Nonlinear Guided Wave Path Interaction for Damage Detection and Imaging of Composite Structures

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ABSTRACT

Composite materials are taking an increasingly important role across various industries, particularly in aerospace and high-end automotive engineering, due to their exceptional strength-to-weight ratio, corrosion resistance, and design flexibility. However, the anisotropic and layered nature of composite structures makes them susceptible to hidden damage such as delamination, matrix cracking, and fiber breakage that may not be visible externally but can critically compromise structural integrity. Therefore, the damage detection of composite structures holds paramount importance in the realm of industrial safety. This paper presents a nonlinear guided wave path interaction technique for damage detection and imaging for composite structures. This study initiates with the discussion on mixed frequency response of nonlinear ultrasonics. An in-depth theoretical analysis via Finite Element Modeling (FEM) was carried out to investigate the wave interaction mechanism. Simulation results show that nonlinear mixed wave components are generated, which could provide indicative information for localizing particular damage sites on the plate. The effective generation of guided wave modes is investigated, where the pure wave mode excitation is accomplished through a tuning procedure. To practically realize the damage localization, two arrays of piezoelectric wafer active sensors (PWAS) are placed on a composite plate, in order to generate and record the nonlinear ultrasonic feature variations, while different center frequency propagating waves are travelling along multiple wave paths simultaneously, crossing each other for involving nonlinear interactions at the damage sites. The characteristic features extracted from multiple signal channels are combined to create a color-mapped image of the damage condition on the composite plate. Finally, based on the quantification algorithm, damage can be imaged, utilizing the nonlinear interaction intensity between crossing propagation guided wave-paths. The findings of this research possess superb application potential for damage detection of composite structures for enhancing manufacturing quality and avoiding unexpected failures in industry. This paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: damage detection; nonlinear guided wave path interaction; nondestructive testing; nonlinear ultrasonics; composite structures

1. INTRODUCTION

Due to their strong fatigue and corrosion resistance performance, as well as their ease of processing, composite materials have been widely used in engineering fields such as aviation aircrafts, space structures, and high-end automobiles in recent years [1-3]. However, in practical scenarios, unavoidable damage events such as fiber breaking, delamination, debonding, or cracking often occur due to environmental and operational factors and are difficult to detect. If these damage sites are not identified promptly, they could lead to significant economic losses and casualties [4]. To ensure the reliability and safety of structures, there is a desperate need for rapid and effective Structural Health Monitoring (SHM) technologies.

Ultrasonic guided waves have become a focus in the field of SHM due to their advantages of long propagation distance, low attenuation, and high sensitivity to damage [5-9]. Currently, research on damage detection based on ultrasonic guided waves primarily involves comparing the signals from healthy and damaged states along the same wave path [10, 11], or utilizing the time-reversal method to damage visualization. For instance, Wang et al.[12] proposed using the focusing properties of the time-reversal phenomenon of guided waves to reconstruct signals, which significantly enhanced the accuracy of damage location estimation in aluminum plates. Xu et al. employed a novel baseline-free method for damage imaging using Lamb waves based on a hyperbolic algorithm [13]. Zuo et al. presents a novel model-based 2D multiple signal classification (MUSIC) damage identification algorithm for plate-like composite structures [14]. The probabilistic weighted imaging algorithm does not require prior knowledge of guided wave propagation in structures and avoids the interpretation of complex temporal histories in real structures, offering high computational efficiency and suitability for automatic processing, effectively assessing damage locations and shapes in complex structures like composite panels [15]. However, Michaels noted that the performance of the probabilistic weighted imaging algorithm for damage assessment is directly related to the number of sensors deployed [16]. Besides, phased array time delay and superposition imaging has been widely used due to its simplicity and capability for real-time image reconstruction. Habermehl et al. utilized an ultrasonic phased array system to inspect flat components made of carbon fiber-reinforced polymer composites in aircrafts [17]. The results indicated that this system's detection speed and imaging quality surpassed those of traditional ultrasonic inspection methods. Yu et al. embedded the wavenumber-frequency dispersion relation of guided waves into the imaging algorithm during the inspection of plate-like structural components using an ultrasonic guided wave phased array and achieved enhanced accuracy in damage imaging [18].

