Wind turbine blade health monitoring with piezoceramic-based wireless sensor network

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In this paper, a piezoceramic-based wireless sensor network (WSN) was developed for health monitoring of wind turbine blades with active sensing approach. The WSN system has an access point that coordinates the network and connects to a PC to control the wireless nodes. One wireless node functions as an actuator to excite an embedded piezoceramic patch with desired guided waves. The remaining wireless nodes function as sensors to detect and transmit the wave responses at distributed locations. The damage status inside the blade was evaluated through the analysis of the sensor signals. Based on wavelet packet analysis results, a damage index and a damage matrix were developed to evaluate the damage status at different locations. To verify the effectiveness of the proposed approach, a static loading test and a wind tunnel test were performed in the Laboratory of Joint Wind Tunnel and Wave Flume at Harbin Institute of Technology (HIT), China. Experimental results show that damage in wind turbine blades can be detected and evaluated by the proposed approach.

Keywords: piezoceramics; active sensing; wireless sensor network; structural health monitoring; wind turbine blade

1. Introduction

Moisture absorption, fatigue, wind gusts, or lightning strikes, among other factors, may cause damage to wind turbine blades. From the wind turbine accident statistic data (1975–2009) provided by the Caithness Windfarm Information Forum [1], the biggest number of wind turbine accident is due to blade failure (total of 167 incidents). It is important to perform structural health monitoring (SHM) to detect damage before structural failure of wind turbine blades occurs. Traditional SHM methods for wind turbine blade include the following: (1) visual inspection; (2) tap test; (3) acoustic emission (AE) [2–7]; (4) infrared thermography [8–10]; (5) electro-mechanical impedance-based method [11]; (6) optical fiber-based approach [12–18]; and (7) piezoelectric transducers [19,20]. Unfortunately, visual inspection cannot detect cracks inside blades and is not suitable for automated and real-time applications. Tap tests and infrared thermography are not suitable for in situ fatigue monitoring. The optical fiber approach can only measure local properties where the sensor is located. On the other hand, properly embedded piezoelectric transducers can offer real-time, wide range monitoring of an entire structure.

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In this paper, a piezoceramic-based wireless sensor network (WSN) system was developed for automated real-time health monitoring of wind turbine blades. A distributed piezoceramic transducer system was formed by embedding water-proof coated piezoceramic patches in predetermined locations in the composite blades. Desired guided waves were generated by a selected piezoceramic patch as an actuator to propagate through the entire composite blade. Wave responses were detected by other distributed embedded piezoceramic patches. The wave propagation response in the wind turbine blade will be attenuated due to acoustic impedance mismatch at the damaged area. Thus, the damage status inside the blade can be evaluated through the analysis of the sensor signals. In the proposed approach, wavelet packet analysis was used as the signal processing tool to extract damage features from sensor signals. Based on wavelet packet analysis results, a damage index and a damage matrix were developed to evaluate the damage status at different locations. To verify the effectiveness of the proposed piezoceramic-based health monitoring approach, a static loading test and a wind tunnel test were performed in the Laboratory of Joint Wind Tunnel and Wave Flume at Harbin Institute of Technology (HIT), China. Experimental results show that damage in wind turbine blades can be detected and evaluated by the proposed approach with the help of the WSN.

2. Proposed piezoceramic-based WSN

The proposed automated real-time piezoceramic-based WSN is composed of an embedded piezoceramic sensor network and a wireless communication system. In the proposed WSN, one piezoceramic patch was used to generate desired guided waves to propagate through the entire composite blade; wave responses were detected by the other distributed piezoceramic sensors. The detected sensor signals were transmitted through the wireless communication system from sensor nodes to PC for analysis.

The distributed sensor network was formed by embedding water-proof coated piezoceramic patches in predetermined locations in composite wind turbine blades during the fabrication process. As shown in Figure 1a, the sensor locations 1, 2, and 5 were chosen to encompass as much of the blade as possible, while sensor locations 2 and 3 helped to monitor for cracks that may occur parallel to the blade. Due to the small size of the piezoceramic patches, the structural integrity of the blade was affected minimally. At each sensing point, three piezoceramic patches were placed on the top surface, bottom surface, and internal layers, as shown in Figure 1b. In this research, lead zirconate titanate (PZT) type of piezoceramic material was used due to its strong piezoelectric effect and high Curie point.

