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Tuned double-coil EMATs for omnidirectional symmetric mode lamb wave generation

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ABSTRACT

This paper investigates a method to generate only symmetric omnidirectional Lamb waves and proposes specially-tuned double-coil EMATs. While methods to generate omnidirectional Lamb waves have been reported, the symmetric mode is typically accompanied by unwanted antisymmetric modes. The double spiral coil works as a wavelength filter but the relation between the coil geometries and the wavelength of the symmetric mode that minimizes the unwanted antisymmetric mode has not been established. Axisymmetric analysis was performed to find the relation. Excellent rejection of antisymmetric modes with successful symmetric mode generation was confirmed by experimental results that favorably agree with the theoretical results.

1. Introduction

The methods for imaging defects in a plate have recently received widespread attention as effective NDE (nondestructive evaluation) techniques. Defect imaging in a plate can be performed by various imaging algorithms: phased array beamforming [1–4], SAFT (synthetic aperture focusing technique) [5,6], TFM (total focusing method) [7,8], and so on. One of the major issues in imaging is to develop a transducer to generate only the desired wave mode. Among various transducers, a transducer that generates and measures omnidirectional elastic waves may be preferred for efficient imaging. Because Lamb waves have been widely used for defect imaging in a plate among various guided ultrasonic waves, omnidirectional Lamb wave transducers, such as piezoelectric transducers [9–12], electromagnetic acoustic transducers (EMATs) [13–16] and magnetostrictive patch transducers [17] have been developed. In the present study, we propose a new omnidirectional Lamb wave transducer based on EMATs.

Lamb waves can be classified as symmetric modes (S0, S1, S2, …) with symmetric motion about the mid-plane of a plate and antisymmetric modes (A0, A1, A2, …) with antisymmetric motion. The symbol n in Sn and An denotes the mode number and S0 and A0 denote the lowest symmetric and antisymmetric Lamb wave modes, respectively. Since the number of Lamb modes increases with increasing frequency as shown in Fig. 1, it is necessary to excite only the desired mode for efficiency. Until now, however, no method has been developed to generate the desired symmetric mode selectively without generating unwanted modes based on EMATs. Consequently, we aim to develop an EMAT which generates only the desired symmetric Lamb mode and suppresses unwanted antisymmetric Lamb modes. We propose a ‘tuned double-coil method’ for that.

EMATs generate guided ultrasonic waves in a conductive structure with magnets and coils; the configurations of magnets and coils determine the modes of the generated Lamb waves. (Further details are described in the beginning of Section 2.1.) Fig. 2(a) and (b) show the configurations of EMATs for generating symmetric and antisymmetric Lamb wave modes, respectively. Although the configuration of an EMAT shown in Fig. 2(a) is designed for symmetric modes, it is difficult to generate only the desired symmetric Lamb wave mode selectively, because of the accompanying antisymmetric Lamb wave modes. In reference [14], the method for exciting symmetric modes with controlling coil diameters, coil widths and frequencies has been discussed, but no study to achieve better mode control of an EMAT for the S0 mode Lamb wave has been reported.

The researches on mode control of an EMAT have usually focused on enhancing the A0 mode and suppressing the S0 mode with the configuration shown in Fig. 2(b). Seher et al. [18] optimized a magnet diameter and a liftoff distance between a magnet and a plate using a genetic algorithm to excite the A0 mode and

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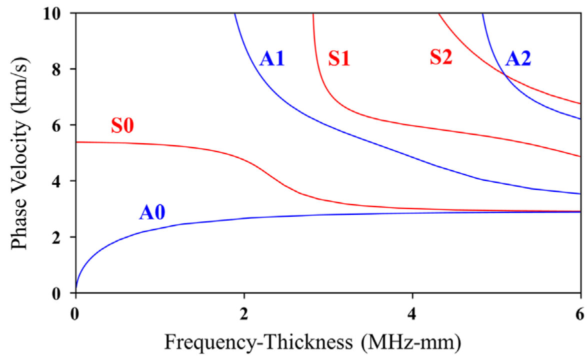

Fig. 1. Phase velocity curves of Lamb waves in an aluminum plate. *Sn*: n^{th} symmetric mode, *An*: n^{th} anti-symmetric mode (n=0, 1, 2, …).

minimize the S0 mode. Nagy et al. [19] calculated the relation of the inclination angle of a Lorentz force to the amplitudes of the A0 and S0 modes and found the optimal angle which maximizes the A0/S0 amplitude ratio. These methods, however, are difficult to apply to the selective S0 mode excitation of an EMAT.

