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TOPICAL REVIEW

Structural health monitoring for a wind turbine system: a review of damage detection methods

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Abstract

Renewable energy sources have gained much attention due to the recent energy crisis and the urge to get clean energy. Among the main options being studied, wind energy is a strong contender because of its reliability due to the maturity of the technology, good infrastructure and relative cost competitiveness. In order to harvest wind energy more efficiently, the size of wind turbines has become physically larger, making maintenance and repair works difficult. In order to improve safety considerations, to minimize down time, to lower the frequency of sudden breakdowns and associated huge maintenance and logistic costs and to provide reliable power generation, the wind turbines must be monitored from time to time to ensure that they are in good condition. Among all the monitoring systems, the structural health monitoring (SHM) system is of primary importance because it is the structure that provides the integrity of the system. SHM systems and the related non-destructive test and evaluation methods are discussed in this review. As many of the methods function on local damage, the types of damage that occur commonly in relation to wind turbines, as well as the damage hot spots, are also included in this review.

Keywords: wind power generation system, structural health monitoring, non-destructive testing, sensors and actuators, damage detection

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Development of renewable energy sources has been rapid since the emergence of the world energy crisis into the public arena in the 1970s, and since then the urge for a clean energy to counter the greenhouse effect has been a prominent research driver. Among other applications of renewable energy technologies, the wind turbine technology has an edge because of its technological maturity, good infrastructure and relative cost competitiveness. Figure 1 shows a typical horizontal axis wind turbine configuration and figure 2 shows the common components inside the nacelle.

In order to harvest more energy through higher efficiencies and due to cost-effective considerations, the size of the wind turbine has increased over the years. Table 1 shows the typical figures for a horizontal axis wind turbine and figure 3 shows the wind turbine size evolution over the years.

There are many problems in the wind industry, some of which are as follows.

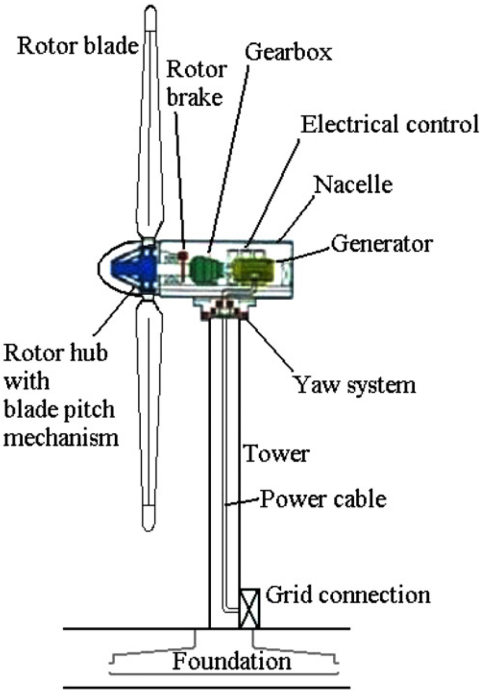


Figure 1. A typical configuration of a horizontal axis wind turbine system [1].

(1) It is difficult to perform inspection and maintenance work considering the height of the turbine.
(2) Accidents have been reported, some of which have been fatal.
(3) The location of the wind turbine, usually at remote mountainous or rough sea regions, adds even more challenges to the task of maintenance and repair.
(4) For those countries which have poor lifting and handling equipment such as cranes, fork lifts, etc, yet are interested to generate power through wind turbines; the functionality of the turbine system is also a great concern.
(5) The stake becomes higher and higher when the price of the wind turbine increases together with the capacity to become a gigantic expensive structure.

Table 1. Typical figures for wind turbines [2].

Rated power (kW)	Range of hub height (m)	Blade length (m)	Price excluding foundation (1000 US$)[a]
150	35–60	12–13	–
600	45–80	19–23	510–670
1000	50–90	26–29	960–1410[b]
1500	60–110	31–37	1530–2030[b]
2000	60–100	34–39	1860–2200[b]

[a] Based on 1 Euro equivalent to 1.13 US dollar in year 2003.
[b] Excluding medium voltage transformer.

(6) To improve safety considerations, to minimize down time, to lower the frequency of sudden breakdowns and associated huge maintenance and logistic costs and to provide reliable power generation, the wind turbines must be routinely monitored to ensure that they are in good condition [3].

Among all the monitoring systems, the structural health monitoring (SHM) system is of primary importance because structural damage may induce catastrophic damage to the integrity of the system. The SHM of the wind turbine system or its related non-destructive testing methods are discussed here. A SHM system that is reliable, low cost and integrated into the wind turbine system may reduce wind turbine life-cycle costs and make wind energy more affordable. The SHM information gathered could be used in a condition-based maintenance program to minimize the time needed for inspection of components, prevent unnecessary replacement of components, prevent failures and allows utility companies to be confident of power availability. In addition, SHM may allow the use of lighter blades that would provide higher performance with less conservative margins of safety [4]. Furthermore, a wind turbine with lighter blades can respond to wind changes more quickly and so capture more energy [5]. A SHM is also very useful in tackling the fatigue issue because predicting the exact life of a wind turbine component is extremely difficult due to their long designed service life of 10–30 years. In addition, it is difficult to ascertain the extent

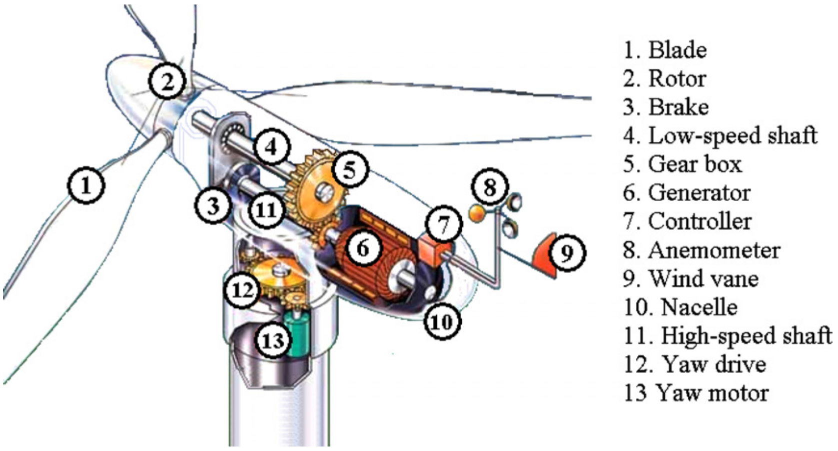


Figure 2. Components inside a wind turbine nacelle.

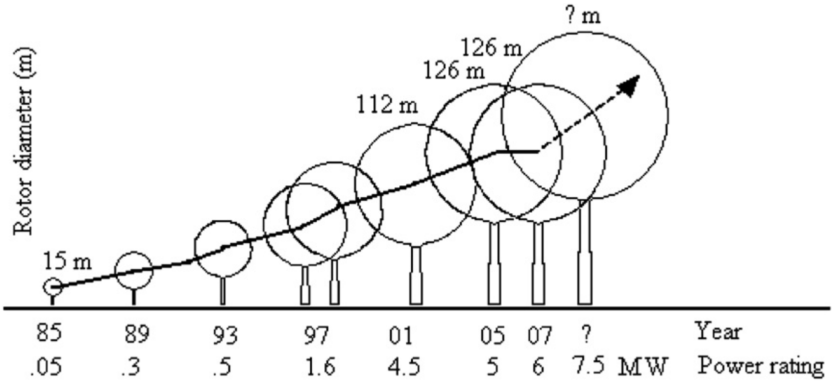


Figure 3. Wind turbine size evolution. The 7.5 MW system is under development by Clipper Windpower Plc.

Table 2. Wind turbine SHM system categorized by characteristics [3].

Function	Advantages	Benefits
Early warning	Avoid breakdown	Avoid repair cost
	Better planning of maintenance	Minimized downtime
Problem identification	Right service at the right time	Prolong lifetime
	Minimize unnecessary replacements	Lowered maintenance costs
	Problems resolved before the time of guarantee expires	Quality control operations during time of guarantee
Continuous monitoring	Constant information that the system is working	Security; less stress

of fatigue damage that might have occurred to a component. Thus, a SHM system is needed to continuously monitor the condition of the turbine system and warn of possible failure [5].

According to Farrar and Sohn [6], a SHM system is defined as the process of implementing a damage detection strategy for engineering infrastructure related to aerospace, civil and mechanical engineering. Damage here is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. There are many causes of structural damage such as moisture absorption, fatigue, wind gusts [7], thermal stress, corrosion, fire and even lightning strikes [2]. Wind turbine blades manufactured of non-conducting fibre composite materials without any conducting components are frequently struck by lightning, particularly at the outermost part of the blade [2].

In general, the development of successful SHM methods depends on two key factors: sensing technology and the associated signal analysis and interpretation algorithm [8]. The components of the SHM are made up of system state definition, data acquisition, data filtration, feature extraction, data reduction, pattern recognition and decision making. Each of these components is equally important in determining the state of health of a structure [18].

The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of structural health. For long term SHM, the output of this process gives periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable ageing and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure [6]. As for a wind turbine SHM system, these can be categorized by the functional characteristics of the system as shown in table 2.

The benefits of having a fault detection system are as follows [9].

(a) *Avoidance of premature breakdown*: prevent catastrophic failures and secondary defects.

