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A Numerical Investigation of Lamb Wave Damage Diagnosis for Composite Delamination Using Instantaneous Phase

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***Abstract*—This paper presents a study of Lamb wave damage diagnosis of composite delamination using instantaneous phase data. Numerical experiments are performed using the finite element method. Different sizes of delamination damages are modeled using finite element package ABAQUS. Lamb wave excitation and responses data are obtained using a pitch-catch configuration. Empirical mode decomposition is employed to extract the intrinsic mode functions (IMF). Hilbert–Huang Transform is applied to each of the resulting IMFs to obtain the instantaneous phase information. The baseline data for healthy plates are also generated using the same procedure. The size of delamination is correlated with the instantaneous phase change for damage diagnosis. It is observed that the unwrapped instantaneous phase of shows a consistent behavior with the increasing delamination size.

***Keywords*—Delamination, lamb wave, finite element method, EMD, instantaneous phase.

I. Introduction

COMPOSITE materials are widely used in various industries due to their significant advantages over traditional metals, such as superior specific strength and stiffness, corrosion resistance and lower weight [1]. However, the damage mechanisms of composites are complex and not well understood. Most composite damages result from loading, fatigue, impact or manufacturing defects. Delamination is a particular and serious failure mechanism between composite plies which may not directly be visible but can severely affect the structural strength [2]. Current non-destructive evaluation (NDE) methods have been adopted for damage detection, assessment and prediction in the field of structure health monitoring (SHM) in which the present condition of a structure is predicted by using measured data. Lamb wave is a type of ultrasonic guided wave, and has been shown to propagate long distances in plate-like structures with little energy loss. Lamb wave has drawn extensive attentions from the field of damage diagnosis. The fundamental idea behind Lamb wave-based damage detection is that Lamb wave interacts with different types of internal damages. Consequently wave characteristics such as time of flight (ToF), traveling velocity, and the amplitude can be altered by discontinuities in the path of wave propagation. Existing studies have shown that Lamb wave has become a robust technique for damage identification in both metallic and composite materials [3], [4]. Despite considerable efforts have been made in this area, practical engineering applications of Lamb wave–based damage monitoring are still limited due to the dispersive characteristics of Lamb wave, experimental conditions and operation uncertainties. On the other hand, Lamb wave propagation mechanism in composites is very complex, making it difficult to perform reliable numerical analysis. To reduce the experimental work, finite element method (FEM) is usually employed to obtain representative signal data and capture the underlying damage mechanism in composite structures. Hong et al. presented an approach to locate fatigue damage with nonlinear Lamb wave using finite element simulations. In the study linear and nonlinear damage indices are calculated to quantify the damage [5]. Shen and Giurgiutiu investigated the finite element model of Lamb wave interacting with linear notch cracks and nonlinear breathing cracks. Results of the study show a good agreement between the experimental data and the numerical simulation data [6]. These reported studies demonstrate that finite element method is an effective tool to simulate Lamb wave in damaged structures for the purpose of developing damage assessment methods. To process the signal data for damage assessment, a majority of common SHM methods are centered on modal analysis of vibration in frequency domain. However, modal analysis relies on the global deformation introduced by the local damage. It is highly nontrivial to reliably detect small damages using modal methods [7]. In view of this difficulty, other methods are proposed and investigated. Hilbert-Huang transform (HHT) is a relatively new approach for joint timefrequency analysis and has been applied to the investigation of structure health monitoring [8], [9]. Existing studies show that HHT for SHM using FEM simulations data is able to identify natural frequencies, and the results are in agreement with realistic experimental data.

In this paper a damage assessment method of composite delamination based on Lamb wave and finite element simulation is presented. A pitch–catch configuration of Lamb wave data acquisition is modeled using the finite element package ABAQUS to generate data representing the realistic data acquisition. Different sizes of delamination damages are considered. EMD method is used to extract the IMFs from the Lamb wave data, and Hilbert is applied to the IMFs to obtain the instantaneous phase information. The instantaneous phase information is correlated with the sizes of delamination

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damages. The rest of the paper is organized as follows. First the instantaneous phase method based on EMD is briefly introduced. Next, the procedure of FE simulation of Lamb wave propagation in composite plates is given. Following that data processing using the proposed method is presented. Finally conclusions are drawn based on the current study.

