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Low-frequency 3D ultrasonic phased array imaging method using ultra-multiple laser scanning for concrete inspection

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1. Introduction

Concrete infrastructures have suffered from damage due to aging, which might result in catastrophic accidents. To ensure their safety and reliability in a sustainable way, nondestructive internal inspection is one of the key technologies. Ultrasonic phased arrays (PA) have been widely used for nondestructive internal inspection in industrial fields. However, most PAs use a 1D array transducer, which produces 2D images. Hence, it cannot measure the accurate size of the defects with 3D geometries that can be generated in actual structures. Furthermore, since the main target of PAs is metallic structures, the operating frequencies for a typical PA is on the order of MHz, which is too high to inspect concrete structures because of high scattering and attenuation. Available low-frequency array transducers with hundreds of kHz for crack measurement are severely limited because of the fabrication difficulty.[1)]

On the other hand, we have developed a novel 3D PA imaging method, piezoelectric and laser ultrasonic system (PLUS).[2-5)] PLUS can achieve high-resolution 3D images by combining an ultra-multiple-element (>1000) 2D receiver array based on the mechanical scan of a laser Doppler vibrometer (LDV) with a piezoelectric transmitter. Furthermore, the frequency can be arbitrarily selected only by changing a piezoelectric transmitter, since the LDV has a broad reception bandwidth from 0 through 25 MHz. Although the PLUS has been applied to metallic samples using MHz frequencies, it can be extended to utilize lower frequencies for highly attenuative materials such as concrete.

In this study, we propose a low-frequency PLUS using the frequencies in the order of hundreds of kHz for the internal inspection of concrete infrastructure. After describing the concept of low-frequency PLUS, we examined its fundamental 3D imaging capability in a concrete sample.

2. Principle of Low-Frequency PLUS

Figure 1 shows the schematics of low-frequency PLUS. For ultrasonic transmission, a low-frequency (hundreds of kHz) piezoelectric transducer is used for visualizing highly attenuative materials. The transmitter is placed on a large wedge and ultrasonic waves are obliquely inputted into a sample. The waves scattered at defects are then received by an LDV. 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. From a dataset of the received waveforms, we can obtain a high-resolution and high-sensitivity 3D image in post-processing using an imaging algorithm[2-5)] derived from the ultrasonic sound speed and geometric relationships.

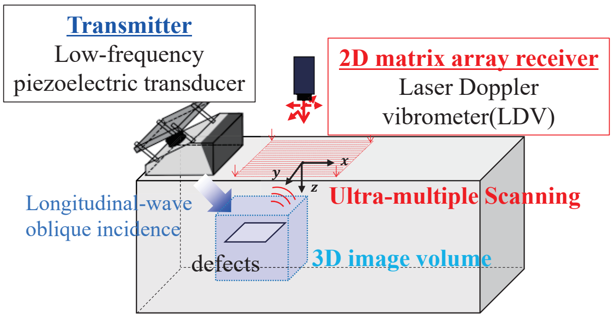

Fig. 1 Schematics of low-frequency PLUS.

3. Experiment

Given the use of low frequency, we first examined the duration of incident wave since it is one of the factors determining the image resolution, as shown in **Fig. 2**. A low-frequency piezoelectric transducer (500 kHz) was set on a large wedge fabricated for this application. This transducer was excited with a voltage of 100 V and a one-period square wave. The wedge was designed for the oblique incidence of longitudinal waves at 45° into the concrete sample. Figures 2(b) and 2(c) show the incident wave measured at the side of the concrete sample and its wavelet transform result. Despite the use of a 500 kHz piezoelectric transducer, the frequency component of the incident wave was around 200 kHz because of the attenuation of the high-frequency component during the propagation of ultrasonic waves through concrete, whereas the short-pulse wave was observed, which is promising a high temporal-resolution imaging.

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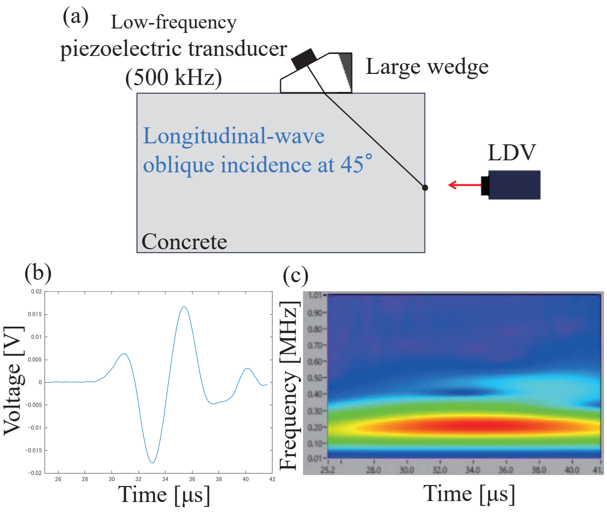

Fig. 2 (a) Measurement conditions (b) Incident waves (c) Wavelet transforms results.

