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Application of Damage Detection Techniques using Wind Turbine Modal Data*†

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Abstract

As any structure ages, its structural characteristics will also change. The goal of this work was to determine if modal response data from a wind turbine could be used in the detection of damage. The input stimuli to the wind turbine were from traditional modal hammer input and natural wind excitation. The structural response data was acquired using accelerometers mounted on the rotor of a parked and undamaged horizontal-axis wind turbine. The bolts at the root of one of the three blades were then loosened to simulate a damaged blade. The structural response data of the rotor was again recorded. The undamaged and damage-simulated datasets were compared using existing damage detection algorithms. Also, a novel algorithm for combining the results of different damage detection algorithms was utilized in the assessment of the data. This paper summarizes the code development and discusses some preliminary damage detection results.

Introduction

Being able to detect damage is a prerequisite in being able to monitor the health of a structure. To simulate damage, reversible damage was induced in a wind turbine blade on an installed and normally operating wind turbine in the field. The test machine was an AOC (Atlantic Orient Corporation) 15/50 wind turbine[1]. This wind turbine has a horizontal rotor axis and operates in a downwind (from the tower) configuration. There are three blades on the 15-meter diameter rotor. The wind turbine is rated at 50-kilowatts in 11.0 meter/second winds (24.5 mph) at a hub height of 25 meters (82 feet). The wind turbine is located just outside of Bushland, Texas, at the U.S. Department of Agriculture – Agriculture Research Service facility.

Figure 1 is a photo of one of the three wind turbine blades on the rotor. This vertically orientated blade was instrumented more than the other two blades. A diagram of the nodal (accelerometer) locations on the wind turbine rotor is shown in Figure 2. (Note: Because of a faulty acquisition filter the accelerometers at nodes 4 and 8 were not used.) Nodal points 1 through 10 were located on the vertical blade, nodal points 109 and 209 were at the tips of the other two blades, and nodal point 1000 was at the hub. Most nodal locations, like nodal point 10, had a single accelerometer, oriented in the flap-wise direction (perpendicular to the blade chord plane). Nodal point 9, however, had a biaxial accelerometer set: one accelerometer was oriented flap-wise, the other was oriented in the edge-wise direction (parallel to the

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blade chord plane). Nodal point 1000, at the hub, had a triaxial accelerometer set. There were a total of 16 accelerometers mounted on the rotor. The modal results were reported in a previous paper.[2]

A set of data for the damage analysis was obtained from three different blade conditions. First, a set of modal data was obtained on a "healthy" wind turbine that represented the structure before any bolts were loosened. This set served as the baseline data set. To simulate damage, the bolts at the root of the vertical blade were loosened; this was to simulate a bad hub-to-blade joint. A second data set consisted of a lightly damaged case; the bolts were loosened and re-torqued to 41 Newton-meters (30 ft-lbs) with 0.3 cm (1/8") rubber gasket spacers inserted between the hub and the blade (See Figure 3). The bolts are normally torqued to 271 N-m (200 ft-lbs). The final data set consisted of data from a heavily damaged case. This data set was acquired from the structure after all ten blade bolts were completely loosened and the blade was left hanging by its bolts. In actuality, because of the rotor coning angle and the hub design, the vertical blade was in contact with the hub on the tower side, although all bolts were indeed loose. This contact remained during natural wind excitation.

A simple damage detection analysis based on the frequency shift of two dominant flap-wise bending modes near 3 Hz proved to be inconclusive; so a more extensive analysis was necessary.[3] The implementation of a more extensive analysis is the basis for this paper.

Damage Detection Background

Structural damage detection is based on a comparison between response from a "pre-damage" state and a "post-damage" state. The data can be in the form of a modal response (changes in damping, natural frequency, and/or mode shapes), a static response, frequency response functions, or time histories. The detection algorithms considered here are global methods (i.e., the entire structure is analyzed at once) as opposed to traditional local nondestructive testing (NDT) methods (i.e., the structure is evaluated in small patches). A global method can be used to provide a snapshot of the health of the structure to determine if a NDT analysis is necessary.

