

Review

A Review on Piezoelectric Transducer-Based Structural Health Monitoring for Wind Turbine Blades

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Abstract: Piezoelectric transducers have emerged as highly effective tools for structural health monitoring (SHM) in the renewable energy sector, particularly for wind turbine blades subjected to complex operational and environmental stresses. These sensors convert mechanical stimuli such as strain, vibration, and pressure into measurable electrical signals, enabling real-time and non-destructive evaluation of blade integrity. This review presents a comprehensive overview of the working principles, sensing mechanisms, and deployment strategies of piezoelectric transducers for condition monitoring of wind turbine blades. The advantages of this technology, including high sensitivity, early damage detection, and potential for integration into intelligent predictive maintenance frameworks, are highlighted. In addition, environmental influences, material coupling challenges, and signal processing complexities affecting sensor performance are discussed. Finally, emerging trends in piezoelectric-based SHM systems and their role in extending blade lifespan and improving overall energy efficiency are outlined.

Keywords: piezoelectric transducers; structural health monitoring (SHM); wind turbine blades; predictive maintenance; vibration sensing; renewable energy systems

1. Introduction

In many countries, wind energy has become cost-effective as a means of decarbonization and energy efficiency [1]. Onshore wind turbines built in 2035 are expected to have an average output of 3.25 MW, a hub height of 130 m, and a rotor diameter of 174 m, while offshore wind turbine capacity is expected to reach 250 m rotor diameter, 17 MW by 2035. The hub height is 130 m [2]. As turbines increase in size to produce more power, the structure of wind turbines becomes increasingly damaged [3]. Analysis of wind turbine failures shows that 12% of damage is due to operational failures, 9% is due to environmental damage, and blade failures account for 23% of all damage during fire shutdowns. 23% of the total damage is 23%. These failures can be caused by many factors such as moisture absorption, depletion, strong winds, heat stress, corrosion, fire, and lightning [4].

It is reported that the operational and maintenance costs of a 500 MW offshore wind farm account for approximately 26% of the total lifecycle cost over a 25-year service period. A significant proportion of these costs are associated with blade inspection, repair, and replacement, as blades are continuously exposed to aerodynamic loading and harsh environmental conditions. Therefore, reliable and early-stage blade health monitoring is essential to reduce downtime, prevent catastrophic failures, and improve overall cost efficiency [5,6]. Impedance-based methods are one of the well-studied SHM methods and have been regularly proven to be useful in



determining mechanical, aeronautical, and demographic damage. Different failure types of wind turbine accidents are illustrated in Figure 1 [7,8].

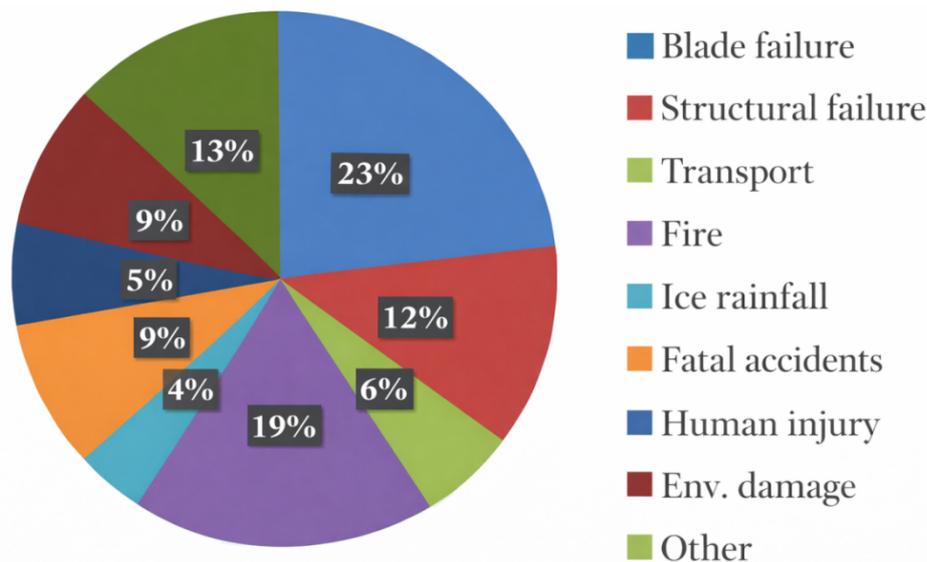


Figure 1. Failure types of wind turbine accidents

Impedance-based methods are also suitable for early damage and severity assessment, which are important for SHM systems. In simple terms, this method uses a surface-based omnidirectional piezoelectric transducer of a basic model to determine the electromechanical impedance response in the ultrasonic frequency domain. The impedance response changes as the damage model evolves by representing the local host dynamics [9]. Since this method uses short wavelengths in the high-frequency region, it is easier to detect small problems near the sensor. Unlike the local vibration method, the local impedance method uses local frequency fluctuations, sometimes up to 1 MHz It is easily accessible. Comparison between NDT and SHM technology is described in Table 1.

Table 1. Comparison between NDT technology and SHM technology.

