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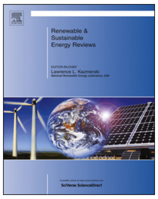

A survey of health monitoring systems for wind turbines

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ABSTRACT

Wind energy has played an increasingly vital role in renewable power generation, driving the need for more cost-effective wind energy solutions. Health monitoring of turbines could provide a variety of economic and other benefits to aid in wind growth. A number of commercial and research health monitoring systems have been implemented for wind turbines. This paper surveys these systems, providing an analysis of the current state of turbine health monitoring and the challenges associated with monitoring each of the major turbine components. This paper also contextualizes the survey with the various potential benefits of health monitoring for turbines.

Contents

Abbreviation: AE, acoustic emissions; AWEA, American Wind Energy Association; CBM, condition-based maintenance; CFRP, carbon fiber reinforced polymer; CM, condition monitoring; CWIF, Caithness Windfarm Information Forum; DAU, data acquisition unit; EWEA, European Wind Energy Association; FBG, fiber Bragg grating; FEM, finite element model; FFT, fast Fourier transform; FRP, fiber reinforced polymer; FTIR, Fourier transform infrared spectroscopy; GFRP, glass fiber reinforced polymer; HAWT, horizontal axis wind turbine; HM, health monitoring; LIDAR, light detection and ranging; MCSA, motor current signature analysis; MEMS, microelectromechanical system; MFC, macro-fiber composite; NDE/T, nondestructive evaluation and testing; NREL, National Renewable Energy Laboratory; NSET, nonlinear state estimation technique; OMA, operational modal analysis; OWI-Lab, Offshore Wind Infrastructure Lab; O&M, operations and maintenance; RES, Renewable Energy Systems; RF, radio frequency; RFID, radio-frequency identification; RM, reactive maintenance; RPS, renewable portfolio standard; SCADA, supervisory control and data acquisition; SHM, structural health monitoring; SM, scheduled maintenance; SNL, Sandia National Laboratories; VBDD, vibration-based damage detection; WSN, wireless sensor network

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1. Introduction

The wind energy industry has grown quickly since the early 2000s. Global wind capacity reached close to 370 GW by the end of 2014, with China alone installing over 23 GW in 2014 [1]. Wind penetration has increased as well: in 2014, the U.S. state of Iowa generated over 28% of its electricity from wind power [2], and in 2013, wind supplied up to 68.5% of Spain's demand coverage [3]. Additionally, the European Wind Energy Association (EWEA) is tracking plans for over 98 GW of offshore capacity [4], and offshore wind is expected to continue to grow.

Some of wind energy's growth is due to increased public awareness of impending climate issues; another factor is the decreasing cost and increasing output of wind energy systems. Yet another driver of growth has been government policy, such as the adoption of renewable portfolio standards (RPSs) by a majority of U.S. states, requiring utilities to obtain a portion of the electricity they supply from renewable sources. The American Wind Energy Association (AWEA) expects utilities to choose wind to fulfill over 40% of all RPS requirements put in place as of 2013 [5]. With these factors contributing to increased demand, more cost-effective solutions for wind energy are sought to meet this demand and make wind even more attractive.

An emerging approach to reducing wind energy costs is to make wind turbines smarter. Sensing systems deployed on each turbine can collect data that could be used for a variety of purposes. A number of such systems for wind turbines already exist and provide benefits such as online health monitoring (HM) and load mitigation. Many other uses for such systems can be imagined, such as providing data to turbine control processes to maximize wind farm efficiency. Because of this, HM and other data collection systems are expected to play an important role in wind energy's future.

In fact, as time goes on, HM of wind turbines becomes more important and more attractive. Turbines have rapidly grown in physical size, and correspondingly, in power generation. This means that each turbine is becoming a greater source of revenue, and mitigating downtime is becoming more critical. Additionally, larger components are generally more expensive to maintain and replace. More and more wind farms are being sited offshore, where remote monitoring is particularly useful. And finally, wind energy is becoming a larger part of the world's electrical generation portfolio, so wind turbines are going to be relied upon for consistent operation more and more. Therefore, increased interest in systems for smart wind turbines is expected. This paper is intended to provide a contextualized, practical introduction to these systems.

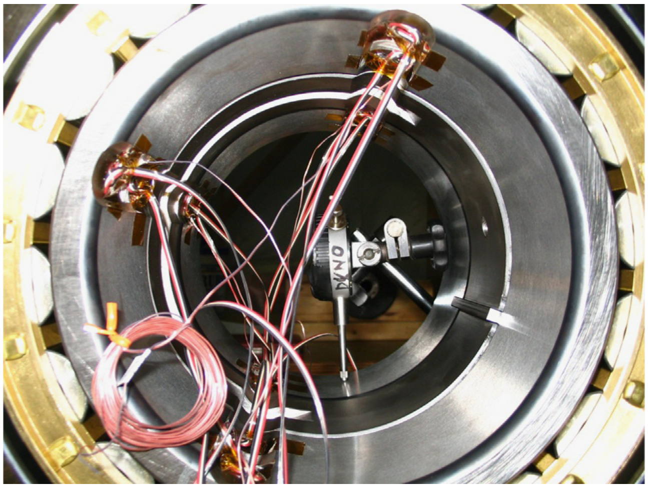

Fig. 1. Instrumentation of a gearbox bearing. Photo by Jeroen van Dam, NREL 19680.

Existing surveys of HM for wind turbines tend to focus on monitoring techniques [6–11], such as sensing technologies, with minimal attention given to the systems perspective. Existing lists of systems [12,13], while useful, are not intended to provide much context about monitoring, and also do not cover academic and research systems. Finally, existing surveys tend to either focus on particular turbine components, or provide little context about for which component a technology is suited. The goal of this paper is to provide a comprehensive, component-by-component survey of existing HM systems for wind turbines. Contrasting with existing surveys, the primary focus is at the system level. Specific sensing technologies and data processing techniques are discussed to the extent required to contextualize the systems and discuss future directions, but for more details on sensing technologies and analysis techniques, readers are encouraged to refer to other sources. This paper is also intended to provide context and high-level background on HM and the challenges faced by industry and researchers applying HM to wind turbines.

The remainder of this paper is organized as follows. The next section provides background information on HM. Section 3 presents a discussion of the motivations for monitoring wind turbines and an overview of the challenges and current state. Sections 4–7 examine challenges, existing systems, and the future for HM of turbine nacelles, foundations, towers, and blades, respectively. Finally, the discussion is concluded in Section 8.

2. Health monitoring

This section presents background information about HM in general. As discussed in Section 3, the potential uses of a turbine's sensing system are not limited to traditional HM. However, the bulk of existing systems are designed for HM-related purposes, so HM is discussed here to provide context.

The definitions of HM and related topics are not consistent in the literature. In this paper, HM refers to the process of using a sensing system to detect damage to an object, with damage being defined as a change in the object's properties that adversely affects current or future performance [14]. This paper defines condition monitoring (CM) as HM applied to machinery, and structural health monitoring (SHM) as HM applied to structures. This paper distinguishes HM from nondestructive evaluation and testing (NDE/T) by further defining HM as online, continuous monitoring using a permanent or semi-permanent sensing system installation. By this definition, an HM system could use NDE/T technologies for damage detection. The use of vibrations for damage detection will be referred to as vibration-based damage detection (VBDD). Both CM and SHM commonly employ VBDD, though other methods do exist and will be discussed.

2.1. Condition monitoring

In this paper, CM is defined as HM for rotating or reciprocating machinery. VBDD is a key technique for components such as drive shafts, bearings, gearboxes, and generators. One proven monitoring method is to use sensors such as piezoelectric accelerometers, attached to the component or its casing, to obtain dynamic characteristics such as vibration velocity [15]. For example, Fig. 1 shows instrumentation of a bearing in a wind turbine gearbox. If the dynamic characteristic being measured changes significantly from the reference, or undamaged, state, then damage is present. Industries with a history of CM may have databases of vibration signatures for machinery that can be used to diagnose the specific problem associated with a particular change.

Another common CM method comes from tribology, the study of moving surfaces interacting with each other. This includes analysis of lubrication and of wear. Oil samples can be analyzed to determine viscosity, levels of contaminants such as water, coolant, or fuel, and size, shape, composition, and count of solid particles. Traditionally, detailed analysis requires expensive laboratory equipment, and a regular sampling schedule is required [16]. However, recent advances in sensing technology have made more and more oil analysis tools available for continuous monitoring [17].

Oil monitoring can serve two purposes. The first is to measure the quality of the oil. This allows optimization of the oil changing schedule and prevents damage from operation with poor quality oil. The second purpose of oil monitoring is to measure wear on the machinery. For instance, the presence of large particles, an excessive amount of particles, or particles of a particular shape can indicate impending failure or abnormal wear conditions [16]. This type of detailed analysis is still typically performed offline, in a laboratory [18].

Other CM techniques include motor current signature analysis (MCSA) and acoustic emissions (AE). MCSA is analogous to vibration analysis, but monitors the current fluctuations in the electrical motor driving the machinery instead of the physical vibrations of the machinery. In contrast, AE detects damage by measuring the elastic waves emitted from a rapid release of strain energy in a material, which happens when the material undergoes stress or when damage occurs. While AE is considered more sensitive than vibration techniques, the disadvantage of AE is that, due to attenuation of the elastic waves, AE sensors need to be close to the point of stress or damage in order to be effective. This is often not practical in moving machinery [19].

Fig. 2. Structural failure in a wind turbine blade. Photo by Mike Lascut, used with permission.

Overall, CM is a well-developed field. CM systems are regularly used by the transportation and manufacturing industries, among others [20]. Online oil monitoring is used in applications ranging from automobiles to electrical transformers [21]. A typical CM system uses wired analogue sensors connected to some type of data acquisition unit (DAU), so future advancements in CM will likely include miniaturization, digitization, and modularization of data collection systems. Also, CM data still often requires an expert to interpret, so ease of use is another area for improvement.

2.2. Structural health monitoring

SHM is here defined as HM applied to a structure in order to monitor its integrity or estimate its lifetime. Rytter [22] outlines four levels of damage detection for an SHM method:

1. Detection – the method indicates damage might be present.
2. Localization – the method indicates where the damage likely is located.
3. Assessment – the method estimates the severity of the damage.
4. Consequence – the method evaluates structure safety, given the damage.

While a system of the fourth level is ideal, systems of the lower levels are generally simpler and easier to implement.

Farrar and Worden [14] and Worden et al. [23] discuss damage in terms of length-scales and time-scales. The length-scale classifies the damage in terms of physical scope. For instance, the damage may be only at the material level, as in a natural defect, or the damage may be at the structural level, as in a failed wind turbine blade like that shown in Fig. 2. An SHM system for a wind turbine should be able to detect damage at the component level, meaning that damage requiring a repair should be detected well before component failure occurs.