Due to the anisotropic property of composite materials such as carbon fiber reinforced polymer (CFRP), guided waves travel with different speeds in various directions. Therefore, tomography imaging methods are found to be more suitable by researchers for damage imaging in composite structures, as there is no need to consider the wave skew phenomenon, eliminating the deviation of imaging accuracy. Numerous tomographic schemes have been developed, with some of the most prominent methods including the time-difference-of-arrival (TDOA) imaging technique, the energy arrival method, and the Reconstruction Algorithm for the Probabilistic Inspection of Damage (RAPID) [19-21]. These approaches have significantly contributed to advancements in tomographic imaging and damage assessment. Among them, the tomographic approach based on RAPID is well-suited for efficient implementation utilizing ultrasonic guided wave features. Based on the existing research in the literature, the technology based on linear ultrasonic features has matured. However, damage detection and imaging technique using nonlinear ultrasonics has not been extensively explored. Nonlinear ultrasonics have been reported to be more sensitive to incipient structural damage and may provide a new perspective for baseline free damage evaluation.

This paper builds on the tomography imaging method with a novelly proposed nonlinear wave path interaction approach, utilizing piezoelectric wafer active sensors (PWASs) to achieve damage imaging in composite laminate panels. This paper starts with the discussion on the mechanism of nonlinear wave path interaction-based tomography, followed by numerical analysis. A Finite Element Model (FEM) is established to showcase the special signal features after multiple wave interaction at a general nonlinear source. Then, an imaging algorithm is presented and a LabVIEW program is leveraged to automatically control the active sensing process. Finally, a series of experiments are conducted to demonstrate the effectiveness of damage imaging using a PWAS sensor array.

2. NUMERICAL INVESTIGATION ON NONLINEAR WAVE MIXING

To develop the fundamental understanding of nonlinear wave path interaction method, numerical simulation was conducted via COMSOL. To investigate the mechanism of the proposed method, two transmitter PWASs are placed on a plate structure, one for low frequency pumping wave excitation and the other for high frequency probing wave generation as shown in Figure 1. A contact interface is set in the middle of the plate representing a general damage-related source of Contact Acoustic Nonlinearity (CAN). A receiver PWAS is placed on the other side to capture the nonlinear response through the interactive wave path. The pumping and probing waves are chosen as a 160 kHz sine wave and a 260 kHz 20-count tone burst, respectively.

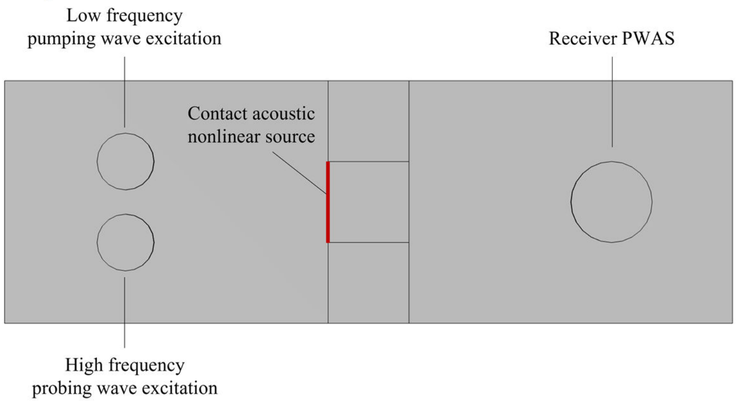

Figure 1. A general numerical model for investigating the mechanism of nonlinear wave path interaction.

