LA-UR-12-24351
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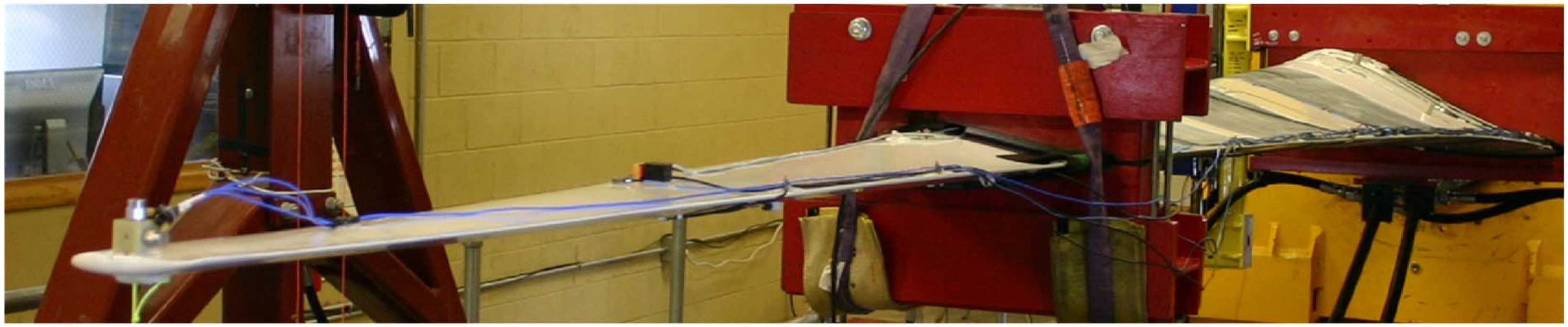
Intended for: First International Conference on Advances in Structural Health Management and Composite Structures, 2012-08-29/2012-08-31 (Jeonju, Jeonbuk, ---, Korea, South)



Incipient Crack Detection in Composite Wind Turbine Blades

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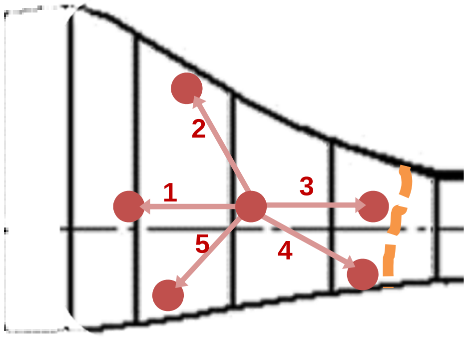
ASHMCS 2012
August 29-31, Jeonju, Korea

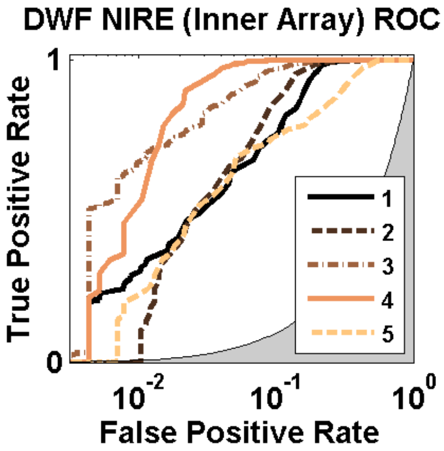
Abstract

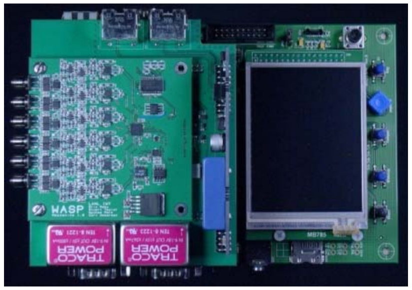
- **This paper presents some analysis results for incipient crack detection in a 9-meter CX-100 wind turbine blade that underwent fatigue loading to failure. The blade was manufactured to standard specifications, and it underwent harmonic excitation at its first resonance using a hydraulically-actuated excitation system until reaching catastrophic failure. This work investigates the ability of an ultrasonic guided wave approach to detect incipient damage prior to the surfacing of a visible, catastrophic crack. The blade was instrumented with piezoelectric transducers, which were used in an active, pitch-catch mode with guided waves over a range of excitation frequencies. The performance results in detecting incipient crack formation in the fiberglass skin of the blade is assessed over the range of frequencies in order to determine the point at which the incipient crack became detectable. Higher excitation frequencies provide consistent results for paths along the rotor blade's carbon fiber spar cap, but performance falls off with increasing excitation frequencies for paths off of the spar cap. Lower excitation frequencies provide more consistent performance across all sensor paths.**

Outline

- **CX-100 wind turbine blade**
  - Research blade from SNL
  - 9m, Composite structure
- **Fatigue loading**
  - harmonic excitation
  - ~8.5M cycles to failure
- **Instrumentation**
  - Sensor Arrays
  - Hardware
- **Experimental Data**
  - Diffuse wave-field measurements
  - Ultrasonic Guided waves
- **Experimental Results**
  - Fatigue crack detection performance
  - Sensor diagnostics
- **SHM system Deployment**

