating-advancing transition. The ACVH polar indicates blade circumferential excitation outboard. Spectra (i.e.; 0.65 per rev (3.51Hz) to 8 per rev (40 Hz) highlight instrumented component modal content.

5. RESEARCH RESULTS

In the following sections, investigations of load propagation due to roll axis excitation are performed. Coherence assessments study interactions between control and rotor component response. The nature of the loading is identified spectrographically. Correlation studies assess maximum oscillatory loading conditions associated with each response type. Comparative studies assess variability of loading conditions between hover and forward flight.

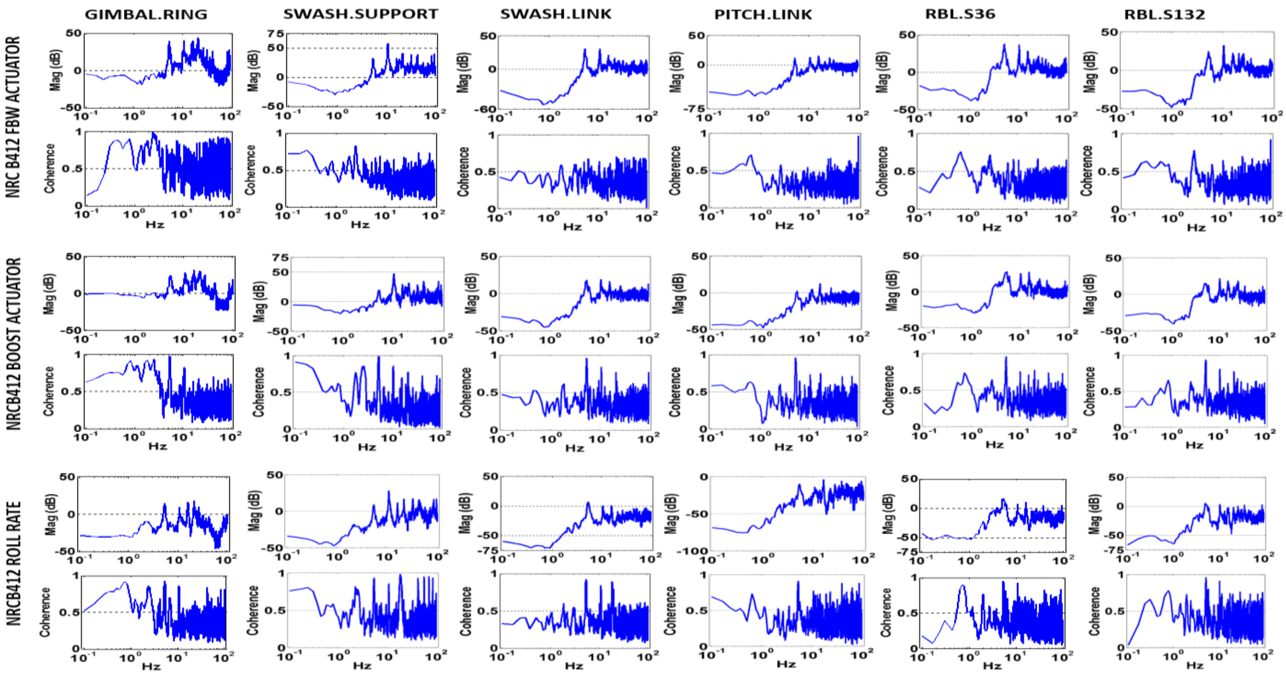

Figure 11: NRC Bell412 Hover Roll-Axis Frequency Sweep Coherence Study, Low Bandwidth Direct Drive Response (Top Row) FBW Actuator to Instrumented Components, (Middle Row) Boost Actuator to Instrumented Components, (Bottom Row) Roll Rate to Instrumented Components

5.1 Hover Coherence Observations

Coherence is defined as the fraction of the output spectrum having linearity with the input spectrum. A rapid drop in coherence may indicate errors in signal amplitude and phase (i.e.; off-axis inputs, signal noise, etc.). Acceptable coherence in flight dynamics suggests thresholds of 80%. In aeromechanics, without Bell412 design information (failure conditions, fatigue limits, etc.), thresholds cannot be assessed and coherence trend behavior is analyzed.

A hover frequency sweep coherence study is performed tracing loading from rotor system non-rotating (gimbal ring, swashplate support) to rotating (swashplate link, pitch link, rotor blade inboard/outboard) frames. This, in relation to NRC FBW and Bell boost actuation, as well as aircraft roll rate. The Direct Drive roll-axis sweep is performed over an 80 s. period, at low altitude (20 to 80 ft AGL.) and speed (< 10 knots) as well as under moderate normal G (2 Gz) and roll rates (±30 degs/s.)

In **Figure 11**, interactions between NRC Bell412 FBW Actuator (Row 1), Boost Actuator (Row 2), and aircraft roll rate (Row 3) as inputs and component loads as outputs are analyzed. Components studied by Column include; Gimbal Ring (Column-1), Swashplate Support (Column-2), Swashplate Link (Column-3), Pitch Link (Column-4), Rotor Blade Inboard (S36) Chordwise Bending (Column-5), Rotor Blade Outboard (S132) Chordwise Bending (Column-6). For each component: x-axis (frequency (Hertz)), y-axis (input magnitude (dB)) and coherence (dimensionless).

Coherence between the FBW and Boost actuators and the non-rotating rotor control (gimbal ring, swashplate support), depicts the highest values at low frequencies from 0.1 to 1 Hz. It tends to be 0.5 to 0.8 for low frequencies. Boost actuator coherence tends to be higher at lower frequencies than that of other components. Coherence in rotating rotor control components (swashplate link, pitch link) tended to be 0.4 to 0.7 over 0.1 to 1 Hz for both FBW and boost actuation.

Of interest is the lower coherence of rotor blade lagwise strain at station 36 (inboard) versus at station 132 (outboard). It's the soft inplane hingeless rotor lag dampers that attenuate this energy in the 0.1 to 2 Hz range. Load magnitudes of the rotor blade and rotor control system are low at low to mid frequencies. This is due to Bell412 lead-lag and torsion load mitigation design. Rotor blade reflex (positive reflex to blade trailing edge), rotor blade trim tabs (nose-up blade pitching moment) reduce blade torsional moments. This limits energy in the swashplate link, pitch link, and rotor blade inboard section. It is also noted that coherence falls sharply at some 3 Hz due to pilot input cutoff and sweep generated attitude roll-rate amplification of the 1^{st} chordwise regressive mode at 0.65/rev or 3.5 Hz.

