Nonlinear Ultrasonic Imaging Method for Closed Cracks
閉口き裂を映像化する非線形超音波フェーズドアレイの基礎的検討

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A new method for detection and sizing of closed crack is described which uses transient waveform of subharmonics with half input frequency in ultrasonic nondestructive evaluation. In analogy to the resonant characteristics of vibration of bubbles in liquids, we formulate an equation for resonant excitation of subharmonics at partially closed cracks. The equation has been partially verified by comparison between experimental and calculated waveforms. An apparatus for imaging closed cracks in critical components such as in atomic power plant is described.

Keywords: nonlinear ultrasound, fatigue crack, crack size measurement

1. Introduction

Although ultrasound is the most sensitive method among nondestructive evaluation methods for detection and sizing of cracks, detection of those without any gap between the crack faces, often referred to as 'closed cracks', is difficult because they are almost transparent to ultrasound. In order to solve this problem, the nonlinear ultrasound of cracks has been extensively investigated [1]-[3], where the superharmonics with integer multiples of input frequency is generated. However, the signal-to-noise (S/N) ratio of superharmonics is not very high, because it is generated in many class of objects such as piezoelectric transducers, liquid coupler and electronic amplifiers. On the other hand, subharmonics with odd multiples of half input frequency has higher S/N because it is generated at more limited object, such as contact between solids [2]-[5] or bubbles in liquid [6]. However, application of subharmonic wave to crack sizing in time domain measurement had not been attempted.

In this situation, we proposed to use subharmonics in closed cracks to reduce error in crack size measurements [7]-[10]. After theoretical [7] and experimental [8] investigation of generation of subharmonic wave at closed cracks, we proposed a nonlinear imaging method and showed a preliminary result on fatigue cracks [9] . We also found a resonant nature of vibration of cracks at a tail part of waveform generated by a large amplitude input wave [10]. Based on those, we propose a framework for crack size measurement using a time domain signal of subharmonic wave.

2. Resonance characteristics of subharmonics

To investigate the nature of nonlinear ultrasound including not only the superharmonics but also subharmonics, we tried to reproduce experimental subharmonic waveform. Although an exact treatment of cracks requires intensive numerical calculations, we employ a simple equation to reproduce an essential feature suitable for obtaining physical insight on the phennomena [7, 10]. In this model, we assume that the output side crack face is driven by the input side crack face whose motion is known and is identical to the displacement waveform of incident waveform.

This approximation gives,

$$\ddot{x}+\Gamma\dot{x}+\omega_R^{2}(x-x_s)=F^{*}(x-a\sin\omega_I\,t) \quad (1)$$

where x is the position of output side crack face, Γ is the normalized damping factor, F^* is the interaction force between two crack faces, and x_s is equilibrium value of x where no interaction force is operated. The force function on the right-hand-side of eq. (1) can be either the extended Lennard-Jones force [7], [10] or a bilinear force. Coefficients of eq. (1) are equivalent to those in [7] and [10], but normalized so that the angular resonance frequency $\omega_R = \sqrt{k/m}$ is used, instead of the stiffness k mass m of the output crack face. Eq. (1) represents a forced vibration excited at an angular frequency, $\omega = \omega_I$. However, if $F^* = 0$, it represents a free vibration at the resonant frequency $\omega = \omega_R$.

3. Time domain measurement of subharmonics

We conducted experiments on a fatigue crack in an aluminum alloy (Al7075). The fatigue crack was extended from a notch in a three-point bending fatigue test up to 15 mm, with a maximum and minimum stress intensity factors of 14 kgf/mm$^{3/2}$ and 2 kgf/mm$^{3/2}$, respectively which were selected to form a closed crack [8]. The subharmonic wave was observed in a transmission configuration using an obliquely incident longitudinal wave with a polystyrene wedge. A sinusoidal wave with a frequency of 7.0 MHz was produced by a wave generator, and this wave of 20 cycles was amplified by a gated amplifier. The displacement amplitude of a longitudinal wave at the crack position was estimated to be larger than 20 nm p-p using a laser interferometer.

The validity of eq. (1) has been partially verified by agreement between experimental and calculated subharmonic waveform [7,10] as shown in Fig. 1. The parameters used for the calculation are given in ref. [10]. As the bending force increased the relative magnitude of subharmonics was increased in the experimental results (a), which was reproduced in the calculated results (b). The tail effect showing a single pulse with low center frequency in (a) was also reproduced (b), whose angular frequency is given by the resonance frequency ω_R.