The WSN was developed with Texas Instruments MSP430 microcontrollers (Texas Instruments, Dallas, TX, USA) connected to CC2500 radio ICs. With this combination, a very low-power WSN can be implemented for the proposed health monitoring system. The WSN, as shown in Figure 2, is designed for SHM of wind turbine blade via active sensing approach using three separate programs on various nodes. A single node runs the access point software to form a wireless network and communicate with a PC. Either a sensor or an actuator node can be used for this purpose. The access point software begins by initializing the network stack, setting the microcontroller clock speed, and initializing a serial port for communication with a PC. The program then enters a continuous loop in which it checks for network traffic and checks the status of semaphores controlling the functions of the system. All of the sensor nodes connected to PZT patches ran an end device program designed for sensor functions; additionally an actuator node runs an end device program designed for actuator functions.
The WSN system has an access point that coordinates the network and connects to a PC to control the wireless nodes. One node functions as an actuator to create a sweep-sine excitation that can travel through the wind turbine blades. The remaining nodes function as sensors to capture and transmit the excitation response at each sensor location. Figures 3 and 4 show the picture and the block diagram of the sensor node components; Figures 5 and 6 show the picture and block diagram of the actuator node components. The sensor nodes are powered by a 3-Volt battery pack while actuator nodes require a 12-Volt battery, which also generate 3.3 Volts for the microcontroller.

3. Health monitoring algorithm

In the proposed health monitoring algorithm, an energy vector is formed on the basis of wavelet packet analysis results to reveal energy components in different frequency bands. A damage index and a sensor-history damage index matrix (SHDIM) are formed based on
wavelet packet analysis results to evaluate the damage severity. The advantage of wavelet packet analysis is that it enables the inspection of relatively narrow frequency bands over a relatively short-time window.

In the proposed approach, the sensor signal $S$ is decomposed by an $n$-level wavelet packet decomposition into $2^n$ signal sets $\{X_1, X_2, \ldots, X_{2^n}\}$. $E_{ij}$ is the energy of the decomposed signal, where $i$ is the time index and $j$ is the frequency band ($j = 1, \ldots, 2^n$). $X_j$ can be expressed as

$$X_j = [x_{j,1}, x_{j,2}, \cdots, x_{j,m}]$$

(1)
where $m$ is the amount of sampling data. Additionally, the energy of the decomposed signal is defined as

$$E_{i,j} = x_{j,2}^2 = x_{j,1}^2 + x_{j,2}^2 + \cdots + x_{j,m}^2$$  \hspace{1cm} (2)$$

The energy vector at a time index $i$ is defined as

$$E_i = [E_{i,1}, E_{i,2}, \cdots, E_{i,2^n}]$$  \hspace{1cm} (3)$$

Various kinds of damage indices have been developed for health monitoring of civil structures in recent years. Root-mean-square deviation (RMSD) is a commonly used damage index to compare the difference between the signatures of healthy and damaged states. In the proposed approach, the damage index is formed by calculating the RMSD between
the energy vectors of the healthy state and the damaged state. The energy vector for healthy data is $E_h = [E_{h,1}, E_{h,2}, \ldots, E_{h,n}]$. The damage index at time $i$ is defined as

$$I = \sqrt{\frac{\sum_{j=1}^{2n} (E_{i,j} - E_{h,j})^2}{\sum_{j=1}^{2n} E_{h,j}^2}}$$

(4)

The proposed damage index represents the transmission energy loss portion caused by the structural damage. When the damage index is close to 0, the composite blade is in a healthy state. When the damage index is larger than a certain threshold value, damage has begun to appear in the composite blade. In this case, a greater index corresponds to a more severe damage.

To demonstrate damage development at different locations of the composite blade, SHDIM is defined as

$$M_{m \times n} = [I_{i,j}]_{m \times n} \quad (i = 1, \ldots, m; j = 1, \ldots, n)$$

(5)

where the matrix element at the $i$th row and the $j$th column, $I_{i,j}$, is the damage index of the $i$th PZT at the time of the $j$th test (i.e., $i$ is the sensor index, $j$ is the time index), $m$ is the total number of PZTs, and $n$ is the total number of tests. The damage status at different locations of the composite blade at different test times can be described by a three-dimensional damage index matrix plot.

4. Experimental setup and testing program

To verify the effectiveness of the proposed PZT-based WSN, the following two types of tests were performed for the wind turbine blades at HIT in China: a static loading test and a wind tunnel test. In each test, the tested wind turbine blade was instrumented with 15 PZT patches.

4.1. Static loading test

In the static loading test, displacement control was implemented to elevate the free end of the wind turbine blade shown in Figure 7a and b. The displacement of the free end was
increased at a constant rate until failure of the blade occurred. During the loading test, the proposed piezoceramic-based health monitoring approach was implemented to evaluate the damage status at different displacement values. To evaluate the damage, a 10-s sweep-sine excitation was generated by the embedded PZT actuator; the responses were detected by the distributed PZT sensors and transmitted to PC through the wireless communication system.

