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# DAMAGE DETECTION IN COMPOSITE STRUCTURES VIA SCANNING LASER DOPPLER VIBROMETRY USING LINEAR AND NONLINEAR ULTRASONIC WAVE FEATURES

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## ABSTRACT

*This study presents the modeling and experimental investigation of damage detection and evaluation methods based on the linear and nonlinear features of ultrasonic guided waves while they interact with possible structural damage sites. Such wave damage interaction features are visualized via the full field imaging capability of SLDV. First, numerical modeling is conducted to develop an in-depth understanding of the mechanism behind the wave damage interactions. A coupled-filed transient dynamic finite element model is constructed with a simulated delamination area. The modeling of Contact Acoustic Nonlinearity (CAN) is realized by defining the contact surfaces at the delamination area. The linear ultrasonic features such as the trapped modes as well as the nonlinear features such as the mixed frequency response are illustrated using the numerical simulation. Based on the numerical study, experimental investigations are further conducted. Experiments are performed to explore linear ultrasonic technique for damage quantification. For the linear case, the detection utilizes a short tone burst in both spatial and temporal domain, generated by a Piezoelectric Wafer Active Sensor (PWAS); the trapped wave energy and a directional vector field technique are adopted to visualize an impact damage in a carbon fiber composite plate. The nonlinear detection methodology combines a continuous resonant low frequency harmonic pumping wave with a high frequency tone burst probing wave, simultaneously generated by two PWAS transducers on both sides of the specimen to take advantage of the mixed nonlinear interactions between the vibro-acoustic waves and the structural damage. This study shows that both linear and nonlinear ultrasonic techniques possess great application potential for the damage detection and quantification in composite structures. The paper finishes with summary, concluding remarks, and suggestions for future work.*

Keywords: composites, Scanning Laser Doppler Vibrometry, damage detection, guided waves, nonlinear ultrasonics

## 1. INTRODUCTION

Due to the strong and light-weight features, composite materials have been widely used in various industries. However, the Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) strategies for composite materials still need improvements as the failure mechanism and modes are quite complex and hard to predict in composites. Besides, delamination is a typical damage type for composites, which is mostly hidden under the laminate surface and hard to be noticed. This feature brings additional challenge to conventional NDE techniques.

Ultrasonic guided waves have been recognized as one of the prevailing tools to develop NDE and SHM techniques as the inherently appealing features including strong penetration, fast propagation, and high sensitivity to damage [1]. The signal features of the guided wave can be colloquially divide into linear features and nonlinear features. Linear features mainly explore changes in damage-scattered waves such as delay in time-of-flight (TOF), energy dispassion, and mode conversion. While detection techniques utilizing nonlinear features are based on the premise of Contact Acoustic Nonlinearity (CAN) happening between the delamination interfaces [2]. The nonlinear features which are often exploited include sub-harmonics, higher harmonics, mixed frequency response and so on. Linear ultrasonics is sensitive to gross defects or open cracks while nonlinear ultrasonics can work well in detecting evenly distributed micro- cracks or degradation [3]. Yet, a real-word delamination in composites often initiate from matrix cracking. Under cycle loads, the deboning will evolve into fiber breakage [4]. Thus, linear and nonlinear ultrasonic techniques may

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complement each other, contributing to the development of a comprehensive SHM and NDE system.

Extensive reach efforts have been exerted on delamination detection using ultrasonic guided waves. Compared with sparse sensor array method, the Scanning Laser Doppler Vibrometry (SLDV) is a very useful tool for the analysis of wave interaction with discontinuities [5]. Tian et al. investigated the guided wave field interacting with delamination damage in laminated composite panels with SLDV and proposed a filter reconstruction imaging method to locate and quantify the damage [6]. Moreover, SLDV can be utilized in more complex structures such as aircraft wings [7]. E.V. Glushkov et al. also adopted the scanning wave field to validate the multiple wave reflections within the delamination region and wave trapping effects [8]. In addition, the nonlinear counterpart has also been investigated. Dziedziech et al. proposed a new synchronous mixed frequency excitation to achieve the damage localization ability, the key element of which was the localized wave packets adopted from the probing wave [9]. The SLDV experiment was conducted in laminated composites for impact damage detection by Klepka and his colleagues [10].

This research focuses on investigating the delamination detection methodology in composites based on both linear and nonlinear ultrasonic features using SLDV. The mechanism of the utilized features is demonstrated with a 3D coupled-filed transient dynamic finite element model. For the linear case, after simulating the trapped modes effects, a corresponding energy based delamination detection strategy is conducted experimentally. Moreover, a direction vector field technique is proposed to optimize the energy damage index. For the nonlinear case, a resonant vibro-acoustic modulation (VAM) excitation methodology is deployed. The sideband effect is adopted to achieve the goal of damage detection and quantification. This paper finishes with summary, concluding remarks, and suggestions for future work.

