Image Fusion Based on Single-frequency Guided Wave Mode Signals for Structural Health Monitoring in Composite Plates

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ABSTRACT

This paper presents the application of ultrasonic guided waves to the detection and imaging of discontinuities by using a distributed sparse transducer array in a quasi-isotropic composite plate. Considering the anisotropic property of composite plates, a group velocity polar profile of the S_0 mode at 200 kHz in different azimuthal directions in the plate was first measured by experimental techniques and achieved good agreement with theoretical predictions. The 2D visualization of single and double simulated discontinuity locations in the composite plate can be achieved by the combination of ultrasonic guided wave technology and a discrete ellipse imaging algorithm. Furthermore, three types of algorithms, namely full summation, full multiplication, and summation and multiplication combination, were employed to reconstruct the discontinuity location. The results show that summation and multiplication combination can enhance the image fusion ability of discontinuity information in the composite plate compared with the other two algorithms. Therefore, this ultrasonic guided wave technique based on the discrete ellipse imaging fusion approach can be effectively used for accurate discontinuity detection and imaging of anisotropic composite plate structure.

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Introduction

Composites are extensively used in numerous industrial areas such as aerospace, automotive, wind power and civil construction due to their high stiffness-to-weight ratio, good fatigue resistance and easy-processing properties. However, because of the complex processing technology and harsh working conditions, the failure forms of composites such as interlaminar shear delamination, fiber fracture and matrix cracking are frequently found during the production process production and use of composite structures. It is very important to evaluate the safety state of composite structures effectively and conveniently. As an emerging technology, structural health monitoring (SHM) is being increasingly considered for better safeguarding composite structures to avoid expensive or even catastrophic failures. As one of the more commonly used SHM approaches, the ultrasonic guided wave testing method is particularly effective for fast, large-area interrogation of composite structures with high sensitivity to discontinuities, low-energy loss and mode tuning (Rose, 2002). Furthermore, ultrasonic guided wave imaging with spatially distributed transducer arrays offers a fast, reliable, cost-efficient and therefore promising technique for damage visualization and characterization (Hall and Michaels, 2010; Hall et al., 2011; Michaels et al., 2011). However, three types of artifacts will affect the quality and localization accuracy of discontinuities: phasing artifacts, extra signal artifacts, and signal alignment and distortion artifacts, (Michaels and Michaels, 2006). These artifacts may appear at different locations on the different images using spatially distributed transducer arrays. An appropriate image fusion algorithm can be used for multiple image combination to highlight the discontinuity information and effectively reduce the various artifacts (Clarke and Cawley, 2011; Moll et al., 2010). A recent study superimposed the image obtained from each actuator and sensor signal path to reconstruct potential damage area (Ng and Veidt, 2009). Another study used two imaging fusion algorithms based on both the summation and multiplication processes for discontinuity imaging in aluminum based on distributed sparse transducer arrays (Yu et al., 2010). Two further studies applied a distributed sparse piezoelectric transducer array to generate guided waves in plates and proposed multi-frequency signal fusion technology to improve the image quality for obtaining accurate damage localization (Michaels and Michaels, 2006; Michaels et al., 2011). All of these researchers showed good application potential using imaging fusion for composite SHM.

In this paper, the excitation frequency of the ultrasonic guided wave mode, S_0 mode, in a composite plate was optimized, then the group velocity of this S_0 mode in different azimuthal directions was also measured for discontinuity imaging. For the implementation of discontinuity imaging in the composite plate, a distributed sparse transducer array was constructed to acquire single-frequency signals of S_0 mode for SHM in composite plates. Finally, based on these obtained single-frequency guided wave signals, a discrete ellipse localization technique was used for discontinuity imaging. Furthermore, three types of image fusion algorithms were used to combine multiple images to reconstruct and highlight the discontinuities. Based on these image fusion results, the reconstruction ability and robustness to discontinuities of these image fusion algorithms were evaluated.

Group Velocity Measurement of Ultrasonic Guided Waves in Composite Plate

Group velocity of ultrasonic guided waves at a certain frequency varies with propagation direction in anisotropic composite plate. Therefore, it is necessary to measure group velocity of ultrasonic guided waves in different azimuthal directions experimentally for defect location and imaging.

Choice of Excitation Frequency

The anisotropic nature of composite structures introduces complex phenomena to wave propagation, such as direction-dependent phase and group velocities (Pan et al., 2006; Rhee et al., 2007). Furthermore, ultrasonic guided wave propagation shows a pronounced dispersive behavior. In general, considering high attenuation of composite plates, the first two fundamental guided wave modes, A_0 and S_0, are often considered for damage detection (Quaegebeur et al., 2010). Compared with the A_0 mode, which is highly dispersive, the S_0 mode exhibits lower dispersion and attenuation in the low frequency range. Moreover, the S_0 mode has the fastest group velocity and thus can first be received. These properties will benefit signal interpretation. Therefore, it is satisfactory to use the S_0 mode for discontinuity detection of composite plates.

Even with the same ultrasonic guided wave mode, different frequencies have different propagation characteristics, such as dispersion, anisotropic velocity profile and so on. As a result, on condition that the transducers are determined, it is necessary to choose the proper excitation frequency of the S_0 mode to enhance the discontinuity detection ability of ultrasonic guided waves. Here, the chosen transducer was a circular piezoelectric element with through-thickness polarization. Its diameter was 18 mm and its thickness was 0.5 mm. In these experiments, the test specimen was a T300/QY8911 quasi-isotropic carbon fiber composite plate with the dimensions of 650 × 600 × 1.5 mm and 10 plies of the stacking sequence [45/–45/0/90/0] symmetric. The thickness of each ply was 0.15 mm.

