A Review on Experimental Methods in Health Monitoring Techniques for Wind Turbine Blade

Kulkarni Sourabh Sadanand[a,*], Patil Suresh Abasaheb[b]

[a] *Research Scholar, Department of Technology, Shivaji University, Kolhapur, 416004, Maharashtra, India*
[b] *Principal, Government Polytechnic Malvan, Sindhudurg, 416606, Maharashtra, India*

Abstract

This paper is an attempt to summarize the experimental methods in health monitoring techniques applied to wind turbine blade. Techniques like acoustic emission, ultrasonic, vibration based, wavelet analysis, visual inspection, machine learning etc. are reviewed in order to identify, localize and determine the severity of damage. From literature, it is observed that there are some methods having lot more potential to identify various defects but yet not utilized at their level best. In this regard, the paper summarizes the potential of techniques to identify the damage occurred in wind turbine blade so far which will be beneficial to carry out further research. It was concluded that techniques based on acoustics emission, ultrasonic and vibration has much potential to identify, localize and determine the severity of damage. However combining any two techniques can increase the potential of method to give more realistic results with the aid of machine learning. Finally a suitable case study is presented in short.

Keywords: Wind turbine blade (WTB); finite element method (FEM); Structural health monitoring (SHM) system; acoustic emission (AE); operational modal analysis (OMA).

---

1. Introduction

In today's energy crisis, world has put an emphasis on increased utilization of renewable energy. When it comes to renewable energy, solar power may get immediate attention but there is another energy source as promising and reliable as solar power and that is wind power. It was estimated that global annual potential of on shore and off shore wind power is around 840000 Terra Watt Hours almost 40 times world's annual power consumption. Like solar power, adoption of wind power is growing fast and cost has dropped over years of research. The average diameter of commercial wind turbine rotor in 1980 was 17 m generating power around 0.07 MW. Now a day's average diameter of wind turbine rotor is 116 m generating power around 2.4 MW. This achievement of huge rotor size and substantial drop in cost is possible due to advancement in material technology. Since wind turbine undergoes various loads and changing environmental conditions they are prone to damage. Failure of such system will not be economical hence they have to be monitored regularly to avoid catastrophic failure. To keep the wind turbine in operation, implementation of condition monitoring system (CMS) and fault detection system (FDS) is important and for this purpose a sound knowledge of these systems is essential. CMS plays a vital role to establish a condition-based maintenance and repair, which can be more beneficial than corrective and preventive maintenance. Many faults can be detected while the defective component is still in operation. Necessary repair actions can be planned in time and need not be taken immediately. This fact is important for off-shore plants where undesired conditions such as storm, high tide etc. can prevent any repair actions for a long duration. Large and frequent fluctuations in wind intensity and directions can cause serious problems in harvesting this energy. The failure is uncertain but losses due to sudden faults and damages can be minimized by installing monitoring systems for early warning purpose. It will result in minimized production losses and this will contribute to make the existing system more efficient and reliable.

To have a brief overview of present research in the field of health monitoring of wind turbine blade, some reviews were studied. After going through the reviews [1–15], it was observed that for a particular defect, which technique is utilized for the heath monitoring of wind turbine blade is not summarized. In this paper an attempt is made to summarize the potential of health monitoring technique to detect various damages. The damage identification techniques that can be used as a health monitoring technique for wind turbine blade are shown in Figure 1.

Various theoretical studies like power coefficient

---

[*] Corresponding Author
Email address: `sskulkarni6493@gmail.com` (Kulkarni Sourabh Sadanand)

Table 1: Abbreviation

AE	Acoustic Emission	LWL	Locally Weighted Learning
CAS	Coupled Aero Structure	MAC	Modal Assurance Criteria
CMS	Condition Monitoring System	MSDC	Mode Shape Difference Curvature
CNN	Convolutional Neural Network	MSE	Modal Strain Energy
CNT	Carbon Nano Tubes	MSSA	Multivariate Singular Spectrum Analysis
CoMAC	Coordinate Modal Assurance Criteria	NDT	Non Destructive Technique
CPT	Classical Plate Theory	NExT	Natural Excitation Technique
CWT	Continuous Wavelet Transforms	OMA	Operational Modal Analysis
DOF	Degrees of Freedom	p-LSCF	Poly-reference Least-Squares Complex Frequency-domain
DTM	Differential Transform Method	ROM	Reduced Order Model
DWT	Discrete Wavelet Transforms	SHM	Structural Health Monitoring
FDS	Fault Detection System	SSI	Stochastic Subspace Identification
FEM	Finite Element Method	STFT	Short Time Fourier Transform
FFT	Fast Fourier Transform	TAD	Twist Angle Distribution
FRF	Frequency Response Function	WECS	Wind Energy Conservation System
FRP	Fiberglass Reinforced Plastic	WSN	Wireless Sensing Network
GFRP	Glass-Fiber-Reinforced-Polymer	WT	Wind Turbine
LSTM	Long Short Term Memory	WTB	Wind Turbine Blade

analysis [16], principle of virtual work [17], Euler Bernoulli beam analysis using differential transform method (DTM) [18] as well as considering geometric nonlinearities and coupling between axial and flapwise vibrations [19], non - linear dynamic response of wind turbine blade under influence of gravity [20, 21], variation in amplitude, frequency of support point motion, rotational speed, frequency ratio $\left(\frac{\omega_2}{\omega_1}\right)$ and the damping ratio ξ [22] and non – linear wind turbine wing model by Monte Carlo simulation excited by stochastic support motion [23] were contributed to establish a mathematical model of wind turbine blade. Over these traditional formulation of model, it was observed that the mixed formulation (combination of theoretical and finite element approach) simplifies the determination of constraint forces and moments within the beam finite element and at the boundaries which allows connectivity between the finite elements and rigid bodies [24]. For this formulation two subsystems viz. flexible body (tower and blades) and rigid body (nacelle, hub) can be taken under consideration. In following section, the experimental methods that can be used for health monitoring of wind turbine blade are reviewed.

