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Multi-Mode Nonlinear Ultrasonic Phased Array for Imaging Closed Cracks

複数モード非線形超音波フェーズドアレイによる閉じたき裂の映像化

Yoshikazu Ohara[1†], Jack Potter[2], Hiromichi Nakajima[1], Toshihiro Tsuji[1], and Tsuyoshi Mihara[1] ([1]Tohoku Univ.; [2]Univ. of Bristol)

小原良和 [1†]，Jack Potter[2]，中島弘達 [1]，辻俊宏 [1]，三原毅 [1] ([1] 東北大, [2] ブリストル大)

1. Introduction

Nondestructive inspection of closed cracks is one of the most challenging problems in ultrasonic testing (UT), since an ultrasound penetrates through the closed cracks. To solve this serious problem in many industrial fileds, nonlinear ultrasonics has been expected to be a primary means. Recently, the visualization techniques using ultrasonic phased arrays to measure the local elastic nonlinearity originating from closed cracks, referred to commonly as nonlinear ultrasonic phased array imaging, have been proposed and have had their efficacy demonstrated in closed-crack specimens.[1-4)]Note that the imaging techniques are based on the nonlinearly scattered longitudinal waves for longitudinal wave incidence. On the other hand, nonlnear scattering at closed cracks can generate not only longitudinal but also mode-converted shear waves, which may have different characteristcs from longitudinal one. Therefore, we proposed to use both nonlineary scattered longitudinal and mode-converted shear waves in nonlinear ultrasonic phased array imaging, which is called multi-mode nonlinear ultrasonic phased array imaging.[5,6)] It has been experimentally demonstrated in specimens with simple vertical closed fatigue crack. However, it has yet to be examined in a closed stress corrosion cracking (SCC) with complicated branches.

In this study, we examined the multi-mode nonlinear ultrasonic phased array in complexly branched SCCs. We formulated the imaging algorithm based on the use of longitudinal and mode-converted shear waves for a closed-crack imaging method, subharmonic phased array for crack evaluation (SPACE). Subsequently, multi-mode SPACE was applied to a complely branched SCC specimen.

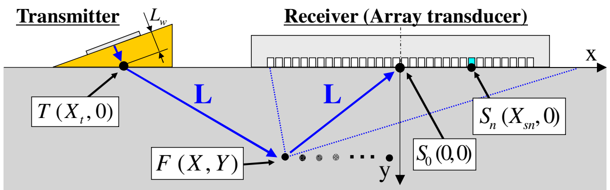
2. Principle of Multi-Mode SPACE

To use both longitudinal and mode-converted shear waves for multi-mode SPACE, there is no need to change the experimental configuration, as shown in **Fig. 1**. Before formulating imaging algorithms, we briefly explain the concept of SPACE. In this implementation, a $LiNbO_3$ single crystal with a polyimide wedge is used for generating intense ultrasound, and a phased array transducer is used as a receiver for focusing on reception. By irradiating intense ultrasound on closed cracks, the scattering of fundamental and subharmonic waves occurs at open and closed parts of cracks, respectively. These scattered waves are received by the array transducer. The waveforms received by each element are digitally filtered to extract fundamental and subharmonic components, respectively. Subsequently, they are shift and summed for a focal point following delay laws;

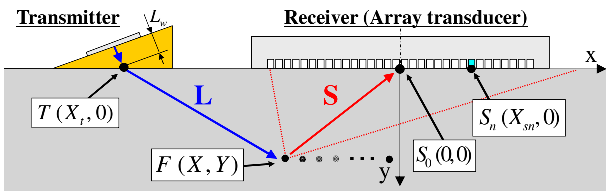
$$t_n = \frac{L_W}{V_W} + \frac{\sqrt{(X_t - X)^2 + Y^2}}{V_L} + \frac{\sqrt{(X_{Sn} - X)^2 + Y^2}}{V_L}, \quad (1)$$

$$t_n = \frac{L_W}{V_W} + \frac{\sqrt{(X_t - X)^2 + Y^2}}{V_L} + \frac{\sqrt{(X_{Sn} - X)^2 + Y^2}}{V_S}, \quad (2)$$

where Eqs. (1) and (2) are for longitudinal and mode-converted shear waves, respectively. Here t_n is the propagation time from the transmitter through a focal point $F(X, Y)$ to an element $S_n(X_{sn}, 0)$ of the array transducer, $T(X_t, 0)$ is the incident point on the interface between the transmitter and



(a) Nonlinearly scattered longitudinal wave



(b) Nonlinearly scattered mode-converted shear wave

Fig. 1 Formulation of imaging algorithm based on longitudinal and mode-converted shear waves generated by nonlinear scattering at closed cracks.

