Ultrasonics 64 (2016) 139–150

Contents lists available at ScienceDirect

Ultrasonics

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

One sensor acoustic emission localization in plates

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ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 21 July 2015
Accepted 25 August 2015
Available online 3 September 2015

Keywords:
Acoustic emission
Mindlin plate
Time reversal
Source characterization
Structural health monitoring

ABSTRACT

Acoustic emissions are elastic waves accompanying damage processes and are therefore used for monitoring the health state of structures. Most of the traditional acoustic emission techniques use a trilateration approach requiring at least three sensors on a 2D domain in order to localize sources of acoustic emission events. In this paper, we present a new approach which requires only a single sensor to identify and localize the source of acoustic emissions in a finite plate. The method proposed makes use of the time reversal principle and the dispersive nature of the flexural wave mode in a suitable frequency band. The signal shape of the transverse velocity response contains information about the propagated paths of the incoming elastic waves. This information is made accessible by a numerical time reversal simulation. The effect of dispersion is reversed and the original shape of the flexural wave is restored at the origin of the acoustic emission. The time reversal process is analyzed first for an infinite Mindlin plate, then by a 3D FEM simulation which in combination results in a novel acoustic emission localization process. The process is experimentally verified for different aluminum plates for artificially generated acoustic emissions (Hsu–Nielsen source). Good and reliable localization was achieved for a homogeneous quadratic aluminum plate with only one measurement.

1. Introduction

Many damage mechanisms involve some sort of sudden stress release or stress redistribution in the loaded structure. The transient nature of these mechanisms leads to elastic waves propagating away from the damage zone. These waves traditionally are called acoustic emissions (AE) and are used for monitoring the structural health of a mechanical part. In contrast to ultrasonic inspection, AE monitoring is a passive inspection technique which does not require an interrogating wave in order to scan the structure. AE waves are generated by the damage mechanism itself and the method is therefore ideal for monitoring the structural health of mechanical parts in operation. However, only active damage processes are detectable and the detection of such damage zones depends on the type of loading.

Locating an AE event is traditionally done by trilateration, which requires arrival time identification of a wave at different sensors, very similar to the localization of the epicenter of an earthquake from arrival times. More recently, researchers developed alternative techniques for localization of AE in mechanical structures. A thorough review of the latest AE localization techniques is given by Kundu [1]. He found two main research directions, one striving for minimal a priori knowledge requirements, the other for using as few sensors as possible. Beamforming and optimization algorithms allow robust localization results using at least four sensors. Often, AE are to be detected in structural components and hence the AE waves are multimode and propagate dispersively. Therefore, considering the modal nature of these AE wave problems, fewer sensors suffice to localize AE events and these techniques are known as modal acoustic emission (MAE), see e.g. [2–4]. The benefit of using fewer transducers are of either economical nature or offer monitoring capabilities in situations, where only limited access is possible. In the case of plate structures, MAE typically requires the identification of arrival times of extensional and flexural wave modes. Since the two modes propagate with different group velocities, the propagated distance of the waves can be calculated with the knowledge of the respective velocities. Three main concerns come with the application of MAE. (1) First of all, the measurement signal is often composed of many wave reflections and of multiple AE's. As a result, identification and separation of flexural and extensional wave modes from the same event is not straightforward, especially when using only one transducer [4]. Methods to decouple incident and reflected waves in plates are reported in [5]. (2) Errors in arrival time determination are a main source of the localization uncertainty. Accurate arrival time picking is further complicated by

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http://dx.doi.org/10.1016/j.ultras.2015.08.010
0041-624X/

noise in the signal. (3) The MAE method implies that the measured waves propagated along direct paths from AE source to sensor. Non uniformities or interruptions in the wave paths are not compensated in the calculation [1].

This paper discusses an alternative method closely related to MAE. As in MAE, the suggested method utilizes the dispersive and multi-modal nature of waves propagating in plate-like structures. However, instead of analyzing arrival times of different wave modes, analyzing the distorting effect of dispersion on the wave signal builds the basis for locating AE events. By doing so, many of the previously mentioned issues can be avoided while requiring even fewer sensors in the process.

As a dispersive wave propagates, the pulse shape changes. The overall amplitude of the pulse envelope decreases and the duration of the pulse increases because the frequency components which form the pulse travel at different velocities. After having recorded the pulse shape of waves generated by an AE event at a given location, a time reversal (TR) simulation is set up, in which the measured signal is reversed in time and used to virtually propagate back the waves measured in the experiment. Thereby, as the waves propagate back in the virtual structure, dispersion is reversed and the wave achieves maximal amplitude at its origin, i.e. the AE location. This procedure has been discussed for 1D structures in guided wave applications [6] and for 1D structures in AE applications [7]. A key element in these publications was to only model flexural wave motion in the TR simulation even if the signal contains contributions from other modes as well. This has the effect that, from all the modes in the signal, only the one whose kinematics are supported in the simulation will recover its original shape. Other modes and vibration sources will also be treated as flexural waves in the TR simulation and therefore immediately disperse and fade out because the dispersion characteristics in the experiment and in the simulation do not match for these non-flexural waves. This feature massively increases the method's robustness in low signal-to-noise scenarios and is especially suited for AE tests where the number and distribution of modes in the signal is unknown. In regard of this approach, it will be sufficient to investigate the TR process for flexural waves only, knowing that other modes will not disturb the AE localization process.

