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Resonance of the circumferential shear horizontal wave converted from the T(0,1) mode guided wave at an axial notch
軸方向ノッチでT(0,1)モードガイド波からモード変換した円周SH板波の共鳴

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1. Introduction

Recently, the mode conversions from the T(0,1) mode to some shear-mode-wave propagating along the girth at an axial notch have been revealed based on both the experimental results [1,2] and the FEM numerical calculations [2]. The experimental and numerical investigations dealing with the resonances of the converted shear modes were also carried out [1,2]. This paper shows evidently that the converted mode are the circumferential shear horizontal (CSH) wave based on the approaches from the FEM numerical calculations, the theory, and the experimental evaluations of the converted waves. The theoretical predictions of the resonant frequencies agreed very well with the experimental results.

2. Numerical simulations

Large scale FEM (ComWave^{TM} [3]) was employed to investigate the phenomena. An axial notch (3 mm in depth, 3 mm in width, and 30 mm in axial length) was introduced in 60.5 mm outer diameter and 3.9 mm thick aluminum pipe. 11 cycle tone burst signals were used for the generation of the T(0,1) mode. **Figure 1** shows snapshot of amplitude distributions after passing the T(0,1) mode through the notch for 52.7 kHz, respectively. The axially blinking stripes were clearly confirmed at around the notch, which indicate the 3 cycle standing wave along the girth. These resonant phenomena were confirmed at around 35.1, 52.7, and 70.3 kHz in the frequency range from 30 to 80 kHz. In addition to the notch-reflected-waves, the other axial guided waves propagating backwardly due to the resonances was also confirmed at the frequencies, which must be the trailing ringing signals that were experimentally observed [4].

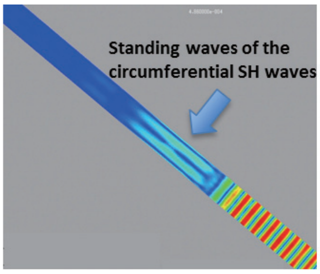

Fig. 1 Resonant CSH wave along the girth observed as axially blinking stripes (52.7 kHz, FEM simulation).

Table I. Theoretical resonant frequency

Angular wave number	C-Lamb wave		C-SH wave
	CL_1 mode	CL_2 mode	CSH_0 mode
2	**3.2**	**68.2**	**35.1**
3	**9.1**	**96.2**	**52.7**
4	**16.9**	**-**	**70.3**

3. Comparison with theory

The standing waves must be made up of both clockwise and counterclockwise circumferential guided waves (the CSH wave or the circumferential Lamb (CL) wave). Dispersion relations of the circumferential guided waves are described normally as relations between the frequency and the angular wavenumber. Here the angular wavenumber is defined as number of wavelengths in the girth. Since the standing wave are generated when the angular wave number takes the natural numbers, the resonant frequencies can be obtained easily with the dispersion relations. **Table I** shows the theoretical resonant frequencies of both the CSH and CL waves. From the comparison of the simulation results and the theory, it can be confirmed that the standing waves are not the CL waves but are the CSH waves. **Table II** summarizes the other experimental resonant frequencies observed previously [1] and the corresponding theoretical values. Coincidences were confirmed.

4. Experimental verification

Dimensions of the specimen pipe and the defect are as same as those used in the FEM simulations. Frequency variation (30-50 kHz) of time domain signals was shown in **Fig. 2**. There are the first arrival packets at around 0.9 ms in all the frequencies. The trailing ringing signals were found at around 35 and 50 kHz. **Figure 3** shows reflection coefficient as a function of frequency. Circles indicate amplitude of the first arrival packets. Line indicates calculation results using a reflection model of the defect [5] that is based on the

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characteristic acoustic impedance. Previous results [5] showed the coincidences between the calculations and the experimental results regarding the axisymmetric defects. However, in the present case of non-axisymmetric defects, very large differences between the experiments and the calculations could be found. Squares in Fig. 3 shows amplitudes obtained by subtracting the ringing amplitude from the amplitude of the first arrival packets, which takes relatively similar values to the calculations.

