LA-UR- 11-04298

Approved for public release; distribution is unlimited.

Title: A full-scale Fatigue Test of 9-m CX-100 Wind Turbine Blades

Author(s):

Gyuhae (NMI) Park, INST-OFF, LANL
Kevin M. Farinholt, AET-1, LANL
Stuart G. Taylor, INST-OFF, LANL
Charles R. Farrar, INST-OFF, LANL

Intended for: The 7th International Workshop on Structural Health Monitoring, Stanford, CA, Sept. 13-15, 2011

Los Alamos
NATIONAL LABORATORY
EST. 1943

COVER SHEET

Title: *A full-scale Fatigue Test of 9-m CX-100 Wind Turbine Blades*

Authors (names are for example only): Gyuhae Park
Kevin M. Farinholt
Stuart G. Taylor
Charles R. Farrar

ABSTRACT

This paper presents the SHM result of a 9m CX-100 wind turbine blade under full-scale fatigue loads. The test was performed at the National Renewable Energy Laboratory. The 9-meter blade was instrumented with piezoelectric transducers, accelerometers, acoustic emission sensors, and foil strain gauges on the surface of the blade. The blade underwent fatigue excitation at 1.8 Hz for defined intervals, and data from the sensors were collected between and during fatigue loading sessions. The data were measured at multi-scale, high frequency ranges for identifying fatigue damage initiation, and low-frequency ranges for assessing damage progression. High and Low frequency response functions, time series based methods, and Lamb wave date measured by piezoelectric transducers were utilized to analyze the condition of the turbine blade, along with other sensing systems (acoustic emission). A specially designed hardware developed by Los Alamos National Laboratory was also implemented for performance comparison. This paper summarizes considerations needed to design such SHM systems, experimental procedures and results, and additional 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. Monitoring the structural health of the turbine blades is particularly important as they account for 15-20% of the total turbine cost. In addition, blade damage is the most expensive type of damage to repair and can cause serious secondary damage to the wind turbine system due to rotating imbalance created during blade failure. 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.

Gyuhae Park, Kevin M. Farinholt, Stuart G. Taylor, Charles R. Farrar, Los Alamos National Laboratory, USA

The authors have been investigating several design parameters of SHM techniques and the performance of high-frequency active-sensing SHM techniques, including Lamb wave propagations, frequency response functions, and time series based methods, as a way to monitor the health of a wind turbine blade using piezoelectric sensors. In addition, a multi-scale sensing is proposed in order to assess the influence of structural damage on the low-frequency dynamic response of a blade. With the proposed sensing strategy, a series of full scale fatigue tests were performed in collaboration with Sandi National laboratory and National Renewable Energy Laboratory (NREL). This examination is a precursor for planned full-scale deployment of a SHM system an operational CX-100 Rotor Blade to be flown in the field. The first part of the paper shows the results of low-frequency vibration and high-frequency SHM tests. The full-scale fatigue test is still under way at NREL at the time of writing this paper, and some experimental setups are only presented.

VIBRATION TESTS OF THE BLADE

The test structure of a 9-m CX-100 blade [1] is shown in Figure 1. The blade was mounted to a specially designed massive metal frame in a way to simulate a fixed-free condition. First, a roving hammer test was used, employing three shear accelerometers (PCB 352C22) and four piezoelectric transducers (APC, a half inch diameter) and a modal impact hammer (PCB 086D20). The impact hammer tip was selected to excite up to 150Hz, which contains the first several modes. The blade was impacted at several points along the length and chord of the blade in the both flap-wise and edge-wise direction. A total of 4096 time domain data was measured at each time frame with the sampling frequency of 320 Hz. 5 averages were made for frequency response estimation with no window used.


Figure 1. Test setup: a 9m CX-100 blade under a fixed-free condition

The modal test results after processing the measured data are shown in Table 1. The results will be used for model validation studies, which are being performed by the authors' research team. The first several fundamental modes of the blade are also compared to those measured by piezoelectric transducers and accelerometers. The idea behind this test was to use piezoelectric sensors for multiple purposes; the device can be used to detect the onset and monitor the growth of structural damage in the blade using higher frequency excitations, as will be shown in the next section, and the same device can be used for identifying lower-order global modes to assess the effect of structural damage. The fundamental modes measured are shown in Figure 2. As can be seen, the piezoelectric transducers identify the resonant frequencies of a structure with the same accuracy provided by an accelerometer. After the modal test, two saddles were added to the structure to provide a higher fatigue load, which shows in the figure 3. This change in the structural condition significantly modifies the resonant frequencies as shown in the table 1.