To evaluate the temporal resolution of subharmonic wave and to extract ω_R from experimental waveform, the time-frequency spectrum analysis was performed. Figure 2 (below) shows a subharmonic waveform with tail effect for the same sample as in Fig. 1. Figure 2 (top) shows a magnitude of wavelet transform using the Gabor function mother wavelet. The input frequency was 7.0 MHz and the subharmonic freqnency was 3.5 MHz. It was shown from

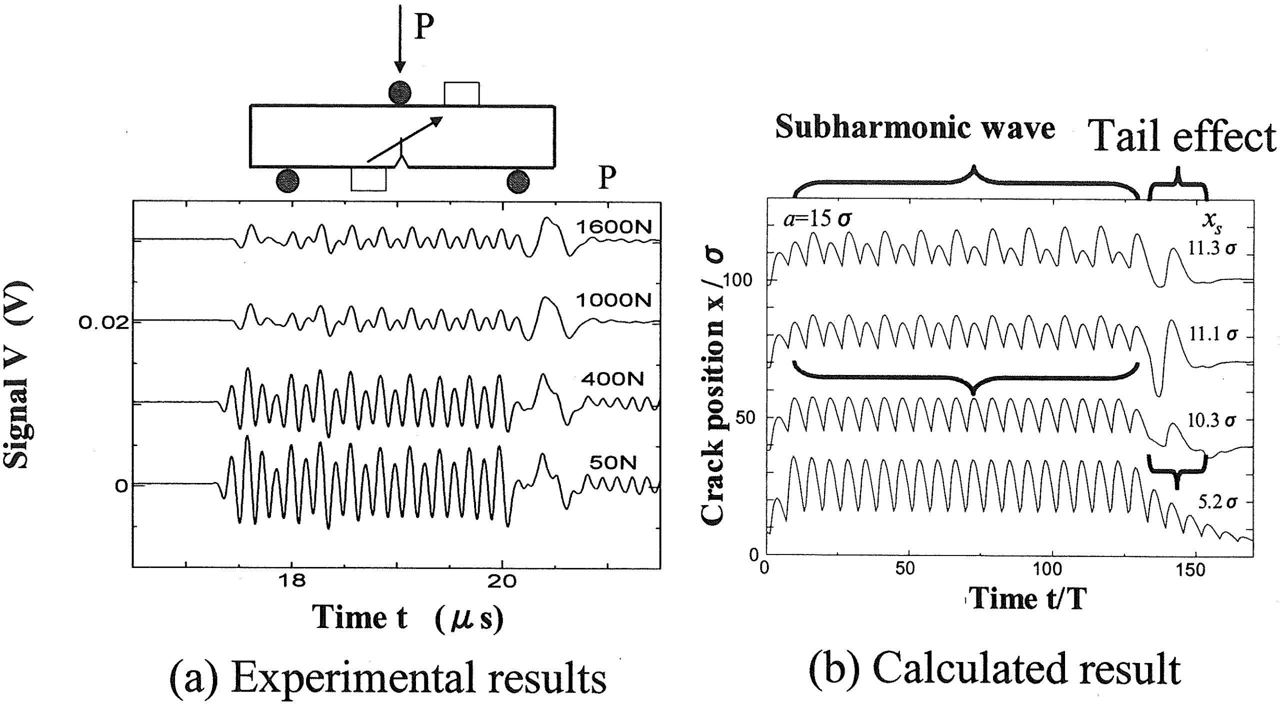

Fig. 1. Subharmonic waveform with different closure forces

the wavelet image that the subharmonic component was established in less than 1 μs. The arrival time (20-21 μs) and frequency (2.5 MHz) of the tail effect was also clearly observed in the wavelet image. Since the frequency of tail effect is approximately equal to the resonance frequency according to eq. (1), the resonance frequency is estimated to be 2.5 MHz.

In a reflection configuration advantageous for crack size measurement, we developed a nonlinear imaging method [9]. We show a preliminary result for subharmonic imaging of the same specimen in Fig. 3.

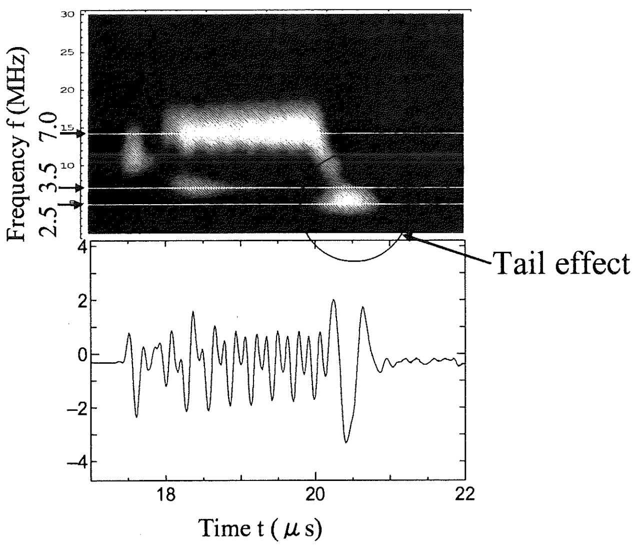

Fig. 2. Wavelet transform of subharmonic wave and tail effect in transmission configuration

It is found that the source of the subharmonic wave was observed only around the crack tip and it shows that the crack tip is partially closed because of the subharmonic excitation (the back surface echo is too strong to be completely suppressed by electronic filters). Since the size of the crack tip image was 1-2 mm, each source may be spatially resolved even if there are multiple sources. In fig. 3, the total length of crack was estimated to be around 20 mm, although much smaller crack can be imaged and measured with this spatial resolution. We note that such a measurement can provide a practical sizing tool of closed cracks, since such a crack size measurement can not be possible by the linear phased array, if the crack is strongly closed.

