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Scanning Laser Vibrometry Imaging of Fatigue Cracks via Nonlinear Ultrasonic Guided Wave Scattering and Mode Conversion

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ABSTRACT

This paper presents the Scanning Laser Vibrometry (SLV) imaging of fatigue cracks by taking advantage of the nonlinear ultrasonic guided wave scattering and mode conversion phenomena. The investigation starts with the numerical modeling using the Local Interaction Simulation Approach (LISA) to demonstrate the distinctive scattering and mode conversion features at rough fatigue cracks. During the wave crack interactions, nonlinear higher harmonics are generated from Contact Acoustic Nonlinearity (CAN). In addition, the microscale rough crack surface condition may introduce mode conversion between the symmetric and antisymmetric Lamb modes. After the theoretical analysis, SLV experiments are conducted on an aluminum plate, where fatigue cracks are nucleated from a rivet hole. The damage imaging scheme utilizes the post-processing techniques via Fast Fourier Transform (FFT), frequency domain filtering, and Inverse Fast Fourier Transform (IFFT) to eliminate the linear wave field, leaving only the scattered higher harmonics in the images. In this way, the fatigue cracks can be distinguished from structural features such as rivet holes and stiffeners. This paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: structural health monitoring, nondestructive evaluation, guided waves, nonlinear ultrasonics, scattering, scanning laser vibrometry, fatigue cracks, damage imaging

1. INTRODUCTION

Scanning Laser Vibrometry (SLV) has shown its superb capability in damage imaging for Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) [1]. The wave field images may provide straight forward information for damage detection and quantification. This is usually achieved by imaging and post-processing of the scattered waves at the damage locations. Fatigue cracks have imposed considerable challenges for the NDE and SHM communities, because they are barely visible and hard to detect. Nonlinear ultrasonic techniques, on the other hand, have been reported as a sensitive approach to finding out such incipient structural changes [2]. Thus, combining nonlinear ultrasonics with SLV may facilitate the improved imaging and detection of fatigue cracks.

Due to its dense spatial measurement feature, the SLV enables the imaging of barely visible structural damage types, such as delamination and fatigue cracks. Tian et al. proposed a global-local sensing method to rapidly visualize impact damage in composite plates [3]. Kudela et al. took advantage of the trapped guided wave modes in the delaminated layers for damage detection in composite structures [4]. Fromme investigated ultrasonic guided wave scattering for fatigue crack characterization using non-contact measurements [5]. Chan et al. continued this high frequency guided wave laser testing approach to monitor the fatigue crack growth in multi-layer model aerospace structures [6]. To detect the fatigue cracks nucleated from a fastener hole, Masserey and Fromme conducted both finite difference modeling and experiments with laser interferometer [7, 8]. Staszewski et al. conducted a series of pioneer research to detect fatigue cracks in metallic structures using Lamb waves and 3D SLV [9, 10].

However, the aforementioned research endeavors generally focused on extracting damage information using the linear scattering signals. On the other hand, nonlinear ultrasonic technique may provide more sensitive results. When guided waves interact with fatigue cracks, Contact Acoustic Nonlinearity (CAN) could arise, which may introduce distinctive signal features, such as sub/super harmonic generation, DC response, mixed frequency modulation response (sideband effects), and various frequency/amplitude dependent threshold behaviors [11]. Liu et al. adopted the noncontact measurements and nonlinear modulation method, which allowed the visualization of fatigue cracks using SLV [12, 13].

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Lim et al. further conducted the study to develop the field application of the baseline free nonlinear ultrasonic modulation approach and successfully detected the fatigue cracks [14]. These pioneer investigations on applying nonlinear ultrasonics for SLV visualization of fatigue cracks generally adopted the side-band effect. In addition, the excitation of vibrations and acoustics was achieved via a high energy laser equipment and the sensing of the vibro-acoustic signals was enabled by another set of measurement SLV [15, 16]. The advantage of such a sensing scheme is that the entire procedure can be realized in a complete non-contact manner. However, the generation of the vibro-acoustic response stems from the thermo-acoustic effect of the structural materials. Thus, the high energy laser excitation needs to be carefully calibrated. The laser thermal spikes introducing material defect and damage becomes a considerable concern for sensitive materials.