(b) *Reduced maintenance cost*: inspection interval can be increased with on-line inspection, and replacement of intact parts is avoided by condition-based maintenance.

(c) *Supervision at remote sides and remote diagnosis*: large turbines are usually built at remote sites.

(d) *Improvement of capacity factor*: with early warning of impending failures, repair action can be taken during low wind season and hence will not affect the capacity factor.

(e) *Support for further development of a turbine*: the data obtained can be used to improve designs for the next generation of turbines.

With a reliable SHM system, a promising maintenance and repair strategy for wind turbines, especially those offshore, can be planned. Maintenance and repair actions can be worked out on demand and during suitable weather conditions. Mobilization costs for staff, materials and craning equipment can be optimized [10].

2. Structural damage

Damage can occur at any component or part of the wind turbine; it can be anything from a failure in the concrete

Table 3. Possible wind turbine damage [12].

Assembly	Possible defects
Rotor blade	Surface damage, cracks, structural discontinuities Damage to the lightning protection system
Drive train	Leakages, corrosion
Nacelle and force- and moment-transmitting components	Corrosion, cracks
Hydraulic system, pneumatic system	Leakages, corrosion
Tower and foundation	Corrosion, cracks
Safety devices, sensors and braking systems	Damage, wear
Control system and electrics including transformer station and switchgear	Terminals, fastenings, function, corrosion, dirt

Table 4. Component reliability and failure rate h^{-1} [15].

Component	Failure rates
Tip break	1.000×10^{-4}
Yaw bearing	1.150×10^{-5}
Blades	1.116×10^{-5}
Bolts	1.116×10^{-5}
Hub	1.116×10^{-5}
Generator	0.769×10^{-6}
Gearbox	0.630×10^{-6}
Parking brakes	2.160×10^{-6}
Tower and anchor bolts	1.000×10^{-7}

base to a failure of the blades themselves, a bolt shears, a load-bearing brace buckles and so on [1]. Cases of structural damage are reported from time to time from places such as Wales, Scotland, Spain, Germany, France, Denmark, Japan and New Zealand [11]. In Germany, 2002, a blade broke in mid-turn with an audible 'crack'. Pieces were found scattered throughout surrounding fields [1]. In another case, a blade torn off flew as far as 8 km and through the window of a house. An extensive documentation of accidents is available at http://www.caithnesswindfarms.co.uk. The possible types of damage that can occur are tabulated in table 3.

A study in Germany [13] shows that, in their experience, damage frequency to all the mechanical systems and to the structures is almost equal. Their experience over 15 years is shown in figure 4, including failure of both mechanical and electrical components. The failures for mechanical components range from 4% for structural parts/housing and gearbox to 7% for rotor blades. Another study shows that the break of the blade tip and the damage of yaw bearing are the most frequent damage for a typical wind turbine system. The component failure rate per hour from this study is shown in table 4 [14].

Although structural damage can happen to any structural component, the most common type of damage is rotor or blade damage and tower damage [16]. Extensive attention has been given to the structural health of blades as they are the key elements of a wind power generation system, and also because the cost of the blades can account for 15–20% of the total turbine cost [2]. It has been shown that the blade damage is the most expensive type of damage to repair and also has the greatest repair time [2]. Furthermore, rotating mass unbalance due to minor blade damage can cause serious secondary damage to the whole wind turbine system if prompt repair action is not taken and this can result in the collapse of the whole tower [11].

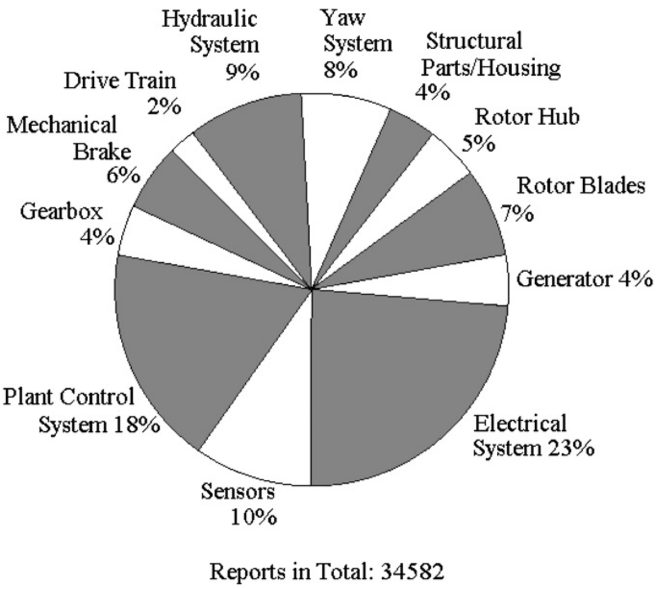


Figure 4. Unforeseen malfunctions percentage for wind turbines at a wind farm in Germany over 15 years [13].

In order to understand the blade damage, the anatomy of a blade must first be understood. The main elements of a wind turbine blade are shown in figures 5 and 6. Another design with spar caps is shown in figure 7. The materials of the contemporary blades are usually fibre-reinforced composites with the majority of wind turbine blades being made of glass fibre/epoxy, glass fibre/polyester, wood/epoxy or carbon fibre/epoxy composites [17]. The use of carbon-fibre-reinforced plastic (CFRP) to manufacture the turbine blade has also increased with increasing rotor size. There is a main spar tube, and the upwind side and downwind side of the blade are constructed and joined together at both the leading edge and the trailing edge using adhesive.

Damage to a blade can occur in various ways. Typical damage in turbine blades is listed in table 5 [5, 18, 19] and a sketch of the damage types is available in figure 8. Damage created in the laboratory test can be found in figures 9–11. Complete images of the damage can be found in [18].

Damage to the tower is also common. The tower can be made of several materials. Early towers were made of steel lattice; however, the numerous connections are exposed to corrosion, and the weak diagonals are often sensitive to wind

Table 5. Typical damage of wind turbine blades [5, 18, 19].

Type	Description
Type 1	Damage formation and growth in the adhesive layer joining skin and main spar flanges (skin/adhesive debonding and/or main spar/adhesive layer debonding)
Type 2	Damage formation and growth in the adhesive layer joining the up- and downwind skins along leading and/or trailing edges (adhesive joint failure between skins)
Type 3	Damage formation and growth at the interface between face and core in sandwich panels in skins and main spar web (sandwich panel face/core debonding)
Type 4	Internal damage formation and growth in laminates in skin and/or main spar flanges, under a tensile or compression load (delamination driven by a tensional or a buckling load)
Type 5	Splitting and fracture of separate fibres in laminates of the skin and main spar (fibre failure in tension; laminate failure in compression)
Type 6	Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load (skin/adhesive debonding induced by buckling, a specific type 1 case)
Type 7	Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin (gel-coat cracking and gel-coat/skin debonding)

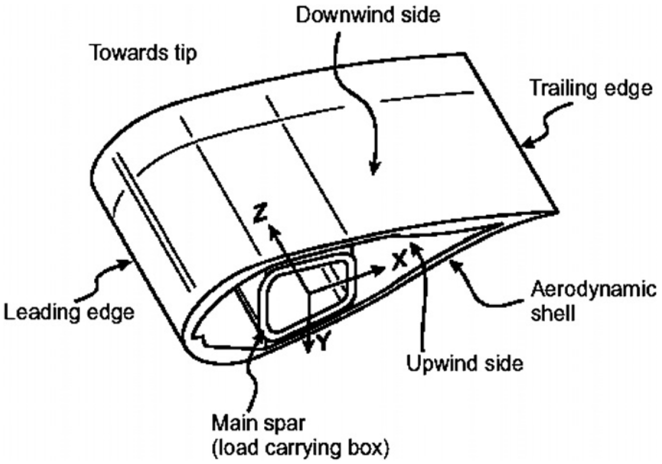


Figure 5. The main elements of a wind turbine blade [18].

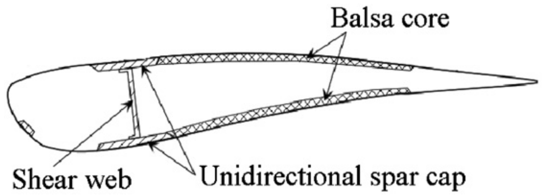


Figure 7. Cross-sectional view of another design of blade with a spar cap.

excitation. This type of tower was found insufficient to support the higher capacity turbine. Later towers were then constructed from cylindrical steel tubes. According to [20], in the case of towers exceeding 85 m height, steel tube towers were no longer able to balance the vibration excitation and so concrete towers were developed which were more appropriate for the conditions. Unfortunately, concrete towers are not infallible and suffer from the problem of thermal constraints, which may cause cracking and thus influence the natural frequency and reduce the stiffness properties.

