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Accurate measurement of pipe wall thickness in noncontact manner by a circumferential Lamb wave generated and detected by a pair of air-coupled transducers

エアカップルセンサで励起した円周方向伝搬の Lamb 波による精密肉厚測定

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1. Introduction

A novel method of an accurate estimation of a pipe wall thickness by detecting a minute difference of an angular wavenumber of a circumferential (C-) Lamb wave [1,2] is presented in noncontact manner. The C-Lamb wave circling along a perimeter of a pipe is transmitted and received by a pair of noncontact air-coupled ultrasonic transducers. For the accurate detection of the angular wavenumber, a large number of tone-burst cycles are used so as to superpose the C-Lamb wave on itself. In this setting, the amplitude of the superposed region changes considerably owing to the minute phase changes of the superposed C-Lamb wave. It was confirmed that the maximum error of the estimated thickness to theoretical one was around 10 μm.

2. Principle of Measurement

Here, we used the CL_1 modes of the C-Lamb wave propagating in a 114.5 mm outer diameter and 3 mm thick aluminum (Al) pipe. Dispersion relations of the CL_1 mode in frequency range around 340 kHz are depicted in **Fig. 1**. It is confirmed that the angular wavenumber is the least increased with an increase of thickness loss. It is normally too difficult to distinguish such a small difference. The principle [3] of the present method is described using an illustration of an experimental apparatus (**Fig. 2**). A pair of air-coupled transducers were employed. The C-Lamb wave is generated by the transmitter and is detected by the receiver after propagating a half along the perimeter of the pipe (0-th lap wave) as shown in Fig. 2. The C-Lamb wave is recursively detected on its every n-times lap along the perimeter (*n*-th lap wave). When the number of the tone-burst cycles of the C-Lamb wave is large enough to superpose the C-Lamb wave on itself, the amplitude of the superposed regions changes due to their interferences. The amplitude can be described as following equation:

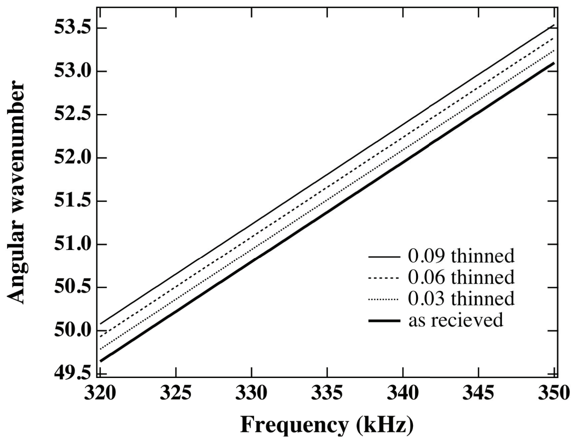

Fig. 1 Dispersion relations of the CL_1 mode C-Lamb wave for different wall thinnings.

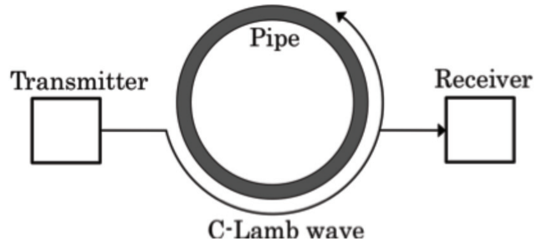

Fig. 2 Experimental setup. A Face-to-face setting of a pair of the air-coupled transducers was employed. Incident angles of the longitudinal wave to the pipe surface were set at the critical angle, 8˚, between the CL_2 mode and air.

$$A = \sum_{m=0}^{n} \left| A_n \exp 2\pi i m p \right| \qquad (1)$$

where A_n and p are amplitude of each circling wave and angular wavenumber of the C-Lamb wave, respectively. **Figure 3** shows calculated amplitudes (n=1) for various wall thinnings as a function of frequency. The amplitude peaks shifted on the frequency axis with an increase of wall thinning.

3. Experiments

Experimental setup is depicted in Fig. 2. 150-cycle tone-burst signals were generated and amplified to 300V peak-to-peak and fed into the transmitter to

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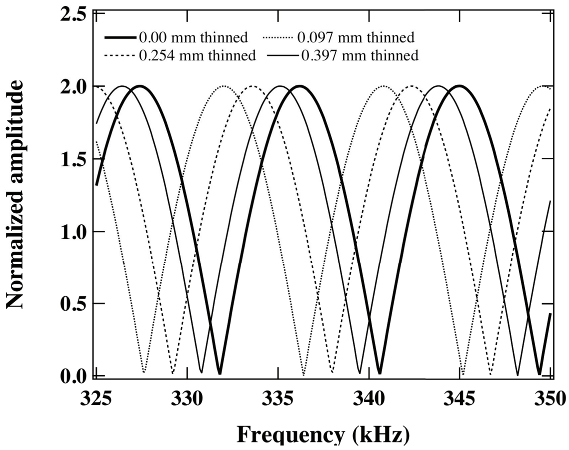

Fig. 3 Calculated normalized amplitude of superposed (0-th and first laps) region of the circumferential Lamb wave as a function of frequency.

