LA-UR- 11-00503

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Title: Modal Analysis and SHM Investigation of CX-100 Wind Turbine Blade

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Intended for: IMAC XXIX A CONFERENCE AND EXPOSITION ON STRUCTURAL DYNAMICS, Jacksonville, FL, January 31-February 3, 2011.

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Vibration Testing and Structural Damage Identification of Wind Turbine Blades

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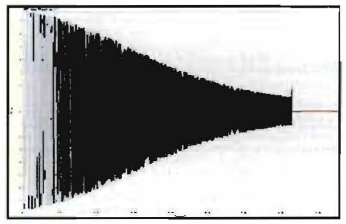
Abstract

This paper presents the dynamic characterization of a CX100 blade using modal testing. Obtaining a thorough dynamic characterization of these turbine blades is important because they are complex structures, making them difficult to monitor for damage initiation and subsequent growth. This dynamic characterization was compared to a numerical model developed for validation. Structural Health Monitoring (SHM) techniques involving Lamb wave propagation, frequency response functions, and impedance based methods were also used to provide insight into blade dynamic response. SHM design parameters such as traveling distance of the wave, sensing region of the sensor and the power requirements were examined. Results obtained during modal and SHM testing will provide a baseline for future damage detection and mitigation techniques for wind turbine blades.

Modal Analysis and SHM Investigation of CX-100 Wind Turbine Blade

Krystal Deines
Timothy Marinone
Ryan Schultz



Kevin Farinholt & Gyuhae Park

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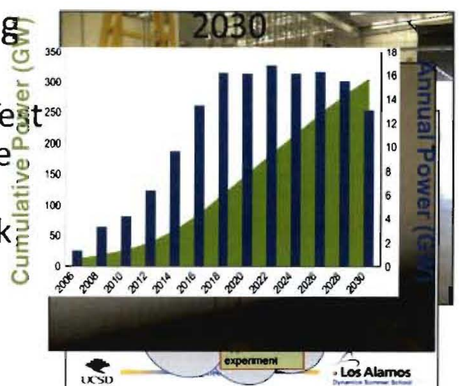
Agenda

- Introduction
  - Background
  - Objective
  - Previous Work
- CX-100 Modal Testing
  - Free-Free Test
  - Free-Free w/Mass Test
  - Fixed-Free Test
- SHM
  - Frequency Range
  - Environmental variability
- Conclusions
  - Future Work

20% Wind Power Goal for 2030



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20% Wind Power Goal for 2030

DOE Goal to produce 20% energy from wind by

lighter and more efficient blades. Lower Safety Factor makes them more likely to fail

- When turbine does not run due to failure, power is not produced.
- Power= $

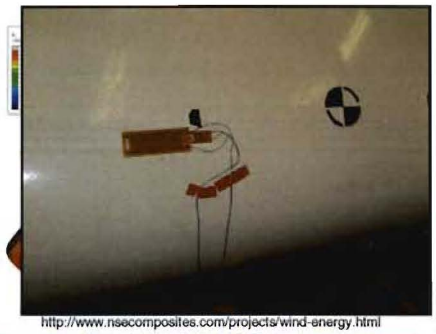
Wind Turbine Blade Failure

- Rotor Blade Failure is not common (6%)
- However, Rotor Blade Failure is often catastrophic and expensive
- Failure of blades often causes failure of turbine

http://www.innovensys.com/en/what-we-do/design-for-six-sigma

Predicting Blade Failure

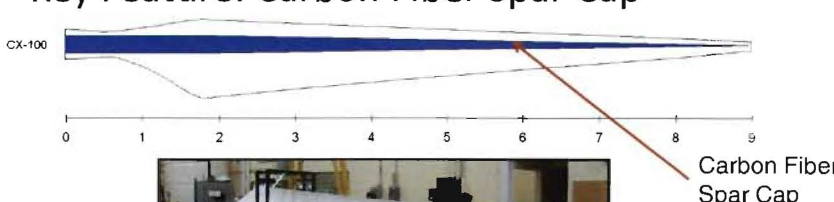
- Structural Health Monitoring / Numerical Model
  - Real time monitoring of blade health / Analytical models used for failure prediction
  - Requires baseline data / Models need to be correlated with test data



http://www.nsecomposites.com/projects/wind-energy.html

CX-100 Description

- 9 Meter Experimental Blade designed by Sandia National Laboratories
  - TX-100, CX-100, BSDS
- Key Feature: Carbon Fiber Spar Cap