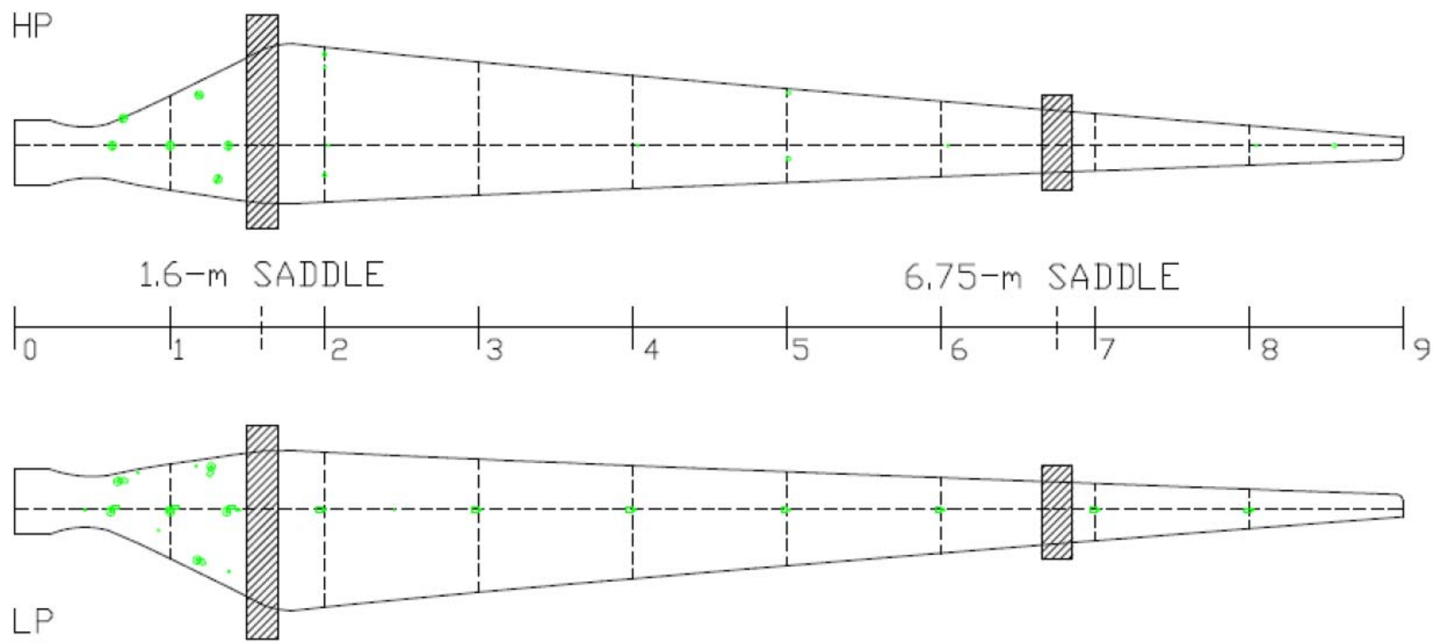






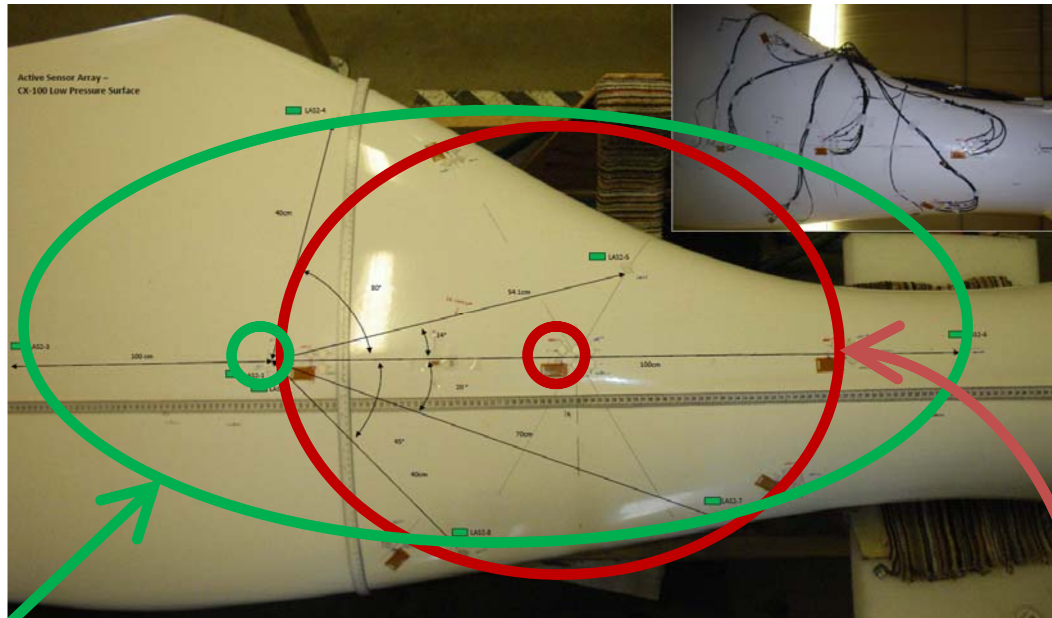
The CX-100 Wind Turbine Blade

- Designed at SNL
- 9-meters long
- Balsa wood frame
- Fiberglass Body
- Carbon Fiber Spar Cap
- Thick root section

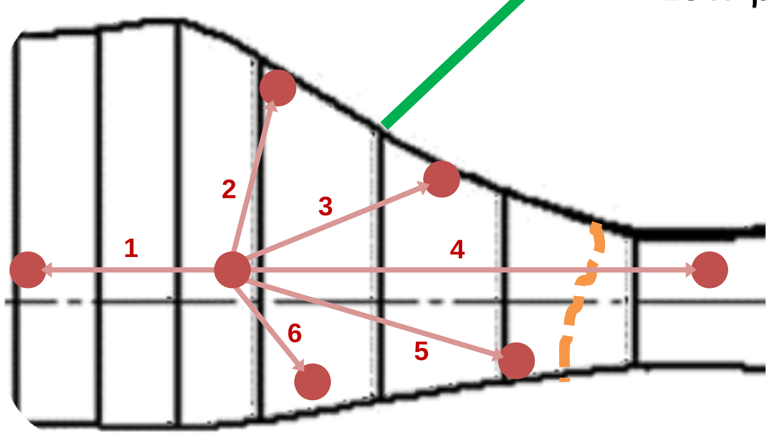


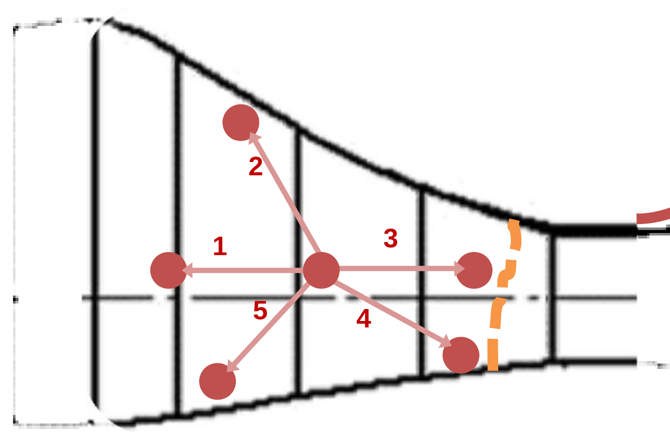
Sensor Arrays for Fatigue Test (LP Side)

- **Active arrays on Low-Pressure Surface**
  - LP-A1: LASER Inner
  - LP-A2: Metis 1
  - LP-A3: WASP
  - LP-A4: LASER Outer
- **The inner array observes a 0.75 m diameter region centered 1m from the root**
- **The outer array observes a 2m diameter region 1.5m from the blade root**



Low pressure surface transitional root area



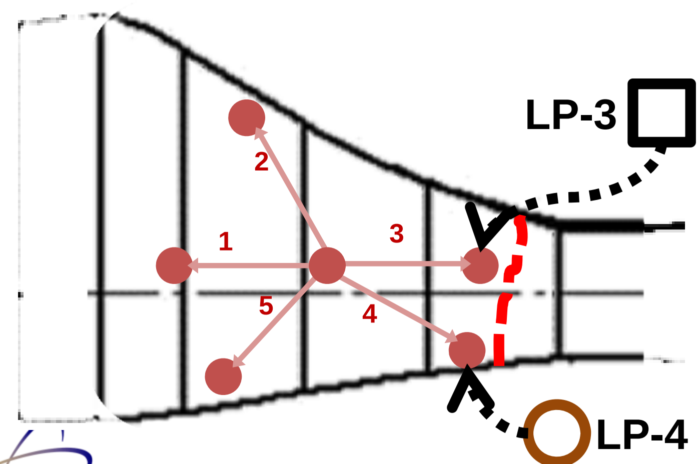


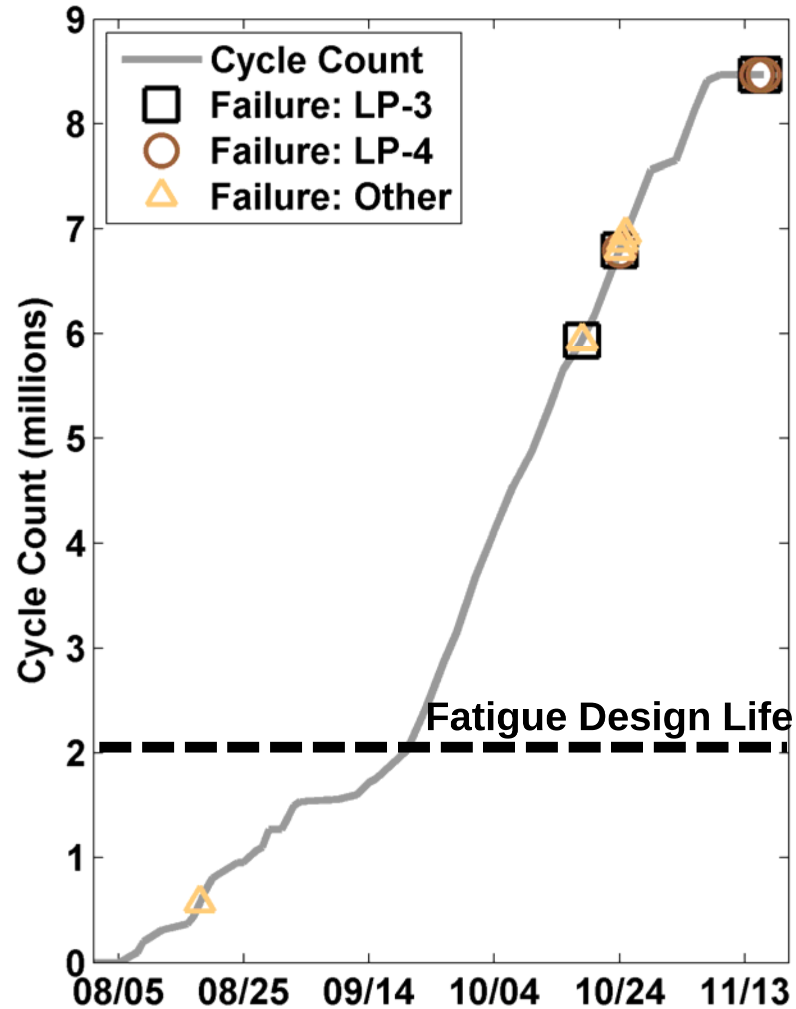
Fatigue Test Operation

- Fatigue test conducted at NREL's National Wind Technology Center.
- Excitation using Universal Resonant EXcitation (UREX).
- Moment Distribution Saddles at 1.6m and 6.75m
- Excitation at first natural frequency (1.8 Hz)
- Multiple Sensing and Diagnostic Systems Deployed

Cycle Accumulation and Sensor Failures

- Twelve sensors failed through the course of the test, one of which failed near the test start.
- Many failures were precipitated by the blade's catastrophic failure.
- The majority of failures occurred near the crack (locations LP-3/4).
- Almost all failures, including those at other locations (OL), occurred after the blade had undergone over three times (3x) its rated fatigue life.





