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Delamination localization in wind turbine blades based on adaptive time-of-flight analysis of noncontact laser ultrasonic signals

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1. Introduction

Recently, there have been many installations of wind turbines worldwide thanks to its relatively low power generation cost compared to other renewable energy sources. The power currently generated by wind turbines is over 370 GW worldwide, and the wind generated power continues to grow over 20% every year.\textsuperscript{[1]} The annual maintenance cost for wind turbines is over $1\ M/MW,\textsuperscript{[2]} and 8.2% of downtime of the wind turbines are attributed to damage on wind turbine blades.\textsuperscript{[3]} Wind turbine blades are vulnerable to various types of damage including delamination as they are composed of a number of laminates. However, because damage is often hidden inside and invisible from the outer surface, there is a huge demand for effective techniques for detecting them.
To tackle these problems, nondestructive testing (NDT) and structural health monitoring techniques using discrete contact transducers are proposed to inspect wind turbine blades. For example, fibre Bragg grating sensors are embedded into wind turbine blades to measure operational loads \[4\] and detect impact responses.\[5\] Acoustic emission (AE) techniques detect and localise crack initiation by measuring acoustic waves released by crack formation and growth using AE sensors.\[6,7\] Piezoelectric transducers are used to generate guided waves and measure reflection and scattering produced by the interactions of guided waves and damage.\[8–11\] However, their \textit{in situ} applications are limited because (1) dense sensor installation is required to guarantee high damage sensitivity and localisation accuracy, (2) sensor installation and maintenance inside the blades are challenging and (3) power and data transmission using cables are particularly difficult for rotating wind turbine blades.

Due to the aforementioned issues, there is an increasing interest in noncontact NDT techniques. Air-coupled transducers (ACTs) are noncontact ultrasonic solution, which can generate and measure ultrasonic waves without any couplant.\[12\] However, their standoff distance between ACT and the target surface is usually limited to several centimetres for effective ultrasonic wave generation and measurement. X-ray radiography is a fast and efficient imaging solution, but its field application should be very carefully reviewed due to safety issues.\[13\] Recently thermography-based wind turbine blade inspection techniques, which measure differences in heat propagation between the intact and damage regions, have been proposed by many researchers.\[14–16\] However, their application is usually limited to detection of near-surface damage.

Laser ultrasonic scanning and imaging techniques, which visualise ultrasonic wave propagation and its interaction with a damage, have been introduced.\[17–21\] Here, ultrasonic waves are generated and measured by noncontact laser devices. Note that the surface treatment of the target structure is often necessary to improve laser measurement performance. In such cases, the reflectivity of the laser signal can be improved by placing a retroreflective tape or by applying a special spray. Laser ultrasonic imaging techniques have following advantages compared to other NDT techniques: (1) as they use laser beams for ultrasonic wave generation and measurement, a large area can be inspected using scanning mirrors; (2) even incipient damage can be visualised and detected using high-resolution scanning; and (3) long-range inspection up to 10s of metres is possible. In spite of all these advantages, one of the biggest hurdles for their field applications is its scanning time. For instance, when a pulse laser with a 100 Hz repetition is used and the response time signals are averaged 100 times to achieve a good signal-to-noise ratio (SNR), scanning of 5 cm \(\times\) 5 cm region with 2-mm spatial scanning resolution takes about 10 min.

