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Pipe Wall Thinning Evaluation through the Arrival Time Delay of A0 Lamb Wave Using Magnetostrictive Patch Transducers

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Abstract Guided wave technology is advantageous for fast inspection of pipe wall thinning since the guided wave propagates long distance. In this investigation, the method to evaluate gradual wall thinning in a pipe based on the arrival time delay with magnetostrictive patch transducers is presented. Low frequency A0 Lamb waves were generated and measured by the present transducer and it was applied to arrival time delay measurement experiments on a test pipe having gradual wall thinnings artificially manufactured. From experiments, consistent results that wall thinning increases the arrival time delay of A0 waves were obtained. Consequently, the feasibility of the magnetostrictive patch transducers to evaluate wall thinning was verified.

Keywords: Arrival Time Delay, A0 Mode, Lamb Wave, Magnetostrictive Patch Transducer, Pipe Wall Thinning

1. Introduction

Wall thinning of a pipe is obviously one of serious problems in structural safety of a nuclear power plant (NPP). Wall thinning mostly caused by flow accelerated corrosion (FAC) may lead to a severe accident so the detection and monitoring of wall thinning is an important issue in nondestructive evaluation and structural health monitoring of NPP (Dooley and Chexal, 2000). At present, conventional ultrasonic test to evaluate pipe thickness through measuring direct echo from back wall has been applied for wall thinning inspection. However, this method is very time and cost consuming since thickness should be measured at a lot of point and insulating materials should be removed at entire inspection region. As for pipes in NPP, inspection efficiency is a significant factor since the total length of pipes in NPP usually amounts to several hundred kilometers.

Among various NDE techniques, much attention has recently been paid to the guided wave based one for wall thinning inspection (Tuzzeo et. al., 2001; Murfin and Dewhurst, 2002; Park et. al., 2005). Since guided wave can propagates up to tens or hundreds of meters along a pipe, onetime inspection covers so large range even without moving transducers. Therefore, it can be said that the guided wave technique is advantageous for fast inspection and online monitoring due to its long range propagation features.

When a propagating guided wave meets a wall thinning, various phenomena occur simultaneously such as reflection, transmission, scattering, mode conversion, and so on. To measure and analyze the reflected wave from wall

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thinning boundary is a most simple and basic method for the detection of wall thinning. However, the reflection is often not enough to detect and it happens at multiple positions at wall thinning part since the typical shape of wall thinning by FAC is usually wide and irregular. The arrival time delay of guided waves could be an alternative. When the guided wave propagates through wall thinning part, the wave speed changes since the group velocity depends on the thickness of waveguide. So the wall thinning can be evaluated based on the arrival time delay of guided wave through wall thinning part (Tuzzeo et. al., 2001; Park et. al., 2005). This may be better choice for wide and gradual wall thinning though depending on the shape of wall thinning.

The proper selection of the guided wave mode and transducer is very critical for the wall thinning inspection based on the arrival time delay of guided wave since wave modes should clearly be identified in the measured signal. In this investigation, the fundamental antisymmetric mode of Lamb waves (A0) is concerned. Specifically, A0 mode at low frequency range below the cutoff frequency of the A1 mode is considered. In this frequency range, the A0 wave could easily be identified since there exist only two kinds of Lamb wave mode, A0 and S0 waves and their group velocities is quite different from each other. Moreover, A0 is very dispersive whereas S0 is almost nondispersive at very low frequency region.

To generate and measure the A0 mode at the given frequency range, magnetostrictive patch transducers (Cho et. al., 2006) are employed. This transducer can efficiently generate and measure the Lamb waves below 150 kHz at thin plate like structures (Cho et. al., 2006). Also, it has simple structure and, in principle, can be applied at high temperature. Therefore, the measurement of arrival time delay of A0 wave using the magnetostrictive patch transducer may be an effective method for long range inspection or monitoring of pipe wall thinning in NPP.

In this work, the wall thinning inspection experiments were conducted at a test pipe made of steel. Gradual and large wall thinning which was artificially manufactured in a pipe was concerned. The arrival time delay of A0 wave was measured at several frequencies. Experimental results show that the arrival of A0 wave delays more at propagating along more thinned area, which corresponds with the estimation. Consequently, the feasibility of the present methods for the inspection of pipe wall thinning in NPP was successfully verified.

