3Pa1-4

Ultrasonic focusing by designing a stacked thin plate region

Takaaki Fukuchi‡, Takahiro Hayashi, and Naoki Mori (Osaka Univ.)

1. Introduction

Controlling elastic wave propagation has been widely studied as phononic crystals, acoustic metamaterials, and acoustic metasurfaces. Ultrasonic focusing, one of the applications of wave propagation control, is commonly applied in diagnostic imaging equipment, and has recently been utilized in nondestructive testing in the industrial field as well. Phased arrays are arrays of multiple elements arranged in a linear fashion. When transmitting waves, the timing of the excitation of each element is delay-controlled to enable oblique incidence or focusing at an arbitrary angle. [1),2)] Compared to conventional inspection methods, phased arrays enable inspection over a wide area without mechanical scanning. However, they have the disadvantage that the cost of the equipment is high because of the multi-channel structure that requires a phase shifter to control the delay for each element.

In this study, we propose a method of ultrasonic focusing for single-channel input by analyzing the propagation characteristics of Lamb waves in a stacked area of thin plates.

2. Focusing with a phase controller by Lamb waves

Lamb waves, a type of guided waves propagating in an elastic thin plate, are characterized by their velocity dispersion and multimode nature. **Fig. 1** shows the phase velocity dispersion curves of S0 mode, a type of Lamb wave symmetric mode, and A0 mode, a type of antisymmetric mode.

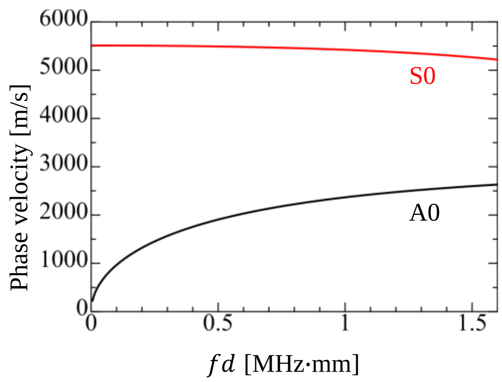

Fig. 1 Phase velocity dispersion curves of Lamb waves.

When frequency is assumed as a constant, the phase velocity of the A0 mode depends on the thickness of the plate and varies significantly in small thickness range. As shown in **Fig. 2**, this property can be used to control the phase difference at the exit of a stacked thin plate region of different thicknesses designed in the middle, and to transmit waves propagating in an oblique direction when transverse waves are incident on that stacked thin plate structure.

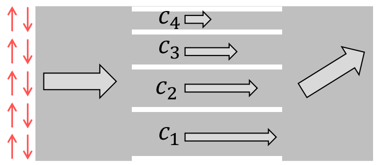

Fig.2 Schematic figure of controlled transmitted wave.

The authors showed that the structure in which such a layered structure is periodically repeated can form a wave field dominated by transmission waves propagating at a desired angle. [3)]

Ultrasonic focusing with a stacked thin plate region can be explained using the phase difference control of Lamb wave described above and interference based on Huygens principle. As shown in **Fig. 3**, when the Lamb wave A0 mode is propagated from the left end of the region where thin plates are stacked with layer thicknesses increasing step by step from the center layer with the smallest layer thickness, a phase difference occurs at the region exit because the wave speed increases in sequence from the center layer.

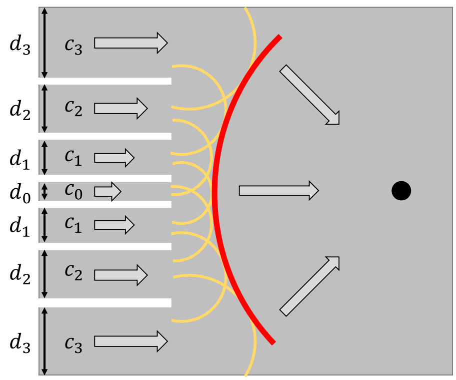

Fig.3 Schematic figure of ultrasonic focusing by designing a stacked thin plate region.

When the thickness of each layer is adjusted so that the phase difference is on a circular arc, the sum of the transmitted waves from each layer focuses on a certain focal point by Huygens' principle.

