LA-UR- 10-01821

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Title: SHM of Wind Turbine Blades using Piezoelectric Active-Sensors

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Intended for: 5th European Workshop on Structural Health Monitoring, Sorrento, Italy, June 29-July2, 2009

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Cover page

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ABSTRACT

This paper presents a variety of structural health monitoring (SHM) techniques, based on the use of piezoelectric active-sensors, used to determine the structural integrity of wind turbine blades. Specifically, Lamb wave propagations, frequency response functions, and time series based methods are utilized to estimate the condition of wind turbine blades. For experiments, a 1m section of a 9m CX100 blade is used. Overall, these three methods yielded a sufficient damage detection capability to warrant further investigation into field deployment. A full-scale fatigue test of a CX-100 wind turbine blade is also conducted. This paper summarizes considerations needed to design such SHM systems, experimental procedures and results, and practical implementation issues that can be used as guidelines for future investigations.

INTRODUCTION

Wind turbines are becoming a larger source of renewable energy in the United States. The turbine manufacturers have been increasing the length of the turbine blades, often made of composite materials, to maximize power output. As a result of severe wind loadings and the material level flaws in composite structures, blade failure has been a more common occurrence in the wind industry. Therefore, it is imperative that a SHM system be incorporated into the design of the wind turbines in order to monitor flaws before they lead to a catastrophic failure.

The goal of this study is to investigate the performance of high-frequency active-sensing SHM techniques, including lamb wave, frequency response functions, and time series based measurements as a way to monitor the health of a wind turbine blade with piezoelectric sensors. An array of piezoelectric sensors on a 1m section of a 9m CX100 blade are used as a test structure under the laboratory setting. A full-scale fatigue test of a CX-100 wind turbine blade is also underway in collaboration with Sandia National Laboratory (SNL).

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TEST STRUCTURE AND PROCEDURES: CX100 BLADE

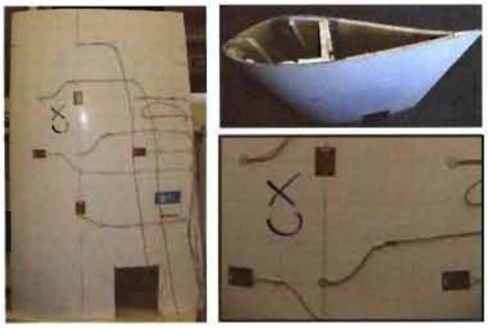

Figure 1. The 1-meter section of the CX-100 wind turbine blade

A 1-meter section of a CX-100 blade [1] was provided by the wind energy group at SNL. This blade section has been instrumented with several piezoelectric active sensors, including nine 0.5" diameter lead zirconate titanate (PZT) patches and four 1.5 x 1 inch macro-fiber composite (MFC) flexible patches. A photograph of the blade section is shown in Fig. 1, along with a view of its cross-section and a close-up of the mounted instrumentation. Simulated damage was introduced by applying some industrial putty (typical size of 2.25 inch^2) to the surface of the blade section. The putty simulates changes in the damping of the structure in a localized area, similar to the effects of delamination formation in composite structures.

SHM TECHNIQUES AND RESULTS

Lamb Wave Propagation

Lamb waves are mechanical waves corresponding to vibration modes of plates with a thickness on the same order of magnitude as the wavelength. The changes in wave attenuation, reflection, or time-of-flight are typically used to detect and locate damage. Various signal processing methods have been proposed to enhance the interpretation of the measured Lamb wave signals to detect and locate structural damage. These methods, which are based on changes in wave attenuations using wavelets, time-frequency analysis, wave reflections and scattering, and time of flight information, are well-summarized in [2].

For our study, after the Lamb wave data were taken from multiple paths in the blade, the time domain data were converted into the frequency domain after applying a band-pass filter. To determine an acceptable variation in the responses, multiple baseline measurements were taken under different boundary and environmental conditions. This bank of baseline responses provides a foundation to compare with the damaged cases. If damaged is induced, the responses converted in the frequency domain potentially depict a distinct change in either the shape or the frequency content of the response signal versus the baseline measurements. Finally, correlation coefficients between the baseline and damaged responses data in the frequency domain were used as a single damage index, which allows for a decision to be made on the structural integrity of the system. One of the experimental results is shown in Fig. 2. In most cases, this method could detect the simulated damage in the test, but only when damage was introduced close to the sensor-actuator paths. This low spatial detectability results from the relatively high damping present in composite structures, which limits the distance the Lamb wave can travel. Furthermore, with the presence of the spar inside of the blade, the selection of the wave frequency was not always straightforward; piezoelectric transducers should be installed in such a way that they can avoid wave scattering caused by the spar.