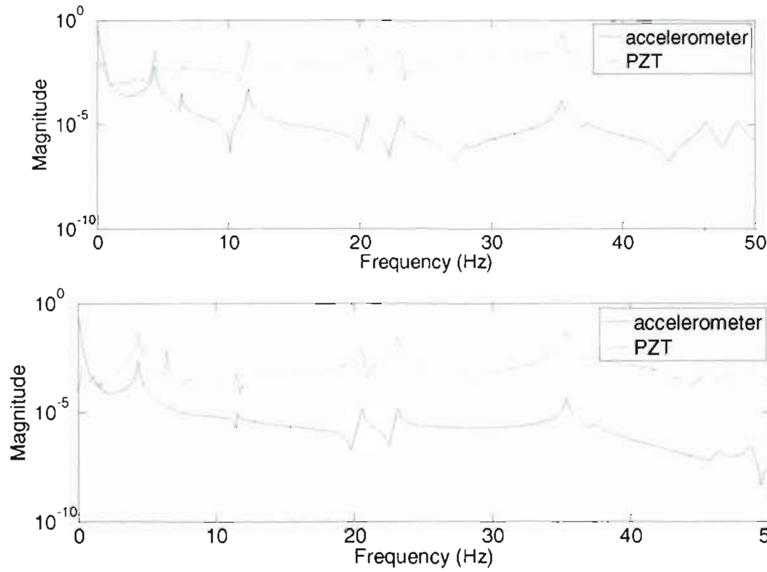

Figure 2: Frequency response functions of the blade up to 50 Hz at two different locations.

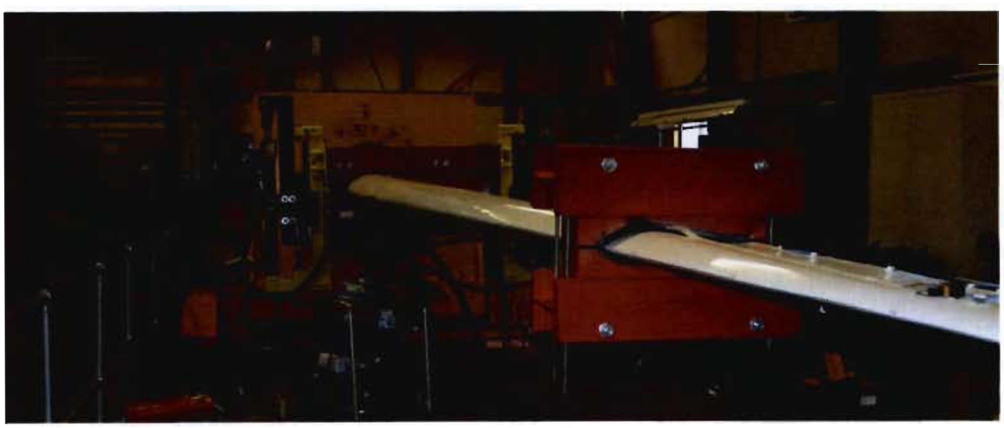

Figure 3: Experimental setup after adding two weights

Table 1: Modal Results for CX-100 Rotor Blade with the fixed-free Boundary Condition

Mode	Frequency (Hz) – before adding weights	Frequency (Hz) – after adding weights	Description
1	4.35	1.82	1st Flap Bending
2	6.43	2.68	1st Lag Bending
3	11.51	9.23	2nd Flap Bending
4	20.54	12.72	3rd Flap Bending
5	23.11	14.68	2nd Lag Bending
6	35.33	18.86	4th Flap Bending
7	46.27		1st Torsion
8	48.64	24.43	3rd Lag Bending

TEST CONFIGURATIONS

The CX-100 blade was instrumented with more than 50 piezoelectric transducers. The location of the sensors and the actuator in relation to the blade geometry is shown in Figure 4. As the fatigue test is still underway at the time of writing, only transducer configurations, SHM techniques, and some baseline measurements are shown in this paper. A specially designed hardware developed by Los Alamos National Laboratory was also implemented for performance comparison.