Previous Work - Modal Testing of Wind Turbine Blades

- Griffith and Carne (2010)
  - Modal Testing of BSDS Blade w/Seismic Mass
  - Approach to simulate fixed boundary condition without fixed apparatus
- Adams and White (2010)
  - Modal Testing of CX-100 Blade i
  - Demonstrated support has effec frequencies

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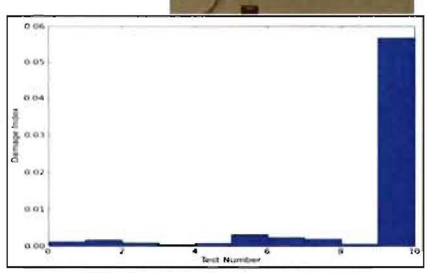
Previous Work - Structural Health Monitoring of CX-100

- Light-Marquez et al
  - Lamb Wave, Frequency and Time SHM techniques examined
  - Simulated Damage on 1 Meter Section
  - Good local damage detection



Light-Marquez, A., Sobin, A., Park, G., Farinholt, K., "Structural Damage Identification in Wind Turbine Blades using Piezoelectric Active-sensing," Proceedings of the IMAC XXVIII, Feb. 1-4, 2010, Jacksonville, FL.

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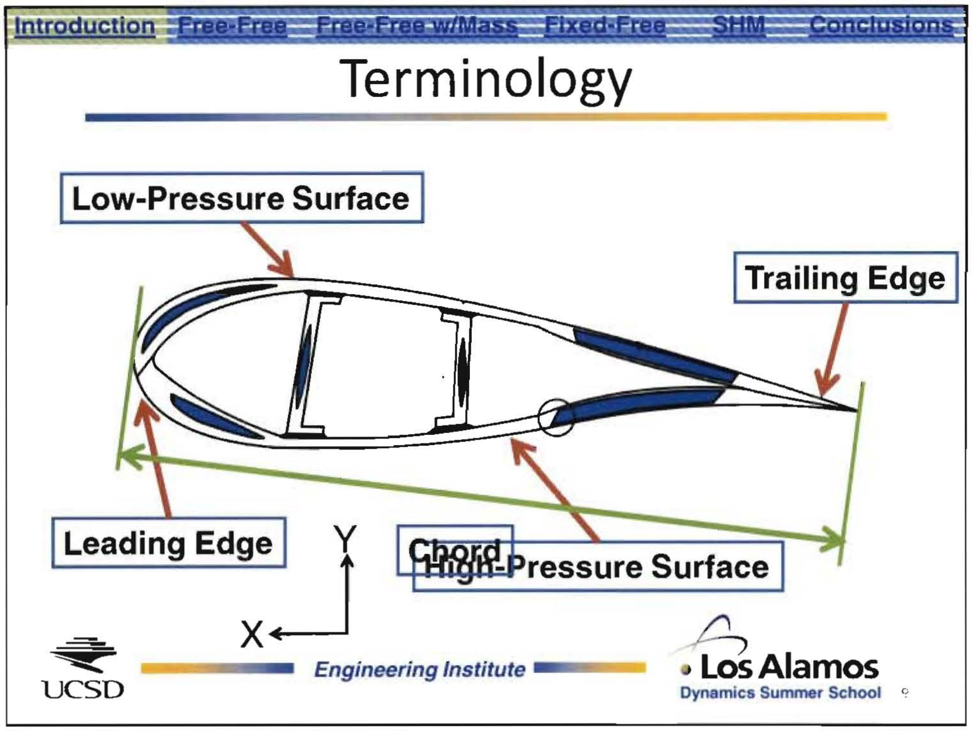
Introduction Free-Free Free-Free w/Mass Fixed-Free SHM Conclusions
Terminology
Low-Pressure Surface
Trailing Edge
Leading Edge
Chord
High-Pressure Surface
Y
X
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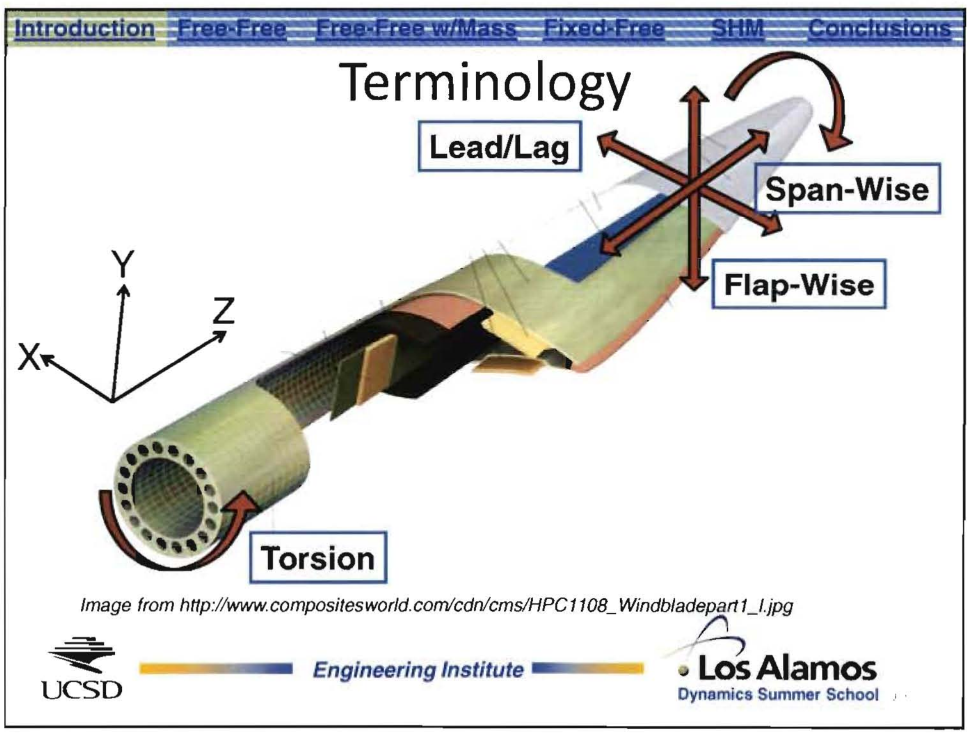
Introduction Free-Free Free-Free w/Mass Fixed-Free SHM Conclusions
Terminology
Lead/Lag
Span-Wise
Flap-Wise
Y
Z
X
Torsion
Image from http://www.compositesworld.com/cdn/cms/HPC1108_Windbladepart1_l.jpg
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Free-Free

