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DAMAGE DETECTION AND IMAGING FOR COMPOSITE STORAGE TANKS UTILIZING ULTRASONIC GUIDED WAVES

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ABSTRACT

Storage tanks, widely used for containing hazardous or high-pressure gases, are susceptible to damage due to factors like corrosion, cyclic inflations, and external impacts. The failure to promptly and accurately detect such damage can lead to catastrophic events, including leaks, explosions, and environmental contamination, posing severe risks to public health and safety. Moreover, timely detection plays a crucial role in maintaining the operational efficiency of storage facilities, avoiding costly downtime and ensuring compliance with strict safety regulations. Therefore, the detection of damage in storage tanks holds paramount importance in the realm of industrial safety and environmental conservation. Thus, this paper proposes the advancement of damage detection technology, utilizing the guided waves by detecting the variation of ultrasonic features for different damage conditions.

By carrying out an in-depth theoretical analysis via Finite Element Modeling (FEM), the sensitivity of the probing ultrasonic wave characteristics is studied systematically. The effective generation of guided wave modes is investigated, where the pure wave mode excitation is accomplished through a tuning procedure. To realize the damage localization, a three-dimensional numerical model is established by considering random defects placed on the surface. Two arrays of active sensors are placed on the tank, in order to record and evaluate the signal amplitude variation, while the propagating waves are travelling along the composite structure. Consequently, via the comprehensive consideration of transducer dimensions, center frequency, and propagating wave modes, the most effective damage detection setup is achieved and the sensing signals are recorded by the piezoelectric wafer active sensors (PWAS). Simulation results show that significant features such as the variation of the signal amplitude are fully captured, which are related to the presence of the damage along the wave path. Additionally, the Time of Flight (TOF) of sensing signals could further provide indicative information for localizing the particular defect on the tank. By changing the size, location, and quantities of defects, the feasibility and accuracy of this damage detection method is verified through the numerical analysis. The characteristic features extracted from multiple received signals are combined to reconstruct a color map of the damage condition on the storage tank. Finally, based on the quantification algorithm, damage can be imaged, utilizing crossing propagation paths of guided waves. The findings of this research possess superb application potential for the damage detection in composite tanks for enhancing the safety of storage systems. This paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: damage detection; storage tank; structural health monitoring; ultrasonics; composite structures; damage imaging

1. INTRODUCTION

Due to their strong fatigue resistance, corrosion resistance, and ease of processing, composite materials have been widely used in engineering fields such as aviation aircraft, subways, and automobiles in recent years[1-3]. However, in practical engineering, unavoidable damages such as fiber cracking, delamination, debonding, or cracking often occur due to environmental factors and are difficult to detect. If these damages are not identified promptly, they could lead to significant economic losses and casualties[4]. To ensure the reliability and safety of structures, there is an urgent need for rapid and effective structural health monitoring technologies. Ultrasonic guided waves have become a focus in the field of structural health monitoring 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 path[10, 11], or utilizing the time-reversal method to locate damages. For instance, Wang et al.[12] proposed using the focusing properties of the time-reversal method to reconstruct signals, which significantly enhanced the accuracy of damage location detection in aluminum plates. Xu et al.[13] employed a novel baseline-free method for damage localization using Lamb waves based on a hyperbolic algorithm. Zhao et al.[14] conducted comparative studies on different imaging methods and concluded that the Reconstruction Algorithm for the Probabilistic Inspection of Damage (RAPID) could obtain high-quality reconstruction images quickly. Liu et al.[15] used an improved RAPID to eliminate the uneven distribution observed in non-damaged cases during delamination defect detection in composite boards. Zuo et al.[16] presents a novel model-based 2D multiple signal classification (MUSIC) damage identification algorithm for plate-like structures in composite materials. However, their research lacks investigation into multiple damage locations in composite boards. 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 boards[17]. However, Michaels[18] noted that the performance of the probabilistic weighted imaging algorithm in damage assessment is directly proportional to the number of sensors deployed. Besides, phased array time delay and superposition imaging is widely used due to its simplicity and capability for real-time reconstruction. Habermehl et al.[19] utilized an ultrasonic phased array system to inspect flat components made of carbon fiber-reinforced polymer composites in aircraft. The results indicated that this system's detection speed and imaging quality surpass those of traditional ultrasonic inspection methods. Yu et al.[20] embedded the wave number-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. This effectively enhanced the accuracy of damage imaging.

