3P2-8

Improvement of selectivity in nonlinear ultrasonic phased array based on fundamental wave amplitude difference with calibrated scaling factors

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1. Introduction

Accurate crack depth measurement is essential for assessing the structural strength of power plants, aircraft, and other structures. To this end, ultrasonic phased array (PA) is industrially used because ultrasound is highly scattered at the crack tip. However, when cracks are closed by compressive residual stress or oxide films, the ultrasound can pass through the cracks, making them undetectable. This can lead to the underestimation or overlook of cracks, potentially resulting in catastrophic accidents.

To accurately visualize closed cracks, various nonlinear ultrasonic PAs have been developed, where the effect of nonlinear contact vibrations of crack faces is captured by PA.[1)] Among them, the fundamental wave amplitude difference (FAD) is promising for practical application, as it can indirectly measure all nonlinear components by measuring only the fundamental wave.[2)] This enables highly sensitive measurement with a single array transducer. However, some PA systems sometimes have inherent nonlinearity, which can lower the reliability of FAD.[3)] The previous studies clarified that a few PA systems are suitable for FAD since they have less inherent nonlinearity. On the other hand, it has been recently proposed that the effect of a highly nonlinear PA system can be suppressed to a certain extent for FAD by introducing a calibrated scaling factor,[4)] where the calibration was carried out by selecting a response at the boundary between the crack and notch as a reference of a linear scatterer. However, such a response may not be a perfectly linear scatterer. This might cause imperfect calibration.

In this study, we modified the calibration method for FAD by using a perfectly linear scatterer (i.e., a notch without having cracks) as a reference. The effectiveness was demonstrated in a fatigue-crack specimen for different-voltage FAD.[5,6)]

2. Principle of FAD with a calibrated scaling factor

FAD is based on the incident-wave-amplitude dependence of fundamental components. Assume that ultrasound is focused on linear and nonlinear scatterers (e.g., notches at $\mathbf{r}_\mathrm{L}$ and closed cracks at $\mathbf{r}_\mathrm{NL}$, respectively). The incident wave amplitude is varied from a small amplitude A_1 to a large amplitude $A_2 = \alpha A_1$, where α is an amplitude ratio. Let $I_1(\mathbf{r})$ and $I_2(\mathbf{r})$ be the fundamental wave response obtained at a position vector $\mathbf{r}$ for A_1 and A_2, respectively. Ideally, while $I_2(\mathbf{r}_\mathrm{L}) = \alpha I_1(\mathbf{r}_\mathrm{L})$, $I_2(\mathbf{r}_\mathrm{NL}) \neq \alpha I_1(\mathbf{r}_\mathrm{NL})$ due to the nonlinear losses or threshold phenomena[6)] caused by contact vibrations of crack faces. Therefore, by measuring the deviation ΔI from the linearity using

$$\Delta I(\mathbf{r}) = \alpha I_1(\mathbf{r}) - I_2(\mathbf{r}), \qquad (1)$$

the response of closed cracks can be extracted (**Fig. 1(a)**). Note that ΔI can be positive for nonlinear losses[2)] and negative for threshold phenomena.[6)]

The above theory is based on the assumption that $A_2 = \alpha A_1$. However, an inherent nonlinearity in a PA system sometimes disrupts this assumption, which causes non-negligible artifacts.[3,6)] In this study, we propose to obtain a calibrated scaling factor α', based on the measurement of a perfectly linear scatterer, although the previous studies used a response of a part of the crack.[4)] By introducing α', eq. (1) can be modified to

$$\Delta I = \alpha' I_S - I_l. \qquad (2)$$

This can suppress the artificat for FAD (Fig. 1(b)), promoting the practical application of FAD.

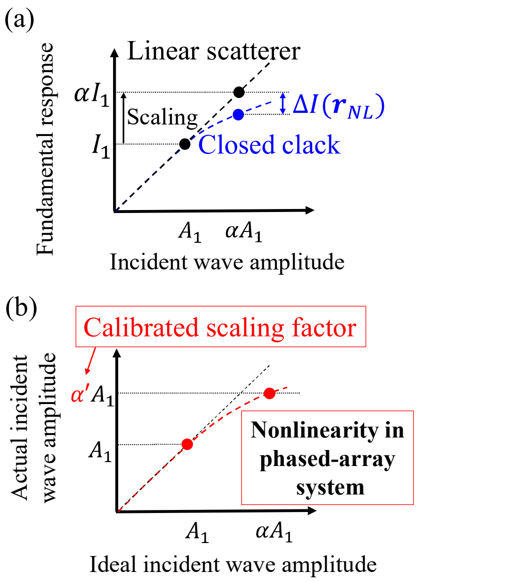

Fig. 1 Principle of FAD with calibrated scaling factor: (a) Incident-wave-amplitude dependence of fundamental responses, (b) Calibrated scaling factor for compensating the nonlinearity in PA system.

