DETECTION OF AXIAL CRACKS IN A BENT PIPE USING EMAT TORSIONAL GUIDED WAVES

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Abstract: The feeder pipe in the pressurized heavy water reactor (PHWR) is exposed to a possible leakage during operation. Because of the geometrical complexity of the pipe and its inaccessibility due to a high radiation environment, it is difficult to examine the defect by the conventional ultrasonic method. The guided ultrasonic inspection was chosen for the inspection of the pipe. The torsional mode has many advantages for obtaining a higher sensitivity and lower attenuation for the crack. The torsional guided waves were generated and received by an array of electromagnetic acoustic transducers (EMAT). The feasibility of detecting the axial cracks is investigated through a series of experiments with artificial notches on the bent pipe.

Keywords: Guided wave, Torsional mode, Crack detection, Bent pipe inspection

Introduction: The feeder pipe in a pressurized heavy water reactor (PHWR) is a pipe to supply the coolant to the pressure tube and the heated coolant to the steam generator for power generation. Approximately 380 pipes are installed on the inlet side and outlet side each with two bent regions in the 600 MW-class PHWR, as shown in Fig. 1. After a leakage in the bent region in a PHWR nuclear power plant, it is required to examine all the pipes in order to ensure the integrity of the pressure boundaries. It is not easy, however, to examine all the pipes with the conventional ultrasonic method, because of a high dose of radiation exposure and a limited accessibility to the pipe. The ultrasonic guided wave method could be a solution and as such two guided wave approaches are suggested to detect and evaluate the cracks in the feeder pipe. First, in order to get rid of the limited accessibility, an axial guided wave mode could be selected for screening purposes. When a specific pipe is suspected as to be defective, the circumferential guided wave technique could be applied for a quantitative evaluation of the crack. In this paper, a torsional mode approach using an EMAT is suggested to detect the cracks in the bent pipe, based on the previous investigation on a flexural mode axial guided wave approach and a circumferential guided wave approach [1,2]. An array of EMAT for the generation of a torsional mode and a separate EMAT for the reception of the reflected signals were designed and fabricated. The experimental data from a series of notches were analyzed for the evaluation of the detectability of the method.

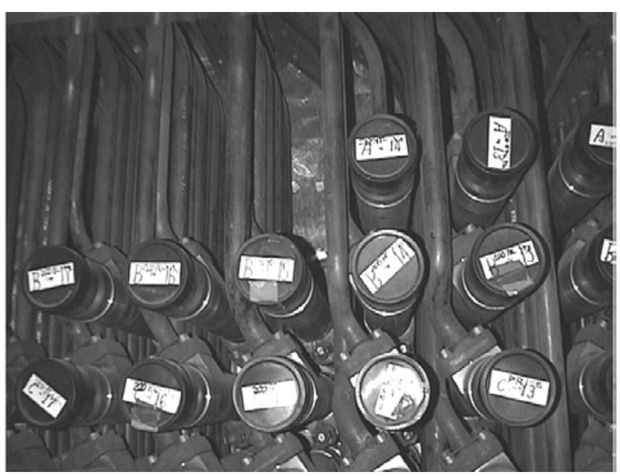


Fig. 1 Feeder pipes in the pressurized heavy water reactor.

Dispersion curves for the axial guided wave in the pipe: An axial 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 [3-10] and can be implemented for the examination of the feeder pipe. However, because an infinite number of modes are theoretically possible and the dispersion characteristics of the guided wave, where the propagation velocities of the modes are changed with the frequency and thickness, the dispersion relationship for the specific dimension of a feeder pipe should be determined in advance and the inspection parameters should be optimized. Based on the mathematical formulations [3-5], a computer program for the calculation of the dispersion curves was developed and the dispersion curves of the phase velocity and group velocity were calculated for the dimension and bulk wave velocity of the feeder pipe, shown in Fig. 1 and Fig. 2.

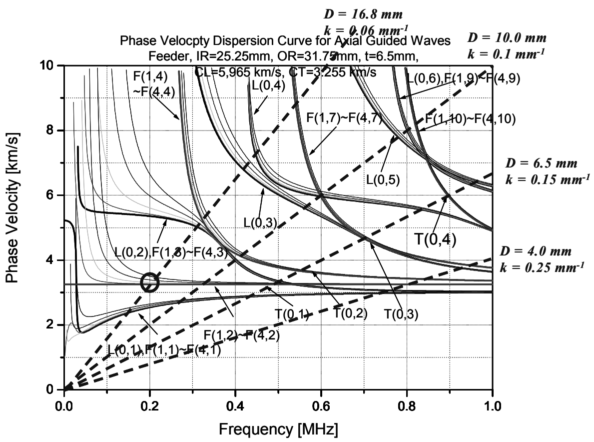


Fig. 2 Phase velocity dispersion curve for the feeder.

