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Generation of omni-directional shear-horizontal waves in a ferromagnetic plate by a magnetostrictive patch transducer

Hong Min Seung, Yoon Young Kim *

School of Mechanical and Aerospace Engineering and Institute of Advanced Machinery and Design, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, South Korea

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ABSTRACT

It this study, omni-directional shear-horizontal wave transduction is performed using a specially configured magnetostrictive patch transducer in a ferromagnetic plate. For a ferromagnetic plate, unavoidable magnetic flux leakage into the plate not only results in poor transduction efficiency but also generates unwanted waves within the plate. These problems must be overcome to inspect ferromagnetic plates using the transducer. Therefore, we investigate the reasons for the poor performance and propose a method to improve its performance. The effectiveness of the proposed method was validated through simulations and experiments.

1. Introduction

The use of an array of omni-directional guided wave transducers is an attractive method to efficiently inspect large plate structures [1,2]. Because transducers are essential components of array systems, investigations focusing on the development and application of omni-directional guided wave transducers for use in nondestructive evaluation (NDE) are commonplace [1–7]. In these studies, omni-directional Lamb wave transducers were primarily used, as it is easier to generate Lamb waves than shear-horizontal (SH) waves. The first omni-directional SH wave transducer was only recently developed [6] using magnetostrictive patch transducer (MPT) technology [8]. The performance of this transducer was successfully evaluated by wave transduction experiments in a non-ferromagnetic (aluminum) plate. For subsequent discussions, this transducer is referred to as an omni-directional SH wave magnetostrictive patch transducer (OSH-MPT). The reason why a shear-wave transduction mechanism is preferred for NDE applications is that SH waves possess several advantages over Lamb waves [9–11], such as the non-dispersive property of the fundamental mode (SH0) and the ability to resist influence from fluid loading. Accordingly, the use of OSH-MPTs for the NDE of ferromagnetic plate, a widely used material in industrial applications, needs to be considered. Therefore, in this work, we investigate the issues and difficulties associated with using an OSH-MPT for ferromagnetic plates. Additionally, we propose practical solutions to overcome these difficulties.

Fig. 1 shows a schematic configuration of an OSH-MPT bonded to a plate. Before explaining the detailed configuration of the transducer, we note that MPTs operate on the basis of magnetostriction [12–15], a coupling effect between the change in the magnetic field and a mechanical deformation of a magnetostrictive material (in this case, a thin nickel patch). An OSH-MPT consists of a thin annular magnetostrictive patch and a magnetic circuit made of a cylindrical permanent magnet and a specially wound coil. The circuit provides a magnetic field to the patch that is bonded onto a test plate. The patch functions as a wave-actuating and sensing unit. If the static magnetic field produced by the magnet and the dynamic magnetic field produced by the coil are orthogonally applied to the patch, a time-varying shear deformation is generated in the patch as a result of the Wiedemann effect [12]. This in turn excites SH waves in the test plate. The transducer can also be used to measure SH waves propagating in a plate by the reversed Wiedemann effect (more detailed descriptions of the transducer are provided in Section 2.1). We consider a case when an OSH-MPT is installed on a ferromagnetic plate for wave transduction. In this case, the magnetic field provided by the magnetic circuit is not applied just to the patch but also to a test ferromagnetic plate. As reported in earlier experiments using a ferromagnetic pipe [16], such magnetic flux leakage can be problematic.

To demonstrate the problems caused by magnetic flux leakage, SH guided wave experiments in a ferromagnetic plate were performed using a fabricated transducer, as shown in Fig. 2(a). Fig. 2(b) compares the experimentally measured SH waves using a pair of OSH-MPTs in a pitch-catch manner in a non-ferromagnetic (aluminum) and a

* Corresponding author. Tel.: +82 2 880 7154; fax: +82 2 883 1513.
E-mail address: yykim@snu.ac.kr (Y.Y. Kim).

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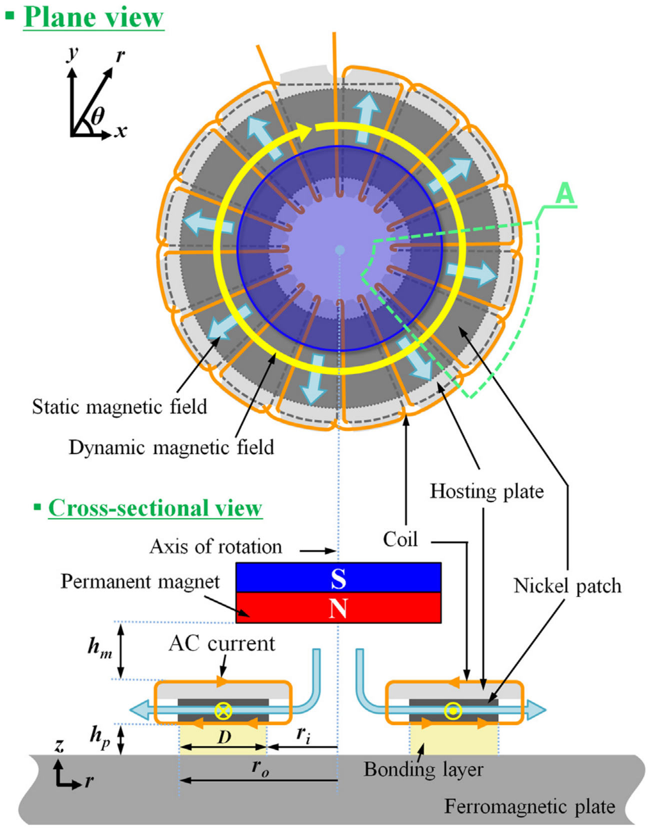

Fig. 1. (a) Schematic configuration of an OSH-MPT bonded to a ferromagnetic plate. The radial static magnetic field generated by the magnet and the circumferential dynamic magnetic field generated by a coil are indicated on the patch. The width of patch (D), the distance between the lower part of the coil wound along the patch and the top surface of a test plate (h_p), and the distance between the magnet and the upper part of the coil wound along the hosting plate (h_m) are defined. The test plate is ferromagnetic.

