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Laser Generation of Focused Lamb Waves

Kyungyoung Jhang†, Hongjoon Kim, Hyunmook Kim and Job Ha

Abstract An arc-shaped line array slit has been used for the laser generation of focused Lamb waves. The spatially expanded Nd:YAG pulse laser was illuminated through the arc-shaped line array slit on the surface of a sample plate to generate the Lamb waves of the same pattern as the slit. Then the generated Lamb waves were focused at the focal point of which distance from the slit position is dependent on the curvature of slit arc. The proposed method showed better spatial resolution than the conventional linear array slit in the detection of laser machined linear defect and drill machined circular defect on aluminum plates of 2mm thickness. Using the focused waves, we could detect the linear defect and the circular defect with the improvement of spatial resolution. The method can also be combined with the scanning mechanism to get an image just like by the scanning acoustic microscope(SAM).

Keywords: Laser-ultrasonics, Lamb wave, focusing, arc-shaped line array, spatial resolution

I. Introduction

Lamb waves are guided elastic waves propagating in plate structures parallel to the boundary surfaces (Vikotorov, 1967). The propagation of these wave modes allows for the inspection of plates and strip materials along the length of the sample thus providing the possibility of a considerable saving in time over a C-scan of the sample (Karautkramer and Karautkramer, 1977). Recently, many considerable applications of Lamb wave have been studied to defect detection in metal (Alleyne and Cawley, 1992), composite plates (Guo and Cawley, 1994; Pierce et al., 1997), sheet thickness measurement (Dewhurst and Shan, 1990), elastic constant evaluation (Rogers, 1995) and bonded metal joint inspection (Bork and Challis, 1995). The traditional method of launching Lamb waves is to utilize a compression transducer coupled to sample plate with a matching wedge such that an effective spatial matching into the desired Lamb wave mode is obtained by (Vikotorov, 1967). An additional technique is to employ laser generation (Scruby and Drain, 1990). Attractive features of a laser-ultrasound include its non-contact nature, reproducibility, broad bandwidth and capability to launch a variety of acoustic modes. Preliminary works on laser-acoustic sources were conducted (e.g., Hite, 1963). In these methods, however, laser generated Lamb waves had wide bandwidth, low directivity, and low sensitivity. Several techniques have been investigated to increase the amplitude and to narrow the bandwidth of laser generated signals. One approach was the temporal modulation of the laser source (Pierce and Jarzynski, 1995). Another method was controlling the shape and phase of laser source to generate Lamb waves with narrow band and high directivity. However, most

Received October 1, 2002. † Corresponding Author: School of Mechanical Engineering, Hanyang University, Hangdang-dong 17, Seongdong-gu, Seoul 133-791, Korea, kyjhang@hanyang.ac.kr

of them were to use linear array to get narrower-band and higher-directivity wave (Cerniglia et al., 2000; Jhang et al., 2001). In this study, an arc-shaped line array slit was used to generate a focused Lamb wave. The proposed method showed better spatial resolution than the conventional linear array slit in the detection of laser machined linear defect and drill-hole defects on aluminum plate. The technique can improve the inspection ability of laser-generated Lamb waves for small size defects with the improved resolution.

2. Experimental Arrangement

Fig. 1 shows the experimental arrangement for the laser generation of the focused Lamb wave in a target plate. The source laser was a Q-switched Nd:YAG laser system. The diameter of laser beam was expanded into about 20mm by a beam expander. The Expanded laser beam was transmitted through the arc-shaped line array slit and worked as an Lamb wave source with the same shape of the slit on the sample plate. The sample was an aluminum plate of 2mm thickness. The generated Lamb wave was detected by a pinducer (contact) or air coupled transducer (non-contact), and the wave signal was monitored by an oscilloscope. A standard GPIB data interface allowed signals to be transferred from the oscilloscope to a personal computer for subsequent data processing and storage.

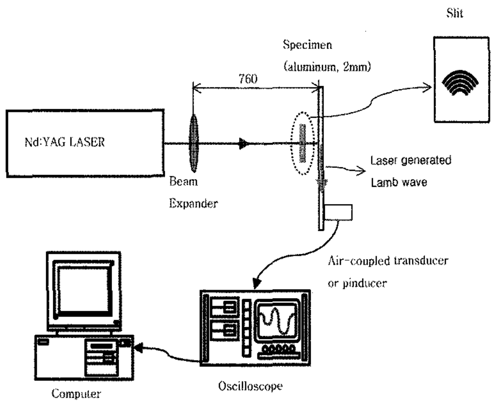


Fig. 1 A schematic of experimental setup

3. Design of Arc-Shaped Slits

In order to design the arc-shaped slit, three parameters should be determined; the line spacing, number of lines, and the focal length.

