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Delamination monitoring in CFRP laminated plates under noisy conditions using complex-wavelet 2D curvature mode shapes

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Abstract
Delamination monitoring in carbon fiber reinforced polymer (CFRP) laminated plates is crucial to ensure the integrity and safety of the structures that accommodate the plates. To identify delaminations in CFRP laminated plates, the two-dimensional (2D) curvature mode shape method is a prevailing method that features instant and simultaneous determination of the presence and location of the delamination. However, this method has two noticeable deficiencies in characterizing incipient small-sized delaminations, namely lack of damage sensitivity and inadequate noise robustness. To this end, this study proposes a new dynamics feature of the complex-wavelet 2D curvature mode shape to discriminate small-sized delaminations. This feature is delicately formulated based on the integration of the 2D curvature mode shape with the complex wavelet. The complex-wavelet 2D curvature mode shape is superior to the 2D curvature mode shape by virtue of its stronger damage sensitivity and noise robustness. These merits can be attributed to the adjustable localization and the multi-scale properties of the second-order Gabor wavelet, respectively. Proof of concept of the complex-wavelet 2D curvature mode shape is numerically undertaken in a finite-element laminated CFRP plate with a small-sized delamination, with emphasis on sensitivity to damage and robustness against noise. The applicability of the feature is experimentally validated on a CFRP laminated plate with a small-sized delamination, whose mode shapes are acquired via the non-contact measurement using a scanning laser vibrometer. The numerical and experimental results show that the complex-wavelet 2D curvature mode shape can effectively designate the presence and location of the delaminations in CFRP laminated plates under noisy conditions.

Keywords: mode shape, curvature mode shape, complex wavelet, CFRP laminated plate, delamination monitoring, complex-wavelet 2D curvature mode shape, scanning laser vibrometer

(Some figures may appear in colour only in the online journal)

1. Introduction

Carbon fiber reinforced polymer (CFRP) laminates are increasingly utilized in aerospace, mechanical, and civil engineering for their low density, high strength and stiffness, and resistance to fatigue and corrosion. However, impact-caused delamination damage is the major concern for the safety of CFRP laminated plates [1–5]. Impact such as hailstone strike, bird strike, or dropping of tools can cause delaminations between interfaces of plies in CFRP laminated
plates. Incipient small-sized delamination damage can be barely judged from the appearance of a CFRP laminated plate, and is referred to as barely visible impact damage (BVID) [3]. Incipient delaminations can accumulate and develop, then induce entire destruction of structures. Hence, delamination monitoring is crucial to ensure the integrity and safety of the structures that accommodate the CFRP laminated plates [6–8]. To this end, delamination identification methods have been rapidly developed in recent years.

Delaminations in CFRP laminated plates can be detected by local inspection techniques such as x-ray [9], C-scan [10], ultrasonic imaging [11]. However, the approximate region of delamination needs to be known a priori [12]. In the recent two decades, global methods including the strain method [13–17], eddy current method [18, 19], electrical potential method [20], thermography method [21–24], shearography method [25], and wave method [26, 27] have been developed, whereby delamination-caused changes of specific physical quantities at delamination locations can be utilized to detect and locate delaminations.

Recently, the vibration method for identifying delaminations in CFRP laminated plates has attracted increasing attention. Gaudenzi et al [28] utilized a couple of piezoelectric patches to actuate and sense the vibration of CFRP plates. Delamination features could be extracted from the vibration response by the wavelet packet transform and enhanced by linear discriminant analysis (LDA). The experimental results showed that delaminations could be effectively detected by this method. By such actuating and sensing techniques, Nardi et al [29] detected the delamination in CFRP laminated plates using the auto-regressive model and LDA. Their experimental results showed that the presence of the delamination could be effectively detected. Polimeni and Meo [30] presented the nonlinear resonance ultrasound and nonlinear wave modulation spectroscopy methods based on the nonlinear behavior of delaminations. Shifts of resonance frequencies and harmonics on the spectrum clearly detected the presence of delaminations in carbon fiber composite plates. Singh et al [31] established finite-element (FE) models of carbon fiber reinforced composite plates to study the nonlinear vibration created by the opening and closing of the delamination gap. The presence of harmonics indicated the nonlinearity caused by the delamination. Araújo dos Santos et al [32] measured mode shapes of a carbon fiber reinforced epoxy plate using the TV holography and acoustic excitation. Differences in the 2D curvature mode shapes (CMS$^{2D}$) between undamaged and damaged plates were used to identify impact-caused delaminations. The results showed that the method could clearly locate the delamination. Pérez et al [33] proposed a curvature damage factor that was formulated using natural frequencies and CMS$^{2D}$ of pristine and damaged CFRP plates. Their experimental results showed that the curvature damage factor could determine the location of the impact-caused delamination.

