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A "Design of Experiment" Approach to the Performance of Lamb Ultrasonic Wave-Based Structural Health Monitoring of Aeronautical Carbon Fibre Reinforced Polymer Laminates

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The present paper investigates, through the Design of Experiment (DOE) methodology, the performance of Lamb wave-based Structural Health Monitoring (SHM) by using PZT transducers which are surface bonded onto aeronautical carbon fibre reinforced polymer (CFRP) laminates. The experiments highlight the chance of exciting a pure A_0 Lamb wave mode, actuating at low frequencies [0;50] kHz; in addition, via a pair of PZT, the magnitude of the diagnostic signal and consequently the signal to noise ratio (SNR) is amplifiable. Hence a rigorous 2^k factorial design method has been applied to study the influence of the following three factors on the SHM approach: the frequency of excitation, the dimension and the position of delamination defects artificially recreated using Teflon patches. After processing the sampled data with the discrete and continuous wavelet transforms, respectively for denoising and extracting the features of the signal, the SHM approach is shown to be able to detect small delaminations in the range from 8 to 24 mm, regardless of their location in the CFRP laminates. The frequency and the interaction between the position and the dimension of defects are demonstrated to be the most influencing factor.

1. Introduction

CFRP composites have been developed since the '60s and allow the design of resistant and innovative light weight primary structures, replacing traditional metallic materials, due to their high strength–weight and moduli-weight ratios, excellent fatigue strength as well as fatigue damage tolerance; another advantage is their non-corroding behaviour. However, their intensive structural use remains limited due to, among other factors, several peculiar damage mechanisms which are able to quickly degrade the mechanical properties and result in high maintenance costs caused by the service interruptions required for carrying out periodical non-destructive testing (NDT) inspections. An increasingly proposed solution in the literature is the application of a structural health monitoring (SHM) approach which, in the aeronautical field, has shown, according to Chang (1999), the potentiality of decreasing the overall costs of NDT by 30%. The present paper investigates this possibility by focusing on the application of the DOE methodology to the performance of Lamb ultrasonic wave-based SHM, using PZT transducers surface bonded onto aeronautical CFRP laminates. The choice of a DOE approach is based on the well-known fact that the success of an ultrasonic SHM approach requires the knowledge of the most influencing factors and their mutual influences which up to now have not been studied, but have been considered individually in the published research. In particular, a rigorous 2^k factorial design method is applied to study the influence of the following factors on a SHM approach: the frequency of excitation, the dimension and the position of the defects. Since the worst type of damage in a composite structure is delamination, this research particularly focuses on this kind of defect, obtained artificially by using Teflon patches. To achieve this objective, experimental elastic moduli of the CFRP lamina necessary for defining the propagation of an elastic wave are firstly illustrated and the information is subsequently used to simulate the Lamb wave dispersive propagation properties through the semi analytical finite element (SAFE) approach. Information about the dispersive behaviour of such waves is needed to best fit the Lamb wave-based SHM to the target structure and to thereby allow the design of all aspects of the SHM process, i.e. the way to activate and receive the diagnostic signal, the type of PZT transducers, etc. Finally, the DOE approach is applied to two composite panels and the sampled data are analysed with the discrete and continuous wavelet transforms. The CFRP system adopted in this research is a quasi-isotropic layup 17 ply $[0/+45/0/-45/90/-45/0/+45/\underline{90}]_s$, one of the most representative carbon fibre laminates in the aeronautical field, as N. Toso, J. Alastair (2011) show in their EASA framework, made of unidirectional prepreg SAATI EH-550/T800S lamina.

2. Experiments on CFRP lamina and laminate

Since the propagative properties of an elastic wave depend on both physical and elastic properties, the first necessary step is the definition of the effective elastic moduli of the lamina constituting the target quasi-isotropic carbon-fibre laminate. CFRP laminates belong to a special class of orthotropic materials, called transversely isotropic. Their mechanical behaviour $\boldsymbol{\sigma} = [C]\boldsymbol{\varepsilon}$ requires five independent elastic constants: E_{11}, E_{22}, G_{12}, ν_{12}, ν_{23}. According to ASTM-D 3039 and 3518, experimental tensile tests have been conducted on four types of coupon tests (each one having five specimens per test condition): UD 0°, UD 90°, UD ±45° and a quasi-isotropic layup. The coupon types one to three allow the definition of the in-plane tensile properties E_{11}, E_{22}, ν_{12}, ν_{21} and, in a simplified way, the in-plane shear response G_{12}. Coupon four is used to evaluate the elastic properties of the target quasi-isotropic layup.
An electro-mechanical tensile test machine MTS-Alliance RT/100 (maximum load 100kN) and two half Wheatstone bridges, compensated in temperature through a ''Dummy'', dedicated to the longitudinal and transversal strains form the basis of the experimental setup; the used strain gauges refer to CEA06250UT350. Figure 1 displays the stress-strain curves (obtained from the extensometer data) and the typical failure mode of the different specimens.