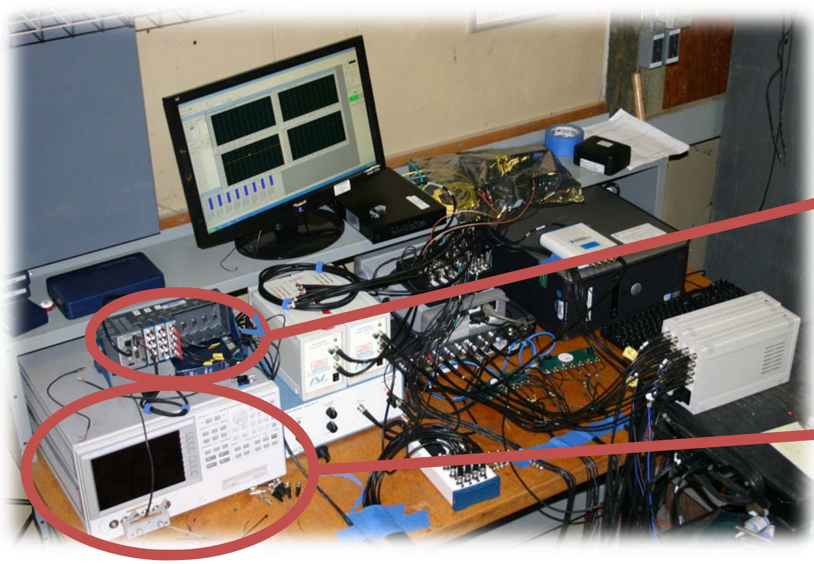
Passive/Diagnostic Sensing Systems

National Instruments - cRIO

- **Passive sensing at 1.6kHz**
  - Accelerometers
  - Piezoelectrics
  - Internal microphone
- **Commercial DAQ for embedded applications**

Sensor Diagnostics (HP4291A)

- **Impedance measurement sweeps from 1kHz to 30kHz**
- **Imaginary part of Admittance can indicate sensor bond condition**
- **Measurements taken approximately once/week**



Active Sensing Systems

Ultrasonic Guided Waves

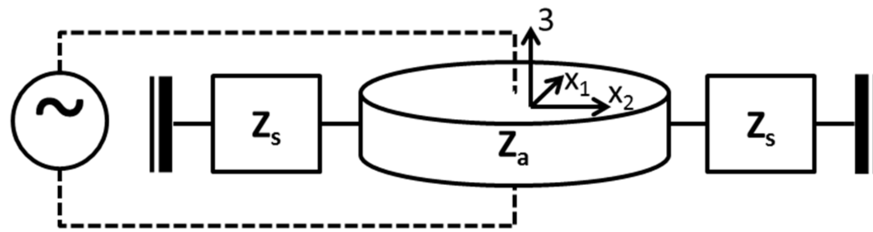
- **Metis IntelliConnector**
  - 10 MHz sampling rage
  - Excited from 50-250 kHz at 25 kHz intervals
  - One sensor array on each blade surface; 0.5-m transmission distances.

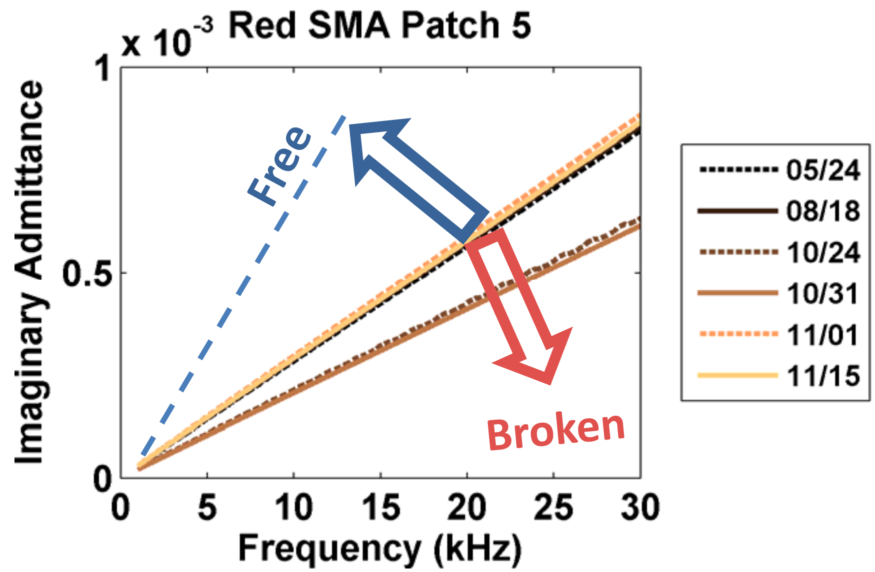
Diffuse Wave Fields

- **$\text{LASER}_{\text{USB}}$ by LDS Dactron**
  - White noise excitation from 100 Hz to 40 kHz
  - Two sensor arrays low pressure surface
    - 0.35-m and 1-m transmission distances, respectively
- **Wireless Active Sensing Platform (WASP)**
  - Active/Passive sensing with 100 kHz bandwidth
  - Multiple sensing modes
    - Active, Passive, Impedance
  - Autonomous or web-driven data acquisition
  - Onboard processing power
  - Externally amplified excitation

Sensor Diagnostics Overview

- This test utilized circular PZT patches bonded to fiberglass.
- The bonding state of the patches is reflected in their capacitive behavior.
- Changes in that behavior can be inferred from the slope of the imaginary part of the admittance curve.
- An increased slope indicates a more free-free condition.
- A decreased slope indicates a reduction in capacitance, usually a result of breakage.



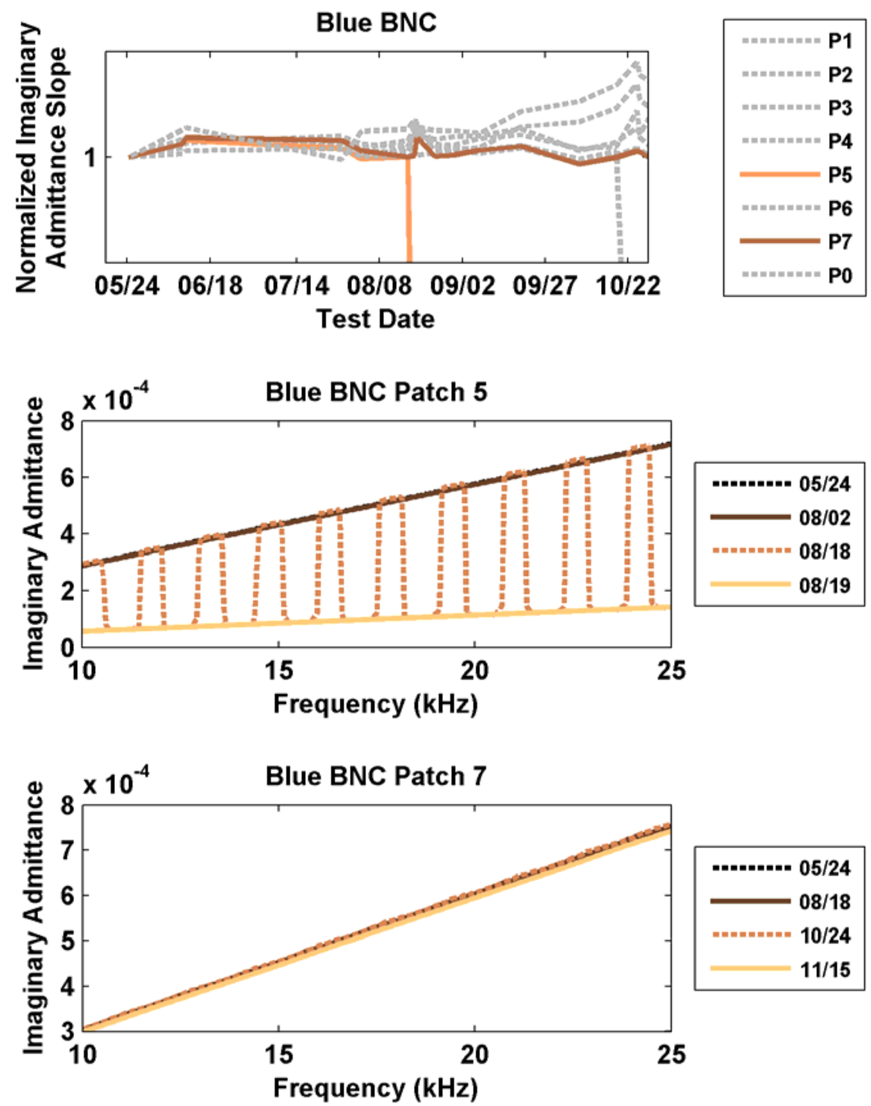


$$Y(\omega) = \frac{I}{V} = i\omega a\left(\bar{\varepsilon}_{33}{}^{T} - \frac{Z_s(\omega)}{Z_a(\omega)+Z_s(\omega)} d_{3x}^{2}\hat{Y}_{xx}{}^{E}\right)$$

