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Title: Experimental Assessment of NLBeam for Modeling Large Deformation Structural Dynamics

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EXPERIMENTAL ASSESSMENT OF NLBEAM FOR MODELING LARGE DEFORMATION STRUCTURAL DYNAMICS

Sarah Dalton, Clemson University; Lisa Monahan, University of Pittsburg; Ian Stevenson, Rose Hulman Institute of Technology; D.J. Luscher, Los Alamos National Laboratory; Gyuhae Park, Los Alamos National Laboratory; Kevin Farinholt, Los Alamos National Laboratory

ABSTRACT

With the growth of the wind energy industry, it has become apparent that gear boxes in wind turbines, which link the blades to the generator, tend to wear down faster than anticipated. This phenomenon is not clearly understood; one theory is that existing wind turbine modeling approaches used to design the turbines do not properly account for nonlinearities caused by large amplitude blade deformations. To help understand the effects of geometric nonlinearities, a novel finite element based code, *NLBeam*, has been developed to simulate structural dynamic responses of wind turbine blades by employing the geometrically exact beam theory. This research focuses on assessing the adequacy of *NLBeam* by comparing simulation to experimental results. Three aluminum blade surrogates with different geometries were tested by applying large amplitude base excitations while assuring the surrogates stayed within the elastic range. A variety of orientations were utilized changing the dynamic characteristics of the surrogates and reflecting actual turbine blade behavior. The results are used to guide future development of *NLBeam* which will be coupled with large scale simulations of wind plants in a Computational Fluid Dynamics based program developed at Los Alamos National Laboratory called *WindBlade*.

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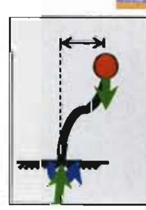
Los Alamos National Laboratory

Outline

Motivation

Research Procedure
- -Experiment
- -Modeling



Results and Discussion

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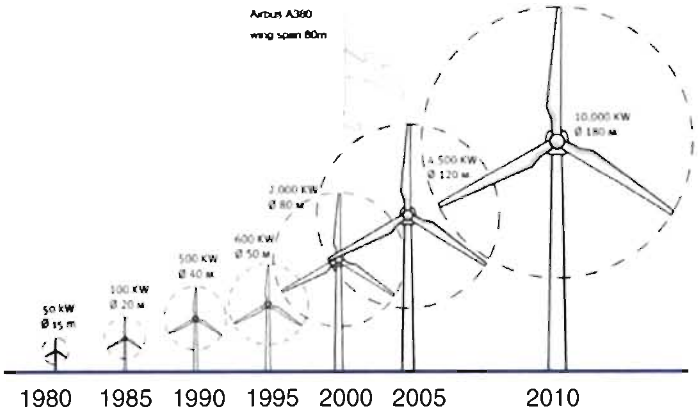
Motivation

- Wind plant sizes are growing, as well as the size of the turbine blades themselves.



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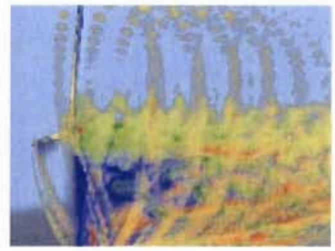
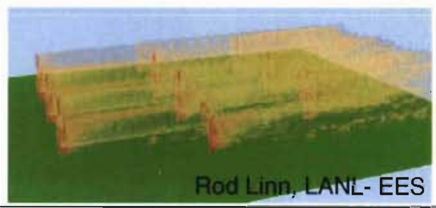
Motivation

Modeling wind turbines is very difficult; its made worse when modeling full plants.



Simulations developed by LANL *WindBlade*



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NLBeam

- Finite Element (FE) based code to model the geometric nonlinearities experienced in wind turbine blades

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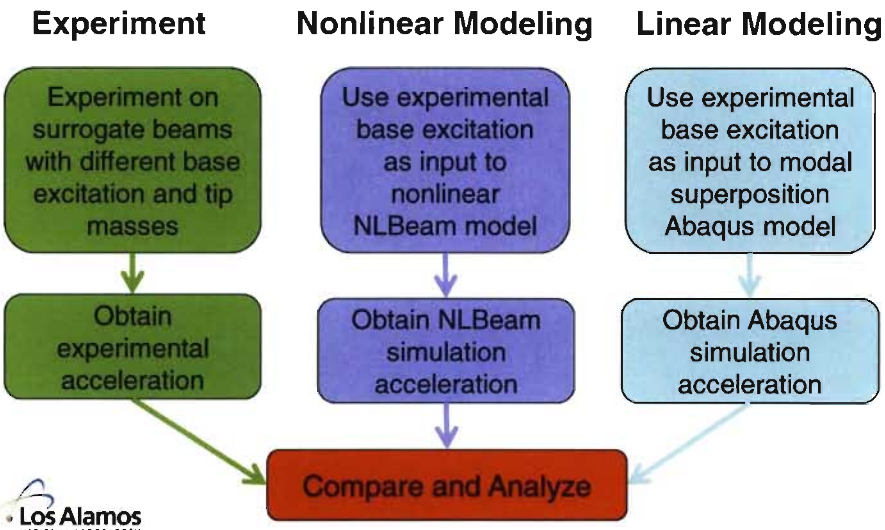
Research plan



