3P2-13

Observation of non-classical elastic nonlinearity in ultrafast phased-array imaging with large-displacement pump excitation

Yoshiaki Ishizuka [1‡], Sinan Li [2], Yoshikazu Ohara[1*]
([1]Tohoku Univ.; [2]Verasonics Inc.)

1. Introduction

Nonlinear ultrasonic phased array (PA) utilizing the crack opening/closing dynamics has been studied to measure closed cracks accurately. Although the performance of the measurement depends on the ability to induce the large displacement required to cause the crack opening/closing vibration,[1)] displacement generated by MHz order ultrasound that is generally used for testing metal materials was limited to tens of nm. On the other hand, the combination of mechanical or thermal loading with ultrasonic phased array has been studied to cause the contact vibration effectively.[2,3)] However, the former is limited to laboratory measurements using a large testing machine, while the latter uses temperature changes of the specimen and requires a long time for repeated measurements.

As a different means, the low-frequency vibration (pump waves) at kHz frequency range has been used for the nonlinear ultrasonics based on the waveform measurement (probe waves) at MHz frequency range. Since a typical phased array (probe waves) has a much lower frame rate than the kHz frequency range for pump waves, we proposed plane wave imaging (PWI) to realize ultrafast imaging for high-speed contact vibration of crack faces.[4)] The pump excitation at kHz frequency is capable of a large displacement incidence with more than 1000 nm, which is two orders higher than conventional methods. PWI can monitor the high-speed phenomena. This can extend the applicable objects for nonlinear ultrasonic phased array. The first proof of concept was carried out for contact testing,[4)] whereas water immersion testing is sometimes required for industrial applications. Furthermore, this method can be a tool for exploring nonclassical nonlinear phenomena (conditioning, hysteresis, recovery, etc.),[5)] which has been observed in higher nonlinear materials, such as rocks and sandstones.

In this study, we extended the ultrafast PWI with pump excitation to water immersion method, where a local water tank was installed. We performed not only the accurate measurement of closed-crack depth but also a fundamental investigation of nonclassical nonlinearity (hysteresis) through detailed analysis.

E-mail: ‡yoshiaki.ishizuka.p4@dc.tohoku.ac.jp,
*ohara@material.tohoku.ac.jp

2. Principle

Figure 1 shows the schematics of ultrafast imaging with pump excitation for water immersion testing. To cause the contact vibration effectively, the excitation of low-frequency (kHz) pump wave is utilized for the input of large displacement with over 1000 nm. During the pump excitation, PWI based on the plane wave incidence (MHz) is applied to monitor the high-speed crack opening/closing behaviors. PWI transmits a plane wave using an array transducer, and the scattered waves are then received by the same one. Subsequently, the recorded signals are post-processed following the delay and sum imaging algorithm. Importantly, the frame rate of PWI can be increased up to the pulse repetition rate. The delay law for water immersion testing is derived based on Fermat's principle, where the refraction at the interface between water and the top surface is considered. For the transmission and reception paths, the plane wave and cylindrically scattered wave propagations are assumed, respectively. The crack response in the PWI image can be changed because of the pump excitation, whereas the other scatterers and reflectors can not be changed. Therefore, by subtracting the PWI image obtained before the onset of the pump excitation from that during the pump excitation, the response changes due to the high-speed opening/closing vibration of the crack can be extracted.

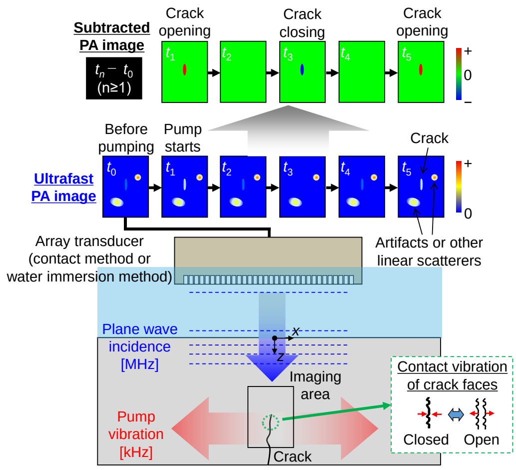

Fig. 1 Nonlinear ultrasonic phased array based on PWI with pump excitation for water immersion testing.