Q: Why Free-Free?

1. Simple setup

2. Easy to correlate model to

Q: Wha… …ree-Free?

1. There's no such thing as free-free testing.

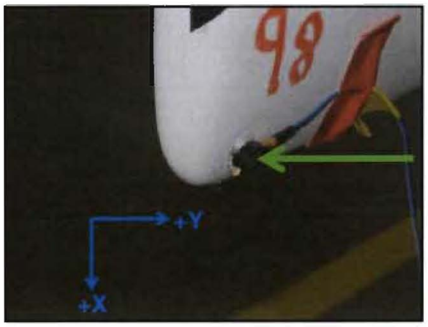
2. Care must be taken in the supporting of the blade to not distort modes of interest

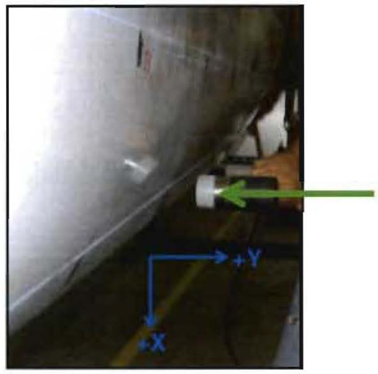
Free-Free Modal Test #1

Use … de to capt…

Impact & Measurement Directionality

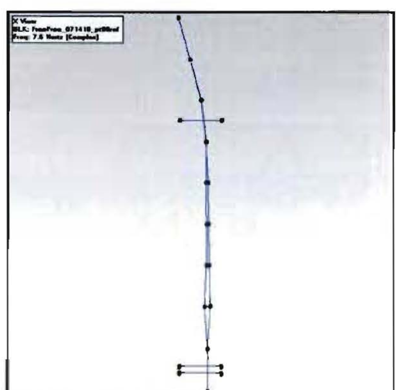
- *Impact & measure parallel with Y-axis*