Sensor Diagnostics Examples

NI Active Sensing Array

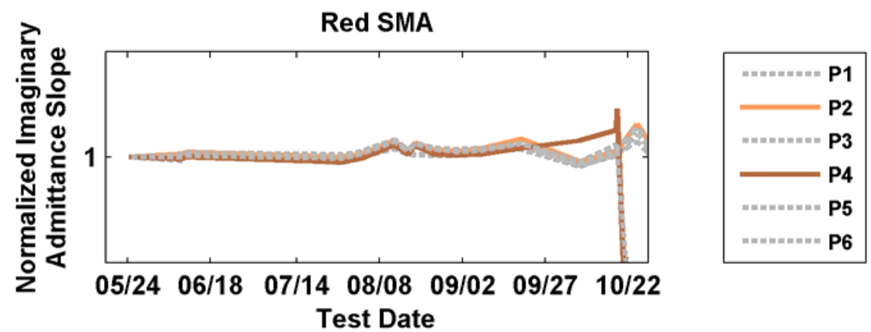
- **Patch 5 broke early in the test**
  - Some data were collected during fatigue loading
  - First example of breathing crack behavior in this test
  - The patch was not immediately replaced
  - Fully broken behavior was exhibited the next day, following the lower slope
- **Patch 7 remained healthy**
  - This patch sat at 7m, and saw very low strains

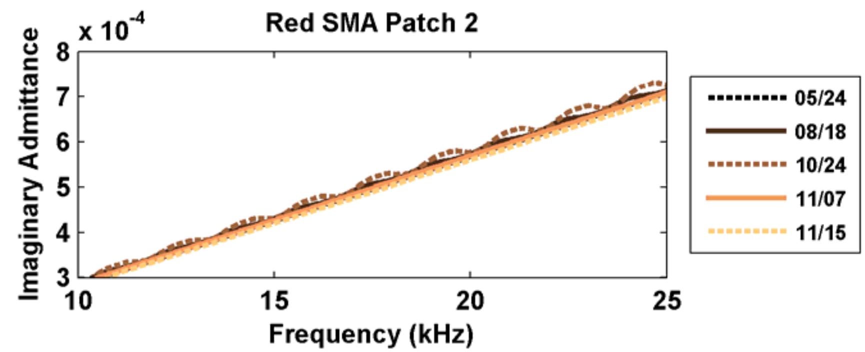


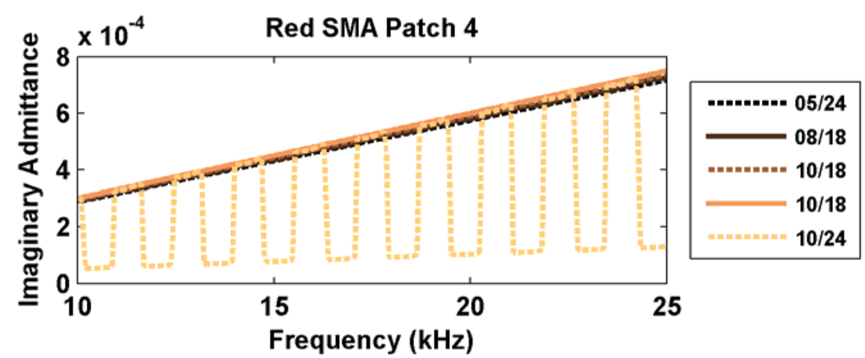
Sensor Diagnostics Examples

WASP LP Array

- **Patch 2 remained healthy.**
  - Some data were collected during fatigue loading
  - Located within 1m of the blade root, this patch saw high fatigue strains.
  - The structural impedance is cyclic for data collected during fatigue loading.
- **Patch 4 sat directly atop the ultimate failure.**
  - As the crack formed, the blade surface softened.
  - This patch was ultimately replaced twice.





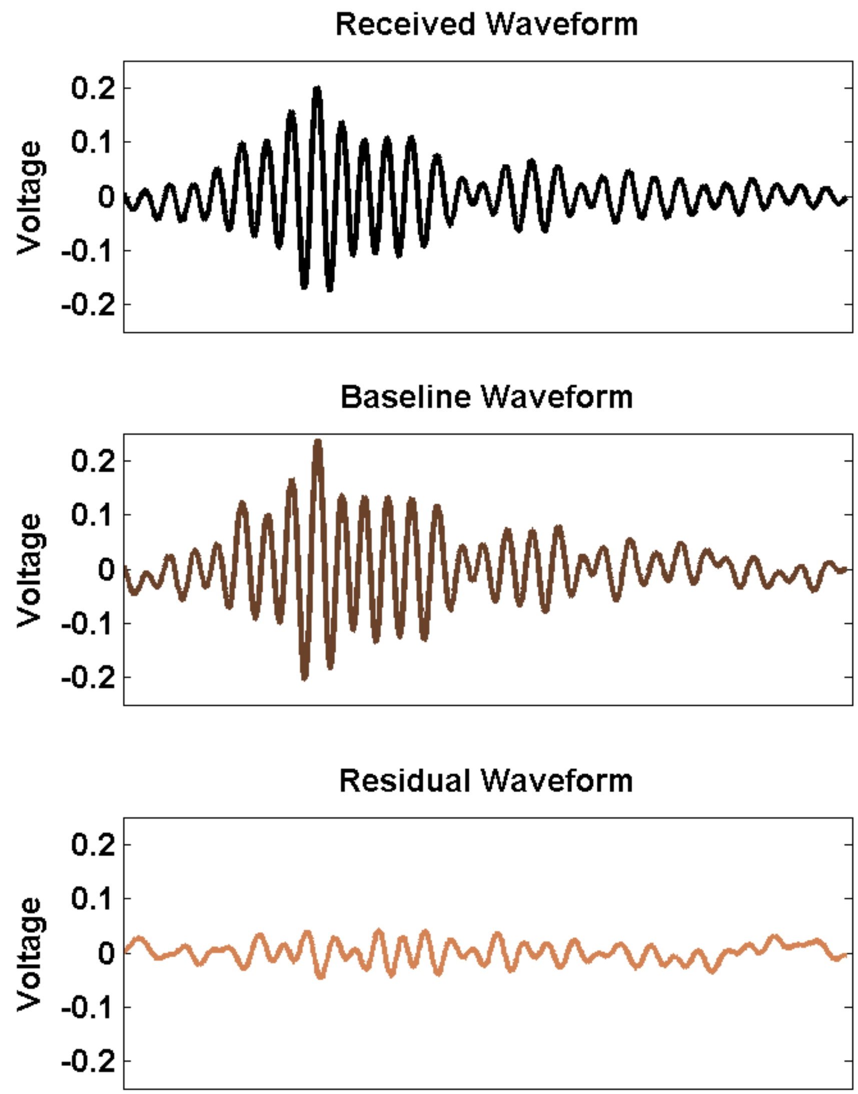


Test Statistics: Guided Waves

- **Match all test waveforms with a baseline waveform minimizing norm of their difference.**
- **Compute each residual as the difference between a waveform and its baseline.**
- **Compute Test Statistics**
  - **Normalized Residual Energy (NRE)**
  - **Correlation Coefficient Complement (CCC)**

$$NRE = \frac{\sum \mathbf{v}_i^{\ 2}}{\sum \mathbf{w}_j^{\ 2}}$$

$$CCC = 1 - \sum \frac{\left(\tilde{y}_i - \mu_{y_i}\right)\left(\tilde{y}_j - \mu_{y_j}\right)}{\sigma_{y_i}\sigma_{y_j}}$$