3. Numerical experiments

In order to verify the ultrasonic focusing using the proposed structure, wave propagation was analyzed using the finite element software COMSOL Multiphysics. Assuming the situation where the vibration transmitted from the transducer is focused in the specimen through a waveguide with a stacked thin plate region, the calculations were performed in the region shown in **Fig. 4**. The center of the right end of the stacked plate region is defined as the origin of the xy coordinates, and the position of the focal point is expressed as (f_x, f_y). The left end is bonded to the transducer, and a 6-cycle 1.0 MHz transverse wave is propagated from the left end of each layer. The upper and lower boundaries of each plate in the left stacked plate region are set as traction free boundaries. The specimen is considered large enough, and the top, bottom, and right edges are assumed to be absorption areas to suppress reflected waves. Assuming that the waveguide and specimen are aluminum alloy, the longitudinal wave velocity and transverse wave velocity are 6400 m/s and 3170 m/s, respectively, and the density is 2700 kg/m^3. The minimum plate thickness is 0.4 mm and the layers are stacked so that the plate thickness increases using the method described in **Sect. 2**. However, if the plate thickness exceeds the cutoff thickness of 1.6 mm, higher-order modes of Lamb waves are generated. In that case, thin plates with a thickness smaller than 1.6 mm were stacked so that the contribution to the focal point was delayed by exactly an integer multiple of the period of the transverse wave.

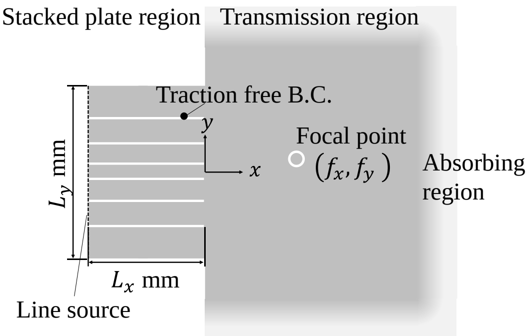

Fig. 4 Calculation region.

3. Calculation results

Figs. 5 and **6** show the numerical results of wave propagation at the time when the incident wave reaches the focal point under the above conditions. The color is the vertical component of the rotation of the displacement vector $\boldsymbol{u}$, which represents the transverse wave component.

The ultrasonic waves with arc-shaped wavefronts were observed propagating to the focusing point indicated by the white circle. The layers at the top and bottom edges of the stacked area are layers with remaining thickness and do not contribute to the focusing. This mismatching at the edges causes the straight forwarded waves from some of the layers.

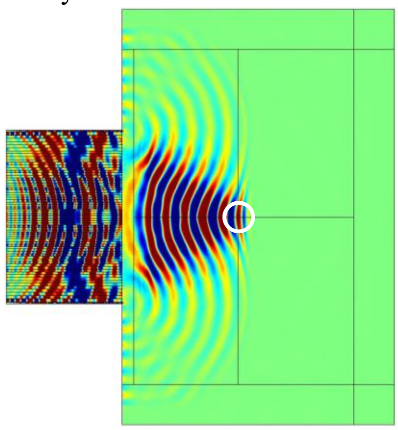

Fig. 5 Wave motion($L_x = 20$ mm, $L_y = 30$ mm, $f_x = 20$ mm, $f_y = 0$ mm).

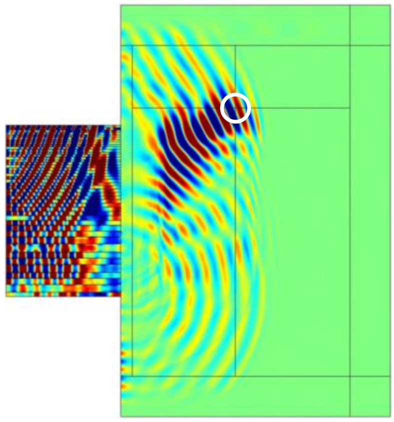

Fig. 6 Wave motion($L_x = 20$ mm, $L_y = 30$ mm, $f_x = 20$ mm, $f_y = 18$ mm).

4. Conclusion

This study examined ultrasonic focusing using a stacked region of thin plates of various thicknesses as a waveguide. Using the property that the phase velocity of the Lamb wave A0 mode varies depending on the thickness of the plates, we showed that it is possible to focus the synthesized transmitted waves from the stacked plate regions with different thicknesses. We will try to improve the focusing accuracy and focus S0 modes using the same method.

References

1) S-C.Wooh and Y.Shi: Wave Motion. **29** (1999) 245-265.
2) S-J. Song, H. J. Shin and Y. H. Jang: Nucl. Eng. Des. **214** (2002) 151-161.
3) T. Fukuchi, N. Mori, T. Hayashi: Jpn. J. Appl. Phys. **61** (2022) SG1048.