Estimation of Operational Loading and Deflection with Inertial Measurements

Wind Turbine Blade Workshop

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May 14, 2008
Overview

- Can the operational state be determined with inertial measurements?

**Loading (L)**
- Quasi-Static
- Dynamic Excitation
- Loads Control
- Design Validation (Reduce Blade Weight)
- Usage Accumulation
- Fatigue
- Damage Detection
- Impact Detection (transport)

**Deflection (δ)**
- Design Validation
- Tower Interaction
- Loads Control

**Hub Forces & Moments (F,M)**
- Torque Estimate
- Transients to Bearings
- Gearbox Excitation
- Gearbox Diagnostics
Outline

- Inertial Measurements with Accelerometers
- TX-100 Lessons Learned
- Smart Rotor Blade
- Summary
Inertial Measurements I
Accelerometer Design (Courtesy J. Lally, PCB®)

- Shear Mode ICP Accelerometer

- Capacitive DC Accelerometer
Inertial Measurements II

Accelerometer Characteristics

- **Beneficial Characteristics**
  - “Global” Inertial Measurement
  - Industrially Packaged
  - Repair Options
  - Low Sensitivity to Attachment Change
  - Thermal Stability
  - Cost of Data Acquisition Low and Decreasing
  - Long Life

- **Application Challenges**
  - No Absolute Reference
  - EMI and RF Noise
  - Lightning Protection
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Approach
Accelerometer Sensor Arrays

- Sensor Groups
  - Passive Low Frequency
    - PCB 3711
      (0 - 100 Hz, 40 & 100 mV/g)
  - Active & Passive
    - PCB 208C01 & 712A02
      (0.1 - 36000 Hz, 500 mV/lb)
  - Passive High Sensitivity
    - PCB 356B18
      (0.5 - 3000 Hz, 1 V/g)

- Array Locations

Damage
Displacement
**Signal Processing**

- Example Time History Processing to Minimize Leakage
Displacement II

Tip Deflection

Lead-Lag Displacement

Displacement (in)

0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3

Fatigue Cycles

0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3 3.25 3.5 3.75 4

x 10^6

ADDED 100LBS MASS (IN ATTEMPT TO GO TO 170% LOAD)

REMOVED 100LBS MASS (AND ACHIEVED 160% LOAD)

ADDED MASS, INCREASED LOAD TO 132%

INCREASED LOADS TO 110%

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Load Identification

Modal Filtering

- **Purpose:** Monitor dynamic excitation in near real-time as a function of mode shapes.

- **Approach:** Modal vectors can be applied directly to response measurements:

\[
\begin{align*}
\{x_1(t)\} &= \begin{bmatrix} \psi_{11} & \psi_{12} & \psi_{13} \\ \psi_{21} & \psi_{22} & \psi_{23} \\ \psi_{31} & \psi_{32} & \psi_{33} \end{bmatrix} \begin{bmatrix} a_1 e^{i\omega_1 t} \\ a_2 e^{i\omega_2 t} \\ a_3 e^{i\omega_3 t} \end{bmatrix}
\end{align*}
\]

- **Results:**
Impact Identification

Experimental

- **Purpose:** Determine impact locations and levels for damage assessment.

- **Problem:** Under-determined problem when using single tri-axial sensor to monitor entire rotor blade:

  \[ X_{3 \times 1} = H_{3 \times 87} F_{87 \times 1} \]

- **Approach:** Assume impact occurred at only one location and solve many over-determined problems:

  \[ F_{n \times 1} = \left( H_{n \times 3}^{T} H_{3 \times n} \right)^{-1} H_{n \times 3}^{T} X_{3 \times 1} \quad \text{with} \quad n = 1 \ldots 87 \]

- **Results:** 93% of 87 locations correctly identified with a force estimation accuracy of 98.7%.
Damage Assessment

Fatigue Setup and Crack Growth

- TX-100 in UREX Fatigue Apparatus

- High Pressure Side Crack Growth
  - 2.4 M Cycles 65° Crack
  - 4 M Cycles 20° Crack
Passive Damage Detection

In-plane Deflection Damage Detection

Agreement between crack growth and changes in deflection.
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Smart Rotor Blade I

Objectives

- Build data driven model of turbine blade using static rotation, stiffness tests, and modal analysis
- Estimate rotor deflection and rotation with focus at the tip
- Estimate mean wind loading
- Estimate dynamic wind loading
- Investigate blade thermal sensitivity
- Determine minimum number of measurements
- Perform passive damage monitoring
- Investigate if response measurements at fixed gearbox components can determine loading to the rotor blade
- Determine loading from blades transmitted to the gearbox
Smart Rotor Blade II

Sensor Array

- Capacitive DC Accelerometers

- Typical Cross Section Sensor Arrangement

Triaxial Sensor

Build-up

Single Axis Sensor
Smart Rotor Blade III

Mean Wind Load Monitoring

- **Deflection and Curvature**

- **Calibrate with Static Rotation and Stiffness Tests**
Smart Rotor Blade IV

Modal Filtering

1st Bending Mode (0.1587 Hz)

2nd Bending Mode (0.4443 Hz)

3rd Bending Mode (0.6409 Hz)

\[ \begin{align*}
\{ x_1(t) \} & = \begin{pmatrix} \psi_{11} & \psi_{12} & \psi_{13} \end{pmatrix} \begin{pmatrix} a_1 e^{i \omega_1 t} \\ a_2 e^{i \omega_2 t} \\ a_3 e^{i \omega_3 t} \end{pmatrix} \\
\{ x_2(t) \} & = \begin{pmatrix} \psi_{21} & \psi_{22} & \psi_{23} \end{pmatrix} \\
\{ x_3(t) \} & = \begin{pmatrix} \psi_{31} & \psi_{32} & \psi_{33} \end{pmatrix}
\end{align*} \]

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Modal Decomposition

Modal Filtering

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Estimation of Blade State with Inertial Measurements

- Blade state estimation useful for active loads control, usage monitoring, and design validation.
- Inertial measurements are proportional to the blade loading.
- Accelerometers are fully developed for industrial application.
- Displacement and modal coefficients were determined in TX-100.
- Impact and Damage was detected on the TX-100.
- Smart Blade sensor array will allow investigation of all objectives.
- Blade deflection relative to centripetal acceleration will be used to determine mean loading.
- Dynamic loading will be determined through spectral analysis and modal filtering.
Acknowledgements

Sandia National Laboratories
Wind Energy Technology Center

Jose Zayas
Mark Rumsey

Contract #791571