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DETECTING LOCALIZED MICRO-DAMAGE USING NONLINEAR INTERACTION OF COUNTER-PROPAGATING LAMB WAVES

**Wujun Zhu, Yanxun Xiang[1], Changjun Liu,
Fu-Zhen Xuan**
Key Laboratory of Pressure Systems and Safety of
MOE. School of Mechanical and Power Engineering,
East China University of Science and Technology
Shanghai, China

Mingxi Deng
College of Aerospace Engineering,
Chongqing University
Chongqing, China

ABSTRACT

Nonlinear Lamb wave mixing provides a potential method to assess the localized material degradation in plate-like structures. The sum harmonics generated by the nonlinear mixing of counter-propagation Lamb waves under internal resonance criteria were acquired through scanning an aluminum alloy plate with localized micro-damage and closed crack in finite element simulations and experimental measurements, respectively. Both results illustrate the capability of the nonlinear interaction of counter-propagating Lamb waves to detect localized micro-damage.

Keywords: wave mixing, Lamb wave, damage evaluation

1. INTRODUCTION

Plate-like structures are widely used in the aerospace, automotive, and chemical industries, where they can be subjected to complex service conditions, in which micro-cracks, fatigue, creep, or corrosion damage may occur, leading eventually to catastrophic failure. Nonlinear interaction of ultrasonic waves is an emerging technique to quantitatively localize and evaluate these micro-damage at an early stage to avoid the failure of entire structure, because of their exceptional sensitivity to the material degradation. For Lamb waves, theoretical investigations presented the conditions of the phase matching and non-zero power flux for the cumulative generation of the secondary Lamb waves [1-4]. Self-interactions of Lamb waves have been studied to generate the cumulative second harmonic Lamb waves, which have been illustrated to be capable of evaluating the plastic deformation, fatigue and creep damage at the early stage of material degradation [5-7]. However, the second harmonics is generally an average result regarding the damage in the region between the transmitter and the receiver, and can also be contaminated by external nonlinearities. Lamb wave mixing recently investigated can overcome these shortcomings with the generation of Lamb waves at the sum and/or difference frequency [8-10]. While the mixing of Lamb waves propagating in the same direction is difficult to guarantee highly accurate damage localization because of the relatively large mixing zone, the mixing of Lamb waves propagating in opposite directions can appreciably reduce the size of mixing zone.

In this work, finite element simulations and experimental measurements were performed to detect the micro-damage and the closed crack, respectively, using the secondary Lamb waves at the sum frequency generated by the nonlinear interaction of the counter-propagating Lamb waves. Both results illustrate the capability of the nonlinear interaction of counter-propagating Lamb waves to detect localized micro-damage in plate-like structures.

2. MODE TRIPLET SELECTION

Considering an isotropic and homogeneous plate without attenuation and dispersion, within the second order perturbation approximation and normal mode expansion method, the internal resonance criteria for cumulative generation of secondary Lamb waves are phase matching and non-zero power flux, expressed as [1-4]:

$$\boldsymbol{k}_{a\pm b} = \boldsymbol{k}_a \pm \boldsymbol{k}_b \tag{1}$$

$$f_V + f_S \neq 0 \tag{2}$$

Where $\boldsymbol{k}_{a\pm b}$, $\boldsymbol{k}_a$ and $\boldsymbol{k}_b$ are the wave vectors of the two primary and the sum or difference Lamb waves, respectively. f_V and f_S are the power flux through the volume and the surfaces of the plate, respectively. The non-zero power flux condition indicates the symmetry characteristics of the secondary Lamb waves. Specifically, the interaction between two Lamb waves with the same (opposite) symmetric

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[1] Contact author: yxxiang@ecust.edu.cn

characteristics lead to the symmetric (antisymmetic) secondary Lamb waves [11]. The phase matching condition ensures the synchronism of the primary and secondary Lamb waves, and defines the propagation direction of the secondary Lamb waves. Specifically, for the counter-propagating Lamb waves, the wavenumber of the secondary Lamb waves at the sum frequency can be expressed as $k_{a+b} = k_a - k_b$. Based on these internal resonance criteria, the S1 mode at 2.95 MHz is expected to be generated by the nonlinear interaction of counter-propagating S0 modes at 1.13 MHz and 1.82 MHz in a 1-mm-thick 6061-T6 aluminum alloy plate.

