**DEVELOPMENT OF AN ORIENTATION-ADJUSTABLE PATCH-TYPE MAGNETOSTRICTIVE SENSOR FOR DAMAGE DETECTION IN A PLATE**

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**Abstract:** The coupling phenomenon between stress and magnetic induction, known as magnetostriction, has been successfully applied to generate and measure elastic waves. Most applications of this phenomenon thus far, however, are rather limited to cylindrical ferromagnetic waveguides. The main objective of this work is to present a new patch-type, orientation-adjustable magnetostrictive transducer that is applicable for non-ferromagnetic metallic or non-metallic waveguides. The existing patch-type transducer consisting of a ferromagnetic patch and a racetrack coil is useful to generate elastic waves only in one specific direction. However, the transducer developed by the present authors can transmit and receive elastic waves propagating along a desired direction with one nickel patch installation at a given location. Our magnetostrictive transducer consists of a circular nickel patch, a figure-of-eight coil, and a couple of bias permanent magnets. Because of the unique configuration of the transducer, the propagating direction of the generated elastic wave can be freely controlled since the assembly of bias magnets and the coil is not bonded to the magnetostrictive patch, unlike in the existing transducer. This work reports some experimental results to measure guided waves in plates by the proposed transducer.

**Introduction:** Recently, magnetostrictive transducers have received much attention for guided wave based non-destructive evaluation (NDE) because of several advantages such as non-contact detection, cost-effectiveness, and long-range inspection[1-8]. The magnetostrictive transducer is based on the magnetostriction effect denoting the coupling phenomenon between mechanical stress and magnetic field. Usually most of the applications of the magnetostrictive transducer had been limited to ferromagnetic objects since the magnetostriction effect occurs only in ferromagnetic materials, for instance, Fe, Ni, and Co. In order to overcome this weakness, Kwun[7] proposed a patch-type magnetostrictive transducer employing a ferromagnetic patch. Light *et al.*[9] used a nickel strip for a ferromagnetic patch, and bonded it to non-ferromagnetic plates. Fig. 1 shows a typical configuration of the patch-type transducer. It is composed of a magnetostictive patch bonded to a non-ferromagnetic plate and a racetrack coil. If an electric current flows along the coil, magnetic field is induced in the patch. By the magnetostriction effect, the induced magnetic field generates strain

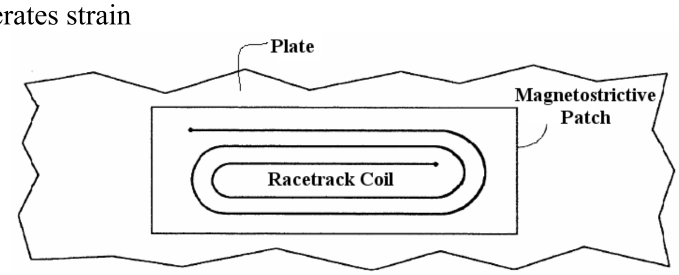



Figure 1 The patch-type magnetostrictive transducer by Light *et al.*[9]

of the patch which then develops stress in the plate. Here, the direction of the stress wave generated by the transducer is mainly governed by the direction of the magnetic flux in the nickel patch, so the direction can be easily controlled by rotating the assembly of the bias magnets and the coil of the transducer. Because the orientation of the stress wave direction is easily adjustable, the developed transducer is called the Orientation-adjustable Patch-type Magnetostrictive Transducer (OPMT). The performance of OPMT will be demonstrated by wave experiments in aluminum and acrylic plates. Several experimental studies show that the Lamb waves and the SH waves can be generated and measured very effectively along any designated direction.

**Theoretical background:**

**A. Magnetostriction effect:** When a ferromagnetic material such as Fe, Ni, and Co is placed under a magnetic field, its physical dimension changes. This phenomenon is called the Joule effect[10]. The inverse phenomenon that the change of dimension yields a magnetic induction is called the Villari effect[11]. The magnetostriction effect usually denotes both the Joule effect and the Villari effect. A general theory on the magnetostrictive effect covering up to hysteresis and irreversibility can be found in Jiles[12].

In a magnetostrictive transducer, the coil supplies the excitation magnetic flux to a ferromagnetic material and also converts the magnetic induction induced by the stress developed in the material to an electromotive force. To use the transducer as an actuator, excitation current is supplied to the coil and then magnetic flux is produced around coil by Ampere's law[13]. The ferromagnetic material subject to magnetic strength changes its physical dimension by the Joule effect. Therefore, we can generate elastic waves in a ferromagnetic material. On the contrary, if elastic waves propagate in a ferromagnetic material, the magnetic flux is induced by the Villari effect. Then, the magnetic induction flows though the coil which converts the magnetic flux to an electromotive force by Faraday-Lenz law[13]. In this situation, the transducer works as a sensor.

**B. Guided waves in a plate:** Thin plates will be used throughout this investigation, so the mechanics of the guided waves in thin plates will be briefly given. It is known that there exist two kinds of guided waves in a thin plate: the Lamb waves and SH (shear horizontal) waves. When the symmetric Lamb wave propagates, a particle in a plate moves in the vertical plane of the plate. One the other hand, when the SH wave propagates, a particle moves horizontally in normal direction of propagation.

