Improvement in the Identification of a Crack Tip Echo in Ultrasonic Inspection using Large Displacement Ultrasound Transmission

T Mihara¹ and H Ishida²
¹Professor, Graduate School of Engineering, University of Toyama, JP
²Senior Researcher, Institute of Nuclear Safety System, Incorporated, JP
E-mail: mihara@eng.u-toyama.ac.jp

Abstract. As an improvement in the imaging technique for the low S/N ratio of crack tip echo in ultrasonic inspection, we developed the Subharmonic Phased Array Crack Evaluation (SPACE) system. Although the pulser of conventional SPACE can generate large, over tens of nm, displacement ultrasound at a crack, it is effective only for closed cracks and not effective for most industrial cracks. For general use of the SPACE system in industrial inspection, we need to develop larger displacement ultrasound incidence equipment considering crack openings of the order of several nm to sub μm. In this study, we developed a high voltage excitation SPACE and larger amplitude ultrasound incident to a crack using a high voltage proof transducer. The suitability of the developed system was investigated using typical models of cracks.

1. Introduction

Accurate sizing in industrial inspection is a particular requirement of ultrasonic inspection to guarantee the strength of aging infrastructures. All the industrial ultrasonic inspection techniques, such as the tip echo method, time of flight diffraction (TOFD) and phased array, have used the crack tip diffraction echo. Thus, the measurement accuracy of all these industrial methods depends on the detection of the industrial crack tip. Although almost all crack tip detection using conventional ultrasonic inspections is accurate, it is difficult to detect the crack tips of some cracks because of the low signal to noise ratio (S/N ratio) of the crack tip diffraction echo caused by crack closure or by the large ultrasonic scattering noise, and so on. In these cases, correct judgment of the crack tip diffraction echo is sometimes difficult even for skilled engineers. Thus, new techniques are demanded to assist in the reliable determination of a crack tip. For this purpose, we developed the Subharmonic Phased Array for Crack Evaluation (SPACE) system [1-6]. Imaging in the SPACE system uses synthetic aperture procedures and additional digital filtering by improving a commercial phased array system. As a result, the fundamental image (for an incident frequency of ω, the ω image) and the subharmonic image (the ω/2 image) are able to be obtained independently using the SPACE system. We have demonstrated the use of the SPACE system in sizing the crack for a fatigue crack and a Stress Corrosion Crack (SCC) especially for a closed crack, which until now has been difficult to detect using conventional ultrasonic inspection techniques.

In this study, we investigated the validity and limitation of the existing SPACE system for the measurement of simulated industrial cracks, which were provided as model specimens for a nuclear
power generator. Furthermore, after the development of the high voltage SPACE system, as well as improving the transmit transducer, we investigated the validity of using the new SPACE system to extend the applicable limitations for generating subharmonic ultrasound at industrial cracks in the existing SPACE system.

2. SPACE Measurement System

The SPACE system is the first imaging system to use subharmonic ultrasound, which is able to obtain the fundamental and subharmonic images independently. Its schematic diagram is shown in Fig. 1. Subharmonic ultrasound is considered to be generated by clapping only at crack surfaces, which is the advantage in identification procedures of the crack tip, and is a more reliable indicator in accurate inspection than superharmonic ultrasound because large superharmonic ultrasound generates images even at ultrasonic wedges and couplants other than at a crack. It combines aperture synthesis procedures and digital filter processing using the commercial phased array system of PAL-3. The ultrasonic transmitter of the SPACE system used a high voltage pulser with a maximum excitation of 2200 V, which is standard equipment in nonlinear ultrasound measurement [3].

![Fig.1 Schematic diagram of SPACE](image)

To use reliable fundamental and subharmonic images in ultrasound measurement, narrow band burst excitation is required. However, when we use commercial or hand-made transducers for subharmonic ultrasound using high voltage burst pulses, these transducers can be damaged by heating and electrical shorting because of the high level of acoustic energy.

After the trials resulting in damaged transducers, we decided to use the transmit pulser below 500 V excitation voltage as the standard measurement condition for quantitative measurement conditions in our laboratory. An example of measurements, in these conditions, on aluminium alloy with a closed fatigue crack, is shown in Fig. 2 [3]. Because of crack closure, a crack tip echo was not detected by linear ultrasound of the fundamental image and, in contrast, a subharmonic image did detect the crack tip.

