Baseline-free delamination inspection in composite plates by synthesizing non-contact air-coupled Lamb wave scan method and virtual time reversal algorithm

Zenghua Liu¹, Hongtao Yu¹,², Junwei Fan¹, Yanan Hu¹, Cunfu He¹ and Bin Wu¹

¹ College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, People’s Republic of China
² Beijing Aerospace Measurement & Control Corp. Ltd, Beijing 100041, People’s Republic of China

E-mail: liuzenghua@bjut.edu.cn

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Abstract

In the paper, we combined air-coupled Lamb wave scan method and virtual time reversal (VTR) algorithm and proposed a composite baseline-free delamination inspection technique of composite plates. According to VTR algorithm, time reversal process is virtually performed through signal operations and the hardware manipulation for time reversal is not required. Baseline-free damage inspection can be achieved by comparing the first input actuation signal with the reconstructed final signal obtained by VTR algorithm. An air-coupled Lamb wave scan method combined with VTR-based probabilistic imaging algorithm is developed for delamination inspection of composite plates. Carbon fiber-reinforced composite plates with the delaminations of different shapes and sizes were experimentally tested. The testing results are well in accordance with the actual delamination locations and sizes as well as the results obtained with the commercial point-to-point immersion C-scan system.

Keywords: virtual time reversal, composite plate, delamination inspection, air-coupled ultrasonic, Lamb wave scan

1. Introduction

Fiber-reinforced composite materials are becoming the competitive alternatives to traditional metallic materials in different fields, such as aerospace, civil engineering, and energy engineering, because of their attractive properties including the high strength, high stiffness, and low weight. However, the manufacturing process may randomly result in unwanted defects in composite plates. Damages may also occur during the service life of composite plates under continuous cyclic loading, rapid changes in local temperature, and impact loading [1]. One of the most common damages in composite plates is delamination [2]. Delamination tends to reduce compressive strength, stiffness, and damping properties of composite structures and may lead to catastrophic accidents. To ensure the integrity and reliability of composite plates, it is required to carry out delamination inspection during the manufacturing process and service life of composite plates.

