Sandia National Laboratories
2010 Wind Turbine Blade Workshop

Sensor Systems and Applications

Mark A. Rumsey
Wind and Water Power Department
Sandia National Laboratories

July 20, 2010

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Presentation Outline

- **Motivation - Our Drivers for Sensors**
- **Challenges and Opportunities**
- **Project Goals and Approach**
- **Status of Sensored Blade Projects**

Motivation - Our Drivers for Sensors

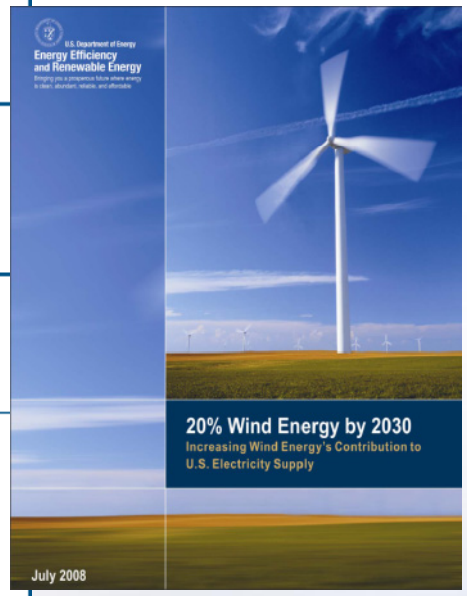
Sandia National Laboratories

Why Sensors?

Sensors are directly involved in:

Technical Area	Potential Advances	Performance and Cost Increments (Best/Expected/Least Percentages)	
		Annual Energy Production	Turbine Capital Cost
Advanced Tower Concepts	• Taller towers in difficult locations • New materials and/or processes • Advanced structures/foundations • Self-erecting, initial, or for service	+11/+11/+11	+8/+12/+20
Advanced (Enlarged) Rotors	• Advanced materials • Improved structural-aero design • Active controls • Passive controls • Higher tip speed/lower acoustics	+35/+25/+10	-6/-3/+3
Reduced Energy Losses and Improved Availability	• Reduced blade soiling losses • Damage-tolerant sensors • Robust control systems • Prognostic maintenance	+7/+5/0	0/0/0
Drivetrain (Gearboxes and Generators and Power Electronics)	• Fewer gear stages or direct-drive • Medium/low speed generators • Distributed gearbox topologies • Permanent-magnet generators • Medium-voltage equipment • Advanced gear tooth profiles • New circuit topologies • New semiconductor devices • New materials (gallium arsenide [GaAs], SiC)	+8/+4/0	-11/-6/+1
Manufacturing and Learning Curve*	• Sustained, incremental design and process improvements • Large-scale manufacturing • Reduced design loads	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21

Source: 20% Wind Energy by 2030, Table 2-1, p. 41.



Sandia National Laboratories

Sandia Wind Research

Core Competencies
Enabling Technology

- Design Tools
- Sensors
- Aerodynamics & Aeroacoustics
- Testing
- Reliability Analysis
- Materials & Manufacturing
- Integration Technology Acceptance

Tools, Processes, Test Results, Analyses

Projects
Industry-oriented Applications

- Advanced Manufacturing Initiative (AMI)
- Innovative Concepts
- Sensor Blade Projects
- Reliability Database
- SMART Rotor
- STAR Blade
- Integration Studies & KAFB/SNL Wind Farm
- Certification & Standards

Tech Transfer

Wind Industry

Sandia National Laboratories

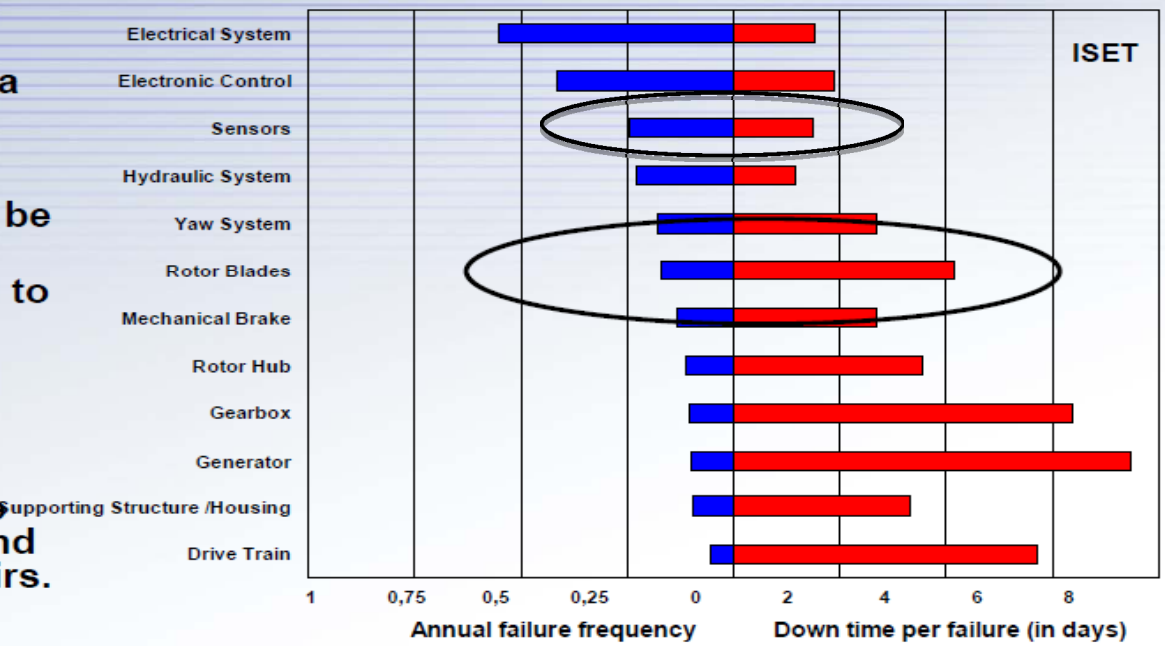
Challenges and Opportunities

Challenges – Wind Turbine Reliability

"80% of the blades that require repair have never been flown."
Gary Kanaby, Knight & Carver Wind Blade Division.

Blade Reliability

- Blades are being delivered to the site in a condition that often requires additional treatment of quality issues before they can be installed
- Rare installations need to have all the blades replaced after the discovery of a batch problem
- Blade failure can cause extensive down time and lead to expensive repairs.
- *Blade reliability issues need early attention because of the lost production and cost of significant failures*



Historical European Experience (Paul Kühn, ISET)

Blades are in the middle – medium failure rate, relatively high cost. US environments may be more aggressive.

Sandia National Laboratories

Source: Veers and Hill, 2008 Blade Workshop (http://www.sandia.gov/wind)

Project Goals and Approach

Project Goals and Approach

Increase energy capture, improve reliability, and enhance grid compliance for 20% wind by 2030

Approach:

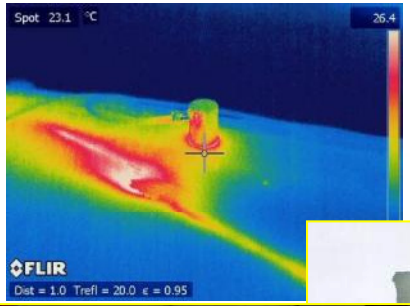
- Apply **Diagnostic Tools** in the field and lab R&D testing environment.
- Develop **Quality Assurance Tools** for the manufacturing environment.
- Determine the "Effect of Defects" in support of the **Blade Reliability Collaborative (BRC).**
- Evaluate and implement sensing systems to enable a **SMART Rotor**.

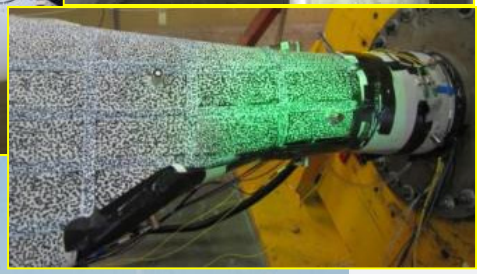
  (SMART ≡ Structural and Mechanical Adaptive Rotor Technology)
- Enable **Adaptive and Self-organizing** wind turbines and wind farms.
- Demonstrate **operational monitoring** of a utility-scale wind turbine.
- Produce a prototype operational monitoring system.

