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## Structural Health Monitoring of Wind Turbines

Todd Simmermacher, George H. James III, John E. Hurtado  
Sandia National Laboratories  
Albuquerque, NM

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## ABSTRACT

To properly determine what is needed in a structural health monitoring system, actual operational structures need to be studied. We have found that to effectively monitor the structural condition of an operational structure four areas must be addressed: determination of damage-sensitive parameters, test planning, information condensation, and damage identification techniques. In this work, each of the four areas has been exercised on an operational structure. The structures studied were all be wind turbines of various designs. The experiments are described and lessons learned will be presented. The results of these studies include a broadening of experience in the problems of monitoring actual structures as well as developing a process for implementing such monitoring systems.

## INTRODUCTION

Structural health monitoring, at the present time, is most efficiently developed on a case by case basis. There exists no formulation or technique that will work on all or even many different structures. A hardware specific approach is necessary to determine the best methodology to monitor a class of structures such as wind turbines. Each system has its own methods of revealing damage and "gotch ya's" that need to be determined before an effective health monitoring program can be initiated.

An operational structure is defined as one which can perform, is performing, or has performed its intended function as opposed to a laboratory test article or a computer model. Operational structures are often geometrically complex and may be too large to test in a laboratory. These structures are rarely truss-like and in fact tend to be more plate-like. Also, the boundary conditions associated with such

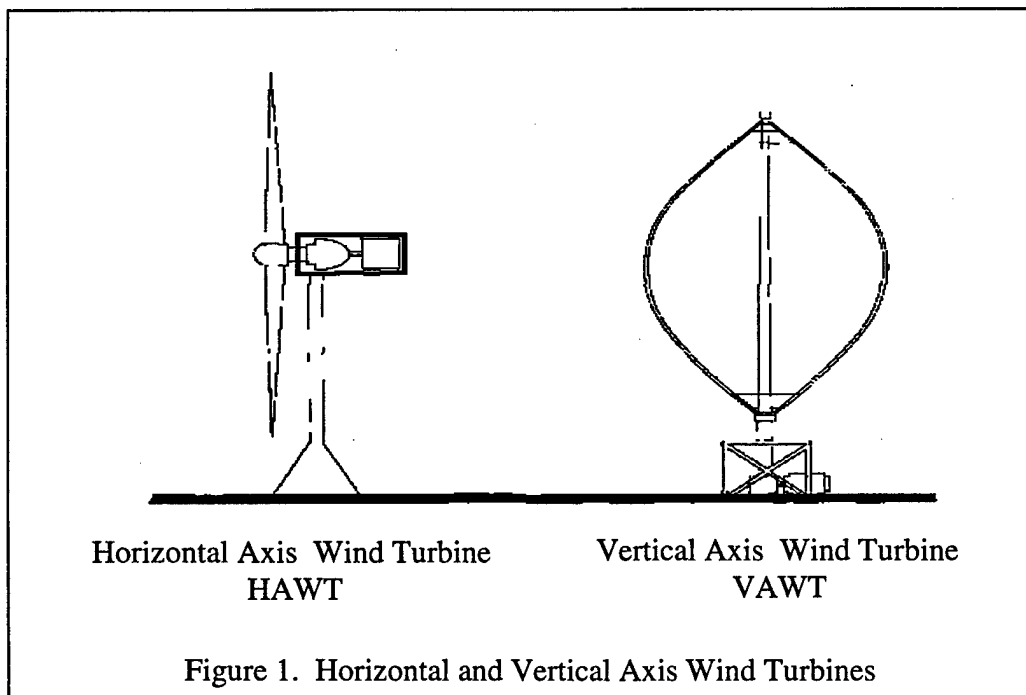
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Todd Simmermacher, Postdoctoral Research Assistant, [twsimme@sandia.gov](mailto:twsimme@sandia.gov)  
George H. James, Technical Staff Member, [ghjames3@aol.com](mailto:ghjames3@aol.com)  
John E. Hurtado, Technical Staff Member, [jehurta@sandia.gov](mailto:jehurta@sandia.gov)  
Sandia National Laboratories, Mail Stop 0557, Albuquerque, NM 87185-0557

structures are not as well known as a laboratory test structure or a computer model. Finally, the environment associated with an operational structure (e.g. weather, traffic patterns, or location) is usually changing and has a serious impact on the measured structural response. Therefore, it is challenging but desirable to perform health monitoring research and development on structures possessing such characteristics.

