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Resonant phenomena of circumferential Lamb waves generated by eight transducer-elements located evenly on the circumference and wall thickness measurements
円周等間隔に８つ設置したセンサで励起した円周ラム波の共鳴現象と配管の肉厚測定法

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1. Introduction

Piezoelectric ring-shaped sensor (PeRS) [1)] as well as magnetostrictive sensor (MsS) [2)] has been widely used for guided wave inspection of piping. The PeRS is normally consisted of plural transducer elements located along circumference at regular interval. Due to the structure, in addition to the axially propagating torsional mode guided waves, circumferential (C-) Lamb waves [3)] have also been generated as spurious waves at the same time. Especially in the resonant conditions determined by both the specific frequencies and locations of sensor elements, the C-Lamb waves are dominantly and preferentially generated as actual spurious signals that may distort axially propagating waves. In this paper, this troublesome phenomena are used not for the axially propagating guided waves but much usefully for the measurements of wall thicknesses.

2. Principle of Measurement

Resonant phenomena are occurred with the PeRS in the harmonic relation between the wavelength and the location of sensor elements. **Figures 1(a)** and **1(b)** illustrate the resonant standing waves in the circumference at angular wave numbers (AWNs) of 2 and 8, respectively, along with the pipe and eight transducer elements. The AWN is the value that is defined as number of wavelengths within a circumference. For example, all the eight transducer elements are driven simultaneously in the same phase direction (arrows in Fig. 1(b)) for the resonance of the AWN 8. On the other hand, the transducer elements ① and ⑤ in Fig. 1(a) are driven inversely with the elements ③ and ⑦ for the resonance of the AWN 4. The resonant frequency versus the AWN (dispersion relation of the C-Lamb wave) is shown in **Fig. 2**. The specific resonant frequency takes different values at different AWNs. Since the specific resonant frequency changes with wall thickness of piping, it can be estimated by measuring its frequency.

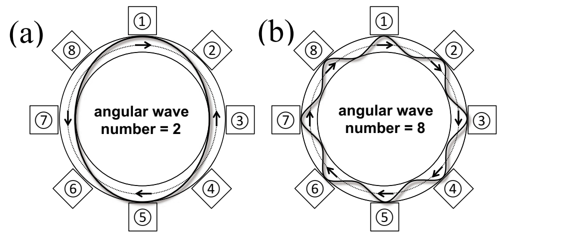

Fig. 1 Illustrations of resonant standing waves in pipes at angular wavenumbers 2 and 8. Arrows indicate relative vibration direction of each element.

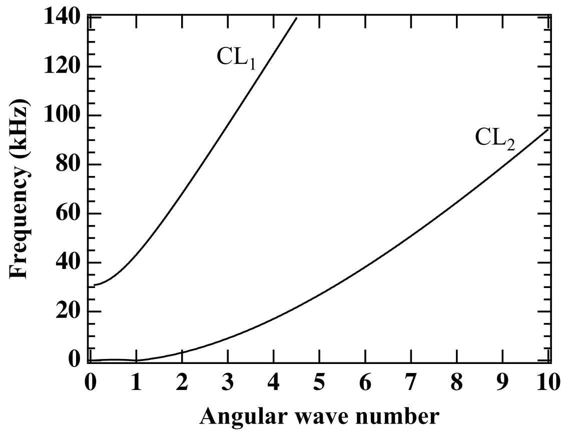

Fig. 2 Dispersion relation of the CL_1 and CL_2 modes of the circumferential Lamb wave.

3. Experiments

The two sets of the PeRSs having eight transducer elements for each were employed. Two sets were used for excitations and detections of the C-Lamb waves, respectively. They were fixed on the pipe. The distance between the two sets was set to be 30 mm along the axial direction. 60.01 mm outer diameter (O.D.) and 2.032 mm wall thickness (v_s = 3088 m/s, v_l = 6460m/s) and 60.52 mm O.D. and 3.937 mm wall thickness (v_s = 3132 m/s, v_l = 6441 m/s) aluminum (Al) pipes were used for the specimens.

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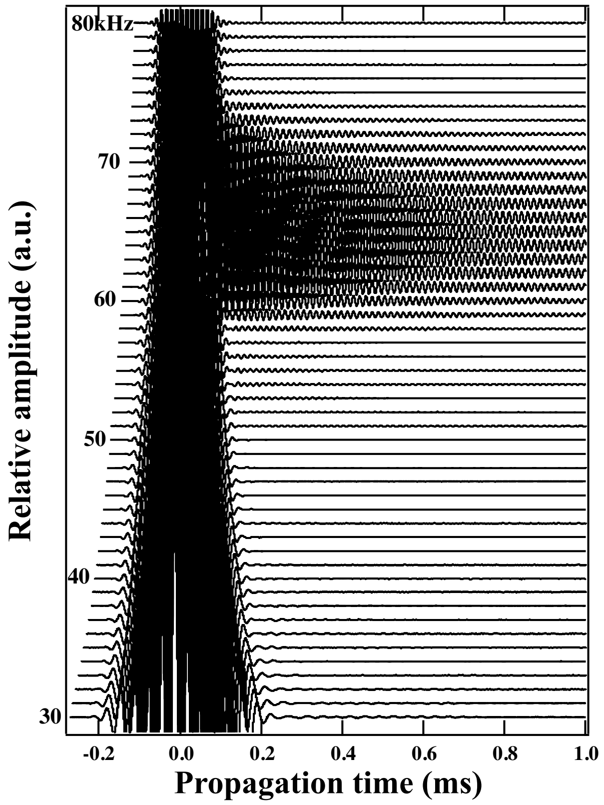

