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IN-FIELD USE OF LASER DOPPLER VIBROMETER ON A WIND TURBINE BLADE*†‡

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Abstract

One of our primary goals was to determine how well a laser Doppler vibrometer (LDV) could measure the structural dynamic response of a wind turbine that was parked in the field. We performed a series of preliminary tests in the lab to determine the basic limitations of the LDV for this application. We then instrumented an installed parked horizontal axis wind turbine with accelerometers to determine the natural frequencies, damping, and mode shapes of the wind turbine and rotor as a baseline for the LDV and our other tests. We also wanted to determine if LDV modal information could be obtained from a naturally (wind) excited wind turbine. We compared concurrently obtained accelerometer and LDV data in an attempt to assess the quality of the LDV data. Our test results indicate the LDV can be successfully used in the field environment of an installed wind turbine, but with a few restrictions. We were successful in obtaining modal information from a naturally (wind) excited wind turbine in the field, but the data analysis requires a large number of averaged data sets to obtain reasonable results. An ultimate goal of this continuing project is to develop a technique that will monitor the health of a structure, detect damage, and hopefully predict an impending component failure.

Introduction

The failure of a wind turbine blade in the field is usually accompanied by damage to other wind turbine components and sometimes other wind turbines. The event means loss of revenue, loss of equipment, usually negative public relations and, at the very least, a hit on the credibility of the wind turbine manufacturer. It would be advantageous to avoid these outcomes altogether. There will be an increasing need, as a fleet of wind turbines ages, to be able to assess the health of the structures, in particular, the wind turbine blades.

During a blade fatigue test in the laboratory environment there is also the desire to predict the impending failure of a wind turbine blade. Fatigue testing of wind turbine blades can often take over a month to complete. By detecting impending blade failure, monitoring equipment, which cannot be operated for a month at a time, can be enabled just prior to failure to facilitate detailed monitoring of the event.

Currently, the inspection for damage of wind turbine blades involves applying non-destructive testing (NDT) methods such as visual inspection, dye-penetrant or ultrasonics.[1] These NDT techniques are

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very useful in certain situations, but for a large number of wind turbines in the field the techniques become too time consuming, expensive, and generally only look at localized areas on the structure.

What is desired is a technique that could conveniently monitor and predict impending component failure, in particular, a wind turbine blade failure. We are looking for a parameter or signature that will indicate global structural changes. Modal analysis has shown promise in assessing the health of other structures (bridges, aircraft panels, NASA shuttle rudder, space station, etc), and wind turbine blade resonant tests in the laboratory have shown that modal information is useful in assessing the health of the blade.[2]

Modal analysis is an experimental technique used to determine the vibrational (modal) characteristics of a structure.[3] A typical modal analysis test consists of measuring the response at various points on a structure, typically using accelerometers, to a given stimulus input provided by the test personnel. This necessitates access to the structure both to mount the accelerometers and to provide the input.

The Natural Excitation Technique (NExT)[4] is a method that uses an ambient excitation, such as the wind, to provide the input. Using NExT in conjunction with a non-contacting sensor such as the laser Doppler vibrometer (LDV), we are hoping to minimize the setup time for a modal test. This is an important issue when many wind turbines must be tested in a short period of time, as would be the case during a health assessment.

We are investigating the possibility of using a LDV as a remote sensing device to conveniently obtain the modal information of an installed wind turbine. In this paper, accelerometer and field-measured LDV data, which has been concurrently gathered, are compared to assess the quality of the LDV data.

As a field testing platform, we chose a parked Atlantic Orient Corporation (AOC) 15/50 wind turbine[5] that is maintained and operated at the U.S. Department of Agriculture - Agriculture Research Service (USDA-ARS) facility in Bushland, Texas. The horizontal axis, 3-bladed, rigid hub, downwind, free-yaw rotor has a diameter of 15 meters (49.2 feet). The blades are made of wood-epoxy laminates. Each blade was designed to weigh about 125 kg (275 pounds). (The blade tested has a name-plate weight of 305.4 pounds.) The centerline hub height is 25 meters (82 feet). The rotor free-yaws but was manually moved and bolted into a desirable orientation for our tests. The rotor was orientated so the surface being monitored by the LDV was in direct sunlight, a worst case scenario. We chose this wind turbine for no other reason than it was available, conveniently situated for testing, and the winds could almost be guaranteed (a requirement for our NExT tests) at the Bushland site.