In this study, a two-level scanning strategy is proposed to expedite the scanning of a large inspection area. First, coarse scanning of the entire blade is performed with a low spatial resolution for initial delamination localisation. Then, dense scanning is performed only within the identified delamination region with a high spatial resolution for delamination visualisation. This study especially focuses on the coarse scanning step, where delamination is localised using an adaptive time-of-flight (TOF) analysis. First, laser ultrasonic responses from two pitch-catch pairs, called inspection pairs, are obtained within a given specific coarse scanning region. Then, potential delamination locations are estimated through TOF analysis of delamination reflected waves. Once potential delamination locations are estimated, ultrasonic measurement is repeated near the potential locations for improved delamination localisation. These steps are repeated for every coarse scanning regions within
the target wind turbine blade. There has been several works using TOF techniques with surface-mounted transducers,[22,23] and Gannon et al. [24] and Michaels et al. [25] proposed two-level approaches with surface-mounted transducers. However, the proposed localisation technique has following advantages: (1) fully noncontact ultrasonic excitation and measurement scanning is available; (2) excitation and sensing positions are adaptively placed with updated delamination information; (3) velocity profile is instantaneously obtained for delamination localisation within anisotropic specimens; (4) ambiguity in delamination localisation is eliminated using an outlier analysis; and (5) Baseline data is not required for damage detection, localisation and visualisation. The performance of the two-level laser scanning and proposed delamination localization technique is validated by detecting delaminations in a 10-kW glass fibre-reinforced plastic (GFRP) wind turbine blade.

This paper is organised as follows. Two-level ultrasonic scanning for wind turbine blades and a delamination localisation technique based on adaptive coarse scanning are proposed in Sections 2 and 3, respectively. Details on TOF technique are described in Section 4. The experimental set-up and results obtained from a 10 kW GFRP wind turbine blade are presented in Sections 5 and 6, respectively. Finally, this paper concludes with a brief summary and discussions in Section 7.

2. Laser ultrasonic scanning for wind turbine blade inspection

2.1. Overview of the laser ultrasonic scanning

Figure 1 presents a schematic overview of the proposed two-level scanning of a wind turbine blade using a noncontact laser ultrasonic scanning system. The ultrasonic scanning system is composed of a pulse laser for ultrasonic wave generation, a laser Doppler vibrometer (LDV) for ultrasonic measurement, and a controller. As indicated by its name, the proposed two-level scanning inspects a wind turbine blade in two levels: coarse scanning for delamination localisation and dense scanning for delamination visualisation. First, coarse scanning of the entire blade is performed with a low spatial resolution for initial delamination localisation. Then, dense scanning is performed only within the identified delamination region with a high spatial resolution for delamination visualisation.

This approach significantly reduces the inspection time compared to the conventional laser ultrasonic imaging, where dense scanning is performed for the entire wind turbine blade. For example, to scan the 10 kW wind turbine blade (3.5 m long and 0.5 m wide) with 2 mm scanning resolution, ultrasonic responses should be measured from 437,500 measurement points \((437,500 = \frac{3500 \text{ mm}}{2 \text{ mm}} \times \frac{500 \text{ mm}}{2 \text{ mm}})\). As for the proposed two-level scanning, the initial delamination localisation with 5-cm coarse scanning resolution requires 700 measurement points \((700 = \frac{3500 \text{ mm}}{50 \text{ mm}} \times \frac{500 \text{ mm}}{50 \text{ mm}})\), and additional 625 points \((625 = \frac{50 \text{ mm}}{2 \text{ mm}} \times \frac{50 \text{ mm}}{2 \text{ mm}})\) for the subsequent dense scanning, resulting in the total measurement points of 1325. In conclusion, the inspection time is reduced by 99.7 % (from 437,500 to 1325 s assuming 1 s measurement time for each measurement point).

2.2. Configuration of laser ultrasonic scanning system

Figure 2 shows the configuration for the laser ultrasonic scanning system. A pulse laser is used for ultrasonic wave generation. When a pulse laser beam is emitted onto an infinitesimal
Figure 1. Schematic diagram of the proposed two-level scanning of a wind turbine blade using a noncontact laser ultrasonic system. The ultrasonic scanning system is composed of a pulse laser, a LDV and a controller. First, coarse scanning of the entire blade is performed with a low spatial resolution for initial delamination localisation. Then, dense scanning is performed only within the identified delamination region with a high spatial resolution for delamination visualisation. This two-level scanning significantly reduces the inspection time.