Among the vibration methods to identify delaminations in CFRP laminated plates, the CMS$^{2D}$ method is a prevailing method that features instant and simultaneous determination of the presence and location of the delamination [34]. It has an advantage in locating delaminations over other vibration methods that can only detect the presence of delaminations. However, for incipient small-sized delaminations, the two noticeable deficiencies of the CMS$^{2D}$ method, i.e., lack of damage sensitivity and inadequate noise robustness, hinder its applicability to damage detection and localization [35]: slight changes in the CMS$^{2D}$ caused by small-sized delaminations can be obscured by the global trends of the CMS$^{2D}$; on the other hand, small spatial sampling intervals are required to match the size of the delamination, whereby noise components inevitably involved in densely sampled mode shapes can cause intense noise interference in the CMS$^{2D}$ due to the second-order differentiation. Addressing these two deficiencies of the CMS$^{2D}$, this study proposes the complex-wavelet (CW) 2D curvature mode shape (CW-CMS$^{2D}$), a dynamics feature that is delicately formulated based on the integration of the CMS$^{2D}$ with the CW. The CW-CMS$^{2D}$ features much stronger damage sensitivity and noise robustness than the CMS$^{2D}$ owing to the mathematical properties of the CW, and is therefore capable of detecting and locating small-sized delamination in CFRP laminated plates under noise conditions.

The rest of this paper is organized as follows. Section 2 introduces the CMS$^{2D}$ and the CW, based on which the CW-CMS$^{2D}$ is formulated. Section 3 numerically proves the concept of the CW-CMS$^{2D}$ for detecting and locating small-sized delaminations in CFRP laminated plates, with emphasis on its sensitivity to damage and robustness against noise. Section 4 experimentally validates the applicability of the CW-CMS$^{2D}$ to delamination identification in CFRP laminated plates, whose mode shapes are acquired via non-contact laser measurement using a scanning laser vibrometer (SLV). Section 5 presents the conclusions of this study.

2. Complex-wavelet 2D curvature mode shape

2.1. 2D curvature mode shape

The CMS$^{2D}$ of a plate is the sum of the partial derivatives of the mode shape $W(x, y)$ with respect to $x$ and $y$, denoted as $\nabla^2 W(x, y)$ [36, 37]:

$$\nabla^2 W(x, y) = \frac{\partial^2 W(x, y)}{\partial x^2} + \frac{\partial^2 W(x, y)}{\partial y^2}. \quad (1)$$

For a vibrating thin plate, the bending moments $M_x(x, y)$ and $M_y(x, y)$ in the $x$- and $y$-directions can be expressed as [38]

$$M_x(x, y) = -D(x, y)\left(\frac{\partial^2 W(x, y)}{\partial x^2} + \nu\frac{\partial^2 W(x, y)}{\partial y^2}\right), \quad (2.1)$$

$$M_y(x, y) = -D(x, y)\left(\frac{\partial^2 W(x, y)}{\partial y^2} + \nu\frac{\partial^2 W(x, y)}{\partial x^2}\right), \quad (2.2)$$

where $D = \frac{Eh^3}{12(1-\nu^2)}$ is the flexural rigidity with $E$ the Young’s modulus, $\nu$ the Poisson ratio, and $h$ the thickness of the plate. By substituting equation (2) into equation (1), $\nabla^2 W(x, y)$ can be further expressed as [35]

$$\nabla^2 W(x, y) = -\frac{1}{1 + \nu}\left(\frac{M_x(x, y)}{D(x, y)} + \frac{M_y(x, y)}{D(x, y)}\right). \quad (3)$$
Equation (3) reveals the mechanism of the CMS2D for representing damage in a plate: damage can change the local flexural rigidity of the plate and this change entails alteration in the CMS2D; hence, the modification of the CMS2D can manifest the presence and location of damage in the plate.

