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Title: *Passive Damage Monitoring of Wind Turbine Rotor Blades Using Cyclic Signal Processing*

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ABSTRACT

As of Q1 2011, 41,400 MW of wind energy had been installed in the US and those installations are on pace to achieve the US DOE goal of 20% wind energy by 2030. With this increased level of penetration from wind generation, the stability of the electrical grid will become dependent on the reliability of offshore and terrestrial wind turbines. Structural health monitoring (SHM) integrated into the Operations & Maintenance (O&M) strategy of wind plants has the ability to both increase reliability and reduce O&M costs. Sandia National Laboratories Wind Energy Technologies Department (SNL) has been actively researching SHM technologies at the sub-component, component, and full system levels in both computational and experimental efforts for both terrestrial and offshore wind plants. SNL commissioned the fabrication of a Sensored rotor blade during Spring 2008 as a test bed for promising wind rotor monitoring technologies, including strain gages, fiber Bragg gratings, RTD temperature sensors and accelerometers. Following operational testing, the rotor blade was shipped to the National Renewable Energy Laboratory National Wind Technology Center to test structural health monitoring techniques during a fatigue to failure rotor blade test. To understand the structural state of the rotor blade, a method was devised to estimate Frequency Response Functions from the fatigue excitation and response. The results showed that the method for estimating FRFs could be used to monitor the fatigue test magnitude, phase and structural characteristics throughout the 2M cycle test.

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INTRODUCTION

As of Q1 2011, 41,400 MW of wind energy had been installed in the US (approximately 2% of all electric power) [1]. The annual rate of installations is on pace to achieve the US DOE goal of 20% wind energy by 2030 [2]. With this increased penetration of wind in the overall electric generation, the stability of the electrical grid will depend on the reliability of wind turbines. Offshore wind plants will also require increased reliability and reduced operations and maintenance (O&M) costs in order to provide cost competitive energy. Structural health monitoring (SHM) integrated into the O&M strategy of wind plants has the ability to both increase reliability, by automatically and continuously tracking the state of structural health of the plant, and reduce O&M costs, by allowing for control of the damage growth rate and predictive maintenance.

Wind turbines are designed and built with an emphasis on providing the lowest cost of energy delivered to the consumer. This focus leads to many interesting challenges for SHM that are not necessarily encountered in other applications.

First, to minimize the upfront capital costs turbines are built with the lowest possible cost per pound for bulk materials and this leads to relatively high thresholds for manufacturing defects when compared to aerospace applications. Consequently, in some cases, defects have to be monitored as the initiation sites of damage mechanisms, and yet, in other cases, defects do not lead to damage and must be automatically disregarded by SHM systems.

Secondly, the overall monitoring hardware system must be relatively low-cost in order to maintain the goal of low upfront capital costs of wind turbines. Therefore, SHM methods that require high-channel count or high-value hardware are difficult to justify. However, application of these types of intensive SHM systems may be more practical when used in conjunction with global sparse arrays to provide a combined global / local monitoring approach.

Lastly, the SHM system must produce reliable estimates of the structural health (minimize false-positives), while also maintaining high system reliability by not reducing the overall reliability of the wind turbine due to failures of the SHM system itself.

To address these issues Sandia National Laboratories Wind Energy Department (SNL) has been actively researching SHM technologies at the sub-component, component, and full system levels in both computational and experimental efforts for both terrestrial and offshore wind plants [3]. One SHM approach of SNL is to use operational deflection shapes to identify changes to local stiffness that may not significantly change overall global system parameters, such as natural frequencies. Conversely, the intent is to develop a minimalistic system that does not monitor too locally as to require high-channel count arrays. The ultimate vision is for the system to provide damage indicators that would be used to either focus more localized sensor arrays or initiate offline detailed inspections from more traditional non-destructive evaluations. In the following discussion, advancements of methods to estimate operational deflections and frequency response functions (FRF) from forced operations using cyclic averaging are presented.

LITERATURE REVIEW

Wind turbines, particularly those located offshore where access and maintenance costs are high will require SHM systems in order to reach the goal of 20% wind energy by 2030 from reliable and cost competitive wind plants [2]. Smart turbines are envisioned to estimate operational loading, detect damage, and actively adapt to short time constant wind conditions [4,5]. Given these performance objectives, smart rotor blades must incorporate health monitoring techniques that estimate the operational state of the rotor, detect damage, and transmit this information to an active control mechanism in the blade. The monitoring information should also be useful to the turbine operator and designer for maintenance planning and design validation and improvement.