Based on the existing research on damage detection and localization by these researchers, the technology for locating damages in planar structures has matured. However, damage detection in curved structures has been less explored. Addressing this issue, this paper builds on the tomography imaging method and employs curved piezoelectric wafer active sensors (PWASs) on composite material storage tanks to identify damage regions and image both single and multiple damage locations. This method effectively detects and locates damages in curved structures.

This paper starts with the numerical model design of the composite storage tank and corresponding PWASs, followed by the method mechanism discussion. A general Finite Element Model (FEM) is established to verify the feasibility of the damage detection method. Besides, based on the imaging algorithm, the damage can be visualized and a LabVIEW program is leveraged which is able to automatically control the whole process. Finally, a series of experiments is conducted to demonstrate the effectiveness of both single and multiple damage locations imaging under different conditions.

2. NUMERICAL INVESTIGATION OF DAMAGE LOCALIZATION ON COMPOSITE STORAGE TANK

2.1 Numerical model of storage tank and PWAS array

The target structure of this research is a hydrogen storage tank, a cylindrical container constructed from carbon fiber composite material, with dimensions of 50 cm in diameter and 80 cm in length. The layup of this carbon fiber structure is arranged in a [0°/45°/90°/45°/0°/-45°/-90°/-45°/0°] sequence to characterize its internal structure. A finite element model of this structure was developed using COMSOL software for simulation purposes, as shown in Figure 1. Additionally, to facilitate signal excitation and reception, two arrays of curved Piezoelectric Wafer Active Sensors (PWAS) are placed on the surface of the tank, conforming to the tank's curvature, one as actuators and the other as receivers. This sensor array system enables real-time monitoring and assessment of the tank's structural health, thereby ensuring the safety and reliability of hydrogen storage applications.

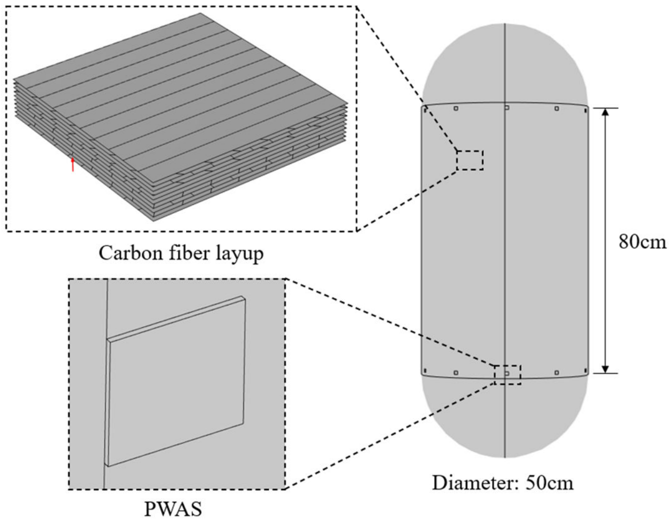

FIGURE 1: ILLUSTRATION OF COMPOSITE STORAGE TANK NUMERICAL MODEL

2.2 Mechanism of damage localization and imaging

Ultrasonic guided waves propagate through structures and scatter at sites of damage, leading to distinct changes in the characteristics of the signals received by sensors under pristine and damaged conditions, such as alterations in signal amplitude and time of flight. These changes can be effectively utilized to assess the damage state and location within the structure. To verify the feasibility of this principle on the target structure, a simple numerical simulation is conducted with a pair of PWASs placed on the surface. Two cases are studied, including pristine and damaged ones. The damage is placed at the center along the sensor path, established by significantly reducing local stiffness of the material covering a certain area. After the typical tuning process, the excitation signal is selected as a 5-count tone burst signal with the center frequency of 200 kHz. According to Figure 2, significant variation of signal characteristics is observed, such as reduction of the signal amplitude and lagging of time of flight, indicating the feasibility of damage detection method on curved structures.

