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An Evaluation of Sensing Technologies in a Wind Turbine Blade: Some Issues, Challenges and Lessons-Learned[*†]

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ABSTRACT

The Department of Energy and the Sandia National Laboratories Wind Power Technology Department have initiated a number of wind turbine blade sensing technology projects with a major goal of understanding the issues and challenges of incorporating new sensing technologies in wind turbine blades. The projects have been highly collaborative with teams from several commercial companies, universities, other national labs, government agencies and wind industry partners. Each team provided technology that was targeted for a particular application that included structural dynamics, operational monitoring, non-destructive evaluation and structural health monitoring. The sensing channels were monitored, in some or all cases, during blade fabrication, field testing of the blade on an operating wind turbine, and lab testing where the life of the blade was accelerated to blade failure. Implementing sensing systems in wind turbine blades is an engineering challenge and solutions often require the collaboration with a diverse set of expertise. This report discusses some of the key issues, challenges and lessons-learned while implementing sensing technologies in wind turbine blades. Some of the briefly discussed topics include cost and reliability, coordinate systems and references, blade geometry, blade composites, material compatibility, sensor ingress and egress, time synchronization, wind turbine operation environments, and blade failure mechanisms and locations.

Keywords: sensing technologies, wind turbine blades, blade manufacturing, testing

1. INTRODUCTION

The Department of Energy (DOE) is committed in making wind energy a viable option for the electric utility industry. To meet this challenge there have been several technology improvements identified in the DOE 20% by 2030 report and initiative that can be implemented, such as, sensors for smart rotor monitoring and control.[1] Historically, reliability, cost and simply the current state of the technology (lack-of-need) have limited the use of sensor systems in the blades of a wind turbine.

Figure 1 shows the approximate groupings of key sensors (indicated by hollow dots) in a typical utility-size wind turbine that is installed and operated in the field today. Note the lack of sensors in the outboard span of the wind turbine blades. The next generation of utility-size wind turbines will require additional sensors in the outboard span of the wind turbine blades, to enable advanced control strategies to optimize system performance and to provide condition and structural health monitoring over the full life cycle of the blade.

However, in order for a blade sensing system, or any new wind turbine sensing system, to be successful, the sensing system reliability[2,3] has to be maintained throughout the useful life of the structure. The additional capital cost of the sensing system has to be justified, and this can only be convincingly done by demonstrating a reduction in the cost of energy.[4]

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The use of sensing systems certainly is not new to the wind industry or the national labs. What is new is the need to understand the issues and challenges of implementing sensing technologies in wind turbine blades. The wind turbine and the environment in and around a wind turbine present unique requirements to sensing systems. Any company who has or is implementing blade sensing technology will certainly come across many of the challenges mentioned in this paper.

Sandia National Laboratories (SNL) has been doing research and development on wind energy technology since 1976. The sensing system knowledge and expertise reported in this paper has been acquired over those years while designing, building and testing several families of horizontal axis wind turbine (HAWT) blades (up to 9-meters long) at SNL.[5] Some applicable knowledge and experience has been carried over from previous research and development on a series of vertical axis wind turbine (VAWT) designs, developed at SNL, culminating in 1989 with the 34-meter VAWT with blades 56-meter in length.[6,7]

This paper describes some key issues, challenges and lessons-learned in the process of implementing sensing technologies in wind turbine blades over the course of the life of a wind turbine blade in a research environment. The topics were chosen based on importance, wind energy technology relevancy, and in particular, the deficiency of discussion in other forums. In most cases the issues, challenges and lesson-learned are briefly mentioned (due to necessity), so the intent is to bring the topics to light for further inquiry and research by the reader. Where applicable, references to more information are provided.

Figure 1: Annotated photo showing key sensor locations (hollow dots) in a typical utility-size wind turbine.

2. SNL BLADE SENSING TECHNOLOGY PROJECTS

A series of projects have recently been initiated at SNL that have focused specifically on understanding the implementation, operation and maintenance of several new promising sensing technologies that could be used in wind turbine blades.

In 2007, SNL had a twist-bend-coupled-experimental TX-100 blade fatigue tested at the National Renewable Energy Laboratories / National Wind Technology Center (NREL/NWTC) test site.[5,8,9] The blade test was also used as a platform to test several new sensing systems that were not initially planned in the experiment.[10] Teams from Purdue University, NASA Kennedy Space Center, and Virginia Tech instrumented the TX-100 blade. The TX-100 lab tests involved a series of static tests and a fatigue test to blade failure.

Later in 2007, SNL initiated a project called the Sensor Blade 1 project.[11] The Sensor Blade 1 project was a highly collaborative effort with teams from Aither Engineering, Inc.; Micron Optics Inc.; NREL/NWTC, Purdue University; TPI Composites, Inc. and the U.S. Department of Agriculture – Agriculture Research Service (USDA-ARS). Several teams converged at TPI Composites, the blade manufacturer, to install and test their sensors in the blade as the Sensor Blade was being fabricated. The Sensor Blade was an unmodified SNL carbon-experimental CX-100 wind turbine blade.[12] After blade fabrication the blade was shipped to the SNL and USDA-ARS Wind Energy Technology Test Site in Bushland, Texas, where several teams again converged to test their sensing systems in the Sensor Blade in the field on an operating wind turbine. After the sensing systems were evaluated in the field, the Sensor Blade was shipped to the NREL/NWTC located south of Boulder, Colorado. And again, several teams converged at the NREL/NWTC where the Sensor Blade was subjected to several static tests and one fatigue test to blade failure. Laboratory test partners were from Electric Power Research Institute (EPRI), Intelligent Fiber Optic Systems (IFOS), Laser Technologies, Inc. (LTI); Los Alamos National Laboratories (LANL), Luna Innovations, NASA Kennedy Space Center, Physical Acoustics Corp., and the University of Massachusetts – Lowell (UML). Each team provided instrumentation that was targeted for a particular wind application that included structural dynamics, operational dynamics, non-destructive testing, structural health monitoring and manufacturing quality assurance. In some cases the acquired Sensor Blade 1 datasets are still being analyzed. This particular project identified numerous sensing issues and challenges, several of which will be described in this paper.

