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INTEGRATION OF A FLIGHT LOADS MEASUREMENT SUITE INTO THE NRC FLY-BY-WIRE BELL 412 ADVANCED SYSTEMS RESEARCH AIRCRAFT

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ABSTRACT

As part of a military flight loads research program, the National Research Council of Canada - Flight Research Laboratory integrated a flight loads measurement suite (FLMS) into the NRC-FRL Bell 412 Advanced Systems Research Aircraft. In the rotor system rotating frame, main rotor blade, pitch link, and swashplate link loads were captured. In the control system's non-rotating frame, swashplate support, gimbal ring, and boost tube cylinder loads were captured. FLMS flight testing demonstrated airworthiness and reliable data acquisition, as well as valid and consistent measurements. Data acquired had a signal-to-noise ratio of 35 dB in primary response with a structural spectrum of up to 100 Hz. Initial testing provided confidence in application of the FLMS in flight research associated with life cycle management, high bandwidth control, and structural response of fly-by-wire rotorcraft.

NOMENCLATURE

AETE	Aerospace Engineering Test Establishment
ASRA	Advanced Systems Research Aircraft
FBW	Fly-By-Wire
FCC	Flight Control Computer
FLMS	Flight Loads Measurement Suite
FRL	Flight Research Laboratory
HES	Hall Effect Sensor(s)
NRC	National Research Council
RSCM	Rotor State Computer Module
RSMS	Rotor State Measurement System
Vne	Vehicle Never-Exceed Speed
BB()	Beamwise Bending, Instrumented Rotor Blade
BT()	Boost Tube Cylinder, Instrumented
CB()	Chordwise Bending, Instrumented Rotor Blade
Col	Collective
DISP.	Displacement, Hall Effect Sensor Measurement
GR	Gimbal Ring, Instrumented
Lh, Rh	Left Hand, Right Hand
MOM.	Moment, Rotor Blade Bending
NORM.	Normalized, Loads Data (Also **NRM.**)
PL	Pitch Link, Instrumented
p	Integer value of flight load harmonic response
SL	Swashplate Link, Instrumented
SS	Swashplate Support, Instrumented
S36	Inboard Main Rotor Blade Station, S36
S132	Outboard Main Rotor Blade Station, S132

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INTRODUCTION

Flight loads measurement technology plays a critical role in validation of vehicle design theory, substantiation of production vehicle certification methodology, and experimental flight research.

Loads measurements verify knowledge of the interaction between helicopter flight control and structural response in high bandwidth helicopters. Rozak et al. [1] 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 handling techniques designed to limit flight loads. Industry applications of these techniques in fly-by-wire (FBW) rotorcraft include Bell-Boeing V-22 structural load alleviation [2] and Sikorsky load alleviation control [3] for the S-92F, UH-60M, and CH-53K.

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. The UH-60 Airloads Program [4], a flight loads survey featuring extensive instrumentation, has been central in many validation studies of rotorcraft analytical code for over a decade.

In context of the rotorcraft structural life cycle, loads measurement systems and data are most critically applied at the certification stage. Loads data provides a basis for specification validation and component integrity analysis during flight test qualification. Furthermore, manufacturers utilize this data to derive component fatigue life. Usage monitoring techniques were developed to evaluate component life during helicopter operations. Two methods are Flight Condition Monitoring (which addresses evaluation of maneuver severity) and Flight Loads Monitoring (which addresses measurement of component loads). 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) [5]. Bell Helicopter has been developing techniques and technologies for condition based maintenance for application to its rotorcraft production line [6]. Applications include structural health monitoring, diagnostics, and prognostics. 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.

Loads measurement systems have also played key roles in rotorcraft flight research. The NRC Flight Research Laboratory operates two experimental fly-by-wire variable stability rotorcraft; the Bell 205A Airborne Simulator and the Bell 412 Advanced Systems Research Aircraft (ASRA). Integration of specialized state measurement technology into these platforms was required for safety monitoring as well as on-going research. To this end, NRC-FRL integrated Rotor State Measurement System (RSMS) technology into these platforms. In the case of the Bell 205A, rotor flapping technology was developed to monitor teetering rotor hub flap limits to prevent mast contact during fly-by-wire engagements. In the Bell 412 ASRA, the RSMS was a vital technology used to extend research capabilities. NRC-FRL integrated sensors for measuring hingeless rotor hub yoke and blade root displacement dynamics using Hall Effect Sensors (HES) [7]. Target research areas included system identification and high bandwidth control.

In 2007, the NRC-FRL embarked on a flight research program in rotorcraft life cycle management for the Canadian Forces. The objective was to assess the interrelationship between flight control response types and rotorcraft structural loads. To perform this task, the NRC-FRL integrated a flight loads measurement suite (FLMS) into the Bell 412 ASRA that consisted of existing RSMS technology as well as instrumented components on loan from the Canadian Forces Aerospace Engineering Test Establishment (AETE). The FLMS design enabled monitoring of both rotating and non-rotating frame component loads.

The purpose of this paper is to describe the FLMS hardware components and associated instrumentation, the methodology applied in their calibration and airworthy integration, and the development of supporting software. Time and frequency domain assessments of data gathered during a recent 13-maneuver low-speed flight test engagement is provided to reveal data quality.

TEST AIRCRAFT

The Bell 412 Advanced Systems Research Aircraft is an airborne simulator derived from the Bell 412HP helicopter. This medium size, twin-engine helicopter has a gross take-off weight of 11,900 lbs., and is powered by a Pratt & Whitney PT6T-3BE Twin-Pac turboshaft engine rated at 1800 SHP. The aircraft features a 4-bladed soft-inplane hingeless rotor system which generates high control power and low response time delays. Installed in the ASRA is an experimental simplex fly-by-wire control system used for research purposes. The single string architecture consists 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 control software.

The FLMS measured the influence of flight control response types on structural loads in the rotating and non-rotating frames of the rotor and flight control systems. Its sensors integrated into the main rotor and control hardware as well as interfaced with the aircraft data acquisition systems. The Bell 412 ASRA, as well as its hingeless rotor hub and controls, are depicted in Figure 1.

