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Junzhen Wang, Yanfeng Shen, "Lamb wave virtual time reversal damage detection algorithm with transducer transfer function compensation," Proc. SPIE 10972, Health Monitoring of Structural and Biological Systems XIII, 1097222 (1 April 2019); doi: 10.1117/12.2514200

SPIE.

Event: SPIE Smart Structures + Nondestructive Evaluation, 2019, Denver, Colorado, United States

Lamb wave virtual time reversal damage detection algorithm with transducer transfer function compensation

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ABSTRACT

This paper presents a Lamb wave virtual time reversal algorithm with transducer transfer function compensation to eliminate the transducer influence for dispersive, multimodal Lamb waves. This virtual time reversal procedure builds upon a complete 2D analytical model for Lamb wave generation, propagation, and reception. The analytical solution shows that, with the transducer transfer function compensation, a perfect reconstruction of the original excitation waveform can be achieved for both symmetric and antisymmetric Lamb wave modes. In addition, the Finite Element Modeling (FEM) and experimental validations are further performed to verify the compensated virtual time reversal procedure. Finally, a time reversal tomography experiment is conducted with a piezoelectric transducer array for structural damage imaging. The Lamb wave virtual time reversal algorithm with transducer transfer function compensation can achieve more accurate and robust damage imaging results. The paper finishes with discussion, concluding remarks, and suggestions for future work.

Keywords: Time reversal, structural health monitoring, Lamb waves, transducer transfer function, tuning, damage detection, imaging

1. INTRODUCTION

Lamb waves serve as good candidates for structural health monitoring systems due to their nice properties of long propagating distances and sensitivity to structural changes[1]. The time reversal techniques based on Lamb waves have been widely investigated for damage detection. Baseline-free imaging algorithms have been developed via the backward propagation of the scattered waves[2-4]. Sohn et al. employed a wavelet transform technique to improve the time reversibility of Lamb waves in composite structures[5]. Watkins and Jha presented a Modified Time Reversal (MTR) method[6], in which the transmitter would emit the time-reversal signal into the system again, whereas in the conventional TR procedure, the transmitter and the receiver would have to take turns to send ultrasonic waves into the structure. To reduce the practical hardware operations, Liu et al. proposed a Virtual Time Reversal (VTR) algorithm and inspected delamination with non-contact air-coupled Lamb wave scan method in a carbon fiber-reinforced composite plate[7]. The VTR technique only needs a typical pitch-catch active sensing signal; the time reversal procedure is replaced by computerized virtual signal operations. Cai et al. utilized VTR-based method with damage scattered wave packages to improve spatial resolution of the diagnostic images[8].

However, it has been noticed that, in the application of time reversal methods, even for a pristine wave path, the reconstructed waveform may deviate from the original excitation signal. It is because the tuning effects from the wave-transducer interactions may modify the frequency components of the sensing signals, causing waveform distortions during the electro-mechanical energy conversion process. Recently, Kim et al. explored the VTR technique using non-dispersive, fundamental shear horizontal waves to detect holes in a metallic plate; they demonstrated that transducer transfer function compensation can considerably improve the quality of the diagnostics images[9]. Although the wave generation mechanism of Piezoelectric Wafer Active Sensors (PWAS) has been well studied, the transducer transfer function compensation for multimodal, dispersive Lamb waves has been seldom considered for TR techniques. It should be pointed out that Xu and Giurgiutiu have taken advantage of the tuning effect to realize single mode time reversal process[10]. However, the transducer influence on the multimodal Lamb waves at arbitrary excitation frequencies has not been considered for the improved time-reversibility.

In this paper, the Lamb wave virtual time reversal algorithm with transducer transfer function compensation is proposed for improved damage detection. This research initiates with a 2D analytical model of the pitch-catch active sensing

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Health Monitoring of Structural and Biological Systems XIII, edited by Paul Fromme,
Zhongqing Su, Proc. of SPIE Vol. 10972, 1097222 · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2514200

procedure. The reconstructed signal from analytical solution, FE simulations are compared before and after the transducer transfer function compensation to demonstrate the improvement of the time-reversibility. Finally, VTR tomography imaging experiments are performed; the comparison before and after compensation algorithm images are given to showcase the improved diagnostic capability of our new approach.