Key Features	NDT Technology	SHM Technology
Transducers	Ultrasonic, electromagnetic, eddycurrent, visual, etc.	Acoustic emission, strain gauges, fiber optics, piezoelectric sensors,etc.
Detection Mode	Direct inspection of the material or structure.	Continuous monitoring of the material or structure.
Detection Time	Typically, immediate or within a short time after inspection.	Real-time or near real-time monitoring.
Downtime	Requires temporary shutdown of the asset for inspection.	Minimal or no downtime required for monitoring.
Inaccessible Region	May have limitations forinspecting inaccessible areas.	Can monitor inaccessible areasusing wireless or remote sensing techniques.
Detection Capacity	Can detect defects and anomalies,but may not be able to predict future failures.	Can detect and predict potentialfailures through continuous monitoring and data analysis.

The main advantages of impedance-based techniques are summarized as follows [10]:

- The technique is cost-effective as it provides low-cost, lightweight and fast-response etc.
- Self-testing piezoelectric transducers (e.g., PZT).
- Finding the impedance field of the working sample.
- High resistance to premature failure due to high-frequency and short-wave excitation.
- Cost of large SHM machines.

There are limitations such as small measurement range, influence of temperature and noise on the impedance response, and need for impedance data prior to testing. However, many complex operational problems have been developed for non-destructive testing [11] and noise and environmental compensation. These have improved the performance of impedance-based techniques, making them strong contenders for the successful development of SHM systems for wind turbines. Over the years, damage has been observed in concrete structures [12], pipelines [13]

steel connections [14] and aerospace systems. They can also be used to monitor soil, cables and corrosion [15]. Therefore, the impedance-based SHM method is suitable for damage assessment of wind turbines in operation [16,17]. In [18] published a comprehensive review of various SHM techniques for wind turbines and discussed the unique advantages of impedance-based techniques. A brief review of current methods for SHM technology in the wind energy industry was presented [19]. Specific issues of wind turbine blade maintenance models are discussed in detail in a recent paper by [20] presented a comprehensive review of non-destructive methods used for SHM and maintenance of wind turbine systems over the past two decades. 2022 has attracted great attention from the academic community. The text [21] mentions the advancement and complexity of this SHM technology. In a systematic review, [22] also mentioned physics-based and data-driven approaches to impedance-based SHM.

Several review studies have addressed structural health monitoring of wind turbines using vibration-based methods, acoustic emission, ultrasonic inspection, and data-driven approaches. Existing reviews primarily focus on general SHM frameworks, operational condition monitoring, or non-destructive testing techniques across multiple turbine components. However, a dedicated and physics-oriented review concentrating on piezoelectric transducer-based SHM for wind turbine blades covering sensing mechanisms, electromechanical impedance theory, guided wave challenges, durability constraints, and emerging data-handling strategies remains limited. This review aims to fill this gap by providing a comprehensive and application-focused evaluation of piezoelectric transducer-based SHM techniques for wind turbine blades, highlighting both current capabilities and future research directions.

2. Piezoelectric Transducers Based SHM System

2.1. Piezoelectric Transducers

The ability to convert all types of energy into electricity and other factors makes piezoelectric materials special. Due to the piezoelectric effect, they are ideal for detecting and controlling vibrations in structures. Piezoelectric transducers are produced in various shapes such as disks, fibers and patches, and they can be combined in various structures.

2.2. SHM System Architecture

The piezoelectric transducer-based SHM system for wind turbine blades includes the following points:

- One of the key components of the piezoelectric transducer-based SHM system is the sensor network. The network consists of carefully placed piezoelectric sensors that can be mounted on surfaces. These sensors detect mechanical vibrations, strains, or other forces generated by the work. The sensors convert physical phenomena into electrical signals to provide information about the health of the turbine blades. Carefully designed sensor networks closely monitor critical areas to ensure adequate protection of the turbine blades.
- The Data Acquisition Unit (DAU) is the basis for collecting and storing electrical signals generated by piezoelectric sensors. The DAU processes these signals, amplifies them if necessary, and converts them into an easy-to-analyze digital form. It ensures that all sensor data is accurate and stored for further analysis. This unit usually contains an analog-to-digital converter (ADC) that converts the analog signal from the sensor into a format suitable for storage and processing [23].
- Predictive algorithms are software tools that evaluate the SPU's processing data to identify and assess potential damage or configuration issues. The algorithm uses statistical models, machine learning techniques, or algorithms to determine the severity of damage and predict future maintenance needs [24,25].

3. Blades Structure and Its Failure

3.1. Structure of Blade

Composite materials glass fiber, carbon fiber, balsa wood or foam are used to build wind turbine blades. These materials' small weight improves both the efficiency and strength-to-weight ratio [26]. Structure of wind turbine blade is demonstrated in Figure 2.

The construction is characterized by vertical shear webs that are bonded to the upper and lower spar caps using an extremely durable adhesive, enabling the support of all blade stresses while maintaining torsional and bending stiffness. The blade's exterior is coated with gel to prevent water intrusion and UV deterioration [27]. The blade consists of two sides: a pressure side with high pressure and low velocity, and a suction side with low pressure and high velocity [28].