One structure that has received much attention at Sandia National Laboratory is the wind turbine. It is a good representative structure to describe the systematic approach described in this paper. Also, the wind turbine is a structurally simple structure where the dynamics can easily be physically interpreted. In addition, a failure of a wind turbine blade can have severe consequences, as that can damage other blades, the tower, internal mechanical systems, other wind turbines, or to workers. The failure means loss of revenue, loss of equipment, and usually negative public relations. Therefore there is much interest in the renewable energy community to develop reliable and quick health monitoring systems for wind turbines.

There are two basic types of wind turbines that will be studied in this work. They are identified by the orientation of their axis. The first is the Vertical Axis Wind Turbine (VAWT). This turbine has its axis of rotation perpendicular to the ground, like an eggbeater (Fig. 1). The VAWT is not dependent on the wind direction for its performance. The more traditional propeller style Horizontal Axis Wind Turbine (HAWT), also shown in Fig 1, in contrast, requires the ability to yaw in response to a change in wind direction. The two structures can be studied together since both are basically beam-like, have similar maintenance procedures, have the same operating environments, and are rotating structures.



This paper is separated into four sections. The first section will summarize the concept of operational evaluation. The next section will describe laboratory mock-ups that were used for fatigue and Laser Doppler Vibrometer (LDV) studies. These studies provided information on modes of failures and also gave some insight on some of the modal characteristics of a blade. In the third section, two field experiments will be described. These tests provided experience on testing large structures with low frequencies. In the final section, a field test on a HAWT is described that was performed to study the effectiveness of an LDV in the field and the observability of simulated damage on a blade. This test utilizes much of the experience developed in the other sections. Taken together, these sections address each of the four technology areas which are necessary for implementing a structural health monitoring system: determination of damage-sensitive parameters, test planning, information condensation, and damage identification techniques.

## **OPERATIONAL EVALUATION**

The operation evaluation development has centered around techniques needed to answer two questions in the implementation of a structural health monitoring system:

- 1) What data needs to be acquired to track important structural changes?
- 2) How is this data to be collected in the operational environment?

The answer to these questions can be found by a three step process. The first step utilizes engineered flawed specimens to develop an initial understanding of which parameters are sensitive to the expected damage and to validate the diagnostic measurements. The use of analytical tools such as experimentally-validated Finite Element Models (FEM) can be a great asset in this process.

The next step utilizes damage accumulation testing during which significant structural components of the structure under study are subjected to a realistic accumulation of damage. This may require induced-damage testing, fatigue testing, corrosion growth, temperature cycling, etc. to accumulate certain types of damage in an accelerated fashion. Hence, a study of the relationship between damage level and measured parameters is possible as well as determining initial information concerning sensor placement, data acquisition interval, and, possibly, environmental effects. As with the initial step, a verified analytical model is extremely useful as the available information is increased.

The final step is operational implementation. This step in the process concerns the final selection of sensors, data acquisition, monitoring intervals, excitation sources, and baseline data set. This step deals with the full structure in its actual environment and may require a verified analytical model. Aspects of all three steps in the operational evaluation development process have been studied in this work.

## LABORATORY STUDIES

Before any health monitoring methodology can be implemented, laboratory studies must be performed. Studies on specimens of the actual structure provide insight into failure modes of the structure, help to develop an intuition about the vibrational characteristics of the structure, as well as to help determine what parameters are most sensitive to damage. Studies on engineered specimens, which may or may not be exactly representative of the actual structure, can provide valuable information on instrumentation issues, signal processing algorithms, and damage detection procedures that will be of use on the operational structure. Both types of experiments are described in this work.

## ENGINEERED SPECIMENS

The engineered specimens described in this work were developed for aircraft damage detection. They were used to understand and refine the use of the LDV. Issues that were addressed were data condensation, pointing issues, and also gaining basic experience with this new technology. This work is directly applicable to wind turbines as a potential non-contacting measurement system. Instrumenting an operational wind turbine is a non-trivial task. Through the use of a LDV, a large time savings may be realized. The use of the LDV on an operational wind turbine will be described in the last section of this paper.