2. 2D ANALYTICAL MODEL FOR LAMB WAVE ACTIVE SENSING

Based on the analytical solution in severs existing literatures[11], [12], the complete coupled-field 2D analytical model for the pitch-catch active sensing procedure was constructed to identify the target transducer transfer function. Figure 1 presents a typical pitch-catch procedure. Lamb waves are generated by the transmitter through the inverse piezoelectric effect, converting electrical excitation into the mechanical disturbances. The mechanical oscillations will be guided along the plate structure forming multiple Lamb wave models traveling with different wave speeds. Finally, the mechanical wave motion will be picked up by the receiver, where the mechanical energy is converted back into the electrical sensing signal.

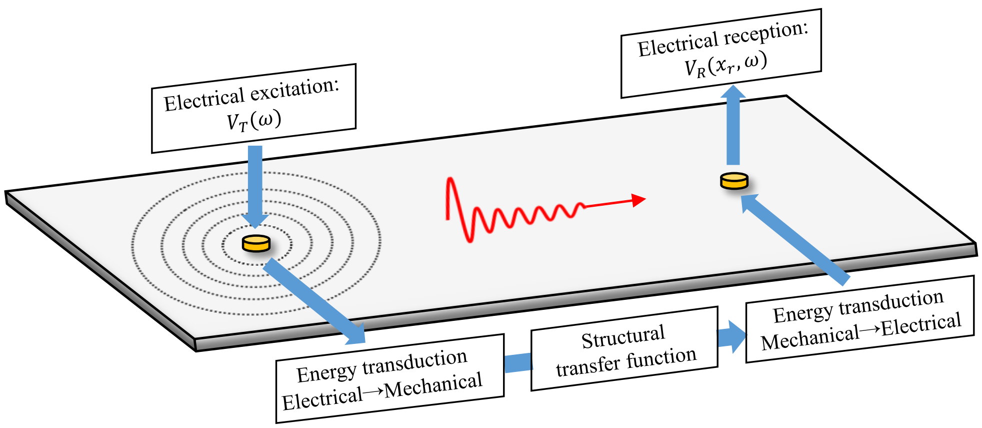

Figure 1. A typical pitch-catch active sensing procedure.

The detailed derivation of 2D Lamb wave active sensing solution between two circular PWAS transducers can be found in Ref. 13, 14. The transducer transfer functions for both S0 and A0 mode are considered, which would be compensated in the virtual time reversal algorithm. It should be emphasized that the compensation algorithm includes both the piezoelectric transduction and the 2D wave propagation inside the host structure.

The details of such compensation algorithm and discussion can be found in an extended journal report by the authors. This paper does not intend to include all the step-by-step derivations. It aims at communicating our key results with the SHM and NDE community.

3. SIGNAL RECONSTRUCTION RESULTS

To illustrate the efficacy of transducer transfer function compensation, the signal reconstruction quality compared with the conventional VTR is presented in this section. The difference between the reconstructed signal and the excitation waveform is usually used as a baseline free index for evaluating structural damage The damage index (DI) or the time reversibility index is widely adopted taking the signal correlation concept as[5]

$$DI = 1 - \frac{\left|\int_{t_0}^{t_1} I(t)V(t)dt\right|}{\sqrt{\int_{t_0}^{t_1} I^2(t)dt \int_{t_0}^{t_1} V^2(t)dt}} \tag{1}$$

where $I(t)$ represents the input excitation signal; $V(t)$ denotes the final reconstructed signal from VTR algorithm; t_0 and t_1 define the time interval over which the signals are compared. For TR signals, they represent the starting and ending time instance of the input tone burst signal.

3.1 Analytical results comparison

Figure 2 presents the reconstructed signals before and after the transducer transfer function compensation. The reconstructed signal utilizing the conventional VTR algorithm could not match well with the excitation waveform. This is especially true for S0 mode, which means the tuning phenomenon remarkably changes the frequency components of the S0 mode signal. By comparison, the analytical solution after compensation renders a perfect agreement between the reconstructed signal and the excitation waveform for both S0 and A0 modes. Such an improvement stems from the fact that the transducer influence was completely compensated by the compensation algorithm.