Our Interest in Sensors

- Diagnostic Tools
- Model Validation
- Quality Assurance Tools
- Sensor System Evaluations
- Operational Monitoring
- Smart Adaptive Turbines

NREL/National Wind Technology Center
Boulder, Colorado



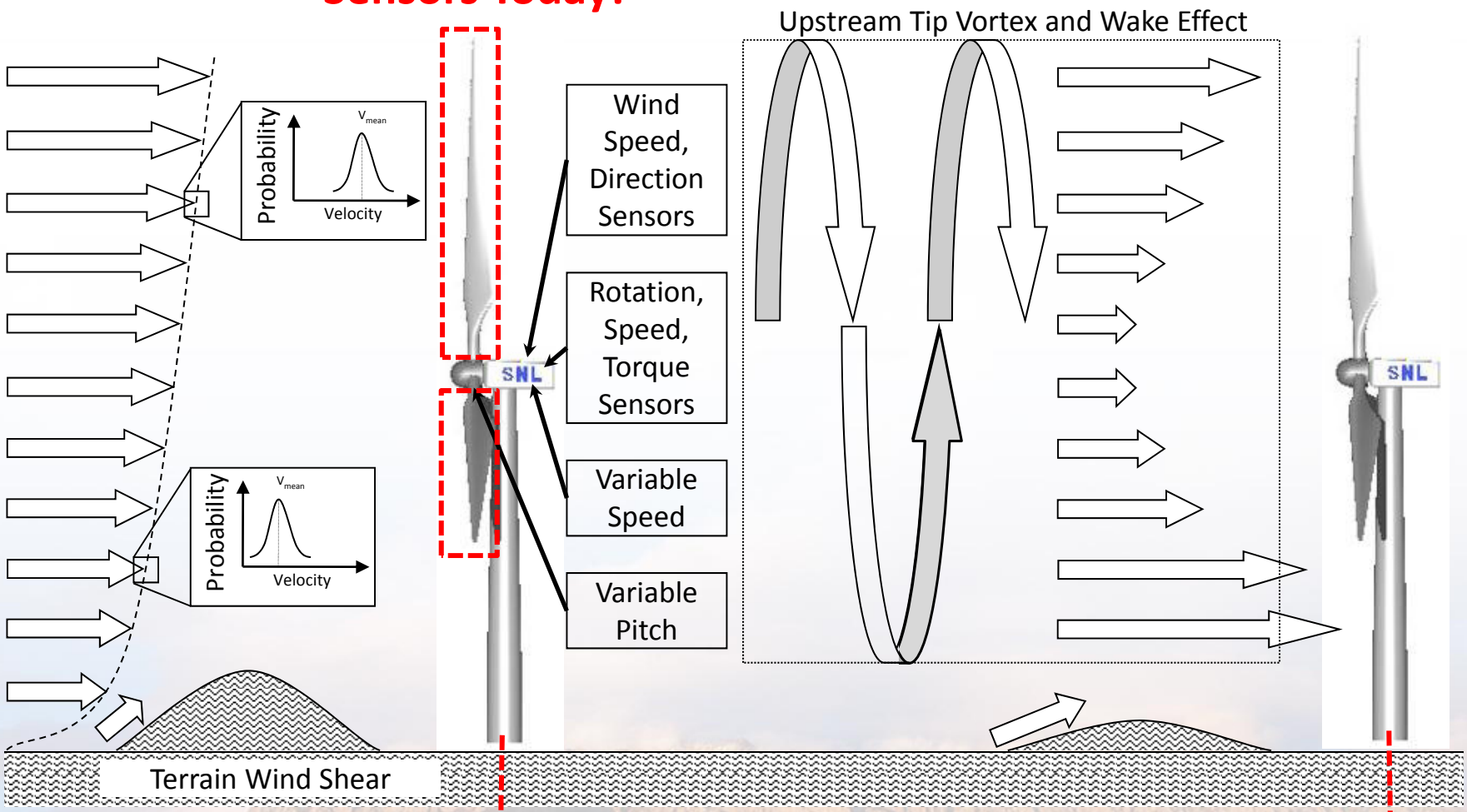


SNL and USDA-ARS
Wind Energy Test Site
Bushland, Texas

NREL USDA ars Sandia National Laboratories

Modern Wind turbine

Few to No Rotor Sensors Today!



No Adaptive or Self-Organizing Turbines Today!

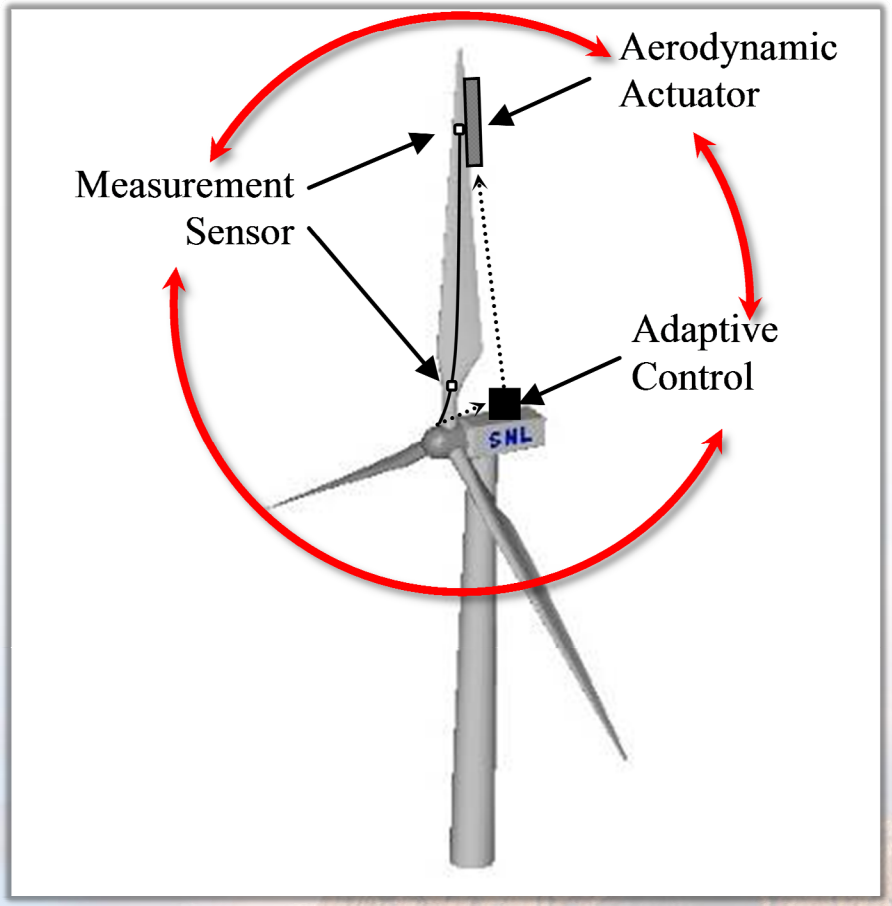
Operational Monitoring

Operational Monitoring is an Enabling Technology

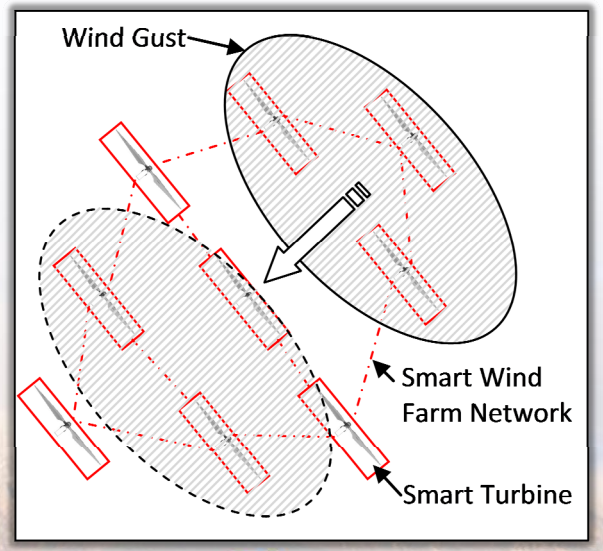
- **Estimate site-specific applied loading and resulting deflection (state awareness)**
- Monitor oscillating, gust, and extreme loads which cause fatigue and rapid life usage (decrease O&M cost)
- Track time-varying structural characteristics (temperature, surface finish)
- **Track instantaneous maximum power coefficient (Cp) that is a function of individual blade pitch, blade actuators, etc. (increase in performance, increase in revenue)**
- New observer for existing controls (pitch, speed, and yaw)
- Advanced controls observer (advanced rotor project)
- Wind farm observer to increase energy capture and reliability (wind gust, wake effects)
- **Adaptive and predictive collective wind farm control**
- Archived operational loads (non-design, skewed, and oscillating fatigue)
- Predictive gearbox maintenance (un-balanced loading)
- Rotor damage detection
- Prognostic Operations (damage state and future load estimates)

A Smart Adaptive Wind Turbine Farm

Operational Monitoring



- Operational Monitoring of a wind turbine estimates the loads and deflections using available measurements and inference algorithms.
- Operational Monitoring enables the development of adaptive turbines and wind farms.



