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Development of an Array of EMAT for a Long-Range Inspection of a Pipe Using a Torsional Guided Wave

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Abstract A torsional guided wave mode in a tubular structure has many advantages in obtaining a higher sensitivity and lower attenuation for a defect, because it shows no dispersion characteristics and no radial displacement for a tubular structure. Many attempts have been made to excite and receive torsional guided waves by conventional piezoelectric transducers, but only a few examples are used during a practical field inspection. In this study, an array of electromagnetic acoustic transducers (EMATs) were for an excitation and reception of the torsional guided waves in a pipe was designed and fabricated. The signal patterns were analyzed based on various beam path length. The feasibility of detecting the defects was investigated through a series of experiments with artificial notches on a pipe.

Keywords: Guided Waves, Pipe Inspection; EMAT, Torsional Vibration Mode

1. Introduction

There are several incidents involving a leakage, degradations, and failures of pipes which are in the categories of a safety class as well as a non-safety class in nuclear power plants (NPP). Therefore, it is desirable to examine all the pipes in order to ensure the safety and integrity of a NPP. It is not easy, however, to examine all the pipes in a NPP with the conventional ultrasonic methods, because of a high dose radiation exposure and limited accessibility to the pipes.

The ultrasonic guided wave method could be an option, as it has many advantages when compared to the conventional ultrasonic method. The guided wave can propagate along thin and large plate-like structures or long tubular structures, and provide comprehensive information for large areas of structures with a minimal preparation, such as insulation removal, scaffolding, excavation, coating removal, etc. It can also inspect inaccessible areas remotely without moving the probe along the test pieces.

Among the various vibration modes, the torsional vibration mode has many advantages over the longitudinal or flexural vibration modes. Torsional vibration mode has no dispersion, that has no velocity change with the frequency, and results in a sharp signal pattern in the time domain. Also it has no radial displacement in a tubular structure, and the signal is relatively less affected by the outer medium, such as the case of a water-filled pipe. Therefore the torsional vibration mode can be propagated for a longer distance with a lesser attenuation. Even with these advantages listed above, it is not easy to fabricate a transducer with conventional piezo-electric elements. Many attempts have been made to excite and receive guided ultrasonic waves by conventional piezoelectric transducers, but only a few examples are used during a practical field inspection (Kim and Kwon, 2003).

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An EMAT (Electromagnetic Acoustic Transducer) consists of permanent magnets to produce the bias fields within the material under test, and coil elements to induce a dynamic field and eddy currents in the surface region. Many designs of EMAT for an excitation and reception of an ultrasound have been proposed (Thompson, 1978; Alers and Burns, 1987; Hirao and Ogi, 1999). The orientation of static magnetic fields produced by permanent magnets and the geometry of the pick-up coil are essential factors in determining ultrasound modes and their sensitivity. The parameters of any EMAT design are generally related to their physical size, the design of the magnetic circuit, the pick-up coil configuration and the pre-amplifier for an impedance matching.

A torsional vibration mode, *T(0, 1)* by using an array of EMATs is suggested to detect cracks in a pipe in this work. Based on the dispersion curves for the guided wave in a pipe, an array of EMATs for an excitation and reception of the torsional guided waves was designed and fabricated. The capability of detecting the defects was investigated through a series of experiments with artificial notches on a pipe.

2. Dispersion Curves

The guided wave technique in a pipe or tubular structure for a long-range non-destructive testing and evaluation method has been actively developed for the last two decades (Gazis, 1959; Rose, 1999; Kwun and Bartels, 1996; Alleyne and Cawley, 1996; Shin and Rose, 1998; Cheong et al., 2004). However, because an infinite number of vibration modes are theoretically possible and the dispersion characteristics of the guided wave, the dispersion curves for a pipe under test should be determined in advance and the inspection parameters should be optimized. Based on mathematical formulations (Gazis, 1959; Rose, 1999; Ditri and Rose, 1992), a computer program for the calculation of dispersion curves was developed. The dispersion curves of the phase velocity and the group velocity were calculated for the dimensions and bulk wave velocity of a pipe with an outer radius of 31.75 mm and a wall thickness of 6.5 mm, as shown in Fig. 1 and Fig. 2.