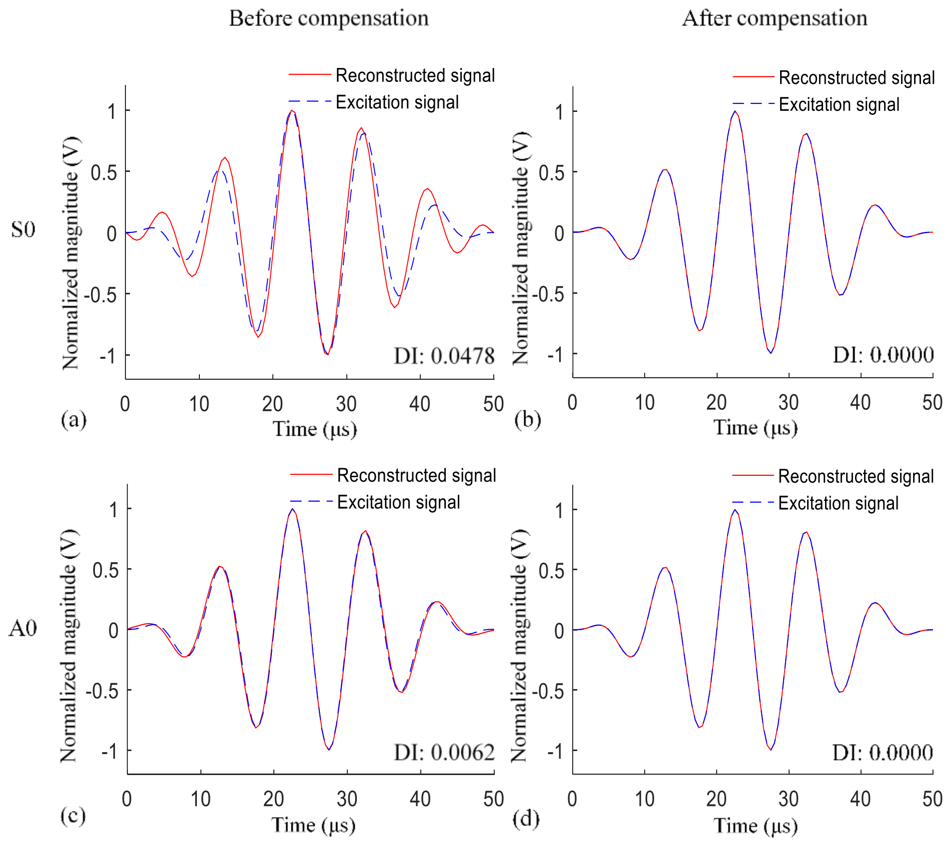

Figure 2. Virtual time reversal analytical results: (a) S0 mode before compensation; (b) S0 mode after compensation; (c) A0 mode before compensation; (d) A0 mode after compensation.

The analytical solution allows the TR procedure to maintain its virtual operation capability, which averts additional hardware intervention. However, the proposed algorithm should guarantee the improved time reversibility for application in both numerical models and experiments. Such an aspect will be presented in the following two sub-sections.

3.2 Finite element simulation results comparison

The pitch-catch procedure was simulated using FEM as shown in Figure 3. The specimen was a 1-mm thick aluminum plate. Non-reflective Boundary (NRB) was implemented around the model to eliminate the boundary reflections[15]. SOLID5 coupled filed element in AMSYS was used to simulate the piezoelectric transducers. SOLID45 eight node structural element was adopted to mesh the plate. Absorbing Layers with Increasing Damping (ALID) were implemented to construct the NRB.

Figure 4 presents the FE simulation reconstructed signal before and after the transducer transfer function compensation. The reconstructed S0 mode deviates much from the excitation waveform than A0 mode using the conventional VTR method. However, after the transducer transfer function compensation, the reconstructed signal agrees quite well with the excitation signal. As for A0 mode, smaller difference before and after compensation can be found, which follows the similar trend as the analytical solution.

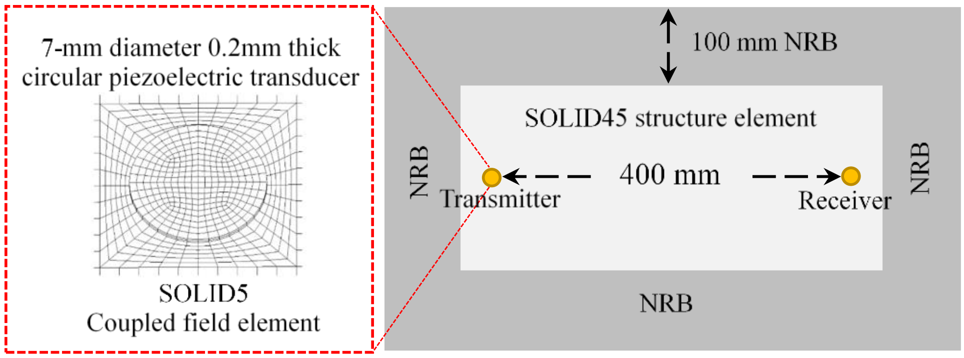

Figure 3. Finite element model for the pitch-catch procedure.