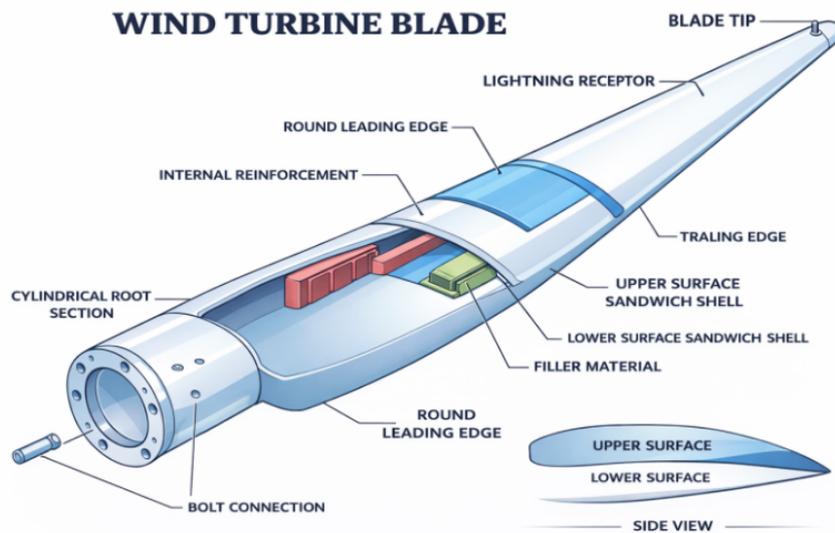


Figure 2. Wind turbine blade structure.

3.2. Region Vulnerable to Damage

The four common locations of a blade that are most vulnerable to damage is the upper spar cap, the maximum chord, the root of the blade, and the chord length between 30% and 70% from the blade root. They identified two areas where erosion and fissures are most likely to happen. The region between the root section and two-third of the blade length is mainly subjected to cracks. However, erosion can occur at any location on the leading edge, typically found in the tip region because of the higher speeds than those in other regions.

3.3. Causes of Failure of Wind Turbine Blades

There are four primary categories of failures that can occur with wind turbine blades:

1. **Lightning Damage:** It includes shell and tip detachments, delamination, and debonding in the upper and lower shells [29].
2. **Leading Edge Erosion:** The primary causes of leading-edge erosion are airborne particles, which include rain, hail, sea spray, dust, and sand, as well as UV light, humidity, and moisture [30].
3. **Structural Fatigue Damage:** Throughout the course of a wind-powered wind turbine's life, repeated loads may cause structural fatigue damage [31].
4. **Damage from Icing:** The accumulation of snow or ice on blade structures exposed to the icing atmosphere results in damage from icing [32].

4. SHM Techniques Based on Piezoelectric Transducers

Piezoelectric transducers can be used in conjunction with a variety of SHM approaches to track the condition of wind turbine blades. Among the methods that are most frequently employed are:

4.1. Ultrasonic Detection

A tried-and-true method for finding flaws in composite and other types of materials is ultrasonic detection [33]. The ultrasonic signal/image allows for both damage localization and detection in the application to WT blade SHM. For instance, it makes it possible to check the laminate for delamination beneath the blade surface and dry glass fibers. Figure 3 shows the primary function of ultrasonic detection.

In thin composite wind turbine blades, ultrasonic monitoring is predominantly governed by Lamb wave propagation rather than bulk wave behavior. Lamb waves exhibit strong dispersion characteristics, meaning their phase and group velocities vary with frequency–thickness product, material anisotropy, and lay-up configuration of composite laminates. Among the various guided wave modes, the fundamental symmetric (S_0) and antisymmetric (A_0) modes are most commonly exploited for blade SHM applications. The S_0 mode is less dispersive at lower frequencies and is particularly effective for long-range inspection, whereas the A_0 mode exhibits higher sensitivity to surface-breaking defects and delamination due to its dominant out-of-plane displacement. Effective ultrasonic-based SHM therefore requires careful mode selection, excitation frequency tuning, and dispersion compensation strategies to ensure reliable damage detection in thin composite shells. These

challenges are particularly pronounced in wind turbine blades due to their large dimensions, complex geometry, and material heterogeneity.

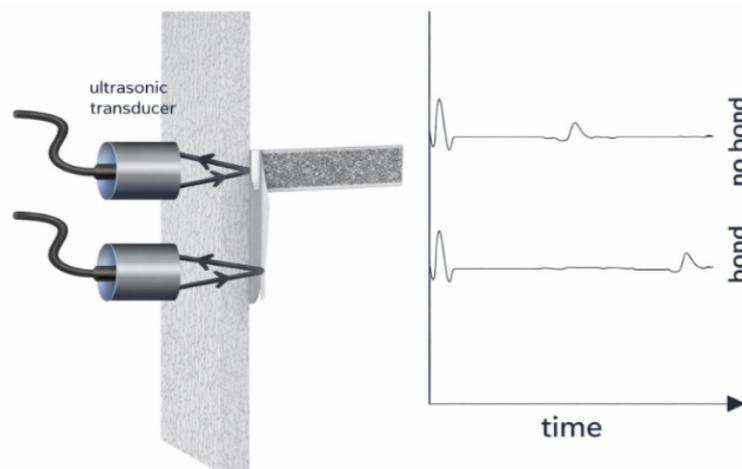


Figure 3. Ultrasonic detection procedure.

Furthermore, the external environment such as background temperature, vibration, noise, etc. has less of an impact on ultrasonic detection. Consequently, blade SHM has an efficient and trustworthy tool in ultrasonic detection. These benefits have led to the commercialization of blade SHM techniques based on ultrasonic sensing. Additionally, the prototype system has been effectively used to examine full-scale WT blades indoors [34]. In contrast to conventional ultrasonic testing using external probes, embedded or surface-bonded piezoelectric transducers employed in guided wave-based SHM systems do not require liquid couplants, making them more suitable for long-term and in-situ monitoring of wind turbine blades.

