DAMAGE DETECTION ON A WIND TURBINE BLADE SECTION

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ABSTRACT. A scanning laser vibrometer and piezoceramic actuators are used for detecting damage on a section of a wind turbine blade. The laser is a non-contact sensor that can measure vibration at a large number of points on a structure over a wide frequency range. Piezoceramic patches are used to generate the vibration without mass-loading the structure. Three different methods are used for detecting damage. The methods are based on changes in transmittance functions, frequency response functions, and operational deflection shapes. Damage simulated by a steel plate clamped to the blade was detected by the three techniques.

NOMENCLATURE
FRF = Frequency Response Function
TF = Transmittance Function
ODS = Operational Deflection Shape
dof = Degree of Freedom
x(t), v(t) = Displacement and velocity vector
f(t), f_0 = Excitation vector and scalar components
\omega_0 = Excitation frequency
Re = Real part
H = Receptance FRF matrix
i = \sqrt{-1}
M, C, K = Mass, damping, stiffness matrices
N = Number of measurement points
h, d = Healthy and damaged structure

1. INTRODUCTION
Fatigue damaged rotor blades can fail and cause catastrophic damage to a wind turbine. In wind farms, aerodynamic interaction between different turbines can cause unpredictable and excessive loads on the rotors. These loads accelerate fatigue damage of the blade. In addition, normal aerodynamic loads and loads due to changing gravity moments cause fatigue damage of the blades. These blades are made from fiberglass, which is a cost-effective material for this application. However, because of the low specific modulus of fiberglass, the blade natural frequencies are low and the deflections of the cantilevered blade can be large. For a design lifetime greater than ten years, the blades accumulate a large number of load cycles and fatigue life is an important design consideration. Predicting the exact fatigue life of a blade is difficult, and it is difficult to tell the extent of fatigue damage that might have occurred to a blade. Thus, a method is sought to determine the condition of the blade and warn of possible failure.

A structural health monitoring system is being considered to detect minor damage sites before they can combine and propagate to cause failure of the blade. The blades can fail near the root section or the third of the blade near the root. Buckling of the surface of the blade at the maximum chord section is one type of failure. The blades may operate for a large number of cycles with little reduction in strength and elastic properties, and then the fatigue damage propagates quickly to failure. Health monitoring of the rotor blades and timely identification of potential failure areas can prevent failure of the entire Horizontal Axis Wind Turbine (HAWT). This would reduce wind turbine life-cycle costs and the cost of energy. The health monitoring technique proposed is to examine the condition of the blades in the field using a low number of man-hours of labor. A condition-based maintenance program using health monitoring information can minimize time needed for inspection of components, prevent unnecessary replacement of components, prevent failures, and improve the availability of power. In addition, health monitoring can possibly allow the use of lighter higher performance blades with less conservative margins of safety.
Various existing techniques [1] including visual inspection, C-scan, laser interferometry, acoustic emissions, and shearography can detect damage in composite rotors. These techniques are labor intensive, or inaccurate, or difficult to use due to measurement noise during operation, or accessibility of the blade is required for an extended time. Currently, a number of techniques are being investigated for damage detection using vibration measurements [2-6]. Vibration measurements might identify damage inside the blade without having to map over the surface of the entire blade with a sensor.

In this paper, three vibration-based techniques are tested to detect damage on a section of a fiberglass wind turbine blade. The concept for health monitoring under investigation here assumes the wind turbine is stopped for the measurements. A Scanning Laser Doppler Vibrometer (SLDV) is used to measure the vibration because it can measure many points quickly without contacting the blade. Piezoceramic patches are used to excite the blade because they are in-situ and convenient to use, the excitation is more repeatable than when using conventional shakers, and high frequency excitation can be used which is more sensitive to damage than lower frequency excitation from wind loading. Also, the piezoceramic patches can be used to detect larger damage during operation of the turbine. The SLDV can be used to detect initiating damage or to investigate in detail damage indicated during operation.

2.0 DAMAGE DETECTION TECHNIQUES

Three methods investigated for damage detection use FRFs, TFs, and ODSs. All the methods are based on using FRFs measured from the SLDV. The SLDV system computes ODSs and FRFs and these are written to a universal file by the SLDV system. The universal file is converted to MATLAB input files which can be read by different algorithms in a damage detection toolbox being developed. The three methods are briefly discussed here.

