Damage Detection in Composites by Noncontact Laser Ultrasonic

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DAMAGE DETECTION IN COMPOSITES BY NONCONTACT LASER ULTRASONIC

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ABSTRACT

This study proposes an instantaneous damage localization technique for composite structures using noncontact laser ultrasonics. First, a velocity profile of the target composite structure is obtained by measuring wave velocities on paths with various directions. Second, laser ultrasonic responses from two excitation-sensing pairs, called inspection pairs, are obtained. Then possible damage locations are estimated through time-of-flight triangulation of damage reflected waves. Once possible damage locations are estimated, ultrasonic response collection is repeated near the estimated locations for precise damage localization. The proposed technique has following advantages over existing technique: (1) It does not require any sensor installation; (2) Wave velocity profile, which has been mandatory information for time-of-flight triangulation, can be easily experimentally constructed; and (3) It can localize damage with a high precision with its scanning capability. The feasibility of the proposed technique is examined by localizing a delamination in a real 10 kW wind turbine blade.

KEYWORDS : *Laser ultrasonics, Damage detection and localization, Time-of-flight triangulation, Composite structures, Wind blade.*

INTRODUCTION

Composite materials are widely used for various industries and applications thanks to their high strength with low weight and volume. However, composite structures are vulnerable to damages as they are fabricated by bonding layers of laminates. Though tremendous time and efforts are spent for inspection to avoid such problems, the detection and localization of them is a challenging task as they often occur between laminates and are invisible from external surfaces.

A set of techniques based on piezoelectric sensor arrays is taking high interest thanks to its damage localization capabilities [1-4]. These damage detection methods depend on the specific sensors placement and can take advantage of damage-reflected, damage-transmitted waves or both. In the damage-reflected approach time-of-flight triangulation can be distinguished that uses the time of arrival of damage-reflected waves at the sensors [4]. A more sophisticated approach is called beamforming or phased array imaging taking advantage of constructive and destructive wave interference. The phased arrays are comprised of sensors with carefully defined spacing depending on wavelength [5]. However, these techniques require a number of sensor installations, which is a daunting task and diminishes the system integrity. Obtaining wave velocity profile of the inspecting structure also requires additional sensor installation. Moreover, as the installed sensor is fixed, inspection range is limited only to nearby of the phased array.

A damage localization technique using laser ultrasonics is proposed in this study to tackle these problems. This technique is also based on time-of-flight triangulation, but it uses noncontact lasers for generating and measuring ultrasonic waves. By using noncontact lasers, following advantages are achieved: (1) It does not require any sensor installation; (2) The wave velocity profile can be easily obtained through laser ultrasonic generation and measurements; and (3) With its scanning capability, it covers larger region and localizes damage with high spatial resolution.

This paper is organized as follows. Section 1 explains the working principle of the proposed damage localization technique. In Sections 2 and 3, the performance of the proposed technique is examined using a real 10 kW wind turbine blade with a simulated delamination. Finally, this paper concludes with a brief summary and discussion in Section CONCLUSIONS.

1 DAMAGE DETECTION USING NONCONTACT LASER SCANNING

1.1 Laser-based Ultrasonic Generation and Measurement

In this study, the ultrasonic wave generation and measurement is performed with noncontact laser devices. A pulse laser is used for the ultrasonic generation. When a pulse laser beam is emitted onto an infinitesimal area of a target structure, a localized heating of the surface causes thermoelastic expansion of the material and generates ultrasonic waves [6]. Parameters for the laser ultrasonic generation, such as the peak power, pulse duration and beam size, should be carefully designed to avoid surface damage called ablation.

The corresponding ultrasonic waves are measured with a laser Doppler vibrometer (LDV). When a laser beam is reflected from a vibrating target surface, the frequency of the returned laser beam is shifted. LDV measures this frequency shift and relates it to the out-of-plane velocity of the target surface based on the Doppler effect [7]. The accuracy of the velocity measurement highly depends on the intensity of the returned laser beam. Thus, the incident angle of the laser beam should be carefully controlled and often a special surface treatment is necessary to improve the reflectivity of the target surface.