4.2. Infrared Thermography

The temperature on the surface of a structure is measured using infrared thermography. The thermography image can be used to easily identify and locate a structural flaw since it alters the continuity of the structure and, consequently, the temperature distribution. Blade SHM falls in the same general category as this [35]. Infrared thermography has been widely used to monitor the state of a variety of equipment and structures, including bearings, gearboxes, power electronic converters, motors, generators, and more. This is because of its easy-to-understand detection results and efficacy in identifying subsurface flaws. Additionally, it is effective in identifying subsurface flaws in WT blades [36]. Since infrared thermography performed the blade's full-field measurement, it allows for effective SHM of WT blades in lab settings. However, the environment surrounding temperature has the potential to affect the detection findings of infrared thermography. Because the temperature difference caused by an incipient flaw will be minimal and hence obscured by ambient temperature, it will be difficult to detect the defect in the WT blade. Figure 4 highlights the demonstration of infrared thermography.

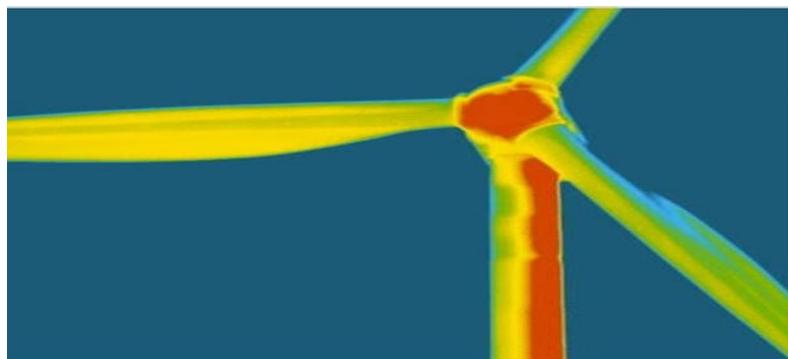


Figure 4. Demonstration of infrared thermography.

In addition to the non-destructive testing methods listed above, a variety of other techniques, including X-rays, laser Doppler vibrometers, electrical resistance-based damage detection, and others, also exhibit promise as WT blade SHM methods [37]. To maintain the paper's short context, they won't be further described, though, because

they are not widely used approaches. From the explanation above, it can be concluded that a blade SHM technique that is successful must meet three fundamental requirements.

5. Electromechanical Impedance (EMI)-Based SHM

Another active SHM methodology that piezoelectric transducers promote is the electromechanical impedance (EMI) technique. The electrical characteristics of a piezoelectric transducers are monitored in the EMI-Based SHM in order to detect damage. Damage close to the transducer alters the structure’s resonance properties and stiffness, which in turn alters the transducer’s electrical impedance because of the electromechanical interaction. The diagnostic process of active SHM usually starts with comparing the current sensor responses with baselines, or previously recorded sensor responses, from the intact structure. The information regarding any destruction or other abnormality that may be present is contained in the discrepancies among two signals set. Since [38] first presented the EMI approach in 1993; it has drawn a lot of attention for use in damage detection applications in mechanical, aeronautical, and civil infrastructure engineering [39]. Numerous efforts have been undertaken in the field of system development, 2-Dimensional or 3-Dimensional numerical modeling and simulation [40], and theoretical models [41]. Figure 5 shows the electromechanical impedance (EMI)-based SHM.

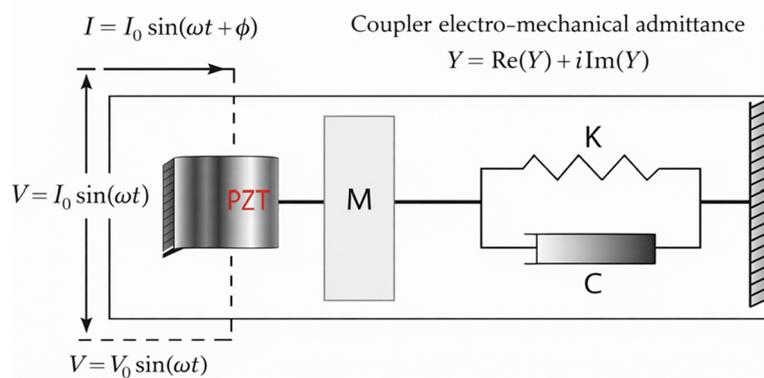


Figure 5. Electromechanical Impedance (EMI)-based SHM.

The system operated by a piezoelectric transducer is considered a Spring-Mass-Damping (SMD) system based on the earlier research. The EMI approach measures the electrical characteristics of a piezoelectric transducer that is integrated in or installed on its host structure, as seen in Figure 5. In the EMI approach, the transducers function as both sensors and actuators. According to classical EMI theory, the complex electrical admittance $Y(\omega)$ of a piezoelectric transducer can be expressed as given Equation (1):

$$Y(\omega) = j \cdot \omega \cdot C_p \cdot [1 - (k_{31}^2 \cdot Z_s(\omega)) / (Z_s(\omega) + Z_p(\omega))] \tag{1}$$

where C_p is the clamped capacitance of the piezoelectric transducer, k_{31} is the electromechanical coupling coefficient, $Z_s(\omega)$ represents the mechanical impedance of the host structure, and $Z_p(\omega)$ is the intrinsic mechanical impedance of the piezoelectric transducer. Any structural damage, such as cracking, delamination, or stiffness degradation, alters the local mechanical impedance $Z_s(\omega)$ by modifying stiffness k , mass m , or damping c . These changes are directly reflected as measurable shifts in the electrical admittance spectrum of the piezoelectric transducer. Consequently, EMI-based SHM provides high sensitivity to early-stage, localized damage, particularly in high-frequency excitation regimes where short wavelengths dominate the response.

