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Large-displacement Incidence by Simultaneous Focusing of Longitudinal and Shear Waves for Ultrasonic Phased Array

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1. Introduction

Cracks significantly weaken the material strength of structures and mechanical components. Therefore, high measurement accuracy of crack depth is essential to prevent serious accidents. However, the cracks generated in structures and mechanical components are sometimes closed because of compressive residual stresses or other factors. Ultrasonic waves can penetrate through such closed cracks, causing the underestimation or overlook of closed cracks. To solve this problem, several types of nonlinear ultrasonic phased array has been developed. Among them, fundamental wave amplitude difference (FAD)[1,2], which is based on the nonlinear incident-wave-amplitude dependence of fundamental responses, is highly practical because it allows us to take a measurement only by using the array transducer alone. The key to the success of FAD is how high incident wave amplitude can be generated in samples to cause the contact vibration of crack faces. However, the excitation voltage must be kept below a certain level to prevent the destruction of the array transducer itself. Hence, there was a limit to the realization of large-displacement incidence, and sometimes the incident wave amplitude was insufficient to cause the contact vibration of closed cracks. Note that the focusing of longitudinal (L) waves based on delayed excitation is only used in typical ultrasonic phased array, including our study.

On the other hand, in the biomedical field, acoustic tweezers[3] have also been realized by controlling the sound field sophisticatedly, where phase control of the incident wave was combined with typical delayed excitation. However, the application has been limited to liquids or airs in which only L waves can propagate.

In this study, we propose a method for increasing the incident wave amplitude by simultaneous focusing of L and shear (S) waves with a 1D array transducer by utilizing the delay and phase control. We demonstrate the proof of concept by numerical simulation.

2. Principle of Simultaneous Focusing

In a typical phased array, as shown in **Fig. 1(a)**, L-wave focusing is utilized with a 1D array transducer, whereas both L and S waves can propagate in solids, in contrast to liquids and airs. Therefore, we propose simultaneous focusing of both modes using a single array transducer for L waves. Figure 1(b) shows schematics of the principle. First, S waves are transmitted using the edge effect of each element. Note that S waves with antiphase relation to each other are generated from both edges of each element when the array transducer for L waves is excited. Delayed excitation of the S waves causes the cancelation of the S waves at the focal point when the focal position is below the array center. Hence, the phase control is introduced in addition to the delay control, as performed in the biomedical field. Furthermore, the delayed excitation of L waves is carried out after an appropriate time lag so that the L and S waves focus simultaneously at the focal point.

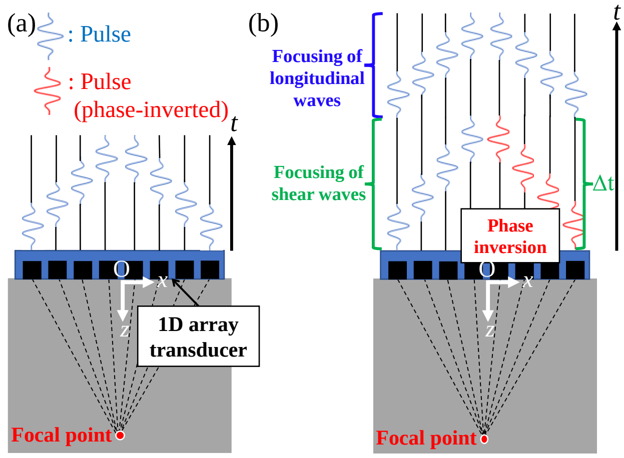

Fig. 1 Schematics of focusing in phased array: (a) a conventional method for focusing L waves, (b) the proposed method for focusing L and S waves simultaneously.

3. Numerical Simulations

To prove the concept of the proposed method for simultaneous focusing of L and S waves, we performed numerical simulations using a finite element simulation software, ComWAVE. **Figure 2** shows the simulation model. A 1D array transducer with 128 elements and 0.5 mm pitch was used, and 5 MHz, 3 cycles incident waves were transmitted from each element with appropriate delay and phase control applied. We used an aluminum alloy with a

L-wave speed of 6380 m/s, a S-wave speed of 3130 m/s, and a density of 2700 kg/m^3 as a specimen. The Courant number was 0.8. The mesh size and number were 0.0313 mm and 2529450, respectively. Absorption layers are set to reduce calculation costs.

