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Guided wave-based identification of multiple cracks in beams using a Bayesian approach

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ABSTRACT

A guided wave damage identification method using a model-based approach is proposed to identify multiple cracks in beam-like structures. The guided wave propagation is simulated using spectral finite element method and a crack element is proposed to take into account the mode conversion effect. The Bayesian model class selection algorithm is employed to determine the crack number and then the Bayesian statistical framework is used to identify the crack parameters and the associated uncertainties. In order to improve the efficiency and ensure the reliability of identification, the Transitional Markov Chain Monte Carlo (TMCMC) method is implemented in the Bayesian approach. A series of numerical case studies are carried out to assess the performance of the proposed method, in which the sensitivity of different guided wave modes and effect of different levels of measurement noise in identifying different numbers of cracks is studied in detail. The proposed method is also experimentally verified using guided wave data obtained from laser vibrometer. The results show that the proposed method is able to accurately identify the number, locations and sizes of the cracks, and also quantify the associated uncertainties. In addition the proposed method is robust under measurement noise and different situations of the cracks.

1. Introduction

1.1. Structural health monitoring

Structural health monitoring (SHM) has attracted much attention as it plays a vital role in ensuring safety, reliability and serviceability of a range of infrastructures in civil, mechanical and aviation engineering. It provides a tool to continuously examine the integrity of structures and presents essential information of any damage and deterioration at the early stage. Numerous damage detection techniques have been developed to provide safety inspection for structures in the field of SHM. Conventional non-destructive evaluation (NDE) techniques are generally limited in inspecting a very small region of the structure and not applicable to inspect inaccessible locations. Efficient damage inspection requires the pre-knowledge of possible damage locations, which is usually not available in practical situation for NDE. Acoustic emission [1] is a passive technique that is able to monitor the generation and growth of defects but it is not applicable to detect existing defects. The vibration-based techniques [2] have the capability to detect and locate the damage in entire structures. However, they are insensitive to incipient defects as they are based on low vibrational frequency data.

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1.2. Guided wave damage identification

Guided wave (GW) has been proven sensitive to small and various types of damages [3,4]. GW is a mechanical stress wave, which can be actuated by piezoelectric transducers installed on structures and its propagation is confined to the structures guided by structural boundaries. It can be used to inspect large area of the structures as it is able to propagate a long distance. In recent years, GW has demonstrated significant capabilities in damage detection [5] in a variety of structural components, which are commonly categorised into one- (1D) and two-dimensional (2D) waveguides. The characteristics of GW propagation and its interaction with damage have been studied for 1D waveguides (e.g. pipes [6]) and beams [7,8] and 2D waveguides (e.g. plates [9]).

Based on the identified damage information, the damage detection process has four different levels, i.e. determine i) damage existence, ii) damage location, iii) damage severity and iv) remaining service lifespan of structures prediction [10]. In the literature different types of damage detection techniques have been developed for 2D waveguide and most of them are able to identify the existence, location and severity of the damages. For example, numerous advance damage detection techniques, such as damage imaging [11,12], maximum-likelihood estimation [13], diffraction tomography [14,15], phased-array beamforming [16], model based approach [17,18] and the Bayesian interface [19,20] were developed for plate-like structures. In contrast, most GW based damage detection techniques for 1D waveguides were limited in identifying the existence and location of damage [21].

1.3. Model-based approaches

There are two major approaches in GW damage detection of 1D waveguides: the non-model and model based approaches. Most research of GW damage identification focuses on non-model based approaches. Generally, non-model based approaches apply forward algorithm to detect damage by recognising the subsequent changes in certain features between the damaged and healthy state of structures. However, accurate baseline signal is difficult to obtain because it normally contains numerous unnecessary data, such as noise from environments, natural vibration of the structures and data acquisition systems. Although different signal processing techniques have been recently proposed to extract the damage information in the measured signal, these studies only roughly quantified the severity of the damage. For example, Hossein Abadi et al. [22] proposed a pattern recognise technique to detect step damage on a thick steel beam based on discrete wavelet transform of GW signal. Experimental results demonstrated that the damage location was appropriately detected and its depth was estimated. Amjad et al. [23] utilized the changes in time-of-flight and phase to detect circular hole-type damage in 1D waveguide. Different signal processing techniques such as Fast Fourier Transform (FFT), Wigner-Ville Distribution Transform (WVDT), S-Transform (ST) and Hilbert Huang Transform (HHT) were employed to improve the quality of the GW signal in identifying the damage size.

Model-based approach is capable to characterise more complicated damage by updating a damage model. The damage parameters, such as damage location and geometry, are treated as unknown parameters and updated through minimising the discrepancy between the simulated and measured data. This approach is able to provide more quantitative information in the damage identification, and hence, this paper focuses on using the GW model-based approach for multiple cracks identification of beam-like structures.

1.4. Modelling of GW propagation and scattering

Methods of modelling the GW propagation can be found in the literature [24]. Generally, GW propagation could be numerically modelled by conventional finite element (FE) method [25], while this method is impractical for model-based damage identification. The mesh size of the FE element usually needs to be small enough to ensure the accuracy in simulating the GW propagation but it is computational expensive. Other numerical methods, such as finite difference method [26], would confront convergence problem when the GW propagates through different materials. Finite strip element method [27] is difficult to be applied to geometry-complex structures. Boundary element method [28] is inefficient for simulating large structures. The frequency-domain spectral finite element (SFE) method has been widely applied in most GW model-based damage detection techniques [7,29,30] because of its computational efficiency. It has been used for damage identification, for example, based on genetic algorithm (GA) in beam-like structure with a symmetric open crack [29] and in composite beams with delamination [30], and Bayesian statistical framework combined with simulating annealing (SA) [31] and particle swarm optimization (PSO) algorithm [7] in a beam with a step damage. However, because the frequency-domain SFE method requires one side of the structure to be infinitely long, it is unsuitable for modelling practical and complex structures.

Time-domain SFE method, which is also called the p-version FEM [32], has the same flexibility in model discretisation as conventional FEM. The method uses high-order approximation polynomials to reduce the number of elements. Also, the application of Gauss-Lobatto-Legendre (GLL) nodes, leads to a diagonal mass matrix, and hence, the dynamic equilibrium of the model can be solved efficiently by explicit central difference method. In addition, the Runge effect is avoided by the application of this GLL-node element [33]. The time-domain SFE modelling has been proven to be an effective tool in simulating GW propagation for 1D and 2D waveguides [34]. In this paper, the time-domain SFE method is utilised to simulate both fundamental longitudinal (S_0) and flexural (A_0) GWs propagation based on the Mindlin-Herrmann rod [35]