The direction of laser beams can be easily controlled using a galvanometer. Galvanometer is an optical device composed of two mirrors, and the angle of these mirrors can be controlled using electrical signals. The laser beams can be radiated to the target point by rotating these mirrors to appropriate angles.

1.2 Damage Localization using Time-of-flight Triangulation

Experimental construction of wave velocity profile is required in prior to use the proposed technique. For this, ultrasonic waves generated from the excitation point are measured at the fixed sensing point. As the distance between them is a known value, the velocity of the laser generated ultrasonic waves can be calculated. The full velocity profile can be obtained by repeating this process with other excitation points around the sensing point.

Figure 1 represents the overall scheme of the proposed damage localization technique. Step (1): Two arbitrary pairs of excitation and sensing points, called as inspection pairs, are selected. Ultrasonic responses are obtained for each inspection pairs, by generating ultrasonic waves at the excitation point and measuring the corresponding response at the sensing point. Step (2): Each ultrasonic response is analysed based on the time-of-flight triangulation. Then the possible reflection source locations can be visualized. Here, the direct arrival component can be eliminated by considering the arrival time of it. Step (3): If there is any damage, this will role as a common reflection source for both inspection pairs. Then the regions, where considered as possible reflection source location for both inspection pairs, are estimated as the possible damage locations. Step (4): Though there is a single damage, there can be more than one estimated damage location. To distinguish the true damage location, additional inspection pairs are selected. Here, thanks to the scanning capability and noncontact nature of the laser devices, these inspection pairs can be located to the most proper location without any limitation. Step (5): By repeating Steps (2) and (3) with the new inspection pairs, possible damage location is estimated. Step (6): By integrating results from Step (3) and Step (5), the damage location can be identified.

