Mechanical Systems and Signal Processing 83 (2017) 385–405

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Damage detection using modal frequency curve and squared residual wavelet coefficients-based damage indicator

Chen Yang, S. Olutunde Oyadiji *

School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, M13 9PL, UK

ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form
18 April 2016
Accepted 13 June 2016
Available online 12 July 2016

Keywords:
Damage detection
Modal frequency curve
Discrete wavelet transform
Squared residual damage indicator

ABSTRACT

A theoretical and experimental study of the frequency-based damage detection method has been presented in this paper. Based on the eigenvalue problem and perturbation assumption of defect in modal response, the theoretical basis of the modal frequency curve method is established. The extraction of defect characteristics from the modal frequency curve via discrete wavelet transform is illustrated. The above background leads to the development of a new multiple-mode damage indicator for damage localisation and a damage estimator for size prediction. Then, the proposed method has been applied to aluminium samples with pre-defined damage sections. Finite element modelling and experimental testing results are presented to demonstrate the performance of the method. Additionally, detectability with respect to the various mass ratios is investigated to support the ability of the method in real applications. The numerical and experimental results suggest that the use of the damage indicator provides a more robust and unambiguous damage identification than the sole use of the wavelet coefficients of the modes investigated. In addition, the damage estimator predicts the defect size to a satisfactory level.

1. Introduction

There has been an increasing development and use of light, stiff, multi-layer and multi-functional components and structures in modern engineering designs [1]. In order to ensure the state of structural health of these components and structures, suitable inspection and evaluation approaches are necessary. Several traditional inspection methods (e.g. visual inspection, magnetic particle inspection) for surface defect detection, such as cracks and notches, are not available for internal defect in multi-layer structures. Despite the relative high cost of operation of other non-destructive detection methods, such as ultrasonic inspection and thermography, there are also limitations due to specimen surface types and qualities. As a cost-effective direct structural integrity assessment method, vibration-based structural damage detection methods have received increasing attention for real applications [2].

Several researchers have studied the effect of frequency change of a structure in the damaged state with respect to the intact state. Earlier works on the frequency change approach for beam-like structures have been reported in [3–6]. Gadelrab [7] studied the frequency change due to damage in a two-layer laminate beam using finite element method. He showed that frequency shift depends on the defect locations and boundary conditions. Kessler et al. [8] showed that the reduction of the

* Corresponding author.
E-mail addresses: chen.yang@manchester.ac.uk (C. Yang), s.o.oyadiji@manchester.ac.uk (S.O. Oyadiji).

http://dx.doi.org/10.1016/j.ymssp.2016.06.021

frequency is generally proportional to the reduction of global stiffness due to interface defect in structures at lower vibration modes. Several numerical modelling techniques of damaged structures have been reviewed by Della and Shu [9]. They stated that the effect of natural frequency change is generally found to be a function of the size and locations of the defects. Alnefaie [10] showed that the defect-induced variation of mode shape is more distinct for higher flexural vibration modes. Salawu [11] reviewed the numerous literatures available on damage identification based on the shifting of natural frequencies. The review showed the feasibility of using accurately measured modal frequency data in damage detection and condition monitoring for engineering structures. Comprehensive reviews of the structural health monitoring approaches using vibration-based methods are also reported in [12]. Although the modal frequencies of structures can be precisely measured with cost-effective arrangement of sensors (using few sensors) in real applications, the change of the modal frequency may not provide enough information for defect locations compared with mode shapes, as stated by Yam et al. [13,14].

To improve the localisation of the damage using frequencies, a modified frequency-based damage detection method has been proposed by Zhong and Oyadiji [15,16]. The method uses the variations of the modal frequency data as a roving mass is traversed to various locations on a beam in order to detect and localise cracks in beam-like structures through vibration testing. The concept of using the modal frequency curves and its high-order spatial derivatives for crack detection has been demonstrated using measured frequency data. Recently, the above frequency-based approach has been studied by Zhang et al [17,18] on a damaged plate and cylinder by calculating the residual values from the 2D gapped smoothing method (GSM). The above studies have been focused on the application of the method and revealed the applicability in practice. However, the theoretical basis of the frequency curve (or surface) concept in damage detection is not well established. Especially, the assumption of unchanged mode shape under applied concentrated mass loading in [15,17] is only valid for sufficiently small mass ratio condition. Moreover, the previous works based on the numerical differentiation or gapped smoothing approaches are known to be less sensitive compared to the wavelet approaches. The connection of the frequency curve method with wavelet transform is illustrated in the present paper.