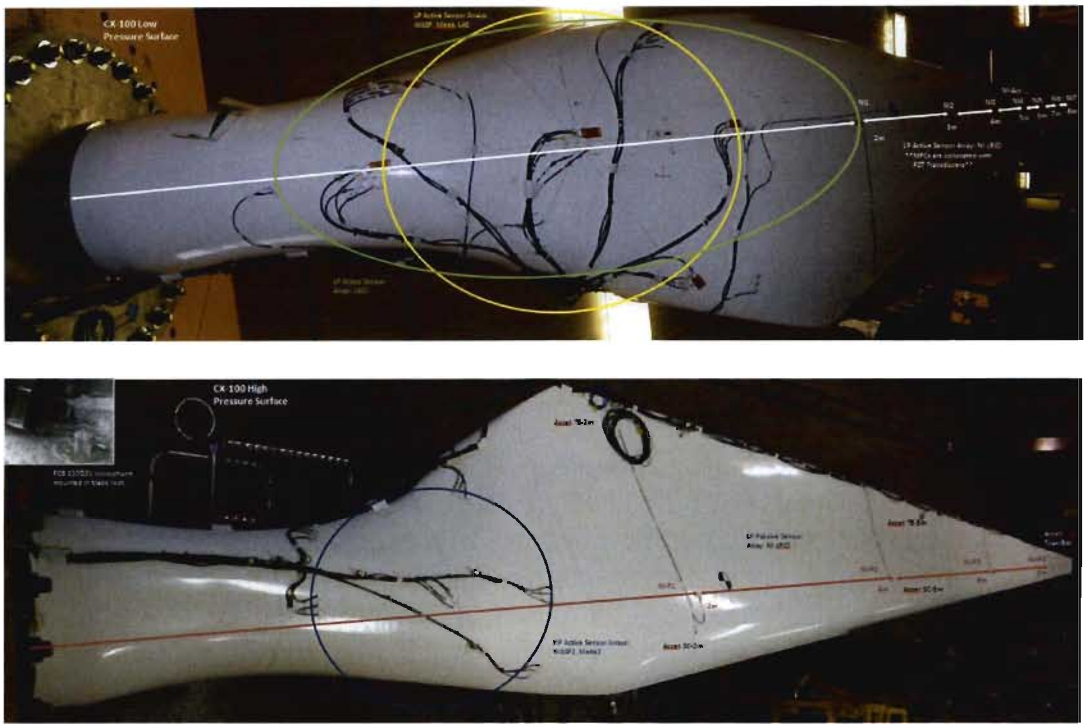

Figure 4: Snapshots of sensor layouts top: low pressure side, bottom: high pressure side.

Lamb Wave Propagations

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 the reference [2]. For our study, the frequency content and amplitude changes of the first arrival wave are used as a damage sensitive feature. It should be noted that, due to a relatively damping, the composite blade has a very limited distance for a Lamb wave to travel. Furthermore, with the presence of the spar inside of the blade, the selection of the wave frequency was not always straightforward. Therefore, multiple frequencies in the range of 50 to 225 kHz were selected as excitation frequencies. The hardware designed by Metis, co was used for acquisition of Lamb waves. The Lamb wave transducers were installed in both the high and low pressure side of the blade close to the root section, with the maximum distance of 0.4 m.

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. By utilizing piezoelectric active-sensors, the FRF could be measured in the range of tens or hundreds kHz ranges, which allows the method to be sensitive to small defects in the structure and not affected by low-frequency operational condition changes [3]. This method has shown the success in our previous studies, where simulated damaged conditions were imposed. In our previous study, this method showed an intriguing ability to localize and 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 test will be conducted using an excitation frequency bandwidth of 0.5 – 40 kHz on each sensor-actuator combination at a sampling rate of 80 kHz. The collected data will then be converted to the frequency domain using FFT for the start of the fatigue cycling and at each cessation thereafter. The FRF obtained from the blade in the pristine condition will be used to predict the system response from for data collected at testing interval. The correlation coefficient or root mean squared deviation (RMSD) between the baseline and a new test data will be used as a feature to track the progression of structural change over the course of the fatigue test. The commercially available DAQ system (B&K) is used for excitation and sensing of FRF. It should be noted that a specifically designed hardware developed by the authors' research team, referred to as Wireless Active Sensing Platform (WASP) is also used for damage detection performance comparison. The same sensor-actuator location used for Lamb waves are employed for this analysis.

