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Development of low-frequency 3D ultrasonic phased array for visualizing crack-type defects in highly attenuative materials

Yuto Fujikawa[1‡], Takumi Yamada[1], Tomoki Nagata[2], Hyo Eun Joo[2], Yuya Takahashi[2], Timothy James Ulrich[3,4], Marcel C. Remillieux[3], Yoshikazu Ohara[1*]
([1]Tohoku Univ.; [2]Tokyo Univ.; [3]Los Alamos National Laboratory; [4]Texas A&M Univ.)

1. Introduction

Currently, the aging of concrete structures has become a global social issue. The aging can lead to various types of damage, such as cracks, delamination, rebar corrosion, and erosion. Cracks can accelerate the deterioration by creating pathways for gas and liquid infiltration, potentially leading to rebar corrosion that decreases the structure's durability. Therefore, quantitative nondestructive inspection techniques for measuring the direction, depth, and distribution of cracks are required to ensure the safety and reliability of concrete structures.

Visual testing and hammering test are widely used as on-site inspection methods for concrete infrastructure. However, they only detect surface and subsurface defects, respectively. For the nondestructive internal inspection, the low-frequency ultrasonic phased array (PA), MIRA, has been developed and commercialized.[1)] MIRA can achieve the internal imaging of high attenuative concrete by using a very low frequency of 55 kHz to reduce the effects of attenuation. However, the use of such a very low frequency significantly weakens the scattered waves from the crack tips, making it difficult to image the cracks.

On the other hand, we have developed a 3D PA imaging method, piezoelectric and laser ultrasonic system (PLUS)[2-7)], which combines a piezoelectric transducer as a transmitter and the two-dimensional scan of laser Doppler vibrometer (LDV) as a receiver. PLUS can achieve high-resolution 3D images through a 2D matrix array receiver with thousands of LDV receiving points. Furthermore, the frequency for PLUS can be arbitrarily selected by changing the frequency of the piezoelectric transmitter, since the LDV has a broad reception bandwidth from 0 to 25 MHz. We have reported the development of PLUS for 5 MHz and 15 MHz for metallic samples.[2-6)] For concrete structures, low-frequency PLUS was proposed by adopting a low-frequency (hundreds of kHz) piezoelectric transmitter, where the fundamental performance was demonstrated to visualize delamination in concrete sample.[7)] On the other hand, such a frequency for PLUS has the potential to visualize crack-type defects since it is higher than 55 kHz used in MIRA.

In this study, we applied the low-frequency PLUS to crack-type defects in highly attenuative materials. First, we explain the concept of the low-frequency PLUS, then describe the sample preparation, and finally demonstrate the fundamental 3D imaging capability of crack-type defects.

2. Principle of Low-Frequency PLUS for visualizing crack-type defects

Figure 1 shows the schematics of low-frequency PLUS. For ultrasonic transmission, a low-frequency (hundreds of kHz) piezoelectric transducer is used to visualize crack-type defects in highly attenuative materials. The transmitter is placed on a large wedge, and ultrasonic waves are obliquely inputted into a sample. An LDV then receives the waves scattered at defects. By repeating the same process while scanning the LDV in two dimensions, a 2D matrix array receiver with more than 1000 receiving points is simulated, which is not feasible with a piezoelectric array transducer. A 3D image is created by the post-processing of a dataset of the received waveforms using an imaging algorithm,[2-7)] which was derived from the ultrasonic sound speed and geometric relationships.

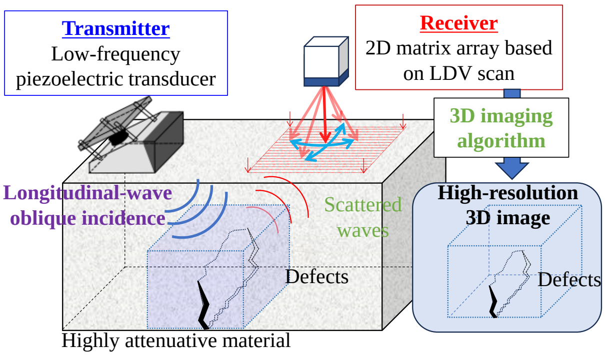

Fig. 1 Schematics of low-frequency PLUS.

3. Sample Preparation

We fabricated mortar samples as an attenuative materials, as shown in **Fig. 2**. We first mixed cement, fine aggregates (5 mm or less), and water, then poured the mixture into a mold, and

E-mail: ‡yuto.fujikawa.q6@dc.tohoku.ac.jp,
*yoshikazu.ohara.b3@tohoku.ac.jp

cured it for 28 days under sealed conditions (Fig. 2(a)). Here, the water-cement ratio was set to 55%, which is typical for infrastructure. The fabricated mortar sample is shown in Fig. 2(b). The sample size was 400 mm × 200 mm × 200 mm, and we introduced a slit with 1 mm width at a depth of 160 mm as a crack-type defect (Fig. 2(c)). Note that the slit is thought to be more challenging than the delamination,[7)] because the ultrasonic scattering at the slit tip is much weaker than the ultrasonic reflection at the delamination.