The time-scale of damage refers to the length of time over which the damage takes place. For a wind turbine, long time-scale damage includes fatigue, the weathering of the protective coatings of the blades and tower, the corrosion of the tower, and the erosion and delamination of the blades. Short time-scale damage includes lightning strikes, impact damage, extreme winds, and earthquakes. A comprehensive SHM system for wind turbines would be able to detect all of these types of damage, though a variety of detection methods may be required.

SHM's roots are in NDE/T. Early studies of dynamic properties for damage detection examined modulus and damping. In 1978, Adams et al. [24] identified natural frequencies as a property of a structure that could be measured anywhere on the structure but still provide damage localization and characterization. Since then, VBDD has developed as a prominent method of damage identification for structures because it detects damage on a global scale, requiring relatively few sensors and no prior knowledge of the damage location. The fundamental idea of VBDD in SHM is that, because of a structure's material properties, it responds a particular way to outside forces, such as wind. As the structure takes damage, its material and dynamic properties change, so its response to forces also changes. VBDD SHM systems are designed to detect these changes in order to characterize the damage [25].

VBDD techniques have expanded to include numerous methods in addition to natural frequencies, such as mode shapes, modal strain energy, residual force vectors, and statistical methods. Carden and Fanning [26] performed a comprehensive literature review of VBDD SHM methods in 2004 and concluded that no one method had been invented to identify any given type of damage to any given structure. Furthermore, they noted disagreement in the literature as to the

Fig. 3. Fiber optic sensors are being used for SHM of the Parthenon in Athens, Greece, during renovation. Photo by Lee A. Wymore, used with permission from CRD Group.

effectiveness of various methods, and noted a lack of tests performed in the field. These observations appear to still hold.

In the search for a better method, a number of non-VBDD methods have been developed, especially for use with composite materials such as concrete and fiber reinforced polymers (FRPs) like those used in wind turbine blades. One such method is AE, but as in CM, AE only detects local damage and thus requires sensors close to the point of damage, which may not be feasible on a large structure if the location of damage is not known beforehand. Infrared thermography techniques work well in laboratory settings, but most require the target material to be actively heated, so online monitoring of large structures using infrared is not yet practical. Many other NDE/T techniques suffer from similar setbacks.

For a simpler approach, moisture and temperature profiles of a composite material can indicate health and inform lifetime estimates, as these factors contribute to cracking and delamination. Also, numerous types of sensors, such as piezoresistive strain gauges and fiber Bragg grating (FBG) fiber optic sensors, can be used to simply measure strain on a structure. This type of instrumentation can identify stress hotspots and, with the ability to trend over time, can be used to infer the stability of a structure's health or make lifetime estimates through fatigue analysis. Another straightforward method is to monitor the width of an already-existing crack, looking for changes over time [27,28].

In recent years, a number of enabling technologies for SHM have advanced considerably. For instance, computer chips that contain both a microprocessor and a wireless communication unit now cost only a few dollars. This type of integration and miniaturization allows for the creation of cost-effective and powerful wireless sensor networks (WSNs) [29,30] consisting of self-contained nodes that can be powered with energy scavenged from the environment. Additionally, sensors that can easily interface with such systems, such as sensors based on microelectromechanical systems (MEMS), are becoming more accurate and more prevalent. These sensors are manufactured in mass quantities at low prices using technologies adapted from semiconductor fabrication [31]. With hardware of this caliber available, SHM appears poised to make the transition from scattered research applications to mainstream industry, especially in the monitoring of critical infrastructure such as wind turbines.

In addition to cost and the choice of sensors, SHM presents many more challenges, such as data processing, analysis, and management. Also, SHM is an interdisciplinary field, requiring a range of expertise. For example, the complete design of an SHM system for a wind turbine blade might require an NDT/E expert to understand what needs to be monitored, an electrical engineer to design a sensor, an aerospace engineer to determine where the sensors can be placed, a computer engineer to network the sensors together, a statistician to process the acquired data, and a civil engineer or wind energy expert to make recommendations based on the results.

But these challenges are surmountable. Even in its current form, SHM is being used for a variety of purposes worldwide, from monitoring restoration projects to evaluating critical infrastructure like roads and bridges. In Athens, Greece, the structural integrity of the Parthenon's west facade is being monitored while the monument is being renovated. The monitoring is performed by a fiber optic sensing system designed by CRD Group [32], shown in Fig. 3. In UK, government mandates have encouraged automated SHM systems to evolve from traditional monitoring techniques for structures such as dams and nuclear power plants [33]. In South Korea, an extensive wireless SHM system was deployed to a large bridge and was used to successfully identify characteristics such as mode shapes of the bridge deck [34,35]. SHM applications like these are expected to become more widespread as the technology becomes more affordable and the systems become more advanced.

3. Health monitoring of wind turbines

This section presents background on HM of wind turbines, including the motivations for HM of wind turbines and an overview of turbine monitoring in general. Specific systems for monitoring the various components of turbines are discussed in later sections.

3.1. *Motivation*

HM of wind turbines has a wide variety of motivations because the data collected by an HM system could have many uses. Clearly, in order for an HM system for wind turbines to be viable, the benefits it provides must outweigh the costs of implementing and maintaining the system, as well as storing, processing, and evaluating the data. However, the benefits of an HM system are complex and can be hard to quantify. Below, these benefits are discussed in terms of maintenance, wind farm management, and other motivations.

3.1.1. *Maintenance*

HM can potentially reduce ongoing operations and maintenance (O&M) costs for each outfitted turbine. In 2011, the National Renewable Energy Laboratory (NREL) estimated that annual O&M cost per MW was around $17,000 for a typical onshore wind project and $46,000 for an offshore project [36]. Unlike traditional power plants, these costs are spread out over many distinct but similar structures (the turbines), and over a relatively large geographic area (the wind farm). Additionally, turbines are often located in remote areas, such as offshore, requiring time, money, and planning to visit for inspection or maintenance.

Lower maintenance costs are a traditional benefit of HM because HM allows for more efficient maintenance practices. Current maintenance practices for wind turbines are generally a combination of two strategies [37], known throughout the literature by many names, but referred to here as

1. *Scheduled maintenance* (*SM*): periodically performing a set of prescribed maintenance tasks, such as replacing certain parts and changing gearbox oil.
2. *Reactive maintenance* (*RM*): fixing or replacing components when they fail.

HM enables an alternative, predictive strategy, often referred to as condition-based maintenance (CBM) [38,39], in which the

Fig. 4. Wind turbine failure from high winds shortly after a blade was repaired. Photo by Green Mountain Power, NREL 16713.

Fig. 5. Dynamic characterization testing of a turbine in 1999. The tower is struck with a hammer and the resulting vibrations are measured with accelerometers. Photo by David Parsons, NREL 07388.

operator performs maintenance when a component shows signs of damage or impending failure. This strategy reduces the amount of maintenance required and ensures that the maintenance performed is worthwhile. This reduces O&M costs both in terms of labor and materials, and also improves inventory management.

Additionally, if an HM system provides early warning that the component is failing, the replacement can be secured and the maintenance can be performed at convenience. This reduces downtime and increases production. The notion of convenience can also directly reduce costs, especially for offshore sites. NREL estimates that, for a 500 MW offshore wind farm, O&M costs can be cut by over $20 million per year simply by reducing weather-induced delay for maintenance crews to access turbines [37].

The O&M benefits of HM are frequently cited for the drivetrain, generator, bearings, and other mechanical and electrical components of a turbine, but less so for the major structural components. While structural failures of wind turbines are rare, they do occur. The Caithness Windfarm Information Forum (CWIF), an organization dedicated to halting the spread of wind turbines in the Caithness area of Scotland, tracks all publicly known wind turbine accidents. In 2013, CWIF recorded 29 incidents of blade failure, defined as failure which “results in either whole blades or pieces of blades being thrown from the turbine”. A total of 280 total instances of blade failure have been noted since the 1990s. CWIF also lists 145 instances of structural failure dating back to the 1980s, with structural failure defined as “major component failure under conditions which components should be designed to withstand” [40].

Both blade and structural failure are costly. GCube, a renewable energy insurance provider, reported average claims of $240,000 for blade damage and $1.3 million for foundation damage in 2012 [41]. Gearbox, generator, and transformer damage claims were similarly priced. HM could allow damage leading to failures like these to be identified and repaired before failure occurs [42].

From a more general cost/benefit perspective, for HM to see widespread adoption, the economic benefits of a system must at least recover the costs of installing and maintaining that system. A number of studies have examined these economics. For example, Nilsson and Bertling [43] found that converting 47% of RM events into CBM events would recover the cost of an HM system. Besnard and Bertling [44] found that HM was more economical for wind turbine maintenance than offline NDE or visual inspections when crack initiation rates were high and time to failure was short, assuming regular visual or NDE inspections. Van Dam and Bond [45] estimated that an HM system could recover its costs, purely from CBM benefits, up to 70% of the time.

Finally, maintenance-related benefits of HM can only be realized if the HM system is reliable. Any false positive from the HM system will result in waste from the investigation and potential replacement of a part that is still in good condition. On the other hand, a false negative could allow damage that would have been detected in regular inspections to worsen to the point of component failure. If the operator cannot assume the HM system reliably identifies all faults, then regular inspections or part replacements still need to be performed, and the HM system becomes less attractive.

3.1.2. *Management*

HM of wind turbines could also have a number of benefits in terms of wind farm management, such as increasing power production. For instance, HM data could be used to provide input and feedback for a control system used to dynamically pitch the blades, maximizing individual turbine output. Similar systems are already being used to mitigate blade stresses [46–48]. Or, data could be shared among turbines to combat wake effects or provide advance notice of weather conditions, optimizing generation for the entire wind farm.

HM could also increase generation by minimizing downtime; if a component fails with no warning, the turbine may not be able to generate electricity for the time it takes to acquire a replacement, hire the needed transportation and installation equipment, schedule a favorable maintenance window, and perform the maintenance. But if the HM system provides advance warning, the turbine could be operated up until the maintenance window. Studies indicate that decreased downtime could have large economic benefits; for example, Nilsson and Bertling [43] found that a 0.43% increase in availability would recover the costs of an HM system.

HM could also be used to quickly verify structural safety [14] and estimate remaining lifetime. This could be useful for bringing turbines back to online after an earthquake, lightning strike, or storm. Additionally, this type of information could guide the process of turbine retirement and refurbishment, allowing a turbine or parts of a turbine to safely continue operating beyond their original life expectancy. This data could also allow a turbine to be automatically shut down if stresses exceed a threshold, both preventing failure and helping to mitigate public safety concerns regarding wind turbines. Data about ice formation on blades could be used for a similar purpose [49].

