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AN ON-LINE MONITORING TECHNIQUE FOR A PIPE THINNING

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Abstract

A new novel technique for the pipe thinning is introduced, which is one of the major issues regarding the structural fracture of pipes in nuclear power plant. The method is to inspect a large area of a piping system at a time on an on-line basis monitoring. The basic idea came from the fact that the group velocity of an impact wave is dependent on a wall thickness of the piping. That is, if the group velocity is measured, the wall thickness can easily be estimated. To obtain a group velocity, a time-frequency analysis is utilized. This is because an arrival time difference between the flexural waves can be measured easier in time-frequency domain than a time domain. To test the performance of this technique, experiments have been performed for a plate and elbow type pipe. Results show that the proposed technique is effective for monitoring the pipe thinning at an early stage.

1. INTRODUCTION

There are various kinds of piping system in the secondary cooling systems of nuclear power plants and coal-fired power plants. In these systems, high pressure and high temperature fluids are moving at a high speed, and this can cause a pipe thinning through a flow accelerated corrosion (FAC).

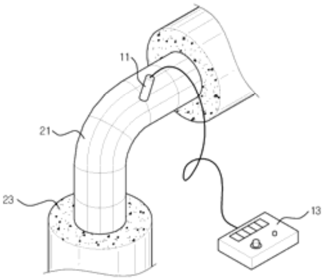
In 2004, it was reported that because of a pipe thinning, there was a coolant leakage in the Mihama nuclear power plant in Japan, and several individuals were killed. As we can see in this case, a pipe thinning in a power plant not only cause financial and time losses, but it also takes people’s lives. So it is very important to monitor and supervise the pipe thinning.

As of now, the most widely used monitoring method uses ultrasonic waves to estimate the thickness of a pipe wall. This method measures the thickness of dozens of check points in pipes by an ultrasonic-type sensor one by one, and it estimates the degree of a pipe thinning. So, as the number of check points in pipes increases, it requires more and more time and manpower to install the sensors. Furthermore, if the pipes are surrounded by insulation materials, it has to be removed before the sensor is installed, and this causes additional expenses. Also in the case where the number of pipes for a monitoring is too high, it is impossible to judge the degree of a pipe thinning quickly, so this method's applicability falters.[1]

In this paper, we suggest a new method for monitoring a pipe thinning which gets over the shortcomings of the existing method. It uses two vibration sensors which can be installed easily on the outside of pipes so as to calculate the energy transmission velocity a of impact, and estimates the thickness of a pipe wall more quickly and accurately.

2. THEORETICAL BACKGROUND

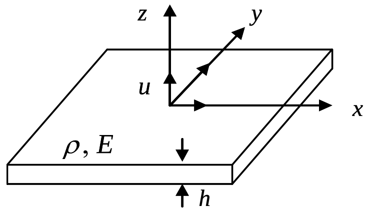
A flexural wave traveling along pipes proceeds with a difference group velocity which correlates to the thickness of a pipe wall. Conversely, if the group velocity is known, it is possible to estimate the thickness of a pipe wall. In this chapter, we discuss the relationship between a group velocity and the thickness of a pipe wall in the case of a plate model. And we propose a method that measures a group velocity and estimates the thickness of a pipe wall.



- **Figure 1** Conventional method for measuring a pipe thinning by using an ultra sonic wave, where 11 is an ultra sonic sensor, 21 is a pipe, 13 is a data acquisition system, and 23 is an insulation material.

2.1 Group velocity in a plate type structure

As is shown in Figure 2, a surface wave traveling on a plate which consists of the same material and has a uniform thickness in the elastic domain is called a Lamb wave[2]. Lamb wave is divided into two wave groups each of which has different properties. One is the S wave which is a symmetric mode, and the other is the wave which is an asymmetric mode. 0th order S wave mode is called the S0 wave, which is also called the quasi-longitudinal wave. And the 0th order A wave is called the A0 wave, which is also known as the flexural wave. These quasi-longitudinal waves and flexural waves have the lowest frequencies among the S and A waves, so it is possible to detect them with a normal vibration accelerometer.



- **Figure 2** Plate model, where x,y,and z are coordinates, u is a displacement in z direction, h is a thickness, ρ is a density, and E is the

Young's modulus.