3. FINITE ELEMENT SIMULATIONS

Finite element simulations were performed on a two dimensional 6061-T6 aluminum alloy plate with the thickness of 1 mm. As shown in Fig. 1, the micro-damage was given in a local region from 270 mm to 290 mm, where the hyperelastic material was adopted with the Murnaghan material model, while the rest region was given linear material properties. Two S0 modes were excited simultaneously by imposing longitudinal displacements at ends of the plate with Hanning-windowed sinusoidal tone bursts at 1.13 MHz and 1.82 MHz, respectively.

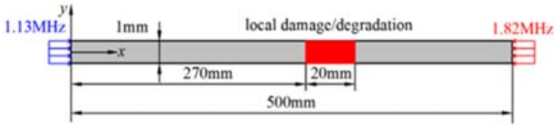

FIGURE 1: SCHEMATIC DIAGRAM OF A TWO DIMENSIONAL MODEL WITH LOACAL DAMAGE.

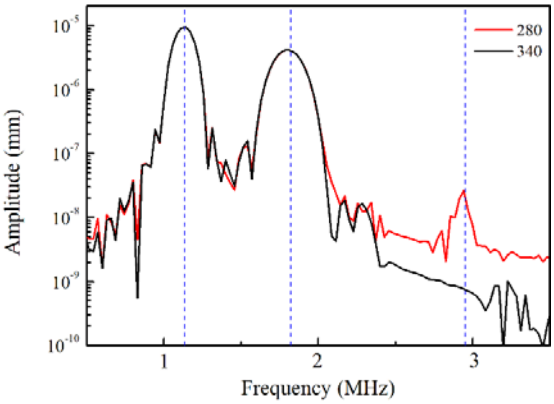

FIGURE 2: FREQUENCY SPECTRA OF THE RECEIVED SIGNLAS AT 280 AND 340 MM.

To scan the plate, time delays were added to the excitation sources to move the middle of the mixing location from 220 mm to 340 mm with an interval of 20 mm, where the pulses excited from two sources were expected to overlap completely. The out-of-plane displacement components on the surface were recorded at these mixing locations. Fast Fourier Transform (FFT) was performed on the received signals to acquire the amplitudes of two primary Lamb waves, A_1 and A_2, and the sum harmonics A_s. Fig. 2 shows the frequency spectra of the received signals at 280 and 340 mm. The amplitudes of two primary waves keep almost constant at the intact and damaged regions. The amplitude of the sum harmonics was apparently observed at the damaged regions, while the secondary Lamb waves at sum frequency were rarely generated at the intact regions. Fig.3 shows the acoustic nonlinearity parameters $A_s/(A_1*A_2)$ with respect to the mixing location. It can be seen that the $A_s/(A_1*A_2)$ acquired at the micro-damage regions is much larger than that obtained in the intact regions. The nonlinear acoustic nonlinearity parameter of the counter-propagating Lamb waves was corroborated to be effective to localize the local material damage or degradation in plate-like structures.

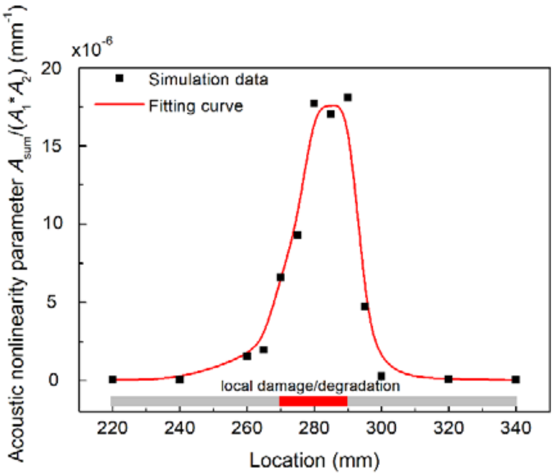

FIGURE 3: ACOUSITC NONLINEARITY PARAMETER $A_s/(A_1*A_2)$ VERSUS THE MIXING LOCATION.