In general, at lower frequencies between 0.1 and 1 Hz, roll rates have high coherence with non-rotating rotor control and rotating rotor system loads. There is high coherence between actuation and non-rotating rotor control loads and moderate coherence between actuation and rotating rotor control loads. Low coherence exists between actuation and inboard main rotor blade chordwise loading (S36).

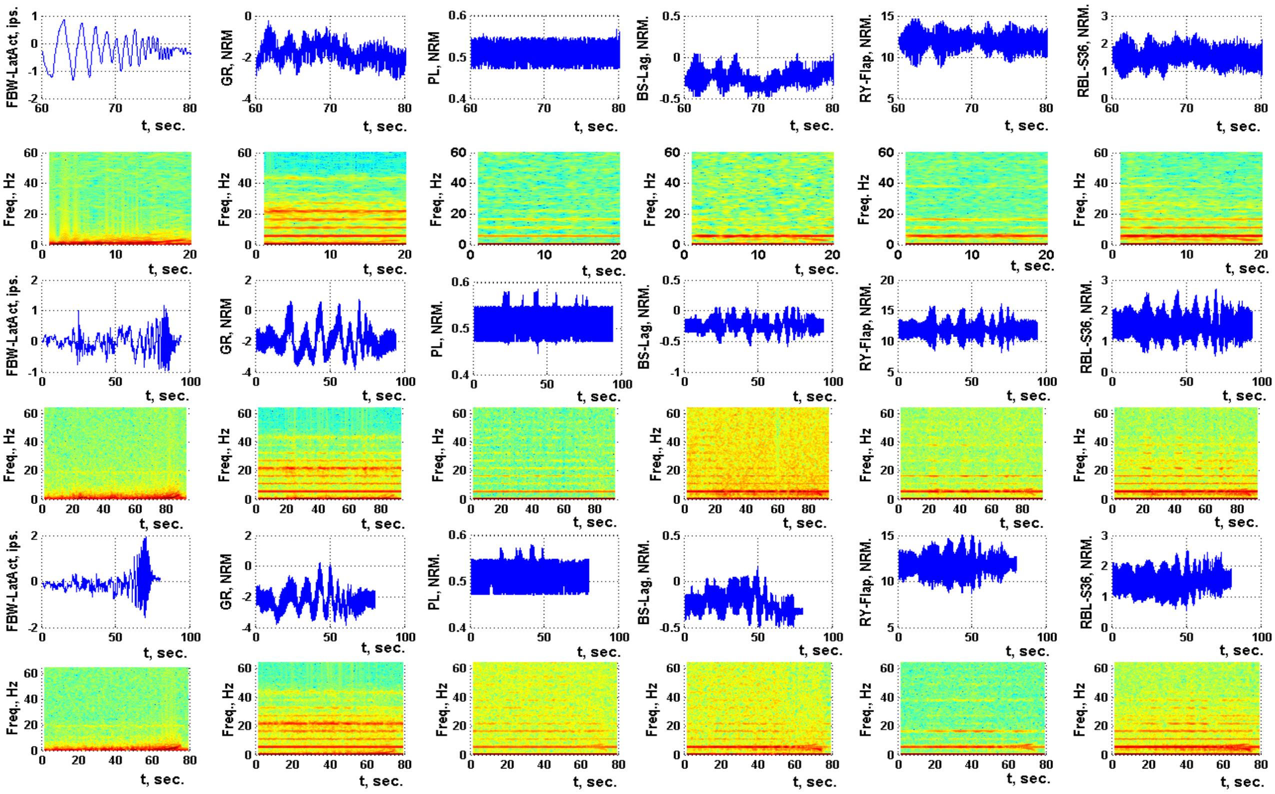

Figure 12: NRC Bell412 Hover Roll-Axis Frequency Sweep Spectral Response Study (Top 2 Rows) Direct Drive Response Type, (Middle 2 Rows) Rate Damped (RD1) Response Type, (Bottom 2 Rows) Attitude Command Attitude Hold Response Type

5.2 Hover Spectral Response Observations

A study of helicopter rotor control, rotor dynamics, and flight control system coherence provided insight into the inter-relationships of response. Spectrograms provide temporal and frequency domain information. For roll frequency sweep testing, a spectrographic study is performed to assess load propagation behavior between control actuation and the non-rotating and rotating frames of the rotor system. The term excitation denotes the establishment of a non-damaging load condition.

In **Figures 12 and 13**, Direct Drive (DDRV, Rows 1-2), Rate Damped (RD1, Rows 3-4), and Attitude Command Attitude Hold (ACAH, Rows 5-6) response types are investigated. Flight system elements studied include by Column (C-1 to C-6):

- FBW Actuator Input (C-1),
- Gimbal Ring (C-2),
- Pitch Link (C-3),
- Rotor Blade Spindle Lag (C-4),
- Rotor Hub Yoke Flap (C-5),
- Blade Inboard (S36) Chordwise Bending (C-6).

For component spectrograms; x-axis represents time (seconds) and y-axis represents frequency (Hz) due to excitation by the roll axis frequency sweep and due to the helicopter's operating environment.

Observations of hover spectra indicated:

A. Flight Control, FBW Actuator Input (C-1);

- Frequency sweeps of 80 to 90 second duration excited the lateral axis of the aircraft. The Direct Drive (DDRV, Row-1) input differed from both Rate (RD1, Row-2) and Attitude (ACAH, Row-3) excitations in input amplitude sequence. RD1 and ACAH match in excitation duration, however RD1 depicts higher frequency amplitude.

B. Rotor Non-Rotating Frame Gimbal Ring (C-2);

- Gimbal Ring excitation indicated responses of modes from low frequencies out to 30 Hz with similarity between RD1 and ACAH responses.

C. Rotor Rotating Frame Pitch Link (C-3);

- Pitch Link excitation associated with ACAH indicated broad resonance out to 60 Hz versus mode excitation of RD1 out to 20 Hz.

