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Nonlinear elastic multi-path reciprocal method for damage localisation in composite materials

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ABSTRACT

Nonlinear ultrasonic techniques rely on the measurement of nonlinear elastic effects caused by the interaction of ultrasonic waves with the material damage, and have shown high sensitivity to detect micro-cracks and defects in the early stages. This paper presents a nonlinear ultrasonic technique, here named *nonlinear elastic multi-path reciprocal* method, for the identification and localisation of micro-damage in composite laminates. In the proposed methodology, a sparse array of surface bonded ultrasonic transducers is used to measure the second harmonic elastic response associated with the material flaw. A reciprocal relationship of nonlinear elastic parameters evaluated from multiple transmitter-receiver pairs is then applied to locate the micro-damage. Experimental results on a damaged composite panel revealed that an accurate damage localisation was obtained using the normalised second order nonlinear parameter with a high signal-to-noise-ratio (~11.2 dB), whilst the use of bicoherence coefficient provided high localisation accuracy with a lower signal-to-noise-ratio (~1.8 dB). The maximum error between the calculated and the real damage location was nearly 13 mm. Unlike traditional linear ultrasonic techniques, the proposed *nonlinear elastic multi-path reciprocal* method allows detecting material damage on composite materials without a priori knowledge of the ultrasonic wave velocity nor a baseline with the undamaged component.

1. Introduction

In the last decade, carbon fibre–reinforced plastic (CFRP) composite materials have been increasingly used in different sectors, from aerospace to automotive and civil, due to their good in-plane mechanical and lightweight properties. However, composites are susceptible to low velocity impacts that can generate barely visible impact damage (BVID), micro-cracks and delamination, which can irreparably affect the integrity of the structure. In particular, if the impact occurs at very low velocity, damage can be a mixture of splitting between fibres, matrix cracking, fibres fracture and internal delamination due to inter-laminar shear and tension. These damaged modes weaken the mechanical properties of the structure and can be completely invisible when viewed from the external impacted surface. Hence, both linear and nonlinear ultrasonic structural health monitoring (SHM) techniques based on sparse transducer arrays have been developed in the last few years to provide an early warning and increase of safety of composite components [1–6]. Linear beamforming techniques, such as the statistical maximum-likelihood estimation [7] and the reconstruction algorithm for probabilistic inspection of damage (RAPID) [8] have shown a high level of accuracy for the detection and localisation of damage in composites. However, linear ultrasonic techniques typically rely on the measurement of wave scattering and reflections, as well as changes of macroscopic elastic features caused by the presence of damage such as wave attenuation and group velocity. Hence, these methodologies may lack of sensitivity to micro-flaws due to low acoustic impedance mismatch at damage location. Moreover, linear ultrasonic methodologies with sparse transducer arrays require the knowledge of waveforms associated to the undamaged component, which is generally difficult to obtain.

On the other hand, ultrasonic waves propagating in a damaged structure at a particular driving frequency can generate "clapping" motion of the region normal to the crack interfaces or nonlinear friction (rubbing) between the defect surfaces excited by small tangential stresses. This result in the creation of nonlinear elastic effects such as higher harmonics and sub-harmonics of the excitation frequency, which can be used as signature for micro-damage detection. A number of authors have recently focused their studies on the nonlinear behaviour of ultrasonic waves in composites, both numerically and experimentally [9,10]. Typically, both the second and third order nonlinear elastic responses are used for material

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damage identification and localisation [11]. Ciampa et al. [12,13] and Malfense-Fierro and Meo [14] use the second order harmonic response and nonlinear inverse filtering technique in order to detect damage in multi-layered media.

This paper presents a novel in-situ nonlinear ultrasonic approach, here called nonlinear elastic multi-path reciprocal (NEMR) method, for the localisation of micro-damage in composite components. A sparse array of surface bonded ultrasonic transducers is here used to measure the second harmonic nonlinear elastic response associated with the material damage by means of the normalised classical second order nonlinear coefficient and the bicoherence parameter. The micro-damage localisation is then achieved by analysing the reciprocal relationship of these nonlinear coefficient calculated from multiple transmitter-receiver pairs. The paper is outlined as follows: in Section 2 there is an introduction to the nonlinear parameters involved; in Section 3 the NEMR technique is explained in detail; Section 4 shows the experimental set-up; in Section 5 it is possible to read the experimental results; in Section 6 the main conclusions are discussed.

2. Nonlinear parameters

According to Section 1, both micro-cracks and delamination, when excited by ultrasonic waves can generate nonlinear material responses. These elastic effects can be analytically modelled by using the classical nonlinear elasticity (CNE) theory [15]. Assuming a one-dimensional longitudinal wave propagation along the x-direction, the elastodynamic wave equation [16] can be expressed as the power series of the strain $\varepsilon_x = \partial u(x,t)/\partial x$ as follows

$$\rho\frac{\partial^2 u(x,t)}{\partial t^2} = \frac{\partial \sigma}{\partial x} = (\lambda + 2\mu)\left[\frac{\partial}{\partial x}\left(1 + \beta\varepsilon_x + \delta\varepsilon_x^2\right)\varepsilon_x\right] \tag{1}$$