Free-Free #1 Mode Shapes & Frequencies

Mode	Frequency (Hz)	Description
1	7.61	1st Flap Bending
2	18.1	1st Lag Bending
3	20.2	2nd Flap Bending
4	32.2	3rd Flap Bending
5	45.1	2nd Lag Bending
6	50.5	4th Flap Bending
7	63.9	1st Torsion
8	70.1	3rd Lag Bending



video

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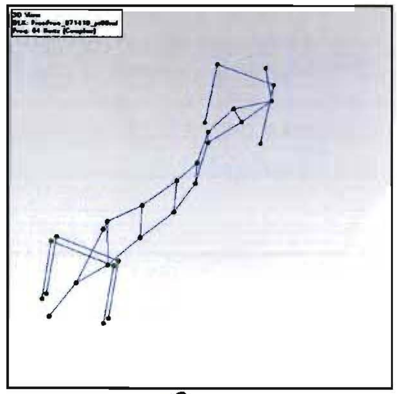
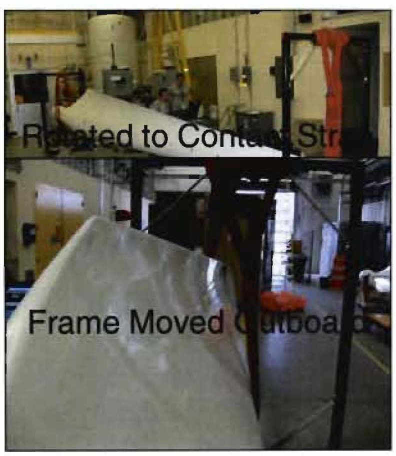


video

Do the Supports Effect the Modes?



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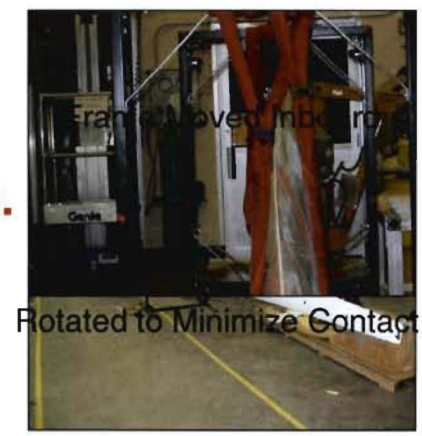
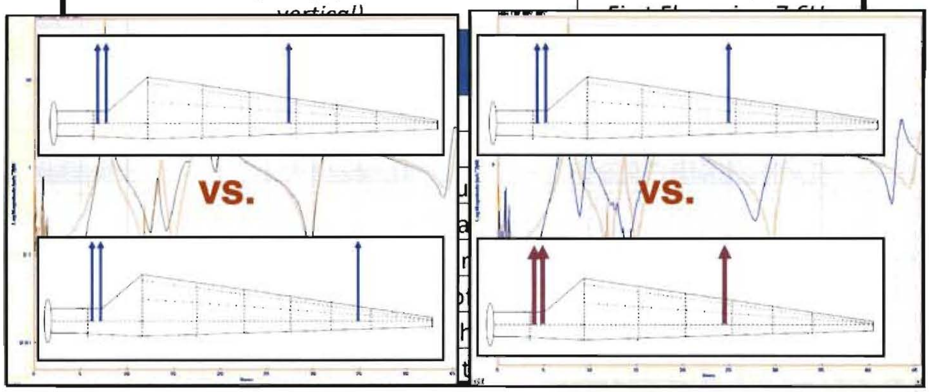


Do the Supports Effect the Modes?

Baseline (Black) vs. Bracketed Frame (Orange)

Baseline (straps at 0.41, 0.57 & 6.5m, tip vertical)

Baseline (Orange) vs. Moved Out to Tip (Blue)



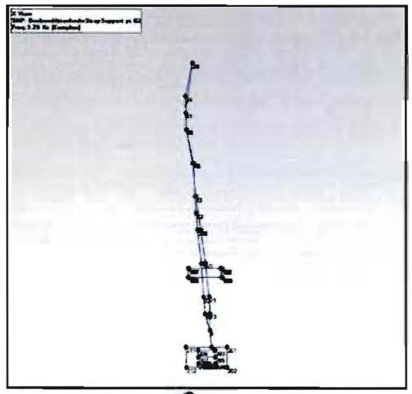
All plots: FRF Magnitude vs. Frequency

Free-Free Test #2

- Want to induce strain at root absent in Test #1
- Bolt Blade to Fixture (mass added to root)
- Fixture NOT bolted down

