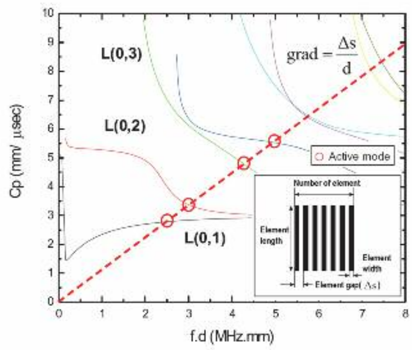
Laser-generated ultrasound evaluation of wall-thinning in carbon steel elbows

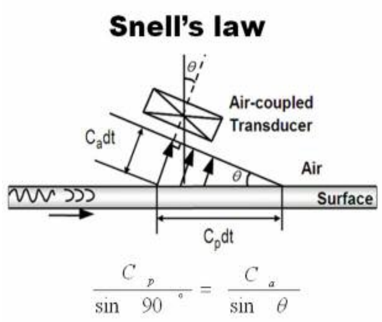
By Do-Youn Kim, Seung-Joon Lee, Joon-Hyun Lee, Younho Cho, Graduate School of Mechanical Engineering, Pusan National University, Korea
Jan D Achenbach, Center for quality Engineering and failure prevention, Northwestern University Evanston, 2137 N. Tech Drive, #327, Evanston, IL 60208, USA

Wall thinning of carbon steel pipe is one of the most serious problems in nuclear power plants, and in particular wall thinning of carbon steel elbows caused by FAC (Flow-Accelerated Corrosion). Therefore non-destructive elbow inspection methods are essential for safe plant operations.
Carbon steel is one of the principal structural materials in power plants. Localised wall thinning caused by FAC occurs inside elbows due to high flow temperatures, pressure and velocity causing an undetected, worsening defect can have serious consequences. Therefore structural evaluation of elbows with local wall thinning is important to maintain the integrity of coolant piping systems. Most inspections are carried out using point by point examination, an inefficient method which requires a lot of time to inspect large structures compared to inspection using guided waves.
An ultrasonic guided wave technique is a powerful detection tool and offers several benefits over conventional ultrasonic methods including lower cost, ease of operation, and testing speed. Moreover, broad-band, multi-mode guided waves, such as those generated by a laser system, have the potential to detect flaws of various sizes. For the purpose of this study the characteristics of the guided wave will be shown when it passes through the elliptical defect of an elbow. A laser generation/air-coupled transducer ultrasonic hybrid system was employed as a way of detecting the elbow defect using guided wave.

Figure 1. Optional receipt of guided wave mode.



(a) Phase velocity of selected mode in Dispersion curve



(b) Determination of receipt angle for specific mode

In addition, a linear slit array was used for the directivity of the laser-generated guided wave and the determination of wavelength. An air-coupled transducer as a guided wave detector was controlled to detect specific modes among guided waves by adjusting its receiving angle to the leak direction of the selected mode.

Selective generation and reception

The problem in laser based guided wave testing is the difficulty in generating a desired mode due to the dispersive nature of Lamb waves. While the excitation of a particular mode is made by a laser pulse, the different components of the wave will travel at different speeds and at least two modes are present even at a low frequency range. This could make the evaluation of a defect difficult due to interpretation of the signal received.
In this study, the selective generation and reception of guided wave modes are achieved by a technique that uses the relation of dispersion curves and a linear slit array. Figure 1(a) shows the process of selective generation using this linear slit array. The elements gap (Δs) in Figure 1(a) is equal to the wavelength of generated modes and is illustrated as the diagonal line with a slope of Δs/d in Figure 1(a).
The active modes lie at the intersection points between the line and the phase velocity of the dispersion curves, and therefore it is possible to generate specific modes selectively by adjusting the element gap. The method to receive the modes generated by the above-mentioned technique is to rotate the air-coupled transducer by the angle based on Snell's law for the

Wavelength [mm]	Mode	Frequency [kHz]	Phase velocity [mm/µsec]	Receiving angle [θ˚]
8mm	L (0,1)	305	3.2	6.09
	L (0,2)	382	3.6	5.4