SENSORED ROTOR BLADE

Sandia National Laboratories commissioned the fabrication of the Sensored Rotor Blade during the spring 2007 as a test bed to evaluate promising wind rotor monitoring technologies, including strain gages, fiber Bragg gratings, RTD temperature sensors and accelerometers. A SNL CX-100 wind turbine rotor blade design [6] was selected as the test bed and fabricated by TPI Composites in Providence, RI. Triaxial accelerometers were embedded within the rotor blade at span-wise locations of 0, 1.74, 6.5 and 8 meters along the shear web, as shown in Figure 1a. The rotor blade was thoroughly ground tested at the USDA Conservation and Production Research Laboratory in Bushland, TX and then mounted and operated on a Micon 65/13M wind turbine, as shown in Figure 1b. Details of this work can be found in [3]. Following operational testing, the rotor blade was shipped to the National Renewable Energy Laboratory National Wind Technology Center (NREL/NWTC) to test structural health monitoring techniques during a fatigue to failure rotor blade test, as shown in Figure 1c.

The fatigue test of the Sensored Rotor Blade was performed using the NREL Universal REsonant Excitation system (UREX) located at the max chord of 1.74 m as shown in Figure 1c. This system was composed of mass bearing and load transferring saddles (colored red and yellow), MTS hydraulic shakers (black), and inertial masses (green). The UREX apparatus rests on the rotor blade, which was oriented with the low-pressure (downwind) side facing vertically down, and did not connect to the ground. This configuration and the weight of the UREX equipment resulted in a static deflection that was similar to the deflection produced from steady wind applied to the operational rotor. The rotor blade was cycled about this deflected position by inertial forces generated from the sinusoidal displacement of the inertial masses on the UREX. Reaction forces from the inertial forces were passed through the saddle into the blade and then into the root of the rotor blade, which was fixed to a large reaction mass that was assumed to be a perfectly cantilevered boundary condition. A simple lumped parameter model for vertical force from the UREX resonator, F_1, resulting displacements, X_i, stiffness elements, K_i, and mass elements, M_i is shown in Figure 2. In the following work, experimental data from the fatigue test was used to experimentally assess the steady-state frequency response function of the rotor blade.

(a) (b) (c)

Figure 1. (a) Two triaxial and one uniaxial accelerometers and RTD temperature sensor mounted near shear web termination at the 8 m station during rotor blade fabrication. (b) Sensored rotor blade (white box) mounted atop Micon 65/13 wind turbine at USDA in Bushland, TX prior to operational monitoring. (c) Fatigue test of the Sensored rotor blade by the UREX system at NREL/NWTC.

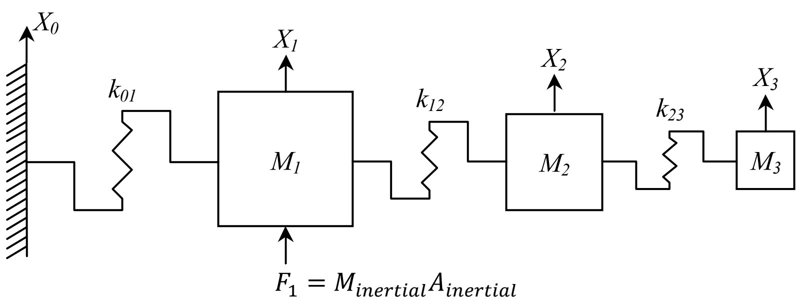

Figure 2. Lumped parameter model for CX-100 rotor blade cantilevered for fatigue to failure test where the UREX resonator is represented by a forced boundary condition applied to degree of freedom 1.

The fatigue test was initiated on January 14 and ended on April 8 of 2010 when the blade had reached approximately 3 million cycles and was damaged to an inoperable extent. The accumulation of cycles is shown in Figure 3a. Throughout the fatigue test, 10 minute recordings were acquired from the array of triaxial accelerometers that were located along the shear web in the rotor blade and on the UREX system. The UREX forced the rotor blade at a single frequency that was retuned every few days. Figures 3b,c illustrate a power spectral density (PSD) estimate of inertial force from the UREX at max chord and the response acceleration at 8 meters, respectively. These figures illustrate the driving force and corresponding response at approximately 2 Hz and then harmonics at 4, 6, 8 Hz, etc. Additionally, the response in Figure 3b shows wide-band energy “humps” between 5 and 15 Hz which were due to the modal response (system resonances) of the rotor blade to the broadband excitation also provided by the UREX. Figure 3b also shows that, by the design of the UREX, the broadband force magnitude of the PSD was many orders of magnitude lower than the force magnitude at the driving frequency of ~2 Hz. Therefore, the remainder of the discussion was focused on estimating and characterizing the force and response of the rotor blade to this single driving force.

