Engineering Structures 132 (2017) 494–507

Contents lists available at ScienceDirect

Engineering Structures

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

Wavelet-based analysis of mode shapes for statistical detection and localization of damage in beams using likelihood ratio test

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A R T I C L E I N F O

Article history:
Received 11 December 2015
Revised 18 November 2016
Accepted 22 November 2016

Keywords:
Damage detection and localization
Mode shape
Wavelet
Principal component analysis
Likelihood ratio

A B S T R A C T

This paper presents a case study on statistical procedures for the detection and localization of damage along a beam. Tests are performed on a specially designed beam consisting of an assembly of three bolted sections under laboratory conditions to simulate various levels of incremental damage at two possible locations along the beam. Incremental damage is simulated by sequentially removing plate elements at each location. In this work, damage detection algorithms are tested to detect low levels of incremental damage which is usually challenging given the high noise to signal ratio. The beam is tested for two end restraint conditions, pinned-pinned and fixed-fixed. The detection algorithm combines various statistical techniques with a wavelet-based vibration damage detection method to improve the detection of low levels of incremental damage and further proposes a novel likelihood-based approach for the localization of damage along the beam. A Continuous Wavelet Transform (CWT) analysis is applied to the first mode of vibration of the beam obtained from a set of 16 equally spaced unidirectional accelerometers measuring dynamic acceleration response of the beam. A Principal Component Analysis (PCA) is performed on the wavelet coefficients in order to extract the main patterns of variation of the coefficients and to filter out noise. The scores of the first principal component are shown to be highly correlated with damage levels as demonstrated by statistical tests on changes on the location parameter of the scores in successive damage states. Given that statistically significant damage is detected, a Likelihood Ratio (LR) test is proposed to determine the most likely location of incremental damage along the beam. The results indicate that the algorithm is very efficient to detect damage at multiple locations and for the two end restraint conditions investigated.

1. Introduction

In recent years, Structural Health Monitoring (SHM) has received considerable attention in the literature as a means of monitoring the safety and reliability of important civil engineering structures such as bridges [1]. Visual inspections or low-level localized nondestructive investigations are costly and labor intensive when applied to large-scale structures and provide partial information of the global state of the structure. To complement this information, vibration-based surveys are becoming more popular due to the efficiency in deploying the instrumentation and the wealth of resulting data on the dynamic properties of the structures. Local damage identification techniques such as ultrasonic and X-ray methods are not applicable to inspect concealed and inaccessible portions of structures and the data cannot be extrapolated to uninspected portions of the structures. Structural condition assessments based on visual observations and local damage identification techniques also vary greatly as a function of the personal experience and technical expertise of the inspector. In view of these limitations, vibration-based surveys can provide a good assessment of the global structural condition by performing measurements at a relatively small number of accessible points [2].

Incremental damage can be identified from changes in the dynamic characteristics of the structure, which are influenced, by changes in mass, stiffness, boundary conditions, and geometric properties. Modal parameters such as natural frequencies and mode shapes are the most popular global parameters used for damage detection. However, these have been found to perform poorly to detect low levels of incremental damage for tests performed on existing bridges without some form of pre and/or post-treatment [3]. A recent review on the use of natural frequencies for the detection of damage indicates that damage can be

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http://dx.doi.org/10.1016/j.engstruct.2016.11.056
0141-0296/

detected for large structures only when the level of damage is significant and measurements are done precisely [4]. Modal damping ratio is very sensitive to environmental conditions and there is no consistent correlation between system damping and damage [5–7]. Hence, this parameter is not as reliable for damage detection. Both natural frequencies and damping can only provide information on the presence of damage and cannot provide information on its likely location.

In-situ applications of global modal-based damage detection techniques applied to bridges indicate that natural frequencies are less sensitive to low levels of damage than mode shapes [3,8]. The selection of mode shapes and/or the derivatives of the mode shapes have been used by several researchers as a means to detect and locate damage. Localization of damage is based on either direct or indirect use of mode shapes. Direct or traditional use of mode shapes is based on a direct comparison of modal shapes for intact and damaged states as demonstrated through finite element models or experimental tests [9]. In the latter case when data from the intact state is unavailable, the baseline data is usually generated using a finite element model [2]. The indirect use of mode shape is based on modern signal processing techniques such as wavelet analysis applied to the mode shapes [10]. Artificial Neural Network (ANN) models have also been used to predict the extent and location of damage using modal shape differences from numerical models of a simple beam and a multi-girder bridge [11]. However, this method has limited applicability given that it requires data in damaged and undamaged states in order to train the neural network model, which is not possible for ageing structures [12].