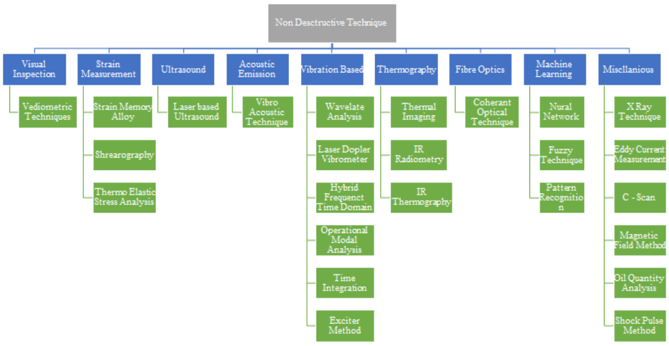

Figure 1: Classification of damage identification techniques

2. Experimental Methods

Generally the NDT's are utilized as a health monitoring technique to identify, localize and determine the severity of the damage. This section includes the summary of various experimental methods (NDT's) that can be used as health monitoring techniques for wind turbine blade.

2.1. Visual Inspection

One of the simplest and promising technique to identify occurrence of damage is the Visual inspection. However, it is not able to provide early warnings for possible damage. Using visual inspection, discontinuities in blade can be characterized in four types viz. 1) Transverse, longitudinal and surface cracks, 2) Edge cuts, crushing and side separation, 3) Surface or coating pores, surface damages, holes or penetrations 4) reworked areas [25]. It was observed that due to surface changes, longitudinal crack and coating damage appear frequently. Any minute damage cannot be seen easily with naked eyes, it is the ability of observer to identify the damage even of small size. This puts the limitation to identify the damage in its early stage or to determine the possibility of damage. However it was tested that video metric technique can be utilised to detect the damage in blade and has potential to be used in SHM systems [26]. Based on advanced videogrammetry, Guan et al. [27] proposed a series of techniques to detect structural defects in the blades during their normal operation.

2.2. Acoustic Emission

Acoustic Emission (AE) is a phenomenon of propagation of elastic (acoustic) waves in solids due to some irreversible changes in its internal structure. Acoustic waves are formed due to presence of crack, plastic deformation, temperature gradients, external forces etc. In other words, Acoustic emission is caused due to rapid release of stress energy. This release of energy is due to changes in internal structure. The presence of such emission can be utilized to identify possible damage in structure. AE techniques is based on use of such acoustic energy in the region of damage to analyze the health condition of structure. It has ability to detect, localize and determine the severity of damage having very small magnitude which is very difficult to detect by visual inspection present in the structure. To get more promising results and avoid attenuation of signal, AE sensors has to be close to the source. However, ability of AE in detecting, localizing and characterizing depends on position of sensor [28] and number of sensors used is dependent on selection of threshold limit [29]. As a matter of fact large number of sensors are required to analyse the health condition of structure. Large number of sensors lead to large number of input data involving noise. To reduce such amount of data and noise, one has to employ certain algorithm to data acquisition system which will facilitate to have required amount of input data reducing noise as well.

In case of small wind turbine with variable speed, rotor speed is important parameter while measuring acoustic signal [30]. Rotor speed helps to determine sound emission for a particular design of blade as well as the cause behind varying sound emission in small wind turbine blade (below 10 kW). From Table 2 it is shown that to avoid flutter speed, certain parameters in wind turbine needs to be altered.

Table 2: Effect of electric loading and flutter speed on small wind turbine

Blade	**Change in parameter**	**Flutter speed delay**	**Loading**
1 kW	Length decreased by 9.2%	200 rpm	-
	Increased stiffness	Flutter not occurred	Electric loading
10 kW	Thick airfoil with aft camber	Flutter not occurred	-

A fatigue test on FRP blade showed that the root region of the blade being less susceptible to damage [31] and most of the blade failure was initiated by delamination at the rear sandwich panel [32]. To simulate in service loading condition, cyclic loading using resonant masses may be helpful. A comparative experimental study between the technic based on AE and Coherent optical (Electronic Shearography) revealed that AE technique being more useful in analysing the health condition during manufacturing and working stage [33]. It was observed that AE when implemented as SHM with wireless sensing technique can well perform in in situ monitoring of a 300 W offshore wind turbine at Newcastle University, UK [34].

2.3. Vibration Based Techniques

Vibration based technique utilizes determination of modal properties like frequency, mode shape, damping etc. to identify, localize and determine the severity of damage. Such technique uses comparison of these properties for healthy and damaged structure. Any shift in modal properties will indicate the possible damage. Over the years, vibration based technique has proven its importance in analyzing health condition of structure. This method has ability to indicate possible damage in its early stage which will be beneficial to avoid catastrophic failure of structure.

2.3.1. Wavelet analysis

Techniques based on Wavelet transform being used to analyse modal properties of structure. Meaning of wavelet is a small portion of the wave. This technique uses mathematical function which divides given function into various frequency components forming a wavelet. Later on these wavelets being studied. In other words, the wavelets are scaled and translated copies of a fast-decaying oscillating waveform (mother wavelet)[35]. Wavelet analysis enables the inspection of narrow frequency bands over a short-time window. Wavelets are used to represent the functions with some discontinuities and to deconstruct and reconstruct finite, non-periodic and/or non-stationary signals. Doliński and Krawczuk [35] classified them into Discrete Wavelet Transforms (DWT) and Continuous Wavelet Transforms (CWT). CWT's has ability to operate over every possible scale and translation while DWT's uses a particular subset of scale and translation values or representation grid. Based on wavelet theory, Multivariate Singular Spectrum Analysis (MSSA) can be useful tool to identify damage based on vibration measurement technique. Loh et al. [36] studied detection of delamination in wind turbine blade using MSSA and convenience driven stochastic subspace identification (SSI). Later uses response data only to identify damage in structure while prior uses input excitation as well as response data. Hence it can be stated that MSSA has potential to be applied as data pre – processing to enhance subspace identification as well as feature extraction.