This paper presents a fatigue crack detection strategy utilizing nonlinear ultasonics and SLV. The ultrasonic wave field is introduced by piezoelectric transducers and measured via the SLV. Numerical modeling results will be presented on Lamb wave scattering and mode conversion at rough fatigue cracks. The nonlinear scattering and mode conversion features will be employed for the fatigue crack imaging using SLV measurements. Different from previous investigations, this research focuses on adopting the higher harmonic generation phenomenon for damage detection. The signal post-processing technique will be presented. Experiments on an aluminum plate with multiple rivet holes are conducted. A fatigue crack unzipping through three rivet holes is visualized using the proposed nonlinear ultrasonic SLV approach. The paper finishes with summary, concluding remarks, and future work.

2. LAMB WAVE SCATTERING AND MODE CONVERSION AT FATIGUE CRACKS

The nonlinear scattering and mode conversion of Lamb waves at fatigue cracks may provide valuable information for damage imaging. Special features of nonlinear interactions between guided waves and fatigue cracks have been investigated using the Local Interaction Simulation Approach (LISA) [17]. Shen and Cesnik have developed the methodology for the quantitative analysis of the nonlinear scattering and mode conversion phenomena [18]. Moreover, the consecutive exploration on the rough fatigue crack surface influence further demonstrated that the mode conversion into A0 mode was made possible at the higher harmonics from an incident S0 wave field [19].

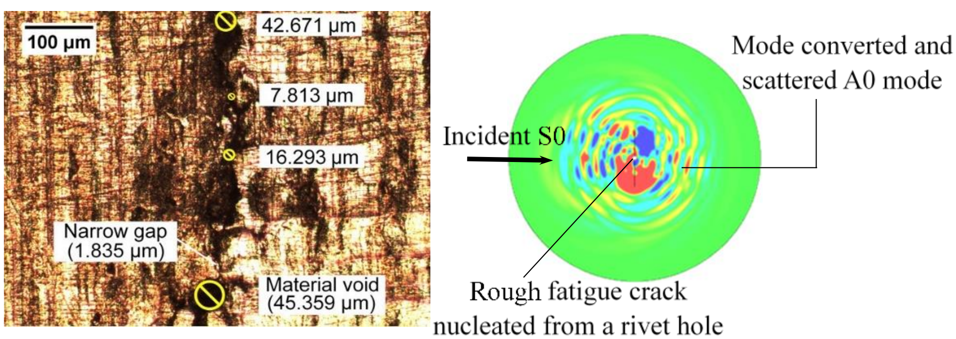

Figure 1: Rough fatigue crack surfaces and the scattered wave field from incident S0 mode.

Figure 1 presents the micro image of the fatigue crack surfaces as well as the simulation result of the scattered wave field from incident S0 wave mode. It can be clearly noticed that the crack surfaces are rough with initial openings/voids and closures/pre-stresses. The LISA modeling result shows that, with an incident S0 wave field, A0 waves with short wavelength will be converted from the nonlinear wave crack interactions. The scattering amplitude presents a certain random behavior due to the stochastic distribution of the initial micro characteristics of the rough crack surfaces.

Figure 2 shows the scattering amplitude directivity in terms of Wave Damage Interaction Coefficients (WDICs) for an incident S0 wave field at 100 kHz. For the details of WDIC concept and extraction methodology, the readers may refer to Ref. [20, 18]. The mode conversion from S0 mode into A0 mode took place at both the fundamental frequency (100 kHz) and the higher harmonics (200 kHz and 300 kHz). The scattering amplitude appeared strongest at 100 kHz and weakened gradually across the nonlinear superharmonics. The random scattering feature can be noticed as well. However, the strongest scattering lobs happened perpendicular to the crack trace, whereas the scattering amplitude along the crack direction is rather weak. Such a nonlinear mode conversion and scattering phenomenon generating superharmonic responses provide us with the possibility of visualizing the fatigue cracks and differentiating them from the general structural discontinuities, such as rivet holes and stiffeners. The following sections will present our approach and results of using nonlinear scattering wave field for fatigue crack imaging with the SLV.