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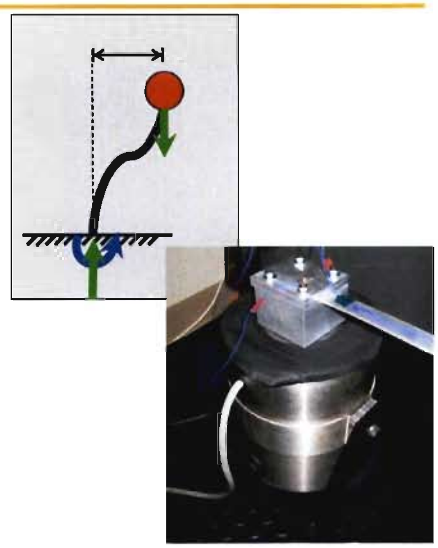
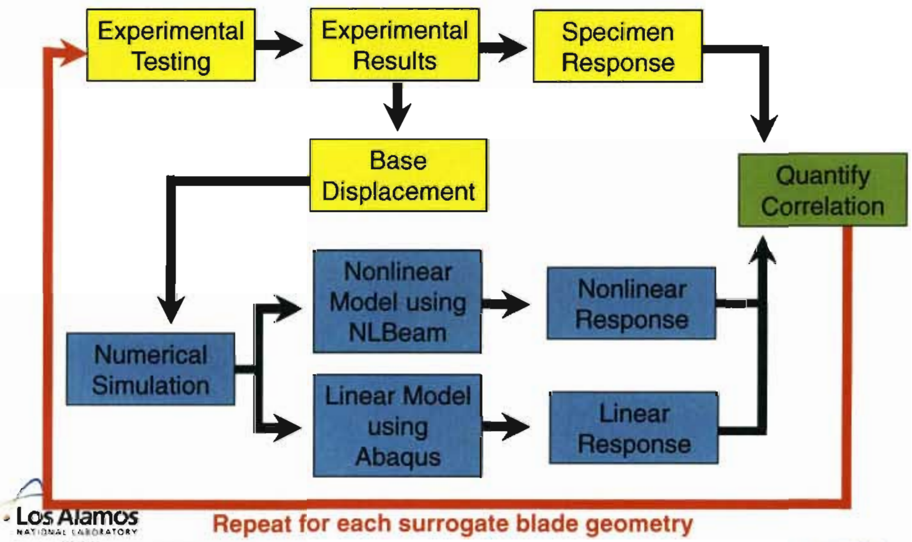


Methodology for Assessment



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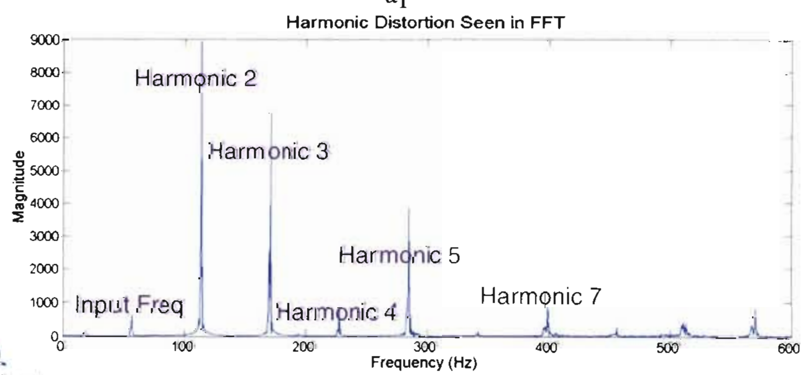
Identifying nonlinearities in experiments

- Harmonic distortion is main metric used

$$H_d = \frac{\sqrt{\sum_n {a_n}^2}}{a_1}$$



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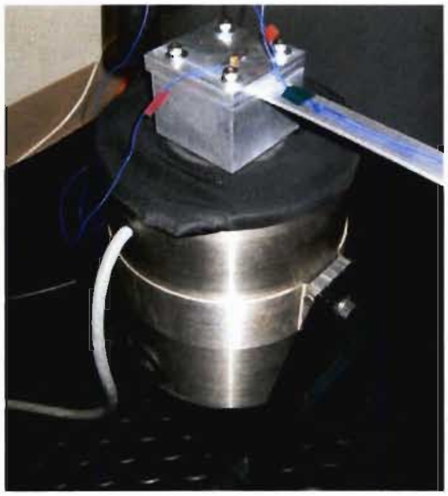
Experiment uses a shaker to excite blades



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Dactron data collection system