Figure 2 shows the excitation signals and the receiver signal containing the nonlinear wave interaction information. Fast Fourier Transform (FFT) was performed on the temporal domain receiver signal to obtain its spectral information. Based on the frequency domain spectrum, nonlinear frequency mixing phenomenon is evident with the specific arising frequency component ($f_1 + f_2$), which serves as the foundation for multiple wave path interaction approach, i.e., if different frequency wave paths cross each other at a damage site and involve nonlinear interactions, mixed frequency response will come into being. By analyzing the magnitude of the new frequency component, diagnostic conclusion can be drawn for the possibility of damage existence on the corresponding wave paths.

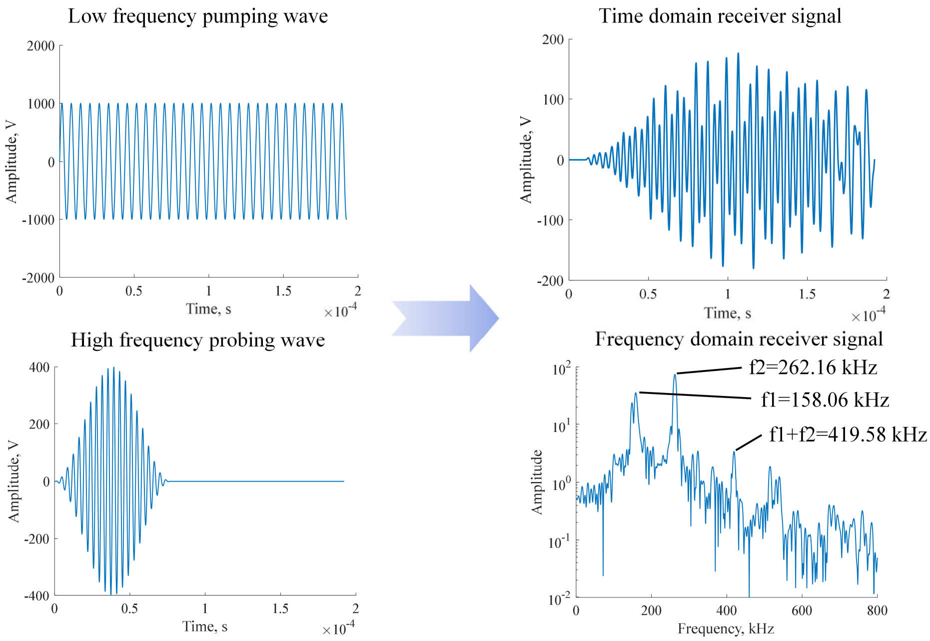

Figure 2. Excitation signals and mixed frequency response from wave path interactions captured by the receiver.

3. NONLINEAR GUIDED WAVE PATH INTERACTION TOMOGRAPHY ALGORITHM

The propagation of guided waves in composite materials demonstrates a special skew angle phenomenon. Such an effect usually leads to inaccuracy of conventional damage imaging methods heavily relying on wave propagation direction estimation, since it is different from phase velocity and hard to estimate. A simple wave skew phenomenon could be illustrated by Figure 3, showing wave propagation in a CFRP laminate with a layup sequence of [0°/45°/90°/45°/0°/-45°/-90°/-45°/0°]. Along zero-degree fiber direction, guided wave propagates along the wave launching direction. However, it reveals a different orientation considering another launching direction, showing an obvious wave skew angle effect.

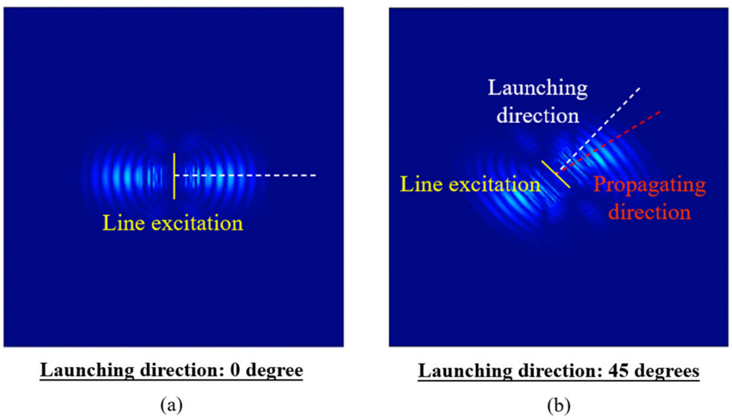

Figure 3. Skew angle phenomenon in a composite laminate with launching directions of (a) 0 degree and (b) 45 degrees.

