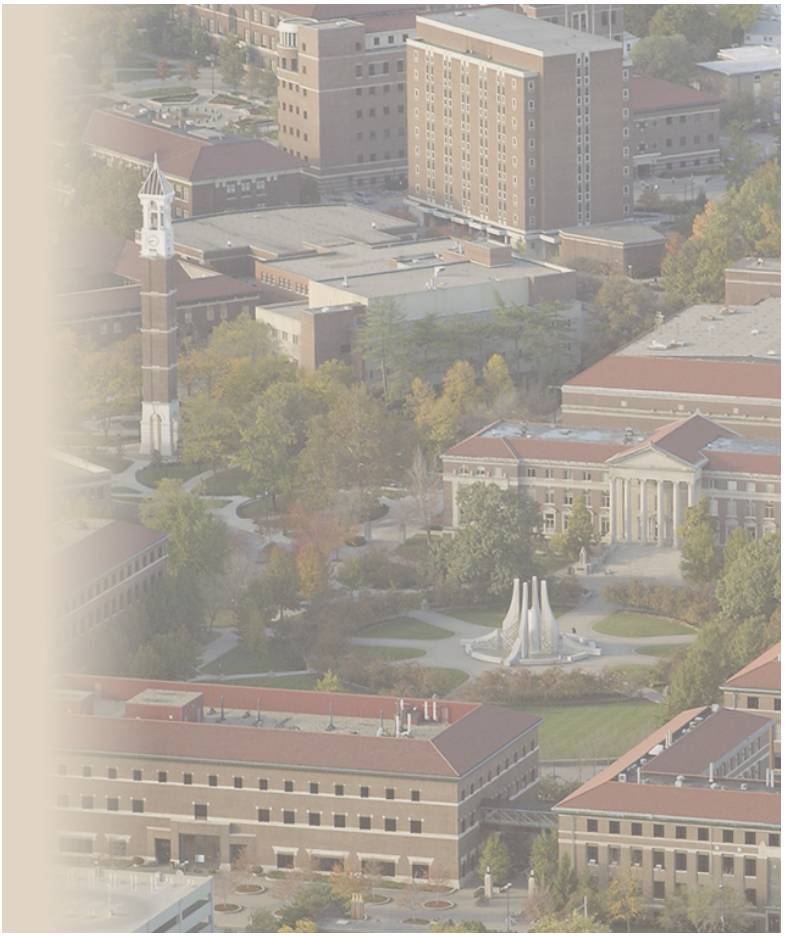
Estimation of Operational Loading and Deflection with Inertial Measurements

May 14, 2008



Wind Turbine Blade Workshop

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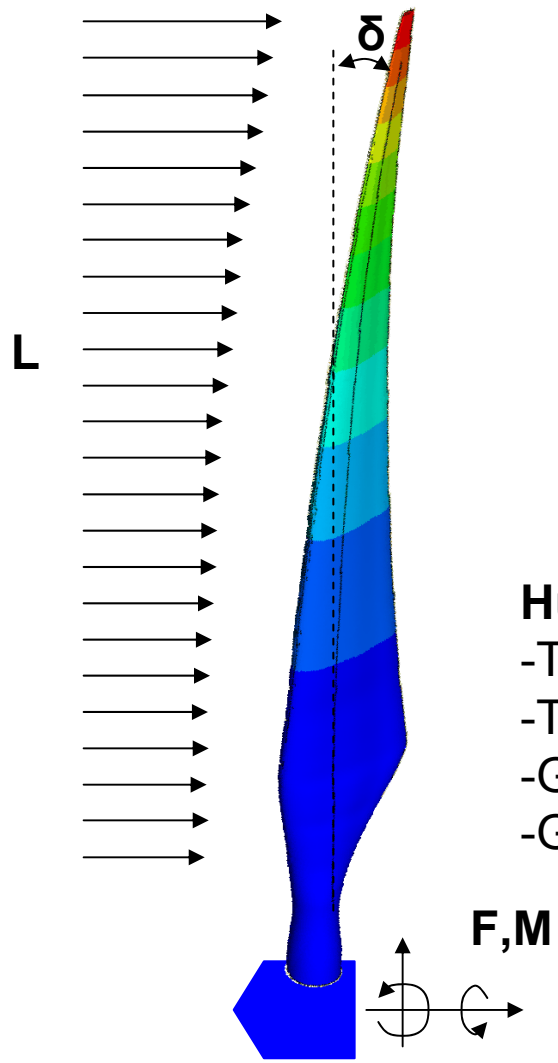
PURDUE UNIVERSITY

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

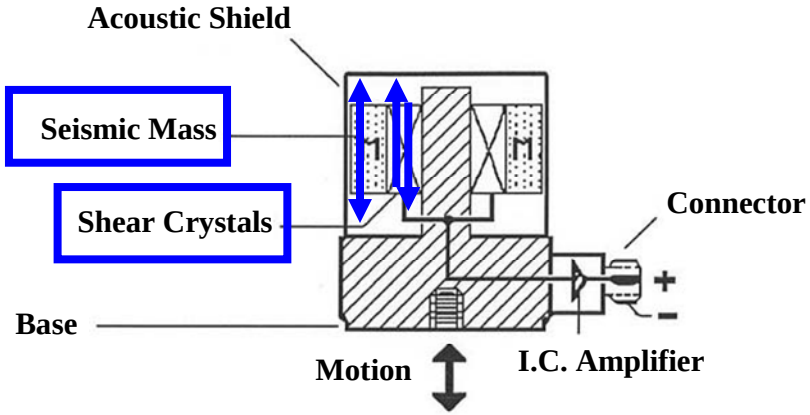
Outline

- **Inertial Measurements with Accelerometers**
- TX-100 Lessons Learned
- Smart Rotor Blade
- Summary