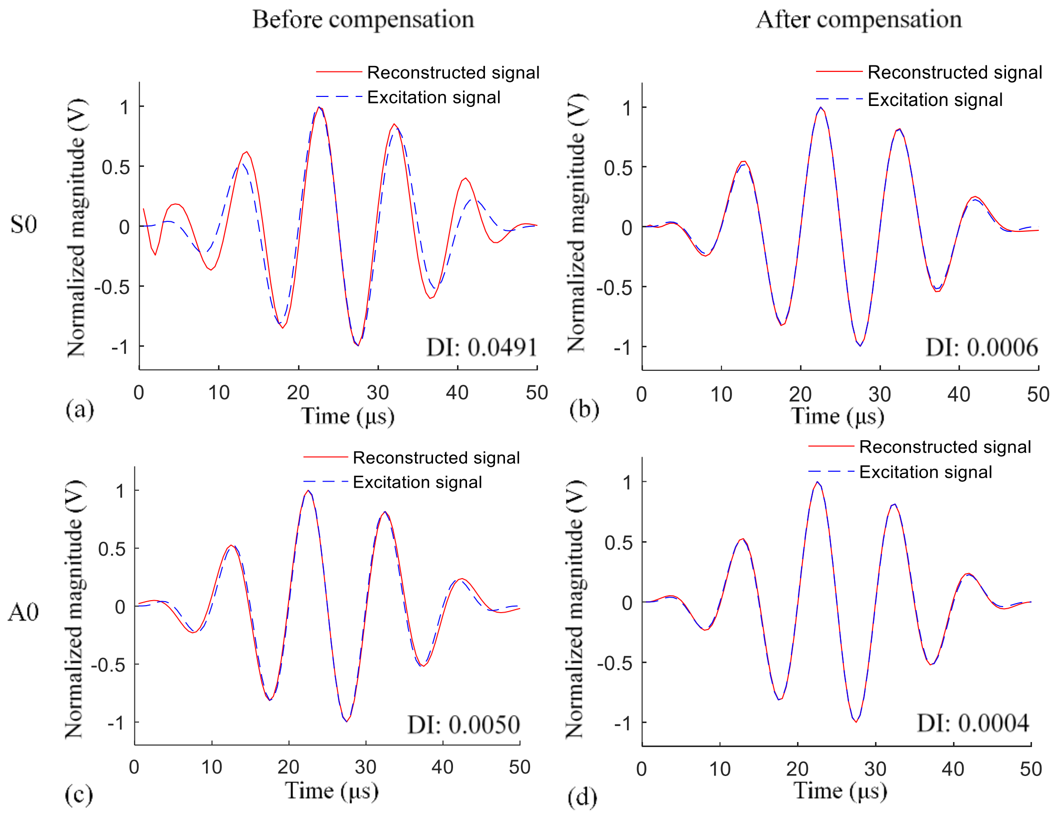

Figure 4. Virtual time reversal FE simulation results: (a) S0 mode before compensation; (b) S0 mode after compensation; (c) A0 mode before compensation; (d) A0 mode after compensation.

3.3 Experimental results comparison

Figure 5 shows the experimental setup for the pitch-catch procedure. The specimen was a pristine 700 mm long, 700 mm wide, and 1 mm thick aluminum plates. The transmitter and receiver transducers were implemented 400 mm away from each other, as the same distance in the analytical and FE modes. Damping clay was implemented surrounding the whole plate to absorbing the boundary reflections. The excitation waveform was generated by the function generator, further amplified by the amplifier, and applied on the transmitter. Guided waves were generated, propagating along the plate, and finally picked up by the receiver. The sensing waveforms were collected by the oscilloscope.

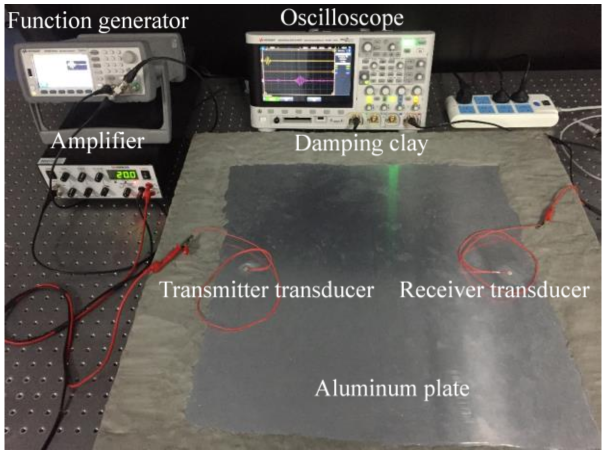

Figure 5. Experimental setup for pitch-catch active sensing.

