A Real-Time Deflection Monitoring System for Wind Turbine Blades Using a Built-In Laser Displacement Sensor

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ABSTRACT

Renewable energy is considered a good alternative to deal with the issues related to fossil fuel and environmental pollution. Wind energy as one of such renewable energy alternatives has seen a substantial growth. With commercially viable global wind power potential, wind energy penetration is further expected to rise, and so will the related problems. One of the issues is the collision of wind blade and tower during operation. To improve safety during operation, to minimize the risk of sudden failure or total breakdown, and to ensure reliable power generation and reduce wind turbine life cycle costs, a structural health monitoring (SHM) technology is required. This study proposes a single laser displacement sensor (LDS) system, where all of the rotating blades could be evaluated effectively. The system is cost-effective as well, as the system costs only a mere thousand dollars. If the blade bolt loosening occurs, it causes deflection in the affected blade. In a similar manner, nacelle tilt or mass loss damage in the blade will result in change of blade's position and the proposed system can identify such problems with ease. With increased demand of energy, the sizes of wind blades are getting bigger and bigger due to which people are installing wind turbines very high above the ground level or offshore. It is impractical to monitor the deflection through wired connection in these cases and hence can be replaced by a wireless solution. This wireless solution is achieved using Zigbee technology which operates in the industrial, scientific and medical (ISM) radio bands, typically 2.4 GHz, 915 MHz and 868 MHz. The output from the LDS is fed to the microcontroller which acts as an analog to digital converter which in turn is connected to the Zigbee transceiver module, which transmits the data. At the other end, the Zigbee reads the data and displays on the PC from where user can monitor the condition of wind blades.

INTRODUCTION

Wind energy has shown substantial growth in present context. The worldwide

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installation of 35.8 GW of wind power capacity in 2010 highlights the fact that wind energy is growing rapidly despite the widespread financial crisis and economic recession. Hence, the global installed wind power capacity reached 194.4 GW by the end of 2010 [1].

However, operational accidents also increased by 3.6 times in 2010 compared to the year 2000 [2]. Blade rotor structures are composed of various components and subsystems that are susceptible to structural damage as well as bearing, spindle, or gearbox failure. The facts show that approximately 63.4% of the structural damage in wind turbines leading to accidents is caused due to sudden deformity or displacement changes between the blade and the tower early in the turbine's life. Relative displacement monitoring of the blades in the tower can thus prevent catastrophic accidents like collision of the wind blade with tower. If such flaws can be detected in advance, it prompts for the implementation of necessary preventive measures. Also, since wind turbines generally have multiple blades, relative comparison of the distance between the blades and the tower is also an important diagnostic element that could help prevent failures due to collision accidents.

In this study, a few possible failure events have been considered that could cause variation in the distance between the blades and the tower and lead to blade deflection and collision. Bolt loosening is one of the causes of blade deflection [3]. Abnormal tilt of the nacelle and the rotor shaft could also cause all of the blades to deflect (Fig. 1(b)), causing collision as the blades come close to the tower due to the nacelle tilt [4]. Fig. 1(c) shows a wind turbine with curved blades (Vestas, v112), which can increase blade stiffness and can be realized by composite manufacturing technologies [5]. Lightning shown in Fig. 1(d) [6] is also one of the factors that cause a mass difference among the blades which results in rotational imbalance [7] which may ultimately lead to collision accidents. This study has proposed a wind power blade deflection monitoring system that consists of a cost-effective, noncontact laser displacement sensor (LDS) that can be installed within the tower that provides real-time health monitoring of the wind turbine blades. A wireless communication system between the LDS controller in the tower and the base station has been realized to monitor the deflection of the wind blades from remote location.

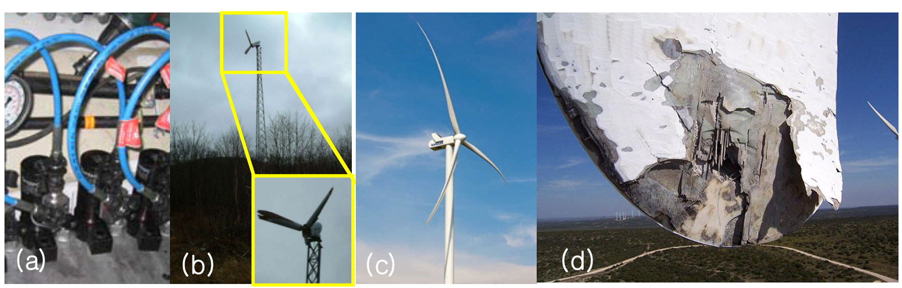

Figure 1. (a) Bolts used in wind turbine blades [3]. (b) Collision accident between the blade and the tower caused by nacelle tilt [4]. (c) Bent wind turbine blade with blade tip closer to the tower (V112-Vestas) [5]. (d) Lightning-induced blade tip damage [6].