As an example of how an HM system could help with management and with maintenance, Fig. 4 shows a turbine that dramatically failed in a severe wind storm after a blade had recently been

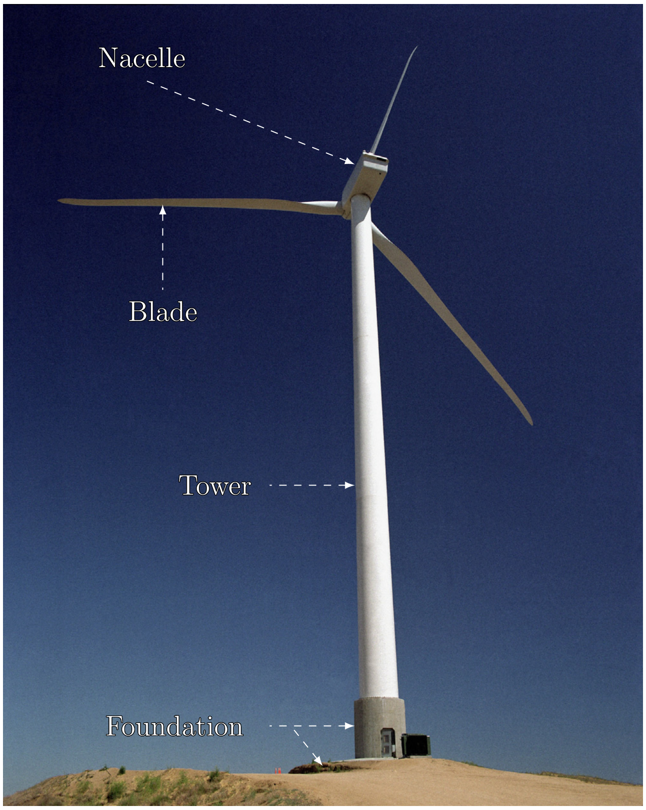

Fig. 6. Major components of a HAWT, as they are discussed here. Adapted from a photo by Warren Gretz, NREL 11148.

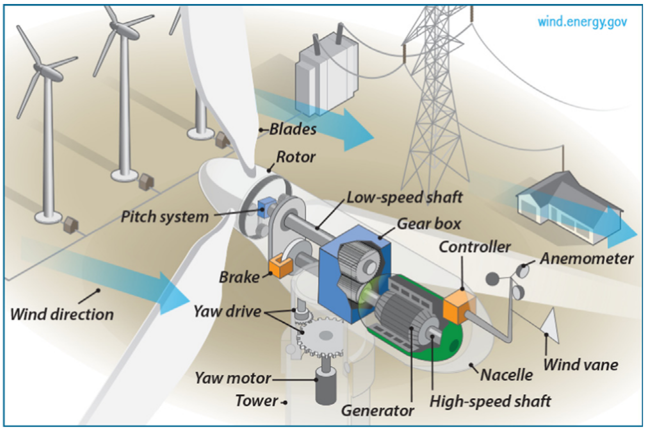

Fig. 7. Cutaway illustration of a wind turbine nacelle. Image from the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

Fig. 8. Installing a gearbox. Photo by Jeroen van Dam, NREL 19257.

repaired. Ideally, an HM system would have been able to both verify if the blade was functioning properly after the repairs, and automatically shut down the turbine and feather the blades during the storm to prevent this failure. This figure also illustrates how a single failure in a wind turbine can cause a complete system failure, making the case for HM even stronger.

3.1.3. Other

The data gathered from an HM system could have a variety of other uses. Strain and dynamic response data could be used to identify structural weaknesses and inform future designs, which could lead to greater reliability or less conservative designs that use less material. An HM system could also be used to monitor environmental conditions that a turbine depends upon, such as permafrost in Alaska and similar locations.

Finally, the type of data gathered from a monitoring system should not necessarily be restricted to traditional HM data. For example, a monitoring system could collect data to help researchers better understand wind farm wake effects, a serious source of power losses [50]. Or, a wildlife monitoring system could trigger a reduction in turbine speed at the approach of a large body of birds or bats, further improving the environmental-friendliness of turbines [51].

3.2. Overview of turbine monitoring

HM for wind turbines is a developing field. While commercial products for monitoring of some components exist [12], and all components have at least had experimental systems tested, the wind energy industry has not yet embraced HM on a widespread basis. Still, related research, such as the dynamic characterization testing shown in Fig. 5, has been ongoing for years [52].

As previously discussed, any HM system needs a positive return on investment to see widespread adoption. For wind energy, this poses a particular challenge because of the nature of a wind farm. A turbine may not be as large as a large bridge or skyscraper, but there could be hundreds or even thousands of them to monitor in a wind farm [53]. This could provide advantages such as design reuse and mass manufacturing, but such advantages are not likely to overcome the current high cost of many kinds of sensing systems that could be used for SHM of wind turbines. Thus, improvements to the basic sensing technology are still important.

Furthermore, mass deployment of a monitoring system requires that installation, setup, and maintenance of the system be simple and inexpensive. Ideally, these tasks could be performed by a technician with minimal training. To maximize the potential uses of acquired data, either sensor placement needs to be standardized so that readings between turbines are comparable, or the system needs to be designed flexibly, such that differences in placement of the sensors between turbines are not a concern.

Another factor for wind turbine monitoring systems is lifetime. Most wind turbines are designed to last at least 20 years, and recent research suggests that they will [54]. A monitoring system would be expected to last just as long, or longer, as monitoring could be used to extend the lifetime of a turbine if the system is able to judge the turbine still structurally sound. Thus, a monitoring system must be robust and long-lived. It must be maintainable, but given the potential scale of a deployment, it should not require regular maintenance, such as manual data collection or replacement of batteries. Both low maintenance and long life will help increase a system's cost-effectiveness.

A final challenge for wind turbine HM is adoption. As Mobley [16] describes, justifying the installation of any monitoring system is difficult; quantifying its benefits after installation is even harder. Currently, adoption decisions must be made based on a limited pool of data. To aid in the adoption of HM in the industry, research in monitoring for wind turbines should aim not only to increase the attractiveness of HM systems, but also to increase the amount of cost/benefit data available for decision-makers interested in implementing a monitoring system.

These are some of the general challenges of designing an HM system for wind turbines. In the following sections, specific challenges and the current state of monitoring for each major component of wind turbines, as depicted in Fig. 6, will be discussed. The discussion assumes an upwind horizontal axis wind turbine (HAWT), the most common type of turbine in utility-scale wind today. This type of turbine is used both onshore and offshore, and the challenges of both will be addressed. While this discussion focuses on megawatt-scale turbines, due to their role in utility generation, many of the challenges and techniques are applicable to smaller turbines as well.

4. Nacelle

The nacelle, positioned on top of the tower, houses the mechanical and electrical equipment used for generating electricity. A cutaway view of a nacelle is shown in Fig. 7. The rotor blade assembly's hub attaches to the nacelle, and the nacelle yaws, or rotates around the axis of the tower, to point the blade assembly into the wind. Inside the nacelle, the drivetrain connects the blade assembly to the generator, often utilizing a gearbox to scale the rotational speed of the shaft connected to the blade assembly up to the rotational speed required by the generator. Other major components housed in the nacelle are the yaw control system, which keeps the turbine pointed into the wind, and the bearings for the yaw system and for the main drive shaft. In general, the components housed in the nacelle can be monitored with well-developed CM techniques similar to other industries, as discussed in Section 2.1. The power converter used to condition the generated electricity should also be monitored, and may be housed in the nacelle or at ground level.

The gearbox is a component of particular concern. Gearboxes have been identified as a leading contributor to turbine O&M costs, and gearboxes in general have not been meeting their design lifetimes, to the point where NREL has established a special program, the Gearbox Reliability Collaborative, to address the problem [55]. Eric Bechhoefer from Renewable NRG Systems illustrates the ideal case for how CM can help: an uptower repair for a gearbox that was identified as needing repair via CM might cost $50K, whereas the fix if the gearbox had instead operated to failure could be as much as $400K, including $250K for the new gearbox and $150K for the crane to swap the new gearbox for the old [56]. Fig. 8 shows a crane being used during a gearbox installation, which includes first bringing down the blade assembly. Direct-drive turbines with no gearbox are also available, but the permanent magnet generators used in these designs tend to be more expensive than the induction machines used in geared systems.

4.1. Existing systems

Monitoring of the components housed in the nacelle is the most well-developed and market-penetrating type of wind turbine monitoring. For instance, supervisory control and data acquisition (SCADA) systems that are built into turbines for the purpose of controlling electricity generation are also increasingly used for basic CM purposes, often through software packages that analyze the data already being collected. For example, changes in electrical output of the generator can indicate impending bearing failure in the drivetrain [57,58] or asymmetries and eccentricities due to other mechanical failures in the generator [59]. As the data required for this type of analysis is already being gathered by SCADA systems, these methods have potential as an inexpensive solution for CM [60]. For a more complete discussion of commercial SCADA systems and analysis packages, see [13].

Another approach to CM is to deploy a system that uses sensors such as accelerometers to collect data more directly related to HM. More and more, this sort of commercial CM system is being integrated into the SCADA system [61], either borrowing data from the SCADA system, or allowing CM results to be integrated into the SCADA displays. Ideally, CM and SCADA systems will continue to merge over time, eventually resulting in one comprehensive system that uses collected data to both provide control feedback and perform HM.

Most commercial CM systems for wind turbines utilize some form of vibration monitoring, similar to established methods in other industries. One notable difference and challenge for wind turbines is the variable speed operation of many types of turbines. While traditional fast Fourier transform (FFT) methods have been developed for machinery that runs at constant speed, the operational speed of a large wind turbine typically depends on the speed of the wind, so data from two points in time may not be directly comparable. Some commercial CM products use other techniques such as AE and MCSA, discussed in Section 2.1, and many also implement basic oil monitoring. An extensive list of commercial systems for CM of wind turbines is given in [12]; a few of these products are discussed here only to illustrate the capabilities of a typical system, and not to evaluate the systems in relation to each other.

An example of a commercially available product is GE's Bentley Nevada ADAPT Wind system [62], which GE claims has saved customers up to $3000 per turbine per year for new units. The system focuses on monitoring of the gearbox, generator, and main bearing, all using accelerometers connected by wires to a processing unit housed in the nacelle. The ADAPT system also uses the turbine's control system as an input, and the ADAPT system can be integrated into the turbine's SCADA system. Tower sway and gearbox oil condition can also be monitored with the ADAPT system.