2.1 Transmittance Function Monitoring

The first method is transmittance function monitoring [7]. Here the technique is specialized for use with a laser vibrometer. The equations of motion for a linear structure with periodic excitation are:

\[ \ddot{X} + C \dot{X} + KX = \text{Re}(f e^{j \omega_d t}) \]  

To solve (1), let \( X(t) = \text{Re}[X(j \omega_d) e^{j \omega_d t}] \) and substitute into (1). This gives:

\[ \text{Re}[AX(j \omega_d) e^{j \omega_d t}] = \text{Re}[f e^{j \omega_d t}] \]  

where \( A = (K - \omega_d^2 M + j \omega_d C) \) is the system matrix, and \( \text{Re}(a+b) = \text{Re}(a) + \text{Re}(b) \) has been used, where \( a \) and \( b \) are some complex constants. Thus, from (2):

\[ X(j \omega_d) = Hf \]  

where \( H = A^{-1} \) is the receptance FRF matrix of the system. The quantity \( X(j \omega_d) \) in (3) is the frequency domain representation of the system displacement response. The system velocity is \( \dot{v}(t) = \text{Re}[V(j \omega_d) e^{j \omega_d t}] \), where the frequency domain velocity response of the system is \( V(j \omega_d) = j \omega_d X(j \omega_d) \). Thus (3) can be written for velocities as:

\[ V(j \omega_d) = j \omega_d Hf \]  

The velocity function given by (4) is used in this testing because the laser vibrometer measures velocity directly, and the velocity FRF is flatter than the displacement or acceleration FRFs. From (4), the velocity frequency response at dof or measurement point \( r \) is:

\[ \dot{v}_r = j \omega_d \sum_{k=1}^N H_{rk} f_k \]  

where \( f_k \) is the \( k \)th element of \( f \), and \( H_{rk} \) is the \( rk \)th element of \( H \). The Transmittance Functions (TFs) are formed as the ratios of the velocity responses at different points on the structure, as:

\[ T_{rs} = \frac{\dot{v}_r / f_0}{\dot{v}_s / f_0} = \frac{\sum_{k=1}^N H_{rk}}{\sum_{k=1}^N H_{sk}} \]  

where \( k = (l_1, l_2, l_3, \ldots, \ldots) \) define the dofs where the forces are applied. The quantities \( h_{r0} = \dot{v}_r / f_0 \) and \( h_{s0} = \dot{v}_s / f_0 \) are the mobility FRFs computed by the SLDV for forces of magnitude \( f_0 \) acting simultaneously at dofs defined by the \( k \) vector. Thus, the TF is computed using the laser data as:

\[ T_{rs} = \frac{h_{r0}}{h_{s0}} \]  

A variance damage indicator between dofs \( r \) and \( s \) is:

\[ d_{rs} = 1 - \frac{\nu_{rs}}{\nu_{rr}} \]  

where

\[ \nu_{rs} = \frac{1}{(f_2 - f_1)} \int_{f_1}^{f_2} \left( T_{rs}^h - \mu_{rs}^h \right)^2 df \]  

and

\[ \mu_{rs} = \frac{1}{(f_2 - f_1)} \int_{f_1}^{f_2} T_{rs}^h df \]  

for the healthy structure. The subscript \( h \) is replaced with \( d \) for the damaged structure. Only \( \nu_{rs}^h \) is stored as

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historical data. The dof corresponding to the peak damage indicator locates the damage, and the indicator is more accurate with symmetric or closely spaced points. An advantage of using TFs is that the excitation force is cancelled and does not need to be measured if it is equal in amplitude at all points where applied. In addition, the ratio of responses partially cancels changes in the TFs due to environmental effects such as temperature changes. Since TFs are ratios of two continuous functions with peaks and valleys, they are quite sensitive to shifts in frequencies or damping caused by damage.

2.2 Frequency Response Function Monitoring
The second approach monitors changes in FRFs to indicate damage. The damage indicator at dofj is:

\[ d_j = \left(1 - \frac{h_{j0}^d}{h_{j0}^r}\right)^2 \]  

The dof corresponding to the peak of the damage indicator locates the damage.