6. Strain Measurement

Commercial evaluations of full-size WT blades frequently include strain gauges, which are typically composed of piezoelectric ceramic materials. They are affixed to the blade surface during the testing in order to gauge the local strain brought on by stretching and bending loads. Thus far, the most affordable and dependable method for identifying and pinpointing surface flaws on the WT blade. It is ineffective, therefore, in identifying joint failure. Moreover, strain gauges are unsuitable for long-term SHM missions due to the dependability problems with piezoelectric ceramic material. An alternate technique to measure the strain along the blade span direction is the distributed strain transducer. Nevertheless, throughout the manufacturing process, the distributed strain transducer must be placed in the blade. As such, it does not apply to the SHM of current blades. Furthermore, it is important to consider whether installing a distributed strain transducer may compromise the structural integrity of the blade.

7. Vibration Monitoring

By examining the dynamic reactions of the blades to external forces, vibration analysis looks into the overall health of the blades [42]. Since the material and structural characteristics of the blades such as their mass, stiffness, and damping determine their dynamic responses, any damage resulting in a change in the structure of the blade should be discernible from the dynamic responses. Since they may be utilized to characterize the dynamic responses, specific vibration features and modal parameters can be tracked to perform a vibration analysis-based blade SHM. The phenomenon of vibration monitoring for wind turbine blade is illustrated in Figure 6.



Figure 6. Vibration Monitoring for wind turbine blade.

Vibration analysis is typically utilized to do a broad evaluation of the blades' state of health. If more than one vibration transducer is utilized in tandem; it can also be used to locate damage. The use of several vibration transducers is justified by the fiberglass composite material used to make the WT blade. The dynamic responsiveness might be considerably impeded by the high damping of composite materials. As a result, only transducers positioned close to the defect's location can react to the blade's crack propagation with sensitivity. Therefore, the cooperation of several vibration transducers is needed to locate damage. Thus far, laboratory fatigue and static evaluations of WT blades have employed a vibration analysis-based blade SHM approach. It is not practical to mount so many vibration transducers on an operational blade, so its in-situ application to blade SHM is unrealistic. Because of this, a different vibration analysis-based blade SHM technique was created in [43] recommended monitoring the vibration of the WT main shaft to achieve blade SHM rather than using transducers installed directly on the blade.

8. Acoustic Emission Monitoring

The purpose of acoustic emission is to measure the energy of transient elastic waves produced when a crack starts and spreads throughout the blade [44]. Acoustic emission enables a comprehensive evaluation of the blade's structural integrity, in contrast to strain measurement, which is limited to identifying localized changes in strain on or near the blade surface. Stated differently, the structural integrity of a large portion of the blade can be monitored by a single acoustic emission transducer as opposed to only a small area.

However, the energy of the elastic waves resulting from the start and propagation of cracks will rapidly decline with distance because of the strong damping of the composite blade material. Thus, in order to locate damage, many sonic emission transducers are typically required. Furthermore, it is discovered that the energy of elastic waves can also be absorbed by modifications to the blade shape and material interfaces. As a result, only when the acoustic emission transducers are positioned at "right positions," that is, in close proximity to the position of the defect, and additionally when there is no material interface on the pathways from the defect to the transducers, can the defect resultant elastic waves be detected from the blade surface. Table 2 highlights the comparison of different SHM techniques.

Table 2. Comparison of Different SHM Techniques.

Techniques	Principle	Advantages	Disadvantages
Wave Propagation	Propagation of elastic waves	Sensitive to crack detection, can be used for long-range monitoring	Requires complex signal processing, susceptible to noise
EMI	Measurement of electrical impedance	Sensitive to early-stage damage, simple implementation	Requires calibration, limited to local damage detection
Strain Measurements	Direct measurement of strain	Provides quantitative information on structural deformation	Requires accurate calibration, may be limited to specific locations
Vibration Monitoring	Analysis of vibration response	Can detect changes in dynamic characteristics	Requires careful interpretation of vibration data, may not be sensitive to all types of damage

9. Applications of Piezoelectric Transducer-Based SHM

An important aspect of wind turbines is health maintenance (HMC). It protects wind turbine blades, which are constantly exposed to dynamic loads, fatigue and environmental disturbances, preserving their integrity and performance. Piezoelectric sensors due to their ability to convert mechanical energy into electrical signals, they offer interesting applications in the control of superfluid dynamics in wind turbine blades. Specific application of piezoelectric transducers in wind turbine blade HMC is as follows:

9.1. Damage Detection

Wind turbines can experience many types of damage, including corrosion, delamination, and cracking. Piezoelectric sensors are often used to detect these types of damage because they are very sensitive to voltage. The sensor can detect changes in electrical signals caused by changes in electrical properties. This information can be used to detect and assess the damage to identify the process. Research results show that piezoelectric sensors can detect changes in signal amplitude and phase to monitor the spread of delamination over time.

