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Damage localization method for plates based on the time reversal of the mode-converted Lamb waves

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ABSTRACT

A damage localization method based on the time reversal focusing of the mode-converted scattered Lamb wave is proposed for plate structures with a non-symmetric defect in the thickness direction. Dual transducers are attached symmetrically on the upper and lower surfaces of the plate to selectively emit and receive the lowest-order symmetric (S0) and antisymmetric (A0) modes. The localization of damage is achieved by the numerical time-reversed (TR) simulation of the mode-converted Lamb wave generated at the defect. To investigate the validity of the proposed method, the signals of the Lamb waves in a plate with a partial-thickness notch are numerically simulated by the three-dimensional elastodynamic finite integration technique (EFIT). When the S0 mode is emitted in the damaged plate, not only the S0 mode is scattered but also the A0 mode is generated due to mode conversion at the notch. Similar mode conversion behavior is confirmed when the A0 mode is emitted. The time reversal of the mode-converted scattered Lamb waves creates focused spots at the damage location without using baseline data for the undamaged plate. The proposed method reduces the magnitude of the artifacts compared to the time reversal of the non-mode-converted Lamb wave, and yields the focused spot whose size is associated with the size of the notch and the half wavelength of the time-reversed wave mode. Furthermore, the proposed method is applied to a plate with a notch-type defect adjacent to an a priori known through-thickness hole, demonstrating the damage localization in a relatively complicated structure.

1. Introduction

Time reversal in acoustics is a wave focusing technique used in various areas, e.g. nondestructive evaluation, medical diagnosis, seismology, etc. When the wave signals recorded by multiple transducers are time-reversed and sent back into the medium, the self-focusing of the wave occurs at its original wave source. Since Fink and co-workers [1–3] established the concept of a time reversal mirror, time reversal acoustics has been applied not only to the focusing of acoustic waves at a desired location and time [4–6] but also to the localization of unknown wave sources or scatterers in various media [7–16].

Lamb waves offer an effective tool for the damage detection and localization in plate-like structures since they can propagate relatively long distances. However, as the propagation distance becomes longer, the time resolution of Lamb wave signals tends to be lower due to their dispersion and multi-modal characteristics. To overcome this difficulty, signal processing techniques such as dispersion compensation [17], two-dimensional Fourier transform [18], and wavelet transform [19–21] were proposed in foregoing studies. These approaches effectively work to determine the arrival time of the dispersive wave modes or to decompose the measured waveform into different modes, but require a priori knowledge about the dispersion and multi-modal characteristics.

Compensation of the Lamb wave dispersion characteristics can be achieved without a priori knowledge through the time reversal process, as reported by Ing and Fink [22]. They developed a time reversal mirror of a 32-element transducer array and demonstrated the self-compensation of the Lamb wave dispersion property using this device. In recent years, the temporal focusing of Lamb waves gathers attention in the damage detection for plate-like structures [23–28]. Park et al. [26] analyzed the time reversal process of the lowest-order antisymmetric (A0) mode which was emitted and received in pitch-catch mode. Their theoretical investigation has shown that the dispersion effect of the A0 mode is compensated in the backward propagation. It has been also shown that the main mode signal (i.e. the temporally focused signal obtained via the time reversal process) is accompanied by several sidebands due to the multi-modal effect of Lamb waves. The presence of possible damage can be evaluated from a damage index which is based

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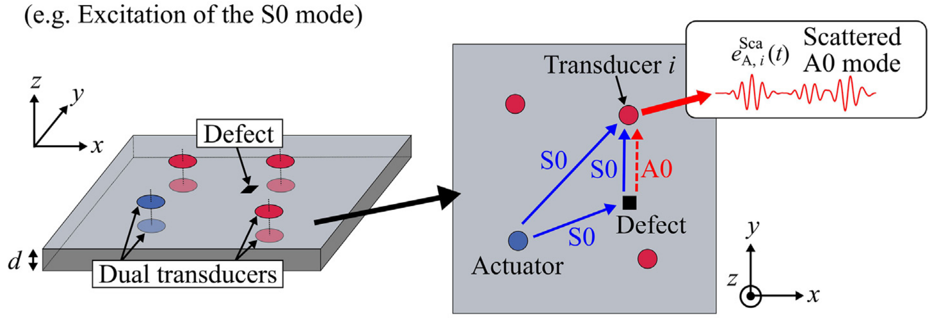
(a) Measurement of the mode-converted Lamb wave
(e.g. Excitation of the S0 mode)