To summarize, this paper will detail the initial results of modal tests using conventional accelerometer techniques and an LDV on a non-rotating wind turbine in the field. The paper describes the steps we are pursuing to develop a health monitoring damage detection technique. The issues that will be addressed in this paper are:

1) Can a LDV be used in the field to obtain wind turbine modal information? What are its limitations?

2) Can modal information be obtained from a naturally (wind) excited wind turbine using accelerometers and LDV technology?

3) Can modal information, from either accelerometers or the LDV, be used to detect a damaged wind turbine blade?

Test Descriptions

The tests conducted within this program are described below. The tests include a set of preliminary investigations conducted at our laboratory in Albuquerque, New Mexico, and a series of field tests conducted at the USDA-ARS in Bushland Texas.

Preliminary Test

Our first test was a series of laboratory investigations conducted at Sandia National Laboratories. These investigations were essentially a feasibility study to determine:

1) If useful velocity data can be obtained when the specimen is a large distance away from the LDV?

2) If the system performs well when the LDV and specimen are in direct sunlight?

In these investigations, the laser light path of the LDV was folded back at 30 meters (100 feet) toward the samples. The setup was a "worst case" scenario regarding sunlight, with the sun shining on the sample and on the face of the LDV—a field application might have one or the other situation, but never both. We used various samples including bare fiberglass, bare aluminum, white gel-coat and white paint. We also coated a sample with 3M "Scotchlite" retroreflective tape and paint. This test proved that, at distances of interest for wind turbine monitoring [30 meters (100 feet) or more], we are required to apply a retroreflective coating of some sort. Both the retroreflective paint and the tape gave good signals at angles of incidence up to 45 degrees and distances up to 61 meters (200 feet), in full sunlight.

Bushland Test Series

We collected a total of 13 data sets at the Bushland facility. A diagram of the field test setup is shown in Figure 1. Figures 2A through 2C are a progressive series of snapshots which show our setup and the wind turbine. The snapshot series begins with a far field picture of the setup and ends with a close-up picture of the tip of the vertically orientated wind turbine blade.

The central components of our data acquisition system were a computer and a Hewlett-Packard (HP) analog-to-digital front end. We sometimes used a HP workstation to drive the HP front end, and other times we used a laptop personal computer. Both of these configurations worked well, and the laptop-based system had the added convenience of portability.

We instrumented the wind turbine rotor with Endevco, Inc., model 7751 accelerometers (nominal sensitivity of 500 millivolts/g) at 13 nodal locations. A diagram of the nodal locations on the wind turbine rotor is illustrated in Figure 3. Nodal points 1 through 10 were located on the vertical blade (see Figures 2B and 3), 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 in Figure 2C, 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 blade chord plane), see Figure 2C. Nodal point 1000, at the hub, had a triaxial accelerometer set. (There was a total of 16 accelerometers mounted on the rotor.) Recall that our principal focus in these experiments was to determine how well a laser system can measure useful vibrational data from a wind turbine that is parked in the field. Thus, we used the accelerometers primarily as a diagnostic tool for the test series setup, and to provide a baseline comparison for the laser data.

The laser Doppler velocimeter (also referred to as a "laser Doppler vibrometer") used for this series of tests is an Ometron, Inc., Vibration Pattern Imaging (VPI) Sensor. It measures the velocity of a moving surface by detecting the Doppler shift in frequency of the scattered reflected laser light. The Ometron instrument contains the laser light source (Class IIIa, eye-blink safe), orthogonal mirrors for aiming the laser beam under computer control, interferometric optics for detecting the Doppler shift and electronics for demodulating the Doppler signal and converting it to a voltage (± 10 volts) proportional to velocity. For our purposes, we treated the output velocity signal of the