To analyse the response of structure entire body has to be excited at once. It seems very difficult for large structure. One of the solution for such problem is a method of Natural Excitation. Another possible solution being use of Wireless Sensing Network (WSN). In this method, piezoceramic patch is used to generate desired wave which propagates through structure and the response can be generated through other sensors. Sensor signals then allowed to pass through wireless communication system to computer for further analysis. To check the potential of WSN using piezoceramic sensor, Song et al. [37] performed static test and wind tunnel test on a wind turbine blade under the influence of induced crack. These experimental results showed the compatibility of using piezoceramic sensor in WSN to monitor the health condition of wind turbine blade. Figure 2 shows experimental setup of blade (TX - 100) fatigue test employing 3 SHMs viz. NASA, Purdue and Virginia Tech.

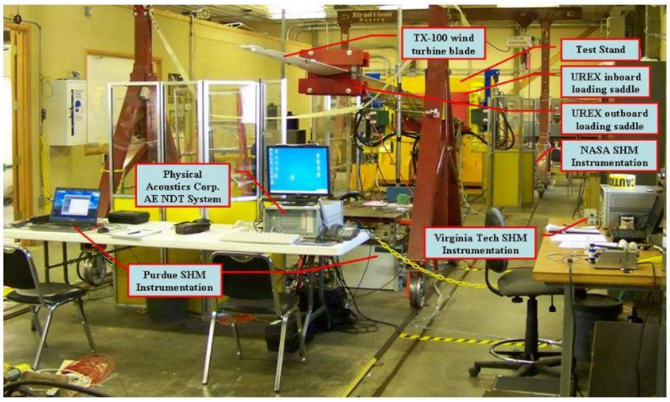

Figure 2: Blade fatigue test setup [37]

2.3.2. Operational Modal Analysis

While performing modal analysis, the structure must be at rest. In case of rotating structure or structure in some motion, application of such modal analysis technique is near about impossible. To extract the damage feature one has to employ operation modal analysis (OMA) to such rotating structure. OMA has ability to extract modal features from measured response making it suitable to carryout modal analysis of big structure. It can be used as a strong tool to monitor the boundary conditions of structures. However it is not sensitive to small cracks or very local phenomena. For a large structures like wind turbine blade, one has to ensure that entire structure is excited so as to measure the response. Here comes the challenge to excite the large structure. A solution to such problem may be given as exciting the structure with natural cause like wind load as natural input. Such technique known as Natural Excitation Technique (NExT). NExT can be termed as predecessor to OMA. Carne and James [38, 39] summarized the research on NExT from 1990 applied to vertical axis wind turbine and horizontal axis wind turbine for both parked and rotating condition. It is inherent that rotor rotation can change the characteristic of aerodynamic excitation thereby limiting OMA to apply on wind turbine [40]. Hence it was observed that OMA violates its assumption under certain conditions. Understanding the limitation of application of OMA as SHM, it is evident that straightforward application of OMA should be avoided. In this regard, Multi-Blade Coordinate transformation (MBC) can be utilized to be data pre-processing prior to apply OMA in order to convert linear time periodic system into a linear time invariant system. MBC allows to integrate the dynamic behaviour of individual blades in a non-rotating frame [41], then the rotor can be combined with other subsystems to analyse the coupled behaviour of the wind turbine. Based on MBC (also known as Coleman coordinate transformation), an approach to apply OMA on a 3 MW wind turbine was given understanding the solution to violation of assumption made in OMA [42].

On application of OMA, Farrar et al. [43] used Fisher's discriminant as a damage indicator in wind turbine structure which uses statistical pattern recognition based on measured response only. Pacheco-Chérrez and Probst [44] proposed a cost effective SHM system based on OMA which is capable to detect and locate longitudinal crack in upper part of blade occurring due to the stochastic excitation by the wind only.

2.3.3. Short Time Fourier Transform

Short Time Fourier Transform (STFT) identifies time frequency distribution related to non-stationary signals. It picks up local frequency which is present for short time period that may be missed by Fast Fourier Transform (FFT). For a given time period, STFT splits the signal in short time segment. FFT is then applied to these short time segments to identify peak frequencies. Lastly by combining all the segments, time frequency distribution of given system is obtained. In case of wind turbine blade, damage can be simulated by reducing stiffness (due to delamination of composite structure) of blade and shift in natural frequency can be identified by STFT [45]. Ulriksen et al. [46] performed experiment on Whisper 500 blade to determine its natural frequency and mode shapes. It was suggested that vibration based technique can be used to analyse the structural health of blade even for small damage. Keeping in mind the fact that any structural change would tend to change its modal properties (Modal frequencies, mode shapes, damping etc.) Ganeriwala et al. [47] performed experiments on a 4 feet wind turbine blade under influence of induced crack (Surface and edge). From experiment it was observed that to have indication of damage, first seven modes may be sufficient while monitoring the changes in modal properties. From the characteristics of vibration, any addition of mass to the system tend to lower its natural frequency. This addition of mass is simulated in terms of accumulation of ice on blade [48] and using Fiber Bragg Grating (FBG) sensor, strain measurement can be performed to detect icing condition on wind turbine blade. Even in vibration based or modal based methods one need to determine their accuracy and efficiency in determining the mode shapes as well as their ability to detect damage. In this regard, Table 3 can be helpful in understanding reliability of various feature extractions and their indication regarding damage.

