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Damage identification method based on continuous wavelet transform and mode shapes for composite laminates with cutouts

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A B S T R A C T

Mode shape has been widely applied in damage identification and localization for plate-like structures. However, each mode shape has its specific sensitivity to the damage at certain location, which results in that the damage extent cannot be identified quantitatively. To improve this deficiency, mode shapes or operational deformation shapes (ODSs) with high frequencies are employed for damage identification to make sure similar sensitivity. In order to enhance the accuracy of damage identification, a damage index is proposed based on the 2D continuous wavelet transform (CWT). Numerical simulations demonstrate that the CWT is more sensitive to damage than gapped smoothing method (GSM), and the proposed method can identify damage quantitatively. Furthermore, a composite plate with cutout was experimentally studied. The damage around the cutout were obviously quantitatively detected by the proposed method with ODSs at high frequencies and are in high agreement with that of ultrasound testing.

1. Introduction

With an expanding application of composite materials in industries, such as aerospace, aircraft as well as energy and civil engineering [1–3], the simple composite structures cannot meet the rapidly growing demands of more complex and multifunctional structural designs. Hence, complicated composite structures, like stiffened composite laminates, sandwich composite structures or composite laminates with cutouts, are increasingly developed and studied. Composite laminates with cutouts, such as the windows of aircrafts, are unavoidable in engineering, but cutouts can result in serious stress concentration or local buckling to induce damage around them [4]. Therefore, how to identify the damage for composite laminates with cutouts is a crucial issue in non-destructive testing (NDT) research field [5,6].

Nowadays, many damage identification methods have been developed for composite structures, such as acoustic emission[7], X-ray [8], thermography [9], ultrasonic C-scan [10], guided-wave method [11] and vibration based method [12] etc. Acoustic emission can only monitor and locate the damage when it is occurring. Thermography, X-ray and ultrasonic C-scan methods are developed for detecting the damage of composite laminates, such as the delamination, debonding and impact damage etc. However, none of them is suitable for on-site monitoring complex structures. Guided-wave methods have the potential for on-site detection, but the difficulty of analyzing the complicated guided waves generally causes a mandatory need of the baseline from intact structure. Nevertheless, vibration based method can be a promising NDT method with the on-site monitoring strategy and baseline-free possibility for composite structures.

Vibration based methods have been developed for damage identification for decades. In the early time, many researchers concentrated on mode frequency based methods to detect the cracks in beam-like structures or rotor gears [13] etc. Mode frequency based methods are attractive because the mode frequency with a good noise resistance can be precisely obtained by only several measured points [14]. However, as a global structural parameter, mode frequency is hardly used in practice to detect damage since the change caused by damage is usually small and undetectable. In addition, the mode frequency has no sensitivity to damage location. With the development of NDT technology, the methods based on mode shapes [15] become more efficient for damage location. In order to enhance the sensitivity to small damage, Pandey et al. [16] firstly suggested that the mode shape curvature was more sensitive to small damage than the mode shape. Furthermore, to improve the effectiveness of damage identification and evaluation, many modern signal processing technologies are introduced to analyze the mode shape or mode shape curvature as a spatial-domain data to detect the discontinuity caused by damage [17]. Although many efforts have been made to propose the NDT methods without baseline, only a few approaches can reach good detection results. Especially, fractal

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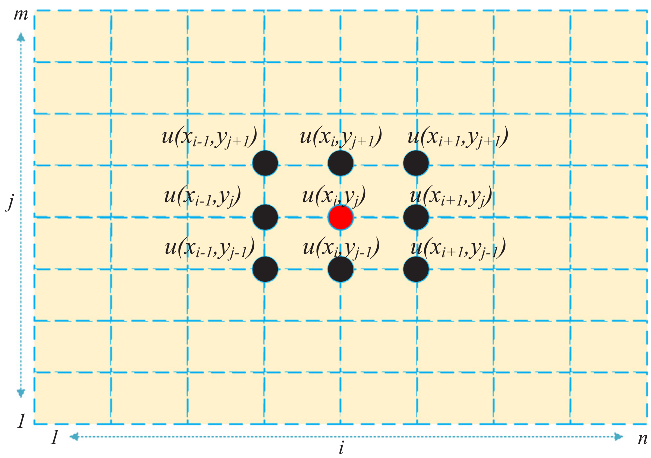

Fig. 1. A schematic of discrete points of vibration data.

Table 1
Material properties of lamina.