3. Experiment

Figure 2 shows the experimental setup. A water tank was installed on the top of a fatigue-crack specimen (A7075, a maximum stress intensity factor K_{max}=4.3 MPa·m$^{1/2}$, a minimum stress intensity factor K_{min}=0.6 MPa·m$^{1/2}$) for local water immersion testing. The array transducer (5 MHz, 128 el., 0.5 mm pitch) was partially immersed. To suppress the artifact due to the multiple reflections between the array transducer and the top surface of the specimen, we selected oblique incidence with 5°, where the water distance was set to 15 mm. Similarly to the previous study,[4] a piezoelectric ceramic disk (ϕ50 mm, 10 mm thickness) glued to the specimen was used to deliver the pump wave, where a heavy backload was used to increase the transmission energy of pump wave. Function generator (WF1946A, NF Inc.) and power amplifier (BA4825NF, NF Inc.) are used to excite the PZT disk. To maximize the pump wave displacement, the pump frequency at 6.948 kHz was selected to be the resonance frequency of the first longitudinal mode. An 800-cycle burst wave at 80 V was fed into the PZT disk. During the pump excitation, PWI was performed by a PA controller (Vantage 128, Verasonics Inc.). The frame rate for PWI was set to slightly less than a half of the resonance frequency, enabling the stroboscopic acquisition at gradually changing the phases of pump wave.

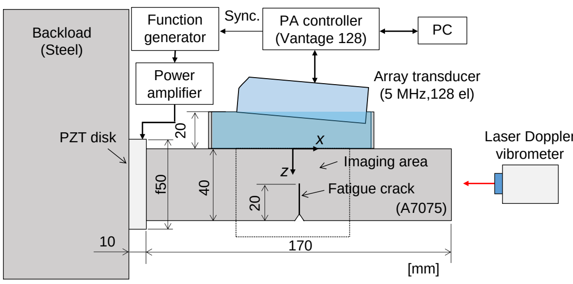

Fig. 2 Experimental setup.

Figure 3 shows the imaging result obtained by PWI during the pump excitation. In Fig. 3(a), in addition to the strong bottom responses, artifacts appeared around the weak crack response. To increase the signal-to-noise ratio, we carried out the subtraction process to the PWI images. In the subtracted images [Figs. 3(b)-3(c)], the crack response was successfully extracted while canceling the artifacts. This enables us to measure the crack depth accurately.

To investigate the nonclassical nonlinearity, the intensity change of the fatigue-crack tip as a function of time in **Figs. 4(a) and 4(b)**. The positive change was dominant, suggesting the fatigue-crack tip was originally closed. Figure 4(c) shows the crack-tip intensity change as a function of the pump strain. This shows the slight hysteresis. This might be understood by the adhesion force.

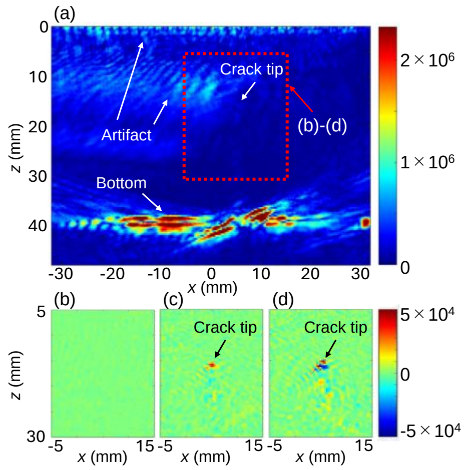

Fig. 3 Imaging results: (a) PWI image, (b)-(d) subtracted images before pumping, at maximum compressive and tensile strain, respectively.

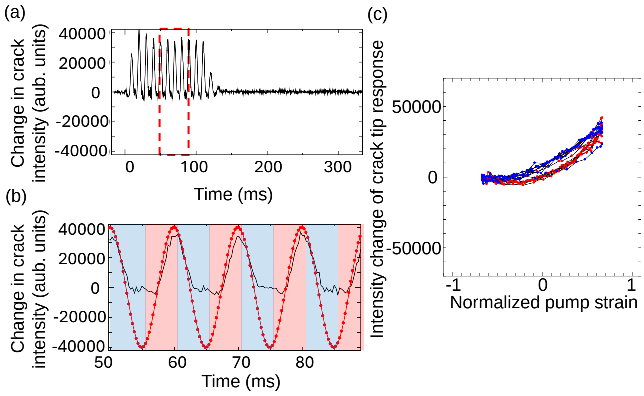

Fig. 4 Intensity change of the crack tip: (a), (b) intensity change and the pump strain change as a function of time, (c) intensity change as a function of the pump strain.

4. Conclusion

We extended the ultrafast PWI with pump excitation to the water immersion method. We performed not only the accurate measurement of closed-crack depth but also a fundamental investigation of nonclassical nonlinearity (hysteresis). This may lead to clarifying the nonclassical nonlinearity of sandstones and rocks.

Acknowledgment

This work was partially supported by KAKENHI (21H04592 and 22K18745), JST FOREST Program (JPMJFR2023).

References

1) K.-Y. Jhang, et al.; Measurement of Nonlinear Ultrasonic Characteristics (Springer, 2020).
2) Y. Ohara, et al.; Ultrasonics, 51 (2011) 661.
3) Y. Ohara, et al.; APL, 103 (2013) 031917.
4) Y. Ohara, et al.; Appl. Phys. Express, 14 (2021) 126505.
5) J. Riviere, et al.; J. NDE, 33 (2014) 216.