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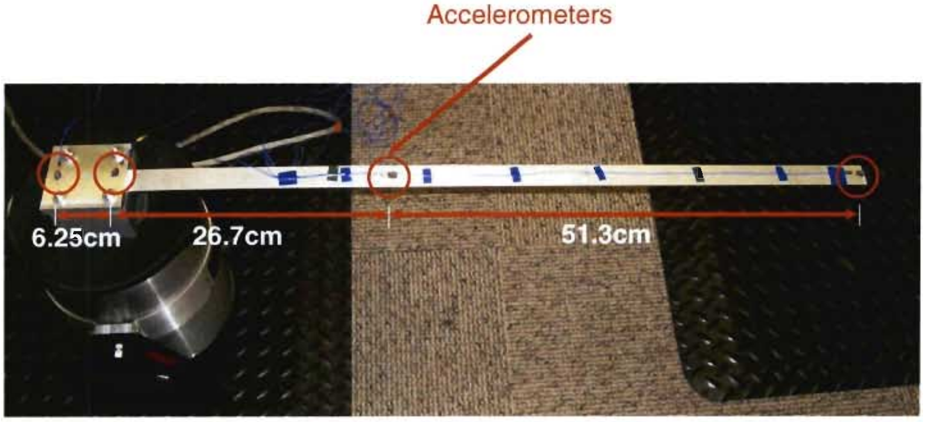
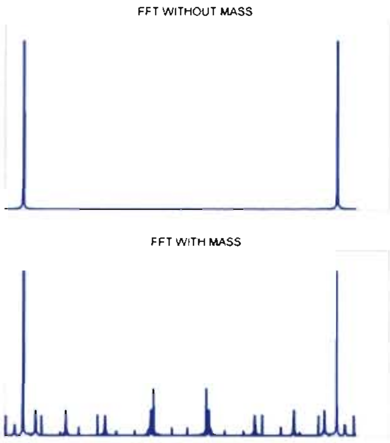
Data is collected with accelerometers



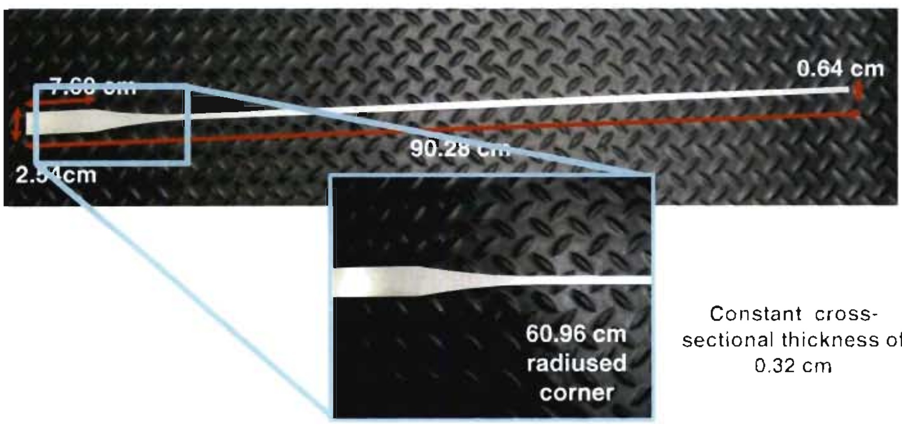
Added mass creates geometric non-linearities



Surrogate blades of varying profiles

Constant cross-sectional thickness of 0.32 cm

Surrogate blades of varying profiles



Constant cross-sectional thickness of 0.32 cm

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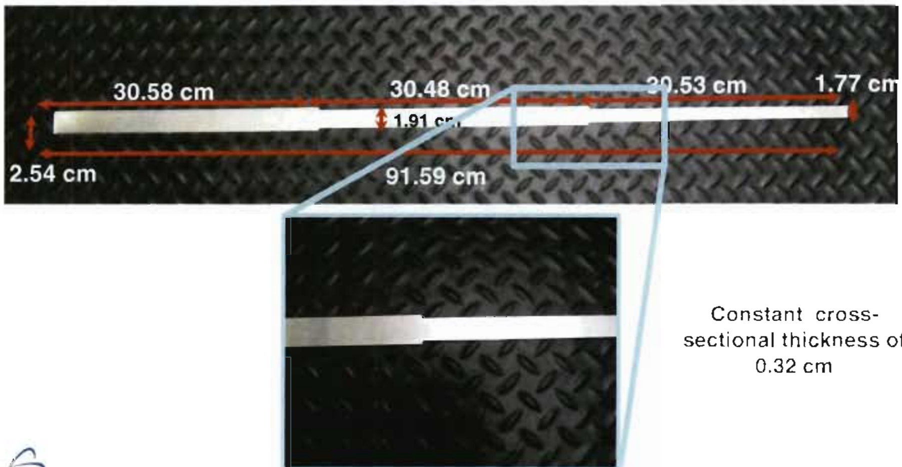
Surrogate blades of varying profiles



Constant cross-sectional thickness of 0.32 cm

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Surrogate blades of varying profiles

