ULTRASONIC PROPAGATION IMAGING FOR *in-situ* WIND TURBINE BLADE DAMAGE VISUALIZATION

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Abstract

Wind power emerges as one of the most promising green energy sources today. To tap the wind with minimum interruption, turbine system health, especially the soundness of the blades must be well maintained. Considering the difficulties and great financial cost of blade inspection using conventional non-destructive evaluation techniques, *in-situ* structural health monitoring techniques utilizing embedded sensors that work well in the field are eagerly desired. For this reason, we propose a portable laser-based long distance ultrasonic propagation imaging (UPI) system suitable for pitch-controllable wind turbines both on-shore and off-shore. When acoustic emission (AE) sensors embedded within the blades detects damage or according to predefined inspection schedule, the portable system is installed to the turbine tower for damage evaluation. By selecting a strategic installation position, the system can inspect all the blade surfaces in turn. It generates Ultrasonic Wave Propagation Movie (UWPM) visible as concentric ultrasonic wavefield emerging from the sensing location. Damages could be quantitatively evaluated from UWPM. A mock-up blade leading edge with 20 mm disbond was inspected at 20 m and 40 m distances as demonstration. The UWPMs for both cases showed normal propagation of ultrasonic wavefield across the leading edge, and wavefield phase discontinuity at disbond location. The length of disbond was successfully evaluated from the length of wavefield phase discontinuity. As conclusion, quantitative damage evaluation for turbine blades at long distance using UWPI method is possible. Improvements of the proposed UPI system as well as development of additional function on aerodynamic surface management are being carried out. It is hoped that this system will contribute to the cost reduction of green energy in the near future.

Keywords: wind turbine blade, damage visualization, long distance laser ultrasound, collimator, acoustic emission sensor, ultrasonic propagation imaging.

1. Introduction

Recently, wind power emerges as one of the most promising alternative energy sources to counter global energy crisis and the climate-change [1]. Many operational problems have been encountered as the wind power industry grows both in term of annual power output and turbine size. Among them, damages related to turbine blade are the most reported. Wind turbine blades are generally made of composite materials that are susceptible to damages. Those damages are usually difficult to be identified through naked eyes and hence suitable damage evaluation method is required. Many non-destructive test and evaluation (NDT&E) techniques as well as structural health monitoring (SHM) techniques could identify the events as well as the locations of those damages through embedded sensors. However, considering the difficulties of performing NDT&E for large turbine blades mounted on high tower, and the great financial cost for bringing down a problematic blade for inspection in laboratory, *in-situ* SHM techniques utilizing embedded sensors that could perform structural integrity evaluation in the wind farm without needing the crane and abseiling personnel as shown in Figure 1 are significantly advantageous over NDT&E techniques.

Generally for wind turbine blade SHM, basic electronic sensors and fiber optical sensor have been adopted for the acquisition of simple data such as strain, acceleration and temperature, while more advance techniques such as acoustic emission (AE) sensing technique, piezoelectric impedance technique and laser Doppler vibrometry have been adopted for damage event detection, failure localization and damage evaluation. Lead zirconate titanate (PZT) piezoelectric sensors and optical fiber sensors are dominant sensors in AE sensing systems for failure-induced wave detection. Those sensors embedded within a turbine blade could detect AE waves associate with micro damages or failure of the blade. Failure location could be obtained from the relative signal amplitude and Time-of-Flight (ToF) of multiple sensors, but quantitative damage evaluation is very difficult [2, 3].

Impedance-based SHM techniques on the other hand work based on the principle of electromechanical coupling between PZT transducers and the monitored blade. PZT transducers are embedded into the monitored blade, and, in the presence of electric fields, they interrogate the blade and record the admittance signatures. A structural damage will alter the blade impedance through mass, stiffness, and damping change at the vicinity of the damage. Consequently, transducers interrogation would generate signatures different from the pre-damage case. Hence damage can be perceived when changes of impedance values around failure area are detected. However, the result is not in image form and failure cannot be visualized [4], which in turn greatly limit its damage evaluation accuracy.