To investigate the fundamental 3D imaging capability of low-frequency PLUS, we made a concrete sample with a delamination (50 mm×50 mm) at a depth of 100 mm. **Figure 3** shows the experimental conditions for the 3D imaging by low-frequency PLUS. The same conditions were used for the transmission as for the incident wave measurements in Fig. 2. The number of receiving points was set to 70×90 points (=6300 points) and the pitch between the adjacent receiving points was fixed to 2 mm in the *x*- and *y*-directions. A dataset of 6300 received waves was recorded at a sampling frequency of 50 MS/s after 256 averaging. We post-processed the waveform dataset to obtain a 3D image around the delamination. The imaging volume was set to 100×100×100 mm^3 with a pitch of 2 mm. Assuming the longitudinal-wave propagation for both incident and scattered/reflected waves, we calculated a delay law using the sound speed of a longitudinal wave.

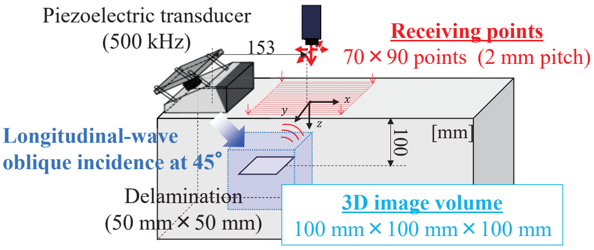

Fig. 3 Experimental conditions.

Figure 4(a) shows the 3D imaging results of the delamination by low-frequency PLUS, and Figs. 4(b) and 4(c) show the B-scan images in the *XZ* and *XY* planes extracted from the 3D imaging results (Fig. 4(a)). From Figs. 4(b) and 4(c), the delamination was visualized at the correct depth of 100 mm. The signal-to-noise ratio was sufficiently high. Furthermore, the response was in good agreement with the actual geometry indicated with a black dashed square (Fig. 4(c)). In the lower left of Fig. 4(b), a strong response appeared at a depth of 150 mm, which is different from the depth of the bottom. This can be interpreted as an artifact due to the mode-converted shear waves generated by the interaction between the incident longitudinal wave and delamination. This would suggest that the low-frequency PLUS can be effectively combined with the multi-mode concept.[5] Thus, we demonstrated the fundamental 3D imaging capability of low-frequency PLUS in attenuative materials.

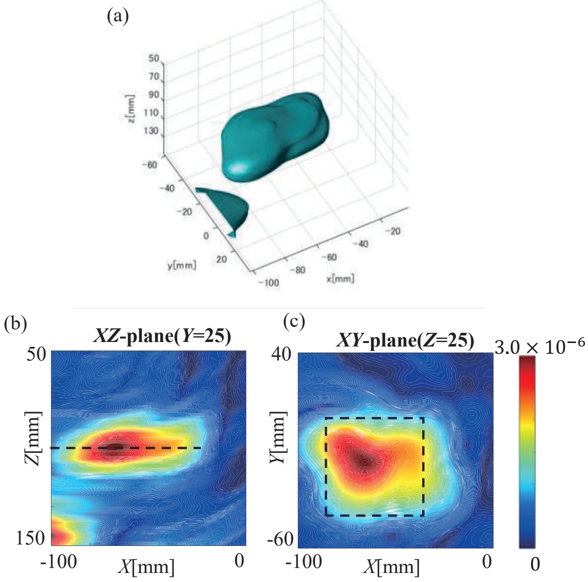

Fig. 4 (a) 3D imaging result of the delamination by low-frequency PLUS. (b)B-scan image in *XZ*-plane. (c)B-scan image in *XY*-plane.

4. Conclusion

In this study, we proposed low-frequency PLUS for highly attenuative materials such as concrete. After describing the principle, we confirmed the generation of short-pulse low-frequency ultrasound. We also demonstrated its fundamental 3D imaging capability of low-frequency PLUS in the concrete sample.

Acknowledgment

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