It should be noted that although the skew angle still exists, the wave energy always propagates in a straight forward manner, as is evident in Figure 3b. Therefore, the tomography imaging methods can readily overcome such a skew angle issue, since a tomography wave path is clearly defined by a pair of trimester and receiver. This makes tomography especially suitable for damage imaging in anisotropic composite materials.

A baseline free damage imaging approach based on nonlinear wave path interaction is proposed, leveraging nonlinear ultrasonic characteristics for damage evaluation. The mechanism of this method is illustrated in Figure 4. Two arrays of PWAS transducers are implemented on the composite laminate. For every sensing step, two transducers from the same side are serving as actuators and all the others on the other side as receivers. A low frequency, continuous pumping wave (f_1) is excited into the structure to achieve structural vibration and a high frequency probing wave (f_2) as a tone burst is transmitted simultaneously. These two wave fields will interact with each other and undergo modulation at the damage position. Finally, the transmitted tone bust will be collected by the sensors. During this process, nonlinear frequency mixing will arise, if the wave path of the probing wave crosses the damage.

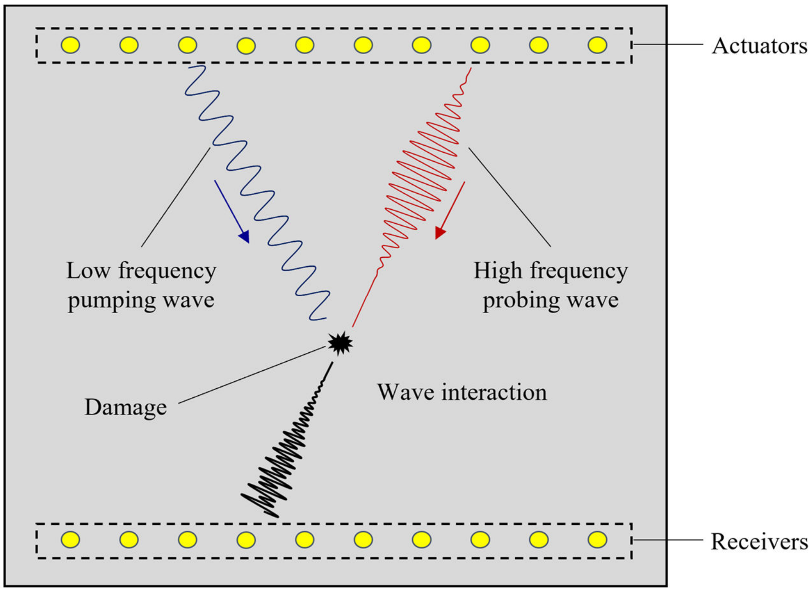

Figure 4. Mechanism illustration of nonlinear wave path interaction tomography in a composite panel.

Theoretically, a new frequency component ($f_1 + f_2$) will appear due to the interaction between low frequency pumping wave and high frequency probing wave at the damage position based on the nonlinear frequency mixing principle. The magnitude of the mixed frequency component is utilized for evaluating the damage existence possibility. Therefore, a novel index named Spatial Damage Index (SDI) is proposed for the tomography construction. Different from the RAPID algorithm, SDI is stated as

$$\mathrm{SDI}_{ij} = \left| \frac{\int_{f_1+f_2-\Delta f}^{f_1+f_2+\Delta f} [X_{ij}(f)] df}{\int_{f_2-\Delta f}^{f_2+\Delta f} \left[X_{ij}(f)\right] df} \right| \tag{1}$$

