ARTICLE IN PRESS

Optics and Lasers in Engineering xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Application of scanning laser Doppler vibrometry for delamination detection in composite structures

Pawel Kudela[a], Tomasz Wandowski[a,*], Pawel Malinowski[a], Wieslaw Ostachowicz[a,b]

[a] Institute of Fluid–Flow Machinery of Polish Academy of Sciences, Fiszera 14 St., 80-231 Gdansk, Poland
[b] Warsaw University of Technology, Faculty of Automotive and Construction Machinery, Narbutta 84 St., 02-524 Warsaw, Poland

ARTICLE INFO

Keywords:
Scanning laser Doppler vibrometry
SLDV
Guided waves
Delamination detection
Mode conversion
Composite materials

ABSTRACT

In this paper application of scanning laser Doppler vibrometry for delamination detection in composite structures was presented. Delamination detection was based on a guided wave propagation method. In this papers results from numerical and experimental research were presented. In the case of numerical research, the Spectral Element Method (SEM) was utilized, in which a mesh was composed of 3D spectral elements. SEM model included also a piezoelectric transducer. In the experimental research guided waves were excited using the piezoelectric transducer whereas the sensing process was conducted using scanning laser Doppler vibrometer (SLDV). Analysis of guided wave propagation and its interaction with delamination was based on a full wavefield approach. Attention was focused on interactions of guided waves with delamination manifested by A0 mode reflection, A0 mode entrapment, and S0/A0 mode conversion. Delamination was simulated by a teflon insert located between plies of composite material. Results of interaction with symmetrically and nonsymmetrical placed delamination (in respect to the composite sample thickness) were presented. Moreover, the authors investigated different size of delaminations. Damage detection was based on a new signal processing algorithm proposed by the authors. In this approach the weighted RMS was utilized selectively. It means that the summation in RMS formula was performed only for a specially selected time instances. Results for simple composite panels, panel with honeycomb core, and real stiffened composite panel from the aircraft were presented.

1. Introduction

Fiber reinforced composite materials are more and more popular in different fields of engineering. These materials are primarily utilized in aerospace, maritime, automotive or wind energy structures. Most important advantage of fiber reinforced composite materials is high strength to weight ratio. These materials are chemically and corrosion resistant. Moreover, they can be formed in parts with complex shapes. Composites with glass fiber reinforcement are electrically nonconducting and therefore they can be utilized in radar technology.

Beside many advantages, fiber reinforced composite materials have also drawbacks. The most important is its vulnerability to delaminations that can be initiated by impact (bird strike, tools drop, etc.). It is a very important problem, because delamination can be invisible on the external surface. Therefore many non-destructive testing/evaluation (NDT/E) methods have been developed in order to assess structural parts made out of composite materials. For this purpose techniques such as ultrasound testing [1,2], eddy currents [3], active thermography [2], X-ray tomography [4], terahertz spectroscopy [1,5,6] and guided waves (GW) have been utilized.

The authors of this paper have focused attention on guided wave propagation method. This method is based on the fact that any kind of discontinuity, like damage, is a source of changes of guided wavefield. In the literature two general approaches can be distinguished: point-wise and full wavefield.

In the first approach, elastic waves are excited and sensed using thin piezoelectric transducers placed on the structure [7,8]. Guided wave signals are registered in small number of transducers. Transducers are arranged in concentrated arrays with different topologies (linear, circular, square, cross-like) [7,9,10] or distributed arrays [11]. It should be mentioned that in point-wise approach Scanning Laser Doppler Vibrometry (SLDV) can be also utilized for sensing, instead of piezoelectric transducers. Such a methodology can be very suitable in prototyping process of piezoelectric sensing network. For this purpose guided waves are still excited using piezoelectric transducer. Sensing process is performed in chosen points representing transducers in sensing network [9,10]. Point-wise approach based solely on piezoelectric transducers can be utilized in Structural Health

* Corresponding author.

http://dx.doi.org/10.1016/j.optlaseng.2016.10.022
Received 29 April 2016; Received in revised form 26 October 2016; Accepted 26 October 2016
Available online xxxx
0143-8166/ © 2016 Published by Elsevier Ltd.

Please cite this article as: Kudela, P., Optics and Lasers in Engineering (2016), http://dx.doi.org/10.1016/j.optlaseng.2016.10.022

Monitoring (SHM). However due to limited number of collected signals, limited amount of information about guided wave propagation can be obtained. Moreover, signals are very complex due to multimodal and dispersive nature of guided waves. Especially, multimodal nature causes problems of interpretation of guided wave signals in complex structures (thickness variation, stiffeners, riveted/bolted/bonded joints, connection of different materials) [8].

In the second approach, full wavefield, piezoelectric transducers or lasers are utilized for guided waves excitation, whereas sensing is performed using SLDV. Wave sensing process is performed for dense mesh of points spanned over the surface of a structure. This allows to register full wavefield and perform visualization of guided wave propagation. In this approach larger number of signals are registered which gives much more data for analysis than in point-wise approach. Full wavefield approach is very useful for analysis of guided wave interaction with structural elements of complex structures. Possibilities of SLDV application in research related to guided wave measurements have been extensively studied over recent years [12–20]. In the research work [12] scanning laser vibrometry was utilized for damage detection in aluminum plates. Different damage severities were investigated. The research work was also supported by numerical analysis based on LISA method. In [13] combination of experimental analysis using laser vibrometry and numerical analysis for the plates were presented. Ruzzene [14] proposed technique for full wavefield analysis in wavenumber/frequency domain for damage detection. This is a filtering technique that improves damage localization results. The author performed numerical and experimental analysis of simple aluminum plate with crack and disbonded tongue and groove joint. In [15,16] scanning laser vibrometry and imaging technique were utilized for detection of hidden delamination located in multi-layer composite. Authors analyzed wave interaction with delamination and utilized several image processing techniques like Laplacian filtering. It should be noted that in the research work [16] completely non-contact system for elastic wave generation and sensing was presented. Elastic wave generation was performed using continuous wave (CW) laser source in connection with photodiode that excites piezoelectric transducer. Elastic wave sensing was performed using conventional scanning laser vibrometer. Non-contact elastic wave generation based on thermoelastic effect was utilized in [17]. Authors utilized broadband excitation based on low power Q-switched laser.