(b) Damage localization by numerical time-reversed (TR) simulation
(Time reversal of the A0 mode)

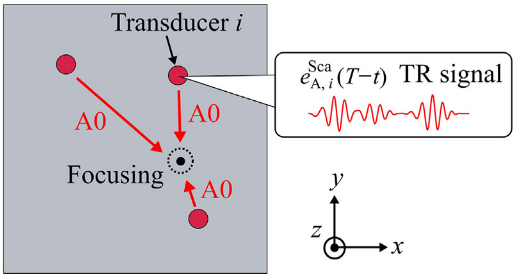


Fig. 1. Schematics of the proposed damage localization method: (a) the Lamb wave measurement using dual transducers and (b) the numerical time-reversed (TR) simulation of the mode-converted scattered Lamb wave at the defect.

on the difference between the input and reconstructed signals in the time reversal process [25,27]. Basically, only the damage located between the emitter and the receiver can be directly detected by this method, although the reconstruction algorithm for the probabilistic inspection of damage (RAPID) was incorporated into the time reversal technique to overcome this difficulty [28].

Spatial focusing of the time-reversed Lamb waves is another approach for the damage localization in plate structures. For a homogeneous plate, several studies have reported the spatial characteristics of the Lamb wave focusing through the time reversal process [29–31]. Park [30] demonstrated theoretically and numerically that the spatial resolution of a focused spot obtained by the time-reversed A0 mode in a homogeneous plate is closely associated with its half wavelength. For the damage localization in plate structures, Wang et al. [32] proposed a synthetic time-reversal method, which incorporated the time reversal concept into the synthetic aperture method. This approach was applied to estimate the location of a circular disk-shaped mass bonded on an aluminum alloy plate. Their concept was extended by Yu and Leckey [33] who evaluated the location and size of an electrical discharge machined slit by the multiplication of the time-reversed signals measured at multiple sensors. In the damage localization by the spatial focusing proposed in previous studies [32–34], however, baseline data for an undamaged structure are usually required to obtain the signals of the scattered wave from the damage because the measured waveforms include the direct wave from an actuator. Furthermore, the time reversal process of Lamb waves is treated merely as time shifting, which is applicable only to non-dispersive Lamb modes.

The aim of this study is to propose a time reversal method of Lamb waves for the damage localization in plates without using baseline data. To this purpose, the mode conversion induced by the damage is incorporated in the time reversal process. Dual transducers are attached symmetrically on both surfaces of the plate to selectively emit and receive the lowest-order symmetric (S0) and antisymmetric (A0) modes in a low frequency range. The damage localization is performed by the numerical time-reversed (TR) simulation of the mode-converted scattered Lamb wave.

In this study, to validate the proposed method, the signals of the Lamb wave in a plate with a partial-thickness notch-type defect are numerically simulated by the elastodynamic finite integration technique (EFIT) [35] instead of the actual measurement. The proposed damage localization method is presented in Section 2, and its verification procedure by the numerical simulation is explained in Section 3. Prior to the discussion of the time reversal of Lamb waves in the damaged plate, the effect of mode types and frequency on the focusing characteristics is studied for a homogeneous plate with no damage in Section 4. Subsequently, the time reversal of the scattered S0 and A0 modes at the notch is examined in Sections 5 and 6.

2. Proposal of the damage localization method based on the time reversal of the mode-converted Lamb wave

2.1. Measurement of Lamb wave signals using dual transducers

A homogeneous and isotropic elastic plate of uniform thickness $|z| < d/2$ is considered in the x-y-z Cartesian coordinate system, where d is the plate thickness. In such a structure, Lamb waves and shear horizontal (SH) guided waves can propagate along the plate. Lamb waves can be classified into symmetric and antisymmetric modes, which can be selectively excited and detected by dual transducers mounted symmetrically on the upper and lower surfaces of the structure [36,37]. The polarization direction of the transducers is assumed to be aligned in the thickness (z) direction. In a sufficiently low frequency range, the propagating modes of the Lamb wave in the plate are only the S0 and A0 modes.

The aim of the proposed method is the localization of a defect with non-symmetric geometry in the thickness direction, without using baseline data. This type of defect is common and can be made by corrosion pitting, for example. As shown in Fig. 1, the proposed method