The CMS2D method is a non-baseline method, that is, with no requirement for structural baseline information, such as temperature, materials, geometry, and boundary conditions. Besides, the CMS2D possesses the property of isotropy, as temperature, materials, geometry, and boundary conditions are typically involved in the measured mode shapes, and the second-order differentiation of the CMS2D can considerably amplify any slight noise present in the measured mode shapes, masking actual damage-caused changes in the CMSs2D [35]. However, noise components are inevitably involved in the measured mode shapes, and the second-order differentiation of the CMSs2D can considerably amplify any slight noise present in the measured mode shapes, masking actual damage-caused changes in the CMSs2D [35].

Rather than directly using the sum of the partial derivatives to represent the $\nabla^2 W$ by equation (1), in this study, an alternative scheme is utilized to equivalently represent the CMS2D: first, the second-order derivatives at $(x_0, y_0)$ in the $x$- and $y$-directions are calculated by rows and columns, along $y = y_0$ and $x = x_0$, respectively [39]; then the results in the $x$- and $y$-directions are totalled:

$$
\nabla^2 W(x, y)|_{x=x_0}^{y=y_0} = \left[ \frac{\partial^2 W(x, y)}{\partial x^2} + \frac{\partial^2 W(x, y)}{\partial y^2} \right]_{x=x_0}^{y=y_0}
\n= \frac{\partial^2 W(x, y)}{\partial x^2} \bigg|_{x=x_0}^{y=y_0} + \frac{\partial^2 W(x, y)}{\partial y^2} \bigg|_{x=x_0}^{y=y_0}
\n= \frac{d^2 W(x, y_0)}{dx^2} \bigg|_{x=x_0}^{y=y_0} + \frac{d^2 W(x_0, y)}{dy^2} \bigg|_{x=x_0}^{y=y_0}.
$$

(4)

Figure 1. Laminated plate with a rectangular delamination (marked in gray) with dimensions in millimeters.

This equivalent calculation procedure of the CMS2D is advantageous for simplifying calculation of the subsequent CW-CMS2D.

2.2. Complex-wavelet 2D curvature mode shape

The second-order Gabor wavelet $G_2(x)$ can be expressed as [40]

$$
G_2(x) = (-1)^2 \frac{d^2 G(x)}{dx^2} = (g''(x) - \gamma^2)
\times g(x) + 2\gamma g'(x)i e^{i\gamma x},
$$

(5)

where $G(x) = g(x)e^{i\gamma x}$ is the Gabor function with $g(x)$ the Gaussian function, $i$ the imaginary unit, and $\gamma$ the frequency translation parameter. The mother wavelet $G_2(x)$ satisfies the zero-mean condition [41]:

$$
\int_{-\infty}^{\infty} G_2(x)dx = 0,
$$

(6)

and the admissibility condition:

$$
\int_{-\infty}^{\infty} \left| \hat{G}_2(\omega) \right|^2 d\omega < \infty,
$$

(7)

where $\hat{G}_2(\omega)$ is the Fourier counterpart of $G_2(x)$ via Fourier transform. Details of the second-order Gabor wavelet can be found in the [40].

The wavelet transform (WT) using $G_2(x)$ can be expressed as [41]

$$
Wf(s, u) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} f(x)G_2^*(\frac{x-u}{s})dx = f* G_2(s, u),
$$

(8)

where $s$ and $u$ are defined as the scale and spatial translation parameters, respectively; $Wf(s, u)$ is called the WT coefficient of $f(x)$; $G_2^*(s, u) = \frac{1}{s} G_2^*(\frac{u}{s})$; $G_2^*(s)$ denotes the complex conjugate of $G_2(x)$; $f* G_2(s, u)$ denotes the convolution of $f$ with $G_2(s, u)$, with $*$ denoting convolution.

