Instantaneous Damage Identification and Localization through Sparse Laser Ultrasonic Scanning

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INSTANTANEOUS DAMAGE IDENTIFICATION AND LOCALIZATION THROUGH SPARSE LASER ULTRASONIC SCANNING

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ABSTRACT

This study proposes an instantaneous damage identification and localization technique through sparse laser ultrasonic scanning. First, an inspection path is selected from an intended inspection region of a target structure. Then, ultrasonic waves are generated at one endpoint A of the path with a pulse laser and the corresponding ultrasonic responses are obtained at the other endpoint B with a laser Doppler vibrometer (LDV). Second, ultrasonic waves generated at point B are measured at point A reciprocally. Once two reciprocal ultrasonic signals are obtained, a damage index (DI) representing the violation of the linear reciprocity on the path is computed by comparing the reciprocal signals. DI will increase when the path passes through damage as this generates nonlinearity to the path. Third, the aforementioned steps are repeated for all predetermined inspection paths within the inspection region by scanning both pulse laser and LDV. Finally, the paths associated with high DI values are identified as damage regions. The effectiveness of the proposed sparse scanning technique is validated using an aluminium plate with a fatigue crack and a composite plate with an impact induced delamination.

KEYWORDS : *Laser ultrasonics, Damage detection and localization, Linear reciprocity, Fatigue crack, Delamination.*

INTRODUCTION

There have been a number of catastrophic failures of civil, mechanical and aerospace structures which caused numerous economic loss and fatalities. As most of them have been occurred from small damages, there is an increasing demand for structural health monitoring (SHM) and non-destructive testing (NDT) techniques which can detect these damages in the early stage.

There has been a volume of studies on SHM and NDT techniques using contact-type sensors such as piezoelectric transducers (PZTs). Alleyne and Cawley [1] studied the interaction between ultrasonic waves and damage numerically and experimentally, and Kessler et al. [2] detected a hidden damage in a composite coupon by comparing the measured ultrasonic signals with baseline signals previously collected from the pristine condition of the coupon. Yeum et al. [3] proposed a baseline-free damage detection technique for a composite plate by measuring the speed change of the Lamb wave mode using a PZT sensor network. Recently, nonlinear wave generation near damage caused by damage-wave interaction [4] is widely investigated. This is known to be especially effective for the detection of incipient crack [5] and delamination [6]. Another well-known technique is called as phased array imaging [7-9]. Here, an array of sensors is installed on the target structure and this sensor array scans around itself by changing the wave propagation direction like a LADAR. By analysing the reflected waves from the damage, the damage location can be identified.

These aforementioned contact-type sensor based techniques often require a number of sensor installations to detect incipient and localized defects. High damage detection resolution and sensitivity requires a dense array of sensors, and it is a daunting task to install these sensors and corresponding cables to the target system. Furthermore, these sensors usually become the weakest links in the system and diminish the overall system integrity. And conventional contact-type sensors are not applicable under harsh environments such as high temperature and radioactive conditions.

Alternatively, there are several noncontact techniques available. Laser ultrasonic imaging technique [10-12] is one of the most promising noncontact damage detection techniques thanks to its high damage detection resolution. This visualizes damage-wave interaction to detect incipient damage, and has been applied for various examples including stationary composite [10], metal [11] and rotating metal [12] structures. However, to visualize damage with a high spatial resolution, it requires increased time consumption for scanning as the inspection region become larger. For example, according to the experimental results of the authors' group, around 10 minutes is required to inspect a 5 cm × 5 cm square region with 2 mm spatial resolution through laser ultrasonic imaging.

To tackle this problem, an instantaneous damage identification and localization technique through sparse laser ultrasonic scanning is proposed in this study. This technique can identify damaged region without any baseline data, by quantifying the violation of the linear reciprocity of the system due to the damage existence. This can dramatically accelerate the inspection speed of laser ultrasonic imaging by localizing target inspection region. For example, according to an estimation for a 3.5 m × 0.5 m rectangular region (conventional size of a 10 kW wind turbine blade), it will require around 7,000 minutes for ultrasonic imaging with 2 mm spatial resolution. However, this time consumption will be reduced to less than 30 minutes if the target is scanned with 10 cm spatial resolution first to identify damaged region with the proposed technique and only the identified region is scanned with 2 mm resolution for ultrasonic imaging.