The line spacing is dependent on what mode and frequency of Lamb wave to be generated. We selected A_0 mode and with the center frequency of 1.75MHz from the preliminary study (Jhang et al., 2002), in which the dominant mode of Lamb wave had been generated by a point laser source and its center frequency was evaluated. The target specimen was the same in this study. Now then we can determine the phase velocity from the dispersion curve shown in Fig. 2 and the wavelength is calculated by

$$V = (\lambda / d) \times (f \times d) \qquad \cdots\cdots\cdots (1)$$

where, V is phase velocity, λ is wavelength, d is the thickness of the plate, and f is frequency of the wave. From the dispersion curve, the phase velocity of A_0 mode Lamb wave is about 2.8km/s. Therefore, the wavelength was determined as 1.5mm, which was adopted as the line spacing of slit.

In the next step, number of lines was determined. The more lines we have, the narrower the frequency bandwidth. But the laser spot was

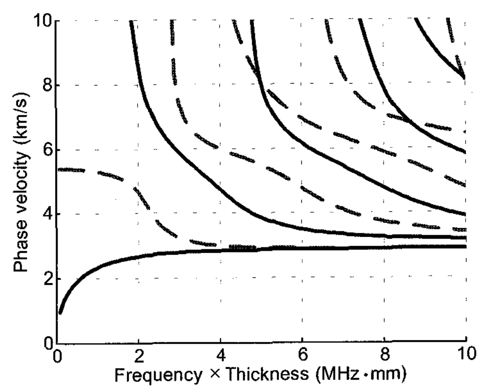


Fig. 2 Dispersion curve of Lamb wave in an aluminum plate (Solid : Antisymmatric mode, Dashed : Symmatric mode)

diameter was limited to 10~20mm, which determined how many lines were allowed. Generally, the number of lines, N, is limited by

$$N = INT(D_s / \lambda + 2) \qquad \text{.............(2)}$$

where, D_s is the laser spot diameter on the slit and INT means integer number. The maximum number of N in this study were between 8 and 15.

Lastly, the focal length of the arc, which was 35mm in this study was determined.

4. Lamb Wave Signal Generated by Arc-shaped Slits

Typical signals recorded at the focusing point are shown in Fig. 3 with shot-time Fourier transform (STFT) contour plot. Peak frequency of the signal generated by line spacing of 1.5mm appeared at about 1.75MHz as it was designed, meanwhile it was about 600kHz when the slit spacing was 4mm. This shows that the frequency of Lamb wave generated by the arc-shaped line array slits can be determined by line space. From the contour plot of STFT, we can find that A_0 mode was dominantly generated.

To verify that the arc-shaped line array slit generates the focused wave in a satisfactory manner, experiments were performed on an aluminum test plates of 2mm thickness. A pinducer was moved from point to point as seen in Fig. 4 to detect the Lamb wave signals and the peak-to-peak value of the signal was measured at each point. Fig. 5 shows the result. Simulation using a simple scalar diffraction theory was performed to compare with this experimental result. The experimental and the simulation results showed similar pattern in the overal intensity distribution. This means that the focused Lamb wave could be generated by the arc-shaped line array slit effectively.