The LDV is a non-contacting measurement system that infers the velocity of the target (test article) by calculating the Doppler shift between the incident and reflected laser beam. This device can be used at a larger distance than most other non-contacting measurement systems such as Nearfield Acoustic Holography (Veronesi and Maynard, 1989) or fiber-optic or capacitance displacement sensors. The laser is pointed at the desired measurement points by controlling the voltage signals into the pointing mirrors. This may be done either by a computer or by manually controlling power supplies. By using a computer controller, automatic scanning is possible. The LDV can allow a higher spatial resolution to be realized than would be possible with accelerometers. A disadvantage of the LDV system is that a stationary reference is necessary in order to determine phase information for the Frequency Response Function (FRF). This is typically an accelerometer but could be another LDV system that does not rove over the structure.

Two LDV tests contributed significantly to the health monitoring of wind turbines. The first was a simulated aircraft panel with a cut stringer (Doebbling, 1993). This test provided a look at the capabilities of the LDV system and where it differs from traditional modal analysis tools, i.e. accelerometers. The test compared output from both the LDV system and accelerometers. A study was also performed on the mass loading effects of accelerometers. Comparisons were also made between two damage detection algorithms. It was found that the LDV was capable of accurately estimating natural frequencies, although signal drop-out problems with the LDV prevented accurate mode shapes to be determined. Since the damage detection algorithms studied required mode shape information, accelerometer data

was used for that study. This test initiated later tests on full scale aircraft structures (Robinson et. al. 1996 and Meza, et. al. 1997).

The second LDV experiment to be describe here was performed on five composite plates (James, et. al 1996). The purpose of this study was to try to determine if the LDV was capable of identifying debonded regions of the plates. The debonds were engineered into the construction of the plates. The plates were 24 inches by 24 inches constructed of a 0.5 inch Nomex honeycomb core sandwiched between four ply T300 plain weave graphite cloth panels. The simulated flaws were typical of what is normally seen in composite aerospace structures. This test utilized a white dye penetrant to decrease the occurrence of signal drop-out as was observed in the test described above. This allowed damage detection algorithms to be evaluated directly using LDV data (Meza, et. al. 1996).

These studies provided many lessons in the use of the LDV. Among these lessons are the need for surface treatment to reduce drop-outs, the need for a reference accelerometer to determine phase information, and the need for efficient data reduction and damage identification algorithms to handle the large amount of data that can be gathered using the LDV system (Robinson, et. al. 1996).

## WIND TURBINE LABORATORY FATIGUE STUDIES

Fatigue studies can demonstrate some of the probable modes of failure for a system and provide information on which parameters should be monitored in an operational structure. They also provide data on the history of the propagation of the failure. This information may be of use in predicting remaining life of a structure as fatigue studies provide a direct connection to the mechanics of the materials used in the structure. Predicting remaining life is ultimately the capability desired of any health monitoring system.

There were two fatigue tests performed on composite wind turbine blades. The first experiment was a resonant fatigue test, during which the test article was excited at its fundamental frequency for an extended period of time. This has the effect of increasing the speed of fatigue (which decreases the length of the test) because the large amplitude strains can be induced at a high rate. A FloWind Corporation blade joint from the 17EHD VAWT was the subject of this initial resonant fatigue test (Rodemen and Gregory, 1994). The test article was a 14 foot long section of pultruded fiberglass blade bonded to steel attachment hardware that would bolt to the tower on the actual turbine. Strain gages were placed at 20 locations to monitor stress concentrations and load transfer characteristics. Thirty-four accelerometers were also used for the structural health monitoring.

A modal test was performed to obtain an initial damping estimate. A difficult task in performing the resonant fatigue test was the selection of a proper excitation source. The final configuration had the blade mounted on a vibration slip table and driven by an Unholtz-Dickie Model T-4000 electrodynamic shaker. The test article was excited at the first resonant frequency (initially at 4.3 Hz). Failure occurred after 22,000 cycles as opposed to the 100,000 estimated. A design flaw was found to be contributing to the premature failure. This was subsequently

corrected by the company. There was a simple analytical model of this structure which assisted in test planning and analysis.