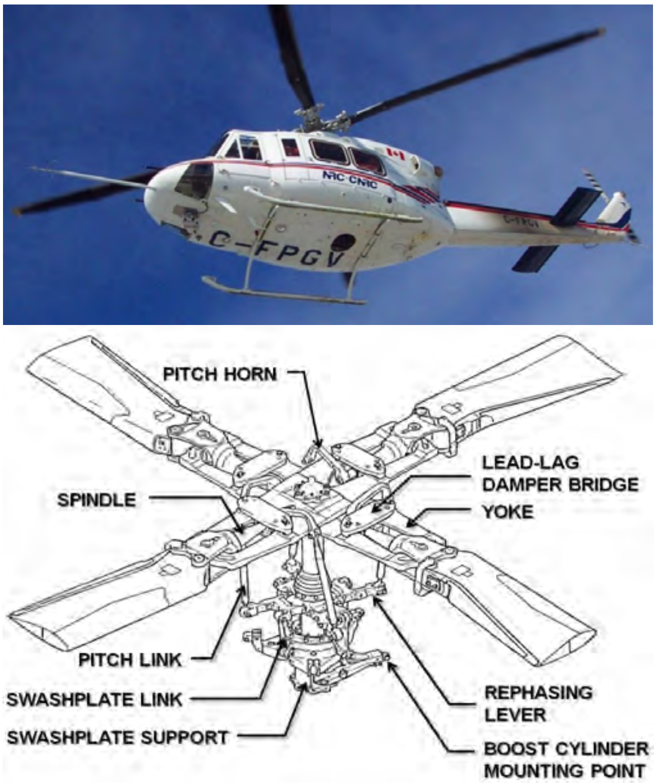

Figure 1: NRC-FRL Bell 412 ASRA, Hingeless Rotor Hub, and Rotor System Controls [8].

The 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 [8].

For this research investigation, the Bell 412 ASRA was used to emulate vehicle response types characteristic of a military FBW helicopter such as the S-92F. The Canadian Forces will operate the CH-148 (a military variant of the Sikorsky S-92F) FBW helicopter in the future. The control response types shown in Table 1 were programmed into the aircraft's flight control computer to provide selectable control modes and bandwidths.

CONTROL RESPONSE TYPES				
	ROLL	PITCH	YAW	HEAVE
GVE	DIRECT DRIVE (OPEN LOOP RESPONSE)		RD	O/D/HH
GVE	RATE DAMPED		RD	O/D/HH
GVE	RATE COMMAND ATTITUDE HOLD		RD	O/D/HH
GVE	ATTITUDE COMMAND VELOCITY HOLD		RD	O/D/HH
DVE	ATTITUDE COMMAND ATTITUDE HOLD		RD	O/D/HH
DVE	TRANSLATIONAL RATE COMMAND		RD	O/D/HH
RD = RATE DAMPED GVE = GOOD VISUAL ENVIRONMENT DVE = DEGRADED VISUAL ENVIRONMENT O/D/HH = OPEN-LOOP / DAMPED / HEIGHT-HOLD				

Table 1: Bell 412 ASRA Flight Control Response Types

INSTRUMENTATION REQUIREMENTS

A survey of loads in the rotor and control system components was required for this life cycle research. Specifically to support the rotorcraft loads analysis, rotating frame loads (main rotor blade, pitch and swashplate links) and non-rotating frame loads (swashplate support, gimbal ring, and boost tubes) were monitored. Loads occurring in these components arise because of an interaction between flight dynamics, control response, and rotorcraft aeromechanics [9].

The Bell 412 composite blade dynamics are an important factor in determining airload propagation throughout the rotor and swashplate system. For example, elastic blade couplings strongly affect rotor lag mode stability. The data obtained from chordwise blade strain measurements would aid in determining load aggravation or resonance. Swashplate linkages transfer direct oscillatory loads from the main rotor blades and their torsion dynamics. The loading of the pitch links are reactions from blade aerodynamic and dynamic pitching moments. Alternating pitch link load characteristics show rapid increase in magnitude at blade stall or when severe compressibility occurs. These loads indicate stall, flutter, and maneuvering load characteristics. Bell 412 swashplate support and gimbal ring loads provide indications of load propagation through the lower swashplate system. Boost tube actuator and cylinder loads are critical measures of design limit loads associated with severe flight control inputs and vehicle maneuvers.

This monitoring set would complement existing NRC-FRL Bell 412 ASRA hub instrumentation (hub yoke flapping and blade root spindle lead-lag displacements, blade azimuth position) associated with the aircraft's rotor state measurement system. The following requirements were central to the FLMS design architecture and its operation:

1. *Measurement Requirements*: Ability to sense and record rotor and flight control system structural response including rotating and non-rotating frame loads (axial, vertical, shearing) and moments (bending).
2. *Integration Requirements*: Minimal maintenance and minimal repetitive installation/removal cycle workloads.
3. *Data Quality Requirements*: Ability to reliably and repeatedly replicate Bell Helicopter design flight loads survey data in both the time and frequency domain.
4. *Airworthiness Requirements*: A systems design that would not interfere with vehicle rotor or control dynamics, affect handling qualities, or limit operations.
5. *System Compatibility Requirements*: A system that was fully compatible with existing aircraft instrumentation (rotating and non-rotating frame) and flight research systems (FBW control and computing).

To meet these requirements, the NRC-FRL acquired instrumented equipment on loan from Canadian Forces AETE which operated an experimental Bell 412. This provided access to components originally instrumented by Bell Helicopter for production flight loads surveying. NRC-FRL then designed interface technology between this equipment and Bell 412 ASRA flight research systems.

INSTRUMENTATION DESCRIPTION

The FLMS architecture consisted of sensing, computation, and data management elements that are described in the following sections.

FLMS Architecture

The FLMS utilized the ASRA rotor state measurement system (RSMS) for two primary purposes. First, measured strain gauge signals were digitally conditioned. Second, the RSMS was used to wirelessly transmit data from the rotor rotating frame to the fuselage non-rotating frame. The RSMS transmitter (Figure 2) and receiver were based on the KMT CT-16 Rotate™ measurement system.

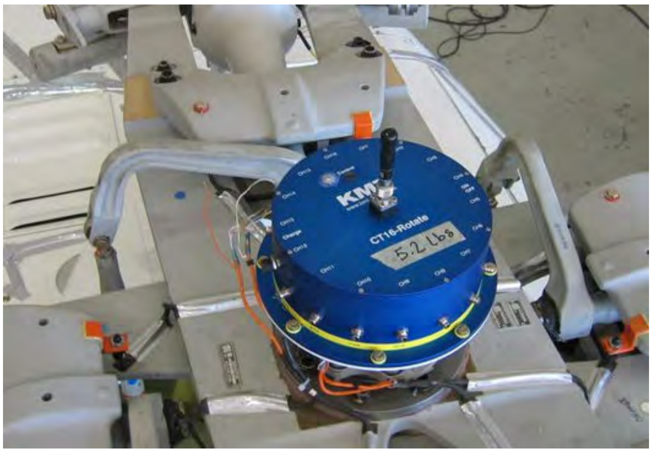

Figure 2: Bell 412 ASRA RSMS Hub Mounted Transmitter

As depicted in Figure 3, the major components of the FLMS architecture included the RSMS architecture, rotating and non-rotating frame instrumentation, rotor state computing, and the aircraft's existing data and computing network.