II. Instantaneous Phase Method

HHT involves two distinct steps: decomposition of signals into intrinsic mode functions (IMF) through EMD and the Hilbert transform of the resulting IMFs [7]. The IMFs have well-behaved Hilbert transforms from which the instantaneous phase can be calculated. Using the method of EMD, data $x(t)$ can be decomposed into N intrinsic mode functions $c_n(t)$ and a residue $r_N(t)$ term,

$$x(t) = \sum_{n}^{N} c_n(t) + r_N(t). \quad (1)$$

After this step, the Hilbert transform is applied to each of the IMFs $c_n(t)$. For a real-valued time-domain signal $c(t)$, the Hilbert transform of $c(t)$ is defined by

$$\tilde{c}(t) = \int_{-\infty}^{+\infty} \frac{c(k)}{\pi(t-k)} \mathrm{d}k. \quad (2)$$

The corresponding analytic signal is then given by

$$z(t) = c(t) + i\tilde{c}(t) = a(t)e^{i\theta(t)}, \quad (3)$$

where $a(t)$ is magnitude function describing the envelope of $c(t)$, $\theta(t)$ is phase function describing the instantaneous phase of $c(t)$. The instantaneous phase $\theta(t)$ can be calculated for an individual IMF. The total instantaneous phase $\theta(t)$ is obtained by summing up each of the individual instantaneous phases as

$$\Theta(t) = \sum_{n=1}^{N} \arctan\left(\frac{\tilde{c}(t)}{c(t)}\right). \quad (4)$$

It is proposed that the total instantaneous phase can be unwrapped from its harmonic nature in order to reveal a linear tendency for damage identification [7], [9]. The total phase at any point A in the structure with respect to a reference point O is defined as the phase difference, and is given by

$$\phi_A(t) = \left|\Theta_A(t) - \Theta_O(t)\right|. \quad (5)$$

III. Finite Element Simulation of Lamb Wave

Composite plates with Lamb wave propagation are modeled using FEM. The material properties of carbon-fiber epoxy are given in Table I. The composite plate has a dimension of $400 \times 200 \times 2$ mm with ten unidirectional plies $[0]_10$, and is shown schematically in Fig. 1. An additional layer of elements for a through-width delamination damage is introduced between the 5th and the 6th plies with a thickness of 0.1 mm. The length of delamination layer varies from 2 mm to 10 mm with an increment of 2 mm. A health model with no delamination damage, i.e., the baseline model, is also established for comparison. Two spots are chosen on the surface of plate model along the center line of the plate as the pitch–catch locations, as shown in Fig. 1. The distance between the two spots is 200 mm. The excitation signal of Lamb wave is simulated by applying the time-varying vertical displacement at the actuator point A. Lamb wave propagates in all direction and is received at the sensor point B. This ensures that the Lamb wave interacts with the delamination damage. Three-dimensional eight-node brick elements (C3D8R) are used to mesh the plate. The size of the element is set as 1 mm, ensuring at least 10 nodes per wavelength to capture all the modes at the excitation frequency. To represent realistic experimental conditions, four boundaries are restricted in all degrees of freedom. The excitation signal applied to the actuator point is a 5-cycle tone burst with a central frequency of 160 kHz obtained by windowing a sinusoidal wave with a Hanning window as illustrated in Fig. 2. The time step length of dynamical analysis is taken as 25 ns due to the millimeter-scale mesh.

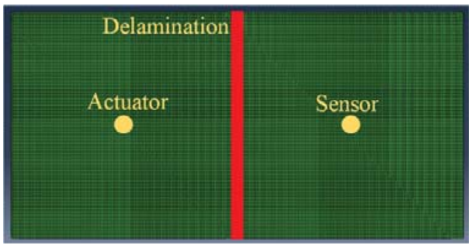

Fig. 1 Finite element model of composite plate

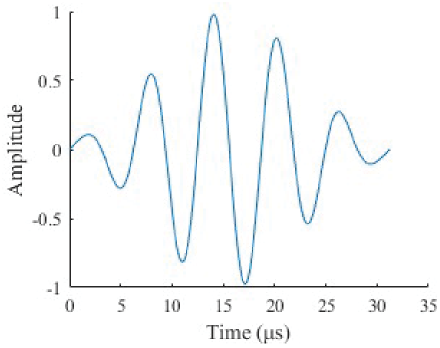

Fig. 2 Excitation Lamb wave

TABLE I
MATERIAL PROPERTIES

Properties	Value
$E_1(GPa)$	135
$E_2(GPa)$	8.8
$E_3(GPa)$	8.8
$G_{12}(GPa)$	4.47
$G_{13}(GPa)$	4.47
$G_{23}(GPa)$	3.45
ν_{12}	0.3
ν_{13}	0.3
ν_{23}	0.3
$\rho(kg/m^3)$	1560