The final test was also a resonant fatigue test on a second pultruded fiberglass VAWT blade obtained from FloWind. This 16 foot section was of a newer and lighter design and did not include the root joint. A resonant fatigue test was planned and performed on this specimen. A free-free configuration was used on this test. The difficult issue in the design of this test was the load transfer fixture. The blade was instrumented at seven strain gage locations and with 70 accelerometers. The excitation frequency of 25 Hz resonated the blade at its fundamental frequency. During the course of the test it became obvious that a large-area non-contacting transducer such as an LDV would have been much more efficient than traditional accelerometers which tended to break off of the structure during the high-level excitation. The blade failed after 15.5 hours of testing and 1.325 million cycles. The failure was an axial crack that was not in the highest stress location. The first two bending modes were unaffected by damage while the first torsion mode decreased in frequency all the way to failure. This would be expected for the observed failure. This test also had the advantage of an analytical model for test planning and analysis.

These studies showed the necessity of maintaining a consistent set of boundary and environmental conditions during laboratory studies. This phase of the process was designed to focus on material, structural, signal processing, and data acquisition issues. More specifically, these tests showed that the damage accumulation and failure does not necessarily manifest itself in the forcing frequencies. For resonant fatigue tests, the use of non-contact sensors and long-stroke shakers would be most beneficial. In all cases, the availability of a simple analytical model assisted in test planning, interpretation of results, and damage detection.

## **FIELD TESTING OF WIND TURBINES**

Obviously, an important aspect of developing a health monitoring procedure is developing an ability to test the structure in the field. Wind turbines present a set of special problems that need to be addressed. One problem is that they typically have very low resonant frequencies, with potentially many modes below 10 Hz. consequently the problem becomes one of excitation. Three methods of excitation have been used: step relaxation, wind excitation, and impact. Another problem is one of instrumentation. Instrumenting a structure which can be as tall as 110 m with accelerometers and all the required cabling can be difficult at best. Two tests are described in this section. The first is a research two meter VAWT which was developed by and tested at Sandia National Laboratories (Carne, et. al., 1988). This turbine was tested both in a parked and in an operating condition. The other turbine is the 110 m EOLE VAWT (Carne, et. al, 1989). This test was performed in a parked condition.

There were two objectives in testing the Sandia two meter research turbine. The first was to verify a Finite Element (FE) code that was developed to calculate

mode shapes and natural frequencies of a rotating VAWT. The FE code included the tension stiffening, centrifugal, and Coriolis terms necessary for a flexible body in a rotating reference. The code was developed in the NASTRAN DMAP (MSC/NASTRAN, 1981) language which allowed these effects to be included in a NASTRAN model. This simplified code development by eliminating the need to write a completely new code.

The second objective of this test was to explore techniques of testing rotating VAWTs. The turbine was tested in a parked and in a rotating configuration. The parked test consisted of 22 accelerometers and was excited using an impact excitation on the tower and on the blades. The modes were lightly damped and measured up to 60 Hz. The rotating test was performed using two accelerometers and seven strain gages. The signals were transmitted through slip rings on the tower. To excite the rotating blades, a method known as step-relaxation was used. This method consists of a pretensioned cable between the tower and a blade with a force transducer and a quick release mechanism on the cable. When the cable is released, a step function is imparted on the system which is measured by the force transducer. Although this method applied force only in the plane of the blades, out of plane modes were excited due to coupling from the Coriolis force. The blade was tested at different rotational speeds from 100 to 600 rpm.

These experiments developed procedures to field test operational wind turbines. The testing of rotating structures required the development of specific experimental and signal processing tools. As an example, follow-on work to these projects developed a procedure called the Natural Excitation Technique (NExT) (James, et. al. 1992) to allow the extraction of modal parameters from an operating wind turbine using only the wind excitation. Also, a significant effort in model updating allowed the development of system identification and model correlation tools and experience during these activities. Several follow-on projects used the lessons learned from these experiments to more fully understand VAWT technology; however, the typical VAWT requires only a single rotating coordinate system and is therefore reasonable to model. In contrast, the HAWT problem requires several coordinate systems to model the various components. More recent work (as discussed in the next section) has concentrated on understanding and monitoring HAWT's.