Figure 1. Abseiling personnel inspecting a turbine blade [5].

Laser Doppler vibrometry (LDV) and scanning laser Doppler vibrometry deserve extra attention due to their potential of non-contact remote health evaluation of wind turbines. This laser-based noncontact sensing technique is suitable for single point sensing or point-wise area sensing. The vibrometry can sense dynamic strain, velocity and acousto-ultrasonic wave remotely. Attempt for in-situ remote NDT&E of a horizontal axis wind turbine using modal analysis was reported [6]. Damage was simulated by loosening the bolts of blade at the root, and the blade was excited either by a single blow from a hammer or by ambient wind. Although damage could not be detected even when the blade was completely loosened and hanging by the bolts, nodal acceleration information of the turbine blade was successfully obtained using LDV. Anyhow, low signal to noise ratio haunts this technique and good signal acquisition was made possible only when retroreflective tape or paint was applied on the blade surface. Another application issue is the degradation of sufficient performance of the retroreflective surfaces due to foreseeable surface contamination during the long service life of turbine. Other noncontact laser-based techniques such as thermography [7] and shearography could not be applied for long distance damage evaluation. For this reason, they are not suitable for on site in-situ wind turbine blade inspection hence their advantages and disadvantages are not discussed here.

The ultrasonic wave propagation imaging (UWPI) method is a damage evaluation imaging method for the ultrasonic propagation imaging (UPI) system [8]. The system utilizes a Q-switched pulsed laser (QPL) as ultrasonic wave generator. Various acousto-ultrasonic sensors could be adopted as ultrasonic receiver. The system scans a structure using laser beam and the UWPI generate the result in ultrasonic wave propagation movie (UWPM) form for damage visualization and evaluation. This method is better than the LDV not only in economical efficiency aspect, but also from practical aspect as surface preparation before inspection is not necessary. In this work, we demonstrated that for a wind turbine blade embedded with AE sensors for failure event detection and localization, a UPI system could be "dropped in" for expanding the sensors functionality as ultrasonic wave sensors for UWPI method. With simple laser beam collimation and laser targeting method, the system becomes a promising *in-situ* long distance SHM system for damage visualization and quantitative damage evaluation of wind turbine blades.

2. Long distance ultrasonic propagation imaging for in-field wind turbine system

We are proposing this SHM inspection method for those wind turbines with embedded AE sensors in blades near damage hotspots, such as leading and trailing edges bonding, and skin-spar bonding. The AE sensors detect AE events and once structural damage is confirmed based on high AE even accumulation at one location, inspection personnel will bring a portable UPI system and fix the system within the turbine tower. The UPI system will scan the problematic blade for damage evaluation. During scanning, the AE sensors work as ultrasonic receiver for the UPI system. Saved ultrasonic data will be processed as UWPM for damage visualization and evaluation. After the inspection, the UPI system could be use for the inspection of other turbine, which means great capital cost saving for large wind farm. Further action could be planned based on UWPM damage evaluation. It should be noted that even when the system is brought to a turbine and fixed within the tower, the laser scanning distance is still great due to the length of the blades. Due to this great scanning distance, the UPI system has some major modifications from conventional UPI system. The prerequisite of applying this inspection method is the entire surfaces of all the blades from one turbine could be completely scanned using the portable UPI system. For this, a strategic system installation location is crucial. To further verify the feasibility of the proposed method, preliminary study was conducted based on a common commercial wind turbine system.

2.1 Commercial wind turbine system

Specific geometrical information of a wind turbine system is needed for further verifying the feasibility of the proposed method as well as to determine a strategic setup position for the UPI system. This setup position is critical to ensure that the entire surfaces of all the blades from one turbine could be completely scanned using the portable UPI system. In this work, Vestas V80-2.0MW was selected. The major geometrical specifications were given in Table 1. System control technique for long distance, high speed and high accuracy targeting were also developed based on this turbine model.