Constant cross-sectional thickness of 0.32 cm

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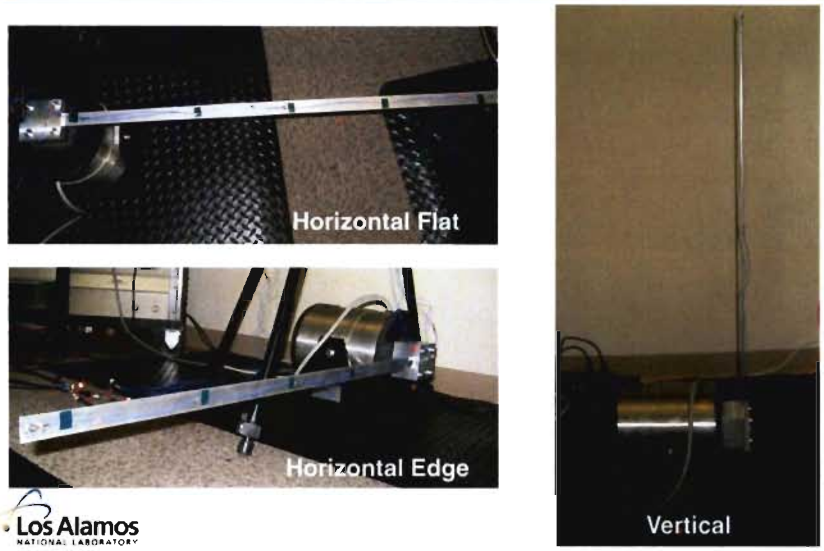
All blades will be tested in three configurations.



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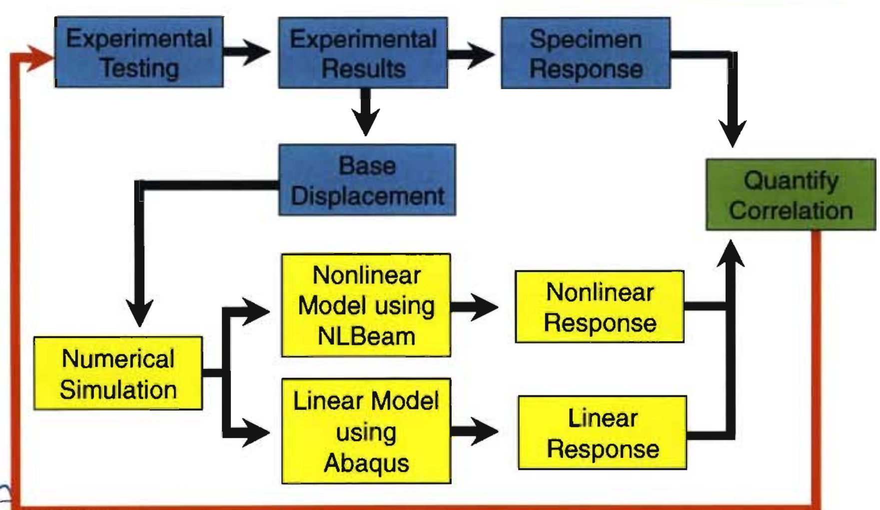
Methodology for assessment



Repeat for each surrogate blade geometry

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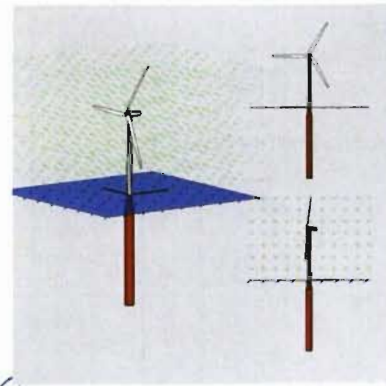
Modeling approaches

FAST

- Uses mode shapes
- Does not account for nonlinearities



Detailed FE Modeling

- Higher fidelity
- Prohibitive computational cost

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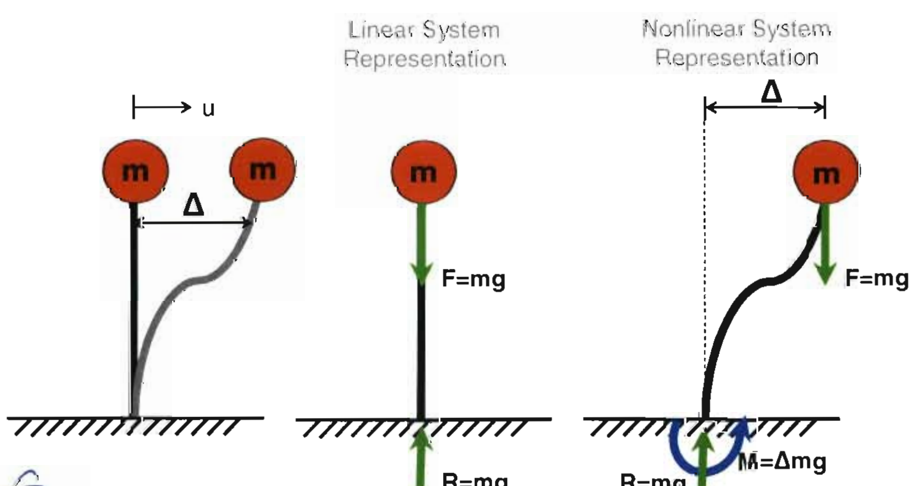
Why utilize a nonlinear model



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Theories behind NLBeam modeling capabilities

Sectional Strains – $\gamma_n = \Lambda^T r_n' - b_1$ — Axial and transverse shears