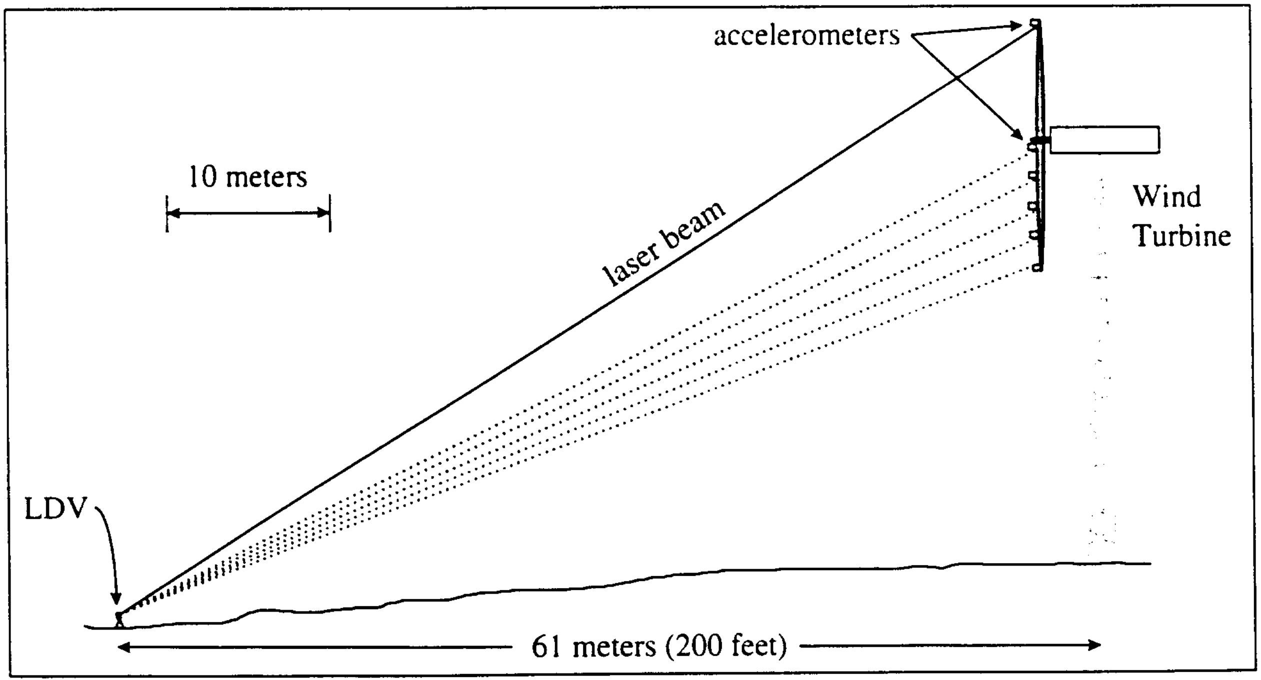

Figure 1. Diagram of the Bushland field test setup, roughly to scale. The view is to the west.

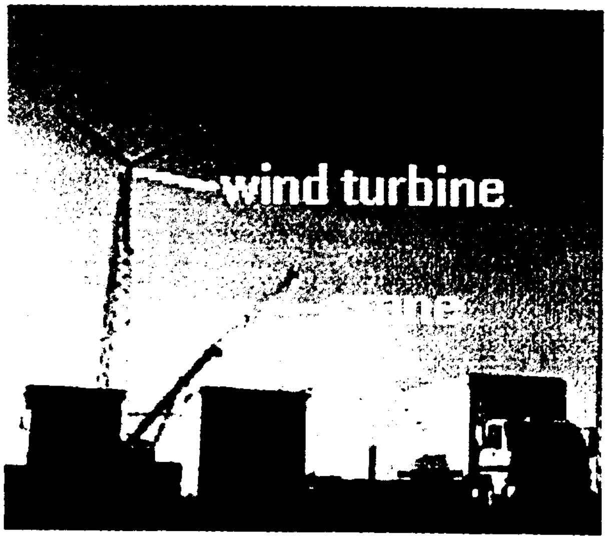

Figure 2A. Bushland test site showing the AOC 15/50 wind turbine and a crane in the background, and the building that housed the LDV (square building in the bottom center of the picture). The crane with a man-bucket was used to gain access to the wind turbine rotor. The computers and remainder of the instrumentation were located in the van on the right.

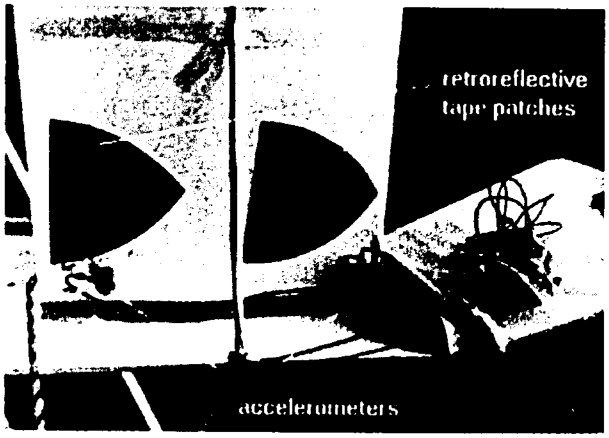

Figure 2C. Close-up view of the tip-brake section of the vertical blade. Note the two retroreflective patches and an accelerometer mounted just below each patch. Nodal location #10 is on the left and nodal location #9 is on the right. The blade chord length at the tip is 406 mm (16 inches).

