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3D Ultrasonic Phased-Array Imaging of Fatigue Cracks Using a Piezoelectric and Laser System (PLUS)
圧電送信と超多点レーザ 2D スキャンによる疲労き裂の 3D 超音波フェーズドアレイ映像化

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1. Introduction

Fatigue cracks are severe defects in aging structures, resulting in the potential of catastrophic accidents. The accurate measurement of fatigue cracks is indispensable for the safe and reliable operations of such structures.1-4) One of the most critical parameters is crack depth, which is essential for estimating material strength. On the other hand, fracture mechanics indicates that crack depth can change in the crack-length direction.5) To achieve more sophisticated management, three-dimensional (3D) measurement of fatigue cracks would be required. It would also play a vital role for the digital twin. Whereas ultrasonic phased array (PA) has been widely adopted in industrial fields, most PAs provide only two-dimensional (2D) images because of the limited number of elements of piezoelectric array transducers.

To open up a new avenue to 3D PA imaging, we proposed a piezoelectric and laser ultrasonic system (PLUS)6). The PLUS combines a piezoelectric transmitter and a mechanical scan of a laser Doppler vibrometer (LDV) to create a 2D matrix array with ultra-multiple elements. In this study, we examine the importance of utilizing ultra-multiple elements of PLUS in a fatigue-crack specimen for high-resolution 3D imaging.

2. Principle of PLUS

The PLUS combines a monolithic piezoelectric transmitter and a 2D matrix array receiver based on the 2D scanning of an LDV, as illustrated in **Fig. 1**. An ultrasonic wave is emitted into a sample at an incident angle by a piezoelectric transducer mounted on a wedge. The waves scattered at defects such as cracks are then received at a point of the top surface by an LDV. The same process is repeated while moving the receiving point over a scan area. A complete dataset of the received waveforms is transferred to a PC through an oscilloscope. It is then post-processed following an imaging algorithm.6) Here, the LDV receiving points correspond to the elements of a piezoelectric array transducer. Hence, the ultra-multiple elements of a 2D matrix array can be readily realized by increasing the number of receiving points, e.g., to the order of thousands, which is much higher than the maximum number of elements for a piezoelectric array transducer. A large-amplitude ultrasonic incidence by a piezoelectric transmitter can compensate for the intrinsically low sensitivity of the LDV. Additionally, an LDV has a broad reception bandwidth, enabling the same system over a broad frequency range just by changing a piezoelectric transmitter.

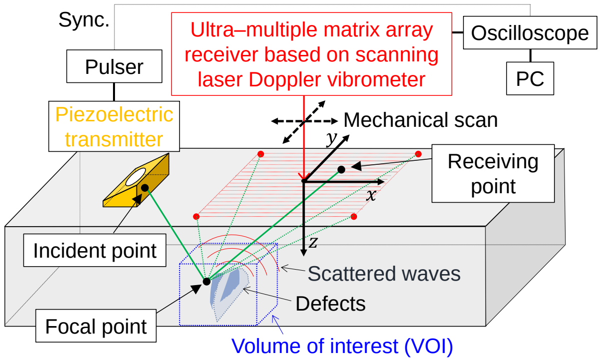

Fig. 1 Schematics of a 3D PA imaging system, PLUS.

3. Experiment

To demonstrate the efficacy of utilizing ultra-multiple elements of PLUS, we formed a fatigue crack in an aluminum alloy A7075 specimen with a three-point bending test. The fatigue conditions were a maximum stress intensity factor of 5.3 $\mathrm{MPa\cdot m^{1/2}}$ and a minimum stress intensity factor of 0.6 $\mathrm{MPa\cdot m^{1/2}}$.1) **Figure 2** shows the experimental configurations. A piezoelectric transmitter (5 MHz, ϕ12.8 mm) was coupled to a wedge to input transverse waves with an oblique incidence of 45°. The transverse wave speed was 3080 m/s. The transmitter was excited by a square wave at a negative voltage of 150 V. Scattered waves were measured at the top surface of the specimen by an LDV (OFV505, Polytec) that has a flat reception bandwidth between DC and 20 MHz. The received signals digitized at a sampling rate of 250 MS/s were averaged 64 times with an oscilloscope and then transferred to the PC for further processing. We repeated this data acquisition process while scanning the LDV over the following scan areas. To examine the efficacy of utilizing ultra-multiple elements, we selected two scanning conditions. One was 256 receiving points (i.e., 16×16) to simulate a maximum number of elements for a piezoelectric 2D matrix array. The other one is ultra-multiple elements, 4118 receiving points (i.e., 71 × 57), which is impossible for piezoelectric array transducers, to demonstrate a high-resolution 3D imaging capability of PLUS. Here the pitch between the adjacent receiving points was 0.5 mm in both *x*- and *y*-directions. The volume of interest (VOI) was set to 26×26×26 mm^3 with pitch 0.5 mm in the *x*-, *y*-, and *z*-directions.