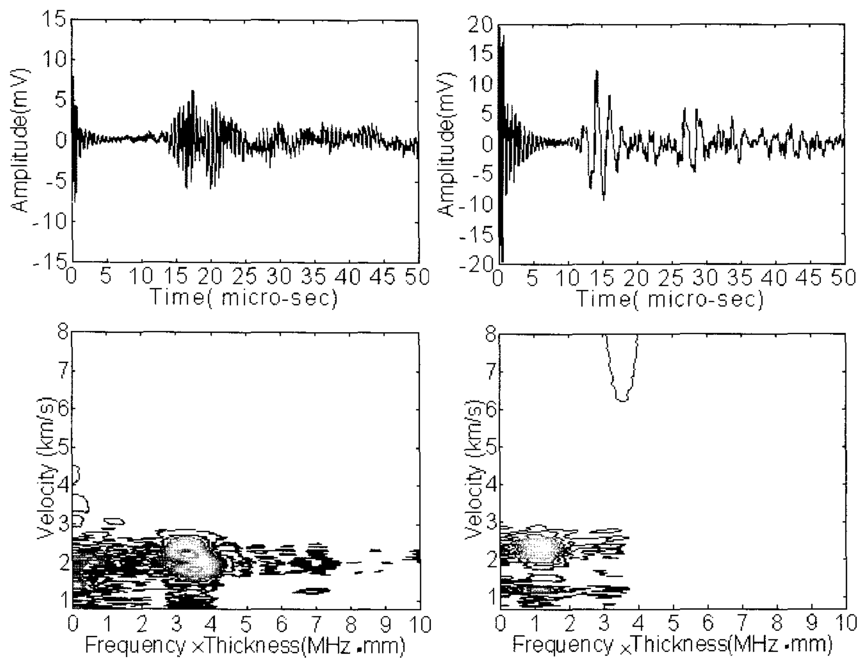


Fig. 3 Lamb wave signals and there contour plots of short-time Fourier transform. The focal length of the arc was 35mm and the thickness of aluminum sample plate was 2mm. (a) 1.5mm line space (b) 4mm line space

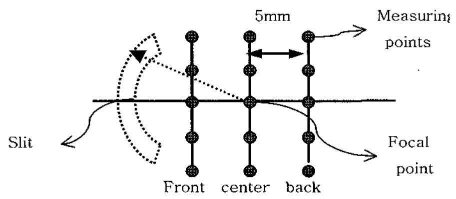
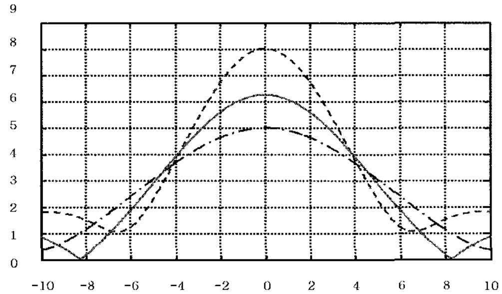
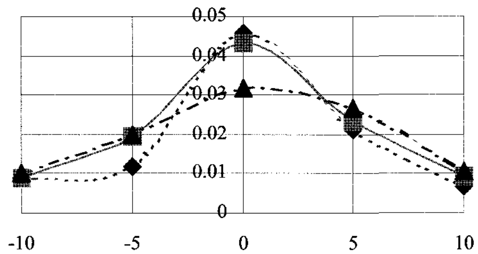


Fig. 4 Lamb wave detection points. The pinducer located on these points and the amplitudes of the Lamb wave signals were measured.



(a)

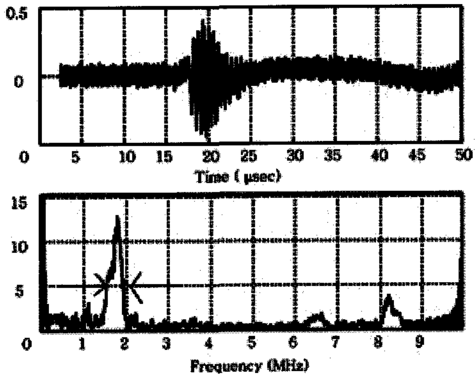


(b)

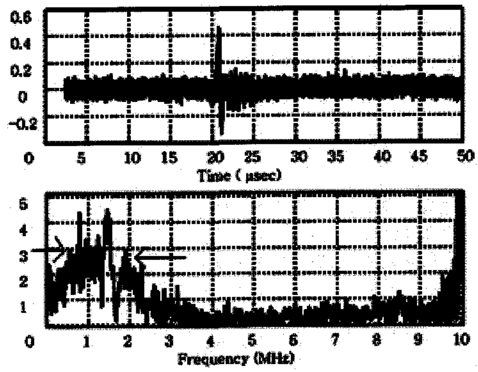
Fig. 5 Wave intensity distribution measured at 5 points along three lines. X-axis : distance from center line in mm, Y-axis : Intensity (dashed : front, solid : center, dashdot : back) (a) simulation (b) experiment

Fig. 6 illustrates the Lamb wave signal generated by the arc-shaped single line compared with the wave generated by the arc-shaped line array. The wave generated by the arc-shaped line array showed relatively narrower bandwidth. This result is coincide with the general knowledge that the more lines generate the narrower band signal.