Though a resonance is advantageous for increasing the magnitude of response, the input frequency does not have to be precisely tuned to the resonance frequency because the sharpness of the resonance is not large in general. Consequently, cracks of varied length can be evaluated by a single input frequency. Nevertheless, variable frequency transmitter is highly desired to cover wide range of crack length.

Eq. (1) is valid in the limit of large crack face penetrating the object, when the input and output sides are clearly defined. For smaller cracks not penetrating the object, it is still effective as a first approximation to reproduce many aspects of subharmonic wave [7,10]. However, further improvement is required for more quantitative comparison with experiment. The next approach is made by introducing a one dimensional elastic body in the model and by discriminating the transmission and reflection configurations.

4. Conclusion

We proposed a framework for crack size measurement using a time domain signal of subharmonic wave. In analogy to the resonant characteristics of subharmonic vibration of bubbles in liquids, we formulate resonant excitation of subharmonic wave from partially closed cracks. The presence of resonance has been partially verified by resembrance between experimental waveform and calculated waveform by a single-degree-of freedom equation of resonant vibration.

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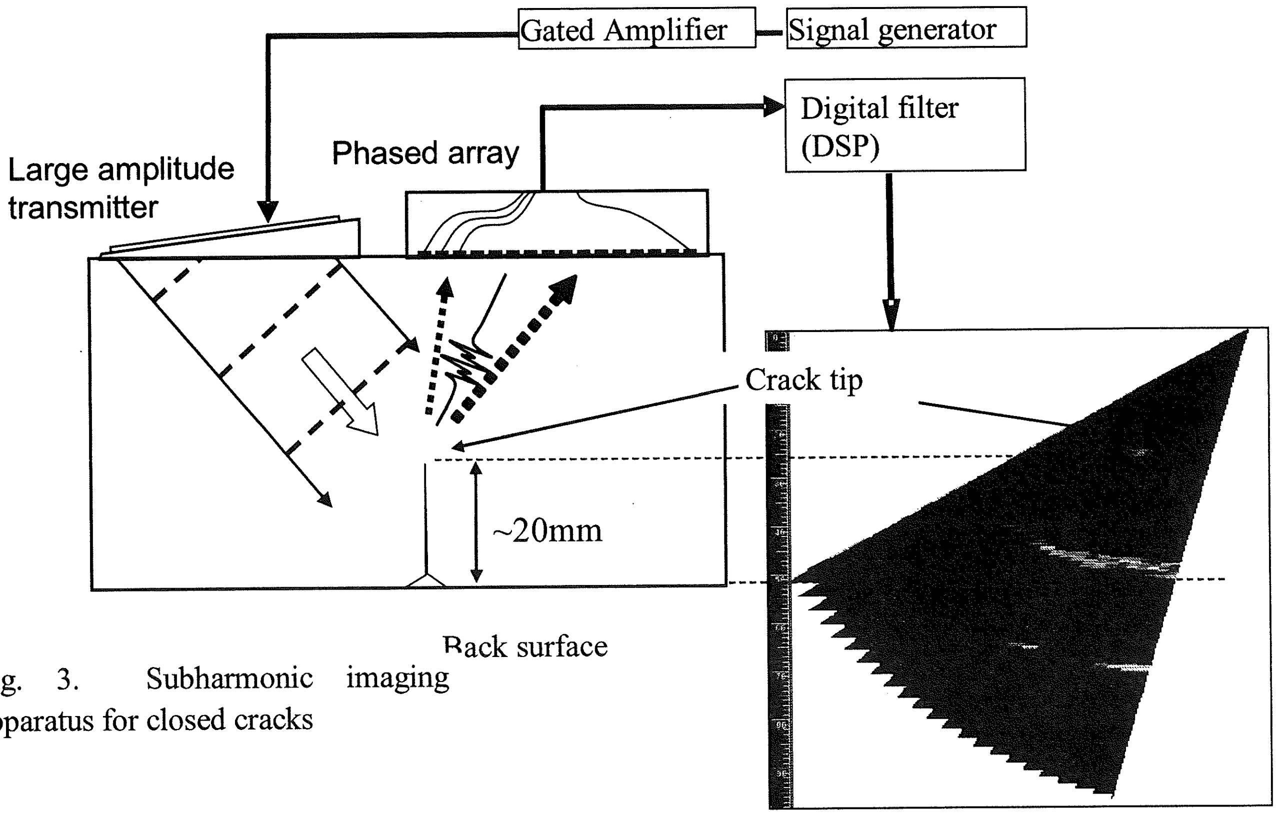

Fig. 3. Subharmonic imaging apparatus for closed cracks

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