The primary processing device in the rotor rotating frame was the KMT CT-16. This device captured data in analog format, performed analog-to-digital conversion, and transmitted this data via radio frequency. The device collected 14 channels of data consisting of strains (blade strains, pitch link strains, swashplate link strains) and displacements (hub yoke flapping displacements, blade root spindle lead-lag displacements). The CT-16 was designed with separate channels to support both voltage and strain signals. For the NRC-FRL dual RSMS and FLMS application, displacement sensing Hall Effect Sensors were processed by voltage channels. Alternatively, 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, by quarter wave whip antennae. A single board computer known as the rotor state computer module (RSCM) processed RSMS data and transmitted this data to the flight control computer. The RSCM acquired raw flapping and lead-lag data and applied calibrations. The module also utilized an azimuth sensor signal to transform RSMS data to the non-rotating frame. The discrete HES used for the azimuth measurement was connected to a custom interface board that generated an interrupt in the RSCM each time the sensor was activated.

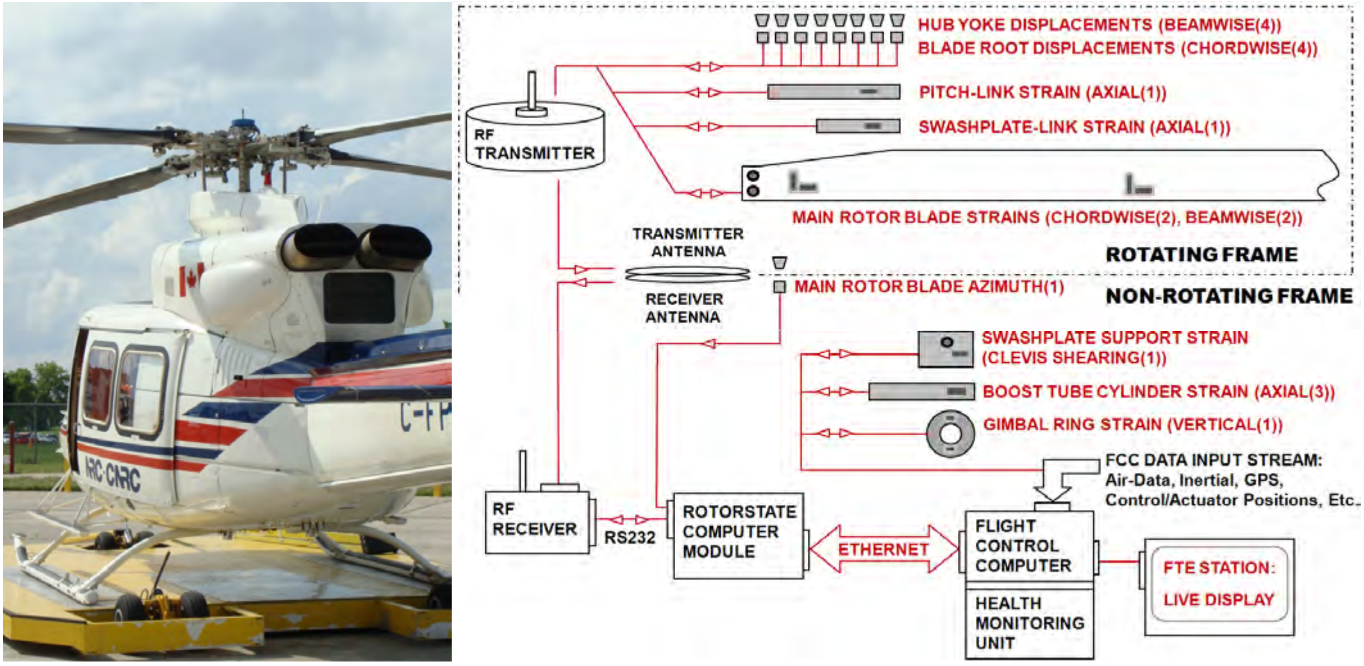

Figure 3: Integrated Bell 412 ASRA Flight Loads Measurement Suite (FLMS) Architecture

A Kalman filter algorithm was then used for real-time estimation of the rotor states including flapping, lead-lag, tilt, coning, RPM, and azimuth. Data output from the RSMS receiver to the RSCM was in RS232 form at 38400 baud. RSMS data was transmitted to the fuselage mounted receiver in the non-rotating frame at a data rate of 1633 Hz.

The FLMS instrumentation included of a series of strain gauge measurements from rotating and non-rotating components. The rotating component strains were associated with an instrumented main rotor blade as well as rotor control pitch and swashplate links. The FLMS utilized the CT-16 internal 5 V power supply for instrument excitation and amplification of these rotating frame measurements. The non-rotating component strains were associated with the lower swashplate assembly, and its gimbal ring and swashplate support. Excitation and amplification of these non-rotating frame measurements was performed by MCR™ strain-gauge amplifiers installed in the aircraft's aft cabin. The units converted microvolt bridge signals into measurable voltage signals. The amplifiers featured constant voltage excitation supplies, differential amplification, and signal-conditioning filters. Additionally, the Bell 412 ASRA had instrumented swashplate boost tube cylinders for monitoring non-rotating control system loads.

In terms of data 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 system maintenance of the RSMS), 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 such as the flight test engineering station monitor.

Main Rotor Blade Instrumentation

The Bell 412 four-bladed hingeless rotor hub is formed by stacking two identical titanium yokes (see Figure 1). The main rotor blade was mounted on the upper yoke stack. The main 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.

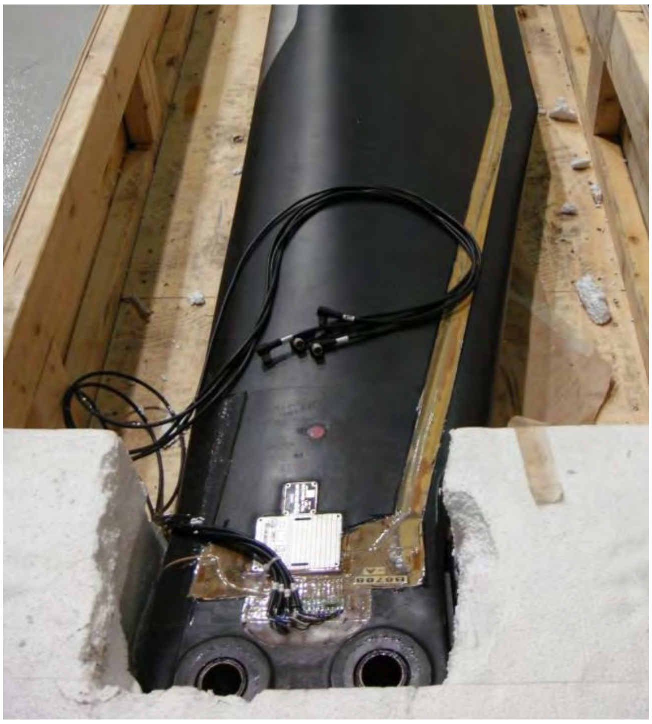

Figure 4: Bell 412 Instrumented Main Rotor Blade

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. All wiring was run along the blade's trailing edge with soldering terminals adjacent to each gauge to ease maintenance and replacement.

