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NON-CONTACT LASER-BASED DAMAGE DETECTION IN COMPOSITE LAMINATES USING LOCAL WAVENUMBER ESTIMATION

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ABSTRACT

The guided waves based imaging techniques have been intensely developed in recent years as quick and accurate NDT solutions for various types of plate structures. One of the more attractive imaging methods is the local wavenumber spectroscopy, which exploits the dispersive nature of the guided waves to detect local thinning, corrosion or delamination type defects. The method paired with the non-contact excitation and detection of guided waves, using laser techniques, is an efficient solution for fast examination of large areas of plate-like structures.

In this paper, we present the application of a laser-based system using local wavenumber estimation (LWE) method as a defect evaluation technique for a multi-thickness CFRP sample with multiple simulated damages. The examined specimen is excited using an Nd:YAG laser and the resulting ultrasound wave field is measured using a scanning laser Doppler vibrometer (SLDV). Data processing using the LWE algorithm produces two dimensional maps, where different plate thicknesses and simulated damages can be clearly visible.

Keywords: guided waves, local wavenumber estimation, laser generated ultrasounds

NOMENCLATURE

SLDV	Scanning Laser Doppler Vibrometer
LWE	Local Wavenumber Estimation
LGU	Laser Generated Ultrasounds
CFRP	Carbon Fiber Reinforced Polymer
ω	temporal frequency
k_x, k_y	wavenumber along Cart. axes x or y
V_f	3D wavenumber-frequency data
V_{bp}	mode- and bandpass filtered data
S_b	width of the Gaussian filter

1. INTRODUCTION

In recent years, laser generated ultrasounds (LGU) and laser vibrometry have gained more attention in the field of NDT. These two laser-based solutions are often combined in a single system, exploiting a possibility to create a fully non-contact diagnostic system and achieve high speed of signal acquisition [1][2]. One of the applications particularly well suited for the application of a non-contact laser-based test setup is the imaging of a guided waves wave field. Based on the analysis of a measured wave field it is possible to infer the information about the presence and location of defects in a plate-like sample. The most often used features in the processing techniques involve the change of amplitude [1,3,4], mode conversion [5,6] or the change of wavenumber of the propagating wave [7–10]. The local wavenumber estimation (LWE) is especially attractive technique as the wavenumber-frequency characteristics of the plate is sensitive to various types of damage, including corrosion, delamination or material thinning.

This paper describes a non-contact damage detection system using guided waves generated with a laser source and measured with a scanning laser Doppler vibrometer (SLDV). The full-field dataset of the propagating Lamb waves is acquired and processed using the LWE algorithm in order to obtain a 2D map of defects. The examined sample is an industrial CFRP demonstrator plate with different thickness zones and several delaminations simulated with Teflon inserts located across the sample. The obtained results show that the method is capable of detecting defects in various thicknesses of the test structure.

2. Description of the diagnostic system

2.1 Wavenumber spectroscopy

The operation principle of the LWE and other related methods is the dispersive property of guided ultrasonic waves. For any given plate structure the dispersion curves can be represented by the wavenumber-frequency plot, which is

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characteristic for this particular plate of uniform constant thickness. When the thickness of the plate or its material properties change this is reflected in the frequency-wavenumber representation – wavenumber values of the modes can shift or new modes may appear altogether. This change can be extracted from the wavenumber-frequency domain of the acquired wave field (which is a 3-dimensional spatiotemporal dataset) and then by using a bank of filters visualized in the form 2D map of the scanned surface. Suppose that the V_f represents the Fourier transform of the spatio-temporal wavefield. In order to track the change of a wavenumber the V_f can be filtered to a single wave mode and then bandpass – filtered around the chosen central frequency f_c. This can be represented using the following notation in the Fourier domain:

$$\mathrm{V_{bp}}(\mathrm{k_x}, \mathrm{k_y}, \omega) = \mathrm{W_m} \mathrm{F}_{bp} V_f(\mathrm{k_x}, \mathrm{k_y}, \omega) \qquad (1)$$

where $\mathrm{W_m}$ is the mode filtering mask and F_{bp} is the bandpass filter represented in the frequency domain. The filtered data V_{bp} can then be decomposed using the wavenumber filter bank in the form of two-dimensional wavenumber windows. This can be described using the 2D Gaussian representation:

$$W\left(k_x, k_y, \omega, n\right) = \exp\left(\frac{\left(\sqrt{(k_x^2+k_y^2)} - k_b(n)\right)^2}{S_b^2}\right) \qquad (2)$$

where $\mathrm{k_b}$ is the radius of the single filter, S_b is the width of the single filter and n is the number of filter in the bank. It is worth noting that in this application the parameters of the window function are constant along the frequency axis. As a result of applying the filterbank the n frequency-wavenumber datasets are produced, each containing the information on particular wavenumber bandwidth. In order to relate them back to the spatial domain the data is transformed using inverse Fourier transform. To reduce the dimensions of the datasets the summation along the temporal axis is performed. In order to enhance the image quality the 3D envelope of each of the n signals can be calculated instead of the direct inverse Fourier transform. Finally, for each xy coordinate of the original wave field the maximum value from n datasets is selected and the corresponding central wavenumber index k_b is assigned to the coordinate. As a result, a 2D map of local wavenumber maxima is created. The procedure is explained in greater detail in [7–9]

2.2 Description of the measurement/acquisition

The LWE algorithm can be implemented in practice with use of a non-contact scanning system. In this work, a Polytec PSV-400 SLDV is chosen as a signal acquisition unit. The generation of the guided waves in the test sample is also realized with a non-contact laser system. Pulsed laser source is used to irradiate the surface of the plate and generate a broadband ultrasonic pulse [11]. In this work the Quantel Ultra Nd:YAG laser system was used delivering peak energy of 100 mJ in a single pulse. The combination of these two laser devices allows to obtain a flexible and effective system for non-contact examination of the plate-like structures. Schematic presentation of the test system is shown in Figure 1.