The Caithness Windfarm Information Forum [16] found that the third most common cause of accidents, caused by the turbines, is mainly related to storm damage of the blades and collapse of the tower. In France, in 2000, a turbine tower broke and toppled over during a storm; however, no further information on the actual cause of damage is available from the wind company. This was the first in a series of such incidents that led to a formal investigation [1]. In Germany, 2000, four turbines experienced sudden and total collapse due to 'concrete damage' at the base [1]. A wind turbine on the not-yet-opened

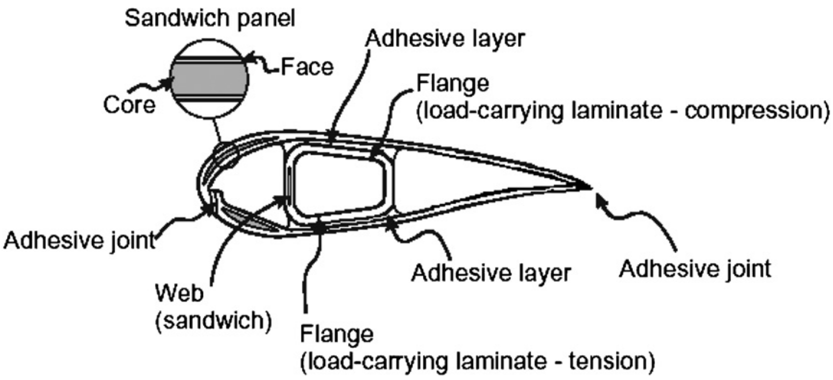


Figure 6. Nomenclature of the different blade construction elements [18]

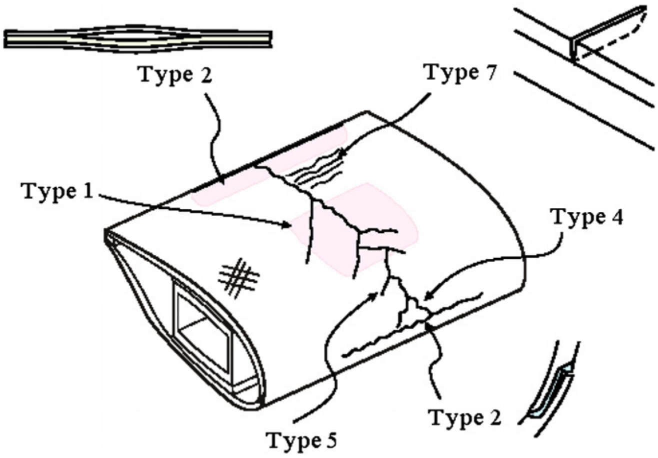


Figure 8. A sketch illustrating some of the common damage types found on a wind turbine blade [18].

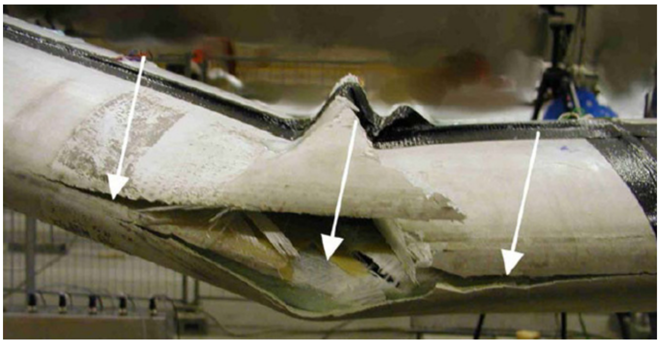


Figure 9. Damage type 2 (adhesive joint failure between skins) at the leading edge [18].

Klondike III wind farm, east of the town of Wasco in the USA, snapped in half, causing a maintenance worker, on the top of the tower, to fall to his death. The turbine broke at a little more than halfway up the tower. It was a fully erected wind turbine, but it had not been in operation [21]. Whole towers have also collapsed in Germany (as recently as 2002) and the United States (e.g., in Oklahoma, 6 May 2005) [11, 16]. The turbine collapse scenario can be seen in figures 12(*a*) and (*b*).

The reasons for wind turbine structural damage can be many. Poor quality control, improper installation and component failure are also responsible for structural damage, especially in the collapse of a new turbine [1, 16]. Lightning can also cause serious structural damage and destroys many towers by causing the blade coatings to peel off, rendering them useless. Fire and strong wind can also damage a wind turbine. The single most critical load is probably the flapwise (chordwise) bending load that arises when the turbine has been brought to a standstill due to high wind, and the blade is hit by the 50 year extreme gust wind [22].

The most dangerous failure is a high wind failure, which occurs when the braking system fails. The braking system in a turbine is designed to stop the rotors in the event the wind is too strong. When the brakes fail, the turbine spins out of control. In Germany, on numerous occasions during 1999, 2000 and 2003, the brakes on wind turbines failed in high wind, causing the rotor to hit the tower at a high speed. This resulted in considerable damage from parts of the blade to the entire nacelle (rotors attached) flying off the tower structure. Blades and other substantial parts have landed as far away as 500 m in typical cases [1].

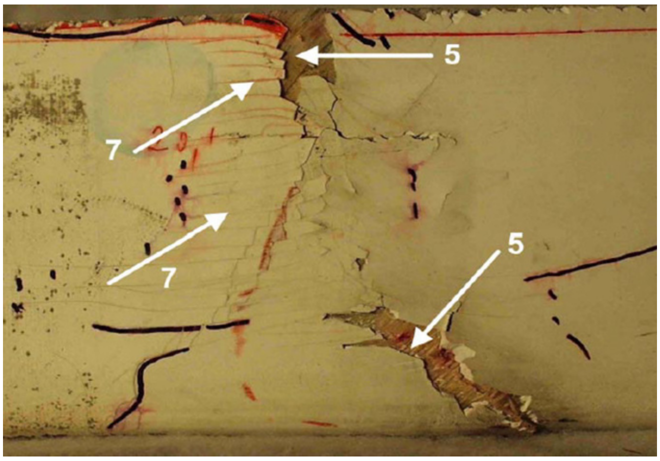


Figure 10. Damage type 5 (laminate failure in compression) and type 7 (gel-coat cracking) at the bottom of the leading edge [18].

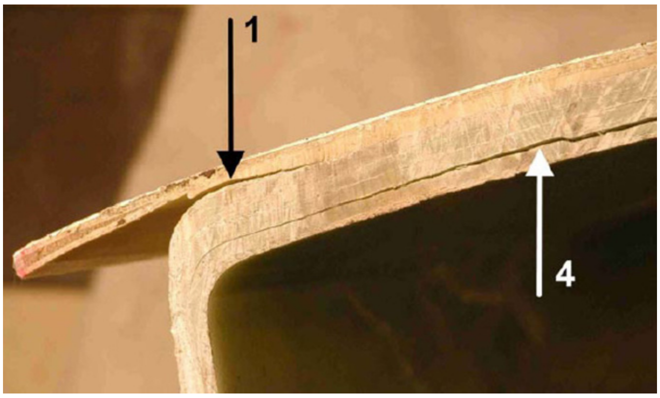


Figure 11. Damage type 1 (main spar flange/adhesive layer debonding) and type 4 (delamination by buckling load) [18].

3. Hot spot

Reliable data regarding the impending failure or damage of certain components can only be acquired by optimally placing sensors at the most appropriate place. Placement of the sensor is paramount in extracting trustworthy data from the SHM system [3]. Alternatively, sensors could be placed only in structural damage hot spots in order to reduce the number of sensors required in the SHM system or to reduce the number of data to be processed and stored. Besides, it is far more difficult to trace fracture origins on failed composite material parts than can be done with many homogeneous materials [5]. Hence, the locations where damage is most likely to occur are presented here.

(a) *30–35% and 70% in chord length from the blade root.* The locations at 30–35% and 70% along the length of the blade from the root section have been found more prone


(*a*) (*b*)

Figure 12. Examples of catastrophic collapse of wind turbines.

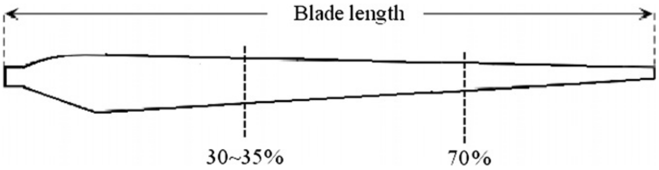


Figure 13. The spanwise location of a blade that is likely to damage [5].

Figure 14. An example of blade damage near 30% in length from the blade root.

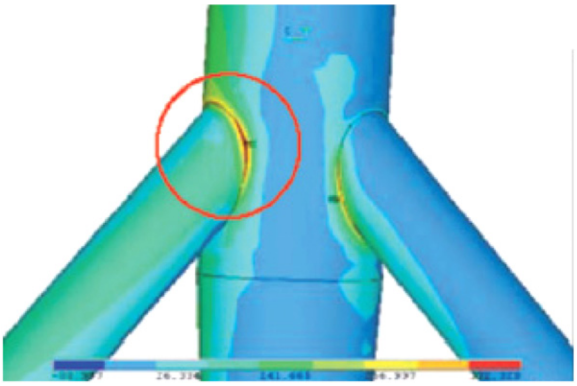


Figure 15. Simulation result showing the stress hot spot of an off-shore wind turbine tower tripod [26].

to damage, by both simulation and experimental methods [5, 23]. Figure 13 illustrates the damage-prone locations on the blade while figure 14 shows an example of damage.

(b) *The root of the blade*. References [5, 24] point out that blade failures sometimes occur near the geometrically complicated root section. The result of the simulation investigation in [25] shows that the root of the blade is subjected to the highest fatigue stress compared to the rest of the blade. This shows good correlation between the two references.

(c) *Maximum chord*. Buckling of the blade skin at the maximum chord section is one type of failure. When this buckling occurs, the blades may operate for a large number of cycles with little reduction in strength and elastic properties, and then the fatigue damage propagates quickly to failure [5].

