Modes Indicate Cracks in Wind Turbine Blades

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ABSTRACT

On-line surveillance of the structural integrity of wind turbines is a critical need in this currently fast growing industry. The structural integrity of the turbine blades themselves is critical to the continued operation of a wind turbine.

It is well known that the resonant or modal properties of a mechanical structure are directly influenced by its physical properties. Hence, any change in the physical properties of a structure should cause a change in its modal parameters. One question is always apparent though; ***"Do structural faults cause significant changes in a structure's modal parameters?"***

In this paper, we present test results from a wind turbine blade with different cracks induced in it. Each result shows that some of the modes of the blade are significantly affected by a crack, and that the modal parameters change more significantly with a more severe crack. Changes in modal frequency, damping, and mode shape are considered.

Using changes in modal parameters to indicate physical damage to turbine blades should be implemented in the on-line continuous monitoring of wind turbines. In such a system, differences between monitored modal parameters and their ***base-line values*** could be compared to both ***absolute*** and ***percentage difference*** warning levels. Comparing changes between operating and baseline modal parameters with warning levels will indicate when the blades of a wind turbine have undergone physical damage.

INTRODUCTION

It is well known that the elastic modes of a structure are strongly affected by its physical properties and boundary conditions. Its physical properties are summarized in its mass, stiffness and damping properties. Its boundary conditions are influenced by its geometric shape and its physical boundary conditions.

In this study, we tested a single wind turbine blade which was subjected to two types of material failures;

1) Cracks along one edge of the blade.
2) Cracks in the surface of the blade.

The blade was tested in a baseline condition with no cracks, and then with various cracks induced in it. The modal parameters of the blade without cracks were compared with those parameters from the blade with a crack. Modal frequencies, damping, and mode shape comparisons are presented.

MODAL TESTS

The blade test setup is shown in Figure 1 below. Thirteen accelerometers were attached to the surface of the blade, and it was impacting with an instrumented hammer at each end and in the middle. The accelerometer locations are labeled in Figure 2.

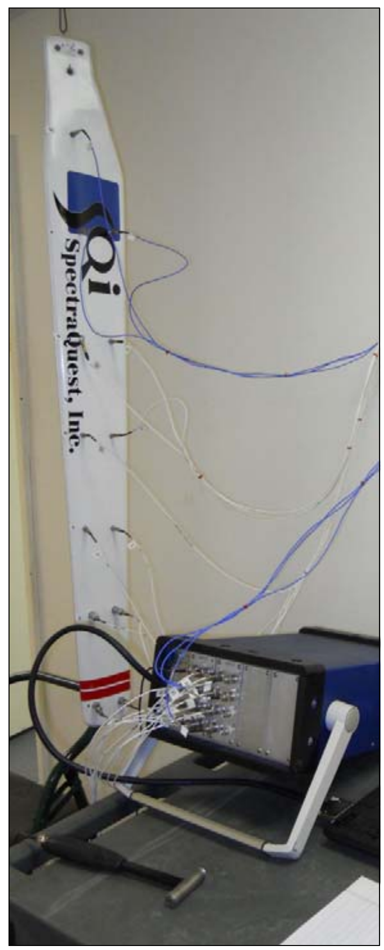

Figure 1 Blade Test Setup.

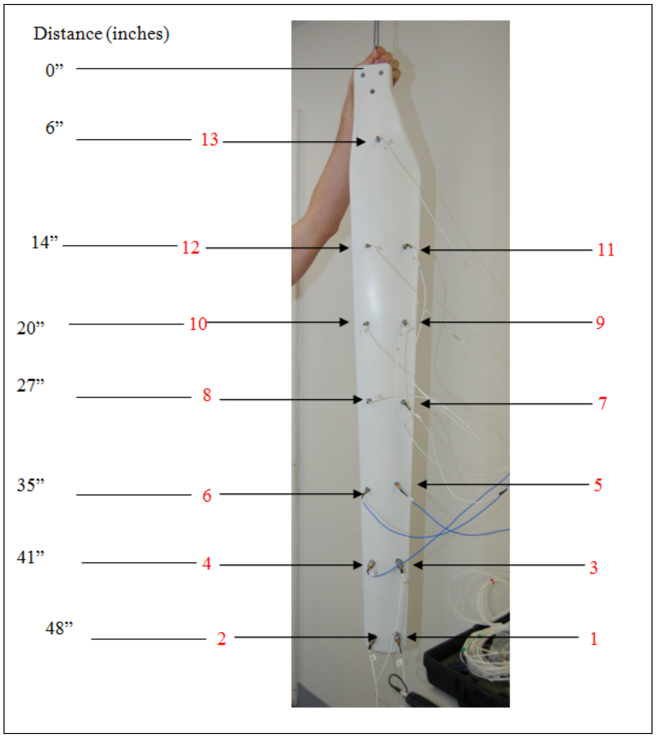

Figure 2 Accelerometer Locations.

