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DELAMINATION DETECTION IN COMPOSITE PLATES USING LINEAR AND NONLINEAR ULTRASONIC GUIDED WAVES

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ABSTRACT

This paper presents a delamination detection strategy for composite plates using linear and nonlinear ultrasonic guided waves via the wave field imaging and signal processing based on Scanning Laser Doppler Vibrometry (SLDV). The anisotropic elastodynamics in composite plates is first studied. Two numerical methods are deployed to analyze the wave mechanics within the composite plates. The Semi-analytical Finite Element (SAFE) method is utilized to obtain the dispersion curves and mode shapes for a carbon fiber composite plate by bonding two quasi-isotropic carbon fiber composite panels together. The Local Interaction Simulation Approach has been employed to investigate the wave propagation and interaction with the delamination. Contact Acoustic Nonlinearity (CAN) between the delamination interfaces during wave damage interaction is presented as a potential mechanism for delamination detection. After developing an in-depth understanding of the wave propagation and wave damage interaction mechanism, active sensing experiments are conducted using the Piezoelectric Wafer Active Sensors (PWAS) and the Scanning Laser Doppler Vibrometry (SLDV). Two delamination imaging methodologies are presented. The first one utilizes the total wave energy to detect the delamination, taking advantage of the trapped modes within the delaminated area. The second one adopts the nonlinear second harmonic imaging algorithm, highlighting the nonlinear interaction traces at the delamination region. The damage detection images are finally compared and fused to provide detailed diagnostic information of the delamination. The damage imaging technique presented in this paper possesses great potential in material evaluation and characterization applications. This paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: delamination, composite, Scanning Laser Doppler Vibrometry, damage detection, structural health monitoring, nondestructive evaluation, nonlinear ultrasonics

1. INTRODUCTION

Composite materials are taking an increasingly important role in aerospace and automobile industries for their strong and light-weight features. However, the failure mechanism and modes are quite complex and hard to predict. Thus, the Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) strategies become critically important to ensure the safe operation of composite structures. However, the evolution of damage in composite structures undergoes several stages, such as matrix cracking, matrix-fiber deboning, delamination, and fiber breakage. During such a procedure, the damage sites are mostly hidden underneath the laminate surface and are hard to be noticed. This brings considerable challenge to the conventional NDE techniques based on optical observations.

Guided waves have been widely researched as an effective interrogating tool for SHM and NDE. They are able to propagate long distances without much energy loss, which enables the monitoring of large structural areas from local active sensing points. Their sensitivity to incipient structural changes further facilitates the detection of various kinds of structural damage [1]. However, composites generally possess anisotropic material properties, which may impose great difficulty on Time-of-Flight (ToF) based guided wave techniques. Moreover, the damping effect in the polymer based fiber reinforced composites is not negligible compared with metallic materials. The wave energy attenuation may arose further challenges for large area inspection, which may dissipate important damage information carried by certain wave modes sensitive to material damping [2].

Pioneer research activities have been carried out for delamination detection using ultrasonic guided waves. Targeting at solving the anisotropic material property challenge, the multiple signal classification algorithm has been proposed for impact damage detection in composite panels [3]. Compared with sparse sensor array methods, the Scanning Laser Doppler Vibrometry (SLDV) has been investigated as a promising tool

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for high resolution damage imaging [4]. Tian et al. proposed a rapid imaging method with advanced signal post-processing techniques for impact damage and delamination imaging in a composite plate using SLDV [5]. Geetha et al. also adopted the scanning wave field for delamination imaging in a composite T-joint, where they demonstrated that the high resolution wave field information may provide insight into the damage detection in composite structures [6]. In addition to the study on the linear information on the ultrasonic signals for delamination detection, the nonlinear counterpart has also been investigated. Chrysochoidis et al. utilized the mixed frequency response between the pumping-probing waves and the delamination for damage detection [7]. Klepka et al. conducted the SLDV experiments and applied nonlinear vibro-acoustic wave modulation technique for impact damage detection in laminated composites [8]. All these pioneer research endeavors demonstrated the scanning wave field from laser measurements as a promising approach for delamination evaluation in composite panels.

This research focuses on investigating the delamination detection methodology using SLDV data. After the discussion on anisotropic elastodynamic wave phenomena using the Semi-analytical Finite Element (SAFE) method and the Local Interaction Simulation Approach (LISA), the SLDV experiments on a carbon fiber reinforced composite panel is presented. Both the linear and nonlinear signal features are studied for delamination imaging.