In 2009, SNL initiated the Sensor Blade 2 and Sensored Rotor projects.[13] These are mostly in-house projects. The Sensor Blade 2 project will be evaluating and gaining experience on several inflow sensing technologies, specifically, a blade-surface-mounted heat-transfer-based aerodynamic sensor array from Tao Systems;[14] and a distribution of pressure taps along a chord on the blade, a Pitot tube, and a pressure scanner. There is also a comprehensive set of structural monitoring instrumentation on the rotor, in particular, arrays of metal-foil strain gages and an array of fiber Bragg grating (FBG) strain and temperature sensors. For these projects existing SNL CX-100 blades were modified to accommodate the sensing systems. This project is also requiring the enhancement of SNL field testing capability to facilitate future testing. The Sensored Rotor (the Sensor Blade 2 is one of three blades on the rotor) is currently undergoing a series of field tests at the SNL and USDA-ARS wind energy test site in Bushland, TX. The Sensored Rotor project will be investigating some fundamental aspects of operational monitoring.

In 2010, SNL initiated the Structural and Mechanical Advanced Rotor Technology or SMART project.[15,16] This project incorporates some of the lessons-learned from previous sensing system projects; sensor implementation, placement and channel count have been optimized based on past test results and computer modeling. In support of the SMART project, and as a future testing platform, three redesigned CX-100 blades were built. The redesign centered around a structural infrastructure in each blade to facilitate the testing of various active aerodynamic mechanisms.

3. SENSORED BLADE REFERENCE POINTS AND SENSING LOCATIONS

A wind turbine blade is an amazing piece of engineering. In terms of the visual appearance, every blade has a complex geometry that is determined by aerodynamic, structural and manufacturing constraints. Figure 2 shows the blade planform, or external surface, at 1-meter stations along a 9-meter SNL CX-100 and TX-100 blade. Note how the blade shape varies from a round planform at the root to a thin airfoil at the tip. Also note how the blade pitch angle varies along the blade from blade root to the tip. The figure also shows the pitch angle for the third (or 3-meter) station. While this planform is for a 9-meter blade, all HAWT blades that have some measure of aerodynamic optimization will exhibit a similar planform.

Referring to Figure 1 again, note the three blades are connected to the hub and become a rotor. Depending on the wind turbine the blades can rotate or pitch on the hub. This rotor assembly is connected to a drive shaft and can rotate with several distinct subcomponents in the drive train inside the nacelle. This rotor and nacelle assembly is connected to and can rotate on a tower, and this entire assemblage is mounted to a foundation yielding a structure with numerous degrees of freedom. In off-shore installations, the foundation is a non-rigid platform that will add another significant degree of freedom.

The point of this discussion is: a sensing location on an operating wind turbine - even a parked wind turbine - will move in a very complex path in space and time, so defining appropriate reference points is critical. Fortunately there are conventions, and the IEC 61400-13 Wind turbine generator systems – Part 13: Measurement of Mechanical Loads standard[17] can be of assistance as a coordinate system is defined for each substructure in a horizontal axis wind turbine. The challenge then becomes determining the actual sensing location on or in the blade in 3D space from these reference points in the coordinates systems.

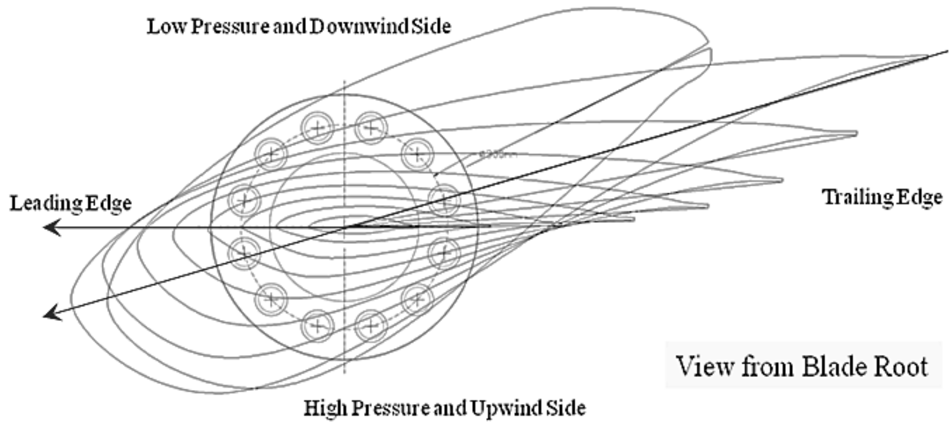

Figure 2: CX-100 and TX-100 blade planform.

Physically determining the actual location of a sensor from these references is the challenge. There are several low-tech methods of mapping sensor locations, such as laying out flexible measuring tape along curved surfaces, or pulled taught, but these methods are inherently inaccurate. Digital image correlation (DIC) and laser tracking are two methods that have been used to provide extremely accurate location measurements. However, the high cost of these high-tech systems limits their universal utility.

During the calibration of a sensing system the orientation of the wind turbine subcomponent that the sensor is mounted to must be accurately determined because gravity and wind/water loading/buffeting will all affect the sensing system response. Knowing the location and orientation of the sensing location is paramount to understanding the response of a sensor and the eventual analysis of the physical phenomena.