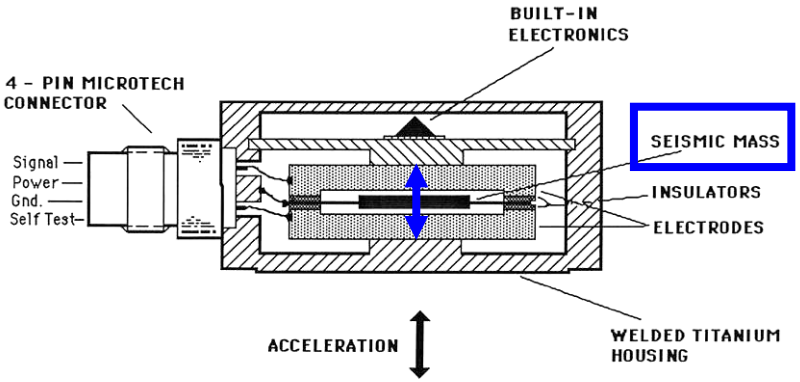
Inertial Measurements I

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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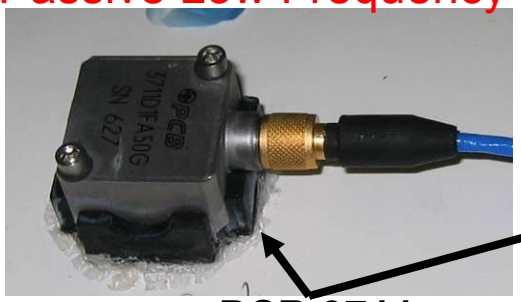
Approach

Accelerometer Sensor Arrays

- **Sensor Groups**

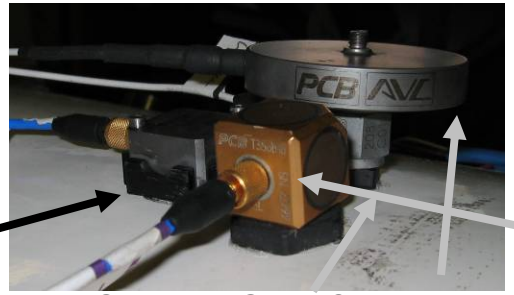
Passive Low Frequency



PCB 3711

(0 - 100 Hz, 40 & 100 mV/g)

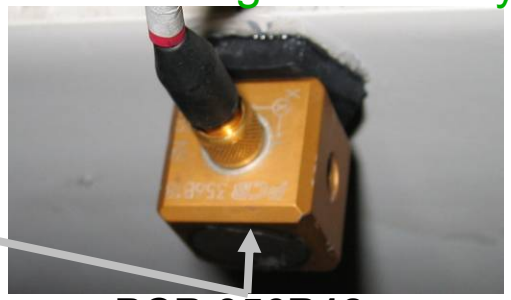
Active & Passive



PCB 208C01 & 712A02

(0.1 - 36000 Hz, 500 mV/lb)

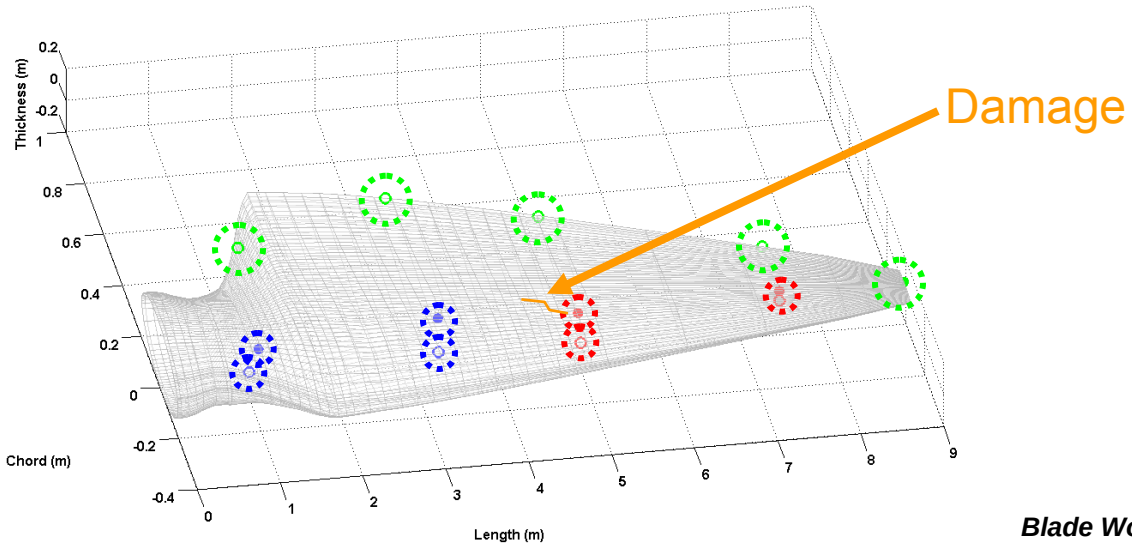
Passive High Sensitivity



PCB 356B18

(0.5 - 3000 Hz, 1 V/g)