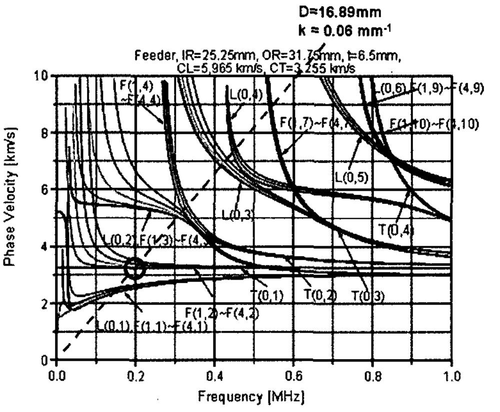


Fig. 1 Phase velocity dispersion curves for a pipe with an outer radius of 31.75 mm and a wall thickness of 6.5 mm and the design parameters for a PPM EMAT.

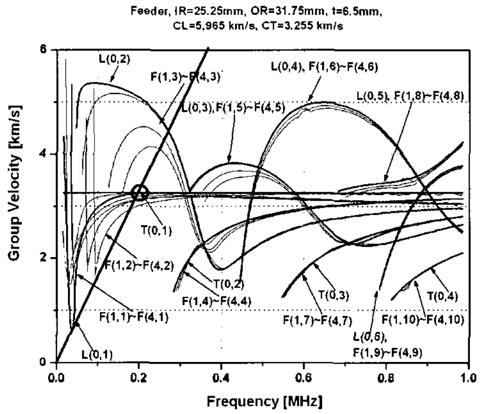


Fig. 2 Group velocity dispersion curves for a pipe with an outer radius of 31.75 mm and a wall thickness of 6.5 mm

The vibration modes and frequencies could be optimized from the group velocity dispersion curves. The longitudinal modes, *L(0, n)* and the flexural modes, *F(m, n)* are almost superimposed except in the lower frequency range, such as the case of *L(0, 1)* and *F(m, 2)(m,n* = 1, 2, 3, ...) etc. The torsional mode *T(0, n)* has similar characteristics to the SH (shear horizontal) mode for the flat plate except for a consideration of the curvature. The torsional mode *T(0, 1)* shows no dispersion characteristics, which means the constant phase velocity and the group velocity are equal to the shear wave velocity.

3. The Design of an Array of EMATs

EMAT can generate ultrasound by applying an alternating current to the permanent magnet, based on the principles of the Lorentz force and the magnetostrictive force. One of the advantages of an EMAT is that the transducer is directly set over the metal surface without an intimate contact. Such an ultrasound can propagate over a long distance and bring the pertinent information back to the receiving sensor. This non-contact nature of an EMAT is the key to establishing a robust implementation, for accommodating unfavorable surface conditions. However, a low energy transfer efficiency of an EMAT results in a low signal to noise ratio. Therefore tone burst method with a high pulse energy and a narrow frequency band is usually used for the excitation of the guided waves. Also, because the impedance match between the coil and the instrument is critical, one should be careful during the design and fabrication of an EMAT.

Guided SH wave EMAT techniques have been investigated and tested for on-site applications (Hirao and Ogi, 1999; Ahn et al., 2004). There are several benefits in the use of guided SH waves for a plate or torsional vibration mode in a pipe such as simpler dispersion characteristics, leading to an easier interpretation of the measurements. Also the guided SH waves tolerate a damping due to the protective coating of polymers, partly because they are independent of the stress-continuity boundary condition at the interface (Ahn et al., 2004).