A LASER DISPLACEMENT SENSOR AS A BLADE DEFLECTION MONITORING SYSTEM

In previous studies, a Laser Doppler Vibrometer (LDV) has been used to determine any faults in the blade but it has limitation of having low signal to noise ratio and also is not practically possible to implement for large area. Other technologies such as fiber Bragg grating and piezoelectric sensors which are attached to the structure is uneconomical and impractical for use in large wind farms. Similarly, other techniques like Photogrammetry and CCD cameras have their own limitations and are impractical for large wind turbines and offshore wind turbines.

The LDS system proposed in this study is very cost effective compared to the LDV system, is very easy to install and easy to monitor the blade displacement from the tower. The LDS system which consists of a sensor head and controller employs triangulation measurement principles, whereby the laser emitter projects an infrared laser beam that creates a spot on the rotating blade surface. Reflected light from the surface is detected by the light receiver inside the sensor head which do not need any special surface preparation to detect the reflected light. The displacement values of the blades are acquired through use of a DAQ system (NI, Terminal block 2120 and Digitizer PCI 6221) in real time to monitor abnormal blade deflection. Similarly, for wireless transfer of the displacement values, an ADC (PIC microcontroller) is used to acquire the analog data and prepare it to be transmitted through Zigbee (2.4 GHz ISM band frequency) over a range of distance.

The displacement is continuously monitored by impinging the laser beam of the noncontact LDS at the rotating blades in an operating condition of a wind turbine system. Damage such as nacelle tilt, bolt loosening, or blade mass loss causes measurement irregularities or changes, indicating the detection of any possible damage. It allows any repair action to be taken readily which can prevents serious accidents. The proposed system could be installed within the wind turbine tower as shown in Figs. 2 (a) – (c). In this configuration, the laser is impinged from the LDS onto the rotating blade to acquire the displacement data. The LDS used in this study can measure a maximum of 60 mm displacement from the center distance of measurement range and has a maximum of 1 KHz sampling frequency, whereas the laser beam size is 1.0 × 2.0 mm and provides a 50 μm resolution. The displacement sensor uses a semiconductor laser as the light source, which has a wavelength of 780 nm and provides 5 mW of output power. The LDS head is 40 (mm) × 43 (mm) × 20 (mm) and is considered to make a through-hole in the tower wall upon installation.

The analog displacement signal measured by the LDS is calibrated to a digital signal through a DAQ board and the blade deflections are then monitored in real time compared with reference signals in a LabView platform-based PC. For a large wind turbine system of a megawatt order, a long-range capable LDS needs to be used. Although the resolution is comparatively lower in such cases, the blade deflection is also comparatively larger thus providing a suitable measurement.

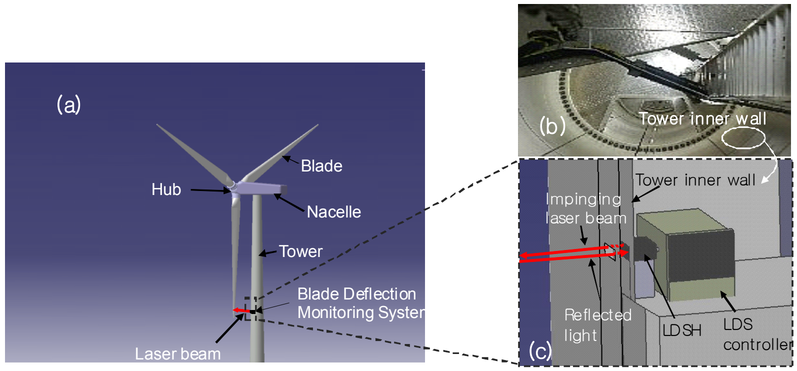

Figure 2. (a) Installation of the blade deflection monitoring system within the tower. (b) Inside the actual wind turbine tower. (c) Inside wind turbine tower with laser displacement sensor (LDS) installation.