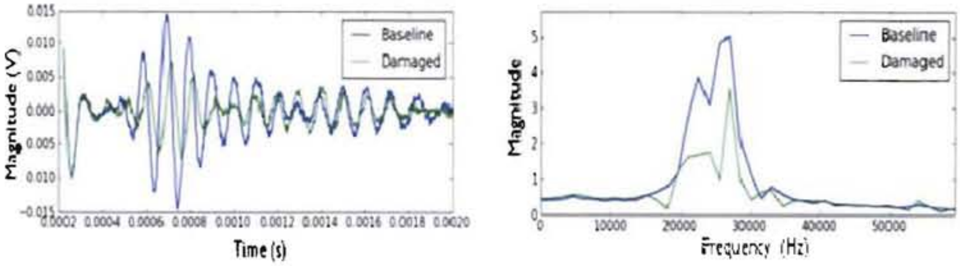

Figure 2. One of the Lamb wave propagations results when putty was applied close to a path.

High-Frequency FRF

The basic concept of high-frequency response functions (FRF) is to use high frequency vibrations to monitor local regions of a structure for changes in the structure's parameters. Damage will alter the stiffness, mass, or energy dissipation properties of a system, which, in turn, results in the changes in the FRF of the system [3]. By utilizing the piezoelectric active-sensors, the FRF could be measured up to hundreds kHz ranges, which allows the method to be sensitive to small defects in the structure and not sensitive to low-frequency operational condition changes.

Initially, the testing was conducted using an input frequency bandwidth of 30-80 kHz on each sensor-actuator combination. One of the experimental results is shown in Figure 3. Although extensive averaging was required to enhance SNR, this method could detect any damaged condition imposed into the blade. With the high-frequency range interrogated and relative high damping present in the structure, the damage localization was also observed, i.e., more pronounced response changes if damage was introduced close to the transducers.

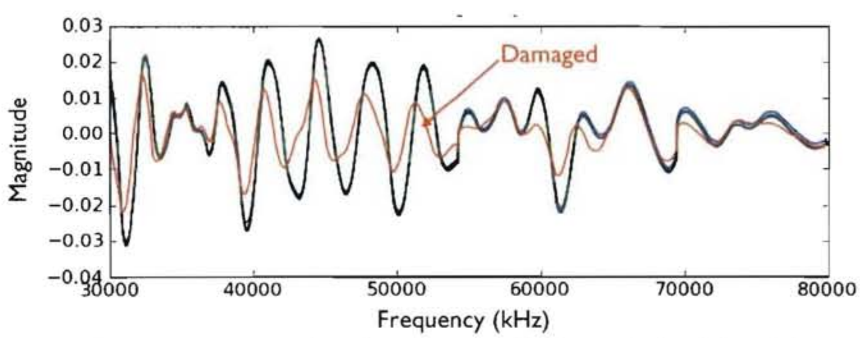

Figure 3. Frequency response functions measured before and after induced damage

Times Series Modeling

Finally, time series predictive models, such as an autoregressive model with exogenous inputs (ARX), can be used as a damage-sensitive feature extractor. An ARX (p,q) model is fit to the data to capture the input/output relationship, which is intended to enhance the damage detection process by utilizing the information associated with a known input provided by a piezoelectric active-sensing system [4]. In SHM, time series predictive models can be used as a damage-sensitive feature extractor based on two approaches: (i) using the residual errors and (ii) using ARX parameters. The first approach consists of using the time series predictive model, with parameters estimated from the baseline condition, to predict the response of data obtained from a potentially damaged structural condition. This approach is based on the assumption either that damage will introduce linear deviation from the baseline condition or that nonlinearities that become present in the structure will be poorly captured by the model. As a result, the linear model developed with the baseline data will no longer accurately predict the response of the damaged system, and the residual errors associated with the damaged system will increase. The second SHM approach involves direct utilization of ARX parameters as damage-sensitive features. A variety of multivariate classifiers can be used to distinguish between the sets of model parameters corresponding to the undamaged and damage classes.