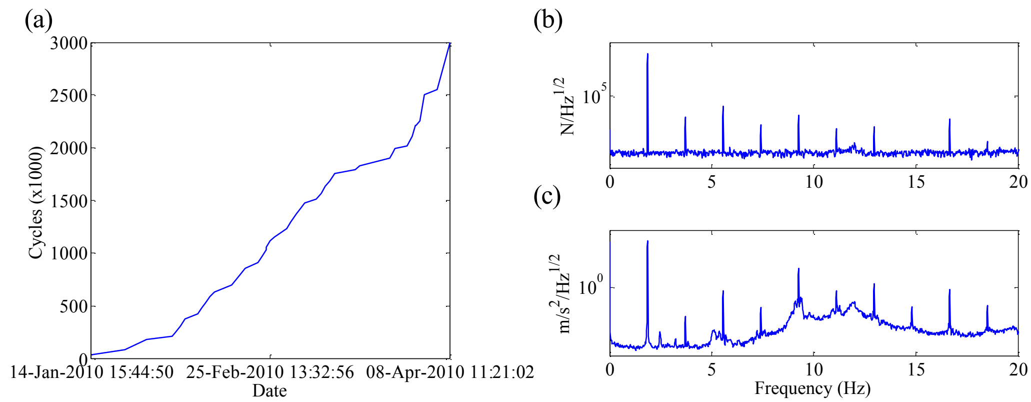

Figure 3. (a) Accumulated fatigue cycles between January 14 and April 8, 2010. (b) Power spectral density function for ten minute recording of inertial force applied at 1.74 meters on January 14. (c) Power spectral density function for ten minute recording of acceleration response at 8 meters on January 14.

In Figure 4a, the inertial force from the UREX (summation of both hydraulic actuators and inertial masses) is shown as a function of fatigue cycles. Initially the force level started at about 1100 N and reduced to approximately 800 N until 1M cycles, after which the force level was incrementally increased every 100-200k cycles. In Figure 4b, the flap-wise deflection magnitude at 1.74, 6.5 and 8 meters is plotted as a function of the number of fatigue cycles. As the load levels were increased from approximately 800 to 1800 N, the deflection response increased from approximately 180 to 260 mm at 8 meters.

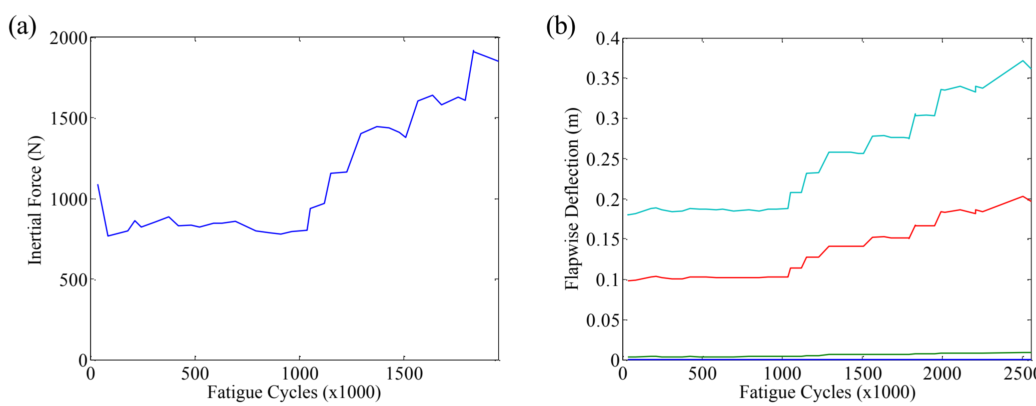

Figure 4. (a) Inertial force as a function of fatigue cycles. (b) Flap-wise deflection at 0 (blue), 1.74 (green), 6.5 (red), and 8 (cyan) meters along the span as a function of fatigue cycles.

To understand the structural state of the rotor blade, a method was devised to estimate FRFs from the fatigue excitation and response. Central to this method were the following assumptions: 1) the fatigue testing consisted of a single driving frequency and harmonics that were recorded in steady state, 2) the rotor blade response was linear and not-temperature dependent, and 3) the driving frequency would not change within a ten-minute recording (although it could vary between recordings).

