Multi-Scale Sensing and Structural Health Monitoring

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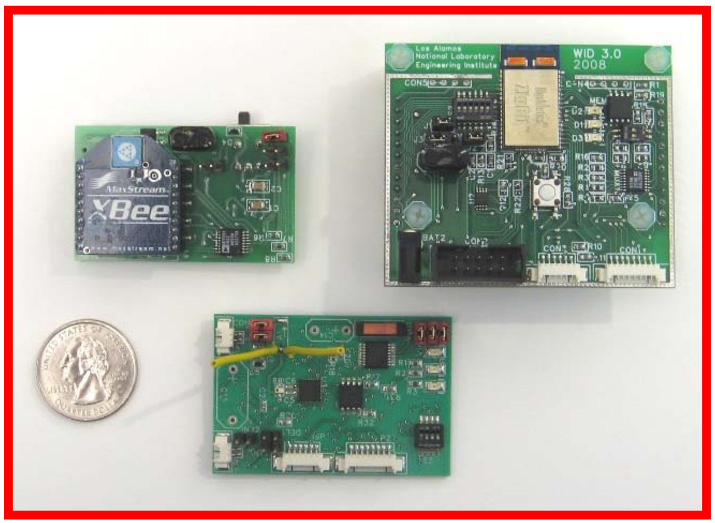
Motivation - IWT Sensing and SHM

- Validate / update physics-based numerical models
- Estimate the current state of the blade, including detection of the onset and growth of damage
- Monitor / predict load characteristics to estimate remaining life in the presence of damage (prognostics)



Challenging Issues in Sensing System Design

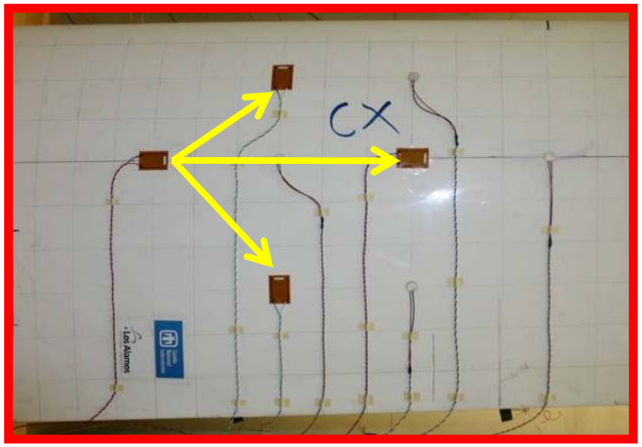
- Critical state of damage is not well defined for wind turbine blades
- Low cost, low power solution with wireless capabilities
- Improved reliability in a robust electronics package
- Optimally configured and installed
  - Maximize observability while minimizing necessary hardware

Courtesy of Wind Systems

Courtesy of gallery.pictopia.com

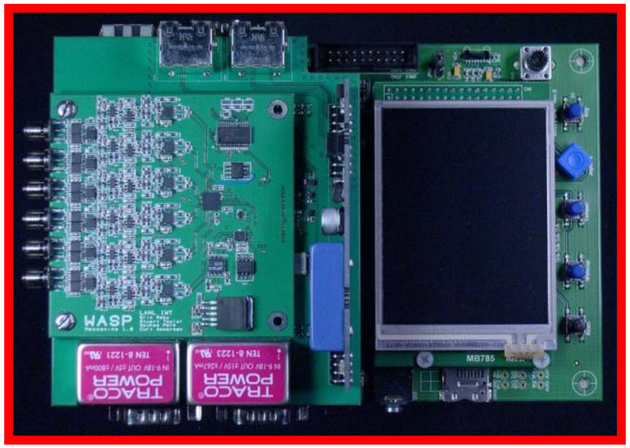
IWT Structural Sensing System

- Multi-scale sensing for SHM and prognostic assessment
  - Local active sensing
  - Global passive sensing
- Piezoelectric transducers are used as sensors and actuators
  - Dual use reduces the total amount of installed hardware
- Develop an integrated hardware / software solution designed specifically for wind turbine applications



Piezoelectrics can serve as both sensors and actuators

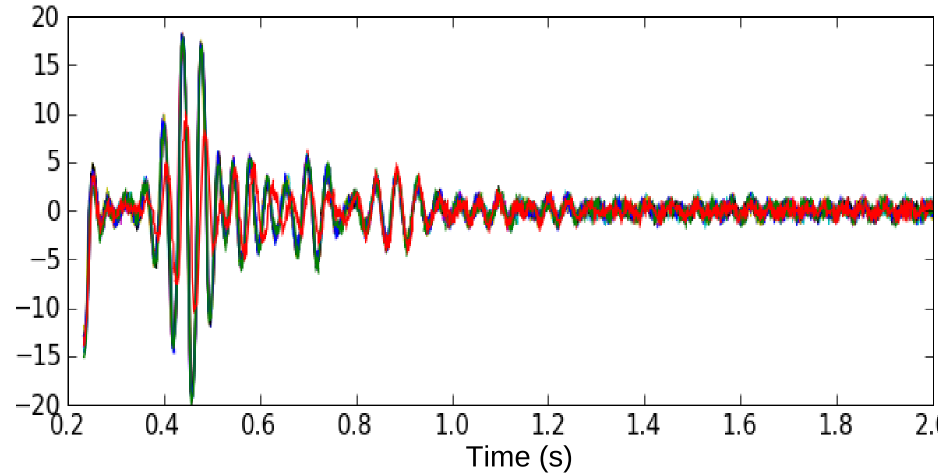
Hardware has evolved from previous experience in civil applications

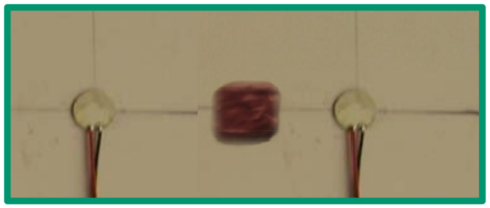


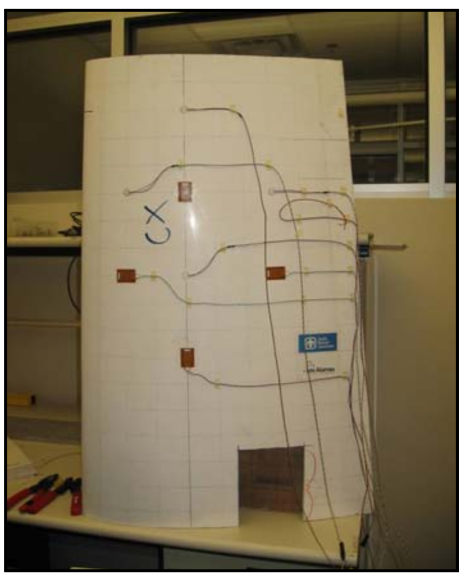
Current prototype of the multi-scale sensing platform

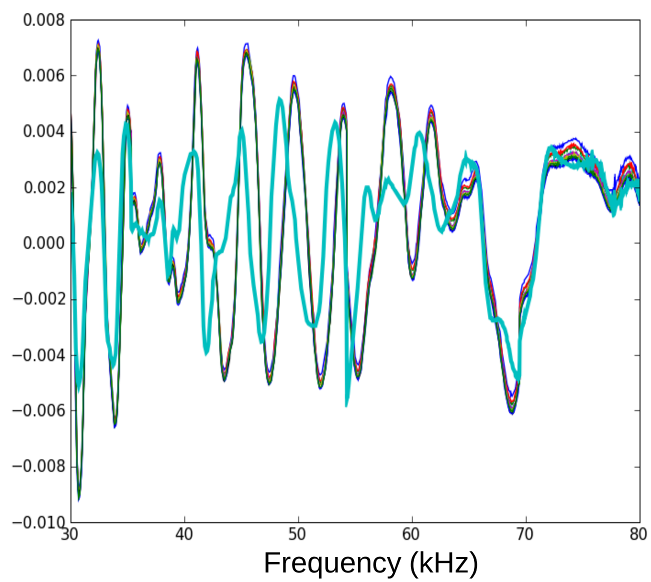
Active Sensing SHM Techniques

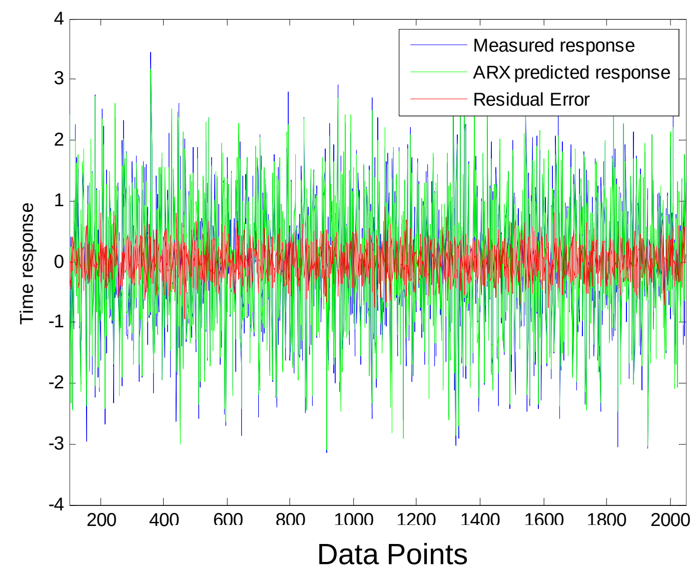
- Lamb wave propagations
- High frequency response functions
- Time series predictive models
  - CX-100 turbine blade 1-m section
  - Introduced simulated damage





