On Quantitative Evaluation of Fatigue Cracks: An Active Way Using Nonlinear Acousto-Ultrasonic Waves

C. ZHOU, M. HONG, Z. SU, Q. WANG and L. CHENG

ABSTRACT

The majority of today's damage detection techniques rely on linear macroscopic changes in global vibration signatures or local wave scattering phenomena. However, damage in real-world structures often initiates from fatigue cracks at microscopic levels, presenting highly nonlinear characteristics which may not be well evidenced in linear macroscopic changes. By exploring the nonlinearities of higher-order acousto-ultrasonic (AU) waves, an active approach for characterizing fatigue cracks was established. Nonlinearities of higher-order AU waves, subjected to the existence and accumulation of fatigue cracks, were explored. Fundamental investigation was carried out to link the nonlinearities of AU waves to the relative distance between a sensing path and the fatigue crack. Results from simulation and experiment match well in between, which can be used to quantitatively evaluate fatigue cracks. Compared with existing detection approaches based on nonlinear AU waves, this method embodies uniqueness including utilization of a permanently attached active sensor network comprising miniaturized sensors, well accommodating the purpose of structural health monitoring.

INTRODUCTION

Engineering structures experience continuous accumulation of fatigue damage, and deteriorate gradually over their lifespan. The longer an engineering structure is in service, the more fatigue cracks it may develop. With safety a paramount priority for all engineering structures, integrity and durability criteria must be strictly met. This

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has substantially entailed nondestructive evaluation (NDE) and structural health monitoring (SHM) techniques over the past two decades.

Amongst various NDE and SHM techniques, those based on acousto-ultrasonic (AU) waves have proven effectiveness in achieving a reasonable compromise among resolution, practicality and detectability. Most of the currently existing AU wave-based NDE and SHM rely on linear wave scattering phenomena (*e.g.*, wave reflection, transmission, mode conversion) upon the interaction between incident waves and damage. Such an inspection philosophy is effective to characterize macroscopic damage such as notch, corrosion or delamination with a dimension comparable with the wavelength. However, it may lose its effectiveness when dealing with fatigue cracks because the interaction between incident waves and tiny fatigue cracks (much smaller than the wavelength) would not lead to phenomenal wave scattering. To overcome such a deficiency, nonlinear acousto-ultrasonics has been increasingly explored, by taking advantage of nonlinearities related to fatigue damage [1-3].

The prevailing nonlinear AU wave-based identification can be divided into two main categories: (i) those based on a mixed frequency response (this category uses a low-frequency but high-intensity structural vibration to modulate high-frequency but low-magnitude AU waves. Upon modulation, existence of fatigue damage can result in a number of frequency sidebands around the input excitation frequency in the frequency domain [2]); and (ii) those based on higher-order harmonic wave generation (this category focuses on additional wave components at frequencies which are multiples of the initial excitation frequency, in recognition of the fact that fatigue damage can cause shift of wave energy, more or less, from the driving frequency to its higher-order (*e.g.*, 2^{nd} or 3^{rd} order) harmonics [3]). The methods in the above two categories have demonstrated effectiveness in qualitatively indicating the existence of fatigue damage. Most of them, however, are unwieldy to quantitative characterization of tiny fatigue cracks (including location, severity, shape and size).

In this study, fundamental investigation was carried out to link the acoustic nonlinearities of AU waves to the relative distance between a sensing path and the fatigue crack, using both simulation and experiment approaches. These correlations can be beneficial to quantitative evaluation of fatigue cracks.