Table 1. Theoretical values of L(0,1) and L(0,2) modes at 8mm wavelength on each defect

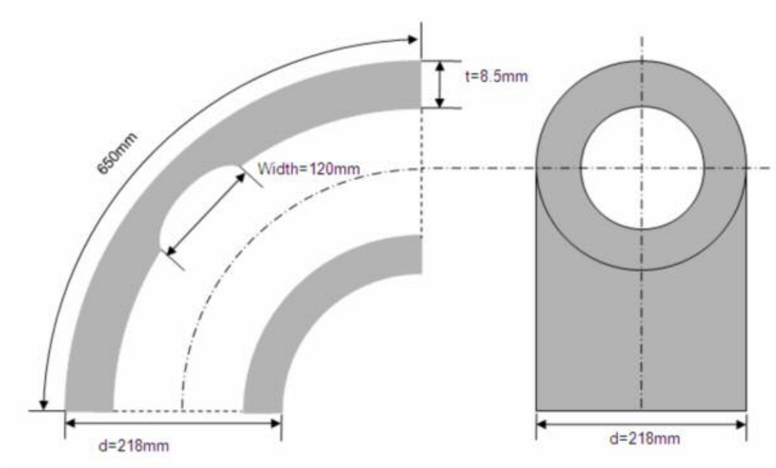


Figure 2. Shape of defects in 8.5mm thick elbows

propagation velocity in air (C_{air}) and the phase velocity of the specific mode (C_p) as shown in Figure 1(b). In this study, the velocity of the wave in air is 340 m/s and the phase velocity of modes is obtained in Figure 1. This study adopted the modes of L(0.1) and L(0.2) as the suitable modes for the experiment because the material is readily excited at a low frequency and the returning signal has a narrow dispersion. Table 1 shows frequencies, phase velocities and reception angles of L(0.1) and L(0.2) modes at 8mm slit spacing. In the process of this calculation, the velocity of the wave in the air was 340 m/s and the phase velocity of the modes was obtained from the dispersion curves in Figure 1.

Specimen and experimental setup

The specimen used in the test was a 8.5mm thick carbon steel elbow. To evaluate the guided wave interaction with defects in elbow, these were compared with defective and defect-free regions. An elliptical defect with a constant width of 120 mm and a depth of 5 mm was machined on the inner surface of a 8.5 mm thick elbow with a diameter of 218 mm. Figure 2 shows the shape of the side and front of the defect on a carbon steel elbow. A schematic diagram of the apparatus used to perform the experiment is shown in Figure 3. The laser and air-coupled transducer were positioned on the same side of the test elbows and act as the generator and detector of the guided wave signal scanning at 20mm steps in the longitudinal direction. A wavelength of fiberized Nd:YAG pulse laser system was used to generate ultrasonic waves at 532 nm and this pulse laser system emitted energy of 32 mJ at one pulse. The beam of this laser illuminated a linear array slit and the transmitted beam acted as a line source on the elbow. The guided wave generated by this source propagated a separation distance starting at 160mm and ending at 380mm between the source to the receiver, perpendicular to the surface of the elbow, and was subsequently detected using the air coupled transducer with a standoff of 5 mm from the outer surface of the elbow. In addition, the signals received from the air-coupled transducer were magnified by the amplifier and displayed through the signal averaging scheme with 1000 sampling data on the screen of oscilloscope. Here, the interval between slits, the width and the number of slits were fabricated 8 mm, 4 mm and 7 respectively.