The CX-100 blade section was excited using a chirp signal (10-20 kHz) and sampled at 51.2 kHz. Random excitation signals were also considered, and the results are similar. Results are shown for a healthy and a damaged case in Figure . Note that the relative value of the prediction error increases significantly for signals measured from the altered structure. The RMS values of the prediction errors are also shown as a bar plot for 150 test cases in Figure 4. Test cases 81 through 104, for which the structural change is easily identified, had the putty placed directly in the path of the sensor-actuator pair. In the other test cases, for which the damage was less easily detectable, the putty had been placed outside the path of the sensor-actuator pair.

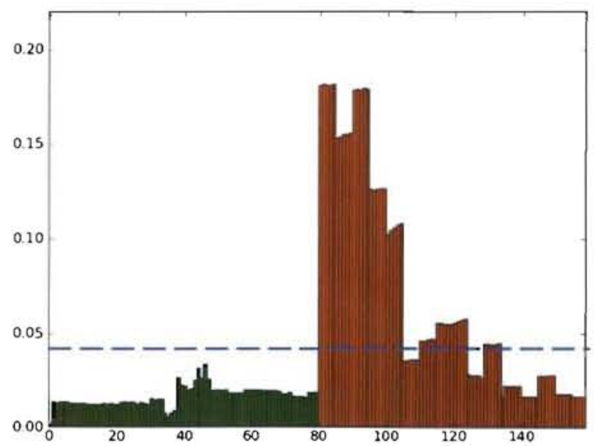

Figure 4. RMS residual error values for 150 test cases

Discussion of Results

Overall, these three methods yielded a sufficient damage detection capability to warrant further investigation into field deployment. Lamb wave testing was capable of detecting damage only when it was close the path of the propagating wave. For this reason, lamb waves could be used to determine the location of the damage. The frequency response method showed an intriguing ability to detect damage when it was located anywhere along the spar of the blade section. This is significant because the majority of the delamination in turbine blades occurs when the skin detaches from the spar. The time series analysis is the simplest of the three techniques and thus the memory and power usage of the system is minimal. This is ideal for a SHM system that needs to be self powered when in operation on a real structure.

CX-100 FULL-SCALE FATIGUE TESTING

At the time of this writing, a full-scale fatigue test of a CX-100 wind turbine blade is underway. The fatigue testing is being conducted by SNL at the National Renewable Energy Laboratory (NREL). An overview photograph of the test setup (courtesy of SNL) is shown in Figure 5. The 9-meter blade was instrumented with eleven 1 x 1.5 inch MFC sensors and one 2 x 4 in MFC actuator. The location of the sensors and the actuator in relation to the blade geometry is also shown in Figure 5. The blade underwent fatigue excitation at 2 Hz for defined intervals, and active-sensing data were collected between sessions while the fatigue excitation source was shut down. These data were collected from the sensing channels at a sampling rate of 60 kHz. Two high-frequency excitation signals were utilized: (1) a 100 to 30,000 Hz chirp signal, and (2) a random excitation signal.

The collected data were fit to an ARX (75, 70) model prior to the start of the fatigue cycling and at each cessation thereafter. The ARX model obtained from the blade in the pristine condition was used to predict the system response from for data collected at testing interval. The standard deviations (SD) of the residual error, which should be close to zero for a well-fitting model, was investigated as a feature to track the progression of structural change over the course of the fatigue test. The SD values of the residual errors calculated at periodic intervals throughout the course of the test are shown in Figure 6. The RMS errors are given for channel 6 on the left side of the figure and for channel 3 on the right side of the figure. Note from Figure 5, that channel 6 was mounted at 0.81 meters, near the root of the blade, and that channel 3 was mounted at 3 meters, where the aerodynamic portion of the blade begins. Based on the significant increase in the RMS value of the ARX prediction error, it is apparent that the structural change is stronger at the root, which is also a high strain region of the blade.

It should be noted that these results are not yet conclusive, as the testing is still in progress. The authors are performing a more thorough data analysis, and the results will be presented in our future report.