Table 1. The major specification of Vestas V80-2.0 MW model [9]

Rotor	Diameter	80 m
Blade	Length	39 m
	pitch angle	95°
Tower	Height	60~100 m optional

2.2 Portable long distance ultrasonic propagation imaging system

Schematic diagram of the proposed SHM system is shown in Figure 2. The laser mirror scanner (LMS), LMS rotator, collimator and Q-switched continuous wave laser (QL) are packaged as an integrated laser targeting system. The laser targeting system has rigid fixture with screw holes for easy attachment and detachment to wind turbine tower. It is installed in the turbine tower 40 m below the hub center, as shown in a Figure 3. The turbine tower has a window opening, allowing the laser targeting system to protrude from within the tower when it is fixed. Using this configuration, laser beam from the laser targeting system will not be obstructed from blade raster scanning. Parking the turbine at rotation angle shown in Figure 4 and by adjusting different pitch angle of the blades, upper surface, lower surface as well as leading edge are exposed to laser beam from LMS. This is possible because the maximum pitch angle of the blade is 95°. Rotate the rotor twice, 120° a time, then all surfaces of all blades are readily exposed to the laser scanning. Using this system configuration, the maximum laser scanning distance is about 40 m at blade tip and root but minimum scanning distance is 35 m at mid span. Anyhow, the difference in distance has no significant effect for the inspection process because UPI system is free from fix laser focusing requirement as oppose to LDV.

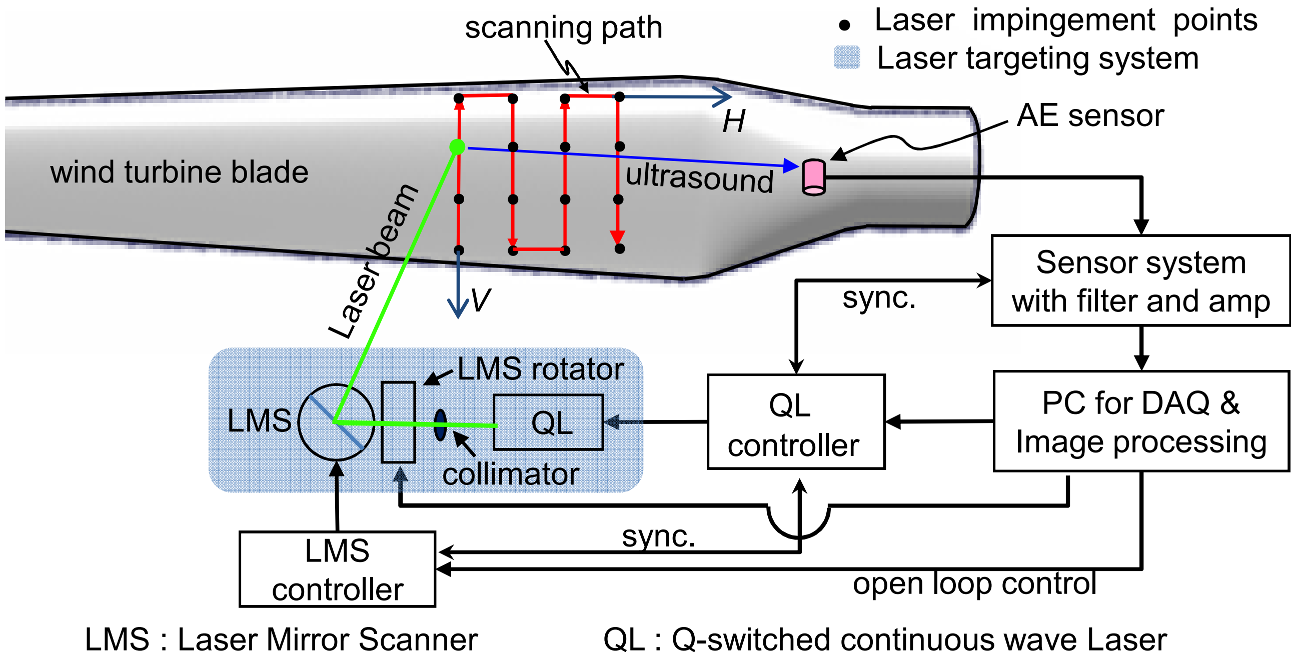

Figure 2. Schematic diagram of ultrasonic propagation imaging system for long distance inspection.