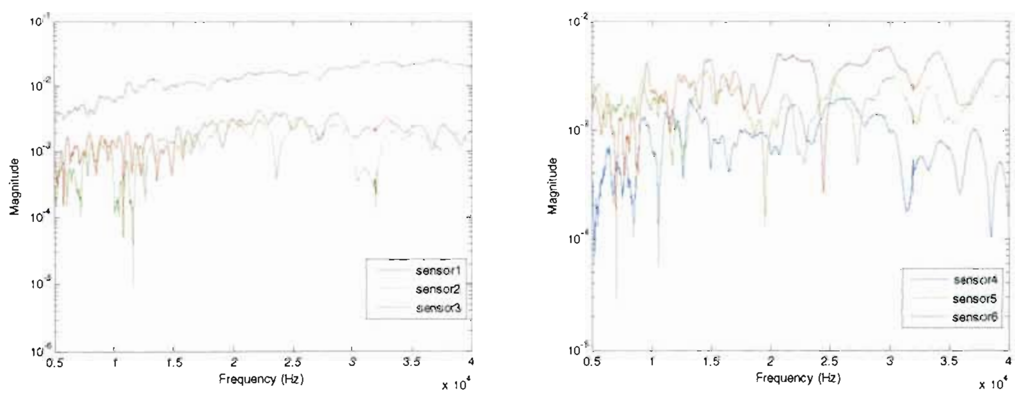

Figure 5 : Frequency response functions data measured by piezoelectric transducers in the frequency range of 5-40 kHz.

Times Series Modeling

Time series predictive models, such as an autoregressive model with exogenous inputs (ARX), are also 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. 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 [4]. A variety of multivariate classifiers can be used to distinguish between the sets of model parameters corresponding to the undamaged and damage classes. The time series analysis is the simplest of the techniques investigated 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.

Sensor Diagnostics using Impedance Measurements

The sensor diagnostic process is one of the most important SHM components as, if there is a response change, one must be able to identify that the change is caused by structural damage or just from a sensor failure. This is especially important for our test as more than two million cycles of fatigue loads are expected to apply to the blade, which adversely affect the installation condition and functionality of piezoelectric transducers. The basis of this method is to track the capacitive value of PZT transducers, which manifests in the imaginary part of the measured electrical admittance. Both degradation of the mechanical/ electrical properties of a PZT transducer and the bonding defects between a PZT patch and a host structure can be identified by the proposed process [5]. This sensor diagnostic process is implemented for this test with an efficient signal processing tools [6], which is not affected by temperature variations or operational condition changes.

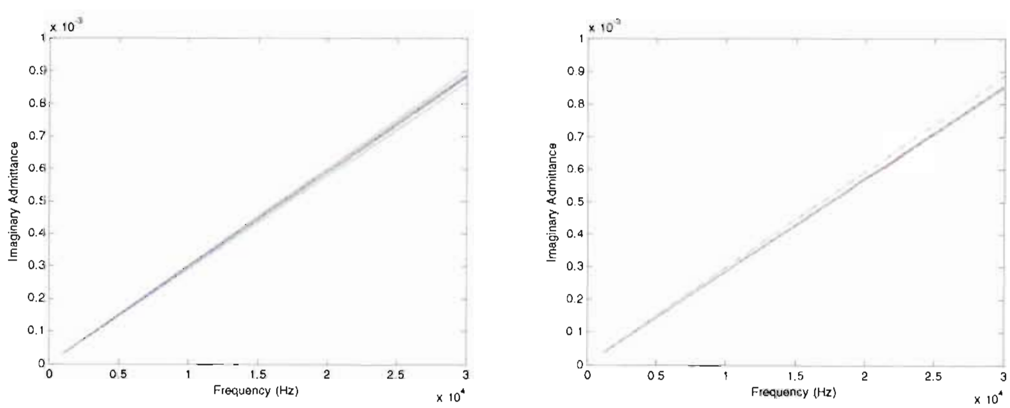

Figure 6: Impedance measurements for sensor diagnostics and validation for selected piezoelectric transducers.