Table 3: Feature extraction and their indication

S. No.	Reliability Indices	Indication	Values
1	MAC	Damage detection	0 to 1
2	CoMAC	Damage location	0 to 1
3	MSC	Detect and localize the slight and early damage	Difference between MSC and Mode Shape
4	MSE	Local and slight early damages	Difference between MSE and Mode Shape

A comparative study between these modal based damage indices was carried out by Rezaei et al. [49] considering geometrical non linearity. The study revealed that MSE damage indices showed promising results to determine damage location and its length considering different rotational speeds and severity of loading. On comparing the algorithms like Transmittance Function, Resonant Comparison, Operational Deflection Shape and Wave Propagation to detect damage based on vibration measurement revealed that Resonant Comparison method is suitable to detect damage on operational wind turbine while for parked wind turbine suitability stands with Operational Deflection Shape [50]. The comparison between such algorithms is shown in Table 4.

Table 5 summarizes SHM systems based on vibration technique with their sensors and feature extraction methods.

2.4. Thermography

An infrared camera is used in thermography to collect the data in form of digital image. Data collected is composed of series of digital images. A computer system is required to initiate the heat lamp and collect the data. Thermal image analysis software is necessary for processing and control of inspection parameters.

The advantages being non-contact type, quick inspection, capacity of imaging large area etc. A small amount of heat (15°C above ambient condition) applied to surface of structure is sufficient to measure the response. The response can be formulated in terms of change in thermal diffusivity to identify the damage. In this regard, a scheme of Thermography [51] as shown in Figure 3 depicts methods by which thermography can be implemented to monitor health of the structure.

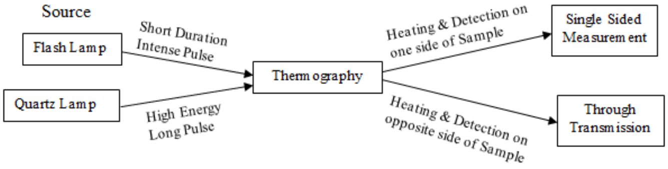

Figure 3: Scheme of thermography

2.5. Ultrasonic

Ultrasonic testing (UT) is based on the propagation of ultrasonic waves in the structure. In ultrasonic testing, an ultrasound transducer connected to a diagnostic machine is passed over the structure being inspected. In case of immersion testing, the transducer is separated from the structure by a couplant like gel, oil or water. However, when ultrasonic testing is conducted with an Electromagnetic Acoustic Transducer (EMAT) the use of couplant is not required. There are two methods of receiving the ultrasound waveform viz. reflection and attenuation. In reflection (or pulse-echo) mode, the transducer performs both sending and receiving of the pulsed waves as sound is reflected back to the device. Reflected ultrasound comes from an interface, such as the back wall of the object or from an imperfection within the structure. A computer system displays the results in form of a signal with an amplitude representing the intensity of reflection and distance, representing the arrival time of the reflection. In attenuation (or through-transmission) mode, a transmitter sends ultrasound through one surface and a separate receiver detects the amount that has reached to it after traveling through the structure. Imperfections in structure between the transmitter and receiver reduces the amount of sound transmitted, thereby identifying the presence of discontinuity. Use of couplant increases the efficiency of process by reducing losses in ultrasonic wave energy due to separation between the surfaces.

Figure 4 describes ways to use Laser Based Ultrasound [51] as a damage identification technique. A comparative study between thermography and laser based ultrasound on T blade and honeycomb panel [51] for detecting damage revelled that thermography being promising in detecting damage and material inclusion for honeycomb panel while laser ultrasound for T blade panel.

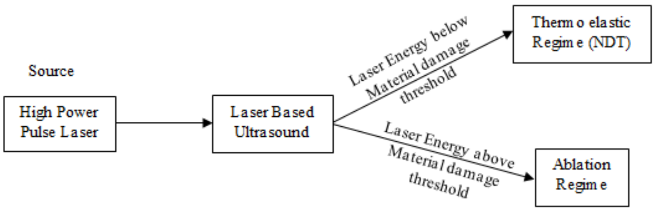

Figure 4: Scheme of Laser Based Ultrasound

2.6. Machine Learning

An important aspect in machine learning to be applied in SHM is to train the algorithm with gathered data. While employing machine learning in SHM, one has to understand and overcome the difficulties associated with detection, localization, assessment and decision making. In context to this a survey of Worden and Manson [52] gives vital information of comparison between machine learning algorithms based on performance on data set and such performance can be assessed via Receiver Operating Characteristics (ROC) curves [53]. Most of the techniques require wind turbine to stop while monitoring its health condition. In this regard, over conventional damage detection methods, machine learning approach is advantageous. While studying the blade fault conditions, a machine learning was utilized with the help of lazy learning approach. Among the chosen classifier, Locally weighted learning (LWL) classifier showed maximum accuracy [54]. Extending the machine learning approach to a case study, stiffness prediction through fatigue test was

Table 4: Algorithms to detect damage based on vibration measurement

Algorithms	**Data Acquisition**	**Damage Indices**	**Sensitivity towards damage**	**Remark**
Transmittance Function	Laser Doppler Vibrometer	Deference in measured structural velocity of healthy and damaged structure	Sensitive to damage and Noise	Clear damage indication, Poor Localization
Resonant Comparison	Piezoceramic Sensors	Deference in response at resonance of healthy and damaged structure	More accurate	-
Operational Deflection Shape	Laser Doppler Vibrometer	Change in Deflection Shape indicate damage	More Accurate	-
Wave Propagation	Piezoceramic Sensors	Deference in time impulse response of healthy and damaged structure	Low sensitivity to damage	-

Table 5: Vibration based SHM systems with their sensors

S. No.	**Sensor**	**Method of Excitation**	**Feature Extraction**	**Quantification of modal property**	**Ref**
1	Piezoelectric Accelerometers	-	p-LSCF	MAC	[43]
2	Piezoelectric Accelerometers	Impact Test	-	MAC	[47]
3	MEMS Accelerometers	-	p-LSCF	MAC	[57]
4	Piezoelectric Accelerometers	Electro dynamic shaker	Machine Learning	Akaike information criterion	[54]
5	Piezoelectric Accelerometers	Natural Excitation	OMA	-	[66]
6	Piezoelectric Accelerometers	-	Autoregressive model	-	-

utilized and accuracy of test result were predicted using Convolutional Neural Network (CNN), Long Short Term Memory (LSTM) Network and hybrid CNN - LSTM network models [55]. To detect icing condition on blade, Li et al. [56] trained Back Propagation (BP) neural network and Radial Basis Function (RBF) neural network based on modal data. Being more accurate, Back Propagation (BP) neural network has ability to predict ice accumulation on blade when it is in operation.