## 2. COUPLED FIELD FINITE ELEMENT MODEL OF A DELAMINATED COMPOSITE PLATE

Having an in-depth understanding of guided wave mechanics in composite structures is essential for developing effective structural health monitoring strategies for composite parts. In this section, a coupled-filed transient dynamic finite element model is demonstrated for the modeling of ultrasonic guided waves in composites. Utilizing this model, both linear and nonlinear ultrasonic features scattered from the damage will be illustrated.

Figure 1 shows the top view of the 3D finite model adopted, which is a 200-mm long, 50-mm wide, and 2-mm thick 4-layer carbon fiber composite plate. The orientation of the layers was $0° - 90° - 90° - 0°$. The simulation task was conducted by the commercial finite element package ANSYS. SOLID185 coupled field structural element was deployed to discretize the simulation domain. Considering both the accuracy and the computational efficiency, the element size was selected to be $1\text{mm} \times 1\text{mm} \times 0.5\text{mm}$. Two actuators were placed on both edges of the specimen. The simulated delamination was placed in the middle of the plate between layer 2 and layer 3, taking the circular shape with a diameter of 10mm. The modeling of delamination and CAN were realized by detaching the corresponding nodes and defining the contact pairs at the delaminated areas, respectively. Guided waves generated by the actuators propagated along the composite plate structure and were scattered at the damaged site. The dynamic out-of-plane velocity wave field was recorded, mimicking the SLDV technique.

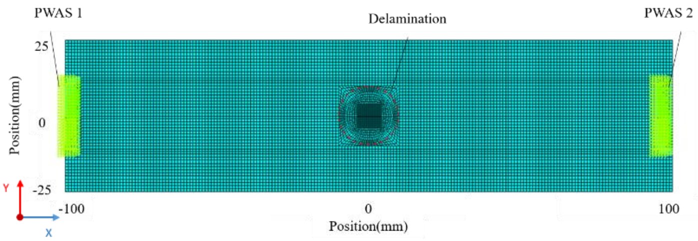


**FIGURE 1:** FULL-SCALE FINITE ELEMENT MODEL.

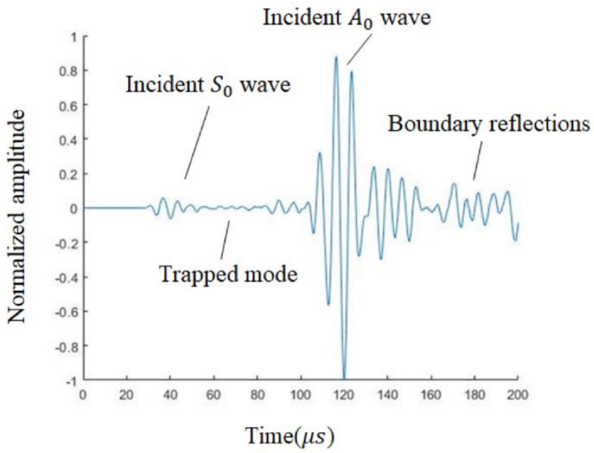


**FIGURE 2:** THE NORMALIZED PITCH-CATCH ACTIVE SENSING SIGNAL.

Since both linear and nonlinear features of guided waves are aimed to be explored in this study, different excitation schemes are needed. The triggering of linear features prefers a short spatial interrogating wave field, rendering an apparent residual trembling phenomenon and furthest extruding trapped mode features. On the other hand, the mechanism behind the nonlinear imaging technique utilized in this study is sideband effect, where the vibro-acoustic waves are preferred to interact with the structural damage. To fully open the crack, the low frequency pumping wave should possess a large amplitude thus powerful. The probing wave should scatter quickly in spatial domain, leaving only the anomalous high-level vibration in the fractured area. Therefore, a 1.5-count, 100 kHz excitation was used for the linear case, while the combination of a 5-count, 70 kHz excitation and a resonant sinusoidal excitation was used for the nonlinear case.

## 3. LINEAR FEATURES FOR DAMAGE DETECTION

This section presents the numerical and experimental investigation of delamination detection and evaluation methods in carbon fiber composite plates using the linear information of the guided waves. The scanning wave filed as well as the trapped mode based delamination imaging results are evaluated.

### 3.1 Numerical Simulation of Trapped Modes

Two transmitters served as the actuator and the receiver respectively, forming a pitch-catch sensing pair. Meanwhile, the instantaneous out-of-plane velocity on the bottom was recorded, simulating the SLDV measurements. The normalized active sensing response at the receiver was depicted in Figure 2. Both evident incident $S_0$ wave and $A_0$ wave appeared in the time trace. Following the incident $S_0$ wave was the trembling caused by the trapped modes. Due to the reflection effects, the $A_0$ wave induced trapped mode was hard to distinguish.