## **FIELD TESTING AND EVALUATION OF A WIND TURBINE**

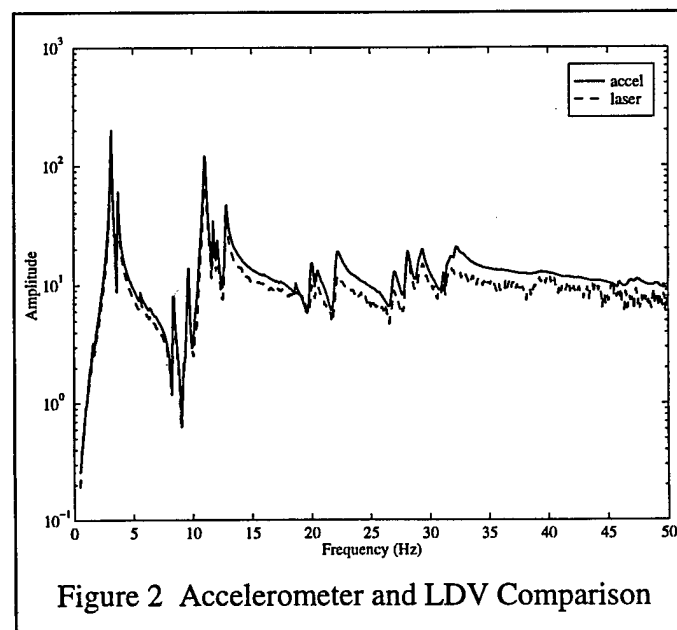
The work up until this point has described tests that are not directly related to health monitoring, but developed critical supporting technologies. The fatigue studies gave information on what failures to expect and some insight on what parameters may indicate impending failure. The plate studies provided experience on the LDV and on information condensation. The full scale modal tests provided insight on successful methods of field testing wind turbines. The next step is to test a HAWT with the objective of health monitoring. This was performed recently in Bushland, Texas on a 15 meter diameter Atlantic Orient Corporation turbine owned

by the United States Department of Agriculture (USDA). The hub of the blade was approximately 25 meters from the ground. The objectives of this test are presented. The data has not been fully analyzed as of yet and therefore will not be discussed.

The primary objective of this test was to see if an LDV could be used in the field for distances that would be expected for use on a wind turbine. To test this, the HAWT was instrumented with accelerometers and retro-reflective tape was placed near the accelerometers. The LDV system was set approximately 210 ft from the measurement points on the blade of the structure. From this setup, the response measured from the accelerometers and the LDV can be compared. Impact testing was performed, so that the input could be measured and a true FRF could be measured.

Another objective of the test was to see if accurate NExT data could be gathered by the LDV. This is requiring the development of scaling algorithms and new test procedures as the sequential nature of LDV data acquisition is somewhat incompatible with traditional NExT. For the Bushland tests, the data from the accelerometers was saved as a comparison with the LDV data. Another check on the quality of the NExT data, two simulated damage cases were inflicted on the blade. The damage was inflicted by loosening the bolts at the root of the blade various amounts to simulate a root failure. If the damage is visible using current state-of-the-art damage detection algorithms and the NExT data, then the NExT data is useful for damage detection.

Preliminary results show that the LDV system performed well in the field at the distance that it was used. The acceleration data, integrated to produce velocities, corresponded well with the LDV velocity data. Figure 2 shows an overlay of the FRF from the impact test for an accelerometer and the LDV for a point on the tip of the blade. The success of the other objectives will be presented elsewhere (Rumsey, et. al, 1997).



## CONCLUSIONS

This paper has presented a broad collection of work performed at Sandia National Laboratories over the last several years which is developing the capability to perform structural health monitoring on operational structures. The electricity generating wind turbine has been used as a target structure for much of this work. This class of structures has allowed all aspects of structural health monitoring technology to be exercised and developed: determination of damage-sensitive parameters, test planning, information condensation, and damage identification techniques. Although different structures may possess different damage-sensitive parameters, the work presented herein has shown that modal frequencies, mode shapes, modal damping, static flexibility, and static stiffness provide a reasonably inclusive set of parameters to choose from. The ongoing full-scale HAWT tests should provide a specific set of parameters for at least one example structure.

Test planning activities have included the development of procedures such as step relaxation testing of fielded structures and NExT for operational structures. Also, techniques which use finite element models for planning and pre-analysis have been developed and proven to be extremely valuable. Information condensation developments have produced new techniques for reducing large data sets rapidly into manageable information sources. This is extremely valuable with devices such as the LDV which can access a great deal of information in a semi-automated fashion. Damage identification techniques which are appropriate for operational structures have been exercised. These include fingerprinting of dynamic parameters but have included experimentally based comparisons of flexibility shapes or matrices as well as dynamic residual formulations using analytical models. Taken as a whole, this work represents a significant body of expertise needed to implement structural health monitoring on operational structures.

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