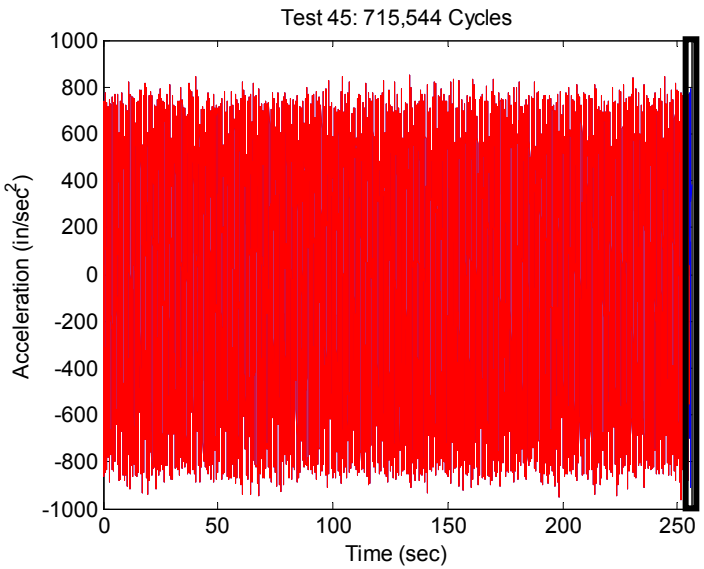
- **Array Locations**

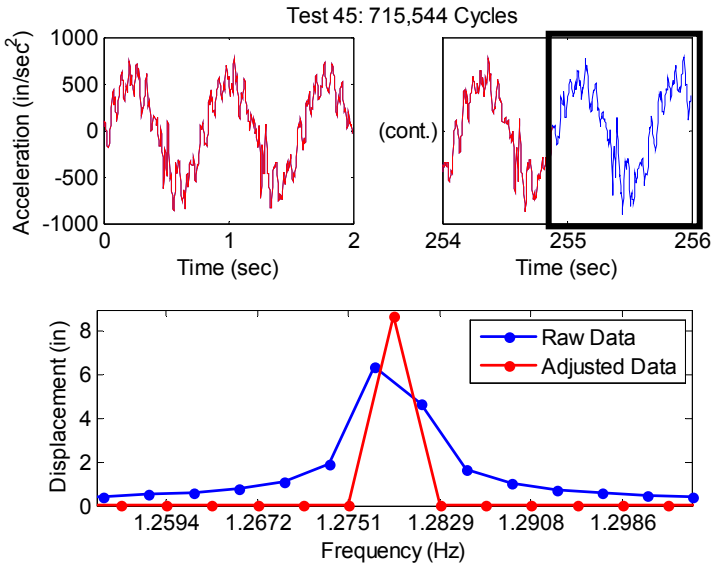


Displacement

Signal Processing

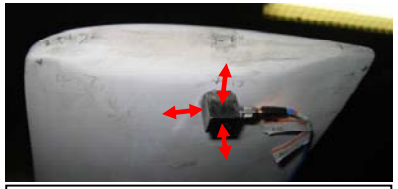
- **Example Time History Processing to Minimize Leakage**