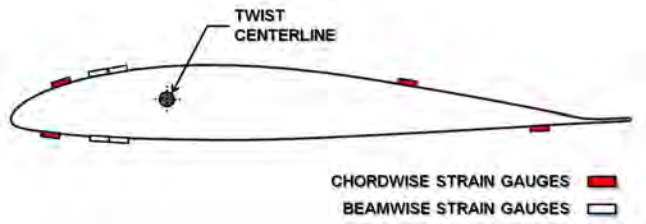

Figure 5: Bell 412 Instrumented Blade Section, Station S132

Pitch Link Instrumentation

The pitch link (Figure 6) was instrumented with a single standard strain gauge bridge for measurement of link axial load. The bridge's gauge pair was located approximately four inches from the link rod end and mounted on the external link tube surface. 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 the boost cylinders, and axial loads from control system cyclic and collective blade pitch commands.

Figure 6: Bell 412 Instrumented Main Rotor Pitch Link

Swashplate Assembly Instrumentation

The swashplate assembly shown in Figure 7 was central to a number of the 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. The bridge's gauge pair was located approximately two inches from the link rod end and mounted on the external link tube surface. 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 measurement of ring vertical load. The bridge locates two pairs of gauges on the circumference of the ring, with each pair lying on the ring's diameter reference line. The swashplate support was instrumented with a single standard strain gauge bridge for measurement of the gimbal ring attachment clevis lateral shearing load. The bridge locates two pairs of gauges on the clevis to measure outboard and inboard bending.

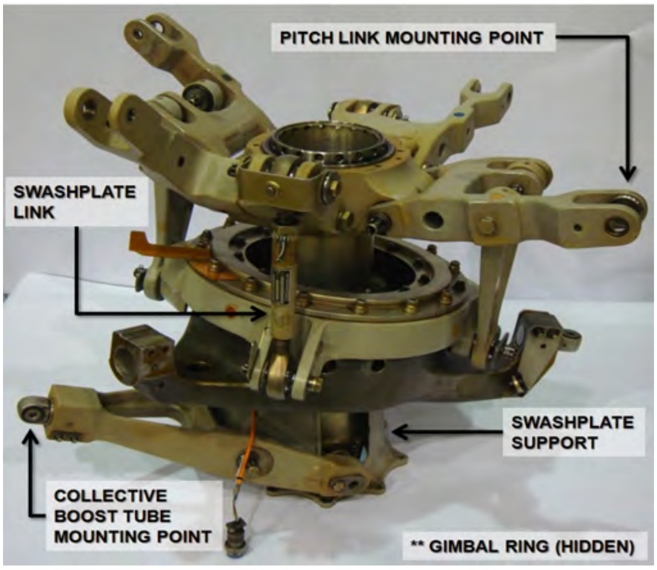

Figure 7: Bell 412 Instrumented Swashplate Assembly

CALIBRATION METHODOLOGY

NRC-FRL calibrated all instrumentation using a method that incorporated off-line and on-line phases. As described in the following discussion, off-line phases referred to component bench-testing, while on-line phases referred to onboard aircraft hardware- and software-in-the-loop procedures.

Rotor State Measurement Systems Calibration

The KMT CT-16 based rotor state measurement system was calibrated off-line by verifying Fluke™ calibrator voltage signals injected into the eight voltage and six strain channels. Signals were processed internally by signal conditioning cards. In on-line calibration, the system was installed on the aircraft where measurement voltage simulation, wireless data transmission, rotor state computer module processing, and LABVIEW™ data display assessments were performed.

Displacement Sensor Calibration

Hall Effect Sensors (HES) respond to excitation from reference magnets with proportional analog voltage outputs. The HES for main rotor yoke flap and blade root lead-lag displacement measurements were tuned and calibrated off-line through bench testing. This involved setting digital sensor process registers and performing on-line gap displacement calibrations. Registers included clamping voltage (for failure detection), temperature coefficients (for temperature dependence of magnetic strength), sensitivity (for digital signal processing multiplication), filtering (for digital low pass filtering), voltage (for signal calibration), and range (for analog-to-digital converter magnetic range). The on-line calibration involved creating displacement to voltage calibration curves for the HES units as installed under the influence of blade deflection. This was done by incrementally varying HES magnet to sensor gap spacing. This gap spacing was accurately measured relative to turning HES mounting screws and calculating linear travel due to thread pitch advancement. Typical HES calibration curves are depicted in Figure 8. These trends depict non-linearity owing to the effect of diminishing magnetic excitation with increasing sensor gap distance.

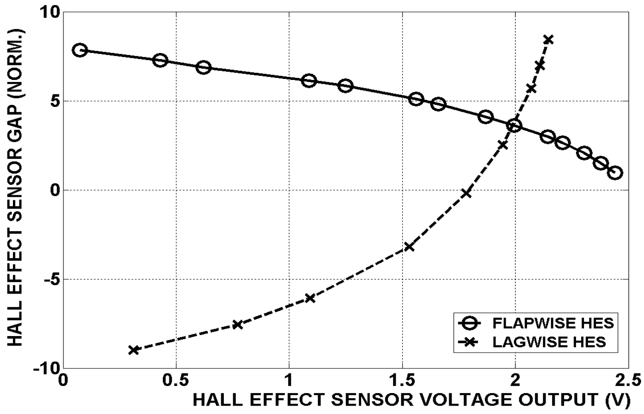

Figure 8: Typical Hall Effect Sensor Calibration Curves

<u>Strain Gauge Calibration</u>

The strain gauge instrumentation for components including the main rotor blade, pitch and swashplate links, gimbal ring, and swashplate support was originally installed and calibrated by Bell Helicopter. This industrial calibration was performed mechanically. Although the exact calibration procedure is unknown, calibrated loads are typically applied to the components. Relative load to component orientation dictates the resulting structural degree-of-freedom response to the applied load, such as in axial, shearing, torsion, or bending moment forms. Procedures to measure and correct off-axis loading (due to the method of load application or component inherent structural coupling) are applied.

AETE provided original reference calibration data with the equipment loan that enabled NRC-FRL to develop and perform a research calibration process. As this strain gauge calibration was performed digitally versus mechanically, several assumptions were made:

1. *Application Scope*: The FLMS would be utilized as a system for interpreting load trends and characteristics until such time as component calibrations could be validated by Bell Helicopter.
2. *Calibration Method*: The FLMS calibration would differ from the original calibration because of factors such as changes in resistance due to NRC-FRL wire harnessing and the application of different voltage amplification systems. The calibration method would mimic instrumentation response from Bell Helicopter data.
3. *Error Magnitude*: The most significant error in the loads measurement would be associated with analog-to-digital conversion bit noise contamination. Figure 9 provides estimates of the error magnitudes on measured loads.

