Non-contact evaluation of thickness reduction of plates and pipes using EMAT-generated guided wave

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Abstract

The evaluation of thickness reduction in structures such as plates and pipes by guided waves is presented. Ultrasonic guided wave techniques have been widely studied and successfully applied to various non-destructive applications with the advantage of long range inspection. Non-contact methods for ultrasonic wave generation and detection have been of a great concern and highly demanded in the guided wave techniques due to their capability of wave generation and reception on surface of high temperature or on rough surface. A non-contact EMAT (Electro-Magnetic Acoustic Transducer) technique for guided waves is illustrated with some applications on monitoring of corrosion simulated thickness reduction in structures. The EMAT technique is successfully applied for the non-contact generation and detection of guided waves in the structures. Promising features based on the dispersive behavior of selected wave modes are found to quantify thickness reduction. The experimental results show that the mode cutoff measurements provide a qualitative scheme to measure thinning defect while the change in group velocity can be used as a quantitative parameter.

1. Introduction

It has been reported that in 1968, Wallance developed a non-contact technique using EMAT (Electro Magnetic Acoustic Transducer) to generate and receive ultrasonic waves in a metallic material with the lift-off of several mm from the surface of the test material. In 1970 and 1980s, the technical advance and various applications of EMAT...
have been carried out by other researchers such as R.B. Thomson \(^3\) and B.W. Maxfield \(^5, 6\).

EMATs are able to generate and receive ultrasonic waves without contacting the surface of test materials by the interaction of magnetic field and Eddy current which are induced from magnets and coils into the test material. Thus, EMATs do not require any pre-process or removal of coating or insulation on the test surface. But, it has been reported that the effective lift-off should be less than 2 mm due to the rapid exponential decay of the electromagnetic force from the surface.

Also another advantage with EMATs is that various wave modes can be generated easily by change in the arrangement of magnets and coils. For example, shear horizontal wave (SH wave) is not easy to generate with conventional PZT transducers due to the coupling problem. But, this problem can be overcome easily by using EMATs since EMATs do not require any coupling media between the transducer and the test material. Ultrasonic guided waves have been noted as an effective method to inspect joints or weld in plates and pipelines. It has been reported that the guided wave techniques are successfully applied to inspection of the airplane \(^{12}\). In the inspection of the corrosion in a aluminum plate using guided waves, it is found that many features of the Lamb waves such as the cutoff frequency, group velocity, and transmission and reflection factors are sensitive to the thickness reduction of a plate \(^{13}\).

In this paper, the use of EMAT is proposed as a new efficient non-contact NDE tool to monitor the thickness variation of corrosion-simulated plates and pipes.

2. Understanding on the Ultrasonic Guided Wave Technique

As well known from earlier works, elastic waves propagating along thickness, \(d=2h\) of a plate satisfy the Rayleigh-Lamb frequency equation.

\[
\frac{\tan(ph)}{\tan(qh)} = \left( \frac{4k^2 pq}{q^2 - k^2} \right)^{\pm 1}
\] ................................. (1)

Where the signs “+” and “-” on the right hand side are for symmetric and anti-symmetric modes, respectively. \(p\) and \(q\) in eqn.(1) represent the corresponding wave vector components of the partial longitudinal and shear modes in thickness direction as illustrated in the equation below.

\[
p^2 = \left( \frac{\omega}{C_L} \right)^2 - k^2 ................................................................. (2)
\]

\[
q^2 = \left( \frac{\omega}{C_T} \right)^2 - k^2 ................................................................. (3)
\]

Where \(\omega\) is the angular frequency and \(k\) is the wave number \(^{11}\).

Dispersion curves for a plate are numerically obtained from the eqn. (1). Fig. 1 shows the phase and group velocity dispersion curves of a steel plate. Mode cutoff regions are
also shown. $C_p$, $C_g$, $f$ and $d$ denote the phase velocity, group velocity, frequency and thickness, respectively.

![Dispersion curves for a steel plate](image)

**Fig. 1** Dispersion curves for a steel plate ($CL=5.8\text{mm/sec}$, $CT=3.2\text{mm/sec}$), $S=$ symmetric modes, $A=$ antisymmetric modes.

Thickness reduction of plates can be detected based on the measurement of various dispersion characteristics of guided wave modes. Especially, the phase velocity of a narrow band signal, which is a function of the wavelength of EMAT, is a key experimental parameter to select a desired mode at a given frequency. Alternatively, other modes can also be generated by frequency tuning. The propagation characteristics of guided wave modes need to be carefully observed to quantitatively evaluate various thickness reductions. In this paper, among those features\(^{(13)}\), the mode cutoff and group velocity changes are used to assess the thickness reduction.

### 3. Principles and Features of Lamb-EMAT

The EMAT generation and reception of ultrasonic waves involve the three following mechanisms: the Lorentz's effect, the magnetic effect and the magnetostrictive effect. The Lorentz's effect exists in a conductive material while the magnetostrictive effect appears in a ferro-magnetic material.

When the magnetic field, $B$, and Eddy current, $J_e$, induced by the coil near the surface are applied to the conductive material, Lorenz force is generated in the normal direction to both magnetic filed and Eddy current. This force moves the material particle in the direction that the force is applied. By applying the alternative current, the force direction is also changed alternatively and consequently, the stress waves are generated and propagated. (Fig. 2)

![Wave generation mechanism of the EMAT](image)

**Fig. 2** Wave generation mechanism of the EMAT
In order to generate Lamb waves with EMATs, the coil and permanent magnets are arranged as shown in Fig. 2. A permanent magnet is located above the meander coil which is designed to have alternative direction of the current flow in each turn. The center frequency of the EMAT is determined by the spacing of the coil. Usually, the spacing of coil is 1/2 of the wavelength. This arrangement of the coil and magnets results in Lamb wave in the conductive materials in which, the particle movement is parallel to the surface.