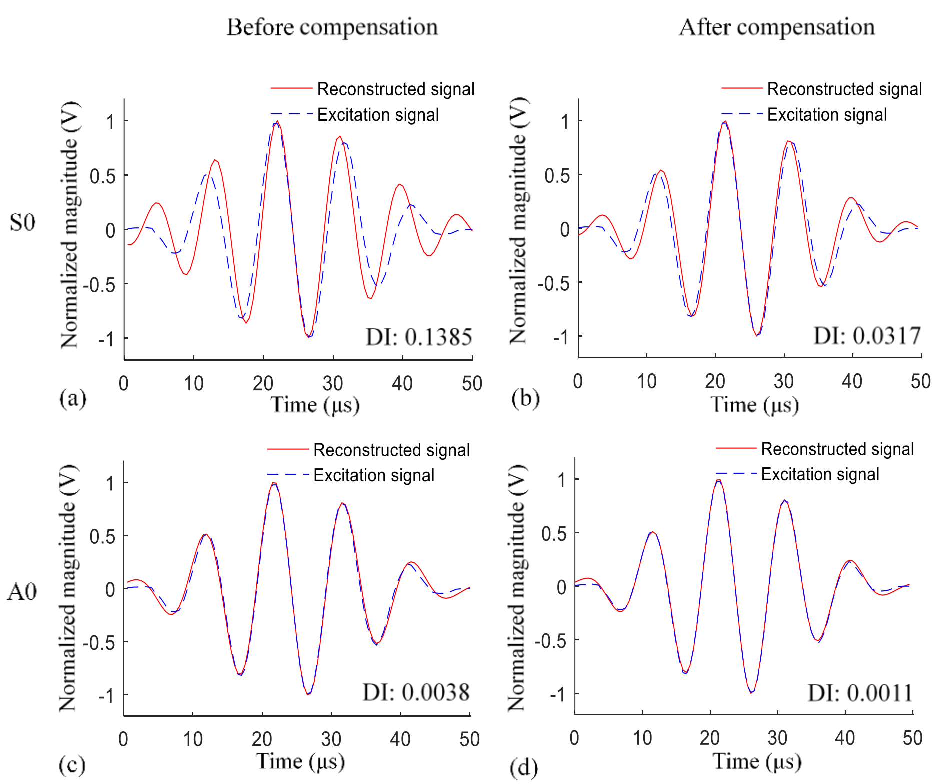

Figure 6. Virtual time reversal experimental results: (a) S0 mode before compensation; (b) S0 mode after compensation; (c) A0 mode before compensation; (d) A0 mode after compensation.

Figure 6 shows the virtual time reversal experimental results. Obvious reconstruction improvements can be noticed after the compensation procedure for both wave modes. Compared with previous analytical and FE simulation results, the deviation between the reconstructed signal and excitation waveform after compensation are greater. This is because inevitable errors may exist between analytical compensation function estimation and the practical transducer instrumentation. Individual sensor deviations, installation operations, and bonding layer involvement may all contribute to such errors. However, the overall tendency and improvement over the conventional VTR results correspond well to the previous investigation results.

4. DAMAGE DETECTION IMAGING VIA VIRTUAL TIME REVERSAL TOMOGRAPHY

To demonstrate and validate the advantage of the proposed transducer transfer function compensation operation, virtual time reversal tomography was performed with the same experimental setup. An active sensing array was designated to establish effective wave path coverage of the inspection area. In this study, both S0 and A0 wave modes were employed for damage imaging as well as the fusion between their diagnostic information to strengthen the imaging quality.

4.1 Experimental setup

Figure 7 presents the experimental setup and the 1-mm thick aluminum plate for damage imaging. A total of 16 piezoelectric transducers were implemented, forming a square shape. The distance between the neighboring transducers was 100 mm. Two rectangular aluminum blocks were bonded on the plate as scatterers to mimic structural damage sites. The dimensions of scatterers are 20 mm long, 10 mm wide and 2 mm thick.