Passive Sensing

The aforementioned active-sensing methods can detect damage, have localized sensing capability, and are less sensitive to operational variations. Another uniqueness of our proposed approach is the dual use of piezoelectric sensors (i.e.

multi-scale sensing); the sensors can detect and locate structural damage using high frequency structural excitation/sensing, and the same sensor can be used to monitor low-frequency response changes, which allows one can estimate the effect of damage on the system level performance. As shown in Figure 4, several piezoelectric sensors were employed along the blade in order to measure the dynamic response of the blade during fatigue load cycle. These piezoelectric sensors are also co-located with accelerometers in order to compare the performance in low-frequency sensing, shown in figure 7. It is expected that, as the fatigue damage initiates and progresses, there will be meaningful changes in the low-frequency response signals. It should be noted that several of these passive sensors are also utilized as active-sensors for exciting and measuring the blade responses at high frequency ranges.

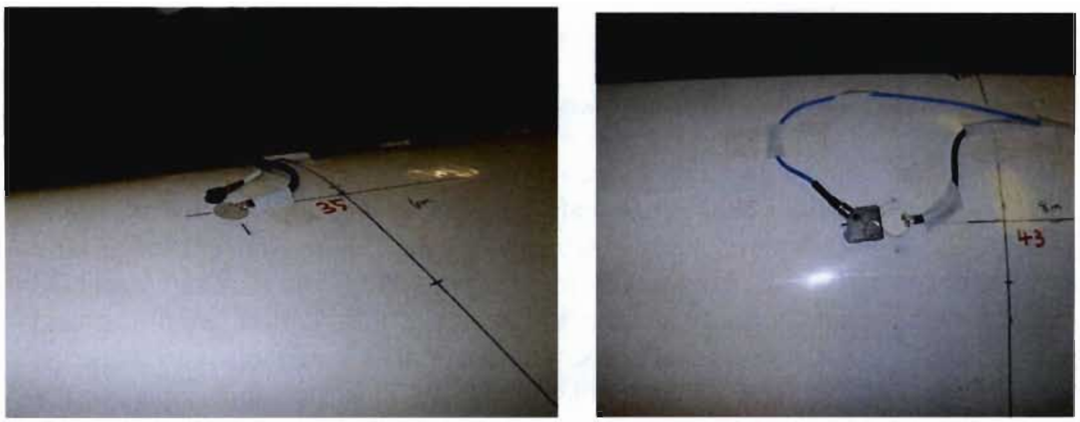

Figure 7: Snapshots of piezoelectric sensors used for passive sensing along with accelerometers for performance comparison

SUMMARY

A full-scale fatigue test of a 9 meter CX-100 wind turbine blade was performed. A multi-scale sensing strategy utilizing piezoelectric transducers were proposed and employed for SHM and prognostic analysis of the blade. These methods can detect damage, have localized sensing capability, and are less sensitive to operational variations. As the fatigue test is still underway at the time of writing, only transducer configurations, SHM techniques, and some baseline measurements are shown in this paper.

ACKNOWLEDGEMENT

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

REFERENCES

1. Berry, D., "Design of 9-Meter Carbon-Fiberglass Prototype Blades: CX-100 and TX-100." SAND2007-0201, Sandia National Laboratories, Albuquerque, NM (2007).
2. A. Raghavan, C.E. Cesnik, "Review of Guided-wave Structural Health Monitoring," *The Shock and Vibration Digest,* 39, 91-114. (2007)
3. Park, G., Rutherford, C.A., Wait, J.R., Nadler, B.R., Farrar, C.R.,"The Use of High Frequency Response Functions for Composite Plate Monitoring with Ultrasonic Validation," *AIAA Journal*, 43, 2431-2437(2005).
4. Figueiredo, E., Park, G., Farinholt, K.M., Farrar, C.R., "Use of Time-domain Predictive Models for Piezoelectric Active-sensing in Structural Health Monitoring Applications," *ASME Journal of Vibration and Acoustics*, in review.
5. G. Park, C. R. Farrar, F. Lanza di Scalea, S. Coccia, "Performance Assessment and Validation of Piezoelectric Active Sensors in Structural Health Monitoring," *Smart Materials and Structures*, Vol. 16, No. 6, pp. 1673-1683, 2006.
6. Overly, T.G., Park, G., Farinholt, K.M., Farrar, C.R., 2009. "Piezoelectric Active-Sensor Diagnostics and Validation Using Instantaneous Baseline Data," IEEE Sensors Journal, Vol.9, No.11, pp. 1414-1421.