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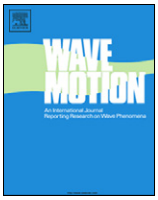

Quantitative guided wave testing by applying the time reversal principle on dispersive waves in beams

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HIGHLIGHTS

- A baseline free method for the detection and quantification of several cracks in beams and hollow cylinders is presented.
- Experimental validation performed on different aluminum beams and hollow cylinders.
- Time reversal process analyzed and discussed for Timoshenko beams.

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ABSTRACT

A method for the localization and characterization of defects in waveguide-like structures is presented in this paper. In contrast to traditional ultrasound and guided wave techniques, a broadband signal is used to enforce strong dispersion of the flexural wave mode. Since dispersion is well compensated in a time reversal experiment we use a time reversal numerical simulation to identify the origin and the original shape of the flexural wave excited at a local non-uniformity due to mode conversion. Limitations of the time reversal process for broadband signals due to multimode and evanescent behavior of guided waves are discussed and eliminated using a Timoshenko beam model. The resulting novel process which uses both flexural and longitudinal wave information allows detection, localization and size estimation of several defects in a beam with only a single measurement. The method proposed is experimentally validated on rectangular solid beams and cylindrical hollow beams with notches of different sizes and positions. Up to three notches could be localized from one measurement, with a maximum error of 3% with respect to the propagation distance. The size was accurately predicted for notches as small as 0.5 mm depth or 8.3% of the cross section, using a generalized spring model of a crack.

1. Introduction

For almost three decades, researchers have investigated the use of guided waves for nondestructive testing and structural health monitoring. Many applications have found their way to industry. The reason for this demand is that guided waves are more convenient for large beam, plate and cylindrical structures due to their ability to interrogate larger distances compared to ultrasonic testing. A recent review on the use and advantages of guided wave techniques has been given by Rose [1]. Advantages of using guided waves come at the price of a more complex wave propagation behavior, i.e. dispersion and multimode propagation [2]. The former refers to the fact that the propagation speed of guided waves in general is a function of frequency. As a consequence, a wave pulse consisting of many frequencies distorts during propagation. It is clear that

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the determination of exact arrival times is more difficult for dispersed waves. Multimode propagation means, depending on the excitation frequency, that more than one wave mode is generated. This is also observed for waves interacting with boundaries and non-homogeneities, e.g. a wave hits a crack and is split into different modes. This complicates the interpretation of the measured signal. Finally, the combination of multimode propagation and dispersion makes it difficult to extract a single wave mode from the signal, because the signal consists of different dispersed modes and reflections which overlap each other. This poses a problem for quantitative nondestructive testing, where one tries to determine the size of a crack from amplitude ratios of wave modes.

All these challenges have long been known and researchers have developed ways to overcome them. Dispersion is generally minimized by working with narrowband signals. The determination of arrival times of dispersed modes is achieved in the time–frequency plane, the transformation done with fast Fourier transformation (FFT) or wavelet analysis, e.g. Kishimoto et al. [3]. However, this has the drawback that frequency precision comes at the cost of time precision due to the uncertainty principle or Gabor-limit, which states, that it is impossible to exactly localize a signal in both frequency and time domain [4]. The extraction of a single mode from a multimode signal is achieved by measuring at multiple locations and then transferring the measured data from time–space domain into frequency–wavenumber domain, see i.e. Alleyne et al. [5] or Hayashi et al. [6] or by using linear prediction algorithms, see Vollmann et al. [7]. The use of dispersion as an indicator for the distance a wave has traveled has already been reported by Wilcox et al. [8], however not in combination with a time reversal (TR) process. The use of a broadband signal in combination with a TR experiment on plates was reported by Gangadharan [9]. It was reported, that, while the method cannot be used as a baseline free technique, an increase in signal to noise ratio and an improvement in spatial resolution was observed. The combination of an experiment with a subsequent numerical TR simulation for cylindrical structures was reported by Leutenegger et al. [10]. The method requires the measurement of the full 3D wave field at an end-face of the structure and allowed localization of single defects at arbitrary location and orientation.

Here, a method originally developed for acoustic emission testing in beams [11] is implemented in a guided wave setting. The method bypasses the typical difficulties found in guided wave testing without the use of frequency transformations or linear prediction. In the cited acoustic emission implementation, only active damage zones are detectable, the method is based on only one wave mode and the character of the waves cannot be influenced. In the present application, an actively excited wave is used to quantitatively inspect the structure for cracks and determine their size. In contrast to acoustic emission localization, this is done by evaluating mode conversion between longitudinal and flexural wave modes. The method makes use of the TR principle that has been extensively studied by Fink et al. [12]. The main difference of the present method with regard to most other guided wave testing methods is that dispersion is not avoided, but builds a main cornerstone in the process. Dispersion is used as a measure for the distance the wave has traveled. The key to resolve this information is a TR numerical simulation. As will be shown, using flexural and longitudinal waves as working modes and a Gaussian shaped excitation signal, the TR simulation not only facilitates the localization of multiple defects from only a single measurement but also allows the separation of a wave mode from a multimode dispersive signal with multiple reflections overlapping in the measured signal. Subsequently, the depth of cracks can be calculated by comparing the mode conversion ratio of longitudinal and flexural waves with an analytical model of the crack based on stress intensity factors.

Effects of evanescent modes, choice of measurement location, noise, and processing of the measured signal on the TR process are discussed. Using the results of the TR process analysis in Timoshenko beams in [11], two equations are derived to compensate for evanescent waves and multimode propagation effects that otherwise break the TR process. With the help of these findings, a method is proposed for the localization and characterization of several cracks in a beam with only a single, one-point measurement of the lateral displacement component. The method is validated with experiments on aluminum beams with different notch locations and sizes.

The motivation for investigating TR concepts on guided waves in one dimensional structures are twofold. On one hand, there are many applications of beam-like structures such as rails, rotor blades, and general truss structures. On the other hand, by restricting the study to a simple one dimensional structure, it is hoped that a better and more intuitive understanding of the physics behind a guided wave TR experiment is achieved. Non-propagating modes, also known as evanescent modes and multimode propagation strongly influence the TR process. These effects occur not only in beam-like structures but also in cylindrical or plate-like structures. However, due to additional complexities such as 2D and 3D effects and higher order modes, the TR process may be more difficult to study in these structures.

In terms of applicability, the method presented may as well be considered for more complex structures since the first symmetric and antisymmetric mode of motion behave very similar at low frequency–thickness numbers.

2. Presentation of method

In order to test the integrity of a structure, a two-step procedure is suggested. In a first step, a guided wave test is performed on the structure of interest, either in through-transmission mode or in pulse–echo mode. A broadband longitudinal wave pulse in the form of a Gaussian function is excited into the structure. As the wave hits one or several defects, partial mode conversion from the nearly dispersion-free longitudinal mode to a dispersive flexural mode occurs. The transverse displacement history is recorded by means of a laser interferometer. After compensating for certain TR effects, presented in Section 2.1.1, we proceed with the second step. A numerical simulation is set up in which the modified and time reversed transverse displacement history is set as the boundary condition of the structure modeled. Note, that the

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