Recent Advances in Nonlinear Ultrasonic Guided Wave Techniques for NDT & SHM

WEIBIN LI and MINGXI DENG

ABSTRACT

The use of nonlinear ultrasonic guided waves for nondestructive testing and structural health monitoring has drawn increasing concern. Higher harmonic generation (HHG) of ultrasonic guided wave propagation was firstly investigated and applied for damage assessment. The key concept for the HHG-based method is to find the "phase matching" modes to generate accumulate nonlinear components versus propagation distance, to improve the signal-to-noise ratio. The major difficulty with HHG method as the NDT technique lies in difficult to distinguish the material nonlinearity from the instrumental systems. In addition, HHG based nonlinear technique can only be used to evaluate the total nonlinearity over the region between transmitter and receiver. Subsequently, guided wave mixing (GWM) technique was proposed. GWM technique has some unique advantages, such as frequency selectivity, which can intentionally avoid receiving unexpected harmonic components induced by instrumental systems, as well as the feature of spatial selectivity of scanning wave mixing zone, which can be used to identify the local defect. Recently, static component generation (SCG) or quasi-static component (QSC) generation of guided wave pulse signals, was systematically explored and proposed. It is shown that the QSC based guided wave technique is an effective means to assess large structures with low attenuative effect. In addition, another breakthrough of nonlinear guided wave, is the expansive investigation on the acoustic nonlinear response of guided wave propagation in the topographic feature structures. The key concept is to build analytical model to find the modes with acoustic energy trapping effect in the feature region. The development of nonlinear feature guided waves (FGWs) technique provide a promising alternative for inspection of topographic feature region of complex structures.

Weibin Li, School of Aerospace Engineering, Xiamen University, South Siming Road, 422, Xiamen 361005, China
Mingxi Deng, College of Aerospace Engineering, Chongqing University, Shazhengjie, 174, Chongqing 400041, China

INTRODUCTION

Ultrasonic guided wave based techniques are becoming the increasingly popular nondestructive testing (NDT) and structural health monitoring (SHM) methods. Possibility to inspect inaccessible or hidden areas and great cost-effectiveness are the key advantages of guided wave-based damage detection approaches [1]. Recently, it has been found that the use of nonlinear ultrasonic waves has been found to be one of the most promising methods for evaluating material micro-structural changes in their early stages [2, 3]. Because of the high sensitivity of the nonlinear ultrasonic approaches and the great advantages of guided wave based techniques, the nonlinear ultrasonic guided waves have drawn significant attentions for material characterization and micro-damage detection [4].

One popular nonlinear ultrasonic guided wave technique is the generation of higher harmonics. Compared to bulk waves, the higher harmonic fields of guided waves are much more complex because of dispersion and multi-mode nature of propagating guided waves. In general, the effect of higher harmonic generation is often very small and can easily be overlooked due to the dispersive nature of guided waves [5, 6]. Consequently, proper mode tuning with physically based feature is essential to enhance the efficiency of higher harmonic guided wave generation and reception. The main drawback of this method is that it is difficult to distinguish the nonlinearity between material and detection system.

The guided wave mixing technique was proposed as a potential alternative to solve these problems [7]. It has been shown that the use of frequency mixing response has some unique advantages over the nonlinear ultrasonic technique based on the higher harmonic generation, such as frequency selectivity, which can intentionally avoid receiving unexpected harmonic components induced by instrumental systems. In addition, the feature of spatial selectivity of scanning wave mixing technique can be used to locate the region of damage [8-10]. However, the strong anisotropy and high attenuation in fiber reinforced layered composites significantly reduce the magnitude of the generated higher/combined harmonics of primary guided wave propagation and meanwhile make the corresponding wave propagation become complicated. It is quite challenging to assess the damage in highly attenuative structures by the measure of higher harmonics/combined harmonics of the primary guided waves.

As one of the acoustic nonlinear responses of ultrasonic waves propagation in solid media, the static component generation of guided waves was reported in recently years, which can promisingly be exploited for NDE of highly attenuative structures circumventing the aforementioned limitations.

In this paper, recent advances of nonlinear ultrasonic guided waves and its applications for NDT and SHM were reported, including the higher harmonic generation, combined harmonic generation as well as static components generation based techniques.