2. ANISOTROPIC ELASTODYNAMICS IN COMPOSITE PLATES

An in-depth understanding of guided wave mechanics in composite structures is essential for the development of effective structural health monitoring strategies for composite parts. This section presents two useful numerical methods for the modeling of ultrasonic guided waves in composites.

2.1 Semi-analytical Finite Element Method

Different from the analytical approaches, the SAFE method discretizes the cross section of the waveguide (plate, rod, or cylinder) with finite elements and uses analytical formulation along the wave propagation direction. The finite element discretization makes SAFE capable of modeling waveguides with arbitrary cross section and material properties. Promising results have been reported using SAFE for calculation of dispersion curves and mode shapes in pipe and rail structures. The application of SAFE method to composite structures showed very good results with the straight forward manner in material property definition. Besides, the SAFE method does not require a root searching procedure like most of the analytical method. Instead, the formulation reaches a stable eigenvalue problem, which is efficient and easy in terms of numerical computation [9].

To model wave propagation in plate structures, one only need 1-D elements to discretize the cross section and describe the mode shapes of guided waves. The SAFE setup in an infinitely wide plate is shown in Figure 1. The waves propagates along x direction with wavenumber ξ at frequency ω.

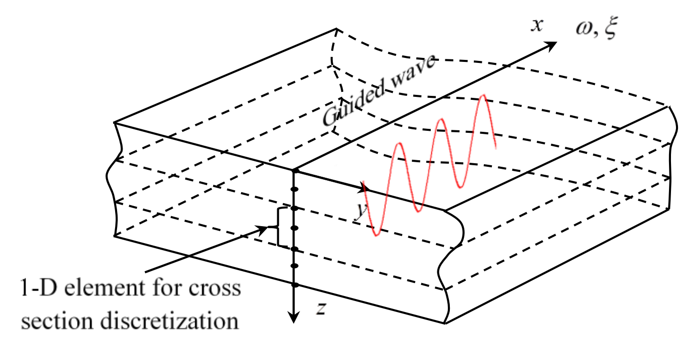


FIGURE 1: SAFE MODEL OF WAVE PROPGATION IN PLATE STRUCTURES

The final SAFE formulation will result in an eigenvalue problem sweeping across the frequency domain:

$$\left[\mathbf{K}_1 + i\xi\mathbf{K}_2 + \xi^2\mathbf{K}_3 - \omega^2\mathbf{M}\right]\mathbf{U} = 0 \qquad (1)$$

where, the finite element stiffness and mass matrices can be found in Ref. [9]. The solution of eigenvalues corresponds to the wavenumbers at each frequency, while the eigenvectors are the associated wave mode shapes. The SAFE formulation has been coded into a Graphical User Interface (GUI), SAFE-DISPERSION, presented in Figure 2 [10]. This software allows the computation of dispersion curves and mode shapes for guided waves in anisotropic composite plates.

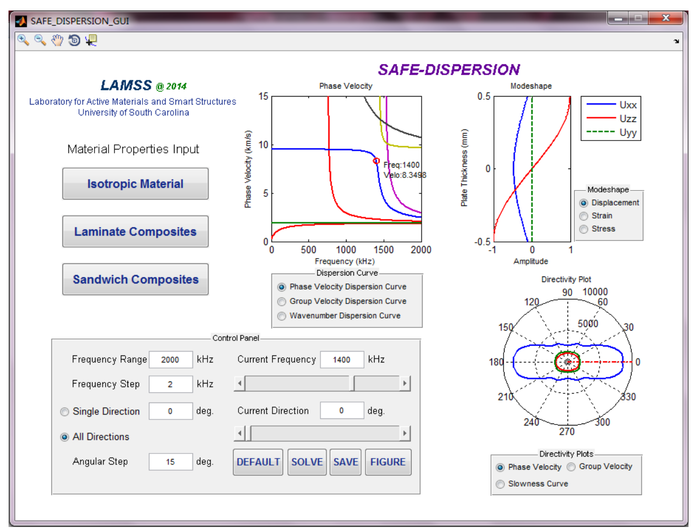


FIGURE 2: SAFE-DISPERSION INTERFACE

In this study, the composite plate made from two 2-mm thick quasi-isotropic carbon fiber reinforced polymer panels bonded together. Figure 3 presents the phase velocity dispersion curve of the guided waves in the composite plate. The multi-modal dispersive characteristics of the waves can be clearly observed. At relatively low frequency band (below 1000 kHz), only three fundamental wave modes exists: fundamental symmetric, antisymmetric, and shear horizontal modes. The symmetric and shear-horizontal modes are less dispersive than the antisymmetric mode. For 1D SLDV, the laser measurement can effectively record the antisymmetric mode, where the wave motion possesses a large component in the out-of-plane direction. Nevertheless, the symmetric and shear-horizontal motion cannot be well captured.