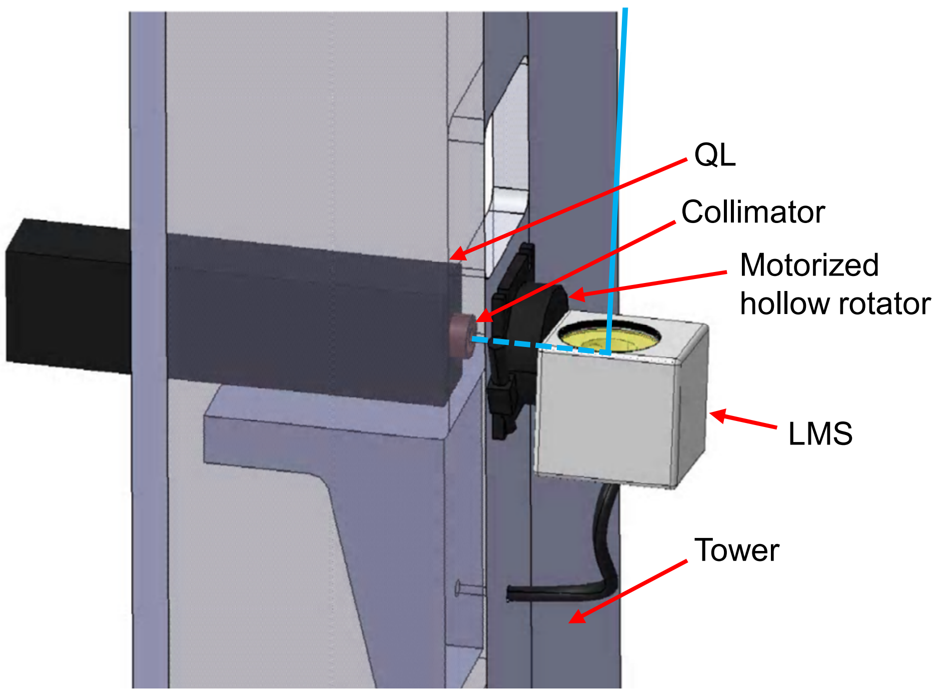

Figure 3. Installation idea for laser targeting system within turbine tower.

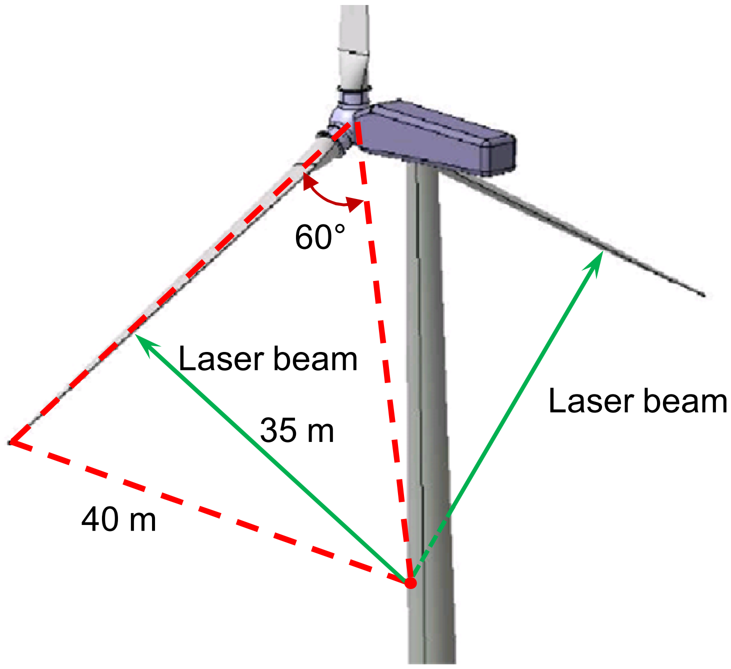

Figure 4. Blade scanning during turbine parking. The maximum and minimum laser beam scanning distances are 40 m and 35 m, respectively.