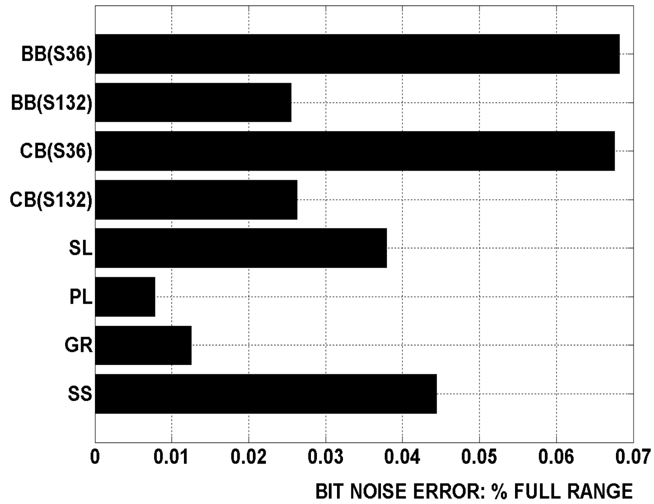

Figure 9: FLMS Instrumentation Bit Noise Error

The digital calibration first involved offline processing, where a Fluke™ process calibrator was used to inject signals directly into component strain gauges to verify wiring and installation integrity, bridge electrical voltage readings, and gauge resistances.

In static online processing with components installed on the aircraft, the Fluke™ process calibrator was used to mimic strain gauges as implemented into the rotor state measurement system. Here, injected voltage simulated measured strain gauge voltage signals. This created component specific error functions between original Bell Helicopter and the current calibrations. These were analyzed and set to null using known excitation voltage, gain, and offset parameters. These parameters could also be used for post-flight conversion of voltage measurements to engineering units by creating calibration coefficients. A typical component strain gauge calibration curve is depicted in Figure 10. As is evident, these trends depicted the same linearity seen in Bell Helicopter calibration data owing to the direct relationship between applied load and strain gauge response.

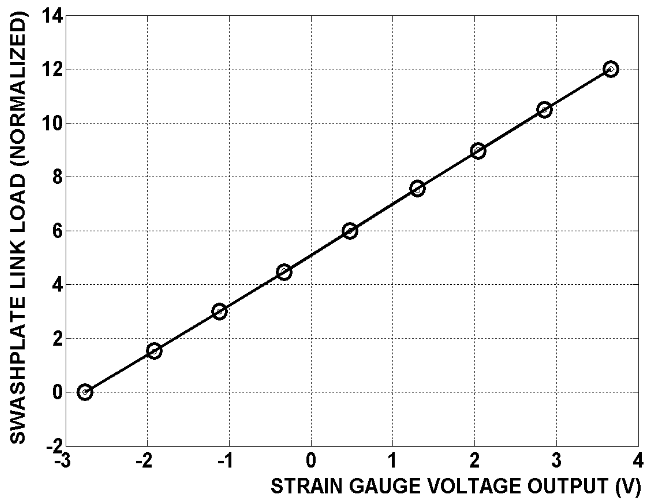

Figure 10: Typical Strain Gauge Calibration Curve

Software Development

To support research applications, a series of software utilities were developed to enable more efficient and effective use of the flight loads data set. This software included on-line and off-line applications. In on-line format, live LABVIEW™ software enabled aircrew to access measured data. In off-line format, MATLAB™ utilities were developed to allow time and frequency domain analysis.

Live Display Software

A data display was developed for integration into the Bell 412 ASRA flight test engineering station. This live LABVIEW™ utility displayed both RSMS and FLMS data parameters through Ethernet packet structures accessed via the Bell 412 ASRA FCC network. The display format in the flight test engineering station allowed users to view multiple parameters or to select individual parameters for singular display. This display was vital for performing functional checks of FLMS operation.

Data Reduction Software

A MATLAB™ based utility was developed for post-flight analysis of flight loads data. The utility provided a number of sub-routines for data reduction. Analyses were developed to coincide with those typical of the rotor aeromechanics and airloads research domain [4],[9]. Analyses included data quality assessments (signal-to-noise, etc.), load statistics assessments (cycle counting, maximum, minimum, average, etc.) and harmonic analyses (spectrum characterization). Data plotting utilities included polar surface, 2-axis, and 3-axis formats for time and frequency domain assessments. This software made use of MATLAB™ tools and several utilities are described here in overview.

Harmonic Analysis: This utility allowed the user to create a variety of time and frequency domain plots for assessment of the loads data harmonic spectrum. The procedure accepted input data at the specified sampling rate, computed the Power Spectral Density (PSD) or Fast Fourier Transform (FFT) of the signal, and calculated the peak-to-peak signal in frequency bands corresponding to fundamental harmonics of the Bell 412 main rotor system. To do this, a fourth-order digital Thompson-Butterworth filter of ±0.5 Hz around each rotor frequency and harmonic was applied. Data statistics such as standard deviation of nominal or filtered signals could be assessed. Finally, the frequency (PSD or FFT) or time (Time History) domain response of the analysis could be plotted. To eliminate phase lag issues, options for single forward as well as dual forward and backward pass filtering were available.

Polar Surface Plot: This utility allowed the user to develop polar plots of rotating frame component data. The data could be plotted between set radii for set polar angles based upon a plot type (mesh or surface) specification. In addition, standard or user-specified polar grid formats were available to define grid appearance (such as line type, grid format, tick format, radii or angle labeling, etc.). A sample polar surface plot for Bell 412 rearward flight main rotor blade beamwise bending data is shown in Figure 11.

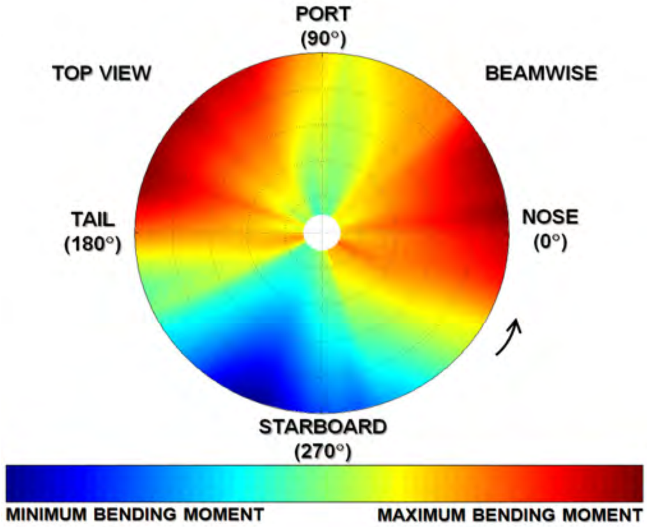

Figure 11: Polar Surface Plot, Beamwise Blade Bending Data

Cycle Plot: This utility allowed the user to develop 3-axis plots (or waterfall plots) where the two independent variables are rotor rotating frame azimuth and component loads data. The alignment of azimuthal time histories from single revolutions from a given time period allowed assessments of event repeatability (steady state data), event dissimilarity (unsteady state data), and the evolution of event characteristics.