EXPERIMENTAL PROOF-OF-CONCEPT

An experimental setup for a typical wind turbine system was designed for this experimental proof of concept that consisted of 1.05 m long wind turbine blades with a rotating motor and a motor controller system. The data from one of the real 50 m long wind turbine blades (2 MW KM43) showed 70 m/s as the blade tip velocity and 20-30 rpm as the rotation velocity and 2-3 s per cycle depending on wind velocity [17]. Thus, 20 rpm was considered the rotation velocity for this research study.

Blade deflection due to bolt loosening

A bolt loosening effect was simulated in one of the blades (Blade 1) with the other two blades kept intact. The laser impinges at a point 100 mm away from the tip of the rotating blades at 20 rpm when the blades pass over the LDS. The reference displacement and damage blade displacement data were acquired before the bolt loosening for comparison to the present state. Bolt loosening resulted in deflection of the corresponding blade, which was monitored and verified experimentally. The reference data acquired before and after bolt loosening for all three blades are shown in Fig. 3 (a). An enlarged view of Blade 1 (Fig. 3 (b)) shows a curved distribution due to the blade's airfoil shape. On the maximum camber of the blade, the incident laser beam was diffused and did not sufficiently reach the receiving end, which led to fault measurements at a few sampling points (Fig. 3(b)). Thus, averaging of the leading edge (first measured value) displacement measurement and the trailing edge (last measured value) displacement measurement was used as the representative value for blade displacement upon comparison of the reference and current displacements.

Two bolts in Blade 1 were loosened by a half and a quarter rotations, respectively. The data were acquired by impinging the laser at the point in the range of 100–500 mm away from the blade tip at 100-mm intervals. Upon monitoring at 100 mm away from the blade tip, the averaged results of comparing the reference and the bolt loosened data showed a deflection of 4.16 mm closer to the tower. The data were analyzed and compared as deflections versus the point of measurement distance from the blade tip (Fig. 4). Greater deflection was detected at the measurement point nearer the blade tip compared to the measurement point that is farther away, which shows decreased deflection close to the blade root. The degree of blade loosening could be clearly distinguished in the form of variation in blade deflection as shown in Fig. 4, in which the blades were loosened by a half and a quarter rotations.

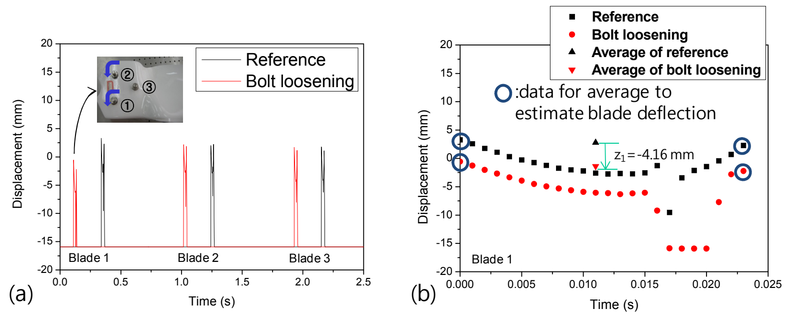

Figure 3. Bolt loosening monitoring at 100 mm from the blade tip: (a) Blade displacement before and after bolt loosening, (b) Comparison of displacements for Blade 1.

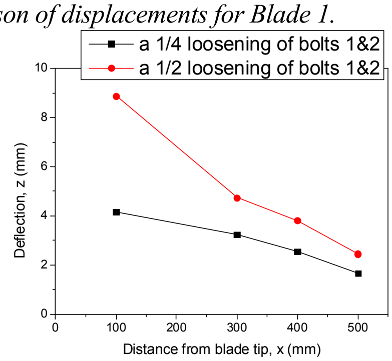

Figure 4. Variation in the amount of deflection upon half and quarter loosening of the bolt at different distances from the blade tip.