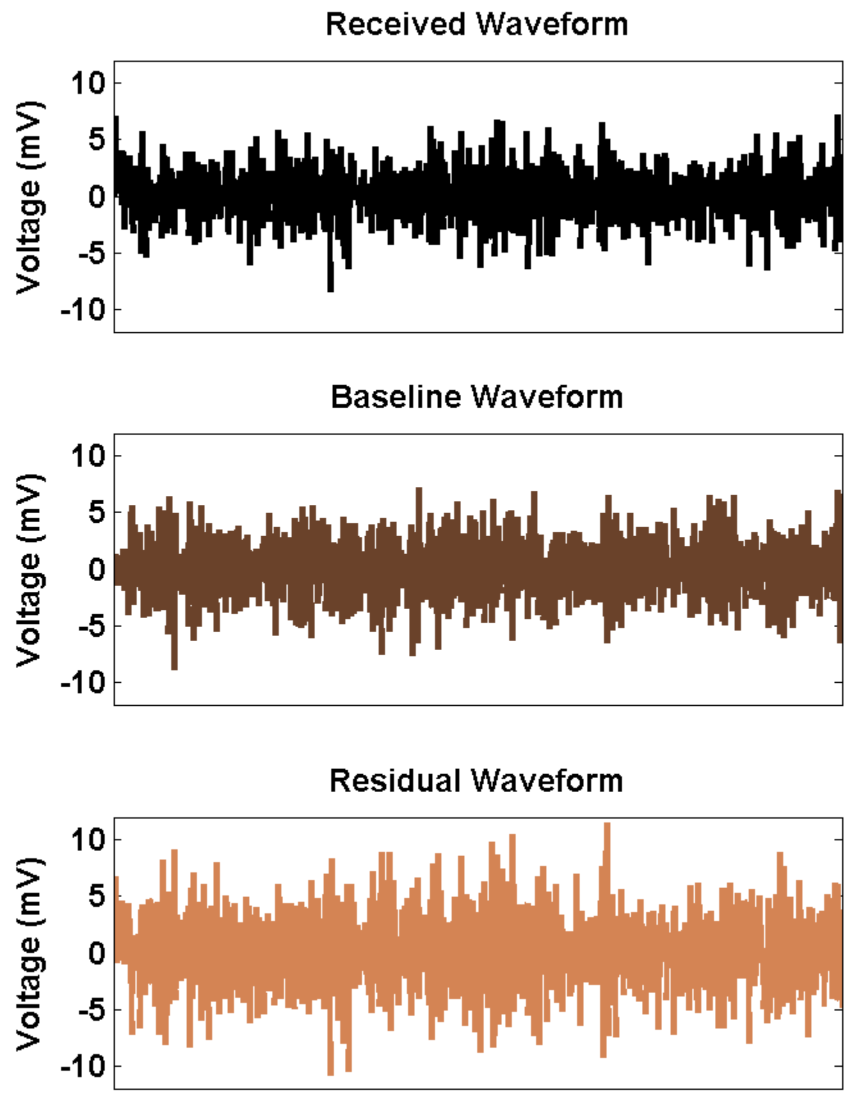


Test Statistics: Diffuse Waves

- **Measurements are colored noise; baseline subtraction produces more colored noise.**
- **Estimate Impulse Response Function (IRF) as iFFT of FRF**
- **Use IRF as test waveforms and compute impulse residual**
- **Compute Test Statistics**
  - **Normalized Impulse Residual Energy (NIRE)**
  - **Impulse Correlation Coefficient Complement (ICCC)**

$$NIRE = \frac{\sum \boldsymbol{\upsilon}_i^{\,2}}{\sum \boldsymbol{\omega}_j^{\,2}}$$

$$ICCC = 1 - \sum \frac{\left(\psi_i - \mu_{\psi_i}\right)\left(\psi_j - \mu_{\psi_j}\right)}{\sigma_{\psi_i}\sigma_{\psi_j}}$$



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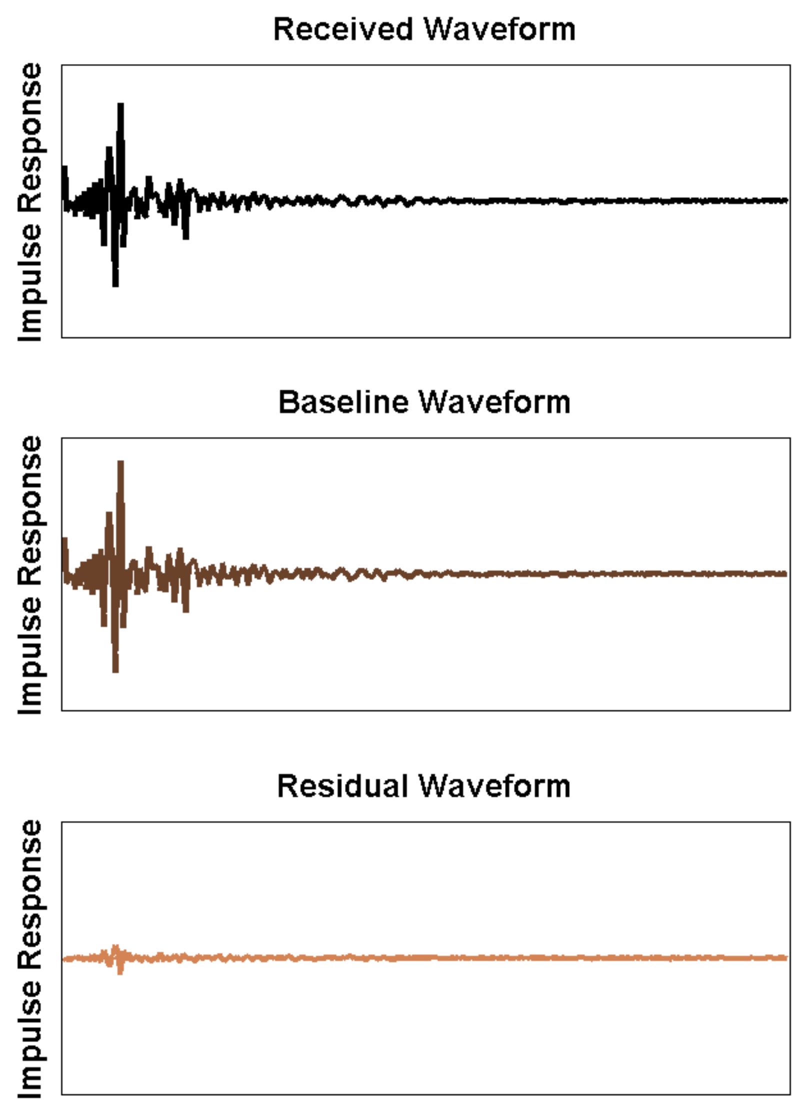
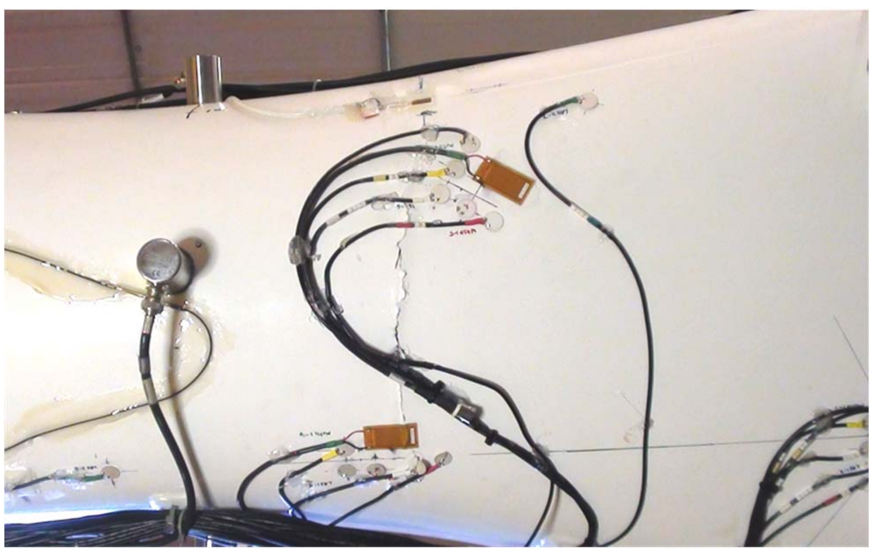
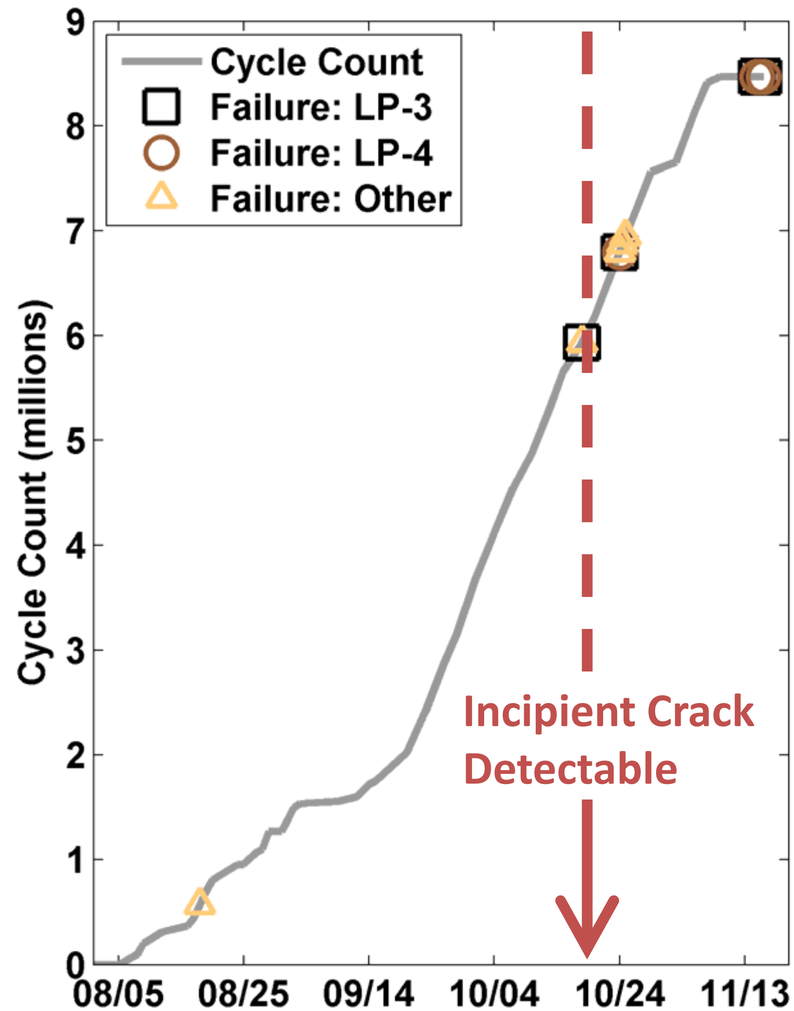