Ultrasonic testing technique, especially Lamb wave-based technique, is one of the promising techniques for the characterization and inspection of composite materials [3–5]. Lamb waves can travel over a long distance in fiber-reinforced laminated composite plates and various Lamb wave methods are used for non-destructive evaluation of composite structures.
modes can interrogate the entire thickness of plates [6, 7]. Guo and Cawley [4] investigated the interaction between symmetric S0 mode Lamb waves and delaminations at different interfaces in a composite plate through finite element analysis and experiment. The results show that delamination does not affect the S0 mode Lamb wave propagation when the delamination is located at the position under zero shear stress. Ramadas et al [8, 9] studied the interaction between antisymmetric A0 mode Lamb waves and symmetric and asymmetrical delaminations with two-dimensional finite element models and air-coupled experimental technique and found that both symmetric and asymmetrical delaminations affected A0 mode Lamb wave propagation. Peng et al [10] investigated the interaction between Lamb waves (both S0 mode and A0 mode) and the delamination in carbon fiber-reinforced composite plates by two-dimensional spectral element method. A0 mode Lamb waves can interrogate the entire thickness of plates, but S0 mode Lamb waves cannot detect the delamination in a symmetric plane. The wavelength of A0 mode Lamb waves is shorter than that of S0 mode Lamb waves at the same frequency, indicating that A0 mode Lamb waves can provide the higher resolution of defect inspection [6]. Therefore, in general, A0 mode is more suitable for delamination inspection. Hay et al [11] compared several Lamb wave tomography approaches for material loss inspection and found that the reconstruction algorithm for probabilistic inspection of damage (RAPID) technique [12, 13] was more sensitive to material loss and not prone to confuse noise and anomalies with structural damage or material loss. Wang et al [14] employed the RAPID technique to locate the artificial damage in the form of a through-thickness hole in a composite panel with five stiffeners and demonstrated that the RAPID technique could be used to characterize damages in highly complex structures. Lamb wave modes are dispersive, thus signal processing is difficult. Several techniques were employed to achieve dispersion compensation. Wilcox [15] presented a rapid signal processing technique to remove the effect of Lamb wave dispersion with the prior knowledge of the dispersion characteristic of Lamb waves in the structure. As an alternative, time reversal method [16] can also mitigate Lamb wave dispersion effect, moreover, the prior knowledge of the dispersion characteristic of Lamb waves in the structure is not required. In the field of structural health monitoring (SHM), time reversal method is widely used for baseline-free damage inspection in metallic and composite plates based on the assumption of linear reciprocity within healthy structures [17–23]. Time reversal-based damage index (DI) or time reversibility index [18, 19] obtained by comparing the input actuation signal with the final signal after the time reversal process can be used to estimate the damage severity of a structure. These research results showed that baseline-free damage inspection can be achieved with time reversal-based DI. To ensure the efficient mechanical energy transfer from the ultrasonic transducer to the specimen, water, glycer, and vaseline are often used as the couplants in practice. However, tested materials may be degraded by these couplants. To resolve these problems, non-contact transducers, such as air-coupled ultrasonic transducer [24, 25], electromagnetic acoustic transducer [26], and laser transducer [27], are employed. The main drawback of air-coupled ultrasonic is the acoustic impedance mismatch between air and tested solid materials. With the development of highly efficient air-coupled ultrasonic transducers and the improvements in high-power ultrasonic transmitting and receiving instruments (e.g., high-dB preamplifier), many researchers already investigated the application of air-coupled ultrasonic transducers in Lamb wave-based inspection due to their non-contact and non-contaminating characteristics. Besides, a relatively pure Lamb wave mode can be actuated and received by air-coupled ultrasonic transducers with specific incident angle determined by Snell’s law [28]. Castaings et al have shown that Lamb waves [29, 30], shear horizontal (SH) waves [31], and surface guided wave modes [32] can be actuated and received with air-coupled ultrasonic transducers in composite materials. Research results showed that A0 mode Lamb waves can be easily actuated and received with air-coupled ultrasonic transducers because their surface motions are predominantly out of the plane [33]. Holland and Chimenti [34] employed air-coupled zero group velocity Lamb waves to inspect and image glass and lucite plates. Schmidt et al [35] adopted air-coupled guided wave scan in delamination characterization because the impact in wound glass fiber-reinforced tubes and experimental results are well consistent with visual inspection. Yan et al [36] presented an air-coupled Lamb wave imaging method for the identification of impact delaminations in a carbon fiber-reinforced composite plate based on the concept of probabilistic damage inspection. The defects were detected and located quite well through three-direction scan. In this paper, non-contact air-coupled ultrasonic transducers are used to actuate and receive A0 mode Lamb waves in carbon fiber-reinforced composite plates. Virtual time reversal (VTR) algorithm is proposed to achieve baseline-free delamination inspection through relieving Lamb wave dispersion effect. An air-coupled Lamb wave scan method combined with VTR-based probabilistic imaging algorithm is developed for delamination inspection of composite plates. A modified RAPID method based on VTR algorithm is performed to obtain air-coupled Lamb wave scan images. The paper is organized as follows: theoretical analysis of VTR of Lamb waves and the definition of time reversal-based DI are provided in section 2. VTR-based imaging method of air-coupled Lamb wave scan is presented in section 3. Section 4 presents the experimental system of air-coupled Lamb wave scan in composite plates. Experimental validation of VTR method is presented in section 5. Experimental test of composite plates with delaminations is presented in section 6. Finally, the conclusions are provided in section 7.

2. VTR algorithm of Lamb waves

Recently, time reversal method has been introduced into Lamb wave-based SHM technique to implement baseline-free damage inspection [17–23]. As shown in figure 1(a),
conventional Lamb wave time reversal process in thin plate with pitch-catch configuration can be divided into three steps. In the first step, a tone-burst signal is actuated from transducer A and then received by transducer B. Then, the received signal of transducer B is reversed in time. In the third step, the time reversal signal is actuated from transducer B and then received by transducer A.