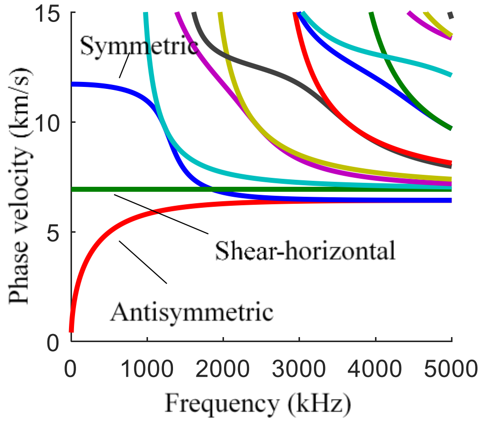


FIGURE 3: PHASE VELOCITY DISPERSION CURVE OF THE 4-MM THICK CARBON FIBER COMPOSITE PLATE

2.2 Local Interaction Simulation Approach

In addition to the SAFE method, the LISA numerical simulations are also conducted to understand the interaction between guided waves and the delamination in composite plates. LISA is a finite-difference based numerical simulation method. It approximates the partial differential elastodynamic equations with finite difference quotients in the discretized temporal and spatial domains. The coefficients in LISA iterative equations (IEs) depend only on the local physical material properties. The SIM enforces the stress and displacement continuity between the neighboring computational cells and nodes. Therefore, changes of material properties in the cells surrounding a computational node can be captured through these coefficients. The final IEs determine the displacements of a certain node at current time step based on the displacements of its eighteen neighboring nodes at previous two/three time steps, depending on whether material damping is considered. For this particular study, the anisotropic damping behavior was implemented in the LISA formulation using the Kelvin-Voigt viscoelastic model. Contact Acoustic Nonlinearity (CAN) was introduced via the penalty method. For details of the derivation for the LISA IEs, the readers are referred to Ref. [11, 12].

Figure 4 presents the LISA simulation result of wave generation, propagation, interaction with delamination, and attenuation for the antisymmetric mode. It can be noticed that when nonlinear interactions take place between the antisymmetric mode and the delamination, symmetric waves may appear due to mode conversion. Wave energy bounces back and forth within the delamination area, forming a trapped mode of local vibration. Due to material damping, the wave energy will then be dissipated, showing a decaying wave amplitude.