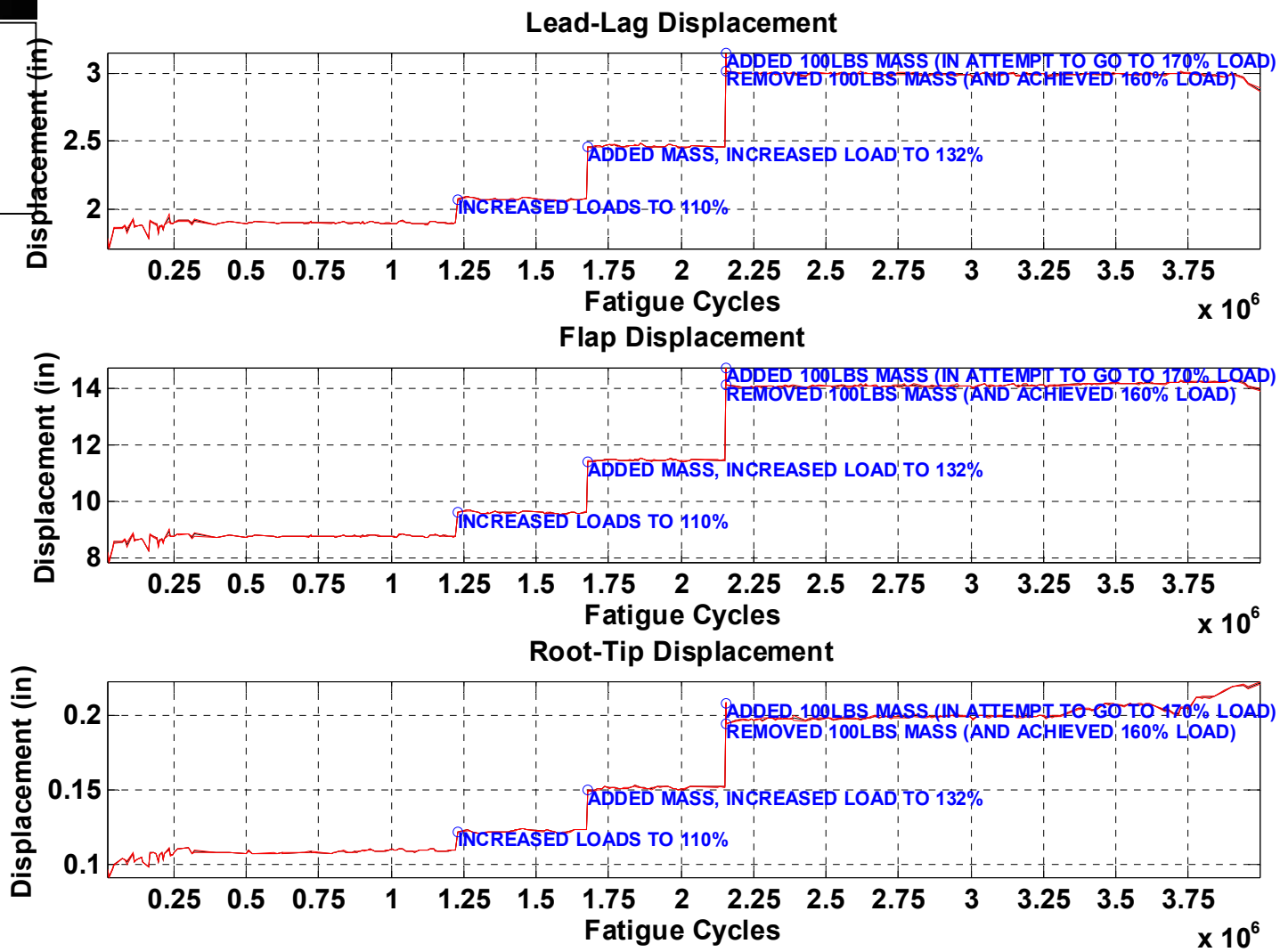




Displacement II

Tip Deflection





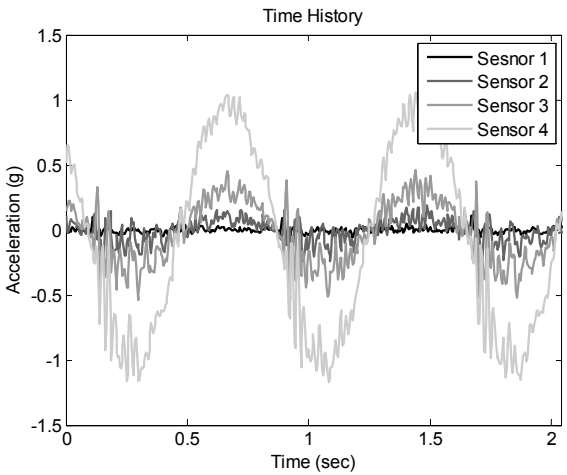
Load Identification

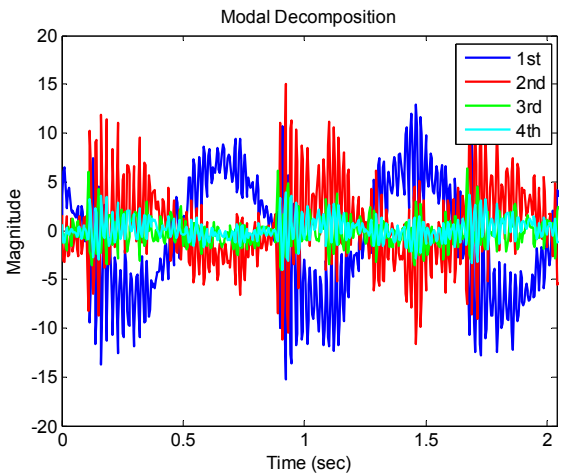
Modal Filtering

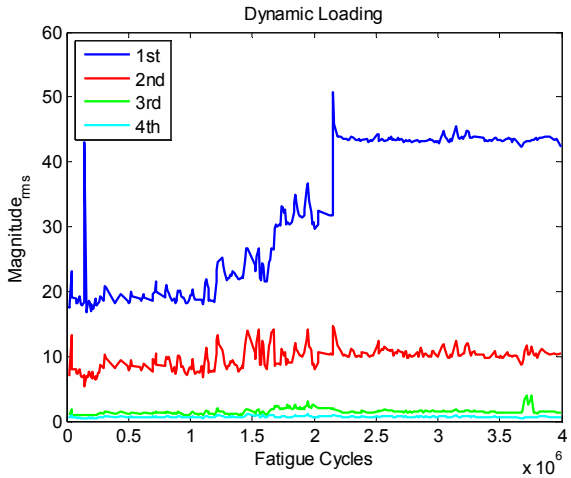
- **Purpose:** Monitor dynamic excitation in near real-time as a function of mode shapes.
- **Approach:** Modal vectors can be applied directly to response measurements:

$$\begin{Bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{Bmatrix} = \begin{bmatrix} \psi_{11} & \psi_{12} & \psi_{13} \\ \psi_{21} & \psi_{22} & \psi_{23} \\ \psi_{31} & \psi_{32} & \psi_{33} \end{bmatrix} \begin{Bmatrix} a_1 e^{i\omega_1 t} \\ a_2 e^{i\omega 2 t} \\ a_3 e^{i\omega_3 t} \end{Bmatrix}$$

