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Development of a Guided Wave Technique for the Inspection of a Feeder Pipe in a Pressurized Heavy Water Reactor

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One of the recent safety issues in the pressurized heavy water reactor (PHWR) is the cracking of the feeder pipe. Because of the limited accessibility to the cracked region and a high dose of radiation exposure, it is difficult to inspect all the pipes with the conventional ultrasonic method. In order to solve this problem, a long-range guided wave technique has been developed. A computer program to calculate the dispersion curves in the pipe was developed and the dispersion curves for the feeder pipes in PHWR plants were determined. Several longitudinal and/or flexural modes were selected from the review of the dispersion curves and an actual experiment has been carried out with the specific alignment of the piezoelectric ultrasonic transducers. They were confirmed as L(0,1)) and/or flexural modes(F(m,2)) by the short time Fourier transformation(STFT) and were sensitive to the circumferential cracks, but not to the axial cracks in the pipe. An electromagnetic acoustic transducers(EMAT) was designed and fabricated for the generation and reception of the torsional guided wave. The axial cracks were detected by a torsional mode(T(0,1)) generated by the EMAT.

Keywords *: guided ultrasonic waves, Non-destructive Evaluation, Crack detection, Feeder pipe inspection*

1. Introduction

The feeder pipe in a pressurized heavy water reactor (PHWR) is exposed to a potential leakage during operation. After a leakage in the bent region, it is required to examine all the pipes in order to ensure the integrity of the pressure boundaries. However, it is not easy to inspect all the pipes with the conventional ultrasonic method, because of a high dose of radiation exposure and the limited accessibility in the region. The 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, the long range axial guided wave technique could be selected. When a specific pipe is suspected as being defective, the circumferential guided wave technique could be used for a quantitative analysis of the crack. In this paper the dispersion curves of the axial guided wave for the feeder pipe were calculated and the wave modes used for the detection of the notches were verified experimentally. The dispersion curves of the circumferential guided waves for the feeder pipe were also calculated and a methodology for the quantitative evaluation of the crack is suggested.

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2. Dipsersion characteristics of guided ultrasonic waves

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[1)-12)] and can be implemented to a long range examination of the feeder pipe. However, because an infinite number of the modes are theoretically possible and the dispersion characteristics of the guided wave, where the propagation velocity of the modes are changed with the frequency and thickness, the dispersion relationship for the specific dimension of a feeder pipe should be determined and the inspection parameters should be optimized.

Based on the mathematical formulations,[1)-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, as shown in Fig. 1. The modes and frequencies can be optimized from the group velocity dispersion curves. The incident angle of the ultrasonic transducer can be determined from the phase