The traveling velocity of the Lamb wave correlates with what kind of material the rigid body consists of, how thick it is, and what the frequency of the wave is, and it can be calculated analytically by the Rayleigh-Lamb equation. The traveling velocity of the A0 wave is given by

$$\frac{\tan(\sqrt{1-\varsigma^2}\cdot kh)}{\tan(\sqrt{\xi^2-\varsigma^2}\cdot kh)} = -\frac{(2\varsigma^2-1)^2}{4\varsigma^2\sqrt{1-\varsigma^2}\sqrt{\xi^2-\varsigma^2}} \qquad (1)$$

$$\varsigma \equiv \frac{C_t}{C_{ph}}, \quad \xi \equiv \frac{C_t}{C_l}$$

where $C_l \equiv \sqrt{\frac{E}{\rho}\times\frac{1-\nu}{(1+\nu)(1-2\nu)}},\ C_t \equiv \sqrt{\frac{G}{\rho}}$

A complete solution of equation (1) is hard to obtain, but a wave traveling velocity according to a frequency can be obtained by a numerical analysis. Ross(1997)[5] suggested a very simple solution which approximates the analytical results above:

$$C_{ph} = C_L' \cdot \sqrt{\frac{1.8\cdot h\cdot f}{C_L' + 4.5\cdot h\cdot f}} \qquad (2)$$

where

$$C_L' = \sqrt{\frac{E}{\rho(1-\nu^2)}} \qquad (3)$$

In the case that two or more components of a flexural wave travel simultaneously because of an impact, a combination of flexural waves gives rise to an envelope distribution. The traveling velocity of this envelope is called a group velocity, i.e. traveling velocity of an wave energy[3]. The definition of a group velocity is given by

$$C_g \equiv \frac{d\omega}{dk} = d\omega\left[d\left(\frac{\omega}{C_{ph}}\right)\right]^{-1} = C_{ph}{}^2\cdot\left[C_{ph} - \omega\cdot\frac{dC_{ph}}{d(\omega)}\right]^{-1} \qquad (4)$$

A complete solution of a group velocity can be obtained by drawing a phase velocity (Cph) value from equation (1) and applying it to equation (4). Using Ross(1987)'s approximate solution, a group velocity is given from equation (2) and equation (4) as:

$$C_g = \frac{3.6\cdot hf\cdot C_L'^{\,2}}{C_{ph}\cdot(C_L' + 9hf)} \qquad (5)$$

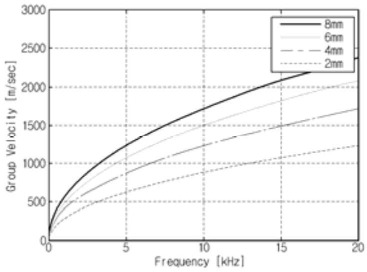
Meanwhile, if the wavelength of a flexural wave is considerably larger than the thickness of a plate, or if a frequency of the flexural wave is low (kh<1), the phase velocity and group velocity can be given simply as[3]

$$C_{ph} \cong \sqrt{\omega}\left(\frac{D}{\rho h}\right)^{\frac{1}{4}} \qquad (6)$$

$$C_g \cong 2\cdot\sqrt{\omega}\left(\frac{D}{\rho h}\right)^{\frac{1}{4}} \qquad (7)$$

Where $D = \frac{Eh^3}{12(1-\nu^2)}$

As is shown in equation (6) and equation (7), the group velocity in plates is twice as large as the phase velocity, and it increases in proportion to the square root of the frequency. When the frequency increases, the group velocity also increases, so the distribution characteristic is that the high frequency components of the wave arrive earlier and the low frequency components later. Because of this characteristic, when an acceleration signal is observed in the time domain, the shape of the wave varies widely with the distance from the source.



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- **Figure 3** Group velocities corresponding to different plate thicknesses(in case of SUS 304).

Fig. 3 shows the theoretical group velocity by using equation (7), where the material the plate is SUS304.