The response of the S_0 mode was measured in the low frequency range in pitch-catch mode using a pair of chosen circular piezoelectric elements. The first waveform in the received signal could be confirmed to be the direct S_0 mode because this is the fastest lamb wave mode in the low frequency range. Figure 1 gives normalized peak amplitudes of the Hilbert envelope of the direct S_0 mode signals in the frequency range of 50 to 300 kHz along the 0° azimuthal direction of the composite plate specimen. The frequency increment was set to 10 kHz. As indicated in Figure 1, the amplitude pattern shows that the mono peak curve and the amplitude peak occurred at 160 kHz.

To improve the sensitivity of the S_0 mode to discontinuities in composite plates, the excitation frequency of this mode with large wavelength or fast velocity should be increased to a certain extent. Here, the excitation frequency of the S_0 mode was confirmed to be 200 kHz. The wavelength of the S_0 mode at 200 kHz decreased to approximately 80% of that at 160 kHz. It will improve the interaction between the S_0 mode and discontinuities; thereby, discontinuity-induced signals can be found more easily. Although the Hilbert envelop amplitude of the S_0 mode signal at 200 kHz was 65% of that at 160 kHz, the signal-to-noise ratio of received signals was still quite good. Therefore, the amplitude loss of the S_0 mode signal at 200 kHz will not almost deteriorate the identification ability to discontinuity-induced signals.

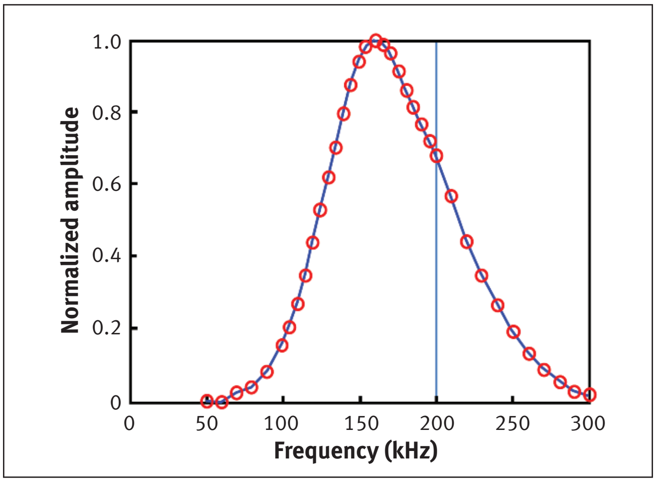

Figure 1. Normalized peak amplitudes of the Hilbert envelope of the direct S_0 mode signals in the frequency range of 50 to 300 kHz along a 0° azimuthal direction of the composite plate specimen.

Group Velocity Measurement S_0 Mode

To locate and image the discontinuities in composite plates, group velocities of the S_0 mode in different azimuthal directions in the composite plate sample need to be measured. Therefore, in this section, group velocities in different azimuthal directions of the S_0 mode were first measured for discontinuity localization and imaging for the quasi-isotropic composite plate specimen. Figure 2 displays the schematic diagram of the experimental setup for group velocity measurement of the S_0 mode in a composite plate. This experimental setup consisted of a computer, function generator, power amplifier, digital oscilloscope, preamplifier, transducers and motion platform with a rotatable circular plate. The material property of the quasi-isotropic composite plate sample is as follows: E_1 = 135 GPa, E_2 = 8.8 GPa, E_3 = 8.8 GPa, G_{12} = 4.47 GPa, G_{23} = 3.45 GPa, G_{13} = 4.47 GPa, ν_{12} = 0.3, ν_{23} = 0.34, ν_{13} = 0.3, ρ = 1560 kg/m^3.

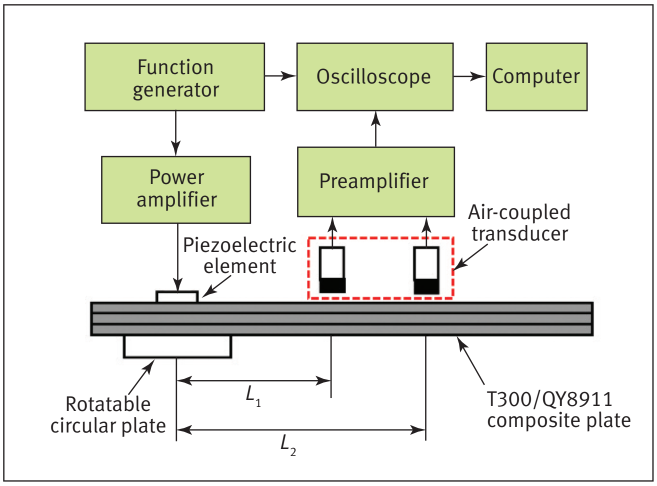

Figure 2. Schematic diagram of the experimental setup for group velocity measurement of the S_0 mode in the composite plate.