Holistic Approach to Operational Monitoring

- Operational turbine motion consists of steady and oscillating components

$$u(z,t) = u_s(z) + u_d(z,t)$$

Approach	Method	Optimization
Quasi-static Load and Response (<1P)	$\hat{u}_s\left(z,\frac{\partial u_s}{\partial z}\right) = \{f(R,L,z)\}_{1\times(n-3)}\left[g(R,L,z_i)\right]^{+}_{(n-3)\times m}\left\{\left.\frac{\partial u_s}{\partial z}\right\|_{z_i}\right\}_{m\times 1}$	$E = \int_{z=0}^{L}\left[u(z)-\hat{u}(z)\right]_{1\times z}\begin{bmatrix} w(z) & & \\ & \ddots & \\ & & w(z)\end{bmatrix}_{z\times z}\left[u(z)-\hat{u}(z)\right]^{T}_{z\times 1}dz = E(U,z_1,z_2,\ldots)$
Dynamic Load and Response (≥1P)	$\{u_d(t)\}_{n\times 1} = [U]_{n\times r}\eta_r(t), \quad with/n \geq r$	$\kappa\left(U_{r\times n}\right) = \left\|U_{r\times n}\right\|\left\|U^{-1}_{n\times r}\right\|$
Damage Detection	$DI = \frac{\Delta k}{Mg} = \frac{W_{healthy} - W_{damage}}{W_{healthy}W_{damage}}$	

Sandia National Laboratories

Status of Sensored Blade Projects

(Sensor Blade 1, 2 and SMART Bladeset)

Sandia National Laboratories

Sensor Blade 1 Objectives

- Evaluate promising sensor technologies.
- Engage and motivate companies, national laboratories, and universities without a wind energy background.
- Investigate issues associated with embedding rotor sensors.
- Develop fundamental understanding and approach for state observers (sensor output) required for smart rotor technology.
- Enhance field testing infrastructure for real-time data acquisition and empirical model extraction.

Sensor Blade 1 Team and Testing Partners

Sensor Blade Team:

Aither Engineering, Inc. (fiberoptic-based sensors)
Jason Kiddy and Chris Baldwin

Micron Optics, Inc. (fiberoptic-based sensors)
Tom Graver and Alan Turner

NREL/NWTC (blade testing, metal-foil strain gages and IR thermography)
Scott Hughes, Jeroen van Dam, Mike Jenks and Michael Desmond

Purdue University (accelerometry-based SHM)
Jonathan White and Douglas Adams

Sandia National Laboratories - Wind and Water Power Dept.
Mark Rumsey, Joshua Paquette, Wesley Johnson and Jon Berg

Sandia National Laboratories - Energy Systems Analysis Dept. (internal video monitoring)
Jeff Carlson and Kevin Brink

TPI Composites, Inc. (blade fabrication)
Steve Nolet and Derek Berry

USDA-ARS (field testing)
Nolan Clark, Adam Holman and Byron Neal

Testing Partners:

EPRI and Laser Technologies, Inc. (laser shearography)
John Lindberg (EPRI) and John Newman (LTI)

Intelligent Fiber Optic Systems (fiberoptic-based sensors)
Vahid Sotoudeh and Aleks Plavsic

LANL (PZT-based SHM)
Kevin Farinholt

Luna Innovations (fiberoptic-based sensors)
Al Heaney and Larry Vicari

NASA – Kennedy Space Center (PZT-based SHM)
Rudy Werlink

Physical Acoustics Corporation and NREL/NWTC (AE NDT)
Al Beattie

University of Massachusetts – Lowell (Digital Image Correlation)
Chris Niezrecki and Chris Warren

Sensor Blade 1 – Monitoring over Life-cycle

1 - Blade Fabrication
(TPI Composites)

2 - Field Testing
(USDA-ARS)

3 – Lab Testing
(NREL - NWTC)

Sandia National Laboratories

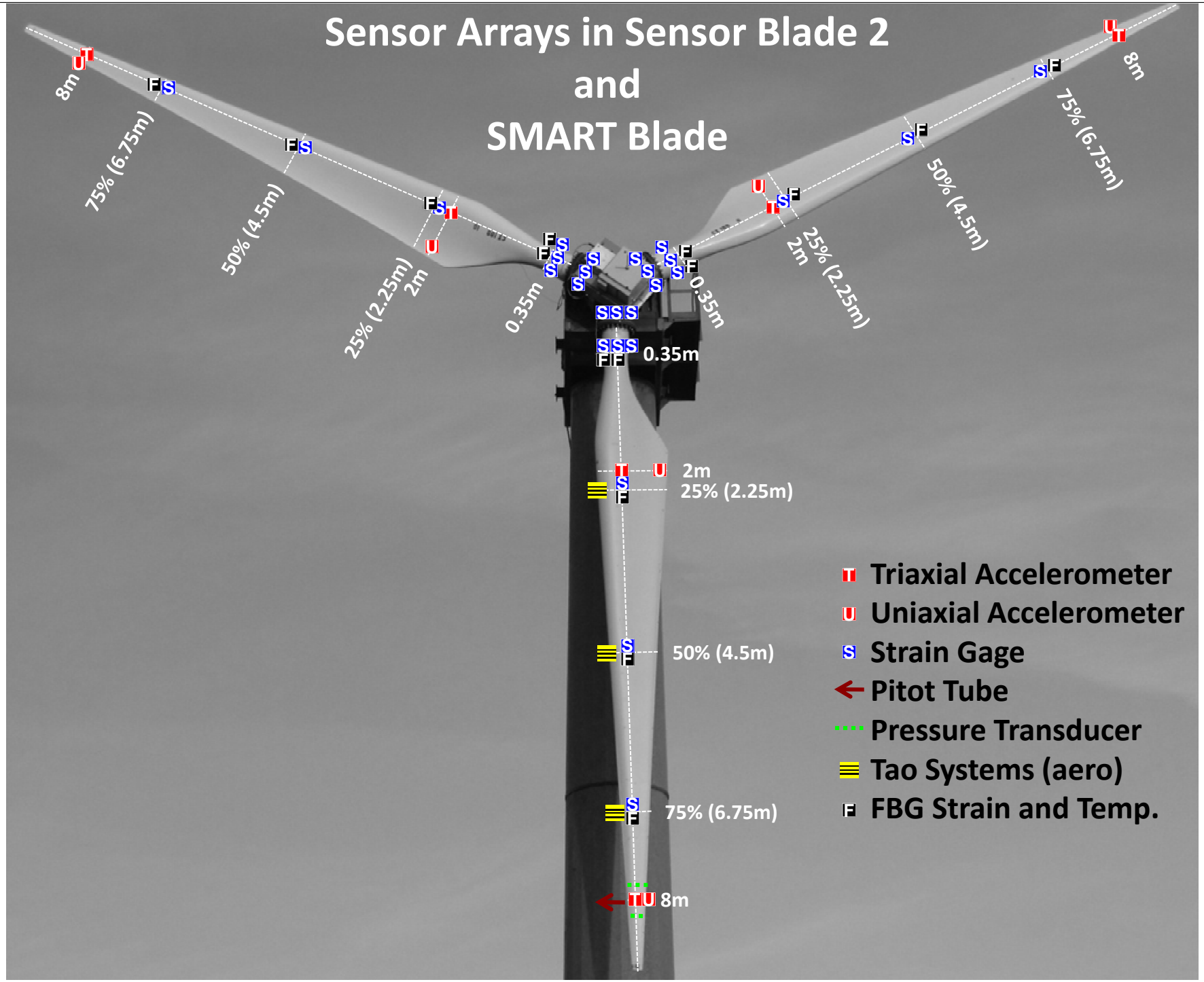
Sensor Blade 1 Outcomes

- Sensors were successfully embedded in the Sensor Blade
- Sensors in the Sensor Blade were monitored throughout the full life-cycle of the blade (blade fabrication, flight tests on a turbine, lab tests (static and fatigue)) – blade failed in fatigue.
- Operational measurements were used to update a computational model of the turbine.
- **Lessons Learned:**
  - Embedded fiber optic sensors failed during the blade cure process
  - Many accelerometers failed due to electrostatic discharge (ESD) in the field
  - Full rotor instrumentation is needed to sufficiently estimate the global turbine dynamics.
- Final Report – due Sep 2010