Furthermore, the measured signal will be analyzed in a specified frequency band only. Constraints for the chosen frequency band come from two sides. On the one hand, the signal must contain flexural waves in a frequency range where dispersion is present. On the other hand, the implemented finite element model is reasonably accurate for flexural waves only up to 50 kHz. We therefore band-limit the AE signal to frequencies between 5 kHz and 50 kHz.

2. Axisymmetric time reversal process for flexural waves in plates

In this paper, we define the TR process as follows: Starting from a transverse displacement disturbance w_0 at location r_0, the disturbance propagates through the material as a number of wave modes, one of them being the flexural wave mode or in the terminology of Lamb waves the A_0 mode. At another location r_m the resulting transverse displacement w_m is recorded, reversed in time and used to re-excite waves in the plate such that the transverse displacement at r_m has the form $w_m^{TR}(t) = w_m(T-t)$, where T is an arbitrary time constant. Part of this second disturbance propagates to the original location r_0, resulting in a displacement response w_0^{TR}. If the TR process succeeds, w_0^{TR} is similar to w_0. This process is now investigated for flexural waves, using Mindlin plate theory [8] which represents a strength of material theory which approximates the first two anti-symmetrical Lamb modes A_0 and A_1. While other modes also contribute to the transverse response, we assume that the signal has been band-limited such that only flexural and shear-thickness wave modes contribute to the transverse response, higher order modes and longitudinal modes are ignored in line with the reasoning given at the end of the introduction section.

The three wavenumbers for Mindlin plate theory are given by:

$$k_1 = \pm\frac{1}{c_p\kappa}\sqrt{\frac{\omega}{2h(1-\nu)}} \times \sqrt{h\omega(2+\kappa^2(1-\nu)) + \sqrt{12c_p^2\kappa^4(1-\nu)^2 + h^2\omega^2(2-\kappa^2(1-\nu))^2}} \quad (1)$$

$$k_2 = \mp\frac{i}{c_p\kappa}\sqrt{\frac{\omega}{2h(1-\nu)}} \times \sqrt{-h\omega(2+\kappa^2(1-\nu)) + \sqrt{12c_p^2\kappa^4(1-\nu)^2 + h^2\omega^2(2-\kappa^2(1-\nu))^2}} \quad (2)$$

$$k_3 = \mp\frac{\sqrt{\pm 1}}{c_p h}\sqrt{\frac{2}{1-\nu}}\sqrt{\frac{3}{2}c_p^2\kappa^2(1-\nu) - h^2\omega^2} \quad (3)$$

with $c_p = \sqrt{\frac{E}{\rho(1-\nu^2)}}$ being the longitudinal plate velocity. The other parameters are: non dimensional factor κ, here $\kappa = \sqrt{\frac{\pi^2}{12}}$, the plate thickness $2h$, the circular frequency ω, Poisson's ratio ν, Young's modulus E, density ρ. The test specimen used in theory and experiment is a 2 mm thick aluminum plate and Mindlin plate theory predicts a frequency spectrum according to Fig. 1.

2.1. Infinite plate

The transverse axisymmetric response for an infinite plate subjected to a point force can be written as a flexural wave and a shear boundary layer, see Fromme [9]:

$$w(r,t) = \sum_{n=0}^{\infty}\left[A_{0n}H_0^2(k_{1n}r) + B_{0n}H_0^1(-k_{2n}r)\right]e^{i\omega_n t} \quad (4)$$

Below the cut-off frequency of the k_2 mode, the term $H_0^1(-k_2 r)$ is associated with an evanescent wave. The Hankel functions of the first and second kind are denoted as H_0^1 and H_0^2 respectively.

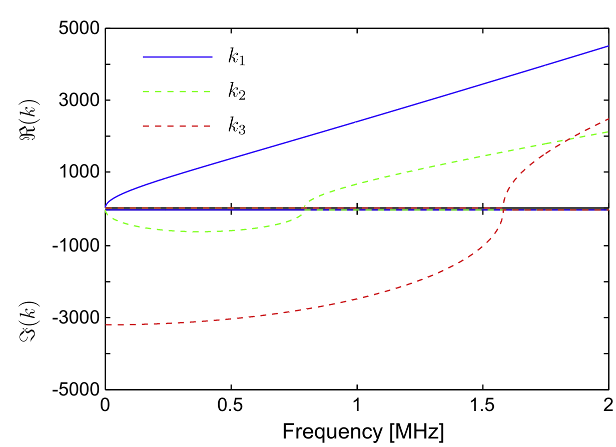

Fig. 1. Frequency spectrum showing the wavenumbers k_1, k_2 and k_3 as a function of frequency according to Mindlin plate theory. The plate thickness is 2 mm and is made of T6 AW-6082 aluminum. The first mode (k_1) will be referred to as flexural wave, the second mode (k_2) as thickness-shear mode with cut-off frequency 0.79 MHz. The third mode (k_3) is referred to as twisting wave and has a cut-off frequency of 1.58 MHz.