4. SENSOR BLADE FABRICATION

4.1. Composite Structure of a Wind Turbine Blade

The wind turbine blade is a composite structure composed of several dissimilar materials. A close-up view of a cross-section of SNL Blade Study Design Study (BSDS) blade[18] is shown in Figure 3. Figure 4 shows the cross-section of SNL CX-100 blade near maximum chord. The photos show layers of fiberglass and carbon fiber, balsa wood, gel coat, and an adhesive that holds the various materials together. All wind turbine blades will have three subcomponents, a high-pressure (HP) skin, an internal structural member often called shear web or box (a shear web is shown running horizontal in the middle of Figure 3), and a low-pressure (LP) skin (shown on the right in Figure 3). The actual design, dimensions and implementation of these subcomponents will vary significantly among blade designs. As can be seen in the figures, there are ply-drops, numerous joints, bond-lines and sometimes (unfortunately) defects. The defects shown on the right in Figure 3 are voids in the adhesive in the bond-line.

Some other significant wind turbine defects are resin-poor/fiber-rich areas causing porosity issues, laminate in-plane and out-of-plane waviness, inadequate bond thickness, disbonds and delaminations. How significant these defects are is of great concern and interest in the wind industry today. Defects are generally small in size in comparison to the large wind turbine blades. To date the effective detection and evaluation of defects involves the use of a combination of wide-area and local inspection techniques. The materials and structural details in a wind turbine blade provide challenges in any successful implementation of a non-destructive inspection or structural health monitoring sensing system. At SNL, blade defect issues are being researched under the "Effects of Defects" subtask in the SNL Blade Reliability Collaborative.[19]

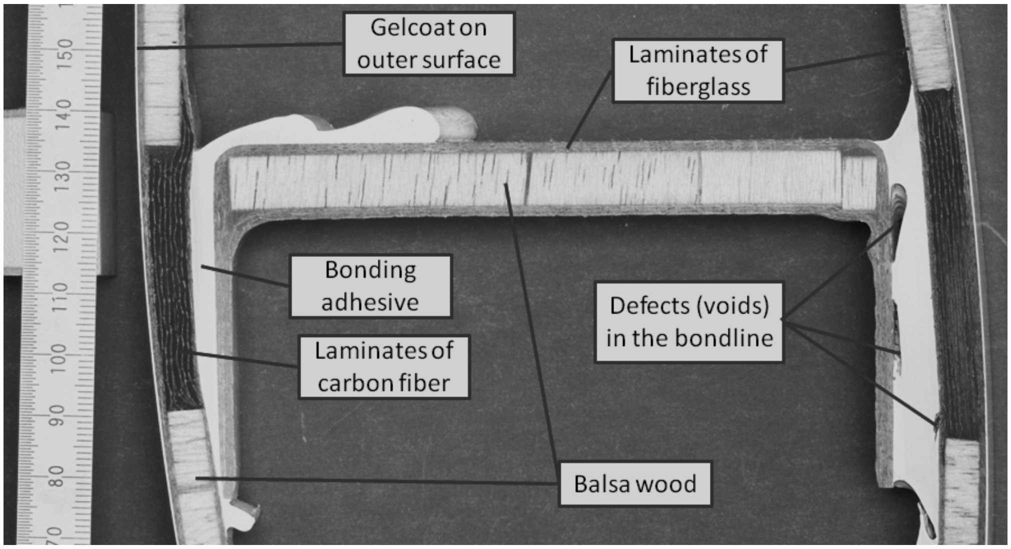

Figure 3: A cross-section of a SNL BSDS 9-meter wind turbine blade revealing the internal structure.

Referring to Figure 4, the blade surface that is in contact with the blade mold is called the A-Side or A-Surface. The blade surface that is closest to the vacuum bag in an infusion process is called the B-Side or B-Surface. On a wind turbine blade, the A-Surface faces the outside environment and is the aerodynamic active surface. The B-Surface is entirely inside the blade.

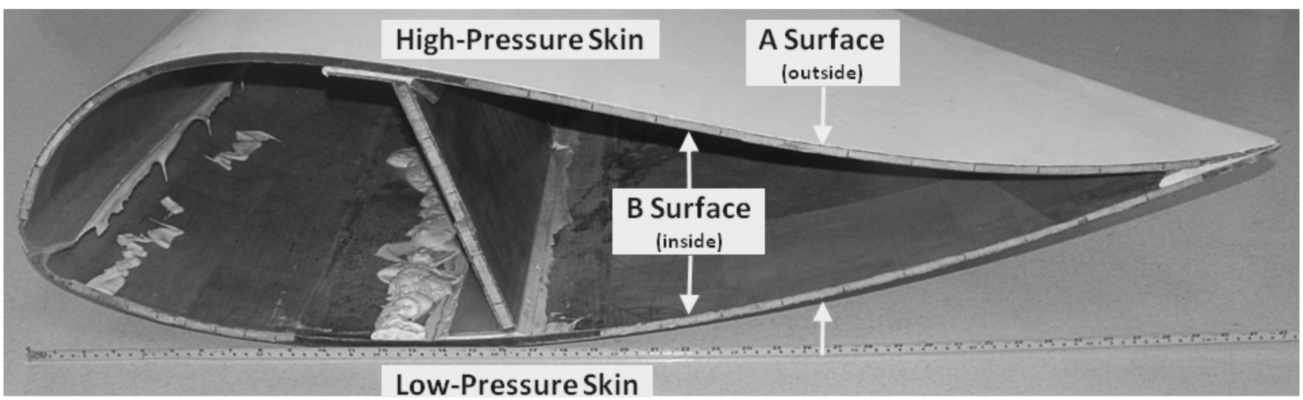

Figure 4: Labeled photo showing a cross-section of SNL CX-100 blade near maximum chord.

There are numerous steps in the fabrication of a wind turbine blade. Figure 5 shows several photographs of staff from several organizations installing sensors in the Sensor Blade 1. In Figure 5A, the photo shows TPI Composites shop floor staff laying down a carbon shear web laminate. TPI Composites staff and an Aither Engineering engineer, in Figure 5B, are implementing the ingress/egress point for the embedded fiberoptic sensor cable in the blade laminates. Figure 5C shows staff from Purdue University and Sandia Labs installing sensors on the inner or B-surface of the fully-fabricated LP and HP skins. Installing sensors in a wind turbine blade currently is a very manual process.