For the simulation, we formulate the incident wave as

$$y(t) = \begin{cases} A\left(1-\cos\left(\frac{2\pi f t}{n_c}\right)\right)\cos(2\pi f t) & \text{if } 0 \le t \le \frac{n_c}{f} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where A is the amplitude, f is the frequency, t is time, and n_c is the number of cycles. When focusing S waves, for the application of phase inversion, the amplitude A was set to 1 if the element is to the left of the focal point on the x-axis, and A was set to -1 if the element is to the right of the focal point on the x-axis. Moreover, considering the delay law derived from the sound speed and geometric relationships, the delayed excitation y_{L} at L-wave focusing, the delayed excitation y_{LS} at first excitation (S-waves focusing) for simultaneous focusing, and the delayed excitation y_{LS} at second excitation (L-waves focusing) for simultaneous focusing can be expressed as the following equations (2) and (3), respectively:

$$y_{\mathrm{L}}(t,n) = y\left(t - \Delta t_{\mathrm{L},n}\right) \quad (2)$$

$$y_{\mathrm{LS}}(t,n) = y\left(t - t_{\mathrm{LS}} - \Delta t_{\mathrm{L},n}\right) + y\left(t - \Delta t_{\mathrm{S},n}\right) \quad (3)$$

where $\Delta t_{\mathrm{L},n}$ and $\Delta t_{\mathrm{S},n}$ are the delay times calculated by the delay laws for focusing of L and S waves, respectively. In addition, t_{LS} represents the difference of excitation time set up for simultaneous focusing of S and L waves.

Figure 3 shows the calculated maximum displacement field near the focal point obtained by performing peak hold regarding displacement during ultrasonic wave propagation. Comparing Fig. 3 (a) and Fig. 3 (b), the maximum displacement field formed by the simultaneous focusing of L and S waves had a larger value of maximum displacement near the focal point than L waves focusing. To evaluate the displacement quantitatively, it was confirmed by numerical simulation that the displacement at the focal point is approximately 6.5 times larger than the incident wave amplitude in the conventional L-wave focusing method, while the proposed simultaneous focusing method provides approximately 8.6 times larger displacement than the incident wave amplitude at the focal point. Thus, it was found that this method can generate a displacement at the focal point that is approximately 1.3 times larger than that of the conventional method under a constant voltage.

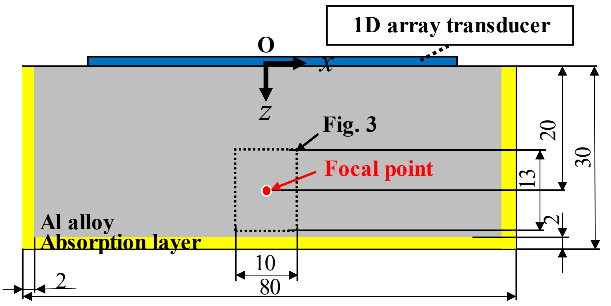

Fig. 2 Simulation model for finite element simulation: Simulation model for focusing L waves and for simultaneous focusing of L and S waves.

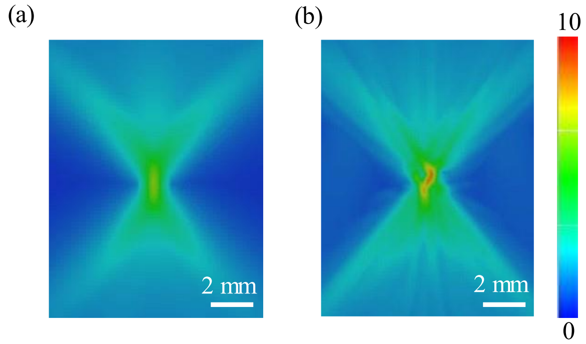

Fig. 3 Calculated displacement field around the focal point: (a) L-wave focusing (conventional), (b) simultaneous L- and S-wave focusing (the proposed method).

4. Conclusions

In this study, we proposed a method for increasing the incident wave amplitude by simultaneous focusing of L and S waves with a 1D array transducer by utilizing the delay and phase control. After describing the concept, we demonstrated its effectiveness in the numerical simulation. In future works, we will experimentally verify this method.

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References

1) Y. Ohara, H. Nakajima, S. Haupert, T. Tsuji, and T. Mihara, Jpn. J. Appl. Phys., **59** (2020) SKKB01.
2) Y. Ohara, T. Umezaki, E. Carcreff, S. Haupert, T. Tsuji, and T. Mihara, Jpn. J. Appl. Phys., **60** (2021) SDDB01
3) Y. Yang, T. Ma, Q. Zhang, J. Huang, Q. Hu, Y. Li, C. Wang, and H. Zheng, IEEE Trans. Biomed. Eng., **69** (2022) 7.