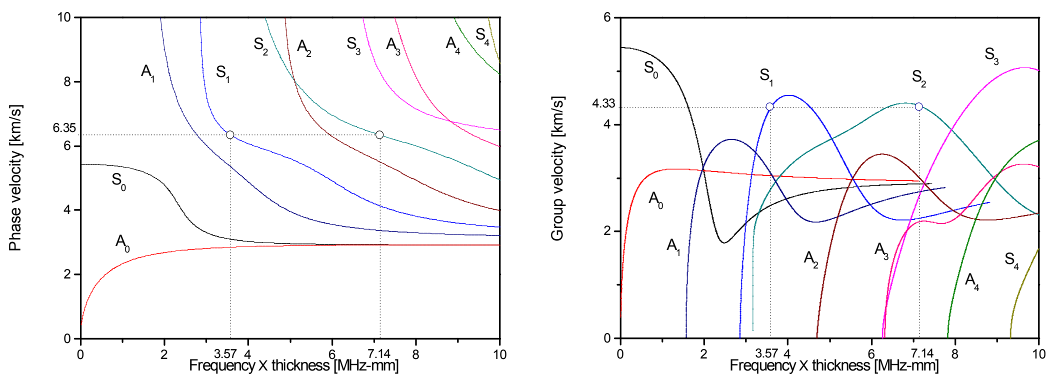
NONLINEAR LAMB WAVES

Lamb waves have been widely used to identify structural damage due to their superb properties including the ability to interrogate a large area using a few transducers, capacity to access hidden components, high sensitivity to different types of damage and potential to be used for on-line health monitoring. Most existing Lamb-wave-based damage identification techniques were developed by canvassing linear properties of Lamb waves such as the wave attenuation, transmission and mode conversion. Such linear methods may be unwieldy to characterise microscopic nonlinear fatigue cracks. In recent, there has been increasing interest in using nonlinear properties of Lamb waves to evaluate the fatigue cracks [4-6].

The nonlinearities of a specimen under inspection are twofold: material nonlinearity and localized defect nonlinearity. The former is described as a nonlinear stress-strain relationship which induces nonlinear terms in the wave equation. The latter refers to localized nonlinearity caused by local contact defects such as a fatigue crack or bolt loosening. Both of them cause the generation of nonlinear properties of Lamb waves.

Provided two conditions are satisfied (the *synchronism* and the *non-zero power flux* [4-6]), the nonlinear characteristics of Lamb waves would be conspicuous and beneficial to describing fatigue damage. Synchronism is referred to as the phase velocity matching (the phase velocity of the second-harmonic mode matches that of the fundamental mode) and group velocity matching (the group velocity of the second-harmonic mode matches that of the fundamental mode). Synchronism is the condition leading to the wave energy shift from the fundamental to second-harmonic mode. Non-zero power flux means that there should be non-zero power transfer from the fundamental to the second-harmonic mode, which can be satisfied by ensuring that the fundamental and the second-harmonic modes are of the same type (both are symmetrical or anti-symmetrical). Upon meeting two conditions, the second-harmonic mode grows linearly as propagation distance, therefore to be cumulative.

Dispersion curves for the phase and group velocities *vs.* frequency·thickness in an aluminium plate were calculated using DISPERSE®, shown in Fig. 1(a) and (b), respectively. Mode pair (S_1, S_2) meet the above two conditions and therefore were selected in this study.



(a) (b)

Figure 1. Dispersion curves of Lamb waves in an aluminium plate: (a) phase velocity vs. frequency×thickness (b) group velocity vs. frequency×thickness.

In order to quantify the degree of nonlinearities of Lamb waves, an acoustic nonlinearity parameter (β) was introduced, which is defined as

$$\beta = \frac{\Gamma_2}{\Gamma_1^2}, \tag{1}$$

where β is the acoustic nonlinearity parameter; Γ_1 and Γ_2 the amplitudes of the fundamental and second harmonic modes, respectively. For the mode pair selected in this study, Γ_1 refers to the S_1 mode at the frequency×thickness of 3.57 MHz×mm, whereas Γ_2 refers to the S_2 mode at 7.14 MHz×mm.

NONLINEARITY PARAMETER *VS*. MEASUREMENT DISTANCE

To perform damage detection at a quantitative level (including location, severity, shape and size), variation in the acoustic nonlinearity parameter (β) with regard to the relative distance between a fatigue crack and a particular sensing path was investigated using both finite element (FE) simulation and experimental validation.