4.2. Sensor Location and Orientation

For the Sensor Blade 1 and SMART blades, several sensors were mounted on the inside skin surface of the HP, LP and shear web. With the blade skins lying in their respective molds, to guarantee no blade deformity due to gravity, the location and orientation of each sensor was determined using a FARO laser tracker system owned by the quality assurance department at TPI Composites. The blade HP, LP and shear web subcomponents were assembled into a blade using an articulating clam-shell jib shown in Figure 5D. The as-built blade has implications related to sensor location and orientation, and will be discussed later in **The As-Built Blade and the As-Designed Blade** section. The location and orientation of sensors on the outside surface of the Sensor Blade 2 were also measured with a similar FARO system.

Figure 5: Photos taken at various points in the fabrication of the Sensor Blade 1.

4.3. Surface Preparations

The external A-surface of a blade is glossy smooth, but it is not flat (over a few centimeters). When a large sensor or probe is applied to the surface, as in a low-frequency Ultrasonic Testing (UT) application, there will be a significant air gap between the probe and blade, and in the case of UT a considerable pool of couplant is needed to close the air gap. The internal B-surface of a wind turbine blade is not smooth, and it is not flat. Careful consideration must be taken to prepare the interface between the sensor and the blade material, before the two are bonded together. This is especially true if the active area on the sensor is very small, such as a fiber Bragg grating sensor on a fiberoptic cable or a metal-foil strain gage. In part because of this concern, Prof. Doug Cairns and his students at Montana State University (MSU) performed a series of sensor surface preparation tests to evaluate the interface between the fiberoptic cable (simulating a FBG) and composite structure.[20] Figure 6 shows a highly magnified image, obtained during one of the MSU tests, of a fiberoptic cable embedded in a composite structure. Note the gap between the fiberoptic cable and the surrounding resin. This gap resulted from inadequate surface preparation.

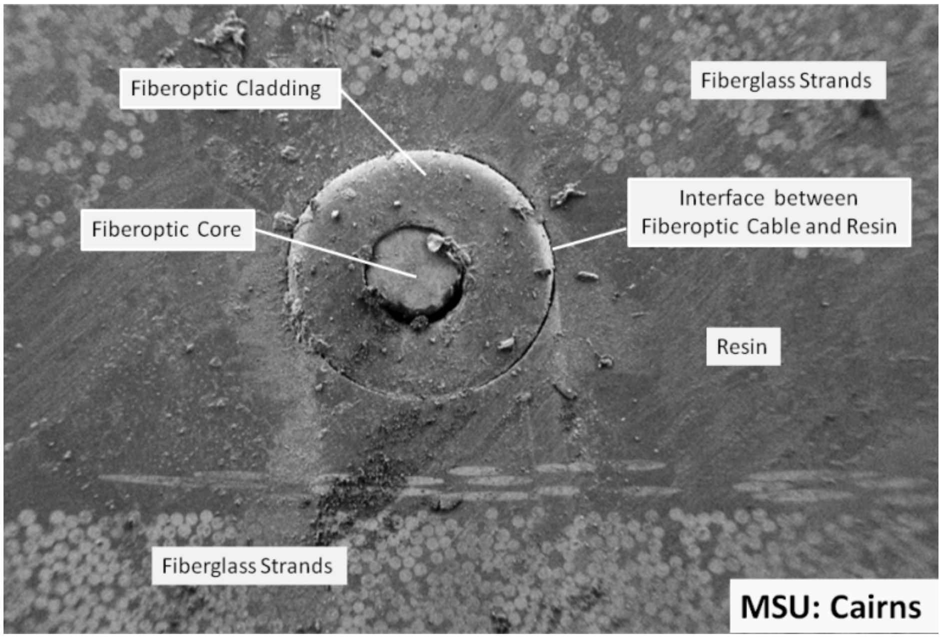

Figure 6: Highly magnified image showing a fiberoptic cable embedded in a composite structure.

4.4. Sensor Cable Management

In a wind turbine blade the sensing unit or transducer is often a considerable distance from the signal processing unit. In all non-wireless sensing solutions the sensing units are tethered to the signal processing unit with a copper or fiber optic cable. Embedding sensors in the laminate stack of the blade introduces the additional challenge of sensing cable ingress and egress as was mentioned earlier. The sensing cable ingress and egress from the laminates of the blade is a challenge and requires careful thought and design. The diagrams for the sensing cable ingress and egress and the implementation steps should be incorporated in the blade layup schedule. The ingress/egress implementation at the time of blade fabrication requires planning and close collaboration with the blade manufacturing staff.

4.5. Blade fabrication affecting sensors

Most wind turbine blade fabrication techniques are based on an infusion process.[21,22] The TPI Composites company uses the SCRIMP method in their blade manufacturing process.[23] The only sensors in the Sensor Blade 1 that were subjected to the blade infusion and post-curing process were linear arrays of embedded FBG sensors on several fiberoptic cables.

Figure 7 shows the response from several FBG sensors that were adversely affected by the application of the vacuum on the stack of laminates during the fabrication of a Sensor Blade 1 skin. We believe the signal loss in the polyimide fiberoptic sensor cable was due to numerous micro-bends caused by the weaves in the laminates.