D. Rotor Rotating Frame Spindle Lag (C-4) and Hub Yoke Flap (C-5);

- Significant resonance of blade root lag displacement occurred relative to the RD1 response type versus lesser response via ACAH. Flap displacement of the yoke most excited by under RD1 versus ACAH response.

E. Blade Rotat. Frame (S36) Chordwise Bend. (C-6);

- More significant rotor blade inboard (S36) chordwise dynamics modes via RD1 than ACAH.

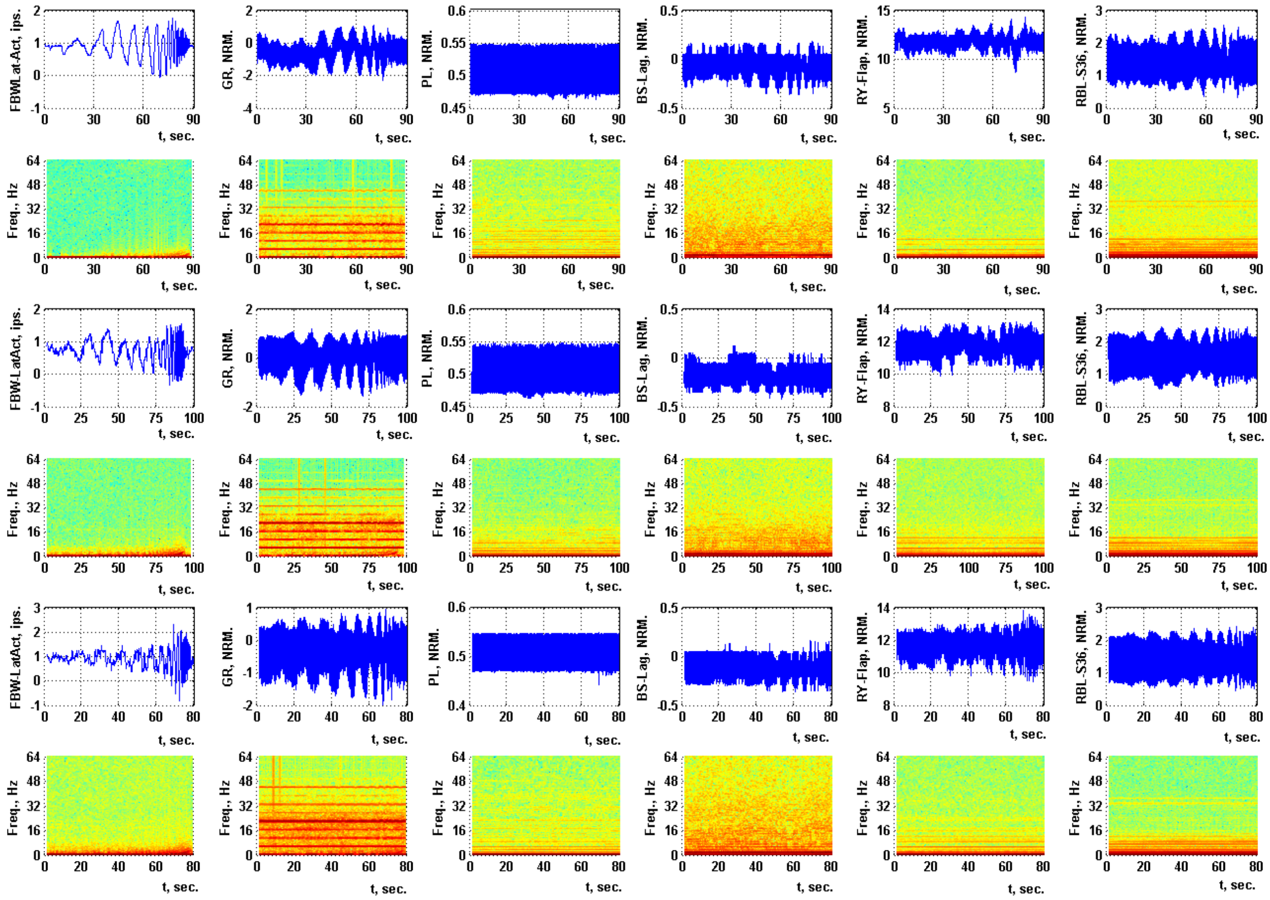

Figure 13: NRC Bell412 Forward Flight Roll-Axis Frequency Sweep Spectral Response Study (Top 2 Rows) Direct Drive Response Type, (Middle 2 Rows) Rate Damped (RD1) Response Type, (Bottom 2 Rows) Attitude Command Attitude Hold Response Type

5.3 Forward Flight Spectral Response Observations

Comparatively for forward flight roll sweeps, a spectrographic study is performed assessing the influence of aerodynamic environment on loading. In **Figure 13**; Direct Drive (DDRV, Rows 1-2), Rate Damped (RD1, Rows 3-4), and Attitude Command Attitude Hold (ACAH, Rows 5-6) are investigated. By Column (C-1 to C-6) flight system elements include:

- FBW Actuator Input (C-1),
- Gimbal Ring (C-2),
- Pitch Link (C-3),
- Rotor Blade Spindle Lag (C-4),
- Rotor Hub Yoke Flap (C-5),
- Blade Inboard (S36) Chordwise Bending (C-6).

Observations of forward flight spectra indicated:

A. Flight Control, FBW Actuator Input (C-1);

- Sweeps of 80 to 90 sec. duration excited the aircraft lateral axis. Direct Drive (DDRV, Rows 1-2) inputs differed from both Rate (RD1, Row 3-4) and Attitude (ACAH, Row-5-6) input excitations.
- RD1 and ACAH sweeps generally match in duration; RD1 has higher frequency amplitude.
-

B. Rotor Non-Rotating Frame Gimbal Ring (C-2);

- Gimbal Ring (GR) depicts excitation out to 48 Hz with similarity between RD1 and ACAH responses. Modal excitation is more prominent and to higher frequency thresholds than in hover.

C. Rotor Rotating Frame Pitch Link (C-3);

- Pitch Link (PL) excitation due to RD1 and ACAH response indicate lower modal prominence than in hover (ACAH to 30 Hz; RD1 to 16 Hz).

