Journal of Sound and Vibration 375 (2016) 200–216

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Multivariable wavelet finite element-based vibration model for quantitative crack identification by using particle swarm optimization

Xingwu Zhang [a,b], Robert X. Gao [b], Ruqiang Yan [b,c], Xuefeng Chen [a,*], Chuang Sun [b], Zhibo Yang [a]

[a] State Key Laboratory for Manufacturing System Engineering, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, OH 44106, USA
[c] School of Instrument Science and Engineering, Southeast University, Nanjing 210096, PR China

ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form
29 March 2016
Accepted 16 April 2016
Handling Editor: L.G. Tham
Available online 29 April 2016

Keywords:
Crack
Quantitative identification
Multivariable wavelet finite element method
Particle swarm optimization
Experiment

ABSTRACT

Crack is one of the crucial causes of structural failure. A methodology for quantitative crack identification is proposed in this paper based on multivariable wavelet finite element method and particle swarm optimization. First, the structure with crack is modeled by multivariable wavelet finite element method (MWFEM) so that the vibration parameters of the first three natural frequencies in arbitrary crack conditions can be obtained, which is named as the forward problem. Second, the structure with crack is tested to obtain the vibration parameters of first three natural frequencies by modal testing and advanced vibration signal processing method. Then, the analyzed and measured first three natural frequencies are combined together to obtain the location and size of the crack by using particle swarm optimization. Compared with traditional wavelet finite element method, MWFEM method can achieve more accurate vibration analysis results because it interpolates all the solving variables at one time, which makes the MWFEM-based method to improve the accuracy in quantitative crack identification. In the end, the validity and superiority of the proposed method are verified by experiments of both cantilever beam and simply supported beam.

1. Introduction

Crack is one of the main and crucial causes for structural failure. This kind of sudden failure is costly to human life and property damage, for example, bridges rupture, aircraft accident and gas turbine accident etc. Therefore, many researchers and engineers devoted their time and energy to find how to detect these crack failures in their early stage so that the human lives and properties can be saved. There are several methods that have been studied or developed in the last several decades for crack detection, which can be categorized into three types, non-destructive method, signal processing method and model-based method. Non-destructive methods (NDE) is the relative mature one in industrial applications, which utilize ultrasonic wave [1], magnetic particle [2], eddy current testing [3,4] and X-ray [5] etc. to find out the existence of cracks.

* Corresponding author.
E-mail address: chenxf@mail.xjtu.edu.cn (X. Chen).

http://dx.doi.org/10.1016/j.jsv.2016.04.018
0022-460X/

Many NDE instruments have been developed, such as magnetic defect detector, industrial computed tomography, eddy current flaw detector etc. However, there are three drawbacks of NDE: (1) it is difficult to detect the cracks in their early stage; (2) it is difficult to implement NDE for very large structures; (3) the experienced workers or engineers are required in NDE implementation [6,7]. The second kind detection method is signal processing, which utilize the features extracted from signals to implement crack detection, such as wavelet analysis [8,9], empirical mode decomposition [10,11], local mean decomposition [12], stochastic resonance [13], time–frequency analysis [14] and sparse analysis [15], etc. However, they mainly focus on rotating machinery and are difficult to achieve quantitative identification. The third one is the model-based method which combines the numerical model and the measured structure modal parameters together to achieve quantitative crack identification. Due to the excellent performance in crack detection, such as nondestructive, convenient, quantitative and easy to implement online etc., the model-based method has attracted many scholars' attention.