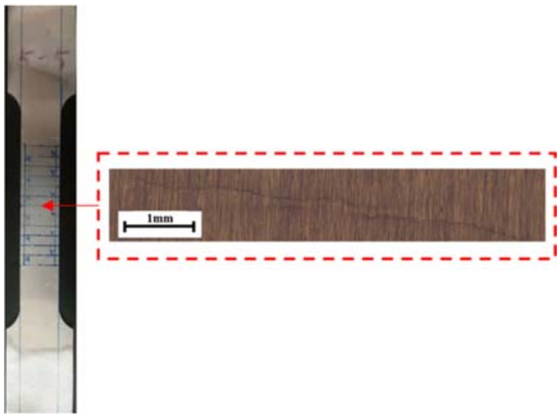

FIGURE 4: THE SPECIMEN WITH A NEARLY 5 MM LENGTH CLOASED CRACK.

4. EXPERIMENTAL MEASUREMETNS

Detection of a closed crack was further experimentally investigated on an aluminum alloy specimens using the nonlinear mixing of counter-propagating S0 modes. The specimens were initially fabricated with the tensile axis paralleling to the rolling direction from an aluminum block, as shown in Fig. 4. The specimen was cyclically loaded to make a nearly 5-mm-length closed crack at the center of the specimen. The closed crack could be observed via an optical microscope with a grinding treatment of surface.

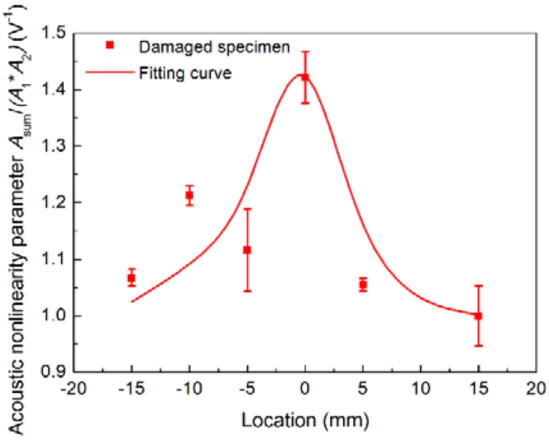

FIGURE 5: NORMALIZED ACOUSTIC PARAMETER $A_{sum}/(A_1*A_2)$ VERSUS THE MIXING LOCAITON IN THE SPECIMEN WITH A NEARLY 5 MM LENGTH CLOASED CRACK.

Assuming that the origin of the coordinate locates at the center of the specimens, the damaged one was scanned from -15 mm to 15 mm with a step of 5 mm. Experimental measurements were repeated five times at each location by completely removing and then reattaching the wedge transducer assembly to the plate. Fig. 5 show the acoustic nonlinearity parameters $A_s/(A_1*A_2)$ with respect to the mixing location for the specimen with a nearly 5-mm-length closed crack, respectively. The $A_s/(A_1*A_2)$ increases drastically near the closed crack in the damaged specimen, which indicates that the nonlinear interaction of counter-propagating Lamb waves was effective to localize the closed crack.

4. CONCLUSION

Finite element simulations and experimental measurements were performed to detect the micro-damage and the closed crack using the nonlinear interaction of the counter-propagating Lamb waves. The acoustic nonlinearity parameters acquired at the micro-damage regions were found to be much larger than that obtained in the intact regions. The nonlinear interactions of counter-propagating Lamb waves were demonstrated to detect the localized micro-damage in plate-like structures.

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