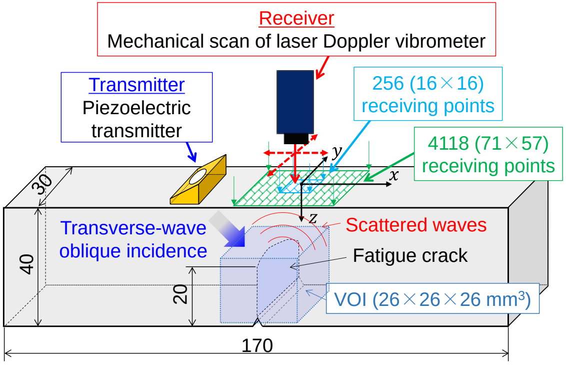

Fig. 2 Experimental configurations.

Figures 3(a) and 3(c) show the 3D images obtained by the PLUS with 256 and 4118 receiving points, respectively. The 3D images showing the responses above a threshold were superimposed on a semitransparent B-scan image in a *YZ* plane at *x*=-23 mm. The B-scan images are also shown as opaque images in Figs. 3(b) and 3(d), respectively. Figure 3(e) illustrates the relationship of the fatigue crack and the imaging regions for Figs. 3(a)-3(d).

For the matrix array with 256 receiving points, the fatigue crack was imaged as a single response. However, the detail of the fatigue crack was not resolved because of a low resolution resulting from the limited number of receiving points. It suggests that 256 receiving points were insufficient to realize a high-resolution 3D imaging.

For the matrix array with ultra-multiple elements, i.e., 4118 receiving points, the fatigue crack was precisely visualized as a collection of multiple scattering points. The image resolution was much higher for 4118 receiving points than for 256 receiving points. Notably, the outline of the fatigue-crack geometry was obtained by connecting the responses at the fatigue crack tips in the *y*-direction, as denoted by a white dotted curve in Fig. 3(d). The geometry showing the maximum depth around the center in the *y*-direction was in good agreement with fracture mechanics.[5] Note that the crack tip in Fig. 3(d) was deeper than that in Fig. 3(b). It suggests that the PLUS with ultra-multiple receiving points is useful for accurate crack-depth measurement.

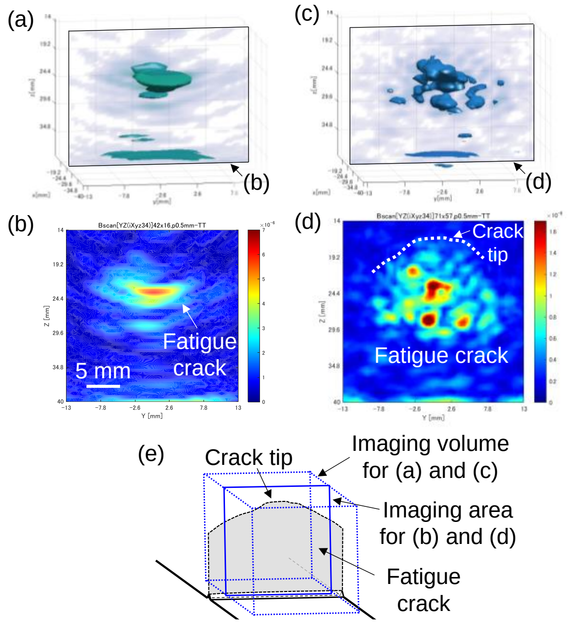

Fig. 3 Imaging results of a fatigue crack by PLUS and a schematic illustration: (a) 3D image and (b) *YZ* image at *x*=-23 mm obtained with 256 receiving points. (c) 3D image and (d) *YZ* image at *x*=-23 mm obtained with 4118 receiving points. (e) Schematics illustrating a relationship between fatigue crack and imaging regions.

4. Conclusions

We examined the importance of utilizing ultra-multiple elements of PLUS for high-resolution 3D imaging in the fatigue-crack specimen. As a result, the PLUS with 4118 receiving points showed a much higher-resolution 3D imaging capability than that with 256 elements, which correspond to a maximum number of elements for piezoelectric array transducers. Further, the PLUS with 4118 receiving points provided the whole geometry of the fatigue crack and the accurate crack depth. Such accurate 3D crack images obtained with the PLUS would lead to more sophisticated management for aging infrastructures.

Acknowledgments

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