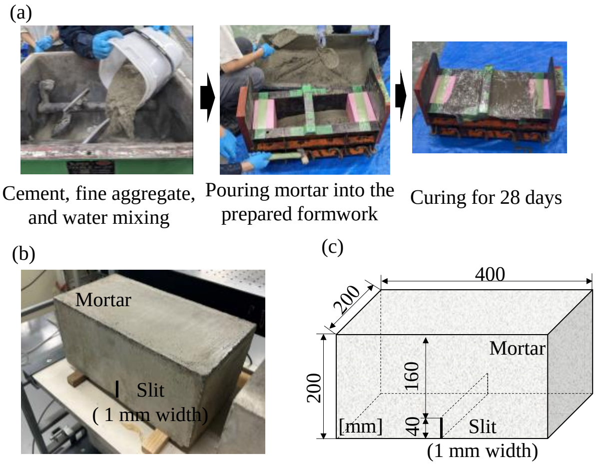

Fig. 2 Mortar sample with a slit (a) Preparation flow, (b) photo, and (c) design.

4. 3D Imaging by a Low-Frequency PLUS

To demonstrate the fundamental 3D imaging capability of the low-frequency PLUS for the crack-type defect, we visualized the slit inside the mortar sample. **Figure 3** shows the experimental conditions for the 3D imaging using the low-frequency PLUS. For oblique ultrasonic incidence, we used a 500 kHz piezoelectric transducer (V189-RB, EVIDENT) with a large wedge, which is expected to detect the crack-type defect. By exciting the transducer with a square wave at 100 V, a 45° longitudinal wave was transmitted into the sample. To simulate a 2D matrix array received, we employed infrared LDV (PSV-500, Polytec). Infrared LDV is expected to markedly enhance the signal-to-noise ratio (SNR) due to their higher output power compared to the He-Ne LDV

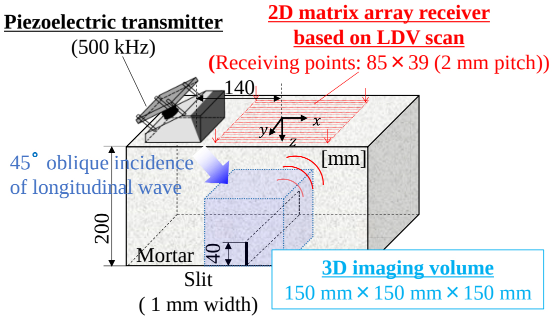

Fig. 3 Experimental conditions

employed in conventional PLUS [2-7)]. The number of receiving points was set to 85×39 points (= 3315 points) at 2 mm pitch. The scattered waves from the slit were then received by the LDV at a sampling frequency of 50 MS/s after 256 averaging. The 3D imaging volume was set to 150 mm × 150 mm × 150 mm around the slit with a 2 mm pitch.

Figure 4(a) shows the 3D imaging results of the slit. Here, we displayed the responses of scattering intensity above a threshold of 7.5×10^{-12}, which is half the maximum value of the color scale. We obtained a high-resolution 3D image of the slit. For further detailed analysis, we extracted the B-scan image [Fig. 4(b)] of the *xz*-plane from the 3D image [Fig. 4(a)]. The slit tip was visualized at the correct depth of 160 mm in high SNR. This experiment confirmed that the low-frequency PLUS has excellent 3D imaging capability to capture the weak scattered waves from the tip of the crack-type defects in highly attenuative material.

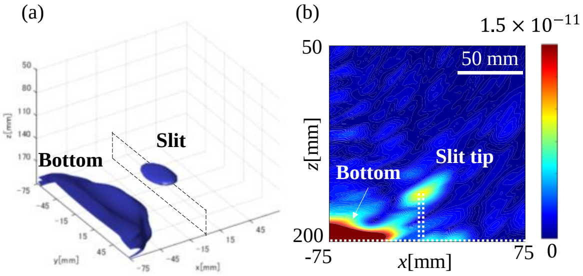

Fig. 4 3D imaging result of the slit obtained by low-frequency PLUS. (a) 3D view (b) B-scan (*xz*-plane at y = 0 mm) image extracted from (a).

5. Conclusions

In this study, we examined the applicability of low-frequency PLUS to crack-type defects in highly attenuative materials. We have introduced an infrared LDV and confirmed the performance of low-frequency PLUS with 3D imaging of the slit inside the mortar sample. In future works, we will verify the effectiveness of the low-frequency PLUS on concrete samples and actual cracks.

Acknowledgment

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