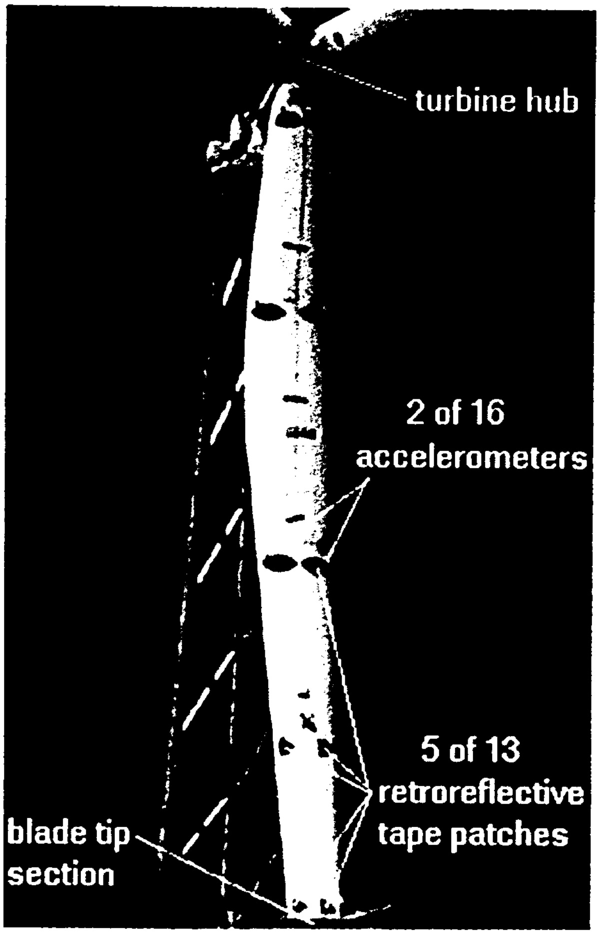

Figure 2B. Telephoto view of the vertical-orientated blade showing the retroreflective tape patches. An accelerometer was mounted adjacent to each of the retroreflective patches.

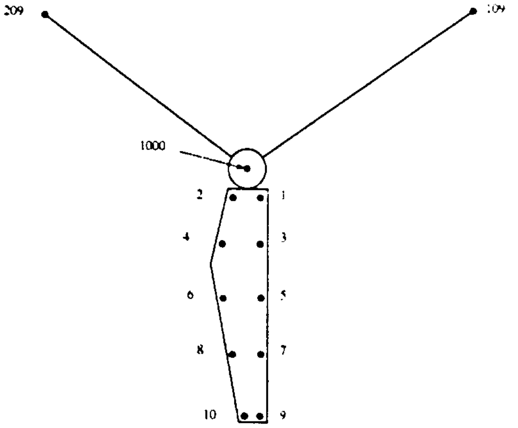

Figure 3. Nodal locations on the wind turbine rotor.

Ometron instrument as just another sensor. The Ometron has three gain ranges: High, Medium, and Low velocity, with a dynamic range of 1.0, 0.1, and 0.01 meters per second respectively. Sensitivity to the laser also varies with range setting, being lowest in the High range setting. (Factory-suggested maximum range, with a retroreflective surface, is 70 m (230 feet) in the High range.) Note that the velocity reading is a *vector* quantity representing velocity *in the direction of the laser beam* (implying this quantity is rarely normal to the surface of measurement and most likely not on the same axis as the matching accelerometer); a geometry correction factor must be applied.