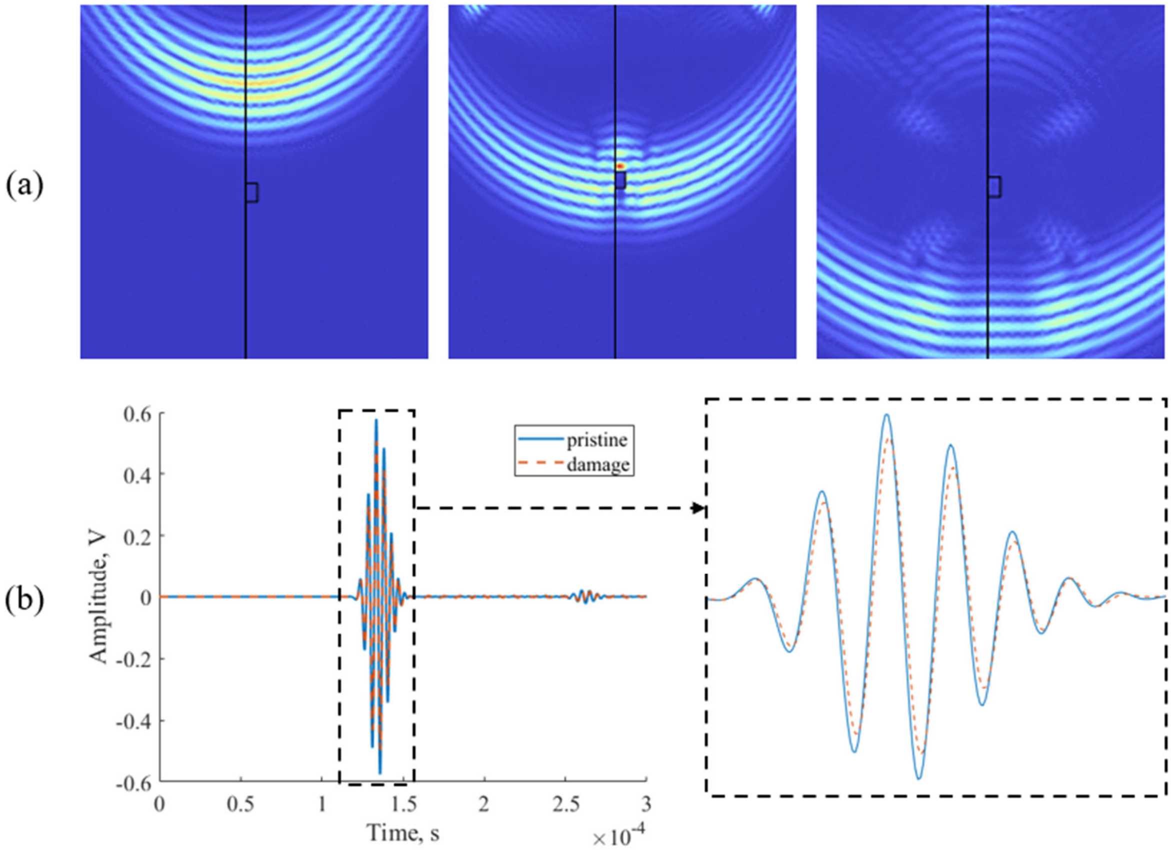

FIGURE 2: (A) DEMONSTRATION OF WAVE PROPAGATING THROUGH DAMAGE; (B) RECEPTION SIGNAL COMPARISON BETWEEN PRISTINE AND DAMAGED CASES

Among various imaging algorithms, this paper employs a weighted imaging algorithm. In practical engineering applications, the propagation of guided waves tends to be complex, and wave signals can be difficult to interpret, especially in composite materials. The weighted imaging algorithm identifies damage by utilizing the differences between pristine and damaged signals without the need for knowledge of wave propagation speeds or other parameters, nor does it require analysis of the complex multimodal characteristics of guided waves or the structural properties of the materials. As guided waves propagate through composite materials, the original excitation signal becomes distorted. This algorithm reconstructs images by comparing the differences in damage at any point within the plate to distances along the same sensor path. Typically, Damage Index (DI) values are used to represent the extent of signal changes caused by damage along the same path. When the pristine baseline signal coincides completely with the damaged signal, it indicates no damage along that path, and the DI value approaches zero. Conversely, the greater the difference between the pristine baseline and damaged signals, the closer the detected path is to the location of the damage, and thus the DI value approaches one. The weighted function is able to indicate the damage index value at pixel points along a path within the detection area. The number of pixel points is 5 times the size of the tested object, contributing to a more precise localization result. To evaluate and locate the damage distribution across the entire detection area, multiple detection paths are required. Consequently, the damage value at any given point within the entire detection area is the cumulative sum of the damage values from multiple detection paths. Based on the fundamental principles, we propose a Spatial Damage Index (SDI) value to characterize the damage condition at any pixel point, which is:

$$SDI(x,y)=\sum_{i=1}^{N_s}\sum_{j=1}^{N_s}\left\{1-\frac{\max\left(F_{\mathrm{d}}(i,j)\right)}{\max\left(F_{\mathrm{u}}(i,j)\right)}\right\}S_{ij}(x,y) \quad (1)$$

where (x, y) represents the coordinates of the pixel point inside the detection area, N_s represents the total sensor numbers, $F_d(i, j)$ represents the reception signal received by sensor j and excited by sensor i under damaged condition, $F_p(i, j)$ represents the reception signal received by sensor j and excited by sensor i under pristine condition and $S_{ij}(x, y)$ represents the spatial distribution function. If the point (x, y) is along the path between sensor i and j, then $S_{ij}(x, y)$ will be 1 within a certain tolerance, otherwise it will be 0. According to the weighted imaging algorithm, the damage value at each point is calculated, and subsequent normalization process is applied to obtain a reconstructed image that displays the location and size of the damage within the structure.

2.3 Single and multiple damage imaging investigation

Based on the algorithm introduced in the previous section, we conducted localization and imaging of single and multiple damages on the numerical model. Initially, 10 PWAS were placed on both ends of the model's surface to form two arrays, used for signal excitation and reception. Due to the difficulty of applying the algorithm and performing imaging on curved surface models, the region of interest was unfolded along the edge between PWAS 1 and 10 to form a rectangle, simplifying the three-dimensional problem into a two-dimensional one according to Figure 3. It ensures both the simplicity and accuracy of damage localization and imaging in the study, thereby facilitating effective analysis.