Sectional Curvature – $\kappa_n = \Lambda^T \Lambda_n'$ — Torsional rate of twist and bending curvature

Sectional Forces and Moments from Strain-Energy Equation

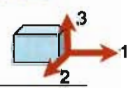
$$F_N = \frac{\delta U}{\delta \gamma} \qquad F_M = \frac{\delta U}{\delta \kappa}$$

$$\begin{Bmatrix} F_{Na} \\ F_{Nv2} \\ F_{Nv3} \\ F_{Mt} \\ F_{Mb2} \\ F_{Mb3} \end{Bmatrix} = \begin{bmatrix} EA_1 & & & \cdots & & 0 \\ & GA_2 & & & & \\ \vdots & & GA_3 & & & \vdots \\ & & & GJ & & \\ & & & & EI_2 & \\ 0 & & & \cdots & & EI_3 \end{bmatrix} \begin{Bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{Bmatrix}$$

Cross-sectional Properties

Section Strains

Section Curvature



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NLBeam finite element formulation

Weak Form of Momentum Conservation

$$R_I = R_I{}^m + R_I{}^d - R_I{}^e = 0$$

Set residuals = 0

Where:

$$R_I{}^m = \int_0^L \begin{bmatrix} N_I{}'\boldsymbol{I} & \boldsymbol{0} \\ N_I\widetilde{\boldsymbol{r}}' & N_I{}'\boldsymbol{I} \end{bmatrix} \begin{Bmatrix} \Lambda \cdot F_N \\ \Lambda \cdot F_M \end{Bmatrix} dx$$

Stress contribution to nodal forces

$$R_I{}^d = \int_0^L N_I(x) \begin{Bmatrix} \rho A \ddot{u} \\ \widetilde{\boldsymbol{W}} \boldsymbol{J}_\rho \boldsymbol{W} + \boldsymbol{J}_\rho \boldsymbol{A} \end{Bmatrix} dx$$

Inertial contribution to nodal forces

$$R_I{}^e = \int_0^L \begin{Bmatrix} N_I \rho A_g \\ \boldsymbol{0} \end{Bmatrix} dx + \sum N_I(x_1{}^*) \begin{Bmatrix} \Lambda \cdot f_{aero} \\ \Lambda \cdot T_{aero} \end{Bmatrix}$$

Nodal force due to external loads

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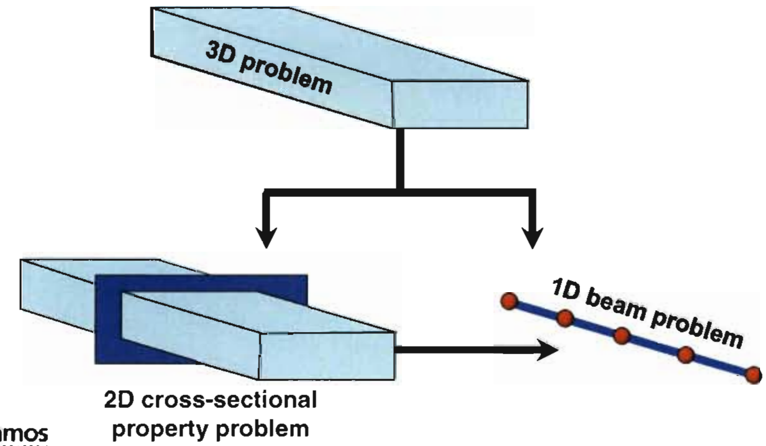
FE Pre-processor

- Geometrically exact beam theory breaks up 3D problem into 2D cross-sectional problem and "1D" beam problem



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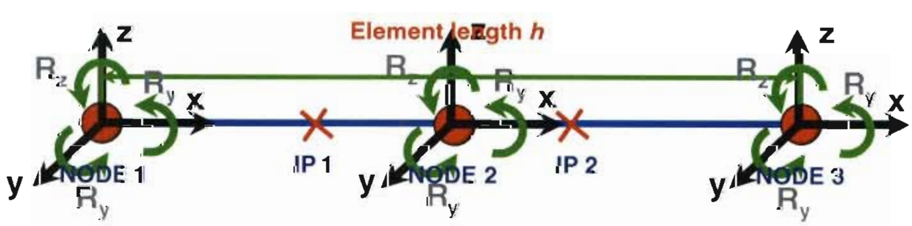
NLBeam modeling methodology

- Utilizes quadratic beam elements, 2 Point Gaussian Integration, Newton-Raphson Solver, with 6 nodal DOF's



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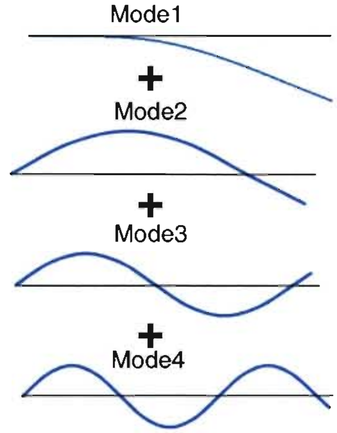
Linear modeling methodology

