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Imaging of barely visible impact damage on a composite panel using nonlinear wave modulation thermography

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ABSTRACT

Thermosonics is a well-established non-destructive evaluation (NDE) technique that uses an infrared camera to visualise material damage by capturing the frictional heating at crack surfaces when the sample under inspection is vibrated. A high power ultrasonic horn is typically used to generate vibrations, which is pressed against the surface of the test component. However, the direct contact between the horn and the surface generates acoustic chaos and high-amplitude vibrations, which can lead to non-reproducible and unreliable measurements and, ultimately, they can harm the structural integrity of components. This paper proposes an alternative to thermosonics, here named as nonlinear wave modulation thermography, for the detection and imaging of material flaws on a damaged carbon fibre composite panel. This material inspection technology combines the concept of nonlinear wave modulation spectroscopy using dual excitation with contact piezoelectric transducers and thermographic equipment. Whilst nonlinear ultrasonic modulation was used to enhance the sensitivity to micro-cracks, an infrared camera was used for defect visualisation. A nonlinear narrow sweep excitation method was employed to experimentally identify the dual excitation frequencies that resulted in high-amplitude damage resonance effects causing frictional heat at crack surfaces. A laser vibrometry system was also used to create a spatial mapping of the amplitude of sidebands. Nonlinear wave modulation thermography has proved to successfully detect barely visible impact damage in composites in a quick and reliable manner, thus overcoming the limitations of traditional optical thermography and thermosonics.

1. Introduction

The drive for weight reduction and the need for materials of high strength and impact-resistance have led to the increased use of carbon fibre reinforced plastic (CFRP) composites in the aerospace industry. However, the assessment of composite materials is particularly challenging for low velocity impact damage, which is commonly referred to as barely visible impact defect (BVID). This material failure can be caused either at the manufacturing stage or during in-service and it can severely decrease the strength of composites thus leading to catastrophic failures. For critical components such as aircraft primary and secondary structures, non-destructive evaluation (NDE) techniques, such as ultrasounds, thermography and eddy currents, are necessary to guarantee that components are free of any harmful damage [1,2]. Active infrared (IR) thermography is a well-established NDE inspection technology for composites that uses external thermal excitation sources such as optical radiation [4], electromagnetic stimulation [5] and acoustic/ultrasonic waves [6] to generate heat in the component under inspection. Optical thermography uses optical flashes or heaters to heat the sample on its surface and then record the temperature decay curve using an infrared camera. However, the usage of external optical thermal sources may limit the image of defects within a few millimetres from the material surface. In addition, the lack of a significant air gap between micro-cracked surfaces may not generate any significant variation of the local temperature needed for damage detection. Thermosonics [7], also known as ultrasonic stimulated thermography or vibro-thermography, relies on the acoustic/ultrasonic excitation of the tested part using a high-power ultrasonic horn. In this technique, material defects are visualised by observing the vibration-induced frictional heat with an IR camera. The primary sources of heat generation in a vibrating crack include frictional rubbing of crack surfaces, plastic deformations and viscoelasticity, which mainly depends on the test material, the type of defect and the applied vibrational stress level [8]. Experimental evidence has shown that 90–95% of frictional energy in sliding contacts is transformed into heat

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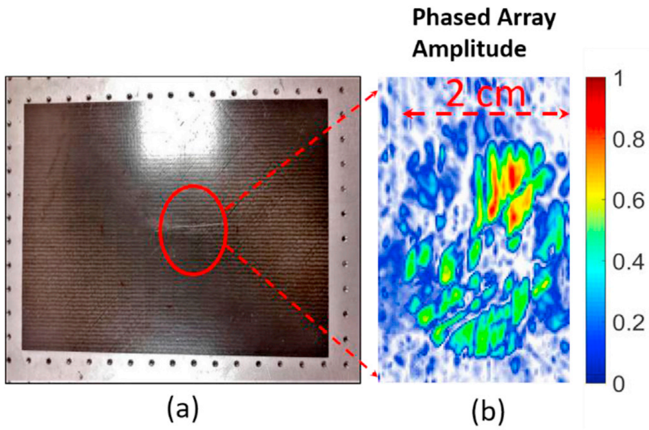

Fig. 1. Top view the CFRP sample (a), ultrasonic phased array images of the impact damage based on normalised amplitude measurements (b). As it can be seen from figure (b), the damaged region has a circular shape.

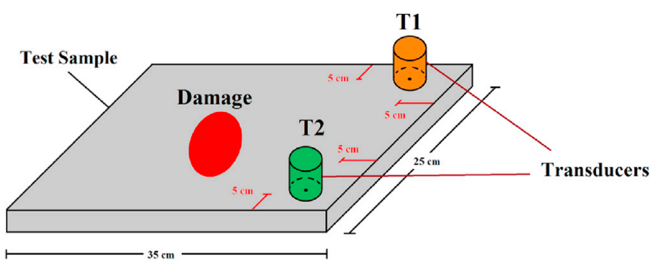

Fig. 2. CFRP test sample and location of transmitter transducers. T1 and T2 correspond to the Panametrics X1020 and the Piezoshaker PS-X-03-6/1000 transducers, respectively.