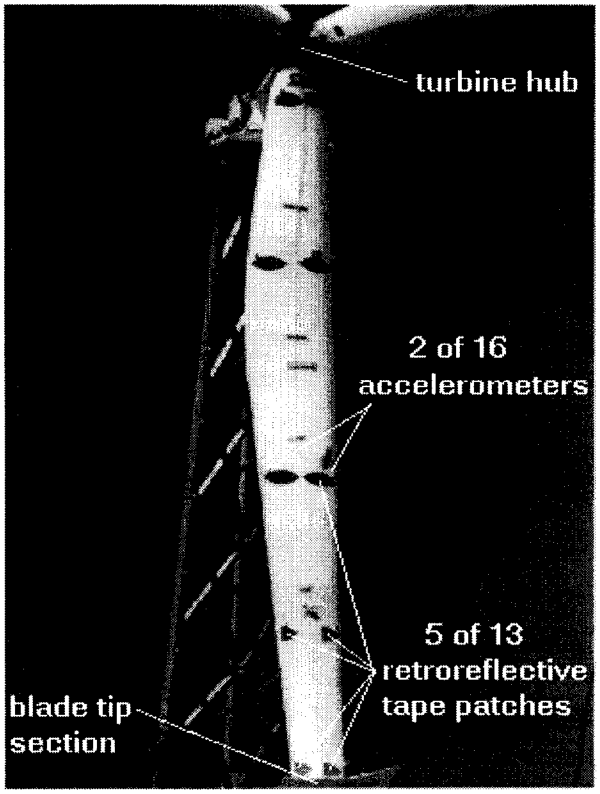

Figure 1. Telephoto view of the vertically oriented blade showing the retroreflective tape patches.

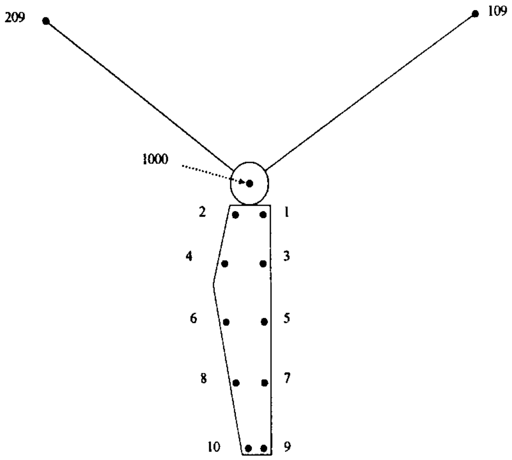

Figure 2. Nodal locations on the wind turbine rotor.

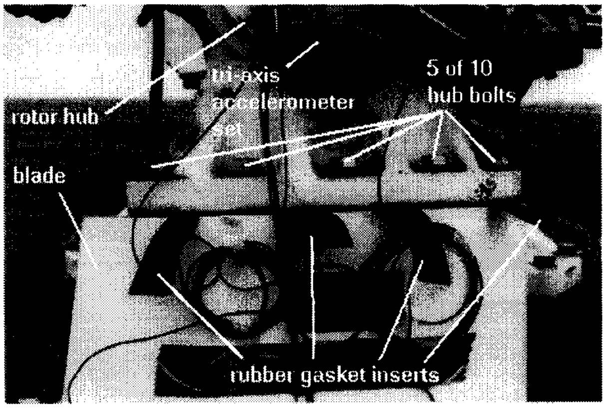

Figure 3. Picture of the AOC 15/50 wind turbine hub-to-blade joint. Note the rubber gasket material inserted between the hub and blade to simulate a damaged joint. The blade chord length at the root is 457 mm (18 inches).

A comprehensive literature review for global damage detection algorithms was performed by Doebling, et al.[4] As a result of this survey a computer program called DIAMOND[5,6] was written. DIAMOND is a toolbox of MATLAB[7] routines that was developed to serve as a framework for the comparative analysis of different damage identification algorithms. This paper describes additional routines that were added to the DIAMOND code, and how the entire DIAMOND toolbox was used to yield damage detection results.

