Ultrasonics 86 (2018) 49–58

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Damage assessment in composite laminates via broadband Lamb wave

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ARTICLE INFO

Article history:
Received 3 July 2017
Received in revised form 8 November 2017
Accepted 10 January 2018
Available online 11 January 2018

Keywords:
Lamb wave
Composite laminates
Pulse compression
Damage localization
Size evaluation

ABSTRACT

Time of flight (ToF) based method for damage detection using Lamb waves is widely used. However, due to the energy dissipation of Lamb waves and the non-ignorable size of damage in composite structure, the performance of damage detection is restricted. The objective of this research is to establish an improved method to locate and assess damages in composite structure. To choose appropriate excitation parameters, the propagation characters of Lamb waves in quasi-isotropic composite laminates are firstly studied and the broadband excitation is designed. Subsequently, the pulse compression technique is adopted for energy concentration and high-accuracy distance estimation. On this basis, the gravity center of intersections of path loci is employed for damage localization and the convex envelop of identified damage edge points is taken for damage contour estimation. As a result, both damage location and size can be evaluated, thereby providing the information for quantitative damage detection. The experiment consisting of five different sizes of damage is carried for method verification and the identified results show the efficiency of the proposed method.

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1. Introduction

In recent years, advanced composite materials like carbon fiber reinforced plastic (CFRP) have been increasingly used in aircraft structures due to their high specific strength, light weight and outstanding design ability [1]. However, due to unexpected damages (i.e. delamination, matrix cracks, etc.) induced during the manufacturing processes or in-service applications, the material strength will degenerate [2]. In order to monitor the status of the composite structure, structure health monitoring (SHM) and nondestructive damage evaluation (NDE) procedures are especially needed. Lamb wave based method is a promising candidate because Lamb waves can propagate over long distances with high velocities and it allows for line scanning [3–5]. In addition, Lamb waves are sensitive to both surface and sub-surface defects, which is suitable for barely invisible damage detection in composite structures [6].

However, Lamb waves are dispersive and multimodal which make the signal interpretation problematic [7]. Especially in composite structures, the comprehensive action of mode tuning [8], attenuation [9] and anisotropy [10] plays a remarkable role in distorting Lamb wave signals, which may restrict the damage feature extraction and make the damage localization and assessment complicated.

In order to localize the damage in composite laminates, ToF based methods are widely used and a variety of methods for high accuracy ToF measurement have been developed, including short-time Fourier transform (STFT) [11], continuous wavelet transform (CWT) [12], warped frequency transform (WFT) [13] and matching pursuit (MP) algorithm [14]. On this basis, Su et al. [15,16] used a piezoelectric transmitter-sensor network and a time of flight (ToF) calculation technique to estimate the possibility of damage occurrence. Yan et al. [17] investigated the applicability of a Bayesian system identification theory for plate-like structures based on ToF measured by CWT, which is effective to identify the damage location. Sharif-Khodaei and Aliabadi [18] used a modified delay-and-sum algorithm to locate impact damage in composite plates, which illustrates the efficiency of the ToF-based localization method in composite laminates. Marchi et al. [19] reported a passive impact damage detection method by using warped frequency transform to estimate the propagation distance, which shows the efficiency for impact source localization. However, the information about quantitative assessment of damages was not provided by the authors.

Dispersion and attenuation are challenges for Lamb wave based damage localization and evaluation in composite laminates. Using limited bandwidth can reduce the effect of dispersion, but it is impossible to concentrate all the energy of a finite duration of input signal at a single frequency. Meanwhile, narrowband Lamb waves have large time duration, which reduces the detection resolution. Broadband Lamb wave with small time duration is a good

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https://doi.org/10.1016/j.ultras.2018.01.005
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choice for high-resolution damage detection [20]. However, the dispersion effect is obvious and the launching power of narrow pulse is restricted by the equipment hardware. In addition, the barely invisible damages (i.e. delamination) in composite structure always have remarkable sizes, which will decrease the performance of damage detection and evaluation methods.

In order to address the above issues, in this paper, broadband A0 mode based detection method is proposed for damage localization and evaluation. To increase the excitation power and detection resolution, pulse compression technique is introduced. On the basis of dispersion compensation, the pseudo-pulse waveform with small width can be obtained, which is beneficial for distance estimation with high accuracy and signal to noise ratio (SNR). According to the loci established by sensing paths, the gravity center of related intersections is calculated, which represents the center of damage. Furthermore, the contour of damage can be determined by finding edge points on the loci that make the gravity center have the shortest distance with each locus. With the help of minimum convex polygon calculation, the area of reconstructed damage can be estimated. As a result, both the damage localization and size can be detected.

The organization of this paper is as follows. The background of pulse compression technique and dispersion compensation method for broadband Lamb wave is firstly reviewed in Section 2. In Section 3, the propagation character of Lamb wave in composite laminates is investigated and the excitation is designed. Damage localization and size estimation method is proposed in Section 4 and experiment validation is carried out with five different simulated damages in Section 5. Conclusions are given in Section 6.