[9]. Crack surfaces would therefore experience larger temperature variations. This temperature raise would be transferred to the surface layers above the defect, thus allowing for damage detection. However, a major limitation of thermosonics is that the acoustic vibration generated by the horn tends to be "chaotic" and highly non-reproducible [10]. The exposure to high-power excitation generated by the horn may also further degrade the structural integrity of components.

The thermographic method presented in this paper, here named as nonlinear wave modulation thermography (NWMT), aims to increase the probability of defect detection and repeatability of thermosonics using nonlinear ultrasonic wave modulation and contact piezoelectric (PZT) transducers [11,12]. In particular, by transmitting two periodic waves in the damaged material, i.e. a high- and low-frequency mode, the amplitude of both frequency components can be modulated due to the interaction of elastic waves with the material damage [13]. As a result of this interaction, new frequencies and associated modes known as higher harmonics (i.e. even and odd multiples) and sidebands (i.e. sum and differences) of the driving frequencies, can be generated [31,14]. Hence, the damage itself can act as a nonlinear mixer of the dual excitation frequencies [15,16]. In an intermodulation experiment on a damaged composite sample using a low input frequency f_1 and a high frequency f_2 with amplitudes A_1 and A_2, respectively [17], a number of sidebands (e.g. f_2-nf_1 and f_2+nf_1, with n a positive integer number) were generated. Moreover, recent studies have highlighted the benefit of exciting the component under inspection at its damage-specific resonance frequency, also known as local defect resonance (LDR) [18–20]. Indeed, if the excitation frequency matches the damage resonance, the vibration amplitude of nonlinear elastic phenomena can be increased. From a physical point of view, the clapping/rubbing of asperities of the two contacting crack surfaces vibrating at their resonance frequency generates high frictional heat at the damage location, which then leads to higher temperature variations across the defect. Such a temperature increase can then be recorded with an IR camera [21,22]. Assuming that the internal structural flaw such as a delamination in a composite laminate of thickness h is represented by a flat bottom hole, i.e. a thin circular defect of radius r, the analytical expression of the LDR frequency f_d is [23]:

$$f_d \cong \frac{1.6d}{r^2}\sqrt{\frac{E}{12\rho(1-\nu^2)}}, \tag{1}$$

where E and ν are the effective elastic modulus and Poisson's ratio of the composite laminate, respectively, ρ is the density and d is the depth of the portion of volume below the defect. Eq. (1) corresponds to the first bending mode of a circular plate with clamped boundaries. For a quadratic-shaped defect with side length l, Eq. (1) becomes:

$$f_d \cong \frac{4\pi d}{3l^2}\sqrt{\frac{E}{6\rho(1-\nu^2)}}, \tag{2}$$

where B_s is the bending stiffness given by $B_s = Ed^3/12(1-\nu^2)$.

However, the experimental determination of the LDR frequency is challenging as it can only be determined through the evaluation of the material response when the tested sample is subject to repeated sweep excitation. Similarly to Fierro et al. [24,25], a nonlinear narrow sweep excitation (NNSE) with a laser vibrometry system was here used to identify the dual excitation frequencies matching the damage resonance. Particularly, NNSE signals followed by dual periodic excitation were transmitted in order to identify the fundamental frequencies f_1 and f_2 of higher amplitude that generated sidebands and resulted in a higher material nonlinear response with larger temperature gradients across the defect. The layout of the paper is as follows: Section 2 provides the experimental set-up, whilst Section 3 illustrates the identification process of the LDR frequency by means of the NNSE method and dual periodic excitation using the laser vibrometry system. Section 4 reports the nonlinear wave modulation thermography results and the comparison with flash thermography. Finally, in Section 5, the conclusions about the proposed NWMT inspection technique are discussed.

2. Experimental set-up

The test sample investigated in this work was a CFRP composite panel with a length of 35 cm, width of 25 cm and thickness of 1.3 cm. No further information was provided by the manufacturer about the lay-up and mechanical properties. The specimen was undergone to low-velocity impact at the energy of 20 *J* and BVID was generated approximately in the centre of the panel (marked as the region A on the sample). Fig. 1 shows a top view of the CFRP panel and the damaged region using ultrasonic phased array measurements. As it can be seen from Fig. 1(b) the extended area of surface delamination is a circular region approximately 2 cm in diameter.

For the ultrasonic signals transmission, a waveform generator (TTi-TGA12104) was connected to two transmitter transducers, i.e. a vacuum Piezoshaker actuator (PS-X-03-6/1000) and a Panametrics narrowband transducer (X1020) with a central frequency of 100 kHz. Both sensors were connected to a high voltage amplifier (Falco Systems WMA-300) in order to increase the output voltage of the waveform generator. All ultrasonic and thermographic tests were performed at the input voltage of 90 V. Such a level of voltage was chosen to provide a clear nonlinear material response in the damaged composite. Fig. 2 shows the position of the transducers relative to the defect location.

The PSV-500 Polytec 2D laser vibrometer was also used to measure the wave field generated by the dual ultrasonic excitation and to determine the LDR frequency. An indium gallium arsenide IR camera (from FLIR, Merlin) with a frame rate of up to 120 Hz, a resolution of 320 × 256