where $X_{ij}(f)$ is the Fourier Transform of the time domain signal $x_{ij}(t)$. After that the images are generated by spatially distributing SDI value in an elliptical pattern with a parameter γ to define the spatial probability distribution. The spatial distribution function is defined as,

$$s_{ij}(x, y) = \frac{\gamma - R_{ij}(x, y)}{1-\gamma}, \quad \text{for } \gamma > R_{ij}(x, y) \tag{2}$$

$$s_{ij}(x, y) = 0, \quad \text{otherwise} \tag{3}$$

where $R_{ij}(x, y)$ is the ratio of the sum of distances of the point (x, y) to the transmitter i and receiver j to the distance between the transmitter and receiver, which is stated as,

$$R_{ij}(x,y) = \frac{\sqrt{(x_i - x)^2 + (y_i - y)^2} + \sqrt{(x_j - x)^2 + (y_j - y)^2}}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} \tag{4}$$

Finally, the image amplitude at each pixel is calculated as the linear sum of the location probabilities derived from each of N transmitter–receiver PWAS pairs. This relationship is expressed as follows:

$$P(x,y) = \sum_{i=1}^{N}\sum_{j=1}^{N} \mathrm{SDI}_{ij} s_{ij}(x,y) \tag{5}$$

4. EXPERIMENTAL DEMONSTRATION OF IMPACT DAMAGE IMAGING

The experimental verification was conducted on a composite laminate panel to showcase the performance of the proposed method. An integrated programing of LabVIEW with Matlab was employed for achieving the automated damage detection procedure. A LabVIEW GUI was developed for user control, automation of signal excitation, acquisition, and subsequent signal post-processing, while Matlab was employed for final damage imaging. The experimental setup, as depicted in Figure 5, utilized a CFRP composite panel as the testing structure, with damping clay applied around its edges as non-reflective boundaries for eliminating the influence of reflected signals on the analysis results. Two PWAS arrays, each with ten PWAS transducers were placed on the upper and lower ends of the plate to realize signal generation and reception, respectively. A NI high-performance data acquisition system served as the signal source, with a power amplifier amplifying the signal and inputting it to the corresponding transmitter PWAS. Finally, analysis software GUI was used to analyze the collected signals and obtain the final imaging results. The nonlinear type damage is set at the coordinate (21, 20) on the composite plate. This representative damage was implemented through a drop-ball impact test. The impact energy was set to 15 Js.