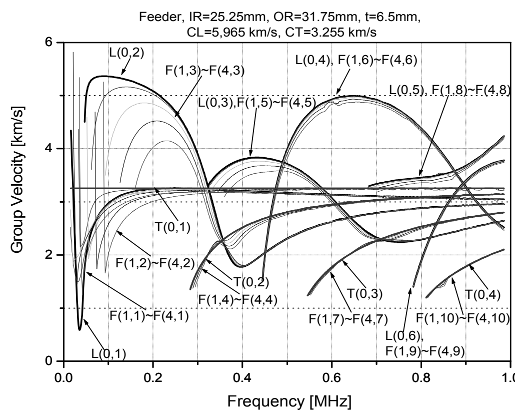


Fig. 3 Group velocity dispersion curves for the feeder.

The mode 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 superposed 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 in the flat plate except for the consideration of the curvature. The torsional mode *T(0,1)* shows no dispersion characteristic, which means the constant phase velocity and group velocity is equal to the shear wave velocity.

EMAT for the torsional mode guided waves: EMAT can generate ultrasound by applying an alternating current with a permanent magnet, based on the principle of the Lorentz force and magnetostrictive force. One of the advantages of EMAT is that the transducer is directly established on 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 EMAT is the key to establishing a robust implementation, accommodating unfavorable surface conditions. However, a low energy transfer efficiency of EMAT results in a low signal to noise ratio. The tone burst method with a high pulse energy and narrow frequency band is used for the generation of the guided waves. Also, because the impedance match between the coil and the instrument is critical, one should be careful in the design and fabrication of the EMAT.

SH guided wave EMAT techniques have been investigated and tested for on-site applications [11,12]. There are several benefits in the use of SH guided waves in a plate or torsional mode in a pipe such as a simpler dispersion characteristic, leading to an easier interpretation of the measurements. A specific guided wave mode can be selected by a driving frequency of the periodic-permanent magnet (PPM) EMAT, based on the dispersion curves shown in Fig. 2. Also the SH guided waves tolerate a damping from the protective coating of lossy polymers, partly because they are independent of the stress-continuity boundary condition at the interface [11].

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

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

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 $\lambda = \boldsymbol{D}$.

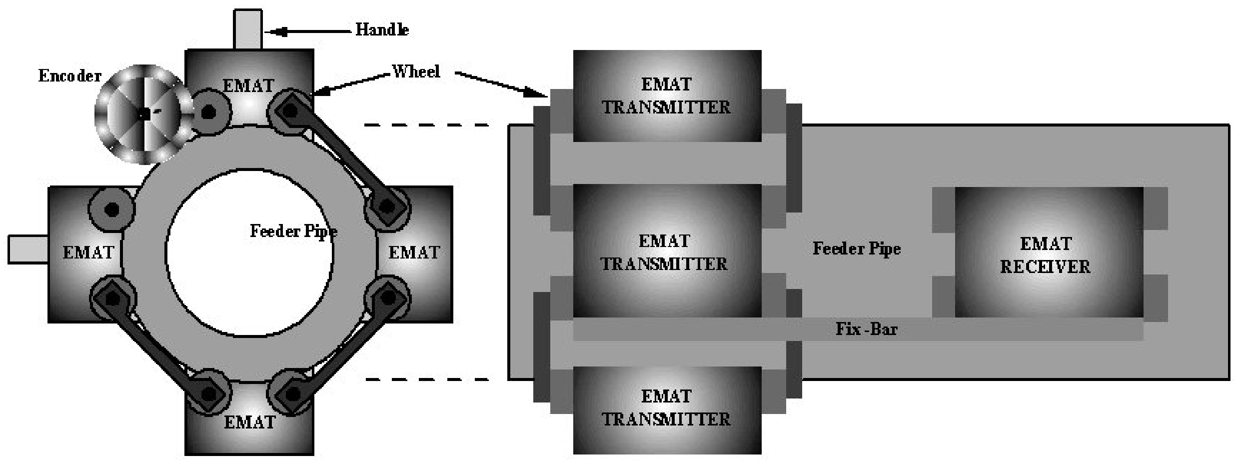


Fig. 4 Design of an array of EMAT for the generation and reception of the torsional guided waves.