At the USDA-ARS facility, we placed the LDV inside a shed at 61 meters (200 feet) and slightly downhill from the base of the tower. This gave us laser ranges averaging 66 meters (215 feet), with incidence angles ranging from 17 to 26 degrees. We put 3M retroreflective cloth patches adjacent to the 13 accelerometer nodal locations. Figure 2C illustrates this clearly for nodal locations 9 and 10, located at the tip of the vertical blade. Most of the football-shaped tape patches measured 15 by 30 cm (6 by 12 inches), but some near the tip had to be cut down as shown. In our series of tests, we aligned the laser so that it was pointing near the center of a nodal patch on the structure. We experienced some implementation issues in using the LDV system in the field, and these issues and some concerns are more fully discussed in our closing remarks.

We used PCB, Inc., amplifiers to power the on-board amplifiers in the accelerometers and to adjust the individual channel gains. We passed the LDV and accelerometer signals through a rack of low-pass brickwall filters with a cutoff frequency set at 50 hertz (Hz). The signals were AC coupled, and the data was windowed using a Hanning window. Our analysis bandwidth was from 0 to 50 Hz. This resulted in a sampling frequency of 128 Hz and a Nyquist frequency of 64 Hz. The resolution over the 50 Hz frequency band was 801 spectral lines, which gives a sample period of 16 seconds.

Our Bushland test series resulted in a total of 13 data sets. Three data sets are from impact tests, where the structure was excited by a single blow from a 5.4 kg (12 pound) hammer. For these tests, we used a small number of averages (5 to 10) to compute the frequency response functions (FRFs) between the input excitation and resulting output motion. We also computed and recorded coherence functions, and auto and cross spectral densities. The other data sets are from tests where the structure was excited by the ambient wind only (i.e., NExT data). For these tests, we used a large number of averages (100 to 200) to compute and record the auto correlation functions of each sensor and the cross correlation functions of each sensor with respect to a particular sensor, which served as a reference. It is important to note that for some of the 13 data sets, we pointed the LDV at one nodal patch for all averages. For the other data sets, we pointed the LDV at a nodal patch for several averages, and we then moved on to another nodal patch for several more averages, eventually sweeping through all of the nodal patches. A test matrix that illustrates the above comments is shown below.

Impact test LDV pointed at one nodal patch only.	**Impact test** LDV sweeps through all nodal patches.
Natural Excitation test LDV pointed at one nodal patch only.	**Natural Excitation test** LDV sweeps through all nodal patches.

Bushland Test Results

In this section we discuss some results of the Bushland field tests. Our data analysis includes traditional modal analysis and analysis using NExT. One objective in performing the data analysis was to determine how well the structural information obtained from the laser data compared with the structural information obtained from the accelerometer data.

Modal Analysis

We begin by focusing on the data gathered from the impact tests. For these tests, we used a small number of averages to compute the FRFs between the input excitation and resulting output motion. Figure 4 shows a semi-log plot of raw FRF data for an accelerometer and the LDV. The accelerometer trace is from the flap-wise accelerometer located at nodal point 9, and the LDV trace is of the adjacent nodal patch. The LDV velocity signal has been differentiated for direct comparison with the accelerometer data. Frequency is plotted along the horizontal axis and FRF magnitude is plotted along the vertical axis. The accelerometer and LDV traces are in very good agreement throughout the frequency band, with exceptional agreement from 0 to 13 Hz.

Figure 5 shows the complex mode indicator functions[6] (CMIFs) that result when only the accelerometers are considered in the data set, and when only the LDV signals are considered in the data set (the LDV was swept from nodal patch to nodal patch to cover the entire structure). The CMIF is an indication of all of the structural modes within the frequency band—the structural modes correspond to the peaks of the CMIF. This plot illustrates that no structural information is lost if one considers LDV measurements only, provided the LDV is swept such that the structure is sufficiently covered.

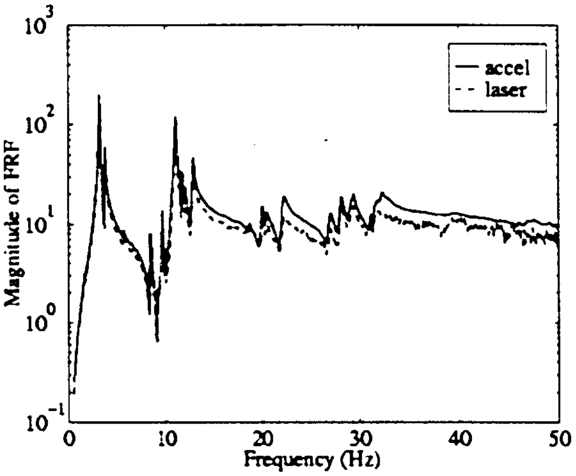

Figure 4. Comparison of Accelerometer and Laser FRF Data.