9.2. Vibration Monitoring

Vibrations in wind turbine blades are caused by mechanical imbalances; wind loads and operating conditions. It is important to pay attention to these vibrations to ensure longevity and prevent serious damage. Piezoelectric sensors integrated into turbine blades can monitor vibrations by monitoring the mechanical modes from the vibrations. Study [45] showed that piezoelectric sensors can be used to monitor turbine blade vibration and detect early signs of damage.

9.3. Fatigue Life Prediction

Wind turbine blades are subjected to cyclic loads that will cause fatigue and failure throughout their service life. The ability to predict fatigue life is important for planning maintenance program and preventing falls [46].

9.4. Structural Integrity Assessment

In order for wind turbine blades to function properly, their structural integrity must be continuously monitored. The SHM system can determine overall structural integrity by analyzing filter patterns [47] and variations in the reliability assessment of wind turbine blades. Researchers have developed a real-time SHM system that can measure the health of the structure by continuously monitoring the distribution of blade along its length.

9.5. Load Monitoring

Monitoring the properties of wind turbine blades is another application area for piezoelectric sensors. SHM technology can help improve blade design and increase engine performance by examining the effects of centrifugal force, gravity, and aerodynamic stress. According to research by [48], piezoelectric-based SHM devices can be used to monitor the electrical properties of wind turbine blades. The sensor's sensitivity to static and electrical components enables immediate monitoring and optimization of wind turbine systems. Figure 7 shows the load monitoring assessment.



Figure 7. Load monitoring assessment.

9.6. Electrical Test

Piezoelectric sensors can be used to record and monitor the health of wind turbine blades. Using piezoelectric sensors, the electrical demand and electrical properties of the blades can be converted into electrical energy for SHM power [49].

10. Challenges of Piezoelectric Sensor-Based Health Monitoring (SHM) Systems

Although piezoelectric sensor-based health monitoring (HMM) systems have many advantages for wind turbine blades, their acceptance and performance are hindered by several issues. These issues arise from physical limitations, environmental changes, processing difficulties, and real-world deployment problems. The main obstacles are as follows:

10.1. Durability and Environmental Resistance

Wind turbine blades are exposed to a variety of environmental factors, including high temperatures, high humidity, precipitation, and exposure to seawater in offshore environments. Piezoelectric sensors, especially those integrated or implanted into turbine blades, must meet these requirements to avoid deterioration over time. Problems such as corrosion, degradation, and material fatigue can all cause sensors to fail. A study by [50] showed that piezoelectric materials used in SHM systems are generally shock absorbent and perform well when exposed to higher pressures. They noted that changes in temperature, in particular, can alter piezoelectric properties and lead to erroneous data.

10.2. Signal Noise and Data Interpretation

Due to the dynamic operating environment of wind turbine blades, there may be a high degree of noise in the sensor reading. Background signals can be generated by wind loads, mechanical vibrations, and the interaction of various materials; Therefore, it is difficult to distinguish the signal generated by the disturbance model from the signal generated by the normal operating environment. Signal processing techniques such as wavelet transform or AI-based algorithms are required to properly filter out the noise and understand the data [51].

10.3. Limited Sensing Coverage

The use of piezoelectric sensors allows only local monitoring, which means that damage can only be detected in the immediate vicinity of the sensor. Wind turbine blades, especially those on large modern turbines, are very large structures. Some limitations of piezoelectric sensors make them inadequate for monitoring all the blades, and adding additional sensors makes the system more expensive and complex. The low sensitivity of piezoelectric transducers hinders the development of SHM. They say many services can be provided by hybrid SHM systems that combine piezoelectric sensors with other types of sensors, such as fiber optic.

10.4. Power Supply and Energy Requirements

When piezoelectric sensors are used in SHM, powering the sensors is a real problem, especially in remote areas. Daily maintenance of offshore wind turbines is expensive and time-consuming and requires constant power supply from the sensors, which makes maintenance difficult. Although harvesting energy directly from the sensor itself is a good method, the received energy may not be sufficient for consistent and reliable monitoring [52].

10.5. Sensor Attachment and Integration

Another issue is the proper integration or integration of piezoelectric transducers into wind turbine components. Sensors should be securely connected or integrated without affecting the structural integrity or aerodynamic performance of the blades. Due to connection problems, thermal expansion mismatch, and equipment modification, sensor connection performance will deteriorate, and thus monitoring efficiency will decrease. [53], integrating piezoelectric sensors into composite wings can cause weak points in the structure to expand under stress. They emphasized the need for advanced technology to ensure compatibility and long-term performance of sensors in the workplace.

10.6 High-Frequency Data Management and Edge Intelligence

Piezoelectric transducers operating in ultrasonic and EMI regimes often function at kilohertz to megahertz frequencies, resulting in extremely high data generation rates. For large-scale wind farms, continuous high-frequency monitoring can rapidly produce terabytes of data, creating challenges in data storage, transmission bandwidth, and real-time processing. To address these challenges, recent SHM research has increasingly adopted edge computing architectures, where preliminary signal processing, feature extraction, and damage classification are performed locally at the sensor or data acquisition unit. This approach significantly reduces data transmission requirements while enabling near real-time diagnostics.

10.7. Cost and Maintenance

In large wind farms, especially offshore wind farms, the installation costs of piezoelectric-based SHM systems are high. The initial cost of the sensor will be very high in addition to the cost of data transmission, signal processing equipment, and routine maintenance. Moreover, the management of these systems creates additional transportation problems, especially in remote or remote areas. When a sensor fails, it is expensive and difficult to replace or repair. A study by [54] reduces costs through regular maintenance.