During impact testing, time domain records of 64000 samples each were acquired from the impact hammer and 13 accelerometers. Each record contained data from 8 consecutive impacts. Three sets of data were taken by impacting in the middle and at each end of the blade. A typical set of the acquired time records (1 impact and 4 responses) is shown in Figure 3.

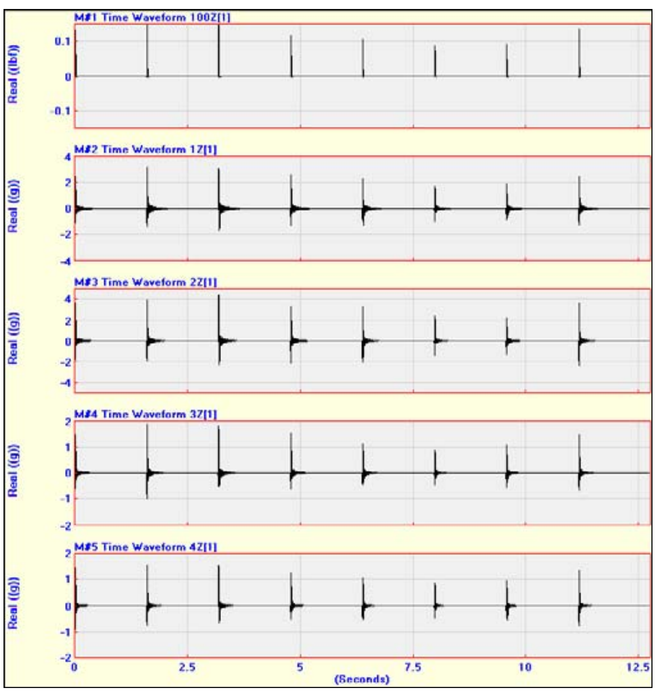

Figure 3 Typical Time Domain Records.

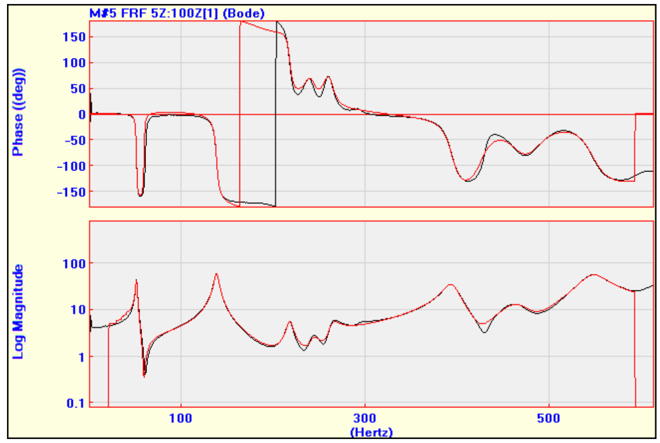

Figure 4 Typical FRF and Fit Function Overlaid.

The acquired time records were post-processed using tri-spectrum averaging (8 averages), with a pre-trigger delay to capture each impact signal and its corresponding responses. FRFs were then calculated from the Auto and Cross spectra. A typical FRF is shown in Figure 4. Each FRF contained 4000 samples of data, over a frequency span (0 to 2563.5 Hz) with frequency resolution of 0.64 Hz. The impact force Auto spectrum dropped off substantially above 800 Hz, so data was only used over the span (0 to 800 Hz).

Modal parameters (frequency, damping, mode shape) were obtained by ***curve fitting*** each set of FRFs. A **red curve fit** function is shown overlaid on the FRF data in Figure 4.