Free-Free #2 Mode Shapes & Frequencies

Mode	Frequency (Hz)	Description
1	3.29	1st Flap Bending
2	8.72	2nd Flap Bending
3	17.6	3rd Flap Bending
4	30.7	4th Flap Bending
5	45.0	5th Flap Bending
6	50.9	1st Torsion



video

Fixed-Free

Q: Why Fixed-Free?

ment

Q: What are some difficulties with Fixed-Free?

2.

tr

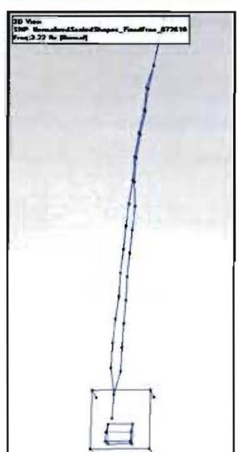
1. There's no such thing as fixed-free testing
2. Care must be taken to determine coupling of blade with fixture
3. Fixture must also be accurately modeled

Fixed-Free Test

- Cantilevered as in service
- Blade bolted to Fixture
- Fixture bolted to Frame

Fixed-Free Mode Shapes & Frequencies

Mode	Frequency (Hz)	Description
1	3.22	1st Flap Bending
2	4.15	1st Lag Bending
3	8.81	2nd Flap Bending
4	16.8	2nd Lag Bending
5	19.2	3rd Flap Bending
6	30.8	4th Flap Bending
7	37.2	3rd Lag Bending
8	43.9	1st Torsion



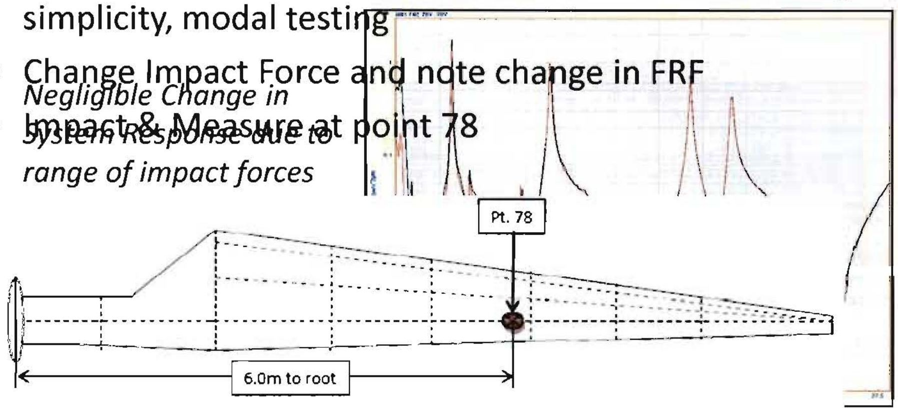
video

Introduction | Free-Free | Free-Free w/Mass | Fixed-Free | SHM | Conclusions

Fixed-Free: Nonlinear?

- Linearity assumption needed for modal simplicity, modal testing
- Change Impact Force and note change in FRF
- Impact & Measure at point 78
- *Negligible Change in system response due to range of impact forces*

250N (black) vs. 510N (red)



Plot: FRF Magnitude vs. Frequency

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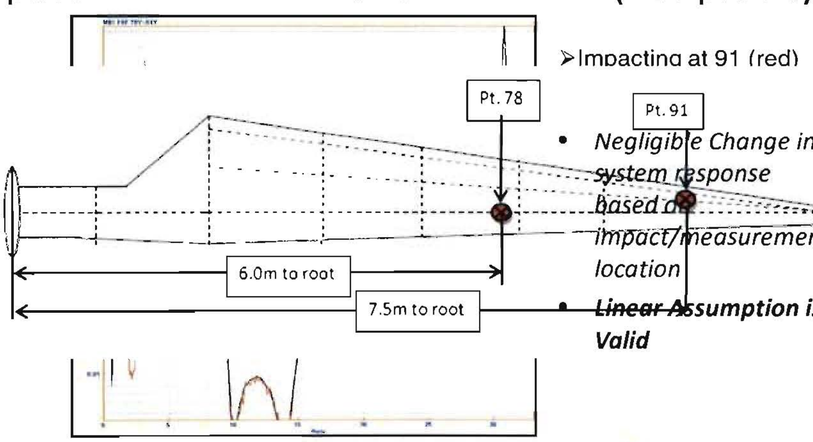
Introduction | Free-Free | Free-Free w/Mass | Fixed-Free | SHM | Conclusions

Fixed-Free: Nonlinear?