2.7. Application / Case Studies

SHM systems if applied to large structures can give early warning before failure. During this time, preventive actions could be initiated to avoid further catastrophic failure. SHM need regular observation over obtained dynamic response. This observation and large amount of data might cause investment of cost and time. Conventional sensors (strain gauges and accelerometers) and newly emerging sensors (fiber optic sensors, AE sensors, piezoelectric transducer sensors and Micro Fiber Composite sensors) are suitable for SHM system. Based on input data and monitoring algorithm, decision policy comes in action. SHM system has no use unless there is a decision making policy attached to it. Figure 5 shows general representation of SHM system [57].

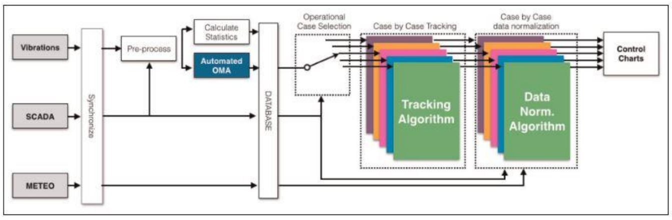

Figure 5: Generalized representation of an SHM system [57]

It was observed that for a 300 kW wind turbine most of the damage occurrence (like superficial cracks, geometric concentrator, abrupt change of thickness etc.) was due to fatigue phenomenon [58]. Kim et al. proposed an Approach which uses vibration and acoustic phenomenon (Vibro - Acoustic Modulation) to detect crack in wind turbine blade [59]. Such technique involves use of structural vibrations during operation as low frequency pumping signal and high frequency probing signal. The measured sideband levels forms basis to identify crack since they are result of modulation between pumping and probing signal. Advantage being blades can be inspected during operation and no need to be stopped. A simulation method involving combination of analytical and FEA forms practical base in the design of Bent Twist Adaptive Blade (BTAB) [60]. By employing such technique, it was observed that the ability of wind turbine to capture energy was improved. However the worth noting point is that, the design is at its basic stage and should involve aerodynamic and structural parameters considering appropriate constraints. The material for blade should be carefully chosen since they undergo numerous loads and change in environmental conditions. Carbon Nano Tubes (CNT) showed promising results to withstand for such conditions [61]. CNT can be hybridized with natural fibers to have an eco-friendly material which possesses high strength, low weight characters making it a suitable advanced material for wind turbine blade. Further it was found that CNT can be used with natural fibers in achieving ecofriendly nature of material. In this regard, Thomas and Ramachandra [62] discussed various materials used for WTB. To avoid debonding, a concept of One Shot Blade (one piece structure) was introduced [63]. However this technique is limited to design of small blades (Upto 10 m). Increased blade length causes complications in its transportation. As a solution, it was suggested to manufacture blade in two segments and join it at the location. Such solution was applied to a 13.4 m blade considering spar beam connection principle [64].

Table 6 depicts comparative illustration between various SHM's found in literature. From the table one can choose appropriate SHM applicable for selected problem. From literature, it was found that most of the SHM's were based on vibration technique due to the fact that it's simplicity in use and less expensive upon use. Using SHM system for an offshore wind turbine at Belwind, Belgium, a continuous health monitoring of wind turbine tower was performed [57]. Extending this research on offshore wind turbine, it is possible to manufacture a blade embedded with sensor which can monitor its health continuously [66]. It was observed that, fiber optic sensor can be well suitable for this purpose. On comparing Digital Image Correlation, shearography, AE, fiber- optic strain sensors, thermal imaging and piezoelectric sensors, it was observed that piezoelectric sensors are less sensitive to localize and quantify the damage [67] while a study on offshore wind turbine in Belgium has given emphasis on the use of accelerometers [68].

3. Conclusion

In present study, almost all aspects of damage detection in wind turbine blade is presented up to date. This review will help the researchers to differentiate between various techniques involved in damage detection of wind turbine blade and selection of feasible approach on application to a structure more likely wind turbine blade. Some worth noting points from this study are given as follows.

1. It was observed that most of the research is based on Euler – Bernoulli's beam theory. However Aero Elastic Theory can give more promising results in determining the dynamic response of Wind turbine blade analytically.
2. Considering aero elastic theory, Perturbation method has ability to provide a good estimation of dynamic response.
3. There is scope to use Timoshenko Beam theory to determine dynamic response of wind turbine blade analytically.
4. Use Mindlin plate theory instead of Classical Plate theory to determine wave speeds of the extensional and flexural modes in GFRP wind turbine blade since the dispersion curve of flexural mode of GFRP did not match the CPT curve.
5. Optimization techniques can be helpful to reduce computation efforts in determining solution to equation of motion.
6. Sampling techniques and stability analysis enables to have more accurate approach.
7. Combining two or more techniques, damage identification can be more realistic and accurate

4. Future Trends

1. Using machine learning approach, multiple defects can be identified at a time enhancing effectiveness of SHM system.
2. The technique based on ultrasonic, acoustic energy emission and vibration based damage detection has proven to be best suitable in case of Wind turbine blade assisted by some algorithms for ease of operation and less complex solution.
3. OMA has ability to extract modal features from measured response making it suitable to carryout modal analysis of big structure. However it is not sensitive to small cracks or very local phenomena.
4. The straightforward application of OMA should be avoided. Some data pre-processing like MBC transformation should be adopted prior to apply OMA in order to convert linear time periodic system into a linear time invariant system.
5. In case of honeycomb panel, thermography can provide more promising results in detecting damage and material inclusion and for T blade panel, laser ultrasound will be more suitable in providing promising results.
6. Hybrid CNN - LSTM model, Back Propagation (BP) neural network and locally weighted learning (LWL) classifier has ability to provide more promising results in Machine learning approach applied to a wind turbine blade.
7. Bent Twist Adaptive Blade (BTAB) can be adopted to enhance the ability of wind turbine to capture energy. Such study was based on a simulation method involving combination of analytical and FEA approach. However the design is at its basic stage and should involve aerodynamic and structural parameters considering appropriate constraints.
8. Carbon Nano Tubes (CNT) has ability to withstand under numerous loads and change in environmental conditions. CNT can be hybridized with natural fibers in order to have an eco-friendly material which possesses high strength, low weight characters making it a suitable advanced material for wind turbine blade.

