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3D Ultrasonic Imaging of Small Defects Using High-Frequency Piezoelectric Transmitter and Ultra-Multiple Laser 2D Scanning

Takumi Yamada[1 ‡], Yoshikazu Ohara[1], T. J. Ulrich[2], Marcel C. Remillieux[2], Toshihiro Tsuji[1], and Tsuyoshi Mihara[1] ([1]Tohoku Univ.; [2]Los Alamos National Laboratory)

1. Introduction

In the aircraft and automotive industries, thinning of structural components has been progressing to reduce the weight of airplanes and cars. To ensure the safety and reliability of those thin components, the detection and accurate sizing of early-stage defects are critically important. Although ultrasonic phased array (PA) is widely used in industrial fields, most PA uses a linear array transducer, producing the two-dimensional (2D) images that are spatially averaged over the elevation aperture of the linear array transducer. This may be insufficient for early damage detection in terms of sensitivity. To overcome this difficulty, high-frequency 3D PA imaging using a 2D array transducer would be promising. However, the maximum number of elements for nondestructive testing (NDT) application has been limited to 256 because of prohibitive costs. In addition, the high-frequency piezoelectric 2D array transducer fabrication may encounter technical difficulties because of a small inter-element pitch. This may result in the insufficient sensitivity and resolution of current PA techniques.

On the other hand, we have developed a novel 3D PA imaging method, piezoelectric and laser ultrasonic system (PLUS).[1-3] PLUS uses a piezoelectric transmitter and a 2D scan of a laser Doppler vibrometer (LDV). Hence, increasing the LDV scan points can overcome the upper limit of the number of elements for piezoelectric array transducers. Furthermore, the frequency can be arbitrarily selected just by changing a piezoelectric transmitter since the LDV has a broad reception bandwidth. On the other hand, the effectiveness of PLUS has been verified only for a frequency of 5 MHz, which is typically selected for thick samples.

In this study, we propose a high-frequency PLUS that uses a frequency of more than 15 MHz for the NDT of micro defects in thin materials. After describing the concept of high-frequency PLUS, we examined its fundamental performance of 3D imaging capability by comparing the results obtained by a 1D array transducer (15 MHz).

2. Principle of High-Frequency PLUS

Figure 1 shows the schematics of high-frequency PLUS. For high-frequency PLUS, a piezoelectric transmitter with a center frequency of more than 15 MHz to achieve both high sensitivity and high spatial resolution. The transmitter is placed on a wedge for the oblique incidence into a thin sample. The waves scattered at micro defects are then received by an LDV, where the LDV is two-dimensionally scanned to simulate an ultra-multiple 2D matrix array. Note that a laser spot for the reception can be tens of μm. This enables a small element pitch, which cannot be realized for piezoelectric array transducer, for high-frequency 2D matrix array. Subsequently, a dataset of the received waveforms is post-processed by a 3D imaging algorithm derived from the sound speed and geometric relationships.[1,2] Thus, we can obtain a high-resolution and high-sensitivity 3D image.

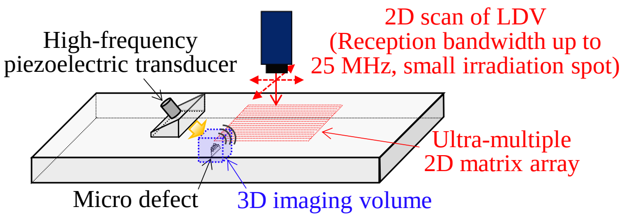

Fig. 1 Schematics of high-frequency PLUS.

3. Experiment

To confirm the fundamental performance of high-frequency PLUS, we made an aluminum-alloy specimen (A7075, 12 mm thick) with a flat bottom hole (FBH) of ϕ1 mm and 3 mm in height.

Figure 2(a) shows the experimental conditions for the 3D imaging by high-frequency PLUS. A piezoelectric transmitter on a wedge was positioned for the oblique incidence of a shear wave at 45°. The excitation voltage was a square wave (15 MHz, 150 V). The LDV was two-dimensionally scanned at 0.25 mm pitch for 3600 (i.e., 60 × 60) receiving points. The received waveforms were recorded at a sampling frequency of 500 MS/s after 256 averaging. We post-processed a dataset of received waveforms to obtain the 3D image around the FBH.

For comparison, we also mechanically scanned a linear array transducer (15 MHz, 32 elements, 0.5 mm pitch) from $x = -1{\sim}1$ mm with a

0.5 mm step (Fig. 2(b)). We obtained B-scan (*yz*-plane) images ($\theta = -15$ to 15° (0.2° step) and $r = 8.5$ to 9.5 mm (0.5 mm step)).