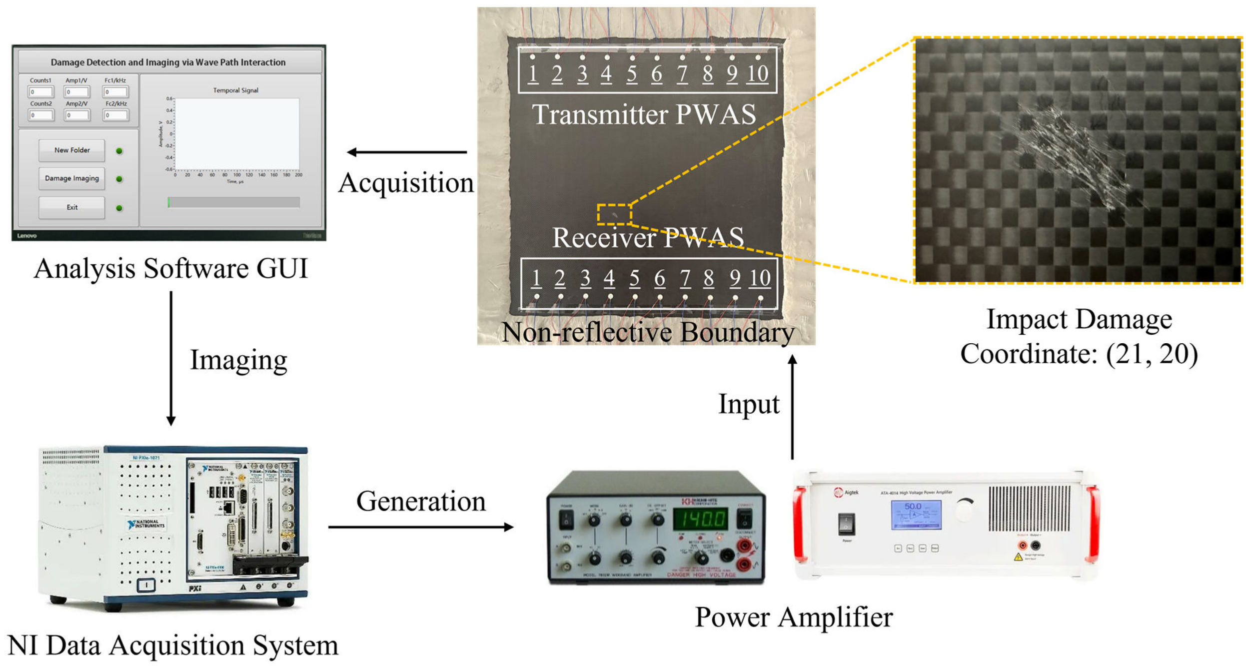

Figure 5. Experimental setup for demonstrating the nonlinear wave path interaction tomography.

After a tuning process, the high frequency probing wave was chosen as a 260 kHz 20-count tone burst signal with an amplitude of 50 Vpp and the low frequency pumping wave was selected as 160 kHz continuous sine wave. The pumping wave is applied on one transmitter PWAS and to engage the nonlinear response, each of the other transmitter PWASs sent out the probing tone burst signal one by one, taking turns. Figure 6 and Figure 7 shows the nonlinear frequency response when the pumping and probing wave paths interacted with each other at the damage position. It can be clearly noticed that the frequency component ($f_1 + f_2$) appeared in the frequency domain of receiver signals. Specifically, along the wave path of transmitter #2 to receiver #5 and transmitter #4 to receiver #4, the nonlinear response showed the highest intensity, which validated the proposed nonlinear wave path interaction method and facilitated the following damage imaging process. However, when the damage is not along the wave propagation path between particular actuators and receivers, no acoustic nonlinearity phenomenon appeared as depicted in Figure 8, which further validated the damage imaging algorithm based on accumulating the related wave path probability. Based on Eq. (1)-(5), the final imaging result is obtained as depicted in Figure 9. The focusing position of the highlighted wave path demonstrated the estimated damage position by the imaging algorithm based on the nonlinear guided wave path interaction method, with the final damage coordinate result of (20, 19.3). Compared to the actual damage position (21,20), it indicates that the proposed method is able to accurately and efficiently evaluate the damage location, which could be utilized for detecting and localizing impact damage in composite structures.

