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Structural health monitoring using time reversal and cracked rod spectral element

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A B S T R A C T

Structural health monitoring (SHM) has received substantial attention in the last decades. Damage detection methods based on dynamic analysis seem to be appropriate to detect large damages, but fail for small ones. Alternative methods use elastic wave propagation allowing a quick and long range test. In this paper, a new approach based on the combination of Time Reversal Method (TRM) and Spectral Element Method (SEM) is proposed to perform structural damage detection. The main novelty is to combine wave-based spectral element model together with time reversal signal processing. Although the methodology is evaluated by numerical simulation, this combination of numerical modeling and time reversal signal processing can be applied as an experimental approach to provide a useful tool for damage detection. Simulated examples of the damage detection method using rod-like structures are illustrated and the results discussed and compared with those from literature.

1. Introduction

Recent methods of structural health monitoring (SHM) are based on the analysis of irregularities observed in Lamb wave propagation in the structure [1–4]. Some SHM methods use the known fact that material discontinuities affect elastic wave propagation in solids [5]. In these methods the elastic waves are generated and captured by an array of sensors embedded within or fixed to the surface of the structure. The frequencies used in this approach are higher than those normally used in experimental modal analysis, but lower than those of the ultrasonic testing [6]. One of the most used methods is the ultrasonic test, where mechanical waves are in MHz, which requires lightly damped structures and the analysis reach only the area below or adjacent to the transducer. The probe should be moved along the entire sample, which is time consuming and requires global access. An alternative and simpler method to locate damage is the use of elastic waveguides. The wavelengths are several times the thickness of the structure, and one order of magnitude larger than that in the ultrasonic test. Since guided waves can travel many wavelengths over a structure, this allows rapid and long range test. The fundamentals of Lamb wave based structural diagnostics and related publications can be founded in the book of Su and Ye [5] and in the review paper by Raghavan and Cesnik [7].

This paper aims to detect damage as well as to locate its position in a rod-like structure using a combination of spectral element method and time reversal method. The proposed approach is developed and implemented using the Spectral Element Method (SEM) to model Lamb wave propagation in rod structures [8,9]. This numerical method has been called by

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different names, such as the dynamic stiffness method [10,11], spectral finite element method [12,13] and dynamic finite element method [14]. The SEM is based on the exact analytical solution of the displacement wave equation, written in the frequency domain and tailored in a similar style as the finite element method (FEM). Uniform structures can be modeled by a single spectral element, which can reduce significantly the number of elements as compared to other similar methods. Since the method is based on the wave equation it performs efficiently at mid and high frequency bands. Consequently, SEM exhibits important features that provides high accuracy and efficiency to model wave based structural damage detection methods. However, there are still some drawbacks, such as difficulties to model non-uniform members and to apply arbitrary boundary conditions for 2D and 3D elements. Cracked rod spectral element used in the paper is a rod element with a transverse, open and non-propagating crack as proposed by Palacz and Krauckzuk [15]. In order to carry out the simulations, the healthy and cracked rod structures are modeled by SEM and implemented in a MATLAB™ computer code.

Time reversibility of wave-based physical processes states that an input signal can be regenerated at the source position if an output signal recorded at another position is reversed in time and sent back to the same source position [16]. It means that the underlying physical processes of waves would be unchanged if time is reversed. The magic of time reversibility has been an amazing idea for human beings from a long time ago. Nowadays time reversibility can be performed, leading not to the amazing situation as in the movie "Back to the Future", but to interesting engineering applications. The paper of Anderson et al. [17] presents an interesting historic review of acoustic time reversal. They have shown that it is a very old concept as applied to waves. The first publication was presented in 1965 by Parvulescu and Clay [18], where they demonstrated experimentally the time reversal process by transmitting a signal from a source to a receiver, time reversed the received signal and broadcast it from the source to the receiver again. During the next decades (1970s and 1980s) other researchers [19,20] created the Optical Phase Conjugators, which are similar to time reversal because they reverse the wave energy, but works only for quasi-monochromatic waves. Further developments of time reversal occurs in 1991 in underwater acoustics research [21] and in the beginning of 1990s Fink and collaborators developed the acoustic Time Reversal Mirror [22–24]. Time reversal in acoustic and elastic mediums is achievable because they can be treated as a wave propagation processes.

For the SHM method proposed in this paper the excitation signal is applied in a point and propagates through the structure. Then, it interacts with a possible failure and results on a scattering wave field. The responses are recorded in some points, reverted in time and injected back to the excitation point. By comparing these signals with the original excitation the damage can be detected. The advantage of the damage detection methods based on time reversibility is its "baseline free" characteristic, which prevents the requirement of an undamaged reference signal, which is challenging to obtain due to environmental effects, manufacturing processes and operational conditions. The SHM methods start to use time reversal technique as a signal processing tool for improving the quality of Lamb wave signals or compensating for wave dispersion [25–28], especially for small damages, weak signals or noisy environment. In the following it was used as an inverse algorithm for damage detection [28–35] as proposed in this paper. The main contribution of this paper lies in combining a wave-based spectral model (SEM) together with time reversal signal processing yet to be reported in the literature. Although the methodology is evaluated by numerical simulation, this combination of numerical modeling and time reversal signal processing can be applied as an experimental approach to provide a useful tool for damage detection in large structures.

In the paper the spectral element method is reviewed including formulations of the elementary, throw-off (semi-infinite) and cracked rod spectral element. The dynamic stiffness matrix of the cracked rod spectral element is rewritten as a closed form solution. Time reversal method is also reviewed and the damage indexes are presented. The simulation were performed using two examples with rod-like structures: healthy (undamaged) and damaged. To both examples the healthy and damaged spectral element are connected with a throw-off element to avoid multiple reflection and obtain clear results. Both structures were excited with a tone burst pulse signal force using a sine wave windowed with a Hanning window. Simulations using healthy and cracked rod models show good agreement with that from literature. The method also confirms its capacity to find out the presence and the severity of the damage. The damage location is also detected with less accuracy then the others, which recommends more investigations to avoid possible results being misunderstood. It was confirmed that the effect of number of cycles included in tone burst signal over the reconstructed signal as demonstrated by Hai-Yan [36]. The presence of very high amplitude components at DC (zero frequency) and close to it were founded, which are related to the undetermined non-propagative waves. In Appendix A it is given as a code in MATLAB™ to implement this computational method.

2. Spectral element method

Over the last decades a variety of analytical techniques have been developed for the treatment of wave propagation problems [8,15]. Presented below are the modelings used in the structures studied in this paper.