Mechanical Systems and Signal Processing 109 (2018) 134–149

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Multi-dimensional signal processing and mode tracking approach for guided wave based damage localization in X-COR sandwich composite

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ARTICLE INFO

Article history:
Received 29 August 2017
Received in revised form 15 January 2018
Accepted 25 February 2018

Keywords:
Ultrasonic guided waves
X-COR sandwich composites
Structural health monitoring
Signal processing
Wave mode tracking
Damage localization

ABSTRACT

This paper presents a real-time signal processing and damage localization framework for ultrasonic guided wave based structural health monitoring of X-COR sandwich composites with a reference-free perspective. The high attenuation nature of X-COR composite significantly limits the ability to detect damage-induced reflected waveforms. Therefore, a novel multi-dimensional signal processing technique, coupled with a mode tracking approach for identifying trajectories and locating wave sources of all wave modes, including damage-induced converted modes, is proposed. The developed framework is experimentally validated using two internal damage scenarios: facesheet delamination and foam core separation. Results indicate that the framework offers not only high accuracy for locating internal damage positions, but also insights into guided wave propagation behaviors in highly complex composites such as the X-COR sandwich composite.

1. Introduction

Advanced light-weight composite structures, such as the X-COR sandwich composite, possess excellent durability, specific strength and stiffness, damping and impact properties that are all advantageous for mechanical and aerospace applications [1,2]. Specifically, the Z-pin of X-COR sandwich composite, which penetrates both the foam core and facesheets, improves the through-thickness compression strength of the structure [3]. However, the architectural complexities associated with pin-penetrated foam core and difficult-to-detect damage scenarios, such as facesheet delamination and foam core separation, can compromise the safety and reliability of X-COR composites. Real-time inspection and monitoring of the operational health of X-COR sandwich composites has received little attention to date. A robust structural health monitoring (SHM) methodology, therefore, is needed to effectively identify and localize the damage states in these advance composites, and to provide meaningful information for estimating their residual life.

Thus far, among SHM technologies, ultrasonic guided wave (UGW) based techniques have proven to be very effective, primarily due to their ability to propagate long distances with minimum energy loss, resulting in a large inspection area [4,5], and capability of interrogating structures in the through-thickness direction. As such, UGW based damage detection and localization techniques are widely used to inspect the structural health of materials including carbon fiber reinforced composites [6]. The guided wave based detection and localization algorithms can be generally classified into two classes: forward

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https://doi.org/10.1016/j.ymssp.2018.02.039
0888-3270/

algorithm and inverse algorithm. The ellipse based method, which is the most widely used algorithm [7–10], is a forward algorithm, which utilizes the time of flight (ToF) information of UGW. ToF is defined as the time lag between the excitation wave mode and the damage-induced reflected wave mode so that a damage ellipse, which contains all possible damage locations, can be further constructed. Diaz Valdes and Soutis (2002) [11], for example, used a pulse-echo method for localizing the delamination in a carbon fiber composite panel. Their results showed that the reflected wave from the delaminated region could be detected, and delamination was successfully localized. In order to explicitly consider the effects of temperature on the accuracy of damage localization, Neerukatti et al. (2015) [12] developed a fully probabilistic methodology based on a temperature compensation algorithm. This method was experimentally validated and showed marked improvements over the traditional ellipse based method. Another ellipse based method, phased array technique, was implemented by Giurgiutu (2006) [13] to develop an embedded ultrasonic structural radar (EUSR) algorithm, and this method showed high accuracy in predicting crack and corrosion in metallic materials. In addition, Kessler et al. (2002) [14] showed that a frequency response method is also an effective tool for damage detection in composite materials. Zak et al. [15] demonstrated a vibration method that detects closing delamination by analyzing the vibration modes and investigating the effects of delamination on the response frequencies. Similarly, Kim et al. [16] developed a modal-strain-based damage detection method for laminated composite structures based on smooth transition of displacements. Contrary to time or frequency domain analysis, high dimensional methods, which investigates guided wave signals in multiple representative domains simultaneously, have shown success in detecting delamination in composite materials; these high dimensional methods typically involve high dimensional signal processing techniques such as time-frequency analysis, frequency-wavenumber analysis and time-space analysis. Liu et al. (2012) [17] implemented time-frequency analysis to identify and localize the damage in a stiffened composite panel. Moreover, a scattering based wave packet tracing method to quantify the group and phase velocities in the time-space domain was developed by Kim and Chattopadhyay [18]. This method was incorporated into the ToF based localization algorithm and showed high accuracy in localizing and quantifying damage in aluminum plates. Using scanning laser Doppler measurements, Michaels et al. (2011) [19] developed a frequency-wavenumber domain analysis, wherein the time-space domain was transformed through a two dimensional Fourier transform in order to detect delamination in composites. Yu and Tian (2013) [20] used space-frequency-wavenumber domain analysis to study how the frequency-wavenumber relation varies in the spatial domain.