2. Arrival Time Delay of A0 Wave by Gradual Wall Thinning

A pipe can be regarded as a plate ignoring circumferential curvature when the diameter to thickness ratio is relatively large. There are only two kinds of guided waves in a plate; Lamb and SH waves. Except the fundamental mode of SH waves (SH0), all the guided waves in a plate are dispersive, that is, the wave propagation speed changes depending on the variation of frequency and plate thickness (Rose, 1999). The wall thinning of a plate leads to the change in the arrival time of the guided wave at a given frequency. Therefore, in principle, the thickness variation by wall thinning can be evaluated through the measurement of the arrival time delay. For better sensitivity to wall thinning, most of all, it is important to determine the wave mode and frequency in which wave speed changes considerably.

Fig. 1 shows the group velocity dispersion

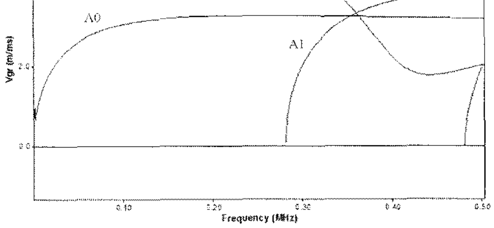

Fig. 1 Group velocity dispersion curve of Lamb waves in a steel plate of 5.8 mm thickness

relation of Lamb waves. With respect to 5.8 mm thick steel plate, the cutoff frequency of the A1 wave is about 280 kHz. Below the cutoff frequency of the A1 wave, only S0 and A0 waves exist. In the present method, the A0 wave below 150 kHz is concerned to measure the time delay of arrival since the group velocity of the A0 wave changes very steeply. In that frequency range, the A0 wave can be easily distinguished from the other wave mode S0 in the measured signal since the S0 wave is far faster and almost nondispersive. Over the cutoff frequency of the A1 wave, more wave modes newly appear and dispersion relation becomes tangled, so mode identification is more difficult. Therefore, the A0 mode at low frequency is most desirable for the present method.

The present method is valid under the assumption that there is no mode conversion at wall thinning area between A0 and S0 waves. If mode conversion occurs between A0 and S0 waves, it is not easy to infer the tendency of the time delay of arrival. Fortunately, it can be assumed that mode conversion hardly occurs since thickness variation is considered to be very gradual (Cho, 2000).

Consequently, it can be obviously estimated that the A0 wave propagates slower as the thickness of the plate is thinner. In addition, the extent of the wave velocity change is larger at a lower frequency.

3. Magnetostrictive Patch Transducers for A0 Wave

To generate and measure A0 waves at a low frequency range, magnetostrictive patch transducers were employed. The magnetostriction refers to the coupling phenomenon between the magnetic field and mechanical deformation. Various types of the magnetostrictive patch transducers have been developed for guided wave measurement (Kwun et. al., 2002; Kim et. al., 2005; Cho et. al., 2006; Cho et. al., 2007). A Lamb wave transducer using a circular magnetostrictive patch was also reported (Cho et. al., 2006). Concerning the permanent installation to pipes in NPP, the magnetostrictive transducer bears many advantages. Most of all, it can be applied in higher temperature zone compared with the conventional piezoelectric transducer since the Curie temperature of ferromagnetic material is usually higher. Additionally, the transducer is more durable and cost-effective.

The employed transducer is composed of a rectangular ferromagnetic patch bonded on a waveguide, a coil, a couple of bias magnet, and a plastic bobbin as illustrated in Fig. 2. The ferromagnetic rectangular patch is tightly bonded to the surface of the pipe with epoxy resin. The size of the patch is 35 mm by 25 mm and its thickness is 0.2 mm. Iron cobalt alloy sheet which bears strong magnetostriction was used as a patch. A couple of neodymium magnets (10 mm by 5 mm by 3 mm) apply bias magnetic field along the patch. The interval between the magnets is 25 mm. Figure-of-eight coil (20 turns) plays a role in exciting and measuring dynamic magnetic field. The bobbin holds the coil and magnets.

It should be noted that the direction of the static bias magnetic field is identical with that of the dynamic magnetic field for Lamb wave. The patch experiences normal deformation in magnetic field direction when the static and dynamic magnetic field is parallel with each other.