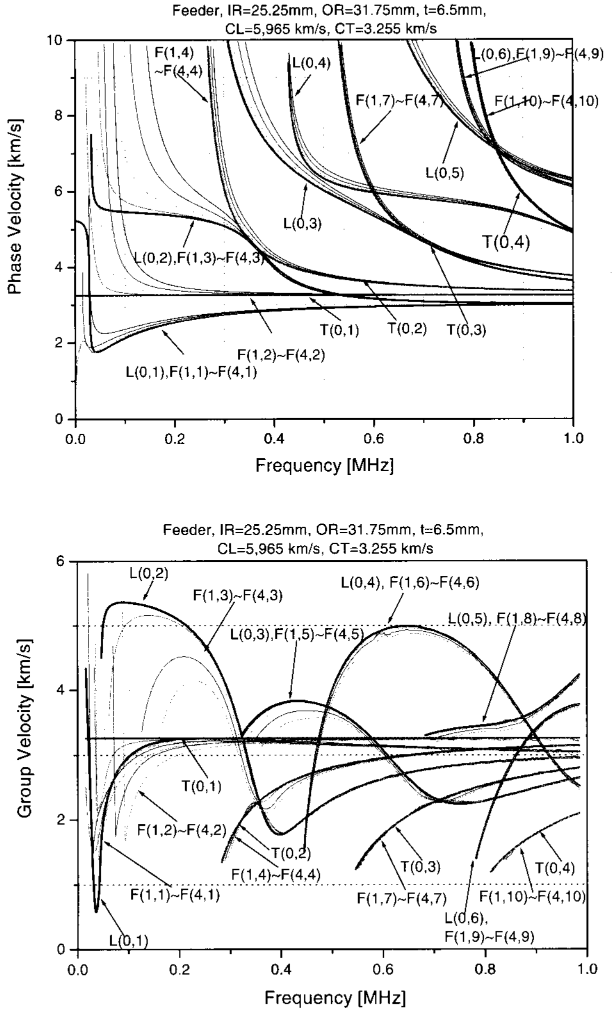
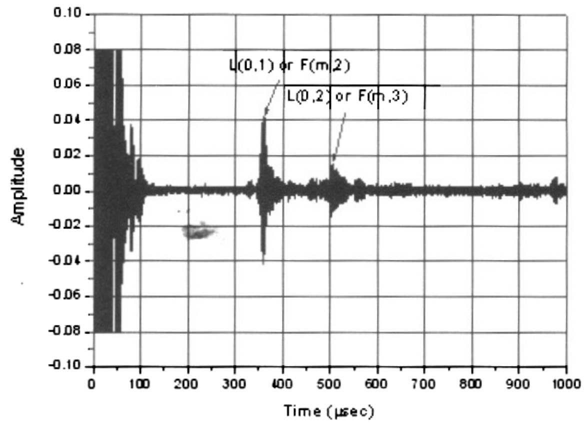
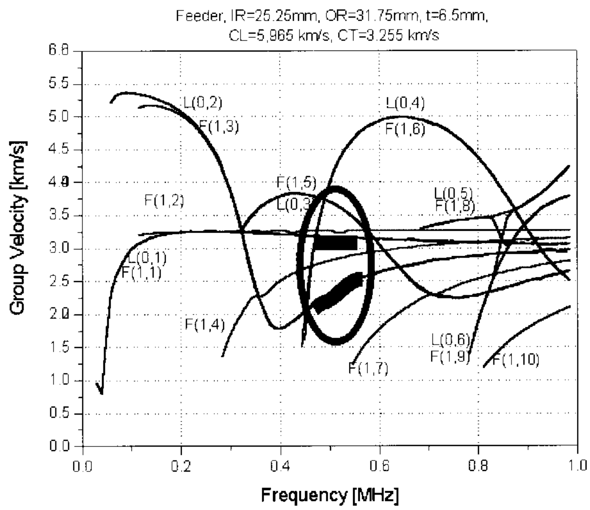


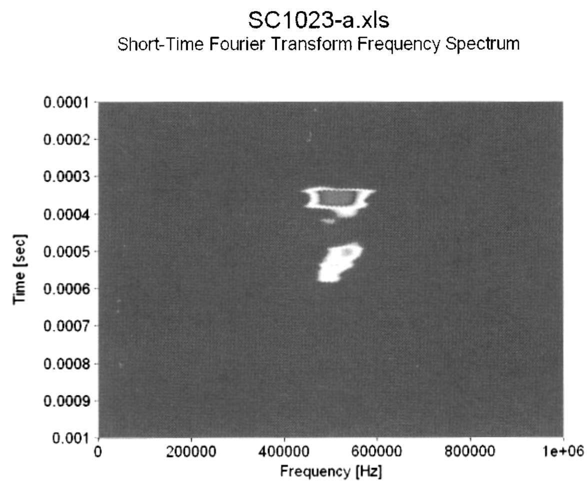
Fig. 1. Dispersion curves of the phase velocity and group velocity for a feeder pipe.



(a) Signal received from the end of a feeder pipe (f = 500 kHz, metal path = 0.5m).



(b) Dispersion curves of the group velocity.



(c) Result of the STFT frequency spectrum.

