Composites Part B 80 (2015) 291–298

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Detection of multiple low-energy impact damage in composite plates using Lamb wave techniques

Pedro Ochôa [a, b, *], Virgínia Infante [b], José M. Silva [c], Roger M. Groves [a]

[a] Aerospace Non-Destructive Testing Laboratory, Faculty of Aerospace Engineering, TU Delft, Kluyverweg 1, 2629 HS Delft, The Netherlands
[b] LAETA, IDMEC, Instituto Superior Técnico, University of Lisbon, Avenida Rovisco Pais, 1, 1049-001 Lisboa, Portugal
[c] School of Aerospace, Mechanical & Manufacturing Engineering, RMIT University, 115 Queensberry Street, Melbourne, VIC 3053, Australia

ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form
20 February 2015
Accepted 4 June 2015
Available online 14 June 2015

Keywords:
A. Prepreg
B. Impact behaviour
D. Non-destructive testing
Ultrasonic Lamb waves

ABSTRACT

This work assesses the suitability of the two zero-order Lamb wave modes to detect multiple barely-visible impact damage in composite material. Three specimens were subjected to damage at three different low-energy levels and one was left as an undamaged reference sample. Ultrasonic Lamb wave modes were selectively generated by surface-bonded piezoceramic wafer transducers in two tuned configurations. By using an algorithm based on the Akaike Information Criterion the time-of-flight of the Lamb modes was determined, allowing their threshold detection capabilities for the studied application to be successfully benchmarked. The results were consistently validated by digital shearography, ultrasonic C-scan and optical microscopy. A study of the effects on structural integrity was completed with an assessment of the damping ratio and residual bending strength proving to be sensitive parameters to the induced damage.

1. Introduction

One of the major steps of the aircraft industry towards the reduction of utilization costs and the increase of structure effectiveness has been the widespread introduction of composite materials. However, contrary to metallic materials, one of the most serious issues related to the use of composites in airframes is their brittle-type behaviour in the presence of Barely-Visible Impact Damage (BVID), which may lead to unexpected failure under fatigue loading [1]. Therefore, the Non-Destructive Testing (NDT) techniques, that have already proven to be able to enhance safety, integrity and durability of aircraft structures over the last fifty years, combined with recently developed measuring and computational technologies, assume a central role in the implementation of Structural Health Monitoring (SHM) systems. An effective SHM system minimizes the ground time for inspections, increases the availability and allows a reduction of the total maintenance cost by more than 30% for an aircraft fleet [2]. NDT methods for an SHM system should be capable of reliably detecting damage-induced changes in local and global properties, which are encoded in the dynamic response of the structure. Amongst these the Lamb wave method has been reported as "one of the most encouraging tools for quantitative identification of damage in composite structures" [3]. To better understand the physical phenomena, Percival and Birt [4] developed and validated a one-dimensional finite element model in order to solve the equations for the propagation of Lamb waves in anisotropic laminates. Using the fundamental symmetric Lamb mode (S_0), Birt [5] successfully evaluated delamination and impact damage in carbon-fibre laminates. Later, Grondel et al. [6] developed a SHM system using Lamb waves and acoustic emissions to detect impact and debonding damages in a composite wingbox. The extraction of signal characteristics can be hindered by the complexity of Lamb wave propagation phenomena. Therefore, to make the identification process easier, Kessler et al. [7], Grondel et al. [8], and Giurgiutiu and Santoni-Bottai [9] have designed several different systems of multi-element piezoceramic (PZT) wafer transducers for optimal and selective generation of damage-sensitive Lamb modes, enabling more accurate damage detection in composite plates. On a production monitoring basis, Miesen et al. [10] demonstrated it is possible to detect flaws in one sheet of unidirectional Carbon Fibre Reinforced Polymer (CFRP) prepreg by capturing Lamb waves with conventional piezoelectric sensors. In a

* Corresponding author. Faculty of Aerospace Engineering, TU Delft, Kluyverweg 1, 2629 HS Delft, The Netherlands. Tel.: +31 628177513.
E-mail addresses: P.A.ViegasOchoadeCarvalho@tudelft.nl (P. Ochôa), virginia.infante@tecnico.ulisboa.pt (V. Infante), jose.silva@rmit.edu.au (J.M. Silva), r.m.groves@tudelft.nl (R.M. Groves).

http://dx.doi.org/10.1016/j.compositesb.2015.06.010
1359-8368/

growing effort to increase the effectiveness of SHM systems new combined approaches have been studied. Pohl and Mook [11] used scanning laser-vibrometry to detect and investigate Lamb wave fields produced by piezoceramic actuators in CFRP plate-like structures, contributing for further clarification of propagation and interface-interaction phenomena. Sotoudeh et al. [12] installed fibre Bragg grating sensors to acquire the Lamb wave response signals of curved CFRP shells excited by a piezoelectric actuator, obtaining the approximate size and location of a delamination through the damage imaging method. Liu et al. [13] successfully performed a detailed numerical and experimental study of the interaction between the fundamental anti-symmetric Lamb mode (A_0) and a delamination in a CFRP plate, using an optimized set-up with air-coupled ultrasonic transducers. Following the same non-contact approach Alleman et al. [14] used a combined set-up with air-coupled ultrasonic actuators and conventional piezoelectric sensors to detect damage in a thin CFRP plate resorting to the Ultrasonic Verification (USV) methodology presented by Pelt et al. [15].