Figure 2. Mode shape with SNR 80 dB.
By ameliorating the CMS\textsuperscript{2D} with the CW \cite{40}, the CMS\textsuperscript{2D} expressed in equation (4) is transformed to the CW-CMS\textsuperscript{2D}, denoted as $W_{sv}^* (u, v)$. $W_{sv}^* (u, v)$ at $(x_0, y_0)$ can be expressed as:

\[
W_{sv}^* (u, v) |_{u=x_0, v=y_0} = W(u, y_0) \ast \overline{G_2} (u) |_{u=x_0} + W(x_0, v) \ast \overline{G_2} (v) |_{v=y_0} = s^2 \frac{d^2}{dx^2} W(u, y_0) \ast \overline{G_2} (u) |_{u=x_0} + s^2 \frac{d^2}{dv^2} W(x_0, v) \ast \overline{G_2} (v) |_{v=y_0}, \tag{9}
\]

where $u$ and $v$ are spatial translation parameters in the $x$- and $y$-directions, respectively, $\overline{G_2} (x) = \frac{1}{\sqrt{s}} G(x \sqrt{s})$. The essential relationship between equations (4) and (9) is that $W$ in equation (4) is convolved with $\overline{G_2}$ in the $x$- and $y$-directions and scaled by $s^2$ in equation (9). The sum of modulus of the two terms in $W_{sv}^* (u, v)$ can be used for damage identification in plates, whose singularity peaks can be used for detecting and locating damage \cite{41}. Owing to the adjustable localization property of the second-order Gabor wavelet \cite{40}, the CW-CMS\textsuperscript{2D} features stronger damage sensitivity than the CMS\textsuperscript{2D}. On the other hand, owing to the multi-scale property of the second-order Gabor wavelet, noise interference can be gradually eliminated as the scale increases \cite{41, 42}. It is worth

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure3.png}
\caption{CMS\textsuperscript{2D} of (a) noise-free and (b) noisy mode shapes.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure4.png}
\caption{(a) CW-CMS\textsuperscript{2D} and (b) its planform.}
\end{figure}
noting that as the CW-CMS$^{2D}$ is linearly transformed from the CMS$^{2D}$, it also features the properties of non-baseline and isotropy.

3. Proof of concept

Proof of concept of the CW-CMS$^{2D}$ to detect and locate small-sized delaminations is numerically undertaken in a CFRP laminated plate simulated by the FE method, with emphasis on sensitivity to damage and robustness against noise.

3.1. Specimen description

A four-layer CFRP laminated plate has dimensions 500 mm $\times$ 500 mm $\times$ 1.5 mm in the x-, y-, and z-directions, respectively. The plate is modeled by the FE software ANSYS with 3D elements whose size is 1.25 mm $\times$ 1.25 mm $\times$ 0.375 mm in the x-, y-, and z-directions, respectively. A 10 mm $\times$ 10 mm rectangular small-sized delamination is modeled by inserting a non-thickness interface between interfaces of the second ply and the third ply; on the non-thickness interface, the coincident nodes in adjacent but separated elements are distributed [43]. The delamination is centered at $x = 125$ mm and $y = 375$ mm, spanning from 120 mm to 130 mm, 370 mm to 380 mm in the x- and y-directions, respectively (figure 1). Without loss of generality, by introducing dimensionless coordinates $\zeta = \frac{x}{500}$ and $\eta = \frac{y}{500}$, the delamination is centered at $\zeta = 0.25$ and $\eta = 0.75$, spanning from 0.24 to 0.26, 0.74 to 0.76 in the $\zeta$- and $\eta$- directions, respectively. The surface of the plate that belongs to the first ply is defined as the front surface and the other surface is the back surface. By the modal analysis, densely sampled out-of-plane mode shapes in the $z$-direction are extracted from $401 \times 401$ densely distributed nodes on the

![Figure 5. Planforms of CW-CMS$^{2D}$ at noise levels of SNR (a) 75, (b) 70, (c) 65, and (d) 60 dB.](image)
back surface; for generality, each mode shape has a unit maximum amplitude.