(d) *Upper spar cap/flange of the spar*. It was found in [5] that the critical point of a blade is at the upper spar cap, 37.5% and 72% of blade length from the root. However, another study in [23] shows that the critical location of the spar cap varies depending on the pitch angle of the blade. At different wind speeds, the blade angle will be changed by the pitch control system and the critical point will change accordingly. However, the critical points at different pitch angles are along the upper flange of the spar. Results in [24] also agree that the spar is a critical component.

(e) *Welded/bolted joins of tripod*. For an offshore wind turbine, it is common to have a tower tripod. The upper central joint of the tripod is the most critical construction for fatigue design, as shown in figure 15 [26]. An example of another tripod design to lower the stress is shown in figure 16.

(f) *Splash zone of tower*. The splash zone is prone to damage due to the exposure of the tower to marine atmosphere. The marine atmosphere is generally considered to be one of the most aggressive atmospheric corrosion environments. Many factors affect the corrosion rate in marine atmosphere, such as humidity, temperature, airborne contaminants and biological organisms [27]. The splash zone of a tower is shown in figure 17. Note that the base part of the tower is already corroded.

4. Damage detection techniques

An ideal SHM system typically consists of two major components: a built-in network of sensors for collecting response measurements, and a data analysis algorithm/software for interpretation of the measurements in terms of the physical condition of the structures [28]. Those methods which are applicable or may have promising application in the near future to the wind turbine system are discussed.

Figure 16. An offshore wind turbine with tripod is under construction. Note that the tripod design is different to the one shown in figure 15 in order to lower the stress at the joints.

Figure 17. A service boat at an offshore wind turbine which has a corroded base.

4.1. *Acoustic emission events detection method*

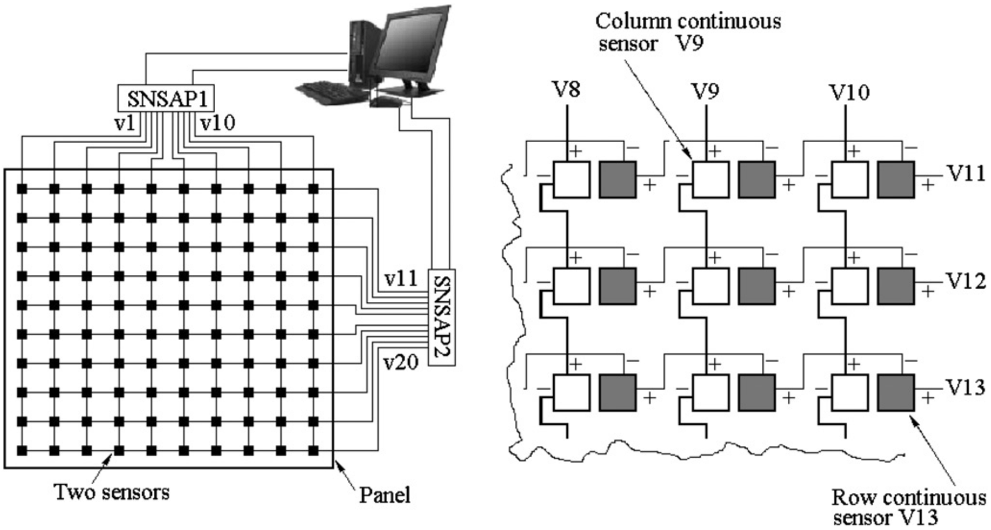
Processes such as cracking, deformation, debonding, delamination, impacts, crushing and others, all produce localized transient changes in stored elastic energy with a broad spectral content. References [29–31] reported that acoustic emission (AE) monitoring during loading of wind turbine blades has offered considerable advantages towards the understanding of the complex damage mechanisms which occur on a turbine blade, and have enhanced the tester's ability to evaluate damage. An AE monitoring of small wind turbine blades certification tests was conducted in [30]. The test revealed an audible cracking sound from the blade and identified the damage area of failure. References [32, 33] use piezoelectric sensors to detect the high-frequency component of the elastic waves (or stress release waves) generated by these energy loss processes within materials and structures. The system can detect much weaker signals in the non-audible frequency domain (20–1200 kHz). Reference [34] shows that fatigue tests of large fibre-reinforced plastic wind turbine blades can also be monitored by AE techniques. Reference [35] shows that the AE signals can be characterized in terms of amplitude and energy, and inferences can be made about the kinds of damage processes taking place in the blade. Reference [32] reports that the AE event will cluster around a certain point at a loaded structure and eventually the structure failed at that particular location. This characteristic is useful in determining the location of the failure points or damage locations. This method can also be used to determine damage criticality, as reported in [35].

References [30] and [31] reported that the characteristics of an AE event which cluster around a potential failure point, and the increase of intensity as damage becomes more critical, can be utilized by pattern recognition software to evaluate the damage. Reference [31] notes that this pattern recognition software has the potential for application to various similar wind turbine blade designs. The consistency in the presence of a distinguishable family of AE data immediately prior to failure also enables the assessment of the blade's ability to withstand specific loads.

In cases where high accuracy of damage evaluation is needed, the number of sensors must be increased and subsequently the number of data output to the signal processing system also increased. In order to reduce the number of data, references [4, 36] proposed a structural neural system (SNS) for SHM. A highly distributed continuous sensor concept, that mimics the signal processing in the biological neural system, is adopted. The continuous sensors for SNS are formed by individual PZT sensors connected in a series, as illustrated in figure 18. Each of the small squares indicates two adjacent sensor nodes, as shown in the magnified view on the right of figure 18. The row continuous sensors are connected to an analogue processor, and the column continuous sensors are connected to another analogue processor. The analogue processors will simplify the data and send only two outputs each to the computer, which greatly reduces both the number of data to be processed and the computer power. The proposed in-service SNS method can detect the AE produced by cracking, delamination, bearing damage, rotor imbalance, flow instabilities, impacts or other material failure modes. It was proved in [4] that the method can detect damage early and track the AE event during the damage growth in a wind turbine blade.

It was also suggested in [37] that multiple piezoceramic patches can be connected together in a series or array pattern to reduce the number of channels of data acquisition needed to detect damage represented by AEs or high strains. References [38, 39] reported that the AE method can be applied to an in-service wind turbine for a real-time rotating blade. A broadband radio transmission system was developed to transmit the AE data from the rotating frame to the ground without losing any signal resolution. The results indicate the feasibility of collecting AE signals from the rotating frame with an acceptable level of noise in low to moderate wind speeds. Further work is required to verify whether or not the noise level increases appreciably with wind speed and whether such signals can be filtered out.

The most common sensor type used in monitoring stress waves in materials is based on a surface-mounted piezoelectric crystal. However, there are many other sensors that exist



(*a*) (*b*)

Figure 18. Architecture of the SNS proposed in [4]: (*a*) each small square indicates two adjacent sensor nodes. In this example, there are ten row continuous sensors and ten column continuous sensors; (*b*) the magnified view at the right shows the detail of sensors arrangement to form row continuous sensors and column continuous sensors.

which either use alternative methods for detecting stress wave activity or use piezoelectric materials in different ways, such as thin film sensors, piezoelectric composite materials, rolling sensors, embedded piezoelectric sensors and optic-based sensors [40].

4.2. *Thermal imaging method*

Thermal imaging method is a subsurface defects or anomalies detection method owing to temperature differences observed on the investigated surface, such as the wind turbine blade, during monitoring by using infrared sensors or cameras [41]. The temperature difference when compared to the sound part is related to the difference of thermal diffusivity and hence indicates material irregularity or damage.

Thermal imaging method can be categorized by the thermal excitation method of the test subject using either passive or active methods. The passive approach thermography is used to investigate materials that are at a different temperature than ambient (often higher) [41]. The passive approach is not common in wind turbine SHM and more modifications are required before it becomes a promising method. The active approach uses an external stimulus source such as optical flash lamps, heat lamps, hot or cold air guns to induce relevant thermal contrasts on the test subject [41]. One specific type of active thermal imaging method is the thermoelastic stress method, which is developed based on the thermoelastic effect. Thermoelastic effect is the temperature change of elastic solid due to the change of stress [42]. Higher acoustical damping, higher stress concentration and different heat conduction near the defective region are expected, and hence the defective region will have a higher temperature [43]. Thermoelastic stress analysis was originally an established technique for determining the stress distribution in isotropic materials by measuring the small changes in surface temperature when a component experiences cyclic loading [35]. The technique has been extended to composite materials [44], although the stress formulation is more complex.

References [35] and [45] proved that thermoelastic stress analysis is useful during fatigue test of a wind turbine blade. The method allows the measurement of the surface stress distribution on a blade during cyclic loading, and indicates stress concentrations and developing sub-surface damage long before any visible surface indications develop. This procedure not only identified the cracked areas in the foam-filled sandwich area, but also successfully identified the root delaminations and trailing-edge crack, and at the same time removed most of the signal noise [46].

High power ultrasound [47] or oscillating stress can be applied to a sample, for thermography, by vibrating it with a mechanical shaker [43]. The capability of this method, called vibro-thermographic or sono-thermographic, to locate and evaluate the size of cracks and impact damage is proven. It can also be used to evaluate voids, stress concentration and bonding quality during the manufacturing of composite materials. Reference [47] reported that it can detect cracks in various types of materials, even on complex shaped components such as turbine blades.