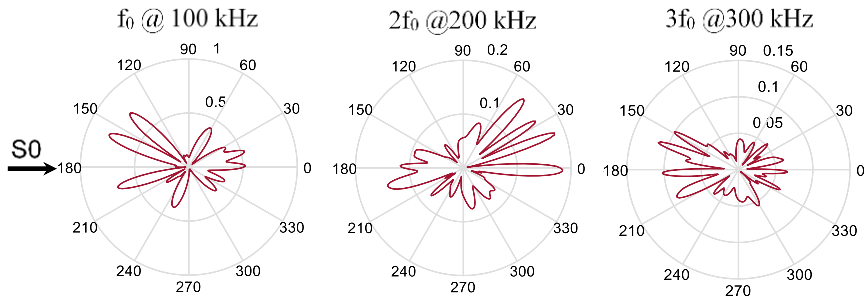

Figure 2: Mode converted and scattered A0 waves at the fundamental frequency and higher harmonics.

3. SCANNING LASER VIBROMETRY FOR ULTRASONIC MEASUREMNT

Figure 3 presents the experimental setup for fatigue crack detection using SLV. The test specimen is a 1-mm thick aluminum plate with eight 4-mm diameter rivet holes. The fatigue crack was nucleated from the fifth rivet hole, unzipping through the neighbors, connecting the fourth and the sixth rivet holes. Three Piezoelectric Wafer Active Sensors (PWAS) were instrumented on the specimen to generate interrogating wave field into the host structure. A Keysight 33500B arbitrary function generator was used to generate the excitation waveform of a 20-count Hanning window modulated sine tone burst centered at 50 kHz. The excitation signal was further amplified by a Krohn-hite 7602M wideband power amplifier up to 150 Vpp and was applied on the transmitter PWAS-1. It should be noted that the back surface of the plate was covered with reflective tape for laser scanning. Thus, the generated wave field will appear from the right hand side, as shown in Figure 5. Guided waves generated by the transmitter propagated along the plate, interacted with the crack, and were finally picked up by the Polytec PSV-400 scanning laser Doppler vibrometer. The time-space wave information was recorded for further post processing. The damping clay was implemented as well to absorb reflections from the top and bottom boundaries.

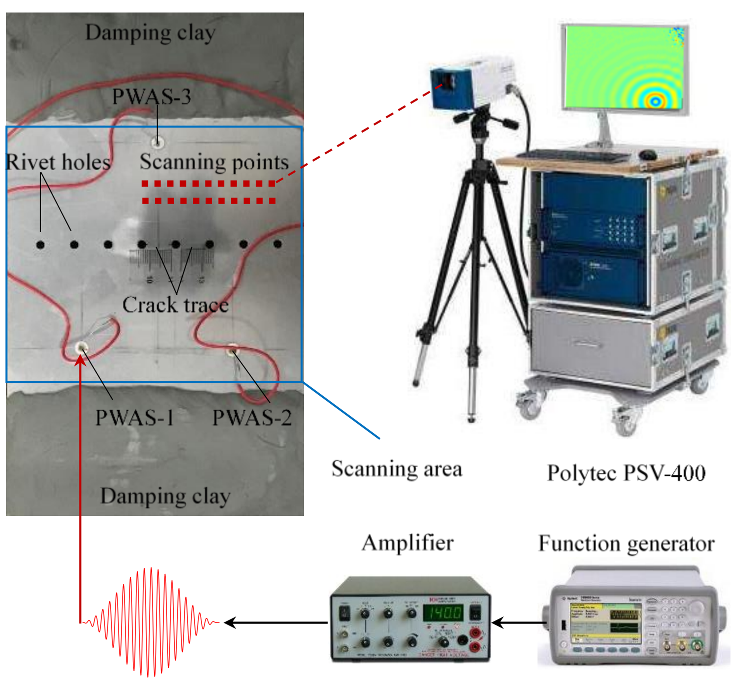

Figure 3: Experimental setup for fatigue crack detection using SLV.