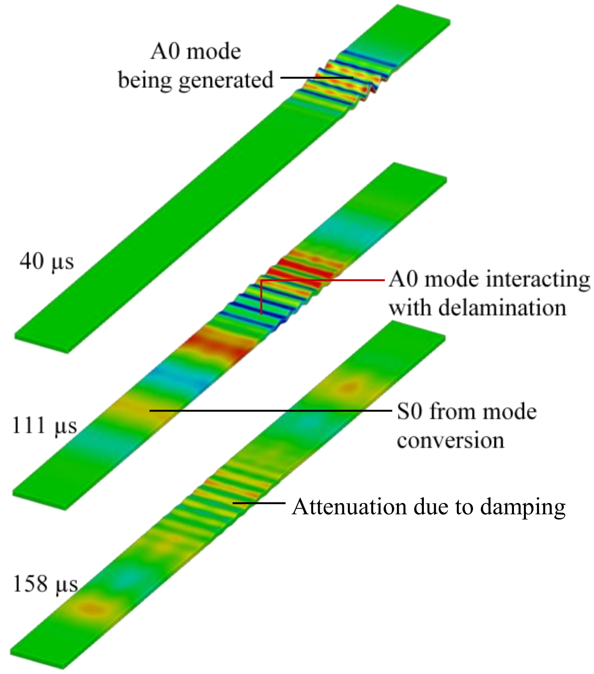


FIGURE 4: LISA SIMULATION OF WAVE PROAPGATION AND INTERACTION WITH DELAMINATION IN THE COMPOSITE PLATE

3. CONTACT ACOUSTIC NONLINEARITY DURING WAVE DELAMINATION INTERACTION

This research strives to utilize the nonlinear information of the wave field for delamination detection. When guided waves interact with the delamination, CAN may happen between the contact interfaces. Figure 5a shows the zoom-in snapshots of 100-kHz S0 and A0 waves interacting with a 20-mm long middle delamination. When S0 mode interacts with the delamination, the deformation is symmetric about the mid-plane. Flexural motion can be noticed in the laminate layers at the delamination region. The interface was opened and closed at various locations along its length. When A0 mode interacts with the delamination, top and bottom layers at the delamination follow flexural motion. The delamination interface was also opened and closed by the interrogating wave at various locations along its length. The contact dynamics at the delamination interface changes the local stiffness periodically and introduce nonlinearity into the sensing signals.

However, the nonlinear dynamics behind is quite complex. It is not only associated with the frequency and mode shape of the interrogating wave field, but also the size dimension and through-thickness location as well. The nonlinear contact behavior is also governed by the microstructural features of the delamination interface. For instance, Figure 5b illustrates the influence of delamination size on the nonlinearity of the sensing signal, considering an idealized kissing delamination scenario. Numerical case studies of 200-kHz S0 wave propagation through middle layer delamination of various sizes were carried out. The delamination size a took the values from 2.5 mm up to 40 mm.

The nonlinearity of the signals was measured by the nonlinear index (*NI*) based on the wave energy ratio:

$$NI = \sqrt{\frac{A_{f2} + A_{f3} + A_{f4}}{A_{f1}}} \quad (2)$$

where A_{f1} represents the spectral amplitude of the wave component at the excitation frequency, while A_{f2}, A_{f3}, and A_{f4} are the spectral amplitude of the wave components at the second, third, and fourth higher harmonics. The sensing signals picked up 300 mm away from the wave source was used to generate the nonlinearity trend plots. Intuitively, the damage should impose stronger nonlinear effects while its size grows. However, the results shown in Figure 5b do not agree with such a common sense. The nonlinear index is very small when the delamination is only 2.5-mm long. When it grows to 5-mm long, the index climbed to a relatively high value, indicating the nonlinearity of the signal is quite strong. However, beyond this value, as the delamination size increases, the nonlinear trend starts to decrease. The *NI* peak seems to show a local nonlinear resonance phenomenon with a wavelength and delamination size match. This results indicate that the nonlinear information from the scanning wave field may not provide resourceful information if the delamination size is much bigger than the wavelength.