Reference [48] reported another excitation method by using a burst of ultrasound into the specimen through a fixed ultrasound transducer. The heating up and cooling down of the specimen are recorded by an infrared camera. This method is proven for detecting thermal damage of a carbon-fibre-reinforced plastic plate, cracks in metal and metal adhesive defects such as non-cured adhesion, missing adhesion and entrapped air. The simultaneous use of several ultrasound transducers that inject lower power density can reduce the possibility of new damage being induced by a high power ultrasound burst in the specimen. This technique can also be used for large structures.

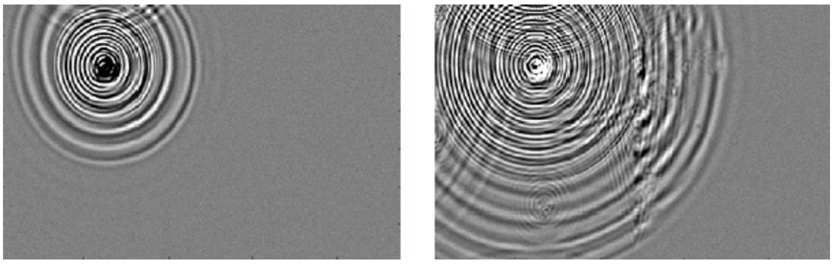

(*a*) (*b*)

Figure 19. Acoustic wavefield images at different propagation times. Wave interactions with both the boundaries of the plate and impedance discontinuities in the specimen are clearly visible on these AWI snapshots.

Thermal imaging method has the advantage of requiring only low load magnitudes and can be used to validate finite element model stress distributions during the early stages of a blade test or to characterize the spread of damage during failure. More investigations are needed for the application of this method to in-service wind turbines due to its sensitivity to spatial and temporal temperature variations [35]. This damage detection technique can be a local technique [49] or a global technique because it is possible to assess the damage from a single or full-field measurement [46], depending on the resolution of the camera. It has the potential to be a promising in-service wind turbine SHM in the future if the excitation method can be simplified.

4.3. *Ultrasonic methods*

Ultrasound is a well-established method for investigating the inner structures of solid objects. Ultrasonic scanning is also very useful for investigating composite structures. The basic principle of the technique is that an ultrasonic wave is passed through the material and is then reflected and/or mode converted by a defect. A transmitter transfers ultrasound waves into the material and the signal from this is picked up by a receiver once it has passed through the material. In the simplest arrangement, the transmitter and receiver are placed on opposite surfaces of the material. The technique may also be applied with a single transmitter/receiver transducer in a pulse-echo mode or with separate transmitter and receiver transducers placed on the same side of the material [40].

Ultrasound probing will typically reveal planar cracks (e.g. delaminations) oriented perpendicular to the direction of sound wave propagation [19]. The transmit time and/or amplitude of the ultrasound is usually monitored. The transit time can be used to determine the position of the defect relative to the position of the transducers while the amplitude can be used to assess the severity of the defect [40]. Damage of length as small as a few millimetres can be detected.

Ultrasonic testing has proved its effectiveness in a variety of applications, for example, inspection of adhesively bonded multilayered structures, laminated composite components, including detection of delaminations and interlaminar weakness [50]. In the case of adhesively bonded multilayered structures, relatively limited success has been obtained with the ultrasonic technique. It is suitable for detecting delamination and cracks in adhesive that are oriented at right angles to an ultrasonic wave propagation, impact damage, voids and porosity [40].

Acoustic wavefield imaging (AWI) is another variation of the ultrasonic method. Reference [51] used a sparse array of permanently mounted piezoelectric transducers to generate acoustic waves which propagate through a structure. An external air-coupled transducer acts as a receiver and is scanned over the surface of the specimen. Ultrasonic waveforms are recorded from each location of the pixel grid for the AWI image and then stored waveforms are processed and displayed as consecutive time slices, as shown in figure 19. Propagating waves are visible as a concentric wavefield emerging from the embedded source transducer. Interactions with discontinuities in the structure are visible as scattered waves [51].

The transducer pair for AWI can be composed of a laser ultrasonic generator and a laser interferometric sensor [52, 53]. Alternatively, if a structure already contains ultrasonic transducers under the built-in SHM scheme, either a laser ultrasonic generator or receiver can be used to realize the ultrasonic pitch–catch [54]. If the built-in transducer is used as an ultrasonic transmitter, the laser interferometric sensor, air-coupled transducer, electromagnetic acoustic transducer (EMAT) or contact transducer can be used as the scanning sensor for AWI. Since the ultrasonic wavefield imaging technology provides a scanned movie or snapshots, it can provide easy explanations on the wave propagation mechanism and the interaction of the wavefield with structural damage [54].

4.4. *Modal-based approaches*

Modal-based methods are among the earliest and most common damage detection methods used, principally because they are simple to implement on any size structure. Structures can be excited by ambient energy [55], an external shaker or embedded actuators, and embedded strain gauges, piezoceramics or accelerometers can be used to monitor the structural dynamic responses [56]. The basic idea behind this technology is that modal parameters, notably frequencies, mode shapes and modal damping, are functions of the physical properties of the structure (mass, damping and stiffness). Therefore, changes in the physical properties, such as reductions in stiffness resulting from the onset of cracks or loosening of a connection, will cause detectable changes in the modal properties [57–60]. Structural damage detection is based on a comparison between the response from a 'pre-damage' state and that from a 'post-damage' state [60]. Since changes in modal properties, or properties derived from these quantities, are being used as indicators of damage, the process of modal-based damage detection eventually reduces to some form of pattern recognition problem [58, 59].

The use of mode shapes to study the dynamic behaviour of structures requires that a number of accelerometers be installed on the structure [8]. Another variation is to study the curvature mode shapes and wavelet maps. The residual of a mode shape is the difference between the damaged and undamaged mode shapes. The curvature of the residual of a mode shape is the second derivative of the residual of this mode shape. This is referred to as the curvature mode shape. Next, a wavelet map is constructed for each curvature mode shape. This method can accurately predict the location of the damage [8]. Since the wavelet number indicates the location of damage, the accuracy of this method depends on the number of wavelet coefficients contained in the signal.

References [5] and [7] reported the use of PZT patches at hot spots to compare the resonant frequency. In this approach, the exciting actuator is located at the centre of a symmetric region so that localized symmetrical properties of the structure can be exploited to minimize the need for pre-damage data and to compensate for changes in the structure not related to damage. Damage is determined using the differences in the response at the resonances of the healthy and damaged structure.

Ambient excitation can also be used and is more attractive since it allows modal analysis to be performed under service condition of the structures and does not require any artificial exciters [55].

There is another type of modal-based damage detection method called resistance-based damage detection method. It is a unique modal-based approach because it is capable of detecting local damage. It has been developed by utilizing the electromechanical coupling property of piezoelectric materials. The basic concept of this approach is to monitor the variations in the electrical impedance of piezoelectric materials, which is directly related to the mechanical impedance of the host structure, and will be affected by the presence of structural damage. According to [61], when a PZT patch attached to a structure is driven by a fixed alternating electric field, a small deformation is produced in the PZT wafer and the attached structure. The dynamic response of the structure to the mechanical vibration is transferred back to the PZT wafer in the form of an electrical response. Only local response of the structure will be transmitted to the sensor if the frequency of the excitation is high enough. When a crack or damage causes the mechanical dynamic response to change, it is manifested in the electrical response of the PZT wafer. Through monitoring the measured electrical impedance and comparing it to a baseline measurement, one can qualitatively determine that structural damage has occurred or is imminent.

The localized nature of the sensing region provides an advantage in that the impedance sensor is less sensitive to boundary condition changes or any operational vibrations, which usually affect lower order global modes [62]. This method has been shown to be effective in detecting damage in various structures including composite structures [63, 64]. A wireless SHM system was also demonstrated in [65] to sense the loosening of bolt joint for an aluminium structure. Corey *et al* [64] used this method to detect damage on a wind turbine blade. They introduced damage in a controlled way by adding mass and clamping as well as actual damage at various locations of interest on the blade section. Their results show that impedance-based SHM was able to detect damage on the blade section and it seems that this SHM method is a promising method to use on blades either in critical locations or in conjunction with other SHM methods which both utilized the same PZT patches.

The digital image correlation technique can be adapted as a modal-based method for wind turbine too. This method utilizes a digital video camcorder to capture the video of an area of interest on the target structure. The area of interest is patched with pattern of white spots on a black background. A digital image correlation algorithm is then used to compare the video frames of the pattern with a baseline image. The displacement of the area of interest can be obtained in real time and the global structural integrity can be known using model analysis. This method has been applied to flexible bridges [66] to determine their dynamic displacement and natural frequency. The result showed that it is comparable to the resolution of a laser vibrometer but much more cost effective. A 3D version of this method is also available (for example [67–69]), but its effectiveness as *in situ* SHM of wind turbine is yet to be validated.

4.5. Fibre optics method

An optical fibre is a glass or plastic fibre designed to guide light along its length. Optical fibres are widely used in fibre-optic communication, which permits transmission over longer distances with less loss and at higher data rates than other forms of wired and wireless communications, and they are immune to electromagnetic interference. Optical fibres are also used as sensors in SHM in various forms as follows.