It should be noted that a large number of wave cycles (20 counts) was chosen for the excitation waveform to effectively trigger the nonlinear oscillations at the fatigue crack. The sampling frequency of SLV determined that the accurate measurement frequency could reach 120 kHz. Since the superharmonics are the measurement target, our excitation frequency was set as 50 kHz, rendering a second harmonic at 100 kHz, within the meaningful data collection range.

4. DAMAGE IMAGING VIA NONLINEAR ULTRASONIC SCATTERING WAVES

This section presents the signal processing algorithm as well as the fatigue crack case study imaging results. It should be noted that the purpose of this conference publication aims at communicating our recent research progress with the SHM and NDE community. More details and case study results will be reported in a future journal publication.

4.1 Signal processing algorithm for second harmonic extraction

Figure 4 presents the signal processing algorithm used in this study. The essence of the algorithm focuses on the extraction of the nonlinear second harmonic response from the measurement wave field. The Lamb waves generated by the transmitter mainly contained the fundamental frequency at 50 kHz, yet carrying very weak inherent nonlinearity from the electronic equipment and the adhesive layer. The linear interactions between the guided waves and structural discontinuities, such as the rivet holes, will only introduce scattering and mode conversion phenomena at the fundamental frequency. On the other hand, the nonlinear interactions between the interrogating wave field and the fatigue crack will introduce nonlinear scattering and mode conversion effects at the superharmonic frequencies (100 kHz, 150 kHz, etc.). Such localized nonlinear phenomena offers great potential for fatigue crack detection and imaging.