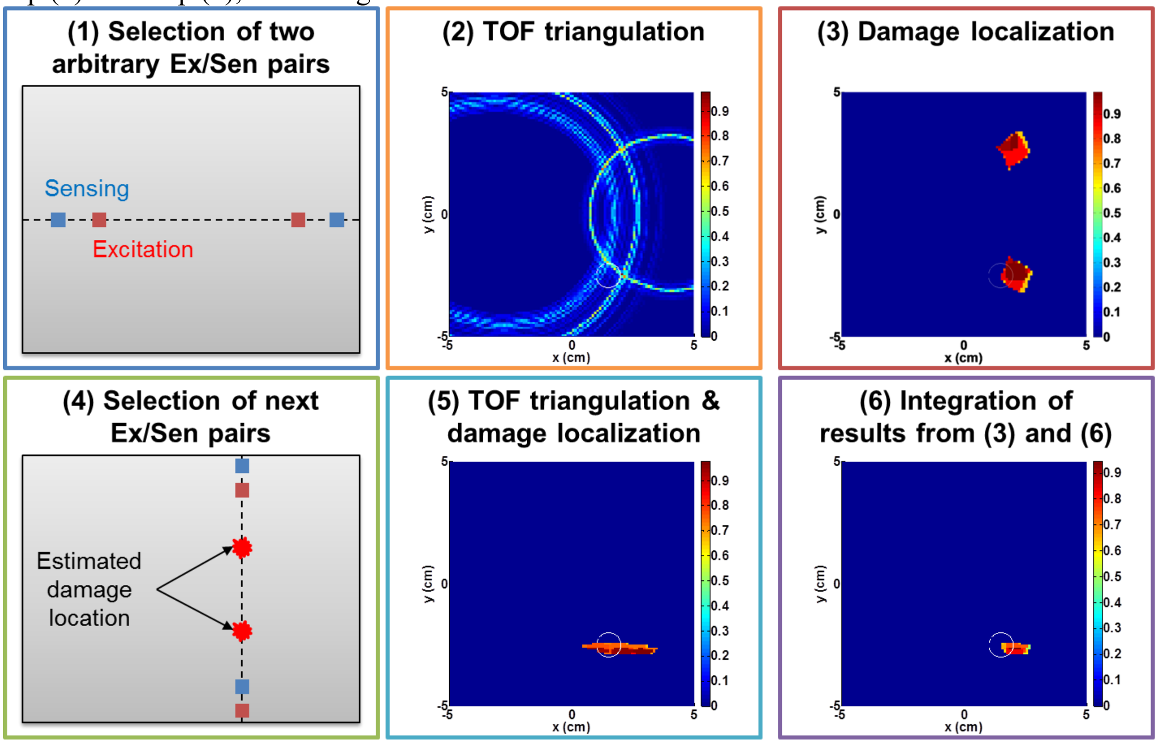


Figure 1. Schematic diagram of the proposed damage localization technique. Step (1): Two arbitrary inspection pairs (excitation and sensing point) are selected and ultrasonic responses are obtained; Step (2): For each response, the possible reflector location is visualized using time-of-flight triangulation; Step (3): The region where reflection ellipses from each inspection path intersects is considered as the possible damage location; Step (4): To distinguish the exact damage location, additional inspection pairs are selected; Step (5): Possible damage location is estimated by repeating Steps (2) and (3) with the additional inspection paths; Step (6): By integrating results from Steps (3) and (5), the damage location is identified.

Time-of-flight triangulation is a process to estimate where the measured waves come from. In the area of interest, a square mesh of points (P_i) is defined. In this study, the spacing between mesh is set as 1 mm. The task for the numerical algorithm is to assign to a point of the mesh a numerical value extracted from the signals. A registered signal may include damage induced wave reflections and the goal is to determine to which point they correspond. Let us consider a single inspection path. In order to perform damage detection, first the distances $|EP_i|$ and $|SP_i|$ are calculated. Here, E is the excitation point, S is the sensing point and P_i is one of the mesh points. These distances are used to cut out a part of the signal, F, and this part is assigned to P_i. F has a length of $T = 1/f_l$ with centre at

$$\mathrm{t_i} = \frac{|EP_i|}{c_{EP_i}} + \frac{|SP_i|}{c_{SP_i}} \tag{1}$$

where c_{EPi} and c_{SP_i} is the wave velocity in the direction of EP_i and SP_i, respectively. f_l is the lowest frequency allowed by the band pass filter that filters the measured signals.

F is a discrete function with a length of N, where $N = T/f_S$ and f_S is the sampling frequency. The registered signal is mapped into point P_i by taking its wave energy.

$$\mathrm{DI(P_i)} = \sqrt{|EP_i| + |SP_i|} \sum_{n=1}^{N} F_n^2 \tag{2}$$

where F_n is the *n*th index of *F*.

These procedures are repeated for all mesh point. Such signal processing approach causes that the *Max*(P_i) lies on an ellipse with loci at E and S [8] in the case of isotropic material, as c is independent from direction of wave propagation. In case of anisotropic material, the expected shape is more complex [9].

2 EXPERIMENTAL SETUP FOR PROPOSED TECHNIQUE VALIDATION

The effectiveness of the proposed technique is examined using a commercial 10 kW wind turbine blade (Figure 2). The target blade has rough dimensions of 3.5 m width, 0.45 m height, and 3 mm thickness. This blade is made of glass fiber reinforced plastic (GFRP), consists of 6 plies with a layup of $[0/\pm 45]_S$. A 10 mm diameter Teflon tape was inserted between the 3rd and 4th ply during fabrication of the blade to simulate internal delamination.