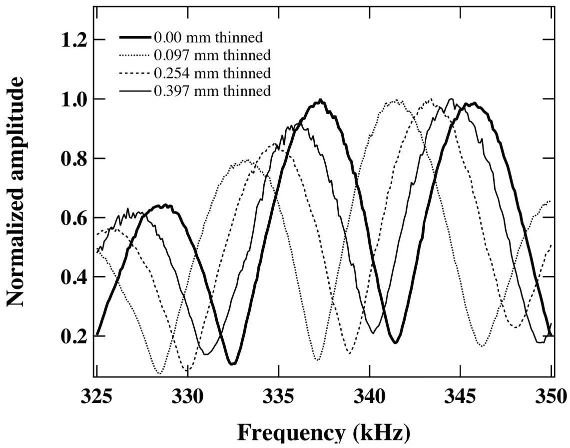

Fig. 4 Experimental results of normalized amplitude as a function of frequency for different wall thickness losses.

the CL_1 mode C-Lamb waves. The received signals were amplified to 90dB. A digital oscilloscope was employed to observe and store the detected signals. The center frequency of the air-coupled transducers was 340 kHz. 300 times averaging sequence in the digital oscilloscope and a 10 kHz width 48dB/Oct band-pass filter were used to improve the signal to noise ratio (S/N). The center frequency of the input signal was varied from 325 to 350 kHz at 0.1 kHz intervals. 114.5 mm outer diameter and 3 mm thick Al pipes were used. 10 different wall thinnings (0.0 mm to 1.0 mm) were introduced to the inner surface of the Al pipes by a lathe. A universal length measuring machine (Tsugami T-ULM500) having a 1 μm nominal accuracy was used to measure the wall thicknesses of all the Al pipes.

4. Results

Normalized amplitude as a function of frequency is shown in **Fig. 4**. In comparison to the theoretical results (Fig. 3), the peak amplitudes shown in Fig. 4 decreased with a decrease of the frequency because of the center frequency (340 kHz) of the air-coupled transducers. In contrast to this, the peak frequencies were almost same as those estimated by the theoretical calculations. The peak frequency as a function of wall thickness loss is shown in **Fig. 5**. Circles and dotted lines are the experimental results and the theoretical calculations, respectively. The theoretical calculations were carried out on the basis of ref. [1] with the longitudinal and transverse wave velocities (c_l = 5850 m/s, c_t = 3230 m/s). It was obviously confirmed that the experimental results agreed excellently with the theoretical calculations. The maximum error between the experiments and theory was around 10 μm.

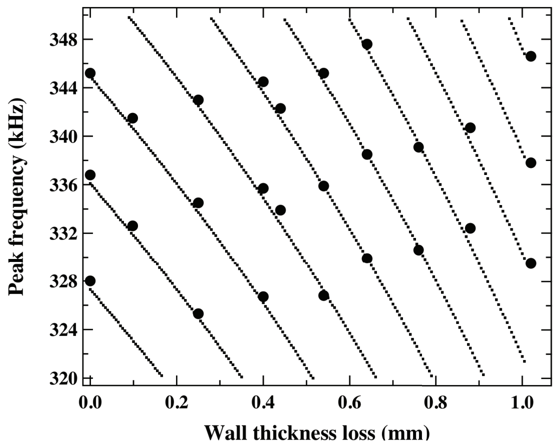

Fig. 5 Peak frequency as a function of wall thickness loss. Closed circles and dots indicate experiments and the theory.

5. Conclusion

This paper described a novel method to estimate a wall thickness of a pipe in noncontact manner using the circumferential (C-) Lamb waves generated and detected by a pair of noncontact air-coupled ultrasonic transducers. In this method, a large number of tone-burst cycles are used to superpose the C-Lamb wave on itself. A wall thickness can be obtained accurately by measuring the amplitude of the superposed region because the amplitude changes considerably owing to the minute change of the wall thickness. The experimental results agreed very well with the theoretical estimations.

Acknowledgment

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