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Omnidirectional shear horizontal wave based tomography for damage detection in a metallic plate with the compensation for the transfer functions of transducer

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ABSTRACT

Guided-wave based damage detection for plates has been widely studied for structural health monitoring. Because most of the earlier studies used dispersive Lamb waves, substantial efforts had to be made to alleviate the dispersive and multi-modal nature of Lamb waves and the effect of surface conditions. In contrast, shear-horizontal (SH) waves have better propagation characteristics suitable for the detection of damages in plates, but SH waves have not been widely used due to the lack of efficient methods to generate and sense omnidirectional SH waves. The objective of this study is to construct diagnostic images of damaged plates by using omnidirectional SH waves with a special emphasis on the compensation of the frequency-dependence of the SH wave transducers. The compensation is necessary to have reliable diagnostic images because its frequency-dependent characteristics considerably can affect imaging quality if they are not considered. Consequently, simplified, yet effective, models representing the transfer functions of the omnidirectional SH wave magnetostrictive patch transducer (OSH-MPT) are developed in this paper. To visualize the position and shape of the structural damages in a metallic plate, the virtual time-reversal imaging method is used and two alternative techniques are considered to compensate for the effects of the transfer functions of transducers in the imaging processes. The imaging results after the compensation appear quite promising, suggesting that the omnidirectional SH wave based enhanced time-reversal imaging can be an efficient inspection method for plate structures.

1. Introduction

Structural health monitoring (SHM) techniques based on guided waves have attracted a great deal of attention in the past 20 years. The major advantage of using guided waves is that inspecting over long distances with excellent sensitivity is possible with relatively few transducers [1,2]. Moreover, guided wave transducers are generally cheap, light-weight, detachable, and are less susceptible to interference from low frequency ambient vibrations. Detailed reviews on the guided wave based SHM techniques are available [2,3]. In particular, imaging techniques based on guided waves are intuitive, because the damage location can be found by visualizing a region of interest. One such technique uses a guided wave tomography [4] where a region surrounded by a sparse transducer array is investigated in a pitch-catch manner.

Most earlier imaging methods used dispersive Lamb waves and not SH waves even though the lowest SH (SH_0) wave mode is non-dispersive. Therefore, additional dispersion compensation is inevitable with the Lamb waves, which make the imaging methods complex and less efficient. SH_0 wave is most convenient since it is not dispersive. In addition, SH waves are not sensitive to surface condition of waveguide (i.e., the plate) and do not suffer from mode conversion or phase shift when they are reflected from the boundary surface [5]. On the other hand, omnidirectional transducers are preferred over unidirectional ones in the sparse transducer array systems as well as the phased array systems to scan and image large surface plates fast and efficiently. Various omnidirectional SH (OSH) wave transducers have been only recently devised using magnetostrictive patches (MPTs) [6–8], electromagnetic acoustic transducers (EMATs) [9], and a face-shear piezoelectric ring array [10]. For SH wave based tomography, Li and Cho

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used SH_0 waves, albeit directional ones, for imaging the corrosion wall thinning in a plate [5]. They used directional MPTs and a baseline subtraction method to construct the diagnostic image of the damages on all possible source-receiver ray paths. Wei et al. also imaged the wall thinning in a plate by using the first-order SH (SH_1) wave MPTs [8]. Their omnidirectional SH_1 MPT may have restrictions on sending and receiving SH_1 waves in all directions due to its open circle shape. Thus, they used the cross-hole tomographic method and the simultaneous iterative reconstruction technique (SIRT) to image the distribution of the slowness (the reciprocal of the group velocity of the SH_1 wave) due to the wall thinning on the source-receiver ray paths. However, no diagnostic imaging using a spatially distributed array of fully omnidirectional SH transducers was investigated to visualize the positions and shapes of damages. The imaging method should be applicable whether damages are located on the source-receiver ray paths or not.

Another aspect to consider is to minimize the effects of the frequency-dependent transfer functions of the transducer on time-reversal imaging. The time reversal method is widely used for baseline-free damage inspection in composite and metallic plates. In earlier time-reversal studies, the narrow-band tone burst signals below the cut-off frequencies of the higher Lamb wave modes with a wavelet-based signal processing technique [11] were used to enhance time reversibility of the reconstructed signal by assuming the frequency-independence of the transducer transfer functions. However, any ultrasound transducer would exhibit some degree of frequency-dependent responses over a finite bandwidth, which causes the input waveform to change during the conversion process. Accordingly, the reconstructed waveform after the time-reversal process and the initial input waveform do not match. However, studies to compensate the frequency-dependence of the transducer transfer functions are rare although the compensation can significantly improve imaging quality.