Fig. 2. Comparison of the group velocity dispersion curve and the result of the STFT frequency spectrum from the signal received at the end of the feeder pipe.

velocity dispersion curves. The longitudinal modes, L(0,n) and the flexural modes, F(m,n) are almost super-imposed except in the lower frequency range, such as in the cases of L(0,1) and F(m,2) (m, n=1, 2, 3,⋯) etc. The longitudinal modes can be generated by an axisymmetrical alignment of the transducers, and the flexural modes by a non-axisymmetrical alignment.

3. Implementation of longitudinal / flexural guided wave modes

A high power pulser (Ritec RAM 10000) was used for the generation of an ultrasound and the time domain signals were displayed on a digital oscilloscope with a sampling frequency of 1 GHz. In order to verify the wave modes, the short time Fourier Transformation (STFT) was performed for the signal from the end of the pipe, as shown in Fig. 2. After comparison of the signal processed with

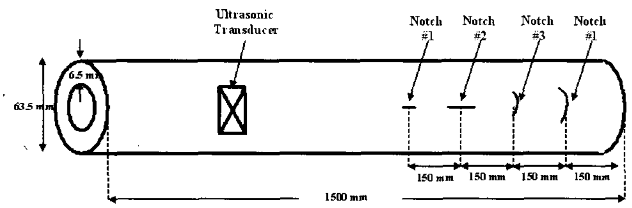
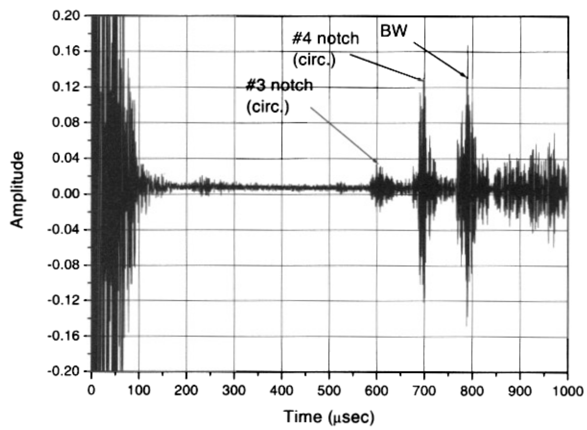
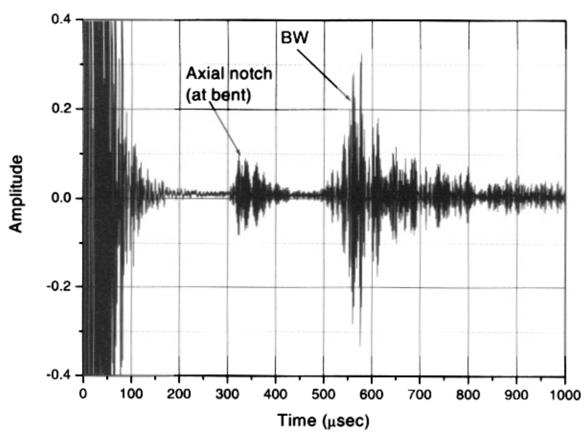


Fig. 3. Configuration of the artificial notches in a feeder pipe.



(a) Guided wave signal from a straight pipe with 4 notches (f= 500 kHz, F(m,2) mode)



(b) Guided wave signal from a bent pipe with a notch (f=500kHz, F(m,2) mode)

Fig. 4. Axial guided wave signals from the artificial notches of the feeder pipes.

Table 1. Dimensions of artificial notches on bent feeder pipe

Notch	Length (mm)	Depth (mm)	Width (mm)
#1 (axial)	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	3.25 (50%t)	0.15

the STFT and the group velocity dispersion curves, it was verified that the L(0,1) and/or F(m,2) and L(0,2) and/or F(m,3) modes had been generated in the experimental condition. Because the velocities of the F(m,2) and/or L(0,1) modes are faster than the F(m,2) and/or L(0,2) modes at the frequency of 500 kHz, the F(m,1) and/or L(0,1) modes might be better for the detection of the flaws.