Offset Plot: This utility allowed the user to create a 2-axis plot featuring ordinate offsets when plotting multiple cycles of rotor rotating frame component data versus a second independent variable. The offset eliminated data overlapping such that the stacked trends revealed event sequences. This plot was useful for more critical assessment of 3-axis cycle plot information.

Rainflow Analysis: Fatigue damage assessment is based upon a statistical analysis of load cycles. The Rainflow Analysis utility allows the user to perform cycle counting analysis. The analysis applies the rainflow cycle counting algorithm that is widely used in fatigue life assessment of structures under non-constant amplitude loading. Applied to the FLMS strain data, the utility can extract load cycles and half-cycles with different amplitudes and mean values. A sample cycle histogram for Bell 412 rearward flight main rotor blade beamwise bending data is shown in Figure 12.

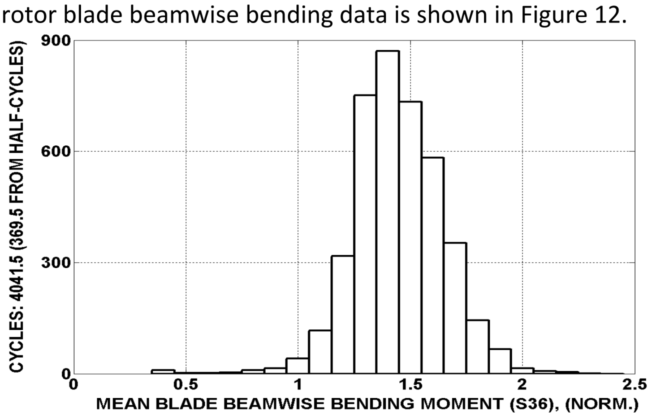

Figure 12: Cycle Histogram, Beamwise Blade Bending Data

The following sections provide an assessment of flight data using several of these analytical formats.

FLIGHT TEST QUALIFICATION

Experimental instrumentation can cause destabilizing aerodynamic and inertial response in rotor and control systems that have been noted in previous Bell 412 research [10]. A dedicated qualification program addressed both FLMS airworthiness and data quality. During the airworthiness portion, aircrew assessed vehicle ride qualities, handling qualities, and performance.

Airworthy Systems Integration

Prior to the installation of the equipment, NRC-FRL Maintenance, Instrumentation, and Airworthiness Groups performed thorough component assessments. The blade was master balanced, links were re-built and adjusted to nominal lengths, and swashplate assembly free-play limits were assessed. All instrumentation was inspected for acceptance. Following installation, the FLMS components were dynamically tracked and balanced using an optical RADS™ system. The system enabled setting of pitch link reference height, blade mass distribution, and blade aerodynamic lift distribution through blade tab angulations.

All vibration and tracking specifications were met. As depicted in Figure 13, typical FLMS integrated vibration surveys indicated 1/rev vibration magnitudes fell within the 0.4 ips range for ground idle to high speed flight operations.

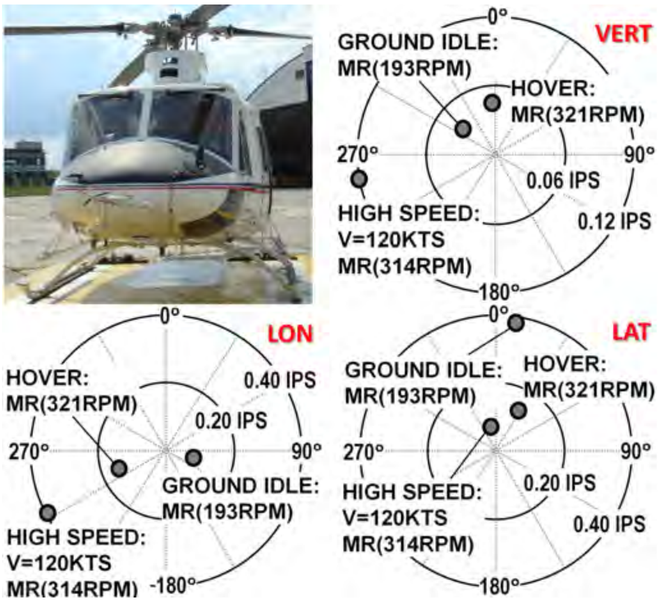

Figure 13: Typical 1/rev RADS™ Systems Vibration Survey

Performance, Handling, and Ride Qualities Assessment

A series of maneuvers were flown to subjectively evaluate changes in aircraft ride qualities, handling qualities, or performance, caused by the FLMS integration. A typical series of maneuvers flown included:

- Take-offs and landings from paved surfaces,
- Hover, vertical climb, and translational flight,
- Departure, climb, and acceleration,
- Level cruise flight to Vne,
- Slalom with large and aggressive cyclic inputs.

No unusual aircraft responses, such as changes in aircraft ride or handling qualities, were exhibited. The FLMS installation was cleared for flight research applications.

FLIGHT DATA ANALYSIS

FLMS data quality was evaluated by ensuring proper time and frequency response content, display of correct magnitude trend activity with vehicle state information, as well as internal and external response consistency. A sampling of normalized results from data analysis of ground operations and low speed maneuvers is provided. The data set that was assessed consisted of 13 maneuvers including landings, ground-runs, hover, bob-up, acceleration-deceleration, side-step, rearward flight, roll reversal, and control input sets (ground-run (control sweep), hover (cyclic doublet, frequency sweep)). Aircraft configuration and flight data is provided in Table 2:

PARAMETER	DATA
Crew	2 Pilots, 2 FTEs
Stability Augmentation System	Off
Fly-By-Wire Control System	Off
Weight Coefficient (CW/σ) Range	[0.057, 0.061]
Normal G-Loading Range	[3.404, -0.561]
Advance Ratio Range	[0, 0.132]
Pressure Altitude Range (ft.)	[0, 175]
Relative Winds (deg., kts.)	(300, 7)
Pitch Rate Range (deg./sec.)	[27.643, -11.662]
Roll Rate Range (deg./sec.)	[58.995, -52.583]
Yaw Rate Range (deg./sec.)	[51.015, -48.411]

Table 2: Flight Conditions for the 13-Maneuver Data Set

Loads Trending Assessment

The FLMS was required to characterize loads with or without influences of flight dynamics. Loads generated for controls sweeps during ground running were compared with loads generated during flight maneuvers to observe trending. On the ground, where aircraft flight velocity and attitude rate are not factors, rotor systems loads are induced by control demand, rotor operating conditions (RPM, blade pitch settings, etc.), rotor blade coupled flap-lag-torsion response, and wind/inflow conditions.

