Engineering Structures 67 (2014) 50–60

Contents lists available at ScienceDirect

Engineering Structures

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

On the selection of advanced signal processing techniques for guided wave damage identification using a statistical approach

Ching-Tai Ng *

School of Civil, Environmental & Mining Engineering, The University of Adelaide, SA 5005, Australia

ARTICLE INFO

Article history:
Received 14 August 2013
Revised 22 February 2014
Accepted 24 February 2014
Available online 20 March 2014

Keywords:
Damage identification
Statistical approach
Signal processing
Fourier transform
Hilbert transform
Wavelet transform
Guided waves
Probability density function

ABSTRACT

Advanced signal processing techniques are widely used to detect damage in structures. The current study proposed a statistical approach to the identification of structural damages using guided waves. Various signal processing techniques were applied in order to determine and improve the ways in which damage in a structure can be identified for remediation. The proposed statistical approach not only provides a quantitative identification of the damages, but can also quantify the uncertainties associated with the damage identification results. This allows the performance of various signal processing techniques to be evaluated and compared in terms of accuracy and the degree of uncertainty associated with the damage identification results. Damage identification was initially conducted using time domain guided wave signals so that the results could be used as a benchmark. Four signal processing techniques were then considered. Hilbert transform was used to extract the signal envelopes. Fast Fourier transform was applied to transform the guided wave signals from the time domain to the frequency domain. Gabor wavelet transform was employed to extract the wavelet coefficients from time–frequency domain. Discrete wavelet transform was used to decompose the guided wave signals. The frequency domain signal, signal envelopes, wavelet coefficients and discrete wavelet decomposed signals were then employed separately to identify the damages in conjunction with the proposed statistical damage identification approach. Laboratory experiments were conducted and the data were used to verify the proposed statistical approach. The levels of accuracy and degree of uncertainty associated with the damage identification results by each of the signal processing techniques were compared in detail. The results reported in this paper show that a suitable signal processing technique combined with the proposed statistical approach produces more robust identification of damages in a structure.

1. Introduction

1.1. Overview

Identifying damage at its early stage is paramount to maintaining the safety and integrity of structures and reducing the risk of catastrophic failure. The development of robust and cost effective damage identification techniques to guarantee the safety of structures has therefore always been of particular interest in engineering. In the last two decades, with the refinement of computers and sensors, a variety of sophisticated damage identification techniques has been developed to ensure structural integrity and safety [1–4].

Vibration-based damage identification methods [5–11], which rely on low-frequency vibration characteristics of structures to identify damages, have been extensively investigated, for example, especially in the fields of civil and mechanical engineering. Although low-frequency vibration methods can be used to globally monitor structures, they are generally not sensitive to local incipient damages [4], however, which means that damages as small as a centimeter and can threaten the safe operation of structures. For example, metal corrosions and fatigue cracks are hard to be detected and are potential lead to catastrophic failure in the structural components of engineering structures, such as bridges, planes, oil platforms and trains. These incipient damages are not easy to identify. Therefore, in recent years, high-frequency approaches have been explored, such as guided wave propagation [12], acoustic emission [13] and impendence measurements [14].

Guided waves have been widely recognized to be promising for damage detection. They are elastic waves whose propagation characteristics depend on structural boundaries. The excitation frequencies of these waves are at several hundred kilohertz and the corresponding wavelengths are of the order of millimeters. Since,

* Tel.: +61 08 8131 1237.
E-mail address: alex.ng@adelaide.edu.au

http://dx.doi.org/10.1016/j.engstruct.2014.02.019
0141-0296/

in general damage can be identified if the wavelengths are of the same order as the damage size, guided waves are sensitive to small damages. Furthermore, guided waves can propagate over long distances with little loss of energy, making them ideal for large area and cross sectional monitoring of structures and cost effective [12]. In recent years a significant amount of research has been carried out to investigate their use [15–20].

1.2. Damage identification using guided waves

Damage identification can be described as a four-level process [4] that aims to determine (i) the existence of damage, (ii) the location of damage, (iii) the type of damage and (iv) the severity of the damage.

In general the existence and location of damage can be identified from guided wave data without additional information. For example, damage can be expected when guided wave reflected from the damage is observed in the measured signals, and the location of the damage can be identified by using the arrival time of the reflected wave [12]. However, additional information is essential for determining the type of damage and its severity. In practice, the types of damages common to structures of various material compositions can be pre-determined by an experienced engineer, and only a limited number of sensors is installed on the structural component.

