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Identification of cracks in thin-walled structures by means of wavenumber filtering

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ABSTRACT

This research is related to a signal processing of full wavefield data as an effective tool for detection, localization and visualization of a crack growth in thin-walled structures. Full wavefield data of propagating Lamb waves in structures such as plates and shells made out of metallic alloys and composite laminates contain a wealth of information about wave pattern anomalies due to occurrence of a damage. The aim is to demonstrate a method for enhancing damage visualization in structures such that estimation of the length and orientation of the crack can be easily obtained. The proposed signal processing involves application of discrete fast Fourier transform, wavenumber domain filtering and inverse discrete Fourier transform. The method is further enhanced by a technique for compensation of the wave attenuation so that the effects of structural damage have the same influence regardless of the location. The concept is first illustrated on numerically simulated data, and then tested on experimental results. In the experiments, full wavefield measurements are obtained using a scanning laser Doppler vibrometer, which allows the measurement of displacements and/or velocities along three axes over a user-defined grid. In the proposed method only out-of-plane velocities are used. Tests performed on simple aluminum and composite plates with artificially introduced longitudinal cracks confirm the effectiveness of the method and its potential for application to the inspection of a variety of structural components.

1. Introduction

Crack development in metallic structures is one of the most important concerns in transportation and civil engineering. Current methods of damage detection include visual inspections, classical techniques of nondestructive testing (NDT) and vibration/modal based methods. The majority of NDT techniques are based on regular ground inspections involving disassembling/assembling parts of structures which are laborious and thus expensive. The vibration/modal-based methods are not sensitive enough to detect small damage [1]. Hence, the trend is to use integrated structural health monitoring (SHM) systems [2].

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SHM systems consist of actuator–sensor networks resembling the human nervous system. Its purpose is to detect unusual structural behaviors in quasi-real-time, locate a problem, determine the importance of the problem, and trigger remedial actions. Recent developments in SHM include applications of acousto-ultrasonics and guided waves for damage identification [3]. Despite of advancements in this field it is still challenging to build robust autonomous SHM system, mainly due to the enormous number of sensors which must be used in order to achieve good sensitivity. Piezoelectric, macro fiber composite, wedge, interdigital or phased array transducers, piezo-paints, optical fiber sensors and micro-electro mechanical systems (MEMS) cannot compete with human neurons in regards of size. Additionally, installation and cabling can be costly and labor-intensive. Often the transducers and cables are vulnerable to damage and become the weakest link in the system, potentially increasing the maintenance costs [4].

In most applications, guided waves are generated and received by actuator–sensor pairs distributed over the test specimen according to specific configurations. The fundamentals of this type of operation consist in evaluating the characteristics of propagation along the wave path between each actuator–sensor pair. This technology has demonstrated its effectiveness in detecting small damages and discontinuities in the structure. The identification of the precise location of damage, however, requires the application of additional algorithms which process the information obtained by a distributed sensor array [5]. As a result only very dense sensor network is able to indicate approximate location of the damage, but an estimation of the size of the damage is often impossible. It is especially true because for most sensors it is necessary to apply algorithms for compensation of temperature and loading effects influencing propagation of waves [6,7].

It should also be noted that many contact transducers are not applicable under harsh environments such as high temperature and radioactive conditions. Also for certain applications, it is not desirable to use contact transducers because the added transducers can alter the dynamic characteristics of the target structures.

To address these shortcomings of contact transducers, it is possible to adopt noncontact laser measurement techniques, which have been extensively studied in the last decade [8–12]. Scanning laser Doppler vibrometer (SLDV) allows to register full wavefield in elements of a structure instead of single point measurements acquired by traditional sensors. In this way new possibilities for monitoring of structures arise enabling visualization of elastic waves interacting with various types of damages. A SLDV is used to measure the velocity of the inspected surface in points belonging to a predefined grid. Scanning the grid and post-processing the data allows the detection and the visualization of the full wavefield as wave propagates in the structure. The resulting images describe the main features of the propagating wave and show its interactions with discontinuities that may be encountered along the wave path. Measurements obtained with the SLDV can be combined with effective signal and imaging processing algorithms to support damage identification.

Nevertheless, dense grid of SLDV measuring points required in these algorithms causes that the time of measurement is quite long. The technique is not close to online monitoring and does not fall in the category of SHM. On the other hand it is expected that better, faster devices able to capture full propagating wavefield will be developed in future.

It should be noted, that in practical applications of SLDV technique for damage detection there must be an access to the surface of inspected structure. Moreover, the surface should reflect enough laser source back to the unit head to give reasonable signal to noise ratio. In order to overcome this issue special reflective tape might be bonded to the clean and smooth surface. But this process could be cumbersome in practice.

SLDV has been used for the first time for Lamb wave propagation measurements by Staszewski, et al. [1]. They used five-cycle 75 kHz sine wave with the Hanning window envelope as the excitation signal. The response was compared with piezoelectric sensor signal as well as numerical results showing good performance of the laser vibrometer. The first attempt of Lamb waves measurements by using SLDV were quickly employed to fatigue crack detection in metallic plates [13]. The simple index of the damage intensity was proposed as a root mean square (RMS) of registered signals and used for visualization of cracks [13], holes and slits [8].

Most of the full wavefield studies of propagating waves have been addressed to damage detection in aluminum specimens in the form of notches, holes and slots or fatigue cracks of the order of 10–40 mm in length [8,9]. Also, measurements by high frequency SLDV have been applied to small (about 5 mm long) fatigue crack localization in aluminum plate [14]. In this case excitation frequencies between 400 kHz and 600 kHz were used and damage visualization was performed by classic RMS method.

Much more refined damage visualization methods are based on frequency-wavenumber domain filtering introduced by Ruzzene [10]. He demonstrated a method for enhancing damage visualization in a structure using wave propagation through the application of incident wave removal procedures. Such procedures which operate in frequency-wavenumber domain have the objective of removing the wave generated by the transducer to obtain a residual wavefield that contains only contributions of scattering waves (i.e. not only waves scattered by damage but also scattered from features of structure such as stiffeners or rivets). The residual wavefield analysis can be used for baseline-free detection and characterization of defects. This technique was successfully applied for damage localization in isolated fragments of thin-walled aluminum plates [10] as well as composite panels [12]. Moreover, the application of the 3D Fourier Transform enables mode separation and analysis of reflection and mode conversion due to notch defects [12].

The frequency-wavenumber filtering approach was further automated and improved by calculation of momentary standing wave energy [4]. Moreover, the presented technique was completely noncontact because, in contrast to piezoelectric excitation used in previously mentioned methods, Y-K An, et al. used Nd:YAG laser for ultrasonic excitation [4].

Three approaches were presented by Tian, et al. [15], namely: frequency-wavenumber analysis, space-frequency-wavenumber analysis and local wavenumber domain analysis. Essentially, due to wave reflections at crack location as well