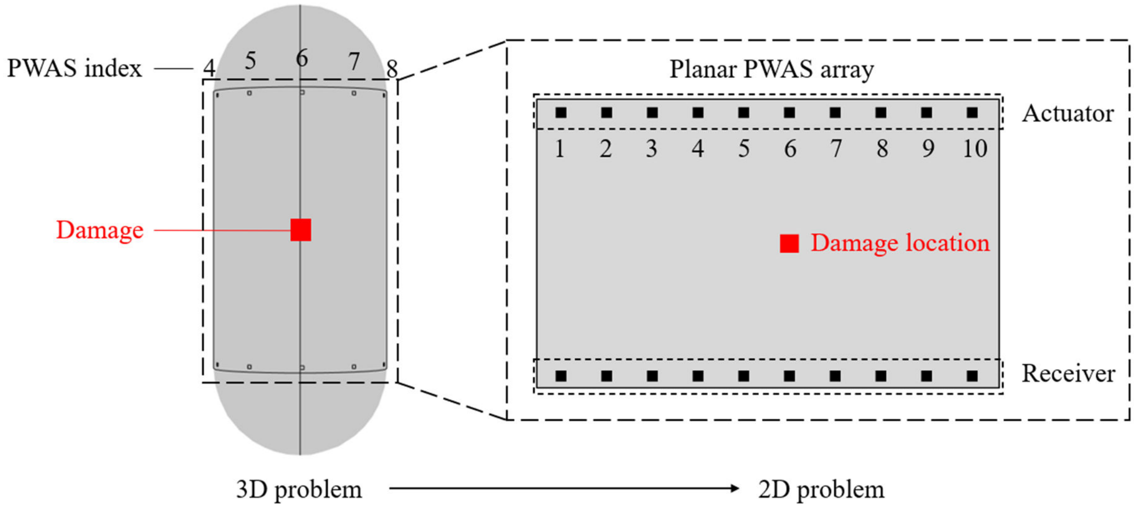

FIGURE 3: DEMONSTRATION OF PROBLEM SIMPLIFICATION FROM 3D TO 2D UNDER THE CONDITION OF SINGLE DAMAGE

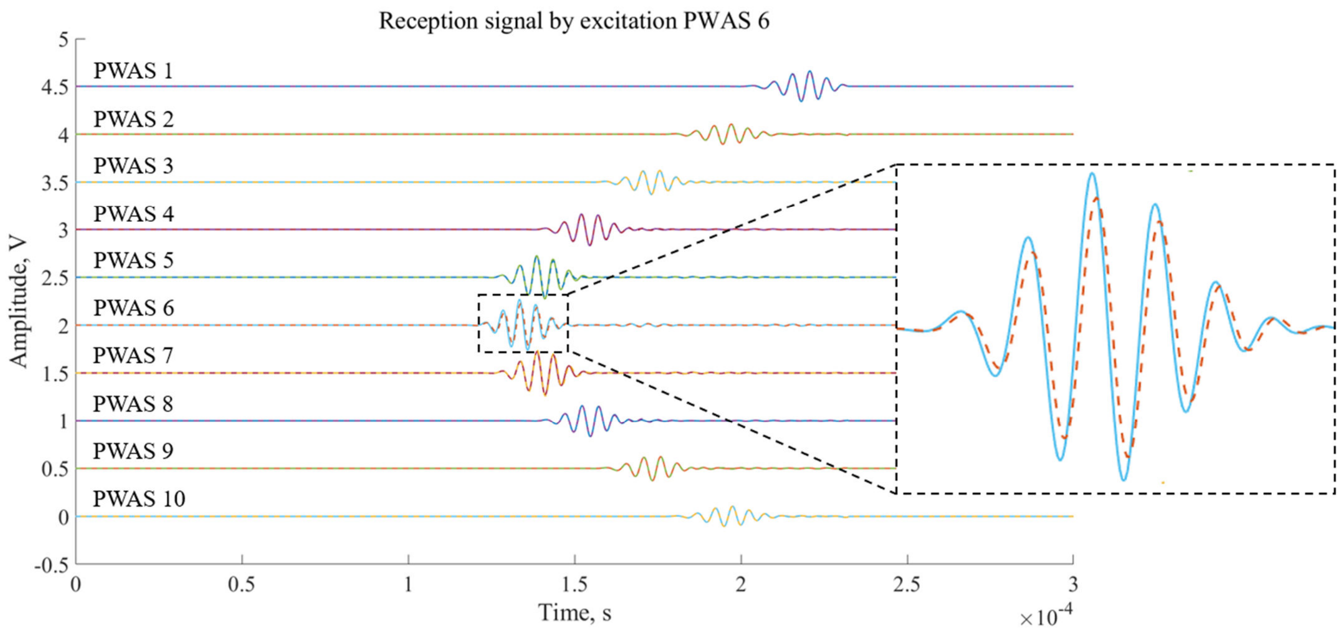

FIGURE 4: RECEPTION SIGNAL ILLUSTRATION BY EXCITATION PWAS 6 AND CHARACTERISTIC VALUES CAPTURE

Focusing on the simulation conditions for single damage, the red square in Figure 3 represents the location of the damage, precisely between excitation and reception PWAS 6. To achieve localization and imaging of this damage, each excitation PWAS from 1 to 10 was actuated sequentially, and the PWAS array at the receiving end collected signals during excitation from each sensor, thus obtaining the SDI values for the entire region of interest and inferring the location of the damage. For example, Figure 4 illustrates the receiving signals from the PWAS array at the receiving end under excitation from PWAS 6. Consistent with theoretical expectations, apart from the receiving signal from PWAS 6, the signals received by the other PWASs remain unchanged compared to the pristine condition. However, a significant variation is observed in the receiving signal from PWAS 6, characterized by a decrease in signal amplitude and delayed time of flight, indicating the presence of damage along this path. Thus, both amplitude and flight time can be served as criteria for determining the location of damage. Therefore, final image indicates the exact position of the preset damage based on these two factors, as shown in Figure 5.