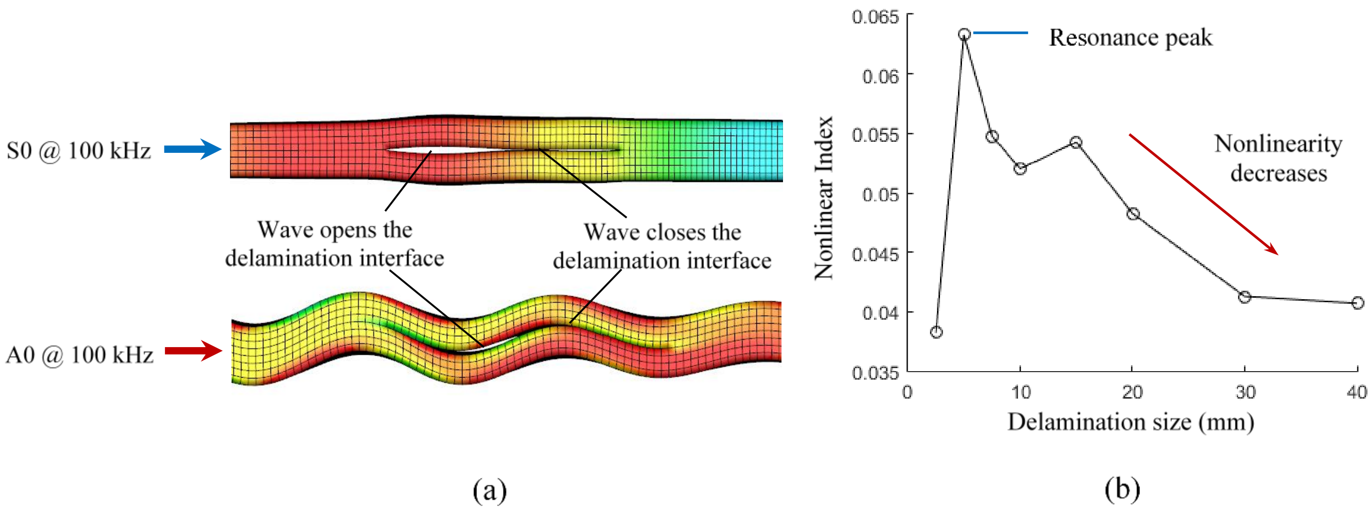


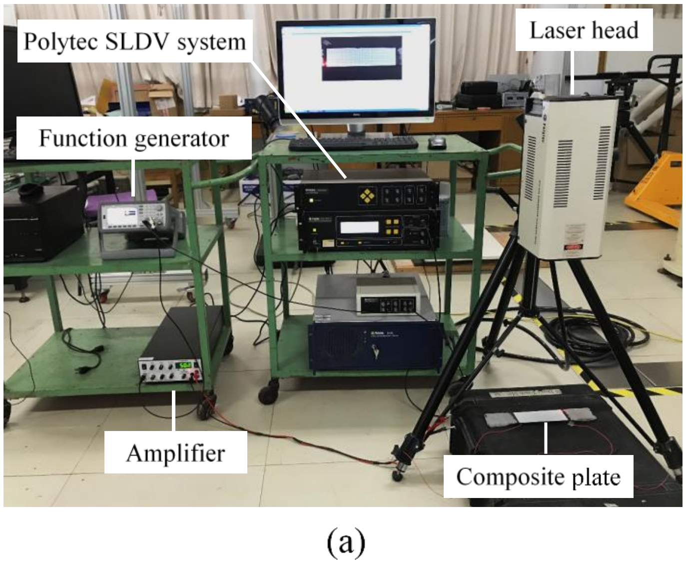
FIGURE 5: DELAMINATION INTERFACE BEING OPENED AND CLOSED UNDER CYCLIC WAVE INTERACTION

4. SCANNING LASER DOPPLER VIBROMETRY FOR WAVE FIELD IMAGING

After developing an in-depth understand of the wave dynamics and contact mechanics of the guided wave delamination interaction procedure, SLDV experiments were conducted to detect delamination in the composite plate. Figure 6a presents the experimental setup for the SLDV tests. A Keysight 33500B arbitrary function generator was used to generate the excitation waveforms Hanning window modulated sine tone burst signals. The excitation was further amplified by a Krohn-hite 7602M wideband power amplifier up and was applied on the transmitter PWAS. Guided waves generated by the transmitter would propagate along the composite specimen, interact with the delamination, and finally be picked up the scanning laser beam into the Polytec SLDV system.

Figure 6b demonstrates the details of the specimen under investigation. The specimen was manufactured by bonding two 2-mm thick quasi-isotropic carbon fiber composite plates together using a strong adhesive. Two PWAS transducers with different sizes and shapes were install on the composite strip on both ends. Both PWAS transducers would serve as the remitter, emitting guided waves into the structure. The purpose of such a setup is to generate different guided wave patterns in terms of amplitude and directivity in the composite panel. Damping clay was implemented on the two edges of the plate to eliminate boundary reflections. The delamination was created by inserting a sharp blade into the middle layer where the adhesive was applied. It should be noted that such an operation would form an unknown area of delamination inside the plate. The distance between the delamination interfaces is large at the location of blade insertion. However, the interface may be closed or touching each other in the deep locations far away from the breaking point.

Since this study aims to explore both linear and nonlinear signal features for delamination detection, different excitation schemes are needed. The mechanism behind the linear imaging technique resides in the trapped mode feature, where a short spatial interrogating wavefield is preferred to render an apparent residual trembling phenomenon. On the other hand, the triggering or development of nonlinear dynamics prefer the temporally periodic, narrow-band excitation. Thus, a 5-count, 100-kHz excitation was used for the linear case, while a 20-count, 50-kHz excitation was used for the nonlinear case. The rationale behind the choice 50-kHz stem from the fact that the focus would be on the second harmonic component at 100 kHz, and the sampling frequency of the SLDV can only guarantee the measuring accuracy up to 120 kHz.



