NDT and E International 100 (2018) 64–73

Contents lists available at ScienceDirect

NDT and E International

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

A new method to detect delamination in composites using chirp-excited Lamb wave and wavelet analysis

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ARTICLE INFO

Keywords:
CFRP
Lamb wave
Composite
Delamination
Chirp
Wavelet analysis

ABSTRACT

Lamb waves offer an efficient way for monitoring the structural integrity of large carbon fiber reinforced polymer (CFRP) structures. This paper presents a new method that is able to detect and assess delamination's length in anisotropic CFRP plates. It uses a chirp signal, which contains a wide range of frequencies, as excitation. Thus the material is interrogated by Lamb waves with various wavelengths. This method is based on that, for a specific delamination length, only some particular frequency components are disturbed. Simulation and experimental results show that the lowest frequency that is perturbed by a delamination decreases as the delamination length increases. Therefore, by observing which frequency components of the chirp-exited Lamb wave are disturbed, delamination length can be estimated. Wavelet analysis is implemented for better comparison of signals at multiple frequencies.

1. Introduction

The use of composite materials in aerospace, naval and automobile industries is becoming more and more common. Composite materials such as carbon fiber reinforced polymer (CFRP) can have better performance than metallic materials in many situations due to their high strength-to-weight ratio. CFRP plates usually have several layers, and each layer is reinforced by carbon fiber in one or two directions. The in-plane strength of CFRP plates is improved by fibers but the inter-layer strength is relatively weak. Therefore, delamination between neighboring layers is the most common type of defects that appears in a composite plate [1,2]. Lamb wave testing is one of the most promising methods for detecting delaminations due to its high efficiency and accuracy. Lamb waves are guided ultrasonic waves that can travel long distances in plate-like or tubular structures with relatively low attenuation. With only one action of launching and receiving, the area between the two transducers can be tested.

The interaction of Lamb waves with a delamination has been studied and results [3–6] indicate that the waves will be separated as transmitted waves and reflected waves, and mode conversions happen at the edges generating new modes. A delamination can be detected either by observing the reflected waves in a pulse-echo configuration or by observing the changes that occur to the transmitted waves in a pitch-catch configuration. In the pulse-echo configuration, Hu showed that reflected waves are generated when a Lamb wave enters and exits the delamination, and the reflection at exit is much larger [7]. Peng [8] and Liu [9] both studied how reflected and transmitted waves change with the length of delamination, and proposed a localization method for the delamination based on the time-of-flight of the reflected wave. Valdes [10] also used reflected waves to identify delamination. Hayashi [11] and Guo [12] both studied reflected waves when a delamination is located at different thickness positions, and concluded that no reflection can be observed with symmetrical excitation when a delamination exists in the mid-plane. In the pitch-catch testing configuration, Kang [13] showed that new wave packets can be observed due to mode conversion at the delamination. Some studies [14–16] have reported that a delamination can cause a delay of the arrival time of the transmitted wave. Li [17] and Ramadas [18] concluded that Lamb waves travel independently and at different speeds in the two layers separated by a delamination, and the delamination length can be determined by measuring the difference of time of arrival of the two wave packets. Many challenging problems, such as the superposition of waves, make the Lamb wave signals difficult to interpret, so efficient signal processing is paramount to extract useful information from signals. Wavelet transform has been used in Lamb wave testing in some studies [4,7,13,19–21]. Pan [19] and Su [20] used wavelet transform to get features in time-scale domain, and applied artificial neural network to quantify the position and the size of delamination. Li [21] studied the application of wavelet transform in Lamb wave testing and compared the results for different mother wavelets.

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https://doi.org/10.1016/j.ndteint.2018.08.004
Received 7 March 2018; Received in revised form 2 July 2018; Accepted 12 August 2018
Available online 18 August 2018

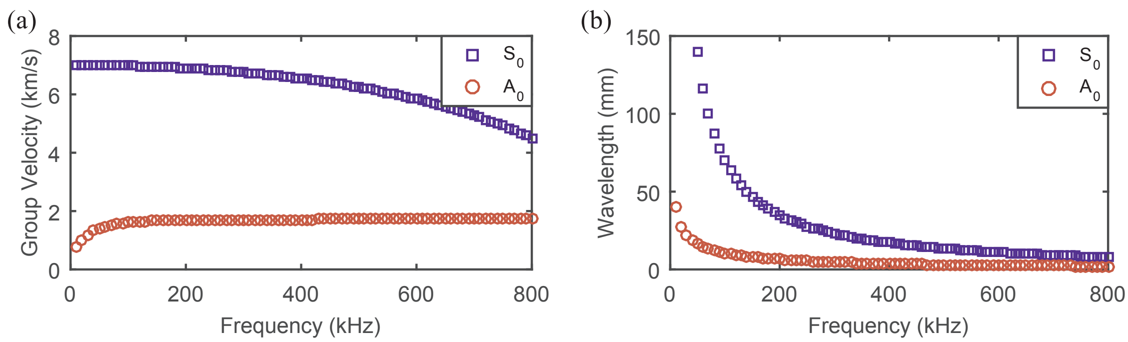

Fig. 1. Dispersion curves of a 4-ply composite: (a) group velocity, (b) wavelength.