D. Rotat. Spindle Lag (C-4) & Hub Yoke Flap (C-5);

- Blade root spindle lag (BS-Lag) displacement occurred relative to the RD1 response type with broader excitation via ACAH observed. Hub Yoke Flap (RY-Flap) displacement most excited by RD1 versus ACAH response below 16 Hz.

E. Rotating Frame (S36) Chordwise Bend (C-6);

- There is equivalence in excitation of chordwise blade inboard (RBL.S36) of RD1 and ACAH; RD1 depicts more response at higher frequency while ACAH more response at lower frequencies.

Spectrographically studies indicated that rate, attitude, and hold response types load the rotor system differently, likely based on vehicle quickness, flight speed, and attitude retention air loading.

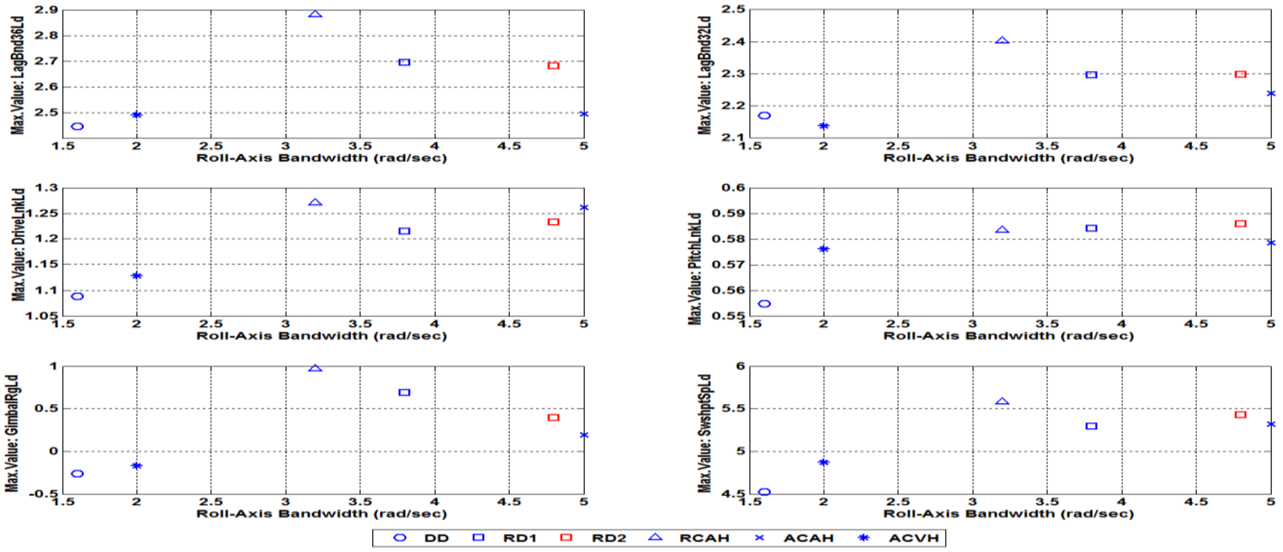

Figure 14: NRC Bell412 Hover Roll Frequency Sweep, Correlation of Response Types to Component Loads

5.4 Hover Correlation Observations

Further assessments may provide insight into loading conditions associated with configuration changes in the rotor control system due to pilot inputs and actuation due to control response types. The challenge is establishing the nature of the loading (i.e.; inertial, elastic, force, aeromechanical or aerodynamic, or reaction).

The following provides observations on the correlation between component maximum oscillatory loads and control response due to frequency sweep excitation in Low-Speed Hover and Forward Flight (**Figures 14 and 15**, respectively). Components studied; Gimbal Ring (Row-3, Column-1), Swashplate Support (Row-3, Column-2), Swashplate Link (Row-2, Column-1), Pitch Link (Row-2, Column-2), Rotor Blade Inboard (S36) Chordwise Bending (Row-1, Column-1), and Rotor Blade Outboard (S132) Chordwise Bending (Row-1, Column-2). For each component, the x-axis represents bandwidth (rad/s.) and the y-axis, maximum oscillatory load (normalized).

Observations for the Low-Speed Hover frequency sweep test case (**Figure 14**) are as follows:

A. Component Load Observations

- The Swashplate Support is exposed to the highest loading (fixed frame); the Gimbal Ring loads are the lowest in the fixed frame'
- The Pitch Link is the least loaded component (rotating frame); Rotor Blade Chordwise Bending (Inboard, Station S36) is the highest loaded component in the rotating frame.
- Ranking of component loads (Lowest to Highest) is Gimbal Ring, Pitch Link, Swashplate Link, Rotor Blade Chordwise Bending (Inboard, Station S36), Rotor Blade Chordwise Bending (Outboard, Station S132), Swashplate Support.

B. Response Type Observations

- The Rate-based response type is associated with the highest loading in all components.
- Attitude-based response types ACAH and ACVH are associated with the lowest loading in all components except when considering Direct Drive (DDRV).
- Hold function response types (-AH, -VH) may associate with highest loading conditions.

C. Non-Rotating Frame (Gimbal Ring, Swashplate Support) Observations

- The lowest bandwidth response type (ACVH) associated with the lowest loading conditions aside from Direct Drive (DDRV).
- The highest bandwidth response types Rate Damped (RD1, RD2) may be associated with a spread of low, moderate, or highest loading conditions across all components.
- RCAH is associated with the highest loading of all response types for Pitch Link loading.
- The highest bandwidth response types Attitude Command Attitude Hold (ACAH) may be associated with a spread of low, moderate, or highest loading.
- The mid-bandwidth response type Rate Command Attitude Hold (RCAH) is generally associated with high loading conditions.

D. Rotating Frame Controls (Drive Link, Pitch Link)

- RD1 and RCAH are associated with the highest loading of all response types for the Pitch Link and Drive Link.

E. Rotating Frame Thrust Generation (Rotor Blade Chordwise Bending (S36, S132))

- RCAH is associated with the highest loading of all response types for Rotor Blade Chordwise Bending (Inboard, Station S36), Rotor Blade Chordwise Bending (Outboard, Station 132).