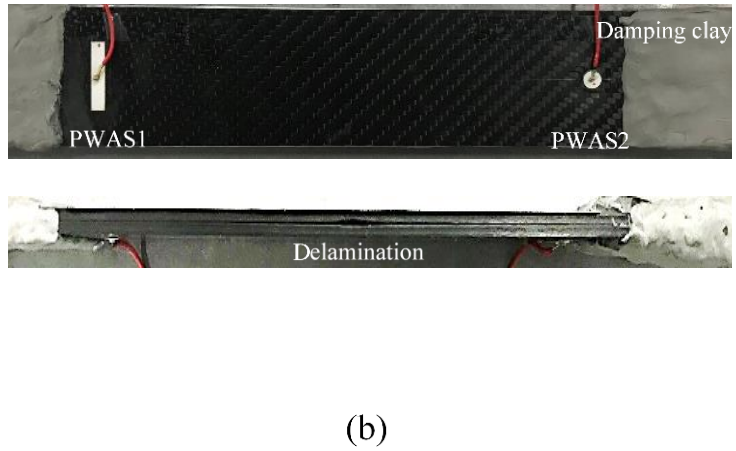


FIGURE 6: (a) EXPERIMENTAL SETUP FOR SLDV TESTS; (b) SPECIMEN DETAILS OF SENSORS AND THE DELAMINATION

5. DELAMINATION DETECTION RESULTS

This section presents the scanning wave fields as well as the delamination imaging results using both linear and nonlinear information of the guided waves.

5.1 Linear Wave Field Imaging Results

Figure 7 presents the wave propagation snap shots from SLDV measurements. Both PWAS1 and PWAS2 excitation cases are shown, demonstrating the wave generation, propagation, interaction with the delamination, and trapped mode formation. Clear wave generation and propagation patterns can be identified. However, when the wave front hit the delaminated area, distortions of the spatial wave field were noticed. Guided waves were then bounced back and forth within a region, forming trembling motions with slightly different wavelengths. Although the wave delamination interactions can be seen, yet the delamination area is not clear and needs further signal processing to be revealed.

Figure 8 presents the signal post processing results using the linear information of the wave field. The temporal integration of the absolute value of the wave amplitude was carried out numerically. Figure 8a shows the amplitude image for PWAS1 excitation case; Figure 8b illustrates the image for PWAS2 excitation case; Figure 8c presents the fused image from both cases using both multiplication and addition algorithm.