Inspection location and size of inspection area are determined by AE sensor system. The size of the inspection area depends on the accuracy of information feed by the AE sensors. The more accurate the information is, the smaller inspection area could be used. Various sensor systems such as PZT-based AE sensors and optical fiber-based AE sensors or their combination could be used as ultrasonic reception part of the UPI system. When the portable system is secured at the designated position and the rotor is parked at angle shown in Figure 4, the scanning system can be activated. The QL fires laser beam pulses and the collimator lens collimates the laser beam pulses. Two laser mirrors of the LMS reflect the collimated laser beam pulses to impinge the target turbine blade for raster scanning, as shown in Figure 2. LMS rotator is used to rotate the LMS for scanning either the left or the right blade. For each of the laser beam impingement point, an ultrasonic wave is created through thermoelastic effect. It should be noted that the energy level is not in the plasma regime which would cause surface ablation, but is always in the ultrasonic regime [10]. The wave propagates through the blade and reaches the AE sensor bonded on inner surface of blade, as illustrated in Figure 5. The signals are then digitized and saved for result processing.

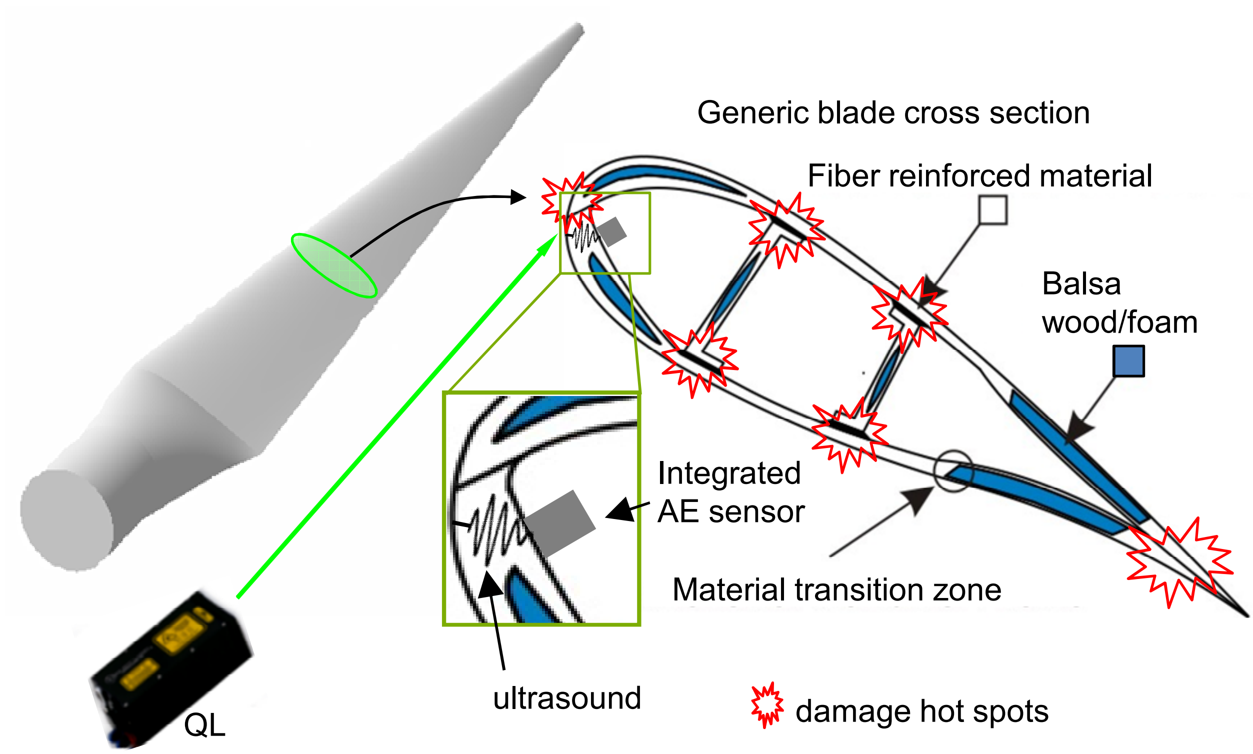

Figure 5. Laser-induced ultrasonic wave reception using AE sensor embedded in turbine blade.

