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Ultrafast Phased Array Imaging with Pump Excitation: an Application to Closed Crack Characterization

ポンプ励振と組み合わせた超高速フェーズドアレイイメージング：閉じたき裂評価への応用

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1. Introduction

During the past four decades, nonlinear acoustic/ultrasonic methods have been studied not only for nondestructive evaluation (NDE) of closed cracks and micro damage in engineering materials[1,2] but also for characterization of granular or cracked geo-materials.[3] Among them, dynamic acoustoelastic testing (DAET)[4] is one of the most powerful approachs to explore various kinds of dynamic elastic nonlinearity such as clapping, hysteresis, slow dynamics, etc., which are very important for both NDE and geoscience. The method relies on dynamically exciting a sample with a low frequency (LF) vibration (pump excitation), which applies a strong strain periodically. Simultaneously, a high frequency ultrasonic wave (probe wave) probes the changes in wave speed and in attenuation as a function of the strain induced by the pump excitation. Thus far, the probe wave is transmitted by a monolithic transducer, so even with an image reconstructed from a mechanical scanning[5], the spatial resolution is very much constrained because of the lack of focusing on signal receptions. In addition, the speed of measurement over a wide range is limited by the scanning.

Recently, the ultrafast imaging, typically acquired with thousands of frames per second, has been developed and primarily applied in biomedical applications, such as to capture very fast tissue motions[6] and/or to improve the sensitivity of weak signal detections.[7] In this paper, we combine the pump excitation with ultrafast phased array imaging, to propose a new NDE method for closed crack imaging as well as a new tool for studying dynamic elastic nonlinearities. In this preliminary study, we characterize a closed fatigue crack specimen and examine the hysteretic effect of crack response.

2. Ultrafast imaging with pump excitation

The objective is to investigate the dynamic elastic nonlinearity of contact interfaces such as closed cracks at a pump frequency of a few kHz. We pump the sample simultaneously when ultrafast imaging is acquried. Unlike B-scans or full matrix captures, ultrafast imaging usually transmits and receives plane waves so as to cover the entire region of interest in a single transmit and receive cycle, pushing the frame rate towards the fundemental physical limits, that is the round-trip sound travel time. Once the echo data is received, the image is reconstructed relying on focusing on reception with appropriate focal law applied. In the proposed method, the LF strain field is assumed to be quasi-static during the time of acquisition of one ultrafast imaging frame. This allows one to image the dynamic crack responses in tensile and compressive phases of the pump wave with a much higher spatial resolution and much more quickly over a wide area than DAET using a monolithic transducer.

3. Experimental setup

The experimental setup is shown in **Fig. 1**. A closed fatigue crack sample[1] (A7075) made by three-point bending fatigue test was used, where the crack depth was approximately 20 mm. A PZT disk was bonded to the bottom of the sample, and a heavy steel backload was bonded to the other side of the PZT to impose fixed-free boundary conditions. The sample was pumped by the PZT at the first resonant frequency, corresponding to a quarter wavelength resonance, around 6.925 kHz, which was measured by a laser vibrometer. The excitation was 40V, 800 cycle sinusodal waves, which is consdiered long enough for the crack responses to reach the steady state.

An array transducer (5MHz, 128el, Imasonic) was attached to the left side of the sample to image the dynamic crack response during the pump excitations. The data acquistion was performed with an open ultrasound research platform (Vantage 128, Verasonics). Plane waves were transmitted and received with a pulse repetition rate of 3.4 kHz, resulting in an imaging acquistion at 3400 fps. Consequently, the crack response to the pump wave at 6.925 kHz are downsampled shown in red in Fig. 1. Neverthless, once the crack response reaches to

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the steady state, 27 consetcutive ultrafast imaging frames fully recover the crack dynamics within a single pump exciation cycle. The ultrafast imaging was precisely synchronised with pump wave.

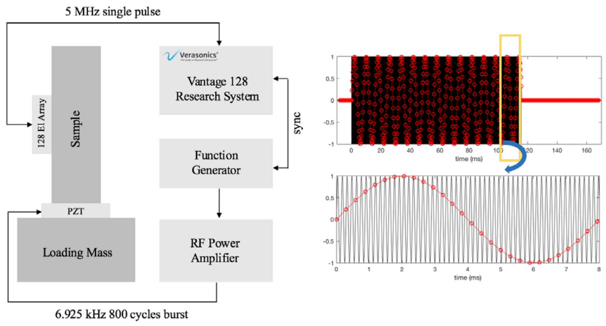

Fig. 1 Schematic experimental set-up (left); pump wave down-sampled by ultrafast imaging (right).