Sensor Blade 2 Objectives

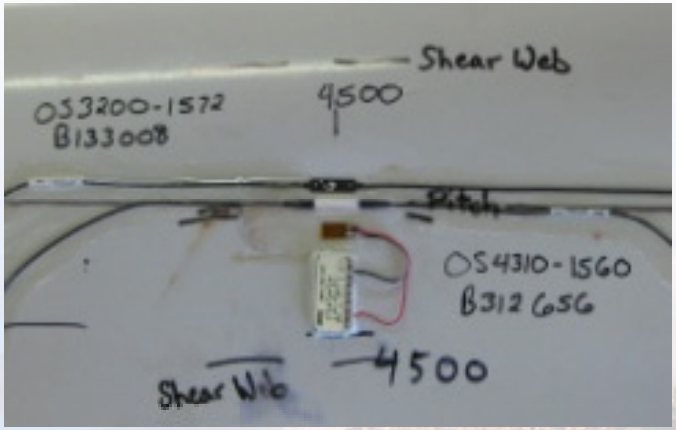
- Apply lessons-learned from Sensor Blade 1 project
- Develop aerodynamic and structural observers for SMART bladeset.
- Improve sensor reliability.
- Quantify trade-off between sensor locations and accuracy.
- Estimate the phase lag between different sensor systems.
- Study electrostatic effects on wind turbine rotor blades.

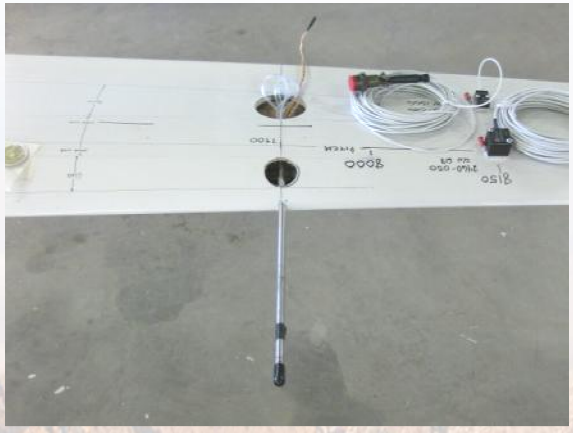
Sensor Arrays in Sensor Blade 2 and SMART Blade



Status of Sensor Blade 2 Project

- 3-ea CX-100 rotor blades have been prepared for sensor installation.
- TAO System (aero), Pitot Tube, Pressure Scanner, fiber Bragg gratings (FBGs), Accelerometers, and Strain Gages have been installed.
- New version of ATLAS data acquisition system has been received and is being tested for performance.

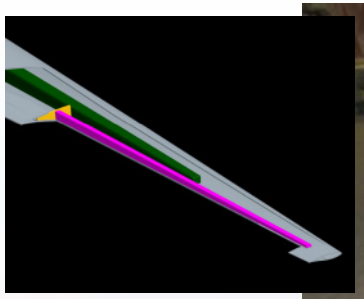


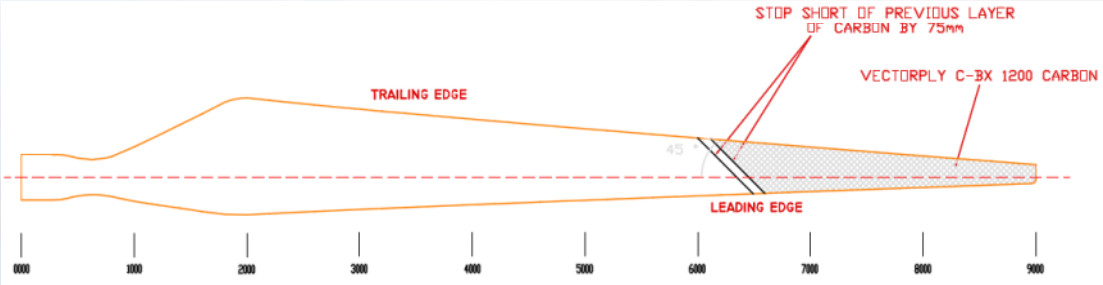


Sandia National Laboratories

Status of SMART Rotor Project

- Modify CX-100 blade design into a SMART blade – spring 2010
- 3-ea modified CX-100 rotor skins have been fabricated – today
- Installation of blade sensors and completion of SMART bladeset fabrication – Aug 2010
- Start field testing – late FY10





Thank You!

Sandia Labs Sensors Team:

- **Sensor and Sensor Systems Lead**
  - Mark A. Rumsey, 505-844-3910, marumse@sandia.gov
- **Operation Monitoring , Analyst and (future) Field Testing Lead**
  - Jon White, 505-284-5400, jonwhit@sandia.gov
- **Analyst and Sensor Integration**
  - Jon Berg, 505-284-0905, jcberg@sandia.gov
- **Sensor Integration and Field Test Technician**
  - Wesley Johnson, 505-284-1177, wjohnso@sandia.gov

Backup Slides

Operational Monitoring with Inertial Measurements

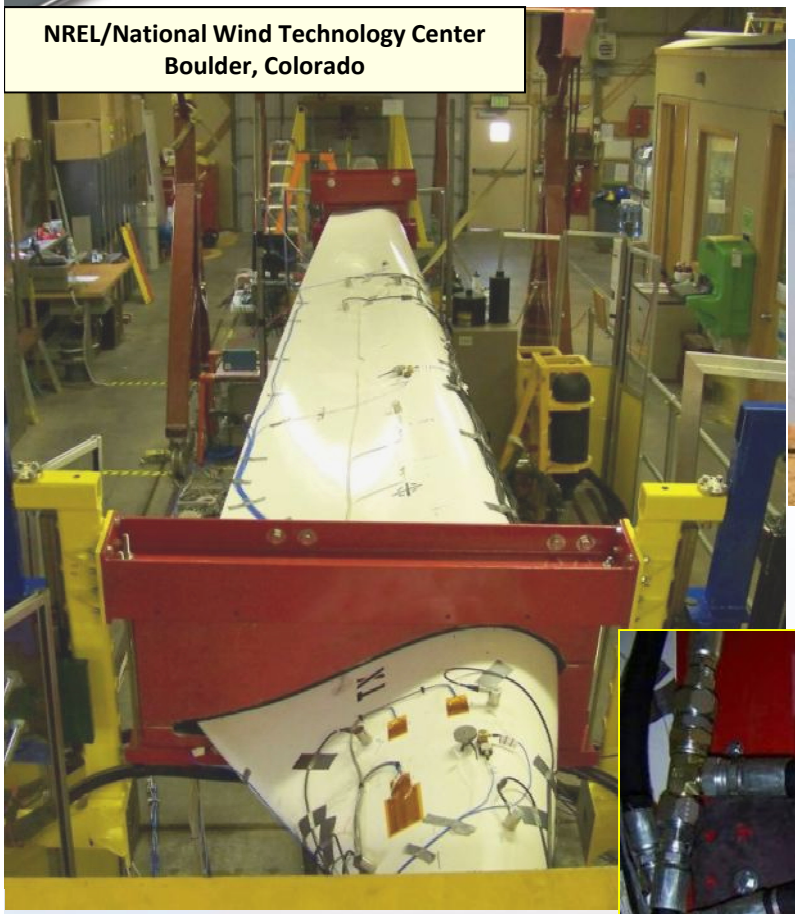
- An **Operational Monitoring** approach has been developed.
  - **Quasi-static deflections** were monitored with DC accelerometers that used the centripetal acceleration plane as a reference.
  - **Dynamic deflections** were monitored with modal filters that transformed a small number of sensor measurements into estimates of the global mode shapes.
  - **Passive damage detection** was accomplished using differential in-plane displacements.
  - **Active damage detection** was performed using piezo-electric actuators to implement the Method of Virtual Forces.

- Prototype SENSORED Blades have been manufactured and tested.