3.2. Detecting and locating small-sized delaminations

To simulate actual measurements with environmental noise components involved in mode shapes [44], white Gaussian noise is generated using the AWGN module in Matlab and added to the noise-free mode shape to constitute a noisy mode shape. A measured mode shape with signal-to-noise ratio (SNR) 80 dB is arbitrarily selected and demonstrated in figure 2, which appears as a relatively smooth surface with no visible noise interference.

3.2.1. CMS2D. The CMS2D $\nabla^2 W$ is obtained from the noise-free mode shape by equation (4), and shown in figure 3(a). It can be seen from figure 3(a) that the global trends dominate the $\nabla^2 W$ and obscure the change caused by the small-sized delamination. In the $\nabla^2 W$ obtained from the noisy mode shape (figure 3(b)), it can be seen that intense noise interference has an overwhelming influence on the $\nabla^2 W$. As mentioned in the introduction, lack of damage sensitivity and inadequate noise robustness severely impair the capability of the CMS2D to detect and locate small-sized delaminations in laminated plates.

3.2.2. CW-CMS2D. The CW-CMS2D $W_8^*$ is obtained by equation (9) with the optimal $\gamma$ being 3 after several trials. By increasing the scale parameter to the satisfying value $s = 8$, noise interference in $W_8^*$ (figure 4(a)) is significantly reduced. Noticeably, abnormal wavelet coefficients occur near the boundaries of $W_8^*$, referred to as the boundary effect of the WT on a signal with finite length. Interpolation [45] and padding [46] methods are two types of manipulation to deal with this boundary effect. For simplicity in practice, another simple type of manipulation of vanishing abnormal wavelet coefficients [35, 43, 47, 48] is employed in this study. The $W_8^*$ in figure 4(a) bears a sharply rising singular peak, clearly designating the presence of the delamination. In its planform (figure 4(b)), the top of the peak clearly pinpoints the delamination: the identified delamination is centered at $\zeta = 0.25$ and $\eta = 0.75$, spanning from about 0.24 to 0.26, 0.74 to 0.76 in the $\zeta$- and $\eta$- directions, which corresponds to the actual delamination location.

3.2.3. Noise robustness. To further verify the noise robustness of the CW-CMS2D, noise levels over a wide range decreasing from SNR 75 to 60 dB with a step of 5 dB are considered for the mode shape of the plate. At the noise level of SNR 75 dB, the scale is increased from 8 to 9 to better suppress the increased noise interference; the peak in the $W_8^*$ still unambiguously pinpoints the delamination (figure 5(a)). At the noise levels of SNR 70, 65, and 60 dB, $W_{10}^*$, $W_{11}^*$, and $W_{12}^*$ are generated at scale $s = 10, 11, \text{ and } 12$, as shown in figures 5(b)–(d), respectively. Although noise-caused burrs become more and more intense, the singular peaks can still be clearly identified at the actual delamination location.

4. Experimental validation

The applicability of the CW-CMS2D is validated on a CFRP laminated plate with a small-sized delamination, whose mode shapes are acquired via non-contact laser measurement using a SLV.
4.1. Experimental specimen and setup

The CFRP laminated plate consisting of four plies has dimensions $500 \text{ mm} \times 500 \text{ mm} \times 1.5 \text{ mm}$ in the $x$-, $y$-, and $z$-directions, respectively. A delamination ($15 \text{ mm} \times 15 \text{ mm}$) was manufactured by inserting a rectangular Teflon sheet between the interfaces of the second ply and the third ply when the laminated plate was fabricated. The $50 \mu\text{m}$ thick Teflon sheet can be regarded as having no thickness compared to the ply. The delamination is centered at $x = 125 \text{ mm}$ and $y = 375 \text{ mm}$, spanning from $117.5 \text{ mm}$ to $132.5 \text{ mm}$, $367.5 \text{ mm}$ to $382.5 \text{ mm}$ in the $x$- and $y$-directions, respectively (figure 6). In dimensionless coordinates, the delamination is centered at $\zeta = 0.25$ and $\eta = 0.75$, spanning from $0.235$ to $0.265$, $0.735$ to $0.765$ in the $\zeta$- and $\eta$- directions. At the delamination location, the surface of the laminated CFRP