Two kinds of transducers were applied here. One of them was the circular piezoelectric element, which was identical to those already used to measure the amplitude of the S_0 mode. It was glued to the center of the composite plate surface and used as the transmission source to generate ultrasonic guided waves omnidirectionally in the composite plate. The other transducer was composed of two noncontact air-coupled transducers with a center frequency of 200 kHz and used as receivers. These air-coupled ultrasonic transducers were circular gas matrix piezoelectric composite transducers with a diameter of 12.5 mm. They were fixed on the motion platform along the same line with the piezoelectric element and were L_1 =150 mm and L_2 = 200 mm away from the center of the piezoelectric element. These two receivers were used to make accurate group velocity measurement of the S_0 mode possible. Group velocity of the S_0 mode was calculated from the arrival time difference between the two receivers, which was determined using the peak time of the Hilbert envelopment of the first wave packet, that is, the S_0 mode for a given distance from the excitation source to these two receiver transducers. Obviously, the distance difference, $\Delta L = L_1 - L_2$, between these two receivers equaled 50 mm. The composite plate sample was put on the rotatable circular plate. By rotating the plate, the signals at different directions in the composite plate could be acquired. Figure 3 gives the experimental group velocity polar profile of the S_0 mode at 200 kHz for the composite plate. In this figure, both experimental results and theoretical predictions are presented and are in good agreement with each other. This result also illustrates that, as expected, group velocity of the S_0 mode varied greatly with the azimuthal direction and thereby is dependent on the azimuthal angle. The group velocity polar profile information of the S_0 mode will be used in the discontinuity imaging algorithm.

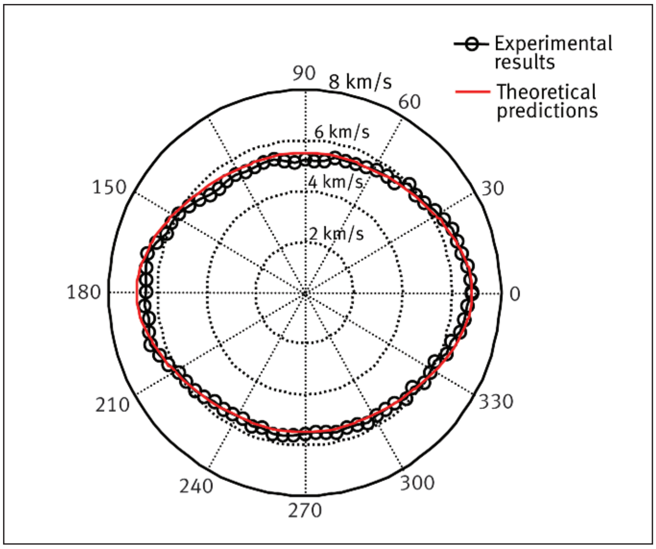

Figure 3. Group velocity polar profile of the S_0 mode at 200 kHz.

Discrete Ellipse Imaging Fusion Approach

In this section, discontinuities localization is performed by using discrete ellipse localization technique. Furthermore, three types of imaging fusion approaches are used to highlight discontinuities location and their achievement are also given and discussed.

Discrete Ellipse Localization Technique

The paper addresses the application of the discrete ellipse localization technique to localize the discontinuities in composite plates. Figure 4 illustrates this technique by using a distributed sparse transducer array. Each of the transducers in

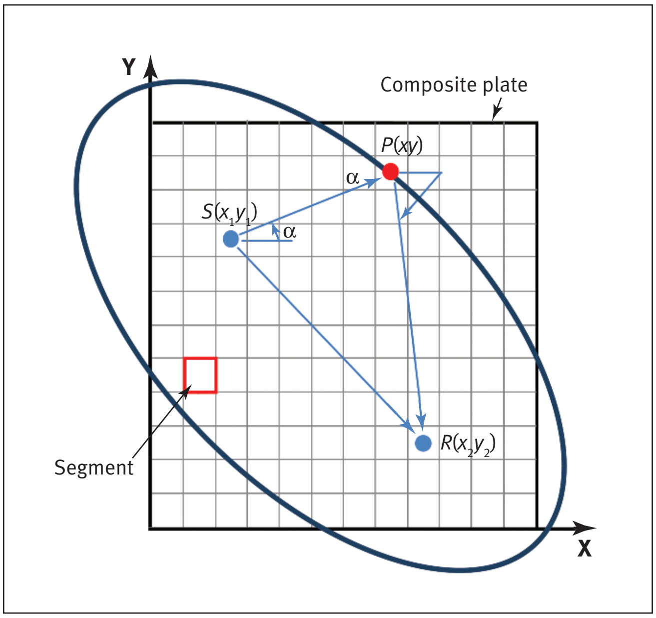

Figure 4. Discrete ellipse localization technique using a distributed sparse transducer array.

the array can be used as both actuator and sensor for transmission and reception of ultrasonic guided waves, respectively. As is shown in this figure, the composite plate was spilt into discrete segments with dimensions of 5 × 5 mm. In this figure, only two transducers were shown for simplicity. Points *S* and *R* represent the transmitter and receiver of the *i*th transducer pair of a transducer array distributed on the surface of composite plate, respectively. These two transducers can be regarded as two foci of an ellipse, and an ellipse can be drawn based on these two fixed transducer locations.

Considering the coordinate of an arbitrary discrete segment, point *P*, in the composite plate is (x,y), shown in Figure 4. The transmitter and receiver of the *i*th transducer pair were located at the coordinates (x_1^i, y_1^i) and (x_2^i, y_2^i). Given the directivity of ultrasonic guided wave propagation in the composite plate, the time of flight, t_i^{xy}, of guided waves reflected from point *P* can be calculated to be:

$$(1)\qquad t_i^{xy} = \frac{\sqrt{\left(x_1^i - x\right)^2 + \left(y_1^i - y\right)^2}}{c_g\left(\alpha_t\right)} + \frac{\sqrt{\left(x_2^i - x\right)^2 + \left(y_2^i - y\right)^2}}{c_g\left(\alpha_r\right)}$$

where

α_t is the azimuthal angle from the transmitter to point *P*,
α_r is the azimuthal angle from point *P* to the receiver,
$c_g(\alpha_t)$ and $c_g(\alpha_r)$ are group velocities of guided waves along azimuthal directions of α_t and α_r, respectively.