The defects identified by various techniques are indicated in Table 7 found in literature. The scope of techniques may lie beyond the table. ★ indicates defects identified by the technique found in literature while □ indicates possibility of technique to detect the damage by author's perception.

5. Acknowledgment

Acknowledgements: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors

Table 6: Comparison in SHM Techniques

S. No.	**SHM Technique**	**Ability to detect Damage**	**Associated Cost**	**Sensitivity**	**Contact Type**	**Ref**
1	Acoustic Emission	Very small, Location and size of damage	Expensive	High	Contact	[66]
2	Vibration based	Moderate size	Cheap	Moderate	Contact	[66]
3	Fiber Optics	Adhesive failure	Expensive	High	Contact	[66]
4	Strain Measurement	Small	Moderate	Moderate	Contact	[66]
5	X ray	Location and Size	-	-	Non-Contact	[66]
6	Ultrasonic	Location and Size (Delamination)	Moderate	High	Contact	[66]
7	Digital Image Correlation	full-field identification	-	-	Non-Contact	[67]
8	Shearography	full-field identification	-	-	Non-Contact	[67]
9	Thermal Imaging	full-field identification	Expensive	High	Non-Contact	[67]
10	Pattern Recognition	full-field identification	Moderate	High	Non-Contact	[65]

Table 7: Techniques used to identify defect so far

Damage Identification Technique	**Fiber Defect**	**Fatigue damage**	**Crack Location**	**Severity of damage**	**Wave Defect**	**Delamination**	**Debonding**	**Mass Change (Detection and Location)**	**Edgewise Crack**	**Integral deformation**	**Damage length**	**Bottom Erosion**
Shearography	★	★	□	□	-	□	□	□	□	-	-	-
Digital Image Correlation	□	□	★	□	★	□	-	□	□	-	-	□
Fiber Optics	-	★	□	□	□	□	-	□	□	□	□	-
Piezoelectric Sensors	□	★	□	□	-	□	□	□	□	□	□	-
Thermal Imaging	-	★	★	□	□	★	★	□	□	□	□	□
Acoustic Emission	□	★	★	★	□	□	□	□	□	□	□	-
Vibration Based Technique	-	★	★	□	-	-	-	★	★	-	-	-
Video Metric technique	-	□	□	□	-	□	★	□	□	★	□	□
OMA	-	□	□	□	-	-	-	★	□	-	□	★

References

[1] Y. Amirat, M. E. Benbouzid, B. Bensaker, R. Wamkeue, Condition monitoring and ault diagnosis in wind energy conversion systems: a review, in: 2007 IEEE international electric machines & drives conference, Vol. 2, IEEE, 2007, pp. 1434–1439.

[2] E. Madi, K. Pope, W. Huang, T. Iqbal, A review of integrating ice detection and mitigation for wind turbine blades, Renewable and Sustainable Energy Reviews 103 (2019) 269–281.

[3] Y. Du, S. Zhou, X. Jing, Y. Peng, H. Wu, N. Kwok, Damage detection techniques for wind turbine blades: A review, Mechanical Systems and Signal Processing 141 (2020) 106445.

[4] W. Yang, P. J. Tavner, C. J. Crabtree, Y. Feng, Y. Qiu, Wind turbine condition monitoring: technical and commercial challenges, Wind Energy 17 (5) (2014) 673–693.

[5] K. Pugh, J. Nash, G. Reaburn, M. Stack, On analytical tools for assessing the raindrop erosion of wind turbine blades, Renewable and Sustainable Energy Reviews 137 (2021) 110611.

[6] L. Mishnaevsky Jr, Repair of wind turbine blades: Review of methods and related computational mechanics problems, Renewable energy 140 (2019) 828–839.

[7] E. Artigao, S. Martín-Martínez, A. Honrubia-Escribano, E. Gómez-Lázaro, Wind turbine reliability: A comprehensive review towards effective condition monitoring development, Applied energy 228 (2018) 1569–1583.

[8] M. A. Drewry, G. Georgiou, A review of ndt techniques for wind turbines, Insight-Non-Destructive Testing and Condition Monitoring 49 (3) (2007) 137–141.

[9] O. Parent, A. Ilinca, Anti-icing and de-icing techniques for wind turbines: Critical review, Cold regions science and technology 65 (1) (2011) 88–96.

[10] D. Li, S.-C. M. Ho, G. Song, L. Ren, H. Li, A review of damage detection methods for wind turbine blades, Smart Materials and Structures 24 (3) (2015) 033001.

[11] H. Zhou, H. Dou, L. Qin, Y. Chen, Y. Ni, J. Ko, A review of full-scale structural testing of wind turbine blades, Renewable and Sustainable Energy Reviews 33 (2014) 177–187.

[12] B. Yang, D. Sun, Testing, inspecting and monitoring technologies for wind turbine blades: A survey, Renewable and Sustainable Energy Reviews 22 (2013) 515–526.

[13] F. P. G. Márquez, A. M. P. Chacón, A review of non-destructive testing on wind turbines blades, Renewable Energy 161 (2020) 998–1010.

[14] Z. Yang, Y. Chai, A survey of fault diagnosis for onshore grid-connected converter in wind energy conversion systems, Renewable and Sustainable Energy Reviews 66 (2016) 345–359.