2.3 Operational Deflection Shapes
Operational deflection shapes computed by the SLDV system in the healthy and damaged condition are compared to detect damage. Changes in curvature of the ODSs are used to locate the damage.

3. DAMAGE DETECTION EXPERIMENT
An eight-foot long section of a fiberglass wind turbine blade shown in Figure 1 is used to test the damage detection techniques. The blade section is supported by a rope and elastic cords to prevent rigid body motion and give nearly free-free boundary conditions. The SLDV shown in Figure 2 is positioned about fifteen feet from the blade. Since the laser reflectivity from the bare fiberglass blade was very poor, reflective safety tape was bonded at twenty points on the blade (4 rows, 5 columns) to improve the signal level. The intensity of the reflected laser from the tape was found to be very good. Still, curvature of the blade reduces reflectivity at some points, and small motions of the blade due to ambient vibration in the laboratory causes speckle pattern motion. Thus poor reflectivity occasionally still occurred. Three piezoceramic patches were bonded on the blade, one 2" X 1.5" X 0.02" actuator patch is located at the center length of the blade, and two 2" X 1" X 0.01" sensor patches are located between the center patch and ends. The sensor patches are for use during operational monitoring, and are not used in this experiment. A periodic chirp signal of 200 volts peak is used to excite the blade to perform the FRF computations. The amplitude of the vibration of the blade is small away from the exciter patch, and above about 2KHz the vibration level drops off and the repeatability of the measurements is reduced.

Three tests for the healthy blade were performed. The repeatability of the peaks of the FRFs was reasonably good, and the three healthy data sets are downloaded to MATLAB. To simulate reversible damage, a steel plate 8.5" X 6.2" by 0.75" (~12 lbs.) is clamped to the blade at the edge near dofs 11 and 16, as shown in the left bottom of Figure 1. Two sets of FRF data for the damage case are downloaded to MATLAB. The healthy and damaged raw FRFs plotted for twelve of the twenty measurement points are shown in Figure 3. The damage algorithms are run and the results are reported below.

Translational TFs between dofs 1 and 5, 6 and 10, 11 and 15, and 16 and 20 are shown in Figure 4. For a perfectly symmetric structure and excitation, and no damage, these would be equal to one for all frequencies. The presence of random noise in the FRFs, especially near the non-resonant and anti-resonant points, can introduce false indications of damage. In an effort to minimize the effect of such noise, clipping of FRFs below a small pre-determined magnitude is used in computing the TFs. In this case, all FRFs with a magnitude below 3e-4 are set to this real number. Different clip levels can give different conclusions about the location and magnitude of the damage. The relatively high clip levels used here minimize effect of the non-repeatable and noise in the experiment. From the TFs, the variance damage indicator in (8) is computed and is shown in Figure 5. Damage is indicated near or between dofs 11 and 15. For the healthy case, the variance would be near zero.

The FRF damage indicator is computed using (9) with the same clip level as above. A contour map plotting all FRFs is shown in Figure 6. The small areas of close contours at dofs 16 and 19 indicate the largest damage, and that the damage effect is most pronounced around 1300 to 1400 Hz. For no damage, the contours would be near zero.

Operational deflection shapes for the healthy (1378 Hz) and damaged (1374 Hz) blades are shown in Figures 7 and 8, respectively. The ODS are shown for different phase angles, 40 degrees apart. The different curvature of the two cases indicates damage. The damage was not very obvious for other ODS that are not shown.

4. CONCLUSION
This experiment indicates the feasibility of using piezoceramic patches for excitation and a SLDV to measure vibration to detect damage. Further testing of different damage cases and types is needed. To increase the frequency range of the test and repeatability, a second large patch has been placed on the opposite side of the blade, and a slower periodic chirp will be used. A finer
measurement grid is also being used to more accurately locate damage using curvature TFs.

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REFERENCES
Figure 3. Averaged FRFs, healthy (3 avgs) and with damage (2 avgs)

Figure 4. Transmittance Functions, healthy and with damage (clip level=3e-4)
Figure 5. TF variance damage indicator

Figure 6. FRF damage indicator $|1 - \text{FRF damaged/FRF healthy}|^2$
Figure 7. Operational deflection shapes at 1378 Hz, no damage

Figure 8. Operational deflection shapes at 1374 Hz, with damage