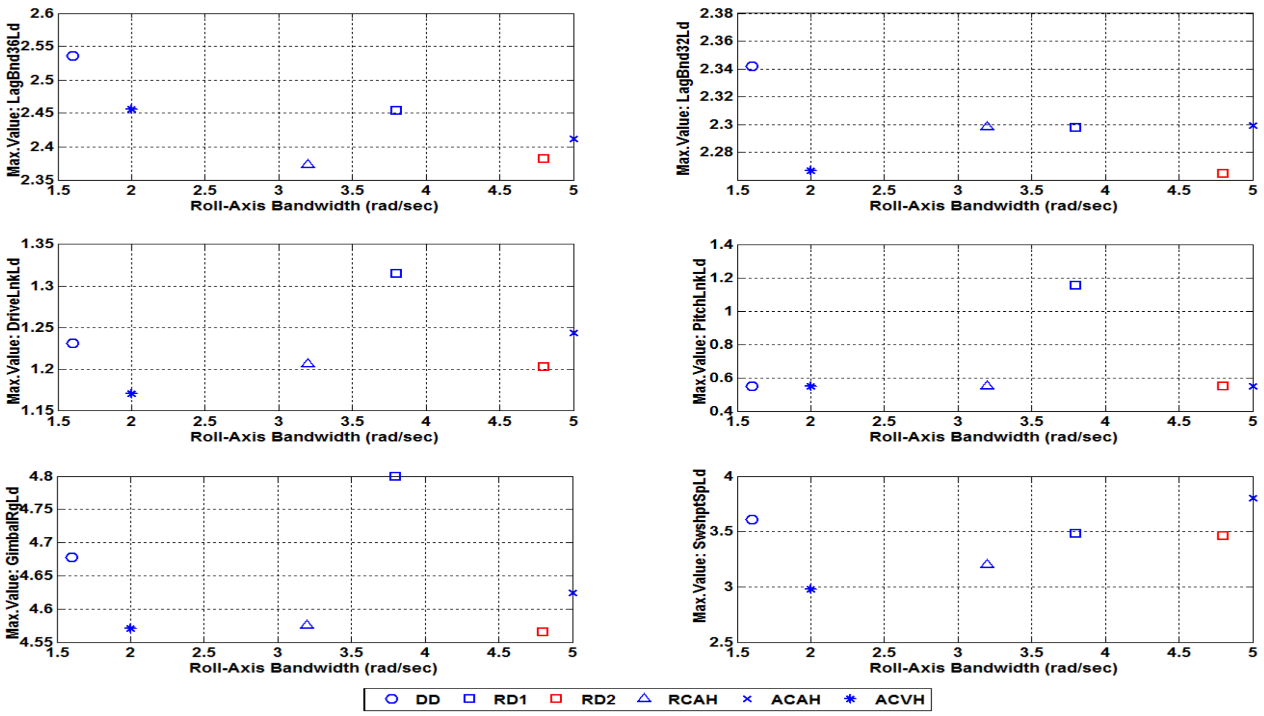

Figure 15: NRC B412 Forward Flight Roll Frequency Sweep, Correlation of Response Types to Loads

5.5 Forward Flight Correlation Observations

For comparison to the low-speed case, the correlation between component maximum oscillatory loads, control response types, under roll axis frequency sweep testing for the Forward Flight case is provided in **Figure 15**.

Observations for the Forward Flight frequency sweep test case are as follows:

A. Component Load Observations

- The Gimbal Ring exposed to the highest loading (fixed frame); the Swashplate Support loads are the lowest in the fixed frame.
- The Pitch Link is the least loaded component (rotating frame); Rotor Blade Chordwise Bending (Inboard, Station 36) is the highest loaded component in the rotating frame.
- Ranking of component loads (Lowest to Highest) is Pitch Link, Swashplate Link, Rotor Blade Chordwise Bending (Outboard, Station 132), Rotor Blade Chordwise Bending (Inboard, Station 36), Swashplate Support, Gimbal Ring.

B. Response Type Observations

- The Rate based response type associated with the highest loading in all components.
- Attitude based response type associated with the lowest loading in all components except for Rotor Blade Chordwise Bending (Inboard, Station 36) inboard.
- The Hold function of response types (RCAH, ACAH, ACVH) may associate with highest loading conditions.

C. Non-Rotating Frame (Gimbal Ring, Swashplate Support) Observations

- The lowest bandwidth response type Attitude Command Velocity Hold (ACVH) is associated with the lowest loading conditions.
- The highest bandwidth response type Rate Damped (RD1, RD2) may be associated with a spread of low, moderate, or highest loading conditions
- Rate Damped (RD1) is associated with the highest loading of all response type for the Gimbal Ring.
- The highest bandwidth response type Attitude Command Attitude Hold (ACAH) may be associated with a spread of low, moderate, or highest loading.
- The mid-bandwidth response type Rate Command Attitude Hold (RCAH) is generally associated with low loading conditions.

D. Rotating Frame Controls (Drive Link, Pitch Link)

- RD1 associated with the highest loading of all response types for the Pitch Link and Drive Link.

E. Rotating Frame Thrust Generation (Rotor Blade Chordwise Bending (S36, S132))

- Direct Drive (DDRV) is associated with the highest loading of all response types for Rotor Blade Chordwise Bending (Inboard, Station 36), Rotor Blade Chordwise Bending (Outboard, Station 132).

5.6 Flight Speed Variability Study

A study of the impact of flight speed on component loading conditions was performed to investigate the influence of parameter variability.