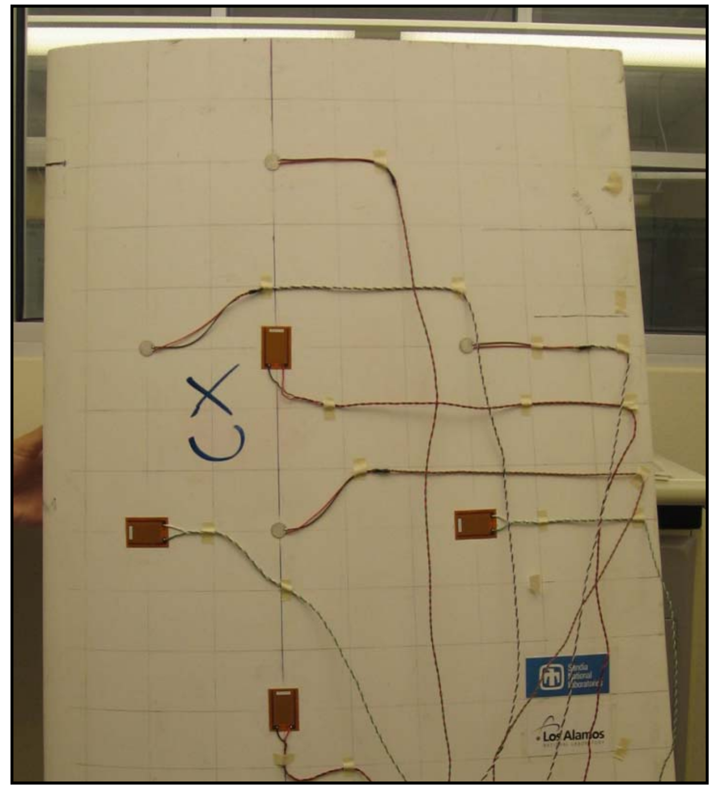




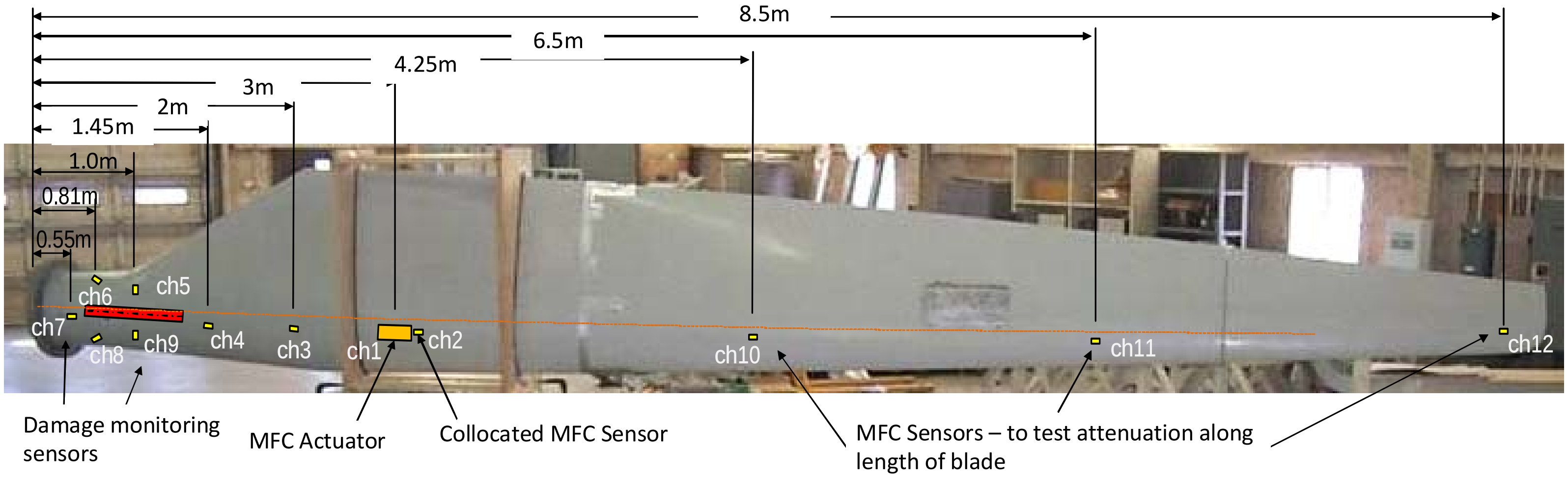


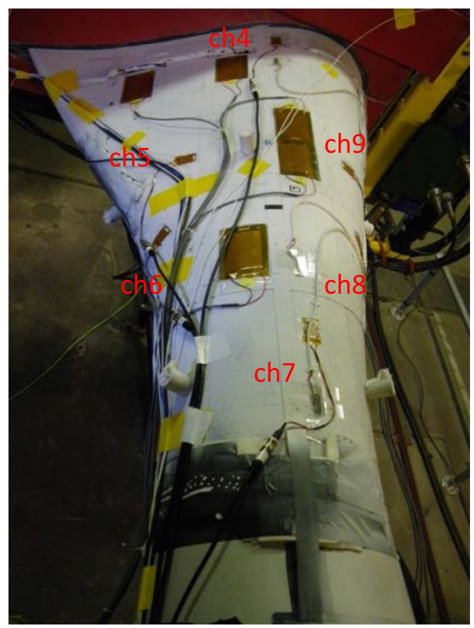
Active Sensing: Method Comparison

- Lamb wave propagations
  - Detect and locate damage
  - Requires higher electric power, extremely small propagating distance (< 0.5 m)
- Frequency domain (up to 80 kHz)
  - Damage localization capabilities
  - Moderate power and memory usage
- Time series analysis
  - Similar capabilities of FRF methods while requiring less measured data
  - Low power requirements
  - Electromagnetic interference