FE Simulation

An aluminium plate measuring 400 mm (long)×240 mm (wide)×4.5 mm (thick) with an encastre boundary condition was considered, as shown schematically in Fig.2. A triangular notch, 15 mm in base and 25 mm in height, was assumed at the centre of the upper edge of the plate, serving as a fatigue crack initiator (to be in line with the following experiment). A surface crack, 4 mm in length, from the tip of the notch in parallel with the plate width was modeled, the depth of which was set to be 2.25 mm (half of the plate thickness). In the model, the crack had a uniform gap of 0.2 mm between two defining surfaces. A contact-pair interaction was imposed to two crack surfaces to stimulate the contact acoustic nonlinearity arising from fatigue cracks. Ten circular piezoelectric lead zirconate titanate (PZT) elements, 5 mm in diameter for each, were allocated on the plate, forming five actuator-sensor paths $A_i - S_i$ ($i = I, II, III, IV, V$), with the distance to the centre of the fatigue crack being 0, 10, 20, 30, 40 mm, respectively. For each actuator-sensor path, the distance between the actuator and sensor remained 200 mm.

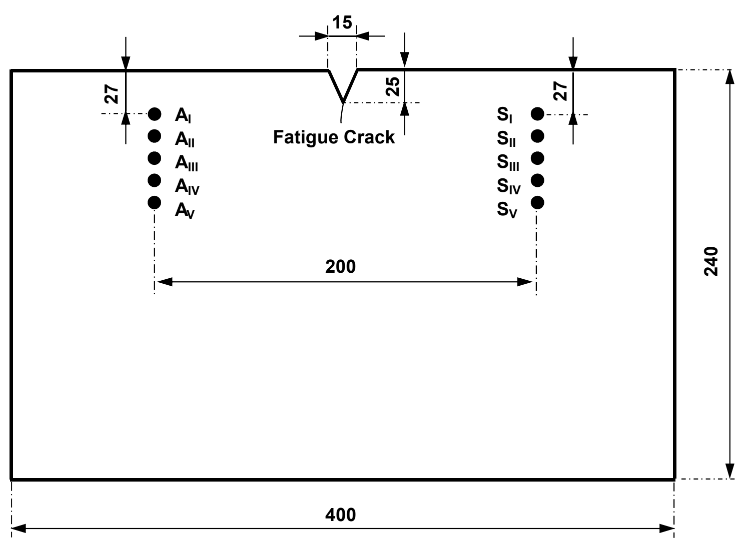


Figure 2. Specimen configuration (unit: mm).

The plate was meshed using three-dimensional eight-node brick elements. In the vicinity region of the crack, meshing was in particularly refined with the element size less than 0.25 mm, guaranteeing that at least 15 elements were allocated per wavelength of the excited S_1 wave mode. For the far-field regions of the plate, relatively sparse meshing was applied. Eight elements were allocated through the plate thickness, resulting in approximately six million elements in total for the entire plate.

Sixteen-cycle Hanning-window-modulated sinusoid tonebursts at a central frequency of 800 kHz (corresponding to the frequency×thickness of 3.57 MHz×mm for the current selection of plate thickness) were excited as the input signal. Uniform in-plane radial displacement constraints were applied on FE nodes of the PZT actuator model to generate incident waves. Dynamic simulation was carried out using commercial FE package ABAQUS®/EXPLICIT due to its good performance in simulating wave propagation. The captured wave signals were obtained by calculating the strains at the locations where PZT sensors were collocated.

A typical time-domain signal acquired in the simulation via sensing path $A_I - S_I$ was exhibited in Fig. 3. The signal was subsequently processed using short time Fourier transform (STFT) to obtain its time-frequency spectrogram, shown in Fig. 4.