The inverse method, which is another class of damage detection algorithm, quantifies the damage in the composite. Yam et al. (2003) [21] developed a vibration based method using an artificial neural network to map the relationship between output signals and damage size or location. Image processing based techniques [22] are also available for nondestructive evaluation (NDE) purposes. For X-COR sandwich composites, as presented in this study, Neerukatti et al. (2016) [23] developed a hybrid NDE/SHM method for damage detection. Their results indicated that ultrasonic C-scan and flash thermography can successfully detect, localize, and quantify internal damage, and that the presence of damage can lead to mode conversion when using UGW based SHM technique.

In spite of the aforementioned advances, UGW based damage localization methods continue to experience many challenges. As suggested by Diamanti et al. (2004) [24], UGWs have greater attenuation due to the presence of a low-stiffness core than those propagating in traditional metallic and composite materials, challenging the detection of damage-induced reflected waves. Li et al. (2017) [25] showed that the presence of Z-pins in X-COR sandwich composites made the signals received by the sensors more complex, i.e., inducing nonlinearity and larger attenuation. In addition, Neerukatti et al. (2016) [23] claimed that the sensor placement was a critical issue for damage detection in X-COR sandwich composites. Similarly, as will be discussed in Section 2.1 of this paper, it is difficult to detect the reflected wave that is induced by delamination in X-COR sandwich composites due to the highly attenuation fact of host structure. This, in turn, restricts the utility of many traditional ellipse based methods. On the other hand, the size of the transducers attached on the structures used for real-time SHM presents significant challenges for both the spatial sampling rate of Fourier transform for wavenumber-frequency analysis and the image resolution of image processing based algorithms. Moreover, a reference-free localization algorithm is highly desirable because it eliminates the need for a 'healthy' baseline, thereby reducing the fabrication cost associated with advanced composite structures such as X-COR sandwich composites. Finally, it is important to note that the concept of a 'healthy' baseline is often misleading due to the presence of manufacturing induced flaws.

In this paper, a novel multi-dimensional signal processing and mode tracking approach with a reference-free perspective is developed for the damage identification and localization in the media with large attenuation fact. In current experimental methodology, the reflected wave cannot be easily detected due to the issues of X-COR sandwich composite mentioned above. In this work, an alternative approach is proposed, where, instead of detecting reflected waves, the damage-induced converted wave modes are used as indicators of internal damages [17]. An advanced signal processing technique called matching pursuit decomposition (MPD) [26] is used to effectively de-noise the signals in the time-frequency domain. The de-noised signals are then processed using a Hilbert transform based envelope detection technique [27] to isolate wave modes from each other in the time domain and to construct the time-space representation (TSR) using the spatial information of the sensors. An iterative mode tracking algorithm is then developed to track all the wave mode trajectories in the time-space domain, localizing the wave sources while providing a fundamental understanding of the mode conversion mechanism involved in the UGW based SHM framework. Then, X-COR sandwich panels with two artificially seeded damage scenarios, i.e., facesheet delamination and foam core separation, are used to validate the developed framework.

The remainder of this paper is organized as follows. Section 2 introduces the mathematical formulations of multi-dimensional signal processing and the mode tracking approach for damage localization. Section 3 describes the experimental