As shown in figure 1(b), Watkins and Jha [37] presented a modified time reversal (MTR) method. Theoretical analysis and experimental measurements showed that MTR method and the conventional time reversal method yield similar signals at the end of time reversal process. In the MTR method only one transducer is required to actuate signals and the other transducer to receive signals, whereas in the conventional time reversal method, two transducers are required to act as transmitter and receiver respectively. In this paper, the MTR method is employed because it is convenient in experimental work.

2.1. Theoretical analysis of VTR of Lamb waves

Theoretical analysis for time reversal of Lamb waves has been conducted by several researchers. Wang et al [17] theoretically investigated time reversal of Lamb waves in a homogenous plate with Mindlin plate wave theory. Park et al [18] studied time reversal of low-frequency \(A_0\) mode Lamb waves in composite plate based on Mindlin plate wave theory. Time reversal of a single Lamb wave mode and dual Lamb wave modes (\(A_0\) and \(S_0\)) were investigated by Xu and Giurgiutiu [20] with the exact solutions of the Rayleigh–Lamb equation. Theoretical analysis of MTR method was conducted in Fourier space [37]. This paper presents the theoretical analysis of Lamb wave time reversal process in thin plate with pitch-catch configuration in the view of signal and system. According to the transducer arrangement shown in figure 1(b), in the first step from A to B, the signals received at transducer B in the frequency domain, \(f_{B1}(\omega)\), can be expressed as:

\[
f_{B1}(\omega) = f_{A1}(\omega)G(r, \omega),
\]

(1)

where \(f_{A1}(\omega)\) is the first actuated signal at transducer A; \(G(r, \omega)\) is the frequency response function for the transmitter–receiver sensing path; \(r\) is the distance between transducer A and transducer B; \(\omega\) is the angular frequency. Note that the time reversal operation of a signal in the time domain can be implemented by taking the complex conjugate of the Fourier transform of the signal in the frequency domain. Therefore, the reversed signal in the second step can be expressed as:

\[
f_{TR}^*(\omega) = \frac{f_{B1}(\omega)}{f_{A1}(\omega)},
\]

(2)

where the superscript * denotes a complex conjugate. In the third step, the reversed signal is applied at transducer A. The reconstructed final signal at transducer B can be expressed as:

\[
f_{B2}(\omega) = f_{TR}^*(\omega)G(r, \omega) = f_{B1}(\omega)G(r, \omega).
\]

(3)

In the view of signal and system, based on equation (1), the frequency response function \(G(r, \omega)\) can be represented as:

\[
G(r, \omega) = \frac{f_{B1}(\omega)}{f_{A1}(\omega)}.
\]

(4)

After substituting equation (4) into equation (3), the reconstructed final signal at transducer B can be represented as:

\[
f_{B2}(\omega) = f_{B1}(\omega)G(r, \omega) = f_{B1}(\omega) \frac{f_{B1}(\omega)}{f_{A1}(\omega)}.
\]

(5)

According to equation (5), VTR algorithm can be achieved, as illustrated in figure 1(c). This equation shows that the reconstructed final signal at the end of time reversal process can be obtained by simple signal operations of \(f_{A1}(\omega)\) and \(f_{B1}(\omega)\) in frequency domain. The second and third steps in time reversal process can be virtually carried out by taking...
signal operations based on equation (5) because the first actuated signal \( f_{A1}(t) \) and the received signal \( f_{B1}(t) \) are known in the first step of time reversal process. The time domain signal can be obtained through transforming the frequency domain results into the time domain. In this proposed VTR algorithm, it is only required to set actuating–receiving manipulation once in typical pitch-catch configuration and the practical hardware manipulation because time reversal process is not required any more.

### 2.2. Definition of time reversal-based DI

Damage classification is accomplished through comparing the first input actuation signal with the reconstructed final signal at the end of the time reversal process. Based on the assumption of linear reciprocity within a healthy structure, the reconstructed final signal and the first input actuation signal are almost the same after normalization. However, when the structure damage exists in the transmitter–receiver sensing path, Lamb waves propagating along this path may be mode-converted, reflected or scattered by the damage and linear reciprocity of the structure breaks down. Thus, the difference between the reconstructed signal and the first input actuation signal can tell the presence of the damage in the structure without the requirement of a baseline. The time reversal-based DI or the time reversibility index is defined as [18, 19]