EDGE CRACK TESTS

The first kind of induced blade failure was a series of cracks along one edge of the blade, as shown in Figure 5. Four modal tests were performed so that the modal parameters of the blade with no crack could be compared with the parameters of the blade with edge cracks;

Test 1: No edge crack
Test 2: 5 inch edge crack
Test 3: 10 inch edge crack
Test 4: 20 inch edge crack

SURFACE CRACK TESTS

Following the first four tests, the blade was epoxy’d back together, and a second series of cracks were induced in the surface of the blade. A surface crack is shown in Figure 6. Four more modal tests were performed so that the modal parameters of the blade with no crack could be compared the parameters of the blade with surface cracks;

Test 5: No surface crack
Test 6: 1.3 inch surface crack
Test 7: 2.6 inch surface crack
Test 8: 3.9 inch surface crack

Figure 5 Edge Crack

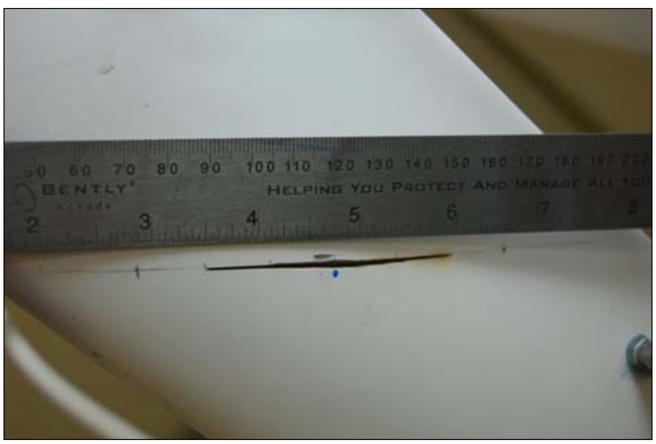

Figure 6 Surface Crack

MODAL PARAMETERS FOR EDGE CRACKS

The modal frequencies obtained from the four edge crack tests are plotted in Figure 7. As expected, the frequencies trend downward with increased severity of the crack. This is because the edge cracks caused a decrease in the blade stiffness.

Modal damping for the four edge crack cases is shown in Figure 8. Most of the ***damping changes from the baseline*** are ***negative,*** except for modes 2 and 3 which are ***positive***. A ***negative change*** means that the crack created ***less damping*** in the mode. A ***positive change*** means that the mode was ***more heavily damped***.

