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Development of large-displacement laminated transducer and its application to SPACE

大振幅積層探触子の開発と SPACE 映像化への適用

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1. Introduction

Ultrasonic crack evaluation is typically based on the measurement of the crack tip echo. It is, however, difficult to detect cracks in complex structures and highly attenuative materials because of the complexity of the sound field and a lot of non-crack responses. Nonlinear ultrasonics[1)] is promising as a solution to this problem. Our group proposed a novel imaging method, subharmonic phased array for crack evaluation (SPACE),[1-3)] to visualize cracks with a high signal-to-noise ratio (SNR). SPACE utilizes the irradiation of a large-displacement ultrasonic wave onto a crack, which can generate the subharmonic wave owing to the contact vibration of the crack faces. Importantly, such subharmonic generation only occurs at cracks, resulting in high SNR in crack imaging. However, SPACE has been applied only to closed cracks because of an upper limit of incident wave amplitude. In this study, we develop a laminated transmitter to realize a larger-displacement incidence and then combine it with SPACE towards the industrial application of SPACE.

2. SPACE with a laminated transducer

Figure 1 shows a schematic illustration of SPACE using a laminated transducer. As described in detail later, a laminated transducer used in this study is composed of five piezoelectric elements, including one insulating layer. Each element is excited by a different pulser with an appropriate delay time to achieve constructive interference of the incident wave. We selected soft PZT with a high piezoelectric strain constant and a large capacitance. Note that soft PZT is not commonly used for ultrasonic flaw detection because of too low electrical impedance. For soft PZT elements, we have developed an SiC transistor-based high-current pulser. By combining a laminated transducer with the four SiC pulsers operated by a delay controller, large-displacement ultrasonic wave with a frequency of *f* is insonified onto the cracks, which can generate the subharmonic scattered wave (*f* /2) due to the contact vibration of the crack faces. The scattered waves are received with an array transducer. By filtering the received waves around *f* and *f*/2 and then applying delay-and-sum processing, the fundamental array (FA) and the subharmonic array (SA) images are obtained. Note that the subharmonic generation exhibits threshold behavior. That is, an incident wave amplitude above a threshold is required for the subharmonic generation. Therefore, the development of an efficient laminated transducer can extend the application fields of SPACE.

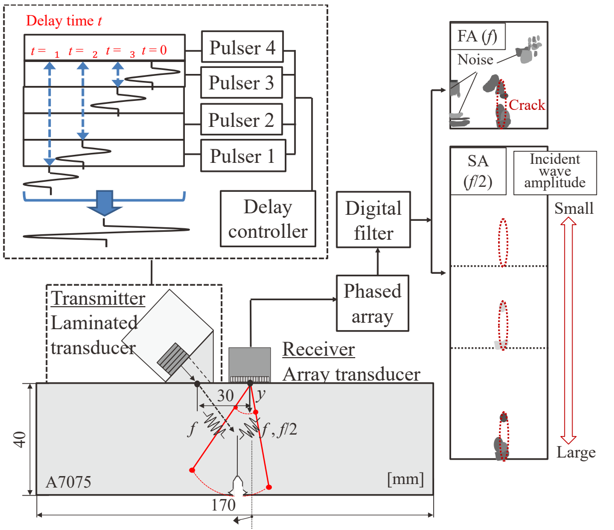

Fig. 1　Schematic illustration of SPACE using a laminated transducer.

3. Fabrication of a laminated transducer

To fabricate a laminated transducer, we bonded five soft PZT elements (**Fig. 2(a)**) with an adhesive on a wedge. Here we selected an aluminum alloy A7075 as a wedge material to increase the transmission coefficient. We then wired the electrodes on the PZT elements into coaxial cables. After bonding a case on the wedge, we filled the space within the case with a resin (Fig. 2(b)).

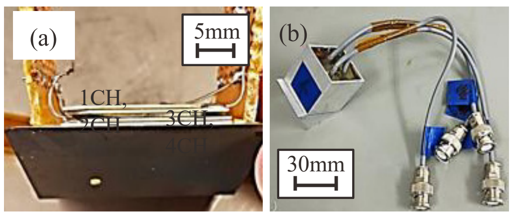

Fig. 2　Photos of laminated transducer: (a) internal structure, and (b) fabricated laminated transducer.