\[
DI = 1 - \frac{\int_{t_0}^{t_1} I(t)V(t)dt}{\sqrt{\int_{t_0}^{t_1} I^2(t)dt \int_{t_0}^{t_1} V^2(t)dt}},
\]

where \( I(t) \) is the first input actuation signal; \( V(t) \) is the final reconstructed signal by using time reversal method; and \( t_0 \) and \( t_1 \) define the time interval over which the signals are compared. In this paper, \( t_0 \) and \( t_1 \) are respectively the starting and ending time points of the time reversal interception window. The value of DI becomes zero when the reconstructed final signal coincides with the first input actuation signal exactly. If the reconstructed final signal deviates from the input actuation signal, the time reversal-based DI value increases and approaches 1. Therefore, damage severity can be evaluated with the value of DI. Furthermore, it can be obtained that DI is zero for \( I(t) = \beta V(t) \), where \( \beta \) is a generic constant. Therefore, linear attenuation of a signal does not affect the time reversal-based DI.

### 3. VTR-based imaging method of air-coupled Lamb wave scan

#### 3.1. Reconstruction algorithm for probabilistic inspection of delaminations

To implement visualization of damage localization and damage assessment, several Lamb wave tomography algorithms are developed [11–14]. The RAPID technique, in which the computed tomography algorithms are combined with Lamb wave features, is widely used in Lamb wave SHM. It is assumed that the presence of a localized damage on the sensing path will generate the Lamb wave signal in the RAPID technique. The RAPID technique relies on integrated signal changes caused by damage, and it is not based on the detailed characteristics of each extracted wave component in the acquired wave signals, but the signal difference coefficient (SDC) of Lamb wave signals received from the selected sensing paths with or without damage. The damage occurrence probability at a certain point can be reconstructed with the severity of the signal change and its relative position to the transducer pair. The damage distribution estimation for the entire monitoring area is a linear summation of all the effects obtained from every possible transmitter–receiver transducer pair [11].

Assuming that there are \( N \) transducer elements in a circular array in total, possible direct sensing paths are shown in figure 2(a). The damage occurrence probability at the position \((x, y)\) within the monitoring area \( P(x, y) \) can be written as [13]

\[
P(x, y) = \sum_{j=1}^{N-1} \sum_{k=j+1}^{N} P_{ik}(x, y)
= \sum_{i=1}^{N-1} \sum_{k=1}^{N} SDC_{ik} E(R_{ik}(x, y)),
\]

where \( P_{ik}(x, y) \) is the damage distribution probability estimated with the transmitter \( i \) and receiver \( k \) transducer pair; \( SDC_{ik} \) is the SDC of the transducer pair \( ik \); \( E(R_{ik}(x, y)) \) is the non-negative linearly decreasing spatial distribution function of transducer pair \( ik \) used to estimate the energy distribution of Lamb wave ray; \( R_{ik}(x, y) \) is the relative distance between 

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**Figure 2.** (a) Circular transducer array and (b) the distribution function in RAPID technique [13].
the position \((x, y)\) and the transducer pair \(ik\). With the transmitter and receiver as two focal points, a set of ellipses can be drawn, as shown in figure 2(b). All the points at an ellipse have the same total distance to the transducer so that they have the same damage distribution probability.

3.2. VTR-based probabilistic imaging algorithm for air-coupled Lamb wave scan

The probabilistic imaging algorithm for air-coupled Lamb wave scan in this paper is a modified version of the RAPID technique, VTR-based RAPID technique. For VTR-based RAPID technique, the DI based on VTR algorithm instead of the SDC is used to estimate the damage severity of the selected sensing path because it can achieve baseline-free damage inspection. As illustrated in figure 3(a), the air-coupled ultrasonic transducer arrangement method is based on the pitch-catch configuration. During the scan process, a pair of air-coupled ultrasonic transducers are clamped on the scan mechanism and moved together along the direction which is perpendicular to the wave propagation direction. The damage can be located and reconstructed with only two orthogonal direction scans.

In order to extract the shape of the defect and improve the reliability and accuracy of the inspection, two different imaging fusion algorithms, including full summation and full multiplication [38], were proposed for the defect inspection.