- **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:

$$X_{3\times1} = H_{3\times87} F_{87\times1}$$

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

$$F_{n\times1} = \left(H_{n\times3}^{T} H_{3\times n}\right)_{n\times n}^{-1} H_{n\times3}^{T} X_{3\times1} \qquad w/n = 1\ldots87$$

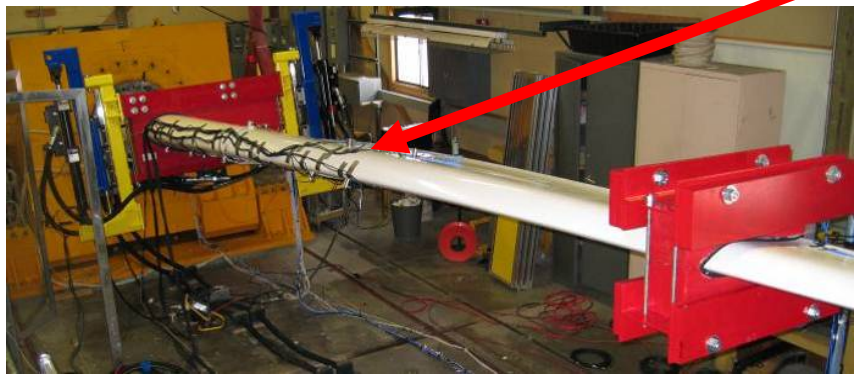
- **Results:** 93% of 87 locations correctly identified with a force estimation accuracy of 98.7%.