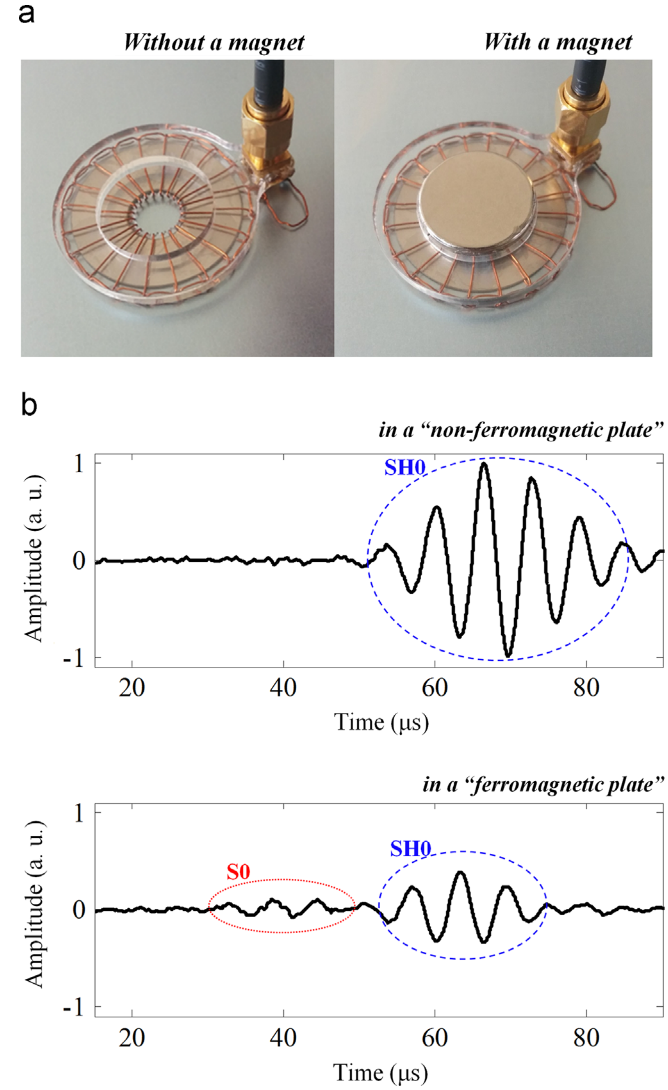

Fig. 2. (a) Prototype of an OSH-MPT installed on a ferromagnetic plate ($h_p=0$). (b) Time based signals experimentally measured in a pitch-catch manner by using a pair of OSH-MPTs installed on a non-ferromagnetic (aluminum) and a ferromagnetic (AISI1008) plate respectively. For the ferromagnetic plate (lower figure), the amplitude of the SH0 mode substantially decreased and the unwanted S0 mode was measured.

ferromagnetic (AISI 1008) plate. The experiments were carried out at 150 kHz with a similar setup to that shown in Section 3.2 using the same OSH-MPT and the same input current. From the comparison in Fig. 2(b), two important observations are made. First, the amplitude of the measured signal of the lowest SH wave mode (SH0 mode) in the ferromagnetic plate is much smaller than that of the wave in the non-ferromagnetic plate. More importantly, an unwanted wave mode (identified as the lowest symmetric Lamb wave mode or the S0 mode) is measured prior to the SH0 mode in the ferromagnetic plate. The decreased transduction efficiency for the SH0 wave mode and the generation of the unwanted S0 mode is likely related to magnetic flux leakage. However, we should investigate why these problems occur and determine how to overcome them. Earlier related studies [17–21] showed that a reduced magnetic field in the magnetostrictive material is responsible for the amplitude decrease in the desired wave mode. In this case, the reason for the reduced magnetic field in the patch is the magnetic flux leakage into the ferromagnetic plate. Additionally, because the generation of the unwanted Lamb wave mode is unique to the application of OSH-MPTs in ferromagnetic plates, it needs to be clearly explained. Then, a method to increase the amplitude of the desired SH wave mode without generating the undesired S0 wave mode can be suggested. Numerical simulations and wave experiments were conducted to validate the methods developed to make OSH-MPTs applicable to ferromagnetic plates.

2. OSH-MPT for a ferromagnetic plate

In this section, the detailed configuration of an OSH-MPT is presented. Then, we investigate how the magnetic flux leakage problems discussed in the introduction are related to the specific parts of an OSH-MPT that is installed on a ferromagnetic plate.

2.1. Transducer configuration and issues

Fig. 3 shows the plane-view drawings of part A indicated in Fig. 1. Fig. 3(a) shows the detailed winding of the coil and the AC current flow. The coil is used to apply a circumferential dynamic magnetic field to the patch as shown in Fig. 1 (the cylindrical permanent magnet is placed on the patch to apply a radial static magnetic field). Therefore, the coil is wound radially all over the patch in the circumferential direction, similarly to toroid coils. For uniform and robust coil winding, a nonconductive hosting plate with notches along the inner and outer circumferences is placed over the patch. The coil is wound in an "a–b–c–d" order (see Fig. 3(a)) in accordance with the AC current flow. More details on the coil winding are provided in [6].

The magnetic fields generated by the magnet and coil are also shown in Fig. 3(b). Among these magnetic fields, the combination of the radial static magnetic field (H_r^S) and the circumferential