Figure 2. Schematic diagram of the laser ultrasonic scanning system. Pulse laser excitation and LDV measurement is controlled by the controller. By controlling the angles of the galvanometers, laser beams can be positioned to prescribed measurement points within the wind turbine blade.
area, a localised heating of the surface causes thermoelastic expansions of the material and ultrasonic wave generation.[26] It should be noted that pulse laser parameters such as the peak power, pulse duration and beam size should be carefully designed to avoid surface damage called ablation.[27] Furthermore, precaution is necessary for eye safety.

Corresponding ultrasonic waves are measured by an LDV. When a laser beam is reflected from a vibrating surface, the frequency of the returned laser beam is shifted. The LDV measures this frequency shift and relates it to out-of-plane velocity of the surface based on the Doppler effect.[28] As the measurement accuracy of LDV is highly dependent on the intensity of returned laser beam, the incident angle of the laser beam should be carefully controlled to maximise the intensity of the returned laser beam and minimise speckle noise.[29] Often a special surface treatment is necessary to improve the reflectivity of the target surface.[28]

The direction of each laser beam is controlled using a galvanometer. The galvanometer is composed of two mirrors, which can rotate in two orthogonal directions. By rotating these two mirrors in appropriate angles, laser beams can be positioned at any prescribed positions within the target specimen and scan the specimen.

3. Delamination localisation based on adaptive coarse scanning

3.1. Overview of the proposed delamination localisation technique

This paper especially focuses on delamination localisation through coarse laser scanning, and delamination visualisation through dense laser scanning is developed in [30]. Figure 3 represents the overview of the proposed adaptive delamination localisation using a non-contact laser ultrasonic scanning system. First, the entire inspection surface of the wind turbine blade is divided into multiple coarse scanning regions. Second, for a given specific coarse scanning region, the presence and location of a delamination are identified according to the following three phases:

In Phase I, two arbitrary excitation and sensing point pairs, called inspection pairs, are selected. Then, two potential delamination locations, if any, within the given coarse scanning area are estimated through TOF analysis [31] of ultrasonic signals measured from two inspection pairs using a noncontact laser ultrasonic scanning system. For an actual single delamination location, two potential delamination locations are estimated due to the symmetric nature of the TOF analysis. To identify the actual delamination location, Phase I is followed by Phase II. If no potential delamination location is identified in Phase I, Phase I is repeated for the next coarse scanning region without proceeding to Phase II.

In Phase II, additional ultrasonic signals are obtained to select the actual delamination location from the two potential delamination locations estimated in Phase I. Here, new inspection pairs are adaptively selected based on the estimated delamination information. Two additional inspection pairs are selected near one of the potential delamination locations identified in Phase I, and TOF analysis is performed using the obtained ultrasonic signals to confirm if the tested potential delamination location is the true one. This step is also repeated for the other potential delamination location identified in Phase I.

In Phase III, delamination estimation results obtained from Phases I and II are combined to further improve the confidence in delamination location. Finally, Phase I, and Phases
II to III if necessary, are repeated for every coarse scanning regions defined on the target wind turbine blade.
3.2. Determination of the coarse scanning size

To maximise the effectiveness of the proposed two-level scanning, the coarse scanning size should be determined carefully. Figure 4 represents the experimental relationship between the SNR of laser ultrasonic waves measured from the target 10 kW wind turbine blade and its propagation distance. SNR drops as the propagation distance increases, and it reaches around 27 dB when wave propagation distance is 14 cm.

The size of the coarse scanning region should be determined so that reflection from any delamination within the coarse scanning region can be successfully detected with a good SNR. The preliminary experiments performed on the 10 kW blade in Section 5 reveals that the amplitude of the waves reflected from a delamination is around 10% of the amplitude of the incident waves. Furthermore, the reflection waves can travel up to 14 cm, maintaining SNR of above 6 dB. This level of SNR indicates that the amplitude of the reflection signal is about two times larger than the noise level. Based on these observations, the spacing between two inspection pairs, or the coarse scanning size, is determined to be below 7 cm. Note that this coarse scanning size is valid only for the blade tested in this study, and it should be determined for each target specimen considering its ultrasonic propagation characteristics.