3.2.1. Full summation algorithm. The probability of damage occurrence at position \((x, y)\) at each direction produced from the path of each transmitter and receiver pair are added directly. Considering that the energy of the Lamb wave ray in each direct transmitter–receiver air-coupled sensing path covers a large strip-shaped range [36], the final VTR-based probabilistic imaging algorithm can be expressed as

\[
P(x, y) = \sum_{m=1}^{M} \sum_{n=1}^{N_m} p_{mn}(x, y)
= \sum_{m=1}^{M} \sum_{n=1}^{N_m} vDI_{mn} E(R_{mn}(x, y)),
\]

where \(P(x, y)\) denotes the probability of damage occurrence at the position \((x, y)\); \(M\) is the number of scan directions; \(N_m\) is the number of scan steps in the scan direction \(m\); \(p_{mn}(x, y)\) is the damage distribution probability estimation from the \(n_{th}\) scan step in the \(m_{th}\) scan direction; subscript \(mn\) indicates the \(n_{th}\) scan step in the \(m_{th}\) scan direction; \(vDI\) is VTR-based DI and can also be expressed by equation (6). However, in equation (6), \(V(t)\) is the reconstructed final signal with VTR algorithm, not the final signal reconstructed by using conventional time reversal method or MTR method. Due to the strip-shaped air-coupled Lamb wave ray, \(R_{mn}(x, y)\) is defined as the distance between the position \((x, y)\) and the center of the air-coupled Lamb wave ray and formulated as

\[
R_{mn}(x, y) = \begin{cases} 
|y - y_T| & y_T = y_R, \\
|x - x_T| & x_T = x_R,
\end{cases}
\]

where \(x_T, y_T, x_R,\) and \(y_R\) indicate the coordinates of the transmitter and receiver on \(x\) axis and \(y\) axis, respectively. \(E(R_{mn}(x, y))\) is the Gaussian decreasing function to estimate the energy distribution of the air-coupled Lamb wave ray and can be formulated as

\[
E(R_{mn}(x, y)) = \begin{cases} 
\frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{R_{mn}(x, y)^2}{2\sigma^2}} & R_{mn}(x, y) \leq D, \\
0 & R_{mn}(x, y) > D,
\end{cases}
\]

where \(D\) determines the width of the air-coupled Lamb wave ray and \(\sigma\) determines the decreasing ratio of Gaussian function. Herein, according to trial and error method, the parameters \(D\) and \(\sigma\) are respectively chosen as 12.5 mm and 0.3.

3.2.2. Full multiplication algorithm. The damage occurrence probability at the position \((x, y)\) on the path of each transmitter and receiver pair is obtained through the multiplication calculation among the damage occurrence probabilities at different directions. Therefore, the damage
probability in the composite plate is defined as

$$P(x, y) = \prod_{m=1}^{M} \sum_{n=1}^{N} p_{mn}(x, y) = \prod_{m=1}^{M} \sum_{n=1}^{N} \nu D_{nm} E(R_{nm}(x, y)). \quad (11)$$

The choices of parameters are the same as that in the former full summation algorithm.

4. Experimental system of air-coupled Lamb wave scan in composite plates

4.1. Experimental setup

The schematic diagram of experimental setup of air-coupled Lamb wave scan in composite plates is shown in figure 4(a).

The experimental setup consists of a high-power ultrasonic measurement system Ritec-RAM5000 with a high-dB pre-amplifier, a personal computer (PC), an oscilloscope, a scan mechanism, and a pair of air-coupled ultrasonic transducers. The Ritec-RAM5000 is used to actuate high-power tone burst voltages for the actuation of the transmitting transducer and to amplify the received signal of the receiving transducer. The operation of the Ritec-RAM5000 is controlled by the developed procedural control software in a PC. The oscilloscope is used to acquire and store the received Lamb wave signals. The air-coupled ultrasonic transducers employed here are circular gas matrix piezoelectric composite transducers produced by the Ultran Group (model: NCG200-D13). These unfocused air-coupled ultrasonic transducers have a center frequency of 200 kHz and the bandwidth at −6 dB is 62 kHz. Three axis motions of air-coupled ultrasonic transducers can be achieved with the scan mechanism shown in figure 4(b).
The air-coupled ultrasonic transducers are clamped to the scan mechanism with the transducer fixtures. The transducer fixtures can be adjusted to orient the air-coupled ultrasonic transducers at a special incident angle for the actuation and reception of the selected Lamb wave signals.