10.8. Temperature Sensitivity

Piezoelectric materials exhibit temperature-dependent behavior that is inherently nonlinear. Key performance parameters, such as the piezoelectric charge coefficient (d_{33}), dielectric constant, and electromechanical coupling factor, vary with temperature and can significantly influence sensing performance. At elevated temperatures approaching the Curie temperature, piezoelectric materials undergo depolarization, resulting in a substantial loss of piezoelectric functionality. Therefore, temperature compensation strategies and careful material selection are essential for reliable long-term SHM of wind turbine blades operating under variable environmental conditions [55].

10.9. Brittleness of Conventional PZT Ceramics

Conventional lead zirconate titanate (PZT) ceramics, while highly sensitive, are inherently brittle and exhibit limited conformability to the curved and aerodynamically optimized surfaces of modern wind turbine blades. These limitations can lead to premature sensor failure under cyclic loading, vibration, and thermal expansion mismatch. To overcome these challenges, flexible piezoelectric alternatives such as Macro Fiber Composites (MFC) and Active Fiber Composites (AFC) have gained increasing attention. These materials consist of piezoelectric fibers embedded within polymer matrices, providing enhanced flexibility, damage tolerance, and improved bonding reliability on curved composite surfaces. Compared to monolithic PZT patches, MFC and AFC sensors demonstrate superior fatigue resistance, reduced risk of cracking, and improved survivability under long-term operational conditions. Their mechanical compatibility with composite blade materials makes them particularly suitable for in-situ, long-term SHM of wind turbine blades.

11. Future Trends and Research Directions

Model health monitoring (SHM) has gained significant attention in the wind energy industry due to the increasing demand for reliability and economy of scale. PZT or piezoelectric sensors have become a key technology in this field, providing unique results for SHM of wind turbine components. PZT-based SHM systems use positive and negative piezoelectricity to detect structural defects. In this mechanism, mechanical stress generates electrical signals and vice versa. This equipment can be used to monitor many elements of the wind turbine, such as blades, tubular towers, machines and foundations. They are lightweight and non-invasive. Considering that many models need better, immediate and flexible maintenance, they seem promising in solving these problems. The application of these systems in wind turbine blades, tubular towers, substructures and foundations is discussed in detail below.

11.1. Blade Monitoring

One of the most important parts of a turbine is the wind turbine blade. During operation, they are exposed to many harsh elements such as heat, wind, electricity [56]. Product degradation, fatigue cracking, delamination and corrosion (especially at the edge) are caused by prolonged exposure to oil. In addition to being expensive to repair, blade maintenance can be costly. PZT monitors stress, vibration and acoustic emissions to detect small changes in the reliability of the blade structure.

The PZT system supports the maintenance of the turbine blade health through the following means [57]:

1. **Vibration monitoring:** Dynamic stresses applied to wind turbine blades can cause vibrations. These vibrations can be detected using piezoelectric sensors placed at the points of the inspected surface to detect changes in frequency or amplitude. Differences in vibration patterns may indicate the onset of delamination or fatigue cracking.
2. **Strain Sensing:** Strain in blade materials can be accurately measured using PZT-based strain sensors. The high sensitivity of these sensors is important for detecting short-term damage that cannot be detected by visual inspection. Continuous monitoring allows workers to predict when the blade will reach its fatigue point [58].
3. **Acoustic emission detection:** Structural defects (such as cracks or delamination) emit loud sounds. PZT sensors are very effective in detecting these particles.
4. **Integration with smart materials:** Self-healing materials are being studied in conjunction with piezoelectric transducers. By combining smart data with PZT analytics, wind turbines can detect damage and initiate repair processes themselves, reducing maintenance costs and downtime. PZT sensors are widely used in renewable energy devices and can provide accurate, instantaneous information about healthy structure, increase turbine efficiency, and reduce overall energy costs [59].

11.2. Tubular Tower Overview

The structure of a wind turbine is a tubular tower that supports the weight and wind force of the turbine parts, including the nacelle and rotor. Like the forks, towers can also be damaged by wear and tear, especially in coastal areas where heavy weather can wear down equipment. Early detection of cracks and buckling in towers is important to prevent damage [60]. Figure 8 demonstrate the concept of tubular tower monitoring.



Figure 8. Tubular tower monitoring.

The following are some ways that piezoelectric transducers-based SHM can improve tubular tower monitoring:

1. **Vibration and analysis:** PZT sensors can detect the natural vibration frequency of the tower. Changes in these frequencies can be indicative of cracks or loose bolts, as well as other problems in the tower. Real-time identification of these problems through continuous monitoring can prevent serious accidents [61].
2. **Corrosion Detection:** Offshore wind turbines are particularly susceptible to corrosion due to the salt content in the air. PZT-based sensors can be installed on the tower to detect early signs of corrosion. These sensors measure the electrical conductivity of the metal, allowing construction workers to work and providing a better understanding of the corrosion rate [62].
3. **Fatigue analysis:** Since the load is heavy, the fatigue of the tube towers will expand rapidly. Since PZT sensors are sensitive to the formation of microcracks, they can warn workers about the existence of microcracks before a critical event occurs. The sensors can also monitor the growth of these cracks and provide important information to estimate the remaining service life [63].
4. **Bolt Preload Monitoring:** The bolts that hold the tower sections together are important to maintaining the integrity of the turbine. PZT-based SHM systems can measure changes in sound waves to track the stress in the bolts [64]. If the bolts begin to loosen, the acoustic signature will change, allowing early detection and repair.
5. **Coastal health monitoring:** Real-time remote monitoring of the health tower is especially important for the difficult sunset entering the wind turbines. And very expensive. Saves you physical inspection and operating costs. PZT can be combined to provide real-time status [65]. The rest will be provided by electricity generation and wireless communications. Smarter PZT-based SHM systems are now available for tubular towers.