For brevity the method major steps are shown in Figure 5. First, the inertial force time history was curve fit using the Complex Exponential curve fitting algorithm [7] to estimate the driving frequency, amplitude and phase (damping was assumed to be nearly zero). Second, the results of the curve fitting were used to determine the oscillation vector, i.e. at what point within a full oscillation was each time-digitized data point obtained. Third, the data known as a function of both time and now oscillation was re-sampled in terms of a constant oscillation sample rate (instead of a constant time sample rate). Lastly, the FRF H1 estimator [7] was used for the data re-sampled with a constant oscillation sample rate. This data could be windowed with a rectangular window with minimal leakage due to the rotational re-sampling. Figure 6a shows the estimated driving frequency from the curve fitting as a function of fatigue cycles shift from 1.85 to 1.83 Hz. In Figure 6b the FRF magnitude for a flap-wise response at 8 meters is illustrated with very narrow peaks at the per-oscillation harmonics (1, 2, etc.) and corresponding narrow band unit valued coherence. The coherence indicates that any excitation besides the per-oscillation was not linearly related to the UREX input.

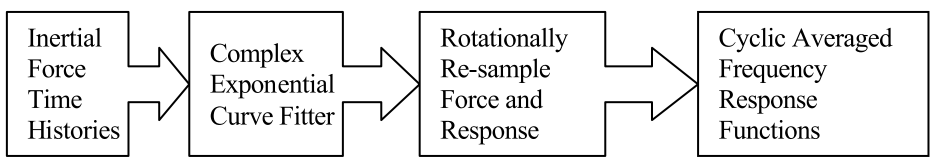

Figure 5. Signal processing steps to generate cyclically averaged frequency response functions.

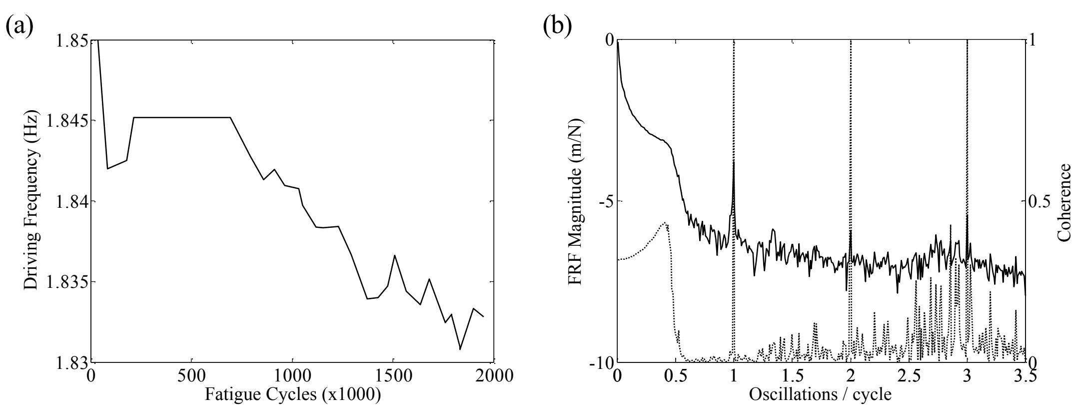

Figure 6. (a) Oscillating frequency of UREX fatigue system. (b) Comparison of FRF magnitude (solid) and coherence (dashed) for first recording of the flap-wise response at 8 meter.

In Figure 7a, the FRF magnitude and phase for flap-wise response at the 1.74, 6.5, and 8 meter stations of the rotor blades at the once per-oscillation frequency are shown as a function of fatigue cycles. These FRFs were only plotted up to 2M cycles because one of the accelerometer cables on the inertial masses broke. However, the FRFs in Figure 7a show a reducing magnitude as cycles increase, particularly between 1M and 2M cycles. The phase was unsteady for the first 800k cycles with a range between 70 and 90 degrees and then reached steady state at 90 degrees after 1M cycles. The span-wise distribution of the FRF magnitude also showed that for the same unit input an increasing response with distance outboard of the UREX was evident, i.e. increasing flexibility towards the tip. Figure 7b is similar to Figure 7a, except that the magnitude of the FRF was smaller by a factor of two (twice as stiff) and the phase was -90 degrees ahead of the inertial force. In Figure 7c, the span-wise FRF illustrated similar patterns to 7a, except that the magnitude was twenty times smaller than the flap-wise stiffness (twenty times stiffer). Lastly, in Figure 7d the FRF between the inertial force and the UREX saddle that transferred force to the rotor blade showed that the magnitude was relatively constant, excluding the range between 200k and 700k cycles where the leading-edge and trailing edge FRFs indicate decreasing and increasing stiffnesses, respectively.

