The 8th TSME International Conference on Mechanical Engineering
12-15 December 2017
Bangkok, Thailand

AMM0010

Development of the novel non-contact AE sensor using air-coupled ultrasonic transducer for plates and cylinders

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Abstract. Contact type sensors with piezoelectric transducer (PZT) element are generally used in the acoustic emission (AE) method. However, it is difficult to utilize the contact sensor for measurement in downsized specimens with complicated shapes owing to difficulty in sensor attachment. Therefore, AE monitoring with non-contact type sensors is required. The non-contact sensor generally faces the issue of low S/N ratio due to acoustic impedance mismatch occurring in air-coupled sensors. Additionally, in our previous study, we reported that the S/N ratio further decreases depending on the shape of the material surface while performing AE measurement using the air-coupled ultrasonic sensor. In this study, air-coupled AE sensor with high sensitivity has been developed by utilizing the wavelength of elastic wave. The developed sensor is composed of arrayed air-coupled ultrasonic transducers and the length of the array was decided as per the wavelength of the AE signals. Relationship between the sensitivity of the developed AE sensor and length of the sensor was initially studied via transmission in a flat plate. The sensitivity was the highest when the array length was set to the A0-mode wavelength of the Lamb wave propagating in the plate. The cylinder specimen showed a similar tendency. Moreover, the sensitivity changed according to the angle of the sensor involving the wavelength of the sensor obtained from Snell's law. The sensitivity of the developed sensor was higher than that of a single sensor.

1. Introduction

In recent years, highly safe and accurate monitoring and inspections are required for structures such as aged industrial machinery. The acoustic emission (AE) method is one of the techniques capable of nondestructively monitoring a structure. However, conventional contact type sensor cannot be attached to a complicated shaped or small device. Therefore, we developed a system capable of measuring AE in a non-contact manner using air-coupled ultrasonic technique. We constructed a system using commercially available air-coupled ultrasonic sensors and succeeded in detecting AE during fatigue test [1]. However, the constructed system faced the problem of insufficient sensitivity as compared to the contact type sensor, and the sensitivity varied depending on the surface shape of the object to be inspected. Therefore, in this study, we study the relationship between the sensitivity, the angle of a sensor and the wavelength of elastic wave in air, and develop a sensor that can detect AE with high S/N ratio by using air-coupled ultrasonic sensor elements such that the detection efficiency improves. Moreover, based on the position and angle of the sensor element, we report the sensor shape that can be used to detect AE with high S/N ratio and investigate AE measurement results using it. In this study, a new sensor was created based on the wavelength of the Lamb wave and the sensor angle obtained from Snell's law.

2. Theoretical

2.1 Lamb wave dispersion curve

Lamb wave is a kind of elastic wave propagating through a flat plate. This wave propagates two-dimensionally in the plane and has a smaller attenuation factor compared to the wave propagating three-dimensionally, so it is widely used for non-destructive inspection. In this study, a new noncontact AE measurement system was constructed focusing on the Lamb wave. In particular, the speed dispersion of Lamb waves was focused on. In this wave, the group velocity is dispersed according to the frequency. figure 1 shows the group velocity dispersion of Lamb waves propagating on an aluminum plate with a thickness of 5 mm.