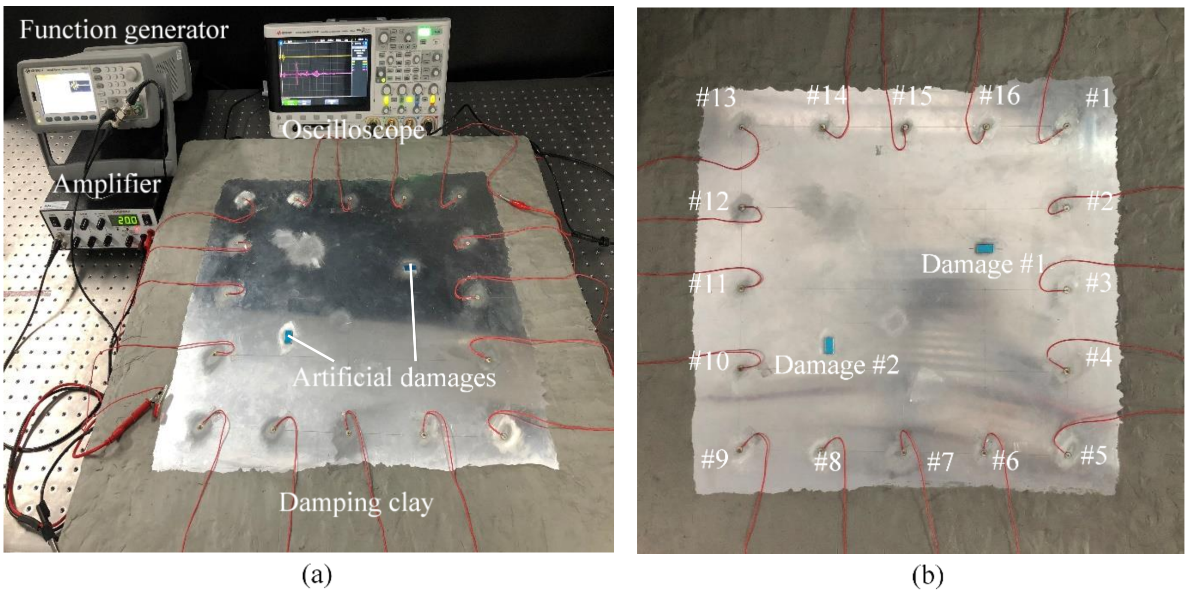

Figure 7. VTR damage imaging tests: (a) experimental setup; (b) specimen with a square active sensing PWAS array.

In this active sensing array, each transducer can serve as both a transmitter and a receiver. A 20 Vpp 5-count Hanning window modulated sine tone burst signal centered at 200 kHz was applied on the electrode of each piezoelectric transducer. Such an excitation frequency rendered comparable wavelength to the scatterers dimensions, so as to offer sensitive diagnostic information. For each transmitter, the corresponding farthest seven transducers would serve as sensors. The sensing array operated in a Round-Robin fashion. Therefore, a total number of 112 pitch-catch wave paths were involved, achieving effective coverage of the inspection area.

4.2 Example signals

Two typical transducer paths, pristine and damaged, are chosen as examples for showcasing the efficacy of transducer transfer function compensation. Figure 8 and Figure 9 present the reconstructed signal for S0 and A0 modes. For the pristine path, after compensation, the reconstructed signal demonstrates much better time reversibility. In addition, the difference of reconstructed signal between the pristine and the damage paths after compensation becomes greater than before compensation. For example, the damage index of the reconstructed A0 mode for both pristine and damaged paths are over 0.2. However, after compensation, the damage index of the reconstructed signal in the pristine path reduced to 0.0038, and the damage index in the damaged path increased to 0.6137. Thus, greater differentiability between the pristine and damaged paths has been achieved. Consequently, the compensation algorithm can significantly improve the damage imaging quality.