Modal Identification Techniques

In this work, two modal identification techniques were used along with a Ritz vector extraction method. The two modal identification techniques were already implemented in the DIAMOND code. The first is the Rational Polynomial Curve Fit[8], which is a high-order frequency domain technique that uses orthogonal polynomials to estimate the coefficients of a rational polynomial representation of the frequency response function[9]. The second is the Eigensystem Realization Algorithm (ERA) [10], which is a low-order time domain modal parameter estimation algorithm.

The Ritz vector extraction code was added to DIAMOND and was based on the Ritz Realization Algorithm (RRA)[11]. Ritz vectors have been shown to be more sensitive to damage or modal change than the normal mode shapes. The vector identification procedure involves the development of a state-space model of the structural system using time response data. The code written for this work uses the A, B and C state-space matrices calculated in ERA. The first load dependent Ritz vector is the static deflection of the structural system due to a unit applied load. The first Ritz vector is obtained from the solution of

$$\overline{A}x_1 = -\overline{B} \qquad (1)$$

The static deflection, y_1, due to a unit load at the input stimulus location can be determined as

$$y_1 = \overline{C}x_1 \qquad (2)$$

Additional orthogonal vectors are extracted using inverse iteration and the modified Gram-Schimdt orthogonalization procedure[12]. The Ritz vectors are used as mode shapes in the damage detection algorithms.

Damage Detection Techniques

For this study, three damage detection techniques were used. Two of the methods were available in DIAMOND. The basic idea of the first, Strain Energy[13, 14], is the division of the structure into a series of beam or plate-like elements, and then the estimation of the strain energy stored in each element both before and after damage. The curvatures of the mode shapes are used to approximate the strain energy content[9].

The second set of techniques applied is based on changes in the modal flexibility matrix. The flexibility matrix is estimated from the mass-normalized measured mode shapes, $[\Phi]$, and modal frequencies squared, $[\Lambda]$, as

$$[G]=[\Phi][\Lambda]^{-1}[\Phi]^{T} \qquad (3)$$

This matrix is used to estimate the static displacements that the structure would undergo as a result of a specified loading pattern. The Uniform Load Flexibility method[15] involves specifying a unit load at all measurement degrees of freedom (DOF), then comparing the changes in the resulting displacement pattern before and after damage. The Point Flexibility method[16] specifies the application of a unit load at each measurement DOF one at a time, then looks for a change in the resulting displacements at the same point before and after damage[9].

The third technique coded into DIAMOND for this study is the Structural Translation and Rotation Error Checking (STRECH) technique[17]. With this technique, mode shape differences are calculated between healthy and damaged cases. A global comparison of the ratios of these corresponding differences is used to identify the physical locations on the structure where stiffness differences exist between the two cases. STRECH ratios were calculated between each of the two nodes, which make up tracelines of the geometry. (See Figure 4.)

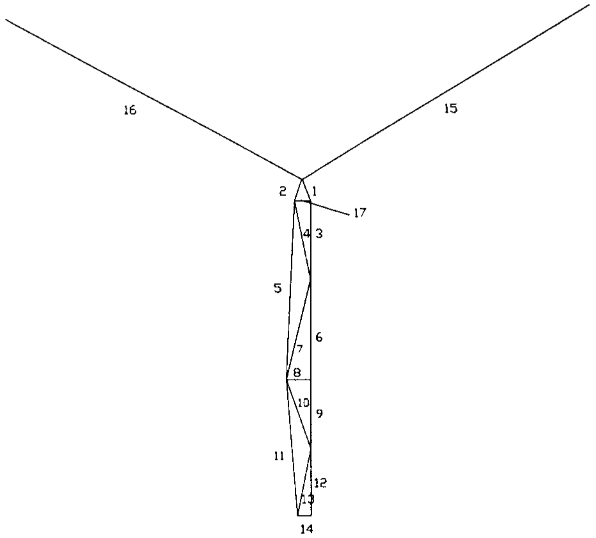

Figure 4. Geometry tracelines used in damage detection algorithms.