- Efforts made to keep all modeling parameters identical in both linear and nonlinear models
- Difference being Abaqus model captures only linearity through Modal Superposition of first 4 bending modes
  - Neglects any nonlinearity due to geometry



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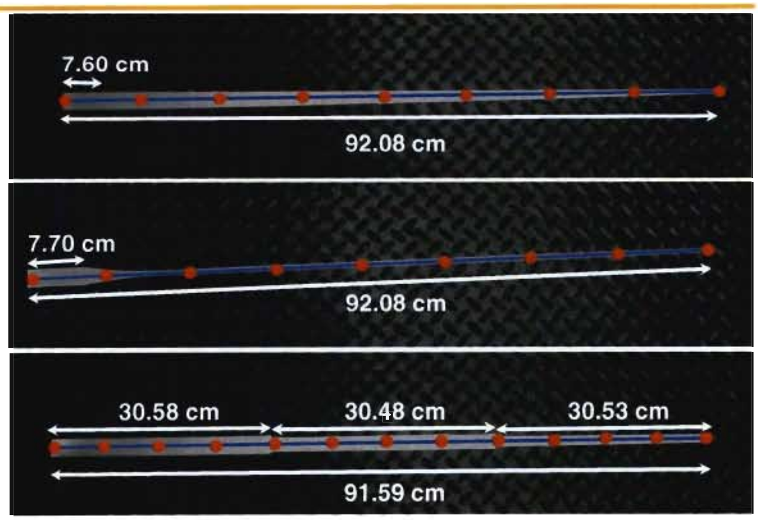
Geometry used

Linear Taper Beam

Radial Taper Beam

Discrete Taper Beam



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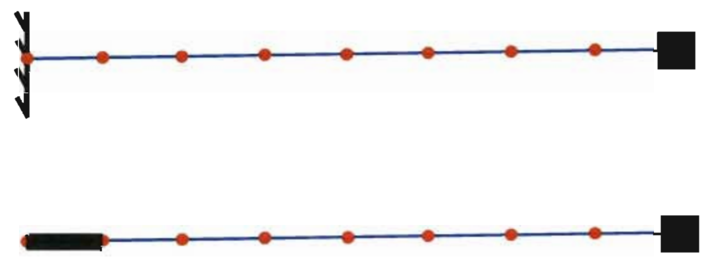
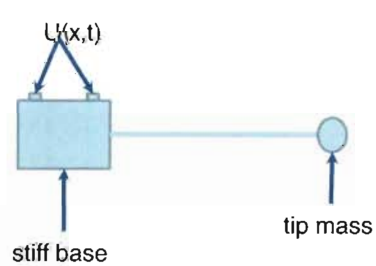
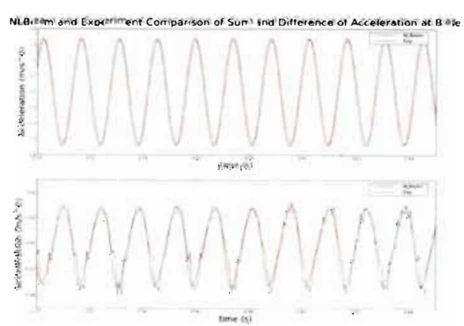
First model and changes necessary



Model boundary condition considerations

- Input displacement at two locations on base to account for rocking
- Increased base stiffness
- Modeled point mass at tip





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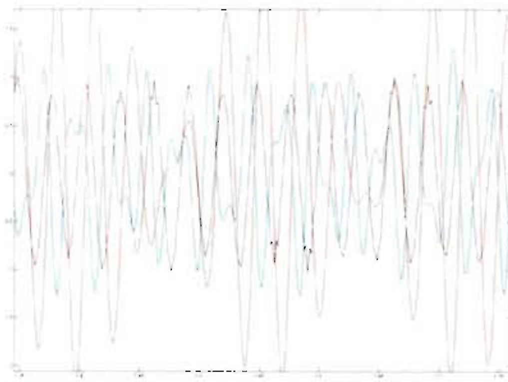
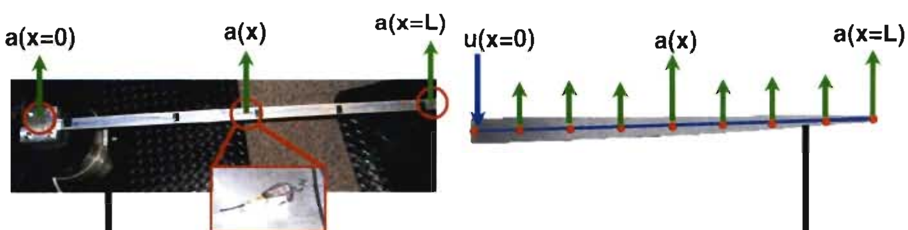