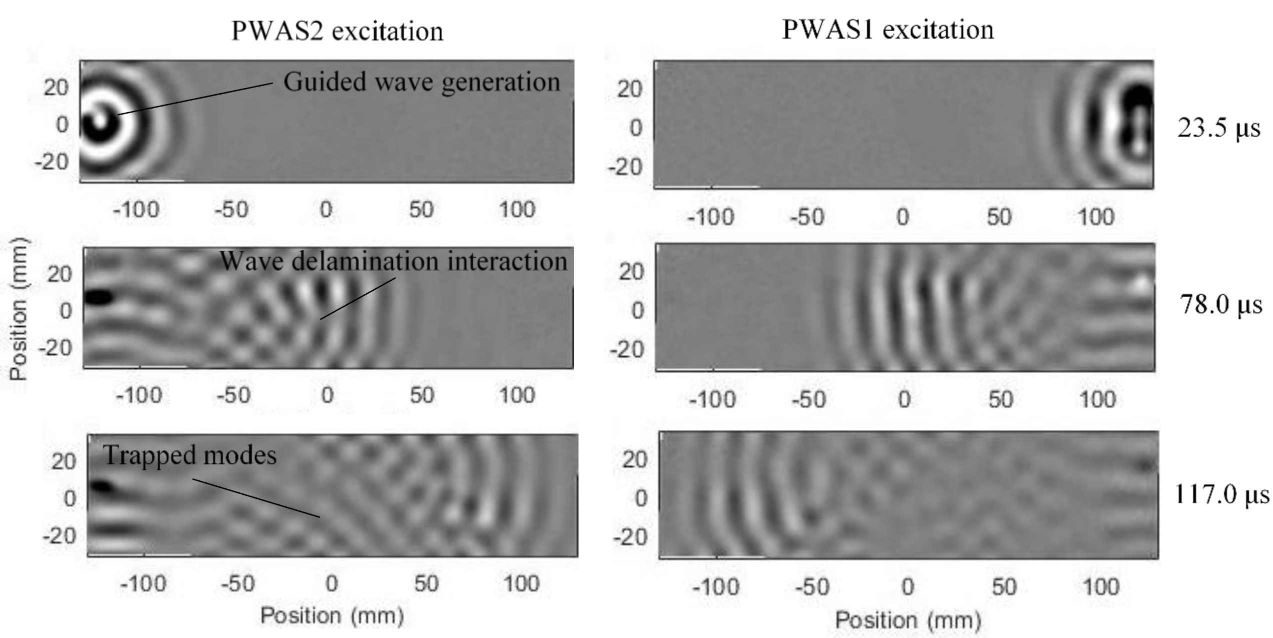


FIGURE 7: WAVE PROPAGATION IMAGE SNAP SHOTS FROM SLDV MEASUREMEN

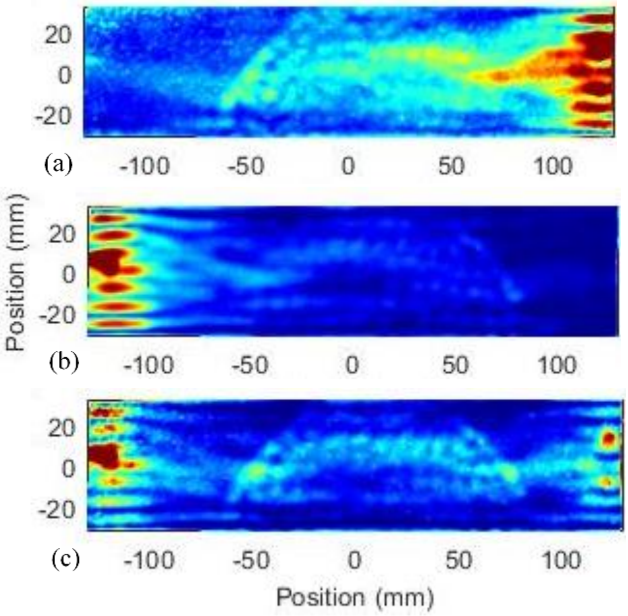


FIGURE 8: POST-PROCESSING IMAGING RESULTS FOR DELAMINATION QUANTIFICATION: (a) PWAS1 EXCITATION CASE IMAGE; (b) PWAS2 EXCITATION CASE IMAGE; (c) FUSED IMAGED FROM BOTH CASES

$$EN = \alpha EN_1 \bullet EN_2 + \beta\left(EN_1 + EN_2\right) \tag{3}$$

where, EN_1, EN_2, and EN denote the amplitude integration image pixel matrices of the PWAS1, PWAS2, and fused cases. α and β are weighting parameters, which took the value of 1 in this study. The fused image clearly presents a half-circular high pixel value area, rendering a remarkable evaluation of the delamination. It should be noted that the delamination area was unknown from a blade insertion. And the SLDV technique can effectively quantify the delamination region. It can be deduced that the blade insertion caused a wide opening at the cutting side. The delamination nucleated from this side line and progressed towards the inside of the composite plate, cracking the adhesive in front of the blade, forming a half-circular advancing area.

5.2 Nonlinear Wave Field Imaging Results

After showing the effectiveness of the linear wave field information for the delamination quantification, the nonlinear counterpart was also investigated. The extraction of the nonlinear wave delamination interactions was performed by addition and subtraction of wave field information, taking into account that the nonlinear system does not obey the principle of supper position. Thus, three wave generation cases were conducted, as shown in Figure 9: PWAS2 excitation, PWAS1 excitation, PWAS1 + PWAS2 excitation. Since, 50 kHz was used as the excitation frequency, the wave fields possessed much longer wavelengths than the 100 kHz excitation case, shown in the previous subsection. Then, the wave fields were normalized to the maximum amplitudes of each transducers. The final wave field to be processed was the subtraction among these three normalized information, i.e.

$$WF = WF_{PWAS1+PWAS2} - \left(WF_{PWAS1} + WF_{PWAS2}\right) \tag{4}$$

Thereafter, the temporal signals are transformed into their corresponding frequency spectra through the Fast Fourier Transform (FFT). In addition to the fundamental frequency response at 50 kHz, nonlinear superharmonic components at 100 kHz should also appear due to the nonlinear interactions. Then, these spectra are filtered with a frequency domain pass-window function centered at 100 kHz with a bandwidth of 50 kHz. After the filtration, the signal only contains the second harmonic component. Subsequently, inverse fast Fourier transform (IFFT) is performed on the signals, rendering the time traces of the nonlinear response.

