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Title:	TIME SERIES PREDICTIVE MODELS OF PIEZOELECTRIC ACTIVE-SENSING FOR SHM APPLICATIONS
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Time Series Predictive Models of Piezoelectric Active-Sensing for SHM Applications

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In this paper, the use of time domain data from piezoelectric active-sensing techniques is investigated for structural health monitoring (SHM) applications. Piezoelectric transducers have been increasingly used in SHM because of their proven advantages. Especially, the use of known and repeatable inputs at high frequency ranges makes the development of SHM signal processing algorithm easier and more efficient. However, to date, most of these techniques have been based on frequency domain analyses, such as impedance-based or high-frequency response functions (FRF) -based SHM techniques. Even with Lamb wave propagations, most researchers adopt frequency domain or wavelets analysis for damage-sensitive feature extraction. This process usually requires excessive averaging to reduce measurement noise and more computational resources, which is not ideal from both memory and power consumption standpoints. Therefore in this study, we investigate the use of autoregressive models with exogenous inputs (ARX) with the measured time series data from piezoelectric active-sensors. The test structures considered in this study include a section of CX-100 wind turbine blade and a 2 x 2 ft composite plate, where the plate was subjected to a series of impact loadings to induce damage in the form of fiber delimation. The performance of this technique is compared to that of traditional autoregressive (AR) models, traditionally used in low-frequency passive sensing techniques, and that of FRF-based analyses, and its superior capability in SHM is demonstrated. This paper outlines the advantages of this method over traditional frequency-domain analyses and provides guidelines for using time-series data from active-sensors for real-world SHM applications.

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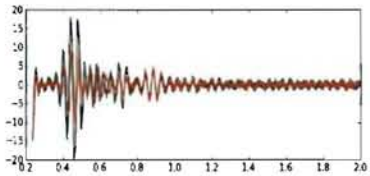
Outline

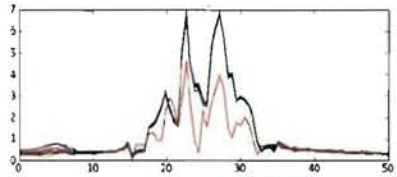
- The application of time series predictive models obtained from piezoelectric active-sensing techniques is presented for SHM.
- Time series autoregressive models with exogenous inputs (ARX) are implemented to extract damage sensitive features.
- Experimental results will be summarized to demonstrate the capability of the proposed method.

http://earth2tech.files.wordpress.com/2008/10/suzlon-turbine.jpg

SHM based on Piezoelectric Active-Sensing

- Being increasingly used
- The methods includes electro-mechanical impedance methods, high-frequency response functions, guided waves.
- Most of these methods have been based on frequency domain (impedance) or other approaches for damage sensitive feature extraction.
  - Excessive averaging, intensive computation
- Predictive models of time series data obtained from piezoelectric active-sensing technique have not been extensively used in SHM applications.

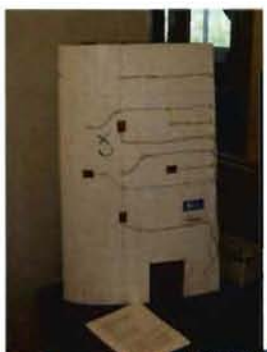




SHM of Wind Turbine Blades

- Why Turbine Blades?
  - Most expensive component to repair
  - Rotational imbalance results in additional damage
  - Huge, remote locations, wireless desirable
- We investigated several active-sensing techniques to detect damage in composite turbine blades (Light-Marquez et al. 2010)

tpiblog.tspadventures.com/2007/07/wind-energy-everywhere.html



http://biology.usgs.gov/cro/ScienceInYourState/Montana/MT-brd.htm

Time Series Models

- An autoregressive (AR) model predicts the current time point in a series as a linear combination of *n* previous time points.

$$x_i = \sum_{j=1}^{p} \alpha_j x_{i-j} + \varepsilon_i$$

- The AR representation can be extended to an autoregressive with exogenous inputs (ARX) by including the effect of input to a system

$$x_i = \sum_{j=1}^{p} \alpha_j x_{i-j} + \sum_{j=0}^{q} \beta_j y_{i-j} + e_i$$

- An ARX (*p,q*) model is used to capture the input/output relationship, utilizing the information associated with a "known" input provided by a piezoelectric active-sensing system.
- A proper model order selection is critically important.

SHM using Time Series Models

- Damage sensitive feature extractions
  - Residual Errors: Use the time series predictive model estimated from the baseline condition to predict the response of data obtained from a potentially damaged structural condition.
  - ARX Parameters
- Have been extensively used passive-sensing SHM techniques.
- Some advantages:
  - Applicable to nonlinearity detection
  - A well-established topic (e.g. speech pattern recognition)
  - Algorithms can be easily embedded into digital signal processers

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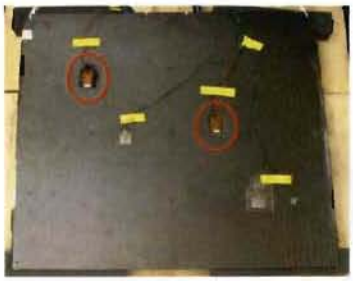
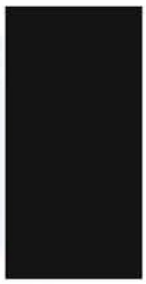
Experimental Investigation – Composite Plates





- Five impacts were given to the plate using a gas gun at different locations and velocities to initiate delamination.
- Two Macro-fiber composites (MFC) are bonded on one side of a 24 x 24 x 0.25 composite plate to measure the time domain data (Random excitation, sampling frequency of 51.2 kHz).
- Lamb wave were also measure using 16 PZT transducers on the other side of the plate.