4.2. Composite plate specimens

In this paper, the specimens are 16-layer quasi-isotropic carbon fiber-reinforced composite plates with [(0/45/90/−45)_S]_T lay-up. Each layer of the composite plate is 0.14 mm thick and hence the total thickness is 2.24 mm. The material properties of these composite specimens are listed in Table 1. For the composite specimens with delamination, delamination damage is artificially introduced by inserting Teflon film (0.05 mm in thickness) between the selected layers during the lay-up procedure.

5. Experimental validation of VTR algorithm

To experimentally validate the proposed VTR algorithm, MTR operation and VTR operation are performed simultaneously with the same experimental setup and transducer arrangement. The dimensions of the composite specimen are 800 mm (length) × 30 mm (width) × 2.24 mm (thickness). Figure 5 illustrates three-dimensional view and side view of transducer arrangement for experimental validation of VTR method. As shown in figure 5, air-coupled ultrasonic transducer A is placed in the position above the composite specimen and 225 mm away from the left end of the composite specimen. Air-coupled ultrasonic transducer B is placed in the position 200 mm away from the transducer A in the same side of the composite specimen. To actuate and receive the relatively pure A0 mode Lamb waves, the incident angle of both the transducer A and the transducer B are adjusted to 14° [28]. As illustrated in figure 5(b), the distance from air-coupled ultrasonic transducers to the surface of composite specimen, \( h \), is small. In this experiment, \( h \) was confirmed to be about 10 mm.

The MTR process is implemented through three experimental steps. Figure 6 gives the accentuated and received signals during the time reversal process. For the MTR method, in the first step, a 5-cycle 200 kHz sinusoidal tone burst modulated by a Hanning window shown in figure 6(a) is firstly applied on the transducer A and the first received signal of the transducer B is plotted in figure 6(b). In the second step, the received A0 mode Lamb wave signal is intercepted by a 50 μs width rectangular window and reversed in time domain, as shown in figures 6(b) and (c), respectively. In the third step, the reversed signal is applied at the transducer A, and the reconstructed final signal is plotted in solid line in figure 6(d). By comparing the reconstructed signal obtained from the proposed VTR algorithm with that obtained from the MTR method in figure 6(d), it is observed that the reconstructed final signal based on VTR algorithm is well consistent with that based on MTR method.

6. Experimental test of composite plates with delaminations

Four carbon fiber-reinforced composite plate specimens with the delaminations of different shapes and sizes are scanned with the developed air-coupled Lamb wave scan technique and VTR algorithm in this section. Each composite testing specimen has a size of 800 mm (length) × 800 mm (width) × 2.24 mm (thickness). A 30 mm × 70 mm rectangular delamination, two circular delaminations with the diameters of 60 mm and 30 mm and a trapezoidal delamination are introduced into the four composite specimens separated by inserting Teflon film (0.05 mm in thickness) between the fourth and fifth layers during the lay-up procedure. The dimensions and locations of the delaminations are illustrated in figures 7(a)–(d). As illustrated in figures 7(a)–(d), the scan areas enclosing the delaminations are all 200 mm × 200 mm. The composite testing specimens are scanned from positive sides. The positive side scan and the located layer of the delamination in composite plate specimen are illustrated in figure 8.

The lay-up direction of the first fiber is defined as the reference angle (0°) and the scan angles in the experiment are based on the reference angle. The distance between the

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**Table 1.** Material properties of 16-layer carbon fiber-reinforced composite plate.

| Property | \( E_1 \) (GPa) | \( E_2 \) (GPa) | \( E_3 \) (GPa) | \( G_{12} \) (GPa) | \( G_{13} \) (GPa) | \( G_{23} \) (GPa) | \( ν_{12} \) | \( ν_{13} \) | \( ν_{23} \) | \( ρ \) (kg m\(^{-3}\)) |
|----------|----------------|----------------|----------------|----------------|----------------|----------------|-----------|-----------|-----------|--------------|
| Value    | 135            | 8.8            | 8.8            | 4.47           | 4.47           | 3.45           | 0.3       | 0.3       | 0.34      | 1560         |
transmitter and receiver in the pitch-catch configuration is 200 mm. During the scan process, the transmitter and receiver are moved simultaneously as a unit. The incident angles of both the transmitter and receiver are 14° such that $A_0$ mode can be the most efficiently actuated and received in the composite testing specimens [28].