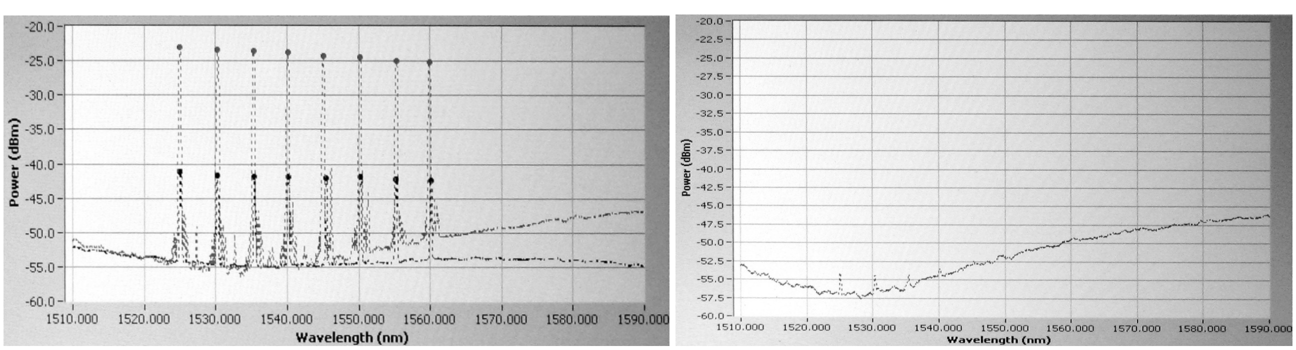

Figure 7: Signal strength of arrays of embedded FBG sensors before and after the blade skin was vacuum bagged.

In the post-cure process the blade skins and shear web are put in an oven and the substructures are subjected to an elevated temperature that is designed to accelerate the hardening of the infused resin and hardener. The higher the temperature the faster the resin hardens, within reason. If a sensor is embedded in the laminates of the blade skin, the sensor will be subjected to the post-curing process of the substructures or the fully-assembled blade. If the sensor is being used to monitor the structure during the curing process, the sensor operating temperature limit, which is less than the storage temperature, must not be exceeded. The curing temperature can be set to not exceed these sensor temperature limits. The Sensor Blade 1 substructures were infused with an Epoxy resin/hardener and post-cured at a temperature of 150°F for 4-hours.

4.6. The As-Built Blade and the As-Designed Blade

Every as-designed blade has an intended outer aerodynamic profile and an intended internal structure. The as-built blade is the blade after it is fully assembled on the manufacturing floor. There will be deviations between the as-designed and the as-built blade. The as-built blade should be compared to the as-designed blade, and deviations from documented tolerances called out in the procurement order should be documented, and corrected if possible, before the blade leaves the blade manufacturing facility. This should be done as part of the manufacturing quality assurance (QA) process. Deviations from the expected blade geometry and mass properties will have an effect on the structural and aerodynamic performance of the blade. For the sensors, the sensing locations and orientations may also be adversely affected.

5. FIELD TESTING SENSOR BLADE

All SNL research blades have been field tested at the SNL and USDA-ARS Wind Energy Technology Test Site located in Bushland, Texas.[24] For the Sensor Blade 1 project, several SNL and non-SNL teams converged at the field test site to learn how their sensing system performed in the Sensor Blade on an operating wind turbine. After the blade sensing systems were checked out, a series of on-the-ground tests were performed on the Sensor Blade. The first tests obtained blade sensor system calibration datasets. Figure 8 shows several teams obtaining calibration datasets from their respective sensing systems as the wind turbine blade was loaded with a series of known loads during an edge pull test. The blade was loaded by a series of loads at different but known blade orientations. With an established coordinate system and reference points (referring back to Section 3.), the calibration tests can be done quickly and accurately. A key test after calibration was the full model test of the Sensor Blade.[25] After on-the-ground calibrations and tests, the Sensor Blade and two other CX-100 blades with matching mass properties, were installed on a modified Micon 65/13M, 100-kiloWatt, test wind turbine. The sensing systems were connected into the full testing configuration and checked out. The first series of tests were in-the-air calibrations of the sensing systems where the blade was loaded with known loads, with the blade, rotor, nacelle and turbine in known orientations.

Figure 8: Photo showing technical staff from many organizations performing on-the-ground calibration tests on their respective sensing systems at the SNL and USDA-ARS field test facility in Bushland, Texas.

After the in-air calibrations, the sensing systems, Sensor Blade and test turbine were subjected to a series of operational monitoring tests.[26,27,28,29] Figure 9 shows the Sensor Blade, and an extensive combination of data acquisition equipment, mounted on the test turbine hub.

5.1. Slip Rings

Because the subcomponents in a wind turbine can move in relation to each other, getting information in the form electronic signals from one substructure to another can be challenging. In a copper-wire based setup, slip rings are often used between the hub and the nacelle. (Between the nacelle and the tower, drop-cables, copper wire or fiberoptic cables, are sometimes used. However, the nacelle must not be yawed too many times in one direction on the tower or the cables will be damaged. Twisted drop-cables need to be un-twisted.) Most utility-size commercial wind turbines have a set of power-quality and instrumentation-quality slip rings between the hub and the nacelle to relay power and electronic signal information, respectively, between the two subcomponents. Instrumentation-quality slip rings are expensive so there may not be available slip-ring channels on a commercial wind turbine. It is for this reason that data and information is often relayed on and off the rotor using a form of wireless technology. Wireless systems have their own issues.

Figure 9: Sensor Blade 1 mounted on a test turbine at the SNL and USDA-ARS wind energy technology test facility in Bushland, TX

5.2. Time Synchronization

The information obtained from a sensor in time and space is only useful if it can be referenced to other information separated in time and space. This is especially true in wind energy research where the sensing systems can be spatially separated, such as with the inflow sensors on meteorological towers and sensors in subsystems throughout a wind turbine. At the SNL and USDA field test in Bushland, TX, the maximum separation between systems is about 150 feet. The challenges in determining sensor spatial separation relates directly to coordinate systems and references, and this was briefly discussed in the Section 3.

The temporal relationship between signals is also crucial. The time synchronization relationship between data acquisition systems has to be known, ideally, deterministically. Historically, time synchronization between these spatially separated data acquisition systems has been a challenge to implement on a wind turbine. At SNL we have been utilizing the timestamp obtained from GPS signals in every spatially separated data acquisition system.[30,31] There are new time synchronizing approaches, such as IEEE 1588[32] and EtherCAT[33], that promise microsecond level synchronization.