Damage Assessment

Fatigue Setup and Crack Growth

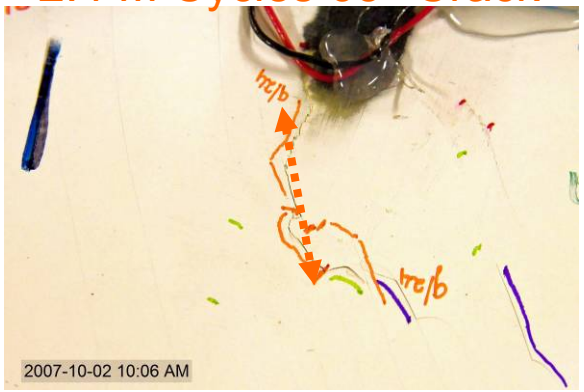
- **TX-100 in UREX Fatigue Apparatus**

Damage Location



- **High Pressure Side Crack Growth**

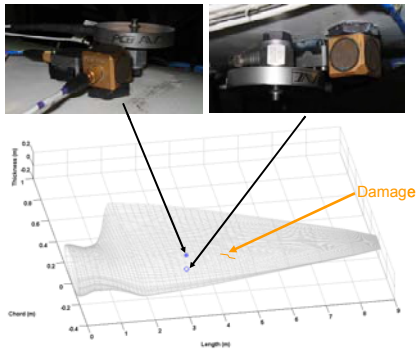
2.4 M Cycles 65° Crack

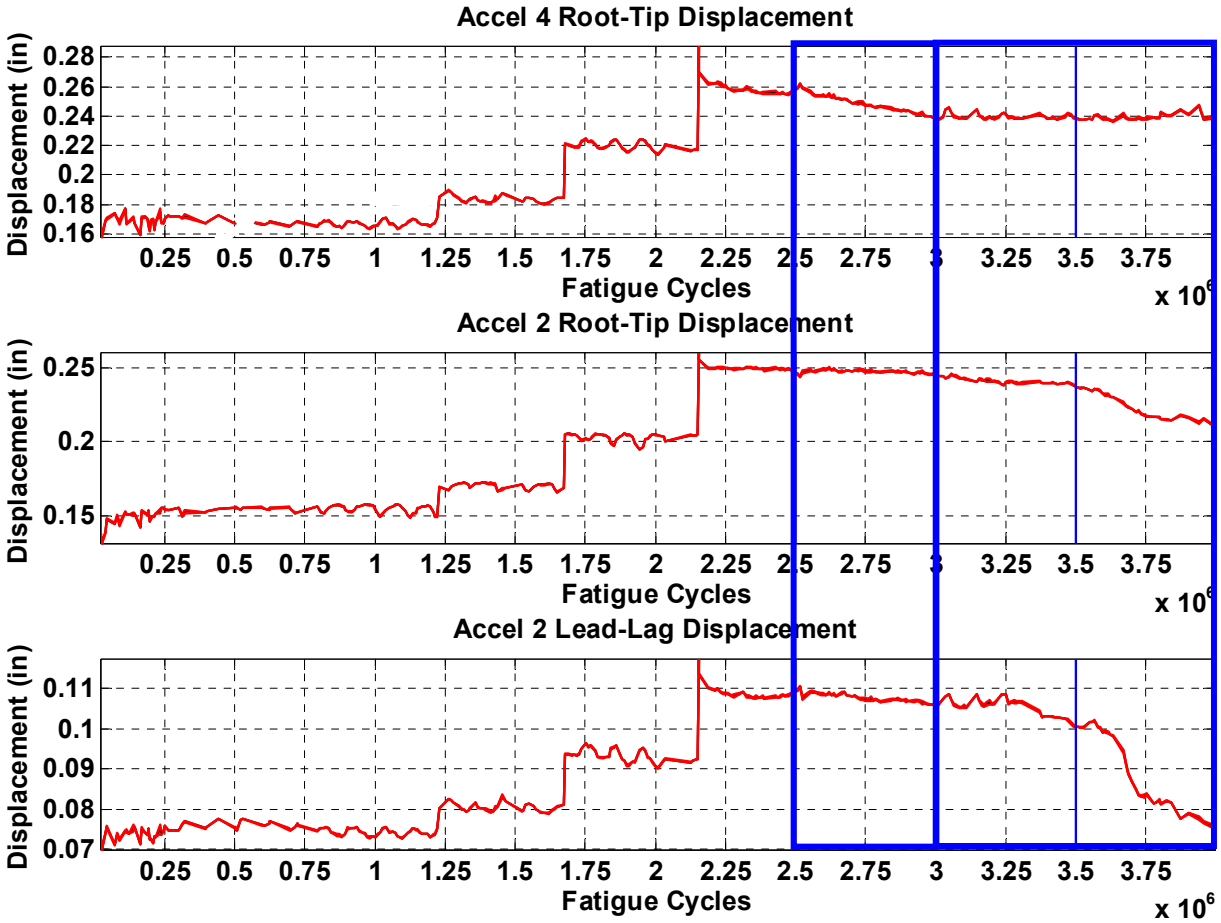


4 M Cycles 20° Crack

Passive Damage Detection

In-plane Deflection Damage Detection





Agreement between crack growth and changes in deflection.

Outline

- Inertial Measurements with Accelerometers
- TX-100 Lessons Learned
- **Smart Rotor Blade**
- Summary

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

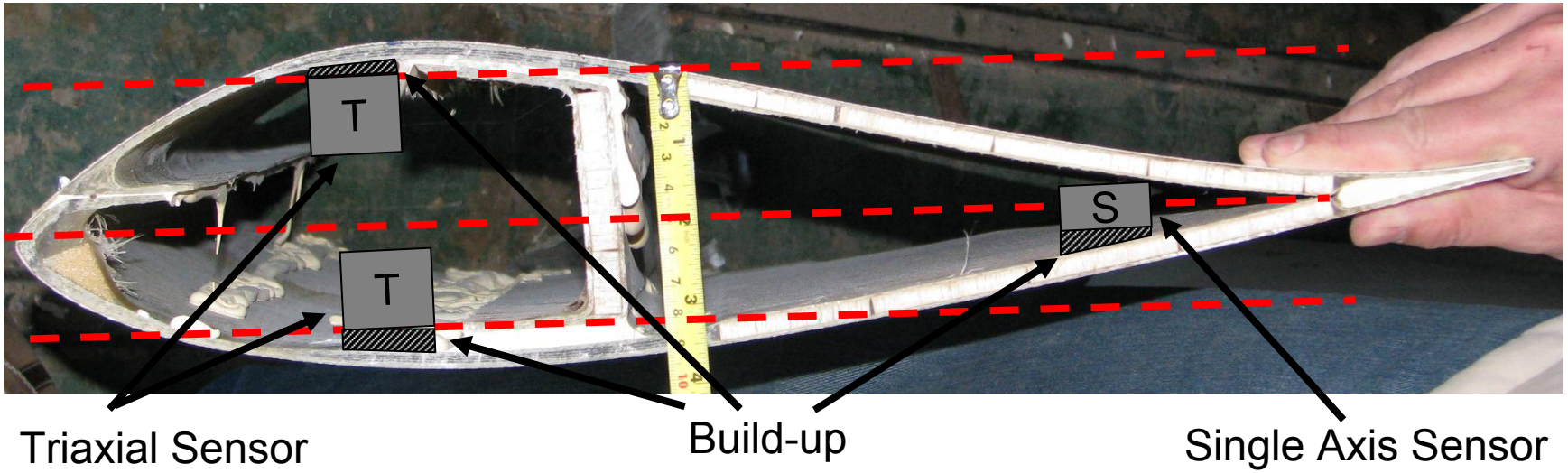
Sensor Array

- **Capacitive DC Accelerometers**

PCB 3713 Triaxial

PCB 3711 Single Axis

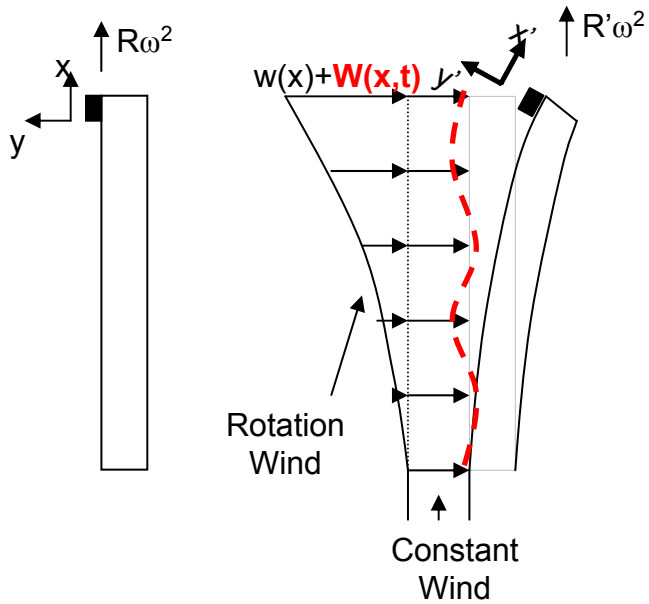
- **Typical Cross Section Sensor Arrangement**