With these results we concluded that the characteristics of Lamb wave generated by the proposed method were obtained as designed.



(a)



(b)

Fig. 6 Variation of frequency bandwidth as number of lines. (a) line array(8 lines) (b) single line

5. Defect Detection

In the actual application to the detection of defects, the proposed method has superior spatial resolution compared with the conventional method using linear array. In order to confirm this, we prepared another slit with linear array of which spacing and number are the same as the arc-shaped line array to compare the defect detection results.

Two kinds of artificial defects, a laser machined linear defect and a drill machined circular defect, were inspected in the experiments. Both the linear defect of 0.5 mm in width and 10mm in length and drill-hole with 5 mm in diameter were machined in aluminum plates. These defects went through the plates. The focal point of the arc-shaped line array was aligned at the center of the defects. The plates with the defects were scanned over 30mm range to the perpendicular direction of wave propagation in 1 mm step. An air-coupled transducer with 2.25 MHz center frequency was used to detect the wave reflected at the defect. Fig. 7 shows the experimental setup for defect detection. A high-pass filter was used to eliminate the noise of audible sound because the air-coupled transducer is very sensitive to the air-transmitted audible sound from laser-generated ultrasound source.

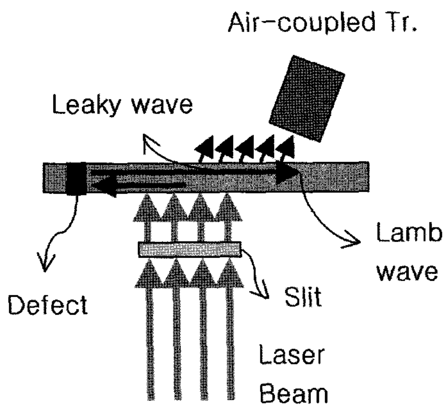


Fig. 7 A schematic of experimental setup for defect detection.

Fig. 8 shows the intensity distribution of signals reflected from the linear defect. In the case of linear array, the wave intensity was constantly increased as the reflected point was approaching to the center of linear defect, and it was constantly decreased as the point was moving away from the center. In this case, we cannot determine the edge of defect clearly. In the case of the arc-shaped line array, however, intensity distribution was more sharply increased at around the edge of the linear defect, thus we can identify the defect size more clearly. This fact is more evident from the result obtained for circular defect shown in Fig. 9. The intensity distribution of the reflected signals increased very sharply at the center position of defect. On the other hand, it is very broadly distributed in the case of linear array.

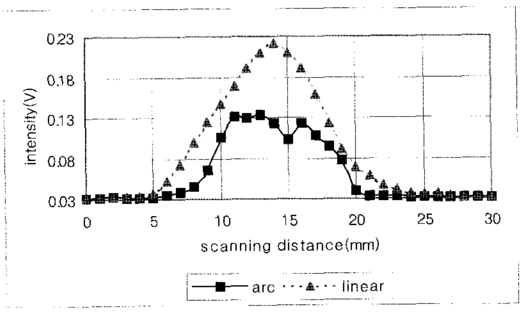


Fig. 8 Intensity distribution of signals reflected from the linear defect. Sample plate with defect was scanned to the direction of defect length.

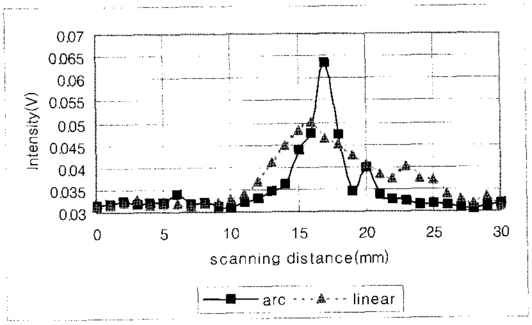


Fig. 9 Intensity distribution of signals reflected from the drill-hole defect.

6. Conclusion

The arc-shaped line array slit was designed for the laser generation of the focused Lamb wave. At the design stage of the slit, the line spacing, the number of lines and the radius of arc should be considered, where they are related with the mode of Lamb wave to be generated, the bandwidth, and the focal length, respectively. The experimental results showed that the maximum intensity of ultrasound was obtained at the designed focusing point and that the focused Lamb wave could be effectively generated by the designed slits. The focused Lamb waves generated by these slits showed the better spatial resolution than by the conventional line array slit so that the proposed method could be applicable to the inspection of small defects with the improved spatial resolution.

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