5.3. Electrostatic Discharge

All SNL designed blades (currently, CX-100, TX-100 and BSDS) were research blades and were built to demonstrate a new blade concept, and tested to validate structural and aerodynamic computer models. These SNL blades did not incorporate lightning protection in the blades as the blades were never intended to be operated for long periods of time. Diagnostic equipment however, has always been installed with various mechanisms of lightning protection. The SNL blades were constructed of mostly non-conductive materials, except for the carbon fiber laminates (in various configurations) inside the blade skins and the root inserts for mounting the blade. During blade manufacturing there were no intentional steps to electrically connect these carbon laminates to the root inserts, which would have enabled an electrically conductive path to earth ground. To the external environment of a wind turbine, the Sensor Blade (a CX-100 blade) probably is an electrically insulated structure.

During the field testing of the Sensor Blade 1, several accelerometers mounted in the blade failed unexpectedly. Post-mortem by the accelerometer manufacturer indicated electrostatic discharge (ESD) damage within the accelerometers. There were no thunderstorms or other indications of lightning in the area over the duration of the tests. Testing was intentionally scheduled during the time of the year with a low probability of lightning. We currently believe the accelerometer-damaging static electricity was generated from the combination of a high voltage gradient in the atmosphere and the triboelectric effect[34] between the air and the blade surface. The metallic-based accelerometry system provided a convenient electrical path to ground.

The ever-present atmospheric voltage gradients are generated by the Global Electric Circuit (GEC).[35,36] Lightning, which we all are very familiar with, is an extreme form of ESD in the GEC. The atmospheric voltage gradient is most often measured with an electric field mill (EFM). At the time of the Sensor Blade 1 testing, the atmospheric voltage gradient was not being monitored at the USDA-ARS field test site. An EFM system has subsequently been procured and is now monitoring the atmospheric voltage gradient upwind from the test wind turbine. Figure 10, A and B, show the atmospheric voltage gradient on a clear weather day and on a thunder snow storm day, respectively, at the SNL and USDA-ARS Wind Energy Test Site in Bushland, Texas. Note the brief +280-volts/meter and -180-volts/meter voltage gradient spikes in Figure 10(A) on a clear weather day. Using the +5,000-volts/meter peak value shown in Figure 10(B), on a stormy day, a sensor at the tip of the blade on vertically-orientated 9-meter blade, on a conductive 25-meter-high steel hub and turbine tower, could conceivably see 45,000-volts when referenced to earth ground. And just minutes later the voltage gradient swings to -3,000-volts/meter. These voltage levels are extremely destructive to unprotected electronic instrumentation. The GEC phenomena will be a challenge for any copper-wire-based sensing and active-aero-actuation system in a wind turbine blade. As a result SNL is investigating this GEC phenomenon in the Sensored Rotor and SMART Rotor projects.[16] Each of the three SMART blades incorporates a conductive skin that is connected to a traditional blade lightning protection scheme. The lightning protection hardware in each blade is grounded to earth ground through the conductive turbine structure.

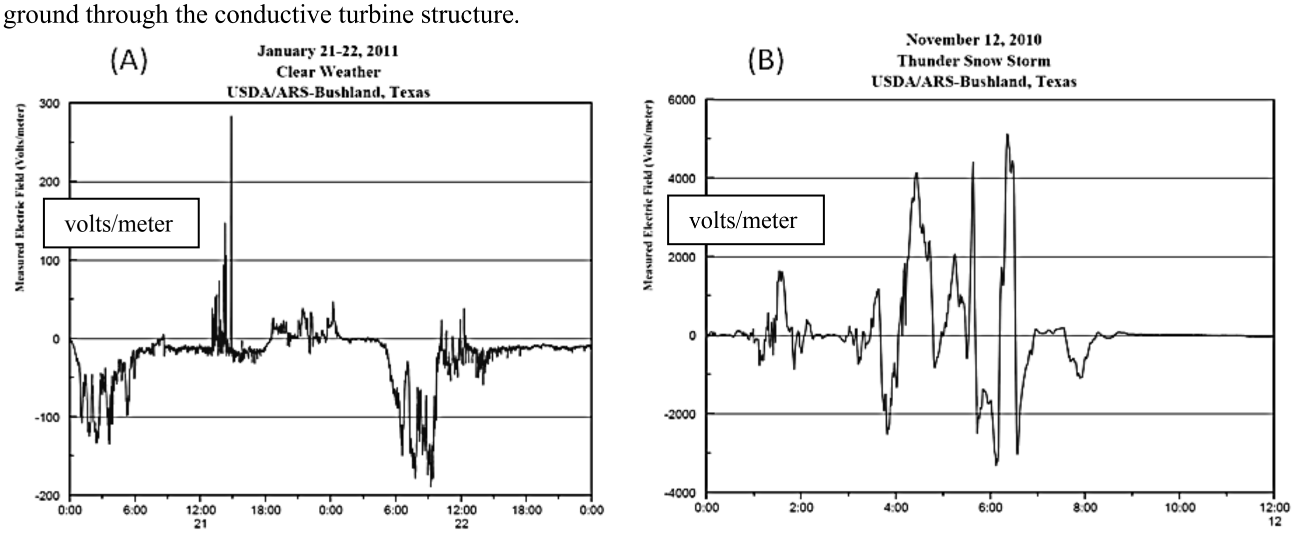

Figure 10: Time-history plots of the atmospheric voltage gradient during a clear weather day (A) and a snow storm day (B) at the SNL and USDA-ARS Wind Energy Test Site in Bushland, Texas. In (B), note the +5,000 to -3,000 v/m swing in a few minutes.