To illustrate the simplicity of the concept, consider the displacements of two nodes that make up a traceline. If z_1 is the displacement (in an arbitrary direction; x, y, or z) of the first node and z_2 is the displacement of the second node (in the same direction), then z_{12} is defined as the difference:

$$z_{12} = z_2 - z_1 \tag{4}$$

Two comparison models exist for the same system. One is the healthy model (denoted superscript h) and the other is the damaged model (denoted superscript d). The translational STRECH ratio for each traceline of the three-dimensional geometry is then given by:

$$S_t = \sqrt{\frac{\left(x_{12}^d\right)^2 + \left(y_{12}^d\right)^2 + \left(z_{12}^d\right)^2}{\left(x_{12}^h\right)^2 + \left(y_{12}^h\right)^2 + \left(z_{12}^h\right)^2}} \tag{5}$$

Modified versions of STRECH ratio can include rotations in the structure.

Damage Detection Results

Healthy structure data sets were obtained using both traditional hammer and natural wind excitation. For both damage cases only natural wind excitation data was used due to time constraints during testing. The first two bending modes of the system were the primary modes used for the analysis since they were the easiest to acquire from all the datasets. The two bending modes are being called the teeter and umbrella mode. The teeter mode is characterized by the lower vertical blade moving out-of-phase with the top two blades, and therefore appears to be teetering about the hub. The umbrella mode is characterized by the lower vertical blade moving in-phase with the top two blades. (See Table 1.)

Table 1. Frequencies of first two bending modes.

Mode Shape	Healthy (HZ)	Lightly Damaged (HZ)	Heavily Damaged (HZ)
Teeter	3.18	3.09	2.95
Umbrella	3.73	3.71	3.67

Likewise, for the Ritz vectors, only the first and second vectors were used in damage detection. Once the healthy and damaged modes or Ritz vectors were extracted, they were compared using the previously mentioned damage detection algorithms.

After comparing the healthy and damaged modes and Ritz vectors using the three methods, damage identification was inconclusive.

Since the damage imposed on the structure was thought to be severe, attention was turned to the response data. The auto-correlation functions of the response data were inspected. The auto-correlation functions, which should have real values, contained complex data. The correlation functions should be symmetric -- they were not.

Discussion

The number, or placement, of accelerometers used in the study appear to be inadequate to detect damage; only three accelerometers surrounded the "damage" in the root area of the blade (nodes 1000, 1 and 2). A finite element model of the blade in healthy and damaged cases is now being analyzed to see if more sensors around the root of the blade will allow damage detection.

During testing, the natural wind-excited data sets were recorded using a pre-trigger. It was found that using a pre-trigger during data acquisition could cause a small time shift difference in the various response data sets. This time shift possibly caused the data sets to compare unfavorably.

It may also prove beneficial to take frequency domain power spectrums then convert to the time domain correlation functions instead of obtaining the time domain correlation functions directly.

The lack of damage detection could also be attributed to the method of simulating damage itself. Although all the bolts were un-torqued in the "heavily damaged" case (simulating a damaged hub-to-blade joint), the blade root was still in contact with the hub on the tower side. This resulted in a stiff metal to metal contact on the tower side and one or several bolts pulled tight on the opposite side. Therefore, with the small forces and motions of natural wind-excitation applied, the root connection could have remained quite stiff.

Before damage can be identified using the acquired data, the source of the flawed data must be pinpointed and rectified.

Conclusions

Our results to date have been inconclusive due to a number of factors just discussed, so it is difficult to draw definitive conclusions at this point in time.

Summary

DIAMOND, a good compilation of modal identification and damage detection techniques, initially developed at LANL, has been enhanced with the addition of a Ritz-vector identification code and a STRECH-ratio damage detection code. There has been a considerable amount of work in learning how to apply the collection of techniques in DIAMOND. The authors do believe that the collection of routines in DIAMOND, along with the recently added enhancements, has utility in wind energy technology applications. Work will be continuing with this project.

Acknowledgments

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