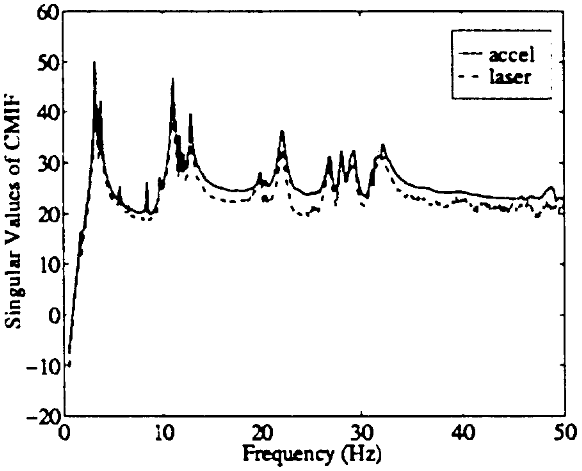

Figure 5. Modal Test Comparison of Accelerometer and Laser (Sweeping) Data.

From a mathematical analysis of the FRFs, we obtained frequency, damping, and mode shape information of the structure. We concentrated on the two large peaks near 3 Hz, and first considered accelerometer FRFs only. We then considered LDV FRFs only, as the LDV was swept from nodal patch to nodal patch.

The analysis shows the first two modes are bending modes in the flap-wise direction, which we are calling 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. Table 1 below lists the frequency, damping, and mode shape information, and illustrates the excellent agreement.

Table 1. Comparison of natural frequency and damping between accelerometer and LDV FRF data for the impact tests.

Mode Shape	Accelerometer Frequency (Hz)	LDV Frequency (Hz)
Teeter	3.19	3.19
Umbrella	3.72	3.72

Mode Shape	Accelerometer Damping (%)	LDV Damping (%)
Teeter	1.18	1.46
Umbrella	1.11	1.16

NExT Analysis

The NExT data analysis was performed using only data from the accelerometers. The resulting natural frequencies and damping ratios are then compared with the results we presented above from the impact test. Again, only the first two bending modes will be considered. Table 2 below summarizes the results of this study. Both the frequencies and damping ratios are well within the expected error for a modal extraction. The frequencies of both modes differ by less than 0.3%. The damping ratios show a larger error, but damping ratios have a larger uncertainty than frequencies. Note that the NExT data produced higher damping ratios in both cases, which is consistent with previous experience.[4]

Table 2. Comparison of natural frequency and damping between impact and NExT data (accelerometer data only).

Mode Shape	Impact frequency (Hz)	NExT frequency (Hz)	error (%)
Teeter	3.19	3.18	0.0
Umbrella	3.72	3.73	0.3

Mode Shape	Impact damping (%)	NExT damping (%)	error (%)
Teeter	1.18	1.58	33.9
Umbrella	1.11	1.27	14.4

There are several concerns with collecting only laser measurements to perform a NExT analysis. First, NExT data analysis typically requires a large number of averaged data sets to obtain reasonable results. This can be time consuming for accelerometer measurements, but the problem is especially compounded if collecting laser measurements only. This is because nodal accelerometer measurements can be recorded in parallel, whereas nodal LDV data must be acquired *sequentially* in time. That is, the LDV must collect a large number of averaged data at a nodal location, and then move on to another location, eventually sweeping through all of the nodal locations. There is an assumption here that the wind is truly random over the large number of averaged data sets. Another concern is that in addition to a data channel, the NExT analysis requires a reference sensor. In this study we selected one accelerometer to serve as a reference channel. If one plans to use LDV data only to collect NExT data, then a reference must also be provided, either via a second LDV system or a single accelerometer mounted to a wind turbine blade.

If many averages of laser data are gathered, a NExT analysis may be fruitful. Below, in Figure 6, we show the cross spectra of accelerometer and laser data at nodal point 10. The accelerometer cross spectrum is computed from 200 averages of the cross correlation function, while the laser cross spectrum is computed from only 10 averages of the cross correlation function. This figure shows that even though we computed many fewer averages of the laser data, the spectral content of the two plots is very similar.

