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Identification of multiple damage using modal rotation obtained with shearography and undecimated wavelet transform

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A B S T R A C T

Due to its high spatial resolution measurements and flexible and contactless experimental setup, shearography, as a non-destructive testing technique, provides effective structural damage identifications. However, this effectiveness can be increased by applying post-processing algorithms to experimentally measured modal rotation fields. In this paper, the authors present a novel method, consisting of shearographic non-destructive testing and 2D undecimated wavelet transform as a post-processing tool. The studies covered tests of the proposed method on simulated modal data of a damaged plate, as well as a validation on real data obtained from shearographic experiments. The results show the high sensitivity of the proposed method to either single or multiple damage, including its edges and its various configurations.

1. Introduction

The development and improvement of methods for structural diagnostics has attracted the attention of the engineering community for many years. As a result, several techniques are now available which are non-destructive and non-invasive. Besides these characteristics, it is also important to have non-contact between the structure and the measurement system. Among the existing non-contact techniques, optical methods are very sensitive and allow high spatial resolution measurements. An example of optical methods, relying on the interference of light and the speckle phenomenon, are electronic speckle pattern interferometry and electronic speckle pattern shearing interferometry [1]. The present paper deals with this last technique, nowadays simply called shearography, which was developed in the early 1970s [2–4]. In more recent decades, shearography has been applied as a tool for flaw detection in composites [5], non-destructive testing (NDT) of aerospace composite materials [6], evaluation of the soundness of bonding using shearography [7], inspection of aircraft and automotive components [8] among other applications.

Since shearography measures the displacement gradient field in a given direction, it is almost insensitive to rigid body movements and thus can be used in harsh environments. It should be pointed out that to obtain the displacement gradient field, the process starts by capturing the intensity of light which is related to the phase, resulting in what is called a phase map. This phase map is very noisy, due, among other origins, to the own nature of the speckle, and presents discontinuities

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that are removed after filtering and unwrapping. With this process we are able to get a filtered continuous displacement gradient field, which for thin plates will correspond to the rotation field in a given direction.

The use of shearography for the identification of local stiffness distribution in beams was reported in [9]. Measurements obtained with shearography were also used for the localization of damage in isotropic and laminated plates [10]. The method proposed in [10] leads to an improvement in damage localization because the number of spatial differentiations needed to compute the modal curvature is reduced when ones uses the rotation field instead of the displacement field. In order to decrease the propagation of experimental noise, a new methodology was proposed in [11] for the computation of the second, third, and fourth order derivatives of the mode shapes at the phase map level. An alternative to improve the damage identification using shearography, by means of the decrease of the propagation and amplification of noise when computing derivatives, is the use of an optimal spatial sampling [12].

Some of the aforementioned references deal directly with the computation of derivatives of the measured data using finite differences. Although these approaches allow for the detection and identification of damage of a considered type, their detection and identification ability as well as filtering out of damage signatures from noisy data obtained from shearographic measurements can be improved. One of the effective approaches allowing such an improvement is the application of various types of wavelet transforms. This approach is widely used for the post-processing of the measurement data, for instance of vibrational mode shapes [13–17]. In particular, the authors of [13,14] applied continuous wavelet transform (CWT) for damage identification, while the studies presented in [15] were based on discrete wavelet transform (DWT). A comparative study of four classical wavelet transforms and many popular wavelets functions is presented in [17], allowing the selection of the most sensitive combinations for structural damage identification based on mode shapes analysis.

The aim of this paper is to present a procedure consisting in a joint method for NDT of structures using effective measurement and processing techniques, namely shearography and wavelet analysis. The application of a problem-oriented wavelet transform with appropriately selected wavelet function and additional enhancement approaches allows the effective detection, localization and identification of damage including its various orientations. Moreover, such approaches will make it possible to improve the resulting maps for more clear presentation of damage signatures, and, as a consequence, its increased distinguishability. Furthermore, the application of an extension to two-dimensional wavelet analysis allows the precise determination not only of a signature of presence and position of damage (as it was performed in previous studies – see [12] for instance), but also shape and spatial orientation of damage, which is an additional advantage of the proposed procedure. In this paper, both shearographic measurements and wavelet analysis are deeply discussed in order to present all the advantages and exact apparatus of the applied procedure. The tests were performed on simulated data obtained with a numerical model of shearography in order to show the abilities of the applied procedure, which were further verified with experimental data. In view of the results, the proposed approach presented in this paper can be considered as an effective NDT method for damage identification in plate-like structures.

2. Theoretical background

This section introduces the fundamentals of shearographic measurements for NDT with the necessary processing of the obtained data. These data are used for structural damage identification purposes as well as for further processing using wavelet analysis.

2.1. Shearography

Shearography has its origin in the speckle pattern, which is created in an interferometer, due to the illumination of a rough surface by coherent light, such as laser light, in an interferometer. Usually this pattern is recorded as an image by a digital camera. The speckle pattern contains information about the displacement derivative. The extraction of this information can be performed using different phase shifting or phase stepping techniques. The temporal phase shifting is applied in the present work. The temporal phase shifting needs the interference phases of the reference and deformed states of the surface of the object, denoted respectively by $\Phi_R(x,y)$ and $\Phi_D(x,y)$. These interference phases are related to two sets of four recorded intensity patterns $I_{R,1}(x,y)$, $I_{R,2}(x,y)$, $I_{R,3}(x,y)$, $I_{R,4}(x,y)$ and $I_{D,1}(x,y)$, $I_{D,2}(x,y)$, $I_{D,3}(x,y)$, $I_{D,4}(x,y)$ according to the following Equations:

$$\Phi_R(x,y) = \arctan\left[\frac{I_{R,4}(x,y) - I_{R,2}(x,y)}{I_{R,1}(x,y) - I_{R,3}(x,y)}\right] \tag{1}$$

and

$$\Phi_D(x,y) = \arctan\left[\frac{I_{D,4}(x,y) - I_{D,2}(x,y)}{I_{D,1}(x,y) - I_{D,3}(x,y)}\right]. \tag{2}$$

The equations above are obtained by solving a nonlinear problem with three unknowns, the additive and multiplicative distortions, and the interference phase [18]. Thus, the solution can only be obtained by considering at least three intensity patterns with known phase shifts. The method with four intensity patterns, with constant phase shift of multiples of $\pi/2$, is