Changes in mode shape curvature have also been used to increase the sensitivity of mode shapes for damage detection and localization in beams [13], a prestressed concrete bridge [14], and structural damage in beams and plates [15]. The investigation of curvature has been further employed in modal flexibility-based techniques as a supplementary index to assess simulated damage in a steel grid structure [16]. Changes in the modal flexibility have also been used to detect and localize damage in finite element models of simple beams [17]. Modal strain energy based methods are another group of widely used damage identification techniques that can be considered an extension of the mode shape curvature (MSC) method [18]. In most curvature-based damage identification techniques, the difference operator is used to compute the curvature of mode shapes, which can magnify noise present in the original mode shape and mask actual changes due to small levels of damage [19]. A comparative study of detection methods based on the Modal Assurance Criterion (MAC), the Coordinate Modal Assurance Criterion (COMAC), modal flexibility, and strain energy concludes that changes in modal strain energy could detect damage more precisely [18]. MAC and COMAC are used to correlate two mode shapes but since damage does not affect significantly mode shapes these methods cannot provide enough evidence of low levels of damage [13]. Stiffness-based differential techniques [20] are another group of damage detection methods that are highly dependent on the number of higher modes used in the calculation of the stiffness matrix. However, these methods have limited applicability because of the difficulty in obtaining accurate data for higher modes of vibration [17].

In general, most modal-based damage detection techniques are not efficient for the detection of low levels of damage in the presence of noise or in the case of multiple damage scenarios. Signal processing and pattern recognition techniques have been proposed to improve damage detection, quantification and localization [2]. The Fourier Transform (FT) is used to convert functions from the time to the frequency domains. For vibration-based applications where the signals are nonlinear and non-stationary, such as in damage detection, the evolving nature of the time-series data is best analyzed with the Short-Time Fourier transform (STFT) [12,21]. However, a tradeoff between time and frequency resolution with STFT limits the ability of achieving a high resolution analysis simultaneously in the time and frequency domains [22]. Fractal Dimension (FD) algorithms have also been proposed to estimate the localized FD of the fundamental mode shape to locate cracks in beams [23]. The damage features are detected by moving a fixed-size window across the fundamental mode shape, which is identified as a peak on the FD curve. However, the contribution of higher modes may provide misleading information on damage. The Hilbert-Huang Transform (HHT) is an innovative energy-frequency-time distribution of the signals that relies on an empirical mode decomposition (EMD) of the data, which allows to decompose a signal into a set of basic functions called Implicit Mode Functions (IMF) before implementing the Hilbert spectral analysis [24,25]. HHT has the disadvantage that the first IMF may cover a wide frequency range and fail to reflect the true frequency pattern of the signal which may cause misinterpretation of the result [26].

Recently, the Wavelet Transform (WT) has been favored over other traditional methods because of its capacity to analyze a signal over a wide range of scales [27]. Basically, WTs are classified into two categories: Discrete Wavelet Transform (DWT) and Continuous Wavelet Transform (CWT). Even though the DWT has good computing efficiency, its main applications are often limited to data decomposition, compression and noise removal [26]. A technique that has been quite efficient to detect localized damage-induced modifications in mode shapes is the CWT. Since mode shapes are more sensitive to local features than natural frequencies, the information contained in the measured mode shapes can be treated as a signal in the spatial domain for processing by the wavelet analysis. A "wavelet coefficient" is calculated in the form of a scalar value at each point of a signal which can be used as an indicator to identify local anomalies, break-down points or discontinuities in the mode shapes [10]. To extend the applicability of CWT to real structures, several authors [19,28,29] demonstrated the results of their experimental studies by identifying small perturbations in the deflection profile of a beam obtained from high resolution laser-based measurements. However, for an actual bridge where a fixed reference point and a stationary environmental condition are required to derive precisely the real deflection shape of the structure, the efficiency of the laser-based scanning technology is limited by its high sensitivity to exposure conditions and ambient vibrations.

Several authors have applied the WT to a variety of structural problems to demonstrate its effectiveness and versatility. Analyses with CWT can be optimized by varying the number of sampling intervals [30] and by applying it to a set of vibration modes in the intact and damaged states [31]. In this application, only the first fundamental mode shape is used since it is the most accurate mode when using standard modal testing methods. In large scale structures, since the amount of energy required for exciting the first natural mode is smaller than for higher modes, the first mode is the most easily and accurately identified [32]. Wavelet analysis provides promising results for the detection and localization of damage compared to other methods; however, its performance can be affected by the presence of noise or of multiple damage locations, which may result in multiple false detections along the structural element. To address these issues quantitatively, the detection of damage can be analyzed using statistical principles. The detection for the presence of damage is formulated as a test of hypothesis [33] where the null hypothesis corresponds to no damage and the alternative hypothesis corresponds to the presence of damage. The test is performed for a significance level (α) which corresponds to the probability of type I error or the probability of rejecting the null hypothesis when the latter is true