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3. Experiment

To experimentally verify the effectiveness of the calibration method for FAD, we prepared two compact tension specimens made of aluminum alloy A7075 (**Fig. 2**). One had only a starting notch, which was used as a linear scatterer for the calibration (Fig. 2(a)). The other had a fatigue crack approximately 10 mm deep extended from a starting notch (Fig. 2(b)), where the fatigue condition was selected as a stress intensity factor range ΔK=8.4 MPa·m$^{1/2}$ and stress ratio R=0.067.

Figure 2 also shows the experimental setup. A 1D array transducer (5 MHz, 64 elements, 0.5 mm pitch) was placed on the top of the specimen. Focusing on both transmission and reception was performed over the imaging area; z = 20 to 45 mm (1 mm pitch) and x = -5 to 5 mm (0.5 mm pitch). For A_1 and A_2, the excitation voltages were set to 48 and 96 V, respectively, thus $\alpha = 2$. The above condition was implemented using a PA controller (Vantage 128, Verasonics), which is the same as Ref. 4).

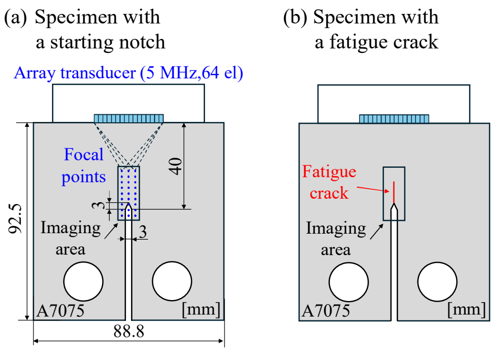

Fig. 2 Experimental setup: (a) Specimen with a starting notch, (b) Specimen with a fatigue crack.

First, we carried out the calibration of the scaling factor in the notch specimen. **Figures 3(a) and 3(b)** show the fundamental (linear) images of the notch (i.e., a perfectly linear scatterer) for 96 and 48 V, respectively. When we applied the scaling factor, $\alpha = 2$, the nonlinear (FAD) image obtained by Eq. (1) exhibited the strong residue, as shown in Fig. 3(c), although the linear scatterer should be ideally canceled in the nonlinear image. This is due to the inherent nonlinearity in the PA system. To calibrate this, we examined the deviation from $\alpha = 2$. As a result, α' was found to be 1.68. Applying this value to Eq. (2), the notch response was suppressed well, as shown in Fig. 3(d).

Therefore, we used this value to image the fatigue crack. **Figures 4(a) and 4(b)** show the imaging results of the fatigue crack for 96 and 48 V, respectively. When we applied the scaling factor, $\alpha = 2$, the nonlinear (FAD) image obtained by Eq. (1) exhibited the strong residue of linear responses, as shown in Fig. 4(c). the crack response was not extracted well. On the other hand, by using $\alpha' =$ 1.68 for Eq. (2), the nonlinear image selectively visualized the whole crack, as shown in Fig. 4(d). Interestingly, the nonlinear image shows both positive and negative responses. This suggests that the nonlinear loss and threshold phenomena complexly occurred depending on the parts of the crack.

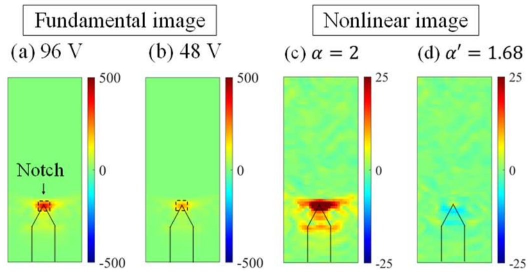

Fig. 3 Calibration of scaling factors using the notch specimen: Fundamental (linear) images at (a) 96 V and (b) 48 V. Nonlinear images at (c) $\alpha = 2$ and (d) $\alpha' = 1.68$.

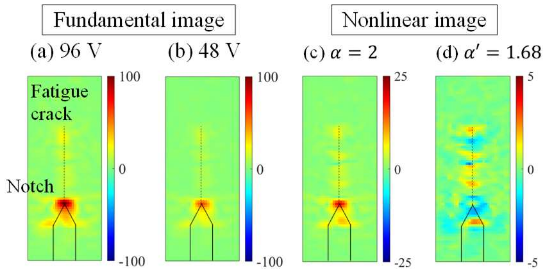

Fig. 4 Imaging results of the fatigue crack: Fundamental (linear) image at (a) 96 V, (b) 48 V. Nonlinear images at (c) $\alpha = 2$, (d) $\alpha' = 1.68$.

4. Conclusions

We proposed a modified calibration method for FAD using a perfectly linear scatterer as a reference. By applying the scaling factor calibrated with the notch specimen, we successfully imaged the fatigue crack with high selectivity using different-voltage FAD.

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