More straightforwardly, snapshots of the dynamic wave propagation around the delaminated area are illustrated in Figure 3. It demonstrates the process of incident $S_0$ and $A_0$ ripples going through the delamination, part of the energy being trapped in the delaminated area and thereafter turning into a new wave source.

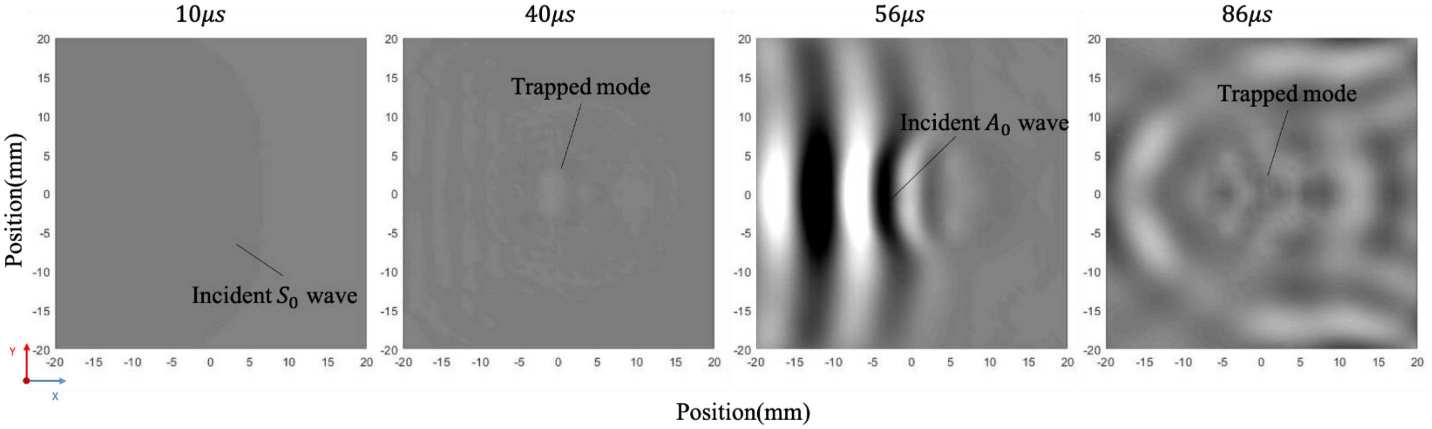
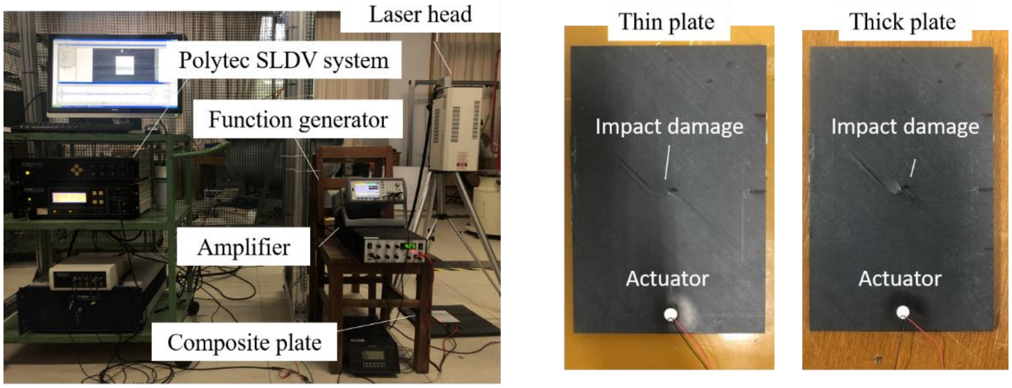


**FIGURE 3:** SNAP SHOTS OF THE DYNAMIC WAVE FIELD AROUND DELAMINATION.

### 3.2 Experimental Setup

SLDV experiments were conducted to detect the delamination in the composite specimens. Figure 4a presents the experimental setup for the SLDV tests. The excitation waveform was generated by a Keysight 33500B arbitrary function generator. The excitation signal was further amplified by a Krohn-hite 7602M wideband power amplifier up and then was applied on the actuator. Ultrasonic guided wave was generated by the transmitter and injected into the specimen. Afterwards, the guided waves would propagate along the composites and interact with the delamination. The entire wave filed was picked up by the Polytec SLDV system.



(a) (b)

**FIGURE 4:** (a) EXPERIMENTAL SETUP FOR THE SLDV TESTS; (b) SPECIMEN LAYOUT DETAILS.

Figure 4b illustrates the layout details of the carbon fiber specimens. According to the thickness, the left one is denoted as the thin plate while the right one is the thick plate. One circular PWAS transducer was installed on both specimens on one end. The delamination was created by the external impact in the middle of the 2 specimens. Impact marks could be observed on both surfaces, with different severities. Straightforwardly, on the thin plate, there was just a depression on the surface. While for the thick specimen, fiber breakage also appeared. It should be noted that such an impact would form an unknown area of delamination inside the plate. The distance between the delamination interfaces was large at the impact area. However, the interface may be closed or touching each other in the deep locations far away from the breaking point.