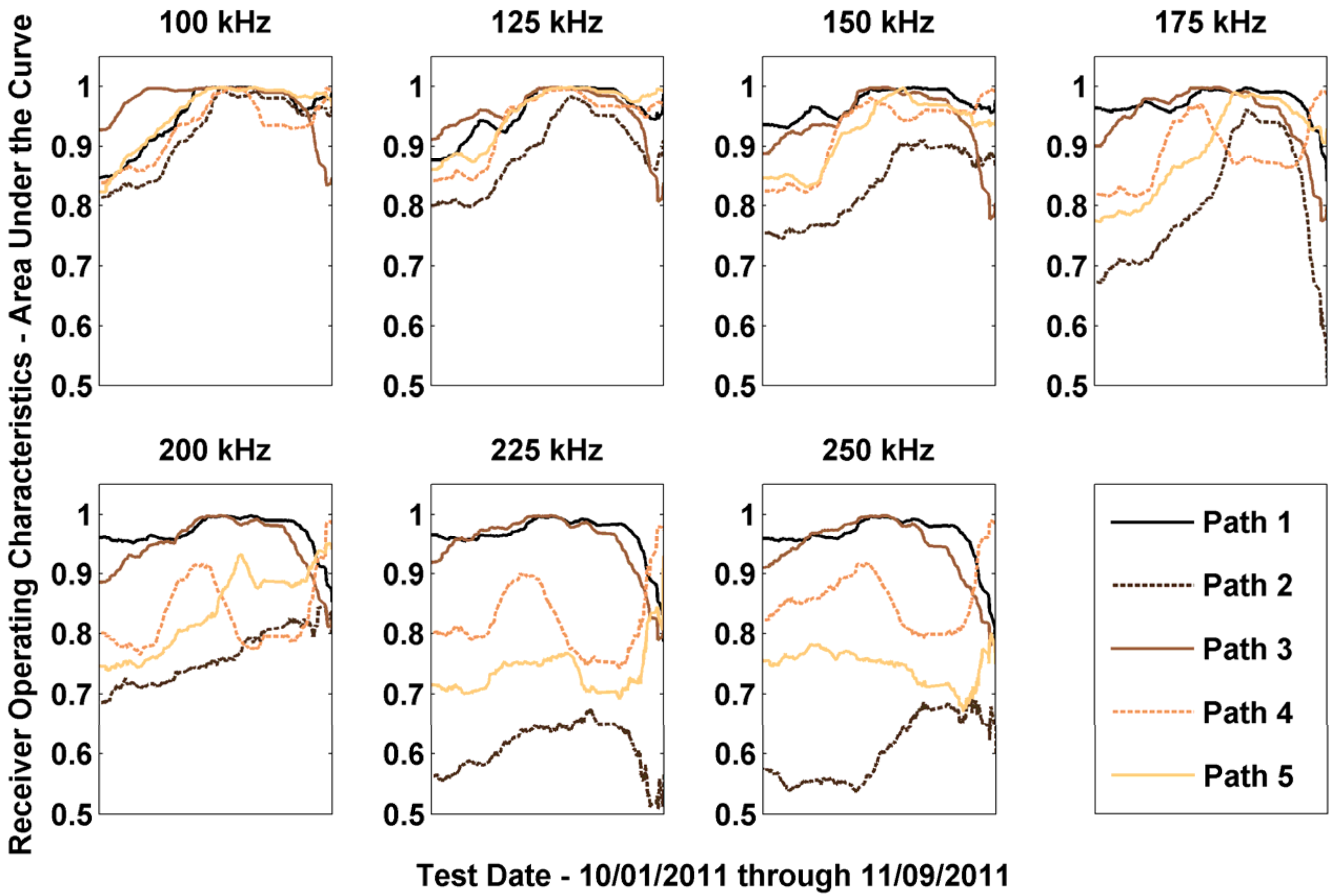
Incipient Crack Detection

- **Incipient Damage became detectable around 10/20/2011**
- **Catastrophic crack surfaced 11/08/2011**