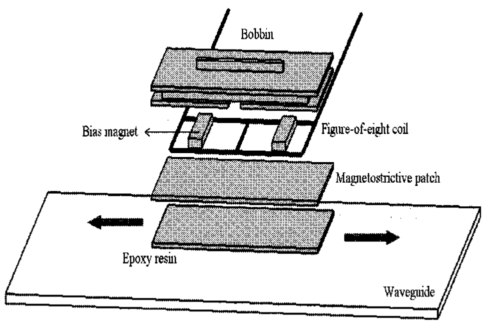

Fig. 2 A schematic diagram of the magnetostrictive patch transducer for Lamb waves

4. Measurement of Arrival Time Delay of A0 Waves

Lamb wave pitch-catch experiments were conducted to measure the arrival time delay by a gradual wall thinning. As shown in Fig. 3, two magnetostrictive patch transducers were installed as a transmitting and receiving transducer respectively. As an excitation pulse, three cycled sinusoidal burst signal generated by the function generator (33250A, Agilent Technologies) was used. The excitation signal was amplified at the power amplifier (AG1017L, T&C Power Conversion Inc.) and transferred to the transmitter. The receiver measured the waves passing through a wall thinning area. The excitation frequencies were 50 kHz, 75 kHz, 100 kHz, and 125 kHz, which were determined to be the dispersive region of A0 wave. Even though the A0 wave is more dispersive far below 50 kHz, the A0 wave cannot be generated very well due to amplifier and transducer operational bandwidth.

A steel pipe was prepared as a test specimen and gradual wall thinnings were artificially manufactured on the outside surface of the pipe. Fig. 4 shows the photograph of the test pipe and the installed transducers. The wall thinnings have parabolically shaped cross section as described in Fig. 5. The distance between the transmitter and the receiver is 600 mm and the length of the thinning is 300 mm. The maximum depth of the

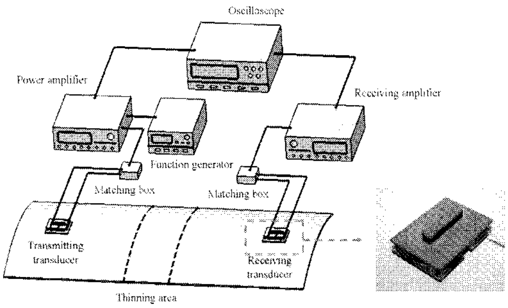

Fig. 3 Experimental setup for Lamb wave pitch-catch experiments in a test specimen

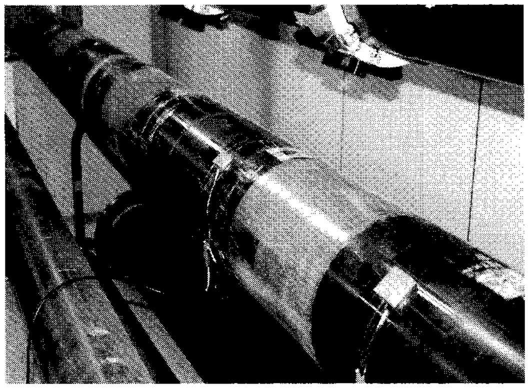

Fig. 4 Photograph of a test pipe with artificial wall thinnings and magnetostrictive patch transducers

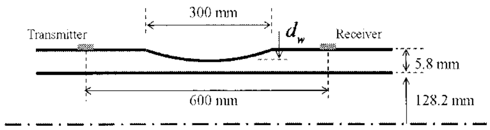

Fig. 5 Configuration of an artificial wall thinning and location of transducer installation

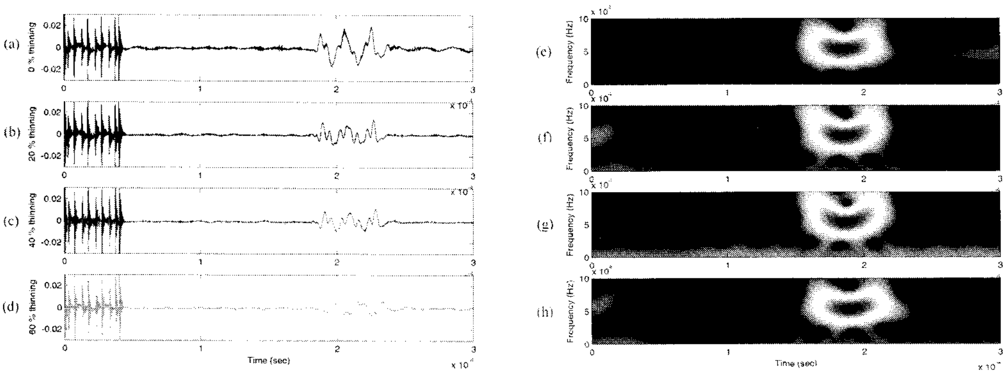

Fig. 6 The measured signals in time domain when three cycle burst sinusoidal pulse was excited at 50 kHz through healthy area (a), and 20% (b), 40% (c), 60% thinning part (d). Their spectrograms through healthy area (e), and 20% (f), 40% (g), 60% thinning part (h)