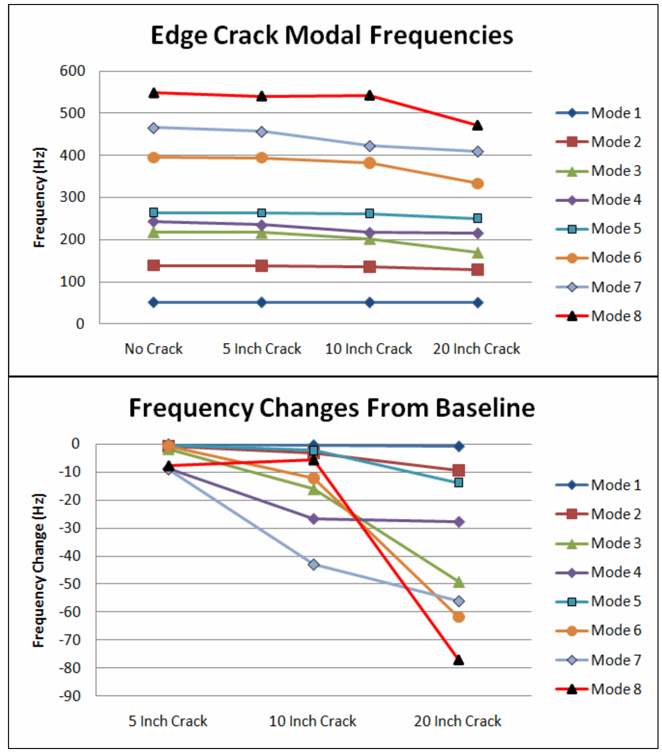

Figure 7

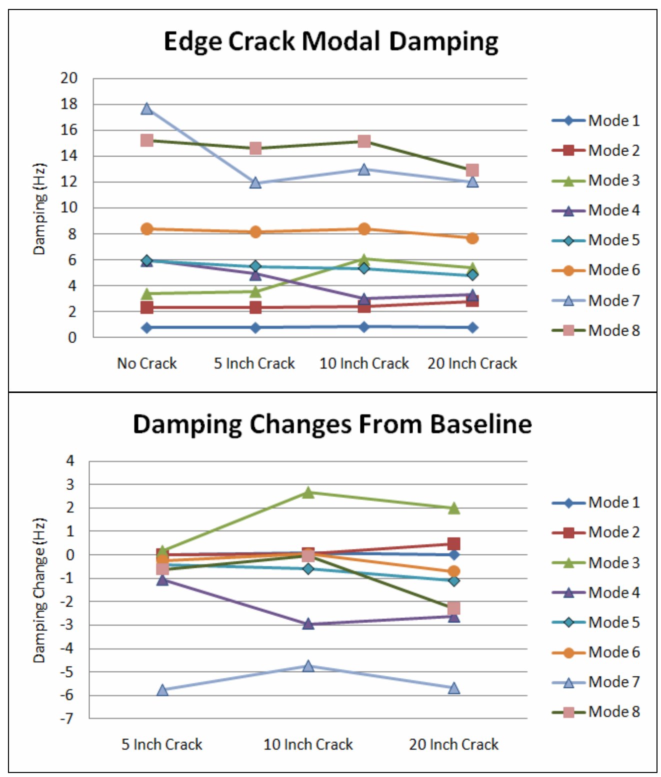

Figure 8

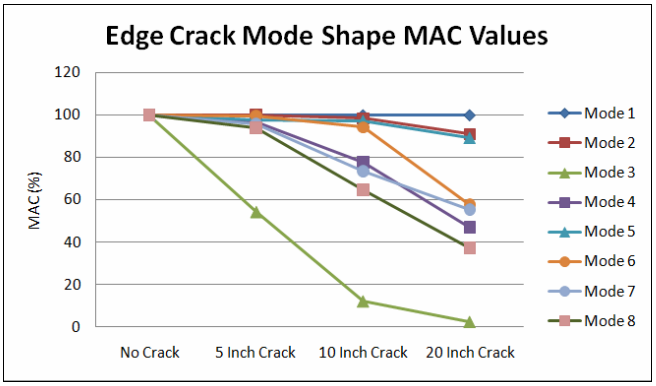

Figure 9

Mode shape MAC (Modal Assurance Criterion) [ref. 3] values for the four edge crack tests are shown in Figure 9. A MAC value of ***100% indicates no change*** in the mode shape.

The MAC values indicate ***little significant change*** due to the 5-inch crack, except for Mode 3. However, the 10-inch and 20-inch cracks caused ***significant changes*** in the mode shapes of several (but not all) modes.

MODAL PARAMETERS FOR SURFACE CRACKS

The modal frequencies obtained from the four surface crack tests are plotted in Figure 10. Most of the frequencies trend downward with increased crack severity, except Mode 4 which trended upward for the 2.6 inch crack. This upward trend was not expected.

Modal damping for the four surface crack cases is shown in Figure 11. All of the damping changes from the baseline are negative, meaning that the surface cracks created ***less damping*** in the blade.

Mode shape MAC values for the four surface crack tests are shown in Figure 12. All MAC values are ***above 98.4%.*** This means that all three surface cracks caused ***very little change*** in the mode shapes.