As a result, the time of flight corresponds to the position of the composite plate. As known, only one ellipse determined by one transducer pair makes it impossible to detect the discontinuity with a reasonable degree of accuracy. For discontinuity location, the signals from at least three different transmission/reception pairs need to be used. The discontinuity can be located and imaged in the composite plate by which several ellipses intercept.

By using this discrete ellipse localization technique, the discontinuities in composite plates can not only be detected but also be localized and imaged.

Discontinuity Imaging and Image Fusion Technique

Based on the aforementioned concept of the discrete ellipse localization technique, the plate was then spilt up into identical discrete segments. The size of these segments can be personally defined according to the specific calculation, following that the smaller the size, the higher resolution of the image, but with lower calculation speed of the program. Here, the dimension of each segment was determined to be 5 × 5 mm.

When ultrasonic guided waves interact with a discontinuity, wave scattering occurs. The signal in the baseline state without a discontinuity is subtracted from that in the current state with the discontinuity directly, and there comes a scattering signal due to the presence of the discontinuity. The scattering signal is filtered using a wavelet and enveloped by the Hilbert transform. Images are constructed of the entire composite plate based on all processed scattering signals of the discontinuity, that is, differenced signals between the current state and the baseline state. Damage may be highlighted in all images by scattered signals from all possible transducer pairs induced by the discontinuities.

The scattering signal $r(t)$ can be obtained by the Hilbert transform, which is caused by the discontinuity. A set of $N_p = N(N-1)/2$ signals can be acquired when the number of the transducers of the distributed sparse transducer array is *N*. The average signal of each segment in the composite plate after processed scattering signal is shifted by t_i^{xy}:

$$(2)\qquad S\left(t;x,y\right) = \frac{1}{N_p}\sum_{i=1}^{N_p} r_i\left(t - t_i^{xy}\right) w\left(t - t_i^{xy}\right)$$

where

$w(t)$ is the windowing function,
t is time of the signal (Michaels and Michaels, 2007).

When the t_i^{xy} is the same as the propagating time from the scattering signal corresponding to a related discontinuity (which means when the zero time place possesses the largest amplitude), the amplitude of each discrete segment and the 2D distribution in the corresponding coordinates can be acquired.

For the convenience of giving prominence to discontinuity information, a logarithmic scale was used to express the amplitude of the images. For the work presented here, first the maximum image amplitude of all the segments, P_0, was determined, and then the logarithmic of the value coming from P_1 divided by P_0 was taken. Here, P_1 refers to the image amplitude of the arbitrary discrete segment. The result is defined as P, which expresses the decibel value of each segment as Equation 3.

$$P = 20\log_{10}\left(\frac{P_1}{P_0}\right) \tag{3}$$

Image fusion refers to the combining, or fusing, of these images to obtain an improved image with perhaps a better damage localization and signal-to-noise ratio (Michaels et al., 2011). The weighted average technique is the most conventional and direct approach to image fusion of low-level data. It is a technique that works directly upon the data source. Since the transducers used in the experiments here were identical, the weighted average could be applied to the fusion of the discontinuity scattering signals, which were obtained by the distributed sparse transducer array.

Based on the weighted average approach, three different types of imaging fusion algorithms, namely, full summation, full multiplication, and summation and multiplication combination, were proposed upon the discontinuity scattered signals obtained. The first two algorithms are commonly used for imaging fusion.

Full Summation Algorithm

Based on the full summation algorithm, the amplitudes at each segment produced from each transmitter and receiver pair of distributed sparse transducer array are added directly; thus the amplitude at an arbitrary segment in the composite plate is defined as:

$$I(x,y) = \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} S_{ij}\left(t_{ij}[x,y]\right) \tag{4}$$

where

S_{ij} is the Hilbert envelopment of the scattering wave signal obtained from the jth receiver when the ith transmitter is excited,

N is the number of transducers (Michaels and Michaels, 2007).

Full Multiplication Algorithm

Based on the full multiplication algorithm, the amplitudes at each segment produced from each transmitter and receiver pair are multiplied directly; thus, the amplitude at an arbitrary segment in the composite plate is defined as Equation 5 (Ihn and Chang, 2008).

$$I(x,y) = \prod_{i=1}^{N} \prod_{j=1, j\neq i}^{N} S_{ij}\left(t_{ij}[x,y]\right) \tag{5}$$

Summation and Multiplication Combination

The amplitude at each segment produced from each transmitter receiver pair is both summed and multiplied. The level of summation or multiplication used can be adjusted according to the requirements. If the number of multiplication amplitudes at a particular segment is zero, the obtained amplitude of each segment in an imaging plot is exactly the same as that of the full summation amplitude. As the number of the multiplications increases, the amplitude will be closer to that obtained using the full multiplication algorithm. Changing the number of multiplications can help enhance the image contrast and reduce the interference of the noise, thus improving the reliability of the discontinuity imaging. The result of this combination strategy is between those using the full summation and full multiplication algorithms.