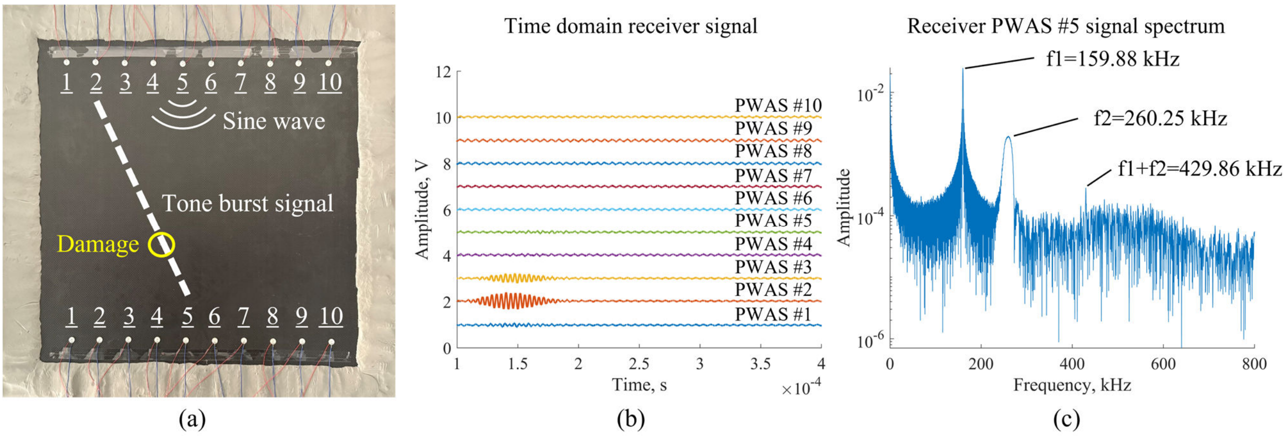

Figure 6. (a) Illustration of experimental signals by exciting tone burst signal at PWAS #2; (b) Time domain signal of receiver PWASs; (c) Signal spectrum of receiver PWAS #5.

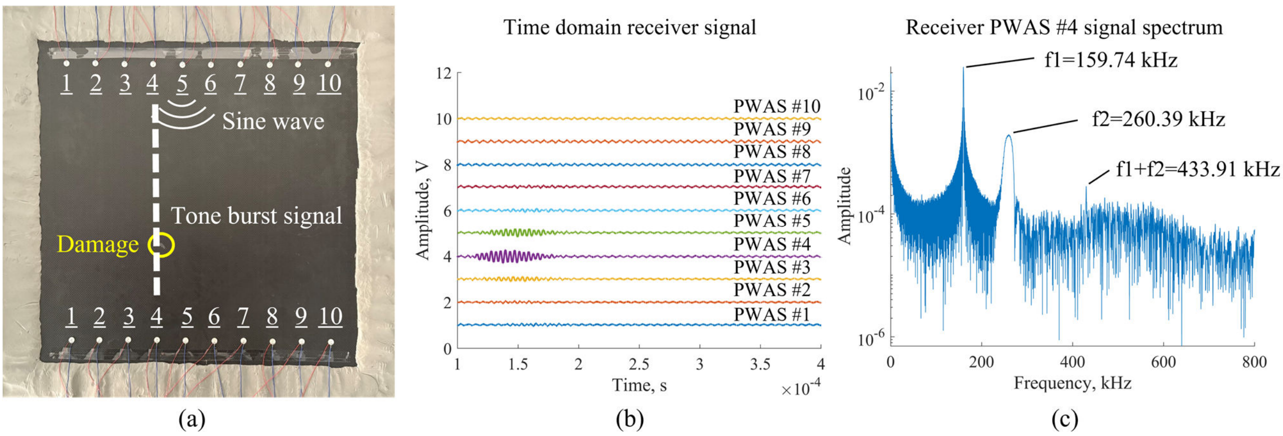

Figure 7. (a) Illustration of experimental signals by exciting tone burst signal at PWAS #4; (b) Time domain signal of receiver PWASs; (c) Signal spectrum of receiver PWAS #4.