6. LABORATORY TESTING SENSORED BLADES

6.1. Laboratory Test Site Availability

There are many reasons to lab test a wind turbine blade. Datasets generate during lab tests are used to validate computer blade design models. Lab testing provides a way to test prototype blade designs. To formally certify that a blade has been built to design specifications, a blade is subjected to a series of well-defined tests by a facility certified to do the testing.[37] One particular useful lab test for testing sensing systems is the test to accelerate the life of a blade. A blade fatigue test attempts to simulate an aggressive loading that a blade on a wind turbine could possibly see in 20-years of field operation, and do it in 1-million cycles in the lab.[37,5] To date there are few laboratories setup to perform these full-blade fatigue tests so the challenge is availability and getting access to these test facilities.

6.2. Sensor Blade 1 Lab Tests

After the Sensor Blade 1 sensing systems were evaluated in the field on an operating wind turbine, the blade was removed from the turbine and shipped to the NREL/NWTC. And again, several teams converged at the NREL/NWTC where the Sensor Blade was subjected to several static tests and one fatigue test to blade failure. Figure 11 shows laboratory blade test setups at the NREL/NWTC. Note in the photos the numerous sensors mounted on the outer skin of the blades. Both blades had sensors mounted inside the blade.

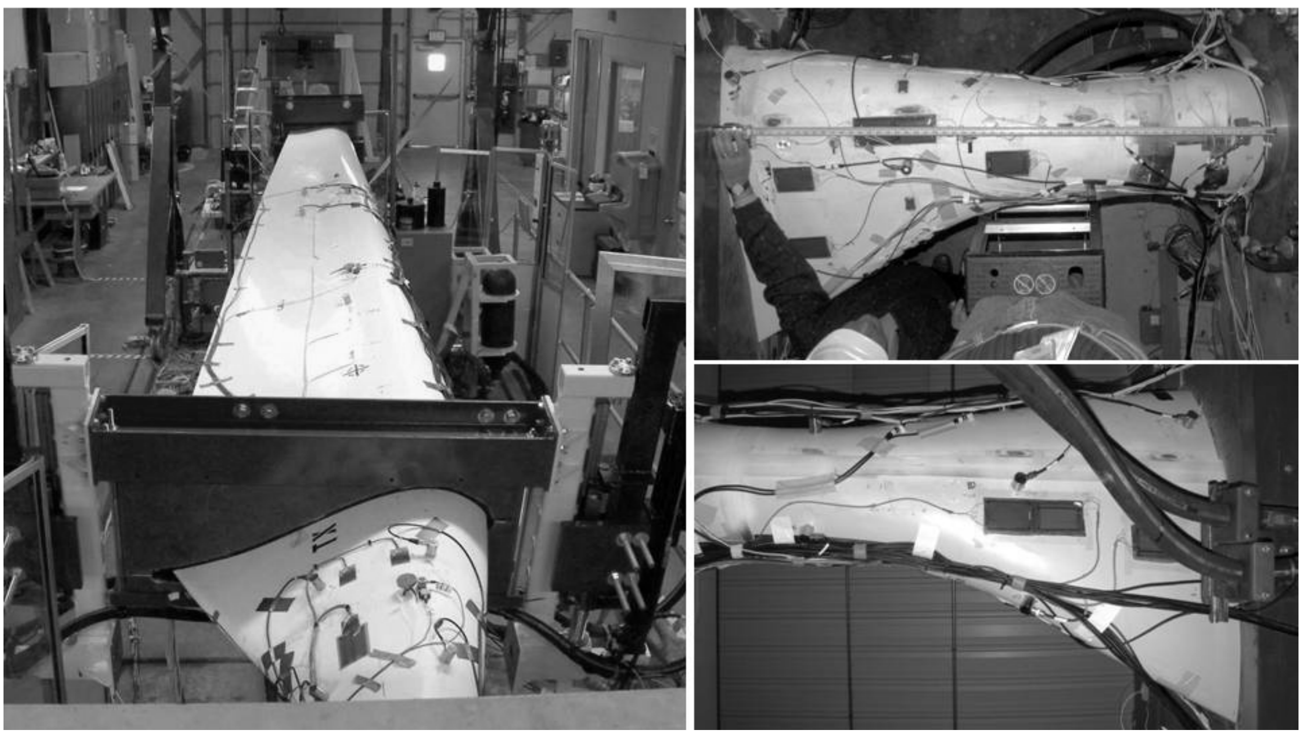

Figure 11: Photo on the left shows a SNL TX-100 research wind turbine blade on a test stand ready for a fatigue test. The photos on the right show the diverse arrays of sensors mounted on the outer skin of the SNL Sensor Blade 1 (a CX-100 blade).

Blade fatigue tests on 9-meter blades, because of the setup and duration, often take 1 to 2 months to complete. Larger, full utility-size blades have taken a year to complete. The fatigue test load frequency on the Sensor Blade proceeded at approximately 1.8 Hertz. However the fatigue test was stopped often to facilitate blade inspections, and to perform tests to exercise and evaluate the sensing systems. For the Sensor Blade 1 project, fatigue testing the blade in the lab provided a controlled environment so the various sensing systems could be monitored and evaluated as the blade gradually failed in fatigue.

6.3. Blade Orientation and Motion during Lab Tests

Depending on the lab test setup and load activation technique, one particular side of the blade could be facing down toward the floor or facing upwards, or at an angle in-between. During a blade loading test the blade surface moves; the root moves very little and the blade tip can move several meters, even for 9-meter blades. The blade surface orientation and range of motion are important considerations as some diagnostic techniques that require a stand-off distance from the blade and a viewing range.

6.4. Blade Failure Mechanisms and Damage Initiation Locations

To strategically place sensors for a damage detection or structural health monitoring application, the blade failure mechanism and the damage initiation point in a blade would like to be known. However, unless there is a failure history of the blade family, or there is a damage initiation model for the blade, this information is not known. To make it more challenging, the wind turbine blade industry is constantly evolving with new blade models being designed, built, sold, installed, and redesigned. Blade failure in the lab can be due to a bad blade design, a blade manufacture-induced defect or in the lab with an incorrect load distribution on the blade.

