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Imaging of three-dimensional crack open/closed distribution by nonlinear ultrasonic phased array based on fundamental wave amplitude difference

基本波振幅差分の非線形超音波フェーズアレイによる 3 次元き裂開閉分布の映像化

Yoshikazu Ohara[1†], Hiromichi Nakajima[1], Sylvain Haupert[2], Toshihiro Tsuji[1], and Tsuyoshi Mihara[1] ([1]Tohoku Univ.; [2]Sorbonne Univ.)

小原良和 [1†]，中島弘達 [1]，Sylvain Haupert [2]，辻俊宏 [1]，三原毅 [1] ([1] 東北大, [2] ソルボンヌ大)

1. Introduction

To evaluate the material strength of aged structures based on fracture mechanics, it is critically important to accurately measure crack depths by ultrasonic testing (UT). However, fatigue cracks are often closed owing to e.g. plasticity-induced closure stress, which may cause the underestimation of crack depths in UT, since ultrasound penetrates through closed cracks. Moreover, crack closure affects not only the detectability and measurement accuracy of cracks in UT but also crack growth rate, which is is one of the important parameters in fracture mechanics and for management of infrastructures. In laboratory, crack closure can be measured by a compliance method of using a clip gage, which provides only a single value as an average, meaning that the distribution cannot be measured, although it is known not to be uniform within a crack. Furthermore, the compliance method is not applicable to actual structures.

Over the past dozen years, various nonlinear ultrasonic phased arrays have been developed for closed-crack imaging.[1-6] One of them is fixed-voltage fundamental wave amplitude difference (fixed-voltage FAD), which is readily implementable in commercial PA and can achieve a high-selectivity imaging of closed cracks.[4-6] In this study, we explore the possibility of fixed-voltage FAD as a new tool for measuring 3D crack open/closed distribution, which will be useful for advancing fracture mechanics and may lead to more sophisticated management of aging structures.

2. Principle of Fixed-Voltage FAD

Figure 1 shows the principle of fixed-voltage FAD, which is based on the measurement of the loss of fundamental wave with increasing the incident wave amplitude, because part of the energy of fudanmental wave is consumed to generate nonlinear components such as higher harmonics and/or subharmonics. To extract the effect, all-elements, odd-elements, and even-elements transmission are employed at a fixed excitation voltage. All-elements transmisison (T_{All}) is regarded as having a large-amplitude incidence among them. Odd-elements (T_{Odd}) and even-elements (T_{Even}) transmission are regarded as having a smaller-amplitude incidence than T_{All}. For linear defects, the subtraction of response for T_{All} from the sum of the responses of T_{Odd} and T_{Even} should produce a value of 0. Note that the nonlinearity arising from piezoelectric elements and liquid couplant can be cancelled, because it has been determined by an excitation voltage. For closed cracks, as shown in Fig. 1, T_{All} can cause the contact vibration of crack faces, resulting in the generation of nonlinear components, whereas T_{Odd} and T_{Even} may not generate such nonlinear components because of smaller amplitude incidence than T_{All}. Hence, by taking the same subtraction processing to extract the loss of the fundamental waves, all nonlinear components can be indirectly measured, and thereby, a closed crack can be selectively imaged while cancelling linear scatterers.

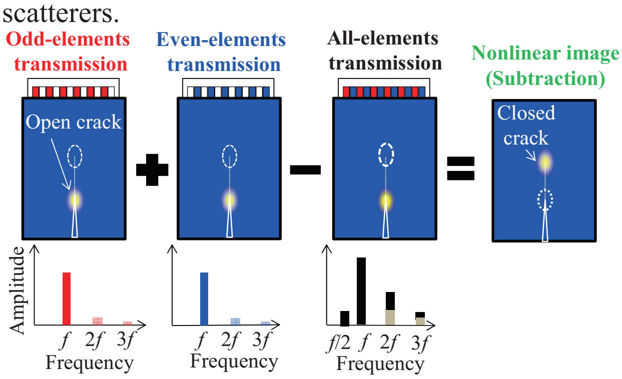

Fig. 1 Principle of fixed-voltage FAD.

3. Experimental Conditions

An experimental configuration is shown in **Fig. 2**. A fatigue crack sample[6] made of an aluminum alloy A7075 was used. As shown in Fig. 2(a), a 128-elements array transducer was placed on the top surface, and was operated by a phased array

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

hardware, OEM-PA 128/128 (AOS, USA). The transmission focal points were set to x=-5 to 5 mm with 0.5 mm step at z=30 mm. Each element was excited by three-cycle burst with 5 MHz and of 145 $V_{p\text{-}p}$. A band-pass filter from 2.5 to 7.5 MHz was employed to extract fundamental components from received waves. The imaging area was chosen to 10×25 mm^2 around the cack and the delay-and-sum processing was done with 0.1 mm step. To examine 3D crack open/closed distribution, the array transducer was mechanically translated in y direction with 4 mm step (Fig. 2(b)).