An effective method for exciting SH waves in a plate or torsional vibration mode in a tubular structure is the use of periodic permanent magnet (PPM) EMAT. A specific guided wave mode can be selected by a driving frequency of the PPM EMAT, based on the dispersion curves shown in Fig. 1. The EMAT consists of a race track shaped coil in close proximity to the metallic specimen and an array of permanent magnets sandwiching the coil against the sample as shown in Fig. 3.

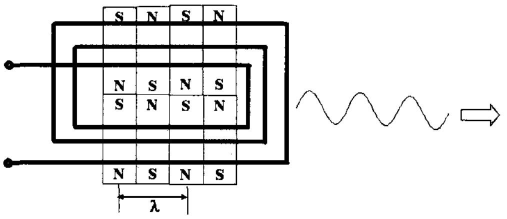


Fig. 3 Design of the period of a PPM-EMAT for SH waves or torsional guided waves.

An array of PPM-EMATs was fabricated to excite a torsional guided wave to propagate along the axial direction of a pipe, as shown in Figs. 4 and 5. A torsional guided wave of *T(0, 1)* vibration mode excited by an array of EMATs can propagate along the axial direction of the pipe and a receiving EMAT will sense the ultrasonic energy from a defect. The relationship between the periodic distance of the coil and the wavelength can be expressed as:

$$\theta = \sin^{-1}(\lambda / \boldsymbol{D}) \qquad (1)$$

where θ denotes the angle from the surface normal, λ and $\boldsymbol{D}$ is the wavelength and the period of the EMAT coil, respectively. The SH wave or torsional guided wave can propagate at the condition of $\theta = 90^\circ$ or $\lambda = \boldsymbol{D}$.

An EMAT was composed of twelve Nd-Fe-B permanent magnets (two rows and each row consists of six magnets) for a periodic magnetic field, and a race-track type coil. The periodicity of the magnets is related to the thickness of the magnets and can be calculated from the phase velocity dispersion curves. From Fig. 1, the periodicity or wavelength or the dimension of the *magnet should be equal from the eq. 1, and is* estimated as 16.8 mm for an excitation of a torsional vibration mode *T(0, 1)* with a frequency of 200 kHz. Because this value can not fit the whole dimension of the EMAT, the distance between each PPM magnet was determined as $\lambda/2 \approx 8$ mm for our torsional guided wave EMATs.

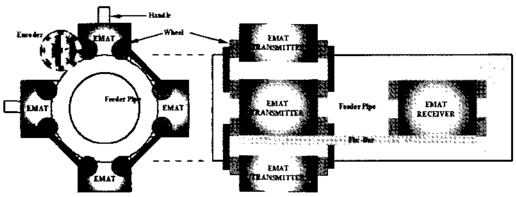


Fig. 4 Schematic drawing of an array of EMATs for an excitation and reception of torsional guided waves

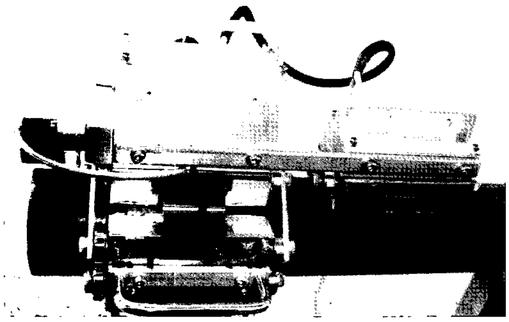


Fig. 5 An array of four EMATs for excitation and an EMAT for reception of torsional guided wave are used.

4. Experimental Results and Discussion

A torsional guided wave with a frequency of 200 kHz was excited by a high power tone burst EMAT instrument and a receiving EMAT acquired the returned ultrasonic signal. The pipe was made of ASTM A106 Grade B (seamless carbon steel pipe for high temperature service). Various artificial notches were fabricated at a distance of 2 m from the end of the pipes by an electro-discharge method. The dimensions of the notches are listed in Table 1.