6.1. The comparison of different damage indices for the image results

In contrast to the proposed VTR-based probabilistic imaging algorithm for air-coupled Lamb wave scan, other signal features are selected and analyzed here, such as amplitude and velocity. Herein, the tested object is the composite plate specimen with rectangular delamination (30 mm × 70 mm). For the acquisition of VTR-based DI of each scan step, VTR process is performed based on equation (5). Then, the VTR-based DI, $v_{DI}$, of each scan step is evaluated with equation (6). However, the damage indices based on amplitude and velocity are defined by the direct wave amplitude and arrival time changes of each scan step.

Several normalized damage indices of two directions (0° and 90°) by 4 mm scan step for composite plate specimens with rectangular delamination (30 mm × 70 mm) are plotted in figures 9(a), (b), 10(a), (b), 11(a) and (b). It is observed that the damage indices obtained based on different methods of the delamination area are larger than those of the healthy area. Under healthy conditions, the values of damage indices are non-zero and show some fluctuations due to the complicated scattering characteristic of Lamb waves, the interaction with delamination, and additional contribution of signal noise. It is noted that the damage indices will rapidly increase when the scan path is located around the edge of delamination.

According to those damage indices and equations (8)–(10) proposed in subsection 3.2, the image results obtained based on full summation algorithm of the delaminations with two orthogonal directions scan (0° and 90°) are illustrated in figures 9(c), 10(c) and 11(c). The results are basically consistent with the actual shapes and locations of the delaminations marked in white lines.

Although the changes in amplitude and velocity are the simple and common signal features according to the definitions of the damage indices, they have some limitations in some cases. For example, once the distance between the actuator and receiver is changed, it is difficult to define the damage indices when excluding the effect of the distance. The damage indices based on the proposed VTR algorithm are not related to amplitude or velocity, but they are correlated to the nonlinear characteristic information in direct wave. Therefore, the VTR-based DI has wider application fields.

6.2. Effects of the scan steps and directions on the image results

Images are reconstructed with equations (8) and (11) proposed in subsection 3.2, in which $N_{\text{act}}$, the number of scan steps...
Figure 7. Illustration of the scan area arrangement and the composite testing specimens with (a) rectangular delamination (30 mm × 70 mm) (b) circular delamination with the diameter of 60 mm; (c) circular delamination with the diameter of 30 mm and (d) trapezoidal delamination. All delaminations are between the fourth and fifth layers of composite plate specimens for the positive side scan.
Figure 8. Illustration of the positive side scan and the located delamination layer in composite plate specimen. $h$ represents the total thickness of the composite plate specimen, 2.24 mm.

Figure 9. The scan results of the 4 mm step for composite plate specimen with rectangular delamination (30 mm $\times$ 70 mm) based on index values of velocity, the normalized damage index values in two directions of (a) 0° and (b) 90°, and (c) the image obtained with full summation algorithm.

Figure 10. The scan results of the 4 mm step for composite plate specimen with rectangular delamination (30 mm $\times$ 70 mm) based on index values of amplitude, the normalized damage index values in two directions of (a) 0° and (b) 90°, and (c) the image obtained with full summation algorithm.

Figure 11. The scan results of the 4 mm step for composite plate specimen with rectangular delamination (30 mm $\times$ 70 mm) based on index values of VTR, the normalized damage index values in two directions of (a) 0° and (b) 90°, and (c) the image obtained with full summation algorithm.
steps in the scan direction is personally selected. To study and evaluate the effect of number of scan steps on the image, three different scan steps (2 mm, 6 mm and 8 mm) are respectively added in the experiment. The normalized VTR-based DI values of two scan directions (0° and 90°) with different scan steps for composite plate specimen with rectangular delamination (30 mm × 70 mm) are plotted in figures 12(a), (b), 13(a), (b), 14(a) and (b). Obviously, the damage localization resolution largely depends on the number of the scan steps. When the number of the scan steps increases (namely the length of scan steps decreases), an adequate location resolution of delamination edge can be obtained.