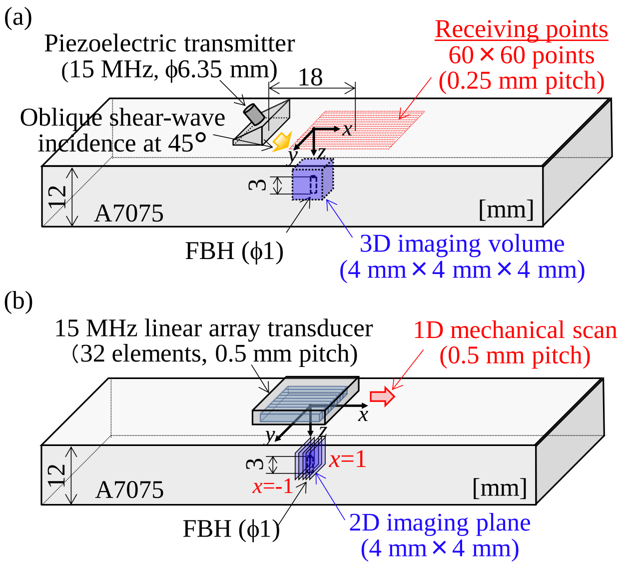

Fig. 2 Experimental conditions of imaging FBH: (a) high-frequency PLUS, (b) linear array transducer.

Figure 3(a) shows the 3D imaging result by the high-frequency PLUS. The top of the FBH was visualized at the correct position. The spatial resolution was higher than that for 5 MHz.[1]

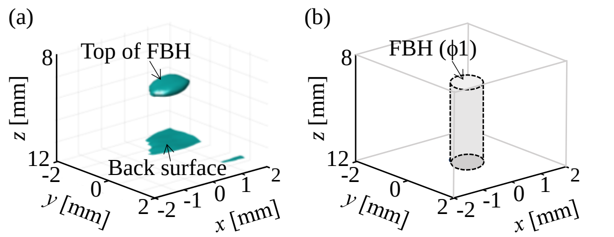

Fig. 3 (a) 3D imaging result of the FBH by high-frequency PLUS. (b) schematic illustration of FBH.

For more detailed analysis, the B-scan (*yz*-planes) images were extracted at $x = -1, -0.5, 0, 0.5$, and 1 mm from Fig. 3, as shown in **Figs. 4(a)–(e)**, respectively. At $x = -0.5$ and 0.5 mm, corresponding to the edge of the FBH, the response was almost half of that at x=0. At $x = \pm 1$ mm, no response was observed. In addition, we quantitatively examined the full width at half maximum of the response in the *x*- direction. As a result, it was approximately 1.1 mm, which was in good agreement with the actual size (1.0 mm). For comparison, the B-scan images obtained by the linear array transducer at $x = -1, -0.5$, 0, 0.5, and 1 mm are shown in Figs. 4(f)–(j), respectively. The B-scan images were almost the same regardless of the *x* position of the linear array transducer, in contrast to Figs. 4(a)-(e). This is because the elevation aperture (10 mm) of the linear array transducer was limited to the resolution in the *x*-direction. Thus, we demonstrated the fundamental 3D imaging capability of high-frequency PLUS.

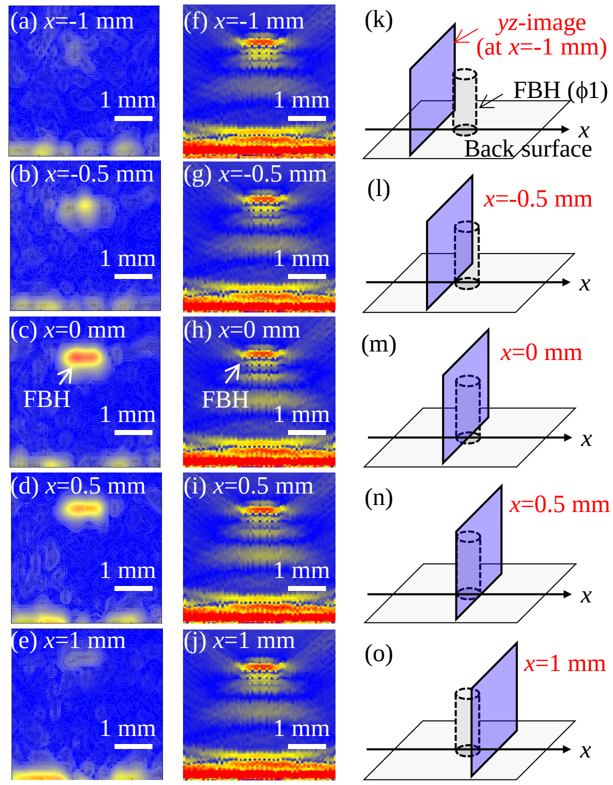

Fig. 4 Imaging results of the FBH and schematic illustrations: (a)-(e) *yz* images extracted at $x = -1, -0.5$, 0, 0.5, and 1 mm, respectively, from Fig. 3, which were obtained by the high-frequency PLUS, (f)-(j) B-scan (*yz*-plane) images obtained at $x = -1, -0.5$, 0, 0.5, and 1 mm, respectively, by 1D array transducer, (k)-(o) schematic illustrations for at $x = -1, -0.5$, 0, 0.5, and 1 mm, respectively.

4. Conclusions

We proposed the high-frequency PLUS for thin materials. After describing the principle, we demonstrated the fundamental 3D imaging capability in the specimen with FBH (ϕ1 mm). On the other hand, the defect used in this study was insufficient to show the high-resolution, high-sensitivity 3D imaging capability of the proposed method. Therefore, we will deal with a smaller FBH and small fatigue crack and perform scattering analysis[3] in those samples.

Acknowledgment

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References

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