Any engineering structure can be treated as a dynamic system which is composed by mass, damping and stiffness. When the crack is generated, the structural modal parameters will vary in a specific manner, which can be regarded as the symbol for crack identification. Therefore, model-based method is proposed to detect cracks and it can be divided into two aspects, forward problem and inverse problem [16]. In the forward problem, the structures with crack are modelled and analyzed by theoretical and numerical method to establish the database between crack parameters and structural modal parameters, such as natural frequencies, mode shapes and mode damping, etc. Then the corresponding vibration parameters in operation are measured and combined with analyzed parameters to obtain quantitative identification results. Modeling the structure with crack is the key step due to the singularity of cracks. Several scholars in solid mechanics, fracture mechanics and mechanical engineering devoted in precise modeling and analysis, and many methods have been developed, such as stress intensity factor [17], crack additional flexibility [18], open crack model [19], breathing crack model [20], transfer matrix method [21] and finite element method [22–24], etc. However, theoretical models are limited in simply structural analysis and difficult to be applied in industrial applications because it is difficult to obtain theoretical expressions and solutions of complex structures with crack. Finite element method (FEM) is a popular way in structural modeling and analysis, but the traditional FEMs are hardly to achieve precise crack modeling and analysis with affordable computation cost because the $1/\sqrt{r}$ (r is the polar coordinate of any node in the crack tip) singularity exists in displacement and strain variables of the crack tip areas. Due to the large gradient and saltation in crack tips, traditional FEMs are difficult to approximate the precise or even correct solutions [25]. Wavelet Finite Element Method (WFEM) is a new numerical method which takes wavelet functions as trial function to interpolate the solving variables. Due to the excellent properties, such as multiresolution, orthogonality etc., WFEM performs excellent in singularity problem modeling with great precision and less computation cost. Daubechies wavelet, B-spline wavelet on the interval (BSWI) and Hermite wavelet are all used to construct wavelet finite element method for structural modeling and analysis. Li and Chen systematically reviewed the wavelet-based numerical method, including wavelet finite element method, wavelet weighted residual method, wavelet meshless method and wavelet boundary method etc. [26,27]. Xiang is one of the scholars who have been involving in the study of wavelet finite element method for a long time. Based on BSWI and Hermite wavelet, Xiang constructed a series of wavelet finite elements for structural analysis of beams, plates and shells, and studied the cracked structural modeling and crack identification for beams [28,29], rotors [30,31] and shells [32]. Dong investigated rotor crack detection, in which WFEM is utilized in forward problem, and EMD and Laplace wavelet are used in inverse problem for high-precision modal parameters identification [33]. Ye studied the quantitative crack identification for pipes based on the second generation wavelet finite element method [34]. By combining numerical model and wavelet transform together, Surace investigated the crack identification for beam structures [35]. By using intensity factor and wavelet analysis, Douka implemented crack depth and size detection of plates [36].

However, current WFEMs mainly focus on one kind of variables, that is, only the generalized displacement variables are taken into account as independent variables, generalized stress and strain are not considered, thus the modeling precision and identification accuracy are limited. Multivariable wavelet finite element method (MWFEM) takes all the three kinds of variables independently in modeling process to improve the modeling precision. Zhang contributed much on MWFEM. By taking BSWI as the interpolation function, he constructed several multivariable wavelet finite elements for structural analysis, including beam [37], thin plate [38,39], thick plate [40], shallow shell [41], etc. Han constructed MWFEM based on wavelet function and Hellinger–Reissner generalized variational principle for solving bending problems of thick plate [42]. Wang proposed a design method of second generation wavelet-based multivariable finite element for static and dynamic analysis of beam structures [43]. However, the present MWFEM mainly focuses on intact structure's modeling and analysis without cracks.

By taking the advantages of MWFEM, a MWFEM-based quantitative crack identification method is proposed in this paper to promote the precision in crack identification. First, the structure with crack is modelled and analyzed by the MWFEM to obtain the data base of vibration parameters. Then the structural vibration parameters in operation are measured by LMS Test.Lab and analyzed through signal processing method. Third, the quantitative identification results are obtained using intelligent optimization of Particle Swarm Optimization (PSO). In the end, several numerical and experimental examples are given to validate the proposed method. By comparing with the WFEM, the superiorities of the proposed MWFEM are proved.