IV. Results and Discussion

Representative signal data of both baseline model and damaged model are obtained using the above FE simulation setup. The excitation and received signal data of the healthy plate are shown in Fig. 3. It can be seen that the received

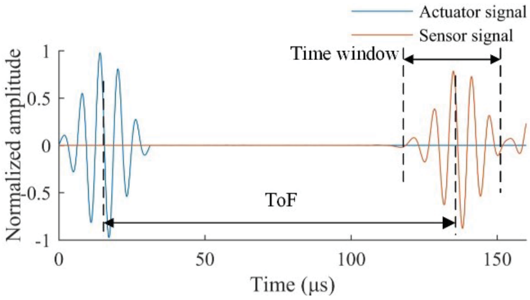

Fig. 3 Illustration of the ToF and time window

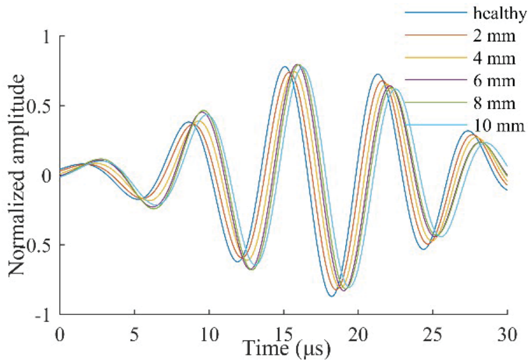

Fig. 4 Comparison of time window for healthy and different delamination sizes

signal data are not exactly same as the input signal data due to the dispersion of wave around the central excitation frequency [10]. It has been demonstrated that Lamb waves in different modes are sensitive to specific types of damage. In particular, Lamb waves in A_0 mode are sensitive to delamination or debonding [11]. Therefore, Lamb wave data in A_0 mode Lamb are used to capture the delamination damages. The first wave packet of the received signal data is used to determine the time window, as shown in Fig. 3. Based on the time of flight (ToF) the group velocity of propagated wave is calculated. The time windowed signal data is then used to identify the existence, dimension and location of damage. Fig. 4 compares the resulting signal data for healthy model and models with the delamination size ranging from 2 mm to 10 mm. It is observed that the time window delays with the increasing delamination size. The delamination can be tracked more efficiently by calculating the instantaneous phase. The unwrapped instantaneous phase is obtained using HHT as described before.

Using EMD method and Hilbert-Huang transform of IMFs, the unwrapped instantaneous phases of wave packets for all models are computed and presented in Fig. 5. The phase difference between healthy and damage signals are compared in Fig. 6. It can be seen that the phase difference increases as the delamination size increases. This implies that the quantification model can be established by correlating the phase difference and the delamination size.

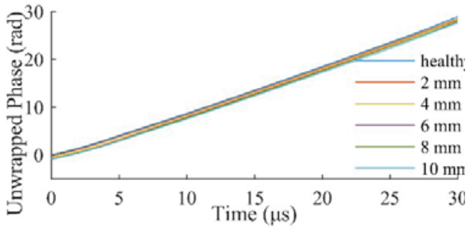

Fig. 5 Unwrapped instantaneous phase for healthy and damage cases

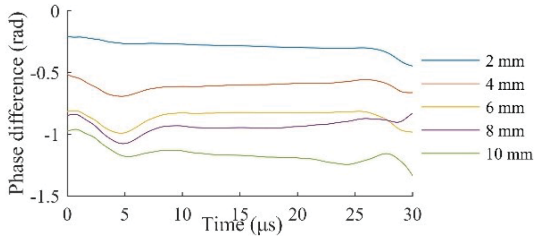

Fig. 6 Phase differences for different damage cases

V. Conclusion

In this paper a study on delamination size assessment of composite plates using Lamb wave and finite element method is presented. Composite plates with different sizes of delamination damages are modeled in the numerical simulation environment. Response signals of a pitch-catch Lamb wave setup are obtained from simulations. The data are processed using EMD method and HHT method. The instantaneous phase information is used to correlate with the size of the delamination damage. It is shown that the unwrapped instantaneous phase is an effective indicator to quantify the size of delamination damage. Further study on realistic experiments are planned for more detailed validations.

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