This paper is organized as follows. Section 1 proposes an instantaneous damage identification and localization technique. In Sections 2 and 3, the performance of the proposed technique is examined using an aluminium plate with a fatigue crack and a composite plate with an impact induced delamination, respectively. Finally, this paper concludes with a brief summary and discussion in Section CONCLUSION.

1 Development of an Instantaneous Damage Identification and Localization through Sparse Laser Ultrasonic Scanning

Linear reciprocity [13] is one of the most fundamental principles in engineering. This implies that a response H_{AB}, corresponding to the excitation from a location A and measured at another location B, is identical to H_{BA}, measured at A corresponding to the identical excitation from B, with an assumption of a linear system. In other words, the impulse response function of the path A to B, $f(t)$, is identical to the one of the path B to A, $g(t)$. However, if the system has nonlinearity, this principle is no more valid as the assumption of a linear system is violated. Thus, the existence of these nonlinear damages can be identified by checking if the linear reciprocity is valid for the target system.

In Figure 1, an overview of the proposed damage identification and localization technique is provided. Step (1): An inspection region and corresponding inspection paths are determined. Step (2): For an inspection path, ultrasonic waves are generated at one endpoint A and measured at the other endpoint B, in other words, H_{AB} is obtained. Then its reciprocal response, H_{BA}, is obtained by generating ultrasonic waves at B and measuring at A. Step (3): Linear reciprocity of the path is examined by comparing two obtained reciprocal responses H_{AB} and H_{BA}. The validity of the linear reciprocity for the path is quantified as a damage index (DI). Step (4): By repeating Steps (2) and (3) for every inspection paths determined in Step 1, DIs for each path are calculated. Then the path with exceptionally high DI is identified as the damaged path and the damage location is localized.

Here, 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 [14]. 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 [15].