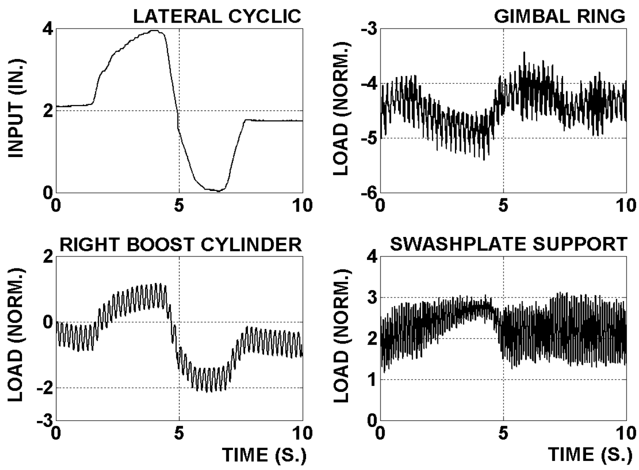

Figure 14: Ground-Run, Lateral Cyclic Sweep, Non-Rotating

Figure 14 depicts trend correlations in non-rotating frame boost cylinder axial, gimbal ring vertical, and swashplate support clevis shearing structural loads for a four inch lateral cyclic input. Figure 15 shows the characterization of the coupled flap-lag-torsion response of the hingeless rotor system in the rotating frame.

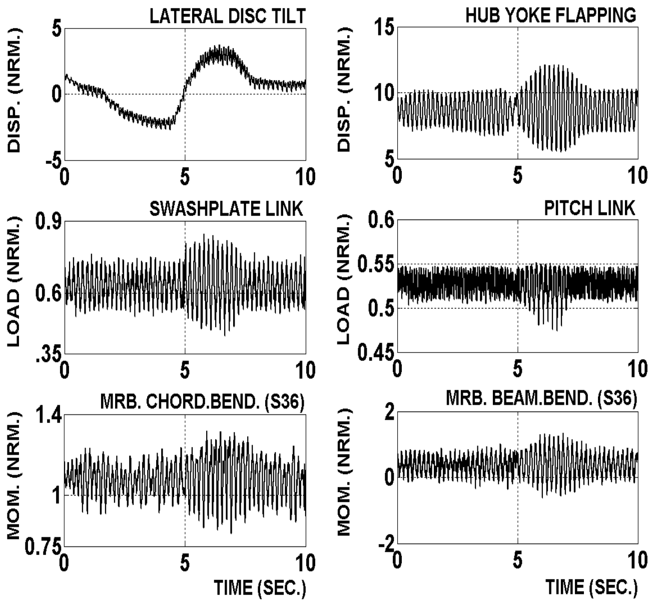

Figure 15: Ground-Run, Lateral Cyclic Sweep, Rotating

The input applied to the non-rotating control system causes lateral tilting of the disc through lateral cyclic blade pitch. The disc tilt response results from correlated structural dynamics and loads in the rotating controls (swashplate and pitch links) and the rotor hub/blade system (hub yoke flapping, chordwise/beamwise blade bending moments). In flight, the loads in the rotating and non-rotating rotor and control systems trend with increasing normal Gz and attitude rate. Utilizing the lateral control sweep performed during a ground run for comparison, increases in surveyed flight loads for a roll reversal are depicted in Figure 16.

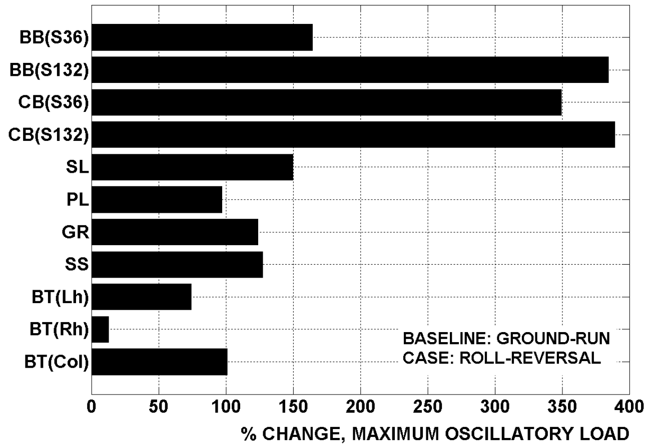

Figure 16: Percent Change in Maximum Oscillatory Loads, Flight Roll Reversal vs. Ground-Run Lateral Cyclic Sweep

In the rotating frame, beamwise and chordwise blade bending moments increased 1.5 to 4 times. Blade control linkage (swashplate and pitch links) axial loads increased 1 to 1.5 times. In the non-rotating frame, swashplate support, gimbal ring, left boost tube, and collective boost tube loads increased from 0.75 to 1.3 times.

Consistency Assessment

The FLMS was consistent in measurements from both external and internal perspectives. External consistency required known correlations between non-rotating and rotating frame loads and flight states to be evident.

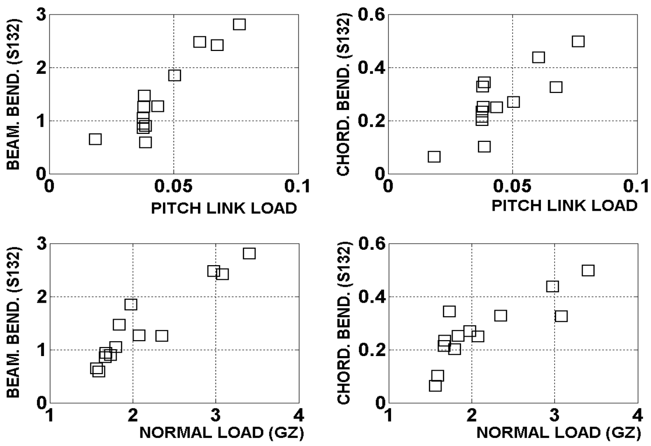

Figure 17: Trending: Blade Bending, Pitch Link Load, and Gz

As depicted in Figure 17, hingeless rotor structural flap-lag-torsion coupling and flight state correlation is evidenced in assessing the 13 maneuvers referred to at the beginning of the Flight Data Analysis section. Increases in beamwise and chordwise bending moments, pitch link axial load, and normal Gz trend from lowest loading (ground-run) to highest loading (roll-reversal) maneuver cases.