For ultrasonic generation, a Nd:YAG pulse laser (Quantel Ultra Laser) with 20 mJ peak energy and 8 ns pulsewidth was used. This laser beam direction was controlled using a Scanlab Scancube10 Galvanometer. Corresponding ultrasonic waves were measured by a Polytec PSV-500 LDV. Here, a refroreflective tape was attached on the sensing points to increase the reflected light intensity and improve velocity measurement quality. The ultrasonic waves were measured over 200 μs with a sampling frequency of 2.56 MHz and 100 times averaging in the time domain. A bandpass filter with 50 kHz lower cutoff frequency and 250 kHz upper cutoff frequency was applied for signal enhancement by reducing noise outside the signal bandwidth.

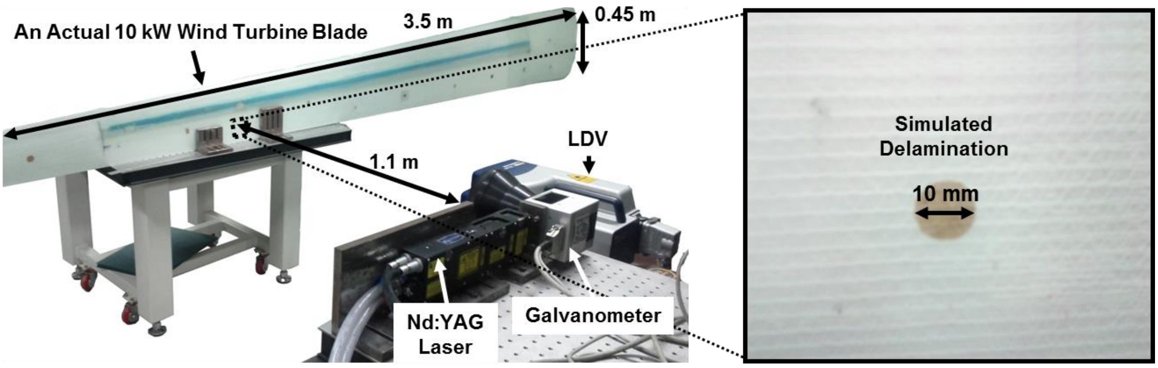


Figure 2: Tested wind turbine blade and its simulated internal delamination

3 DELAMINATION DETECTION AND LOCALIZATION USING THE PROPOSED TECHNIQUE

3.1 Velocity Profile Construction

Ultrasonic wave velocity profile of the wind blade is constructed experimentally and represented in Figure 3. The sensing point is fixed and the excitation points are set to be 2 cm away from it. The excitation points are positioned every 15° from 270°(-90°) to 90°, so that total number of excitation points is 13. Velocity profile from 90° to 270° can be easily obtained from the previous data set thanks to the blade's symmetric laminate layup.