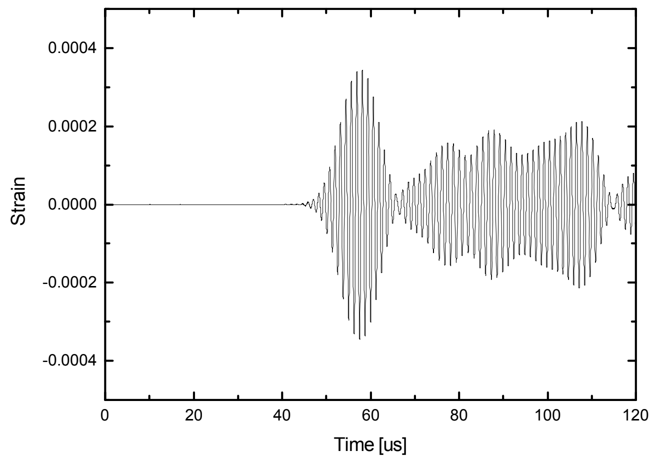


Figure 3. A typical time-domain signal acquired via sensing path $A_I - S_I$ in FE simulation.

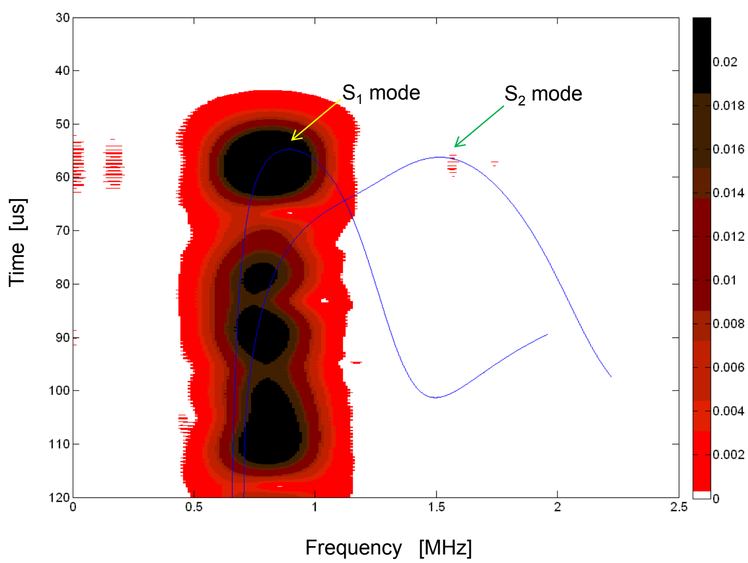


Figure 4. Time-frequency spectrogram of the signal in Figure 3 obtained using STFT.

STFT was demonstrated effective in isolating individual modes in the AU wave signals from the others, benefiting signal interpretation. Upon application of STFT, the fundamental and second harmonic components (S_1 and S_2 modes) of the captured AU wave signal were separated and extracted as a function of time, which are shown in Fig. 5(a) and (b), respectively. From Fig. 5, the magnitudes of the fundamental and second harmonic modes were obtained, and the correspondingly obtained acoustic nonlinearity parameter (β) was calculated as $\frac{0.000378}{0.0455^2} = 0.1826$ in terms of Eq. 1. Repeating the processing aforementioned, β for every single sensing path $A_i - S_i$ ($i = I, II, III, IV, V$) was obtained, to form a relationship correlating the acoustic nonlinearity parameter of a particular sensing path with the relative distance between this path and the fatigue crack, displayed in Fig. 6 (the dotted line).