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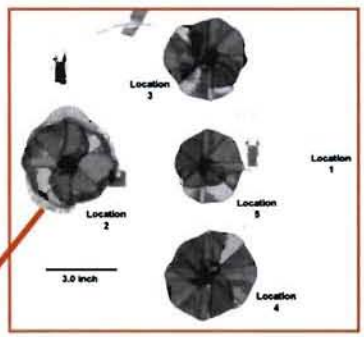
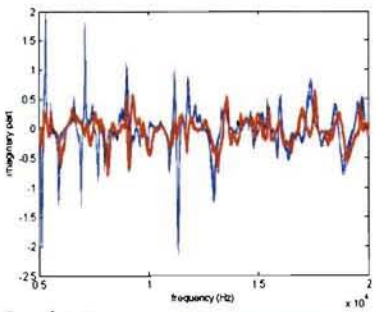
FRF with Ultrasonic Validation (Park et al. 2006)





The delaminated area is well-correlated to damage indicator feature extracted from frequency response functions.

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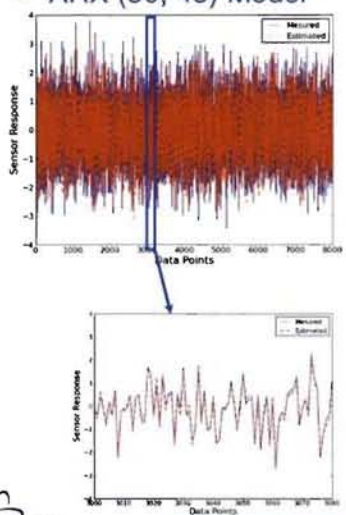
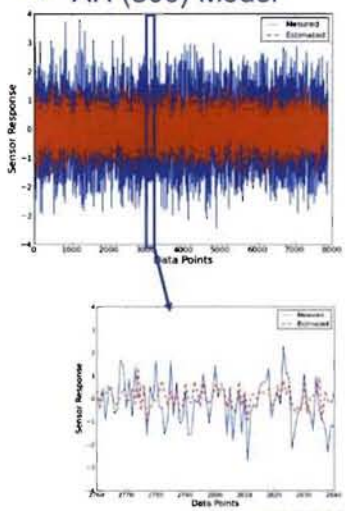
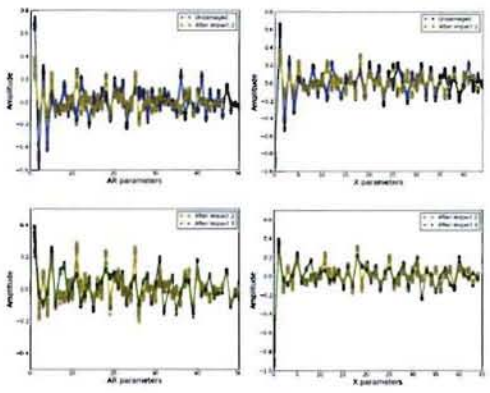
Applications of Predictive Models: AR vs. ARX

- ARX (50, 45) Model
- AR (300) Model





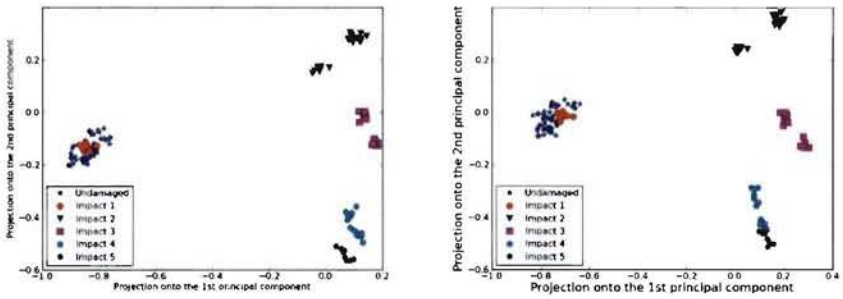
Changes in AR and X Parameters (of the ARX Model) with induced impacts – Correlation Analysis



Tests	Impact Speed (m/s)	Delamination area (mm²)	Maximum damage metric (AR)	Maximum damage metric (X)
Impact 1	31.09	0.00	0.046	0.032
Impact 2	39.93	9813	0.68	0.35
Impact 3	36.88	7361	0.45	0.16
Impact 4	35.66	8935	0.47	0.19
Impact 5	32.92	5032	0.19	0.11

- Correlation coefficients are calculated between each impact and the preceding condition
- The delaminated area is well-correlated to damage indicator feature