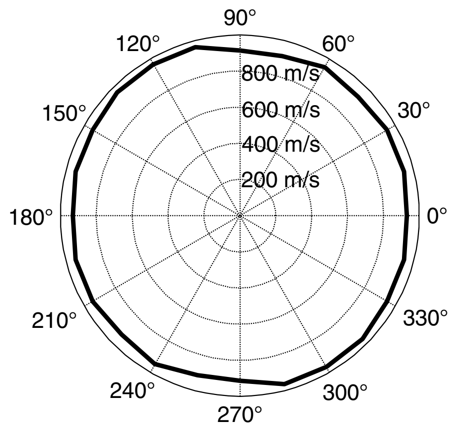
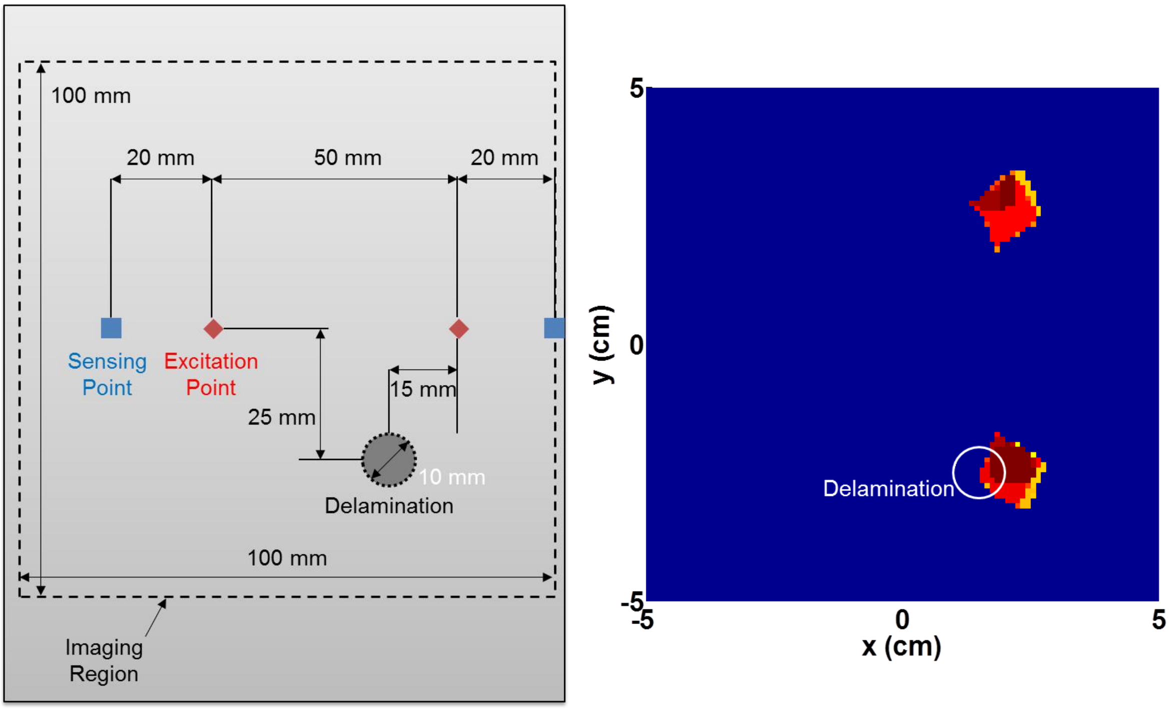


Figure 3: Constructed velocity profile of the wind turbine blade.

3.2 Delamination Detection and Localization Results

Figure 4 (a) shows the arrangement of the first two inspection pairs and the delamination. With an assumption that the delamination location is unknown, two arbitrary inspection pairs were selected. Figure 4 (b) represents the damage localization results using the proposed technique and the measurement data from the selected pairs. White circle indicates actual delamination location and high possibility as the damage location is presented with red colour in the resultant image, which is corresponding to the imaging region indicated in Figure 4 (a). Here two regions are highlighted with red colour. The lower one is close to the actual delamination location but the upper one appears due to the symmetric arrangement between the inspection pairs and the delamination location.