To evaluate the laminated transducer, we measured the out-of-plane displacement at the surface with a laser Doppler vibrometer (**Fig. 3(a)**). Here the measurement position corresponds to the crack position in Fig. 1. Each element was excited by a five-cycle burst with 5 MHz at up to 300 V. As a result, the displacement linearly increased with increasing the excitation voltage (Fig. 3(b)). The maximum displacement was above 100 nm. Note that larger displacement can be achieved since the maximum excitation voltage produced with the SiC pulser used in this study is approximately 750 V.

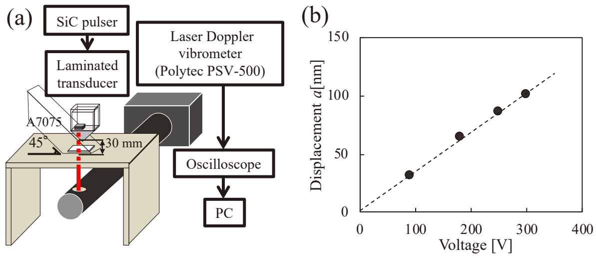

Fig. 3 Displacement measurement of the laminated transducer with a laser Doppler vibrometer: (a) Experimental configuration and (b) incident wave amplitude measured as a function of excitation voltage.

4. Experimental conditions

To verify SPACE using the laminated transducer, we made a fatigue-crack sample (A7075) by a three-point bending test. The fatigue conditions were a stress intensity factor range $\Delta K = 13\ \mathrm{MPa}\cdot\mathrm{m}^{1/2}$ and a stress ratio R= 0.067. We positioned the laminated transducer and a 32-elements array transducer on the top of the sample (Fig. 1). We varied the excitation voltage up to 300 V, corresponding to 101 nm at the crack position. The SiC pulsers were operated with a delay controller and were synchronized with phased array hardware. We set the imaging area with θ= −10 to 35° (2° step) and z = 10 to 40 mm (4 mm step).

5. Experimental results

Figure 4 shows the FA and SA images obtained at the different excitation voltages. The FA images (Figs. 4(a)-4(c)) visualized the crack as well as the notch and the bottom. These images showed sufficient SNRs, whereas such FA images may be insufficient in the case of highly scattering materials, for instance, since ultrasonic scattering at grain boundaries can hide crack response. On the other hand, such linear scattering does not appear in SA images. Hence, we examined the incident-wave-amplitude dependence of the SA images. At a=31nm (Fig. 4(d)), the crack response was weak. This shows that the incident wave amplitude was insufficient to cause the contact vibration of the crack faces, although such incident wave amplitude is larger than those used in Refs. 1-3. By increasing a to 62 nm (Fig. 4(e)) and 101 nm (Fig. 4(f)), the crack response markedly increased. This suggests that the incident wave amplitudes were above the threshold of the subharmonic generation.

We quantitatively examined the intensity of the crack response in the SA images obtained at a= 9 to 101 nm (**Fig. 5**). Here the intensity was calculated as a mean value within a region surrounded by a black square (Fig. 4). As a result, the intensity of the crack response exhibited a threshold behavior. The nonlinear change was an upward convex curve, which was reported in Ref. 2. Thus, we demonstrated the importance of large-displacement ultrasonic incidence in SPACE.

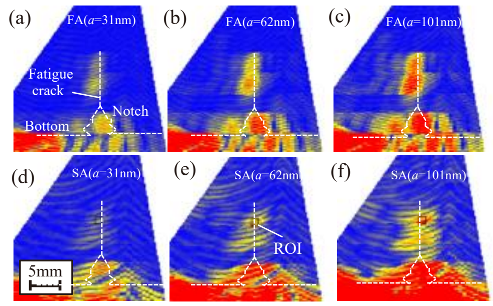

Fig. 4 Imaging results of the fatigue crack obtained at different incident wave amplitudes.

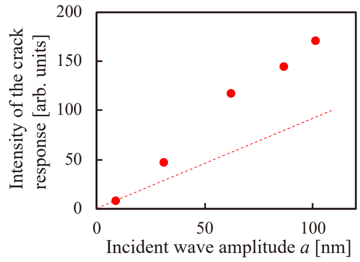

Fig. 5 Relationship between the intensity of the crack response in the SA images [Figs. 4(d)-4(f)] and the incident wave amplitude.

Conclusions

We made the laminated transducer and demonstrated the capability of the large-displacement ultrasonic incidence. We then applied SPACE using the laminated transducer to the A7075 fatigue-crack sample. As a result, the crack response markedly appeared in the SA images by increasing the incident wave amplitude. This shows that the SPACE using the laminated transducer is a practical approach towards the industrial application of SPACE.

Acknowledgments

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References

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