After successful imaging of single damage, multiple damages cases were continued. As shown in Figure 6, two damages were placed at different heights to validate the accuracy of the localization method and the precision of imaging. Following the same analysis procedure as for single damage, the excitation PWAS array was sequentially actuated, and signals from the receiving PWAS array were collected and subjected to the same post-processing steps to obtain the SDI values for each pixel. Based on the obtained planar image, the imaging map was reconstructed to match the cylindrical shape of the finite element model, providing a more intuitive visualization of the corresponding positions of the damage on the model. It is evident from Figure 6 that the damage locations are accurately localized and displayed, thus validating the effectiveness of this method for detecting, localizing, and imaging damage in actual storage tanks. This approach also establishes a solid foundation for subsequent verification experiments.

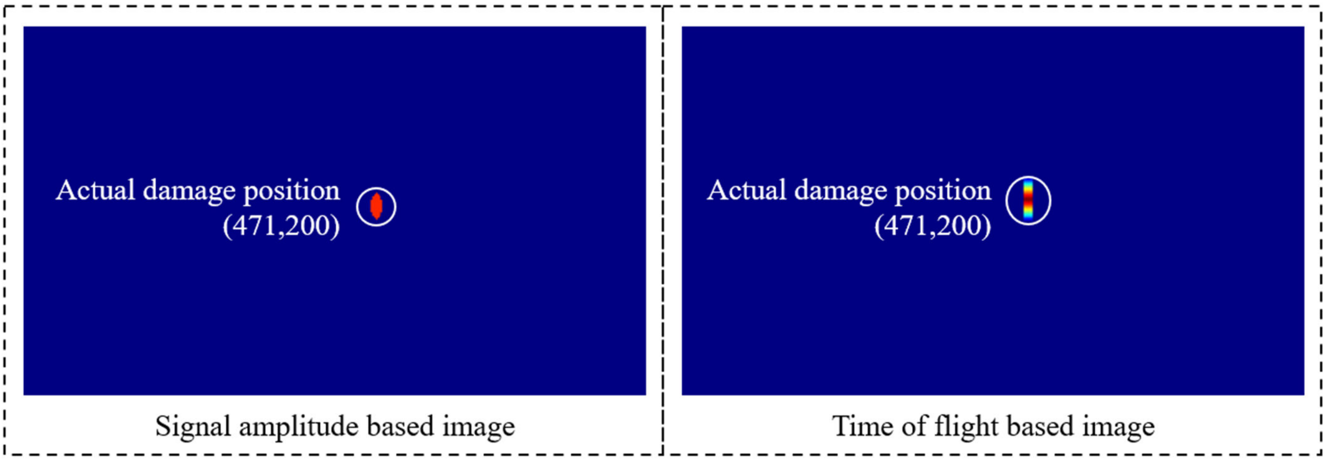

FIGURE 5: IMAGING RESULT OF SINGLE DAMAGE CASE BASED ON SIGNAL AMPLITUDE AND TIME OF FLIGHT

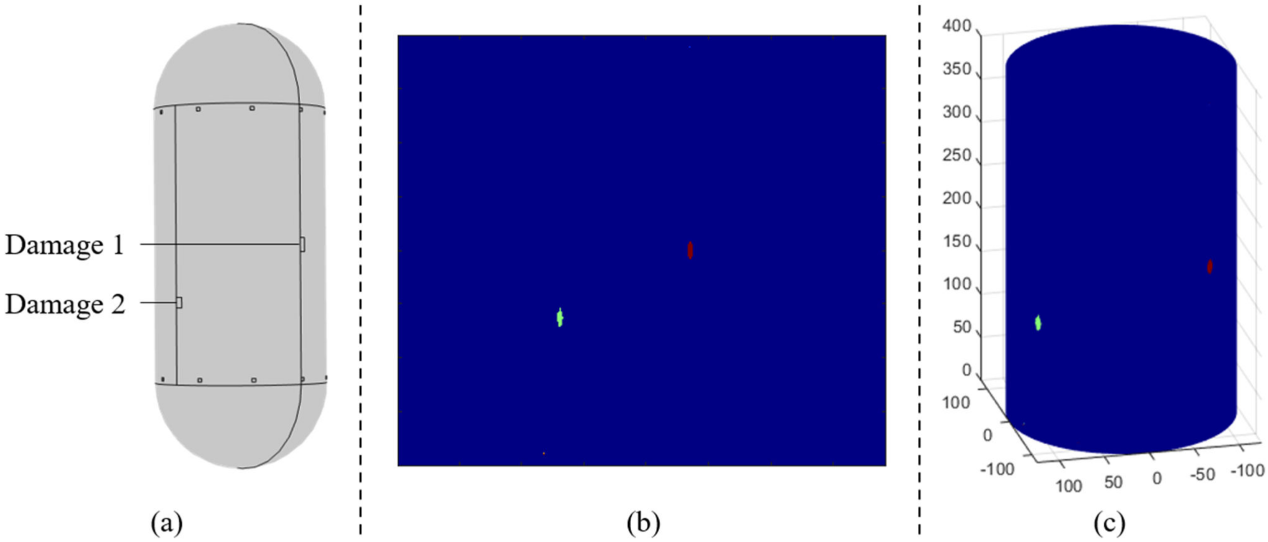

FIGURE 6: (A) NUMERICAL MODEL OF MULTIPLE DAMAGE CASE; (B) IMAGING RESULT OF DAMAGE LOCALIZATION; (C) RECONSTRUCTION OF IMAGE CORRESPONDING TO SHAPE OF NUMERICAL MODEL

3. EXPERIMENTAL VERIFICATION OF TOMOGRAPHY METHOD ON PLATE STRUCTURE

Following the verification of the finite element model simulation, experimental validation was conducted. During the practical experimental process, a combination of LabVIEW and Matlab software was employed for automated damage localization. LabVIEW was utilized for user control, automation of signal excitation, acquisition, and subsequent post-processing analysis, while Matlab was employed for final damage imaging. To validate the feasibility of the program and method, initial validation was performed on a plate. The experimental setup, as depicted in Figure 7, utilized an aluminum plate as the detection object, with rubber clay applied around its periphery to serve as non-reflective boundaries and eliminate the impact of signal reflection on the analysis results. Five PWASs were affixed to the upper and lower ends of the aluminum plate to form excitation and reception PWAS arrays, respectively. A NI high-performance waveform generator served as the signal source, with a power amplifier amplifying the signal and inputting it to the corresponding excitation PWAS. Finally, analysis software was used to analyze the collected signals and obtain the final imaging results. Single and multiple damage experiments were conducted on the aluminum plate by sticking small pieces of rubber clay to specific locations on its surface to represent damage. The imaging results, as shown in the figure, demonstrate that whether single or multiple damages are present, the method can accurately assess the damage locations, facilitating subsequent experimental validation on curved structures.

