Measurement 48 (2014) 208–219

Contents lists available at ScienceDirect

Measurement

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

A signal energy change-based damage localization approach for beam structures

Yonghui An [*], Jinping Ou

Department of Civil Engineering, Dalian University of Technology, Dalian 116023, China

A R T I C L E   I N F O

Article history:
Received 29 August 2013
Accepted 5 November 2013
Available online 16 November 2013

Keywords:
Energy
Curvature
Mean square
Damage localization
Beam structures
Damage detection

A B S T R A C T

Beams are widely used in many mechanical systems and other structures. Accurate damage localization of beam structures still suffers from some limitations. To address these issues, an effective damage localization approach, i.e. the curvature difference probability of logarithm of mean square based approach, is proposed on the basis of a new feature (i.e. the logarithm of mean square) and the curvature method. The feature is computed at every measured node with accelerations before and after damage. Then, curvature differences of the waveforms of logarithm of mean square between the undamaged and damaged status are selected as candidates for the potential damage locations. Lastly, the damage probability of each element is considered to determine the final damaged element configuration. Damage localization of a simply supported beam model with numbers of numerical and experimental damage cases are employed to verify the proposed approach. All results verify that the proposed approach can be used to locate damage well and it exhibits high-noise insusceptibility: it is still effective even if the noise level is up to 15%. Also, the proposed approach does not require a numerical model of the measured structure, all of these lay a good foundation for engineering application.

1. Introduction

Accumulated damage and rapid deterioration is inevitable during the service life of structural systems. Rebuilding the structure is not feasible due to expense and time constraints, a timely maintenance measure is required; therefore, early monitoring of structural damage and well-timed maintenance are necessary [1,2]. A simple and reliable technique of periodic structural condition monitoring is required to estimate the integrity of structures and ensure that the structures provide a continued safe service condition [3,4]. Structural Health Monitoring (SHM) is the process of using a suitable damage identification strategy for various structures, and SHM systems can provide information to access the integrity of a structure [5,6]. The monitoring system must be able to detect and locate the deterioration and any significant change in the structure [4]. Once damage is detected, effective maintenance measures can be taken in time [7]. Damage identification has played an active role for avoiding disaster [8]. Therefore, finding an effective damage identification technique has become the most important issue of SHM.

In the past decades, many damage identification methods have been developed, and approaches based on the structural vibration techniques are increasing in worldwide usage [9]. Dynamic parameters have been widely used, these include: natural frequencies [10], mode shapes [11], modal strain energy [12,13] and flexibility matrices [14]. These methods have made great progress, but accurate structural damage identification in engineering still suffers from some limitations. For those model-based methods, it is not reliable to employ an inaccurate structural model in damage identification [15]. Additionally, some present damage identification techniques cannot be well used due to their low robustness against the noise.

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[*] Corresponding author. Tel.: +86 41184707321.
E-mail address: anyh@uiuc.edu (Y. An).

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http://dx.doi.org/10.1016/j.measurement.2013.11.009

Nomenclature

Parameters	Description
MS	mean square
LMS	logarithm of mean square
CDPLMS	curvature difference probability of logarithm of mean square
PDE	potentially damaged elements
C_k	curvature at node k
L_k	the logarithms of mean square of a signal at node k
$(\mathrm{DI})_k$	damage index at node k
$(\mathrm{VC}^k_{\mathrm{before}})_r/(\mathrm{LC}^k_{\mathrm{before}})_r$	curvature at node k for the rth vertical/longitudinal acceleration response before damage
$(\mathrm{VC}^k_{\mathrm{after}})_s/(\mathrm{LC}^k_{\mathrm{after}})_s$	curvature at node k for the sth vertical/longitudinal acceleration response after damage
$(\mathrm{VC}^k_{\Delta})_{rs}/(\mathrm{LC}^k_{\Delta})_{rs}$	curvature difference at node k for the rth (before damage) and sth (after damage) vertical/longitudinal acceleration response
$(\mathrm{VC}^k_{\Delta})^*_{rs}/(\mathrm{LC}^k_{\Delta})^*_{rs}$	normalized values of $(\mathrm{VC}^k_{\Delta})_{rs}/(\mathrm{LC}^k_{\Delta})_{rs}$

Therefore, it is imperative to develop a damage localization technique with a low dependence on the accuracy of the finite element (FE) model and a strong anti-noise-interference ability.

The purpose of the present work is to find a damage identification feature with high-noise insusceptibility and low dependence on the finite element (FE) model. A fractal dimension-based damage localization technique in early work [16] employs the time history signal to locate the damage directly, shows strong robustness against the noise and the accuracy of the FE model. By analogy, the work will continue to study a new signal processing-based damage identification approach. Two key points [17] should be considered in damage identification: (1) signal conditioning: determining which feature is suitable to describe the signal change due to the damage. This work employs a new mathematical feature, i.e. the logarithms of mean squares of a signal, in which two basic concepts are employed: the logarithm and mean square. The logarithm has many applications, such as self-similarity [18], and Richter scale [19]. The mean square (MS) or root mean square (RMS) of a waveform is a statistical measure of the magnitudes of a varying quantity. In the past years, the RMS-based methods have been used in the monitoring or damage identification, literatures [20–22] reported that RMS value of a vibration signal describes its energy content (power content), and it performs well in tracking the overall noise level [22]. (2) Damage detection: determining which mathematical tool could be selected to deal with the proposed feature. The curvature method is selected as the mathematical tool to deal with the proposed feature. Pandey et al. [23] first proposed the curvature mode shape-based damage identification method; however, it suffers from some limitations concerning the effects of noise and the uncertainty of the mode shapes [16]. This work employs the acceleration signals directly to locate the damage without the modal parameter identification process. As a result, a new signal processing-based damage identification approach, which is named "the curvature difference probability of logarithm of mean square based approach", is proposed.

The remainder of this paper is organized as follows. Section 2 presents the general idea of the proposed approach. Section 3 introduces the detailed steps of the proposed approach. Section 4 investigates some numerical damage cases and provides some detailed discussions for the approach. Section 5 gives the further experimental validation of the proposed approach based on a laboratory model. Finally, Section 6 provides conclusions.

2. General idea of the proposed approach

With the same input, when some elements of a beam are damaged, the relative stiffness of the undamaged elements increases, then the magnitudes of displacement and velocity responses of the undamaged elements decrease; on the contrary, the relative stiffness of the damaged elements decreases, then the magnitudes of displacement and velocity responses of the damaged elements (and possibly the adjacent elements of the damaged) increase [24]. The accelerations response, which is the second derivative of displacement, will change also after damage according to the same rule as displacement and velocity. Inspired by this rule, the present work aims at proposing a new method to locate the damage.

The next step is to find a feature to quantify the changes of acceleration signals from undamaged and damaged structures. If the change of response at every measured node for intact status and damaged status can be measured by the feature, then damage is located in the element whose damage feature of response signals overtly changes before and after damage. Since the responses are influenced by damage, the energy distribution of these signals changes after damage [20]. As stated in the introduction, the RMS values reflect the energy of a signal. Therefore, the MS (or RMS) is selected in this paper to identify the damage.

2.1. With the same pulse excitation magnitude before and after damage

Taking several multiple DOF mass-spring-damper systems for example, Fig. 1 shows the MS values of the accelerations at all the measured nodes before and after damage with the same pulse excitation. Taking Fig. 1(b) as an example to explain the results, Fig. 1(b) shows result of a