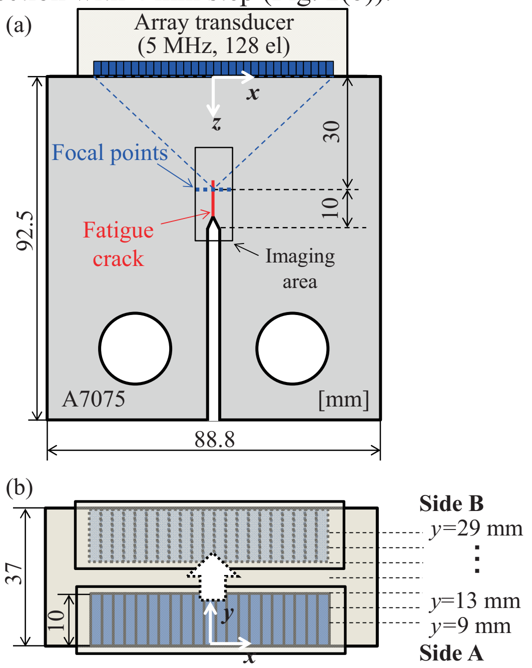

Fig. 2 Experimental configurations.

4. Experimental Results

Figure 3 shows the linear (T_{All}) and nonlinear (=T_{Odd}+T_{Even}-T_{All}) images obtained at y=9 mm to 29 mm with 4 mm step. In the linear images, the crack response was the strongest at y=17 mm, which is the center in y direction, whereas they were weaker in the other positions. In the nonlienar images, the crack was absent around the center part e.g. at y=17 and 21 mm, whereas the crack appeared around the sides A (y=9 and 13 mm) and B (y=25 and 29 mm) as stronger responses than the center part. This reveals that the fatigue crack was open around the center part and was closed around the sides.

In fracture mechanicas, a plasticity-induced crack closure is known as one of the dominant crack closure mechanisms. As illustrated in **Fig. 4**, the plastic zone formed in the vicinity of a crack tip is larger around the sides than around the center, since the sides and center are approximated to have a plane stress and plane strain states, respectively.[7] Note that this knowledge is in a good agreement with the imaging results (Fig. 3). Furthermore, interestingly, the imaging results reveal the clear difference in the closed state between the sides A and B, although both sides are regarded as being identical in fracture mechanics. This suggests that fixed-voltage FAD will be useful as a tool for measuring 3D crack open/closed distribution.

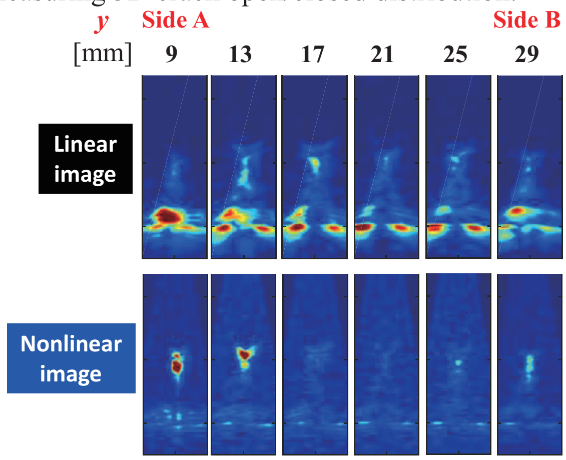

Fig. 3 Linear and nonlinear images of fatigue crack at different measurement positions in y direction.

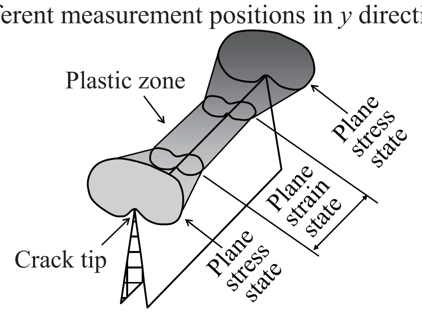

Fig. 4 Schematic illustraion of the plastic zone created around fatigue crack tip.

5. Conclusions

We explored the possibility of fixed-voltage FAD as a new tool for measuring 3D crack open/closed distribution. As a result, the linear and nonlinear images was in an excellent agreement with fracture mechanics. Furthermore, it was found out that fixed-voltage FAD can provide detailed 3D distribution of crack depth and closure, which cannot be measured by a compliance method used in fracture mechanics.

Acknowledgment

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