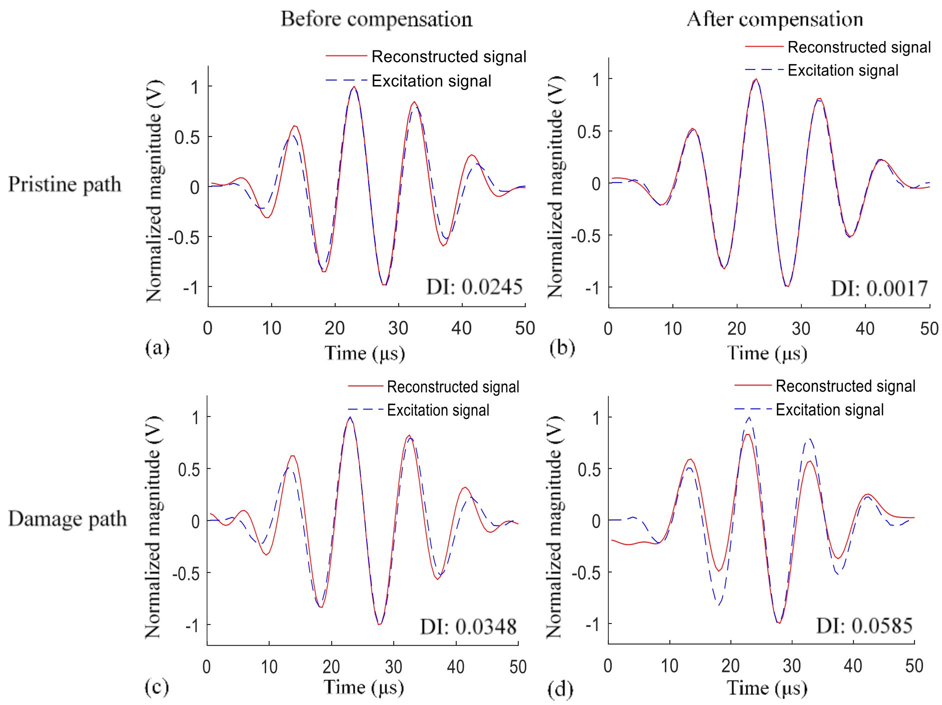

Figure 8. Reconstructed S0 signals: (a) pristine path before compensation (#6-#15); (b) pristine path after compensation (#6-#15); (c) damage path before compensation (#2-#10); (d) damage path after compensation (#2-#10).

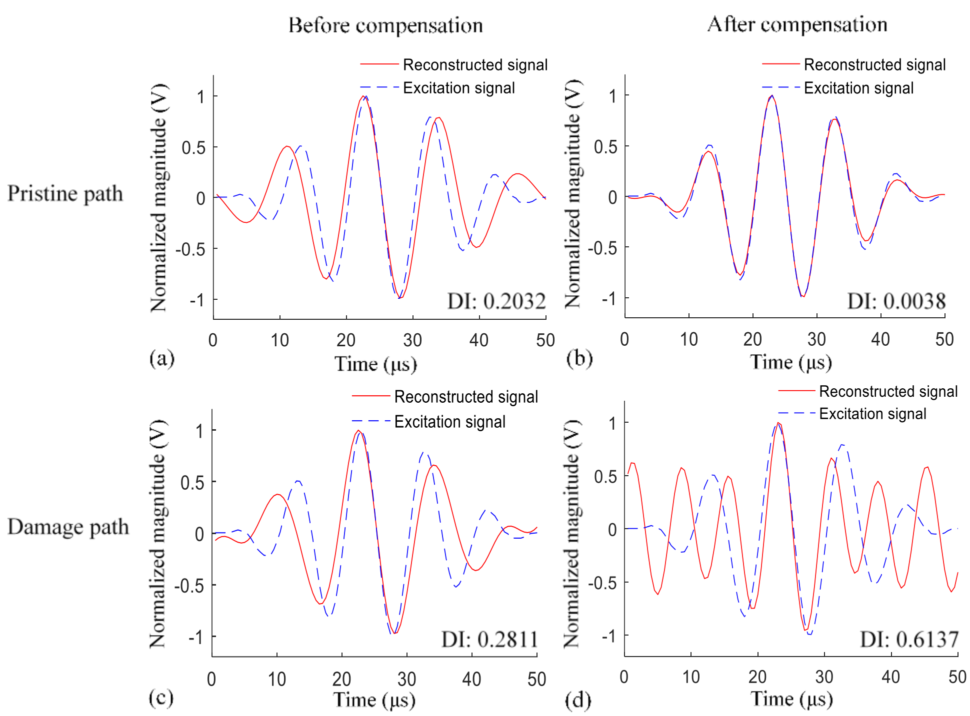

Figure 9. Reconstructed A0 signals: (a) pristine path before compensation (#16-#7); (b) pristine path after compensation (#16-#7); (c) damage path before compensation (#16-#6); (d) damage path after compensation (#16-#6).

4.3 Tomography damage imaging

The summation tomography algorithm was used for both S0 and A0 mode damage imaging. The probability of damage occurrence at position (x, y) at each direction produced by the path of each transmitter and receiver pair are added directly. The fusion diagnostic images of both S0 and A0 modes are normalized and then processed with a point-to-point multiplication algorithm.