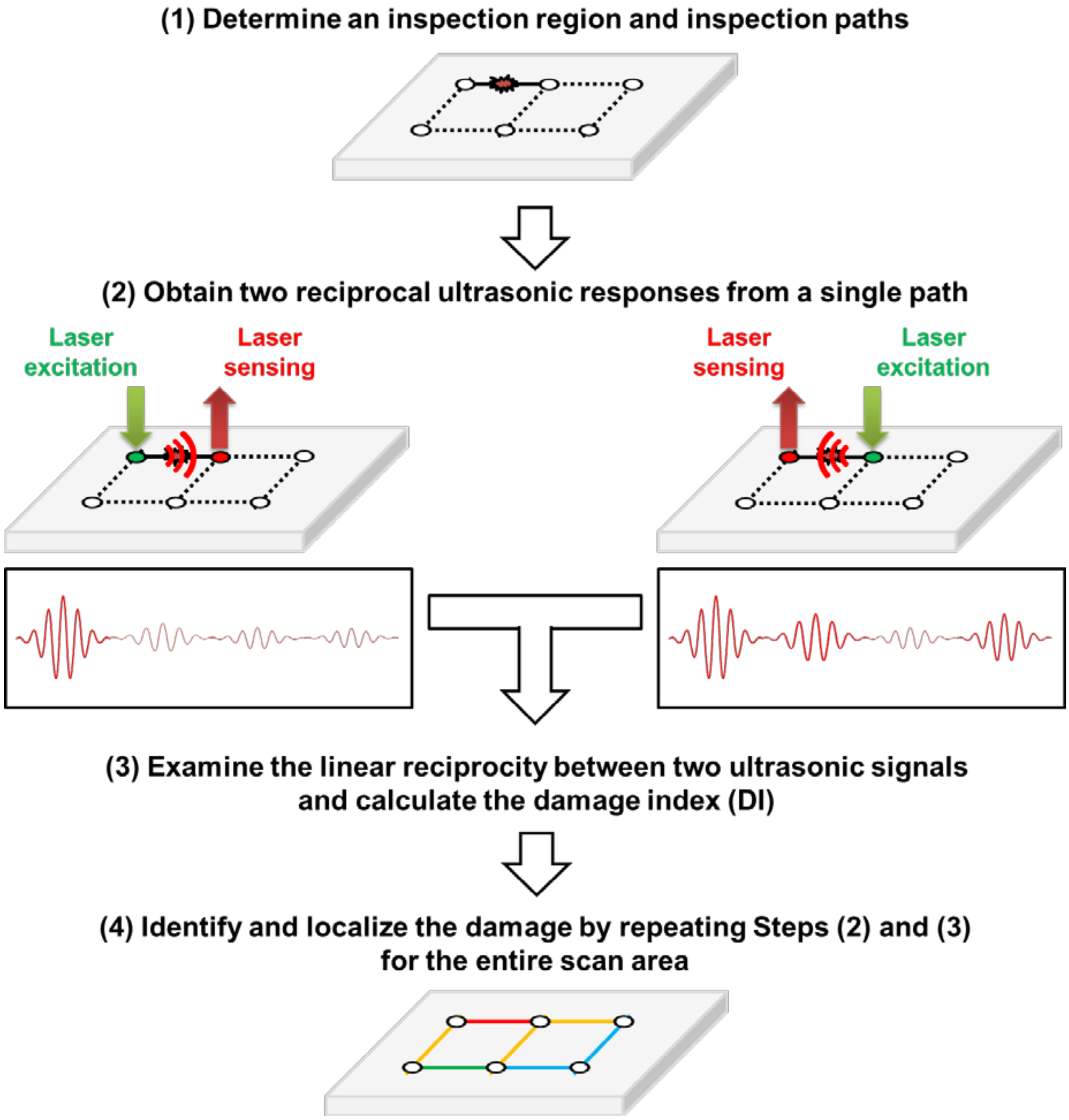


Figure 1: Schematic diagram of the developed damage detection and localization technique through sparse laser scannig. Step (1): A target inspection region and corresponding inspection paths are determined; Step (2): For a single path, two recirprocal ultrasonic responses are obtained; Step (3): The linear reciprocity between two ultarsonic signals is examined and corresponding damage index (DI) is calculated; Step (4): DIs for each paths are calculated by repeating Steps (2) and (3) for the entire inspection paths and the damaged paths are identified using an outlier analysis.

As previously mentioned, the linear reciprocity of the path is examined by comparing two reciprocal responses. Suppose a pulse input, $x_1(t)$, is applied to point A and the corresponding response, $y(t)$, is measured at B. And another pulse input, $x_2(t)$, is applied to point B and the corresponding response, $z(t)$, is measured at A. Here $x_1(t)$ and $x_2(t)$ are set as pulse inputs with slightly different pulsewidth, to consider variation in laser ultrasonic generation due to the surface condition. Then $y(t)$ and $z(t)$ can be represented as follows:

$$y(t) = f(t) \otimes x_1(t) \tag{1}$$

$$z(t) = g(t) \otimes x_2(t) \tag{2}$$

where $\otimes$ is a convolution operator and $f(t)$ and $g(t)$ are impulse response functions for the path A to B and the path B to A, respectively. By taking autocorelation and cross correlation of $y(t)$ and $z(t)$ [16],

$$\begin{aligned} R_{yy} &= y(t) \star y(t) = y(t) \otimes y(-t) = \big(f(t) \otimes x_1(t)\big) \otimes \big(f(-t) \otimes x_1(t)\big) \\ &= (f(t) \otimes f(-t)) \otimes (x_1(t) \otimes x_1(t)) \end{aligned} \tag{3}$$

$$\begin{aligned} R_{yz} &= y(t) \star z(t) = y(t) \otimes z(-t) = \big(f(t) \otimes x_1(t)\big) \otimes \big(g(-t) \otimes x_2(t)\big) \\ &= (f(t) \otimes g(-t)) \otimes (x_1(t) \otimes x_2(t)) \end{aligned} \tag{4}$$