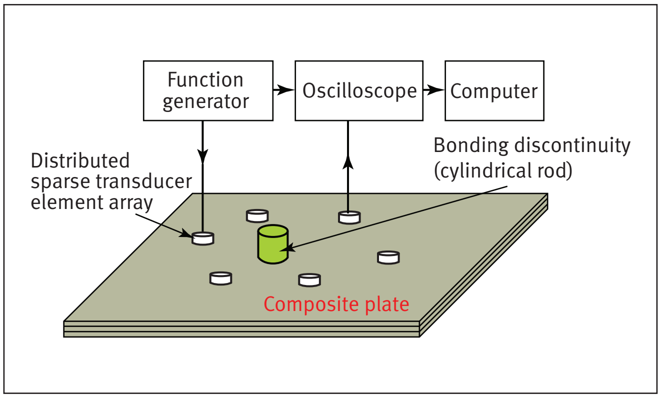

Figure 5. Schematic diagram of the experimental system for discontinuity detection using a distributed sparse transducer array in the composite plate.

Ultrasonic Guided Wave Testing and Discontinuity Imaging Fusion

Figure 5 shows the schematic diagram of an experimental system for discontinuity detection using a distributed sparse transducer array in the composite plate. Six identical circular piezoelectric elements were glued on one surface to construct a sparse transducer array. The sizes of these elements were also the same as that of the element used in the group velocity measurement.

A 10-cycle sinusoidal tone burst modulated by a Hanning window was used as the excitation signal and the center frequency was 200 kHz. The signal triggered by the function generator was stimulated on one of transducer elements of the distributed sparse transducer array as an actuator. Then, the propagating signals in the plate were received by the rest of the transducer elements. This step was then repeated by other transducer elements, and the signals were input into the digital oscilloscope and subsequently stored in the computer.

In these experiments, six transducer elements were used to construct a distributed sparse transducer array. Therefore, 30 groups of ultrasonic guided wave signals could be obtained, among which were 15 independent groups according to the acoustic reciprocity principle. These ultrasonic guided wave signals were collected, including those with and without discontinuities in the composite plate.

For the work presented here, the ultrasonic guided wave technology based on a discrete ellipse imaging fusion approach was applied here to try to pinpoint the simulated delaminations, which were simulated using bonding cylindrical rods glued on the surface of the composite plate.

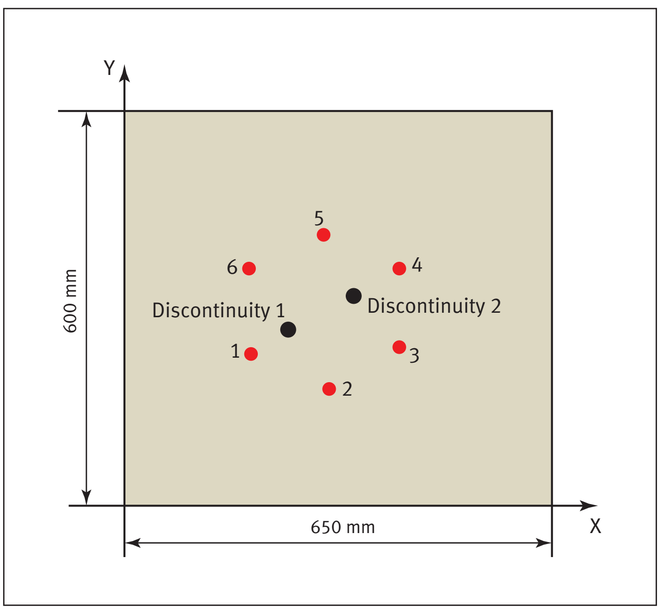

Figure 6. Illustration of the distributed transducer array and simulated discontinuity arrangement on the composite plate.

Despite the discrepancy of guided wave scattering by real delaminations and simulated bonding discontinuities, to a certain extent it was still feasible to simulate delaminations using bonding mass to the surface of the composite plates (Ng and Veidt, 2011). Here, two magnesium alloy cylindrical rods, with 26 mm diameter and 40 mm thickness, were fabricated and glued on the surface of the carbon fiber composite plate as simulated delamination discontinuities successively.

Figure 6 illustrates the distribution of the sparse transducer array and simulated discontinuity arrangement on the composite plate. In this figure, the red dots represent the locations of the transducer elements, while the black dots indicate the locations of bonding discontinuities. Furthermore, Table 1 gives the corresponding coordinates of the distribution of the sparse transducer array and simulated discontinuities in the composite plate.

Only simulated discontinuity 1 was glued on the surface of the composite plate. Figure 7 gives the imaging results of discontinuity 1 by using the different information fusion technique. Figures 7a and 7b give the image fusion results by using the full summation algorithm and full multiplication algorithm, respectively. Figures 7c and 7d give the image fusion results using the same summation and multiplication combination algorithm. However, their multiplication numbers were 3 and 5, respectively. Here, 3 multiplication represents, to an arbitrary segment, a summation and multiplication combination value by firstly obtaining all possible three amplitude combinations and summing these values to obtain a single value for discontinuity imaging. The term 5 multiplication may be deduced by analogy.