Sandia's Full-Scale Fatigue Test at NREL



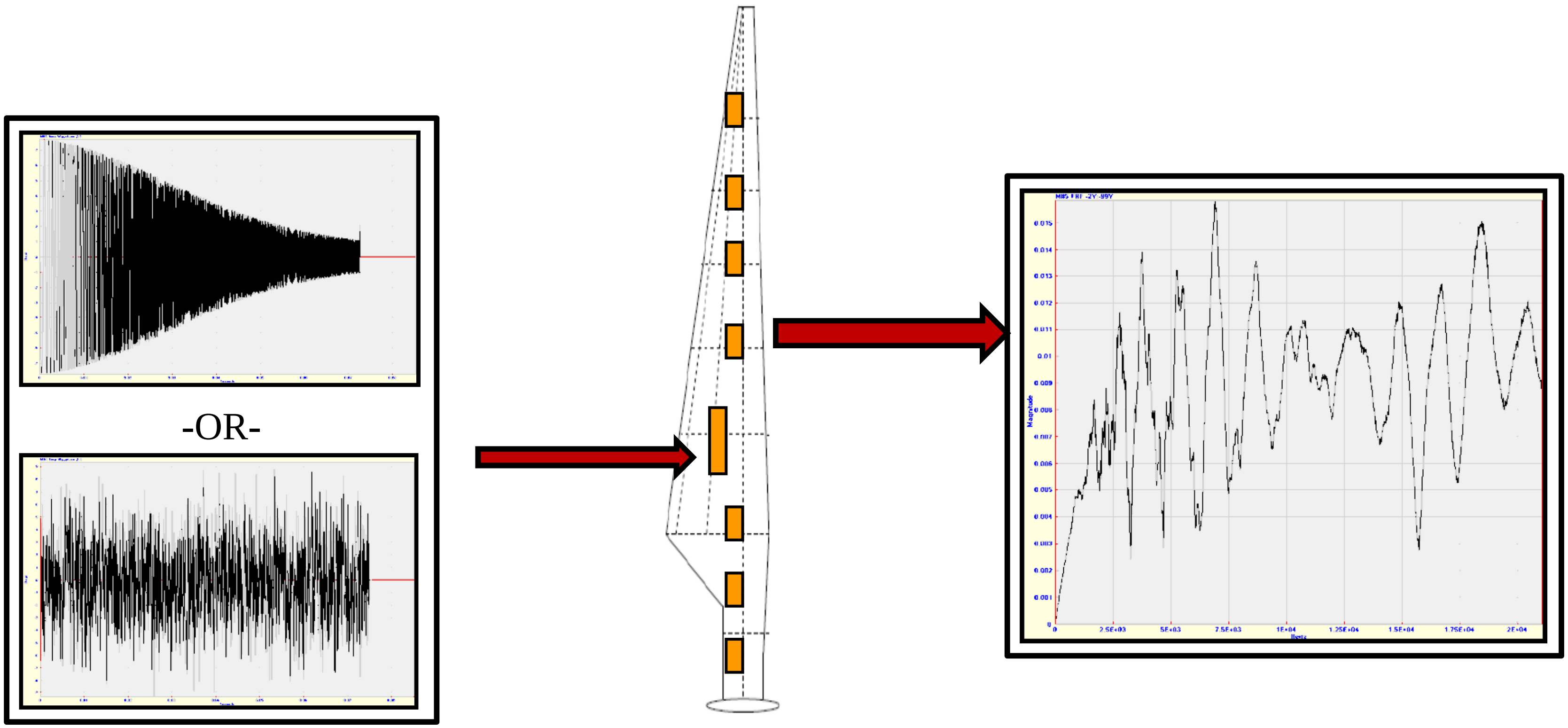


- After 2.3 M cycles, damage was identified visually in the root section
- Measurements were taken from multiple MFC sensors
- Several sensors (Ch. 6, 7, 10) became de-bonded during the test

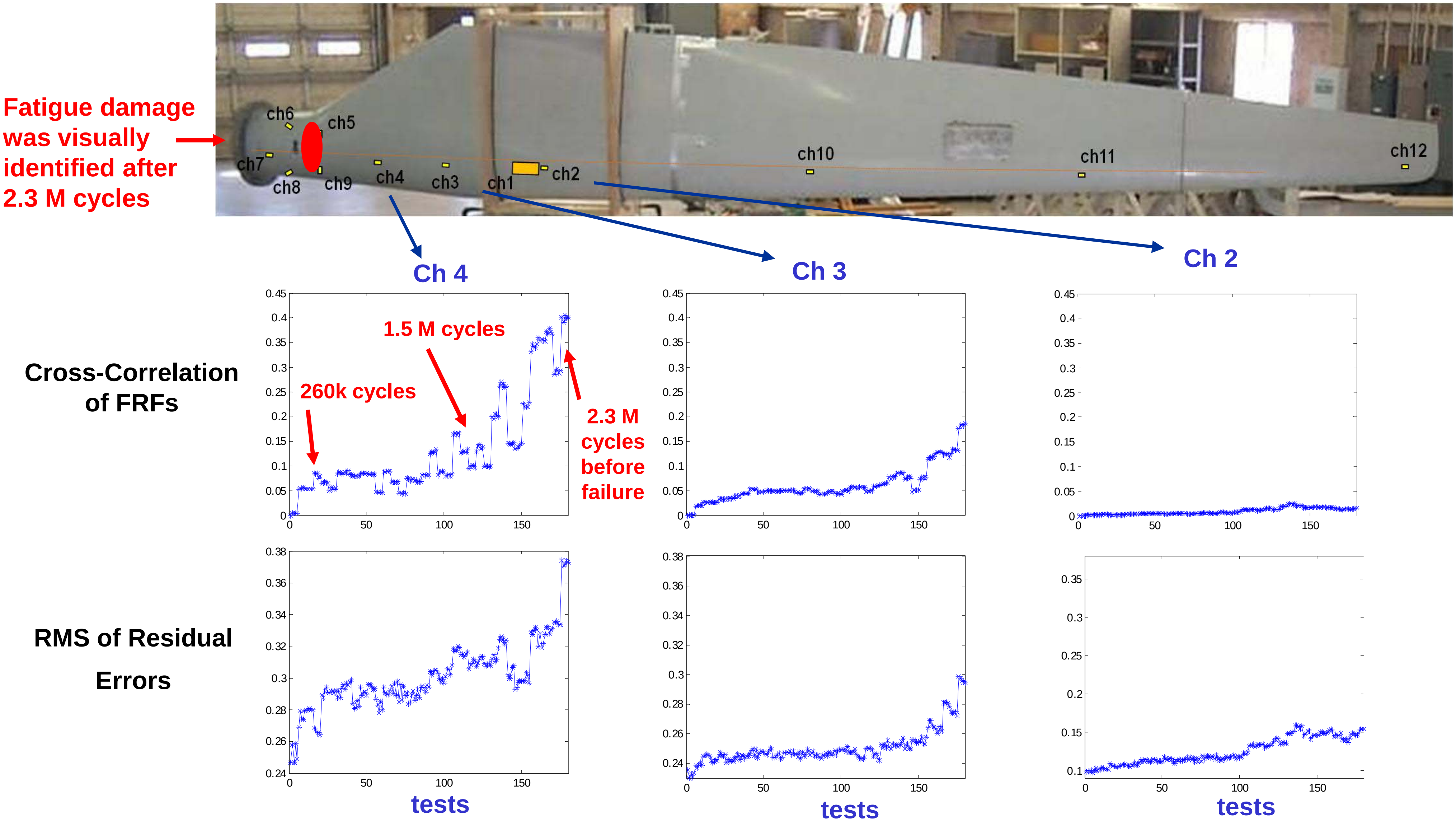
Courtesy of SNL and NREL

Fatigue Test: Active Sensing SHM

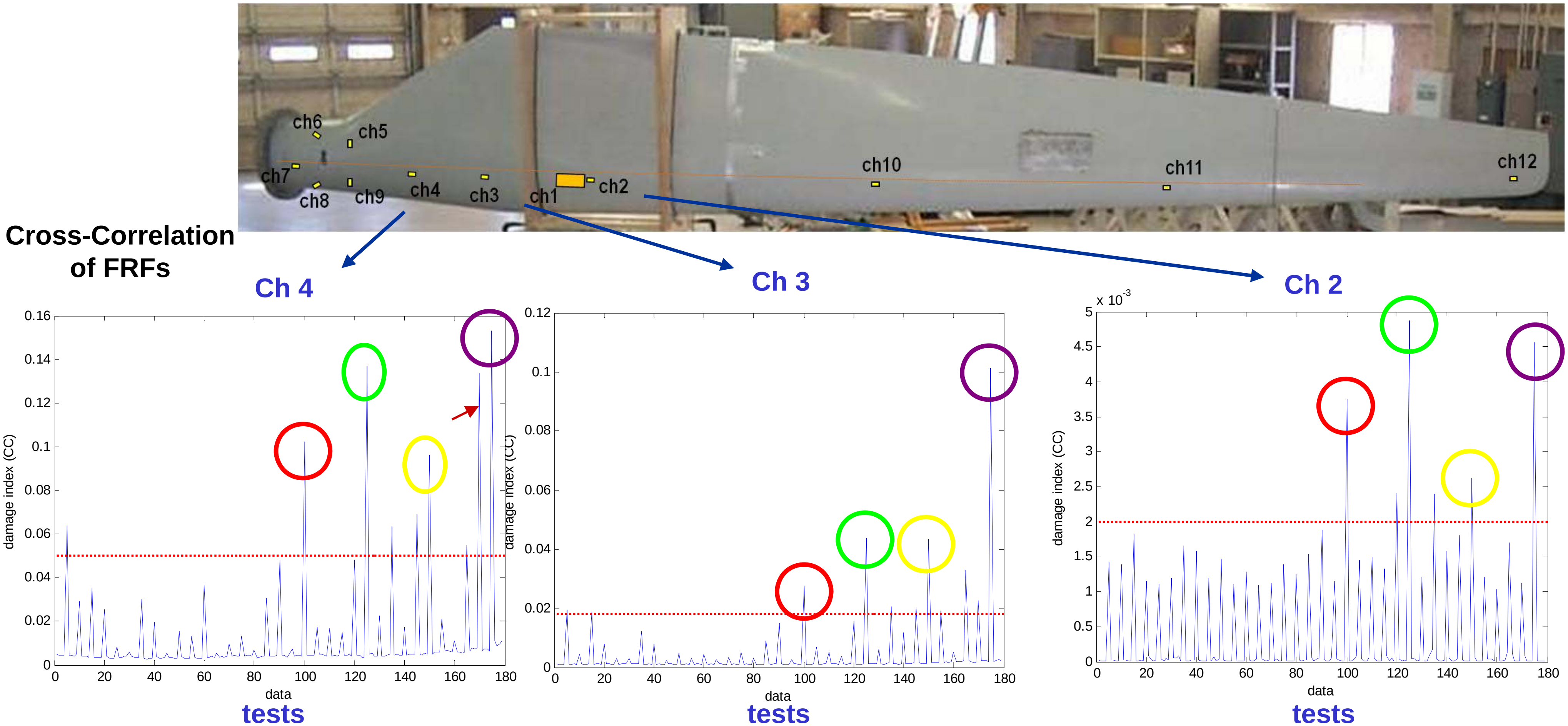
- The MFC actuator was used to excite the system with band-limited (30 to 60kHz) signals
  - amplified sine chirp (30V peak to peak)
  - burst random signal (20V RMS)