4.2. Wind tunnel test

To verify the effectiveness of the proposed PZT-based WSN under dynamic loading, the proposed PZT-based WSN was implemented to perform the health monitoring of wind turbine blades in a wind tunnel test at HIT, China, as shown in Figure 8. Three 1.25-m wind turbine blades with embedded PZT patches were mounted to a standard wind turbine hub. Each blade contained five PZT patches in the same locations as the wind turbine blade, as shown in Figure 1. The sensor and actuator nodes with battery packs were then taped to a plastic box that was cut to fit securely inside the nose cone as shown in Figure 9. A composite wind turbine blade was damaged by cutting a 1-mm deep slot between PZT locations 2 and 3; the slot was later cut 1-mm deeper to create a more severe damage case, as shown in Figure 10. Fourteen AA batteries were placed in seven battery packs to power the sensor network. Four battery packs were connected in series to provide 12 Volts to the actuator node and PZT amplifier. The remaining three battery packs were each used to

Figure 8. Rotating wind turbine with WSN.

Figure 9. Nose cone with WSN.
supply power to two sensor nodes. Health monitoring tests were performed at static (zero wind speed) and 10 m/s wind speed scenarios.

5. Experimental results

5.1. Static loading test

In the static loading test, the composite blade was gradually damaged through a displacement control mode. The damaged blade after the static loading test is shown in Figure 11. The proposed health monitoring approach was used to evaluate the damage development of the composite blade during the static test. From the time response comparison for different tests, as shown in Figure 12, it can be seen that the amplitude of the sweep sine was attenuated by the cracks during the test. Also, the shape of the time response in test 26 changed significantly compared to the healthy state. From the analysis of the SHDIM results, as shown in Figure 13, it can be seen that there is a dramatic increase in damage index values for all the sensors at the displacement value of 125 mm and damage index values subsequently became high. These results indicate that severe damage existed at this...
displacement value and became more severe with subsequent increases in displacement. From the SHDIM results, the displacement value of 125 mm is a prediction point for the structural failure. Also, sensors 1 and 4 have relatively greater damage index values than those of other sensors, which means that the damage status around these two sensors was more severe than other locations and matches with the visual inspection of the wind turbine blade shown in Figure 11. The experimental results show that the critical prediction point
for the structural failure and the damage location information were successfully extracted using the proposed piezo-based WSN.

5.2. Wind tunnel test

In the wind tunnel test, the composite blade was manually damaged to different degrees and the proposed health monitoring approach was used to evaluate the damage severity for a static, zero wind speed and a 10 m/s wind speed scenario. The sweep-sine excitation response was recorded for the static case with the wind tunnel turned off. The wind tunnel was first set to create a wind speed of 8.6 m/s and then 10 m/s. From the time responses under zero wind speed for sensors 1 and 2, as shown in Figures 14 and 15, it can be observed that the amplitude attenuated greatly with the increase of damage severity. From the time responses under wind speed of 10 m/s for sensors 1 and 2, as shown in Figures 16 and 17, it can be observed that the response amplitude also attenuated greatly with the increase of damage severity.

Power spectral density (PSD) analysis reveals the energy distribution of the detected signal in the frequency range. To demonstrate the attenuation of wave propagation energy due to damage, PSD plots of the transmitted data were used to evaluate the damage status. From the PSD plots of sensors 1 and 2, as shown in Figures 18 and 19, respectively, under zero wind speed loading, the energy amplitude has greatly attenuated in a wide frequency range. From the PSD plots of sensors 1–6, as shown in Figures 20–25, respectively, in the 10 m/s wind speed scenario, the energy amplitude was also greatly attenuated in a wide frequency range.
Figure 15. Time responses for sensor 2 (zero wind speed).

Figure 16. Time responses for sensor 1 (dynamic test).
Figure 17. Time responses for sensor 2 (dynamic test).

Figure 18. PSD plot for sensor 1 (zero wind speed).
wide frequency range for different sensors. The experimental results have shown that the proposed PZT-based WSN has successfully detected the wave response and transmitted sensor signals via wireless communication; furthermore, the existence of damage greatly attenuated wave propagation energy in a wide frequency range.
6. Conclusions
A piezoceramic-based WSN is proposed for health monitoring of wind turbine blades. A wavelet packet-based damage index and a damage index matrix were developed to evaluate damage in wind turbine blades. To verify the effectiveness of the proposed PZT-based WSN, a static loading test and a wind tunnel test were conducted using wind turbine blades instrumented with PZTs. The experimental results of the static loading test showed that the proposed approach successfully provided a prediction threshold for structural failure and extracted damage location information from the damage index matrix. The wind tunnel test demonstrated that the proposed approach successfully transmitted active excitation
responses via the wireless communication for a zero wind speed case and at 10 m/s wind speed case. PSD plots of the transmitted sensor data clearly indicated that wave propagation energy was greatly attenuated when the blade was damaged. The proposed health monitoring system has the potential to be implemented on large-scale wind turbines for real-time and automated SHM.
Figure 25. PSD plot for sensor 6 (10 m/s wind speed).

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