



Identification of embedded horizontal cracks in beams using measured mode shapes



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ABSTRACT

Mode shapes (MSs) have been extensively used to detect structural damage. This paper presents two new non-model-based methods that use measured MSs to identify embedded horizontal cracks in beams. The proposed methods do not require any a priori information of associated undamaged beams, if the beams are geometrically smooth and made of materials that have no stiffness discontinuities. Curvatures and continuous wavelet transforms (CWTs) of differences between a measured MS of a damaged beam and that from a polynomial that fits the MS of the damaged beam are processed to yield a curvature damage index (CDI) and a CWT damage index (CWTDI), respectively, at each measurement point. It is shown that the MS from the polynomial fit can well approximate the measured MS and associated curvature MS of the undamaged beam, provided that the measured MS of the damaged beam is extended beyond boundaries of the beam and the order of the polynomial is properly chosen. The proposed CDIs of a measured MS are presented with multiple resolutions to alleviate adverse effects caused by measurement noise, and cracks can be identified by locating their tips near regions with high values of the CDIs. It is shown that the CWT of a measured MS with the n -th-order Gaussian wavelet function has a shape resembling that of the n -th-order derivative of the MS. The crack tips can also be located using the CWTs of the aforementioned MS differences with second- and third-order Gaussian wavelet functions near peaks and valleys of the resulting CWTDis, respectively, which are presented with multiple scales. A uniform acrylonitrile butadiene styrene (ABS) cantilever beam with an embedded horizontal crack was constructed to experimentally validate the proposed methods. The elastic modulus of the ABS was determined using experimental modal analysis and model updating. Non-contact operational modal analysis using acoustic excitations and measurements by two laser vibrometers was performed to measure the natural frequencies and MSs of the ABS cantilever beam, and the results compare well with those from the finite element method. Numerical and experimental crack identification can successfully identify the crack by locating its tips.

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1. Introduction

Vibration-based damage detection has become one of the major research topics in the application of structural dynamics in the past few decades. Various methodologies have been developed to detect, locate, and characterize damage in structures based on vibration measurements, since physical properties of a structure, such as mass, stiffness, and damping, directly determine modal characteristics of the structure, i.e., natural frequencies, mode shapes (MSs), and modal damping ratios [1]. One criterion to categorize the methodologies is whether a model of the structure being monitored is needed. If it is needed, the methodology is model-based; otherwise, it is non-model-based. Model-based methods are capable of detecting locations and extent of damage in structures with a minimum amount of measurement information [2–4].

Model-based methods could have problems due to inaccuracy of models, environmental and other non-stationary effects on measurements, and lack of measurement data in certain frequency ranges [2]. In practice, it is difficult to construct models of most existing structures with high accuracy. Hence, methods that only analyze measured MSs or operating deflection shapes (ODSs) of a structure without the aid of a model can be good alternatives to model-based methods to locate damage, and they are non-model-based ones [5]. Since MSs are not sensitive to damage of small extent, curvatures of MSs, referred to as curvature MSs (CMSs), are used to locate damage [6]. A global trend of a CMS of a beam can be observed, and one needs to isolate the features caused by damage from the trend in order to localize the damage. Differences between CMSs of a damaged beam and those of an undamaged one are localized in a damage region and increase as the damage size increases [7]. A gapped-smoothing method was used to locate delaminations in a composite beam by inspecting smoothness of CMSs [8], and the method was extended to use broad-band ODS data [9]. For each measurement point to be inspected, a gapped cubic polynomial fitting the CMSs or curvatures of ODSs at its four neighboring points was used to eliminate global trends at the point, which is a local method and can be computationally inefficient for a dense measurement grid. The gapped-smoothing method was extended to locate damage in a beam using a global fitting method, where generic MSs were used to fit measured MSs of a damaged beam [10], and the global fitting method was extended to ODSs for damage detection on beams and plates [11]. However, the generic MSs require a priori knowledge of test structures that may not be available in practice. A crucial aspect of damage detection methods using CMSs is the calculation of derivatives of MSs. Optimal spatial sampling intervals were proposed for CMSs to avoid undersampling and oversampling of MS measurements, both of which can have adverse effects on damage detection quality [12]. A novel Laplacian scheme was developed and experimentally validated in Ref. [13] to locate a delamination zone in a composite beam using associated modal curvatures with multiple resolutions, where a local method was applied to eliminate trends of the resulting modal curvatures. Besides CMSs, wavelet transforms of MSs can be used in damage detection, since they are sensitive to localized abnormalities in MSs and can be presented with multiple scales. Cracks were identified in beams using a “symmetrical 4” wavelet function; the position of a crack was accurately identified with the aid of a beam model [14]. Damage in the forms of cracks in beams and thickness reductions in plates was identified using continuous wavelet transforms (CWTs) of MSs; it was manifested as peaks in associated CWT coefficients [15]. However, selections of the wavelet functions there failed to reflect the physical meanings of the resulting CWTs of MSs. While CWTs of differences between MSs of a damaged beam and those of the associated undamaged one can be used to locate cracks with high sensitivities [16], MSs of an undamaged beam are not always available in practice.

Beams with horizontal embedded cracks are studied in this work; they are similar to composite beams with delaminations. Natural frequencies of beams and plates would decrease if delaminations occur; the larger a delamination, the larger the reductions of the natural frequencies [17]. Free vibration analysis of a laminated beam was studied using a layerwise theory in Ref. [18]. Effects of the delamination angle, location, and size, and the number of delaminations on natural frequencies of beams were addressed there. A generalized variational principle was used to formulate equations of motion and associated boundary conditions for the free vibration of a delaminated composite beam; the coupling effect of longitudinal and bending vibrations was shown to be significant for the calculated natural frequencies and MSs [19]. Modal tests were conducted in Ref. [20] using polyvinylidene fluoride film sensors and piezoceramic patches with sine sweep actuation; backpropagation neural network models were developed using results from the beam theory and used to predict a delamination size. A spatial wavelet analysis was used in Ref. [21] to process static deformation profiles of cantilever beams to numerically and experimentally locate delaminations; deformation profiles from dense measurements were smoothed before applying the spatial wavelet analysis.

Two non-model-based methods are proposed in this work to identify embedded horizontal cracks in beams without the use of any a priori information of associated undamaged beams, if the beams are geometrically smooth and made of materials that have no stiffness discontinuities. CMSs are presented with multiple resolutions to alleviate adverse effects of measurement noise. The relationship between CWTs of MSs and CMSs is shown. MSs from polynomials of MS-dependent orders, which fit those of a damaged beam, can well approximate MSs of the associated undamaged one; the MSs of the damaged beam are virtually extended beforehand, beyond boundaries of the beam, in order to improve the approximation of the CMSs from the resulting polynomial fits to those of the associated undamaged one near the boundaries. Differences between MSs of the damaged beam and those from the resulting polynomial fits are used to yield two damage indices: the curvature damage index (CDI) and the CWT damage index (CWTDI) with a Gaussian wavelet function. Superior to the existing methods in Refs. [8–11,14–16] that locally eliminate global trends in resulting CMSs and CWTs of MSs, the proposed methods apply a global trend elimination technique that can reduce computational costs, especially for cases where multiple resolutions and scales are used to calculate CMSs and CWTs of MSs with dense measurement grids, respectively; physical interpretations of CWTDis are provided.

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