One important point which can be drawn from equation (5) and equation (7) is that group velocity is a function of the thickness. So, equation (7) can be rearranged with relation to a thickness as

$$h = \frac{\sqrt{3}}{2} \cdot \frac{C_g^2}{\omega} \cdot \sqrt{\frac{\rho(1-\nu^2)}{E}} \tag{8}$$

As above, if we know what kind of material the plate consists of, thickness h can be obtained by applying measured group velocity to equation (8).

2.2 A new method to measure a group velocity

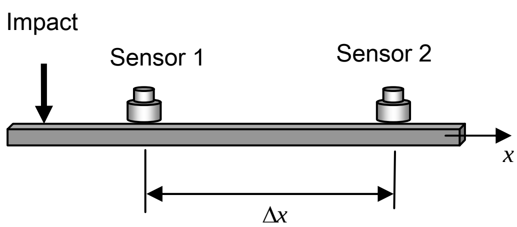


Fig. 4 The method for estimating a group velocity which can be obtained by $C_g = \frac{\Delta t}{\Delta x}$, where Δt is the arrival time difference between two sensors.

As is shown in section 2.1, in order to estimate the thickness of a plate, it is vital to measure the group velocity accurately. Figure 4 shows the method for estimating a group velocity. If we apply an impact at a certain point, the shock waves reach two sensors at a different time. With the distance between two sensors Δx and the arrival time lag Δt, the group velocity is given by

$$C_g = \frac{\Delta t}{\Delta x} \tag{9}$$

As is shown in equation (9), in order to estimate a group velocity with a minimum error, it

is necessary to measure the arrival time lag between sensors, Δt, accurately. But in plates and pipes, as is shown in equation (5) and equation (7), the distribution characteristic is that the traveling velocity of wave components differ from each other according to the frequency, so it is difficult to find the arrival time lag in the time domain.
In this paper, we apply a time-frequency analysis, one of the multi-dimensional analytical methods, in order to find an accurate arrival time lag.

2.3 Wigner-Ville Distribution

In general, there are three time-frequency analysis methods: Short Time Fourier Transform, Wavelet, and Wigner-Ville analysis[6-12]. Of the three methods, we have chosen the Wigner-Ville analysis because of its superior frequency and time resolution. Wigner-Ville distribution is a sort of bilinear TFR(time frequency representation) and defined as follows:

$$\begin{aligned} W(t,f) &\equiv \int_{-\infty}^{\infty} R(t,\tau) e^{-j2\pi f\tau} d\tau \\ &= \int_{-\infty}^{\infty} z(t-\frac{\tau}{2}) z^*(t+\frac{\tau}{2}) e^{-j2\pi f\tau} d\tau \\ &= \int Z^*(\omega+\frac{\varphi}{2}) Z(\omega-\frac{\varphi}{2}) e^{-jt\varphi} d\varphi \end{aligned} \tag{10}$$

where $R(t,\tau) = z(t-\frac{\tau}{2}) z^*(t+\frac{\tau}{2})$ is a time dependent autocorrelation function, z(t) is an analytical function of the signal, and $Z(\omega)$ is a Fourier transform of z(t). That is, the Wigner-Ville distribution is defined as a Fourier transform of a time lag of a time dependent autocorrelation function, and in physical terms, it represents the frequency distribution of the energy of a signal at each time interval.

To sum up, in this paper, we measured the group velocity by calculating the time lag between two sensors in the time-frequency domain, so as to monitor a pipe thinning.

3. EXPERIMENT

So far, we theoretically discussed the possibility of estimating the thickness of a pipe by measuring the group velocity, where we apply a time-frequency analysis in order to estimate the group velocity accurately. In this chapter, we discuss the plate experiment — the simplest case — and the U-shape pipe experiment — the main argument in this paper — which are designed to test the theoretical contents.