4. Results

The top and bottom of **Fig. 2** show the ultrafast images acquired at different phases relative to the pump wave, without and with background subtracted respectively. The background image was acquired when the pump excitation is off. The subtracted images clearly show intensity variations over time in response to crack opening and closing cycles induced by the pump wave. For example, in frame 161, the pixel intensities around the crack are very close to those in the background, indicating that the crack was closed. In frames 165 and 168, the pixel intensities around the crack tip were increased, indicating that the crack was gradually opened. These results suggest that the proposed method is useful in measuring closed crack depth.

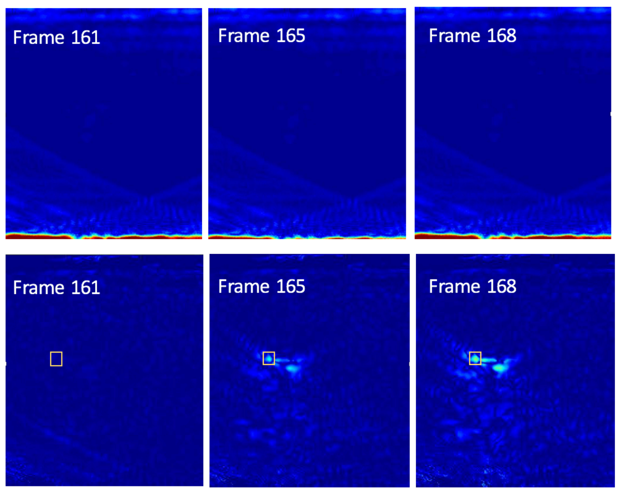

Fig. 2 Ultrafast images acquired at different phases relative to the pump without (top) and with (bottom) background subtracted.

To examine the dynamic nonlinear response in detail, the pixel intensity variation over time averaged over the orange square is shown in **Fig. 3 (a)**. Compared with the pump wave signal shown in **Fig. 3(b)**, the peak intensities in general reside around the peak tension phase as expected, however, there is a slight phase difference observed. To study this phase difference, in **Fig.3(c)** the intensities when the gradient of pump is positive and negative are plotted in red and blue, respectively. As a result, a hysteretic crack response[3-6)] was clearly shown. This suggests that once the crack is opened up, the open state retained for a little while even when the stress tendency is changed to compression.

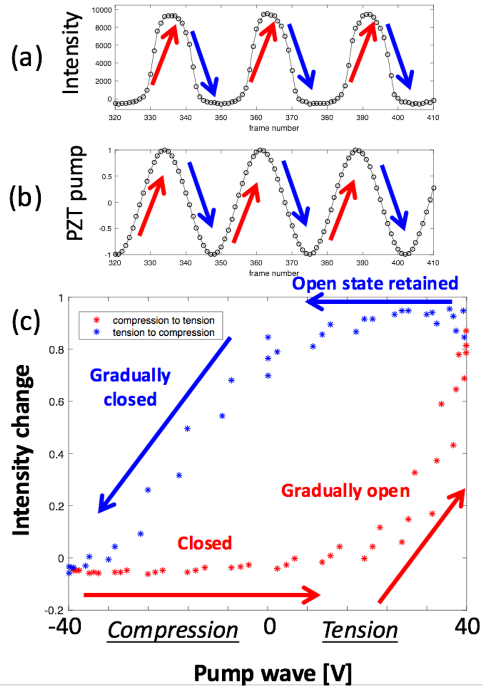

Fig. 3 Pixel intensity change over time (a); pump wave signal (b); hysteretic effect (c)

5. Conclusions

We proposed a new nonlinear ultrasonic imaging method that combines ultrafast imaging with pump excitation. The results show this method can image closed cracks raplidly with good sensitvity, contrast and resolution, which is practically useful for NDT. Furthermore, the hysteretic crack response was observed, suggesting the method could be useful for other fields such as geoscience.

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