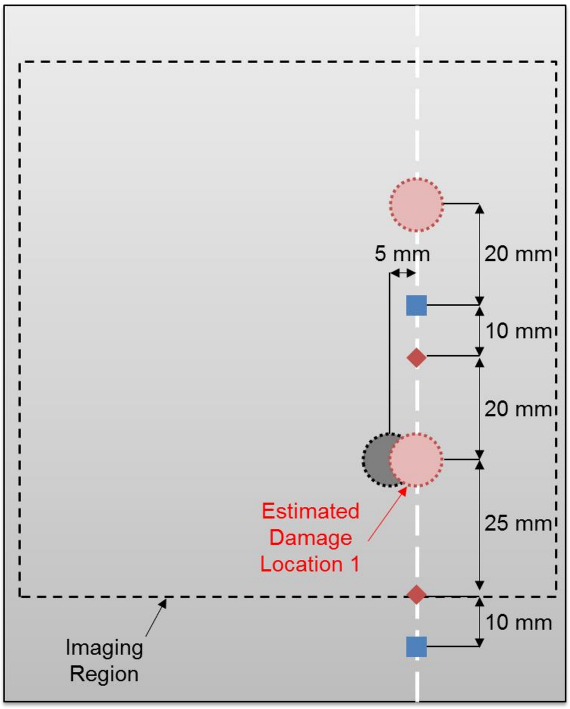


(a) First two inspection pair selection (b) Delamination localization result

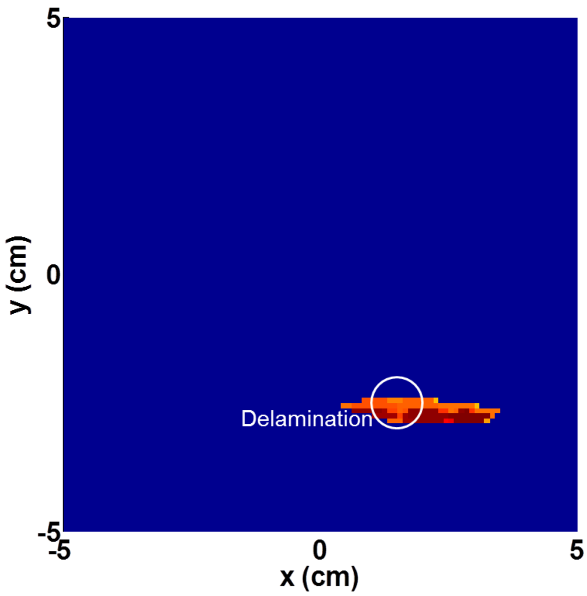
Figure 4: (a) First two inspection pairs and (b) delamination localization result corresponding to the imaging region shown in (a). Because of the symmetry, two possible damage locations in symmetric location are estimated.

Therefore, additional inspection is required to identify the exact delamination location from the estimated two. First, two inspection pairs are determined near the estimated delamination location 1 (lower one) as shown in Figure 5 (a). These inspection pairs are determined to be perpendicular to the first two and passing through the estimated delamination to avoid the symmetry problem. Another two inspection pairs are also determined near the estimated delamination location 2 (upper one) in a similar manner – Figure 6 (a). Corresponding delamination localization results are represented in Figure 5 (b) and Figure 6 (b), respectively.

Figure 7 represents the final image by integrating Figure 4 (b), Figure 5 (b) and Figure 6 (b). The white and black dots indicate the centre of the actual delamination location and the estimated delamination location, respectively. The actual delamination location is very well identified: The centre of the estimated delamination is only 5.4 mm away from the actual delamination centre. Considering that the size of the imaging region is 100 mm and the distance between two inspection paths is around 50 mm, this error value is satisfactory.