Fatigue Test: Active Sensing SHM



Fatigue Test: Active Sensing SHM



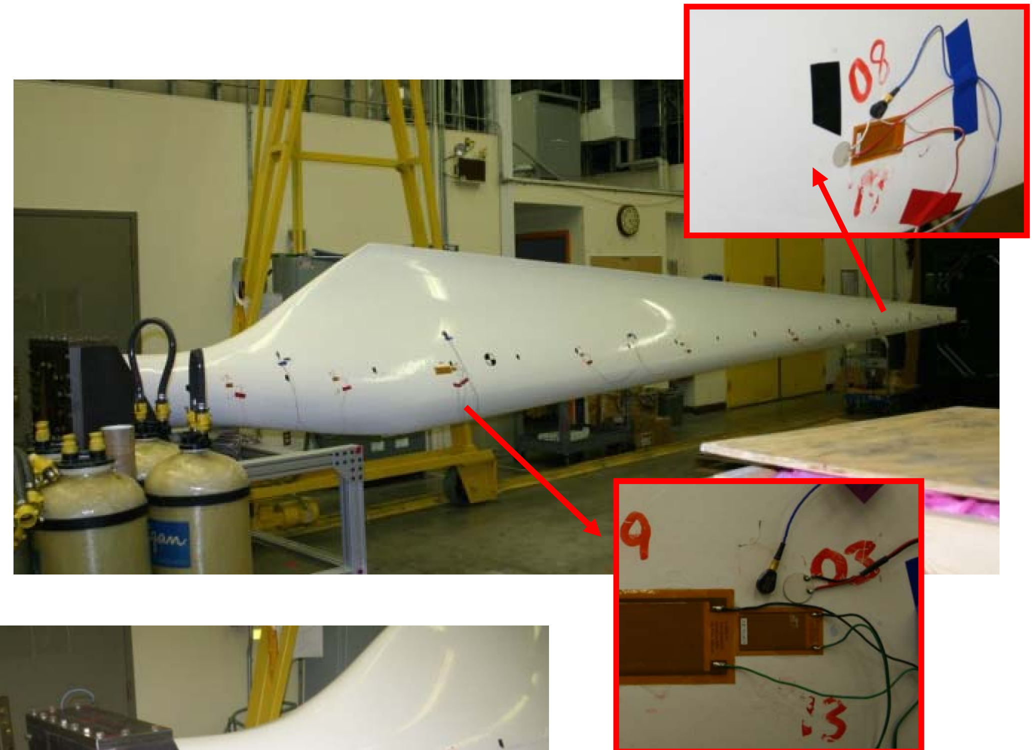
- Corresponds to 1.5 M cycles: acoustic emission systems also noticed changes in emission activities

Lessens Learned / Issues

- Demonstrated that piezoelectric active-sensors could detect and approximately locate damage in the blade.
- Sensors
  - Sensor / actuator locations could be optimized with model input
  - Reliability: three sensors were debonded / broken during the test
- Validation
  - No reference to assess the performance of the sensing system
  - Only high frequency responses - no attempt for multi-scale sensing
- We are planning to address these issues in the fatigue tests scheduled in 2011

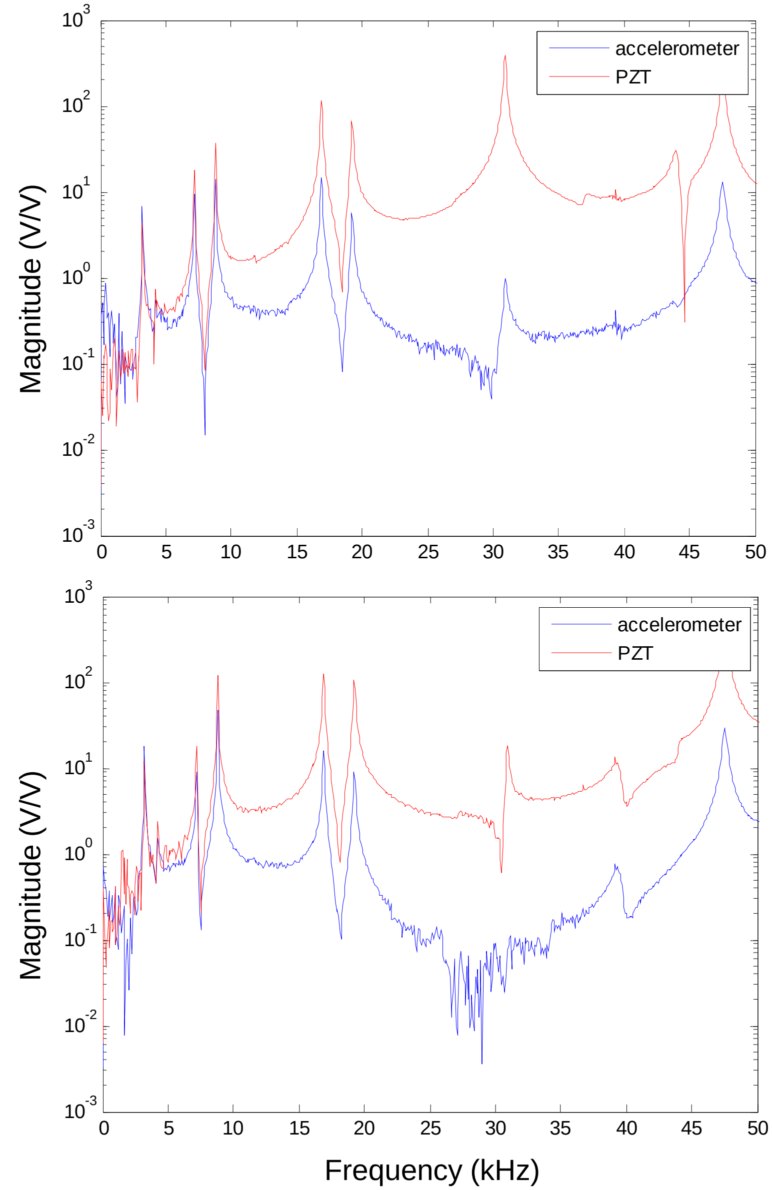
Modal Test of Full-Scale Blade

- Tested a 9-m CX-100 blade with different boundary conditions
  - free-free, clamped-free
- Identified first several modes using accelerometers and passive piezoelectric sensors
- Roving hammer test



Modal Test of Full-Scale Blade

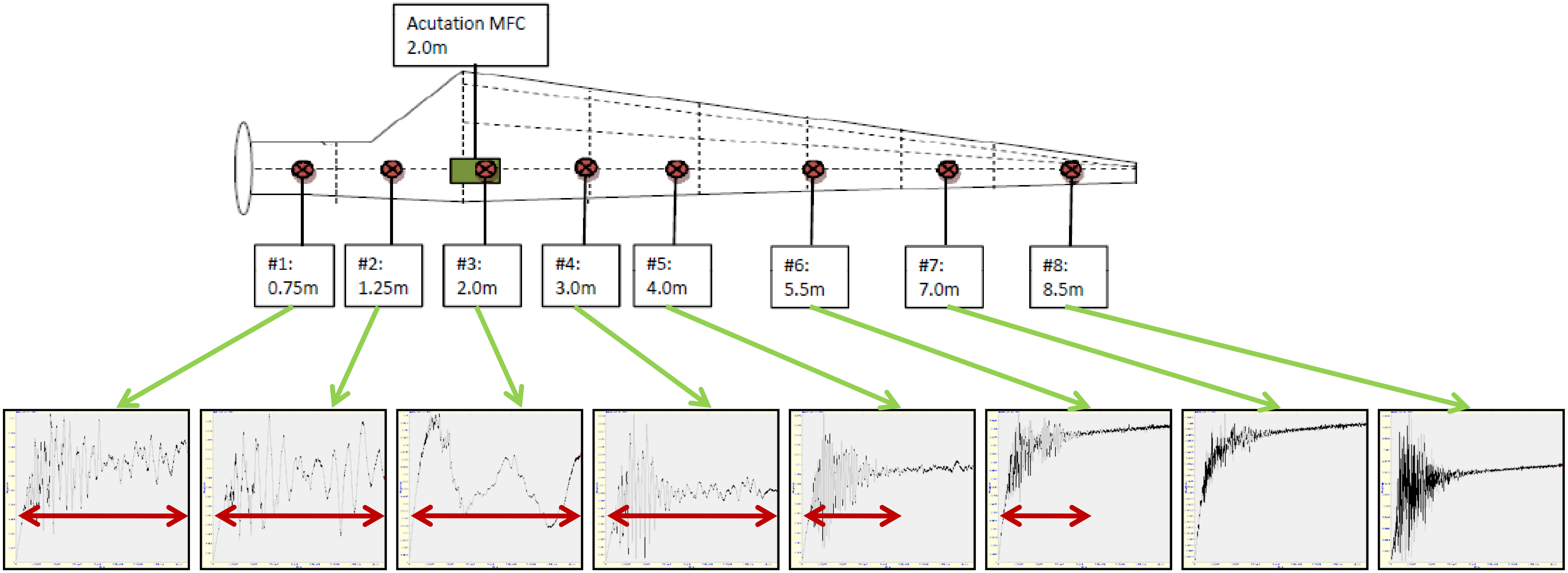
Mode	Freq. (Hz) by Accel.	Freq. (Hz) by PZT	Description
1	3.22	3.22	1st Flap Bending
2	7.14	7.1	1st Lag Bending
3	8.81	8.81	2nd Flap Bending
4	16.89	16.89	2nd Lag Bending
5	19.23	19.23	3rd Flap Bending
6	30.96	30.91	4th Flap Bending
7	44.11	44	1st Torsion