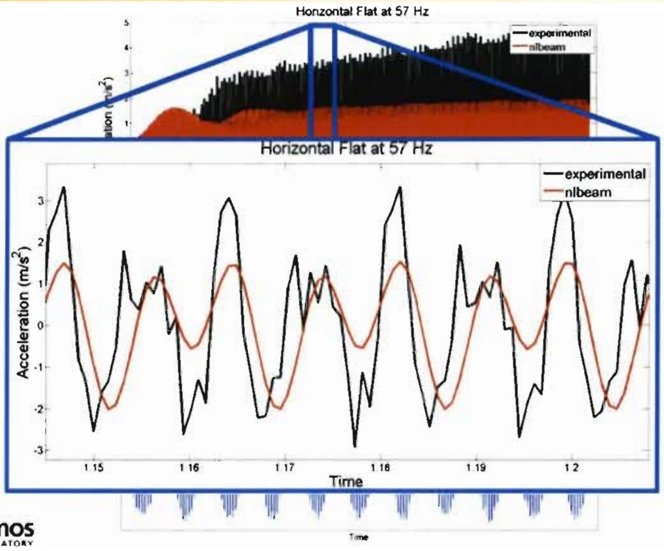
Results and Discussion

Experimental and Model Outputs

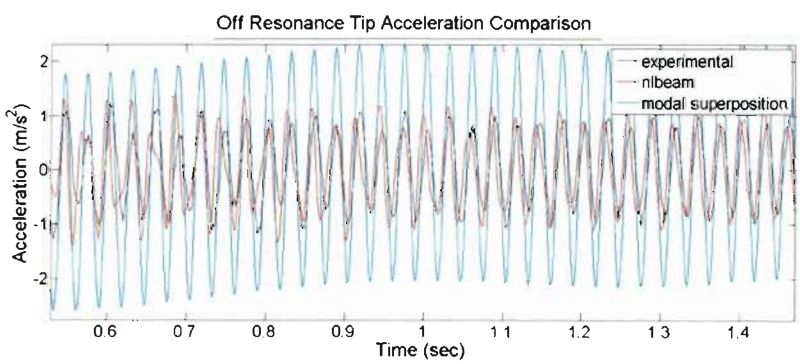


Comparisons
1. Visual Acceleration Correlation Over Time
2. Frequency Domain Comparisons
3. Harmonic Distortion Comparisons

Acceleration of the tip at a natural frequency



Time correlation

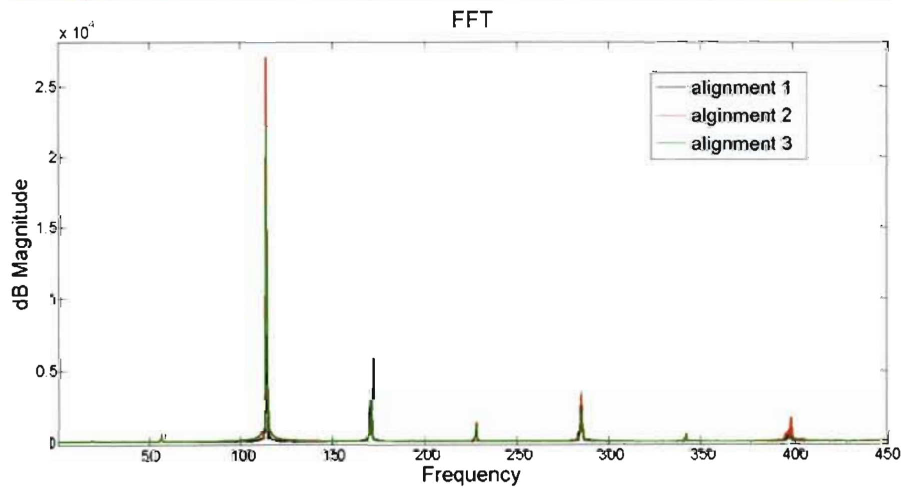


Frequency domain correlations

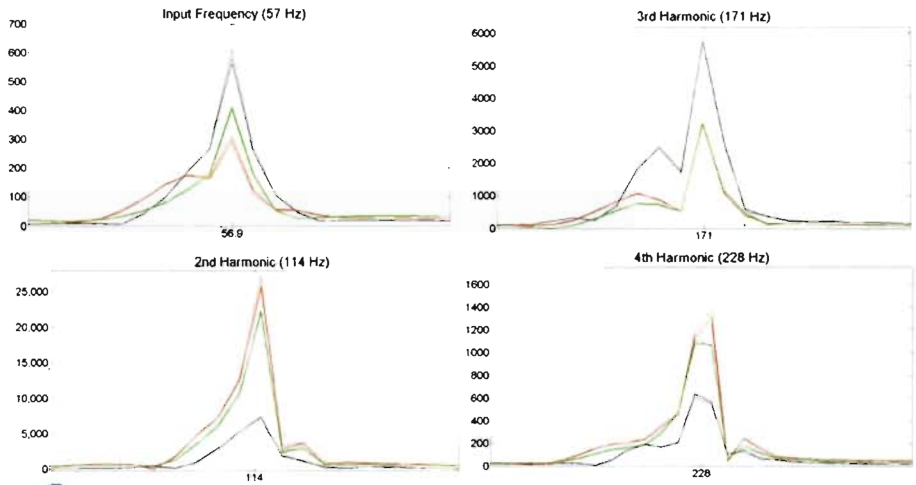
	Flat Horizontal Correlation	Edge Horizontal Correlation	Vertical Correlation
Experiment vs. NLBeam	0.965	0.966	0.955
Experiment vs. Modal Superposition	0.028	0.027	0.031
NLBeam vs. Modal Superposition	0.035	0.030	0.033

$$Correlation = \frac{fft \cdot \overline{fft}}{\|fft\| \times \|\overline{fft}\|}$$