ρ (kg/m^3)	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}
1520.7	174.6	10.3	6.21	6.21	3.64	0.26

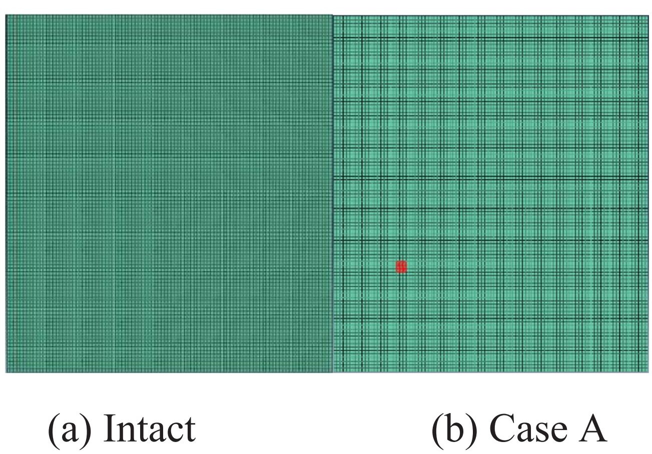

Fig. 2. FEM models (red mark represents the damage location). (a) Intact; (b) Case A. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
mode frequencies of intact and damage laminates.

Model	Mode 1	Mode 2	Mode 3	Mode 31	Mode 32	Mode 33
Intact (Hz)	60.2	63.0	101.8	1180	1205	1289
Case A (Hz)	60.2	63.0	101.7	1180	1205	1288

dimension method [15] and gapped smoothing method (GSM) [18,19] have better performance. In this paper, GSM is chosen as a reference method to compare with proposed method for the damage detection without baseline.

The wavelet transform is one of the most important signal processing methods and can been developed for damage identification. The first application of the wavelet transform is conducted by Liew et al. [20]. They used 1D wavelet transform to detect the crack in a simple supported beam. Then 1D wavelet transform is developed for damage detection of beam-like structures [21–24]. Furthermore, 2D wavelet transform is also developed as a reliable method to detect damage in plate-like structures [25–27]. When the scanning laser vibrometer (SLV) is applied in damage detection of plate-like structures, a no contact measurement with high density data at high sampling rate can be achieved [28], so it provides an opportunity for the continuous wavelet transform (CWT) to analyze the mode shape with higher resolution. Recently, Cao et al. [29] combined Mexican hat wavelet transform with Teager Energy Operator (TEO) to process the mode shape curvatures for the crack detection in beams. The proposed method was demonstrated by several numerical cases of cracked beams in noisy conditions and validated by an experiment of a cracked aluminum beam. Gholizad and Safari [30] proposed a new 2D-CWT based signal processing technology to process the mode shape of space structure as a 2D spatially distributed signal. The reliability and applicability of the method for damage localization in space structures were demonstrated by numerical simulations of three types of double-layer space structures. However, the NDT methods based on mode shapes can identify and locate the damage, but for multi-damage detection, it is difficult to evaluate the severity of each damage quantitatively. This is because the different mode shapes have the different sensitivities for the damage at the same location, and the same mode shape has the different evaluations for the same damage at different locations. Therefore, the vibration-based method needs the baseline to estimate the damage extent in many situations. However, this shortcoming limits the on-site application of this method and needs to be improved to identify multiple damage without baseline.

In this paper, a 2D CWT method is proposed to analyze the vibration data for damage identification of composite laminate without baseline. Firstly, a damage index is proposed by the 2D Morlet wavelet transform to identify a single damage in composite laminate successfully. In a comparison with the GSM, the CWT is more sensitive to damage and has a better noise resistance, especially using high order modes. For multi-damage detections, the damage index is obtained by a combination of several high frequency mode shapes for a better location-free evaluation of damage severity. At last, considering a composite laminate with a cutout damaged by unidirectional tension, the damage was identified experimentally by proposed method using high order operation deformation shapes (ODSs).

2. Damage identification method based on 2D CWT

2.1. Vibration data

For damage identification method based on vibration, the first step is to obtain vibration data like mode shapes or ODSs. Mode shapes can reveal the local information disturbed by the damage, so they can be employed for damage identification and location. In fact, the mode shape is usually less sensitive to damage than the mode shape curvature. Therefore, mode shape curvature is employed in this paper for damage identification. A schematic of mode shape with m× n discrete points is shown in Fig. 1. The curvature $\nabla^2 u$ of point can be calculated by using a centered finite difference method from mode shape $u(x,y)$ as

$$\nabla^2 u(x_i,y_j) = \frac{u(x_{i+1},y_j) - 2u(x_i,y_j) + u(x_{i-1},y_j)}{h_x^2} + \frac{u(x_i,y_{j+1}) - 2u(x_i,y_j) + u(x_i,y_{j-1})}{h_y^2} \tag{1}$$

where h_x and h_y are the uniform grid spacing between the discrete points along x and y directions, respectively.

Damage identification method usually employs more than three mode shapes in one detection to avoid the missing detection on the nodal point of a certain mode shape. In general, mode shapes have different sensitivities to the damage on different locations as mentioned above. Therefore, for the quantitative damage identification, a location-free method needs to be developed, even though it is very difficult for many vibration based methods. Although the exactly same sensitivity of damage for whole detection field is hard to achieve, we attempt to