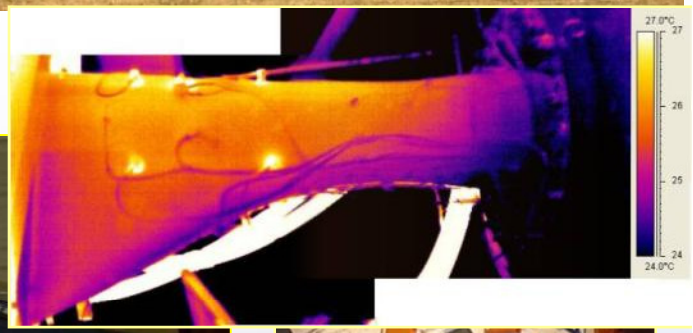
  (Sensor Blade 1, 2 and SMART Blade)

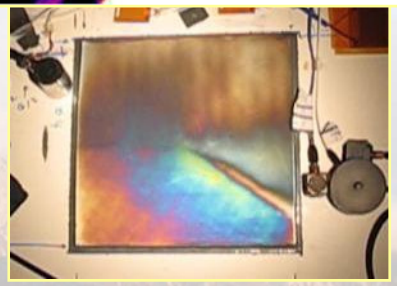
Diagnostic Tools

NREL/National Wind Technology Center
Boulder, Colorado



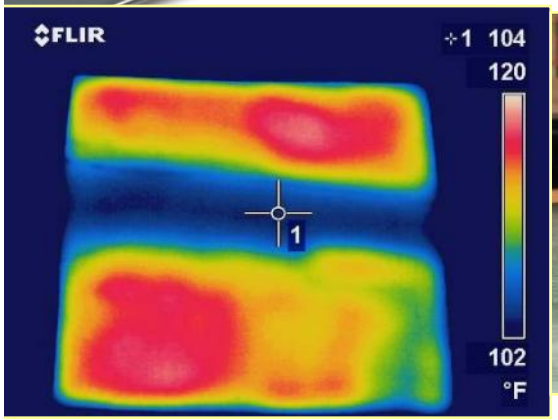
SNL and USDA-ARS
Wind Energy Test Site, Bushland, Texas