Many manufacturers have similar CM systems. Turbine manufacturer Siemens has a system [63] which they specifically note can automatically shut down a turbine, if needed [64]. CM systems for wind turbines are also available from third parties, such as Renewable NRG Systems' TurbinePhD [65]. Some systems have even taken a step past HM and into automated maintenance; for example, SKF's WindCon online CM system can inform SKF's WindLub system

Fig. 9. A typical onshore wind turbine foundation, before backfilling. Photo from the Bureau of Land Management, US Department of the Interior.

when bearings are low on lubrication, and the WindLub system will automatically deliver grease to the bearings [66].

4.2. Future

As discussed, nacelle HM is relatively well-developed and commercialized. One potential area for improvement is more advanced oil analysis. In 2011, Hamilton and Quail [18] reviewed the potential use of various oil analysis technologies for online wind turbine gearbox monitoring. They recommended a combination of techniques be used to achieve sufficient accuracy and diagnostic detail while utilizing cheaper and smaller-scale technologies. For monitoring oil quality, they recommended a combination of fluorescence spectroscopy, Fourier transform infrared spectroscopy (FTIR), solid state viscometers, and photoacoustic spectroscopy. For analyzing wear particles, they recommended ferrography, particle counting, fluorescence spectroscopy, and a simple electrical constant sensor. They believed these technologies could be integrated into one sensing system.

Currently, online oil monitoring is mostly used to detect changes in oil quality or particle count, and offline analysis of a spot sample is used to diagnose the cause of the change [67,21]. The oil monitoring capabilities of the commercial CM systems listed in [12] are essentially limited to trending changes. However, technologies such as FTIR and linear variable filter-based mini spectrometers have high potential for more detailed online diagnosis in the future [61].

Other improvements to nacelle HM could include wireless monitoring systems. In addition to reducing cable clutter, wireless solutions allow for easier installation and use in locations where cabled solutions are not feasible. This technology is available and ready for the transition to industry. For instance, as far back as 2006, BP, Intel, Rockwell, and Crossbow explored the use of a WSN for CM in the engine room of an oil tanker. They found the wireless performance to be satisfactory and their trial system to be robust in the harsh conditions of the ship [68]. However, sustainably powering WSN nodes is a challenge and an area of ongoing research.

Another area for continued research is cost-effective sensor technology. Since the attractiveness and extensiveness of a monitoring system is limited by its price, the development and testing of cheaper sensors for such systems is imperative. For instance, accelerometers based on MEMS can be a small fraction of the price of conventional accelerometers, but these accelerometers currently suffer from noise and resolution constraints. Initial research has shown that MEMS accelerometers have potential for CM of machinery [69,31], but the use of such technology has yet to be proven in the field.

5. Foundation

Onshore wind turbine foundations are typically steel rebar-reinforced concrete, as shown in Fig. 9. A number of different foundations and foundation concepts exist for offshore turbines. For both onshore and offshore turbines, the choice of foundation depends on the location and the environmental conditions. For instance, soil quality and strength affect the size and shape of onshore foundations, whereas water depth is a deciding factor for offshore turbines.

Therefore, a challenge of foundation monitoring is the wide spread of foundation types, even for a given turbine model. Another challenge is that, for onshore turbines, a monitoring system likely needs to be installed during construction. Turbine foundations are often poured by local concrete companies, and installing a sensor system during construction may require extra coordination between these companies and technicians. Finally, for both onshore and offshore turbines, durability and accessibility of sensors is a concern. The long-term survivability of sensors embedded into concrete has yet to be proven [70], though some sensors, such as a MEMS cantilever-based temperature and humidity sensor, have shown promise [71]. Should such a sensor fail, accessing it for maintenance is impractical. Offshore foundations present similar challenges, as sensors may be immersed in salt water, requiring special packaging and diver-based maintenance.

Offshore turbine foundation monitoring systems can build on the experience of monitoring for other offshore platforms, such as offshore oil rigs. However, turbine structures tend to be less massive than these platforms, while the nature of a turbine guarantees the structure will experience large forces from the wind, as well as the waves. Turbine structures are thus designed more for dynamics than bearing capacity [72], and this difference affects the goal and methods of a monitoring system.

5.1. Existing systems

In general, turbine foundation HM is currently limited to research activities and spot applications. Offshore foundation monitoring has received more attention than onshore monitoring, likely due to the more challenging conditions, the more complex structures, and the large number of questions still surrounding the design and deployment of offshore turbines. One example of offshore turbine foundation SHM began in 2010, when a specific failure mode in offshore monopile foundations was detected. The grout between the pile foundations and the tower's transition piece was failing, causing the tower to slip downward by more than 25 mm until caught by supporting brackets used during construction [73].

Strainstall Monitoring installed SHM systems that consist of strain gauges, displacement sensors, and accelerometers. Stresses on the brackets are monitored and fatigue life of critical areas is calculated. Additionally, natural frequencies of the tower are tracked, since a change in tower frequencies could indicate a foundation problem, and some of the systems use inclinometers to track the angle of the tower as well. The sensors are wired to a DAU, and in most cases, data is transferred offsite over a broadband connection. However, in areas where such a connection is not available, hot swap hard drives are collected periodically from the DAU. While originally installed as a reaction to a specific failure mode, these systems have been successful enough that Strainstall has been requested to install them on new turbines as well [74].

An extensive monitoring system has been installed at the Belwind offshore wind farm in the North Sea. The system is an Offshore Wind Infrastructure Lab (OWI-Lab) project, in conjunction with BruWind, Zensor Corrosion Control, and Vrije Universiteit Brussel [75]. The system includes corrosion monitoring for the

Fig. 10. On-site assembly of steel wind turbine tower sections. Photo by Dennis Schroeder, NREL 20843.

foundation using sensors from Zensor [76], as well as load and displacement monitoring for grouted connections and dynamic monitoring for the global structure.

Brincker and Ibsen [77] instrumented a Vestas 3 MW turbine with accelerometers in order to assist a finite element model (FEM) in performing fatigue analysis on a new offshore “bucket” foundation design, with the goal of aiding the design of the foundation and its installation process. The accelerometers used were on the order of a thousand dollars each. This study did not include any submerged sensors, but the type of data used in this study has been gathered underwater in the past using an FBG-based system [78].

In general, in the harsh and noisy environment of offshore foundations, simple solutions that monitor a particular failure mode may be more immediately practical than global monitoring solutions. For instance, for a foundation where posts are inserted into pre-piled jackets in the seabed, the performance of the grouted connection between the post and the jacket is a concern [72]. Instrumenting such a connection with a subsea extensometer is feasible with current technology, and the data would be easy to interpret using a simple threshold-based trigger.

Another potential failure mode of offshore foundations is excessive scouring, where the water erodes the seabed around the foundation's pile to the point of structural instability. Strainstall has a scour monitoring system that tracks the progress of a magnetic collar down the length of a metal tube embedded in the seabed. As the soil is eroded, the collar slips down further, triggering an alert whenever it passes one of the sensors distributed along the length of the tube [79]. Michalis et al. [80] proposed a similar solution, but with no moving parts. A probe with sensors distributed along its length is embedded into the seabed. The sensors have two steel rings that, if buried, have soil between them. If the sensor is uncovered, the capacitance between the rings changes, indicating scour progress.

Onshore foundation monitoring has received minimal attention, though failures do occur. While these failures are often because of installation errors such as improperly tightened tower anchor bolts [81] or improperly settled concrete [82], a monitoring scheme could provide early warning of these issues. Anchor bolt monitoring could be useful to reduce manual inspections, as research has suggested that bolt tension should be checked once every two years [83]. Additionally, foundation monitoring could contribute to a quick evaluation of structural integrity after an earthquake or high-wind conditions, as well as provide peace of mind regarding aging turbines still in service.

Onshore foundation monitoring systems that have been deployed have mostly focused on research of loads and fatigue for design purposes, not SHM. Renewable Energy Systems (RES) Americas and NREL [83], in conjunction with Canary Systems [84], instrumented a gravity base foundation for an 80 m tower. The sensors included earth pressure cells to measure contact pressure between the foundation and the soil, strain gauges to measure strain on the foundation's reinforcement steel, and bolt load cells to measure the tension of the anchor bolts. The sensors were wired into a DAU housed in the tower, and the data was sent to an offsite server over a cellular connection. An example result from the study was that the vertical pedestal reinforcement steel experienced significant load, validating its presence as a critical part of the foundation.

5.2. Future

As further foundation failure modes are identified, solutions specific to these modes can be developed. For example, Currie et al. [85] have begun an SHM study for onshore foundations. They describe a common failure mode for embedded can-type foundations, where the protective coating between the tower and foundation cracks, allowing moisture to enter and erode concrete around the steel can embedded into the foundation. This results in potential vertical movement, up to tens of millimeters, of the tower. The authors proposed a simple monitoring solution to detect this vertical movement at the foundation level, using either infrared, linear variable differential transformer, or Hall-effect sensors. While this solution is straightforward, this particular failure mode may also be detectable by accelerometers attached to the tower for tower monitoring.

Failure mode-based monitoring can be useful, but more general concrete monitoring could also be helpful, especially for onshore foundations. Concrete monitoring systems have been designed and tested for other types of civil infrastructure, such as roads, bridges, and tunnels. Such monitoring has been estimated to provide large reductions in the operating cost of these structures [86]. Onshore turbine foundation monitoring has thus far been largely strain and vibration sensing, but concrete monitoring systems may also measure the temperature or moisture profile of the concrete. These factors contribute to effects such as creep, shrinkage, and deformation [87]. Monitoring of these factors is typically used to expedite the construction process, and commercial systems for temporary temperature and moisture monitoring exist [88].

Another possible method for concrete monitoring is to use AE to track crack propagation [89–91]. Combining AE with temperature and moisture sensing can not only allow for monitoring of the structure, but also lead to better understanding of the structure's response to its environment [92]. The freeze-thaw cycle, for example, is known to contribute to concrete degradation, as is contact with seawater [93].

A concern particular to reinforced concrete is corrosion of the steel reinforcement bars. Polder et al. [94] demonstrated that early detection of corrosion could provide large cost savings. Early detection can be accomplished with a variety of embedded sensors [93]. Since corrosion is an electrochemical process, embedded reference electrodes can detect corrosion via changes in electrochemical potential. Corrosion risk can be monitored with the well-proven “anode ladder system,” which tracks the progress of corrosive conditions using dummy steel bars embedded at various depths in the concrete. These conditions can also be tracked using moisture and chloride sensors.

In terms of wireless advancements, both offshore and onshore foundations present challenges. Underwater sensor networks that use acoustic signals for communication are a current research topic [95]. For onshore foundations, the challenge is concrete. Radio frequency (RF) signals such as those used by WSNs experience fast attenuation when traveling through concrete [96]. This means that high transmission power is required to successfully transmit an RF signal through concrete, and a sensor node embedded in concrete cannot be easily accessed for a battery change.