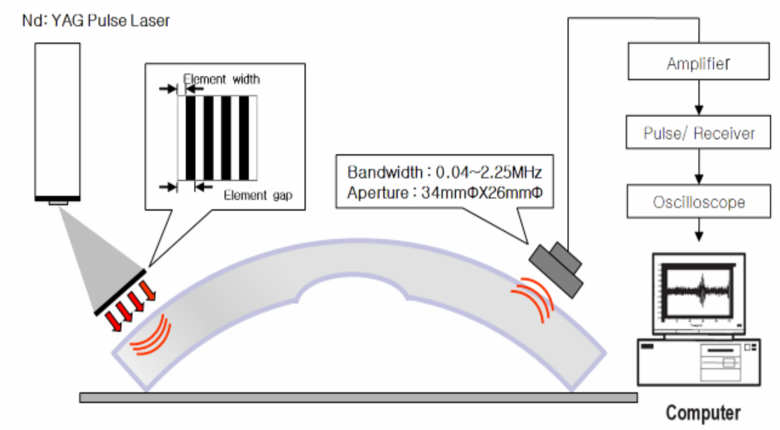


Figure 3. Schematic diagram of experimental setup

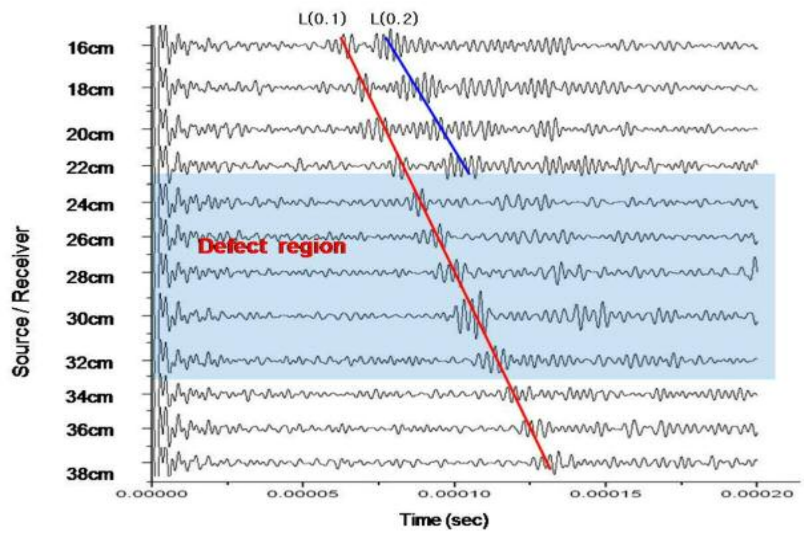


Figure 4. Guided wave signals of L(0.1), L(0.2) mode in elbow with defect region

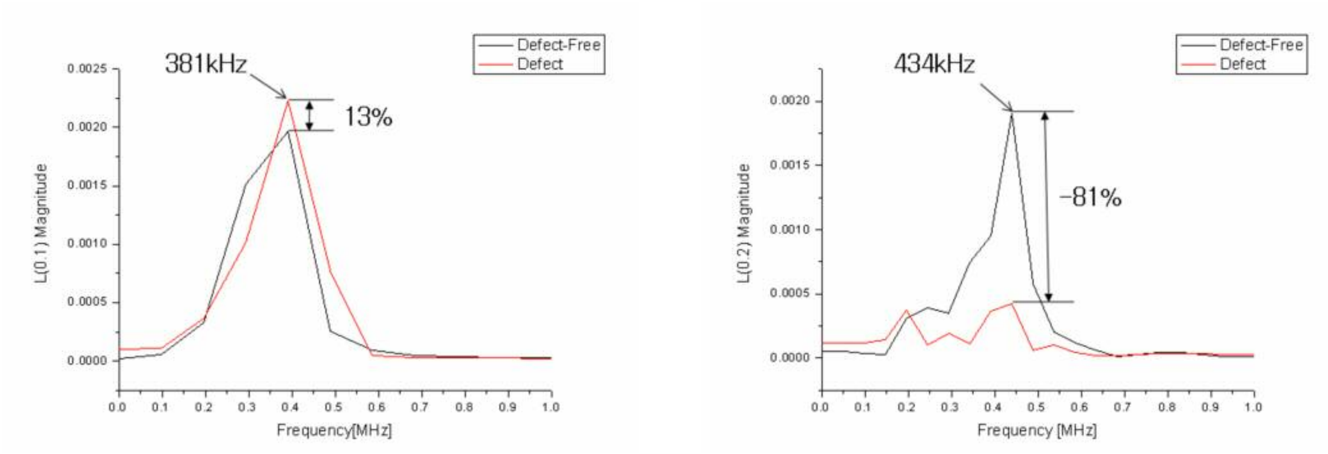


Figure 5. Signal characteristics of L(0.1) and L(0.2) mode on frequency spectrum (a) Frequency spectrum of L(0.1) (b) Frequency spectrum of L(0.2)