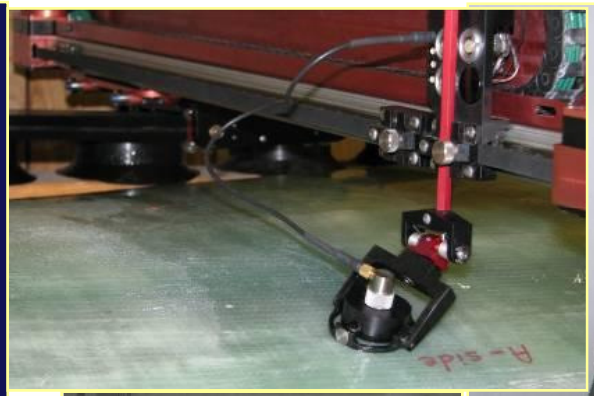




Sandia National Laboratories

Quality Assurance Tools

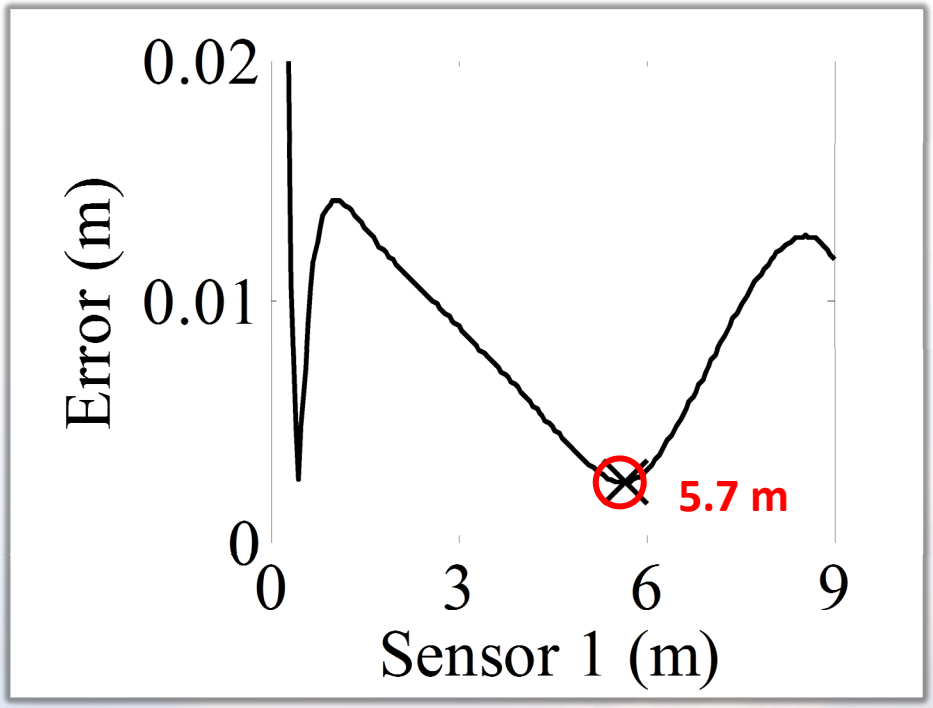




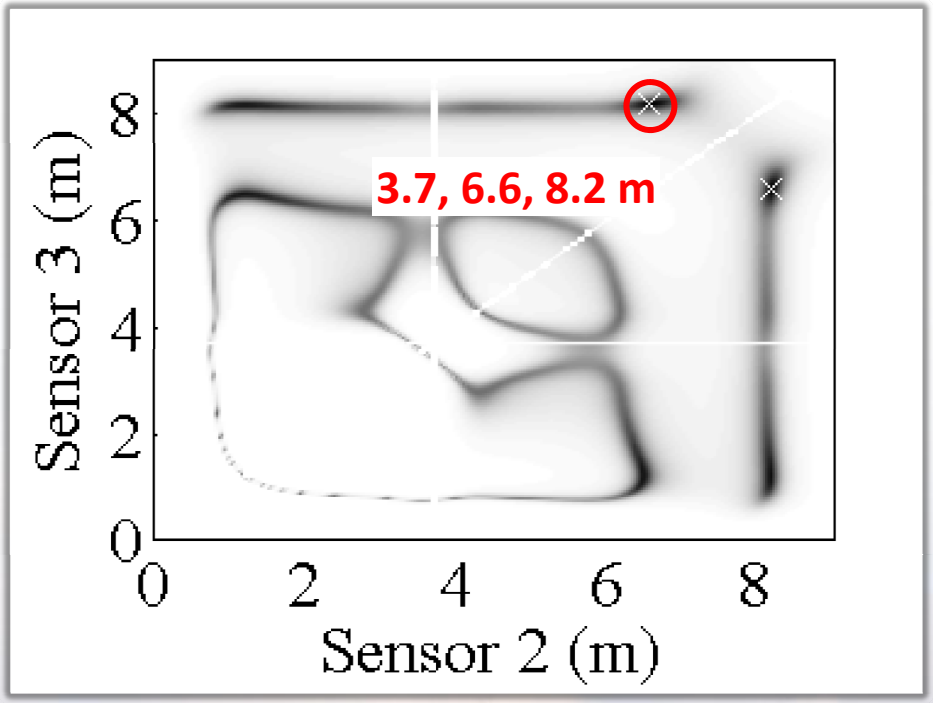
Sandia National Laboratories

Static Deflection Estimation

1st Order Estimator, Single Sensor

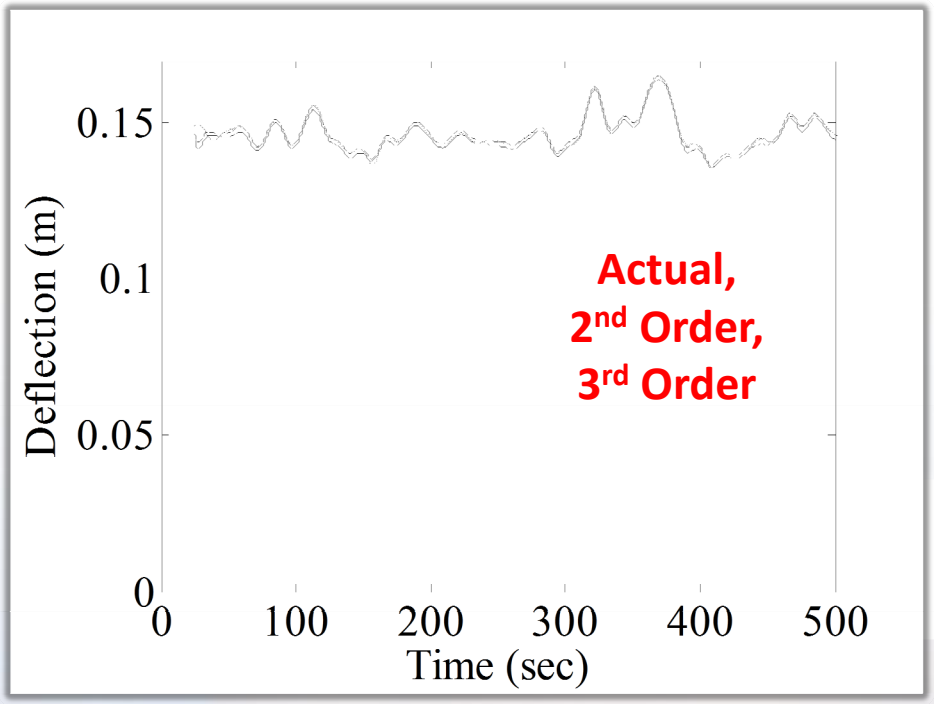


3rd Order Estimator, Triple Sensor

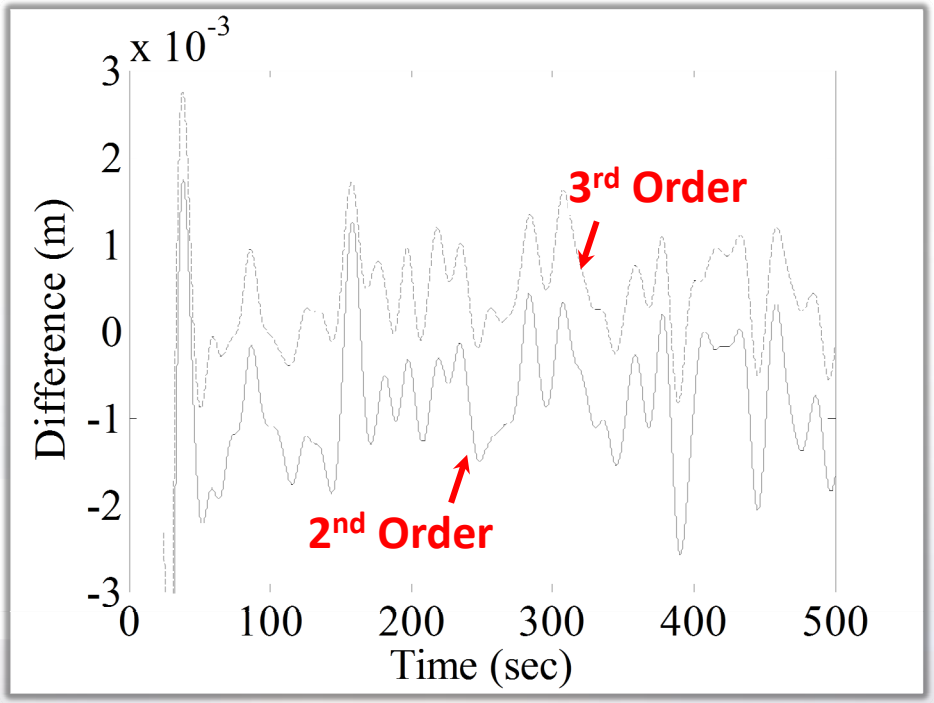


Tip Deflection Monitoring in 10 m/s Class B Turbulence

Turbulent Tip Deflection



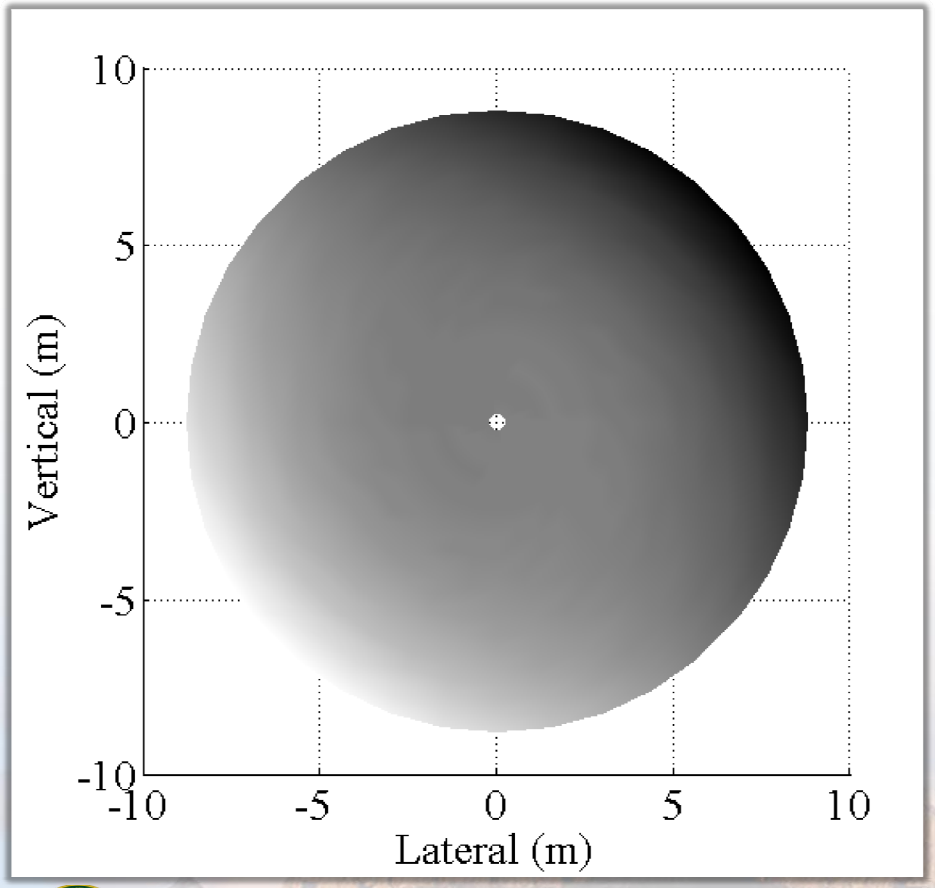
Tip Deflection Difference



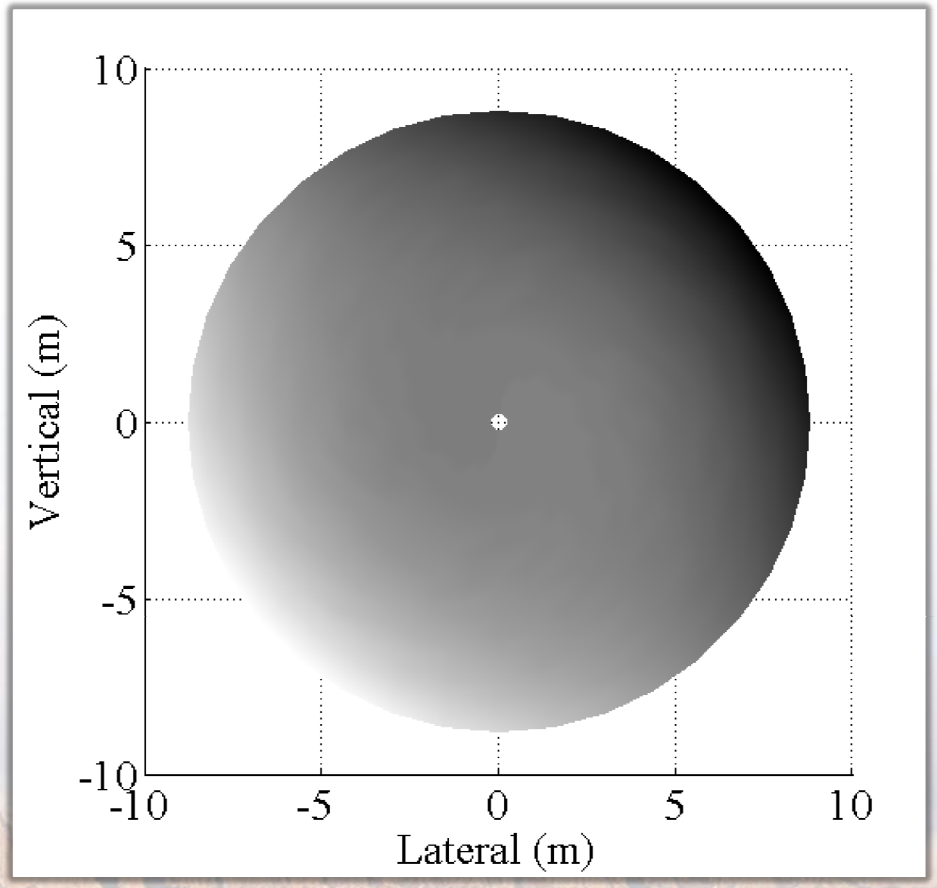
Sandia National Laboratories

Operational Deflection Shape Reconstruction with Minimal Sensor Count

Actual Shape

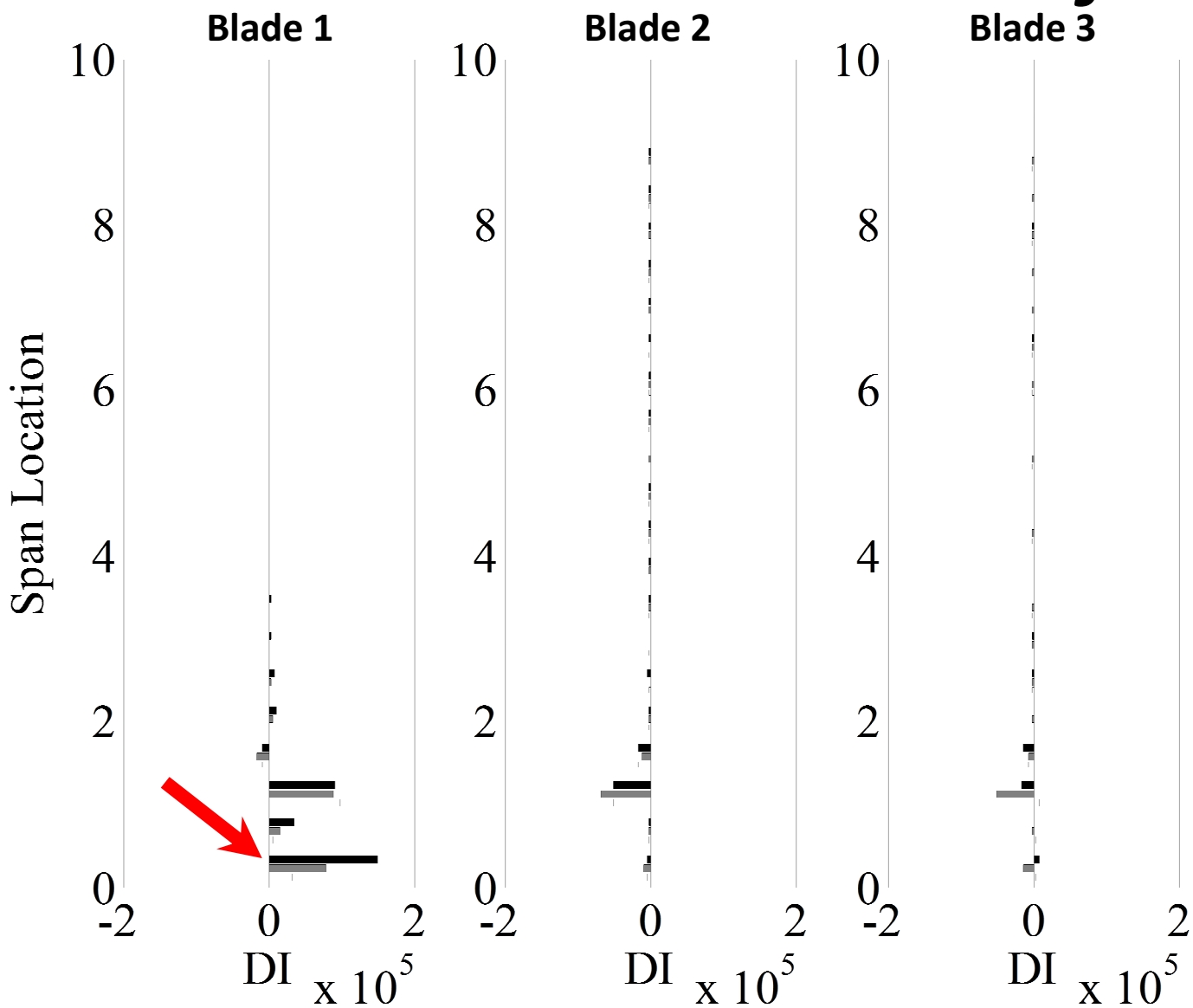


Sensor Reconstructed Shape



Sandia National Laboratories

Damage Detection (stiffness) in Root of Blade 1

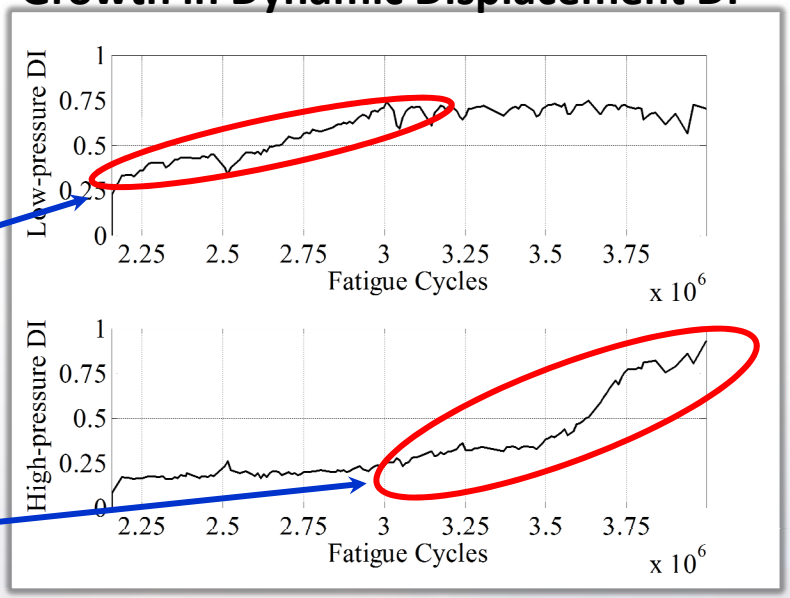


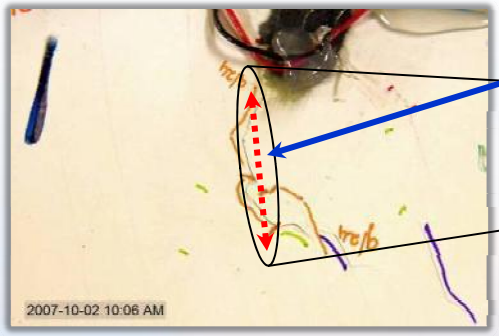
Laboratories

Passive Damage Detection

TX-100 Fatigue to Failure

Growth in Dynamic Displacement DI





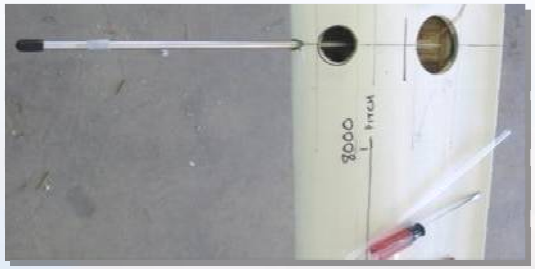
2.5 – 3 M Cycles

3 - 4 M Cycles

Sandia National Laboratories

Status of Sensor Blade 2 Project

- Modified three existing CX-100 blades – today
- Field test modified CX-100 blades – summer 2010
- Apply lessons-learned to SMART Project – today



Sandia National Laboratories

[redo] Sensor Blade 2

- **Goal:** Increase the performance and reliability of wind turbine systems

- **DOE-SNL Program Focus**
  - **Develop expertise in wind turbine rotor dynamics**
  - **Develop expertise with rotor-based sensing systems**
  - **Refocus on application-driven sensor specifications**
  - **Continue to address sensor system life-cycle challenges**
- **Approach**
  - **Develop (refine in some cases) turbine dynamics models**
  - **Test and evaluate promising aerodynamic sensor systems**
  - **[don't like words]Targeted wind projects and applications**
    - **Sensor specifications for Structural and Mechanical Adaptive Rotor Technology (SMART) bladeset**
    - **Wind turbine control**
    - **Wind turbine condition and structural health monitoring**
    - **Manufacturing quality assurance tools**
    - **Improve laboratory diagnostic tools**
    - **Vector to new sensor systems**

