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Acoustic emission localization in beams based on time reversed dispersion

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ABSTRACT

The common approach for the localization of acoustic emission sources in beams requires at least two measurements at different positions on the structure. The acoustic emission event is then located by evaluating the difference of the arrival times of the elastic waves. Here a new method is introduced, which allows the detection and localization of multiple acoustic emission sources with only a single, one point, unidirectional measurement. The method makes use of the time reversal principle and the dispersive behavior of the flexural wave mode. Whereas time-of-arrival (TOA) methods struggle with the distortion of elastic waves due to phase dispersion, the method presented uses the dispersive behavior of guided waves to locate the origin of the acoustic emission event. Therefore, the localization algorithm depends solely on the measured wave form and not on arrival time estimation. The method combines an acoustic emission experiment with a numerical simulation, in which the measured and time reversed displacement history is set as the boundary condition.

In this paper, the method is described in detail and the feasibility is experimentally demonstrated by breaking pencil leads on aluminum beams and pultruded carbon fiber reinforced plastic beams according to ASTM E976 (Hsu–Nielsen source). It will be shown, that acoustic emissions are successfully localized even on anisotropic structures and in the case of geometrical complexities such as notches, which lead to reflections, and cross sectional changes, which affect the wave speed. The overall relative error in localizing the acoustic emission sources was found to be below 5%.

1. Introduction

Acoustic emission (AE) in the field of nondestructive testing according to ASTM E1316-11b Standard Terminology for Nondestructive Examinations refers to transient elastic waves that are generated by the rapid release of energy from localized sources within a material. These AE signals may arise due to growing cracks in monolithic materials or breaking fibers or fiber–matrix cracking in composite materials, see for e.g. Salinas et al. [1] or Kundu et al. [2] and are used as an indicator in nondestructive testing applications to monitor the integrity of critical structures. An important aspect of AE testing is the ability to determine the location of AE sources. The standard procedure for AE source localization relies on the identification of precise arrival times and the knowledge of an appropriate propagation velocity. With these parameters, a triangulation method can be established where the source is identified as the intersection of three circles, whose centers are the sensors' location [3], also known as Time of Arrival Methods (TOA). This approach might sound straight forward, however in reality, several difficulties may arise because of anisotropic materials, reflections and mode conversion due to inhomogeneities and distortion of the waveform due to geometrically induced phase dispersion [4]. However, TOA methods were successfully extended to adapt to these difficulties. Ciampa et al. [5] extended the method with additional transducers to account for anisotropy of composite plates with arbitrary layup. The effect of dispersion on the recorded waveform was studied by Aggelis et al. [6]. He accounted for dispersive effects on AE parameters such as duration or maximal amplitude of an AE event that are typically affected by dispersion. This allowed him to compare AE parameters from sources at different locations.

The detection and or localization of AE sources in geometrically complex structures was often approached by means of neural network-type of methods, that rely on previously obtained training data [7,4]. However, the gathering of proper training data can be quite cumbersome.

Beside TOA methods and neural network methods, there is a group of methods, that explicitly uses lamb wave modes for the

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localization of AE sources. These methods are known as Single Sensor Modal Analysis Location (SSMAL) methods, since they allow the determination of the transducer–source distance with only one sensor [7,8]. The sudden release of energy results in a broadband spectrum and depending on the type of source, the emitted acoustic emissions cover frequencies from kHz to MHz range. Therefore, in plates and beams, these AE events lead to a range of Lamb wave modes. Studies have shown [9], that most of the energy of an AE event propagates in the first symmetric S0 and first antisymmetric A0 lamb mode and higher modes tend to have lower amplitudes and attenuate faster. If one can determine the arrival time difference of these two wave modes, the distance D to the source is:

$$D = \Delta t\left(\frac{C_s C_A}{C_s - C_A}\right) \quad (1)$$

where Δt is the time difference of the two arriving modes, C_S and C_A the group velocity of the symmetric and antisymmetric mode for a particular frequency [9]. Maji et al. [10] used the arrival time difference of several frequencies of only one dispersive mode and then performed the same calculation as Holford [9]. These methods have the advantage of using fewer transducers but are prone to misinterpretation due to mode conversion, reflections or noise in the measurement, since they assume, that the structure is infinite and uniform.

The method presented here is related to the above mentioned SSMAL methods in the sense, that it operates with fewer transducers and that it exploits the dispersive wave nature of AE in 1D structures. A comparison of the SSMAL – and the presented Time Reversed Dispersion (TRD) – method is given in Table 3 in the conclusion section of this paper together with a discussion of the advantages and limitations of the presented method.