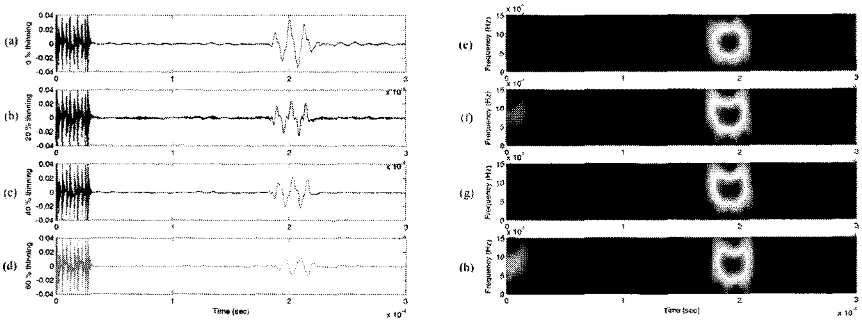

Fig. 7 The measured signals in time domain when three cycle burst sinusoidal pulse was excited at 75 kHz through healthy area (a), and 20% (b), 40% (c), 60% thinning part (d). Their spectrograms through healthy area (e), and 20% (f), 40% (g), 60% thinning part (h)

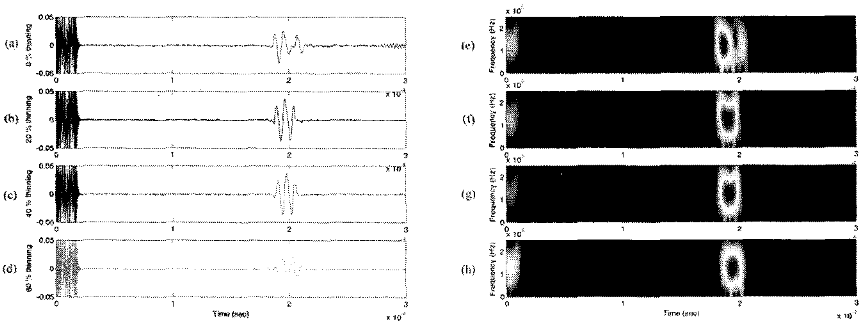

Fig. 8 The measured signals in time domain when three cycle burst sinusoidal pulse was excited at 100 Hz through healthy area (a), and 20% (b), 40% (c), 60% thinning part (d). Their spectrograms through healthy area (e), and 20% (f), 40% (g), 60% thinning part (h)

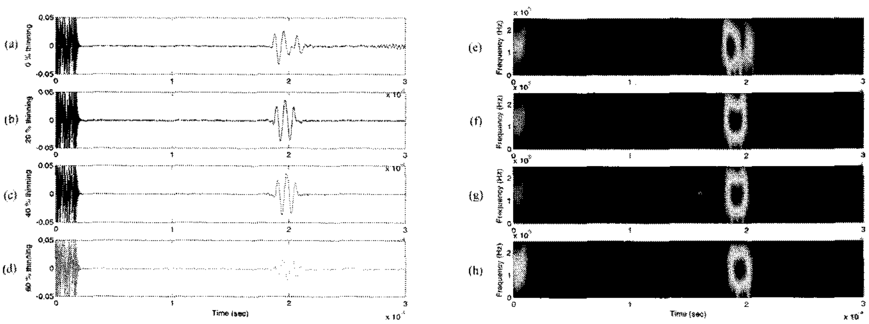

Fig. 9 The measured signals in time domain when three cycle burst sinusoidal pulse was excited at 125 Hz through healthy area (a), and 20% (b), 40% (c), 60% thinning part (d). Their spectrograms through healthy area (e), and 20% (f), 40% (g), 60% thinning part (h)

Table 1. The arrival time of the first positive peak of the A0 waves measured in time domain signals

	50 kHz excitation	75 kHz excitation	100 kHz excitation	125 kHz excitation
0% thinning	1.885×10^{-4} s	1.883×10^{-4} s	1.881×10^{-4} s	1.880×10^{-4} s
20% thinning	1.900×10^{-4} s	1.895×10^{-4} s	1.893×10^{-4} s	1.893×10^{-4} s
40% thinning	1.911×10^{-4} s	1.907×10^{-4} s	1.912×10^{-4} s	1.903×10^{-4} s
60% thinning	2.000×10^{-4} s	1.968×10^{-4} s	1.958×10^{-4} s	1.950×10^{-4} s

wall thinnings d_w are 1.2 mm, 2.3 mm, and 3.5 mm with respect to 20%, 40%, and 60% thinning. The artificial wall thinning shows very gradual variation of thickness even in the most severe case, 60% thinning.