Blade deflection due to nacelle tilting

A nacelle is a cover housing that holds the components of wind turbine like the generator, gearbox, drive train, and brake assembly. In this experiment, the nacelle tilt effect was simulated by deflection of the motor support by 0.5 which created a 3-mm displacement of the nacelle. The resulting blade displacements are plotted and compared in Fig. 5 (a), which was taken from the measurement point 100 mm away from the blade tip. The results showed that the nacelle tilting results in deflection of all the blades. The result was further analyzed and the resultant displacement comparison before and after the nacelle tilt in one of the blades (Blade 1) is presented in Fig. 5 (b). It shows that the 3 mm displacement caused by the simulated tilt resulted in a blade deflection of 45.5 mm. The deflection is greater at the point nearer the blade tip and smaller at the blade root end (Fig 6). Form this experiment result, it could be concluded that such a phenomenon in which deflection occurs in all the blades simultaneously is the result of problem in the nacelle rather than just the individual blade.

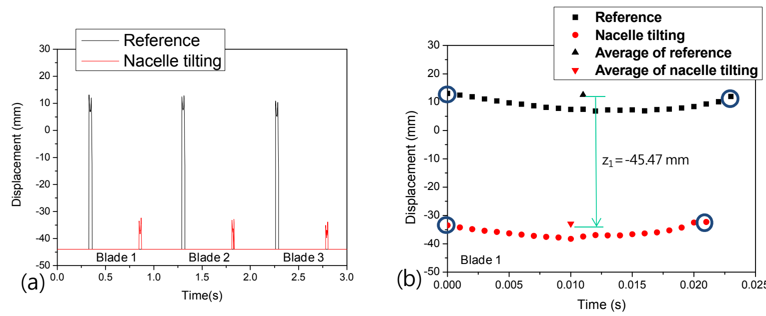

Figure 5. Nacelle tilts monitoring at 100 mm from the blade tip: (a) comparison of blade displacement before and after nacelle tilt and (b) variation in displacement of Blade 1 due to nacelle tilting.

Blade deflection due to mass loss-damaged blade

One of the problems discussed earlier is blade damage by lightning (Fig 1(d)), which causes a mass difference among the blades that leads to rotational imbalance. To simulate the mass loss effect, the upper surface of the blades weighing 30 g was removed. The experiment was conducted by considering the point of measurement range of 200-500 mm away from the blade tip to exclude the 150 mm region with mass loss. The variation in displacement as the result of mass loss as compared in all three blades is shown in Fig. 7 (a), which was measured 200 mm away from the blade tip. Fig. 7 (b) shows the displacement variation comparison of Blade 1 before and after 30 g mass loss. The averaged results show that the 30 g mass loss caused deflections of z_1 = 3.63 mm, z_2 = -1.52 mm and z_3 = -2.03 mm in blades 1, 2 and 3 respectively. The deflections at different mass losses with respect to the distance away from the blade tip or near to the root are compared in Fig. 8.

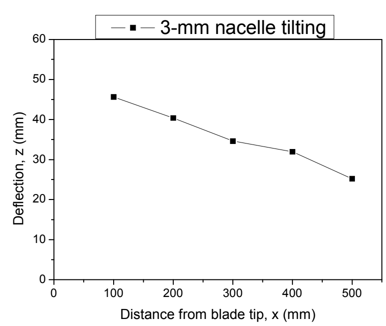

Figure 6. Comparisons of the variation in deflection due to the nacelle tilt at different distances from the blade tip.

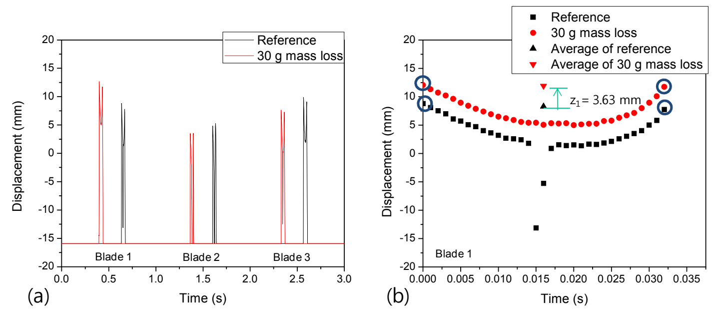

Figure 7. (a) Comparison of blade displacement variation in different blades before and after 30-g mass loss; (b) 30-g mass loss in Blade 1 resulted in -3.63-mm blade displacement.

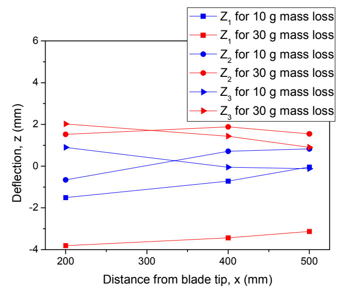

Figure 8. Deflection monitoring results at different mass loss and distances from the blade tip.