4. Laser-based TOF analysis for delamination localisation

This section describes how to perform laser-based TOF analysis for delamination localisation in the prescribed adaptive coarse scanning. First, delamination-induced reflection waves are extracted from the measured ultrasonic signal. Figure 5(a) represents a typical raw ultrasonic signal (blue dotted line) and its Hilbert transform (red solid line). To remove the direct incident waves and retain only the reflected waves, the first arrival wave packet is removed until its amplitude drops to the noise level. Figure 5(b) represents the extracted reflected waves and its Hilbert transform, after removal of the direct incident wave.

Second, reflection energy (RE) at every spatial point in the inspection region is calculated based on the extracted reflected waves. Here, a larger RE value at a certain spatial point indicates that delamination may exist at the spatial point with higher probability than other points. Assuming that a delamination is located at point P as shown in Figure 6, the generated ultrasonic waves travel from E to P and reflected from P to S. Then, the arrival time of the reflected waves at S becomes...
Figure 5. Extraction of the reflection signal from the measured ultrasonic signal: (a) raw ultrasonic signal (blue dotted line) and its Hilbert transform (red solid line). Both direct incident and reflected waves are included. (b) Extracted reflected waves signal (blue dotted line) and its Hilbert transform (red solid line).

Figure 6. Calculation of RE at each spatial point: (1) assuming that the delamination is located at point P, the incident wave travels from the excitation point E to point P and reflected from point P to the sensing point S. Then, the arrival time of the reflection becomes $t = \frac{EP}{v_{EP}} + \frac{PS}{v_{PS}}$; (2) then, the energy of the reflection wave within $t \pm \frac{T}{2}$ is assigned to point P as RE; (3) because the actual delamination location is unknown in advance, steps (1) and (2) are repeated for all spatial points within a signal coarse scanning region.

$$t = \frac{EP}{v_{EP}} + \frac{PS}{v_{PS}}$$ (1)
where $\overline{EP}$ and $\overline{PS}$ indicate the distance between $E$ and $P$, and $P$ and $S$, respectively. $v_{EP}$ and $v_{PS}$ represent the wave velocities in the directions of $\overline{EP}$ and $\overline{PS}$, respectively. Then, the energy of the reflected waves within a time window of $t \pm T/2$ is defined as the RE at $P$. The time window size $T$ is determined as $T = 1/f$, where $f$ is the lowest cut-off frequency allowed by the applied band pass filter.

$$RE(P) = \left( \overline{EP} + \overline{PS} \right) \int_{t-T/2}^{t+T/2} W(\tau)^2 \, d\tau$$

(2)

where $W(\tau)$ represents the measured ultrasonic response. Here, the energy of the reflected waves is multiplied by the travelling distance to compensate for the attenuation caused by omni-directional radiation.[32] Because the actual delamination location is unknown in advance, the above procedures are repeated for every spatial points within a signal coarse scanning region. The spatial point with the actual delamination will have the largest RE value. However, multiple spatial points can share the largest RE value, if the TOF of these spatial points are identical to that of the actual delamination point.

Third, the potential delamination locations are identified from the spatial points sharing the largest RE value. This can be done by introducing an additional inspection pair and identifying spatial points where large RE values are assigned from both inspection pairs. To identify them, the damage index (DI) is calculated for every spatial point $P$ as

$$DI(P) = \min \left( \text{MaxRE}_1(P), \text{MaxRE}_2(P) \right)$$

(3)

$$\text{MaxRE}_1(P) = \max_{\forall P, s.t. \ |P_x-P| \leq R} \left( RE_1(P_x) \right)$$

