3P2-16

Utilization of multiple modes in high-frequency 3D ultrasonic phased array imaging method (PLUS)

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

1. Introduction

Nondestructive testing (NDT) of defects is inevitable for improving the safety and reliability of aging structures and industrial products. Particularly, an early-stage small defect can affect the material strength in thin components commonly used in the aerospace and automotive industry. Thus, a highly sensitive method for small defects in thin components is indispensable. Although ultrasonic phased arrays (PA) are widely accepted in industrial fields, most PAs perform two-dimensional (2D) imaging using a linear array transducer, which cannot resolve the three-dimensional (3D) structure of actual defects. Moreover, a sensitivity for small defects may be insufficient due to line focusing. To solve these problems, the use of a piezoelectric 2D matrix array transducer is one of the effective approaches. However, the number of elements is limited due to cost issues in NDT fields, which may lead to a lack of resolution and sensitivity. In terms of frequency selection, a higher frequency than 15 MHz is valid for thin components or less-attenuative materials. However, the design adopting a small element pitch, which is required for a high-frequency 2D array transducer, makes the fabrication difficult.

To overcome these difficulties, we proposed a high-frequency piezoelectric and laser ultrasonic system (high-frequency PLUS),[1)] which is an extension of PLUS.[2-5)] As described later, the combination of a high-frequency piezoelectric transmitter and a 2D scan of a laser Doppler vibrometer (LDV) enables a high-frequency ultra-multiple 2D array. For PLUS using a typical frequency such as 5 MHz, multi-mode PLUS that utilizes multiple mode-converted scattered waves was also used. The use of multiple modes enables us to obtain more information about defects, and the spatial resolution can be improved by using mode-converted shear scattered waves. However, the multiple mode imaging has yet to be combined with high-frequency PLUS.

In this study, we proposed multi-mode high-frequency PLUS to enhance resolution and imaging capabilities. After describing the concept and imaging algorithm, we performed 3D imaging of simple defects to examine the fundamental performance.

E-mail: ‡takumi.yamada.t5@dc.tohoku.ac.jp,
*ohara@material.tohoku.ac.jp

2. Principle of multi-mode high-frequency PLUS

High-frequency PLUS combines a high-frequency piezoelectric transmitter and 2D scanning of an LDV (**Fig. 1**). A high-frequency piezoelectric transducer is set on a less-attenuative wedge for an oblique incidence. The waves scattered from defects are received by the LDV. Note that the scattered waves contain both longitudinal and mode-converted shear modes. By scanning the LDV two-dimensionally, a 2D matrix array receiver is simulated. Note that a small laser spot diameter (tens of μm) and precise mechanical scanning enable a small element pitch required in a high-frequency array. Moreover, a large aperture, which can receive scattered waves extensively at one measurement, can be realized by increasing the number of receiving points.

To create 3D images utilizing multiple modes, a following 3D imaging algorithm considering mode conversion is applied to a dataset of received waves. The propagation time from the transmitter $\mathbf{r}_\mathrm{T}$ through a focal point $\mathbf{r}$ to a receiving point $\mathbf{r}_{nx,ny}$ of 2D array is calculated as

$$t_{nx,ny,i,j}(\mathbf{r}) = \frac{|\mathbf{r}_\mathrm{T} - \mathbf{r}_\mathrm{I}|}{V_\mathrm{w}} + \frac{|\mathbf{r}_\mathrm{I} - \mathbf{r}|}{V_i} + \frac{|\mathbf{r} - \mathbf{r}_{nx,ny}|}{V_j}$$

where V_w is the longitudinal wave speed in the wedge, and V_i and V_j are the speeds of incident and scattered waves, respectively. i and j are either L for a longitudinal wave or T for a transverse wave. For a longitudinal-wave incidence (i=L), not only the longitudinal (j=L) but also the mode-converted shear (j=S) scattered waves were utilized for imaging.

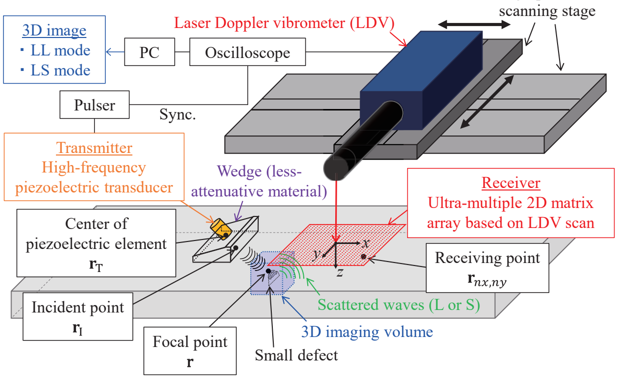

Fig. 1 Schematics of multi-mode high-frequency PLUS.

3. Experiment

To examine the fundamental performance of multi-mode high-frequency PLUS, we made an aluminum-alloy specimen (A7075, 10 mm thick) with a flat-bottomed hole (FBH) of ϕ0.5 mm and 3 mm in height. The longitudinal and shear wave speed V_L and V_T were measured to be 6173 m/s and 3080m/s, respectively.