Experimental results

Figure 4 shows the variation of amplitude in the defect region. In this Figure, it is possible to evaluate the defect by the variation of L(0.1) and L(0.2) modes. Compared to the defect-free region, the amplitude of the L(0.2) mode is clearly decreased in the defect region. This result indicates that as the signal passes the defect region it is affected by defect.

Figure 5 shows the characteristics of the frequency spectra of the L(0.1) mode with the frequency of 381kHz (theoretical value is 376kHz) and L(0.2) mode with 434kHz (theoretical value is 423kHz) distinctly. The plots in Figures 5 (a)-(b) are the frequency spectra of these modes in the 0~2MHz range. As shown in Figure 4, the signal without defect includes both the L(0.1) and L(0.2) modes. However the amplitude of the L(0.2) mode is decreased dramatically in the defect region. Analysis of the frequency spectra were obtained by performing a Fast-Fourier Transform (FFT) of the time-domain waveforms. The magnitude of the L(0.1) mode with the center frequency of 381kHz in the defected region is increased by 13%. However, the L(0.2) mode of waves propagating in the defected region suffers a dramatic attenuation. The maximum decrease in the center peak magnitude of the signal with a frequency of 434kHz is 81%.

Defect localization

The guided waves are received with a constant source/receiver separation along the longitudinal direction. The air-coupled transducer is passed by the center of defect to obtain clear characteristics of defect. Figure 6 shows the results of line scan using the pitch-catch method in the defect region. The maximum magnitude of the frequency spectrum in L(0.1) and L(0.2) modes were plotted as a function of the scan position by scanning at 20mm steps along the longitudinal direction respectively. The L(0.1) mode has the relation between the depth of the defect and variation of the signal. As the depth of elliptical defect is increased, the amplitude of the signal received is increased. The L(0.2) mode using the maximum magnitude of the frequency spectrum is the factor used to distinguish the defect region.

Conclusions

The possibility for measuring wall thickness reduction using the group velocity of guided waves was applied to the elbow. To evaluate the reduction in thickness mode identification was conducted using time-frequency analysis. In the elbow, L(0.1) and L(0.2) modes were applied in the defect-free region, but the amplitude of L(0.2) mode was decreased in wall-thinning and the characteristic the maximum magnitude of the frequency spectrum of L(0.2) mode is varied in the defect region. Therefore it is possible to evaluate wall-thinning of the elbow by using the ratio of L(0.2) to L(0.1) for the magnitude quantitatively 6.

Acknowledgement

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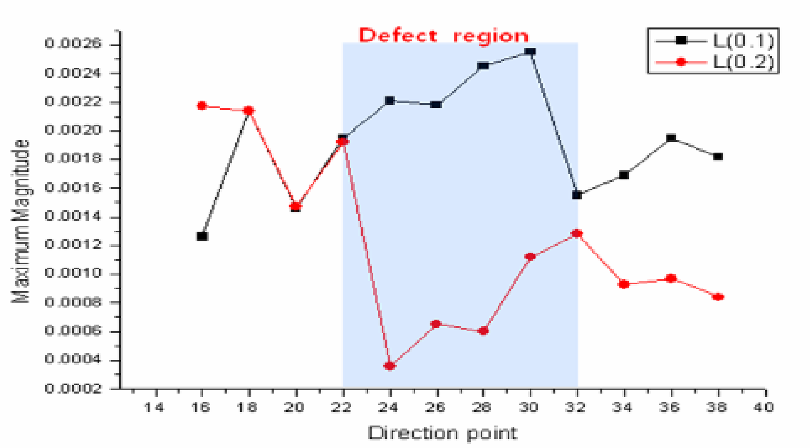

Figure 6. Maximum magnitudes using the line scan technique on the defect region.