$$\begin{aligned} R_{zz} &= z(t) \star z(t) = z(t) \otimes z(-t) = \big(g(t) \otimes x_2(t)\big) \otimes \big(g(-t) \otimes x_2(t)\big) \\ &= (g(t) \otimes g(-t)) \otimes (x_2(t) \otimes x_2(t)) \end{aligned} \tag{5}$$

where $\star$ indicates a correlation operator. If this system is linear, $f(t) = g(t)$ due to the linear reciprocity and

$$f(t) \otimes f(-t) = f(t) \otimes g(-t) = g(t) \otimes g(-t) = I(t) \tag{6}$$

Also with an assumption that $x_1(t)$ and $x_2(t)$ are pulse inputs with a slight difference,

$$x_1(t) \otimes x_1(t) \simeq x_1(t) \otimes x_2(t) \simeq x_2(t) \otimes x_2(t) \simeq x(t) \tag{7}$$

By substituting Equation (6) and (7) to (3) ~ (5),

$$R_{yy} \simeq R_{yz} \simeq R_{zz} \simeq I(t) \otimes x(t) \tag{8}$$

However, if the path contains a nonlinear damage and the system is a nonlinear system, the assumption for the linear reciprocity is violated and Equation (6) and (8) are no more valid. By measuring dissimilarity between these correlation functions, it can be quantified how much the path is linear and how probable the path contains a damage. Let a function $D(\alpha(t), \beta(t))$ be defined as

$$D(\alpha(t), \beta(t)) = \frac{\|\alpha(t) - \beta(t)\|}{\|\alpha(t)\| + \|\beta(t)\|} = \frac{\int_{-\infty}^{\infty} (\alpha - \beta)^2 dt}{\int_{-\infty}^{\infty} \alpha^2 dt + \int_{-\infty}^{\infty} \beta^2 dt} \tag{9}$$

where $\| \quad \|$ indicates a norm operator. This function D is zero when $\alpha(t) = \beta(t)$ and increases as $\alpha(t)$ and $\beta(t)$ are different to each other. Then the damage index (DI) is defined as:

$$\mathrm{DI} = \sqrt{\frac{1}{3}\left[D\big(R_{yy}, R_{yz}\big) + D\big(R_{yz}, R_{zz}\big) + D\big(R_{zz}, R_{yy}\big)\right]} \tag{10}$$

and this represents the disimilarity of three correlation functions. A path with high DI is estimated as a damaged path while a path with low DI may not contain any damage.

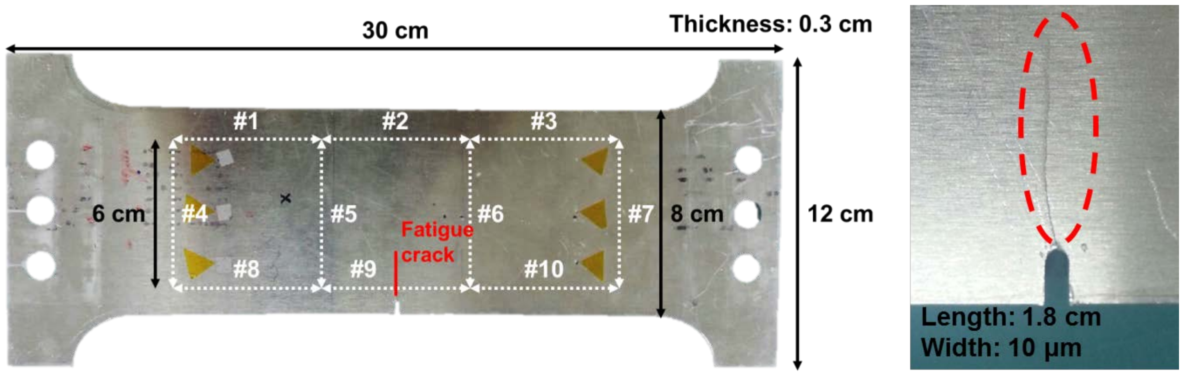
An outlier analysis is introduced here to identify paths with exceptionally high DI values [3]. Step 1: The calculated DIs are arranged in an ascending order. Step 2: A threshold corresponding to 99% confidence interval is computed by fitting a gamma distribution to n smallest DIs. Here, the initial n is selected to be 1/3 of the total number of paths (N). Step 3: If the $n + 1$th smallest DI is larger than the computed threshold, the paths with $n + 1$th smallest DI to Nth smallest DI are considered to be damaged. If not, Steps 2 and 3 are repeated with $n + 1$ smallest DIs until $n + 1$ reaches N.