Good correlation between natural frequency and mode shape measurements using accelerometer and piezoelectric sensors

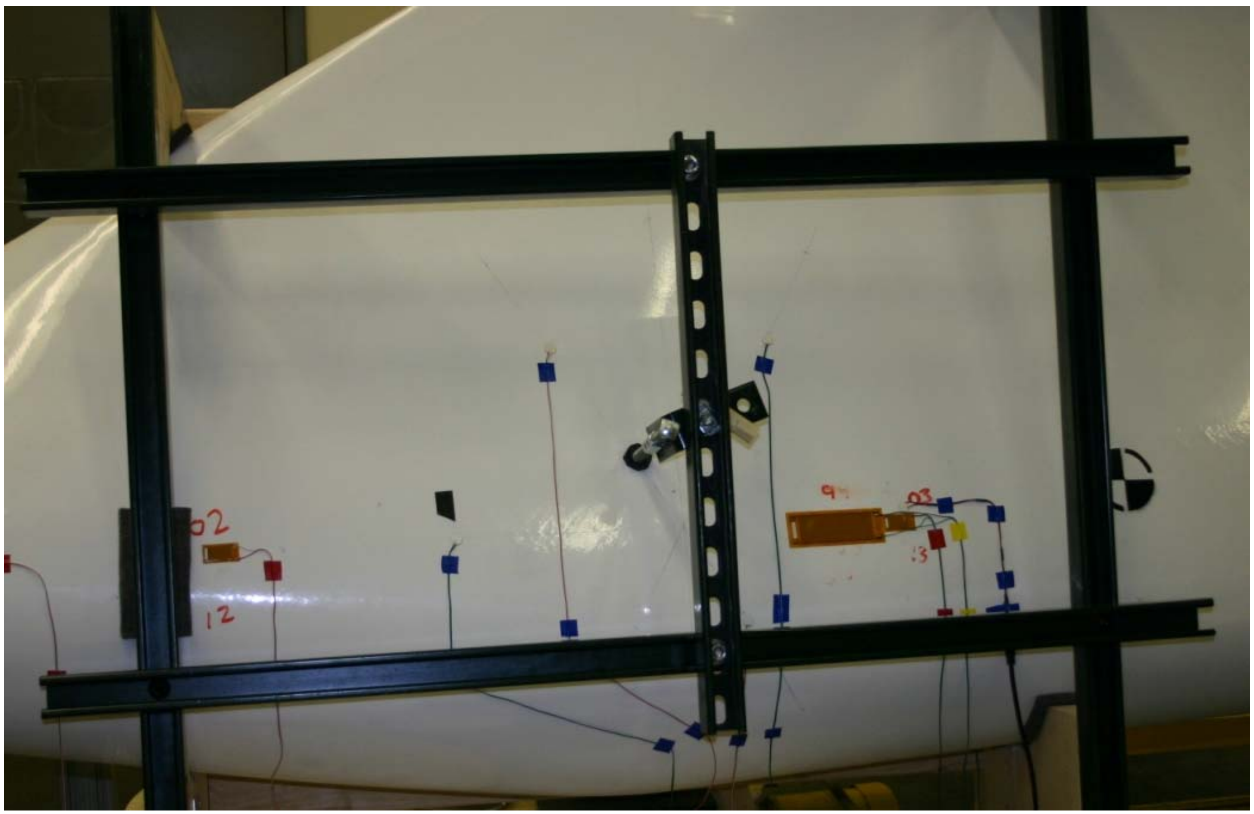
Full-Scale Blade at LANL: Active Sensing

- Compare response at various points
  - Determine effective frequency range at points along length of blade (energy dissipation)
  - 2 actuators are needed to monitor the entire blade

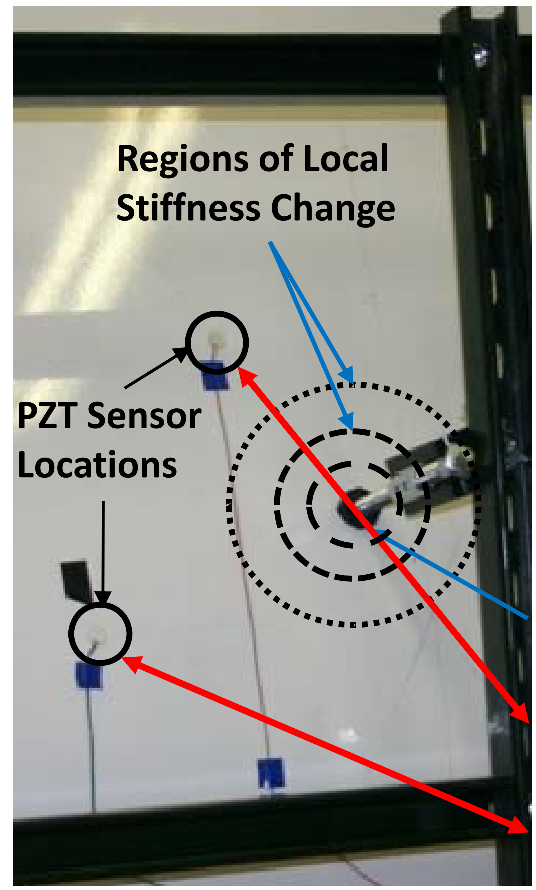


Full-Scale Blade at LANL: Active Sensing

- Local stiffness changes were imposed through the use of a point load
- The location and intensity of damage can be assessed by the response characteristics of each sensor

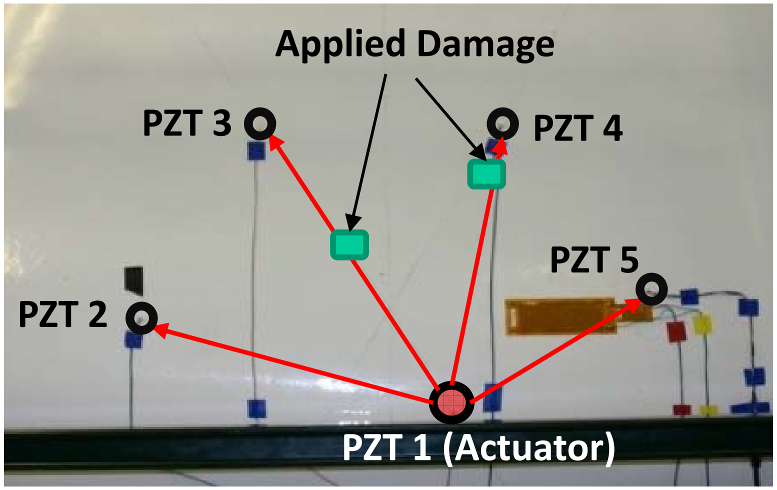


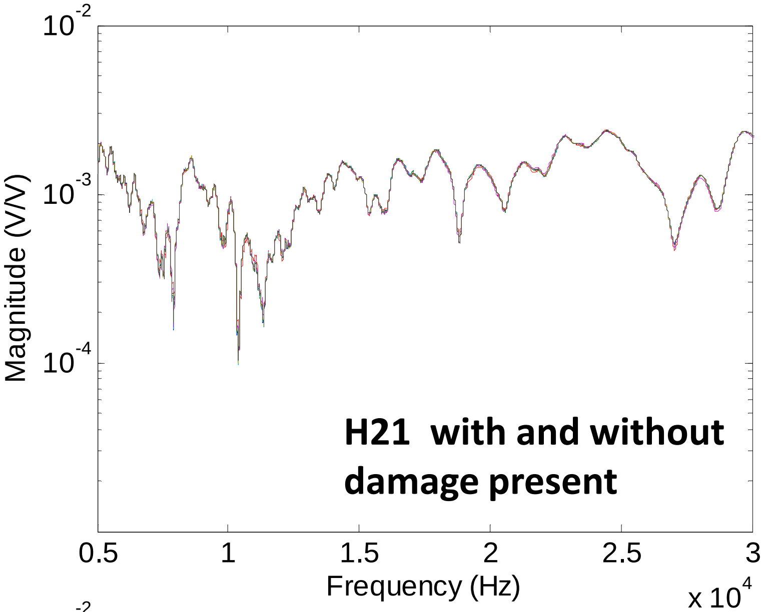
Load Frame used to Apply a Point Load to the Blade