### 3.3 Linear Wave Field Imaging Result

The wave propagation snapshots from SLDV measurements are illustrated in Figure 5. Both thin and thick carbon fiber composite plates cases are shown, demonstrating the wave generation, propagation, interaction with the delamination, and trapped mode formation. The excitation signal was a 100VPP 100 kHz 1.5-cont tone burst signal, powerful enough to vibrate the delaminated area while scatter quickly to highlight the fractured part only. The introduction and propagation traces of the excitation signal was clear in the snapshots. However, when the guided wave front met the delaminated edge, the spatial wave field was distorted. The incident wave was scattered back and forth, inducing vibration motions with slightly different wavelength. Although such distortion could faintly reveal the outline of the impact damage, the delamination was not clear and needed further post-processing.

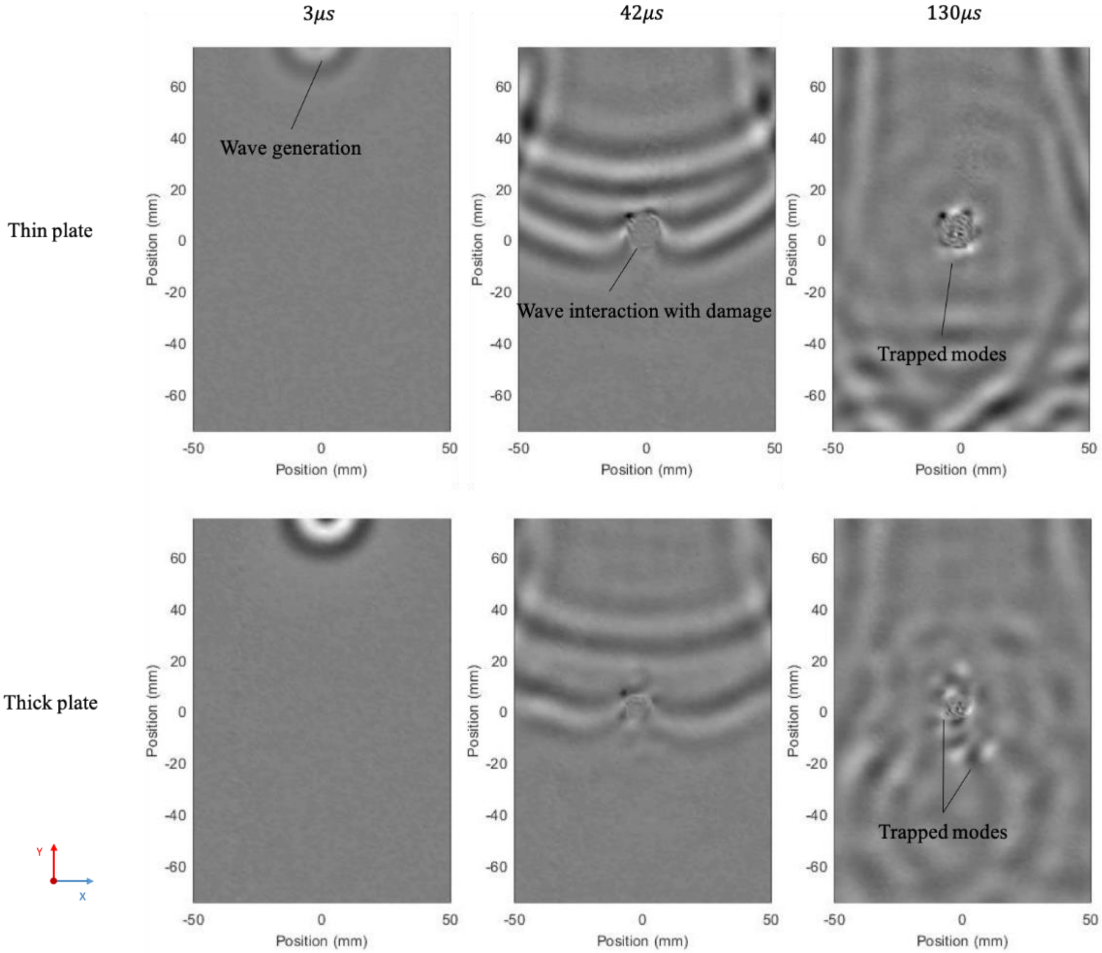


**FIGURE 5:** WAVE PROPAGATION IMAGE SNAPSHOTS FROM SLDV MEASUREMENT.

Figure 6 depicts the signal post processing results based on the linear information from the wave field, i.e., the energy method. It should be noted that the instantaneous response captured by SLDV is the out of plane velocity $v(x,y,t)$. The corresponding energy-based damage index $DI_{energy}$ toke the accumulation of square of specific temporal period responses:

$$DI_{energy}(x,y)=\sum_{t>t_0} v(x,y,t)^2 \tag{1}$$

where $t_0$ denoted the time when the excitation signal totally emits from the PWAS transducer. Such a temporal shifting could eliminate the influence from excitation wave source in the final diagnostic imaging results. Square of velocity corresponded to the wave energy. Due to the trapped modes effect, wave energy in delaminated region would be enormously high compared with the pristine area.