According to equations (8)–(10) of full summation algorithm, the image results with two orthogonal scan directions (0° and 90°) for the composite plate specimen with rectangular delamination (30 mm × 70 mm) at different scan steps are shown in figures 12(c) with the 2 mm step, 13(c)
with the 6 mm step, and 14(c) with the 8 mm step. Combined with the image result obtained with the 4 mm step in figure 11(c), it is observed that the smaller length of scan step indicates the higher resolution of the image as well as the slower scan speed. However, it is preferable to select the 4 mm scan step, which is enough to distinguish the delamination well and does not require too long scan time. Therefore, the length of scan step is determined to be 4 mm in the later experiments to inspect the composite plate specimens with the delaminations of different shapes and sizes.

To identify the delamination shape, it is rather necessary and critical to carry out the scans in different directions. Herein, the schematic of the scan process in different directions with Lamb waves is shown in figure 15(a) in which $\phi$ denotes the rotation angle of scan area in counterclockwise direction. The image results obtained through scanning in another two sets of orthogonal directions (30° and 120°, 60° and 150°) by full summation are illustrated in figures 15(b) and (c), respectively. It is easily found that the distinguished shapes of the delaminations are closely related to the scan directions used in the proposed method for composite inspection because the projected results of delaminations obtained under different scan directions will be necessarily different.

6.3. The assessment of different geometrical delaminations for the image results

Based on the results obtained in subsection 6.2, to judge the shape of the delamination and alleviate the influence of scan directions on image result, the image results obtained in several scan directions should be integrated together for a better visualization of defect identification.

Final images are reconstructed with equations (8)–(11). Three sets of orthogonal directions (0° and 90°, 30° and 120°, 60° and 150°) are employed here for the four composite plate specimens with the delaminations of different shapes and sizes, as shown in figures (16)–(19). The actual shapes and locations of the delaminations are marked in white lines. There are lots of interference signals around the delaminations in the image results shown in figures 16(b), 17(b), 18(b) and 19(b) obtained with full summation algorithm. However, the image results in figures 16(c), 17(c), 18(c) and 19(c) based on the full multiplication algorithm give a higher identification resolution of the defect for the delaminations. Comparing the
actual delamination locations with the results obtained with commercial point-to-point immersion C-scan system shown in figures 16(a), 17(a), 18(a) and 19(a), the delaminations of these composite plate specimens are detected and located in the reconstructed images. Because the transducers are unfocused and have relatively large sizes, the reconstructed shapes and sizes of delaminations are not so precise as the results obtained with the commercial point-to-point immersion C-scan system. However, the immersion C-scan is extremely time-consuming and sometimes even impossible for large-scale composite structures.

7. Conclusions
In this paper, VTR algorithm was proposed for baseline-free damage inspection. In the proposed VTR method, like typical pitch-catch Lamb wave-based testing, only one actuating-
receiving step was required and the hardware manipulation for time reversal process was not required. Delaminations of the selected sensing path can be evaluated through comparing the first input actuation signal with the reconstructed final signal with VTR algorithm. With the VTR algorithm, a non-contact air-coupled Lamb wave scan method was developed for the delamination inspection of composite plates. VTR-based probabilistic imaging algorithm developed from RAPID technique was used to implement damage reconstruction in air-coupled Lamb wave scan process. With the developed air-coupled Lamb wave scan method, four carbon fiber-reinforced composite plates with the delaminations of different shapes and sizes were tested experimentally. The testing results were well consistent with the actual delamination locations and the results obtained with the commercial point-to-point immersion C-scan system. Furthermore, the effects of the scan steps and directions on the image results were also investigated. The inspection results demonstrate that the developed technique obtained through combining non-contact air-coupled Lamb wave scan method and VTR algorithm has good potential to locate and image delaminations in composite plates.

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