where σ is the stress and β and δ are second and third order elastic coefficients, respectively. The second order nonlinear parameter β is typically two or three order of magnitude higher than γ and it can be used as a reliable signature for damage detection. Eq. (1) is generally solved via a perturbation theory that leads to the following expression of the nonlinear parameter β:

$$\beta = \frac{8A_2}{A_1^2 x k^2} \tag{2}$$

In Eq. (2), A_1 and A_2 are the fundamental and the second harmonic amplitudes, respectively, k is the wave number and x is the propagation distance of the propagating waveform from the nonlinear source (i.e. damage location). The second order nonlinear parameter β is a material property (it is constant all over the material) and its formulation [Eq. (2)] is obtained by assuming no material attenuation. To overcome this limitation, in this paper a normalised version of β is used, here defined as $\overline{\beta}$, which is only function of the fundamental and second harmonic amplitudes and may change from point to point within the medium, with the highest value at the damage location. This new normalised second order nonlinear coefficient $\overline{\beta}$ is defined as follows:

$$\overline{\beta} = \frac{A_2}{A_1} = \sqrt{\frac{|P(2\omega_1)|}{|P(\omega_1)|}} \tag{3}$$

where $|P(\omega_1)|$ and $|P(2\omega_1)|$ are the magnitudes of the power spectral densities associated with the fundamental angular frequency ω_1 and the second harmonic angular frequency $2\omega_1$. However, $\overline{\beta}$ relies on magnitude ratios and discards all phase information contained in the acquired waveforms. Higher order statistics (HOS), such as the bispectral analysis, are a valid alternative to the second order nonlinear coefficient as they can be used to measure both the magnitude and phase of the higher order harmonic frequency components [17]. Particularly, the bispectrum B is the two-dimensional Fourier Transform of the third order correlation function and, for a real, zero-mean stationary random process $s(t)$, it is given by:

$$B(\omega_m, \omega_n) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} R_{sss}(\tau_1, \tau_2)e^{j(\omega_m\tau_1 + \omega_n\tau_2)}d\tau_1 d\tau_2 \tag{4}$$

where $R_{sss}(\tau_1, \tau_2)$ is the third order auto-correlation function of $s(t)$. In the frequency domain, Eq. (4) can be rewritten as:

$$B(\omega_m, \omega_n) = E[S(\omega_m)S(\omega_n)S^*(\omega_m + \omega_n)] \tag{5}$$

where $S(\omega)$ is the Fourier Transform of the measured signal $s(t)$ and the asterisk sign "$*$" corresponds to a complex conjugate operation. The three frequency components ω_n, ω_m and $\omega_n + \omega_m$ have a special phase relation, called quadratic phase coupling (QPC) [17], which defined as follows:

$$\varphi_m + \varphi_n = \varphi_{m+n} \tag{6}$$

where φ_n and φ_m are the phases of the signal at frequencies ω_n and ω_m, respectively, and φ_{m+n} is the phase of the signal at frequency $\omega_n + \omega_m$. QPC allows the identification of structural nonlinearity by discarding the signal noise that, differently, is not quadratic phase coupled [18]. Similarly to the second order nonlinear parameter β, also the bispectrum B can be replaced by its normalised non-dimensional counterpart, the bicoherence coefficient b^2, which is defined as follows [17]:

$$b^2 = \frac{|B(\omega_1, \omega_1)|^2}{P(\omega_1)P(\omega_1)P(2\omega_1)} \tag{7}$$

with $B(\omega_1, \omega_1) = E[S(\omega_1)S(\omega_1)S^*(2\omega_1)]$ the bispectrum calculated at the fundamental frequency ω_1. The NEMR damage localisation technique will use either the coefficient $\overline{\beta}$ or b^2 as input and is reported in next Section.

3. Nonlinear Multi-Path Reciprocal (NEMR) method

The NEMR method allows the estimation of damage location on composite panels. A number N of ultrasonic sensors is surface bonded on a composite plate-like structure with impact damage. The NEMR technique is based on the assumption that the closer the receiving sensor is to damage, the higher will be the acquired second order nonlinear response. Hence, a reciprocal relationship is here introduced in order to retrieve the closest point to damage along the path between multiple transmitter-receiver pairs.

According to Fig. 1, X_{ij} is the distance between two sensors S_i and S_j, and the sensor-damage distances are X_{iD} and X_{Dj} with i, $j = 1, 2, \ldots, N$. The reciprocal relationship between each sensor-damage path and the associated ultrasonic nonlinear response is given by:

$$X_{iD} = \frac{X_{Dj}\xi_i}{\xi_j} \tag{8}$$

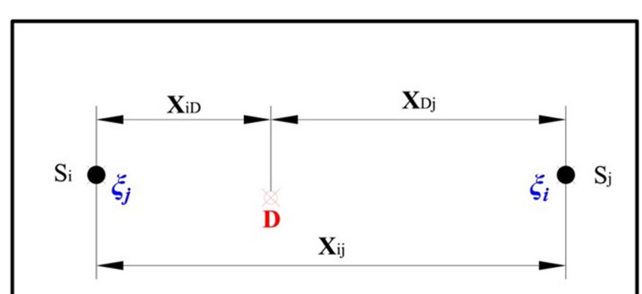

Fig. 1. Scheme for a couple of sensors and relative wave path.