In the past few years, wavelet-based approaches have attracted increasing attention for vibration-based damage detection methods. Hong et al. [19] investigated damage detection based on Mexican hat wavelet coefficients of the fundamental mode shape that were derived using continuous wavelet transform (CWT) and discrete wavelet transform (DWT). They suggested that the number of vanishing moments of wavelets in crack detection should be at least two. However, it is well known that wavelets with lower vanishing moments provide less accurate results in terms of the location of the damage [27]. Chang and Chen [20] used DWT to derive Gabor wavelet coefficients of mode shape data for crack detection and localisation in a beam-like structure. The Gabor wavelet coefficients of the mode shapes are used as the location indicator and the frequency reduction used as the depth estimator of the crack. Nevertheless, the Gabor wavelet coefficients manifested the influences of the boundary which required further smoothing procedure to remove the boundary effects. Douka et al. [21] experimentally studied the symmetrical wavelet sym4 in damage detection of beam-like structures using CWT. They introduced a method to suppress experimental noise in measured mode shapes based on the knowledge of the noise level. Rucka and Wilde [22] proposed a 2D DWT method with biorthogonal filter bior5.5 in damage detection for clamped beam-like and plate-like structures using the fundamental mode shape. The performance of the biorthogonal wavelet in processing the measured mode shape data was validated experimentally. The main limitation of the mode shape method is the number of sensors required to capture the data. Qiao et.al [23] reported the solution to this issue using the Laser Doppler Vibrometer in displacement shape measurement for laminated composite plate. Nevertheless, the high expense of the measurement device limits its general engineering application in reality. Zhong and Oyadiji [24] studied the stationary wavelet transform (SWT) method for crack detection in beam-like structures using measured and reconstructed mode shape data. Their approach determines the difference between the SWT of two sets of mode shape data of beam-like structures with simply-supported boundary conditions. They showed that the use of SWT, which is an up-sampling procedure, gives more crack information than the use of DWT, which is a down-sampling procedure. However, the application of their proposed method is restricted to structures with symmetrical boundary conditions.

A comparison study of several signal processing approaches of mode shape-based damage detection method for a plate-like structure has been reported by Fan and Qiao [25]. Based on the numerical and experimental results for damage with different shapes, the authors pointed out the robust performance of the 2D CWT approach with Mexican hat wavelet compared to such methods as 2D GSM and 2D SEM (strain energy method). Recently, Gökdağ and Kopmaz [26] reported the use of DWT and CWT approach for crack detection in beam-like structures. The method uses DWT approximation coefficient to reconstruct the intact mode shape, which is regarded as the baseline. It then estimates the damage-induced mode shape difference by CWT coefficients. However, the assumption that the DWT approximation coefficient of the damaged data is equivalent to the baseline data may not be generally valid. Recently, Katunin [27] compared the use of 2D B-spline wavelets with respect to other wavelet in the literature under 2D DWT process. The author showed that the 2D B-spline wavelet gave a less noisy performance compared with other wavelets investigated. However, the 2D DWT method does not produce comprehensive damage information in one coefficient surface. It usually needs additional steps to overlay the directional images (coefficients) to obtain the final results. In general, the DWT method produces satisfactory results for damage location for beam-like structures with less computation time compared to CWT. For plate-like structures, the 2D DWT methods require additional steps in image composition. Therefore, it is not as direct as the 2D CWT methods. It is also worth to note that, several previous methods rely on the wavelet coefficients of fundamental mode shape. However, it is well-established that a damage close to a nodal line has less effect on the particular mode. Therefore, the use of single mode data