Fig. 3 Time domain signals of frequency range from 30 to 80 kHz at AWN of 8. The signals due to the resonances can be found at around 60-70 kHz.

4. Results

Time domain signals obtained with the 60.52 mm O.D. pipe at AWN 8 for different frequencies were shown in **Fig. 3**. The large wave packets at around 0 ms in all the signals were T(0,1) mode guided waves propagating along the axial direction of the pipe, which were detected immediately by the detector close to the generator. The resonant phenomena could be seen clearly at around the frequency region of 60 to 70 kHz in Fig. 3. As results of the C-Lamb waves propagating and resonating along their circumferential orbit, leakages of the wave energies could be seen as gradually attenuating waveforms. Figure 4 shows the resonant characteristics. The vertical axis in Fig. 4 shows the amplitude at the time of the 20 periods of each frequency. The resonant peaks were extracted using the least-square fitting of the Gaussian curve to the characteristic curves. **Figure 5(a)** and **5(b)** show the resonant frequency as a function of the wall thickness with respect to the AWN of 2 and 8, respectively. Experimental results agreed excellently with the theoretical predictions (avg. error = 0.92%). Especially in the AWN 8, excellent estimation of wall thickness will be anticipated because the peak frequency changes considerably with a little change of wall thickness.

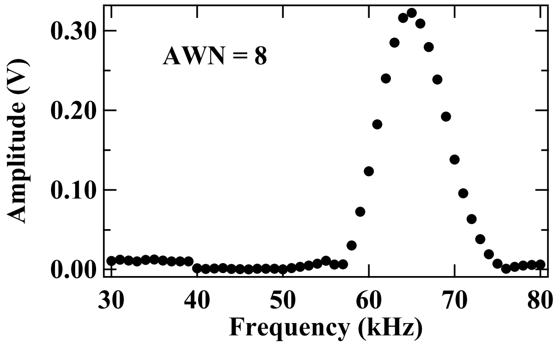

Fig. 4 Resonance characteristics (AWN=8) extracted from Fig. 3.

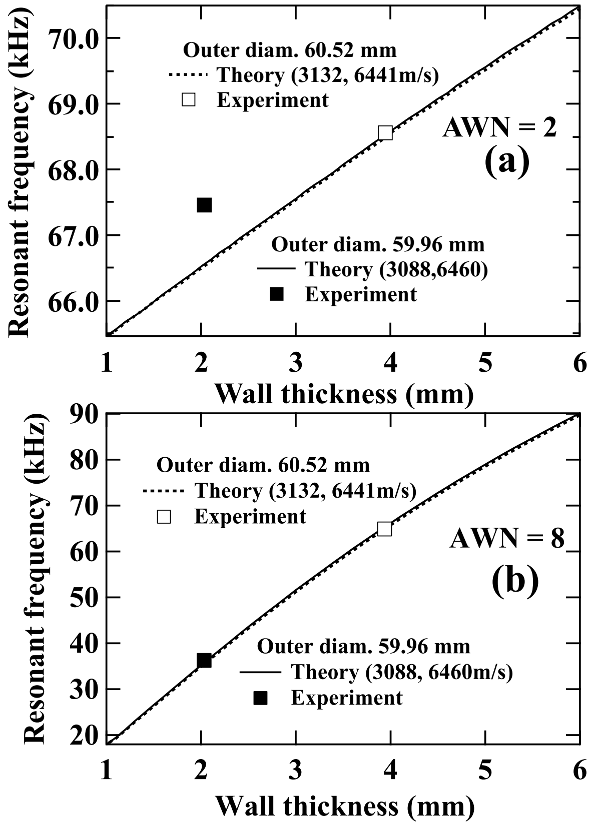

Fig. 5 Resonant frequency as a function of wall thickness of the two different pipe specimens. (a) AWN=2 and (b) AWN=8.

5. Conclusion

Newly developed method for estimating the wall thickness of piping using the circumferential Lamb wave resonating along its orbit was presented. The piezoelectric ring-shaped sensor having eight transducer elements was used to make a resonance condition for estimating the wall thickness. The experimental estimates agreed very well with the theoretical ones.

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