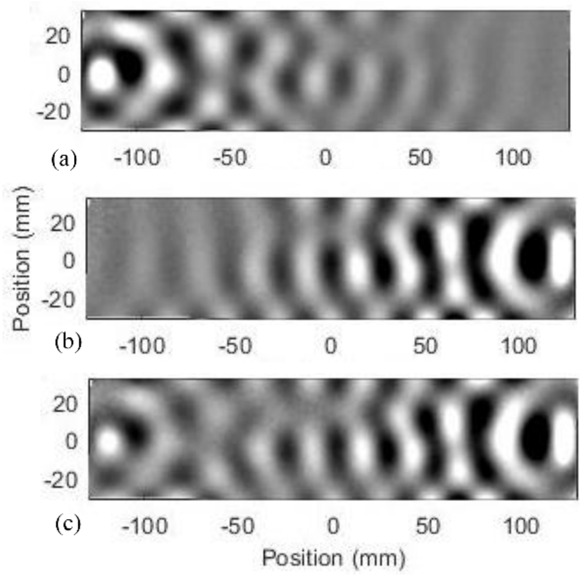


FIGURE 9: WAVE PROAPGATION CASES FOR NONLINEAR ANAYSIS: (a) PWAS2 EXCITATION CASE; (b) PWAS1 EXCIATION CASE; (c) PWAS1 + PWAS2 EXCITATION CASE

Figure 10 presents the imaging result from using the nonlinear wavefield information. No obvious delamination region can be identified. It should be pointed out that this result does not mean the nonlinear imaging technique is not effective. The nonlinear information is not indicative in this case, because the size of the delamination is very large. However, as pointed out in Section 3 and Figure 5, the nonlinearity of the sensing signal depend on many factors. And it has been shown by the LISA simulation case studies that the nonlinear interactions between the guided waves and the delamination may become rather weak when the size of the delamination is large. Thus, this experimental finding also agrees with our numerical prediction. In other words, nonlinear ultrasonic wave field imaging may be sensitive to small size delamination areas, while it may lose its sensitivity as the size of the delamination grows beyond a certain size. For large areas of delamination, on the other hand, the linear information is sufficient and accurate for its quantification and evaluation.

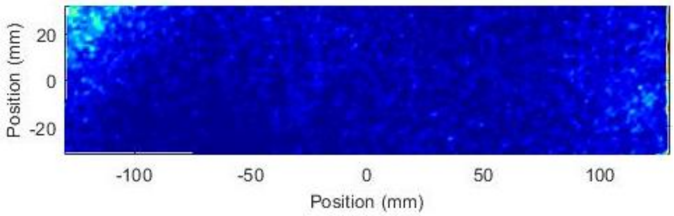


FIGURE 10: POST-PROSESSING RESULT FOR NONLINEAR WAVE FIELD DELAMINATION IMAGE

6. CONCLUSION

This paper presented the Scanning Laser Doppler Vibrometry (SLDV) for the imaging of delamination damage in composite materials. The anisotropic wave elastodyanmics was first studied using the Semi-analytical Finite Element (SAFE) method. The wave propagation and interaction wave delamination was further modeled with the Local Interaction Simulation Approach (LISA). It was found that the nonlinearity of the sensing signal closely depended on the delamination size. The nonlinearity of the sensing signal may grow with the increment of the delamination area. After reaching a critical value, the nonlinearity of the sensing signal would undergo a significant drop, i.e., the nonlinear ultrasonic technique may not be sensitive to large delamination areas. Active sensing experiments were conducted using the Piezoelectric Wafer Active Sensors (PWAS) and the SLDV. Two delamination imaging methodologies were studied. The first one utilized the total wave energy to detect the delamination, taking advantage of the trapped modes within the delaminated area. The second one adopted the nonlinear second harmonic imaging algorithm, highlighting the nonlinear interaction traces at the delamination region. The damage detection images were obtained. The linear wave field information remarkably shown the delamination, presenting a superb capability for damage quantification and evaluation. On the other hand, the nonlinear counterpart was not sensitive to this large delamination area. The damage imaging technique presented in this paper possesses great potential in material evaluation and characterization applications.

The investigation of using nonlinear wave field information for small delamination detection should be conducted in a future study.

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