4.5.1. Plastic optical fibre. Plastic optical fibre can be attached to a test specimen, for example the blade of the wind turbine, to measure loads. The optical power of a light source will reduce when it goes through a plastic optical fibre. The reduction depends on the strain of the plastic optical fibre. This principle can be used to sense the strain in a structure. For example in the experimental setup, the light from a light emitting diode can be focused through a lens and incident into an optical fibre that is attached to a structure. The light through the optical fibre is then incident into a photo detector and the optical power can be measured using an optical power meter. When the load increased, the measured optical power reduced and so can be utilized to detect damage [70]. An example of the result is shown in figure 20 where it is clear that the normalized optical power reduces linearly when the strain increases, but reduces drastically when the crack density in a composite laminate specimen increases [70]. This is the simplest sensing principle and the standard silica fibre can also be operated like the plastic optical fibre.

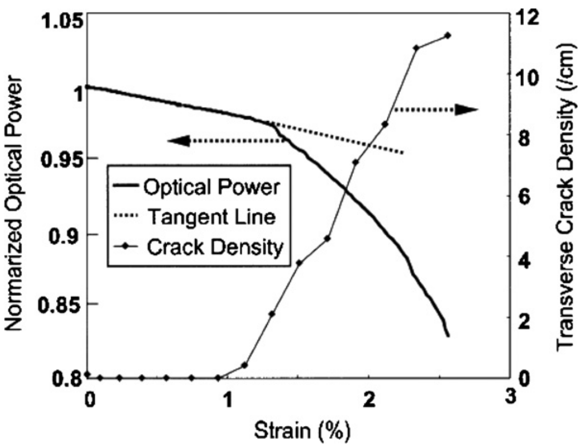


Figure 20. Relation between optical power, crack density and strain of a composite specimen [70].

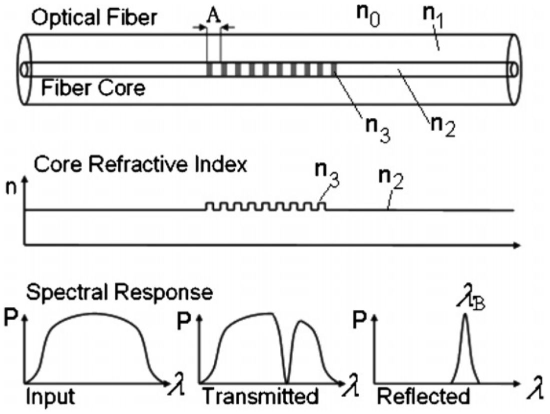


Figure 21. A fibre Bragg grating structure with refractive index profile and spectral response [73].

Fibre Bragg gratings (FBGs) are made by illuminating the core of a suitable optical fibre with a spatially varying pattern of intense UV laser lights that have sufficient energy to break the highly stable silicon–oxygen bonds. This will increase its refractive index slightly. A periodic spatial variation in the intensity of UV light, caused by the interference of two coherent beams or a phase mask placed over the fibre, gives rise to a corresponding periodic variation in the refractive index of the fibre [71]. A FBG is shown in figure 21. This produces multiple mirrors in the core of the fibre which will reflect a narrow part of a broadband light source impinging on it at a wavelength by equation (1), where n_{eff} is the propagating mode effective index and Λ is the perturbation spatial period (i.e. the distance between two consecutive mirrors) [72]:

$$\lambda_{\mathrm{B}} = 2n_{\mathrm{eff}}\Lambda. \tag{1}$$

Equation (1) implies that the reflected wavelength λ_{B} is affected by any variation in the physical or mechanical properties of the grating region. For example, strain on the fibre alters Λ and n_{eff}, and hence it can be used to measure the loads of a structure [71, 72].

FBG sensors can be interrogated with different types of opto-electronic instrumentation, and the resulting information, typically the electrical output signal produced by a photo detector, has to be acquired, sampled and elaborated by means of a dedicated electronic system [72]. The FBG has certain useful characteristics as follows [71].

(a) The sensor is a modified fibre. It has the same size as the original fibre and can have similar high strength. This is in marked contrast to many other types of optical fibre sensors which are either bigger, weaker or both.

(b) Since information about the measurands is encoded in the wavelength of the reflected light, FBG sensors are immune to drifts and have no down-lead sensitivity. The responses to strain and temperature are linear and additive and the FBG itself requires no on-site calibration.

(c) Multiple gratings can be combined in a single fibre by taking advantage of multiplexing techniques inspired by the telecommunications industry. This gives FBG sensor systems the important property of being able to simultaneously read large numbers of sensors on a very few fibres, leading to reduced cabling requirements and easier installation.

Although FBG is used to measure strain, a distribution of FBG over the structure can be used to detect traverse crack evolution [70] and impact damage [74]. The impact event can be detected in real time by measuring both the abrupt change of strain and the time delay in the strain changes between the sensors. By using the difference in arrival time of the strain response, the position of the impact event can be located and further analysis can be done.

It has been shown that AE waves generated during standard pencil-lead breakage or actual damage will propagate on a structure and then modulate the pitch of the FBG [75, 76]. This ability makes the FBG viable to detect structural damage as early as at its onset. Lamb waves generated by a piezoceramic transducer can also be sensed in the same way. The propagation of these AE waves is affected by damage in the material, and FBGs can be used to monitor the subtle strain changes of Lamb waves. FBGs (small diameter fibre of about 50 μm) have been successfully demonstrated as Lamb wave sensors for detecting damage and disbonds in composite materials [77].

Reference [78] reported that a specimen can be heated using flash lamps chamber, and a fibre optic thermal sensor can be used to measure changes in the thermal conductivity of a sample due to impact damage.

4.5.2. *Optical fuse.*

A transverse optical fuse in laminated composites can be used for damage detection. Short lengths of optical fibre can be embedded through the thickness of a graphite/epoxy laminate during the fabrication process. The fibres act as optical fuses, which break in areas of low energy impact damage. If a regular array of fibres is emplaced, the pattern of light transmission through the composite can be used to identify areas of low energy impact damage since unbroken fibres transmit light while broken fibres do not. Simple visual inspection techniques may be employed to detect damage in optically fused structures [79].

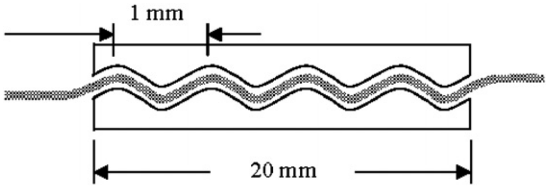


Figure 22. Microbend fibre as sensor for the detection of small displacements.

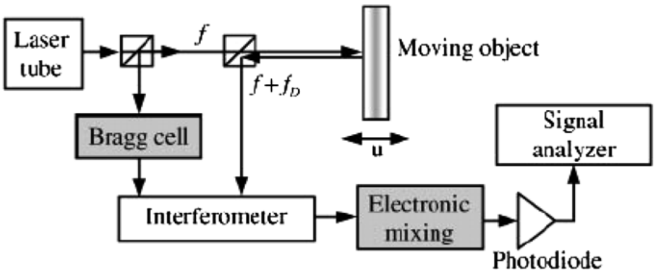


Figure 23. Schematic of a laser Doppler vibrometer system [80].

4.5.3. Microbending fibre. A sensor based on microbending of fibres was developed for the detection of cracks in adhesive joints [19]. It utilizes the fact that the propagation of light through an optical fibre may be strongly affected by bending the fibre. The basic principle of the detector is illustrated in figure 22. When the two solid corrugated parts are moved to, or from each other, the curvature of the fibre changes, affecting the transmission of light through the fibre. The sensor developed was designed to be sensitive to displacements perpendicular to the main axis of the fibre. However, the corrugation and support of the two solid parts may be done so that the sensor is sensitive to shear.

4.6. *Laser Doppler vibrometer method*

The laser Doppler vibrometer (LDV) is a non-contact velocity transducer, based on the analysis of the Doppler effect on a laser beam emerging from a solid surface [80]. When coherent radiation of frequency f emitted by a source interacts with a reflecting or diffusing surface moving at a velocity u, the radiation observed by the source (backscattering configuration) is affected by a Doppler shift (f_D) proportional to the surface velocity. Such frequency shift is given by equation (1), where $u\cos\theta$ is the velocity component along the optical axis [80]:

$$f_D = \frac{2u}{\lambda}\cos\theta. \qquad (2)$$

Applying this method for damage detection, a modal-based approach could be used, where the principle is that damage will cause detectable changes in the modal properties. The signal can then be used to produce frequency/response plots and mode shapes [56]. Figure 23 shows the system used by [80].

The use of scanning LDV (SLDV) as vibration transducer offers many advantages, as it is automatic, has high sensitivity and has non-contacting capabilities. SLDV provides a high spatial resolution of measurement, which can only be achieved by employing a massive number of transducers in the conventional measurement. Moreover, this technique allows measurement of objects that are inaccessible by conventional transducers [55].

In addition, the possibilities of using different methods of excitation, such as forced vibration provided by impact hammer [81], electrodynamic shaker or laser pulse [80, 82, 83] and also ambient response [84], have been reported.

Interestingly, this method can be applied for a rotating system, using a variation called the tracking laser vibrometer. Reference [85] shows that the method can be successfully applied to detect the vibration of a propeller of a boat underwater. This suggested that this method is very promising for application to modal analysis of a rotating wind turbine if the related algorithm can be developed.