From the review of Fig. 2, the period of PPM magnet (pitch of coil) or wavelength can be determined as 16.8 mm at 200 kHz. Because this value can not fit to the whole dimension of the EMAT, the distance between each PPM magnet was determined as $\lambda / 2 \approx 8$ mm for our design of torsional guided wave EMAT.

Experiment: A torsional guided wave with a frequency of 200 kHz was generated by a high power tone burst EMAT instrument and a receiving EMAT acquired the returned ultrasonic signal. The feeder pipe was made of ASTM A106 Grade B (seamless carbon steel pipe for high temperature service). The pipe specimen was bent twice and an artificial notch was fabricated on the bent region by an electro-discharge method, as shown in Fig.5. The dimensions of the notches are listed in Table 1.

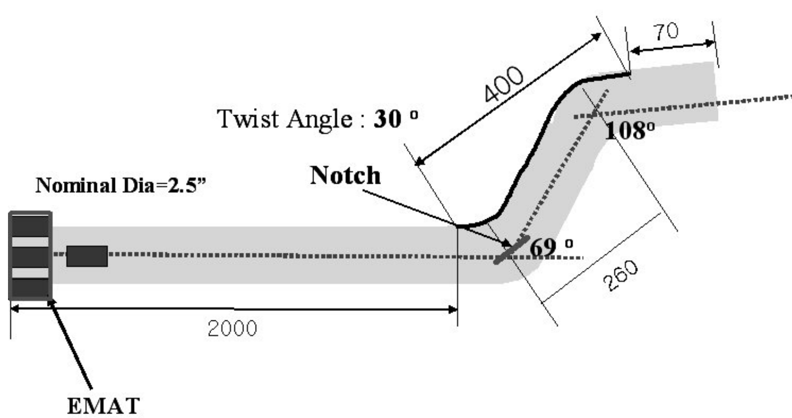


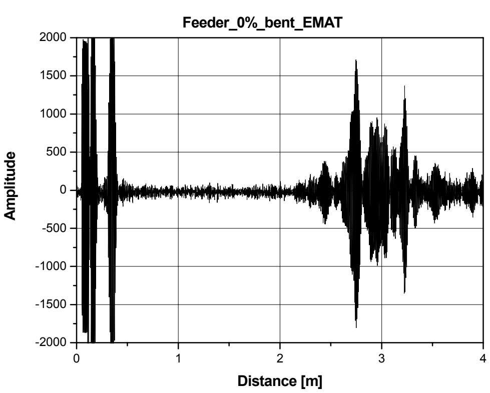
Fig. 5 Configuration of the guided wave examination of the artificial notches in the feeder pipe (unit:mm).

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

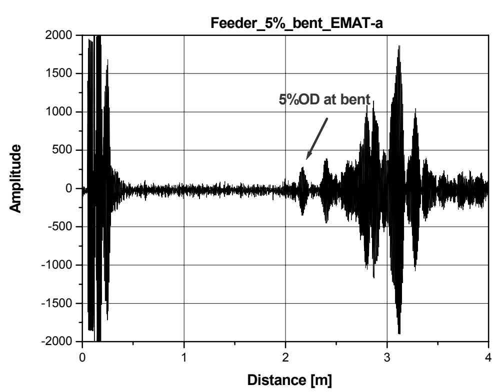
Notch	Length	Depth	Width
#1 (ax ial)	25	0.33 (5% t)	0.15
#2 (axial)	25	0.65 (10% t)	0.15
#3 (axial)	25	1.3 (20% t)	0.15
#4 (axial)	25	2.5 (40% t)	0.15

Results and discussion: The EMAT torsional guided wave signals from the specimens with various depths of notches are shown in Figs. 7(a)~(f). Since there is a distance between the transmitter EMAT array and receiver EMAT, several different beam paths are available and a so called "butterfly-shape signal" appears from a defect or signal source for the case where the transmitter array of the EMATs were located at the end of the pipe. As shown in the phase velocity and group velocity dispersion curves in Fig. 2 and Fig. 3, the *T(0,1)* mode has no dispersion and the acoustic velocity is constant, and equal to the shear wave velocity. The defect signals can be seen easily at the distance of 2.3 m, for the case of the notches with the depth of 5%, 10%, 20%, and 40% of the wall thickness (Figs. 7 (b)~(f)).