In an attempt to circumvent this issue, Ong et al. [97] developed a passive wireless moisture sensor suitable for embedding into concrete. The sensor is based on an inductor–capacitor resonant circuit whose resonant frequency can be remotely queried using a loop antenna [98]. As moisture increases, the dielectric constant of the capacitor's insulator increases, changing the capacitance and the resonant frequency of the circuit. This type of sensor is practical for embedding into concrete because it is robust and requires no power source. However, the required querying unit and the limited querying range make continuous online monitoring with this type of sensor challenging. Radio-frequency identification (RFID) sensors of a similar nature have also been tested [99], but suffer from the same challenges for continuous monitoring.

6. Tower

The wind turbine tower supports the nacelle and blade assembly and allows access to the better wind resources typically found at taller heights. Together with the foundation, the tower must bear not only the weight of the upper turbine components, but also the horizontal forces of the wind on the turbine blades and the rotational forces of the nacelle yawing into the wind. Clearly, the tower is a crucial part of the turbine structure; failure of the tower results in total failure of the turbine. HM can help prevent such failure.

Currently, the most predominant type of wind turbine tower is the tubular steel tower, made of large steel rings welded together into long sections, shown in Fig. 10, which are bolted together during assembly. The World Steel Association claimed in 2012 that about 90% of all turbine towers were tubular steel [100]. These towers are typically around 80–100 m tall, but, in order to produce more power, the trend is toward even taller towers. This has led to alternative tower designs, such as Iowa State University's Hexcrete tower concept [101]. Operators installing GE's 2.75 MW wind turbines currently have a choice of a tubular steel tower of up to 110 m, a 139 m steel/concrete hybrid tower, or a 139 m space frame tower [102].

This variety of designs could lead to a variety of HM systems. The space frame tower concept resembles the steel lattice towers of the early utility-scale wind energy years, but provides an enclosed internal space and is assembled with special bolts that do not require the ongoing maintenance that plagued earlier lattice designs [103]. Thus, in many ways, monitoring the space frame tower should be similar to monitoring a tubular steel tower. Similarly, monitoring a concrete/steel hybrid should be similar to a combination of tubular steel monitoring and concrete foundation monitoring. Therefore, the remainder of this section will focus on tubular steel towers, the dominant product in the market today.

A steel tubular tower is relatively easy to globally monitor using VBDD, but cost is a concern. Sensors can be placed around the weatherproof interior of the tower with minimal trouble. However, the vibrations of such a large structure are very low frequency, with first natural frequencies below 1 Hz [104]. Traditionally, more expensive sensors are required to obtain accurate measurements at such low frequencies. Once such measurements are acquired, damage can be diagnosed using a variety of methods, as noted in Section 2.2. Thus far, systems have tended toward classic methods such as trending natural frequencies or modal parameters, sometimes with the aid of an FEM. Strain and tilt measurements can also be used for fatigue analysis and lifetime prediction.

6.1. Existing systems

Aside from tower sway monitoring built into some turbine CM systems, tower HM has seen little commercialization. However, a number of research systems have been created. One of the most complete turbine SHM systems was a tower monitoring system designed and implemented by Smarsly et al. [105]. The system was installed on a 65 m turbine tower in Germany in 2009 and had been operating continuously for several years at the time of writing of [105]. The sensor array includes nine accelerometers, six inductive displacement transducers, temperature sensors for compensation, and an ultrasonic anemometer mounted on a separate mast next to the tower. Wired DAUs feed the data from the sensors into the server located inside the turbine tower, which also receives data from the turbine's SCADA system. The server periodically sends the data over a DSL connection to an offsite server, where the data is converted and stored in SQL tables. From here, the data is available for remote access via a database connection or a web interface.

The monitoring software extracts modal parameters from the measurement data and uses them to update an FEM. Artificial damage is introduced into the FEM, and the resulting response profile is recorded in a damage catalog that can be used for quick diagnosis in the event that real damage occurs. The stochastic loading data of the structure can also be used for computing failure probabilities and thus lifetime estimates [106]. Finally, the system also features extensive self-monitoring and fault detection to make it as reliable and self-maintaining as possible [107].

Rolfes et al. proposed the Integral SHM-System [108], which compares dynamic stress to vibrational velocity to detect stiffness reduction in a tower. Measurements are used to produce a validated FEM that is used to diagnose damage location and severity. Swartz et al. [109] tested the instrumentation system, composed of eight accelerometers and two strain gauges, on two turbine towers in Germany. They were successfully able to identify the first three modes of a 78 m Vestas tower. The accelerometers used currently cost hundreds of dollars each. The sensors were connected to DAUs that communicated wirelessly with a central unit.

The OWI-Lab monitoring project uses a similar array of accelerometers to perform advanced operational modal analysis (OMA) on an offshore turbine tower. Modal parameters are automatically extracted from the data and tracked over time [110].

Brincker and Ibsen's 2003 foundation study [77] also included tower instrumentation. The gathered acceleration measurements were integrated twice to find displacements, which were used to identify mode shapes. These were then used in a finite element analysis, and the resulting model, to be used in fatigue analysis, was able to calculate displacements and stresses anywhere in the

Fig. 11. Manufacturing of a wind turbine blade. Two outer shell halves can be seen. Photo from SNL.

structure. Similarly, Bang et al. [111] mounted FBG sensors on the inside shell of a 70 m tower and used the online strain measurements to find mode shapes of the tower.

Guo et al. [112] analyzed existing tower vibration data from a single up-tower accelerometer using the nonlinear state estimation technique (NSET), a nonparametric modeling technique that uses past observations to predict future observations, based on the input conditions. If the model prediction deviates significantly from measured values, damage could be present. They found that the model predicted vibrations well, and an offline application of the method was able to detect an anomaly in the data shortly before the turbine was shut down to fix an asymmetrical blade condition. This result illustrates an interesting opportunity in wind turbine HM: the components in turbine structures are so tightly coupled that monitoring one component can reveal problems in another. However, this tight coupling is also a challenge, as it can introduce non-random noise into measurements.

6.2. *Future*

The largest obstacle for widespread turbine tower monitoring is likely the cost/benefit tradeoff. Traditional monitoring systems are expensive, and tower failure is rare and often caused by the foundation or the blades. Therefore, tower monitoring is currently motivated by dynamic characterization as often as damage detection. However, the possibility of cross-component monitoring, such as that discussed regarding [112] in the previous section, may make tower HM more attractive, especially with decreasing sensing system costs.

Some non-traditional sensing systems have been used for towers, and an innovative deployment of these systems could provide continuous HM. Chen and He [113] were able to measure the first natural frequency of a tower using a microwave radar system from over 1 km away from the tower. While price may prevent a permanent monitoring system using this technology from being feasible, the technology does have the advantage of being able to monitor several turbines at the same time, as long as they are all within its panoramic line of sight. Other similar remote monitoring technologies, such as light detection and ranging (LIDAR) systems, have also been proposed for turbine monitoring [114].

Few studies have used non-VBDD methods for tower SHM. Benedetti et al. [115] proposed using perturbations in the local strain field as a damage indicator and validated the method on an FEM of a turbine tower. While straightforward, this method does not provide the convenient global damage detection of VBDD, requiring strain sensors in the area immediately surrounding the damage. A wireless deployment could make this technique more feasible.

Since the towers are steel, electromagnetic or magnetostrictive testing could be a possibility, but these methods currently lack feasibility as continuous monitoring solutions. Optical methods such as image processing could also be useful for detecting surface damage, such as to the tower's anti-corrosive coating. These methods have been explored for turbine blades, but little research has been done into monitoring surface damage of towers, again likely due to the cost/benefit tradeoff.

7. Blades

A wind turbine's blades are responsible for transferring the horizontal force of the wind into the rotational force that drives the turbine's generator. Modern megawatt-scale wind turbine blades are typically over 40 m long and made of layers of glass fiber reinforced polymer (GFRP) material bonded together using a resin. GFRP offers a cost-effective solution to the weight and strength tradeoff that blade designers must balance. Longer blades may use carbon fiber reinforced polymer (CFRP) to increase strength and reduce weight, but the cost of CFRP can be prohibitive. Balsa wood adds extra bending stiffness to the shell of the blade [116].

Blade manufacturing is largely still a manual process, as shown in Fig. 11. The blade structure consists of three parts: two outer shell halves, and an inner shear web. The shear web creates an I-beam inside the blade, allowing for more strength with less material and weight. The blade's cross-section shape, or airfoil, creates the lift force on the blade that produces torque, turning the shaft in the nacelle and generating electricity. The blades connect to the hub with bolts that screw into the root section of the blade. The root itself is a cylindrical structure made of layers of GFRP. A gel coat over the outside of the blade provides protection from minor impacts and moisture, which can cause delamination, the separation of the layers of FRP. Within the hub, a pitch-control system rotates each blade to change its angle-of-attack to the wind, either to increase energy capture, reduce load, or provide aerodynamic braking [117].

Blade HM is particularly challenging because the aerodynamics of the blades are critical for efficient power production, so an SHM system must not interfere with these aerodynamics. Additionally, blades rotate and experience other stochastic loads, such as wind and yaw forces, which creates a noisy sensing environment. An SHM system may monitor various blade characteristics, but distinguishing between damage and changes in the environment can be especially difficult for blades. Fluctuations in temperature, weather, and wind speeds can all cause false positive damage alarms. Additionally, a blade monitoring system's hardware is likely to be exposed to harsh environmental events, such as wind gusts and lightning strikes. Finally, cost presents a particularly large obstacle for blade SHM, because the technologies best suited for monitoring blades tend to be expensive.

7.1. *Existing systems*

Commercial blade monitoring systems have mostly been used for load monitoring applications. As early as 2005, an article [118] discussed two different commercial systems for blades. The two systems, developed by Smart Fibres Ltd. and LM Wind Power (then LM Glasfiber), use FBG sensors to measure the strain in the blade. Though marketed as load monitoring systems, these systems also possess the potential to detect some types of blade damage before failure. Additionally, the LM claims the system can reduce loads by 10–30%, potentially increasing blade lifetime.

The 2014 report by Crabtree et al. [12] lists three commercially available fiber optic systems for blades. Fiber optic sensors are capable of detecting temperature, displacement, acceleration, and strain [119]. Manufacturers can install the sensors during manufacturing, which could provide quality-control during the manufacturing process. Alternatively, wind plant operators can retrofit sensors onto existing blades. Many operators consider fiber optic systems expensive, but the combined purposes of load monitoring, damage detection, and quality control may make these systems more attractive as blades become larger and more expensive.

