Journal of Sound and Vibration 401 (2017) 268–281

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Damage detection via closed-form sensitivity matrix of modal kinetic energy change ratio

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ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form
16 April 2017
Accepted 27 April 2017
Handling Editor: L.G. Tham
Available online 8 May 2017

Keywords:
Damage detection
Modal kinetic energy
Modal kinetic energy change ratio
Closed-form sensitivity matrix

ABSTRACT

In this paper, a new damage detection method based on a damage sensitive feature parameter named Modal Kinetic Energy Change Ratio has been proposed. The sensitivity matrix for the damage identification procedure is calculated by making use of the closed-form sensitivity of eigenvalues of the structure. Numerical simulations and experimental tests were carried out on a beam-like structure in order to examine the reliability and feasibility of the proposed method. System Equivalent Reduction Expansion Technique is employed to omit rotational degrees of freedom of the model. It is demonstrated that this method locates and quantifies structural damage(s) with acceptable accuracy. The best advantage of the proposed method comparing to the ones which are based on modal strain energy is that it is not sensitive to mode shape noise and yields favorable results under moderate noise in natural frequencies.

1. Introduction

In the last three decades damage detection has become one of the most interesting topics in the field of health monitoring of structures. In the early years researchers took advantages of the damage sensitive features like natural frequency, mode shapes, and modal damping. These methods were not very successful because of the existing noise in measurements and relatively low sensitivity to damages that are induced to the entire structure [1]. It is worth noting that maximum differences in mode shapes between damaged and undamaged structure does not really occur in the damaged zone and damage can leak out to the rest of the mode. Furthermore, frequency change will yield near accurate results only in case of large damages [2]. Due to lack of successful damage detection in the earlier methods which use rudimentary features, researchers made up with the idea of inventing or adopting more sophisticated features like mode shape curvature, modal strain energy, flexibility, flexibility curvature and etc. for damage detection purposes. These methods have been reviewed in the literature with details involved in the procedure [3].

Mode shape curvature utilizes the idea that curvature of a beam is inversely related to its stiffness properties. Therefore, in case of stiffness loss it can be an efficient parameter to identify and locate the damage. Pandey et al. [4] showed that absolute differences of mode shape curvature using acceleration mode shapes between healthy (FEM model) and damaged state of the structure can be a good and efficient parameter in damage detection procedure. However, some researchers showed that mode shape curvature using strain-based mode shapes improves the results of damage detection effectively [1].

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http://dx.doi.org/10.1016/j.jsv.2017.04.039
0022-460X/

Modal strain energy (MSE) is another parameter that has received so much attention during the last two decades. This method utilizes the elemental modal strain energy before and after damage conditions. Earlier methods using this parameter could only identify the location of damage. Studies have been done for beam-like [5] and plate-like [6] structures. More sophisticated methods could locate and quantify the extent of damage which has been induced to the structure. These advanced methods require an analytical FEM model of the structure to calculate the sensitivity of MSE with respect to damage in order to quantify the amount of damage that is accumulated in the structure elements [7].

Flexibility methods are based on the idea that the flexibility matrix is the inverse of the stiffness matrix and any reduction in stiffness can increase the amount of flexibility in damaged members which are forming the structure. These methods also require an analytical FEM model just like MSE based methods. However, without making use of analytical model, flexibility methods can be used to locate the damage between two different states of the structure [8].

In the above mentioned methods, the location of damage can be identified with acceptable accuracy. However, sensitivity matrices are required for successful quantification of damage. The earlier methods developed in this field are based on the first order perturbation theory. Fox and Kapoor approximated the first order perturbation of mode shapes as a linear combination of the unperturbed structure and also corresponding natural frequencies [9]. It has been shown that first order perturbation of mode shapes and natural frequencies can be used to form the MSE sensitivity matrix and the results were successful in damage quantification process. Shi et al. [7] for the first time developed an element wise damage sensitivity matrix based on MSE changes in structure elements for quantifying the extent of damage. An improved method proposed by Moradipour et al. [10] reduced the numerical errors of the method developed by Shi et al. [7].

Firstly developed flexibility methods could only locate the damage location [8]. More developed methods could quantify the amount of damage based on the regular flexibility matrix [11]. The adverse effect of truncating higher modes in the damage detection process led researchers to make use of the generalized flexibility matrix. Li et al. [12] for the first time proposed this idea and their numerical simulations showed good accuracy of the method comparing to the regular flexibility method [11].

The first order perturbation expression for mode shapes and natural frequencies made by Fox and Kapoor [9] was approximate. Hence, Lee and Jung [13] derived the closed form sensitivity of the mode shapes and natural frequencies based on changes in stiffness and mass matrix with respect to an arbitrary parameter. In the last few years, Yan et al. derived MSE and generalized flexibility sensitivity matrices based on the closed form sensitivity of mode shapes and their corresponding natural frequencies. The MSE sensitivity matrix proposed by them has a simple and compact algebraic form [14]. This leads to a more accurate sensitivity matrix and also removes the effect of truncating higher modes in the methods proposed earlier [7]. Yan et al. have published two papers recently on the MSE [14] and generalized flexibility method [15]. Their proposed methods is based on the closed form sensitivity of the mode shapes and natural frequencies. Their proposed methods have good accuracy and shown to be efficient in locating and quantifying the extent of damage [14,15].

In the mentioned methods baseline errors and uncertainties are not taken into account. More recently, some researchers have taken model uncertainties into account and proposed methods that can deal with baseline errors [16–18]. These errors can be geometrical or material properties of the considered analytical FEM model. However, in this paper the effect of uncertainties involved in the baseline model are neglected and will be studied in forthcoming works.

In this paper, modal kinetic energy change ratio (MKECR) is used as a sensitive damage feature. Meng and Lin showed that this parameter can identify the location of damage very well. However, they did not discuss about its capability in quantifying the damage [19]. This parameter has received very little attention in the literature and it has been used mostly as a feature to specify the optimum location of sensors not as a damage sensitive feature. The purpose of the present study is to localize and then quantify the extent of damage in the structure by making use of the MKECR parameter. Firstly, the element wise sensitivity matrix of the MKECR parameter is derived and the governing equations are provided. Secondly, numerical examples are carried out in order to examine the feasibility and accuracy of the method under the noise free and noisy conditions. Finally, an experimental test is conducted and the obtained results reveal that this parameter can also be used as a good damage sensitive parameter to locate and quantify the induced damage to the structure.

2. Theoretical background

Structures are usually analyzed by the FEM. Most of the damage detection algorithms utilize FEM models, or FEM formulation in their algorithms. A linear undamped structure with distinct and well-spaced modes is considered. The equation of free vibration for this system in its rth mode of vibration can be written as

$$\left[\mathbf{K}\right]\left\{\boldsymbol{\phi}_r\right\} = \lambda_r\left[\mathbf{M}\right]\left\{\boldsymbol{\phi}_r\right\} \tag{1}$$

where $\left[\mathbf{K}\right]$ and $\left[\mathbf{M}\right]$ are the $N_D \times N_D$ global stiffness and mass matrices of the structure, respectively; and N_D represents the total number of degrees of freedom (DOFs) of the structure. Furthermore, $\{\boldsymbol{\phi}_r\}$ and λ_r are the mode shape and natural frequency of the rth mode of vibration, respectively. The structures usually do not remain in their original or healthy state and damage will be induced to the elements of the structure due to environmental conditions, overload, fatigue, and etc. Similarly, for the damaged state of the structure the free vibration equation of the system will become as follows