In all of these figures, the white plus symbols indicate the location of six transducer elements and the white 'o' symbol designates the simulated damage location. In these figures, it is easy to find that, among all the approaches used here, the full summation algorithm is the simplest and fastest way. However, as the energy used for discontinuity identification is the summation result of all the signals received by the scanning paths, there are many kinds of interference, shown in Figure 7a. Meanwhile, as shown in Figure 7b, the full multiplication algorithm gives the highest amplitude ratio and the

TABLE 1
Coordinates of distribution of the sparse transducer array and simulated discontinuities in the composite plate

Description	X (mm)	Y (mm)	Diameter (mm)
Transducer 1	205	230	18
Transducer 2	325	180	18
Transducer 3	445	230	18
Transducer 4	445	370	18
Transducer 5	325	420	18
Transducer 6	205	370	18
Discontinuity 1	250	280	26
Discontinuity 2	400	340	26

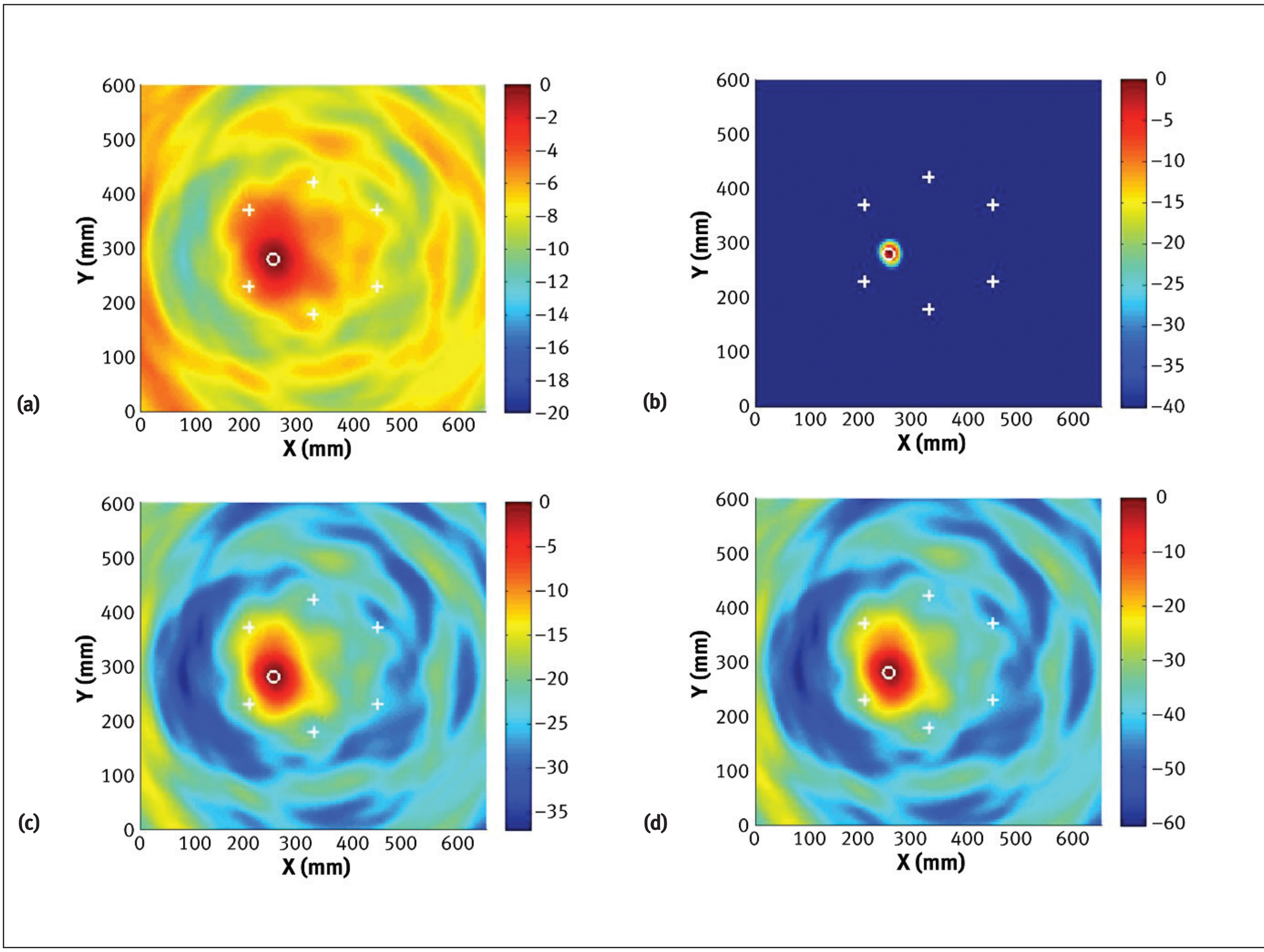

Figure 7. Image fusion results of discontinuity 1: (a) full summation; (b) full multiplication; (c) combination, 3 multiplication; (d) combination, 5 multiplication.

image of the one simulated discontinuity can be well identified. However, it does not provide any indication of the discontinuity location, even if one measurement fails to have the discontinuity pulse, which means low discontinuity tolerance.

As is illustrated in Figures 7c and 7d, the results of the summation and multiplication combination strategy are between those of the full summation and full multiplication algorithms. It is close to the full multiplication algorithm if the number of multiplications is more than that of the full summation algorithm using the summation and multiplication combination algorithm. It is a simple approach with the ability to determine the approximate damage range. Despite the similarity of the two images shown in Figures 7c and 7d, there is still a certain difference between their contrast degree and amplitude ratio, and the latter is more prominent than the former. Therefore, it is important to choose the appropriate image fusion technique for discontinuity reconstruction by the extraction of discontinuity-induced scattering signals in a composite plate, and at last to characterize the overall discontinuity information.