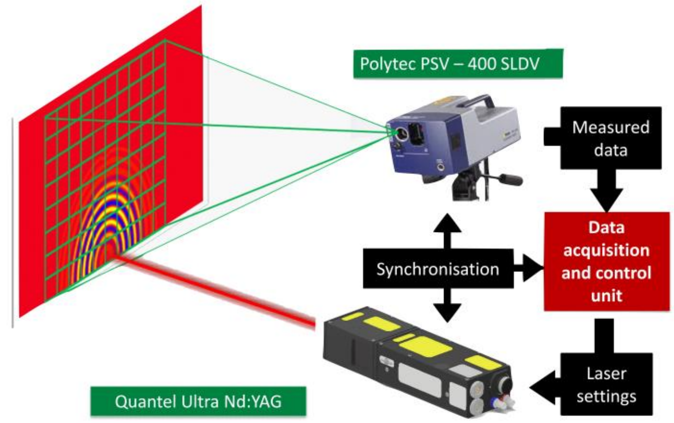

FIGURE 1: Schematic presentation of the non-contact ultrasonic imaging system

3. Example of application

In order to demonstrate the effectiveness of the described test system a CFRP sample with multiple simulated damages was analyzed. The examined specimen consists of six different thicknesses of the fiber layups, ranging from 0.5 to 3 mm. During the manufacturing process several square-shaped Teflon inserts with 6 by 6 mm dimensions have been placed between the plies of the laminate to simulate localized delaminations. For 0.5 and 1 mm thick stages a single delamination per stage has been introduced and for thicker layups (from 1.5 mm up) there are three inserts for each stage of the plate. The inserts were placed at different depths of the laminate which was an additional criterion for the assessment of the proposed damage detection system. Before performing the experiment the retro-reflexive foil was attached to the measured surface in order to improve the quality of the SLDV measurement.

During the measurement, the laser excitation was localized near the edge of the plate at the 1.5 mm thickness stage. The laser was operating in the pulsed mode and was synchronized with the acquisition system using the trigger from the Q-switch signal. The energy of the pulse was lowered to 40% in order to prevent the ablation of the irradiated surface. This allows to safely perform the measurement with the 10 Hz repetition rate of laser pulses. The SLDV was set to scan on a grid of 340 by 115 points with a uniform 1 mm spacing. The obtained spatiotemporal data is organized in the 3-dimensional matrix and the 3D Fourier transform is performed to obtain the $\mathrm{V_f}$ dataset. The resulting wavenumber-frequency representation along the main axis of wave propagation revealed that mainly the A0 Lamb wave mode was generated. The obtained measurement dataset was processed using the LWE algorithm as described in section 2 and focused on the filtered A0 mode. The LWE map was calculated separately for two parts of the plate – the first one including the thicknesses between 0.5 and 1.5 mm (part A) and the other between 1.5 and 3 mm (part B). Two different central frequencies were used to create the LWE maps for the two images, namely 110 kHz for part A and 90 kHz for part B. Due to the different values of the baseline wavenumbers on the consecutive thicknesses of the sample it is very difficult to clearly present the results in a single image. Therefore only the results of the wavenumber estimation for part A are shown in Figure 2. The step changes in the image background indicate the change in plate thickness. The increased wavenumber values within each thickness stage indicate the locations of defects. All four defects present in this section of the plate could be identified. Furthermore, at the 1.5 mm stage the topmost defect exhibit significantly larger local wavenumber value than the other two, allowing for the distinction between the different depths of the delaminations. The LWE of the other half of the plate resulted in a similar quality of estimation. However, from the nine inserts present in this part only eight could be readily identified. This results from the higher attenuation of the thicker portions of the plate, as well as with a larger distance from the excitation location. Additionally, the wavenumber contrast in multi-layered media does not scale proportionally with thickness reduction. Therefore, the sensitivity of the method may be too low for delaminations at greater depths for a given frequency and mode.

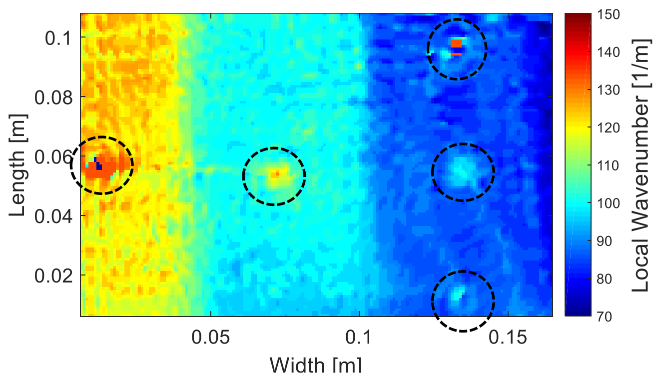

FIGURE 2: The LWE map of the analyzed CFRP plate using a laser-based excitation. The image involves thicknesses from 0.5 to 1.5 mm (part A). The estimation was performed for the central frequency of 110 kHz.

4. CONCLUSION

This work presented an application of the local wavenumber estimation (LWE) method based on the data obtained using the developed non-contact laser-based measurement system. Proposed approach allowed for a successful detection of simulated delaminations introduced in the CFRP component under investigation. We believe that the presented approach offers a viable solution for NDT of thin walled components in both quality control and in-service damage detection applications.

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