3.1 Plate

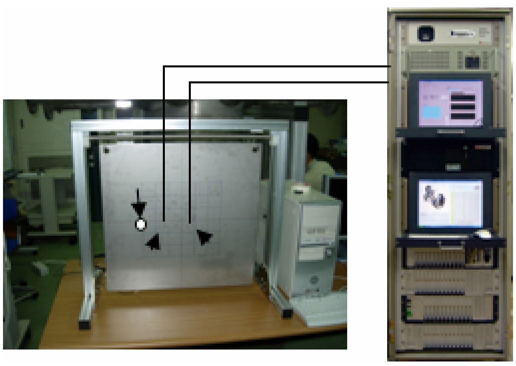
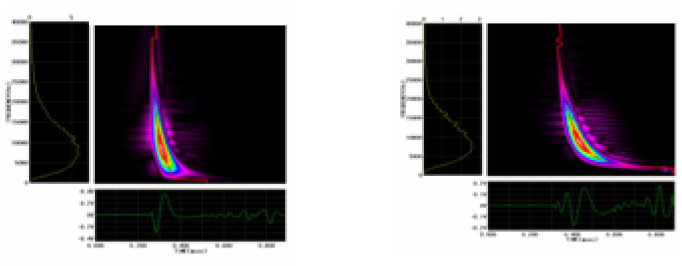


Fig. 5 Experimental setup for plate whose thickness is 2mm. Accelerometers are used for

measuring impact response (B&K type 4374).

Figure 5 shows the experimental setup for 600mm × 600mm SUS304 plate whose thickness is 2mm. The distance between the sensors is 100mm and an impact is applied to a point which is separated from sensor 1 by 100mm and which is on the extended line on which the two sensors are situated.



(a) (b)

Fig. 6 Time-Frequency analysis result for (a) Sensor 1, and (b) Sensor 2

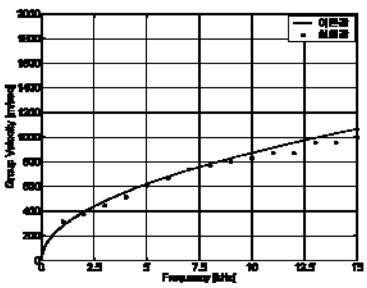


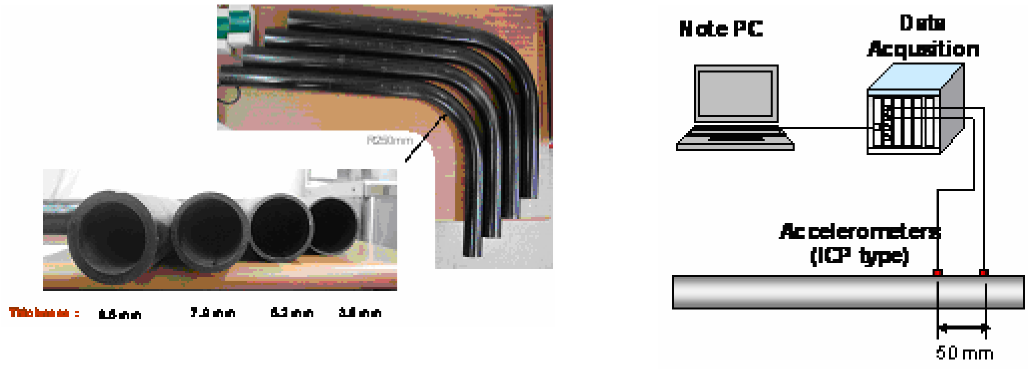
Fig.7 Estimated group velocity. Where solid line is eq. (7) and dotted line means experimental result.

Figure 6 shows the result of the time-frequency analysis for the accelerometer 1 and 2 signals. Figure of lower right represents the acceleration signal and the figure of upper right shows the result of the time-frequency analysis of the acceleration signal. And the left figure shows spectrum. As is shown in Figures 6(a) and 6(b) for the acceleration signal, even if a vibration occurs by the same impact, the shape of the signal differs according to the distance from the source. Therefore, finding the time lag in the time domain leads to a large error because it is difficult to set a reference point. But by using the time-frequency analysis proposed in this paper, we can easily find the time lag between the two sensors at each frequency, as is shown in Figure 6.

After the time-frequency analysis, we can obtain an estimate of the group velocity by inserting the time lag between the two sensors into equation (9), as is shown in Figure 6.
In Figure 7, dotted line indicates the group velocity obtained from the experiment, and the solid line shows the theoretical estimation of the group velocity from equation (7). Comparison of the two lines shows that we can estimate the thickness of a plate by measuring the group velocity.

In Figure 6, if the frequency and the corresponding group velocity are known, it is possible to estimate the thickness of a plate by inserting them into equation (8).

3.2 Elbow pipe



(a) (b)

Fig. 8 Experimental setup for the elbow pipe.