The Crabtree report also lists several VBDD systems, including one composed of accelerometers that are bonded directly to the blade exterior and connected by wires to a DAU in the hub that communicates wirelessly with a receiver in the nacelle [120]. Similar sensors can also be placed inside blades. These sensors can monitor the motion, path, and vibrations of the blades during operation. Changes in any of the monitored characteristics can indicate damage in the blades or rotor hub. Yang et al. [121] noted that VBDD systems can provide useful data at low cost, but are limited by the lack of specific information provided by the data. VBDD systems cannot give information concerning damage type or location. In addition, variability in the wind can cause features in the data that are unrelated to blade or hub conditions.

Due to cost and technical difficulty compared to laboratory settings, few field tests have been performed for SHM of blades. In one example, Schroeder et al. [122] documented the use of a fiber optic system in a blade over the course of two years. The system includes one temperature and six strain sensors. The sensors were attached to the interior of the blade and were capable of detecting strain characteristics over the course of operation. Though the system was not designed for SHM, this type of strain data could be used for fault detection and active safety control. In another example, Blanch and Dutton [123] performed field tests with an AE system. The sensors were attached along the length of the outside of the blade. The tests were performed while the turbine was held static and the blade was artificially loaded. Due to this test method, the system is not practical for commercial use. Online tests were also performed, but the results were inconclusive.

Sandia National Laboratories (SNL) has a SMART Wind Turbine Rotor project [124] that uses sensors to provide feedback to an active aerodynamic control system in the blade. In a field test, the sensing array consisted of accelerometers, metal foil strain gauges, and fiber optic strain and temperature sensors, all of which were housed inside the blade. The blade contained several modifications to protect the sensors from electrostatic discharge, including copper mesh in the skin and a conductive gel coating for the outside of the blade. This protection was required not only for lightning, but also for the electric charge created from the friction of the blade moving through the air.

A research group in Greece has had success in field monitoring with an off-the-shelf AE system applied to a turbine blade [125]. Wired AE sensors connect to a wireless transmitter in the hub, which communicates with a wireless router at the bottom of the tower. This router then connects to the Ethernet network of the turbine, allowing the data to be transmitted over the Internet.

Contrary to the limited number of field tests, numerous tests have been done in laboratories. In a major example, SNL and NREL coordinated with other institutions on tests of a variety of SHM systems for a 9 m test blade [126].

- 30 strain gauges were installed on the gel-coat surface of the blade.
- 24 PAC Model R6I AE sensors were mounted over critical areas on the blade and interfaces inside the blade. The AE system noted significant AE events and then clearly followed the evolution of blade failure.
- NASA implemented an SHM system that included a macro-fiber composite (MFC) actuator and three sensors on one side of the blade and an MFC actuator and two sensors on the other side. The data collected was noisy, but trends in the data were able to identify cracking events.
- Purdue University implemented an array of high sensitivity triaxial accelerometers, low-frequency capacitive accelerometers, piezoelectric actuators, and force sensors distributed over the surface of the blade. The system was capable of detecting and identifying different types of damage.
- Virginia Tech implemented an impedance-based system that consisted of six self-sensing MFC actuators and an impedance analyzer. Though previous tests of this system on a different blade were promising, in this case, the VT test system detected no damage because the sensors were not located close to the failure.

In a different test, NREL, Sandia, and a blade manufacturer worked together to test a blade with bonded piezoceramic patches that both generate and receive stress waves [127]. The raw signals received from sensors near the final failure showed recognizable changes in stress wave parameters. Since this method requires generation of test waves, the interval between tests must be chosen carefully to ensure that damage is detected as early as possible.

Risø National Laboratory compiled test information concerning SHM using AE and fiber optic sensors. Several tests determined the detection and identification capability of the systems [128]. Optical methods such as photogrammetry and laser interferometry have also been tested [104], but these methods suffer from high cost and poor feasibility as continuous monitoring systems.

7.2. *Future*

HM applications outside of wind energy show the capability of alternative methods for monitoring composites like those used in wind turbine blades. Some examples include advanced online AE and active ultrasonic methods developed for composite pressure vessels, solid electrolyte electrochemical sensors for moisture determination in fiberglass and CFRP, and fiber optic sensors using evanescent waves to measure moisture content demonstrated in flight tests on aircraft [129]. A piezoelectric-based embedded sensor/actuator network applied to an aircraft wing for structural integrity monitoring has also proven to be effective. The system employs an ultrasonic guided wave to detect, locate, and monitor damage [129]. Finally, the wind energy industry already uses ultrasonic testing techniques for blade evaluation, but not in an online SHM scenario [130].

Wireless sensors for blades have been proposed [131], and commercial blade monitoring systems frequently use wireless communications between the nacelle and the DAU housed in the hub. However, these systems have not addressed the most difficult challenges of using multihop WSNs with blade monitoring, such as finding a sustainable power source for sensor nodes, or a solution for placement of nodes such that they can be accessed for maintenance, yet do not interfere with blade aerodynamics or structural integrity.

8. Conclusions

HM of wind turbines is in its infancy, but growing strong. The various components of a turbine each present unique challenges to overcome, and the maturity of the HM systems available for the different components varies. CM systems for the mechanical and electrical components inside the nacelle are common, especially in new turbines, but SHM systems for the foundation, tower, and blades are mostly limited to experimental and research installations.

Future work in nacelle monitoring should focus on lowering the cost of the CM systems and improving the usability of the systems for operators. Work in foundation and tower monitoring should include identifying the failure modes of these components and investigating the cost/benefit tradeoffs of monitoring them, with offshore scenarios being a priority. Blade monitoring research should focus on decreasing system cost and improving feasibility for long-term, continuous monitoring, with field studies being preferable.

For wind turbines in general, most SHM-related field studies have focused on instrumentation, with few creating complete SHM solutions. Making the transition from a simple instrumentation system to a useful HM system is challenging, but necessary for the benefits of HM to be realized. This transition requires multi-disciplinary work and knowledge, but should be a focus for future research.

One of the barriers between simple instrumentation and useful HM is the difficulty in collecting, storing, and processing the massive amount of data for a wind farm. Ongoing HM should not be labor intensive, nor should it require an expert, so whatever data processing methods are used should produce straightforward and easy-to-interpret results.

The massive amounts of data generated can also be a powerful tool, and can aid in damage detection by statistical pattern recognition, a type of technique that some researchers consider to be the future of HM [23,14]. Cross-referencing data across wind turbines may lead to effective analysis methods, but most SHM systems are experimentally deployed on a single turbine. Future work in HM of wind turbines should explore the unique possibilities of processing data from hundreds of these highly similar structures. Additionally, research should focus on making HM systems easier to install and use, such that a wind farm-scale deployment would be feasible.

Finally, economic benefits are likely to provide the greatest motivation for HM adoption. Though the potential for cost-saving is widely acknowledged, analytical studies have shown mixed results for current technologies. Therefore, research in HM for wind turbines should also focus on reducing the cost of the HM system and its installation and maintenance, as well as on increasing the probability of detection of faults, so that the economics of HM systems are more attractive. Additionally, research should strive to produce case studies with cost/benefit data usable throughout the research community and industry.

References

[1] Global Wind Statistics 2014. Technical report, Global wind energy council; 2015.

[2] Iowa Wind Energy. Technical report, American wind energy association, Available from: ⟨http://awea.files.cms-plus.com/FileDownloads/pdfs/Iowa.pdf⟩; 2015.

[3] Corporate Responsibility Report 2013. Towards a sustainable energy future. Technical report, Red Eléctrica Corporación; 2014.

[4] The European offshore wind industry – key trends and statistics 2014. Technical report; European Wind Energy Association; 2015.

[5] AWEA State RPS Market Assessment 2013. Technical report; American Wind Energy Association; 2013.

[6] Zhou HF, Dou HY, Qin LZ, Chen Y, Ni YQ, Ko JM. A review of full-scale structural testing of wind turbine blades. Renew Sustain Energy Rev 2014;33(C):177–87.

[7] Tchakoua P, Wamkeue R, Ouhrouche M, Slaoui-Hasnaoui F, Tameghe TA, Ekemb G. Wind turbine condition monitoring: state-of-the-art review, new trends, and future challenges. Energies 2014;7(4):2595–630.

[8] Yang B, Sun D. Testing inspecting and monitoring technologies for wind turbine blades: a survey. Renew Sustain Energy Rev 2013;22(C):515–26.

[9] Amirat Y, Benbouzid MEH, Al Ahmar E, Bensaker B, Turri S. A brief status on condition monitoring and fault diagnosis in wind energy conversion systems. Renew Sustain Energy Rev 2009;13(9):2629–36.

[10] Hameed Z, Hong YS, Cho YM, Ahn SH, Song CK. Condition monitoring and fault detection of wind turbines and related algorithms: a review. Renew Sustain Energy Rev 2009;13(1):1–39.

[11] Ciang CC, Lee JR, Bang HJ. Structural health monitoring for a wind turbine system: a review of damage detection methods. Meas Sci Technol 2008;19(1):2001.

[12] Crabtree CJ, Zappalá D, Tavner PJ. Survey of commercially available condition monitoring systems for wind turbines. Technical report, Durham University School of Engineering and Computing Sciences and the SUPERGEN Wind Energy Technologies Consortium; 2014.

[13] Chen B, Zappalá D, Crabtree CJ, Tavner PJ. Survey of commercially available SCADA data analysis tools for wind turbine health monitoring. Technical report, Durham University School of Engineering and Computing Sciences; 2014.

[14] Farrar CR, Worden K. An introduction to structural health monitoring. Philos Trans R Soc A: Math Phys Eng Sci 2007;365(1851):303–15.

[15] Randall RB. State of the art in monitoring rotating machinery-part 1. Sound Vib 2004;38(3):14-21.

[16] Mobley RK. An introduction to predictive maintenance. Amsterdam, Netherlands: Butterworth–Heinemann; 2002.

[17] Used Oil Analysis: On-Line Sensors, Available from: ⟨http://www.kittiwake.com/online-sensors⟩; 2014 [accessed 9.06.14].

[18] Hamilton A, Quail F. Detailed state of the art review for the different online/inline oil analysis techniques in context of wind turbine gearboxes. J Tribol 2011;133(4):1–18.

[19] Mba D, Rao R. Development of acoustic emission technology for condition monitoring and diagnosis of rotating machines; bearings, pumps, gearboxes, engines and rotating structures. Shock Vib Dig 2006;38(1):3–16.

[20] Byrne G, Dornfeld D, Inasaki I, Ketteler G, König W, Teti R. Tool condition monitoring (tcm) - the status of research and industrial application. CIRP Ann – Manuf Technol 1995;44(2):541–67.