2. Review of Lamb wave pulse compression

In the previous works referred in [20,21], broadband Lamb wave based pulse compression method is introduced to improve the detection resolution and increase the SNR of response signals in SHM applications. The pulse compression technique is wildly used in radar applications to obtain a narrow pulse waveform through long launching duration, which is important for power concentration and resolution improvement [22,23]. Many broadband signals can be employed as excitations, among which linear swept-frequency signal (i.e. Chirp) is often used. For instance, assuming a Chirp signal is from the start frequency f_0 to the end frequency bound $f_0 + B$ over $t \in [0, T]$. The chirp can be written as

$$f(t) = \sin(2\pi f_0 t + \pi B t^2/T) \quad 0 \leqslant t \leqslant T. \tag{1}$$

When taking chirp signal as the excitation, the entire system involved in Lamb wave based detection can be treated as a linear system [24]. On the basis of pulse compression method, the cross-correlation between the excitation signal $f(t)$ and the output signal $g(t)$ is equal to the output signal $c(t)$ when the auto-correlation curve of $f(t)$ serves as the virtual excitation [21]. The pulse compression process can be expressed by

$$c(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} |F(\omega)|^2 H(\omega)\exp(\mathrm{i}\omega t)d\omega, \tag{2}$$

where $|F(\omega)|^2$ represents the Fourier transform of the auto-correlation of the excitation signal and $H(\omega)$ indicates the transfer function. The transfer function consists of amplitude modulation term and dispersion term.

The auto-correlation of chirp excitation when the f_0 is 20 kHz and B is 180 kHz is presented in Fig. 1(a). As can be seen, the energy of the auto-correlation curve is compressed into a sharp pulse in time domain, whereas the original Chirp excitation has a large time duration. In addition, the maximum amplitude of compressed signal is much larger than that of the original Chirp signal shown in Fig. 1(b). Therefore, when the auto-correlation curve acts as the new excitation for Lamb wave inspection, the small time duration can enhance the accuracy and resolution of distance estimation while the large launching power can increase the SNR.

The dispersion effect distorts the Lamb wave signals with the increasing of bandwidth and propagation distance. For broadband Lamb wave pulse compression signals, the strong dispersion would make the pulse waveform spread out in time domain quickly, which makes the ToF extraction impossible. Even in time-frequency domain, restricted by uncertainty principle, the exact information concerning the arrival time of target mode for any frequency cannot be obtained [25]. Thanks to the dispersion compensation method [26], the broadband dispersive waveforms can be restored when the pre-knowledge of dispersion curve of each Lamb wave mode is provided. Hence, the distance can be estimated with high accuracy in distance domain. The compensated waveform $g(t)$ can be written as

$$g(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} |F(\omega)|^2 A(\omega)\exp(\mathrm{i}\omega t)d\omega, \tag{3}$$

where $A(\omega)$ is the frequency-dependent amplitude modulation. The amplitude modulation would distort the waveform which will be discussed in Section 3. In general, the compensated pulse compression Lamb waves have the outstanding performance for damage detection in composite structure.

3. Broadband excitation design for distance estimation in composite laminates

Pulse compression Lamb wave signals have narrow duration width and large launching power after dispersion compensation, which is suitable for high resolution damage detection in composite structure. However, the performance of broadband Lamb waves for damage detection relies on the determination of excitation. To obtain the proper excitation, the related parameters are designed based on the propagation characters of Lamb waves in composite structure. Then, the influence of amplitude modulation on compensated Lamb waves is studied to obtain the accurate propagation distance.

3.1. Mode selection

Lamb waves are multimodal which means there are at least two modes can be existed at any excitation frequency. Both A0 mode and S0 mode have its own intrinsic advantages and disadvantages for damage detection. Before choosing the proper mode for operation, theoretical derivation and experimental study about complex propagation characters of fundamental Lamb modes is carried out to achieve a better understanding of Lamb waves in composite.

The material adopted in this paper is T300/3231 CFRP. The detailed elastic constants used for theoretical derivation are listed in Table 1. The quasi-isotropic composite laminates is employed for investigation. The layup of composite laminates is $[+45/-45/0/90]_{2s}$ and the thickness of each single laminate is 0.125 mm. Then the dispersion curves of Lamb waves were calculated based on laminate plate theory [27,28]. As a result, the phase velocities of some basic symmetric modes and anti-symmetric modes are shown in Fig. 2(a), which provides the basis for dispersion compensation.

Furthermore, the amplitude modulation is studied by an experimental method. In general, the amplitude modulation consists of three parts: attenuation, response of detection system and the mode tuning. For detection system, the response would be affected by the transducer parameters, specimen, coupling condition and so on. Due to the strong attenuation in composite and the response of

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