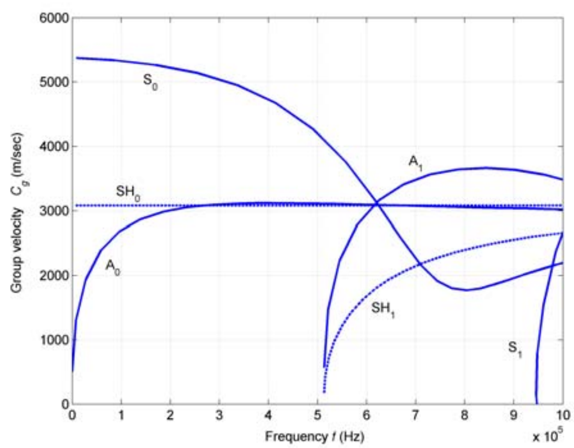



Figure 2 The group velocity – frequency relation of the guided waves in a 3 mm thick aluminum plate.

(Solid lines: Lamb waves, dashed lines: SH waves)

Fig. 2 shows the group velocity dispersion curve of guided waves in an aluminum plate with thickness of 3 mm. The first SH mode, denoted by $SH_0$ in Fig. 2 is non-dispersive, so its group velocity is constant regardless of frequency. Non-dispersive waves are very advantageous for long range inspection since the excited waveform propagates without any distortion. Therefore the $SH_0$ mode is most preferred for the guided wave based NDE of plate-like structures. In general, however, the SH waves are somewhat cumbersome to generate in a plate. Therefore, the first mode of the Lamb wave, denoted by $S_0$ in Fig. 2, is also widely used. Even though the $S_0$ is dispersive, its dispersion may be neglected for frequencies below a few hundred kHz[14-16]. In this work, we will show that both the $SH_0$ mode and the $S_0$ mode can be generated and received by OPMT effectively.

**Orientation-adjustable Patch-type Magnetostrictive Transducer (OPMT):** OPMT is composed of a circular ferromagnetic patch, two bias permanent magnets, and a figure-of-eight coil. The schematic diagram of the proposed transducer is shown in Fig. 3. When OPMT is used, the circular ferromagnetic patch is bonded onto a test specimen at one location while the assembly of the bias magnets and the specially-designed figure-of-eight coil is simply placed on the top of the circular nickel patch. Thus, the assembly can rotate freely while the patch remains bonded onto the test specimen. We can change the direction of the magnetic flux developed by the permanent magnet and the figure-of-eight coil by varying the assembly orientation, so the desired elastic wave propagation direction can be easily selected. The wave propagation direction is basically the same as the magnetic flux direction because the dominant elastic deformation direction of the patch coincides with the dominant magnetic flux direction. One can show that the wave propagating in the dominant magnetic flux direction is the Lamb wave. A SH wave is also generated as shall be seen later.

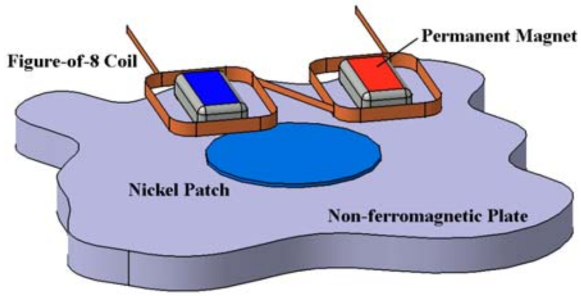



Figure 3 Schematic diagram of an OPMT

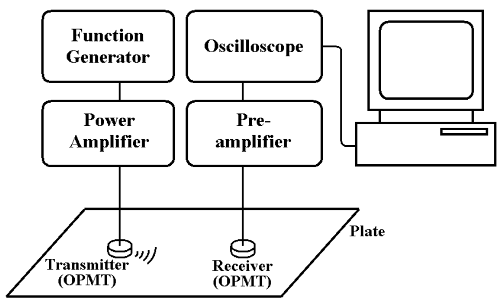



Figure 4 Schematic diagram of the experimental arrangement. (Function generator: Agilent 33120A, Power Amplifier: RAM5000, Pre-amplifier: SR560 , Oscilloscope: Lecroy LT354 )

