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A diagnostic imaging approach for online characterization of multi-impact in aircraft composite structures based on a scanning spatial-wavenumber filter of guided wave

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ABSTRACT

Monitoring of impact and multi-impact in particular in aircraft composite structures has been an intensive research topic in the field of guided-wave-based structural health monitoring (SHM). Compared with the majority of existing methods such as those using signal features in the time-, frequency- or joint time-frequency domain, the approach based on spatial-wavenumber filter of guided wave shows superb advantage in effectively distinguishing particular wave modes and identifying their propagation direction relative to the sensor array. However, there exist two major issues when conducting online characterization of multi-impact event. Firstly, the spatial-wavenumber filter should be realized in the situation that the wavenumber of high spatial resolution of the complicated multi-impact signal cannot be measured or modeled. Secondly, it's difficult to identify the multiple impacts and realize multi-impact localization due to the overlapping of wavenumbers. To address these issues, a scanning spatial-wavenumber filter based diagnostic imaging method for online characterization of multi-impact event is proposed to conduct multi-impact imaging and localization in this paper. The principle of the scanning filter for multi-impact is developed first to conduct spatial-wavenumber filtering and to achieve wavenumber-time imaging of the multiple impacts. Then, a feature identification method of multi-impact based on eigenvalue decomposition and wavenumber searching is presented to estimate the number of impacts and calculate the wavenumber of the multi-impact signal, and an image mapping method is proposed as well to convert the wavenumber-time image to an angle-distance image to distinguish and locate the multiple impacts. A series of multi-impact events are applied to a carbon fiber laminate plate to validate the proposed methods. The validation results show that the localization of the multiple impacts are well achieved.

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1. Introduction

Due to the superior characteristics over conventional materials, composite materials have been gradually adopted in aerospace industry [1–5]. However, the poor impact resistance of such materials may lead to barely visible impact damages and result in stiffness degradation and a significant loss of structural integrity. Therefore impact monitoring of aircraft composite structures is an important research topic in the field of Structural Health Monitoring (SHM).

In the last twenty years, many researchers have been interested in taking advantages of guided wave and piezoelectric (referred as PZT in the rest of this paper) sensor to realize impact monitoring of composite structures [6–11]. In early studies, different kinds of methods have been proposed to realize impact localization and impact energy estimation from the perspective of geometry or mechanics model [12–14]. However, in order to improve signal-to-noise ratio and achieve high accuracy and tolerance of impact localization on real aircraft structures, many studies began to introduce PZT array based imaging techniques to impact localization in recent years, such as impact energy imaging [15,16], time-reversal imaging [17–21], multiple signal classification [22,23]. These methods researched till now have shown the practical application potential of impact imaging techniques based on guided wave in aerospace industry [24–26].

All the literatures mentioned above concentrate on processing guided wave in time domain, frequency domain or time-frequency domain. Comparing with those methods, the spatial-wavenumber filter has been proved to be an effective approach to distinguish propagating direction and different modes of the guided wave, and has been widely researched with a lot of well-performed work published in recent years [27–30]. However, in most of these studies, the wavenumber with high spatial resolution of narrow-band guided wave signal needs to be measured first by using a laser Doppler vibrometer as a spatial sampling device. That is the main reason why these methods can only be applied to off-line damage inspection at the current stage. To improve the feature of on-line monitoring of spatial-wavenumber filter, Purekar and Pines [31] and Wang et al. [32] developed on-line damage imaging methods by taking a linear PZT array instead of a laser Doppler vibrometer as a spatial sampling device but an accurate wavenumber curve must be modeled or measured beforehand in order to perform the spatial-wavenumber filter. These abovementioned researches all concentrate on realizing damage inspection or monitoring by using the spatial-wavenumber filter.

It is well known that impact is a kind of instant event and needs to be monitored on-line continuously. Besides, aircraft composite structures are often struck by multiple impacts occurring simultaneously. This situation may be encountered when an aircraft is passing through a region with rain, dust or hail, which results in multiple damages on the structure [22,33,34]. Thus it is important and necessary to develop a spatial-wavenumber filter based multi-impact imaging method for aircraft composite structures.

Regarding the on-line impact monitoring combining with the spatial-wavenumber filter, several preliminary progresses have been made. Baravelli et al. [35] proposed a guided wave transducer of wavenumber frequency-steerable combing with spatial-wavenumber imaging, and multiple sources imaging of guided wave was realized. However, the sources were only simulated by taking PZT sensors as the excitation. Under this situation, the problem of how to determine the impact occurring time was avoided because the excitation time can be recorded beforehand, but the impact occurring time cannot. In addition, the source localization was only performed on an aluminum plate and the localization accuracy needed to be further improved. In the authors' previous study [36], a model-independent spatial-wavenumber filter based impact imaging and localization method was proposed to achieve impact monitoring without wavenumber measuring or modeling. By extracting frequency narrow-band signal from the wideband impact response signal, the method realized the one-to-one relationship between the wavenumber of the signal and its propagating direction, and was able to locate impact on composite structures without blind angle. However, the method was only applied to single impact imaging. Besides, the impact localization result wasn't given by the spatial-wavenumber image directly and a geometrical localization method needed to be used, which reduced the localization accuracy.

To develop an on-line multi-impact imaging method based on spatial-wavenumber filter for aircraft composite structures, some issues must be addressed.

(1) The spatial-wavenumber filtering of multi-impact signal should be realized in the situation that the wavenumber of high spatial resolution of the complicated impact signals cannot be measured or modeled.
(2) Due to the overlapping of guided wave wavenumbers when multiple impacts occurring simultaneously, it's difficult to identify the multiple impacts and realize multi-impact localization.

In this paper, a scanning spatial-wavenumber filter based diagnostic imaging method for online characterization of multi-impact event is proposed to conduct multi-impact imaging and localization, based on the authors' previous study [36]. With this method, a PZT 2D cross-shaped array which consists of two orthogonal linear PZT arrays is adopted to fulfill the spatial sampling of the multi-impact signal. The principle of the spatial-wavenumber filter for multiple impacts of guided wave is developed and a scanning spatial-wavenumber filter is proposed to realize the spatial-wavenumber filtering of the multi-impact signal without wavenumber measuring or modeling. The continuous complex Shannon wavelet transform is used to extract the frequency narrow-band component of the multi-impact signal. By applying the scanning spatial-wavenumber filter to the multi-impact signal of frequency narrow-band, the wavenumber-time images of the multiple impacts can be obtained first. Then a feature identification method of multi-impact based on eigenvalue decomposition

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