Reference [7] reported the use of SLDV to detect the changes of operational deflection shapes (ODS) to indicate and possibly locate damage. ODS are computed by the scanning laser Doppler vibrometer system for the healthy and damaged structures. A Fourier transformation is performed and the complex vibration response at the particular measurement point is stored. This is repeated for all scan points and the real amplitudes are plotted at selected phase angles. This method is quite accurate in detecting damage since the exact response of the structure is used, subject only to error in performing the Fourier transformation.

4.7. *Electrical resistance-based damage detection method*

This electrical resistance-based damage detection method is different from the resistance-based damage detection method discussed under section 4.4. Reference [86] utilizes the conductive property of the CFRP and proposed an electrical impedance tomography damage detection method. A set of aligned razor blades was used as electrodes on the sides of square CFRP laminates to detect and locate artificial hole damage. Reference [87] demonstrated that the same resistance principle can be used to detect fatigue damage, as the cumulative fatigue damage causes the reduction of stiffness. The electrical resistance gradually increased as the stiffness reduced and showed a very abrupt change when the final fatigue failure was imminent. It has been shown that matrix cracking, delamination and fibre breakage can be detected using this method. References [86, 88] show that the location and size of delamination can be determined. As well as being applicable to a plate like structure, this method is also useful for beam type structures [89].

Reference [90] proposed another method that can be applied to in-service turbine blades. Carbon fibre has high electric conductivity while the polymer matrix of a carbon-fibre-reinforced plastic is an insulating resistor. In practice, CFRP laminates have finite electrical resistance in every direction. This electrical resistance in the transverse direction is much larger than in the direction of the fibre orientation. If a delamination crack starts growing in the

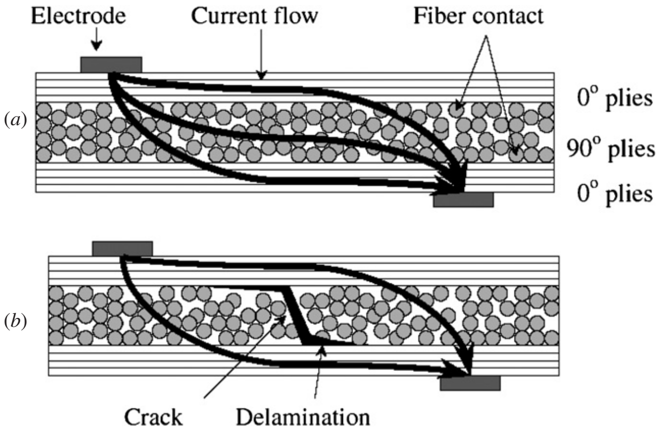


Figure 24. Schema of a practical structure of a carbon/epoxy composite when an electrical current is applied. (*a*) Electrical network structures of the fibre in a CFRP laminate. (*b*) The electrical network is broken with delamination and matrix cracking.

resin-rich interlaminate, the crack breaks the fibre-contact-network between the plies. The breakage of the contact network causes an increase in the electrical resistance of the carbon/epoxy-laminated composites, which enables delamination crack detection by measuring the electrical resistance change in a CFRP composite laminate. A delamination crack is detected using the electrical resistance change between the two mounted electrodes, as shown in figure 24. A wireless delamination detection system is composed of a sensor module that has a ceramic oscillator connected to the electrodes mounted on the composite surface and its receiver. The ceramic oscillator of the sensor module is used for wirelessly transmitting the electrical resistance change data as the oscillating frequency changes to its receiver. The oscillating frequency of the sensor circuit increases with the increase of electrical resistance of CFRP laminates, indicating the occurrence of delamination in the CFRP laminates. The sensor module is 20 mm in length, 15 mm in width and 10 mm in height with only a 4 g mass. When *n* multiple channels are demanded, the required number of sensors is *n*, but only a single receiver is needed.

4.8. *Strain memory alloy method*

Strain memory alloys rely on an irreversible crystallographic transformation for their smart properties. Any SHM system based on this group of smart materials is, therefore, a passive peak system. By 'passive' it is understood that in contrast to active monitoring, a full-time power supply is not required, and data storage facilities are also not required. Instead, power is only necessary during the brief period of sensor interrogation, and the actual reading is stored within the sensor element itself.

The fundamental principle governing the unique behaviour of strain memory alloys is an irreversible strain-induced transformation from one crystal state to another. The parent austenitic crystal structure is paramagnetic while the product martensitic phase is ferromagnetic. The fact that the martensite forms in direct proportion to the strain experienced by the material means that a measurement of magnetic susceptibility could be directly correlated with the peak strain experienced by a component manufactured from strain memory alloy [91, 92]. Alternatively, the alloy can be integrated or embedded into a structure, for example embedded within a laminate during component construction, to provide an indication of the peak tensile strain encountered by the laminate [93].

The changing magnetic susceptibility of the strain memory alloy inserts can be measured using a non-contact susceptibility sensor [92]. For example a superconducting quantum interference device can be used for high-resolution scan or another more portable 'pancake coil' to detect defects [91].

4.9. *X-radioscopy method*

X-rays can penetrate a large number of materials including composites. Typically images are obtained as shadows revealing variations in the integrated attenuation of x-rays along the propagation paths. Thus under the normal mode of operation, x-rays cannot reveal cracks oriented parallel to the rays [19]. Reference [40] reported that this method involves imaging through radiation with wavelengths that require shielding and/or proper safety distances. However, the energy needed is low and safety requirements can be easily satisfied with remote-controlled positioning units. X-ray sources can be small, air cooled and easily implemented for various applications. This method is capable of detecting missing glue between laminates, cracks and voids in the laminates, non-intended orientation of fibres or kink band. Some microfocus sources enable detection of defects less than 10 μm. This method can be used for real-time x-ray inspection for quality control during or shortly after wind turbine blade production. If novel, very compact detectors and small x-ray sources can be developed, in-service non-rotating SHM for the wind turbine is possible.

4.10. *Eddy current method*

Conventional eddy current testing is used for inspection of conductive materials by inducing electrical currents in the test material and recording any variations of the induced currents. Since carbon fibres are electrically conductive [94], wind turbine components made from carbon-fibre-reinforced plastic materials can be inspected using the same principle. A basic eddy current system usually consists of a coil which is excited by an alternating current. The electric current within the coil creates a primary magnetic field surrounding the coil. When brought into the proximity of the test material, the primary electromagnetic field induces currents (eddy currents) in the material tested. According to Lenz's law, the eddy current generates a secondary magnetic field which is opposed to the primary magnetic field, as shown in figure 25.

A variation in the structure of the material inspected, for example the presence of a flaw, will cause a variation in the eddy current flow which will modify the secondary magnetic field [94]. The relationship between both magnetic fields is given by equation (3), where *B* is the secondary magnetic field,

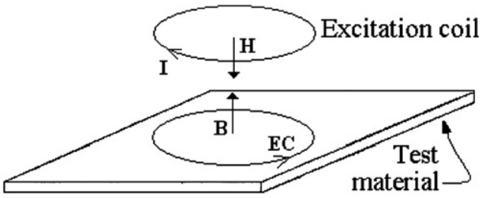


Figure 25. Schematic of a coil excited by an alternating current (I) and showing the direction of the primary (H) and secondary (B) magnetic fields and of the induced eddy currents (EC) in a test material [94].

μ is the magnetic permeability of the material inspected and H is the primary magnetic field:

$$B = \mu H. \tag{3}$$

A change in B will be observed by measuring a variation of the coil impedance [94]. This makes the damage detection and localization possible. However, some *a priori* knowledge of damage location is required in order to use this method effectively [49].

4.11. Algorithms

Many of the damage detection techniques discussed above require algorithms to function, ranging from simple and direct to complex with learning capability. These algorithms are capable of processing the signals from the sensors for damage identification, damage localization, severity assessment, and can be further extended to the prediction of failure, estimation of the remaining service life and decision making to determine the action required for the damage detected. There are also many global monitoring algorithms developed based on the general turbine parameters, and then implemented by keeping in view the main characteristics of the wind turbine [95]. No additional investment in hardware is necessary, but in order to develop a general-purpose algorithm for all turbines, strenuous efforts are needed to ensure that the whole system does not become too complex in defining the relationship between subsystems, components and subassemblies. This approach is not fully matured and lots of time will need to be spent to produce an optimal system [95].

Another objective is to aid the establishment of a proactive condition-based maintenance and repair (M&R) programme, which can be more beneficial than corrective and preventive maintenance [3]. A fault prediction algorithm has the primary function of this system which allows early warnings of structural (or mechanical and electrical) defects to prevent major component failures. Many faults can be detected while the defective component is still operational. Thus necessary repair actions can be planned for the most appropriate time without the need to bring an immediate halt to the system at the point of total failure. This is of special importance for offshore wind turbines where bad conditions (storm, high tide, etc) can prevent any repair actions for several weeks [96]. A review of the algorithms related to SHM and condition monitoring for wind turbine can be found in [3].