2 FATIGUE CRACK DETECTION IN AN ALUMINIUM PLATE

The effectiveness of the proposed technique is examined using an aluminium plate with a fatigue crack (Figure 2). This aluminium plate has dimensions of 30 cm width, 12 cm height, and 0.3 cm thickness with a notch at the middle of its bottom side. A 1.8 cm long and 10 µm width fatigue crack was introduced near the notch through a cyclic loading test. A universal testing machine (INSTRON 8801) with a 10 Hz cycle rate, a maximum load of 25 kN and a stress ratio 0.1 was used.

Ten paths with 6 cm length were determined on the plate for the inspection (Figure 2 (a)). It is designed only a single path (#9) to be passing through the fatigue crack. Ultrasonic responses for each path were collected reciprocally; total 20 responses were collected.

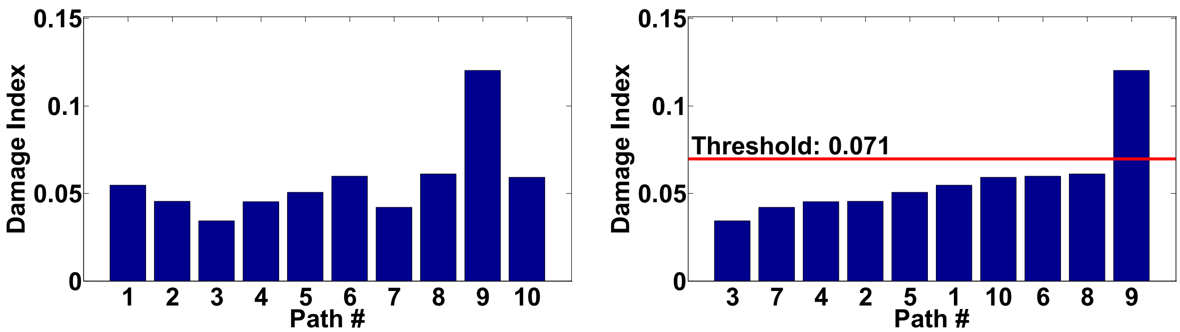
An Nd:YAG pulse laser (Quantel Ultra Laser) with 20 mJ peak energy and 8 ns pulsewidth was used for ultrasonic generation, and the corresponding ultrasonic waves were measured by a Polytec PSV-400 LDV. Here, a retroreflective tape was attached on the measurement point to increase the reflected light intensity and improve velocity measurement quality. The ultrasonic waves were measured over 400 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 210 kHz upper cutoff frequency was applied for signal enhancement by reducing noise outside the signal bandwidth.



(a) Aluminium plate with a fatigue crack

(b) Close-up image of the fatigue crack

Figure 2: (a) Aluminium plate with a fatigue crack, its dimensions, and ten scanning paths and (b) a close-up of the fatigue crack introduced through a cyclic loading test



(a) Calculated DIs

(b) Sorted DIs with an outlier threshold

Figure 3: (a) Calculated DIs for each path in Figure 2 (a) and (b) sorted DIs with an outlier threshold. Only path #9 has a DI above the threshold.

Figure 3 (a) represents the calculated DIs, using Equation (10), for each path on the aluminium plate. DI is dramatically increased for the path #9, which is passing through the crack. This is more distinct when they are sorted (Figure 3 (b)), and DI for the path #9 is twice bigger than DI for path #8. It can be also observed that paths near the crack, e.g. #8 and #10, have higher DI than other paths. This may be affected by crack-reflected waves even though the crack is out of the paths. A damage detection threshold of 0.071 is obtained through the aforementioned outlier analysis and the path #9 is the only path showing DI above this threshold. Therefore this path is identified as the damaged path, as shown in Figure 4.