![Fig.2 Example of the advantage of SPACE on aluminium alloy](image)

As shown here, the SPACE system has been effective in the detection and accurate sizing of an industrial closed crack caused by residual compression stress. Conversely, many industrial cracks can be detected fairly accurately using conventional linear ultrasonic inspection methods, though some of their S/N ratios tend to be lower. If almost all industrial cracks are considered to be open, using the existing SPACE measurement system may be limited to only fully-closed cracks [1-6]. These limitations on the use of the existing SPACE techniques will become an impediment to extending the use of SPACE in industrial inspection fields.

2
3. Evaluation of industrial cracks using the existing SPACE system

To investigate the validity of the SPACE system, several specimens with various fatigue cracks and SCCs were measured using the SPACE system. Series A, the austenitic stainless steel SUS316 specimens (weld material is an Inconel alloy) with multiple SCCs, and series B, the austenitic stainless steel SUS316 weld specimens with a SCC, were prepared. In the future, we plan to slice cross-sections of the specimens to accurately measure crack size, however in this study, the depth of the SCCs was an estimated value. An excitation voltage of a burst of three waves at 400 V was applied as a standard condition for qualitative analysis using a single PZT transducer. An example of the measurement on specimen A is shown in Fig. 3. The figure on the left shows the fundamental image and on the right the subharmonic image. For SCC-1 the fundamental image (a) detected the crack tip, and the subharmonic image (b) did not. From this behaviour SCC-1 is assumed to be an open crack. However, for SCC-2, the depth of the crack tip detected by the subharmonic image was greater than the estimated crack depth and the fundamental image did not detect the crack tip. From this behaviour SCC-2 is assumed to be a closed crack.

4. Large amplitude ultrasound transmission techniques

Although the quantitative mechanism for generating subharmonic ultrasound at a crack has not been investigated until now, the incident ultrasound displacement must be greater than the opening displacement of a crack to generate the subharmonic ultrasound qualitatively [7, 8]. Ultrasound almost ten times greater in amplitude than in conventional ultrasonic inspection has been required for the generation of non-linear ultrasound. Thus, an existing SPACE system chose a high voltage burst pulser with a maximum excitation of 2200 V; however damage to the electrodes and electric-wire bonding of the transducer will occur at repeated voltage burst excitations beyond 500 V. In this research, the structures in the transducer were improved to withstand large voltage burst wave excitations of up to 1100 V for stable subharmonic ultrasound measurement. The details of the structure of the improved transducer are shown in Fig. 4. The various causes of damage to the transducer from high voltage excitation were 1) heating of an electric impedance matching coil, 2)
electrical shorts between electrodes and 3) breaks in the connecting structure between electrodes and the electric wires. To avoid damage, the structure of the electrode for a single PZT element was improved by eliminating the coil of the matching circuit for the measurement using the SPACE system.

Furthermore, instead of the silver/resin paste used in a commercial transducer, a new higher strength silver paste fabricated for operation at a high temperature was used. Because the fabricated temperature of the process is 600°C, which is higher than the Curie point of PZT, a repolarization process with a DC voltage of 1000 V/mm was applied for 30 min at 200°C after the fabrication of the transducer. Before the measurement using this transducer, the reliability of the improved structure for high voltage excitation was investigated using continuous bursts of 10 waves of excitation up to 1100 V for 50 h. The measurement results for the 2 MHz and 5 MHz transducers are shown in Fig. 5. Comparing the high voltage proof tests for transducers of the existing structures and of the improved structures, we confirmed the reliability of the improved transducer. The high voltage new SPACE system combining the improved 5 MHz transducer was applied to several cracks.

5. Application of the high voltage SPACE system for open cracks

We increased the excitation voltage for an incident transducer of SPACE from the existing level of 400–1100 V for several cracks. An example of the results is shown in Fig. 6 for SCC-1 in specimen B. In Fig. 6, the tip echo of crack was clearly detected when using a 400 V excitation for the fundamental image, and the amplitude of the crack tip echo increased linearly with excitation voltages of up to 1000 V. However, the absolute amplitude of the tip echo for this crack was almost 10 dB lower than that for other open cracks for all the excitation voltages.