Effect of orientation on experimental beam response



Effect of orientation on experimental beam response



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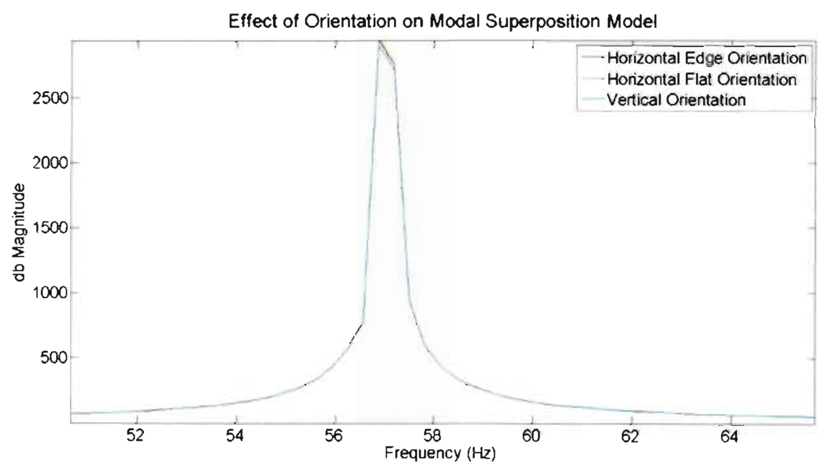
Effect of orientation on modal superposition model



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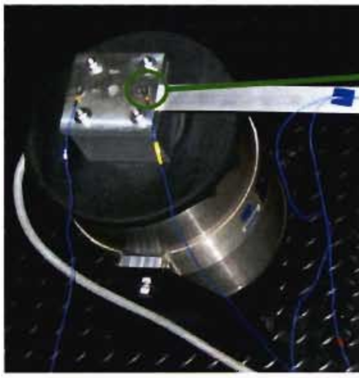
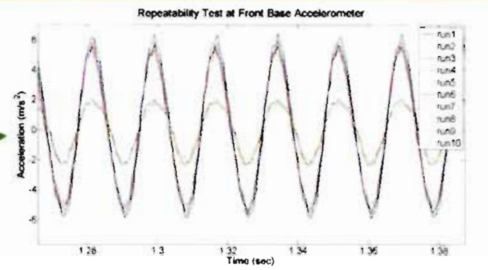
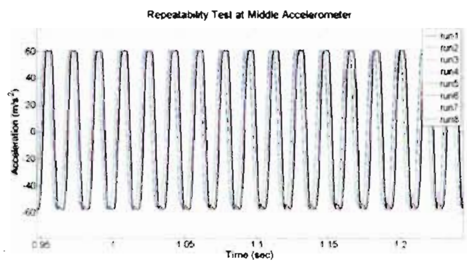
Repeatability test







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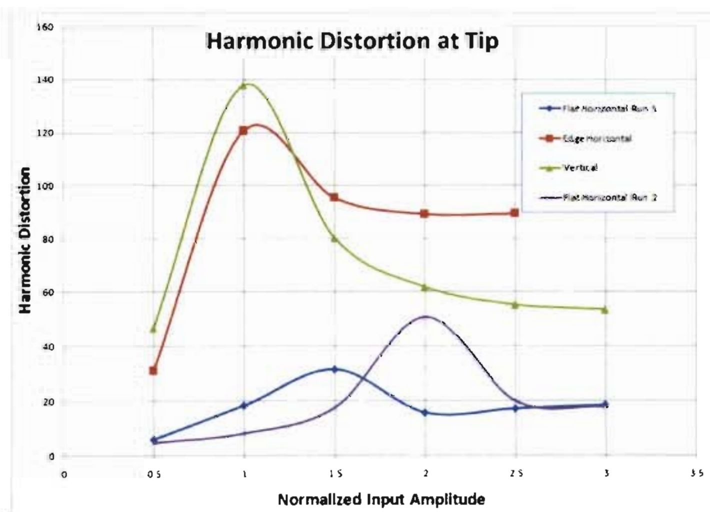
Boundary condition discovery through harmonic distortion



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Conclusion – Future experimental considerations

- Available instrumentation limited our ability to collect data
  - No way to measure rotation, displacement, or strain
  - Limited to four channels
  - Vibrometer
- Given shaker limited amplitude
  - Mechanical stop made large deformation off resonance impossible
- Shaker/base connection increased boundary complication

Conclusion – Future development of NLBeam

- Damping
  - Its important aspect of experimental validation
  - Currently unsupported in NLBeam
- General modeling observation
  - Highly sensitive to phase (caused by rotation) of input signals
- Debugging
  - Solution Convergence determination needs to be improved

Questions?