- Impact and Measure at Pt. 78 and 91 (Reciprocity)

➢ Impacting at 91 (red)



- *Negligible Change in system response based on impact/measurement location*
- ***Linear Assumption is Valid***

Plot: FRF Magnitude vs. Frequency

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Modal Tests Results

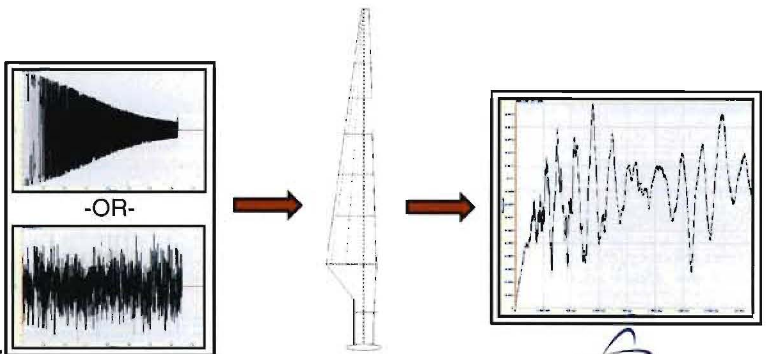
Test:	Mode Frequency (Hz) 1st Flap	2nd Flap	3rd Flap	4th Flap
Free-Free # 1 (Straps Only)	7.6	17.9	32.1	50.4
Free-Free #2 (Fixture + Strap)	3.3	8.7	17.6	30.7
Fixed-Free (bolted to fixture, frame)	3.2	8.8	19.2	30.8

SHM Investigation

- 9 MFC patches glued to high-pressure surface
  - 1 Large Actuation Patch
  - 8 Small Sensor Patches

SHM Investigation

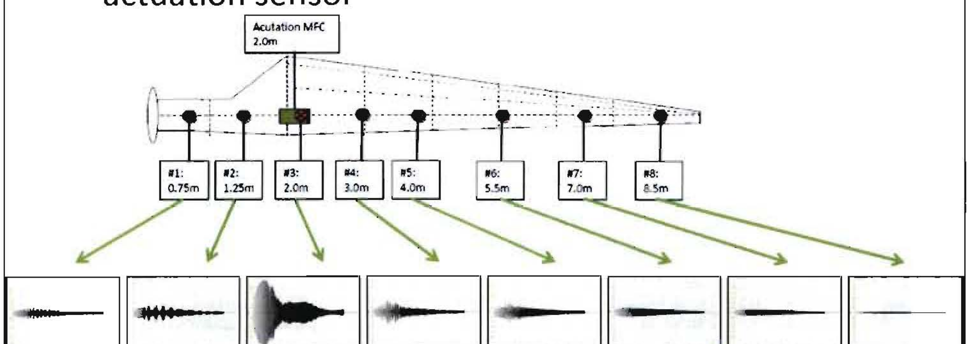
- Actuation MFC supplied with amplified sine chirp (154.8V peak) or burst random signal (179.8V peak) from 10Hz to 20kHz