Figure 7. ROC curve (blue solid line) of the proposed approach. To have high true positive ratio, false positive ratio need to be increased, but this results in worse localisation accuracy. Ninety-nine per cent threshold is selected in the thresholding process to minimise false positive ratio and damage localisation error. Red dashed line represents ROC curve of the random guess.
where RE_1 and RE_2 represents RE values assigned from the first and second inspection pairs, respectively, R indicates the radius of a circular spatial window centres at P, and P_X indicates spatial points within the spatial window. Here, R is determined to be larger than half of the minimum target delamination size. Only the spatial points, where both inspection pairs assign large RE values, will have large DI values. To minimise noise components in the obtained DI values, a thresholding process using an extreme value statistics is employed. [19] First, the probability density function of DI is estimated by fitting a Weibull distribution to the DI values obtained from all spatial points. Second, a threshold value corresponding to a one-sided 99% confidence interval is established. Then, the delamination localisation map is obtained by assigning DI values to the corresponding spatial points within the coarse scanning region. This map highlights only spatial points with the DI values beyond the threshold value.

Finally, the computation of DI maps is repeated in Phases I and II, and the final DI map is obtained in Phase III by multiplying the DI maps of Phases I and II point by point.

\[
\text{DI}_{\text{Phase III}}(P) = \text{DI}_{\text{Phase I}}(P) \times \text{DI}_{\text{Phase II}}(P)
\]

\[
= \text{DI}_{\text{Phase I}}(P) \times \sum_{i=1}^{2} \text{DI}_{\text{Location i}}(P)
\]

where \( \text{DI}_{\text{Phase I}} \) and \( \text{DI}_{\text{Phase II}} \) are the calculated DIIs from Phases I and II, respectively. \( \text{DI}_{\text{Phase II}} \) is obtained by summing DIIs for each potential delamination location, \( \text{DI}_{\text{Location i}} \). If \( \text{DI}_{\text{Phase III}}(P) \) is nonzero, P is identified as a damaged pixel.

Figure 7 represents a receiver operating characteristic (ROC) curve [33] of the proposed approach in damage identification. Here, the true positive ratio and the false positive ratio are defined as:

True Positive Ratio = \( \frac{\text{# of identified damaged pixels in the actual damage}}{\text{# of pixels in the actual damage}} \)

False Positive Ratio = \( \frac{\text{# of identified damaged pixels out of the actual damage}}{\text{# of pixels out of the actual damage}} \)

These ratios are experimentally obtained using data shown in Section 6. When the true positive ratio increases, the false positive ratio also rises. This leads larger intact area to be misidentified as damage and makes it challenging to pinpoint the actual damage location. A threshold corresponding to a 99% confidence level is selected to minimise the false positive ratio and the damage localisation error.
5. Experimental test configuration

5.1. Description of the laser ultrasonic scanning system

Figure 8 represents the configuration of the actual laser ultrasonic scanning system used in this study. For ultrasonic wave generation, an Nd:YAG pulse laser (Quantel Ultra Laser) with 20 mJ peak energy and 8 ns pulse width was used. This laser beam direction was controlled using a Scanlab Scancube10 galvanometer. Corresponding ultrasonic waves were measured by a Polytec PSV-400 LDV. Here, retroreflective tapes were attached on the sensing points to increase the reflected light intensity and improve signal measurement quality. The ultrasonic waves were measured over 200 μs with a sampling frequency of 2.56 MHz and averaged 100 times in the time domain. A bandpass filter with 120–150 kHz band was applied to reduce noise outside the signal bandwidth.

Figure 9. An actual 10 kW wind turbine blade tested in this study: (a) the wind turbine blade and test configuration, (b) artificial delamination simulated by inserting a Teflon tape between the third and fourth ply and (c) the layout of the composite laminate composition within the target wind turbine blade.
5.2. Description of a wind turbine blade specimen

The effectiveness of the proposed technique is examined using a commercial 10 kW wind turbine blade (Figure 9). The target blade has dimensions of 3.5 m length, 0.45 m width and 3 mm thickness. This blade is made of GFRP, consisted of six plies with a layup of $[\theta/\pm 45]_S$. The elastic modulus $E_1$, shear modulus $G_{12}$, and poisson ratio $\nu_{12}$ of the GFRP material are 24.65, 8.52 and 0.476 GPa, respectively. Teflon tapes with 10 and 15 mm diameter were inserted at several locations between the third and fourth ply during fabrication of the blade to simulate internal...