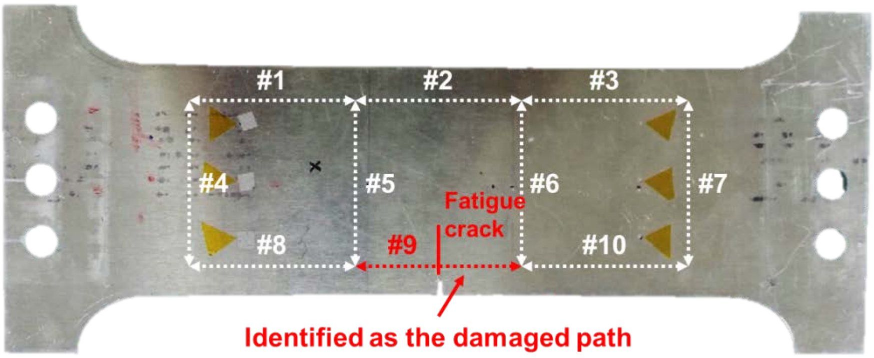
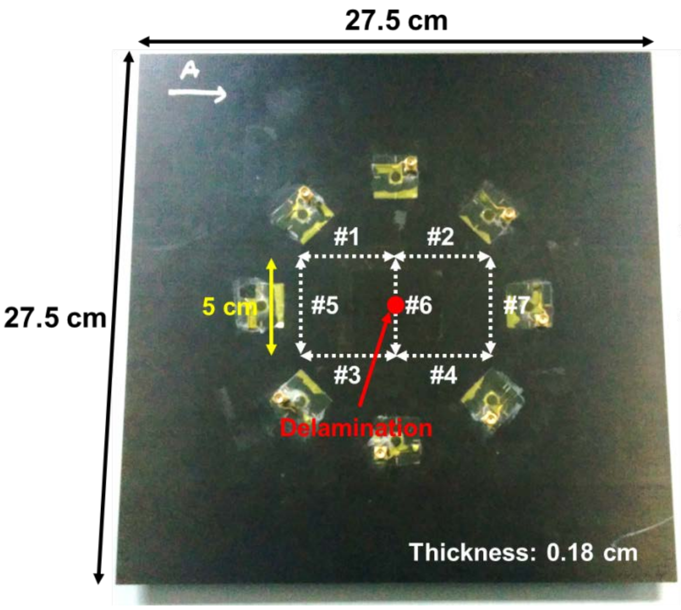


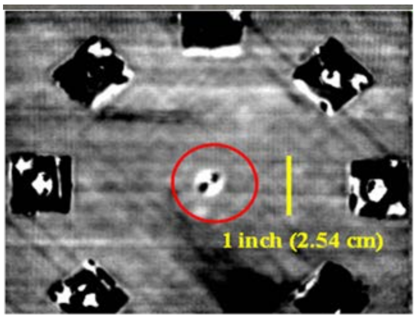
Figure 4: Damage identification results on the aluminum plate. As it has been shown in Figure 3 (b), only the path passing through the fatigue crack (#9) is identified as the damaged path.

3 DELAMINATION DETECTION IN A COMPOSITE PLATE

The proposed technique is also examined using a composite plate with an impact induced delamination (Figure 5). This composite plate is a square of 27.5 cm length and 0.18 cm thickness. A delamination is introduced at the centre of the plate by subjecting several impacts. The formation of the delamination is confirmed from the thermography image as shown in Figure 5 (b). Seven paths with 5 cm length are determined while only a single path (#6) is passing through the delamination. More details on this specimen can be found in [17].