Figure 7. Experimental specimen: (a) CFRP laminated plate with barely visible delamination (b) whose outlines (c) are marked in white.
plate (figure 7(a)) is totally flat, and the delamination can be
barely visible from the appearance even in a zoomed-in view
(figure 7(b)). The surface of the plate that belongs to the first
ply is defined as the front surface and the other surface is the
back surface. Outlines of the delamination are marked in
white on the front surface (figure 7(c)). A circular lead-zir-
conate-titanate (PZT) actuator with diameter of 10 mm is
placed at the geometrical center of the front surface to excite
the plate, while a SLV (Polytec PSV-400) is employed to scan
the whole back surface of the plate covered by reflection tapes. As the laser measurement is non-contact, out-of-plane
vibration responses from $371 \times 371$ densely distributed
measurement points are measured. On the other hand, intense
noise interference can occur in the CMSS$^{3D}$ of densely sam-
ples mode shapes [35, 49, 50]. The experimental setup is
shown in figure 8. After the modal analysis, operating
deflection shapes (ODSs) can be obtained by exciting the
plate using the PZT actuator [51–54] at natural frequencies

![Experimental setup: SLV and CFRP laminated plate covered by reflection tapes.](image)

![Figure 9. ODS.](image)  
![Figure 10. CMS$^{3D}$.](image)
and measuring vibration responses on the back surface using the SLV; such ODSs can be regarded as mode shapes when the damping is small [55].

4.2. Experimental results

4.2.1. CMS 2D. The ODS at the natural frequency of 3184.375 Hz (figure 9) is regarded as the mode shape at that natural frequency. As per equation (4), the CMS 2D $\nabla^2 W$ is obtained and shown in figure 10. It can be seen from the figure that intense noise interference dominates the $\nabla^2 W$, and the presence of delamination in the CFRP laminated plate cannot be detected.

4.2.2. CW-CMS 2D. The CW-CMS 2D $W_s^*$ is obtained by equation (9) with the optimal $\gamma$ being 3 after several trials. By increasing the scale parameter to the satisﬁcing value $s = 8$, the noise interference in $W_s^*$ (figure 11(a)) is basically eliminated. It can be seen from the figure that the $W_s^*$ bears a sharply rising singular peak, clearly designating the presence and location of the delamination. In its planform (figure 11(b)), the top of peak clearly pinpoints the delamination: the identified delamination is centered at $\zeta = 0.25$ and $\eta = 0.75$, spanning from about 0.235 to 0.265, 0.735 to 0.765 in the $\zeta$- and $\eta$- directions, respectively, corresponding to the actual delamination location. The abnormal values of $W_s^*$ have vanished near the boundaries. It should be noted that as the excitation can cause abnormal values in the WT result [43], the $W_s^*$ near the geometrical center where the PZT actuator is placed have vanished as well.

5. Conclusions

Two deﬁciencies of the CMS 2D, lack of damage sensitivity and inadequate noise robustness, hinder the applicability of the CMS 2D to detection and localization of small-sized delaminations in CFRP laminated plates. Addressing this problem, this study proposes the CW-CMS 2D, a dynamics feature that is delicately formulated based on the integration of the CMS 2D with the CW. The numerical and experimental results show that the CW-CMS 2D is capable of designating the presence and location of the delaminations in CFRP laminated plates under noisy conditions. The method holds promise for developing a delamination monitoring system for CFRP laminates. Some conclusions are drawn as follows.

(1) Superior to the CMS 2D, the CW-CMS 2D features stronger damage sensitivity owing to the adjustable localization property of the second-order Gabor wavelet, whereby details of small-sized delamination can be depicted.

(2) Superior to the CMS 2D, the CW-CMS 2D features stronger noise robustness due to the multi-scale property of the second-order Gabor wavelet, whereby noise interference can be eliminated at a satisﬁcing scale.

(3) The CW-CMS 2D method is a non-baseline method, in no need of structural baseline information, such as temperature, materials, geometry, and boundary conditions. Moreover, the CW-CMS 2D possesses the property of isotropy, capable of depicting delamination details in every direction.

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