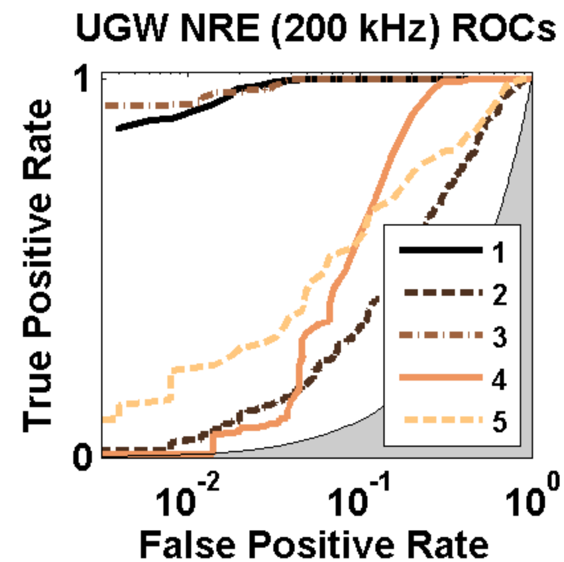


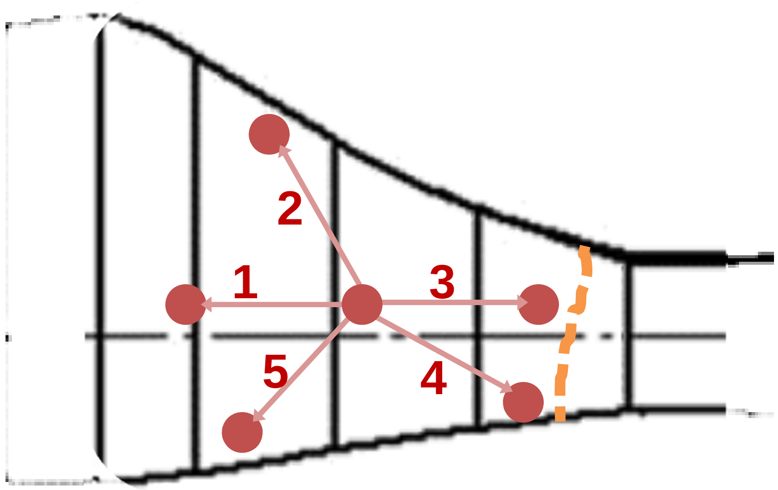
Choosing a Demarcation Date

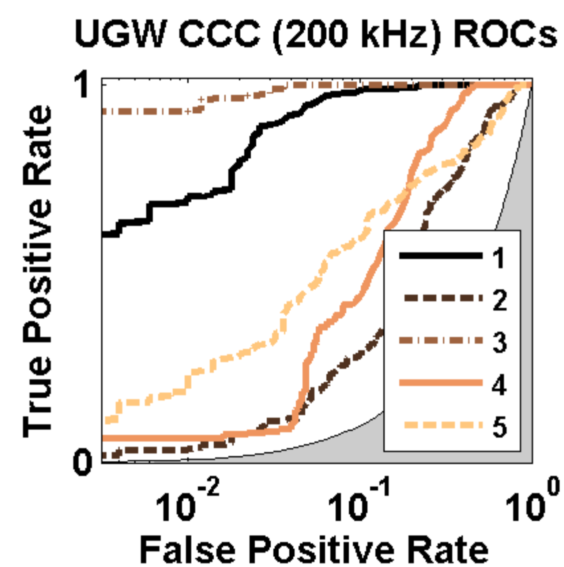


Fatigue Crack Detection Performance

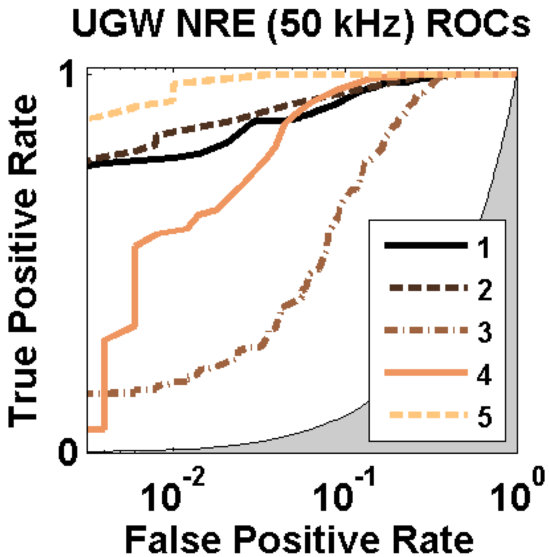
- At 200 kHz, the spar cap may act as a wave guide
- The crack is detectable in either direction (1 or 3)
- Proximity to the crack does not affect the detection performance

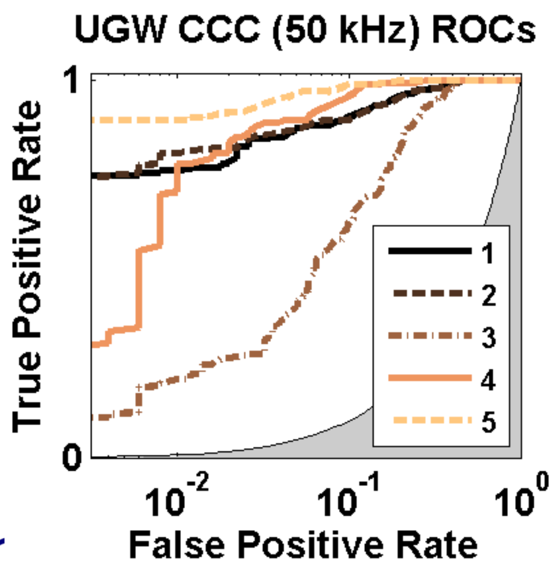




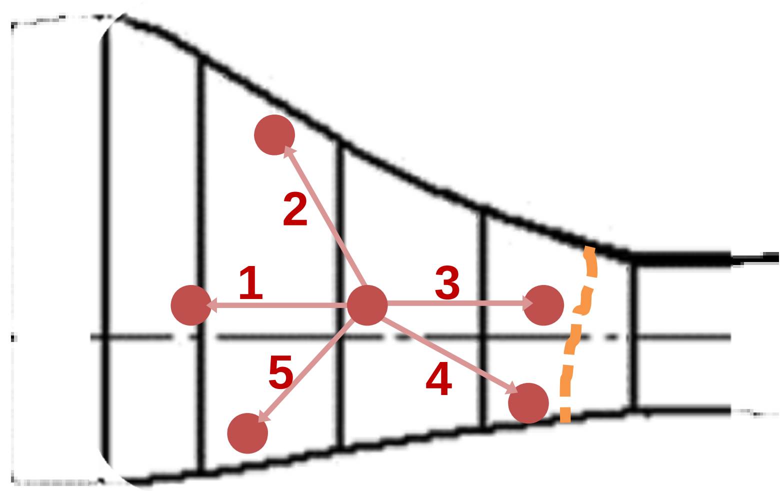


Fatigue Crack Detection Performance



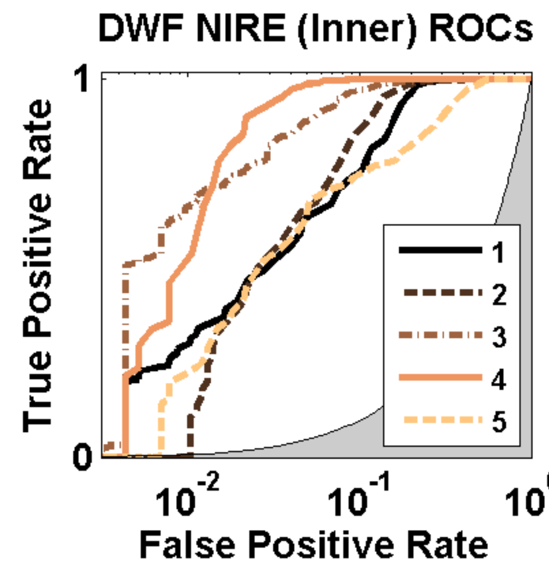


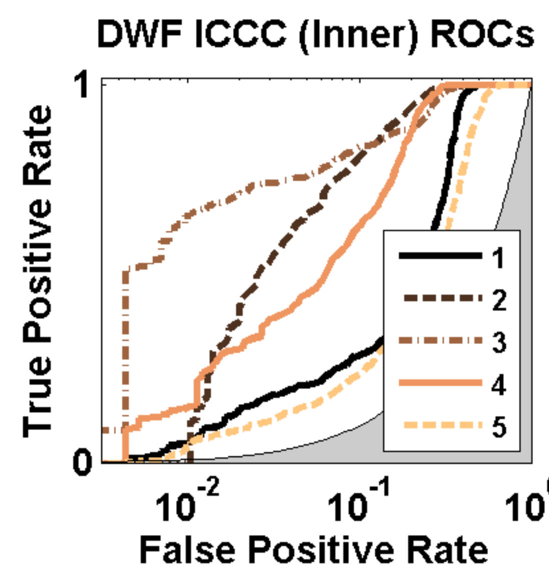
- **At 50 kHz, detection performance with guided waves does not increase with proximity to the crack.**

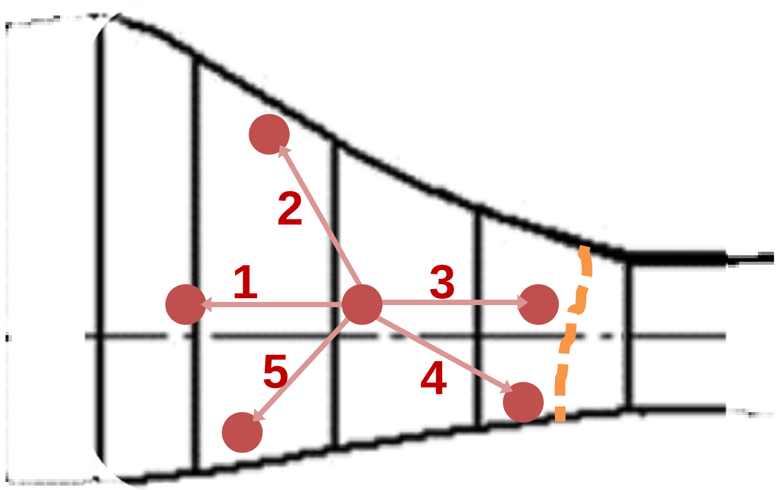


Fatigue Crack Detection Performance

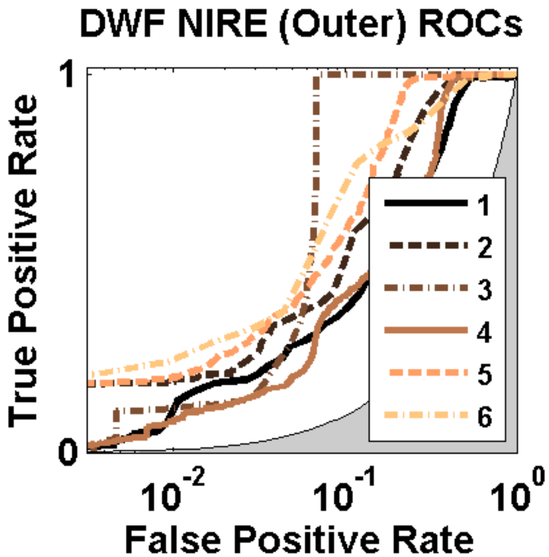
- **With the Inner Array, the energy detector has higher sensitivity near the crack.**
- **The correlation detector has somewhat lower performance.**