Based on the results from previous fatigue tests on other CX-100 blades[5], the Sensor Blade was predicted to fail in the root to maximum chord transition region of the blade, and since the fiberglass and carbon fiber composites in a wind turbine blade are stronger in tension than in compression, the blade often (but not always) fails in compression. Therefore, the test setup for the Sensor Blade was a mixture of configurations and experiences from past tests of CX and TX blades. Sensors were placed on the Sensor Blade around the maximum chord area and on the compression side of the blade.

The circled outlines in Figure 12 and Figure 13 show the failed areas in the TX-100 and Sensor Blade 1 blades, respectively, after being subjected to a fatigue test to blade failure. The failure area in the TX-100 blade was completely unexpected, but could be explained after assessing the test results and re-assessing the blade design.[10,38] Early in the Sensor Blade 1 fatigue test a crack appeared on the LP and HP skin bond-line along the trailing edge of the blade, just in-bound from maximum chord. As the fatigue test progressed the trailing edge crack continued to grow eventually to a length of around 3-feet, but the Sensor Blade did not fail in this area. The Sensor Blade (CX-100) failed by the same failure mechanism and in an area comparable to previous fatigue tests of CX-100 blades.

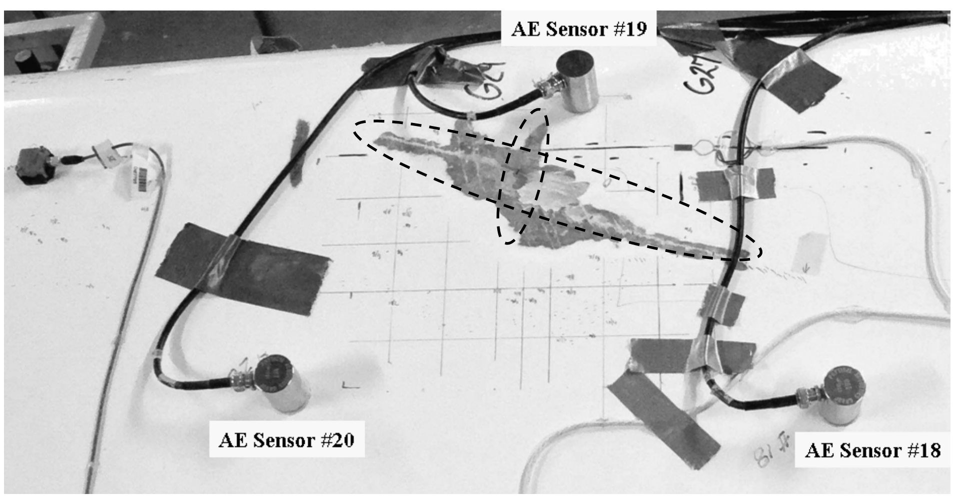

Figure 12: The fatigue test of a TX-100 blade resulted in the blade failing unexpectedly around the mid-span of the blade.

6.5. Sensor System Interference

All sensing systems are susceptible to interference. So testing the susceptibility of a sensing system to interference is a critical test of the implementation of a sensing system. There is far less control of interference variables in the field environment in and around an operating wind turbine than in a laboratory. But even in the laboratory environment there will still be unavoidable sources of interference. In addition to the more common interference sources, like ground loops, the numerous sources of electromagnetic interference (EMI) and temperature fluctuations, there can be interference from other sensing systems. Active diagnostic systems that send out signals to the blade for the purpose of locally loading the blade structure in a way to excite a physical process can interfere with other sensing systems. Even the presence of a sensor from another sensing system may be a cause of interference.

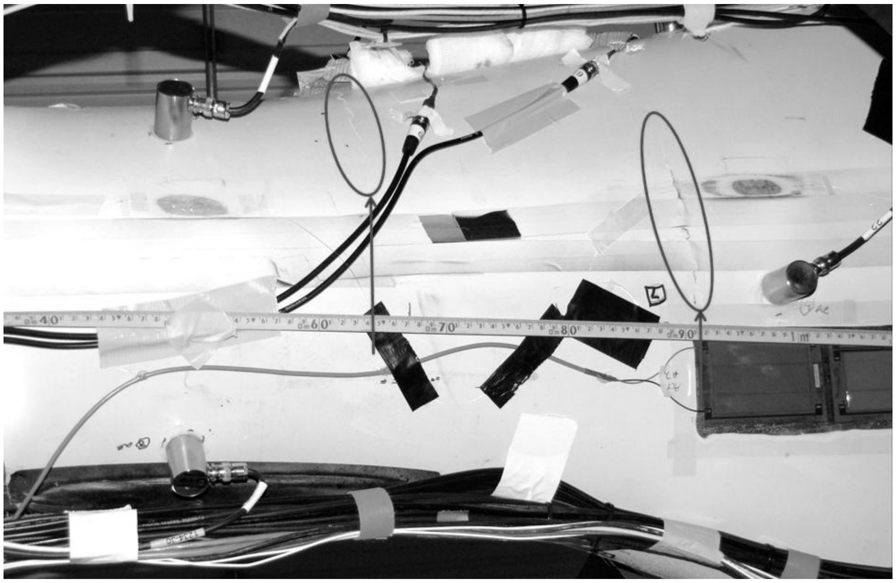

Figure 13: The Sensor Blade 1 failed in two locations shown circled in photo.

7. CONCLUSION

The implementation of a sensing system in a wind turbine blade can be fraught with difficulties and perils, but the ultimate solution can be considered simply as an engineering challenge. Sensing solutions should begin with a dialogue with members of the technical wind community to identify the sometimes unique issues and challenges found in the wind industry. The sensing system design and implementation will require engaging several diverse engineering disciplines, and possibly leveraging applicable knowledge from other industries. For a sensing system solution to be successful the system has to be reliable and be cost effective. There are numerous issues and challenges to implement a working, reliable, cost-effective sensing system, and this paper described some of the less-often communicated issues, challenges and the lessons-learned at various points in the life of a wind turbine blade.

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