E-mail: ohara@material.tohoku.ac.jp

the sample, L_w. is the propagation distance in the wedge. By repeating shift-and-summation process based on Eqs. (1) and (2), respectively, over an imaging area, longitudinal and mode-converted shear subharmonic images can be created.

3. Specimens and Experimental Conditions

To form a deep SCC specimen, we firstly introduced a fatigue crack with a depth of approximately 10 mm in an austenitic stainless steel specimen (SUS304 sensitized at 600 C for 4 h) by a three-point bending fatigue test. The fatigue conditions were a maximum stress intensity factor $K_{max} = 28$ MPa · $m^{1/2}$ and a minimum stress intensity factor $K_{min} = 0.6$ MPa· $m^{1/2}$. Subsequently, we extended the SCC from the tip of the fatigue crack using an SCC apparatus, as shown in **Fig. 2**. This apparatus was designed to immerse the entire fatigue-crack specimen in a cell with a corrosive environment under a static bending load. The corrosive environment was a solution of 30 wt % $MgCl_2$ at 90 °C, and a nominal bending stress of 124 MPa was applied to the crack for 1800 h, which is longer than the previous study[7] in order to introduce more complexly branched SCC.

The experimental configuration is shown in **Fig. 3**. The transmitter was excited by a three-cycle burst with a frequency of 7 MHz at 220 $V_{p\text{-}p}$. 63-elements array transducer with a center frequency of 5 MHz was used. We selected a configuration to receive both forward- and back-scattered waves from cracks, and focused on reception with 0.2 mm steps. A fast Fourier transform (FFT) filter was used to extract subharmonic components from the received waves.

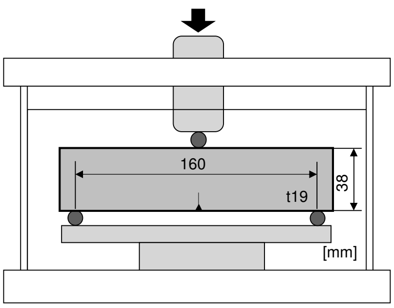


Fig. 2 Apparatus to form deep SCCs.

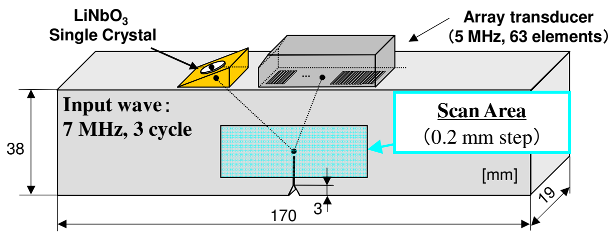
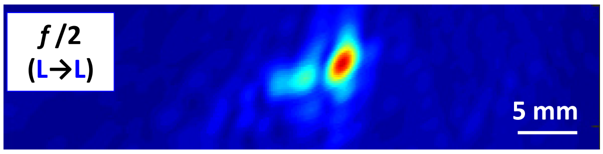


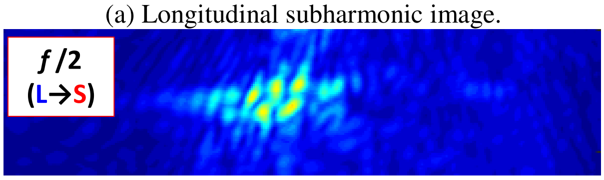
Fig. 3 Experimental configuration.

4. Experimental Results

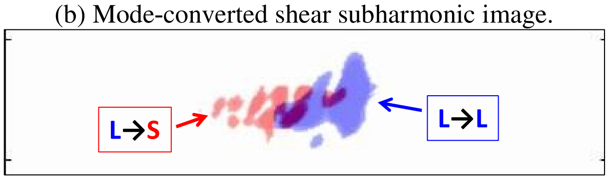
The imaging results based on Eqs. (1) and (2) are shown in **Figs. 4(a) and 4(b)**. The longitudinal subharmonic image (Fig. 4(a)) visualized a few responses, whereas the mode-converted shear subharmonic image (Fig. 4(b)) visualized more multiple responses. It should be noted that the resolution in Fig. 4(a) was higher than that in Fig. 4(b). This is because the wavelength of shear wave is a half of longitudinal one. **Fig 4(c)** shows the superimposition of Fig. 4(a) on Fig. 4(b). This clarify that Figs. 4(a) and 4(b) visualized different parts, although a part of responses was slightly overlapped. This may suggest that both images can be complementary each other.



(a) Longitudinal subharmonic image.



(b) Mode-converted shear subharmonic image.



(c) Superimposition of (a) and (b)

Fig. 4 Subharmonic images of complexly branched SCC.

5. Conclusions

We examined the multi-mode nonlinear ultrasonic phased array in the complexly branched SCCs. The longitudinal and mode-converted shear subharmonic images visualized different parts of SCCs, suggesting that both images can be complementary each other.

Acknowledgment

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