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Damage detection on composite materials with active thermography and digital image processing

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ABSTRACT

This research is focused on the use of active infrared thermography as a non-destructive testing technique for damage detection in carbon fiber reinforced plastics (CFRPs). The aim of this study is to examine the efficiency of various mathematical methods in thermographic data processing, with respect to the thermal excitation method and the type of artificial defect in the CFRP specimens. We applied two techniques of active infrared thermography to CFRP samples with artificial cracks and internal delaminations at known locations. An infrared camera recorded the temperature field and generated a sequence of thermal images. To reveal the defects of the CFRP laminate, the thermograms were processed (a) as 2D images, and (b) as if each pixel was a 1D signal over time. We present representative experimental results, which illustrate that the depiction of the norm of the 1st spatial derivative of temperature and the 2D wavelet transforms proved to be most efficient for crack detection, whereas the 1D Fourier and 1D wavelet transforms did not yield clear results. In contrast, delamination damages could be identified through 1D techniques because the 1D Fourier transform as well as the 1D wavelet transform were very accurate.

1. Introduction

Non-destructive testing (NDT) is an excellent method for the evaluation of structural integrity of materials or components, without interfering with their serviceability. Various NDT techniques have been studied and adopted, including ultrasonic testing, X-ray testing, eddy current thermography, and infrared thermography [1–4]. Infrared (IR) thermography has become a widely used NDT technique [5] for the detection of hidden subsurface defects in a plethora of structural elements and mechanical systems [6,7], such as aircraft parts [8,9], buildings [10], cultural heritage objects [11], electronic components [12], and even the human body [13]. Unlike other non-destructive methods, thermography is a fast non-contact method, suitable for testing large areas of complex geometry, and is capable of identifying multiple damages [8,14]. It is also applicable to a wide range of materials [15,16], including glass and carbon fiber composites [17–19], natural fibers [20], ceramics [21], and metallic materials [22,23]. The wide use of composite materials raised the need for NDT in order to ensure their reliability before and during their life. Thermography is widely used for the testing of CFRPs and other composite materials for damages and other defects [8,16,18]. The method of heating and the mathematical processing methods play a major role in the efficiency of thermography. Particularly in multilayer composite materials, thermography enables the detection of different types of defects/damages (cracks, delaminations, fiber debonding, and mixed mode damages).

In most applications, where objects typically have similar temperature levels, the emitted electromagnetic radiation—also called thermal radiation—ranges between 0.1 and 100 μm (visible, infrared, and part of the UV light wavelength spectrum) [24]. An infrared camera equipped with changeable optics can record the emitted radiation, convert it to voltage values, and then to temperature values (T), resulting in a 2D map of the surface temperature field. IR thermography is categorized into passive and active; both rely on the fact that different materials, or defects in a material, produce variations in the thermal field because of their different thermal properties. Passive thermography does not employ external heating sources, and the specimen temperature should differ from the ambient temperature owing to its operation; for example, testing an aircraft via passive thermography immediately after its landing, or a rotor blade in motion [25]. Active thermography uses external heating sources (halogen lamps, lasers,

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flashes, infrared light, and hot air jets) to activate heat dissipation [15,23,26]. Active thermography can be combined with eddy current excitation—namely, eddy current thermography—where the applied electromagnetic excitation plays the role of the heating source [27]. Thermal waves propagate through the heated specimen, and when they reach inhomogeneities caused by a medium with different thermal properties, the diffusivity coefficient changes. These inhomogeneities could be defects, such as cracks, surface cracks, air/water/material inclusions, delaminations, and debonding damages. Active thermography can be applied through various techniques, including the widely used pulsed thermography, the lock-in or modulated thermography [8,15,16,28,29], and variations of the above [12]. Numerous mathematical processing techniques have been developed to enhance the obtained raw thermograms [19,30–34], and play a major role in the process of revealing the damages.

In the following experiments, we used **a) transient** and **b) pulsed thermography** for the identification of artificially fabricated damages in multilayer CFRPs, and more specifically, for the identification of cracks and delaminations. Transient thermography is more appropriate for the detection of cracks; its application involves a heating element for the thermal excitation of the specimen, while an infrared camera captures the phenomenon. In pulsed thermography, which is suitable for the detection of delaminations, the specimen is heated through an IR lamp pulse, and then an infrared camera records its thermal response. The recorded raw data often contain noise caused by the environment, the reflections and the emissivity variations of the specimen, or by the non-uniformity of the heating.