EFFECT OF TEMPERATURE ON MONITORING

An experiment was conducted to test the effect of temperature variation on the displacement monitoring capability of the LDS sensor. The study showed that temperature variation had a negligible effect on the repetitive measurement as shown in Fig. 9 (a) and (b). The LDS sensor intelligence sensor (OMRON, 3Z4M-J1222) suitable for the small wind turbine specimen in this study has a range of 0 – 50°C but the temperature range of LDS for larger wind turbines can reach up to -30 - 65°C. Since the LDS has a lifetime of hundreds of thousands of hours, it requires replacement only once or twice over a turbine's 20 year operating lifetime.

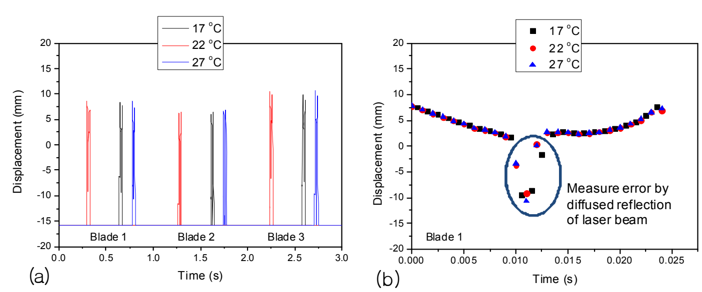

Figure 9. (a) Laser displacement sensor response at various temperatures, (b) Displacement comparison at different temperatures.

WIRELESS MONITORING OF LDS

The output of LDS is analog in the form of voltage. The output voltage from the LDS is linearly proportional to the displacement in millimeters and is transmitted over a distance using Zigbee protocol. The analog output voltage is thus converted to digital form using PIC. The PIC microcontroller is capable of high computational performance at an economic price and has high endurance. The conversion of analog signal to digital and making it ready for transfer is done in PIC. The output from PIC is connected to Zigbee transmitter via MAX 232 which is a multi-channel RS-232 driver/receiver. The output data from PIC is transmitted to Zigbee through serial communication protocol. The digital signal is then transmitted from Zigbee transmitter in the tower to the receiver at the base station below the tower.

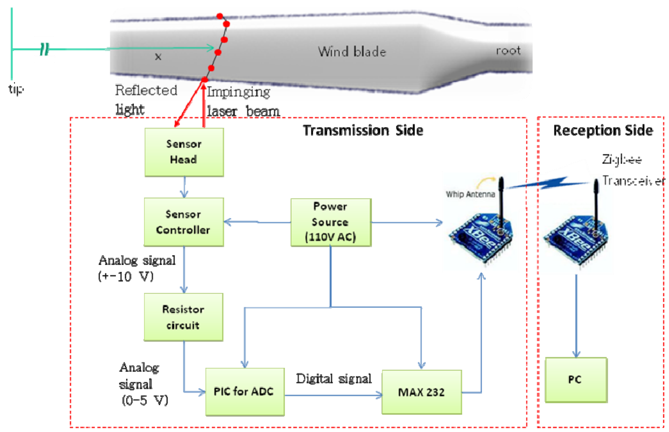

Figure 10. A block diagram showing the wireless module for remote monitoring.

CONCLUSION

Many recent studies of structural health monitoring of wind turbines rely on numerous built-in sensors and energy harvesting elements attached or embedded in the blades, which is both uneconomical and impractical to cover blades of several tens of meters in practical use. This study proposed a single LDS system composed of an LDS head, controller, DAQ, and signal processing module that could effectively monitor deflections of all rotating blades. Contrary to the approaches of sensor installation within the blades, the LDS system was installed in the tower and monitored for any variation in blade displacement.

An experimental proof of concept was conducted to test bolt loosening, nacelle tilt, and mass loss due to blade damage which resulted in blade deflection. The proposed system successfully managed to monitor the deflection to determine the type of damage. The wireless system was devised to monitor the deflection from remote location which enabled the easier and more convenient way of monitoring and identifying the changes as shown in experimental results.

The proposed system was negligibly affected by temperature variation, making it suitable in real-life scenarios. Thus, the cost-effective, compact and easy to install monitoring system for the wind turbines was devised using the laser displacement sensor.

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