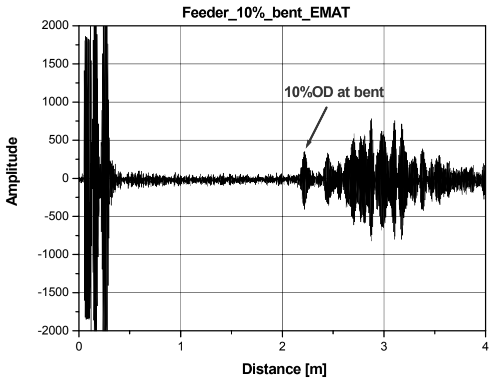
We can expect the signal amplitude to be proportional to the depth, however, the measurement of the signal amplitude does not show such a relationship with the same experimental parameters. Hirao and Ogi [11] reported similar result for a case of SH wave in a plate, as such the signal amplitude is not directly related to the defect depth. It is expected that there is a complicated inter-mode energy transfer at the positions of thickness change, including non-propagating (imaginary) modes whose amplitude decay exponentially from the discontinuities. The explaination of this observation could be due to (1) mode conversion, (2) the group velocity dispersion, and (3) wave diffraction around the discontinuities. The solution of three-dimensional, time-dependent elastic problem can only explain the 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), which resulted in a pure *T(0,1)* mode. There is no group velocity dispersion in this experimental condition and hardly occur a wave diffraction near the discontinuities. It is believed that the complicated signal pattern is from



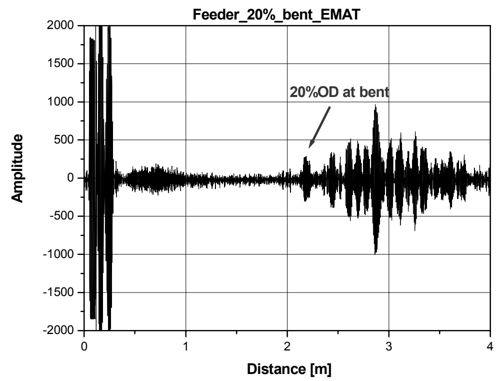
(a) Signal from bent pipe with no defect.



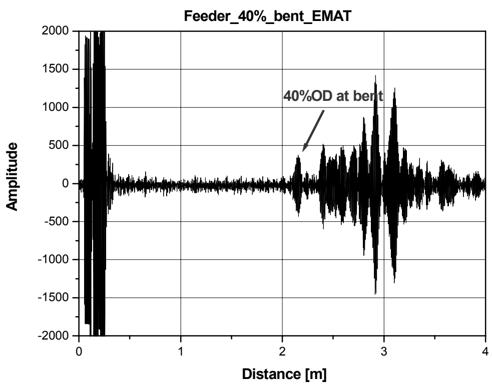
(b) Signal from a notch of 5% of wall thickness of bent pipe.



(c) Signal from a notch of 10% of wall thickness of bent pipe.



(d) Signal from a notch of 15% of wall thickness of bent pipe.



(e) Signal from a notch of 40% of wall thickness of bent pipe.

Fig. 6 Torsional guided wave signals from the axial notches of bent pipe.

the various path lengths or traveling times.

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

Summary:

(1) The EMAT torsional guided wave method was developed for the long-range examination of the axial crack in the feeder pipe in a PHWR nuclear power plant. The phase velocity and group velocity dispersion curves were calculated for the feeder pipe. Based on the dispersion curves, an array of EMAT transmitters and EMAT receivers were fabricated. A torsional guided wave with a frequency of 200 kHz was generated by a high power tone burst EMAT instrument and a receiving EMAT acquired the returned ultrasonic signal. An artificial notch was fabricated on a real feeder pipe specimen after the cold bending process.

(2) We could detect even the notch with the depth of 5% of the wall thickness of the pipe from the distance of 2 meters, but a linear relationship between the notch depth and signal amplitude, was not found.

(3) The torsinal guided wave method with an array of EMAT has shown a great potential for the feeder pipe inspection in a PHWR nuclear power plant and it can be implemented to their in-service inspection, after a proof test, a written procedure and the approval from the nuclear regulatory body,

Acknowledgements:

This work was supported by the Development of Inspection Technology for the PHWR Feeder Pipe Project, as a part of the Long-Term Nuclear R&D Program supported by the Ministry of Science and Technology, Korea.

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