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Detection of Thermal Fatigue in Composite Laminates

Using Nonlinear Ultrasonic Guided Wave

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Abstract: This study develops a new approach to evaluate material degradation of composite laminates by using nonlinear Lamb wave, the correlation between normalized nonlinear parameters and degradation states was studied. Depending on dispersive curve, a specific lamb mode S1 which is phase and group matching was chosen for the practical generation of nonlinear lamb wave. Group delay method was used to separate multi-modes of wave-packet. The results show that it is possible to measure the nonlinearity of composite laminate by using Lamb wave, the measured acoustics normalized nonlinearity using Lamb wave are directly related to material degradation, from these results, it could be concluded that it is possible to use nonlinear Lamb wave to evaluate composite laminates degradation.

Keywords: composite laminates; material degradation; nonlinear lamb wave

1 Introduction

Ultrasonic techniques are well established for non-destructive evaluation(NDE), especially Lamb wave, it has proven to be one of the most widely used ultrasonic-guided wave for damage detecting, the method is based on Lamb wave propagating in plate-like structure, it can propagate over considerable distance without scanning point by point and the wave propagate throughout the entire thickness of structure, which means that it can not only find the surface defects but also internal defects, low energy consumption and great cost-effectiveness are another feature for Lamb wave-based damage detection approach[1-4]. Experimental research and theoretical study of Lamb wave application in composite has been addressed since the late 1980s[5], the exploration of Lamb wave applied in composite laminates got increasingly concern for the usually relatively small thickness compared with length of laminate-structures, Lamb waves are quite suitable for this feature.

However, most of linear ultrasonic NDT technologies are very sensitive to gross defects, but much less sensitive to material degradation. It is well known that material degradation is always accompanied with a certain nonlinear behavior of material properties, and ultrasonic propagation in media is directly related material properties, so nonlinear ultrasonic measurements are proposed a potential tool to characterize material degradation[6-7]. Although nonlinear ultrasonic measurement has been a subject of considerable interest, most of the research focused on nonlinear bulk and surface wave. When it comes to nonlinear Lamb wave, Deng and C. Pruell recently characterized the micro-structure change which caused by fatigue[8] or derived plasticity[9] by using nonlinear Lamb wave in metallic material, it shown that nonlinear Lamb wave could apply for early detection of distribute micro-cracks or material degradation. For composite laminates, the most common defects happened in the material are mechanical fatigue, transverse matrix cracks, debonding and delaminations which size are microscopic. So, compared with linear ultrasonic wave, nonlinear Lamb wave should have greater potential for application in this material.

In this paper, a second harmonic generation measurement during Lamb wave propagation in a kind of widely used composite laminates was used to evaluate the material degradation. In first section, it introduces specimens and experimental system. Next, the methods to choose Lamb wave mode, analysis of generated signal data and nonlinear parameters are explained. In the third section, after testing all specimens under different degraded, the correlation between material degradation degree and nonlinear parameter is found.

2 Specimens and Experimental System

Specimens used in this study were unidirectional and symmetric quasi-isotropic laminates, were made of carbon/epoxy laminates with stacking sequences [0]6. All specimens’ thickness is 1.0 mm, the dimensions were 40 mm×40 mm as shown in Fig. 1. Thermal fatigue was imposed on specimens to fabricate degradation. In Fig.2, it shows that the maximum and minimum temperatures of thermal cycle were respectively of 70°C and -55°C with almost constant cooling and heating time of 15min. the test specimens in this
study were conducted under 0, 100, 200, 1000 thermal cycles.

Measurement of second harmonic amplitude is the goal of nonlinear ultrasonic test. Second harmonic is the wave that contains components at double frequency of the incident wave. The setup of the equipment to monitor the nonlinear ultrasonic wave is shown in Fig. 3, a high voltage tone burst signal of 10cycles at frequency of 2.25MHz generated by the RAM-RITEC ultrasonic measurement system, which was primarily composed of a high power attenuator, a high power 50 Ω Amplifier. A ultrasonic angle changeable transducer with central frequency of 2MHz was used to generate the fundamental wave, and an angle changeable transducer with central frequency of 4MHz was chosen to receive fundamental wave and second harmonic wave. S1 mode is generated for detection of material nonlinearity, since the primary S1mode and generated second harmonic Lamb mode (S2mode) have the same phase velocity and group velocity. A fixed pressure was loaded in the transducers through holders. The transducers are coupled to the specimen with light lubrication oil. The waveform was digitally processed using Short Time Fourier Transformation [STFT] in order to obtain the spectrogram (energy density) to represent $A_1$ at fundamental frequency and $A_2$ at the double frequency.

Nonlinear Lamb wave is more complicated compare with bulk wave and surface wave, one of the difficulties is dispersive feature of Lamb wave, the double frequency second harmonic wave speed is different from fundamental wave mode. Generally speaking, the effect of second harmonic generation is weak due to dispersive nature of Lamb waves. But as primary work reported, the second harmonic of some fundamental Lamb wave modes could have strong nonlinearity when certain conditions are satisfied like internal resonance between fundamental wave mode and generated double frequency second harmonic and non-zero power flux from the primary mode to second harmonic mode. The amplitude of second harmonic Lamb wave grows with propagation distance. The features of these modes are the matching of phase velocities and group velocities between fundamental Lamb wave and second harmonic Lamb wave, another condition is that second harmonic modes are symmetric like showing in the following picture. The S1mode was chosen in current investigation for this mode definitely satisfies above conditions which could
generate accumulative effect second harmonic. Double frequency Lamb wave mode derived by fundamental mode S1 has the same phase velocity and group velocity as primary wave, and the phase velocity and group velocity of the pair wave modes(S1, S2) are almost similar, this characteristic is quite similar as longitudinal wave and surface wave propagating in an unbounded media.