Particle displacement speeds due to the CSH wave resonances along the girth were measured with the laser Doppler vibrometer. **Figures 4(a) and 4(b)** show RF time domain signals of the particle displacement speeds and their amplitudes at 0.9 ms, respectively. Frequency of the signals was 53 kHz, which corresponded nearly to the theoretical angular wavenumber 3. Three cycle standing wave was clearly recognized.

5. Conclusion

Propagation behaviors of the T(0,1) mode guided waves at an axial notch were considered based on the simulations, the theory and the experimental verifications. It was confirmed evidently that the resonances of the circumferential shear horizontal (CSH) waves converted from the T(0,1) mode occurred at an axial notch for specific frequencies.

Acknowledgment

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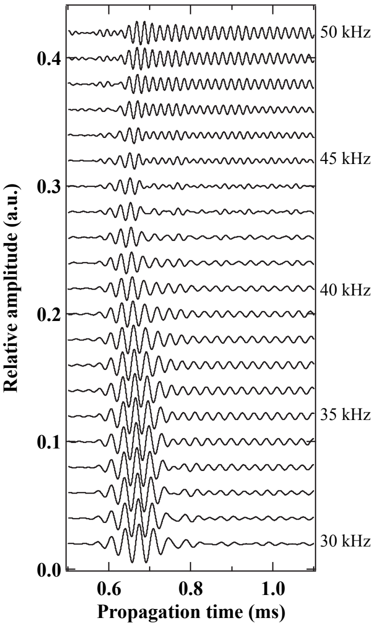


Fig. 2 Frequency variation of RF time domain signals.

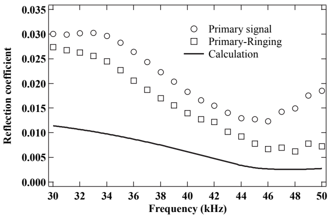
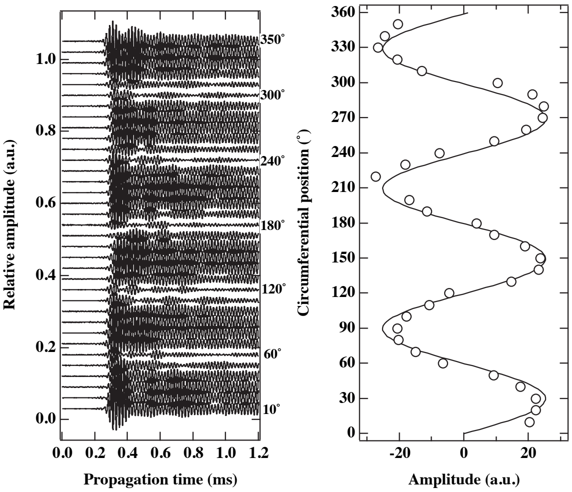


Fig. 3 Reflection coefficient as a function of Frequency.



(a) (b)

Fig. 4 (a) RF time domain signals and (b) their amplitude distribution.

Table II. Comparison between experimental [1] and theoretical resonant frequencies.

	Resonant frequency (kHz)											
	6–5/8 inch pipe						2–7/8 inch pipe					3/4 inch
Experiments by kwun et al	50	56	62	69	75	81.5	35.8	51	67	87	111	120
Theoretical (AWN)	51.4 (8)	57.8 (9)	64.3 (10)	70.6 (11)	77.1 (12)	83.5 (13)	30.5 (2)	45.7 (3)	61.0 (4)	91.4 (6)	106.7 (7)	121.9 (2)

	Resonant frequency (kHz) 12–3/4 inch pipe											
Experiments by kwun et al	23	26	29	32	35.3	38.9	42.6	46.4	50.7	59.2	69.4	79.7
Theoretical (AWN)	22.9 (7)	26.2 (8)	29.4 (9)	32.7 (10)	36.0 (11)	39.2 (12)	42.5 (13)	45.8 (14)	49.0 (15) 52.3 (16)	58.8 (18)	68.6 (21)	78.4 (24)