4. Thinning Defect Monitoring

Fig. 3 shows the experimental setup for detection of thinning defect in aluminum, steel plate and steel pipes using the Lamb wave. Fig. 4 shows a pair of EMATs and coils used to generate and receive the Lamb waves.

In order to consider the case of thickness reduction, the EMATs were placed on the opposite side of the simulated corrosion defects. One of the EMATs was used as a transmitter and the other was used as a receiver. The distance between the EMATs is 250 mm. The test specimens are shown in Fig. 5. In case of an aluminum plate whose thickness is 2 mm and whose size is 1200 x 400 mm as shown in Fig. 5a, three artificial defects to simulate thickness reduction due to corrosion were machined. The area of each defect is 50 x 50 mm and the depths of the defects are 10, 20 and 30% of the plate thickness. In case of steel plates whose thickness is 1 mm and whose size is 800 x 300 mm as shown in Fig. 5b, eight artificial defects simulating different thickness reductions in the range between 3% and 20% of the plate thickness were machined. In case of carbon steel pipes whose thickness is 4.5 mm and length is 2000 mm as shown in Fig. 5c, various defects were machined. The circumferential width of all defects is 30 mm. The lengths of the defects are 30, 40, 50, 60 and 70 mm, and the thicknesses are 3, 5, 7, 10, 15, 20, 25 and 30% less the pipe thickness.
The mode cutoff is one of the characteristics of the Lamb wave: a wave mode disappears or its amplitude decays with the thickness reduction. In order to enhance the detectibility of thickness reduction with mode cutoff, it is ideal to choose the Lamb wave modes near mode cutoff regions (Fig. 1). The experiment results of mode cut-off due to increasing thickness reduction are shown in Fig. 6. In case of an aluminum plate, S1 was chosen as a mode sensitive to thickness reduction in terms of the mode cut-off. Fig. 6a shows the waveforms of S1 mode at the center frequency of 1.4 MHz in the 2 mm-thick aluminum plates with no defect, 10, 20, and 30% thickness reduction, respectively. In case of steel plates and pipes, A1 was chosen as a mode sensitive to thickness reduction in terms of the mode cut-off. Fig. 6b and 6c show the waveforms of A1 mode. The center frequencies are 1.8 MHz and 0.49 MHz in the 1 mm-thick steel plates and 4.5 mm-thick pipes, respectively.

As shown in Fig. 6, it is found that the S1 and A1 modes disappear when the thickness is sufficiently reduced. Therefore, S1 and A1 modes turn out to be useful modes to detect the presence of thickness reduction in the plate and pipe considered here. However, the mode cutoff cannot provide any quantitative evaluation of thickness reduction (8, 9, 10 and 13).

Since the phase and group velocities of guided waves change as functions of frequency and specimen thickness, the change in group velocity can be used for the evaluation of thickness reductions described below.

In order to obtain a correlation between the change in group velocity and thickness reduction, it is better to select the mode whose group velocity is discernibly changed due to thickness (Fig. 1). Therefore, S0 and A1 modes were selected for evaluation of thickness reduction.

As shown in Fig. 7, it is found that S0 and A1 modes change the group velocity due to increasing thickness reductions. In case of an aluminum plate, S0 mode was chosen as a mode sensitive to thickness reduction. Fig. 7a shows the waveforms of S0 mode at the center frequency of 1.21 MHz in the 2 mm-thick aluminum plate with no defect, 10, 20, and 30% thickness reductions, respectively. In case of steel plates and pipes, A1 mode was chosen as a mode sensitive to thickness reduction in terms of the change in the group velocity. Fig. 7b and 7c show the waveforms of A1 mode. The center frequencies are 2.09 MHz and 0.62 MHz in the 1 mm-thick steel plates and 4.5 mm-thick pipes, respectively (8, 9, 10 and 13).
Fig. 6 Change in the amplitude of mode due to increasing thickness reductions in (a) aluminum plate (S1 mode), (b) steel plates (A1 mode) and (c) pipes (A1 mode)

Fig. 7 Change in the group velocity due to increasing thickness reductions in (a) aluminum plate (S0 mode), (b) steel plates (A1 mode) and (c) steel pipes (A1 mode)

Fig. 8 Results of the thinning defect monitoring: (a) aluminum plate, (b) steel plates, and (c) steel pipes
The observed changes in group velocity caused by thickness reduction are plotted on dispersion curves (Fig. 1) in Fig. 8. The theoretical and experimental results show similar trends. According to the experimental results of Fig. 7 and Fig. 8, it is possible to evaluate thickness reduction by the comparison between change of group velocity and theoretical group velocity. However, the dispersion curves of the structure to be tested should be determined prior to the field test because the Lamb wave velocity is highly dependent on the geometry and material properties.

5. Conclusions

In this paper, the thickness reduction in thin plates and pipes using a non-contact guided wave technique was evaluated. The EMATs were successfully utilized to generate and receive Lamb waves in an aluminum plate, steel plates and steel pipes. The dispersive behavior of S1, S0 and A1 modes are used for evaluation of thickness reduction. The experimental results show that the mode cutoff of S1 and A1 modes provide a qualitative measurement to detect the presence of thinning defect and it is also possible to evaluate the thickness reduction quantitatively by measuring the change in the group velocity of S0 and A1 modes.

References and footnotes