5.3. Velocity profile construction

To calculate TOF using Equation (1), prior knowledge of the wave velocity profile is required. Conventional TOF analysis requires placement of multiple discrete transducers for the velocity profile measurement for different wave propagation directions. In this study, the wave velocity profile can be instantaneously obtained thanks to the scanning capabilities of the laser ultrasonic devices. With this feature, the proposed technique can be applied to plate-like structures even with anisotropic material properties. Currently, its application to complex structures with additional structural features such as stringers, spars and rivets is limited. However, with the assistance of the baseline data obtained from the pristine conditions of the structures, damage-induced waves can be readily differentiated from those produced by these additional structural features.

In this particular experiment, the sensing point is fixed in the middle, and the excitation points circulate around the sensing point at a constant distance of 2 cm. The excitation points are positioned every 15° from $-90^\circ$ (270°) to 90°, so that total number of excitation points becomes 13. As the wave travel distance is known and constant for all excitation points, the velocity profile of the laser generated ultrasonic waves can be calculated using their arrival times. The estimated velocity profile is represented in Figure 10.

![Figure 10. Experimentally obtained velocity profile of the target wind turbine blade. As a pulse laser generates broadband ultrasonic waves, the measured signals are bandpass filtered between 120 and 150 kHz to obtain narrowband ultrasonic signals.](image-url)
Note that the wave velocity depends on its frequency, but it is very challenging to generate narrowband ultrasonic waves using a pulse laser excitation. To minimise this problem, a bandpass filter with a very narrow bandwidth has been applied to the measured signals. Also, the measured wave velocity is mainly for the fundamental anti-symmetric Lamb wave mode as the LDV measures the out-of-plane motion of the target wind turbine blade.

6. Experimental test results

6.1. Delamination case #1, 10 mm diameter

6.1.1. Phase I

Figure 11(a) shows the configuration of two arbitrary initial inspection pairs and the location of a 10-mm diameter delamination, which is assumed to be unknown. Using laser-based TOF analysis prescribed in Section 4, DI_{Phase1} map is calculated in Figure 11(b). Due to the symmetric nature of the TOF analysis, two potential delamination locations are identified although there is only one actual delamination location.

6.1.2. Phase II

In Phase II, additional inspection pairs are adaptively configured based on the estimated delamination locations in Phase I. The additional inspection pairs are placed to be perpendicular to the initial inspection pairs, and the line connecting the inspection pairs passes through the potential delamination locations to avoid the symmetry issue as shown in...
Figure 12. Delamination localisation Phase II for the potential delamination location 1 (lower one) identified in Phase I: (a) Configuration of two inspection pairs newly updated for the potential delamination location 1, and (b) DI_{Location 1}^{Phase II} map.

Figure 13. Delamination localisation Phase II for the potential delamination location 2 (upper one) identified in Phase I: (a) Configuration of two inspection pairs newly updated for the potential delamination location 2, and (b) DI_{Location 2}^{Phase II} map. No delamination location is identified as the waves reflected from the delamination are too weak to reach the upper inspection pair.
Figure 12(a). Figure 12 shows (a) the configuration of the two additional inspection pairs near the potential delamination location 1 and (b) corresponding DI Location 1 PhaseII map. The same procedure is repeated for the potential delamination location 2 as shown in Figure 13. Here, no potential delamination location is identified because the waves reflected from the actual delamination location are too weak to be measured by the upper inspection pair. Among the first two potential delamination locations identified from Phase I, only one delamination location is retained in Phase II.

6.1.3. Phase III

Figure 14 represents the final delamination localisation result obtained by combining Figures 11(b), 12(b) and 13(b) using Equation (4). The actual delamination location is estimated with 5.1 mm error. It should be noted that the estimated delamination location is at the edge of the actual one. Wave reflections often occur at the edge of the delamination, where the boundary condition suddenly changes, not at the centre of delamination. This is why this estimated delamination location is near the edge of the actual delamination.