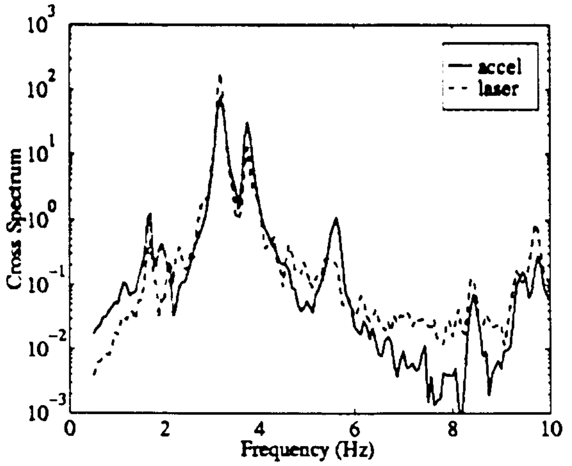

Figure 6. Cross Spectra of Accelerometer Data (200 averages) and Laser Data (10 averages).

Geometry and Stability Issues of the LDV System

One of the main difficulties in this test series was pointing the laser at desired locations. This problem separates into two sub-issues: initial geometry and stability. This LDV was originally purchased as a system, which included test control software implemented on a workstation. This software is capable of taking a known modal "geometry file" and combining that with field measurements of some control points to generate a table of mirror control voltages representing pointing vectors for each desired location. We attempted to use this capability, but we were unsuccessful due to differences between the original geometry file and actual test geometry, and due to difficulty in pointing the laser at the control points. We finally had to point the laser at a known location (we started with the hub), and "walk" the beam to each desired measurement location. We used a Questar, Inc. telescope with fine adjustments on azimuth and elevation to monitor the laser beam location on the rotor—this proved invaluable in this process. When the laser was hitting a retroreflective tape, it was easy to tell where the spot was, but when the spot was on the white gel-coated blade, we could not see it with the naked eye, and it was in fact difficult to see with the telescope. Of course, when the laser beam was not hitting the blade, we could not tell where it was pointing. It took us several hours to generate a table of pointing voltages for the 13 locations on the rotor.

Once the laser was pointed at a given location on the blade, several factors combined to introduce error. Due to either mechanical (e.g., thermal) or electronic effects, the beam wandered a few inches over a few hours time. [Note that a 20 millivolt change in mirror control, the smallest available with this particular system, caused about a one-inch beam translation at the blade, 66 meters (215 feet) away]. After an overnight period (with the electronics turned off), the beam would be displaced up to 30 cm (12 inches), tending to return toward the correct position as the equipment warmed up over an hour or so. The shed has a wooden floor, and if we walked into the shed we displaced the beam several inches, usually causing it to miss the retroreflective tape entirely. (A condition such as one would also encounter if a LDV was used from the back of a instrumentation van.) The parking brake on this turbine is on the high-speed shaft, so gear lash allows the blades to move about 10 cm (4 inches) at the tips, driven by wind. All of these effects combined meant that we had to re-align the laser before each test, and the 15 by 30 cm (6 by 12 inch) tape patches were none too large.

Damage Detection

We intentionally induced reversible damage in the AOC wind turbine blade, with the hope of being able to detect the damage with modal analysis. Being able to detect damage is a prerequisite in being able to monitor the health of a structure.

Damage Detection Background

Structural damage detection is based upon a comparison between some response from a "pre-damage" state to a "post-damage" state. The response analyzed can be 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 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. A complete literature review for global damage detection algorithms was performed by Doebling, et al.

Damage Detection Results

For the damage analysis, we acquired three sets of data on the same day. Damage was simulated by loosening the bolts at the root of the blade. The first set of data was a "healthy" set which represented the structure before any bolts were loosened. This set served as the baseline data set. The second set consisted of a lightly damaged case. We acquired this data from the structure when 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 (Figure 7). The final set consisted of data from the heavily damaged case. This case was acquired from the structure with the blade completely loosened and hanging by the bolts. (The bolts are normally torqued to 271 N-m (200 ft-lbs).)

The frequency analysis showed that there were small frequency shifts for both the teeter and umbrella modes. Table 3 shows the frequency changes for the first two blade-bending modes. The frequencies were extracted from the accelerometers located at the tips of the blades. The frequency shifts are so small that it may be hard to distinguish between a damaged blade and changes due to environmental conditions, test-to-test variations, or differences in analysis techniques.