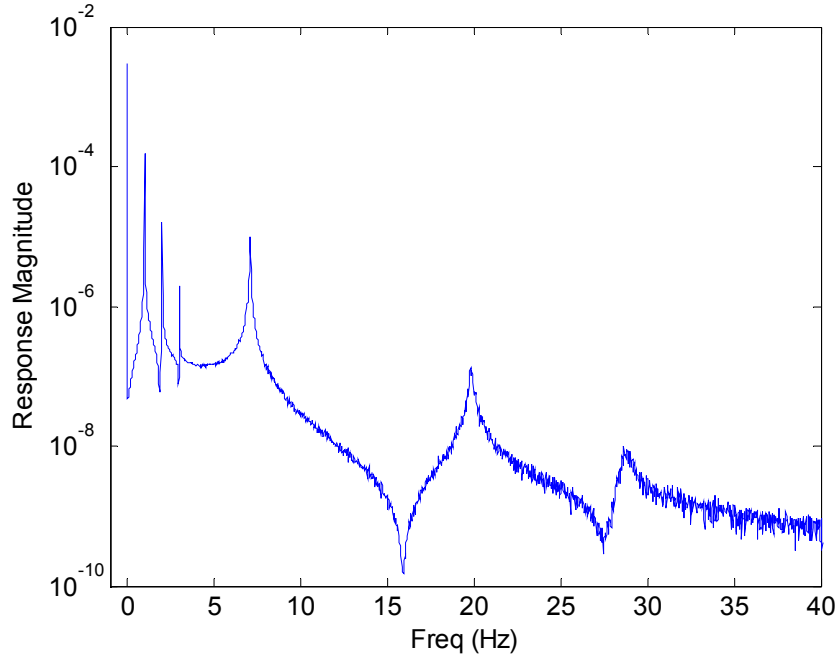


Smart Rotor Blade III

Mean Wind Load Monitoring

- **Deflection and Curvature**

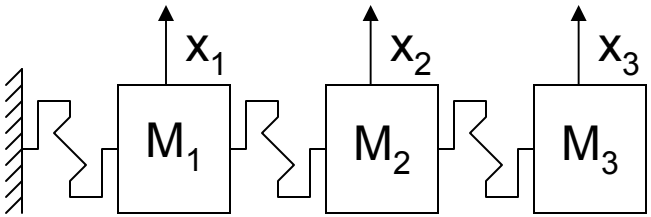




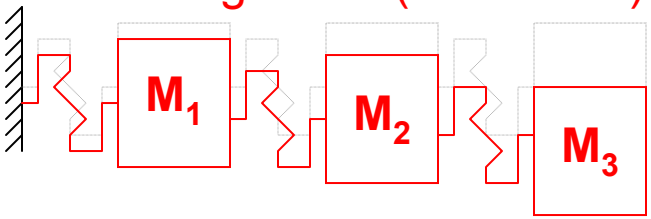
- **Calibrate with Static Rotation and Stiffness Tests**

Smart Rotor Blade IV

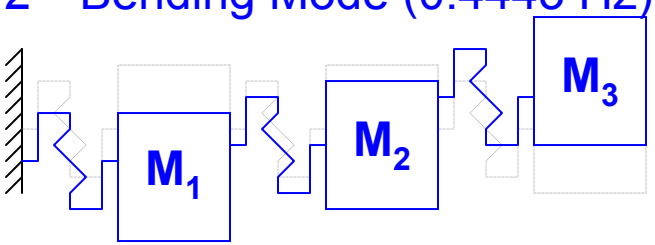
Modal Filtering



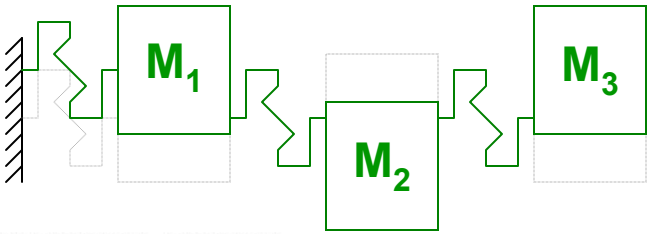
1st Bending Mode (0.1587 Hz)