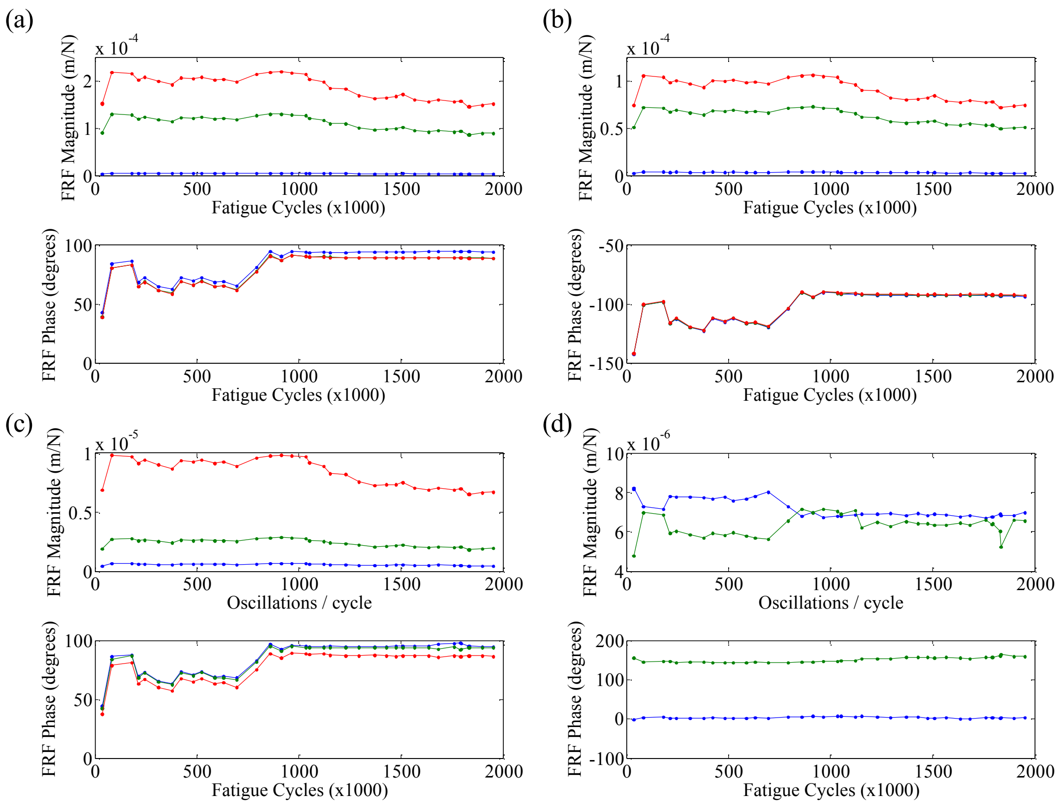

Figure 7. FRF magnitude and phase for once-per revolution frequency in the (a) flap-wise, (b) edge-wise, and (c) span-wise direction at 1.74 (blue), 6.5 (green) and 8 meters (red). (d) FRF magnitude and phase for once-per oscillation frequency in the flap-wise direction at the leading-edge (blue) and trailing-edge (green) UREX oscillator.

The preceding results show that the magnitude and phase of the FRF at the once per oscillation frequency tracked as a function of fatigue cycles is useful for understanding the physical changes that occur to the combine UREX / wind turbine rotor blade system during fatigue testing. For excitation in the flap-wise direction, the edge-wise stiffness was twice and the span-wise stiffness was twenty times larger than the flap-wise stiffness. The flap-wise and span-wise responses were 90 degrees behind and the edge-wise response was 90 degrees ahead of the inertial force. The magnitude of the FRF increased with the span location (i.e. flexibility increased towards the tip). Increasing fatigue cycles led to a reduction in the FRF magnitude in all measurements channels. The explanation for this is either 1) the accumulation of damage that changed the rotor blade structural characteristics, or 2) a nonlinear response to increasing levels of applied inertial force. Lastly, the FRF between the inertial force and UREX saddle remained relatively constant except for the fatigue cycles from 200k to 700k; during these cycles, the leading-edge and trailing-edge saddles became stiffer and softer, respectively.

SUMMARY

SHM systems on operational turbines will assist in meeting targets for wind energy production in a cost effective and reliable manner. To address this, Sandia National Laboratories Wind Energy Technologies Department has been leading the development of SHM system for wind turbines. In this work, an analysis of the Sensor Blade 1 fatigue to failure test was performed. A method to estimate the operational FRF using the inertial actuators was presented and applied to an array of accelerometers distributed throughout the rotor blade. The results showed that the method for estimating FRFs could be used to monitor the fatigue test magnitude, phase and structural characteristics throughout the 2M cycle test. The author would like to thank the staff of NREL/NWTC for their efforts to support the fatigue testing and acquisition of data.

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