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Impact induced damage assessment by means of Lamb wave image processing

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ABSTRACT

The aim of this research is an analysis of full wavefield Lamb wave interaction with impact-induced damage at various impact energies in order to find out the limitation of the wavenumber adaptive image filtering method. In other words, the relation between impact energy and damage detectability will be shown. A numerical model based on the time domain spectral element method is used for modeling of Lamb wave propagation and interaction with barely visible impact damage in a carbon-epoxy laminate. Numerical studies are followed by experimental research on the same material with an impact damage induced by various energy and also a Teflon insert simulating delamination. Wavenumber adaptive image filtering and signal processing are used for damage visualization and assessment for both numerical and experimental full wavefield data. It is shown that it is possible to visualize and assess the impact damage location, size and to some extent severity by using the proposed technique.

1. Introduction

It is believed that matrix cracks in composite laminates are the first type of impact damage. It was shown by Sjoblom et al. [1] that the presence of these matrix micro-cracks does not have a strong effect on the laminate stiffness during the impact. However, they are initiation points for delamination and fiber breaks that change the local and global stiffness of composite laminates and modify the force–displacement curve. For this reason, it is important to detect initiation of delamination often referred to as barely visible impact damage (BVID) and avoid catastrophic failure of a structure. Nondestructive inspection methods providing information of early state delamination have been investigated quite extensively in the literature. Among inspection methods vibrothermography [2–4], ultrasonic testing [5–7] and Lamb wave measurements using Scanning Laser Doppler Vibrometer (SLDV) should be mentioned [8]. The latter one has gained particular attention in the last decade [9–19].

One of the industry's major requirements for integrating new NDT methods into their in-service environment of composite structures is usability by untrained personnel, i.e., the testing must be simple to perform and the results easy to evaluate. There are several contenders available that claim to provide a fast and mobile detection of impact damage-related delaminations. However, those based on ultrasonic testing are too complicated for untrained personnel and the results can only be evaluated for known materials and geometries. Those based on optically excited thermography suffer from low depth resolution and difficult-to-interpret results [20]. Two potential NDT methods that can detect impact damage unambiguously

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are thermo-sonics (which belongs to the vibrothermography category) and Lamb wave measurements using SLDV. The former one is effective if additional information about local defect resonance is provided for optimal excitation. The thermo-sonic method is very fast in comparison to laser Doppler vibrometry but thanks to compressive sensing methods [21] measurement time of laser vibrometer can be significantly reduced.

Lamb waves are generated in an investigated structure by using piezoelectric actuator. Experimental measurements are carried out using scanning laser Doppler vibrometry. Laser vibrometer uses the beam of laser light to measure the velocity field of the vibrating surface. It allows registering full wavefield of propagating Lamb waves in elements of structures. Appropriate signal processing of the full wavefield data can provide detailed visualization of various damage types, including delamination as well as their location and severity.

Most popular full wavefield signal processing methods rely on various frequency-wavenumber filtering and processing algorithms. It includes reflection and mode separation method [10,11], isolated cumulative standing wave energy [12,13], zero-lag cross-correlation imaging [14], local wavenumber domain analysis [15–17] and wavenumber adaptive image filtering [18,19]. This research will focus on the latter one because it is competitive in comparison to other methods as it is demonstrated in [8]. The main advantage of the wavenumber adaptive image filtering is high sensitivity to damage. The method utilizes wave patterns corresponding to the interaction of waves with damage not only for direct waves transferred from excitation source but also coming from edge reflections. Moreover, the method is fully automated. However, the signal processing requires complex mathematical operations. This method is also limited to elements of structures with uniform thickness.

The literature related to delamination or BVID identification by Lamb waves using SLDV is rather limited [12,14–18].

Sohn et al. [12] applied the concept of standing wave energy entrapped in the delamination in a multi-layer composite plate. The delamination was a result of the impact. Nevertheless, impact energy was not given by the authors but they mentioned that a small dent was visible on the impacted side. The proposed signal and image processing highlighted the delamination. The highlighted delamination shape was similar to a thermographic image obtained on the back surface of the inspected plate.

A similar concept of delamination induced standing waves was used by An [14]. He performed imaging of impact induced delamination by two step algorithm. In the first step, the wavefield is decomposed into forward and backward propagating waves using the frequency-wavenumber analysis [10,11]. In the second step, the zero-lag cross correlation in the frequency-space domain between forward and backward wavefields is computed. The method was applied to the composite plate subjected to impact. Again, the impact energy was not given. The created delamination was invisible on the impact surface, but partially broken fibers were observed on the opposite surface to the impact surface. It seems that the level of impact was quite high because A0 mode entrapment at delamination was observed. However, the visualized area of delamination by the proposed method revealed that the delamination diameter was less than 10 mm. Thermographic image confirmed the size of delamination.

The group of various wavenumber imaging procedures was applied for impact-induced delamination detection and quantification in [15–17]. It is interesting to note that a quasi-static indentation technique was used to grow delamination. It gives some control of damage stages. For example in [15] two experiments were performed. In the first one, a 25.4 mm diameter tup was lowered at a rate of 0.127 mm/min until an abrupt reduction in force occurred from 3.97 kN to 2.5 kN. In the second one, the same process was repeated for a 76.2 mm diameter tup until a force of 6 kN was measured. Distinctive wavefield patterns were obtained for these two damage scenarios with much stronger wave scattering at delamination for the latter case. This behavior is directly reflected in the results of the proposed algorithm, rising values of wavenumbers corresponding to delamination area. Similar experiments were performed in [16] but the damage visualization algorithm was improved by the filtering reconstruction imaging and spatial wavenumber imaging. In the case of filtering reconstruction imaging, the filtering mask is created in order to select wavenumber components related to the trapped waves in the delaminated region. In the latter case, short space 3D Fourier transform is utilized through spatial windowing technique. Tian et al. also shown that by wavenumber analysis it is possible to estimate delamination depth [17].

Slightly different delamination type, namely thermally induced, was investigated by Radzienski et al. [18]. The applied wavenumber domain filtering for highlighting a delamination is based on the similar concept of the filtering reconstruction imaging described in [17] but it is performed in an automatic way and is more adaptive. Also, 2D Fourier transforms are involved in the algorithm instead of 3D Fourier transforms. The presented results of delamination visualization were very accurate in terms of delamination location and size.

During the analysis of various experimental data authors found that for low velocity, low energy impacts creates delamination which produces the interaction of Lamb waves that is different than in case of interaction with delamination simulated by a Teflon insert. The latter method is often reported in the literature as a helpful benchmark for delamination identification algorithms [15–17]. However, low energy impacts influence wave propagation pattern less significantly than the Teflon insert making such delamination more difficult to detect. The same conclusion can be drawn from research papers [15–17] in which apart from Teflon inserts also impact induced delamination was investigated. For this reason, both cases will be presented and analyzed in this paper.

The aim of this research is an analysis of full wavefield Lamb wave interaction with impact induced delamination at various impact energies in order to find out the limitation of the wavenumber adaptive image filtering method. In other words, the relation between impact energy and BVID detectability will be shown. Similar studies have not been presented so far.