Table 1 Dimensions of the artificial notches on the bent pipe [unit: mm]

Notch	Length	Depth	Width	Orientation
#1 (axial)	25	0.33 (5% t)	0.15	Circumferential
#2 (axial)	25	0.65 (10% t)	0.15	Circumferential
#3 (axial)	25	1.3 (20% t)	0.15	Circumferential
#4 (axial)	25	2.5 (40% t)	0.15	Circumferential

Since there is a distance between the transmitter EMATs and the receiver EMAT, several different beam paths indicated as t_1, t_2, t_3, t_4 in Fig. 6 are available and a so called "butterfly-shape signal" appears in time domain. Signals from a defect or other reflectors are shown in Fig. 6, for the case where the transmitter array of the EMATs were located at the end of the pipe.

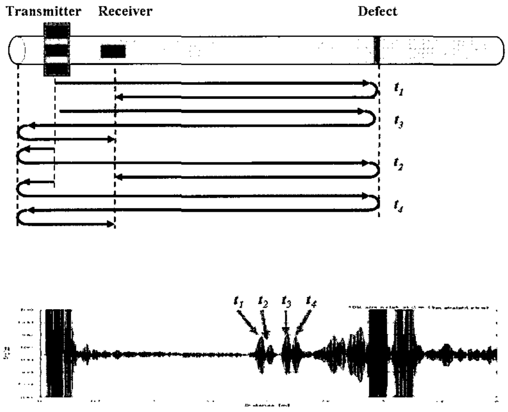


Fig. 6 A butterfly shape signal due to the various beam paths by an array of EMATs.

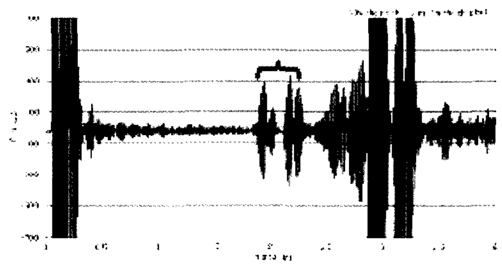
The torsional guided wave signals from the notches with various depths are shown in Figs. 6 (a)~(d). The defect signals can be seen easily at a distance of 2.3 m, for the case of the notches with a depth of 40%, 20%, 10%, and 5% of the wall thickness.

As shown in the phase velocity and group velocity dispersion curves in Fig. 1 and Fig. 2, the *T(0, 1)* mode has no dispersion and the acoustic velocity is constant, and equal to the shear wave velocity. This non-dispersive characteristic of the *T(0, 1)* vibration mode results in a simple and easy signal evaluation.

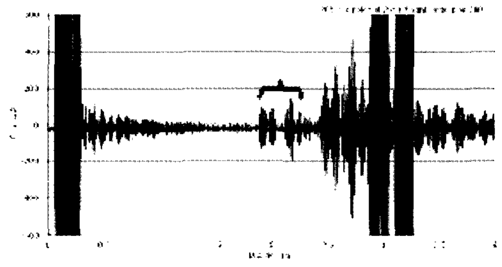
We can expect the signal amplitudes to be proportional to the defect depths, however, the measurement of the signal amplitude does not show such a relationship with the same experimental parameters. Hirao and Ogi (1999) reported a similar result for a case of the SH wave in a plate: the signal amplitude is not directly related to the defect depth.

The explanation of this observation could be due to (1) a mode conversion, (2) a group velocity dispersion, and (3) a wave diffraction around the discontinuities. Only a solution of the three-dimensional, time-dependent elastic problem can explain this observation. The signal from the pipe end (signal at the distance of 3 meter) seems to be complicated, and the signal processing by the short time Fourier transformation(STFT), resulted in a pure *T(0, 1)* vibration mode. There is no group velocity dispersion in this experimental condition and a wave diffraction near the discontinuities is rare. It is believed that the complicated signal pattern is from the various path lengths or traveling times.