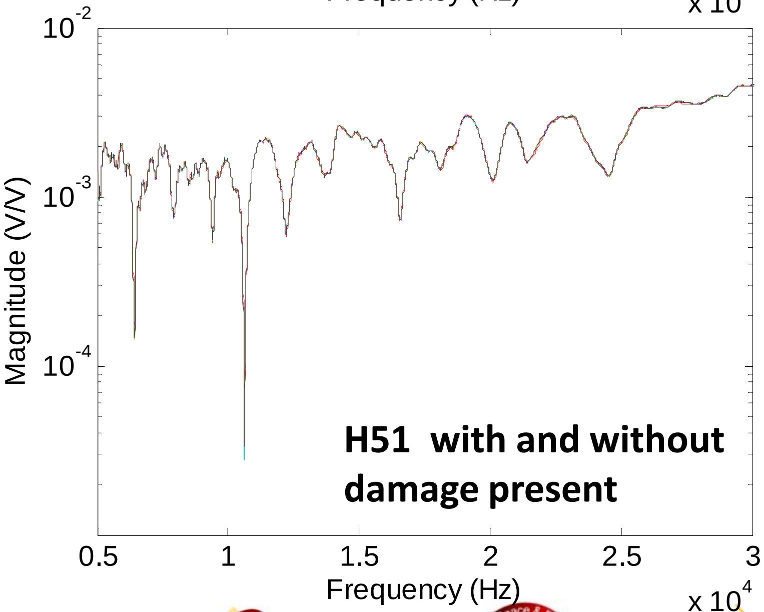


Simulated Damage – Active Sensing

- Damage was applied near PZT 3&4
- Measurements were collected for each of the sensor-actuator paths
  - PZTs 2 and 5 were insensitive to the applied damage

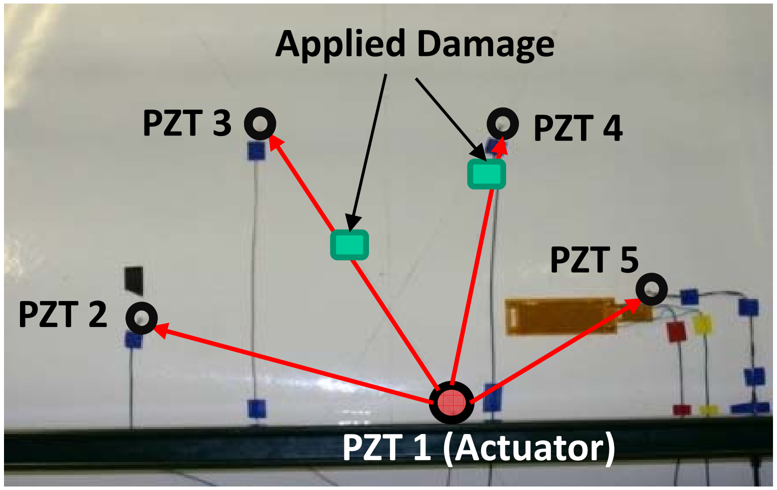


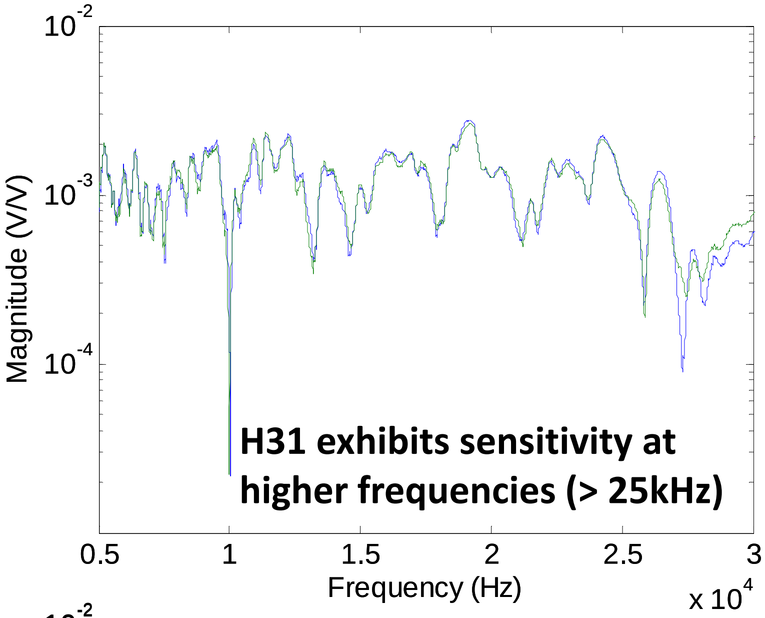


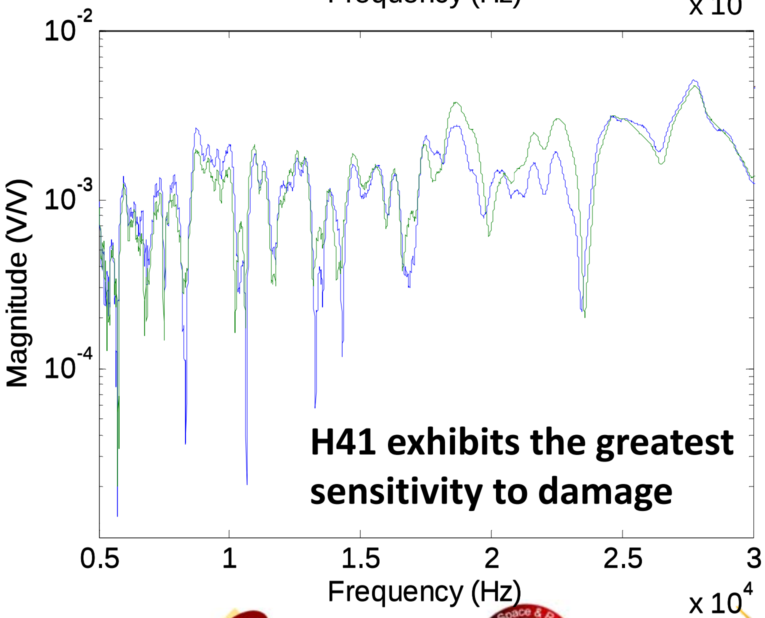


Simulated Damage – Active Sensing

- Damage was applied near PZT 3&4
- Measurements were collected for each of the sensor-actuator paths
  - PZTs 2 and 5 were insensitive to the applied damage
  - The influence of damage can be seen for PZT 3 at frequencies > 25 kHz
  - As expected PZT 4 is the most sensitive to the local stiffness change

