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Nonlinear Ultrasonic Image of Fatigue Cracks by using Laser Doppler Vibrometry

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1. Introduction

A nonlinear acoustic effect is a sensitive tool to detect a micro-scale crack or the early stage of cracking during the fatigue process. Such damage produces a nonlinear stress-strain relationship, and the nonlinearity can be measured by a higher harmonic component in the frequency domain. The 2nd harmonic component and higher harmonic components are subtracted using laser Doppler vibrometry. Because the laser beam can be focused on the smallest spot, the localized nonlinear acoustic parameters can be determined. As the damage increases, the level of nonlinearity increases, which can be used for the diagnosis of micro-cracks. Using a scanning laser beam, localized nonlinear acoustic parameters can be mapped around a cracked specimen. Various nonlinear parameters are chosen and tested around the crack tip, and the most sensitive nonlinear parameter for a micro-crack or closed crack can be optimized

2. Methods and Results

In damaged materials, the nonlinear response is provided by the Contact Acoustic Nonlinearity (CAN) [1]: strongly nonlinear local vibrations of defects owing to a mechanical constraint of their fragments, which generate multiple ultra-harmonics and support multi-wave interactions. Another contribution to the nonlinear spectrum comes from resonance properties of planar defects. Vibrations of a certain mass of materials around a cracked defect are managed by a reduced stiffness, which provides a specific characteristic frequency of the defect and brings about a nonlinear resonance spectrum.

2.1 Experimental Methods

The experimental setup is shown in Fig. 1. A stacked piezoelectric transducer is used for exciting the cracked specimen. A sinusoidal wave with a specific frequency and amplitude generated from a function generator, which is amplified by a high frequency amplifier. The input and output waveforms are monitored by a digital oscilloscope.

A standard 1/2T-1CT specimen with dimensions of 63.5 mm x 61 mm x 12.72 mm was fabricated using SA508-Gr.3 material, which is used for a nuclear reactor pressure vessel. To fabricate a natural close crack, pre-notches for guiding the propagation of cracks were fabricated using electro-discharge machining. A fatigue test was carried out with an Instron universal test machine for fabrication of natural cracks. The specimen was then milled on both surfaces to remove traces of the pre-notches.

A laser Doppler vibrometer (Model Polytec QFV-534) was used for detection of nonlinear components of the local vibration of the specimen [2].

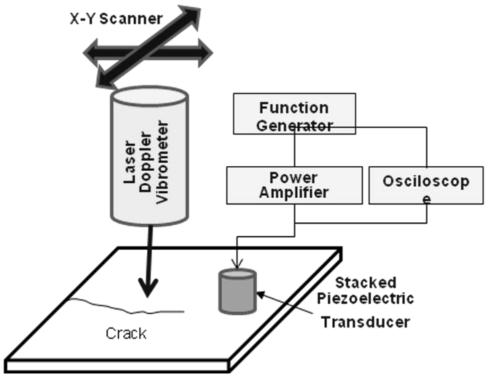


Fig. 1. An experimental setup for a nonlinear ultrasonic imaging system.

2.2 Results and Discussion

At low amplitude of the driving excitation, the nonlinear spectrum follows the non-resonant scenario and comprises the higher harmonic (HH) and the wave and comprises higher harmonic (HH) and wave modulation (WM) frequency components, as shown in Fig 2. As the input amplitude exceeds the threshold value, the resonance instability results in an activation of the ultrasonic sub-harmonic components first. The threshold amplitude depends on the driving frequency: a minimal threshold requires frequency matching to the main sub-harmonic resonance. A further increase of acoustic excitation gives rise to ultrasonic frequency pair instability, and finally the system indicates a chaotic vibration by a so-called generation of a quasi-continuous spectrum [3].

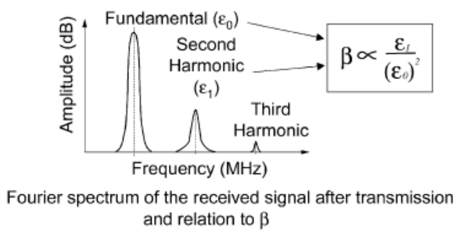
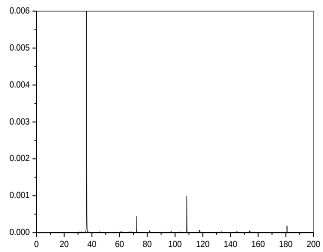
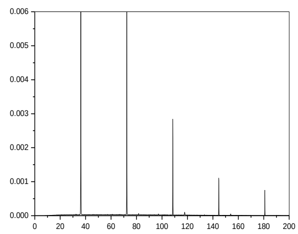


Fig. 2. Generation of a higher harmonics by high power ultrasound and nonlinear ultrasonic parameter β .

A typical example of the frequency spectrum after a fast Fourier Transform (FFT) of a received signal in the time domain is shown in Fig. 3. The frequency spectrum from an intact region shows a strong amplitude of the fundamental frequency, but a smaller amplitude of the higher harmonic component. Compared to Fig 3(a), the spectrum from a cracked region (Fig. 3(b) shows a relatively higher amplitude of higher harmonic components. The nonlinear effect is mainly from the presence of cracks, and many higher harmonic signals acquired from a cracked region. The local variation of the nonlinear acoustic parameter can be acquired by a small laser beam, and the image of a crack can be produced by a scanning laser and processing the received signals. Fig. 4(a) shows a photo of a fatigue crack by optical microscopy, and Fig. 4(b) shows the typical images reconstructed from the third harmonic components of received signal. A higher amplitude in the cracked region results in a similar image of the actual shape of the cracks.

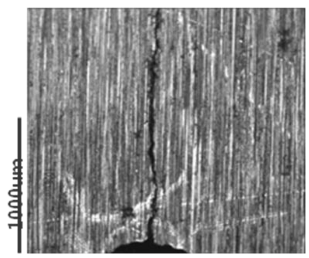


(a) Frequency spectrum from an intact region

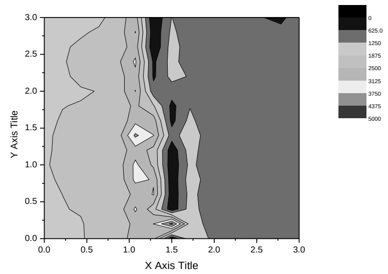


(b) Frequency spectrum from a cracked region

Fig. 3. Typical example of the frequency spectrum shows the higher harmonic components: (a) Intact region, (b) cracked region.



(a) Photo of a crack by optical microscopy



(b) Image of a crack by reconstructing the third harmonic component of the frequency spectrum

Fig. 4. A comparison of the microstructure of a fatigue crack, and a scanned image constructed from a localized nonlinear ultrasonic parameter, third harmonic component in the frequency spectrum.

3. Conclusions

The nonlinear response from a cracked region is subtracted from the frequency spectrum received by a laser Doppler vibrometer. The higher harmonic components from a cracked region are compared to those from an intact region. Images of the crack are reconstructed from a selected higher harmonic component of the frequency spectrum. Because the nonlinear effect is specifically sensitive to micro-cracking, images reconstructed from a higher harmonic component, especially an odd number of higher harmonic components, can be effective for the diagnoses of micro-cracks.

Acknowledgement

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