The UWPI algorithm processes the saved data during the scanning. Using mainstream personal computer, the result UWPM should be available within minutes after the scanning is completed. Total inspection time depends greatly on the size of inspection area and the density of laser impingement point. Typically using a 100 Hz repetition rate laser source for inspecting an area 400 mm×400 mm with laser spatial impingement interval 2 mm, result will be ready in about 7 minutes. The UWPM is visible as concentric wavefield emerging from the sensing point. Any discontinuity in the target blade along the propagation path between the impinging point and the sensing point will alter the ultrasound wave through mode conversion, reflection, diffraction, and scattering. Out of plane damages such as delamination could be detected and visible as abnormal ultrasonic wave propagation within the damage area. In-plane damages such as kissing crack could be detected and visible as scattered wave emerging from a source at the damage location. Debonding damage and crack could be visible as wavefield phase discontinuity, with the length of discontinuity same with the length of damage perpendicular to the direction of wave propagation.

3. Experimental demonstration

For demonstration of long distance ultrasonic imaging, a laser targeting system without the LMS rotator was setup. It comprised of a QL with 1064 nm wavelength, a single lens laser collimator, and a galvanomotor-based LMS, as shown in Figure 6. It is expected that actual system is compact in size to suit the geometry of turbine tower and for high portability. The function of the collimator is to reduce the laser beam divergence from 1.366 mrad to near zero value. Fixed laser beam focusing is not desired due to the varying laser beam travel distance at different position of the turbine blade.

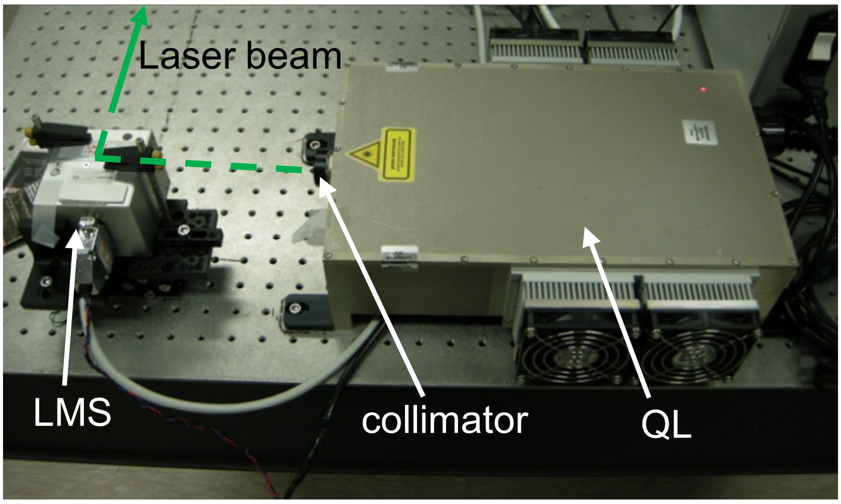

Figure 6. Modified laser targeting system for long distance scanning.