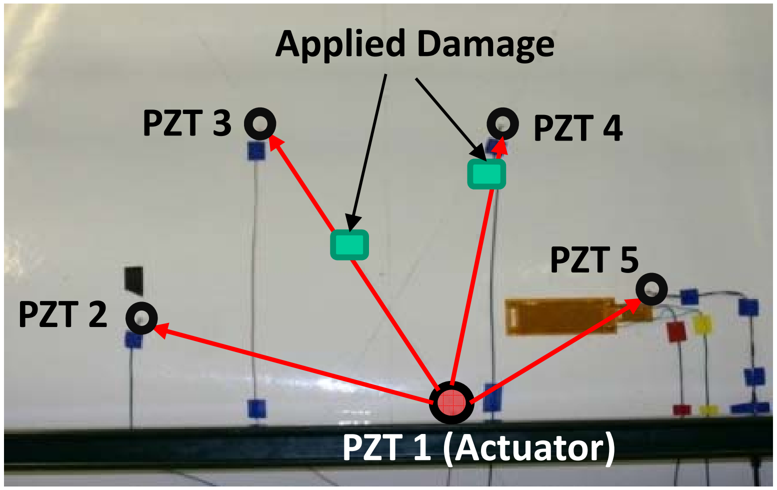


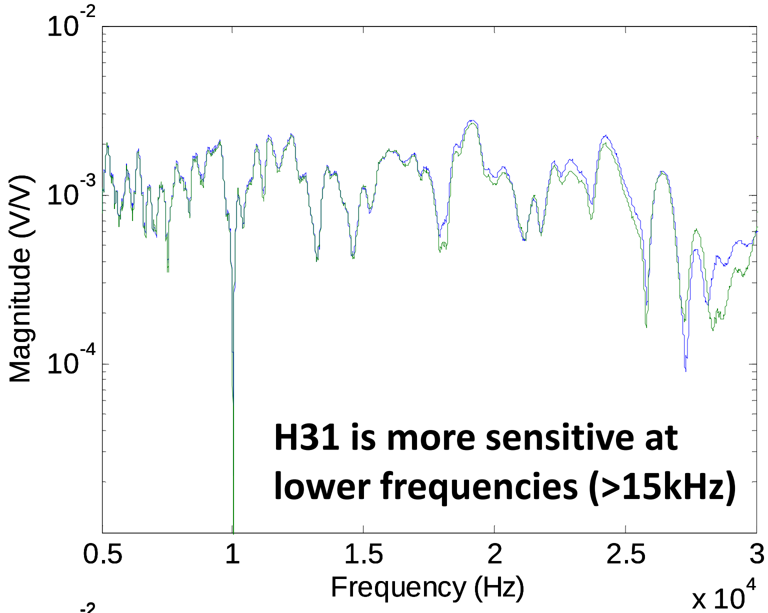


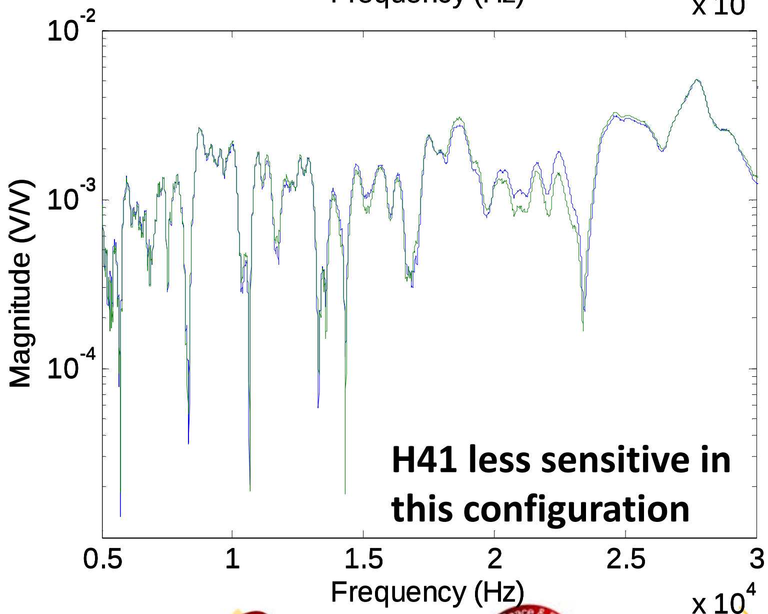


Simulated Damage – Active Sensing

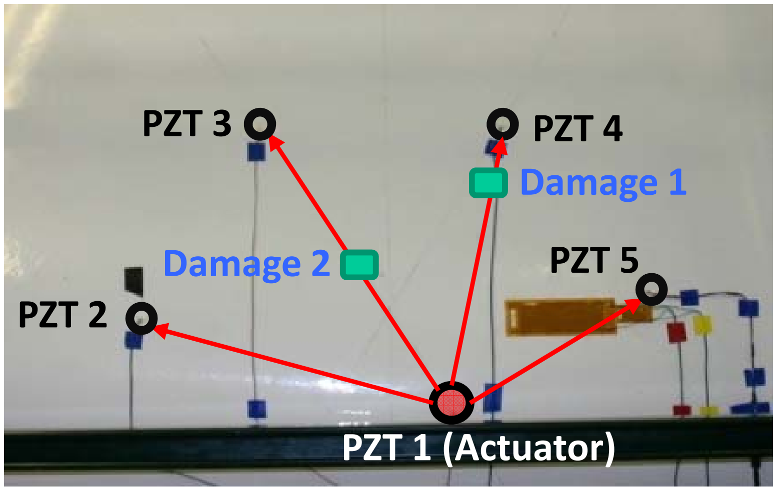
- Damage was applied near PZT 3&4
- Measurements were collected for each of the sensor-actuator paths
  - PZTs 2 and 5 were insensitive to the applied damage
  - As we would expect – PZT 3 shows an increased sensitivity to damage in this location, whereas PZT4 is decreased

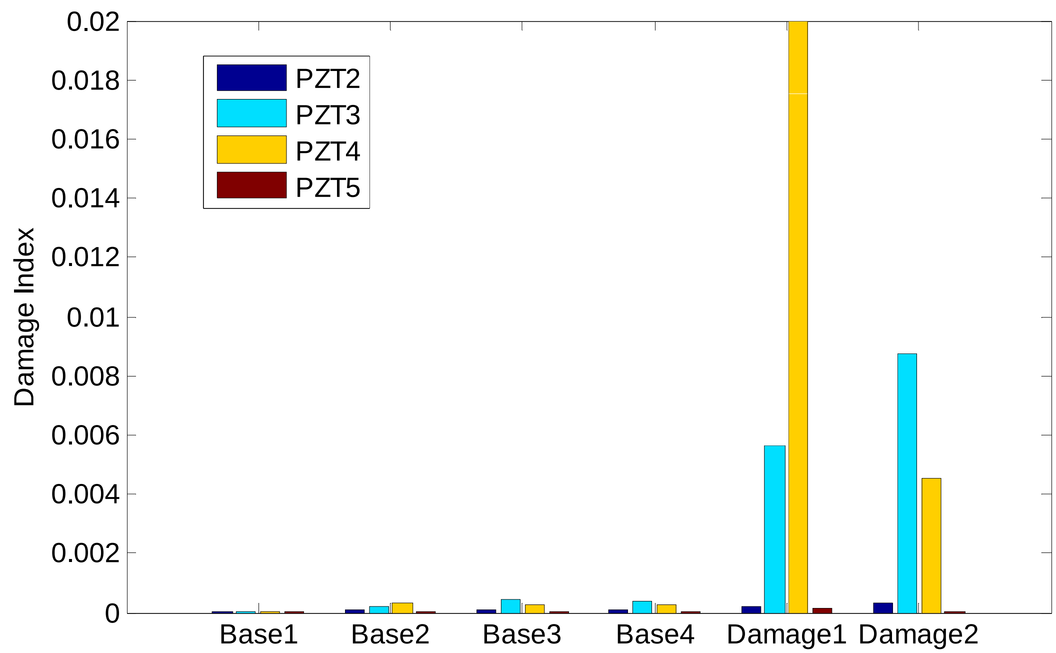






Simulated Damage – Active Sensing

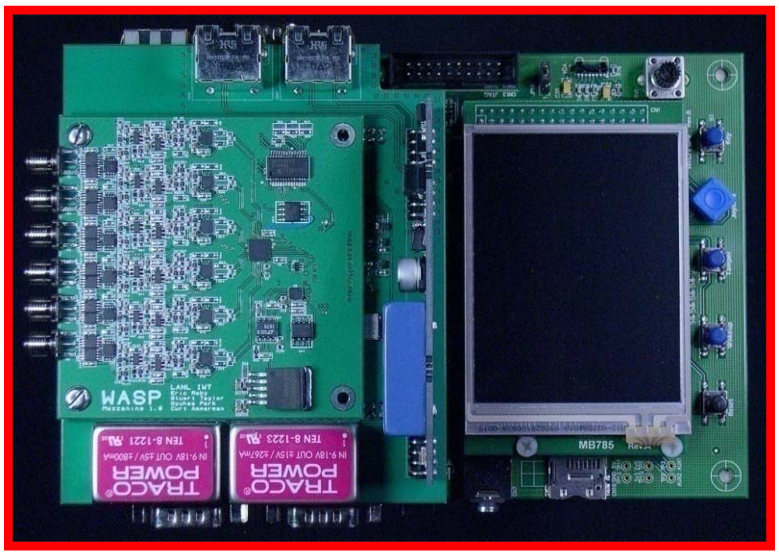


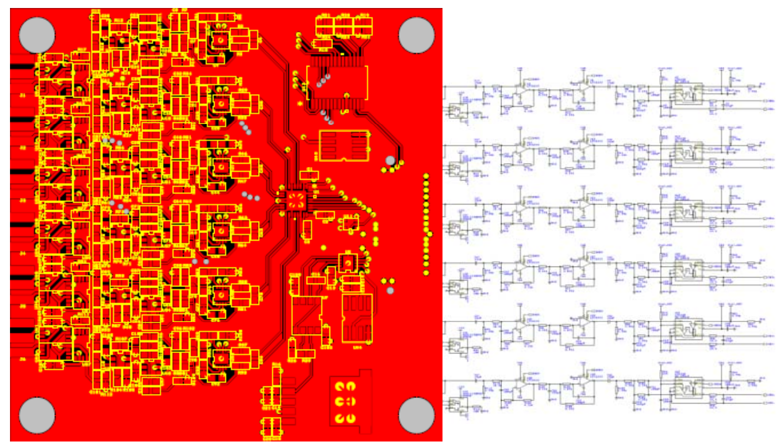


- Demonstrated localization of damage using active-sensing
  - Sensing range: ~ 0.3 m radius for detecting the point load
- Extending this technique to identify damage along the spar cap and through the spar/shear web

Hardware Development:

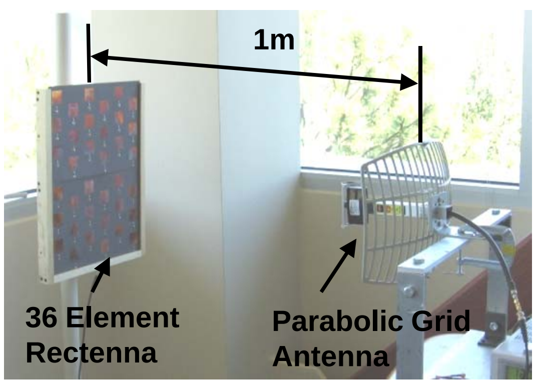
- Embedded Hardware for Multi-Scale Sensing
  - Active / passive capable up to 250 ksps
  - Frequency response, time series analysis, impedance methods
  - Sensor diagnostics
  - Accommodate multiple sensing modalities
  - Web-driven data acquisition
  - Higher (embedded) processing power

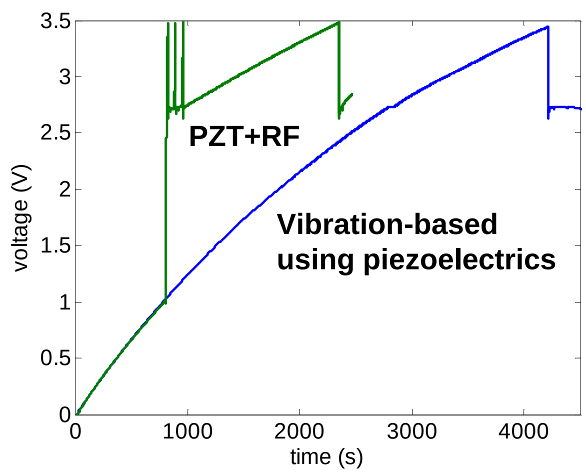




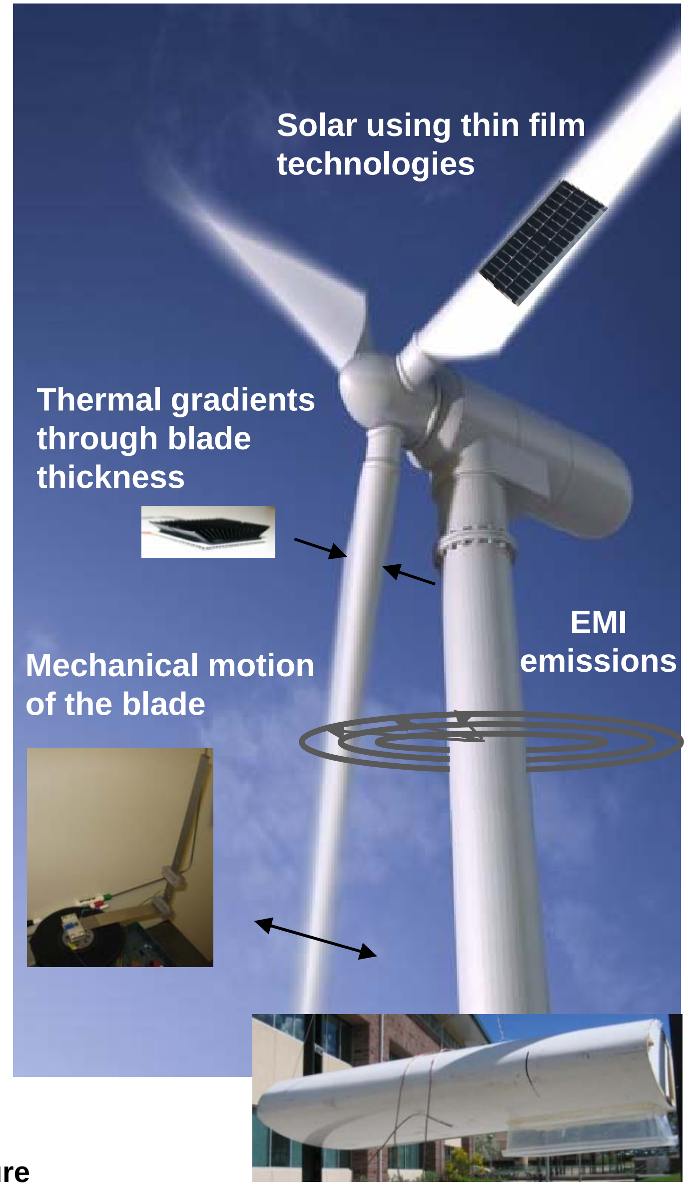
Powering Embedded Hardware

- Power demands will become a major design criteria for long term deployments
  - Currently we are investigating energy harvesting techniques to supplement onboard power sources
- Several sources are available on rotor blades
  - Solar, thermal, kinetic, electromagnetic, etc.
- To provide a robust power source, the harvesting system may need to extract energy from multiple sources



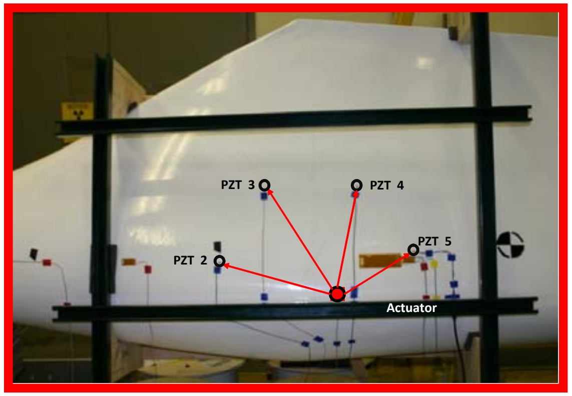


Charging response for civil infrastructure



Summary

- Several experimental investigations have demonstrated the potential of piezoelectric transducers for:
  - Structural Health Monitoring
    - Sensitive to small defects in blades
    - Immune to operational condition changes
  - Multi-scale sensing of wind turbine blades
    - Low-cost, low-power
- A wireless sensor node is being developed to integrate multi-scale sensing and SHM capabilities for damage prognosis



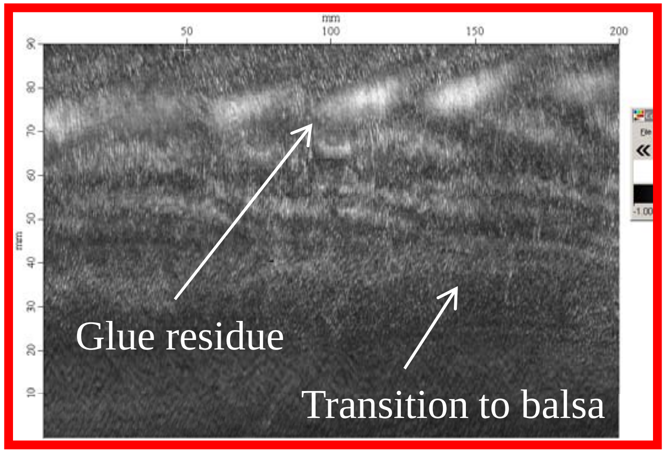
Plans for FY2011-12

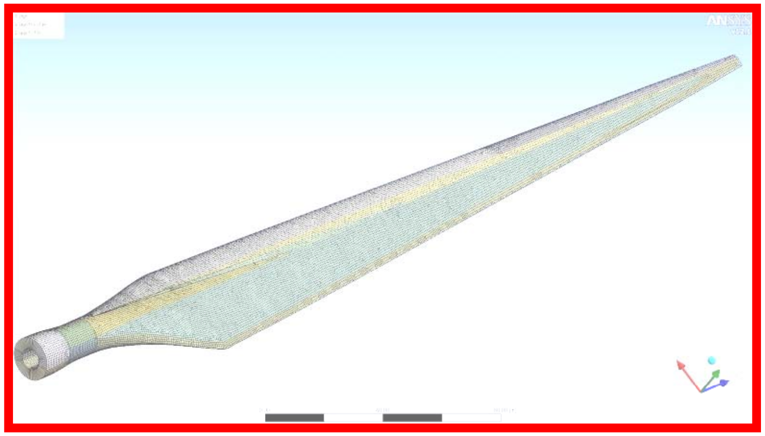
FY-2011

- Full-scale fatigue tests of CX-100 (2011)
  - Collaboration with NREL, UMass-Lowell, SNL, Luna. We are currently open to other participants as well.
- NDE characterization of damage on fatigued CX-100 blade sections (2011)
  - Correlation with SHM results
- NREL's Gearbox CM round robin (2011)
- Fabrication of SHM Rotor Blade (2011)

FY-2011-12

- Integration with damage modeling and advanced data processing (2011-12)
  - Sensor location optimization
  - Prognostic analysis of blade condition
- Collaborative testing of SHM Rotor Blade with Sandia (2012)
  - Onboard SHM (LANL)
  - Operational Monitoring (SNL)
  - Large form PIV (LANL)





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