The main goal of this study is to assess the suitability of the fundamental Lamb modes to detect three different levels of multiple BVID in carbon-epoxy composite plates, and, if possible, to improve the diagnosis capabilities. Digital Shearography with thermal loading and ultrasonic C-scan are used to substantiate the results from the Lamb wave tests. The comparison between these two additional NDT methods is expected to yield important conclusions about their sensitivity to BVID, and to contribute to an improvement of the quality control capability, which is also a means to increase structure reliability. The methodology adopted for this research brings together the novelty of combining the use of zero-order Lamb wave modes for detection of multiple BVID and the detailed benchmarking of their threshold detection capabilities for that particular application, with result validation through other mature NDT techniques.

2. Lamb wave response optimization

When a PZT wafer is bonded to a structure as an actuator, the coupling between the piezoelectric material and the specimen enables the transmission of acoustic waves. The simultaneous strains along the three wafer dimensions, generated through the converse piezoelectric effect, induce shear stresses which excite multiple Lamb wave modes. This unavoidable occurrence for PZT transducers poses a problem as it prevents the generation of a pure (single) Lamb wave mode, and therefore the interpretation of the waveform is more difficult. Nevertheless, the selective generation of Lamb wave modes can be improved by using a multi-element approach.

By mounting a pair of rectangular PZT transducers side by side, as in Fig. 1a), it is possible to enhance the amplitude of a specific mode if the inter-element distance, i_e, is set as a multiple of the wavelength [8]. Therefore, this approach implies previous knowledge of the phase velocity in order to calculate the wavelength. An alternative approach is to mount a pair of circular PZT transducers on both specimen surfaces, as depicted in Fig. 1b). In this case, if the pair is excited in phase, symmetric modes are preferably generated. On the contrary, if the pair is excited in anti-phase, the predominantly generated Lamb modes are anti-symmetric [2]. This approach depends only on the excitation frequency.

Besides tuning the Lamb wave mode selection, it is also crucial to minimize the dispersion phenomenon. For that, the actuation signal parameters, such as frequency, amplitude, number of cycles and pulse shape, have to be optimized.

The choice of excitation frequency has to take into account three aspects [8]. First, the number of Lamb modes should be as small as possible. Secondly, the Lamb modes should be as non-dispersive as possible. Finally, the wavelength should be equal to or smaller than the size of the damage to be detected. These requirements can be addressed by looking at the dispersion curves. The theoretical curves in Fig. 2 and Fig. 3 were calculated by the Vallen Dispersion program, version R2001.0806, from Vallen-Systeme GmbH, by inserting the thickness of the specimens and the velocities of longitudinal and transverse waves (c_l and c_t, respectively) in Table 2. The theoretical curves in Fig. 4 were determined using the formalism presented by Kessler et al. [7]. All the theoretical curves presented were computed assuming a plate made of isotropic material, whose properties are described in Section 3.1. It is relevant to mention that the curves in Fig. 3 agree with those in Fig. 4 for the frequency range 0–650 kHz. After pondering all the selection criteria [16], the chosen excitation frequency for damage detection was 500 kHz. At that frequency, the group velocity curve in Fig. 3 shows that only the S_0 and A_0 Lamb modes exist, displaying nearly non-dispersive behaviour (plateau regions). According to Fig. 2, for the A_0 mode, the phase velocity at 500 kHz is 2555 m/s, yielding a wavelength of 5.11 mm. At the same frequency, the S_0 mode has a phase velocity around 5827 m/s and a wavelength of 11.65 mm.

The number of cycles is one of the most important parameters, because it has direct influence on the frequency content of the signal. The larger the number of cycles, the narrower the bandwidth, and therefore the less dispersive is the Lamb wave propagation [16]. The bandwidth can be further reduced if a Hanning or a Gaussian window function is applied to the original signal, producing an N-cycle amplitude-modulated tone-burst whose

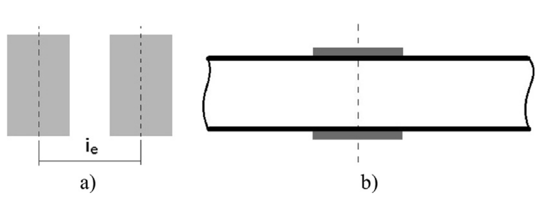

Fig. 1. Improvement of the Lamb wave mode selection, using a) rectangular PZT wafer transducers, and b) circular PZT wafer transducers.

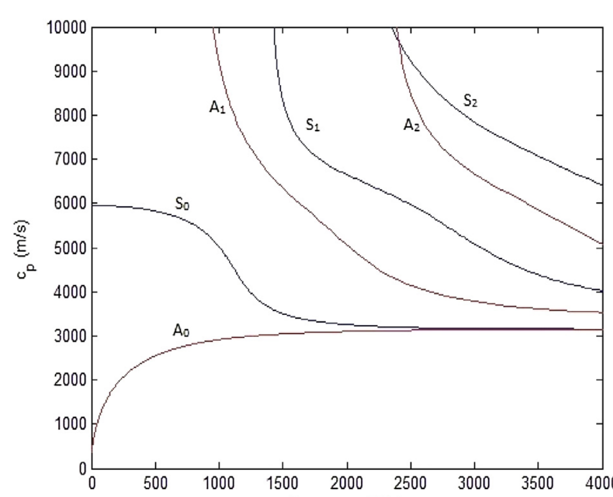

Fig. 2. Phase velocity dispersion curves for an isotropic material with longitudinal wave velocity, c_l = 7200 m/s, transverse wave velocity, c_t = 3368 m/s, and a thickness of 2.24 mm.