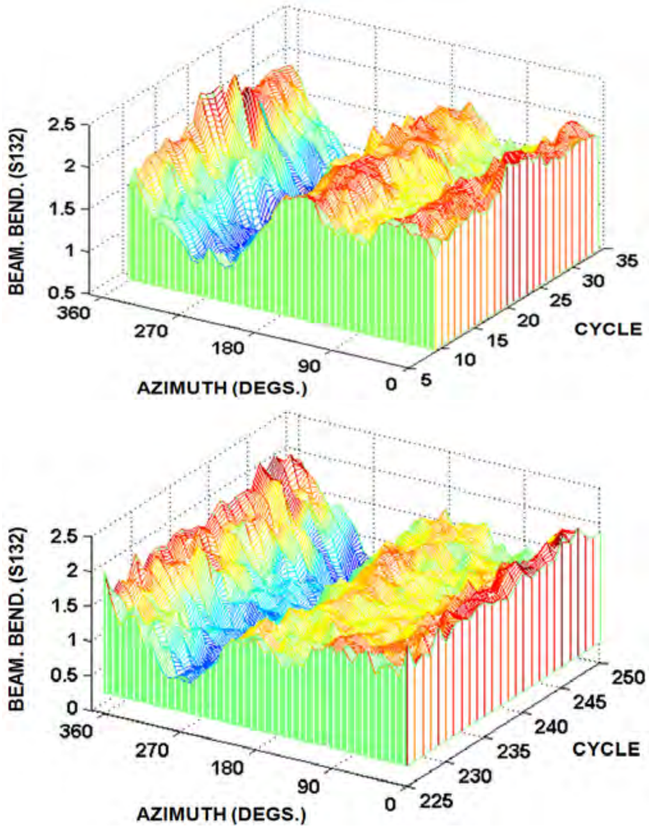

Figure 18: Consistency: Blade Bending in Steady Hover (Top) CW/σ = 0.061, (Bottom) CW/σ = 0.057, (Counter-Clockwise Rotor Revolution: Nose = 0° ; Port-Side = 90°)

Internal consistency required correlation in measurements between sensors, as well as correlation in measurements amongst similar events. In Figure 18, cyclic repeatability is evident in measured blade beamwise bending moments for two separate data records during steady hover conditions. Data for each record was sampled over an 8 second interval representing 43 rotor revolutions. Consistencies such as this were found in all sensors in both the time and frequency domain providing confidence in FLMS operation.

Frequency Content Assessment

The FLMS was required to capture frequency response characteristics of the Bell 412 soft inplane hingeless rotor and control systems. Harmonic analyses should expose both operating and resonant structural responses. The roll reversal, which produced the most elevated loading in all components (see Figure 16), was utilized as a sample case. The roll reversal was performed at low altitude (50-100 ft. AGL), moderate speed (40-50 knots), high normal Gz (3.4 Gz), and high roll rate (59 deg./sec.). Of interest was the characterization of the elevated loading exhibited.

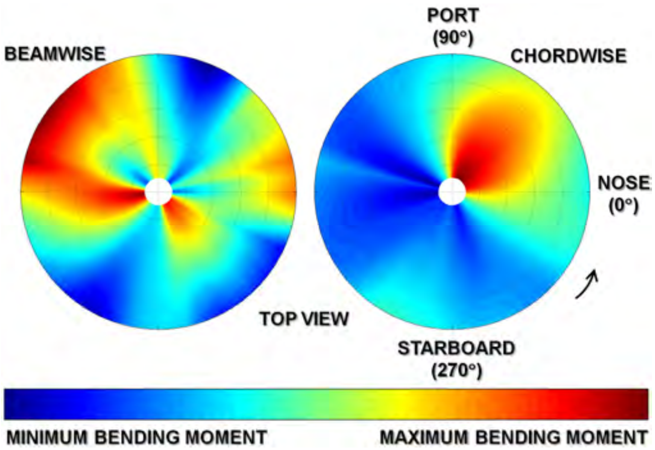

Figure 19: Blade Bending Moments, Roll Reversal

In Figure 19, azimuth plots of average blade beamwise and chordwise radial measurements from inboard (S36) and outboard (S132) strain gauges are presented. The plots represent an 8 second period (43 rotor revolutions) of the 50 second roll reversal maneuver duration. As the blade traverses all quadrants in a chordwise sense, peak loading was limited to the onset of blade retreating flight in the first quadrant. In the beamwise sense, peak loading occurred in blade advancing and retreating flight with inboard, outboard, and full-span moment amplification.

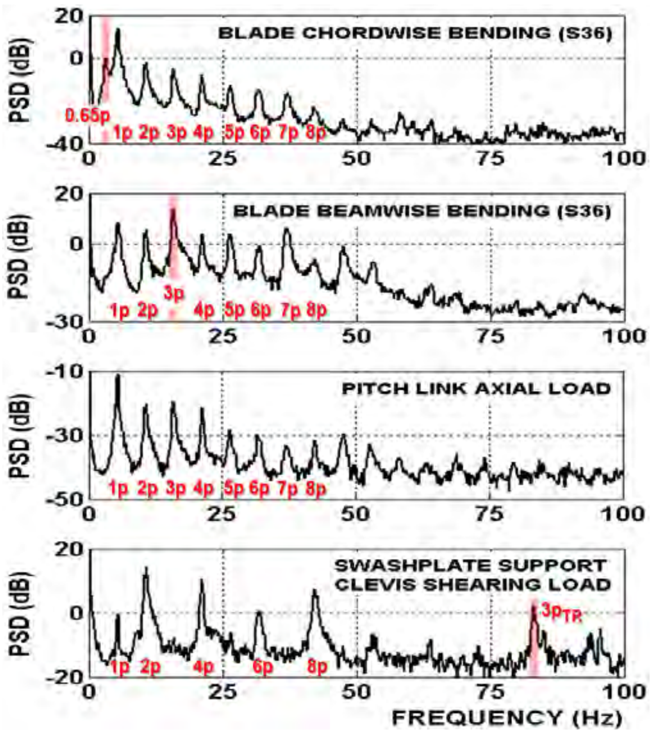

Figure 20: FLMS Spectrum Survey, Roll-Reversal

A PSD survey of the rotor and control system (Figure 20) illustrates FLMS characterization of the roll reversal:

- Data depicted a maximum signal-to-noise ratio of 35 dB in primary response with a spectrum out to 100 Hz.
- Elevated roll attitude-rates amplified the 1st chordwise (regressive) mode at 0.65/rev or 3.51 Hz. This mode is sensitive as the soft-inplane chordwise blade natural frequency is below the 1/rev or 5.4 Hz rotor frequency.
- Forward flight aerodynamics amplified 3/rev or 16.2 Hz beamwise blade response. This could be attributed to the coalescence of the 2nd chordwise mode at 3.13/rev or 16.9 Hz and the 3/rev or 16.2 Hz rotor frequency.
- Rotating rotor blade and pitch link contained p/rev, 4p/rev, and 4p$\pm$1/rev (where; p is an integer) harmonics.
- Non-rotating swashplate support clevis planar shearing response contained 1/rev, 2p/rev, and 4p/rev harmonics.
- Integral (4p/rev) swashplate support response could result from 4p$\pm$1/rev rotor induced flapwise moment, lagwise moment, and in-plane shear. Non-integral (1/rev, 2/rev, 6/rev) swashplate support response could result from inertial and aerodynamic rotor system dissimilarity due to the instrumented pitch and swashplate links, and the blade mounted on rotor hub's upper yoke stack [9].
- Amplification at 83 Hz could be 3/rev tail rotor response.

Conclusions

The FLMS as integrated into the Bell 412 ASRA demonstrated robustness and airworthiness in flight loads data acquisition. Consistency and data quality were demonstrated in both time and frequency domains. Initial testing provided confidence in FLMS application in research associated with life cycle management, high bandwidth control, and structural response of fly-by-wire rotorcraft.

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