The normalized $DI_{energy}$ distribution of the thin carbon fiber composite specimen is shown in Figure 6a. Figure 6b presents the result of the thick carbon fiber composite plate. It should be noted that the inside condition is unknown. And these two post-processed results provided a clear quantification and localization of the impact affected delamination. The higher the value the pixel, the severer the delaminated condition would be. It could be deduced that in the thin specimen the delaminated area was round shape located in the middle. While in the thick composites, the delamination condition was more complex. In the middle, there exists an irregular-shaped high pixel value area. In addition, a slighter-degree-roughly-circular region was distributed in the outer edge. In conclusion, the damage was severer in the thick structure, which caused the delamination in larger range.

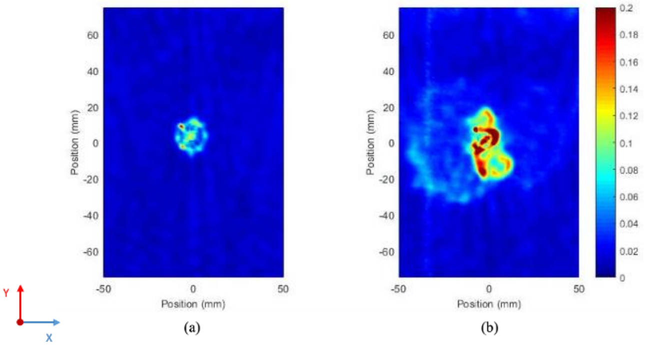


**FIGURE 6:** NORMALIZED POST-PROCESSING IMAGING RESULTS FOR DELAMINATION QUANTIFICATION: (a) THIN PLATE CASE IMAGE; (b) THICK PLATE CASE IMAGE.

### 3.4 The Direction Vector Field Technique

In this section, a new damage detection method, the direction vector field technique, is proposed, which utilizes both the linear features of TOF and trapped modes. The wave field can be transformed into a dynamic vector field indicating the instantaneous wave source. Such approach is developed from acoustic source localization technique after Kundu et al. [11~12]. A right-angle configuration of 3 sensors placed orthogonally is called a 'sensor cluster', schematically shown in Figure 7a. The responses of 3 sensors in the cluster can be utilized to obtain the direction vector $\theta$ of the incoming wave front based on Time-Difference-Of-Arrivals (TDOA):

$$\theta = \tan^{-1}\left(\frac{\Delta t_{20}}{\Delta t_{10}}\right) \tag{2}$$

where $\Delta t_{ij}$ can be assumed as the time shift between sensor $i$ and sensor $j$ which is computed by the cross-correlation technique. This method examines the similarity between the two given signals by computing:

$$\left[F(t)\star G(t)\right](\tau)=\int_{lower\ bound}^{upper\ bound}F(t)G(t+\tau)dt \tag{3}$$

where the lower bound and upper bound represent the starting and finishing time of the selected period. The time shift corresponds to the maximum value of the cross-correlation.

The schematic diagram of the direction vector field is presented in Figure 7b. As a unit sensor cluster can provide the direction information of the acoustic source and the SLDV allows for densely distributed multi-point spatial measurements, each right-angle orientated configuration (containing 3 adjacent scanned points) can be treated as a unit sensor cluster. Hence, the wave-field during a certain period can be transformed into a dynamic direction vector field, pointing to the temporal wave source. Theoretically, at the excitation stage the vector will all point to the actuator area. When the injected guided waves scatter, direction vectors will indicate the location of delaminated area as trapped modes which acts as the new ultrasonic wave source. The amplitude of the dynamic direction vector is the average absolute amplitude of the responses during a certain period, related to the corresponding wave energy.