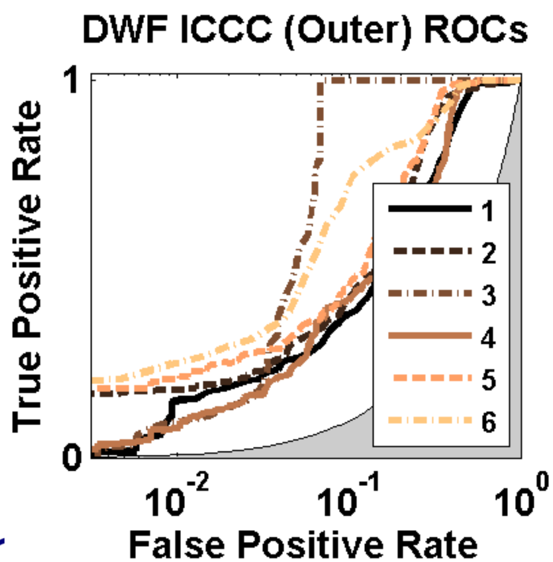




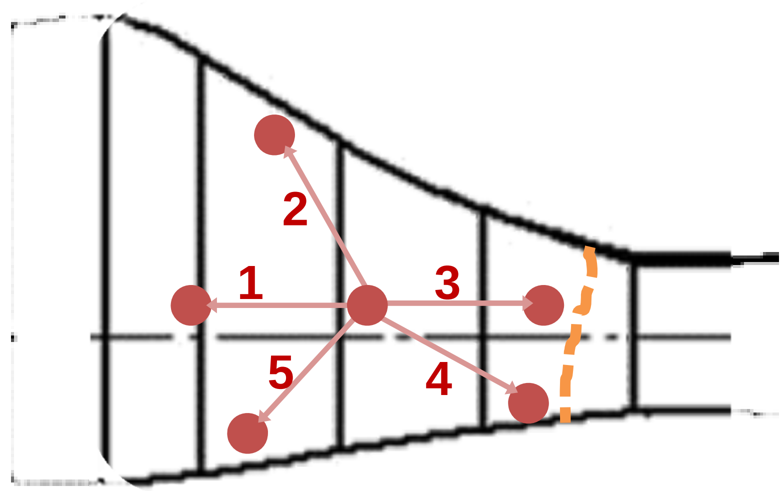


Fatigue Crack Detection Performance



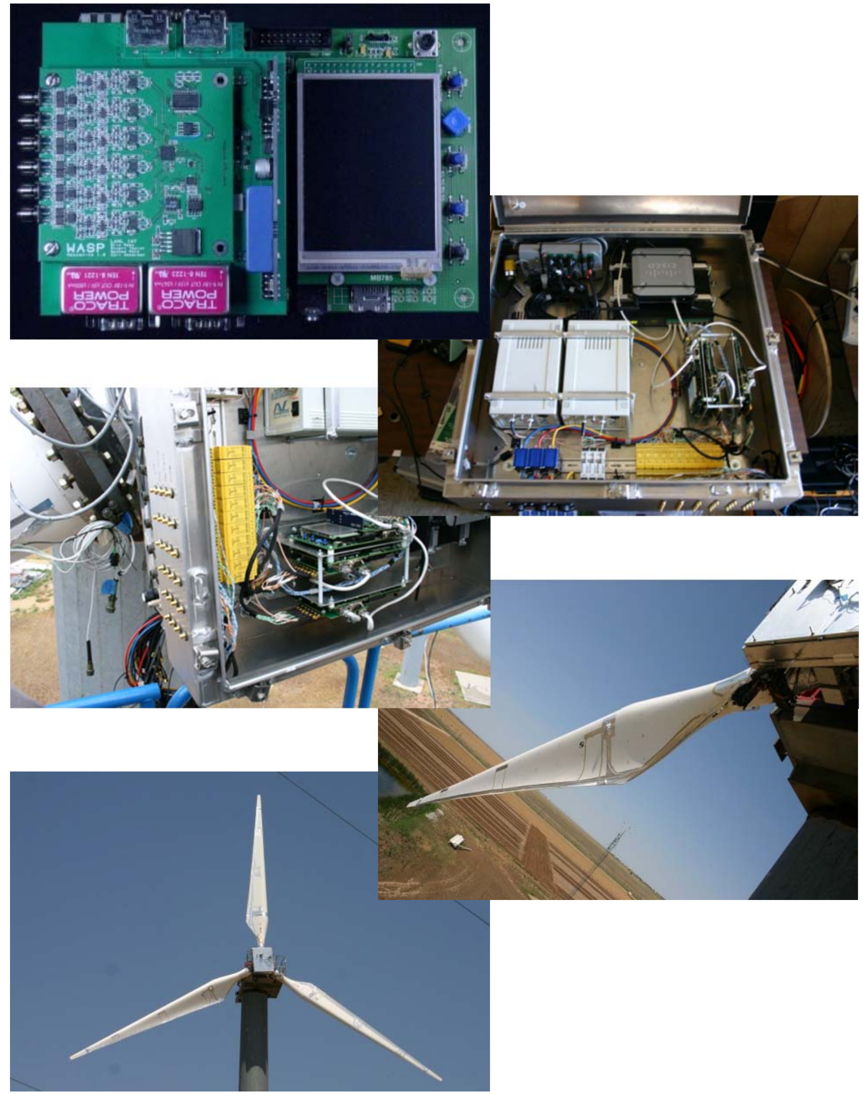


- **The outer array suffers from poor relative performance.**
- **An actuator replacement limits the utility of data after 10/31/11**
  - With the crack forming by 10/20/11, no new baseline for crack detection could be established.



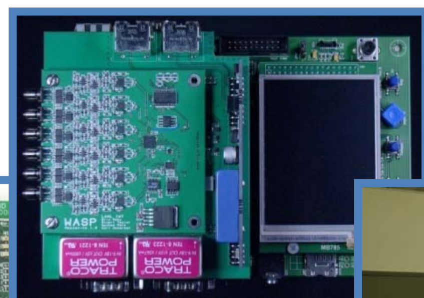
SHM System Deployment

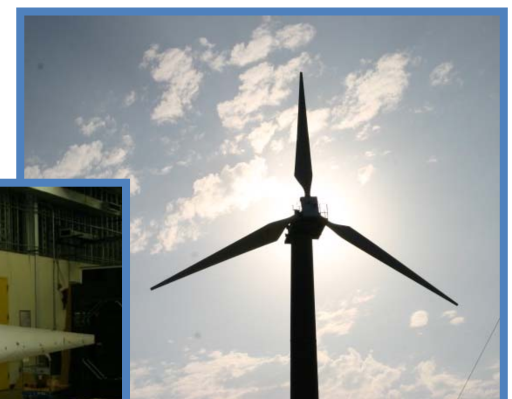
- PZT sensors integrated inside a CX-100 blade
- Accelerometers and fiber optic strain gauges mounted externally
- Electronics for acquisition and communications mounted on hub
- Operational data collected June 2011



Summary

- **Demonstrated in the laboratory:**
  - Fatigue crack detection/location
  - Failed sensor detection
- **Diffuse wave method provided similar results as guided waves**
- **Developed a prototype platform for SHM and SD applications**
- **Deployed that platform on an operating wind turbine**
- **Next (pending funding): "fly" a damaged blade**





Acknowledgments

- **We would like to thank**
  - Mark Rumsey and Jon White from SNL
  - Scott Hughes and Mike Desmond from NREL
  - Pete Avitabile and Chris Niezrecki from U.Mass, Lowell

for their collaborative support and guidance with this research

- **We gratefully acknowledge the support of the U.S. Department of Energy through the LANL/LDRD Program for this work**
- **This research was also partially supported by the Leading Foreign Research Institute Recruitment Program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (2011-0030065)**