Leading edge was selected for experimental demonstration. This is because leading edge is one of the most important damage hotspot for turbine blade and it has complex surface geometry. Its surface geometry is challenging for laser inspection due to the resulting large laser incident angle. The mock up of wind turbine blade leading edge was made from two pieces of CFRP plates, bonded to form an angle 115°, as shown in Figure 7. The size of each plate is 300 mm×200 mm×5 mm. A 20 mm region at the center of the specimen was not bonded to simulate leading edge debonding damage. An amplifier-integrated broadband piezoelectric AE sensor with peak frequency 300 kHz and cut-off frequency 2 MHz was bonded at the back of specimen, 100 mm from the damage. 8 mJ laser with 100 Hz repetition rate was used to scan a 200 mm×200 mm area with scanning spatial interval 0.5 mm. Tenfold amplification and 100 ~ 200 kHz bandpass filtering was used during signal acquisition, while 3×3_2 spatial averaging [11] was used during post-image processing for image smoothing. Two long distance inspections were performed at 20 m and 40 m, and a 1 m short distance inspection was performed as comparison.

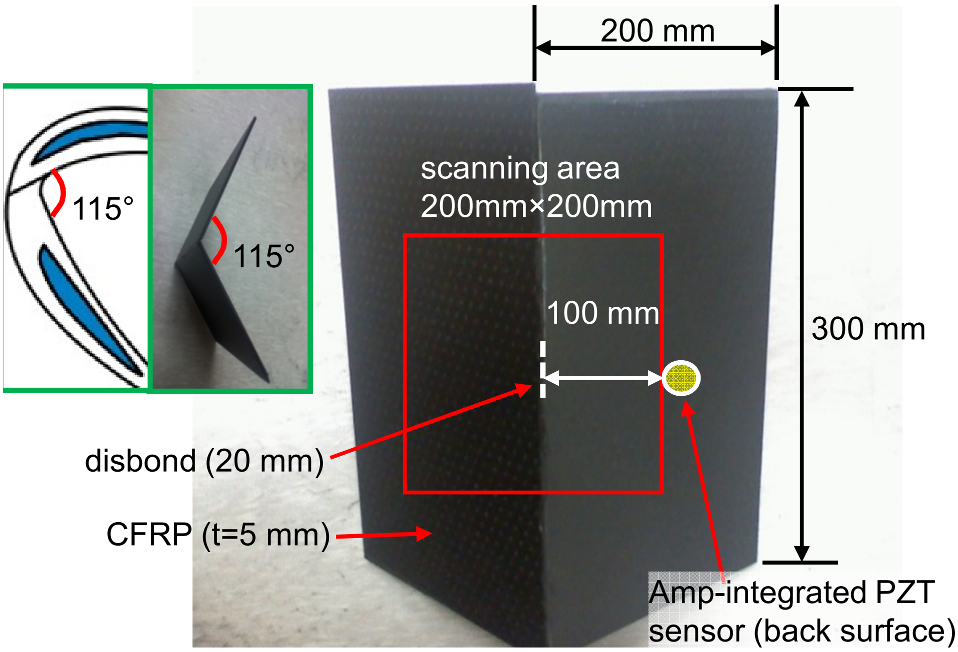

Figure 7. Experimental configuration for the inspection of blade leading edge specimen.

Final result in the form of UWPM was generated and the snapshots at 21 μs, 26 μs and 31 μs were given in Figure 8. Ultrasonic wave could be seen as if propagating out from the sensor location. The amplitude of the wave dropped significantly across the leading edge, but the wavefront remained smooth arc shape. However, when the wavefront met the disbond, as in 31 μs of wave propagation, wavefield phase discontinuity could be seen. The length of discontinuity could be measured as 20 mm, which is exactly same as the length of the disbond.