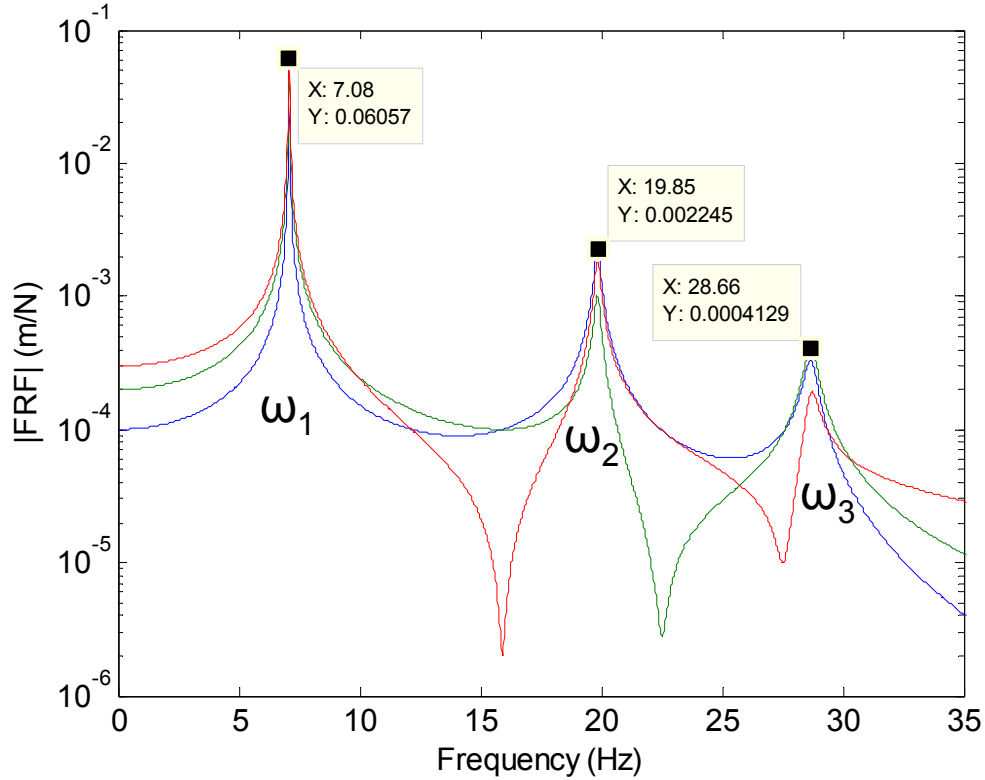


2nd Bending Mode (0.4443 Hz)



3rd Bending Mode (0.6409 Hz)





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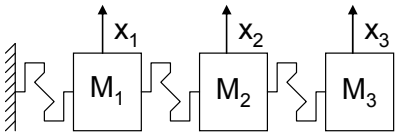
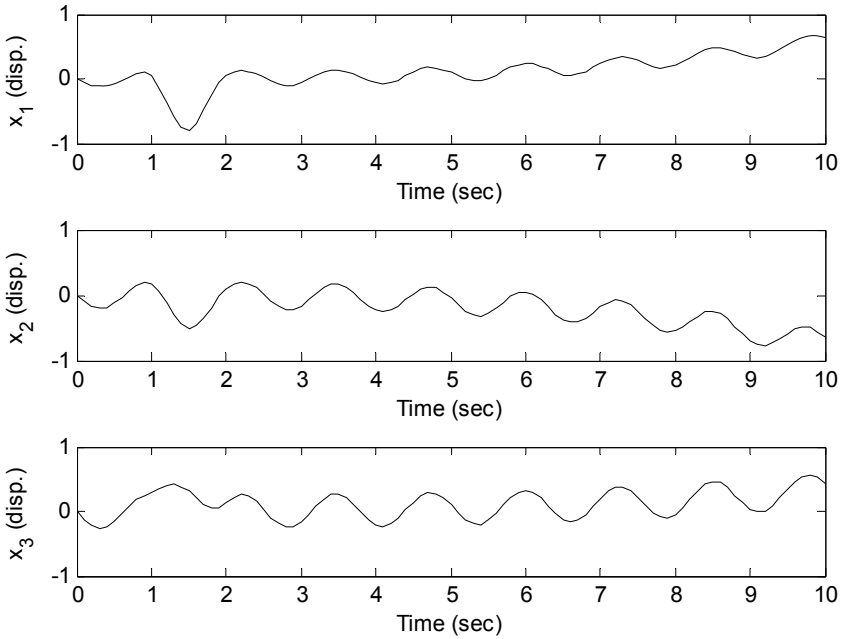
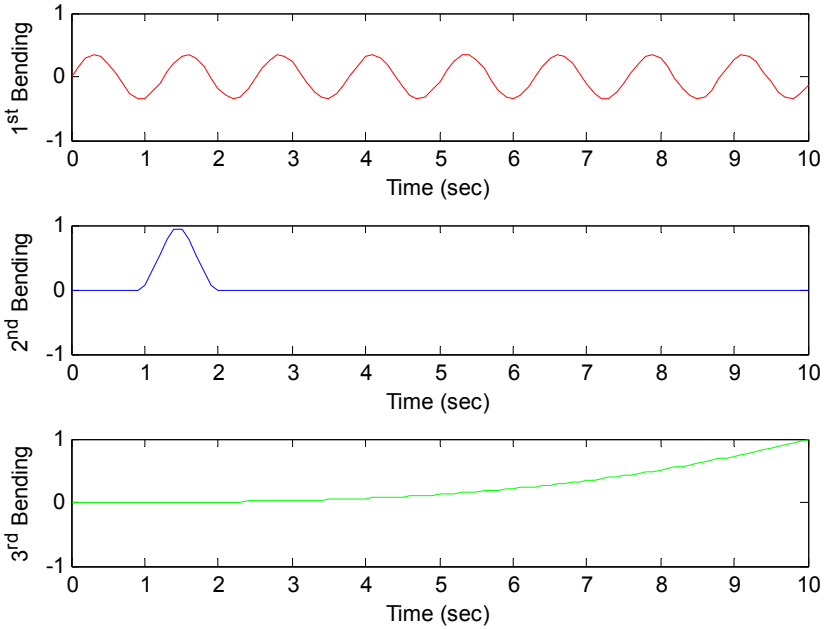


Modal Decomposition

Modal Filtering





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- **Summary**

Summary

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

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