5. Discussion

5.1. Acoustic emission events detection method

AE events detection method is very powerful in detecting any damage mode up to microscale. However, this method is less capable in damage characterization and further damage evaluation if a suitable algorithm is not available. For real-time SHM, damage localization based on wave speed in complex structures may not be the most effective method because the wave speed in a structure is a function of the geometric and material parameters of the structure [36]. An example of different strategies that can be implemented to improve the damage evaluation capability of AE events detection method is the in-service structural neural system (SNS) [36]. The proposed passive SNS has high sensitivity to damage, and simple instrumentation and wiring of the monitoring system. It has 'n' channels of input from the sensors and only two channels of output, which reduce the required number of data acquisition channels to monitor the health of the structure. Most of the signal processing is done in an analogue fashion, which can reduce the cost of maintaining and obtaining a large number of digital data acquisition channels.

As suggested by [4], this SNS strategy is also possible for application in the fabrication of smart turbine blades, where the PZT nerves can be self-powered, and the active fibre composite (AFC) material can also be used for micro power generation to power the embedded signal conditioning and data acquisition/analysis system. Wireless transmission of the reduced health information could simplify the SHM system. The concept for the smart blade is shown in figure 26.

5.2. Thermal imaging method

The advantage of the thermal imaging method is that it is able to produce a full-field measurement in image form. This makes a fast evaluation possible even for a non-professional user. The main problem of the thermal imaging method lies in the thermal excitation method. Passive excitation can be used but is limited to abnormal electrical components that produce excessive heat during operation. This can also be applied to faulty components and moving contacts where excessive friction produces heat. For active excitation, it is not cost effective or labour intensive to excite the turbine on site, even if possible. If thermoelastic stress excitation method is used, its drawback is the need to load cyclically the material being tested, which can result in a growth of the damage while trying to locate existing damage [97]. The need for physical attachment of the loading apparatus to the structure under test is another disadvantage. Finally, if all types of loading are not included in the test program, it is possible for a major flaw to go undetected [97]. Recently, a heat source such as a halogen lamp and ultrasound generated by contact transducers and non-contact pulsed laser have been introduced to overcome the drawback based on the mechanical loading. In particular, non-contact ultrasound-induced thermography may be a promising technology, as in rotorcraft [98], if the massive scale of the recent wind turbines is considered in the SHM system design step.

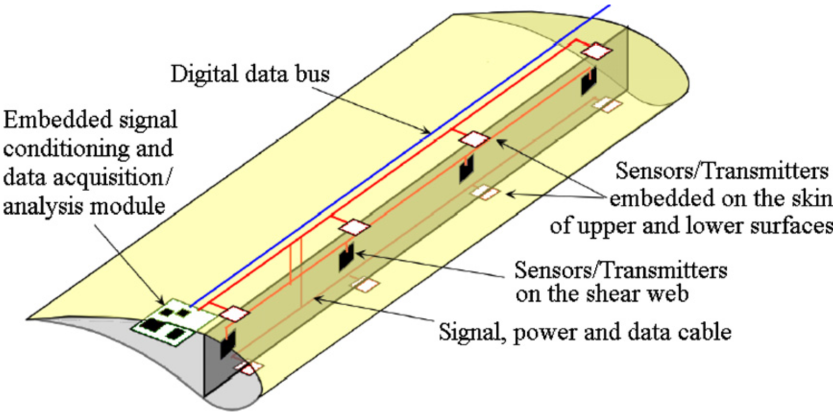


Figure 26. The conceptual design of a smart wind turbine blade using SNS as the SHM system [4].

5.3. *Ultrasonic methods*

Ultrasound methods are not sensitive to single fibre rupture in fibre composites. In some cases multiple fibre rupture results in increased attenuation of the ultrasound waves. However, the change in attenuation caused by multiple fibre ruptures is less than natural attenuation variation in the laminate [40]. The damage localization of ultrasound methods using time of flight strategy is not accurate for complex structures. However, the ultrasound propagation imaging technique can be very promising. When a laser is used as both transmitter and receiver, the technique can be utilized as a remote in-service SHM for wind turbines. Also the installation location of the receiver will be an important design point as in non-contact ultrasound-induced thermography.

5.4. *Modal-based approaches*

Modal-based approaches that use structural dynamics data to locate damage can function without costly (or impossible) dismantling of the structure. It is a possible approach for in-service SHM of structures if high-throughput data acquisition systems, and high-bandwidth piezoceramic sensors and actuators are available [57].

Global modal-based methods are difficult to implement, and the results produced can be mixed and it requires experts to carry out the testing and interpretation [99]. In order to detect damage using modal-based methods, a complete dynamic analysis is often required and is usually performed by a finite element analysis method to locate and quantify the damage [99, 100]. This procedure has several difficulties, as it is not always possible or convenient to measure the vibration response of a structure before damage [100]. Often, the lack of availability of this type of data can make this method impractical for certain applications [58]. Secondly, it is often not feasible to conduct a detailed dynamic analysis of a complete structure and it is sometimes difficult to obtain accurate material properties for a dynamic analysis. Furthermore, it is not easy to extract local information caused by small damage from modal parameters that characterize the global behaviour of a structure [100]. Reference [6] mentioned that local damage may not significantly influence the lower-frequency global response of structures that is normally measured during vibration tests. These problems restrict the widespread acceptance of this method as SHM for wind turbines.

On the other hand, a local modal-based approach is relatively easy to implement. It does not require complete dynamic analysis of the whole wind turbine, and it is promising to be applied to rotating wind turbines provided that the telemetry wireless circuits required and the sensors can be installed at a strategic location within the structures.

5.5. *Fibre optics method*

Plastic fibre optics can be a promising replacement for electrical strain gauges that are not robust on a long-term basis [95]. It is useful in lifetime prediction and safeguarding of the stress level, especially for the blade. Small diameter FBG has also been developed and can be embedded into composite lamina with no reduction of strength [77]. Although FBG strain gauges are commercially available, they were found to be too expensive [19]. A cost-effective FBG interrogation system is needed if it is to be used in a wind turbine SHM.

5.6. *Laser Doppler vibrometer method*

The laser Doppler vibrometer method is a very promising method as it has high spatial resolution of measurement that can only be achieved by employing a massive number of sensors in other methods. It is a non-contacting method, which makes it easy in implementation.

It can employ modal-based techniques or other external excitation. If laser pulse excitation is used, it has possibilities for a remote SHM method for an in-service rotating wind turbine, or in other situations which are hazardous for humans, for example high temperature and voltage. An image or movie, similar to an ultrasound wave propagation movie, can be obtained and the damage evaluation can be simple even to those without *a priori* knowledge about signal processing. However, the laser Doppler vibrometer is still uneconomic for the wind turbine application.

5.7. *Electrical resistance-based damage detection method*

Electrical resistance-based damage detection method is applicable for SHM of turbine blades made of CFRP. CFRP has become more and more important in the manufacture of turbine blades as their size increased. It can be applied to in-service rotating turbines using wireless connection. When n multiple channels are demanded, the required number of sensors is n, but only a single receiver is needed. The limitation for this method is that it is sensitive only to delamination and *a priori* knowledge about the delamination hot spots is required.

5.8. *Strain memory alloy method*

The possibility to apply strain memory alloy as embedded sensors in the manufacturing of blades is possible but the effect upon the load bearing capability of the blade is not clear. More study is needed to find a promising strategy for implementing in the manufacture of wind turbines, including the tower and the fasteners. It also has the disadvantage in the scanning of magnetic susceptibility of wind turbines as all sensing methods currently available are not cost effective and are labour intensive.

5.9. *X-radioscopy method*

An advantage of x-rays is that images are obtained in parallel (not by scanning) like the thermographic approach and hence it is fast, provided that some *a priori* knowledge of damage location is obtained. The problems lie within the interpretation of the x-ray images and safety reasons. Although [40] reported that x-ray sources can be small, air cooled and the safety requirements can be easily satisfied with remote-controlled positioning of the unit, it will only be practical for use in a gigantic wind turbine system when novel strategies for image acquisition are available.

5.10. *Eddy current method*

The eddy current method has the same problem in the data acquisition process where there is currently no promising strategy in scanning an in-service wind turbine blade. Its application is limited to the CFRP component.

6. Conclusions

Considering that adding the SHM sensor system to a wind turbine structure may adversely affect the performance of the turbine, the number and location of sensors are an important issue that has not been addressed to any significant extent in the current literature. Methods that are to be implemented for in-service wind turbines should demonstrate that they can perform well under the limitations of a small number of measurement locations, and under the constraint that these locations be selected without *a priori* knowledge of the damage location.

The fibre optic strain monitoring and/or damage detection methods can be selected to obtain global load conditions and the AE events damage detection method based on built-in sensors is most appropriate for early warning of the onset of damage or to register an impact event. It is sensitive to all kinds of damage up to sub-micron size damage and it can locate the damage or impact quite accurately. The limitation of these methods is the number of sensors required and the signal noise during the operation of the turbine. In addition, wired and wireless networking between the rotating turbine blades and the nacelle is still challenging. If a remote SHM system is considered, then the most promising methods are non-contact ultrasound-induced thermography and ultrasound propagation imaging using the pulsed laser and/or the laser Doppler vibrometer. The rest of the methods discussed can also be applied for non-destructive testing when the results from the *in situ* methods should be completely checked.

Finally, as much emphasis is placed on the environmental benefits of wind power generation systems, they are, as yet, huge and expensive to construct and maintain. Therefore the related industries require SHM systems that can provide cost-effective maintenance programmes which deliver accurate detection of faults as early as possible.

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