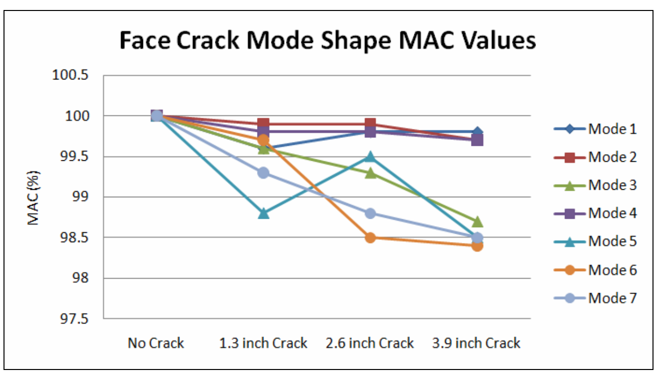

Figure 12

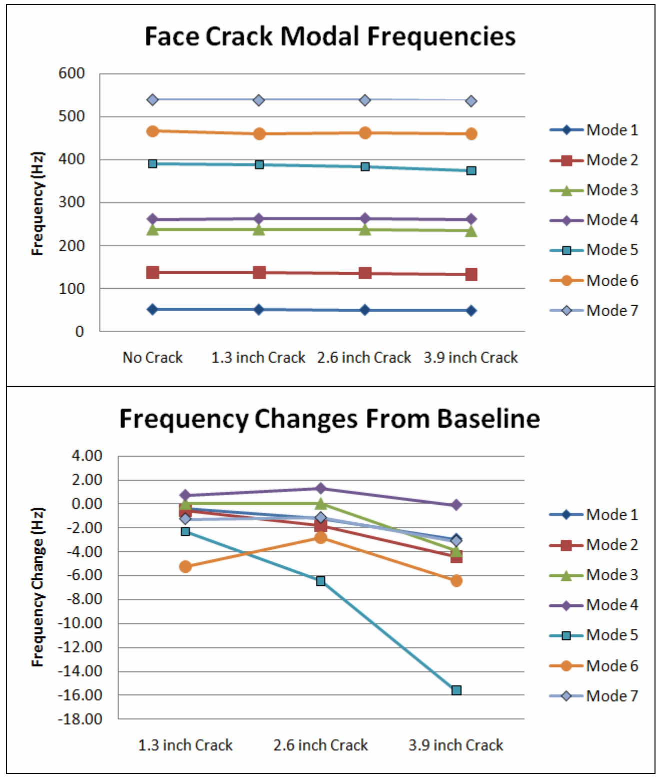

Figure 10

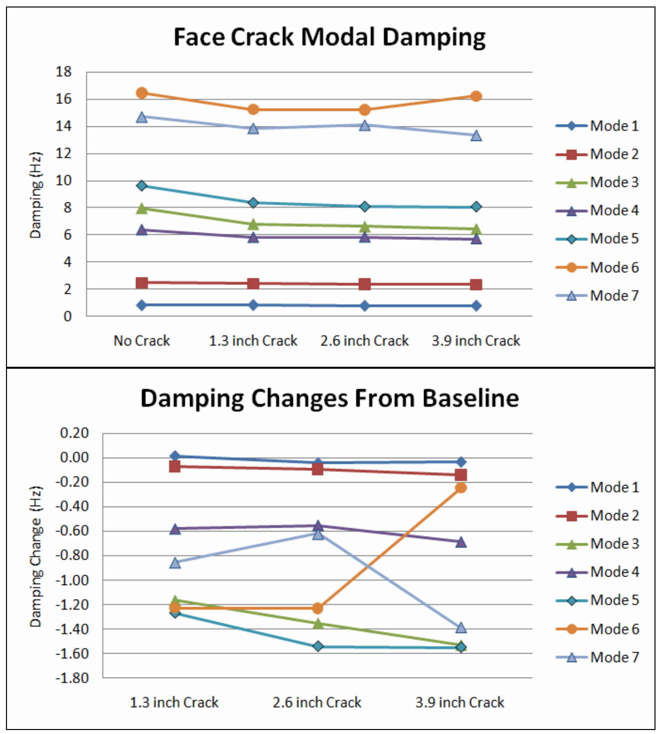

Figure 11

CONCLUSIONS

Eight different modal tests were performed on one of the blades of a wind turbine maintenance trainer and simulator. The blade was approximately 4 feet in length, and was made out of fiberglass. Two types of cracks were inducing into the blade, edge cracks and surface cracks. The purpose of the tests was to determine whether or not ***significant changes*** in the modal parameters of the blade would indicate the presence of a crack.

Thirteen accelerometers where mounted on the blade to obtain an adequate spatial sampling of its mode shapes. The blade was impacted with an instrumented hammer at its ends and its center. In other words, eight different ***three reference*** modal tests were performed on the blade. The acquired data was post-processed and 13 FRFs were calculated for each reference and each test case. Modal parameters (frequency, damping and mode shape) were obtained for the first 8 modes for the edge crack cases, and the first 7 modes for the surface crack cases.

The trend plots of the modal parameters indicated the following;

- The modal parameters of ***modes 1 & 2*** showed ***no significant changes*** due to any of the edge or surface cracks.
- The edge cracks caused ***significant changes*** in ***all*** of the modal parameters of ***modes 3 through 8***.
- The surface cracks caused ***significant changes*** in the modal ***frequency & damping*** of **modes 3, 5, 6 & 7**. The parameters for modes 1, 2 & 4 showed little change.
- The surface cracks showed ***no significant changes*** in the ***mode shapes*** of the first 7 modes of the blade.

Several conclusions can be drawn from this study;

- ***Changes in modal frequency*** were the ***most sensitive*** indicators of the two types of blade cracks tested.
- ***Higher frequency modes*** are ***stronger indicators*** of localized blade cracks than are the lower frequency modes.
- ***Changes in modal damping*** are ***less sensitive*** than modal frequency, but damping did undergo ***significant changes*** in most of the test cases.
- ***Mode shapes*** were ***significantly changed*** by the edge cracks, but changed by less than 2% due to the surface cracks.

In conclusion, these tests showed that monitoring changes in the modal frequency of ***the first seven modes*** may be sufficient to indicate faults in wind turbine blades. Of course, each blade would have to be monitored separately in a wind turbine monitoring system to detect its faults. Moreover, output only Cross spectrum measurements (not FRFs) would have to curve fit, unless the blades were impact tested in the manner similar to the method used here.

Significant changes in modal damping and mode shape also indicated failures in many of these test cases. However, these parameters were less sensitive than modal frequency as indicators of the failures tested.

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