The measured signals are shown in Figs. 6-9 at each excitation frequency. Based on the wave speed, the measured pulse at about 0.2×10^{-3} s is the direct arrived A0 wave from the transmitter. With the present test specimen and transducers, S0 waves were almost not observed. The higher is the excitation frequency, the shorter is the time support of the measured A0 waves. In cases of 50 kHz excitation, the measured A0 waves look quite distorted from the excitation pulse shape due to the higher harmonic components.

To measure the arrival time delay, the time of the first positive peak was acquired as listed in Table 1 at each case. The result shown in Fig. 10 shows that the arrival time delay increases at more severe thinning and at lower excitation frequency. This confirms that the wall thinning can be estimated through the measurement of the arrival time delay of A0 wave. However, though the tendency of the arrival time delay by the extent of the wall thinning is consistent at each frequency, it has very little value, e. g., merely 0.2% delay for 20% thinning at 50 kHz excitation.

Another method to measure the arrival time is to use a spectrogram. The spectrograms of each measured time domain signal are shown in Figs. 6-9. For the time frequency analysis, the short time Fourier transform using the MATLAB function 'specgram' was implemented. Spectrogram expresses conveniently the center time and frequency of the arrived A0 wave. The arrival times of maximal magnitude point in spectrograms are listed in Table 2. The result shown in Fig. 11 also shows similar tendency with the results in Fig. 10.

As far as the excitation frequency is concerned, the most appropriate frequency cannot be decided. At lower frequency, the arrival time delay by wall thinning is bigger whereas the time

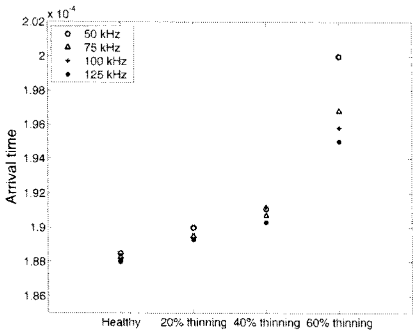

Fig. 10 The arrival time of the first positive peak of the A0 waves measured in time domain signals

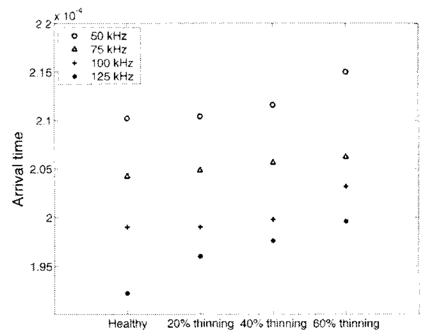

Fig. 11 The arrival time of the maximum magnitude point of the A0 waves measured in spectrograms

Table 2. The arrival time of the maximum magnitude point of the A0 waves measured in spectrograms

	50 kHz excitation	75 kHz excitation	100 kHz excitation	125 kHz excitation
0% thinning	2.102×10^{-4} s	2.042×10^{-4} s	1.990×10^{-4} s	1.922×10^{-4} s
20% thinning	2.104×10^{-4} s	2.048×10^{-4} s	1.990×10^{-4} s	1.960×10^{-4} s
40% thinning	2.116×10^{-4} s	2.056×10^{-4} s	1.998×10^{-4} s	1.976×10^{-4} s
60% thinning	2.150×10^{-4} s	2.062×10^{-4} s	2.032×10^{-4} s	1.996×10^{-4} s

support is large. Also, the performance of the transducer is not reliable that it distorts the excited signal at low frequency. At higher frequency, there exists a limitation that the arrival time delay by wall thinning is small to distinguish.

5. Conclusions

Wall thinning evaluation method using magnetostrictive patch transducers is presented. The arrival time delay of A0 Lamb waves is measured to estimate the change of the wave velocity. The A0 waves between 50 kHz and 125 kHz were generated and measured by the magnetostrictive patch transducer comprising an iron-cobalt alloy patch, a figure-of-eight coil, and magnets. The arrival time delay measurement experiments were conducted on the test steel pipe having artificially manufactured gradual wall thinnings. The arrival time was measured in a time domain signal or a spectrogram. From the experimental results, some conclusions were obtained as

1) The present magnetostrictive patch transducer measures well A0 waves without S0 waves.
2) The gradual wall thinning decreases the velocity of the A0 waves.
3) The arrival time delay is bigger at lower frequency.

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