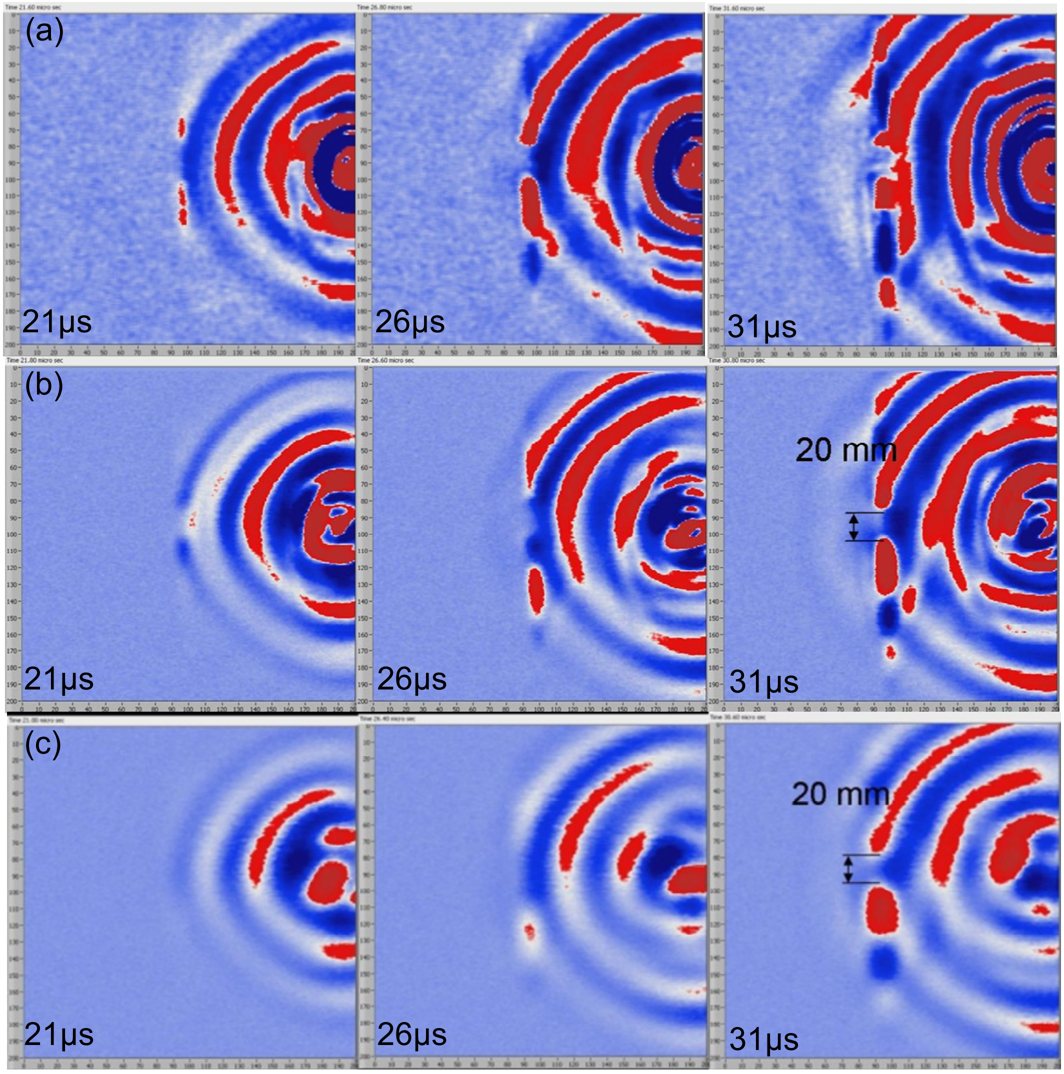

Figure 8. Leading edge disbond damage inspection results for (a) 1 m (b) 20 m, (c) 40 m distance.

4. Conclusion

A portable UPI system for *in-situ* long distance wind turbine blades structural health monitoring suitable for both on-shore and off-shore wind farm was proposed. Embedded AE sensors within turbine blades provide information of damage location based on high AE event accumulation at damage location. The portable UPI system could be fixed within the turbine tower for damage evaluation. The system can be moved for inspecting the next wind turbine. Feasibility study was performed for the evaluation of blade leading edge disbond at 20 m and 40 m. The result proved that quantitative damage evaluation for turbine blades at long distance using the proposed UPI system is possible. Detail compact design and improvements of the proposed system, including the optimization of laser beam collimation, development of better imaging method, as well as development of additional function for aerodynamic surface management are being carried out. Actual turbine blade with real damages is also being acquired for realistic system evaluation. It is hoped that this system will become a robust SHM solution for wind turbine systems and will contribute to the cost reduction of reliable green energy in the near future.

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