Changes in AR and X Parameters (of the ARX Model) with induced impacts – Principle Component Analysis

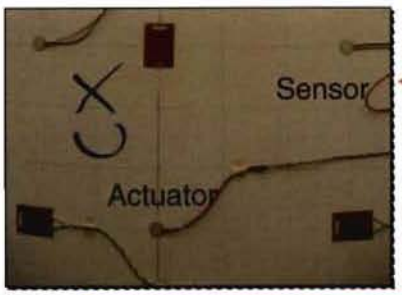


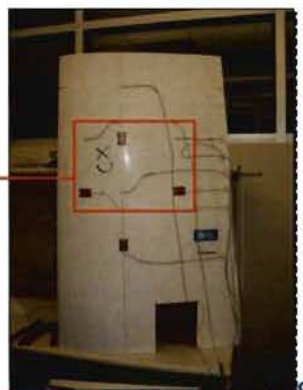
AR Parameters X Parameters

- Similar Results were obtained using any other signal processing algorithms (Mahalanobis distance measure, Residual error analysis etc)

Section of a Wind turbine Blade

- CX-100 1m Turbine Blade Section
  - Sampling Frequency: 51.2 kHz
  - Chirp, Random inputs
- Simulated Damage was introduced





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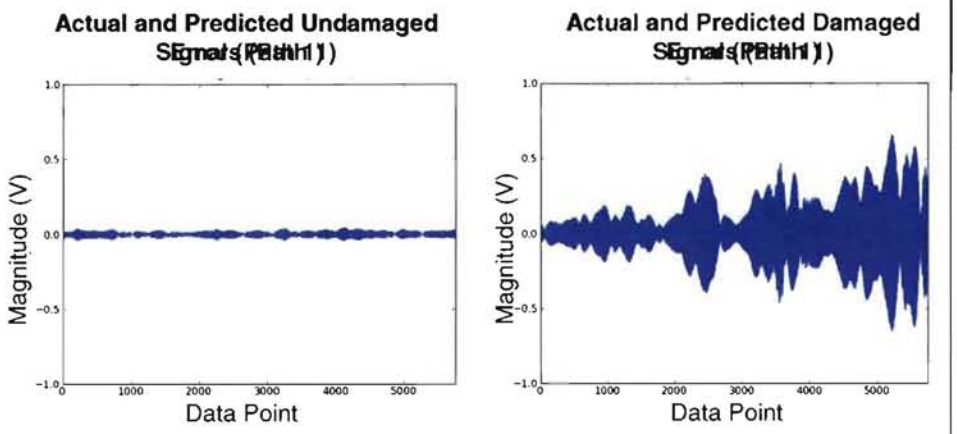
Time Series Analysis



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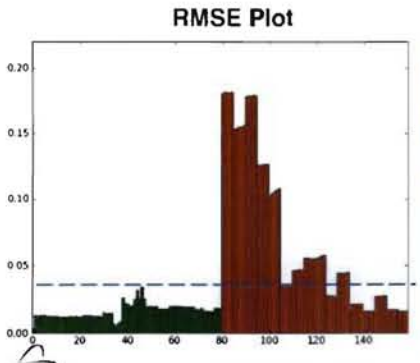
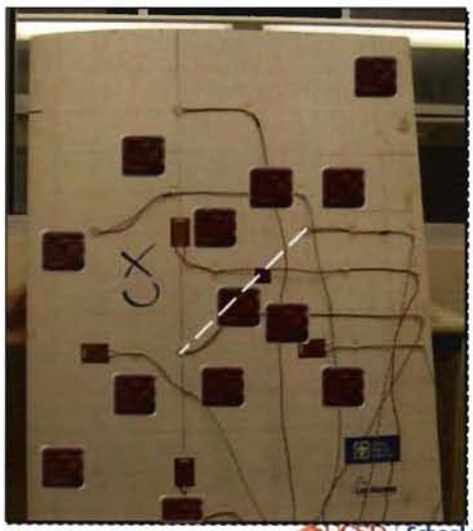
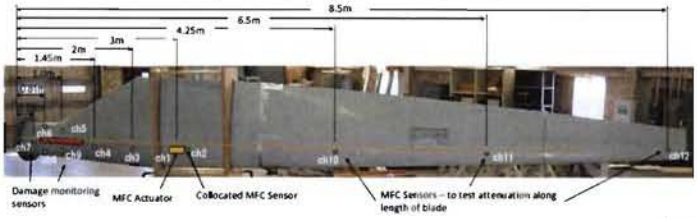
Time Series Analysis

- Path 2
  - Detected Damage
  - Undetected





Sandia's Blade Fatigue test at NREL



Courtesy of Sandia National Laboratory

Conclusions

- Time Series data measured by piezoelectric active-sensors were utilized for SHM.
- The methods were compared favorably with the traditional analysis
- Future work includes
  - Improve the performance, including multiple damage locations, temperature variations
  - Embed the process to wireless hardware

http://earth2tech.files.wordpress.com/2008/10/suzlon-turbine.jpg

Acknowledgement

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