SECOND HARMONIC GENERATION

Second harmonic generation of guided wave propagation in the specimen is the typical acoustic nonlinear response, which can be used for material characterization. The measureable value of amplitude ratio (A_2 / A_1^2) can be qualitatively used to characterize the nonlinearity. Cumulative effect of second harmonic generation of guided wave versus propagation distance is due to the consistent energy transfer from primary wave to second harmonic one. "phase match" is a necessary condition for cumulative second harmonic generation of guided wave. Among all the phase matched guided wave modes, different modes must have different rates of energy transfer efficiency from the primary mode to second harmonic one. Bigger normalized second harmonic wave amplitude (A_2 / A_1^2) corresponds to higher energy transfer efficiency for a given propagation distance. In addition, it is experimentally easier to measure the bigger normalized second harmonic amplitude with a higher signal-to-noise ratio [5, 6]. Thus the efficiency of second harmonic generation of different mode pair can be represented by the slope ratio of normalized second harmonic wave amplitude against propagation distance. Therefore, althrough all phase matched guided wave modes can be used to generate the accumulative second harmonic waves, certain modes are more sensitive than others to material nonlinearity and should be used for such investigation.

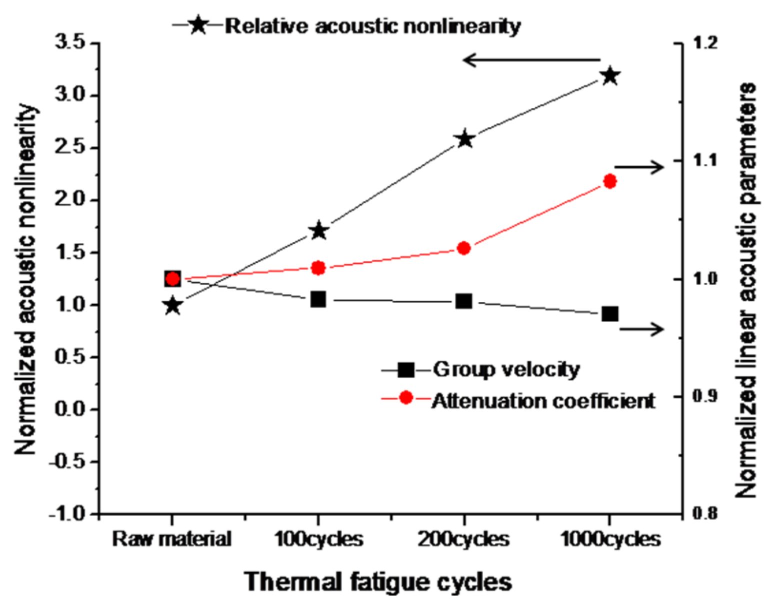

Figure 1. Comparison of the sensitivity of acoustic nonlinearity and linear parameters to thermal fatigue damage in composites.

One typical example for the use of second harmonic generation of Lamb wave to detect thermal fatigue in composites is provided in the paper. Second harmonic generation of Lamb waves was investigated to assess thermal fatigue damage in carbon/epoxy composites laminates. To avoid the dispersive and multi-modes nature of the ultrasonic Lamb wave propagation, a "phase matching" wave mode pair was chosen to generate an accumulative second harmonic wave. Considering the difference of group velocities among different Lamb modes, the group delay method was used to separate the multi-modes of a wave-packet efficiently. The correlation between the acoustic nonlinearity of the ultrasonic Lamb wave and the thermal degradation of the composite laminates was obtained and shown in figure 1. A comparison of the linear and nonlinear ultrasonic parameters variation in different specimens is also conducted. It was shown that nonlinear Lamb wave technique is a promising tool for early detection of thermal damages in composites materials [5].

COMBINED HARMONIC GENERATION

Combined harmonics at sum or difference frequencies can be generated by the cross-interactions of guided wave mixing in tested sample with material nonlinearity. Full mechanism of the nonlinear frequency mixing response caused by the cross-interactions of two guided waves is quite complicated and not yet well understood. Multiple mixing frequency components can be generated during guided waves mixing in specimens with material nonlinearity. It is obscure to determine which combined harmonic mode at the given frequency is more sensitive than the other ones. Considering multiple mixing frequency components can be generated during guided wave mixing, the mixing frequency peak count technique was employed to characterize the material nonlinearity by calculating the area of mixing frequency spectral peaks within a certain frequency range. This method was improved on the basis of sideband peak count (SPC) [10]. Thus, instead of extracting the sum- or different frequency components, the technique based on the combination of guided wave mixing and mixing frequency peak count was investigated to detect the damage.

