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Real-time fast damage detection of shear structures with random base excitation

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ABSTRACT

This paper validates the use of two jerk energy-based damage localization methods, proposed for the regular test with pulse excitation in earlier work, in real-time damage detection of shear structures with random base excitation. First, a 20-story shear structure numerical model is considered to provide numerical validation with random base excitation. Then, performance of the two methods in damage detection is experimentally validated through a laboratory-scale 6-story shear structure model. Both experimental and numerical results of single and multiple damage cases with different levels of stiffness loss indicate that the two jerk energy-based methods can also be used in real-time damage detection of shear structures with random base excitation. The two jerk energy-based methods perform well in the presence of high noise level; moreover, they are model-free that avoid establishing the structural finite element model and model updating.

1. Introduction

In the past two decades, research on damage detection, localization and quantification based on the vibration data has increased significantly. Vibration-based damage detection methods can detect structural damage quickly and cost-effectively, they are promising [1]. Some review papers [2–6] of vibration-based damage detection methods have been published, including damage localization methods and damage quantification methods. These vibration-based methods have made good progress, in which some are used for the regular test with pulse excitation [7], some are used for real-time health monitoring with ambient excitation [8–10].

Considerable research has been devoted to the extraction of damage detection features based on different dynamic parameters [11,12] and finite element (FE) model updating [13], challenges remain in the application of real life and complex structures: (i) Many FE model-based methods [14–16] have been developed and they have made good progress. However, Bagchi et al. [16] pointed out that the use of a FE model presents some problems in the application of vibration-based damage detection methods; Fan and Qiao [5] stated that considerable computational cost in numerical analysis makes model-based methods not suitable for real-time damage detection; moreover, these methods are influenced by the accuracy of FE models. (ii) Some mode shape-based techniques do not require detailed FE models compared with those FE model-based methods and they can be used in real-time structural health monitoring [17]. Rahmatalla and Eun [18] studied a damage detection method based on the distribution of constraint forces from measured flexural strain; Reynders and De Roeck [19] studied a local flexibility-based damage localization and quantification method; Talebinejad et al. [17] conducted a numerical

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study of using four different mode-based damage detection methods including the enhanced coordinate modal assurance criterion, damage index method, mode shape curvature method, and modal flexibility index method on a cable-stayed bridge. However, because the measured mode shapes are high influenced by noise contamination [5,18,20], the anti-noise ability of these methods is still required to be heightened. Hopefully, these methods can be well used with the development of the modal parameters identification techniques. (iii) Many model-free methods, which avoid establishing a FE model and the model updating, focus on the analysis of the time history of responses directly [21–23]. However, it is still an open question that how to extract the most appropriate feature from the response signals [24].

In our opinion, research of vibration-based damage detection should be explored along the following directions in order to be used well in engineering with consideration of their research status: (i) Damage detection methods with low-dependence on accuracy of structural FE models and model-free damage detection methods should be given priority to the development. That is because engineering structures are very complicated with many uncertainties in materials, construction, structural connection parts, and so on; moreover, some structural parts are difficult to be well established in the FE model, for example the boundary conditions cannot be guaranteed the same as the real structure; as a result, some assumptions are introduced. Thus, obtaining an accurate FE model is very difficult and time-consuming. Model-free methods avoid tremendous work in FE model developing and updating. (ii) The hybrid damage detection methods of global and local methods should be adopted in engineering, i.e. the vibration-based damage detection methods (global methods) and non-destructive evaluation methods (local methods) should be combined to detect a structure. Generally, an accurate FE model is required in the damage quantification; it is recommended that damage localization is implemented based on the global methods while damage quantification is considered based on the local methods. (iii) The methods with high anti-noise ability are imperative because the structural responses often have high noise. The inherent anti-noise ability of a damage detection method is required to be improved; at the same time, the anti-noise ability can also be improved by using the mean result of multiple identifications based on different sets of data. (iv) Pulse excitation is commonly used for regular tests; while real-time structural health monitoring methods focus on random excitation mainly. And the real-time damage detection methods are more valuable compared with the regular test methods.

Consider the above first three points, two model-free damage localization methods used in regular test with pulse excitation, termed the Mean Normalized Curvature Difference of Waveform Jerk Energy (MNCDWJE) and the Curvature Difference Probability Waveform Jerk Energy (CDPWJE), have been proposed and validated with pulse excitation in the earlier work [25]. The damage localization results indicate they have good accuracy and they are robust to measurement noise. However, refer to the fourth point, the earlier work only focuses on performances of the two jerk energy-based methods in structures with pulse excitation; their performances in real-time damage detection is still required to be validated.

In the mechanical engineering, aerospace engineering and some other industrial fields, there are some shear structures which receive random excitation in their base all the time when they are in service. The main purpose of this manuscript is to provide a real-time structural health monitoring method for these shear structures. Therefore, the possibility of employing the two jerk energy-based methods in real-time damage detection of shear structures with random base excitation is investigated in this paper. Numerical simulation and experimental validation are conducted for both single and multiple damage cases. The remainder of this paper is organized as follows. Section 2 provides a brief introduction of the proposed two jerk energy-based damage localization methods. Section 3 investigates numerical simulations, in which several single and multiple damage cases of a 20-story shear structure numerical model are considered, and the influence of data length on damage detection results is discussed. Section 4 examines the experimental validation, in which several experimental damage cases are conducted through a 6-story laboratory-scale shear structure model. Section 5 provides the conclusion.

2. Two jerk energy-based damage localization methods

Two jerk energy-based damage localization methods are proposed for regular tests with pulse excitation in earlier work [25], i.e. the MNCDWJE and CDPWJE methods. In this section, the two methods are briefly presented for completeness.

For a discrete set of sampled points given by $a_1, a_2, \ldots, a_N$ (signal a), which are accelerations in this study, the jerk energy-based damage feature JE at measured node k is defined as follows [25]

$$JE_k = \log \sum_{x=1}^{N-1} (j_x^k)^2 = \log \sum_{x=1}^{N-1} \left(\frac{a_{x+1} - a_x}{\Delta t}\right)^2 \quad (1)$$

where k represents the measured node number, Δt is the sampling interval, log is natural logarithm. Waveform of the Jerk Energy (WJE) is created through connecting JE values at every measured node. Then the "curvature" of WJE can be similarly computed through Eq. (2),

$$C_k = \frac{JE_{k-1} - 2JE_k + JE_{k+1}}{h^2} \quad (2)$$

where C_k is the curvature at the node k, JE_k is evaluated at the node k, h is the distance between two adjacent measurement locations. For measured nodes 1, 2, 3, …, i, consider its element numbering sequence is 1, 2, 3, …, i, then the element numbering sequence can be considered as a clockwise closed loop and it can be seen in Fig. 1 (taking $i = 20$ for example). Therefore, C_1 and C_i are calculated based on the following equations: $C_1 = \frac{JE_i - 2JE_1 + JE_2}{h^2}$ and $C_i = \frac{JE_{i-1} - 2JE_i + JE_1}{h^2}$. Thus, elements at all measured nodes including measured nodes 1 and i can be detected.