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Localization of damage with speckle shearography and higher order spatial derivatives

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ABSTRACT

Two speckle shearography systems are described in this paper. The first is based on stroboscopic laser illumination and temporal phase modulation, whereas the second system relies on double pulse laser illumination and spatial phase modulation. These systems are applied to measure the phase maps of modal rotation fields of a damaged laminated composite plate. In order to decrease the propagation of noise, a new differentiation methodology is presented. It relies on the differentiation of the measured phase maps before they are post-processed. This leads to an improvement in the localization of damage. It was found that the fourth order spatial derivative of mode shapes also presents better damage localizations, in particular with the phase maps measured by the first shearography system.

1. Introduction

The use of composite materials in lightweight structural applications, such as those developed in the automotive and aeronautical industries, has seen a huge increase in recent decades. These materials present types of defects and damage mechanisms different from those of metals. The lack of effective and global non-destructive inspection techniques motivated the development of new methodologies based on the vibrational characteristics of structures. Due to the complexity of the problem and the difficulty in finding a robust solution, different approaches have been proposed [1–14]. This large number of approaches indicates that a universal method applicable to all kind of structures and damage types is not available [15]. Nevertheless, methods of damage localization based on the analysis of perturbations or discontinuities in modal curvatures or strain fields are the most well established and applied. Pandey et al. [1] proposed the use of differences between curvature mode shapes of damaged and undamaged beams. Ratcliffe [3] proposed the use of polynomial functions, fitted with the data of the Laplacian operator, which is similar to beam curvatures, and applied it to the damaged modes, instead of the undamaged ones. Sampaio et al. [4] expanded the use of curvatures of mode shapes to a desired frequency spectrum by using frequency response functions (FRF). The FRF curvatures have also been used by Maia et al. [14], but taking into account the number of times that each sensor has a maximum. All these works are applied to the analysis of isotropic beams. Lestari et al. [9] expanded the method of curvature mode shape differences to carbon/epoxy beams. Guan and Karbhari [10] presented an improvement to the computation of curvatures for sparse measurements, based on the use of a

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polynomial depending on vertical displacements and rotations. This polynomial can be differentiated twice to obtain the curvature. Methods based on higher order derivatives have also been developed in recent years. Ismail and Abdul Razak [16] proposed the use of the ratio between the fourth order derivative of a mode shape and the mode shape itself as a damage indicator for Euler–Bernoulli beams. A similar method along with statistical treatment was proposed by Gauthier et al. [17]. Whalen [18] compared the results for second, third and fourth derivatives of the mode shapes using an analytical model of damage. Santos et al. [19] used the Timoshenko beam model and defined several damage localization indicators based on higher order derivatives of modal displacements and rotation fields. Abdo [20] extended some of these damage indicators by applying them to plates, using the summation of fourth derivatives in the x and y directions. The derivatives needed in all these methods can only be obtained by numerically differentiating experimental modal displacements or rotations. In order to minimize the amplification and propagation of experimental noise, due to the numerical differentiation process, accurate modal full-fields measurements are required [21,22].

In conventional experimental modal analysis, the use of accelerometers or other kind of contact sensors, the gluing materials and the need for connecting cables result in the addition of mass to the system. Depending on the masses ratio and its location relatively to the modal amplitude, a significant change in the dynamic behavior of the structure can take place. Moreover, the number of measured points is usually small, leading to a set of sparse measurements. On the other hand, speckle interferometry techniques, such as electronic speckle pattern interferometry (ESPI) and speckle shearography, allow full-field, non-contact and high sensitivity resolution measurements of the modal displacement and modal rotation fields of the structures surface, respectively. The main limitation of the ESPI technique comes from the high density of fringes obtained from measurements of displacements fields, including the rigid-body displacements, which makes difficult the interpretation of the fringe patterns [23–25]. However, speckle shearography provides a way to measure displacement gradients, being therefore practically insensitive to rigid-body motions. In addition, it requires a simpler optical interferometer setup and a laser with low coherence length. Thus, more compact systems can be built, which are also more robust to external perturbations. Shearography is based on the principle of the speckle interference between two wavefronts reflected by the surface of the object. These two wavefronts are laterally shifted, i.e. sheared. This shift can be created using a glass-shaped wedge placed in the front half of the lens, a rotation of two glass plates, a Wollaston prism or a Michelson optical interferometer setup with a slight rotation of one of the mirrors [26]. The last option is preferred, since it allows an easy adjustment of the shearing value. Another alternative, which does not require moving parts, is proposed in Ref. [27]. A comprehensive description of shearography and its applications can be found in Refs. [28–38]. Recent reviews of this technique can also be found in Refs. [39–41].

A damage localization method based on the analysis of second and third order spatial derivatives of measured modal rotation fields is proposed in this paper. Since the rotation field corresponds to the first spatial derivative of the displacement field, the second and third derivatives of the rotations correspond to the third and fourth derivatives of the displacements, respectively. Therefore, the direct measurement of rotation fields has the advantage of reducing the order of the numerical differentiation by one. The modal rotations of a multi damaged laminated composite plate are measured using speckle shearography with stroboscopic laser illumination and temporal phase modulation. The experimental measurements thus obtained present a higher signal-to-noise ratio when compared with previous ones, obtained using speckle shearography with pulsed laser [22]. Besides these improvements in the quality of the experimental measurements, a new differentiation methodology is proposed. Unlike previous works (see e.g. [22]), the differentiation is performed before the phase maps are post-processed, thus leading to a decrease in the propagation of noise. The higher order spatial derivatives of the modal rotations of a laminated composite plate are computed by applying central finite differences. These derivatives are also filtered, using low pass filters. The damages are directly localized by analyzing the perturbations in the second, third and fourth spatial derivatives of the out-of-plane modal displacements. Thus, there is no need for previous knowledge of the undamaged structure behavior.

2. Methods

2.1. Speckle shearography

Speckle shearography has been mainly applied to the measurement of static rotation fields, because of its simple experimental arrangement. However, the measurement of dynamic responses requires the use of more complex illumination and synchronization systems. This leads to an experimental setup which is more difficult to adjust. Therefore, reports on efficient and accurate measurements of vibration responses using speckle shearography are relatively recent [24,42,43]. Before these works, modal rotation fields, which can be viewed as gradients of mode shapes, were approximately measured using the time-average method [26]. This method has the advantages of using the same optical interferometer setup used in the static measurements and allows the observation of the vibration contour fringes at video rate. The method is based on the subtraction of speckle interference patterns produced by stationary harmonic motion of objects during several cycles of vibration. In this case, the recording time is very long compared to the period of vibration. Black intensity fringes are observed as contours of equal amplitude of vibration, being the fringe intensity modulated by the Bessel function J_0, where the contrast decreases with the increase of the fringes order associated with the amplitude of vibration. Only recently, the development and application of spatial phase modulation and temporal phase modulation to speckle