The main difference is however, instead of using a single equation such as Eq. (1), the presented method uses a time reversed (TR) simulation to reverse the process of dispersion and therefore retrieve the origin and shape of the AE event. We will refer to this method as a Time-Reversed-Dispersion (TRD) method. This approach combines the ease of using fewer transducers as found in SSMAL techniques, is more robust because no arrival times must be picked, has wider applicability because the test specimen must not be uniform, and reconstructs the original shape of the AE. The application of a time reversal numerical simulation for guided wave testing was previously studied by Leutenegger and Dual [11] and Ernst et al. [12] for beams. These studies have shown promising results for the localization of notches and cracks in tubes and beams. Other time reversal applications in guided wave settings for composite plates were studied for example by Park et al. [13,14] or by Veidt and Normandin [15], which studied the sensitivity of the method to sense nonlinearities due to delaminations, bonded masses and through holes. The concept of using time reversal mirrors in wave propagation problems was first investigated by Fink et al. [16].

2. Method

Acoustic emissions are typically broadband and therefore give rise to many propagating modes in a beam. Holford et al. [9] found, that most of the energy is carried by the first symmetric and antisymmetric lamb modes. The first antisymmetric lamb mode, here referred to as flexural wave, shows strongly dispersive behavior at low frequency – thickness numbers. Without a priori knowledge of the actual shape of an AE event, the source is assumed to be locally focused in time and space. At the location of the AE origin, the frequency components of the waveform are assumed to be in phase. However, the part of the disturbance that propagates as a flexural wave distorts and diverges as it travels away from the source location.

The presented method for locating AE sources consists of two steps. In a first step, the transverse deflection due to the incident flexural wave is measured at x_m. In a second step, the measured displacement data is reversed in time and set as the boundary condition at x_m^{TR} in a numerical model of the beam. In the simulation, the distorted flexural wave form recompresses and reaches maximal amplitude at the location of its previous origin in the numerical model x_0^{TR}. This allows the detection of the AE source by finding the local maximum in a time–space diagram. This two-step procedure is illustrated in Fig. 1.

After having converged at the location of the AE source, the different frequency components of the flexural wave diverge again, leading to a decrease in the amplitude of the flexural wave. This allows the detection of multiple AE events with a single measurement, even if the different AE waves overlap each other. The method described here requires only a single, one point, unidirectional measurement, because only the dispersion of the flexural wave mode is used. Multiple AE can be detected because the wave amplitudes decrease again after having converged. Multiple AE sources at an identical position are temporally separated in the time space diagram. Acoustic emission parameters extracted from the simulation of several AE sources at different positions can easily be compared because dispersion effects are compensated as a natural side effect of this method. However, the effect of damping on the wave form is not yet compensated.

2.1. Time reversal process in a Timoshenko beam

Here, a beam with the properties given in Table 1 has been considered. The free motion of a Timoshenko beam is governed by the

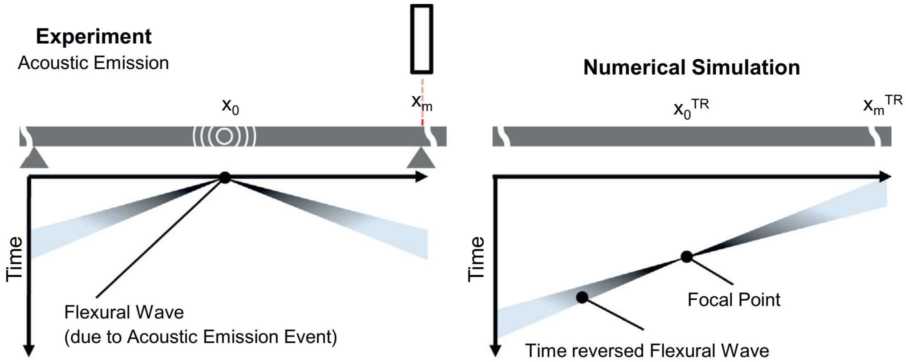

Fig. 1. Illustration of the Time-Reversed-Dispersion (TRD) method. On the left hand side, an acoustic emission event at x_0 on a beam structure leads to dispersing flexural waves. The resulting displacement is recorded at x_m by means of a laser vibrometer. On the right hand side, a numerical model of the beam is used to simulate the time reversal experiment. The dispersed waveform converges at the origin of the source of the acoustic emission.