Mechanical Systems and Signal Processing 25 (2011) 2257–2270

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Computationally efficient delamination detection in composite beams using Haar wavelets

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ARTICLE INFO

Article history:
Received 21 July 2010
Received in revised form
23 November 2010
Accepted 2 February 2011
Available online 19 February 2011

Keywords:
Composite beams
Delamination
Haar wavelets
Neural networks

ABSTRACT

The paper presents an integrated vibration-based method for delaminations detection in homogeneous and composite beams. The method is based on Haar wavelets and artificial neural networks (ANNs). Firstly, scaled modal responses of the structure are expanded into Haar series by Chen–Hsiao method (CHM), and a delamination feature index is constructed. The database of 68 datasets built on Haar wavelet and frequency-based approaches was utilized by different ANNs to establish the mapping relationship between the delamination status and the delamination feature index or frequencies. The results are compared to each other. The simulations show the proposed complex method with delamination index detects the location of delaminations and identifies the delamination extent with high precision ($>90\%$); the approach requires less computations and processing time than the frequency-based approach.

1. Introduction

Fiber-reinforced multi-layer composite materials are increasingly being used in civil infrastructure, vehicles, aerospace and light industry. Damage detection in composite structures and machinery is an important issue in terms of safety and functionality. One of the commonly encountered types of damage in laminated composites is delamination. Delaminations are caused by production stresses or service-induced strains, such as impact of foreign objects, exposure to unusual level of excitation or oscillating load over an extended period of time, etc. [1,2]. The early detection and the continuous monitoring of the delamination for the growth and location are the most important issues in the automatic delamination inspection of in-service composite structures [3].

The vibration-based structural damage detection is a relatively new research topic. The approach has several classifications. According to the structural model, the vibration-based structural damage detection approach can be divided into model-based and signal-based methods [4,5]. The model-based methods reveal the damage locations and severities through the comparison of data obtained during the experiments and with the aid of mathematical model of the structure since structural damages cause changes in the dynamic characteristics. This approach was proposed and experimentally tested by several authors [6–9]; the review and classification can be found in [10]. Contrary to the model-based methods, the signal-based methods do not use the structural model and detect damage by comparing the structural responses before and after the damage. In [11], the frequency response functions and in [12] the shear horizontal waves, derived from mode conversion of the fundamental Lamb wave, were successfully used to extract the damage detection index.

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0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2011.02.003

According to the second classification of the vibration-based structural damage detection approach, it can be divided into traditional and modern-type methods [13]. The traditional methods use only dynamic characteristics of structure, e.g. natural frequencies, mode shapes, modal damping, modal strain energy, etc. The location and severity of damage can be determined by the differences between the structural dynamic characteristics of the damaged and intact structures. The advantage of the method is that insignificant changes in physical properties of a structure due to damage result in detectable variations in modal parameters (natural frequencies, mode shapes and modal damping) [14]. The main insufficiency of the method is how to extract the most important features from the vibration response with the purpose of damage detection. Furthermore, the method depends on experimental data analysis, and therefore it is not convenient for online damage detection. A comprehensive review on the vibration-based damage detection methods was presented by Zou et al. [15]. The modern-type damage detection methods are based on real-time measured structural response signals. This approach overcomes the drawbacks of the common non-destructive testing techniques, such as acoustic emission, scanning, X-ray, etc. [4]. The methodology can include neural networks, genetic algorithms, wavelet analysis, etc. The back-propagation ANN was trained to predict the delamination size and location from the natural frequencies of the beam in [1,2].

The wavelet transform has been applied in structural damage detection by many authors [3,16–20]. The advantage of the wavelet-based methods is that they do not require the analysis of the complete structure. The methods are independent from the time-frequency analysis. The wavelet transform decomposes a signal into a set of basis functions. The product of the transform is wavelet coefficients for different scales. Due to time-frequency localization the wavelet transform has ability to reveal some hidden parts of data that other signal analysis techniques fail to detect [13]. In the recent year articles, non-sufficient interest has been paid to the Haar wavelet functions, which are mathematically the simplest wavelets. Chen and Hsiao [21,22] demonstrated that these wavelets can be successfully approximated the derivatives of functions for solving differential equations. The approach has been developed further by Lepik [23].

In the present work an attempt to apply the Haar wavelets for delamination detection based on beam modal responses is made. The fundamental mode shapes are chosen since they are most accurately determinated by a standard modal testing method [15]. The feasibility of using frequency changes for damage detection is limited since significant damage may cause very small changes in natural frequencies [4,24]. To overcome these difficulties, the present work is focused on the changes in mode shapes as they are much more sensitive to local delaminations in comparison with the changes in natural frequencies [24]. The sensitivity of fundamental mode shapes to damage in cantilever beams with cracks is studied in [25].

The application of the proposed method in real structures includes the measurement of the modal responses, the construction of the delamination feature index and the implementation of the measurements and model into the delamination detection process. The paper is organized into six sections. Section 2 outlines the Haar wavelet method CHM. Section 3 presents the dynamic response of vibrating composite beams with multiple delaminations. In Section 4, ANN modeling for delamination detection is explained. In Section 5, several numerical experiments with different beam models, boundary conditions and delamination cases are described. The predictions of delamination parameters made during the computer simulations are compared with the results obtained by the frequency-based delamination detection. Different ANN learning methods are examined and compared. Section 6 summarizes the main finding and conclusions.

2. Chen–Hsiao Haar wavelet method (CHM)

The Haar wavelets belong to a special class of discrete orthonormal wavelets. The orthonormal wavelets generated from the same mother wavelet form a basis whose elements are orthonormal to each other and are normalized to unit length. This property allows each wavelet coefficient to be computed independently of other wavelets. The Haar wavelet family is a group of square waves:

$$h_i(x)=\begin{cases} 1 & \text{for } x\in\left[\dfrac{k}{m},\dfrac{2k+1}{2m}\right], \\ -1 & \text{for } x\in\left[\dfrac{2k+1}{2m},\dfrac{k+1}{m}\right], \\ 0 & \text{elsewhere.} \end{cases} \tag{1}$$

Integer $m=2^j$, $j=0,1,\dots J$ indicates the level of the wavelet; $k=0,1,\dots,m-1$ is the translation parameter. Integer J determines the maximal level of resolution. The index i in (1) is calculated according to the formula $i=m+k+1$; the minimal value for i is 2, in this case $m=1$, $k=0$; the maximal value of i is $i=2M=2^{J+1}$. The value $i=1$ corresponds to the scaling function for which $h_1(x)\equiv 1$.

Any function $y(x)$ which is square integrable in the interval [0,1] can be expanded into a Haar series with an infinite number of terms [21]:

$$y(x)=\sum_{i=1}^{\infty} c_i h_i(x), \quad i=2^j+k,\ j\geq 0,\ 0\leq k\leq 2^j,\ x\in[0,1], \tag{2}$$