Mechanical Systems and Signal Processing 23 (2009) 1805–1829

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

Damage localisation in plate-like structures based on PZT sensors

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

[a] Institute of Fluid-Flow Machinery, Polish Academy of Sciences, J. Fiszera 14 Street, 80-952 Gdansk, Poland
[b] Faculty of Navigation, Gdynia Maritime University, Gdynia, Poland

ARTICLE INFO

Article history:
Received 3 March 2008
Received in revised form
19 August 2008
Accepted 30 October 2008
Available online 17 November 2008

Keywords:
Lamb waves
Damage localisation
Linear phased array
Piezoelectric transducers

ABSTRACT

In this paper, signal processing algorithms for damage localisation purposes in plate-like structures were proposed. Algorithms use elastic wave propagation phenomenon for damage detection and localisation. As a result of application to signals registered from the structure, special maps are created that indicate damage location. In this work the algorithms were introduced, described and experimentally implemented. Also one example coming from numerical simulation was included. The proposed methods were successfully tested on aluminium alloy specimen and carbon–epoxy specimen.

1. Introduction

This work deals with the problem of damage localisation, which is in the early stage of growth. Information about damage is brought by an elastic wave (Lamb wave) generated in the structure and registered by a piezoelectric transducers made out of PZT material. The investigation is focused on structural components utilised in aerospace structures, namely thin plates made out of aluminium alloys and panels made out of carbon–epoxy composites.

Active health monitoring of an aerospace structures using Lamb waves is modern and a promising technique. Some major advantages of this technique include fast scanning capabilities, low cost, long-range inspection, and testing inaccessible or complex components. Recently, small and conformal piezoelectric ceramics and wafer transducers, either being surface mounted or embedded leave-in-place on structures, have been widely studied for generating and receiving guided waves for structural integrity monitoring. Some of the work has been done by Chang et al. [1,2] and the effect is the commercial product named SMART Layer® utilised with some success for detection of fatigue crack growth [3,4] and bolt loosening [5,6]. A concept of SMART Layer® is based on distributed actuator/sensor network and *pitch–catch* method. The same concept can be successfully realized using ordinary piezotransducer network (application for crack and corrosion localisation has been shown in Ref. [7]). So that it can be concluded that signal processing is more important than hardware solution of monitoring system (crucial are: signal filtering, arrangement of transducers, and damage imaging).

In opposite to time-consuming model-based inverse procedures, Lamb-wave imaging techniques are widely used. The Lamb-wave imaging can be classified as a method of signal processing. The goal of the imaging method is built easy to interpret map which shows the location of the defect and its progression. Such maps are called synthetic aperture focusing technique images [8] (SAFT[9]), difference image based on optimal baseline subtraction [10], defect distribution probability map [7] or damage influence map [11] can be created based on principles of travelling wave packets from actuator through

* Corresponding author at: Gdynia Maritime University, Faculty of Navigation, Institute of Fluid-Flow Machinery, Polish Academy of Sciences, J. Fiszera 14 Street, 80-952 Gdansk, Poland. Tel.: +48 58 6995 285; fax: +48 58 3416 144.
E-mail address: wieslaw@imp.gda.pl (W. Ostachowicz).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2008.10.011

damage to sensor. Both *pitch–catch* and *pulse–echo* techniques are considered by researchers together with the distributed or concentrated transducer networks. The transducer configuration is strictly related to imaging processing and damage localisation maps look different for various configurations.

Two methods of Lamb-wave imaging should be differentiated:

- method based on distance and velocity of travelling wave packets without signal shifting [7,8,10,11] and
- *phased array* method based on signal shifting [12–16].

In the second type of method, Giurgiutiu et al. [12–14] studied Lamb waves in plates using an embedded piezoelectric wafer active sensor (PWAS). Maximum coupling is achieved when the PWAS length equals half the wavelength of a particular Lamb-wave mode as other modes are minimised. Thus, mode tuning can be achieved with the variation of PWAS dimensions [15].

Wilcox [16] investigated omni-directional wave transducer arrays for the rapid inspection of large areas of plate structures. Two types of arrays were investigated. The first consisted of a circular area densely populated with transducer elements and the second consisted of a single circular ring of transducer elements. The second type of array suffers from side-lobes effect. The side-lobes around the signal from a large reflector create an annular zone in the output map within which it is exceedingly difficult to reliably see any signals due to smaller reflectors in other direction. The first type of array produces an excellent concentrated peak at the location of the reflector, but it costs large number of sensors.

In this work, four methods of signal processing tools were developed for Lamb-wave-based damage localisation purposes. Two of them are very effective signal filtering algorithms that initially process the signals and the next two are the localisation algorithms which give the indication of damage location in the structure with high precision. The first proposed damage localisation algorithm can be classified as method without time shifting with the transducer configuration similar to the circular ring, as presented in Ref. [16]. In comparison to phase-addition algorithm presented in Ref. [16], the proposed algorithm with clock-like array is less sensitive to side-lobe effect. The second damage localisation algorithm is based on phased array principles [12–15] and is preceded by sophisticated filtering procedure. In this paper also a fundamental theory of design of phased array configuration has been presented.

The experimental investigation was conducted on materials utilised in aerospace structures, namely thin plate of aluminium alloy and carbon–epoxy panel. In this work, signal processing algorithms were used to localise simulated damage in the specimens. In the composite structure, one damage was introduced and then found using the proposed method. In the aluminium alloy specimen three simulated defects were successfully localised by the means of phased array algorithm. Additionally, for the proper design of a linear phased array, Lamb-wave anti-symmetric mode group velocity was experimentally extracted and on its basis Lamb-wave wavelength was calculated.

2. Lamb waves

Elastic waves that propagate between two parallel surfaces of thin solid plates with free boundary are known as Lamb waves or guided waves. Lamb waves are named after Horace Lamb in honour of his fundamental contribution to this subject. He developed mathematical theory which describes these waves, but what is interesting he never generated these waves in real structure. Lamb waves propagate both as symmetric (S_0, S_1, S_2, …) and anti-symmetric (A_0, A_1, A_2, …) modes, and the number of these modes depends on the product of the excitation frequency and the plate thickness. Only two fundamental modes: S_0 and A_0 propagate up to almost 2 MHz mm in plate made of aluminium alloy. Figs. 1 and 2 show strains in the plate for the case symmetric and anti-symmetric Lamb-wave fundamental mode, respectively.

Characteristic for this type of waves is elliptical particles motion in contrary to Rayleigh waves with circular particles motion. Lamb waves can be generated using: conventional ultrasonic transducer [17,18], piezoelectric transducer [12–15,17] or laser source [17,19,20].

Piezoelectric transducer is the most popular, because it can be light and thin. Moreover, it can work both as generator and receiver of elastic waves. The velocity of Lamb-wave propagation is strongly dependent on the product of frequency

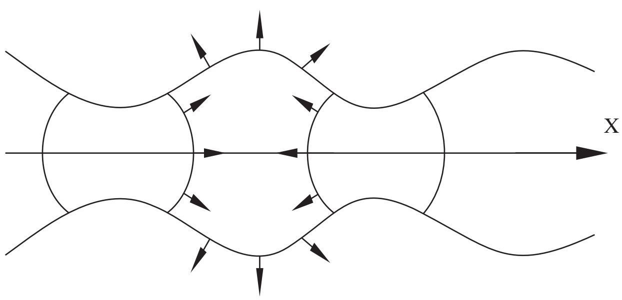

Fig. 1. Symmetric mode plate strains.