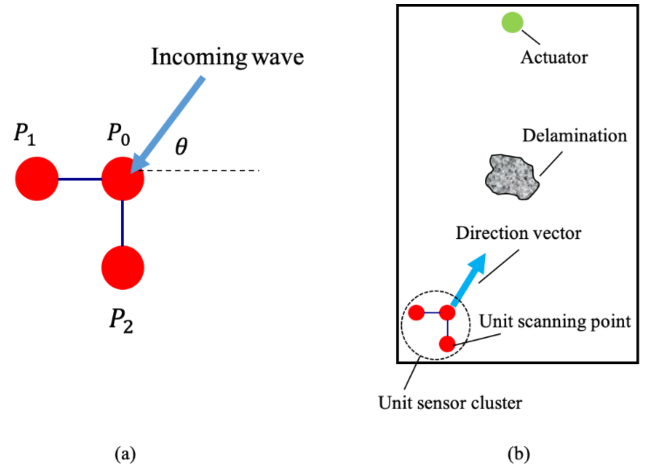


**FIGURE 7:** THE SCHEMATIC DIAGRAM OF (a) THE UNIT SENSING POINT CLUSTER (b) THE DIRECTION VECTOR FIELD TECHNIQUE.

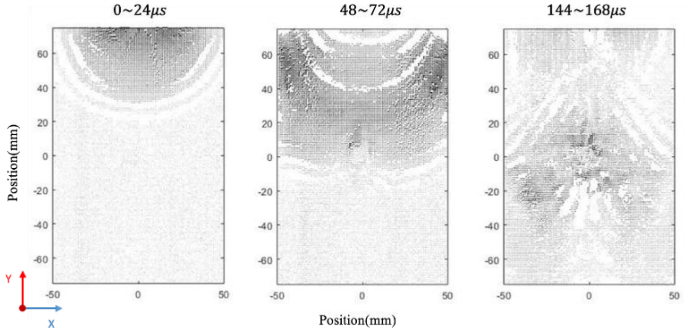


**FIGURE 8:** DIRECTION VECTOR FIELD SNAPSHOTS.

The SLDV experimental results of the thick carbon fiber composite plate was utilized as an example here. The spatial resolution of the scanning points was 1mm. Single time interval was selected to be $24\mu s$. Note that during sliding in temporal domain, the certain time interval needed to overlap with the previous one to reduce artifacts at the temporal boundary, which was $11\mu s$. Figure 8 demonstrates typical snapshots of the dynamic direction vector field. The wave generation, delamination interaction, and trapped modes scenarios are shown. It should be noted that when the sensor cluster was close to the incoming wave front, which meant both $\Delta t_{20}$ and $\Delta t_{10}$ are 0, the corresponding vector amplitude would be set to zero. Therefore, the blank areas in the direction vector field denoted the comprehensive wave front during a certain period. Direction vector field in the middle area was zoomed in in to have a closer observation of the dynamic quiver. As presented in Figure 9, when the excitation had not arrived, the enlarged area was peaceful. However, when the ultrasonic wave front arrived at the delaminated area, wave motion intensity was enormously increased and the direction vector started to point to the direction of the wave source location. Due to the trapped mode induced residual trembling, the energy sustainably growed and direction of the vector shifted quickly, representing the complex wave field bouncing back and forth within the delaminated area.

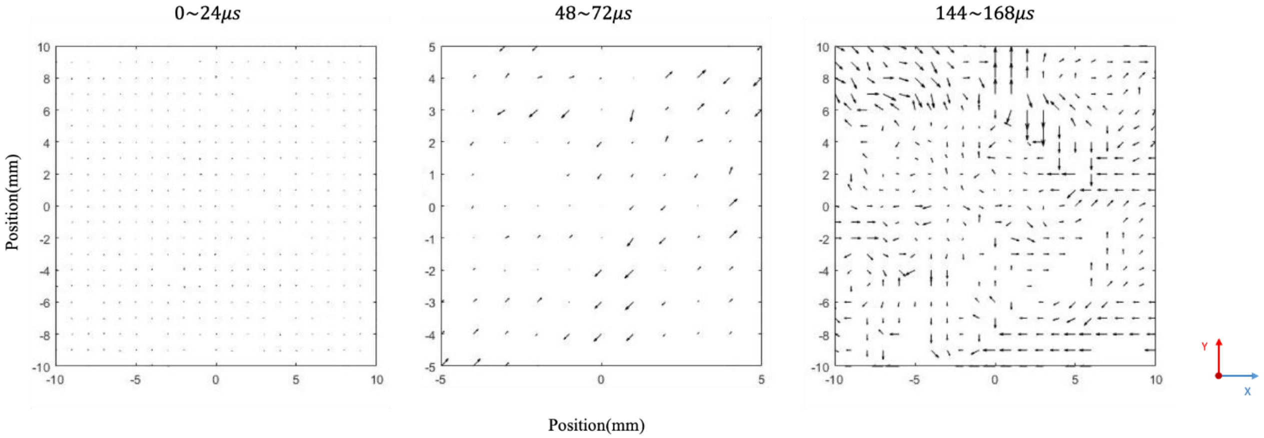


**FIGURE 9:** ZOOM-IN DIRECTION VECTOR FIELD SNAPSHOTS.

A weighted energy damage index evaluation quantity was proposed based on the direction vector field.

$$DI_{weighted} = \sum_{n>n_0} v_{average}{}^2 * abs\left(\Delta\theta\right) \tag{4}$$

where $n_0$ meant the time step when the incident wave had totally emitted from the actuator. Such filtering could decrease the incident wave source effect. $v_{average}$ was the average value of the absolute particle velocity amplitude during the period of a single temporal step. $\Delta\theta$ represented the angle shift between the present and the pervious time step. The result of the normalized weighted damage index is shown in Figure 10. Compared with the result in Figure 6b, the indicated range of the normalized damage index amplitude was the same. The delamination area could be divided into a first-level delamination and a second-level It was obvious that the pixel values of delaminated areas were higher under weighted damage index. The delamination information was magnified, which may facilitate better damage detection in composite structures in engineering practice.