Next, both discontinuities 1 and 2 were glued on the surface of the composite plate simultaneously to further investigate the adaptability and robustness of these imaging fusion algorithms. Figure 8 gives the imaging fusion results of these two simulated discontinuities. According to Figure 8a, it is known that these two discontinuities could be detected and imaged using the full summation technique. But it suffers from numerous problems since the energy used for the identification of the discontinuities was the full summation result of all the signals received along all scanning paths. Figure 8b gives the processing result of the full multiplication algorithm. The scattered energy distribution of the guided wave caused by various discontinuities is different. The energy distribution

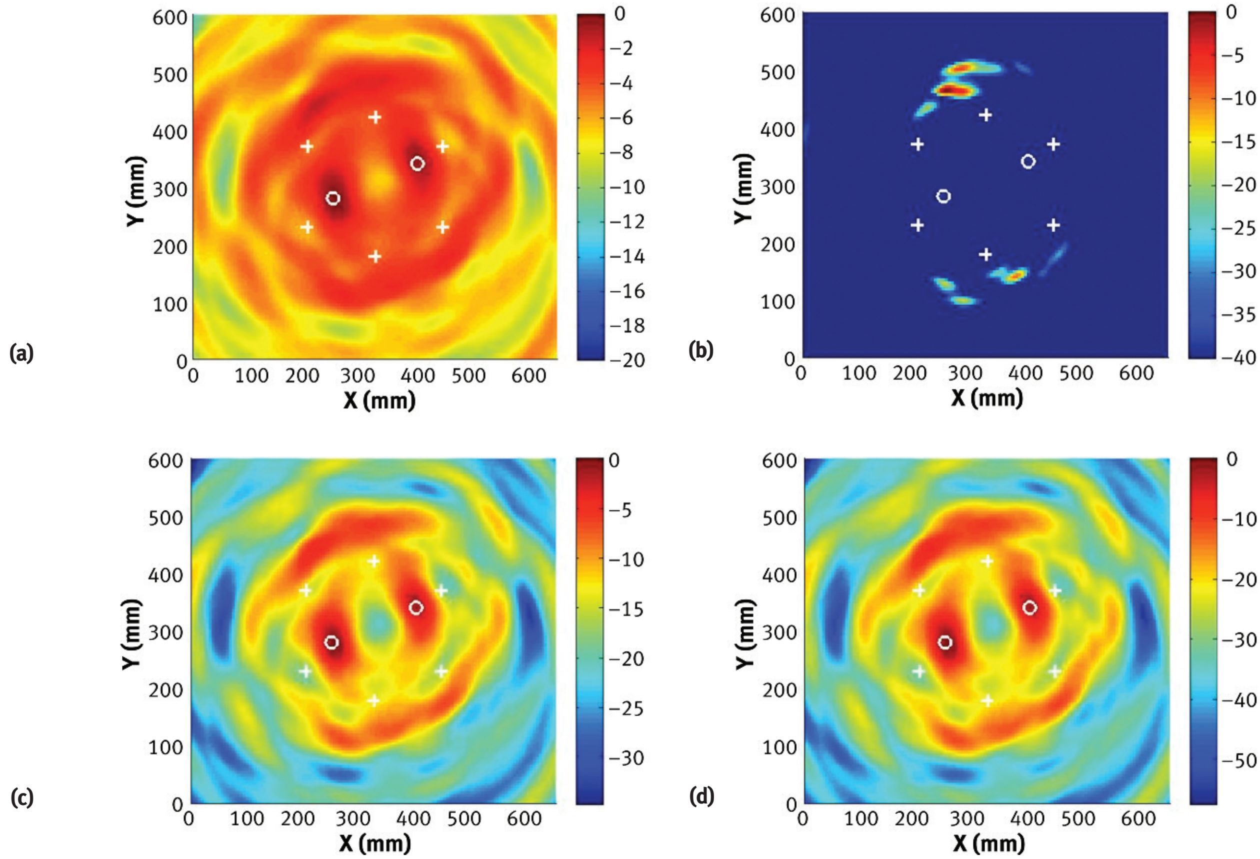

Figure 8. Image fusion results of discontinuities 1 and 2: (a) full summation; (b) full multiplication; (c) combination, 3 multiplication; (d) combination, 5 multiplication.

of guided wave signals in the composite plate will have a drastic change through the full multiplication algorithm on the different energy at each pixel point. Although the contrast result of the image is very prominent, it was found to produce artifacts outside the transducer array, and the discontinuities were hardly identified. Figures 8c and 8d show the results of the summation and multiplication combination technique. From these images, it can be known that this technique helps reduce the interference of artifacts effectively, and it can also determine the approximate damage range.

Figures 9a and 9b give a sectional view of the reconstructed damage localization images of Figure 8a along the X and Y axes through the actual simulated damage positions for the appearance of both bonding discontinuities 1 and 2. Actually, Figures 9a and 9b show the maximum normalized amplitude at any Y or X values for a given X or Y values in Figure 8a. These figures illustrate that the amplitude distribution of the double discontinuities proceeds by the summation and multiplication combination algorithm along the two coordinate axes, X and Y. The area between the two red lines is the actual positions of the discontinuities, while the two peak points of the curve refer to their positions, which means an accurate localization result. Both of these figures show that the reconstructed localization image accurately located these two simulated damages.