Four artificial notches were fabricated on the straight feeder pipe with a diameter of 63.5 mm and wall thickness of 6.5 mm, as shown in Fig. 3 and the notch dimensions are in Table 1. Fig. 4 shows an acquired guided wave signal from the artificial notches on the feeder pipe. Because the axial guided wave propagates along the axial direction, we can expect a reflection from the circumferential notches, but hardly anything from the axial notches. Fig. 4(a) shows the signals from the pipe end (BW), notch #3 and #4 (circumferential notches), but not the signals from notch #1 and #2 (axial notches). On the other hand, a signal from the axial notch in the bent region is as shown in Fig. 4(b).

The flexural modes existing in the straight pipe can be split into two different modes, so called the symmetric and anti-symmetric modes.[13] Certain deviations of the wall thickness and the degrees of ellipticity in the bent region as well as the curved shape may affect the mode separation. The detailed dispersion relationship for our bent specimen is not available at this moment in time. However, we could expect a little deviation from the dispersion curves for the straight pipe[13] and certain flexural modes with a stress along the circumferential direction which might have a sensitivity to the axial flaws in the bent region. It has been reported that the time delay tuning technique of a flexural mode increases its sensitivity to detect discontinuity in the elbow region.[14]

4. Implementation of the torsional guided waves

4.1 Design and fabrication of EMAT for the torsional guided waves

Although the torsional modes propagated along the axial direction, their displacement is along the circumferential direction. These characteristics make the torsional modes sensitive to the axial flaws. In addition, an advantage of the torsional modes in the pipe is the characteristic of a constant acoustic velocity with a variation of frequency, i.e. no dispersion, similar to the shear horizontal(SH) mode in the plate.

However, it is not easy to generate the low frequency torsional guided wave propagation along the axis of the pipe with the conventional piezoelectric transducers. A possible solution is to use the torsional guided wave excited by electromagnetic acoustic transducers(EMATs). A wave source is directly established on the metal surface without an intimate contact. Such an ultrasound can propagate axially over a long distance and bring the pertinent information back to the receiving sensor. This is feasible because of the reduced propagation loss and high transduction efficiency. Also the non-contact nature of EMAT is the key to establishing a robust implementation, accommodating unfavorable surface conditions. A number of EMAT techniques have been investigated and tested for on-site applications.[15),16)] By applying an alternating current to a meander shaped coil with a bias of the permanent magnet induces an eddy current at the specimen surface. The alternating eddy current produces the so called Lorentz force, generating an ultrasound. If the specimen is a ferromagnetic material, a magnetostrictive force can be another source of ultrasound.

We designed an EMAT for the generation and reception of torsional guided waves in a pipe. Fig. 5 shows a schematic design of an array of EMATs for the generation and reception of the torsional guided wave in the feeder pipe. Four elements of EMAT are used for a transmitter and a separate EMAT is used for a receiver. The EMATs were designed for the particle displacement along the circumference and the propagation along the axis of the pipe. Because the feeder pipe is a ferromagnetic material, a major displacement might be due to the magnetostriction. The vibration parallel to the surface of the pipe acts as a torsional mode or SH(shear horizontal) mode and propagates along the axis of the pipe.[17)]

A tone-burst pulse with the frequency of 200 kHz is used for the generation of the torsional guided wave, T(0,1) mode. It should be emphasized that the impedance of the EMAT coil and the instrument be matched very carefully in order to maximize the efficiency of the transmission and the reception of the ultrasound.

4.2 Exiperimental

The feeder pipe of the PHWR was made of ASTM A106 Grade B (Seamless carbon steel pipe for high temperature service). The feeder pipe specimen was deformed twice by a cold bent process, same as in the PHWR plants. Several notches with the dimensions shown in Table 1 were fabricated by the electro-discharge maching(EDM) process. Fig. 6 shows a configuration of the EMATs in the bent feeder pipe.