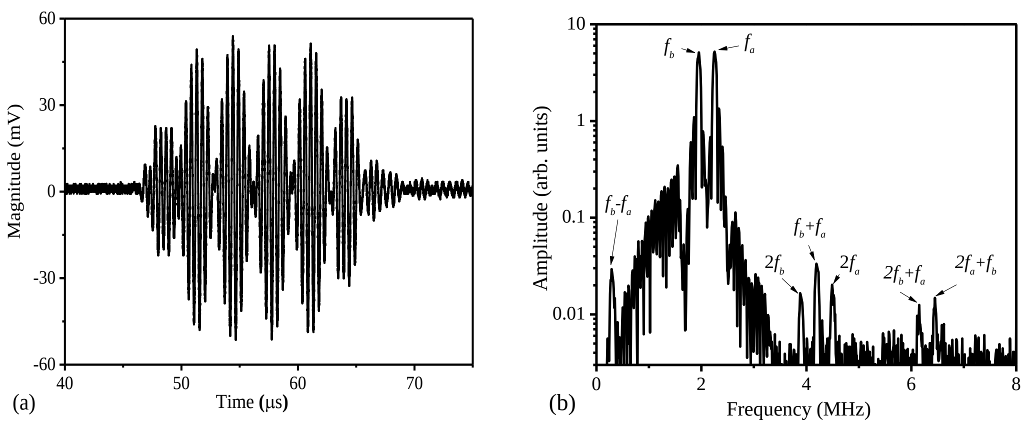

Figure 2. Time-domain signal of both $\mathbf{u}_a$ and $\mathbf{u}_b$ after mixing (a) and (b) its frequency spectrum.

STATIC COMPONENT GENERATION

Static component (SC) generation of guided waves (GWs), which combines the high sensitivity of acoustic nonlinearity to micro-damage and low attenuative effect, has great potential for damage assessment in large structures. The static component is polarized in the primary wave propagation direction with only in-plane displacement. It was shown that the generated static component is cumulative in terms of propagation distance, regardless of whether the phase velocity of the primary and secondary waves is matched or not. Thirdly, it was shown that, under certain circumstances, the magnitude of SCG can be greater than SHG using the same power of primary wave excitation. Given the aforementioned features, advantages of using SCG, such as less excitation restriction and high signal-to-noise ratio in measurements, are attractive for early materials testing and evaluation.

Recently, we investigated the features including mode, waveform, and cumulative effect of the generated SC in composites are numerically investigated by three-dimensional finite element modeling and simulation[11-13]. A dynamic displacement measurement method based on piezoelectric transducers is accordingly proposed and experimentally verified. The cumulative SC pulse generated from primary GW tone-burst with a finite duration, is observed and verified numerically and experimentally. It is found that the magnitude of the generated SC pulse is linearly proportional to the quadratic material nonlinearity. Experimental results demonstrate that the generated SC pulse of GW under group velocity matching condition, is an effective means to assess the hygrothermal damage and low-velocity impact damage in CFRP composite plates. The performed experimental examination validates the feasibility of the proposed approach for damage assessment in CFRP composites. Due to the relatively low attenuation of the SC pulse (whose carrier wave frequency is zero) generated by GW tone-burst, the use of SC generation has a greater potential for nondestructive testing and evaluation of highly attenuative composite structures, than the use of second harmonic generation (SHG) with a double fundamental frequency of the primary GWs. In addition, experimental instruments including the PZT transmitter can not introduce the SC. Consequently, SC generation based nonlinear technique has advantage to isolate the material nonlinearity from the instrument-induced one. It is also important to note that SC generation based nonlinear technique is generally applicable to test over a region between transmitter and receiver rather than a specific location, which is same as SHG based nonlinear technique. However, similar as reported in [14], for imaging and locating the local damage by SHG based nonlinear technique, damage localization can also be realized by the proposed approach. Especially, the generation of SC is only attributed to acoustic radiation induced static displacement components, which is helpful to quantify the degree of damage in high attenuative structure.

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