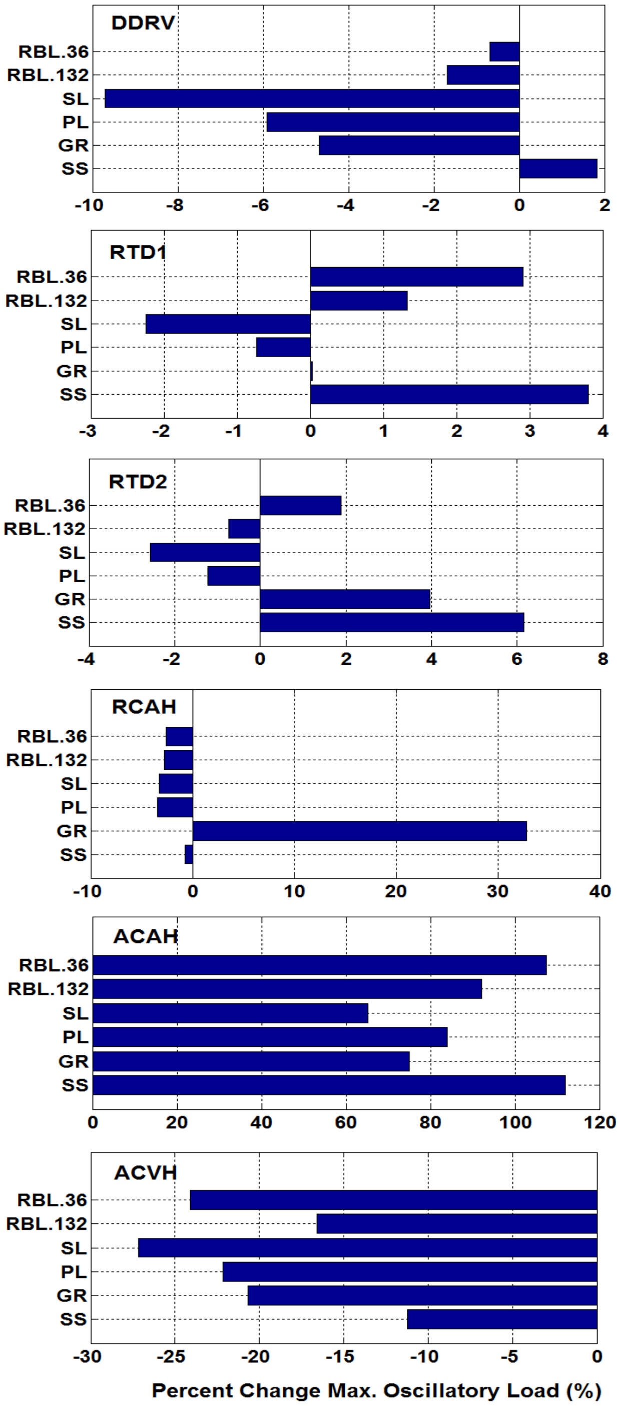

Figure 16: NRC B412 Roll Frequency Sweep Loading Comparison between Hover & Forward Flight, Percent Change of Maximum Oscillatory Component Loads for All Response Types

In this study (**Figure 16**) the percent change of maximum oscillatory loads (for all components and all flight trial response types) between hover and forward flight was investigated.

The key observations from this study indicated;

A. Rate-Based Response, High Bandwidth:

- DDRV, RD1, RD2, and RCAH response types associated with load conditions indicating positive and negative (sign) changes in maximum oscillatory loads between hover and forward flight.

B. Rate and Attitude Response, Low Bandwidth:

- DDRV and RCAH produced loading conditions the were aligned in sign changes for Pitch Link, Swashplate Link, and Blade Chordwise Loading (Inboard S36, Outboard S132) rotating frame components.

C. Attitude-Based Response:

- ACAH and ACVH were associated with load conditions indicating concurrent positive or negative (sign) changes in maximum oscillatory loads across all components.

D. General Response:

- ACAH associated with the highest magnitude percent load changes, followed by ACVH.

6. DISCUSSION

In rotorcraft flight control a representative value of pilot crossover frequency, a measure of a pilot's control input activity, is 2 rad/sec. From **Figure 8** presented earlier in this work, the ADS-33 favorable Level-1 roll-axis handling qualities boundary occurs at a bandwidth of 2.5 rad/sec. for phase delays from 0 to 125 ms. The frequency sweep task bandwidth is assumed to occur in a band of 2 to 3 rad/s.

In the following discussion, observations on the interrelationship between rotor system loading and control parameters (crossover frequency, phase delay, and bandwidth of response types) is provided.

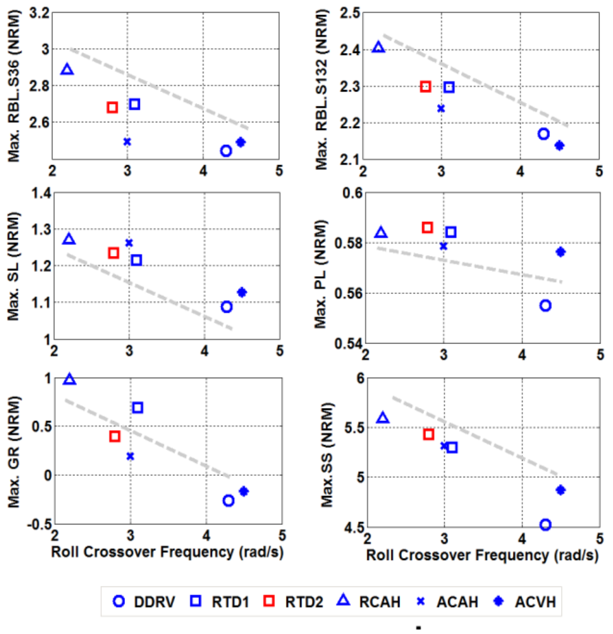

Figure 17: NRC B412 Impact of Crossover Frequency on Loads due to Hover Roll-Axis Frequency Sweeps (Note: Artificial Trend Lines)

In **Figures 17** through **20**, loading conditions as functions of crossover frequency and phase delay are provided for hover and forward flight roll-axis frequency sweep cases. For each component, the x-axis represents crossover frequency (rad/s.) (**Figures 17** and **19**) and phase delay (msec.) (**Figures 18** and **20**) while the y-axis, maximum oscillatory load (normalized). Artificial trend-lines may be applied to support discussions.

In hover (**Figure 17)**, a prominent decreasing trend for all instrumented components is observed that is not present in forward flight. In hover, this trend indicates maximum loading for all components associate with RCAH response at about 2 rad/s. crossover frequency. Minimum loading associates with DDRV or ACVH responses at crossover frequencies greater than 4 rad/s.