[21] Cargol T. An overview of online oil monitoring technologies. In: Proceedings of the fourth annual Weidmann-ACTI technical conference. 2005. p. 1–6.

[22] Rytter A. Vibrational based inspection of civil engineering structures. fracture and dynamics [Ph.D. thesis], defended publicly at the University of Aalborg; Department of Building Technology and Structural Engineering, Aalborg University; April 20, 1993. p. 206.

[23] Worden K, Farrar CR, Manson G, Park G. The fundamental axioms of structural health monitoring. Proc R Soc A: Math Phys Eng Sci 2007;463(2082):1639–64.

[24] Adams RD, Cawley P, Pye CJ, Stone BJ. A vibration technique for non-destructively assessing the integrity of structures. Proc Inst Mech Eng Part C: J Mech Eng Sci 1978;20(2):93–100.

[25] Farrar CR, Doebling SW, Nix DA. Vibration-based structural damage identification. Philos Trans R Soc A: Math Phys Eng Sci 2001;359(1778):131–49.

[26] Carden EP, Fanning P. Vibration based condition monitoring: a review. Struct Health Monit 2004;3(4):355–77.

[27] Astreinidis E, Egglezos D. Instrumented strain monitoring of the Acropolis wall with optical fibre sensors: comparison of the measurements to the analytical predictions. In: Third panhellenic congress of earthquake engineering and seismology. Athens, Greece; 2008. p. 1–3.

[28] DelloRusso S, Juneja G, Gabby B, Dusenberry D. Monitoring and repair of the milwaukee city hall masonry tower. J Perform Constr Facil 2008;22(4):197–206.

[29] Lynch JP. An overview of wireless structural health monitoring for civil structures. Philos Trans R Soc A: Math Phys Eng Sci 2007;365(1851):345–72.

[30] Federici F, Graziosi F, Faccio M, Colarieti A, Gattulli V, Lepidi M, et al., An integrated approach to the design of wireless sensor networks for structural health monitoring. Int J Distrib Sens Netw 2012;2012:1–16.

[31] Albarbar A, Mekid S, Starr A, Pietruszkiewicz R. Suitability of MEMS accelerometers for condition monitoring: an experimental study. Sensors 2008;8(2):1–16.

[32] Parthenon west facade pillars instrumentation, Available from: ⟨http://www.crd.gr/en/projects/instrumentation-projects/parthenon-west-facade⟩; 2014 [accessed 22.06.14].

[33] Brownjohn JMW. Structural health monitoring of civil infrastructure. Philos Trans R Soc A: Math Phys Eng Sci 2007;365(1851):589–622.

[34] Jang S, Jo H, Cho S, Mechitov K, Rice JA. Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation. Smart Struct Syst 2010;6(5–6):439–59.

[35] Jo H, Sim SH, Mechitov KA, Kim R, Li J, Moinzadeh P, et al., Hybrid wireless smart sensor network for full-scale structural health monitoring of a cable-stayed bridge. In: Tomizuka M, editor. Proceedings of the SPIE University of Illinois at Urbana-Champaign, United States: SPIE; 2011. p. 1–15.

[36] Tegen S, Lantz E, Hand M, Maples B, Smith A, Schwabe P. 2011 Cost of wind energy review. Technical report, National Renewable Energy Laboratory; 2013.

[37] Maples B, Saur G, Hand M, van de Pieterman R, Obdam T. Installation, Operation, and maintenance strategies to reduce the cost of offshore wind energy. Technical report, National Renewable Energy Laboratory; 2013.

[38] Ahmad R, Kamaruddin S. An overview of time-based and condition-based maintenance in industrial application. Comput Ind Eng 2012;63(1):135–49.

[39] Jardine AKS, Lin D, Banjevic D. A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech Syst Signal Process 2006;20(7):1483–510.

[40] Summary of wind turbine accident data to 31 December 2013. Technical report, Caithness Windfarm Information Forum, Available from: ⟨www.caithnesswindfarms.co.uk⟩; 2014.

[41] Top 5 Wind Energy Claims. Technical report, GCube Insurance; 2013.

[42] Walford CA. Wind turbine reliability: understanding and minimizing wind turbine operation and maintenance costs. Technical report, Sandia National Laboratories; 2006.
[43] Nilsson J, Bertling L. Maintenance management of wind power systems using condition monitoring systems-life cycle cost analysis for two case studies. IEEE Trans Energy Convers 2007;22(1):223–9.
[44] Besnard F, Bertling L. An approach for condition-based maintenance optimization applied to wind turbine blades. IEEE Trans Sustain Energy 2010;1(2):77–83.
[45] Van Dam J, Bond LJ. Economics of online structural health monitoring of wind turbines: cost benefit analysis. In: AIP Conference Proceedings 1650. Boise, ID: AIP Publishing LLC; 2015: 899–908.
[46] SmartScan: optical blade loads monitoring for wind turbines. Technical report, Smart Fibres; 2010.
[47] Rademakers LWMM, Verbruggen TW. Fibre optic blade load monitoring (FOBM). Technical report, Energy Research Centre of the Netherlands; 2011.
[48] Rademakers L. Fibre optic load monitoring of wind turbines. Technical report, Energy Research Centre of the Netherlands; 2012.
[49] Homola MC, Nicklasson PJ, Sundsbø PA. Ice sensors for wind turbines. Cold Reg Sci Technol 2006;46(2):125–31.
[50] Barthelmie RJ, Frandsen ST, Nielsen MN, Pryor SC, Rethore PE, Jørgensen HE. Modeling and measurements of power losses and turbulence intensity in wind turbine wakes at Middelgrunden offshore wind farm. Wind Energy 2007;10(6):517–28.
[51] May R, Reitan O, Bevanger K, Lorentsen SH, Nygård T. Mitigating wind-turbine induced avian mortality: sensory, aerodynamic and cognitive constraints and options. Renew Sustain Energy Rev 2015;42(C):170–81.
[52] Osgood RM. dynamic characterization testing of wind turbines. Technical report NREL/TP-500-30070, National Renewable Energy Laboratory; 2001.
[53] Watts J. Winds of change blow through China as spending on renewable energy soars, Available from: ⟨http://www.theguardian.com/world/2012/mar/19/china-windfarms-renewable-energy⟩; 2012 [accessed 14.05.15].
[54] Staffell I, Green R. How does wind farm performance decline with age? Renew Energy 2014;66(C):775–86.
[55] Link H, Keller J, Guo Y, McNiff B. Gearbox reliability collaborative phase 3 gearbox 2 test plan. Technical report, National Renewable Energy Laboratory; 2013.
[56] Bechhoefer E. Predicting gearbox health. Wind Syst 2012;3(31):1–4.
[57] Gong X, Qiao W. Bearing fault diagnosis for direct-drive wind turbines via current-demodulated signals. IEEE Trans Ind Electron 2013;60(8):3419–28.
[58] Watson SJ, Xiang BJ, Yang W, Tavner PJ, Crabtree CJ. Condition monitoring of the power output of wind turbine generators using wavelets. IEEE Trans Energy Convers 2010;25(3):715–21.
[59] Amirat Y, Choqueuse V, Benbouzid M. Condition monitoring of wind turbines based on amplitude demodulation. In: IEEE energy conversion congress and exposition. Atlanta, GA: IEEE; 2010. 2417–21.
[60] Yang W, Court R, Jiang J. Wind turbine condition monitoring by the approach of SCADA data analysis. Renew Energy 2013;53(C):365–76.
[61] Wiesent BR, Dorigo DG, Schardt M, Koch AW. Gear oil condition monitoring for offshore wind turbines, Available from: ⟨http://www.machinerylubrication.com/Read/28782/⟩; 2012 [accessed 15.05.15].
[62] Bently Nevada ADAPT Wind condition monitoring solution. Technical report, GE, Available from: ⟨http://www.ge-mcs.com/download/monitoring/GEA18079B_AdaptWindBro_r3.pdf⟩; 2013.
[63] Siemens G2 platform – 2.3 MW geared wind turbines. Technical report, Siemens, Available from: ⟨http://www.energy.siemens.com/us/pool/hq/power-generation/renewables/wind-power/platform%20brochures/G2-Onshore-Platform-brochures-English-Feb2014-WEB.pdf⟩; 2014.
[64] Wind Turbine Technology – Key Technologies, Available from: ⟨http://www.energy.siemens.com/us/en/renewable-energy/wind-power/wind-turbine-technology/key-technologies.htm⟩; 2014.
[65] TurbinePhD. Technical report, Renewable NRG systems, Available from: ⟨http://www.renewablenrgsystems.com/FileLibrary/44e45948f45e4f7097da4207a8af4b83/TurbinePhD_rNRG_Web.pdf⟩; 2013.
[66] Make the most out of your maintenance resources with SKF WindCon online condition monitoring system. Technical report, SKF, Available from: ⟨http://www.skf.com/binary/21-143837/SKF-Wind-Con-Bro-Update_6Nov13.pdf⟩; 2013.
[67] Sheng S, Veers PS. Wind turbine drivetrain condition monitoring – an overview. In: Mechanical failures prevention group applies systems health management conference. Virginia Beach, VA: National Renewable Energy Laboratory; 2011: p. 1–19.
[68] Cassar H. Wireless condition monitoring. In: Intelligent energy conference and exhibition. BP, Amsterdam, The Netherlands: Society of Petroleum Engineers; 2006: p. 1–11.
[69] Thanagasundram S, Schlindwein F. Comparison of integrated micro-electrical-mechanical system and piezoelectric accelerometers for machine condition monitoring. Proc Inst Mech Eng Part C: J Mech Eng Sci 2006;220(8):1135–46.
[70] Ceylan H, Gopalakrishnan K, Kim S, Taylor PC, Prokudin M, Buss AF. Highway infrastructure health monitoring using micro-electromechanical sensors and systems (MEMS). J Civ Eng Manag 2013;19(Sup1):188–201.
[71] Norris A, Saafi M, Romine P. Temperature and moisture monitoring in concrete structures using embedded nanotechnology/microelectromechanical systems (MEMS) sensors. Constr Build Mater 2008;22(2):111–20.
[72] Sparrevik P. Monitoring offshore wind turbine foundations. In: Oceanology international. London, England; 2014. p. 1–26.
[73] Structrual monitoring for offshore wind turbine foundations. Technical report, Strainstall Monitoring; 2014.
[74] Faulkner P, Cutter P, Owens A. Structural health monitoring systems in difficult environments–wind turbines. In: 6th European workshop on structural health monitoring. 2012. p. 1–7.
[75] De Sitter G, Devriendt C, Jordaens PJ. Dynamic monitoring of offshore wind farms. In: Study day on reliability and efficiency in renewable energy sources. Bruges, Belgium; 2013: p. 1–33.
[76] Zensor Corrosion Control. Continuous corrosion monitoring of monopile foundation structures. In: EWEA annual event. Vienna, Austria; 2013: p. 1–17.
[77] Ibsen LB, Brincker R. Design of a new foundation for offshore wind turbines. In: Proceedings of the 22nd international modal analysis conference (IMAC). Detroit, Michigan; 2004: p. 1–8.
[78] Wernicke J, Kuhnt S, Byars R. Structural monitoring system for offshore wind turbine foundation structures. In: European wind energy conference exhibition. Athens, Greece; 2006: p. 1–7.
[79] Wind turbine scour monitoring, Available from: ⟨http://www.strainstall.com/what-we-do/our-systems/structural-monitoring/wind-turbine-monitoring/wind-turbine-scour-monitoring/⟩; 2014 [accessed 28.06.14].
[80] Michalis P, Saafi M, Judd M. Capacitive sensors for offshore scour monitoring. In: Proceedings of the ICE – Energy 2013;166(4):189–97.
[81] Yang J. Ming Yang turbine collapse kills one, injures three, Available from: ⟨http://www.windpowermonthly.com/article/1149772/ming-yang-turbine-collapse-kills-one-injures-three⟩; 2012 [accessed 15.05.15].
[82] Nearly all 22 turbine foundations cracked, Available from: ⟨http://ontario-wind-resistance.org/2011/02/03/nearly-all-22-turbine-foundations-cracked/⟩; 2011.
[83] Hassine JB. Foundation condition monitoring. In: Wind turbine condition monitoring workshop, Broomfield, CO: RES Americas; 2011: 1–24.
[84] Project profile – Wind turbine foundation monitoring. Technical report, Canary Systems; 2012.
[85] Currie M, Saafi M, Tachtatzis C, Quail F. Structural health monitoring for wind turbine foundations. Proc ICE – Energy 2013;166(4):162–9.
[86] Schiegg Y, Steiner L. Cost effectiveness and application of online monitoring in reinforced concrete structures. Mater Corros 2010;61(6):490–3.
[87] Prediction of creep, shrinkage, and temperature effects in concrete structures. Technical report, ACI Committee 209; 1982.
[88] IntelliRock system overview. Technical report, Engius, LLC; 2005.
[89] Rens KL, Wipf TJ, Klaiber FW. Review of nondestructive evaluation techniques of civil infrastructure. J Perform Constr Facil 1997;11(4):152–60.
[90] Kishi T, Ohtsu M, Yuyama S. Acoustic emission-beyond the millennium. Tokyo, Japan: Elsevier; 2000.
[91] Nair A, Cai CS. Acoustic emission monitoring of bridges: review and case studies. Eng Struct 2010;32(6):1704–14.
[92] Grosse CU, Krûger M. Bridge monitoring using wireless sensors and acoustic emission techniques. In: Proceedings of Inaugural International Conference of the ASCE Engineering Mechanics Institute. 2008. p. 1–7.
[93] Bertolini L, Elsener B, Pedeferri P, Redaelli E, Polder RB. Corrosion of steel in concrete: prevention, diagnosis, repair. Weinheim, Germany: John Wiley & Sons; 2013.
[94] Polder RB, Peelen W, Klinghoffer O, Eri J, Leggedoor J. Use of advanced corrosion monitoring for risk based management of concrete structures. HERON 2007;52(4):239–50.
[95] Akyildiz IF, Pompili D, Melodia T. Underwater acoustic sensor networks: research challenges. Ad hoc Netw 2005;3(3):257–79.
[96] Taylor CD, Gutierrez SJ, Langdon SL, Murphy KL, Walton III WA. Measurement of RF propagation into concrete structures over the frequency range 100 MHz to 3 GHz. In: Wireless personal communications. Boston, MA: Springer US; 1997. p. 131–44.
[97] Ong JB, You Z, Mills-Beale J, Tan EL, Pereles BD, Ong KG. A wireless, passive embedded sensor for real-time monitoring of water content in civil engineering materials. IEEE Sens J 2008;8(12):2053–8.
[98] Ghee Ong K, Grimes CA. A resonant printed-circuit sensor for remote query monitoring of environmental parameters. Smart Mater Struct 2000;9(4):421–8.
[99] Hansen W, Surlaker S. Embedded wireless temperature monitoring systems for concrete quality control. Technical report, University of Michigan, Ann Arbor, MI; 2006.
[100] Steel solutions in the green economy. Technical report, World Steel Association; 2012.
[101] Krapfl M. Energy Department supports Iowa State studies of concrete for taller wind turbine towers, Available from: ⟨http://www.news.iastate.edu/news/2014/09/18/turbinetowers⟩; 2014 [accessed 12.05.15].
[102] Smarter and more powerful: introducing GE2.75-120. Technical report, General Electric; 2014.
[103] Davidson R. GE develops space frame tower, Available from: ⟨http://www.windpowermonthly.com/article/1283941/ge-develops-space-frame-tower⟩; 2014 [accessed 24.06.14].
[104] Ozbek M, Rixen DJ. Operational modal analysis of a 2.5 MW wind turbine using optical measurement techniques and strain gauges. Wind Energy 2012;16(3):367–81.
[105] Smarsly K, Hartmann D, Law KH. An integrated monitoring system for life-cycle management of wind turbines. Smart Struct Syst 2013;12(2):209–33.
[106] Hartmann D, Smarsly K, Law KH. Coupling sensor-based structural health monitoring with finite element model updating for probabilistic lifetime