In terms of actually determining damage location [21–23] and extent [24–26], a number of techniques have been developed, particularly in two-dimensional waveguides, such as plates and shells. Relatively less research work has focused on quantitative identification of damages in one-dimensional waveguides, such as rods and beams.

For determining the severity of damages in one-dimensional waveguides with a limited number of sensors, pattern recognition and optimization are two commonly used approaches. Pattern recognition approach, such as supervised learning [27,28], applies prior experience to make sense of new data in the damage identification. Optimization approach [29–32] minimizes the discrepancy between the numerically predicted structural responses and the measured data by altering the damage parameters of a pre-defined model in order to determine the location and severity of the damage in the structure being tested.

1.3. Signal processing techniques for guided wave-based damage identification

Pattern recognition, optimization and most other damage identification methods use the relationship between the structural condition and the damage information contained in the measured data to identify the damage. The process therefore fully relies on information of damage contained in the data provided by the sensors. In practice, the number of sensors that can be installed on the structure is limited and the measured data is usually contaminated by noise. Data pre-processing is necessary to extract the information of damage from the data in order to maximize the performance of damage identification. Staszewski [33] discussed the importance of applying signal processing techniques in damage identification when using a pattern recognition approach. Since pattern recognition has difficulty in dealing with data of high dimensionality, signal processing techniques are generally used for feature extraction and data compression.

Different from pattern recognition, signal processing techniques for the optimization approach do not aim to compress the data, but to improve the sensitivity of the measured guided wave signals to the damage. Yu and Giurgiutiu [34] have demonstrated that the application of advanced signal processing techniques, such as Hilbert transform, continuous wavelet transform and discrete wavelet transform, improves the performance of using the guided waves to locate the damages following a phased-array approach. In general these signal processing techniques have not been specifically developed for data compression, they are suitable for improving the performance of the optimization approach in damage identification.

The study reported in this paper therefore had two main objectives. The first was to enhance the guided wave-based quantitative identification of damage following optimization by applying signal processing techniques. The other objective was to evaluate the performance of the advanced signal processing techniques, such as Hilbert transform, Fast Fourier transform, Gabor wavelet transform and discrete wavelet decomposition, in terms of damage identification. This was achieved by comparing the level of accuracy and degree of uncertainty associated with the damage identification results by each of the signal processing techniques. All data used in the present study were from actual guided wave signals measured in experiments conducted in laboratory.

The paper is organized as follows. A statistical framework for damage characterization is first presented in Section 2. The framework was developed using a Bayesian approach, which not only provides quantitative identification of the damage but also allows the uncertainty associated with the damage identification results to be quantified. The experimental setup used to collect the guided wave signals in damaged beams is then described in detail in Section 3. In Section 4 a computationally efficient spectral finite element method is described. The proposed method is used to model damaged beams for damage identification using the proposed statistical approach. Various advanced signal processing techniques for enhancing damage identification are presented in Section 5. The results of the damage identification and the performance of each advanced signal processing technique are then compared and discussed in detail. Conclusions are presented in Section 6.

2. Statistical framework for damage identification

The current study employed a statistical damage identification framework in conjunction with the damaged beams modeled by the spectral finite element method. The model was able to describe the relationship between the condition of the structure and the information about the damage provided by the guided waves. The damage is identified by changing the damage parameters to minimize the discrepancy between the predicted and the measured guided wave signals. In reality no numerical model can be expected to offer perfect predictions, the number of sensors that can be installed on the structures is always limited and the measured data usually contaminated by noise. Hence any damage identification will produce uncertainties. In addition to quantifying the damages, it is also important to explicitly quantify the uncertainties associated with the damage identification results, which provides valuable information for engineers attempting to undertake appropriate remedial work. In this study the performance of the signal processing techniques was assessed not only in terms of how accurate the results were, but also in terms of the uncertainties in the damage identification.

2.1. Bayesian statistical framework

The proposed statistical framework was based on the Bayesian statistical framework [35]. Different from most of the existing optimization approaches, the Bayesian statistical framework identifies damages by maximizing the posterior probabilistic density function (PDF) of a damage scenario, conditional on the measured data. The Bayesian statistical framework consists of a set of probability