On the other hand, for piezoelectric transducers, an annular array transducer with several annular piezoelectric elements has been developed for omnidirectional Lamb wave mode control [20]. This work compared the comb type and inter-digital type configurations of elements analytically and experimentally. The result shows that there is a relation of the separation between the centers of the elements to the wavelength of the generated wave. The separation in the comb type corresponds to one wavelength and the separation in the inter-digital type, half the wavelength. Glushkov et al. [21] developed an omnidirectional multi-element transducer for selective Lamb mode excitation. In this work, mode control is achieved by tuning the amplitude and the time delay of the input signal for each element. Noticing that the use of several excitation elements can be useful for Lamb wave mode control, we aim to design an omnidirectional EMAT with several excitation coils and propose a method for generating only the symmetric mode Lamb waves.

First, we present the configuration of the proposed EMAT with a double spiral coil. To excite the desired symmetric mode and suppress the unwanted antisymmetric mode at a given operating frequency, the analysis of Lamb wave generation by the Lorentz force induced by the double coil and Lamb wave propagation in a plate is performed. Using the analytic result, we tune the parameters of the double coil to achieve better mode control and suggest the relations of the coil diameters and the coil width to the wavelength of the Lamb wave. Then we present the analytic and experimental verification; the experiments are carried out on a 2 mm thick aluminum plate at a frequency range from 150 kHz to 500 kHz, which is below the first cutoff frequencies of the S0 and A0 modes. Finally, we summarize the observations obtained from the analysis and the experiments.

2. Proposed EMAT

2.1. Magnetic circuit configuration

Before going further, it is worth explaining the principle of Lamb wave generation with existing EMATs, as shown in Fig. 2. Both configurations from Fig. 2(a) and (b) consist of a cylindrical permanent magnet for a static magnetic field and a single spiral coil for a dynamic magnetic field. When an alternating current flows through the coil, a dynamic magnetic field is created around the coil, and then the field induces an eddy current in a conductive structure. The static magnetic field by the permanent magnet and the induced eddy current generate the Lorentz force F_L in the structure.

When EMATs are operated on a ferromagnetic waveguide, both the Lorentz force mechanism and magnetostriction contribute to the generation of elastic waves (see, e.g., [22]). In case of non-ferromagnetic waveguides, such as aluminum plates used for this present study, only the Lorentz force mechanism is responsible for the generation of the Lamb waves.

Because the EMAT configuration for symmetric mode excitation shown in Fig. 2(a) has a magnet of a larger diameter than the coil, the magnetic field from the magnet is almost perpendicularly incident on a plate. Hence, the Lorentz force is generated mainly along the in-plane direction. This distribution of the Lorentz force is suitable for generating symmetric mode Lamb waves which have dominant in-plane displacements. In the case of the EMAT for antisymmetric mode excitation shown in Fig. 2(b), to the contrary, the magnet has a smaller diameter than the coil and the direction of the generated Lorentz force is almost out-of-plane.

To excite the symmetric mode selectively and suppress the antisymmetric mode, we applied a double spiral coil instead of a single spiral coil to the EMAT configuration for symmetric mode excitation, as can be seen in Fig. 3(a). The double spiral coil consists of two coils which are connected to each other. The inner coil, wound clockwise, has an average diameter of D_1 and a width of W_1. The outer coil, wound counterclockwise, has an average diameter of D_2 and a width of W_2.

Fig. 3(b) shows the schematic distributions of the magnetic fields and the Lorentz force in the tuned double-coil EMAT. The

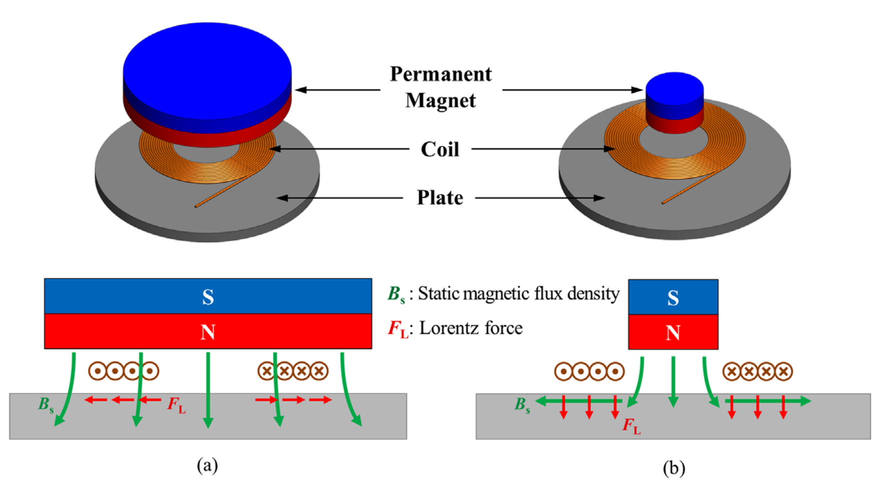

Fig. 2. Configurations of EMATs for (a) symmetric mode Lamb wave excitation and (b) antisymmetric mode Lamb wave excitation [19].