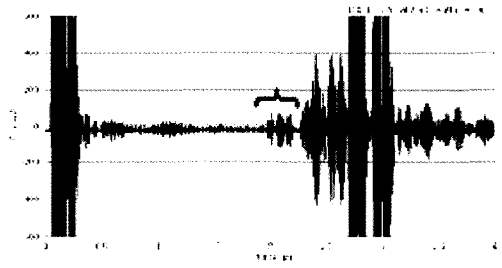
This efficiency of the EMAT is basically affected by the design of the magnets and the coil. The EMAT coil is essentially an eddy current device with the addition of a magnetic field. An effective eddy current coil is one which is tightly coupled electrically to a sample. There are two portions of the EMAT coil: one under a magnetic field and the other that is not. Only the coil area beneath the magnet array generates or receives acoustic signals. The area outside the magnet array is acoustically passive but it still interacts with the surface eddy currents. The eddy currents must form circular paths and these return currents can be efficiently coupled with this "non-magnetized" EMAT coil.



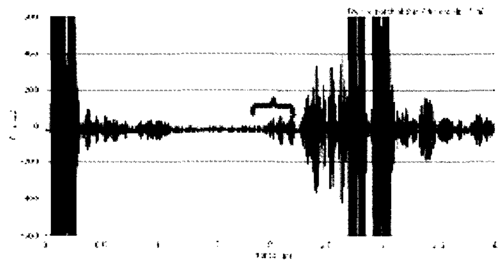
(a) Circumferential notch of 0.4t depth



(b) Circumferential notch of 0.2t depth



(c) Circumferential notch of 0.1t depth



(d) Circumferential notch of 0.05t depth

Fig. 7 Ultrasonic signals reflected from the circumferential notches with various depths on a straight feeder pipe

When the transducer was designed with a minimal length the passive portions of the EMAT coils were folded into the EMAT body to provide the shortest possible length. This design degraded the performance by further isolating the EMAT coil from the surface and loosing its ability to utilize the returning eddy current paths, and by exposing the EMAT coil to an extraneous electrical noise, as shown in Fig. 8.

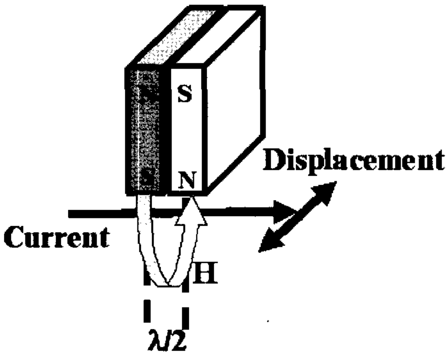


Fig. 8 Explanation of the displacement direction of the SH waves or torsional guided waves with PPM-EMAT.

The present EMAT torsional guided wave method can detect a notch depth of 5% of a wall thickness. When considering a hostile environment and a radiation exposure to examiners, it has shown a great potential for a pipe inspection in nuclear power plants. After a proof test, a written examination procedure and an approval from the nuclear regulatory body, this method will be implemented to an in-service inspection of nuclear power plants.

5. Conclusions

An array of EMATs was developed for the excitation of a torsional vibration mode in a tubular structure. The EMATs were applied for a long-range examination of a pipe. Based on the dispersion curves of the pipe, an array of EMAT transmitters and EMAT receivers was fabricated. A torsional guided wave with a frequency of 200 kHz was excited by a high power tone burst EMAT instrument and a receiving EMAT acquired the returned ultrasonic signal. An artificial notch was fabricated on a pipe specimen. We could detect a notch with a depth of 5% of a wall thickness of the pipe from a distance of 2 meters. A linear relationship between the signal amplitudes and the notch depths was found.

The torsional guided wave method with an array of EMATs has shown a great potential for a pipe inspection in a nuclear power plant and it can be implemented for its in-service inspection, after a proof test, a written examination procedure and an approval from the nuclear regulatory body.

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