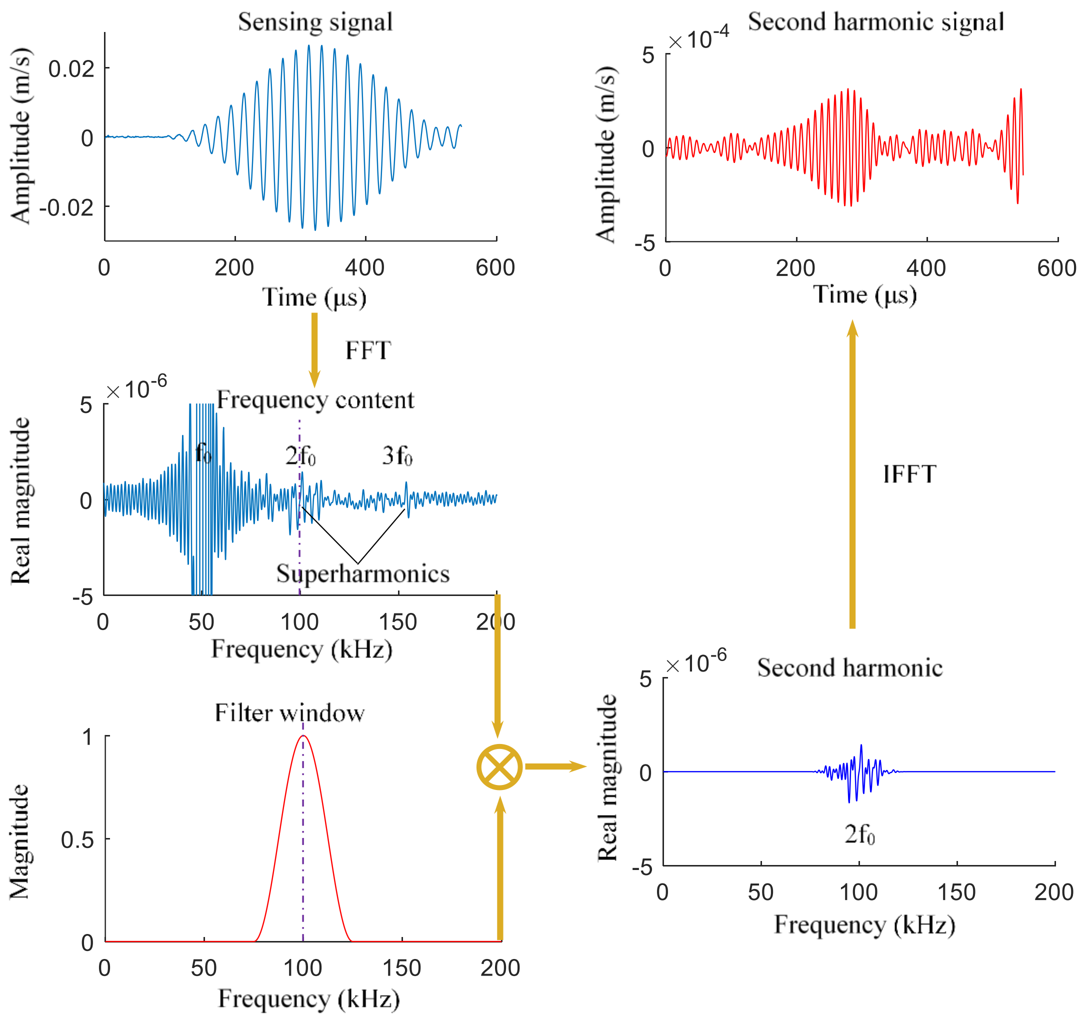

Figure 4: Signal processing flow chart for second harmonic extraction.

The signal processing procedure is realized in the following steps. First, the temporal signals are transformed into their corresponding frequency spectra through the Fast Fourier Transform (FFT). It can be clearly noticed that, in addition to the fundamental frequency response at 50 kHz, nonlinear superharmonic components at 100 kHz and 150 kHz also arise. Then, these spectra are filtered with a frequency domain pass-window function centered at 100 kHz with a bandwidth of

50 kHz. After the filtration, the signal only contains the second harmonic component. Subsequently, inverse fast Fourier transform (IFFT) is performed on the signals, rendering the time traces of the nonlinear response. Finally, the spatial temporal domain wave field is visualized and further post processed via the energy amplitude to reveal the fatigue cracks.

4.2 Fatigue crack imaging results

Figure 5 presents the wave field images before and after the aforementioned post-processing procedure. Figure 5a shows the original wave field image, representing the conventional linear wave propagation. It can be clearly seen that the circular crested Lamb waves were generated by the transmitter PWAS. The interrogating wave field irradiated outwards, spreading across the specimen. The rivet holes can be noticeably identified from the SLV image. However, the rivet holes are structural features rather than structural damage. On the other hand, the fatigue crack image is not clear and barely visible from the image. Figure 5b presents the nonlinear counterpart wave field image after the post-processing. Since the second harmonic resided at 100 kHz, the wavelength became much shorter. It should be noted that the weak inherent nonlinearity brought by the electronic equipment and the adhesive layer participated in the wave generation. The generated second harmonic component can be obviously identified, irradiating from the transducer. It is remarkable that the localized nonlinear mode conversion and scattering wave field can be clearly visualized via the post-processing technique. Such scattered nonlinear A0 wave field stem from the mode conversion from S0 wave incidence on the fatigue crack. Meanwhile, the PWAS generated A0 nonlinear wave field had not arrived at the rivet holes yet. As a consequence, the rivet holes were not present in the image, leaving only the damage as the major scatterer. In other words, the proposed nonlinear wave SLV damage detection methodology enables the imaging of the fatigue crack, avoiding the adverse influence from the other structural features.