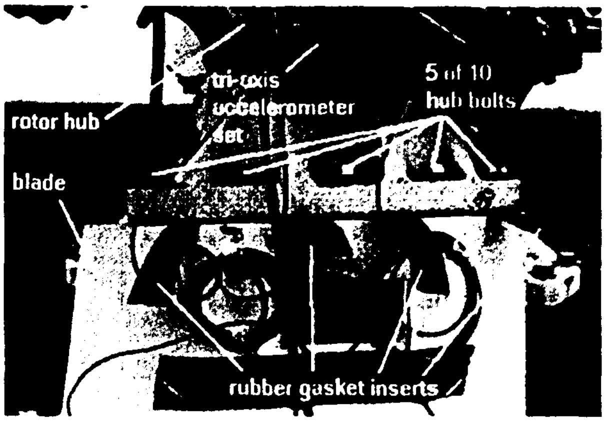

Figure 7. Picture of the AOC 15/50 wind turbine hub-to-blade joint. Note the rubber gasket material inserted between the hub and blade to simulate a damaged joint. The blade chord length at the root is 457 mm (18 inches).

Table 3. Frequency changes due to damage.

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

Conclusions

In the beginning of this paper we presented a few questions regarding the ability of a LDV to acquire field data in the environment of a wind turbine, and to collect wind-excited modal information from a wind turbine. Our findings are summarized below:

1) Can a LDV be used in the field to obtain wind turbine modal information? What are its limitations?

    - The LDV data is adequate for structural testing of wind turbines. However, retroreflective tape or paint is necessary to get LDV data.
    - Determining the LDV initial geometry (target acquisition) is difficult. We need better algorithms, perhaps simpler (PC-based) hardware implementations.
    - LDV drift, both mechanical and electrical, can be a problem. Perhaps dynamic tracking of the retroreflective patch could be

implemented—this would allow smaller patches.

- LDV *sequential* data acquisition requires much longer total data acquisition times than *parallel* acquisition from many transducers (accelerometers). This is especially problematic for the natural excitation technique, which requires many averages for clean data.

2) Can modal information be obtained from a naturally (wind) excited wind turbine using accelerometers and LDV technology?

    - A methodology known as NExT can be used on wind turbines in the field, but the data analysis requires a large number of averaged data sets to obtain reasonable results.

    - In addition to a data channel, the NExT analysis requires a reference sensor.

    - Refer to the fourth bullet in summary question 1.

3) Can modal information be used to detect a damaged wind turbine blade?

    - For damage detection, frequency data alone seems insufficient. However, our failure to detect damage may be because we did not adequately or accurately simulate the damage. More extensive analysis will be necessary.

Summary

We successfully answered several of our initial questions concerning the use of the LDV in the field. The LDV can be used in the environment of, and 61 meters (215 feet) from, an installed wind turbine. We determined the surface being monitored by the LDV must be retroreflective. Bright incident sunlight on the retroreflective surface, however, did not adversely affect the performance of the LDV. While the LDV will work in the field, there were limitations with the existing equipment. Accurately aiming the LDV laser and then maintaining the beam on a point on a surface 61 meters away was a challenge. This limitation does not seem to be major and could be addressed with dynamic tracking methods. Obtaining structural dynamic information from a naturally excited structure, in this case, wind blowing on and through a wind turbine, requires a large number of data averages (10 averages may be too few and 200 averages may be too many). Using a LDV may not be an attractive method for obtaining natural-excited responses because of the length of time required to obtain the data; the LDV acquires data in a single-point-at-a-time mode and the natural-excited (NExT) analysis requires a significant number of averages at several locations. The NExT analysis requires a reference sensor in addition to a data sensor. (A reference sensor ideally sees all the structural dynamics on a structure.) This implies the use of two LDV systems or an accelerometer and an LDV. While the LDV has limitations, it does have the advantage of remotely monitoring a structure. On an installed wind turbine, getting access to the rotor to mount accelerometers and then laying out several long signal cables, can be costly, prohibitive or simply inconvenient.

Our simulation of damage, by loosening the blade-to- hub bolts, did not produce any significant shift in the modal frequencies we looked at. Either there is little information in the modal frequencies (we looked at) or our simulation of damage was not accurate. More work needs to be performed in order to draw any conclusions about damage detection.

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Anthony Gomez, with the Experimental Structural Dynamics Department at Sandia National Laboratories, provided the overall logistics for the field testing; transporting the instrumentation and computers to and from the test site, and setting up and operating the instrumentation.

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