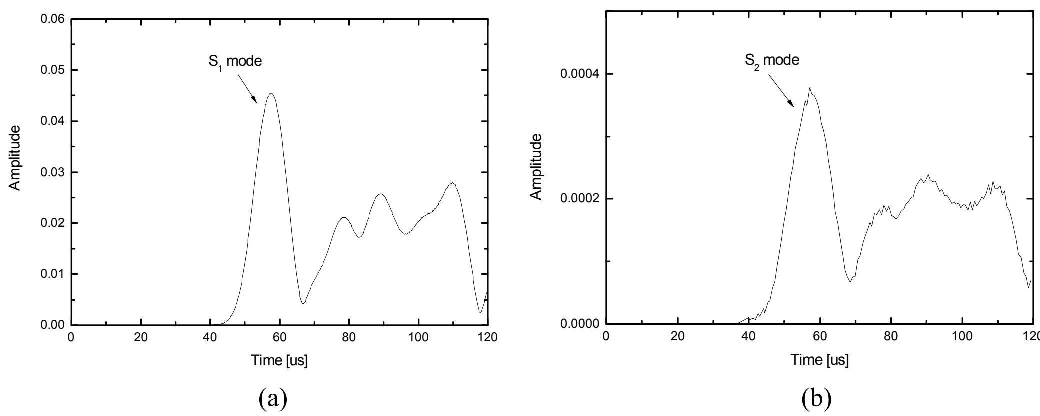


Figure 5. Slices at (a) fundamental frequency (800 kHz); and (b) second harmonic frequency (1.6 MHz) as a function of time extracted from the time-frequency spectrogram in Figure 4.

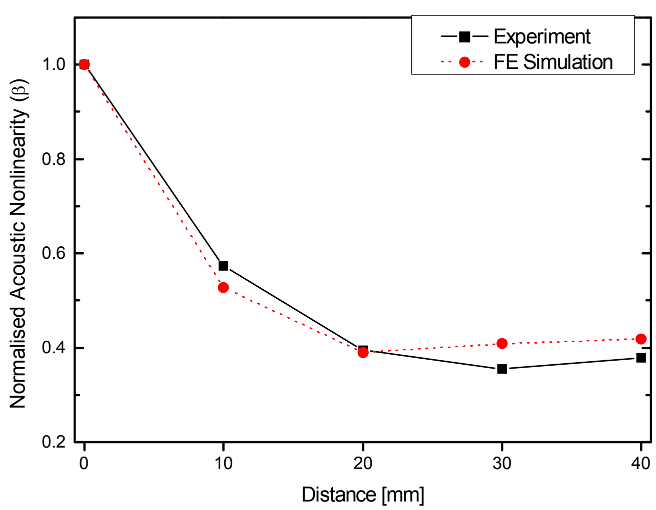


Figure 6. Normalized acoustic nonlinearity vs. distance between a sensing path and the fatigue crack.

Experimental Validation

Experiments were conducted to validate the above FE simulation using the same configurations. The aluminium specimen was photographed in Fig. 7, which was installed on a digitally controlled MTS testing platform, to initiate a fatigue crack. The specimen was subjected to a sinusoidal tensile load with a maximum magnitude of 10 kN at a frequency of 5 Hz. It took about 200,000 cycles to produce a barely invisible fatigue crack of 4 mm in length from the tip of the notch.

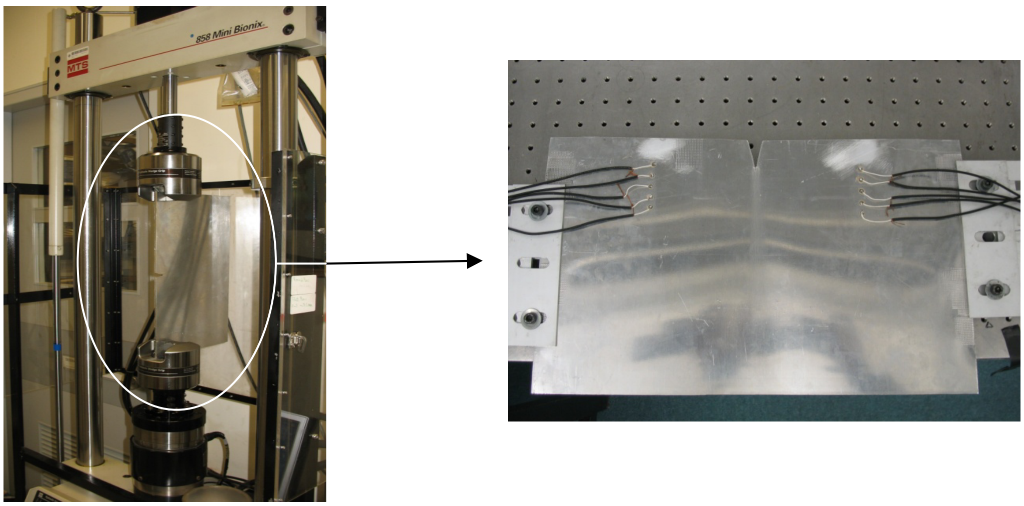


Figure 7. Sample used for experimental validation (left: on MTS fatigue testing platform; right: surface-mounted with the sensor network).

