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Structural Health Monitoring system based on a concept of Lamb wave focusing by the piezoelectric array

Pawel Kudela [a,*], Maciej Radzienski [a], Wieslaw Ostachowicz [a], Zhibo Yang [b]

[a] Institute of Fluid Flow Machinery, Polish Academy of Sciences, Fiszera 14 St, Gdansk 80-231, Poland
[b] School of Mechanical Engineering, Xi'an Jiaotong University, 710049 Xi'an, PR China

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ABSTRACT

Piezoelectric transducer arrays are utilized in Structural Health Monitoring systems as a means for excitation and sensing of elastic waves. Anomalies of propagating waves have enabled to develop damage detection algorithms. Depending on actuation-sensing strategies these algorithms can be classified as pitch-catch and pulse-echo. Despite many signal processing methods such as delay-sum, time-reversal, probability-based diagnostic imaging, etc. the spatial damage information provided by the actuator-sensor paths to reconstruct the damage image is limited. A novel strategy based on Lamb wave focusing is proposed in order to increase damage imaging resolution. In the proposed method all actuators are used at the same time exciting specially designed waveforms so that inspect one specific point of the structure. Damage map is created by applying appropriate signal processing. It uses dispersion curve of selected Lamb wave mode for dispersion compensation. The dispersion curve is acquired by using laser scanning Doppler vibrometer. The damage indicator is calculated based on the energy of compensated signals registered by sensors. It is shown that apart from high energy level at excitation point, energy is concentrated exactly in the damaged region. An example of crack detection and visualization in an aluminum plate is shown confirming the accuracy of the proposed method. Also the proposed method is compared to well-established delay-and-sum algorithm.

1. Introduction

In past decades, Lamb wave has shown its usefulness in Structural Health Monitoring of plate-like and shell-like structures. In order to achieve the best accuracy of the damage localization by wave echoes, the idealized wave package should non-dispersive and steerable. The steering of wave package in space guarantees that all the inspection points can be scanned. The non-dispersive properties provide higher resolution of damage localization. However, d'Alembert formula and frequency-wavenumber relationship prove that the two requirements cannot be fulfilled by single-source excitation Lamb wave.

To address this issue, the Lamb wave beamforming and phased array methods are introduced. The Lamb wave beamforming is inspired by the research on radars.

The earliest investigation about beamforming appears to be performed by Deutsch et al. [1]. They introduced the linear phased array method into the application of Lamb wave self-focusing. Wooh, Shi and Clay et al. [2,3] further investigated the

* Corresponding author.
E-mail address: pk@imp.gda.pl (P. Kudela).

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steering characteristics of the piezoelectric linear array via simulations and experiments. As a consequence of structural symmetry, the linear phased array contains two focuses in steering. One is the desired focus, and the other one is secondary (unwanted) focus caused by the symmetry. The issue of dual focus can be addressed by placing sensors along 2D grids to form 2D arrays. Wilcox et al. [4,5] proposed the omnidirectional guided wave electromagnetic acoustic transducer arrays, which contain a circular pattern of elements. More complex shape, like rectangular, concentric circular, etc. arrays and their characteristics have been investigated by Yu and Giurgiutiu [6,7]. Briefly, the Lamb wave beamforming approaches can be seen as the extension of the conventional phased array, which realizes the steering of the wave by setting appropriate time delays of propagating wave packets [8,9]. The dispersion of Lamb wave, however, degrades the performance of this method in spatial focus. Theoretically, in the absence of dispersion, the phased array should be able to focus waves at a point. In practice, however, a tail in a focused waveform can usually be found as it is shown in the beamforming results [1]. Although, the excitation frequency or the type of actuator can be selected to decrease this effect. Thus, the waves can be steered in particular directions instead of points. The damage localization can be accomplished by extracting some unique features from the reflections from damage.

An alternative solution is the application of steerable actuator called CLoVER invented by Salas and Cesnik [10–12]. They developed a hardware-based technology – a special micro-device which is able to amplify amplitudes of Lamb waves at certain angles by activating the corresponding parts of the actuator. The sophisticated design of wedge-shaped, anisotropic, piezo-composite transducer groups encapsulated in the actuator, allows the wave amplitude along the desired direction to be larger than those for the other directions. Hence, the steering of wave package is realized. The CLoVER still relays on the extraction of wave packets related to reflections from damage. These wave packets are often dispersive and of low time-space resolution, so that it is difficult to obtain precise damage location.

The dispersion problem can be solved by the pre-compensation method proposed by Alleyne et al. [13] and Wilcox [14]. In their research, the excitation is firstly pre-designed to be a wide-band signal to compensate the following dispersive effects along a propagation distance. Building on this excitation, the registered signal can be reconstructed as the original excitation on the given circle, whose radius is defined by the specific distance. This approach is usually realized by SISO (single input single output) system as presented in [15], and hence the wave propagation cannot be steered. Similar to the classical methods based on anomalies of wave propagating, the performance of this method depends on the extraction of wave packets via some damage indices like described in [16].

We propose a novel approach of piezoelectric array steering in which waves energy is not sent to the specific angle but the particular focal point. Moreover, the proposed method uses dispersion compensation to improve resolution. The results of the proposed focusing method is compared with widely used delay-and-sum (DAS) algorithm [17–19].

2. Lamb wave focusing concept

The idea of the proposed algorithm is to use pulse-echo mode by the same array of transducers. The array excites waves so that consecutively focus waves at selected points and registers echo of reflected waves coming from these points (if any). If a damage coincides with a focal point, strong reflection is expected due to high amplitude of waves at the focal point. The reflection is stronger than a reflection of waves excited by a single piezoelectric transducer. Hence, signal processing utilizing reflective waves is more efficient.

The overall Lamb wave focusing concept is presented in Fig. 1. The algorithm scheme consists of three blocks. The first block (blue[1] boxes) corresponds to signal excitation so that focus Lamb waves at the selected point. The second block (orange boxes) corresponds to the processing of registered signals. Third block (red box) is the output of the algorithm in the form of easy in interpretation damage map indicating damage location and severity.

2.1. Select coordinates of focal point

The proposed procedure starts with defining the configuration of sensor array and grid of inspection points. Two examples of possible configurations are presented in Fig. 2. Clock-like configuration of sensors is shown in Fig. 2(a) whereas distributed configuration of sensors is shown in Fig. 2(b). The focal point is denoted by *F*. The coordinate of a focal point is selected from the set of coordinates defining the grid of inspection points. It can be seen in Fig. 2(a) that the focal point does not coincide with damage, denoted by *D*, whereas in Fig. 2(b) the focal point coincides with damage. It should be noted that the grid of inspection points defines the resolution of damage map. The higher density of inspection points results in higher accuracy of damage localization, but it requires longer inspection time because the number of excitations is equal to a number of inspection points.

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.