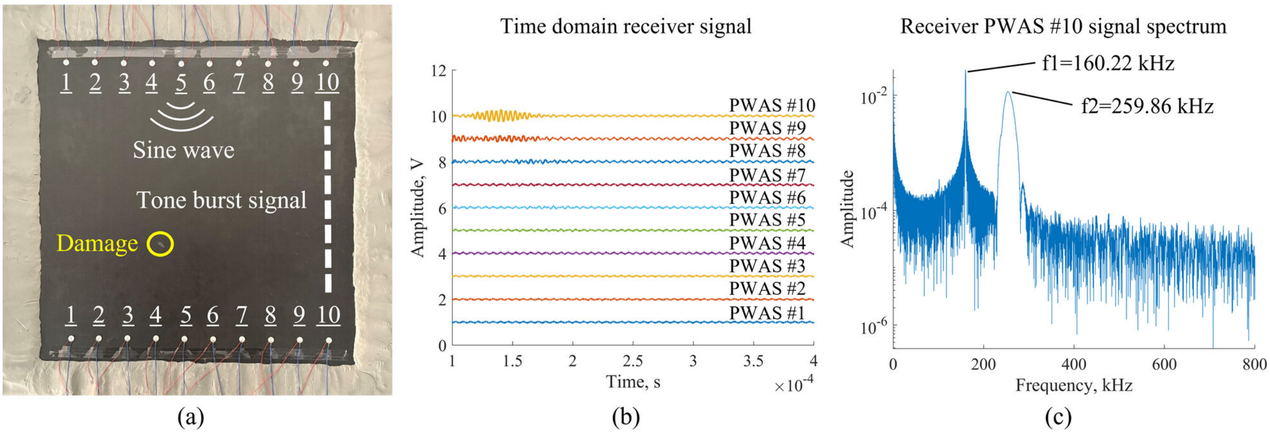

Figure 8. (a) Illustration of experimental signals by exciting tone burst signal at PWAS #10; (b) Time domain signal of receiver PWASs; (c) Signal spectrum of receiver PWAS #10.

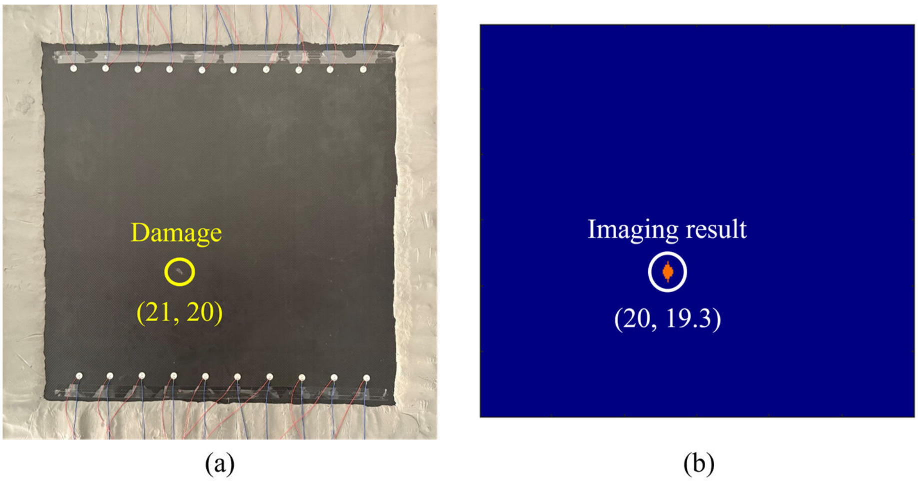

Figure 9. (a) Physical damage position on the CFRP panel; (b) Final damage imaging result based on nonlinear wave path interaction method.

5. CONCLUDING REMARKS AND SUGGESTIONS FOR FUTURE WORK

This paper presented a novel, baseline free damage localization and imaging approach for composite structures by leveraging the nonlinear guided wave path interaction mechanism. It was found that the nonlinear mixed frequency response could provide characteristic values for localizing damage types such as crack and delamination. By comparing the amplitude of the newly generated nonlinear frequency component, it was found that this method provides a new approach to obtaining the spatial damage index (SDI) along tomography wave paths. The experimental verification was conducted on a damaged CFRP laminate. A LabVIEW GUI was developed to achieve the automated active sensing by controlling the sensor array. The imaging result showed good agreement with the physical impact damage, which demonstrated the outstanding performance of the proposed tomography technique.

The future work should involve distributed resonant transducers for better engagement of strong nonlinear modulations. Investigation on improved sensor network design should be carried out for collaborating with the proposed method. This imaging algorithm should be further tested for specimens with multiple damage sites.

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