(a) Composite plate with a delamination

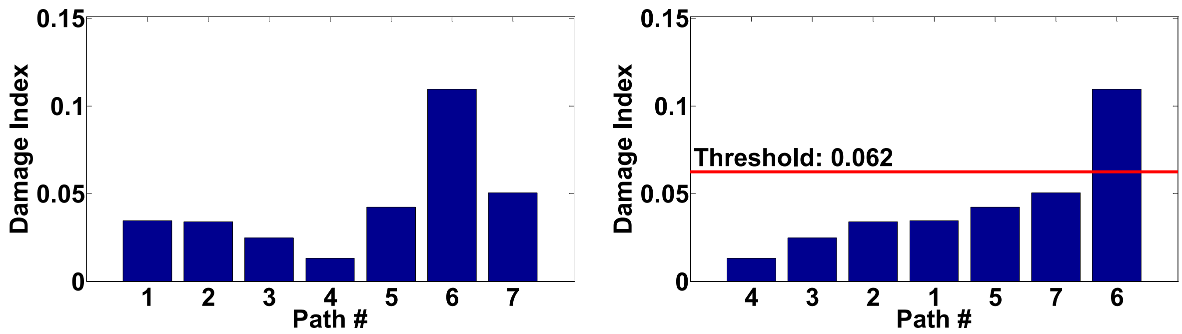


(b) Thermography images of the delamination

Figure 5: (a) Composite plate with a delamination, its dimensions, and seven scanning paths and (b) a thermography image of the impact induced delamination

The ultrasonic generation and measurement was performed in a similar manner as it has been mentioned in the Section 2. Only differences are as follows: the ultrasonic waves were measured over 200 μs, and a bandpass filter with 80 kHz lower cutoff frequency and 230 kHz upper cutoff frequency was applied.

Figure 6 (a) represents the calculated DIs for each path on the composite plate. As it has been in the Section 2 and Figure 3, DI is dramatically increased for the path #6, which is passing through the delamination. The sorted result (Figure 6 (b)) represents this more dramatically, and a damage detection threshold of 0.062 is obtained through the outlier analysis. The path #6 is the only path showing DI above this threshold, and identified as the damaged path as shown in Figure 7.



(a) Calculated DIs (b) Sorted DIs with an outlier threshold

Figure 6: (a) Calculated DIs for each path in Figure 0 and (b) sorted DIs with an outlier threshold. Only path #6 has a DI above the threshold.

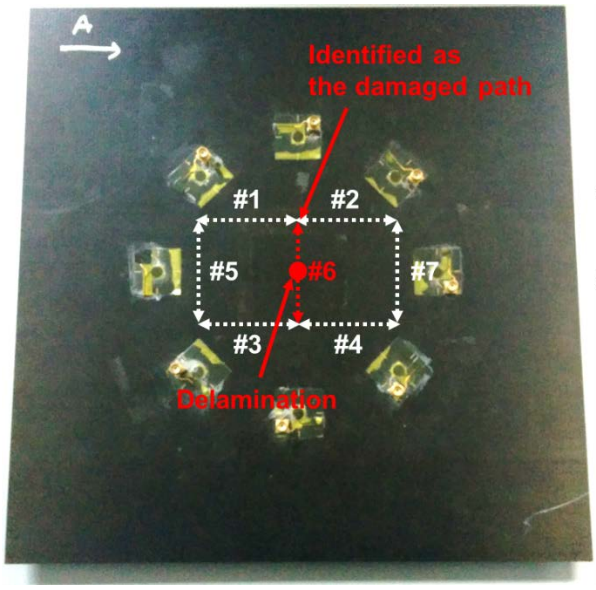


Figure 7: Damage identification results on the composite plate. As it has been shown in Figure 6 (b), only the path passing through the delamination (#6) is identified as the damaged path.

CONCLUSION

In this study, an instantaneous damage identification and localization technique using noncontact laser is proposed. The proposed technique is able to identify damage existence without any baseline data, by comparing reciprocal ultrasonic responses and quantifying their similarity. Using an outlier analysis, the damaged path can be distinguished from intact paths. The feasibility of the proposed technique is examined using an aluminium plate with a fatigue crack and a composite plate with a delamination, and the damaged paths are successfully identified for both cases.

However, special surface treatment with retroreflective tapes is required to obtain ultrasonic response effectively, and this technique cannot pinpoint the damage location while it can only identify the damage existing path location. The possibility of improving its localization performance is being explored by the authors' group.

ACKNOWLEDGEMENT

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