A similar phenomenon, as shown in Figures 7c and 7d was also found. The difference between their contrast degree and amplitude ratio is shown in Figures 8c and 8d. Figures 9c–9f give sectional views of the reconstructed damage localization images of Figures 8a and 8b along the X and Y axes through the actual simulated damage positions for both bonding discontinuities 1 and 2 appearance. It was found that the discontinuity location could be more unambiguously determined in both X and Y directions when the number of

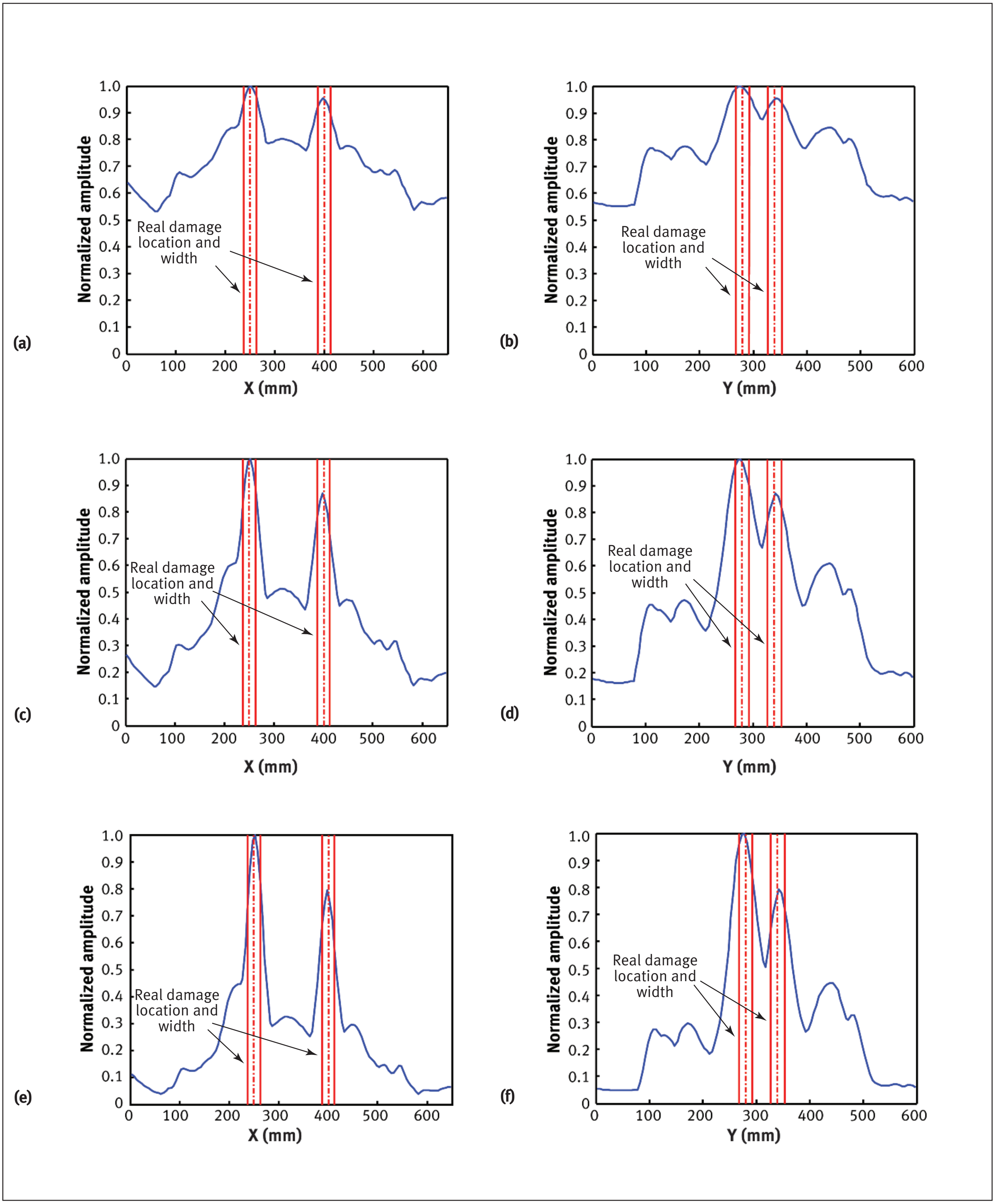

Figure 9. Sectional view of the reconstructed damage localization image of: (a) Figure 8a along the X axis; (b) Figure 8a along the Y axis; (c) Figure 8c along the X axis; (d) Figure 8c along the Y axis; (e) Figure 8d along the X axis; and (f) Figure 8d along the Y axis through the actual simulated damage positions for the appearance of both bonding discontinuities 1 and 2.

multiplication at each segment increased from 3 to 5. Of course, the number of multiplication cannot increase or change randomly, as shown in Figure 8b. When the number of multiplication cannot increase to the maximum, the summation and multiplication combination algorithm will change to full multiplication. However, the discontinuity could not be identified in Figure 8b. Therefore, it is important to choose the proper number of multiplications for the summation and multiplication combination algorithm.

Conclusion

In this paper, the S_0 mode was used for discontinuity imaging in a quasi-isotropic composite plate. Firstly, the excitation frequency of the S_0 mode was chosen to be 200 kHz. The group velocity was in different azimuthal directions of the S_0 mode at 200 kHz for discontinuity location and imaging. From the present work, a conclusion can be drawn that anisotropicity of a composite plate exerts a huge influence on the propagation of the ultrasonic guided waves. Besides, the work gives further proof that the measurement of the group velocity is a radical step in the application of ultrasonic guided wave for the interrogation and localization of composite plates.

The ultrasonic guided wave technology, based on the discrete ellipse localization technique and image fusion approach, was implemented in a quasi-isotropic carbon fiber composite plate, with the aim to locate and image the simulated discontinuities. Three types of imaging fusion algorithms, namely full summation, full multiplication, and summation and multiplication combination, were used for image fusion of the discontinuities. It was found that the summation and multiplication combination could effectively highlight the discontinuity position and remedy the shortcoming of the full summation and full multiplication algorithms.

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