estimation of wind energy converter structures. In: The 8th international workshop on structural health monitoring 2011. Stanford, CA; 2011. p. 1–8.

[107] Smarsly K, Law KH, Hartmann D. Structural health monitoring of wind turbines observed by autonomous software components 2nd level monitoring. In: 14th international conference on computing in civil and building engineering. Moscow, Russia; 2012. p. 1–8.

[108] Rolfes R, Zerbst S, Haake G, Reetz J, Lynch JP. Integral SHM-system for offshore wind turbines using smart wireless sensors. In: 6th international workshop on structural health monitoring. Stanford, CA; 2007. p. 1–8.

[109] Swartz RA, Lynch JP, Sweetman B, Rolfes R, Zerbst S. Structural monitoring of wind turbines using wireless sensor networks. In: ESF–NSF workshop on sensor networks for civil infrastructure systems. Cambridge, UK; 2008. p. 1–8.

[110] Devriendt C, Weijtjens W, El-Kafafy M, de Sitter G. Monitoring resonant frequencies and damping values of an offshore wind turbine in parked conditions. IET Renew Power Gener 2014;8(4):433–41.

[111] Bang Hj, Ko Sw, Jang Ms, Kim Hi. Shape estimation and health monitoring of wind turbine tower using a FBG sensor array. In: 2012 IEEE International Instrumentation and measurement technology conference (I2MTC). 2012. p. 496–500.

[112] Guo P, Infield D. Wind turbine tower vibration modeling and monitoring by the nonlinear state estimation technique (NSET). Energies 2012;5 (12):5279–93.

[113] Chen AJ, He GJ. Wind-induced vibration analysis and remote monitoring test of wind turbine power tower. Adv Mater Res 2013;639–640:293–6.

[114] Mitchell P, Janssen A, Partov Poor B. Development of a high-speed wideband wavelength tunable infra-red laser source for real time wind turbine array sensing applications. Integr Photonics: Mater 2011;8069:1–12.

[115] Benedetti M, Fontanari V, Zonta D. Structural health monitoring of wind towers: remote damage detection using strain sensors. Smart Mater Struct 2011;20(5):055009.

[116] Guillermin O. Developing composite wind blades that will stand the test of time, Available from: 〈http://www.designnews.com/document.asp?doc_id=230009〉; 2011 [accessed 30.06.14].

[117] Lu B, Li Y, Wu X, Yang Z. A review of recent advances in wind turbine condition monitoring and fault diagnosis. In: power electronics and machines in wind applications. Lincoln, NE; 2009. p. 1–7.

[118] Managing the wind: Reducing kilowatt-hour costs with condition monitoring. Refocus 2005;6(3):48–51.

[119] Fiber Optic Sensors, Available from: 〈http://www.scaime.com/en/117/products-services/fiber-optic-sensors.html〉; 2014 [accessed 30.06.14].

[120] BLADEcontrol ®: greater output – less risk. Technical report, Bosch Rexroth; 2014.

[121] Yang W, Tavner PJ, Crabtree CJ, Feng Y, Qiu Y. Wind turbine condition monitoring: technical and commercial challenges. Wind Energy 2014;17 (5):673-93.

[122] Schroeder K, Ecke W, Apitz J, Lembke E, Lenschow G. A fibre Bragg grating sensor system monitors operational load in a wind turbine rotor blade. Meas Sci Technol 2006;17(5):1167–72.

[123] Blanch MJ, Dutton AG. Acoustic emission monitoring of field tests of an operating wind turbine. Key Eng Mater 2003;245–246:475–82.

[124] Berg J, Resor B, Paquette J, White J. SMART wind turbine rotor: design and field test. Technical report SAND2014-0681, Sandia National Laboratories; 2014.

[125] Papasalouros D, Tsopelas N, Anastasopoulos A, Kourousis D, Lekou DJ, Mouzakis F. Acoustic emission monitoring of composite blade of NM48/750 NEG-MICON wind turbine. J Acoust Emiss 2013;31(1):36–49.

[126] Rumsey MA, Paquette J, White JR, Werlink RJ, Beattie AG, Pitchford CW, et al., Experimental results of structural health monitoring of wind turbine blades. In: 46th AIAA aerospace sciences meeting and exhibit. Reston, Virigina: American Institute of Aeronautics and Astronautics; 2008. p. 1–14.

[127] Sundaresan MJ, Schulz MJ, Ghoshal A. Structural health monitoring static test of a wind turbine blade. Technical report, National Renewable Energy Laboratory.

[128] Sørensen BF, Lading L, Sendrup P, McGugan M, Debel CP, Kristensen OJD, et al. Fundamentals for remote structural health monitoring of wind turbine blades – a Preproject. Technical report Risø-R-1336(EN), Risø National Laboratory; 2002.

[129] Hyers RW, Mcgowan JG, Sullivan KL, Manwell JF, Syrett BC. Condition monitoring and prognosis of utility scale wind turbines. Energy Mater 2006;1(3):187–203.

[130] Wind turbine blade inspections, Available from: 〈http://www.upwindsolutions.com/repairs/blade-services/blade-inspection/〉; 2014 [accessed 10.10.14].

[131] Song G, Li H, Gajic B, Zhou W, Chen P, Gu H. Wind turbine blade health monitoring with piezoceramic-based wireless sensor network. Int J Smart Nano Mater 2013;4(3):150–66.