Engineering Fracture Mechanics 131 (2014) 257–268

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Experimental investigation of frequency-based multi-damage detection for beams using support vector regression

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ARTICLE INFO

Article history:
Received 19 August 2013
Received in revised form 7 July 2014
Accepted 2 August 2014
Available online 11 August 2014

Keywords:
Multi-damage detection
Frequency measurement
Wavelet-based element
Support vector regression
Experimental investigation

ABSTRACT

A frequency-based damage detection method in conjunction with the support vector regression is presented. The wavelet finite element method is used for numerical simulation to determinate the relationship database between multi-damage locations/depths and natural frequencies of a beam. Then, support vector regression is applied to extract the damage locations and depths from the database due to its ability in handling nonlinearity, finding global solutions, and processing high dimensional input vector. Finally, a large number of experiments have been carried out to further examine the performance of the proposed method.

1. Introduction

Nondestructive techniques play an important role in quality assurance of structural components and engineering materials at the manufacturing stage and during operation. The present nondestructive techniques, such as ultrasonic testing, radiographic, and thermographic. are commonly used for offline damage identification. These methods are costly and time-consuming for complex or large structures. Furthermore, it is a challenging task to apply these methods for multi-damage detection when the damaged area in a structural component is not accessible by the measurement instrument.

The vibration-based structural damage detection methods [1], based on either mode shape or natural frequency, have been explored for detecting both single and multiple damages. Generally, multi-damage detection in structures is done in two steps as summarized in review literature [2]. The first step is forward problem analysis, which involves the development of the multi-damage detection database of modal parameters (natural frequencies or modal shapes). It is worth to point out that the relationships between the damage parameters (damage locations and depths) and the modal parameters are generally nonlinear. The second step is inverse problem analysis, which includes the identification of damage locations and depths from the multi-damage detection database developed in the first step. To model the crack singularity [3], Lele and Maiti employed numerous eight-node iso-parametric elements to obtain accurate results of the forward problem of beams [4]. However, ill-conditioned finite element equations may still lead to poor simulation results. To reduce computational error, Medhekar and Maiti presented an efficient boundary element method (BEM) to compute the changes in natural frequencies [5]. Based on the improved computational results, Patil and Maiti presented a multiple-damage detection method using frequency measurements [6]. With their method, the beam is divided into a number of segments associated

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http://dx.doi.org/10.1016/j.engfracmech.2014.08.001
0013-7944/

Nomenclature

e_n	the *n*th damage location
c_n	the *n*th damage depth
α_n	the *n*th normalized damage depth
β_n	the *n*th normalized damage location
$< \cdot , \cdot >$	dot product
$\mathbf{g}$	input dataset
$\tilde{\mathbf{g}}$	normalized dataset
$\bar{g}$	the mean value
ε	tolerance error
$\mathbf{X}_i$	the *i*th training sample
H_i^s	the *i*th test sample
b	beam width
h	beam height
L	beam length
E	Young's modulus
μ	Poisson's ratio
ρ	material density
p_1, C	the trade off parameters of SVR
α_n^*	the *n*th detected normalized damage depth
β_n^*	the *n*th detected normalized damage location
δ_i	the *i*th absolute error
f_i	the *i*th noise-free frequency
f_{ni}	the *i*th noise-contaminated frequency
rand	the random number in the range of [0,1]
f_{mi}	the *i*th average measured frequency
E_m^i	the *i*th modified value of Young's modulus
$\overline{\mathbf{K}}$	the global stiffness matrix
$\overline{\mathbf{M}}$	the global mass matrix of

with damage parameters (damage locations and depths). Therefore, this procedure provides a linear relationship between the natural frequency ratios and damage parameters in a beam. However, as Raghebi and Farshidianfar commented, this method only considers a linear relationship between the changes in natural frequencies of the beam and the damage parameters, which may lead to inaccurate and imprecise results in some cases where the relationship is nonlinear [7].

The modal characteristics of a damaged beam with at least two surface damages were summarized by Chasalevris and Papadopoulos [8], Sekhar [9] respectively. They also pointed out that more precise and reliable numerical solution method should be developed to solve both the forward and inverse problems. Li et al. [10] and Xiang et al. [11] developed a single damage detection method based on wavelet beam elements using Daubechies wavelet and interval spline wavelet respectively. Their method shows that the wavelet-based elements can provide a high precision solution for the forward problem. Chen et al. [12] extended the wavelet-based finite element method with reduced number of elements to detect multiple damages in a beam.

To minimize the differences (residuals) between analytical and experimental data, Perera and Ruiz presented a multistage finite element updating procedure for damage identification in large-scale structures based on multi-objective evolutionary optimization [13]. Unlike the model updating method to adjust design variables, Martin and Meinhard presented an approach based on neural networks to detect dynamic parameters in damaged structures [14]. Fernando et al. presented a genetic algorithms based approach to detect damages in a beam [15]. Xiang and Liang developed a two-step approach using a mode shape and the natural frequencies to detect multi-damage in a plate [16]. For experimental analysis, a few studies were done for single and multiple damages on structures [17,18].

Generally, most of the studies in the literature focused on numerical simulations but the results may not be applicable to real structures. Some important issues have not yet been addressed adequately, e.g., the lack of high performance algorithm for solving the inverse problem and the lack of experimental analysis to verify multi-damage detection methods.

Support vector regression (SVR) [19] has recently been established as a powerful tool to solve the inverse problem for damage detection. Based on structural risk minimization principle, SVR have many advantages, such as better generalization ability, no need to specify the number of hidden kernel functions, and unique global optimal solution [19]. Therefore, unlike artificial neural networks (ANNs) [20] and genetic algorithms (GAs) [5], SVR can be relative easy to use in optimization field.

Worden and Lane [21] proposed a support vector classification (SVC) and SVR method to detect bearing faults and frame structure damages, respectively. Isa and Rajkumar employed SVC to predict pipeline defect and intact conditions based on attenuation and natural frequency changes of propagating lamb waves [22]. However, in spite of its effectiveness in the above and other applications, the SVR has not been applied for multi-damage detection. Considering its ability in handling