## 4. NONLINEAR ULTRASONIC FEATURES FOR DELAMINATION DETECTION IN COMPOSITE PANELS

For the case study of nonlinear ultrasonic guided wave technique, two excitation frequencies $f_1$ and $f_2$ were injected to the structure. Due to the mixed-frequency response, the sum or difference of integer multiples of fundamental frequency $f_1$ and $f_2$ would be generated, such as $f_1 + f_2$ and $f_1 - f_2$. Such scenario is so called sideband effect. Mixed frequency response is a widely used tool encompassed in nonlinear ultrasonic techniques to detect small scale of damage. In this study, the delamination condition was quantified by the amplitude of the mixed-frequency response component. Meanwhile, the excitation followed the rule of widely used vibro-acoustic modulation (VAM).

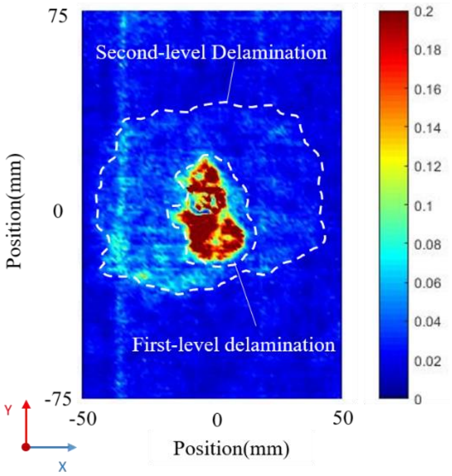


**FIGURE 10:** NORMALIZED WEIGHTED DAMAGE INDEX DISTRIBUTION FOR DELAMINATION QUANTIFICATION OF THE THICK COMPOSITES PLATE.

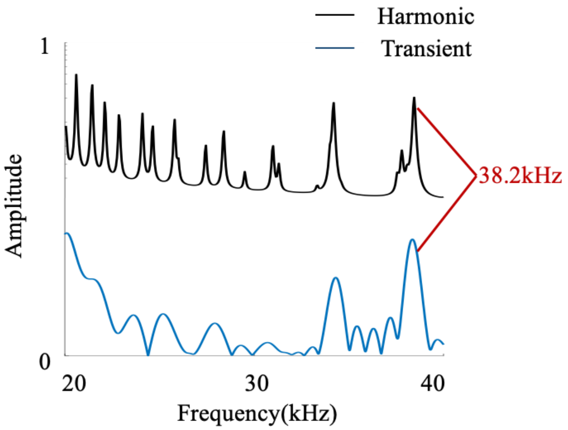


**FIGURE 11:** 3D MODEL RESONANCE FREQUENCY SELECTION: HARMONIC ANALYSISAND TRANSIENT ANALYSIS RESULTS.

Both harmonic and transient analysis were conducted on the composites model to obtain the resonance spectrum, which would provide the guidance for the choice of the pumping wave frequency. The impedance spectrum in 20~30 kHz range acquired from the harmonic analysis is presented in Figure 11. In the transient analysis, the actuator excited an impulse signal. Figure 11 also illustrates the response information in frequency domain from the receiver. These 2 result matched well and the finale selected resonance frequency was 38.4 kHz as denoted in Figure 11.

The frequency selection of probing wave also requires careful consideration. To signify the mixed frequency response, the high frequency probing wave should avoid the integer multiples of the pumping wave, as well as the the sum and difference of the pumping and probing wave. In conclusion, the high frequency was selected as 70 kHz. Figure 2a demonstrates snapshots of the entire excitation process and the out-of-plane responses on the button surface. The resonant pumping wave was firstly introduced. After several rounds of swings, the structure was completely resonated. Then, the high frequency probing wave was introduced, raising nonlinear interaction with the delaminated interfaces. Obvious nonlinear trembling in simulated delamination area could be observed directly from the response snapshots.