[15] M. N. Scheu, L. Tremps, U. Smolka, A. Kolios, F. Brennan, A systematic failure mode effects and criticality analysis for offshore wind turbine systems towards integrated condition based maintenance strategies, Ocean Engineering 176 (2019) 118–133.

[16] A. W. Manyonge, R. Ochieng, F. Onyango, J. Shichikha, Mathematical modelling of wind turbine in a wind energy conversion system: Power coefficient analysis.

[17] A. Baumgart, A mathematical model for wind turbine blades, Journal of sound and vibration 251 (1) (2002) 1–12.

[18] Ö. Özdemir, M. Kaya, Flapwise bending vibration analysis of a rotating tapered cantilever bernoulli–euler beam by differential transform method, Journal of Sound and Vibration 289 (1-2)

(2006) 413–420.

[19] L. Li, Y. Li, H. Lv, Q. Liu, Flapwise dynamic response of a wind turbine blade in super-harmonic resonance, Journal of Sound and Vibration 331 (17) (2012) 4025–4044.

[20] I. Chopra, J. Dugundji, Non-linear dynamic response of a wind turbine blade, Journal of sound and vibration 63 (2) (1979) 265–286.

[21] J. W. Larsen, S. R. Nielsen, Non-linear dynamics of wind turbine wings, International Journal of Non-Linear Mechanics 41 (5) (2006) 629–643.

[22] J. W. Larsen, S. R. Nielsen, Nonlinear parametric instability of wind turbine wings, Journal of sound and vibration 299 (1-2) (2007) 64–82.

[23] J. W. Larsen, R. Iwankiewicz, S. R. Nielsen, Nonlinear stochastic stability analysis of wind turbine wings by monte carlo simulations, Probabilistic engineering mechanics 22 (2) (2007) 181–193.

[24] D. Lee, D. H. Hodges, M. J. Patil, Multi-flexible-body dynamic analysis of horizontal axis wind turbines, Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology 5 (4) (2002) 281–300.

[25] S. Ataya, M. M. Ahmed, E. Ahmed, An investigation of damages in low power wind turbine blades, Journal of Petroleum and Mining Engineering 20 (1) (2018) 80–88.

[26] J. Yang, C. Peng, J. Xiao, J. Zeng, S. Xing, J. Jin, H. Deng, Structural investigation of composite wind turbine blade considering structural collapse in full-scale static tests, Composite Structures 97 (2013) 15–29.

[27] B. Guan, Z. Su, Q. Yu, Z. Li, W. Feng, D. Yang, D. Zhang, Monitoring the blades of a wind turbine by using videogrammetry, Optics and Lasers in Engineering 152 (2022) 106901.

[28] S. Tsiapoki, M. W. Häckell, T. Grießmann, R. Rolfes, Damage and ice detection on wind turbine rotor blades using a three-tier modular structural health monitoring framework, Structural Health Monitoring 17 (5) (2018) 1289–1312.

[29] J. Tang, S. Soua, C. Mares, T.-H. Gan, An experimental study of acoustic emission methodology for in service condition monitoring of wind turbine blades, Renewable Energy 99 (2016) 170–179.

[30] B. Vick, S. Broneske, Effect of blade flutter and electrical loading on small wind turbine noise, Renewable energy 50 (2013) 1044–1052.

[31] A. Beattie, A. Beattie, Acoustic emission monitoring of a wind turbine blade during a fatigue test, in: 35th Aerospace sciences meeting and exhibit, 1997, p. 958.

[32] P. Joosse, M. Blanch, A. Dutton, D. Kouroussis, T. Philippidis, P. Vionis, Acoustic emission monitoring of small wind turbine blades, J. Sol. Energy Eng. 124 (4) (2002) 446–454.

[33] H. Sutherland, W. Musial, Application of nondestructive techniques to the testing of a wind turbine blade: Sandia national labs., albuquerque, new mexico (united states), de93016731/gar, 8pp.(1993), NDT & E International 27 (4) (1994) 209.

[34] O. M. Bouzid, G. Y. Tian, K. Cumanan, D. Moore, Structural health monitoring of wind turbine blades: acoustic source localization using wireless sensor networks, Journal of Sensors 2015.

[35] L. Doliński, M. Krawczuk, Damage detection in turbine wind blades by vibration based methods, in: Journal of Physics: Conference Series, Vol. 181, IOP Publishing, 2009, p. 012086.

[36] C.-H. Loh, K. J. Loh, Y.-S. Yang, W.-Y. Hsiung, Y.-T. Huang, Vibration-based system identification of wind turbine system, Structural Control and Health Monitoring 24 (3) (2017) e1876.

[37] M. Rumsey, J. Paquette, J. White, R. Werlink, A. Beattie, C. Pitchford, J. van Dam, Experimental results of structural health monitoring of wind turbine blades, in: 46th AIAA aerospace sciences meeting and exhibit, 2008, p. 1348.

[38] T. G. Carne, G. H. James III, The inception of oma in the development of modal testing technology for wind turbines, Mechanical Systems and Signal Processing 24 (5) (2010) 1213–1226.

[39] G. H. James III, T. G. Carne, J. P. Lauffer, The natural excitation technique (next) for modal parameter extraction from operating wind turbines, Tech. rep., Sandia National Labs., Albuquerque, NM (United States) (1993).

[40] D. Tcherniak, S. Chauhan, M. H. Hansen, Applicability limits of operational modal analysis to operational wind turbines, in: Structural Dynamics and Renewable Energy, Volume 1, Springer, 2011, pp. 317–327.

[41] E. Di Lorenzo, S. Manzato, B. Peeters, F. Marulo, Modal parameter estimation for operational wind turbines, in: EWSHM-7th European Workshop on Structural Health Monitoring, 2014.