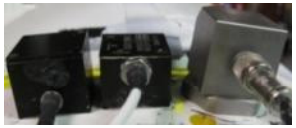
Hardware Technologies

Sensors

Structural

Foil Strain Gage

DC Accelerometer



Fiber Optic FBG Strain Sensor

Resistive Temperature Detector

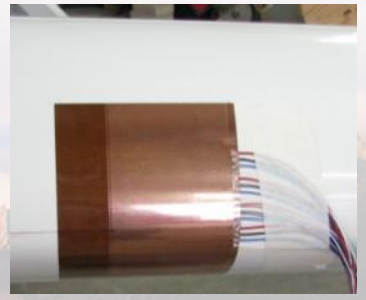
Fiber Optic FBG Temperature Sensor

Aerodynamic

5-hole Pitot Tube

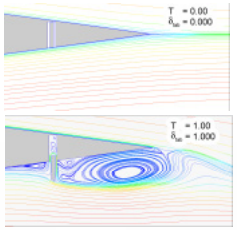
Inflow Array

Stagnation and Separation Point Sensor



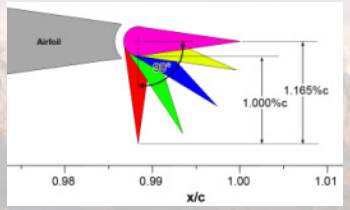
Aerodynamic Actuators

Microtabs



Compliant Structure

Flap



Hardware

SNL Windy

National Instruments CompactRIO

Micron Optics FBG

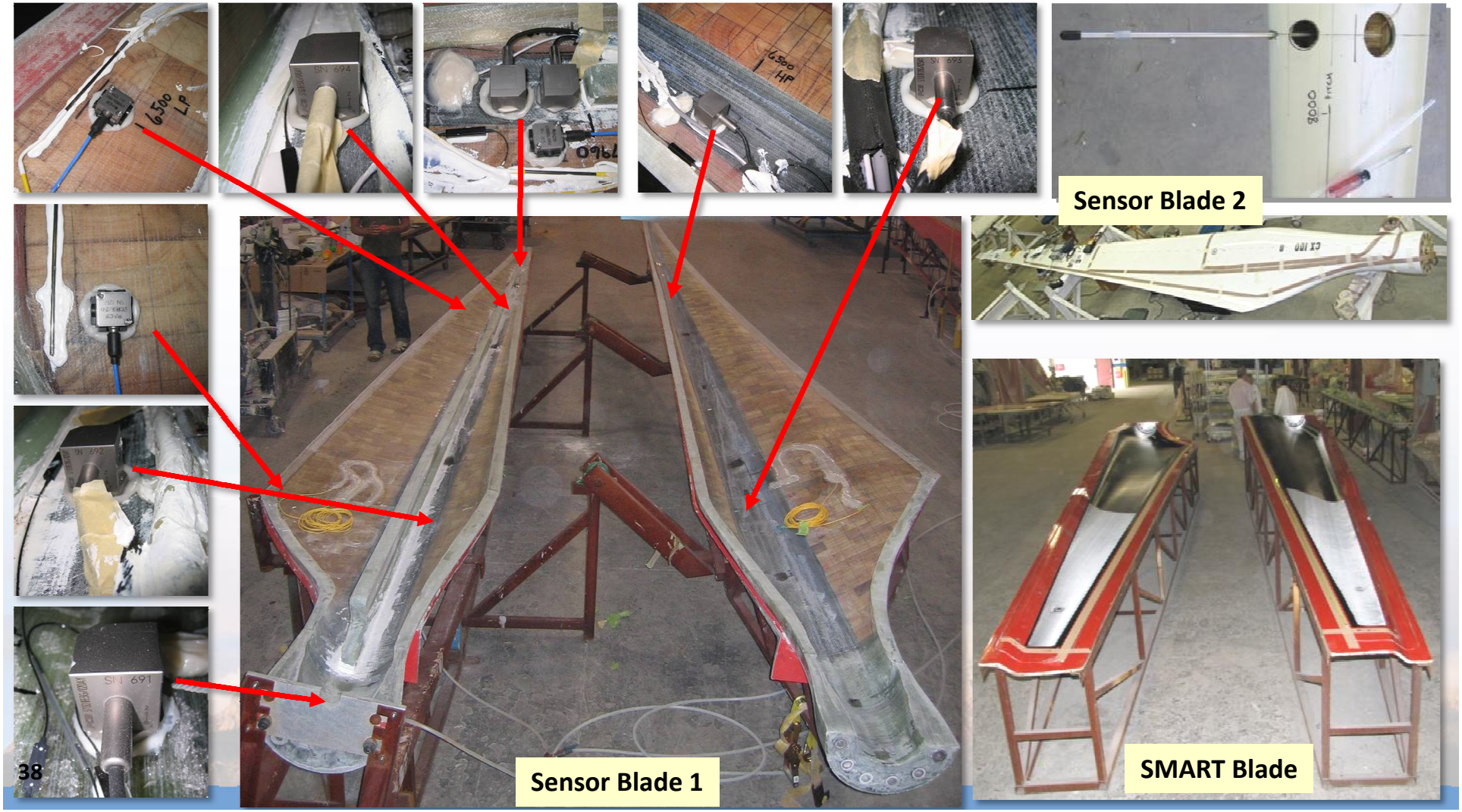
Sandia National Laboratories

Operational Testing of Prototype Sensored Rotor Blade

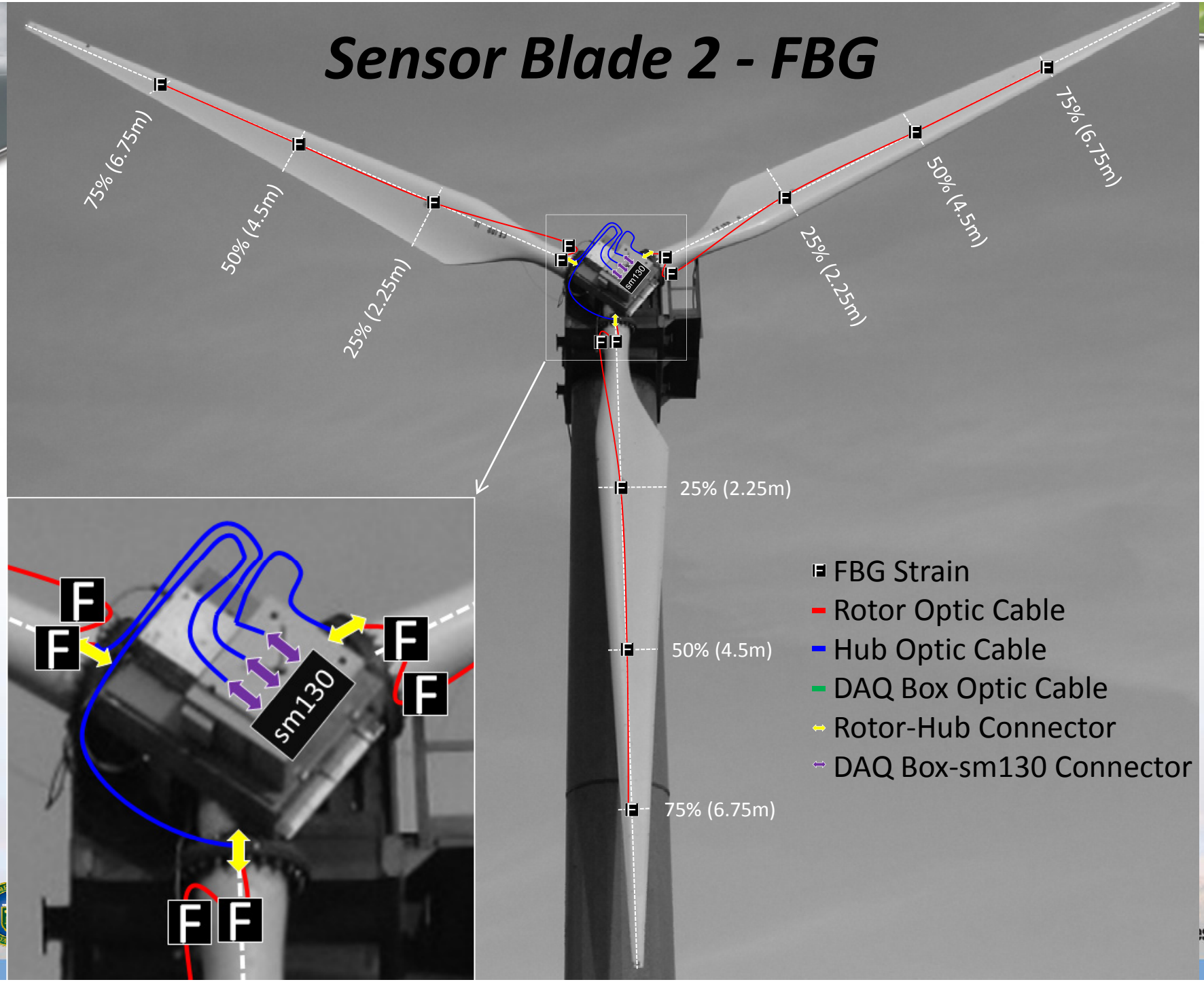
- **Sensored rotor blade was monitored while operating on a Micon 65/13 wind turbine.**

Fabrication of Prototype Sensored Rotor Blades

9-meter Sandia CX-100 rotor blades with embedded sensors



Sensor Blade 2 - FBG



Summary