Lamb waves are dispersive, which means that their group and phase velocities vary with frequency. As a result of dispersion, the received signal will have lower amplitude and longer duration than the excitation. This may cause a reduction of resolution [22,23]. Therefore, broadband excitation is considered unfavorable, and windowed tone burst signal was used in all the previously mentioned studies to narrow the bandwidth of excitation and effectively minimize the dispersion effect. However, studies on broadband excitation can still be found, although few in number.

Acquiring signals at different excitation frequencies is desirable because the best testing frequency is unknown, but implementing tests with narrowband excitation individually is time consuming [24]. Michaels proposed to use chirp signal for excitation and successfully extracted multiple narrowband responses from a chirp response by applying the deconvolution algorithm [24,25]. The extracted narrowband responses are similar to the responses of tone burst excitations. Zeng [26] and Marchi [27] took this result further by proposing compensation techniques to minimize the dispersion effect when using chirp excitation.

In this paper, a broadband chirp signal is used as excitation to detect delaminations in composite plates. The advantage of this method is that the material is interrogated by Lamb waves with various wavelengths at the same time. This method is based on the fact that for a specific delamination length, only some particular frequency components are disturbed. This paper studies the forward problem and it is organized as follows. Section 2 presents the principle of the chirp-excited testing method and some fundamental aspects of the guided wave theory. Section 3 presents finite element simulations to test the feasibility of the proposed method. In Section 4, the chirp-excited testing method is verified experimentally. To show the usefulness of the chirp-exited method, the inverse problem is briefly presented in Section 5, which discusses the estimation of delamination length. Conclusions are finally drawn in Section 6.

2. Fundamental theories

For better understanding of the proposed chirp-excited Lamb wave testing method, some basic aspects of the guided wave theory are introduced in this section. Section 2.1 gives a brief introduction to the basic concepts of Lamb waves. Section 2.2 helps to understand the experimental results by presenting the relationship between frequency and the magnitude of the excited Lamb wave. Section 2.3 presents the principle and concludes about the feasibility of the chirp-excited Lamb wave testing method.

2.1. Dispersion curves of Lamb waves

In a thin plate-like structure with its upper and lower surfaces as boundaries, Lamb waves can be excited and can travel relatively long distances. Lamb waves are dispersive and multi-modal. The dispersive nature means that the group and phase velocities of Lamb waves are dependent on the frequency, and multimodal means that there are more than one mode at any given frequency. In an isotropic plate, the governing equation for the wave propagation is Rayleigh–Lamb equation, which can be decomposed as [29]:

$$\begin{aligned} \frac{\tan(qh)}{\tan(ph)} &= -\frac{4k^2qp}{(k^2-q^2)^2} \quad \text{for symmetric modes} \\ \frac{\tan(qh)}{\tan(ph)} &= -\frac{(k^2-q^2)^2}{4k^2qp} \quad \text{for anti-symmetric modes} \end{aligned} \tag{1}$$

where k is the wavenumber, h is half of the plate thickness, p and q are defined as: $p^2 = \frac{\omega^2}{C_L^2} - k^2$, $q^2 = \frac{\omega^2}{C_T^2} - k^2$, where ω is the angular frequency, and C_L and C_T are longitudinal and transverse wave velocities, respectively. The symmetric and anti-symmetric modes are usually symbolized as S_i and A_i (i = 0, 1, 2 ...). The particles inside the plate have mainly in-plane motion for the symmetric modes and mainly out-of-plane motion for the anti-symmetric modes. By solving Eq. (1), relationships between wavenumber and frequency can be obtained. Below the cutoff frequency of higher modes, only one real solution exists for either symmetric or anti-symmetric modes. Therefore, only the fundamental S_0 and A_0 modes exist.

For multi-layered anisotropic structures such as carbon fiber composites, the equations that determining the dispersion curve are more complicated than in isotropic materials. Besides the reflection of waves at plate surfaces, reflection and refraction of waves also occur between layers. Each layer of the laminate must satisfy the Navier's displacement equations [28]. Equations can be solved by transfer matrix method or by global matrix method [29]. Solving the wave equations is not a fundamental issue in this paper, and the process will not be discussed in detail. The dispersion curves were obtained directly by GUIGUW [30]. For a 4-ply composite plate with 1 mm thickness, the dispersion curves in the direction of the carbon fibers are shown in Fig. 1. The plate has fibers oriented in the following directions: [0ra/90/90/0], and the mechanical properties of each layer are listed in Table 1. Only the fundamental S_0 and A_0 modes exist in Fig. 1 because 800 kHz is below the cutoff frequency of higher modes.

It can be noticed from Fig. 1(a) that S_0 mode has higher group velocity than A_0 mode. When the two modes are excited simultaneously, S_0 mode always arrives earlier than A_0 mode. Due to this feature, using S_0 mode for testing can simplify the signals to be analyzed because the later arrived A_0 mode may be interfered by the reflected S_0 wave from boundaries. Another important feature that can be noticed in Fig. 1(b) is that wavelength decreases with increasing frequency. This feature is the core for the success of the proposed method in this paper and will be discussed in detail in Section 2.3.

Table 1
Mechanical properties of each layer.

Property	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	ν_{12}	ν_{23}
Value	153.67	9.49	4.26	3.44	0.295	0.381