[42] D. Tcherniak, S. Chauhan, M. Rossetti, I. Font, J. Basurko, O. Salgado, Output-only modal analysis on operating wind turbines: application to simulated data, in: Proceedings of European Wind Energy Conference, 2010, pp. 1–10.

[43] C. R. Farrar, S. W. Doebling, D. A. Nix, Vibration–based structural damage identification, Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences 359 (1778) (2001) 131–149.

[44] J. Pacheco-Chérrez, O. Probst, Vibration-based damage detection in a wind turbine blade through operational modal analysis under wind excitation, Materials Today: Proceedings.

[45] B. Fitzgerald, J. Arrigan, B. Basu, Damage detection in wind turbine blades using time-frequency analysis of vibration signals, in: The 2010 International Joint Conference on Neural Networks (IJCNN), IEEE, 2010, pp. 1–5.

[46] M. D. Ulriksen, J. F. Skov, K. A. Dickow, P. H. Kirkegaard, L. Damkilde, Modal analysis for crack detection in small wind turbine blades, in: Key Engineering Materials, Vol. 569, Trans Tech Publ, 2013, pp. 603–610.

[47] S. N. Ganeriwala, J. Yang, M. Richardson, Using modal analysis for detecting cracks in wind turbine blades, Sound and Vibration 45 (5) (2011) 10.

[48] T. J. Arsenault, A. Achuthan, P. Marzocca, C. Grappasonni, G. Coppotelli, Development of a fbg based distributed strain sensor system for wind turbine structural health monitoring, Smart Materials and Structures 22 (7) (2013) 075027.

[49] M. M. Rezaei, M. Behzad, H. Moradi, H. Haddadpour, Modal-based damage identification for the nonlinear model of modern wind turbine blade, Renewable energy 94 (2016) 391–409.

[50] A. Ghoshal, M. J. Sundaresan, M. J. Schulz, P. F. Pai, Structural health monitoring techniques for wind turbine blades, Journal of Wind Engineering and Industrial Aerodynamics 85 (3) (2000) 309–324.

[51] R. F. Anastasi, J. N. Zalameda, E. I. Madaras, Damage detection in rotorcraft composite structures using thermography and laser-based ultrasound, in: SEM X International Congress and Exposition on Experimental and Applied Mechanics, 2004.

[52] K. Worden, G. Manson, The application of machine learning to structural health monitoring, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365 (1851) (2007) 515–537.

[53] E. Figueiredo, G. Park, C. R. Farrar, K. Worden, J. Figueiras, Machine learning algorithms for damage detection under operational and environmental variability, Structural Health Monitoring 10 (6) (2011) 559–572.

[54] A. Joshuva, V. Sugumaran, A lazy learning approach for condition monitoring of wind turbine blade using vibration signals and histogram features, Measurement 152 (2020) 107295.

[55] H. Liu, Z. Zhang, H. Jia, Q. Li, Y. Liu, J. Leng, A novel method to predict the stiffness evolution of in-service wind turbine blades based on deep learning models, Composite Structures 252 (2020) 112702.

[56] F. Li, H. Cui, H. Su, Z. Ma, Y. Zhu, Y. Zhang, et al., Icing condition prediction of wind turbine blade by using artificial neural network based on modal frequency, Cold Regions Science and Technology 194 (2022) 103467.

[57] W. Weijtjens, T. Verbelen, G. De Sitter, C. Devriendt,

Foundation structural health monitoring of an offshore wind turbine a full scale case study, Structural Health Monitoring 15 (4) (2016) 389–402.

[58] J. Marin, A. Barroso, F. Paris, J. Canas, Study of damage and repair of blades of a 300 kw wind turbine, Energy 33 (7) (2008) 1068–1083.

[59] S. Kim, D. E. Adams, H. Sohn, G. Rodriguez-Rivera, N. Myrent, R. Bond, J. Vitek, S. Carr, A. Grama, J. J. Meyer, Crack detection technique for operating wind turbine blades using vibro-acoustic modulation, Structural Health Monitoring 13 (6) (2014) 660–670.

[60] A. Maheri, S. Noroozi, J. Vinney, Application of combined analytical/fea coupled aero-structure simulation in design of wind turbine adaptive blades, Renewable Energy 32 (12) (2007) 2011–2018.

[61] A. Pradeep, S. S. Prasad, L. Suryam, P. P. Kumari, A comprehensive review on contemporary materials used for blades of wind turbine, Materials Today: Proceedings 19 (2019) 556–559.

[62] L. Thomas, M. Ramachandra, Advanced materials for wind turbine blade-a review, Materials Today: Proceedings 5 (1) (2018) 2635–2640.

[63] M. Damiano, A. Russo, A. Sellitto, E. Vecchio, T. Stellato, A. Riccio, Design of a composite wind turbine blade manufactured with the one shot blade® technology, Materials Today: Proceedings 34 (2021) 103–105.

[64] F. Hahn, C. Kensche, R. Paynter, A. Dutton, C. Kildegaard, J. Kosgaard, Design, fatigue test and nde of a sectional wind turbine rotor blade, Journal of Thermoplastic Composite Materials 15 (3) (2002) 267–277.

[65] D. Adams, J. White, M. Rumsey, C. Farrar, Structural health monitoring of wind turbines: method and application to a hawt, Wind Energy 14 (4) (2011) 603–623.

[66] J. He, M. Hutchinson, Fundamentals for remote structural health monitoring of wind turbine blades a preproject 111.

[67] C. Niezrecki, P. Avitabile, J. Chen, J. Sherwood, T. Lundstrom, B. LeBlanc, S. Hughes, M. Desmond, A. Beattie, M. Rumsey, et al., Inspection and monitoring of wind turbine blade-embedded wave defects during fatigue testing, Structural Health Monitoring 13 (6) (2014) 629–643.

[68] W. Weijtjens, T. Verbelen, E. Capello, C. Devriendt, Vibration based structural health monitoring of the substructures of five offshore wind turbines, Procedia engineering 199 (2017) 2294–2299.