Figure 2 shows the experimental conditions. A piezoelectric transmitter (15 MHz, ϕ6.35 mm) was positioned on a wedge for an oblique longitudinal-wave incidence at 45°. The wedge was made of high-density polystyrene. The excitation voltage was a three-cycle square wave (200 V, 15 MHz). The scattered waves received by an LDV(OFV 505, Polytec) were digitized with a sampling frequency of 500 MS/s after 256 averaging. The LDV was mechanically scanned over 61×61 points at 0.25 mm pitch to simulate a 2D matrix array receiver. A dataset of received waves was post-processed to obtain 3D images of FBH for LL and LS modes.

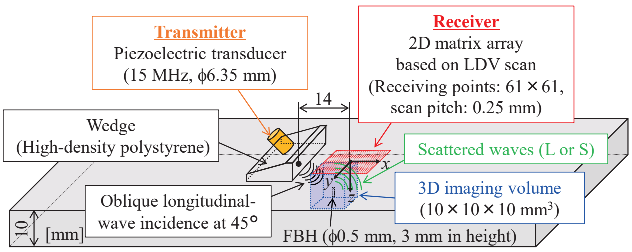

Fig. 2 Experimental conditions for imaging an FBH specimen by PLUS using LL and LS modes.

Figures 3(a) and **3(b)** show the 3D imaging results for LL and LS modes, respectively. The maximum value of the color bar was set to the maximum response intensity of FBH, and the scattering intensity above the half was displayed. The top of FBH was visualized correctly for both LL and LS modes. Figures 3(c)–3(f) show the B-scan images of *yz*-plane and *xz*-plane, where 3(c) and 3(e) are extracted from 3(a), 3(d) and 3(f) are extracted from 3(b), respectively. Although the top of FBH was visualized in high resolution for both modes, the spatial resolution for LS mode was higher than that of LL mode. This is an effect of utilizing the mode-converted shear waves with half of the wavelength of longitudinal waves. Additionally, the top of FBH was visualized with high signal-to-noise ratios for both modes. That means both longitudinal and mode-converted shear scattered waves were sufficiently generated at the top of FBH. Thus, we demonstrated the fundamental performance of multi-mode high-frequency PLUS.

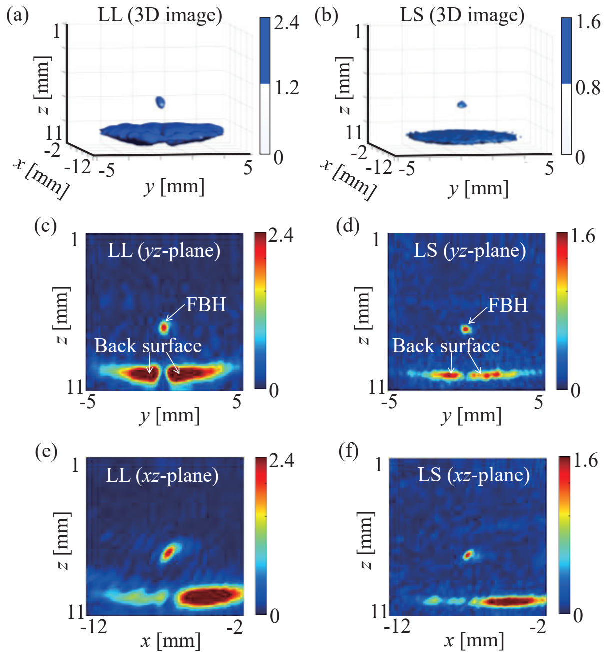

Fig. 3 3D imaging results of FBH specimen: (a),(b) 3D images for LL and LS modes, respectively, (c),(e) B-scan images in *yz*- and *xz*-plane extracted from (a), respectively, for LL mode, (d),(f) B-scan images in *yz*- and *xz*-plane extracted from (b), respectively, for LS mode.

4. Conclusions

We proposed the multi-mode high-frequency PLUS to improve the spatial resolution and 3D imaging capability. After describing the principle and imaging algorithms, we confirmed the fundamental performance with 3D imaging of FBH. Although the FBH was a simple defect, actual defects have a complex structure, which would lead to more complex scattering behavior and mode conversion. A dominant mode of scattered waves may change depending on the location of scattering, which would lead to increasing the usefulness of utilizing multiple modes in high-frequency PLUS. In future works, we will deal with a small fatigue crack specimen and verify the effectiveness of multi-mode high-frequency PLUS.

Acknowledgment
This work was partially supported by JSPS KAKENHI (19K20910, 21H04592, and 22K18745) and JST FOREST Program (JPMJFE2023).

References

1) T. Yamada, et al.: Proc. Symp. Ultrason. Electron., 43 (2022) 3Pb2-2.
2) Y. Ohara, et al.: APL, 117 (2020) 111902.
3) Y. Ohara, et al.: JJAP, 61 (2022) SG1043.
4) Y. Ohara, et al.: Sci. Rep., 12 (2022) 8291.
5) Y. Ohara, et al.: JJAP, 62 (2023) SJ1019.