11.3. Substructure and Foundation Monitoring

Wind turbine foundations and substructures must withstand harsh environmental conditions such as heat, earthquakes, waves, and currents, especially in offshore installations. These stresses can weaken the foundation from corrosion and cause the infrastructure to collapse, leading to total turbine instability [66]. Figure 9 shows the monitoring process of substructure and foundation of wind turbine.

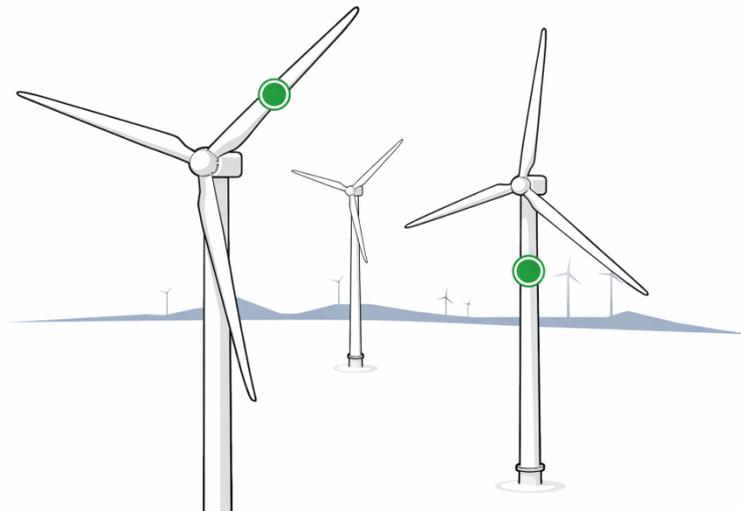


Figure 9. Substructure and Foundation Monitoring.

Systems based on piezoelectric transducers provide several advantages for wind turbine substructure and foundation monitoring:

1. **Scrubbing detection:** silt loading on offshore wind turbine surfaces. This can reduce the weight of the building [67]. PZT sensors can detect changes in the vibration source and indicate unstable conditions.
2. **Fatigue monitoring:** Wind and waves periodically cause loads on the infrastructure. PZT-based sensors can detect cracks in these structures before they occur [68]. Sensors that detect the in-flight acoustic noise produced by the propagating explosion can give you instant information about the nature of the explosion and the condition of the underlying structure.
3. **Seismic Activity Detection:** Seismic activity detection is very important. Foundation and foundation structure for wind turbines in seismically active regions. PZT sensors are used to calculate the forces acting on the foundation due to ground movement, allowing monitoring of stresses in the foundation. Inspect turbines for damage caused by earthquakes [69–72].

4. **Resolution and tilt detection:** As wind turbines age, the foundation will tilt negatively. This will cause the turbine to tilt. This tilt can damage the building or cause corrosion and affect the operation of the turbine. PZT sensors allow operators to resolve problems before they occur. By monitoring the location of the base and the change in slope.
5. **Long-term maintenance:** Offshore wind turbines are generally made of structures with a service life of 20–25 years because the harsh marine environment causes the foundation and infrastructure to age. PZT-based SHM systems can provide continuous information about the condition of these components to accurately predict the service life. Using this information, premature failures can be minimized and mitigated based SHM in marine monitoring. These sensors are suitable for long-term autonomous operation of long-distance offshore wind farms since they can be used by energy storage platforms.

12. Conclusions

This review has comprehensively analyzed the role of piezoelectric transducer-based structural health monitoring (SHM) systems in ensuring the reliability and safety of wind turbine blades. A detailed understanding of blade structure and common failure mechanisms has established the need for real-time, non-destructive diagnostic methods. Various SHM techniques utilizing piezoelectric transducers including electromechanical impedance (EMI)-based monitoring, strain measurement, vibration analysis, and acoustic emission detection have been critically discussed for their effectiveness in detecting early-stage damage and structural deterioration. The review also outlined key applications of these techniques in enhancing blade integrity, predicting fatigue life, and supporting predictive maintenance strategies. Despite remarkable progress, several challenges persist, including sensor placement optimization, signal noise reduction, environmental compensation, and long-term reliability. Addressing these issues through improved materials, advanced signal processing algorithms, and AI-assisted diagnostic frameworks represents the future direction of research. Overall, the current review provides valuable insights into the integration of piezoelectric transducers for wind turbine blade monitoring, highlighting their potential to significantly improve operational efficiency, extend service life, and promote sustainable energy generation in the wind power sector.

Author Contributions

S.A. (Shahryar Altaf): conceptualization, methodology, software; S.K.: data curation, writing—original draft preparation; Z.A.: visualization, investigation; S.A. (Saqlain Abbas): supervision, reviewing, validation; H.R.: software, validation; Z.A. and M.I.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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