Conversely, in the corresponding subharmonic images, the crack tip echo was not detected using 400 and 500 V excitations similar to the conventional measurements in the cases of open cracks. However, at an excitation voltage of 600 V a crack tip echo appeared in the subharmonic image and the amplitude of this echo increased with excitation voltages up to 1000 V. Because the location of the crack tip for the subharmonic image was the same as that for the fundamental image, the appearance of a subharmonic crack tip image could assist the reliable determination of a crack tip with the fundamental image measurement.
6. Considerations on the experiment and future work

To investigate whether the subharmonic image at the crack tip in Fig. 6 was not a leak of the fundamental ultrasound in the filtering process of SPACE, the initial waveform of the RF echo at 1000 V excitation before filtering was subjected to a wavelet transform as shown in Fig. 7. The frequency components of the crack tip echo had two independent peaks of fundamental and subharmonic frequencies. Thus, we confirmed that the subharmonic image at the crack tip in Fig. 6 was not a leak of the fundamental ultrasound but an apparent subharmonic ultrasound.

The amplitude of the crack tip echoes in the fundamental and subharmonic images for SCC-1 are summarized in Fig. 8. The noise level of the measurement was determined using the amplitude of the scattering noise from the microstructures of the welding specimen of austenitic stainless steel.

Fig. 7 Wavelet transform for the RF waveform of 1000 V excitation for SCC-1 in specimen B.

Fig. 8 Amplitude of the crack tip echoes in the fundamental and subharmonic images in Fig. 6.
At an excitation of 400 V, as our standard condition for the existing SPACE system measurement, SCC-1 was considered to be open because the crack tip echo was detected only in the fundamental image. Moreover, because the amplitude of the fundamental crack tip echo for SCC-1 was 10 dB lower than any other fully-opened crack, we estimated, on inspection, that SCC-1 was a semi-opened crack with a lower S/N ratio. The crack tip echoes increased linearly with the increase in excitation voltage amplitude. At an excitation of 600 V, the crack tip echo appeared in the subharmonic image for SCC-1 and its amplitude also linearly increased with the increase in excitation voltage. Thus, we conclude the following: (1) the other fully-opened cracks could be detected clearly using fundamental linear measurements with adequate S/N ratios, and (2) for the semi-opened crack of SCC-1, the detectability and reliability of crack tip detection decreased because of the lower S/N ratio of the crack tip echo. For this semi-opened crack, subharmonic ultrasound was generated when the large amplitude ultrasound with higher than 600 V excitation was incident to the crack for SPACE system measurement. Ultrasonic detectability of crack tips for SCC-1, with a lower S/N ratio in crack tip detection than for other fully-opened cracks in conventional inspection, was improved using the subharmonic image. Furthermore, for the closed crack, subharmonic measurement could be effective as shown in SCC-2 of Fig. 3(b).

In the future, when larger amplitude ultrasound is incident to the crack, we may generate the subharmonic waves even for more opened cracks. In addition, for closed crack measurement, larger amplitude ultrasound will be effective in improving the tip detection of tightly closed cracks caused by the larger residual compression stress from welding processes. Thus, although the maximum displacement from the transmit transducer might be a limitation, we believe that larger amplitude-incident ultrasound will be one of the key techniques in the SPACE measurement system for use in industrial fields.

References

[1] Mihara T, Nomura S, Akino M and S and Yamanaka K 2004 Relationship between crack opening behavior and crack tip scattering and diffraction of longitudinal waves Materials Evaluation 62 943-47
[2] Yamanaka K, Mihara T and Tsuji T 2004 Evaluation of closed cracks by analysis of subharmonic ultrasound Insight 46 (11) 666-70
[3] Ohara Y, Mihara T, Sasaki R, Ogata T, Yamamoto S, Kishimoto Y and Yamanaka K 2007 Imaging of closed cracks using nonlinear response of elastic eaves at subharmonic frequency Appl. Phys. Lett. 90 011902
[4] Ohara Y, Yamamoto S, Mihara T and Yamanaka K 2008 Ultrasonic evaluation of closed cracks using subharmonic phased array JAP 47 (5) 3908-15
[5] Ohara Y, Yamamoto S, Endo H, Mihara T and Yamanaka K 2008 Accurate measurement of closed cracks using subharmonic phased array Nonlinear Acoustics- Fundamentals and Applications (18th ISNA) 18 557-60
[6] Ohara Y, Endo H, Mihara T and Yamanaka K 2009 Ultrasonic measurement of closed stress corrosion crack depth using subharmonic phased array JJAP 48 (7) 07GD01-1-6
[7] Mihara T, Japanese Patent 2012 No. 2012-88113
[8] Mihara T, Kamimura T, Miura Y and Tashiro H, “Development of high amplitude ultrasonic laminated transducer system for ultrasonic inspection 2012 Proceeding of IWPMA 2012 61.

Acknowledgments

This work was partially supported by a Grant-in-Aid for the Innovative Nuclear Research and Development Program (No.120804) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.