2. Mathematical methods

The data are represented as a 3D matrix, whereas 2D images (thermograms) evolve over time, as shown in Fig. 1(a). The value of each pixel represents the temperature at a specific point. The temperature profile of the point corresponding to the healthy area is different from that of the point corresponding to the defective area, as shown in Fig. 1(b). We analyzed the recorded temperature data through digital image processing [33] in order to enhance the images and to reveal the location and the geometry of the defects.

The image processing techniques are divided into two groups: **A)** the processing of spatial values of the measured temperature field at x − y, $T(x, y)$, at a given instant t, (i.e., 2D image processing), and **B)** the processing of the temperature signal of any point (x, y) over time (i.e., 1D image processing).

A) The first approach treats every thermogram as an individual image; therefore, we applied spatial mathematical methods on the overall heated domain: (**i**) the depiction of the norm of the first and second spatial derivative of temperature, and (**ii**) the 2D wavelet transform.

B) The second image processing technique treats the value of every single pixel as a 1D signal over time. Two methods were used here: (**i**) the Discrete Fourier transform, and (**ii**) the 1D wavelet transform.

The chart in Fig. 2 presents all the employed methods. Later, we will collectively present the results obtained from every method, which will be helpful for their comparison.

2.1. 2D image processing

2.1.1. Depiction of the norm of spatial derivatives of the thermal field

The norm of the first and the second spatial derivative of the temperature, $T(x, y, t)$, can be expressed as Eq. (1) and Eq. (2) [32,34], respectively:

$$D_1T(x,y,t) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2}, \tag{1}$$

$$D_2T(x,y,t) = \sqrt{\left(\frac{\partial^2 T}{\partial^2 x}\right)^2 + \left(\frac{\partial^2 T}{\partial^2 y}\right)^2}. \tag{2}$$

As the spatial derivative of the temperature changes abruptly around a defect, and in order to locate and reveal the abrupt change in temperature at specific regions of the CFRP specimen, the depiction of the temperature derivative norm distributions is given in terms of iso-D_1T and iso-D_2T lines at various instants. From the thermograms, discrete values $T^n_{i,j}$ of the temperature $T(x, y, t)$ on each pixel (x, y) at a time instant t were obtained, where $i = x/\Delta x$, $j = y/\Delta y$, $n = t/\Delta\tau$ (Δx, Δy are the dimensions of a pixel element, and $\Delta\tau$ is the time interval between images). The discrete values of D_1T and D_2T on each pixel of the nth thermogram result from Eqs. (1) and (2), respectively, by employing central difference expressions for the spatial derivatives of temperature, as shown in Eqs. (3) and (4):

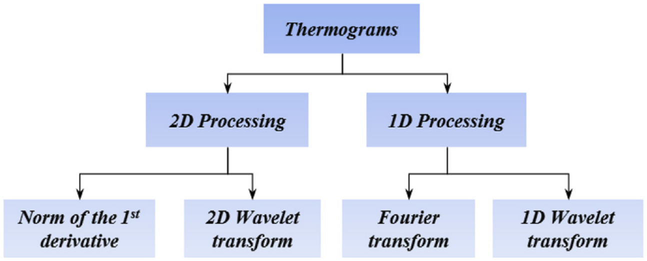

Fig. 2. The employed signal processing methods.

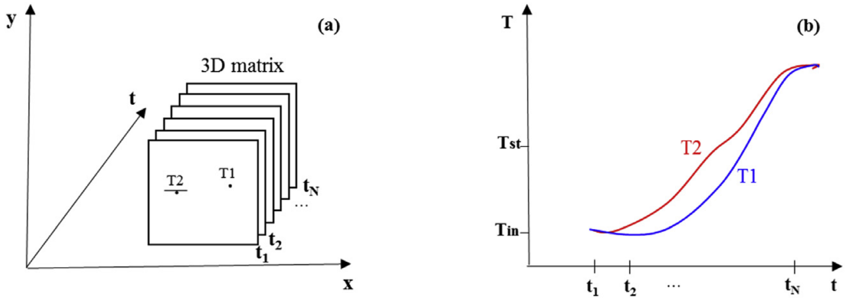

Fig. 1. (a) Sequence of thermograms (3D matrix), (b) temperature profile of a defective (red line) and non-defective (blue line) pixel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)