6.1.4. Delamination visualisation

Now dense laser scanning is performed only around the estimated delamination region in Figure 14. 3 cm × 3 cm square region centred at the estimated delamination location (the black dot in Figure 14) is scanned with high spatial resolution of 2 mm. The other experimental parameters including the pulse laser power and acquisition sampling frequency are identical to the previous coarse scanning. In Figure 15(a)–(c), ultrasonic wave propagation is visualised at different time points and its interaction with delamination is clearly observed. Using standing wave filtering,[19] the delamination location and its size are visualised in Figure 15(d).
Figure 15. Delamination visualisation result by scanning the delamination region localised in Figure 14 with a high spatial resolution of 2 mm. In (a)–(c), ultrasonic wave propagation at 70, 75 and 80 μs and its interaction with the delamination is clearly observed. The delamination location and its size is visualised in (d) using standing wave filtering.[19]

Figure 16. Delamination localisation Phase I: (a) configuration of two initial inspection pairs and (b) DIPhaseI map.

6.2. Delamination case #2, 15 mm diameter

Figure 16 represents (a) the configuration of two arbitrary initial inspection pairs and a 15 mm diameter delamination, and (b) corresponding DIPhaseI map. As the delamination is located along the virtual line connecting two inspection pairs, no symmetry issue is observed here.
With adaptively configured additional inspection pairs, Phase II is performed for the potential delamination location estimated in Figure 16. The configuration of the inspection pairs and corresponding $D_{II}$ map are represented in Figure 17.

By integrating results from two phases, the final delamination estimation result is represented in Figure 18 with 7.7 mm error from the actual delamination centre. As mentioned in the previous example, the estimated delamination location is at the edge of the actual delamination as the reflection mainly occurs at the delamination boundary. Figure 19

Figure 17. Delamination localisation Phase II: (a) configuration of two inspection pairs newly updated for the potential delamination location and (b) $D_{II}$ map.

Figure 18. $D_{II}$ map showing the final delamination localisation estimated by Equation (3). The black dot and cross indicate the centres of the actual and estimated delamination regions, respectively. The localisation error is 7.7 mm.
displays the corresponding delamination visualisation result obtained by applying standing wave filtering, visualising the location and size of the delamination.

7. Conclusion

In this study, two-level laser scanning is proposed to expedite the inspection of a wind turbine blade. By (1) localising delamination with coarse scanning and (2) visualising delamination with dense scanning only within the localised delamination region, the inspection time is reduced by 99.7%, in comparison with the inspection time required for dense scanning of the entire wind turbine blade. Especially, adaptive coarse laser scanning using laser-based TOF analysis is developed for delamination localisation.

The proposed technique has following advantages over existing techniques: (1) it does not require any sensor installation; (2) it drastically reduces inspection time compared to conventional laser ultrasonic imaging techniques; (3) it adaptively places excitation and sensing points with updated delamination information; and (4) it can be effectively applied to anisotropic structures as the wave velocity profile, which is critical information for TOF analysis, can be easily obtained in situ.

The feasibility of the proposed technique is demonstrated by localising and visualising delaminations in a 10 kW GFRP wind turbine blade. Two delaminations, with 10 and 15 mm diameters, are identified with 5.1 and 7.7 mm localisation errors, respectively. As wave reflections mainly occur at the boundary of the delamination rather than at its centre, the centre of the estimated delamination is located near the edges of the actual delamination.

Further studies are warranted before the proposed technique can be applied to more realistic structures. Especially, additional signal processing technique is required to distinguish reflections from the structural boundaries and delamination. This issue is especially important for complex structures having various structural features such as ribs and stiffeners. The possibility of delamination localisation using delamination-induced non-linear waves instead of the linear reflected waves is being explored by the authors’ group to overcome this limitation.
Disclosure statement

No potential conflict of interest was reported by the authors.

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