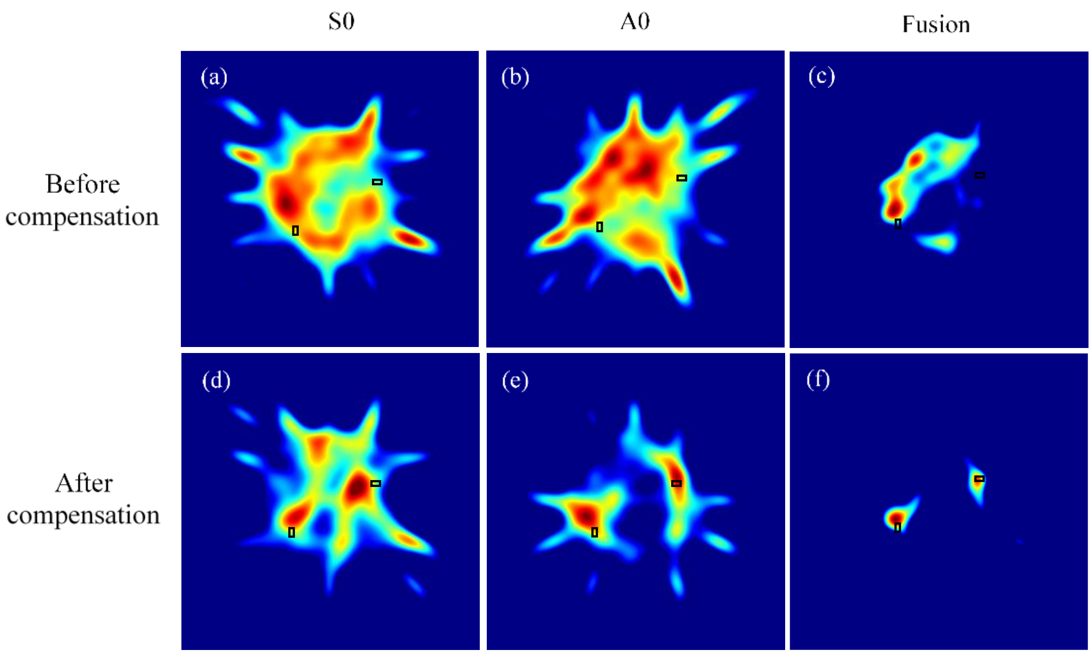

Figure 10. Damage imaging before and after compensation: (a) S0 summation tomography before compensation; (b) A0 summation tomography before compensation; (c) fusion tomography before compensation; (d) S0 summation tomography after compensation; (e) A0 summation tomography after compensation; (f) fusion tomography after compensation.

Figure 10 shows the damage imaging comparison results before and after transducer transfer function compensation. Before compensation, the damage sites cannot be located accurately via the S0 and A0 single mode summation tomography algorithm. The paths crossing the damage sites have not been highlighted. On the contrary, pristine paths present the high-pixel areas; one transducer area also possesses high pixel values. In addition, there are some pseudo-focusing points, which apparently deviate from the true damage position. Although the imaging results can be improved after the fusion tomography algorithm, the first damage still cannot be imaged.

On the other hand, the damage imaging quality is apparently improved after compensation. There are obviously two high-pixel areas in the single mode images, representing the two damage sites respectively. Pristine and damaged paths can be clearly identified, showing the probability of the interrogating Lamb wave passing the damage sites. Although the imaged damage position deviates a little bit from the true damage sites, it has been obviously improved using the fusion tomography algorithm. The damage sites can be accurately located via the fusion image.

5. CONCLUDING REMARKS AND FUTURE WORK

This paper presents Lamb wave virtual time reversal algorithm with transducer transfer function compensation. In the conventional VTR method, the transducer tuning effect modifies the frequency components, As a result, the reconstructed signal could not agree well with the excitation waveform. When it comes to damaged cases, it is hard to tell whether the breakdown of time-reversibility is associated with the presence of damage or the transducer participation.

Case study examples using the analytical solution, finite element simulations, and experiments were presented. It was found that the reconstructed signals after compensation achieved much better time reversibility than those without the compensation. In particular, the reconstructed signals attained from the analytical solution realized the complete reconstruction of the excitation waveform. Finally, a damage imaging experiment was performed to validate the efficacy of transducer transfer function compensation algorithm. The imaging results were considerably improved after compensation. And the imaging fusion technique combining both S0 and A0 mode tomography results showed remarkable diagnostic accuracy.

For future work, the compensation algorithm should be attempted for detecting damage in the anisotropic composite plates. The nonlinear time reversal algorithm should be investigated for detecting fatigue cracks.

ACKNOWLEDGEMENTS

The support from the National Natural Science Foundation of China (contract number 51605284) is thankfully acknowledged.

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