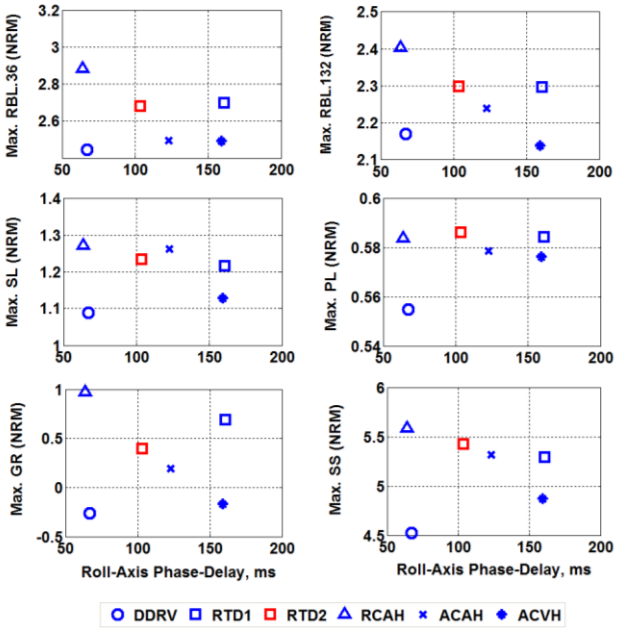

Figure 18: NRC B412 Impact of Phase Delay on Loading due to Hover Roll-Axis Frequency Sweeps

Continuing in hover (**Figure 18)**, trends are less prominent for phase delay relationships. For 50 to 100 ms. of phase delay, maximum loads for all components, associate with RCAH response while minimum loads, DDRV response. For 100 to 150 ms. of phase delay, maximum loads associate primarily with RTD2 response, while minimum loads, ACAH response. For 150 to 200 ms. of phase delay, maximum loads associate with RTD1 response, while minimum loads, ACVH response.

Relative to crossover frequency and phase delay (**Figures 17** and **18**), in the fixed frame of the rotor system the highest magnitude loads are observed in the swashplate support (SS) and lowest in the gimbal ring (GR). In the rotating frame of the rotor system, highest magnitude loads occurred at the inboard station of the rotor blade (RBL.S36) while the pitch links (PL) are exposed to the lowest magnitude loading.

Proceeding to forward flight assessments (**Figures 19** and **20**), overall trends are less prominent. An increasing trend exists for the rotor blade while in the fixed frame, loading is complex. In forward flight (**Figure 19**) for crossover frequency ranges of 2 to 3 rad/s., loading associated with RCAH and RTD2 shows loading equivalences for all components except for the swashplate support (SS) and outboard rotor blade chordwise bending (RBL.S132). For ranges of 3 to 4 rad/s., RTD1 response tends to associate with higher loading except for the swashplate support (SS) and outboard rotor blade chordwise bending (RBL.S132). For crossover frequencies greater than 4 rad/s., highest and lowest loading associates with DDRV and ACVH responses, respectively.

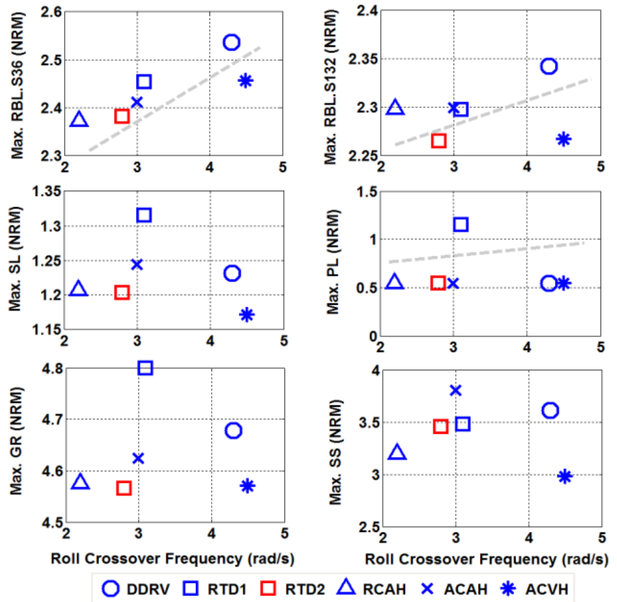

Figure 19: NRC B412 Impact of Crossover Frequency on Loading due to Forward Flight Roll Frequency Sweeps, (Note: Artificial Trend Lines)

With respect to phase delay relationships in forward flight (**Figure 20**), several trends observed in hover are inverted. For 50 to 100 ms. of phase delay, maximum loads for all components, associate with DDRV response while minimum loads, RCAH response. For 100 to 150 ms. of phase delay, maximum loads associate with ACAH response, while minimum loads, RTD2 response. As in hover, for 150 to 200 ms. of phase delay, maximum loads for all components associate with RTD1 response, while minimum loads, ACVH response.

Relative to crossover frequency and phase delay (**Figures 19** and **20**), in opposition to hover and in the rotor system's fixed frame the highest magnitude loads are observed in the gimbal ring (GR) and lowest in the swashplate support (SS). As in hover, for the rotating frame of the rotor system, the highest magnitude loads occurred at the inboard station of the rotor blade (RBL.S36) while the pitch links (PL) are exposed to the lowest loading.

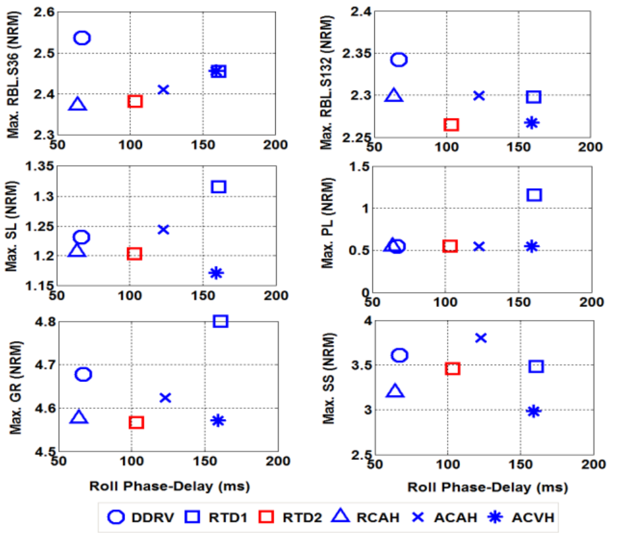

Figure 20: NRC B412 Impact of Phase Delay on Loads due to Forward Flight Roll Frequency Sweeps

7. CONCLUSIONS

In this research, interrelationships between flight control response types and rotor system loading conditions were explored through roll-axis frequency sweep excitation of the NRC Bell412 ASRA soft-inplane hingeless rotor helicopter. It was configured with a Flight Loads Measurement Suite as well as rate and attitude based inner-loop controls laws (Level 1 to 2 or 1.5 to 5 rads/s. bandwidths; 2 to 4.5 rads. crossover). Key observations include:

- Coherence Results: Coherence exists between pilot inputs, FBW actuation, rotor control component loads (non-rotating, rotating frames), hub dynamics, and vehicle rates. Hub degrees-of-freedom damping and blade (reflex, trim) manage excitation of 1^{st} chordwise regressive mode.
- Spectrographic Results: Instrumented rotor component spectra of rate, attitude, and hold -based response types differ, based on vehicle agility, airspeed, and attitude retention air loading.
- Correlation Results: Rate and Attitude -based responses associated with the highest and lowest loading, respectively, for hover and forward flight.
- Comparative Results: Rate-based responses generated mixed sign percentage load changes while Attitude-based responses generated concurrent sign load changes between hover and forward flight. Attitude command with -hold (attitude, velocity) associated with the greatest load changes between hover and forward flight.
- Projections: From this investigation, **Table 4** summarizes the author's key projections on helicopter flight loads research as well as critical conditions for Conventional, Non-Conventional (Future Vertical Lift, Urban Air Mobility, e-VTOL), and Highly Augmented (Autonomous/Intelligent Flight Systems) rotorcraft. These projections are critical as we train and interface pilots to utilize next generation vertical lift flight systems.

Table 4: Summary Comments, Vertical Lift Loading

Vehicle Type	Critical Technology Requirements and Loads-based Projections
Conventional Rotorcraft	▪Continued requirements for FLMS/RSMS research (i.e.; embedded sensors, state estimation, high-order control laws) ▪Continued requirements for FLMS/RSMS industry use for vehicle design and life cycle management
Non-Conventional Rotorcraft & Future Vertical Lift	▪High agility and unconventional mission tasks capabilities may aggravate loading conditions ▪Highly adaptive/varied vehicle configuration changes may aggravate loading conditions (external kits and payloads, novel propulsion and lift systems)
Urban Air Mobility & e-VTOL	▪Flight in varying conditions (gusty environments (i.e.; urban areas) may aggravate loads)) ▪Configurations may be susceptible to loads aggravation (multi-rotor design, composite materials/structures, adaptive/variable flight systems)
Highly Augmented Rotorcraft	▪Rate-based flight control may result in load aggravation (quickness/agility relative to inertia, G-loading, & CG) ▪Attitude-based flight control may result in load aggravation (retention of vehicle state; loading due to airspeed) ▪Hold-based flight control may result in higher load aggravation (retention of vehicle state (attitude, velocity) relative to high load control baseline)
Autonomy & Intelligent Flight	▪Advanced outer-loop functions may aggravate loading conditions (trajectory/path following, avoidance) ▪Flight control transitions may aggravate loading conditions (mode changes, in-loop/on-loop/off-loop, pilot intervention actions)
Pilotage	▪With the advent of flight autonomy and intelligent flight systems, pilot strategies may aggravate loading conditions (changes in pilot experience requirements (maintenance vs. supervisory vs. test pilotage); intervention-based control in autonomous/intelligent aircraft; mis-use of inner and outer loop flight control functions (stick stirring, etc.)

NOTES: Terminology - 'Load aggravation' may imply high load magnitudes, initiation of aeromechanical instabilities, and/or excitation of resonances

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10. REFERENCES

1. Kufeld, R., UH60 Air-load Tutorial, NASA, 2009.
2. Rozak, J.N., Ray, A., Robust Multivariable Control of Rotorcraft in Forward Flight: Impact of Bandwidth on Fatigue, American Helicopter Society - Journal, 1998.
3. Goldstein, K., et al., V22 Control Law Development, American Helicopter Society - Forum 42, 1986.
4. Wulff, O., Fletcher, J.W., et al., Flight Test of Load Alleviating Control and Tactile Cueing, American Helicopter Society - Forum 66, 2010.
5. Adams, D.O., Flaw Tolerant Safe-Life Methodology, NATO Research and Technology AVTP Meeting, 1999.
6. Andrews, J.R., Augustin, M., Advanced CBM Technologies For Helicopter Rotor Systems, American Helicopter Society - Forum 66, 2010.
7. Alexander, M., Gubbels, A.W., et al., Development of a Rotor State Measurement System for the NRC Bell412 ASRA, American Helicopter Society - Forum 59, 2003.
8. Cresap, W., Design and Development of the Model 412, American Helicopter Society - Forum 36, 1980.
9. Alexander, M., Carignan, S., Gubbels, A.W., et al.; Integration of a Flight Loads Measurement Suite into the NRC Bell412 ASRA; 36th European Rotorcraft Forum, 2010.
10. Anonymous; ADS-33 Military Helicopter Handling Qualities Specifications, 2000.
11. Johnson, W., Helicopter Theory, Dover, 1980.
12. Jacklin, S., Mort, R., et al., Comprehensive Helicopter Rotor Instrumentation, AIAA ASME Meeting, 1992.

11. BIOGRAPHY

Marc Alexander is a Senior Canadian Government Flight Scientist specializing in vertical lift flight sciences research and testing. He is employed by the National Research Council of Canada's Flight Research Laboratory (NRC-FRL) and tasked by its Rotary Wing and Flight Controls Group (Ottawa, Canada). He possesses previous experience with the Royal Canadian Air Force (Department of Technical Airworthiness and Engineering Support, Ottawa) and the Aeromechanical Systems Department (United Technologies Research Center, Hartford).

Over Marc's 15-year career as a specialist in applied flight sciences, he has developed diverse experimental flight test expertise in areas of controls, dynamics, flying/handling qualities, and aeromechanics. He applies NRC's variable stability fly-by-wire helicopters in flight research involving autonomous systems development, handling qualities optimization, productivity and safety enhancement, vehicle design, and aircrew education.

Possessing a Canadian Graduate education in Aerospace Engineering from Ryerson University and University of Toronto Institute for Aerospace Studies, he is active in the international vertical lift community. He participated as the Technologies Committee Lead of the NATO AVT-245 Future Rotorcraft Requirements Working Group and upcoming NATO ST-009 on technical support for Next Generation Rotorcraft Capability development. Marc is a Volunteer, Test and Evaluation Committee Member, and Life Time Member of the Vertical Flight Society.