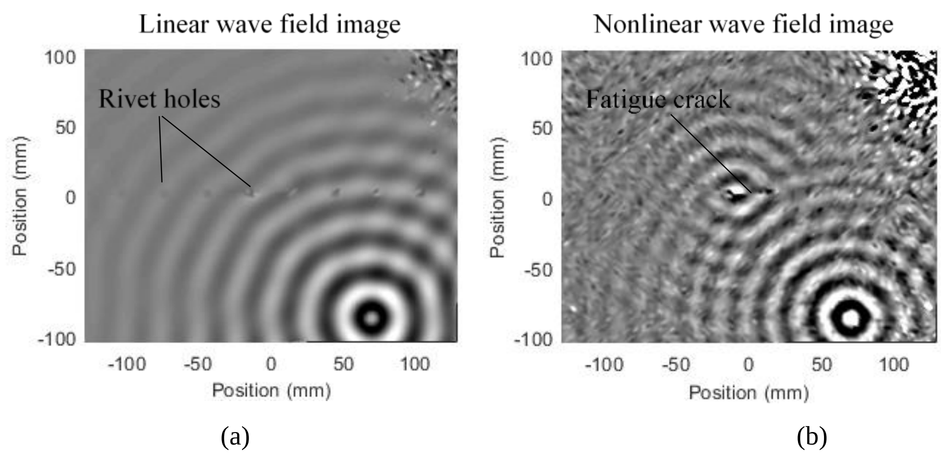

Figure 5; Wave field images before and after the signal post-processing: (a) linear wave field image (before processing); (b) nonlinear wave field image (after processing). (Note the fatigue crack scattered nonlinear wave field can be clearly identified).

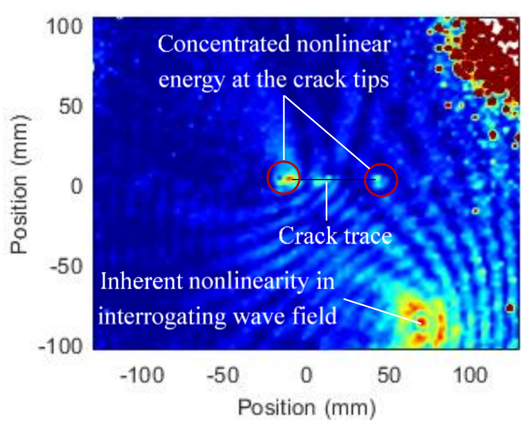

Figure 6: Nonlinear wave field energy profile.

Figure 6 presents the nonlinear wave field energy profile by further integrating the temporal domain signals. The nonlinear energy distribution became very indicative of the fatigue damage. The inherent nonlinearity in the interrogating wave field could be clearly observed. In addition, the nonlinear energy concentrated on the crack tips where strong nonlinear interactions happened. In this way, the fatigue crack was clearly visualized via the nonlinear ultrasonic SLV technique.

5. CONCLUDING REMARKS

This paper presented the investigation of utilizing the nonlinear scattering and mode conversion phenomena for fatigue crack detection via the SLV imaging technique. The nonlinear ultrasonic scattering mechanism was illustrated using the LISA simulations. It was found that the mode conversion from S0 mode into A0 mode was made possible due to the rough crack features. In addition, such mode conversion phenomenon also existed at nonlinear higher harmonics. After the theoretical analysis, SLV case study experiments were conducted on an aluminum plate, where fatigue cracks were nucleated from a rivet hole. The damage imaging scheme was introduced, involving the post-processing techniques via fast Fourier transform (FFT), frequency domain filtering, and inverse fast Fourier transform (IFFT) to eliminate the excitation wave field, leaving only the scattered higher harmonics in the images. The case study showed that the fatigue crack could be clearly visualized and distinguished from other structural features such as the rivet holes. The nonlinear ultrasonic SLV imaging technique possesses great potential for SHM and NDE applications.

For future work, more nonlinear wave phenomena should be explored for damage detection and visualization, combining with the SLV. Further investigation should be carried out using nonlinear ultrasonic SLV for delamination imaging in composite structures.

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