The technique that allow to remove source waves and to separate wave modes was proposed by Michaels et al. [18]. This approach is based on filtering in wavenumber/frequency domain in connection with analysis of resulting residual signals. This technique was utilized for detection of crack initiated from a hole in an aluminum plate and for delamination detection in composite plate. The comprehensive review of methods for analysis of full wavefield measurements was presented in [19]. The authors describe and compare different signal processing techniques that are utilized for visualization of damage localization. The authors performed analysis for metallic plate with a cut. Conducted analysis was based on numerical and experimental results. In numerical part spectral element method in the time domain was utilized. 3D solid spectral elements were applied in the numerical model. The authors compared techniques utilizing: 2D/3D Fourier transform, wavenumber adaptive filtering, wavelet transform and warped curvelet frame method. Transformation of signals from time-space to frequency wavenumber domain using Fourier transform was originally proposed in [21] and later extended by Ruzzene [14]. Adaptive wave number filtering was proposed in [20]. Wavelet transform for signal processing in full wavefield analysis was utilized in [22] and [23]. De Marchi proposed method called curvelet frame method [24]. This approach is based on warped frequency transform (WFT), curvelet transform (CT), wave masking procedure and inverse CT and WFT transforms. The advantage of warped curved frames is possibility of discrimination of waves generated in different sources and propagating in the same direction. The isolated cumulative standing wave energy method was proposed in [25]. This method is based on the fact that crack could be source of standing waves. The authors shown successful application of the proposed method for crack localization. In papers [26–28] local wavenumber analysis was proposed. This method is based on 3D Fourier transform and spatial windowing for full wavefield data. This method utilizes also information about mode conversion phenomenon.

SLDV is very usefully tool for analysis of elastic wave interaction with discontinuities. SLDV was utilized for investigation of interaction of guided wave interaction with cracks [17,29–31], holes and slits [13] in metallic plates. This technique was also utilized for detection of simulated corrosion in pipes [17]. Laser vibrometry was also utilized for composite structures for investigation of wave interaction with delaminations in plates [32–34] and more complex structures like wing [17]. Multiple wave reflections within the delamination region and trapping effect was noticed in [33,35–37].

SLDV technique can be applied for analysis of mode conversion due to mentioned interaction of wave modes with discontinuities. Results of such research were presented in [38]. The authors investigated mode conversion phenomenon that occurred due to interaction of S0 elastic wave mode with notch, hole and riveted joints in metallic structures. This interaction was observed in the form of S0/A0 mode conversion. This phenomenon was also investigated in composite structures where S0/A0 mode conversion due to interaction of S0 mode with delamination was observed [39]. The authors performed numerical and experimental research. They investigated interaction of elastic waves with delaminations with different shapes and locations (planar and in the respect to the thickness). In the numerical part Spectral Element Method (SEM) was utilized. Laser vibrometry was also utilized in research related to continuous mode conversion in carbon fiber reinforced polymer (CFRP) plates. This research was begun by Willberg et al. [40]. Authors observed continuous mode conversion S0/A0 in multilayer composite plate. Conversions occur continuously as result of interaction of guided waves with reinforcement in the form of twill fabric. This phenomenon was also reported in [41].

The aim of this research work is to develop alternative approach for delamination detection which improves quality of resulting damage influence map.

The structure of the paper is as follows. The phenomenon of guided waves interaction with delamination is explained in Section 2. The investigations are performed by numerical simulations and experiments by using SLDV. The research findings are utilized further in Section 3 for development of new delamination identification method. This method is validated experimentally in Section 4. Final conclusions are drawn in Section 5.

2. Study of interaction of guided waves with delamination

CFRP composites were considered with delamination arrangement shown in the Fig. 1. The dot placed at the centre symbolize the piezoelectric transducer. Two cases of delamination placement were

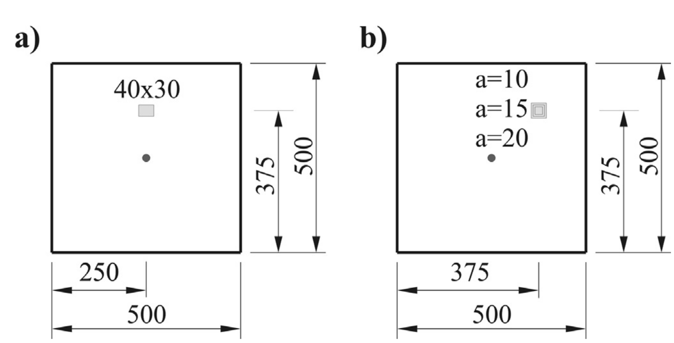

Fig. 1. Investigated composite plate with (a) rectangular and (b) square delaminations (a – length of delamination edge).