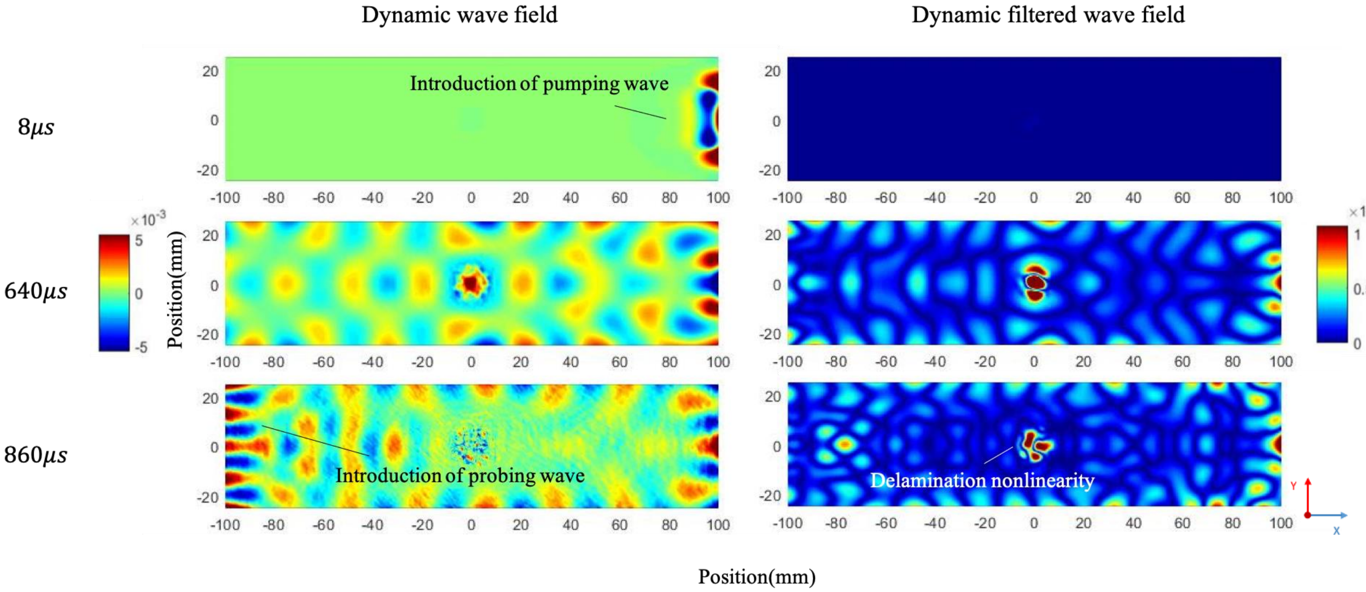


**FIGURE 12:** (a) SNAPSHOTS OF INSTANTANEOUS WAVE FIELD; (b) SNAPSHOTS OF TRANSIENT FILTERED WAVE FIELD.

To extract the nonlinear information of sideband effect, filtering in frequency domain was implemented. After Fourier transform to the responses data, a narrow band filtering window centered at 108.4 kHz was multiplied to retain the mixed frequency response only. Then the filtered data were transformed back into the temporal domain by inverse Fourier transform. Detailed information of the post-process algorithm is shown in paper of Shen [13]. Figure 12b presents the filtered dynamic wave filed. The pixel value was high in the delaminated area while still rendering non-negligible noise of nonlinearity from interrogating wave field.

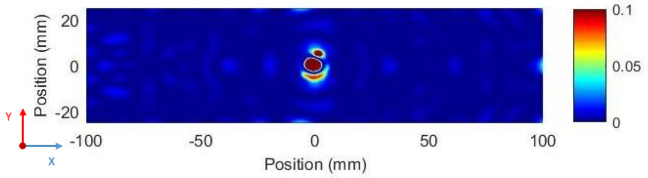


**FIGURE 13:** COMPREHENSIVE NONLINEAR DAMAGE INDEX DISTRIBUTION.

Figure 13 demonstrates the comprehensive nonlinear damage imaging result, the accumulation of the absolute response values during a certain selected temporal period. To maximize the damage induced nonlinearity and minimize the inherent nonlinearity, the accumulation started from the introduction of probing wave and ended at the moment when the incident waves have swept through the plate. The imaging result shows great potential for damage detection in practical tests.

## 5. CONCLUDING REMARKS

This paper presented both the linear and nonlinear ultrasonic features for the development of delamination detection strategies in composite structure. The imaging of dynamic wave propagation and interaction wave fields was depicted by the SLDV. A 3D coupled-filed transient dynamic finite element model was conducted to furtherly illustrate the scenarios of the both linear and nonlinear ultrasonic guided wave features. In the linear case, trapped modes were evaluated using the numerical model. Then experiments on two carbon fiber composite plates with different delamination severities were conducted to manifest the effectiveness of the energy-based damage index algorithm. Furthermore, weighted energy-based damage index algorithm was proposed using the direction vector field technique, through which the delaminated area can be prominent. For the nonlinear ultrasonic case, a resonant vibro-acoustic excitation methodology was adopted. Meanwhile, the damage index in proportion to amplitude of the mixed frequency response was examined. The results showed that the proposed wave field imaging technique may possess great application potential in future SHM and NDE applications.

For future work, further investigation of the nonlinear wave field information for delamination detection will be conducted experimentally.

## ACKNOWLEDGEMENTS

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