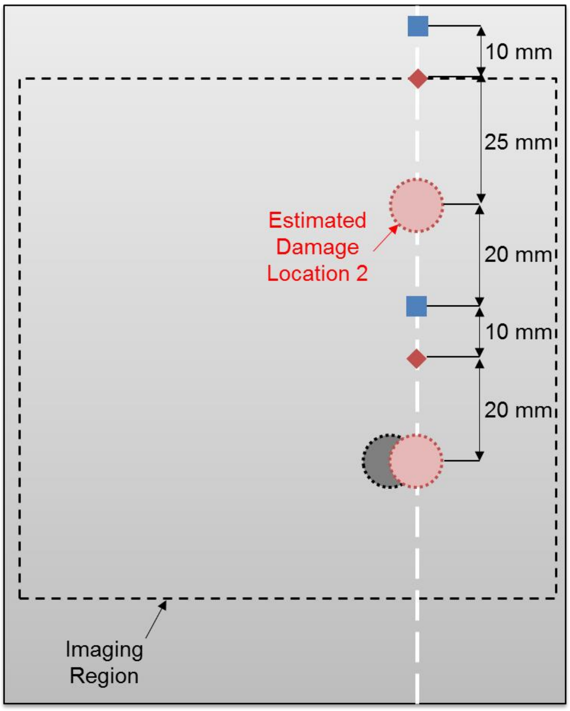


(a) Second two inspection pair selection

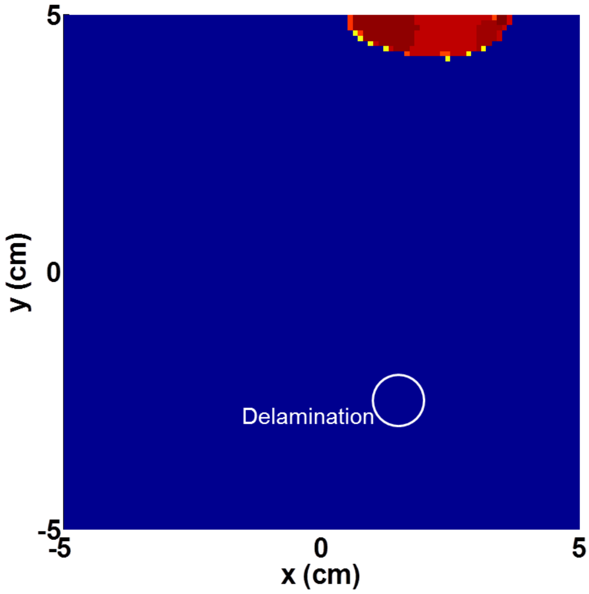


(b) Delamination localization result

Figure 5: (a) Second two inspection pairs selected near the estimated damage location 1 and (b) delamination localization result corresponding to the imaging region shown in (a).



(a) Second two inspection pair selection



(b) Delamination localization result

Figure 6: (a) Second two inspection pairs selected near the estimated damage location 2 and (b) delamination localization result corresponding to the imaging region shown in (a).

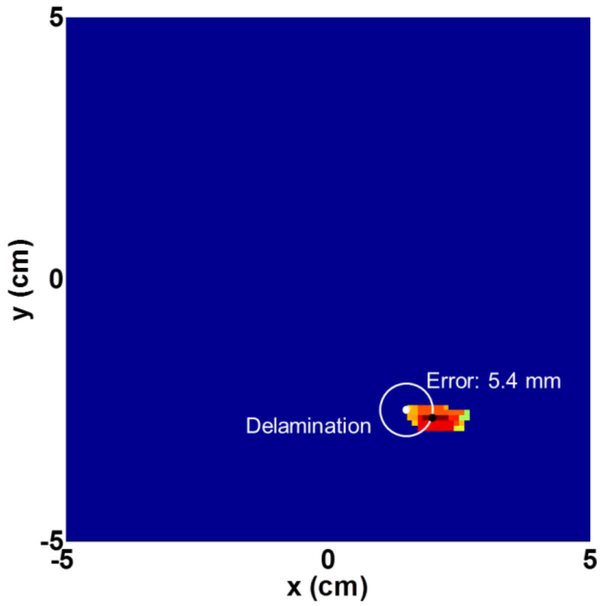


Figure 7: Integrated delamination localization result. The white and black dots indicate the center of the actual delamination location and the estimated location. The localization error is 5.4 mm.

CONCLUSIONS

In this study, a novel damage detection and localization technique is developed using laser ultrasonics. The proposed technique can identify a damage location simply by measuring damage-reflected waves and visualizing them. As this technique uses noncontact lasers to generate and measure ultrasonic waves, no sensor installation is required and adaptive inspection pair selection is available. The feasibility of the proposed technique is demonstrated using a wind turbine blade with a delamination. The delamination is identified with an error of 5.4 mm. However, further studies are needed to improve the applicability of this technique. Especially, additional signal processing is required to distinguish boundary-reflected waves and damage-reflected waves. The possibility of a localization technique using damage-generated nonlinear waves instead of the reflected waves is being explored by the author's group to overcome this limitation.

ACKNOWLEDGEMENTS

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