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Novel Laplacian scheme and multiresolution modal curvatures for structural damage identification

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ABSTRACT

Modal curvature is more sensitive to structural damage than directly measured mode shape, and the standard Laplace operator is commonly used to acquire the modal curvatures from the mode shapes. However, the standard Laplace operator is very prone to noise, which often leads to the degraded modal curvatures incapable of identifying damage. To overcome this problem, a novel Laplacian scheme is proposed, from which an improved damage identification algorithm is developed. The proposed step-by-step procedures in the algorithm include: (1) By progressively upsampling the standard Laplace operator, a new Laplace operator is constructed, from which a Laplace operator array is formed; (2) by applying the Laplace operator array to the retrieved mode shape of a damaged structure, the multiresolution curvature mode shapes are produced, on which the damage trait, previously shadowed under the standard Laplace operator, can be revealed by a ridge of multiresolution modal curvatures; (3) a Gaussian filter is then incorporated into the new Laplace operator to produce a more versatile Laplace operator with properties of both the smoothness and differential capabilities, in which the damage feature is effectively strengthened; and (4) a smoothened nonlinear energy operator is introduced to further enhance the damage feature by eliminating the trend interference of the multiresolution modal curvatures, and it results in a significantly improved damage trait. The proposed algorithm is tested using the data generated by an analytical crack beam model, and its applicability is validated with an experimental program of a delaminated composite beam using scanning laser vibrometer (SLV) to acquire mode shapes. The results are compared in each step, showing increasing degree of improvement for damage effect. Numerical and experimental results demonstrate that the proposed novel Laplacian scheme provides a promising damage identification algorithm, which exhibits apparent advantages (e.g., high-noise insusceptibility, insightful in damage revealment, and visualized damage presentation) over the standard Laplace operator.

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1. Introduction

Structural damage identification methods generally include two basic categories: local inspection methods and global vibration response methods. The limitations of local inspection methods mainly lie in that (1) the vicinity of the damage is known *a priori*; and (2) the structure must be readily accessible for inspections. However, these requirements usually cannot be met in practice [1]. These limitations lead to the development of more viable approaches, such as the global vibration response-based damage identification methods. The basic assumptions of global vibration response methods are that the dynamic parameters, such as natural frequencies, mode shapes, damping ratio, and frequency response functions, are directly related to the physical properties of the structures. Therefore, changes in the dynamic parameters can be used to detect, locate, and even quantify damage [1,2]. To reflect changes in local stiffness using the shift of natural frequencies is the earliest global vibration response method [3,4]. Salawu [5] presented a review on various damage identification methods utilizing the natural frequency information to indicate damage. Nevertheless, several apparent drawbacks influence the ability of natural frequency to reflect damage. For instance, the natural frequency has inferior sensitivity to minor damage and weak ability to locate the damage, and it is easily affected by environmental factors [6]. In contrast to the natural frequency, the mode shapes are found to be a better indicator to damage due to its special representation of spatial information with respect to location of damage. A review on the displacement mode shape-based damage identification was provided by Doebling et al. [1]. Nevertheless, the displacement mode shape is generally accepted to be of inadequate sensitivity to weak damage [7]. As an alternative to the mode shapes, the modal curvature is recognized as a more advanced indicator to damage due to its particular superiority in characterizing minor damage. The utilization of modal curvature to reflect damage was first proposed by Pandey et al. [8], who applied the second-order central difference to approximate the Laplace operator to calculate the curvature mode shape from the displacement mode shape, and they found that the absolute change in modal curvatures between the intact and damaged structures could be used to effectively detect and quantify damage. Salawu and Williams [9] compared the performance of both the curvature and displacement mode shapes for locating damage, and they concluded the advantages of the former over the latter. Stubbs and Kim [10] utilized the modal curvature in the form of damage index to identify damage. The modal curvature was also used as an integral part in strain energy-based damage identification methods [11–14]. Recently, Qiao and co-workers [7,14–17,39] conducted a series of studies on employing the modal curvatures to identify the crack, delamination and impact damages for composite laminated beam or plate structures using surface-bonded piezoelectric sensors.

Although the modal curvature can serve as a pervasive indicator for damage identification, the apparent limitations (or drawbacks) in the method are twofold: (1) using the second-order central difference approximation of Laplace operator to calculate the modal curvature can significantly magnify the original small errors in the mode shape [18] and (2) the rational evaluation of modal curvature requires a sufficient spatial resolution in the measurement of mode shape [19]. With the rapid development of experimental technology, the second drawback of acquiring the sufficient spatial resolution of displacement can be effectively overcome by utilizing advanced measurement instrumentation, such as scanning laser vibrometer (SLV) [15,16]. The SLV is capable of approximately realizing surface-field measurement by synchronously scanning a large number of observation points. However, the first drawback of using the central difference approximation of Laplace operator still remains a crucial theoretical and practical hurdle in the utilization of modal curvature in structural damage identification. Special attentions have recently been paid to overcome the first drawback, and the efforts have been attempted to improve measurement quality in order to alleviate the calculation noise when acquiring modal curvatures. Gautschi [20] observed that the smaller sampling intervals in the mode shapes tend to cause more noise effect when calculating modal curvatures. On the other hand, the larger sampling intervals might cause the degraded modal curvatures due to the truncation error [21]. Shi et al. [22] found that the measurement noise and incompleteness of measured modes produced a great effect on identifying the location of damage. Sazonov and Klinkhachorn [23] theoretically investigated the optimal sampling intervals by minimizing the noise effect in the calculation of modal curvature, but the key parameter of measurement error in their proposed methods could hardly be obtained in practice. Though the above studies [20–23] shed some light on the effect of sampling intervals, they cannot provide a feasible solution to alleviate influence of noise in calculating modal curvatures.

In this study, derived from modification of standard Laplace operator, a systematic damage identification algorithm in a form of a novel Laplacian scheme is proposed, aiming to overcome the "calculation error" drawback of modal curvature in reflecting damage. Unlike the standard Laplace operator, in which only a single modal curvature is generated from the mode shape, the novel Laplacian scheme characterizes the curvature property of a mode shape from a multiresolution point of view. It considers a series of modal curvatures at different resolution scales available to reveal and characterize the damage characteristics. Theoretically and practically, the novel Laplacian scheme effectively overcomes the aforementioned "calculation error" drawback, and it provides a viable damage identification algorithm based on the multiresolution modal curvatures. It should be noted that the novel Laplacian scheme is entirely different from and superior to the "modified Laplace operator" as given in [24].

The rest of the paper is organized as follows. A novel Laplacian scheme is formulated in Section 2. The basic characteristics of novel Laplacian scheme are thoroughly examined using an analytical crack beam model in Section 3. The effectiveness and applicability of novel Laplacian scheme is validated in Section 4 via an experimental program to localize delamination zone in a composite laminated beam, of which the mode shape of the beam is measured by the SLV.