In this study, we developed OSH wave based time-reversal imaging method by using a sparse array of recently-developed OSH wave magnetostrictive patch transducers (OSH-MPTs) [6,7]. The tomographic method used in this study is based on the virtual time-reversal (VTR) method [12], but special efforts are put into compensating for the frequency-dependence of the OSH-MPT transfer functions. We develop simplified, yet accurate, models to predict the transfer functions of OSH-MPT in the sending and receiving operation modes, which are then used to compensate for the frequency-dependence in the time-reversal process. The imaging method that considers the compensation will be called the enhanced virtual time-reversal (EVTR) imaging method in subsequent discussions. There are two approaches to the compensations. The first approach is to apply the compensation to the reference signal and compares the reconstructed signal against the compensated reference signal. The second approach is to do the compensation to the reconstructed signal and compares the compensated reconstructed signal against the initial input signal. The compensation would not be feasible if a simple accurate model for the transfer function of the OSH-MPTs were unavailable.

This paper is organized as follows: Section 2 is devoted to establishing the transfer function models for the used OSH-MPT's. Specifically, the pin-force model is employed to form the transfer function models. In Section 3, we present the EVTR processes by considering the compensation for the transfer function models utilizing two methods for the compensations, which are applied to the reference signal and the reconstructed signal. Section 4 reveals the actual experimental setup and the signal processing in detail. In Section 5, the validity of the developed transfer function models is checked by comparing the theoretical predictions against the experimental results. Additionally, the performance comparison of VTR and EVTR methods with simple waveform is presented. In Section 6, imaging results for a damaged plate with through-thickness holes are presented. The image reconstruction is based on the arrival time difference between the direct wave from a transmitting transducer and the scattered wave from a defect. Finally, Section 7 states the conclusions.

2. Derivation of the OSH-MPT transfer functions

In this section, the transfer functions of the Omnidirectional Shear-Horizontal Magnetostrictive Patch Transducers (OSH-MPT) developed by Seung, Kim and Kim [6] will be derived. We derive the OSH-MPT transfer functions analytically by using its operating principle. The general operating principle of MPTs including the OSH-MPT can be found in Kim and Kwon [13], but the underlying operating principle needed to derive the transducer transfer function is briefly provided below.

2.1. Shear wave generation mechanism model of OSH-MPT

The schematic drawing of the OSH-MPT is given in Fig. 1(a) and (b) consisting of a cylindrical permanent magnet and a toroidally wound coil over a thin magnetostrictive patch made of nickel. A plastic hosting plate has several notches along its circumference and is placed over the patch to facilitate accurate coil winding. The cylindrical magnet provides a static radial magnetic field in the patch and the AC current flowing through the coil produces a circumferential dynamic magnetic field in the patch. Because mutually perpendicular static and dynamic magnetic fields are applied on the annular magnetostrictive patch, omnidirectional shear wave deformation can occur in the patch from the Wiedemann effect [14]. For the magnetic field directions sketched in Fig. 1(a), shear strain will be developed over the whole patch. As the patch is bonded onto (or coupled with) a plate, the mechanism to excite the plate by the induced strain in the patch can be modeled by the pin-force model [15], as depicted in Fig. 1(b). Fig. 1(b) illustrates a set of the resultant pin forces that cause shear deformation in the plate. Due to the distributed shear forces in the circumferential direction along the inner and outer boundaries of the patch, omnidirectional shear stress will be developed in the plate. Due to variations in the shear forces according to time-varying input current on the coil, omnidirectional SH waves propagate radially in the plate from the location in which the transducer is attached.

2.2. The OSH-MPT transfer functions

We will now explain how to express the OSH-MPT transfer function by using the pin-force model explained previously. Referring to Ref. [6], the maximum transducer output can be achieved if the relation $r_o = r_i + \lambda/2$ is satisfied where r_i and r_o denote the inner and outer radii of the magnetostrictive patch, respectively, and λ is the wavelength of the SH wave at the excitation frequency. Thus, the inner and outer radii of the magnetostrictive patch are chosen to be $r_i = \lambda/4$ and $r_o = 3\lambda/4$, respectively, as shown in Fig. 1(a) (from Ref. [6]). Therefore, we will assume that the relation ($r_o = r_i + \lambda/2$) holds for the subsequent analysis in the transducer transfer function.

According to the pin-force model in Fig. 1(b), the plate is excited by the OSH-MPT at 4 different locations. However, it is convenient to define the transfer function of the OSH-MPT as if it excited the plates at a single point $r = 0$. This means that in our model, the spatial difference in the excitation locations will be compensated as the time difference in defining the transfer function of the OSH-MPT defined at $r = 0$. If the magnitude of the shear force intensity applied to the plate is denoted by τ_0, four concentrated