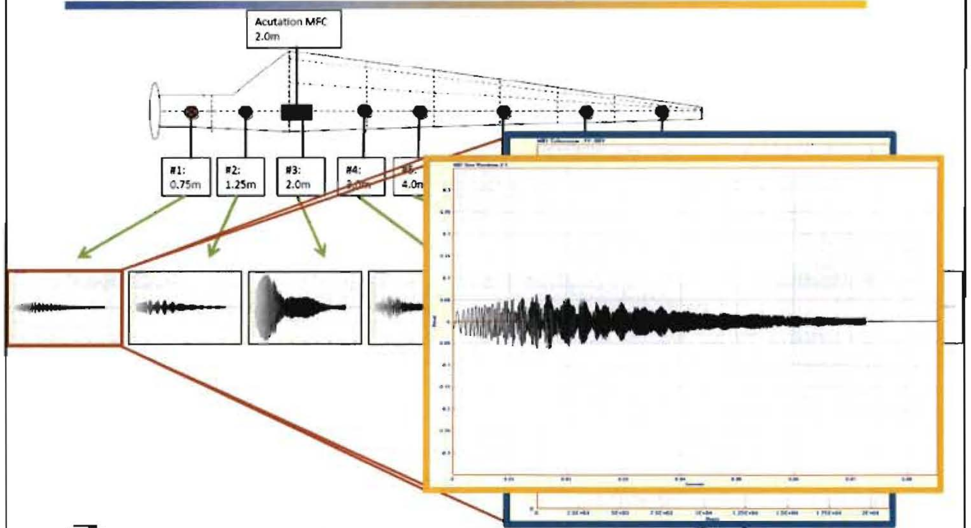
Introduction Free-Free Free-Free w/Mass Fixed-Free SHM Conclusions

SHM Investigation

- Compare time response at various points
  - Amplitude of response maximum closest to actuation sensor



SHM Investigation



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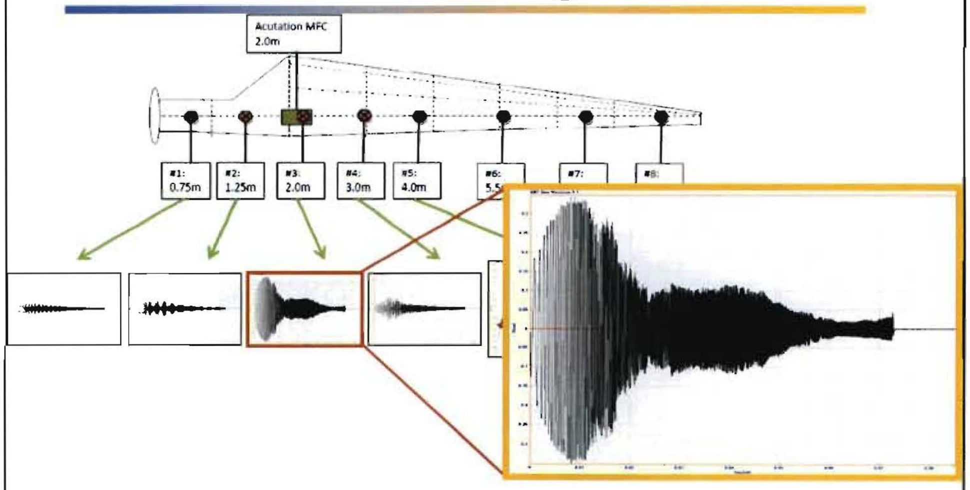
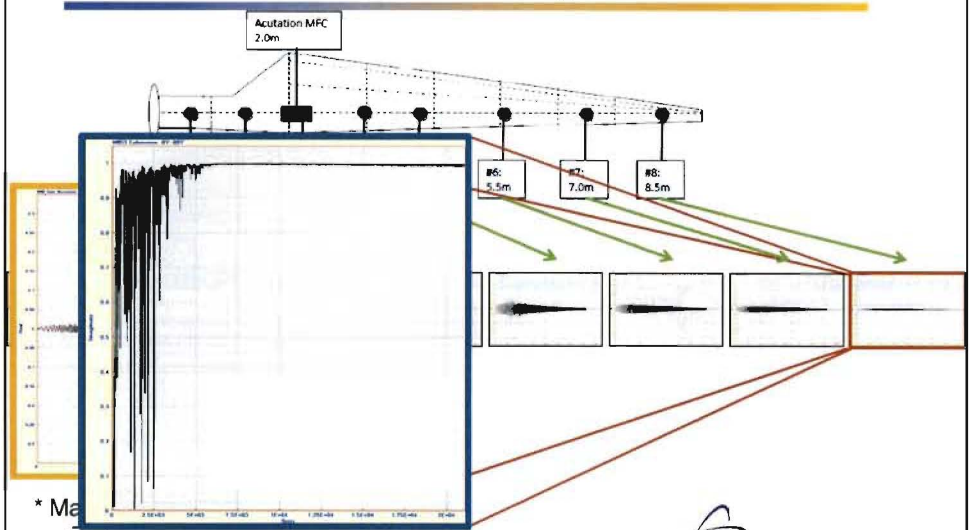
SHM Investigation