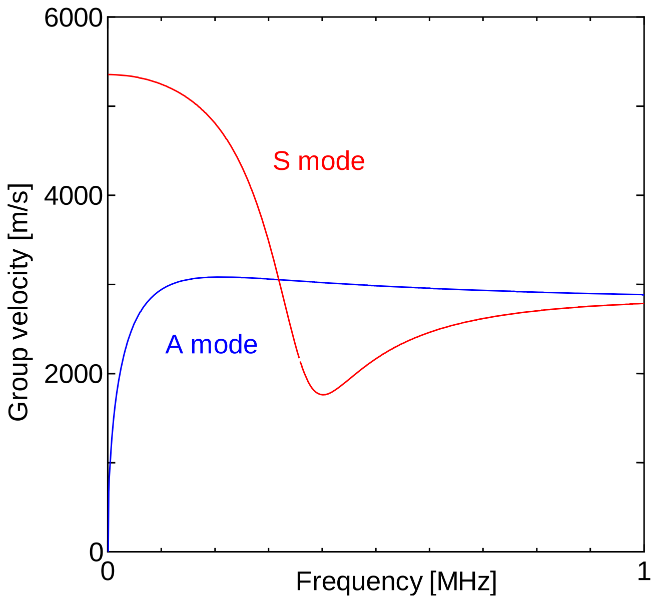

Figure 1. Group velocity dispersion curve of the lamb wave in the aluminum plate

$$\frac{\tan\beta\frac{d}{2}}{\tan\alpha\frac{d}{2}} = -\left[\frac{4\alpha\beta k^2}{(k^2-\beta^2)^2}\right]^{\pm 1} \tag{1}$$

Where

$$\alpha^2 = \frac{\omega^2}{{V_p}^2} - k^2 \tag{2}$$

$$\beta^2 = \frac{\omega^2}{{V_S}^2} - k^2 \tag{3}$$

The terms are wave number $k = \omega/c$ where c is phase velocity and ω is circular frequency; plate thickness is d; longitudinal wave velocity is V_p; and shear wave velocity is V_S.[2]

2.2 Snell's law

When the elastic wave propagates in the two media, the wave refraction phenomenon occurs at the boundary surface. The relation between the incident angle of the traveling wave and the reflection angle at this time is called Snell's law. Snell's law is shown in equation (4) and figure 2. [3]

$$c_1 \sin\theta_2 = c_2 \sin\theta_1 \tag{4}$$

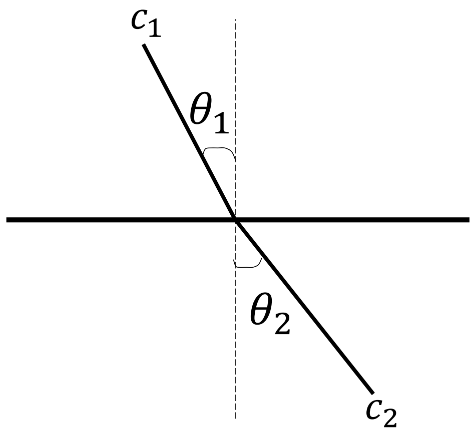

Figure 2. Relationship between incidence angle, refraction angle and velocity.

3. Experiment

AE measurement was performed using a system that consists of 12 air-coupled ultrasonic sensors. Therefore, it was necessary to consider sensors arrangement method that can perform the most efficient measurement. In order to investigate this, experiments on the arrangement angle of the sensors and experiment on the distance between the sensor were conducted.

First, experiments on the arrangement angle of the sensor was conducted. An aluminum plate of 400 ×400×5 mm was used as a test piece. For the sound source, an artificial Hsu-Nielsen source (pencil lead break) was used. The angle of the sensor was varied by 3 ° from 0 ° to 45 °. When $\theta = 3°$, the S/N ratio was maximum. This is consistent with the angle theoretically obtained from the Snell's law.

Second, the experiment on the distance between the sensors was conducted. In this research, the distance between the sensors was determined based on the wavelength of the Lamb wave. This experiment was performed by inputting electric signals obtained from a system incorporating 4 sensors into a measuring device after passing through an optimized band pass filter with an adder circuit. From these results, the distance of the sensor was decided as per Wavelength of A mode wave of Lamb wave propagating in the specimen.

Based on these experiments, a new AE measurement system was developed. By this system, the AE measurement was conducted. Figure 3 shows the experimental setup in this experiment. This system consisted of 12 sensors, a sensorcase, an adder circuit and a band-pass filter (30～50 kHz). Figure 4 shows a waveform measured with a conventional sensor with a resonance frequency close to that of the system we developed, and also shows the waveform measured by the developed system. According to the experimental results, S/N ratio was measured to be 39.4 dB with the conventional sensor and 53.2 dB in the developed system. By comparing these results, it can be seen that the S/N ratio greatly improves. Moreover, if the thresholds are set to be the same for both measurements, the number of noise signals to be measured is lesser for the developed system than for the conventional sensor. This is probably due to fact that the noise signals measured by each sensor are cancelled out.