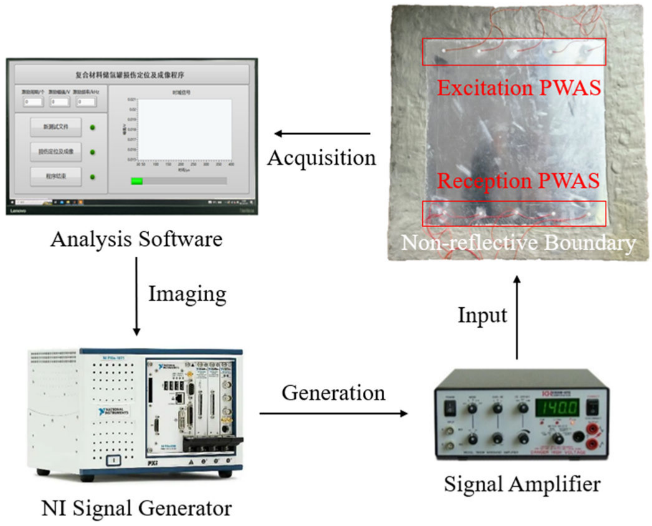

FIGURE 7: DAMAGE IMAGING EXPERIMENTAL VERIFICATION SETUP ON ALUMINUM PLATE

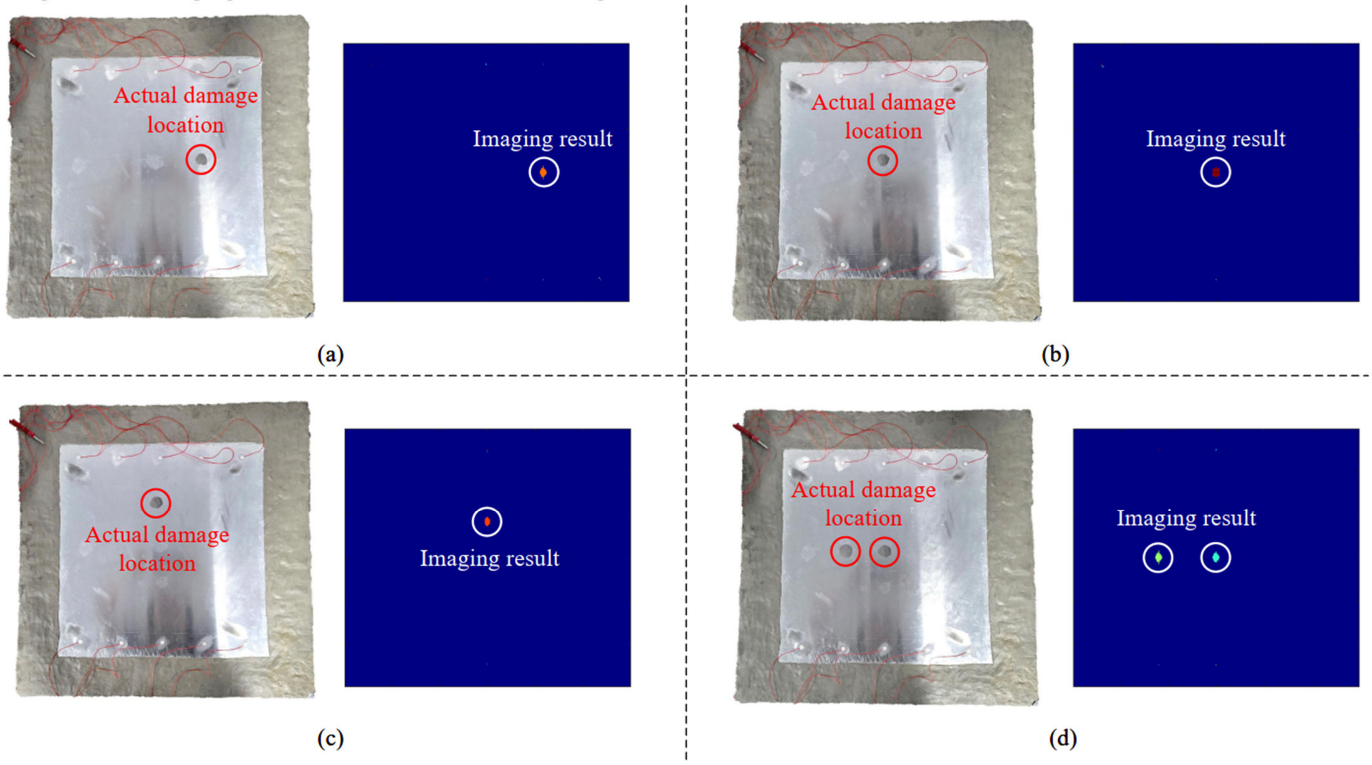

FIGURE 8: DAMAGE IMAGING EXPERIMENTAL VERIFICATION ON ALUMINUM PLATE OF (A) SINGLE DAMAGE; (B) SINGLE DAMAGE; (C) SINGLE DAMAGE; AND (D) MULTIPLE DAMAGES

4. CONCLUDING REMARKS AND FUTURE WORK

This paper presented a damage localization and imaging method for composite storage tank based on weighted algorithm. It was found that the signal amplitude and time of flight could be the characteristic values for localizing damage, allowing the accurate and convenient imaging process. By comparing the received signals from the sensors to pristine conditions, it was found that the weighted algorithm provides significant information for obtaining the spatial damage index (SDI) at any pixel point, which became an important basis for assessing the damage. Tuning experiments were conducted where the excitation center frequency with highest sensitivity and lowest complexity was identified to facilitate the analysis. Aiming at damage localization and imaging, the experimental verification was employed first on an aluminum plate to form an effective and automatic technique, which would provide technical support to guarantee the safety and integrity of storage tank structures.

The future work will focus on the systematic experimental demonstration of the damage localization for practical storage tanks. Investigations should also be conducted to improve the accuracy of localization and image quality.

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