Figure 8 shows the experimental setup for the 4 elbow pipes having four different thicknesses with the same outer diameter In order to examine a pipe thinning effect. The pipes used in this experiment are actually employed in the secondary cooling system of nuclear power plants. Firstly we undertook an experiment with a 9.5mm thick pipe and on after another the same experiments were implemented with 7.0 mm, 5.2 mm, and 3.6 mm thick pipes.

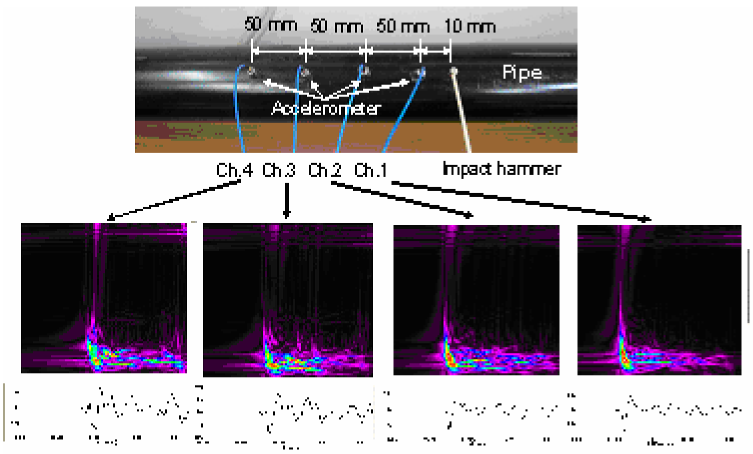


Fig. 9 Time-frequency analysis result for each sensor signal.

Figure 9 shows the result of the time-frequency analysis from the four accelerometer signals when the pipe thickness was 9.6 mm. In Figure 9, the surface waves propagate with a more complex shape than the plate experiment shown in Figure 6. It is because of the curvature effect of the elbow pipe.

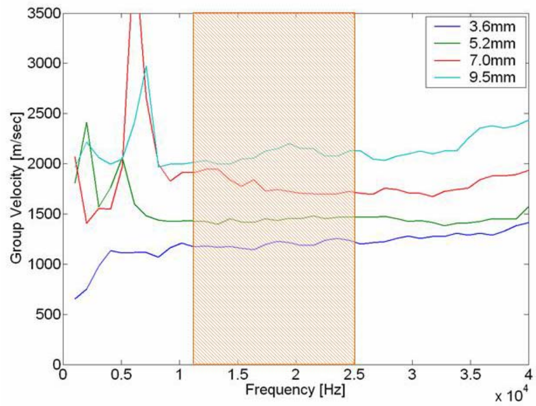


Fig. 10 Estimated group velocities when the pipe thicknesses are between 3.5 mm and 9.5mm.

Using the same method as the plate experiment, Figure 10 shows the estimated group velocity obtained by the Wigner-Ville analysis of two sensor signals when the pipe thicknesses were between 9.5 mm and 3.6 mm. It is shown in the Wigner-Ville distribution of Figure 9 that the area which reveals a good S/N ratio is from 12 kHz to 25 kHz. In this frequency area, the group velocity is approximately estimated to be around 2100m/sec for a 9.6 mm thickness, and 1100m/sec for a 3.6 mm thickness. It means that the group velocity varies according to the thickness of the pipe wall. Therefore, if we use a group velocity as a means for monitoring a pipe thickness, it is possible to analyze it easily, quickly, and accurately.

4. SUMMARY

In this paper, we proposed a method of estimating the degree of a pipe thinning. It uses a measured velocity of a flexural wave traveling along pipes. If the thickness of the wall decreases because of a pipe thinning, the flexural stiffness of the pipes decreases and accordingly, the traveling velocity of the flexural wave decreases. Thus, if we install two vibration sensors outside the pipes and measure the traveling velocity of the flexural waves regularly, we can estimate and monitor the degree of a pipe thinning quickly on an on-line basis. In order to test the proposed method, we have experimented with four different elbow pipes with four different thicknesses and found that the group velocity varies according to the degree of a pipe thinning. Accordingly, it is verified that this method can be used to monitor a pipe thinning.

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