In Fig. 7, it can be shown that the axial notches can be resolved clearly. We tried to establish a correlation between the signal amplitude and the notch depth, but it was not successful at this moment. More experiments and investigations are necessary to identify the reason.

The torsional guided wave technique based on the EMAT is believed to be the most feasible method for the feeder pipe inspection considering the inspection environment. It can be implemented to a field inspection after a performance demonstration or verification test and the approval of a written procedure.

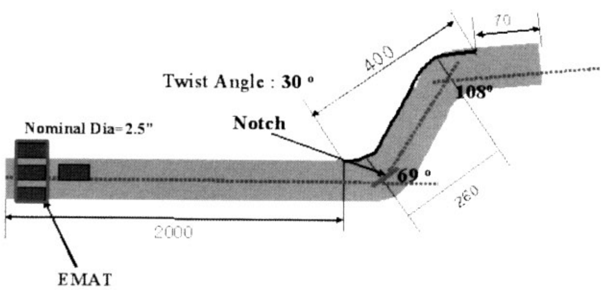


Fig. 6. Configuration of the guided wave inspection of the artificial notches in the Feeder pipe.

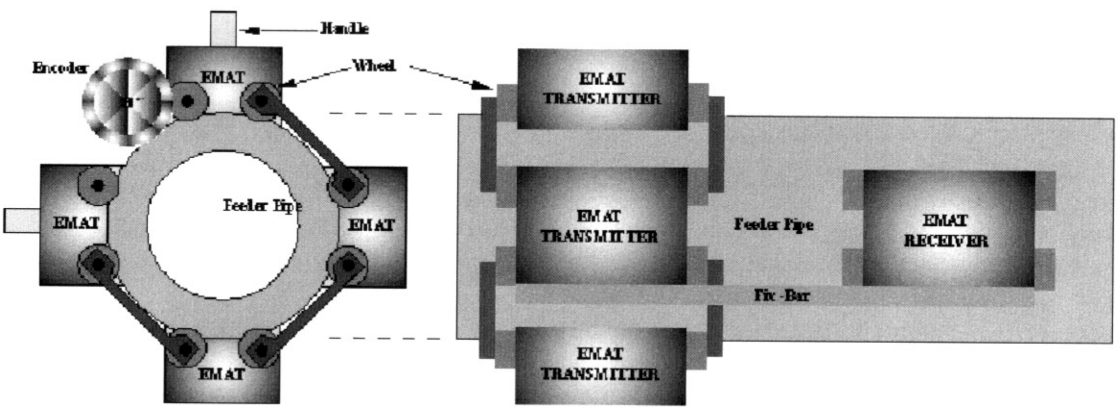
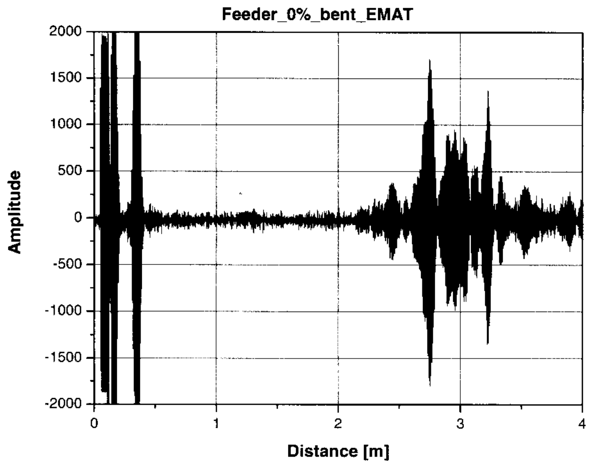
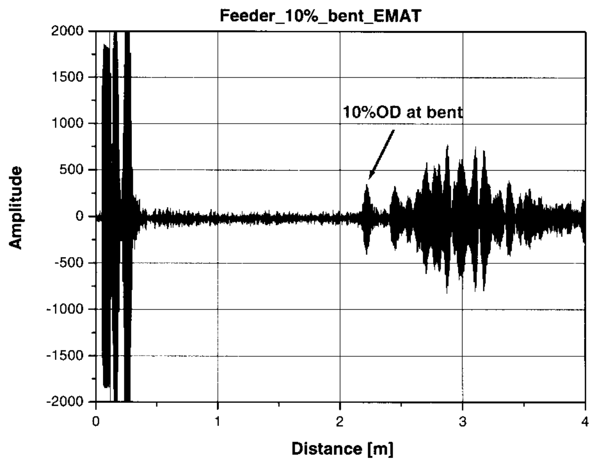