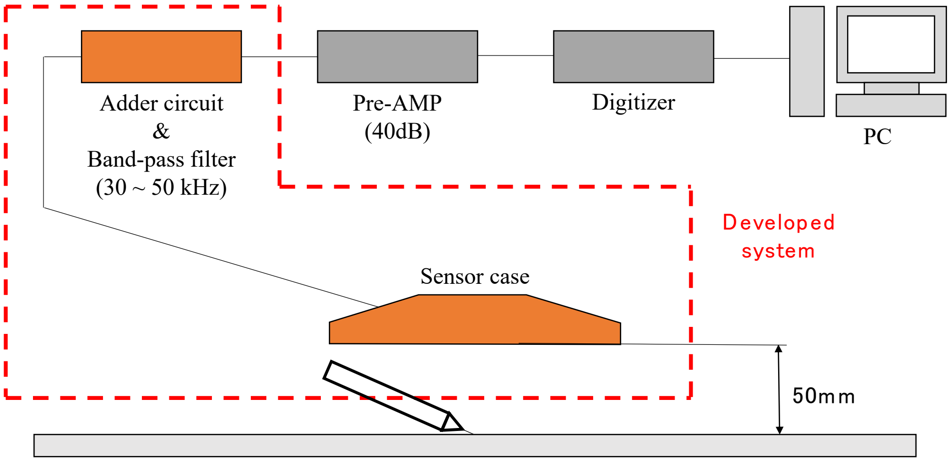

Figure 3. Experimental setup for detecting Lamb wave produced by pencil lead breaking

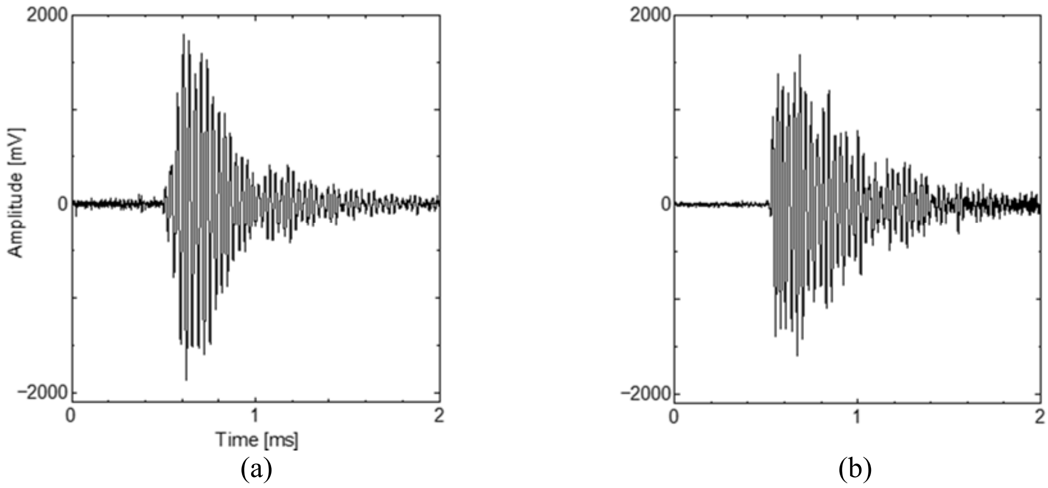

Figure 4. AE wave form detected by (a) a conventional sensor (b) the developed system

4. Conclusion

As per the experimental results, it was found that the system developed in our research performs AE measurement with high S/N ratio. Therefore, this system is sufficiently noise-resistant to be used in a real environment. And, compared with conventional sensors, it became possible to keep the cost very low. However, since several sensors are included in this system, it is larger than conventional sensors; further miniaturization is necessary for using it in a real environment. And, because the sensor element was made very inexpensive, it was poor in durability. It is thought that further improvement is necessary for this as well.

References

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