* Mag vs. time

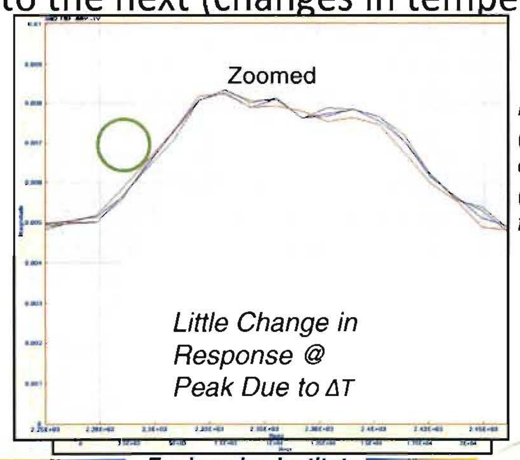
SHM Investigation



* Ma

SHM Investigation

- Determine change in system response from one day to the next (changes in temperature, etc)



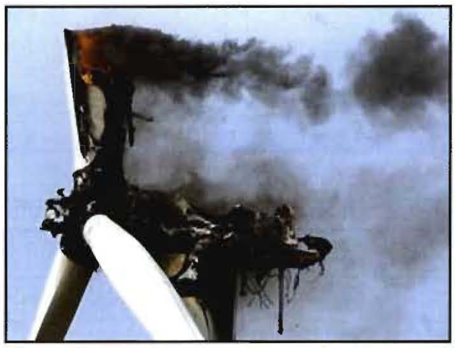
Response at Point 1 (0.75m from root), 4 consecutive days (magnitude vs. frequency)

Day:	Temp. (°F)
1	78.7
2	75.7
3	74.6
4	75.5

Conclusions

Problem:

Wind Turbine Blade Predictive Reliability

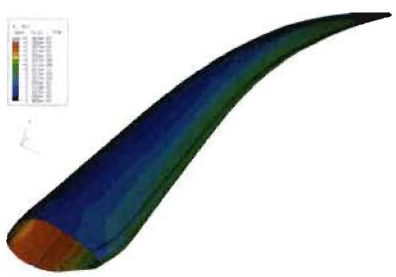


http://wind-power-revolution.blogspot.com/2008/11/wind-turbine-failure-photos.html

Conclusions

Solution:

Validate Numerical Models and Design Effective SHM



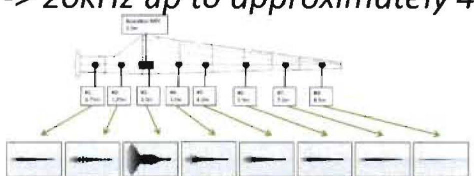
http://www.nsecomposites.com/projects/wind-energy.html

Conclusions

Our Contribution:

- *Determined mode shapes and frequencies of CX-100 blade in 3 different BC configurations to drive V&V*

- *Determined that MFC patches may be used to excite 5kHz -> 20kHz up to approximately 4m from actuator*



Future

- **Modal Testing**
  - Integrate results of modal tests into numerical model of blade for V & V
  - Perform uncertainty quantification study
  - Better represent fixed-free condition with improved fixture
- **Structural Health Monitoring**
  - Simulate damage on blade and detect with MFC sensor patches
  - Relocate actuator/sensors and monitor for optimal signal transfer

Introduction | Free-Free | Free-Free w/Mass | Fixed-Free | SHM | Conclusions

Acknowledgments

- Engineering Institute (Los Alamos National Laboratory)
  - Dr. Charles Farrar
- Vibrant Technology Inc. (ME'scope Software)
- Abaqus, Inc. (ABAQUS Finite Element Software)
- Dr. Peter Avitabile (University of Massachusetts Lowell)

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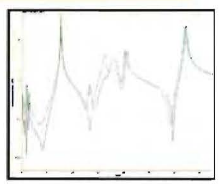
Questions?





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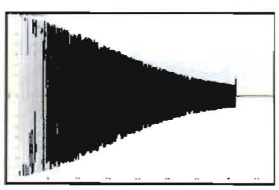
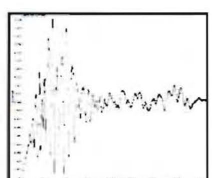

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