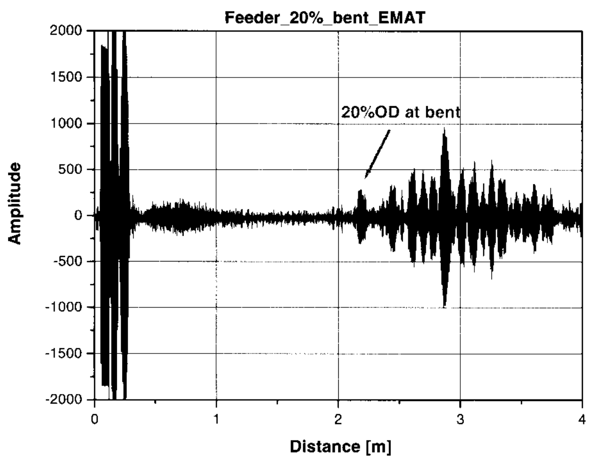
Fig. 5. An array of EMATs for the generation and reception of the torsional guided wave.



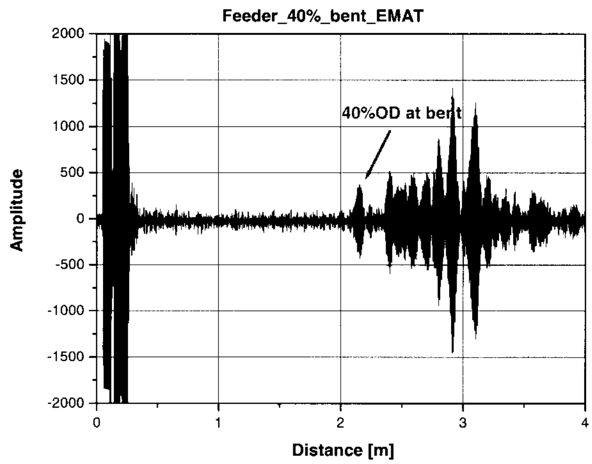
(a) Signal from a bent pipe with no defect.



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



(c) Signal from a notch of 20% of the wall thickness of the bent pipe.



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

Fig. 7. Torsional mode guided wave signals from the axial notches of the bent pipe.

5. Conclusions

(1) A long-range guided wave method for the inspection of a feeder pipe in PHWR nuclear plants has been developed. A computer program to calculate the dispersion curves in the pipe was developed and the dispersion curves for the feeder were determined.

(2) Several longitudinal and/or flexural modes were selected from the review of the dispersion curves and an actual experiment was carried out with a specific alignment of the piezoelectric ultrasonic transducers. They were confirmed as longitudinal(L(0,1)) and/or flexural modes (F(m,2)) by the short time Fourier transformation(STFT) and were sensitive to the circumferential cracks, but not to the axial cracks in the pipe.

(3) An array of electromagnetic acoustic transducers (EMATs) was designed and fabricated for the generation and the reception of the torsional guided wave. The axial cracks were detected by a torsional mode(T(0,1)) generated by the EMAT. It seems there is no correlation between the signal amplitude and the notch depth at this moment.

(4) The torsional guided wave technique based on the EMAT is believed to be the most feasible method for the feeder pipe inspection considering the inspection environment. It can be implemented to a field inspection after a performance demonstration or verification test and the approval of a written procedure.

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