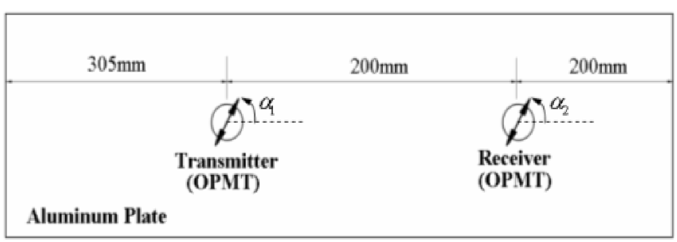
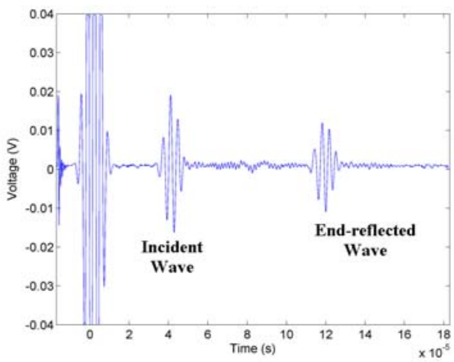
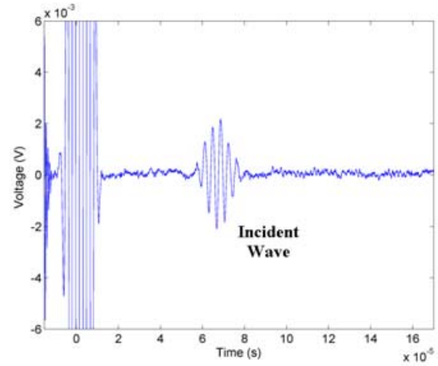



Figure 5 Experimental setup for guided wave generation and measurement by OPMT. The arrows denote the direction of the applied bias magnetic flux.

**Experiments:** The experimental setup is schematically shown in Fig. 4. In order to check if guided waves are properly generated and measured by OPMT, two OPMT's were installed on an aluminum plate (thickness = 3 mm) as depicted in Fig. 5. Two circular nickel patches are bonded on the aluminum plate and orientation-adjustable assemblies of permanent magnets and figure-of-eight coils are placed on the patches. For experiments, the alternating electric current of the Gabor pulse form[17] was sent through the figure-of-eight coil of the wave transmitting transducer. The measures signals are shown in Fig. 6. When the orientations ($\alpha_1$, $\alpha_2$) of the transmitter and the receiver were set to be $0^o$, the signal shown in Fig. 6 (a) was captured by the receiver. The excitation frequency was 280 kHz. Using the traveling distance and the time, the wave speed was estimated to be 5175m/sec. In comparison with the theoretical wave speed (5075m/s at 280 kHz) from the dispersion curve in Fig. 2, we can confirm that the measured wave belongs to the $S_0$ mode of the Lamb wave. When the orientations ($\alpha_1$, $\alpha_2$) of the two transducers are chosen as $60°$, the signal shown in Fig. 6 (b) was measured. Again, from the traveling distance and time interval between two waveforms in Fig. 6 (b), the wave speed was calculated as 3053 m/sec at 280 kHz. By comparing the theoretical wave speed 3080 m/sec of the first SH mode at 280 kHz, the measured signal in Fig. 6 (b) was identified as the first SH mode.

Fig. 7 shows the measured signals for varying values of $\alpha_2$ for the fixed value of $\alpha_1 = 0^o$. (The experiments were conduced on an acryl plate.) The magnitude of the signal reduces as $\alpha_2$ approaches $60^o$. Indeed, the signal measured with $\alpha_2 = 60^o$ almost vanishes, which indicates that the receiving transducer is so oriented to measure




(a) (b)

Figure 6 The measured signals with the setup in Figure 5

(a) $\alpha_1 = \alpha_2 = 0^o$ and (b) $\alpha_1 = \alpha_2 = 60^o$

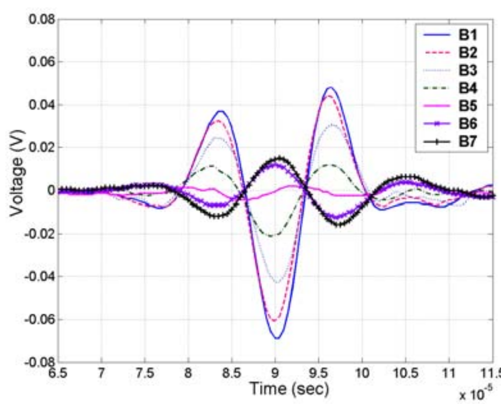



Figure 7 The measured signals for varying values of $\alpha_2$ with the fixed value of $\alpha_1 = 0^o$

($B_1 : \alpha_2 = 0^o$, $B_2 : \alpha_2 = 15^o$, $B_3 : \alpha_2 = 30^o$, $B_4 : \alpha_2 = 45^o$, $B_5 : \alpha_2 = 60^o$, $B_6 : \alpha_2 = 75^o$, $B_7 : \alpha_2 = 90^o$)

the SH wave. When the orientation angle $\alpha_2$ exceeds $60^o$, the sign of the signal changes. By a first-order theoretical analysis[18] of the generated and measured waves by OPMT, one can predict quite accurately the signal behavior shown in Fig. 7.

**Conclusions:** By OMPT, the symmetric $S_0$ wave mode and the horizontal shear $SH_0$ wave mode in a plate were successfully generated and measured. By rotating the orientation of the assembly of the permanent magnets and the figure-of-eight coil placed on the top of the nickel patch bonded onto a test plate, the flux direction, thus the stress wave propagation direction was easily adjusted. To change the wave propagation direction, the nickel patch does not need to be re-installed when OPMT is used. It is expected that OPMT can be an effective means to generate and measure guided waves in plates for damage detection applications.

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