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On the classification of normalized natural frequencies for damage detection in cantilever beam

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ABSTRACT

The presence of a damage on a beam causes changes in the physical properties, which introduce flexibility, and reduce the natural frequencies of the beam. Based on this, a new method is proposed to locate the damage zone in a cantilever beam. In this paper, the cantilever beam is discretized into a number of zones, where each zone has a specific classification of the first four normalized natural frequencies. The damaged zone is distinguished by only the classification of the normalized frequencies of the structure. In the case when the damage is symmetric to the vibration node, we use the unchanged natural frequency as a second information to obtain a more accurate location. The effectiveness of the proposed method is shown by a numerical simulation with ANSYS software and experimental investigation of a cantilever beam with different damage.

1. Introduction

Many of mechanical structures like turbine blade and fixed-wing aircraft can be treated as a cantilever beam. Any change to the material and geometric properties of these structures, which adversely affects their performance is considered as damage. Early detection of damage in these structures can increase their lifetime.

The occurrence of damage in a structure produces changes in its dynamic characteristics such as its natural frequencies, mode shapes and modal damping. So, many engineers and scientists have devoted their efforts towards developing different detection techniques using the dynamic proprieties. The authors in Refs. [1–4] gave a review of a research work on vibration-based damage identification methods. Because of difficulty in measurement of modal damping, the natural frequencies and mode shapes are generally used to detect damage in structures.

Many authors find damaged elements by using a criterion that combines mode shapes or their derivatives of a damaged structure and undamaged one. West [5] was among the early authors of the idea of the use of mode shapes for damage location. He used the modal assurance criteria (MAC) to determine the correlation between mode shapes of a damaged structure and undamaged one. Lieven and Erwins [6] proposed a mode shape based damage indicator named the coordinate modal assurance criterion (COMAC). Homaei et al. [7] introduced multiple damages detection in beam (MDLIBMS criterion) as an operator to detect damaged elements. They considered both transvers and rotational mode shapes of a damaged structure and undamaged one. However, because of the difficulty in measurement of rotational mode shapes, the authors considered only the transvers mode shapes in practical works. Abdo and Hori [8] shown that the mode shapes slopes (the

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first derivative of mode shapes) have better performance of multiple damages location than the displacement mode shapes themselves. Furthermore, they do not need many measurements to locate damage.

Many researchers have used mode shapes curvature (the second derivative of mode shapes) method for damage detection because it is more sensitive to any local changes in mode shapes by amplifying the effects of the damage. Pandey et al. [9] were the first to propose the changes in curvature mode shapes to detect and locate damages in beams. They plotted the absolute differences between the curvature mode shapes of the damaged and undamaged beams for the first five mode shapes in which the damaged area has been represented by a sharp peak. Ravi Prakash Babu et al. [10] used the differences in curvature mode shapes to estimate the location and the depth of the cracks. They concluded that all modes should be carefully examined in order to locate multiple damages. Using a relationship between curvature and bending strain, Chance et al. [11] found that measuring curvature mode shapes directly from the measured strain gives best results than the curvature calculated from the displacement. Yazdanpanah et al. [12] combined the mode shapes, slope and curvature of mode shapes to obtain a new mode shape data based indicator (MSDBI). They concluded that this combination shows a better performance in the multiple damages detection compared with the use of each method alone.

However, all these methods require a model of undamaged structure. With the appearance of modern digital signal processing, the detection can depend only on the experimental data without the comparison with an undamaged structure. In this field, Wavelet transform is the most popular. In Refs. [13–19] the authors used Wavelet transform to decompose the mode shapes of only the cracked structures to detect cracks location by detecting the discontinuity. Xiang and Liang [20] proposed a method to detect two cracks of a cantilever beam in two steps. First, they determined the crack location by applying Wavelet transform to the mode shapes for only the damaged structure. Second, they used the measured natural frequencies as inputs to estimate the depths of the cracks from a database established by Wavelet finite element method. Jaiswal and Pande [21] applied Wavelet transform to the damaged curvature mode shape to amplify the discontinuities. They concluded that the application of Wavelet transform in the curvature is more sensitive than the mode shape for small level of damages in structures.

However, the mode shapes require a set of sensors to measure in every point of the structure, and take time for every measure to estimate detailed mode shapes. The natural frequencies are simple to measure and need a very cheap experimental procedure. For these reasons, many researchers have focused their researches on damage detection from natural frequencies. According to Doebling et al. [1], Lifshitz and Rotem [22] presented the first use of the vibration measurement for damage detection. They used the shifts in the natural frequencies through changes in dynamic modulus. Messina et al. [23] proposed a criterion based on the changes in natural frequencies named the Damage Location Assurance Criterion (DLAC). Later, the authors in [24,25] generalized the approach for multiple damages named the Multiple Damage Location Assurance Criterion (MDLAC). The approach is defined as a statistical correlation between frequencies changes from the analytical predictions and the experimental measurement. Gillich and Praisach [26] show that the curves of the natural frequencies shift have the same appearance for different damage severities in each damage location. So, to locate the damage, they compare the plotted curves of the shift of natural frequencies by measurements with those obtained by the analytically or the FEM, where, the location which gives the most resembles calculated curve, compared to the measured curve indicates the damage location. Later in Gillich and Praisach [27] and Gillich et al. [28], the authors show that mathematically the normalized frequency shift is equal to the normalized square mode shape curvature in the damage location multiplied by a coefficient which is a function of the damage severity. By dividing the normalized frequency shift values for each location to the highest value of the sequence, the authors have eliminated this coefficient, and they obtained a set of values independent of the damage severity. So, the damage can be located by correlation, where, the value of the location for which the pattern best fit the measurements indicates the damage location. Praisach et al. [29] have developed a statistical method using the superposition principle and they found that the frequency changes produced by multiple damages is the same as the sum of frequency changes produced by each single damages. They conclude that the parameters of the individual cracks can be extracted from data obtained by measurements on multiple damaged beams.

Since the natural frequencies of a cracked structure is a function of both the crack location and depth, many researchers used the detection based on the frequency contours methods. Nahvi and Jabbari [30] plotted the contours of the normalized frequencies in terms of the normalized crack location and depth using the finite element method. The authors discretized the beam into a number of elements, and the crack is supposed to be each time in an element with different depths. The intersection of contours with the constant natural frequencies gives the crack location and depth. Barada et al. [31] used an analytical approach with crack modelling using Rotational Spring Approach for plotting contours. Liang et al. [32] modelled the crack as a rotational spring to obtain plots of its stiffness with crack location for any three natural modes. The intersection of the curves gives the crack location and stiffness. Then, the crack depth is given by the use of a relationship between the crack depth and stiffness based on fracture mechanics.

Many researchers considered the crack detection as an optimization problem. The location and depth of the crack would be considered as design variables. Sinha et al. [33] presented a simplified approach to modelling cracks in beams using Euler-Bernoulli beam elements. This modelling approach is based on some modifications in the local flexibility. The crack is detected by simultaneous updating of the crack location and depth in the finite element model through the minimization of the difference between the measured and calculated natural frequencies. Moradi et al. [34] used the bees algorithm to predict a single crack in cantilever beams. The weighted sum of the squared errors between the measured and computed natural frequencies is used as the objective function. The crack is modelled by a rotational spring, whose stiffness could be determined by the depth of the crack. Moezi et al. [35] used modified cuckoo optimization algorithm, where the weighted