Upon completion of fatigue testing, ten circular PZT wafers with a diameter of 5 mm for each were surface-mounted on the specimen using a thin layer of two-component epoxy adhesive. The adhesive is conductive, making the transducers be grounded and eliminating the need for additional electrodes. A lead wire was soldered on the top surface of each PZT wafer, connecting the PZT wafer with a signal generation and acquisition system developed on a *VXI* platform [7]. Shielded wires and standard BNC connectors were used to minimise measurement noise. Sixteen-cycle Hanning-window-modulated sinusoid tonebursts at a central frequency of 800 kHz were generated with an arbitrary waveform generator (Agilent® E1441) and then amplified with a high-voltage linear power amplifier (US-TXP-3) to 80 $V_{p\text{-}p}$, which was then applied on each PZT wafer to generate incident waves. The Lamb wave signals (including both the S_1 and S_2 modes), sensed by PZT sensors, were acquired with a signal digitizer (Agilent® E1438) at a sampling rate of 40 MHz.

Using the same signal processing as that in FE simulation, the relationship between the acoustic nonlinearity parameter (β) and the relative measurement distance was obtained and is shown in Fig. 6 (the solid line).

Results and Discussions

It can be seen from Fig. 6 that the results from FE simulation (the dotted line) and experiment (the solid line) match well with each other, displaying such a quantitative relationship: the largest acoustic nonlinearity parameter (β) is captured when the sensing path right passes through the fatigue crack ($A_I - S_I$ in this case); with an increase in the distance between the fatigue crack and the sensing path, β decreases gradually; when the distance exceeds 20 mm, no significant change in β could be captured. The obtained quantitative correlation could be further used to locate the fatigue crack, as reported in detail elsewhere [8].

CONCLUSIONS

To facilitate quantitative evaluation of fatigue cracks small in size, fundamental investigation was carried out to link the acoustic nonlinearity parameter (β) of a particular sensing path to the relative distance between this sensing path and the fatigue crack, using both FE simulation and experiment. Results from FE simulation and experiment match well with each other. The obtained quantitative correlation can further used to locate the fatigue cracks.

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REFERENCES

1. Jhang, K.-Y. (2009), "Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: A review". *International Journal of Precision Engineering and Manufacturing*, Vol. 10(1), 123–135
2. Aymerich, F. and Staszewski, W.J. (2010), "Impact damage detection in composite laminates using nonlinear acoustics". *Composites Part a-Applied Science and Manufacturing*, Vol. 41(9), 1084–1092
3. Dutta, D., Sohn, H., Harries, K.A. and Rizzo, P. (2009), "A Nonlinear Acoustic Technique for Crack Detection in Metallic Structures". *Structural Health Monitoring-an International Journal*, Vol. 8(3), 251–262
4. Deng, M. and Pei, J. (2007), "Assessment of accumulated fatigue damage in solid plates using nonlinear Lamb wave approach". *Applied Physics Letters*, Vol. 90(12), 121902–3
5. Lee, T.H., Choi, I.H. and Jhang, K.Y. (2008), "The nonlinearity of guided wave in an elastic plate". *Modern Physics Letters B*, Vol. 22(11), 1135–1140
6. Pruell, C., Kim, J.Y., Qu, J.M. and Jacobs, L.J. (2009), "Evaluation of fatigue damage using nonlinear guided waves". *Smart Materials & Structures*, Vol. 18(3), 035003–7
7. Su, Z. and Ye, L. (2005), "Lamb wave propagation-based damage identification for quasi-isotropic CF/EP composite laminates using artificial neural algorithm, Part II: implementation and validation". *Journal of Intelligent Material Systems and Structures*, Vol. 16(2), 113–125
8. Zhou, C., Hong, M., Wang, Q., Su, Z. and Cheng, L. "Diagnostic imaging for fatigue cracks". submitted to *Journal of Intelligent Material Systems and Structures.*