As mentioned before, in this study, the S1 Lamb mode at frequency of 2.25MHz was generated. However, In particular, it is almost impossible to generate the singular mode since the frequency bandwidth of PZT transducer is not narrow enough. As shown in Fig. 5. It is easy to find that the spectrum of frequency is about from 1.75MHz to 2.5MHz, in this spectrum, and the wave velocity is 9.67km/s,( by Snell law, the incident angle is $16.6^\circ$), the possible wave mode is S1 mode and A1 mode. In the experimental work, when generated the S1mode point as shown in picture 4(a), it is unavoidable to generate A1mode meanwhile, but as shown in Fig. 4(b), the group velocity of S1mode are quite different from A1mode, so after a certain propagation distance, wave-packs of S1and A1 will separate finally. Picture 6 shows an example that the separation process of these two modes. In the short propagation distance picture 6(a), multi-modes has not separated. In Picture 6(b) and picture 6(c), propagation distance are 12cm, 16cm respectively, it is could find that two modes begin to separate, since their group velocities are different. In this approach, it is possible to select the S1mode part alone like showing in picture.

![Phase velocity and group velocity dispersion curves for Lamb wave in [0]_6 composite laminates](image1)

**Fig.4** Numerically calculated phase velocity

![Frequency bandwidth of fundamental wave](image2)

**Fig.5** Frequency bandwidth of fundamental wave

Through analysis, the S1 mode will separate singularly after 15cm propagation distance in this investigation. A singular mode S1 was selected and its higher harmonic analysis were made after 15cm.

### 4 Result and Discussion

The physical effect monitored in nonlinear ultrasonic measurements is the generation of second harmonic. Harmonic generation
measurements for micro-structural characterization are typically aimed at determining the nonlinear parameter $\beta$ of the material. Consider the ratio $\frac{A_2}{A_1^2}$ as ultrasonic nonlinearity. $A_1$ is the primary wave amplitude, $A_2$ is the amplitude of second harmonic.

![Image of waveforms](image)

(a) Time domain signal of propagation distance is 4cm

(b) Time domain signal of propagation distance is 12cm

(c) Time domain signal of propagation distance is 16cm

**Fig. 6** The multi-modes separate process as propagation distance

Here measured time-domain signal is processed in time–frequency domain with the short time Fourier transform(STFT) to get its spectrogram. In Fig. 7, a time domain Lamb signal includes fundamental Lamb wave(FLM) and second harmonic Lamb wave(SHLM) was processed with STFT, it could see the primary wave at fundamental frequency and second harmonic at double frequency. FLM and SHLM almost have the same time in the spectrogram after a certain propagation distance, which means that fundamental wave and second harmonic has the same wave speed, it certifies the phase matching characterize of this lamb mode. As [13], nonlinear parameter belt of guided wave could be represented as:

$$\beta = \frac{8A_1}{k^2 c A_1^2} f(w)$$

To lamb wave, $f(w) \neq 1$. 
Fig. 7 (a) Typical time-domain signal (b) spectrogram resulted by STFT

Fig. 8 Normalized nonlinearity versus propagation distance

Usually, in experimental work what we test are just the amplitudes of fundamental wave and second harmonic. The normalized nonlinear parameters could be represented as $\hat{\beta} = \frac{A_2}{A_1^2} \propto \frac{A_2}{A_1}x$, where $x$ is wave propagation distance. It could be found that the ultrasonic nonlinearity has an accumulative effect, which the ratios of second harmonic amplitude and fundamental wave grow with the propagation distance. To make sure what measured from the specimens are truly due to the material inherent nonlinearity but not only due to the nonlinearity arising from the measurement system, demonstration of this cumulative effect is critical. These results in this study are shown in Fig. 8, it is interesting that as propagation distance increasing, the normalized nonlinear parameters increasing more rapidly, one of the possible reasons is that as wave propagating in composite, fundamental wave amplitudes decrease faster because of high attenuation property of this material.

In Fig. 9, it shows the correlation of thermal cycles and normalized nonlinear parameters, as known, thermal cycling will introduce thermal stresses appear in laminates[micro-damage of fatigue, these thermal stresses may induce damage similar to that observed under mechanical fatigue: transverse matrix cracks, debonding or delaminations and other kinds of composite structure degradation. As the thermal cycles increasing, the material degradation degree will become more and more serious. As shown in Fig. 9, during the initial stage of thermal fatigue, the normalized nonlinear parameters increasing is rapid from 0 cycles to 100 cycles or 200 cycles, but much more slowly from 1000 cycles. This result has a good agreement with previous study [12-14] testing metallic material using nonlinear ultrasonic, it also proves that nonlinear ultrasonic has a great potential for characterizing material degradation state of composite material, especially for early stage degradation.
Fig. 9  Normalized nonlinear parameters versus specimens under different thermal cycles

5 Conclusions

The generation of second harmonic in Lamb wave propagation is considered to assess thermal fatigue damage in composite laminates. A phase matching of fundamental wave and second harmonic is required for generating accumulative second harmonic, the fundamental Lamb mode chosen in this study satisfy phase and group velocity matching, moreover, its phase velocity and group velocity are almost similar which has the same characterize as bulk wave. Multi-modes of wave-packet were effectively separated by group velocity delay method. It also minimized the nonlinearity from instructional system. The correlation between measured acoustics normalized nonlinearity using lamb and composite laminates thermal degradation stats shown that it is possible to using nonlinear Lamb wave to evaluate composite laminates degradation. This study develops a practical approach for applying Lamb wave to assess early degradation in composite laminates by higher harmonic generation technique.

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