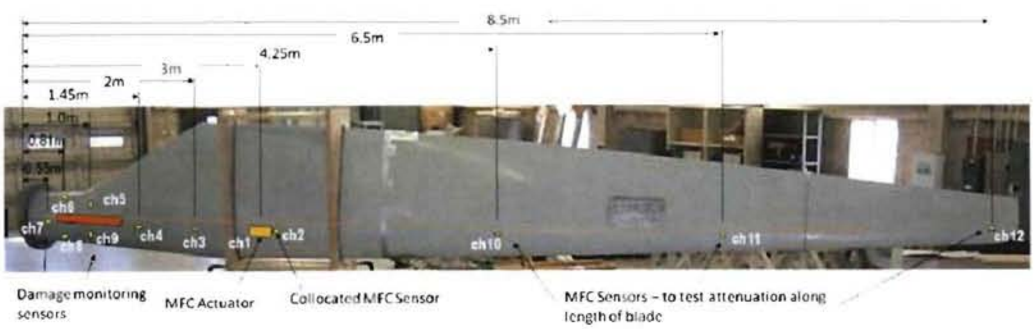

Figure 5. Overview of the fatigue test setup (courtesy of Sandia National Laboratory) A single MFC actuator is used to excite the blade, and 11 MFC sensors are used to measure the signal.

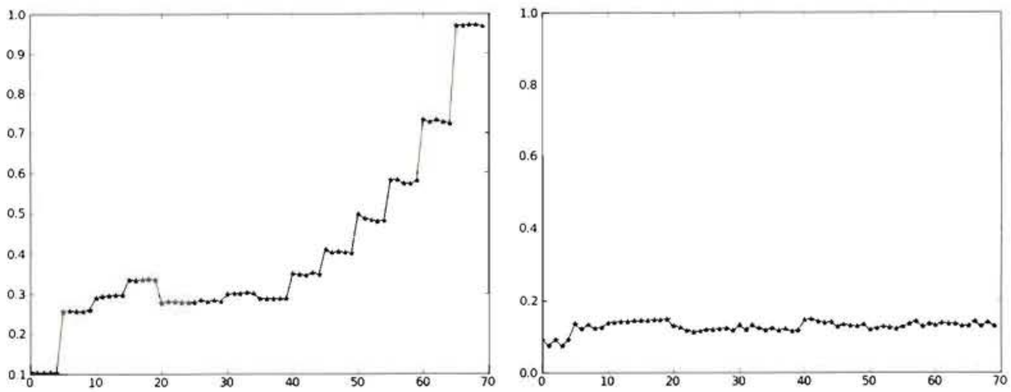

Figure 6.Standard deviation of residual errors for channel 6 (left) and channel 3 (right). Each value represents one test. The data were measured from Jan. 13th to Feb. 18th, 2010.

SUMMARY

This study investigated the several piezoelectric active-sensing SHM techniques, including lamb wave propagations, frequency response, and time series analysis, for wind turbine monitoring. These methods can detect damage, have localized sensing capability, and are less sensitive to operational variations. In order to determine a viable damage detection package for commercial use, actual system testing within operating wind turbine blades needs to be performed. Furthermore, in order to handle real-world turbine blades, future works should focus on the commercialization and implementation concerns (weight, cost, installation, power, etc).

ACKNOWLEDGEMENT

This research was funded through the Laboratory Directed Research and Development program at Los Alamos National Laboratory. The authors also would like to acknowledge Mark Rumsey and Jon White from Sandia National Laboratory for their support and guidance on this study.

REFERENCES

1. Berry, D. (2007). "Design of 9-Meter Carbon-Fiberglass Prototype Blades: CX-100 and TX-100." SAND2007-0201, Sandia National Laboratories, Albuquerque, NM.
2. A. Raghavan, C.E. Cesnik, Review of Guided-wave Structural Health Monitoring, *The Shock and Vibration Digest,* 39 (2007), 91-114.
3. Park, G., Rutherford, C.A., Wait, J.R., Nadler, B.R., Farrar, C.R., 2005, "The Use of High Frequency Response Functions for Composite Plate Monitoring with Ultrasonic Validation," *AIAA Journal,* Vol. 43, No. 11, pp. 2431-2437.
4. Figueiredo, E., Park, G., Farinholt, K.M., Farrar, C.R., "Time Series Analyses of Piezoelectric Active-sensing for Structural Health Monitoring Applications," Journal of Sound and Vibration, submitted