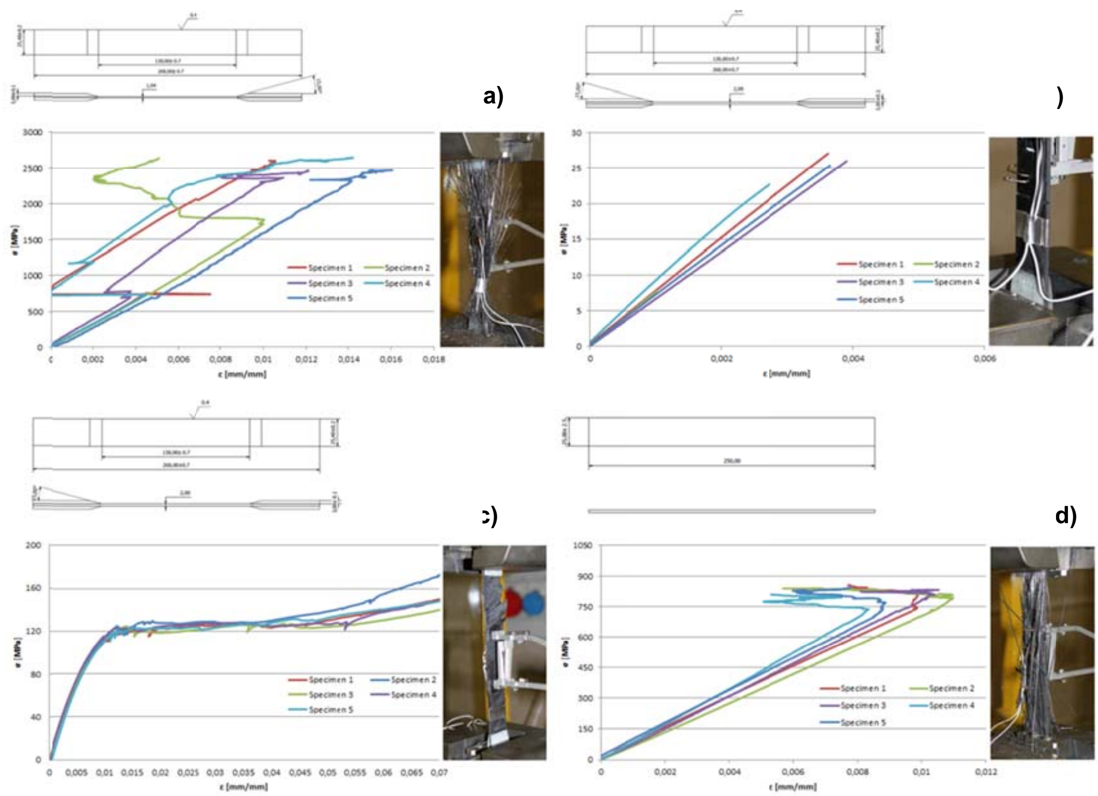

Figure 1: Experimental tensile stress-strain curves and the corresponding failure modes: a) UD 0°, b) UD 90°, c) UD ±45°, d) quasi-isotropic specimen.

Table 1 summarises the experimentally measured elastic moduli of the lamina constituting the quasi-isotropic laminate; respectively μ stands for the mean value, σ for the standard deviation and CV is defined by the ASTM-D 3039 as the sample coefficient of variation (σ/μ).

Table 1: Experimental in-plane properties of the lamina constituting the quasi-isotropic laminate

	$E_{11}\ [GPa]$	ν_{12}	$E_{22}\ [GPa]$	ν_{21}	$G_{12}[GPa]$	$E_{xx}\ [GPa]$	ν_{xy}
μ	159,420	0,323	8,120	0,018	4,68	70,020	0,371
σ	2,471	0,019	0,432	0,001	0,342	1,033	0,002
CV [%]	1,550	5,795	5,326	7,480	7,309	1,475	0,560

3. Semi analytical finite element (SAFE) simulation and design of the SHM process

SAFE is a useful and powerful method for numerical modelling of guided wave propagation in composite laminates of arbitrary layup and cross-sectional geometry, where usually traditional FEM method requires high computational cost and may result in numerical failure, especially with very short wavelengths, as discussed by Bartoli et al. (2006). SAFE approach uses a finite element bi-dimensional discretization of the cross-sectional area since the displacements along the wave propagation direction are assumed to be in the harmonic-plane way; moreover, the typical plate geometry of laminates allows for further simplified simulations through mono-dimensional EF. Solutions about the existence of multiple modes and dispersion properties can be obtained in a numerically stable manner of an eigenvalue and eigenvector problem. Two quadratic 1-D EF have been used to model each of the 17 laminae constituting the quasi-isotropic laminate, on the base of the convergence studies of Bartoli et al. (2006) for dispersive solutions; each element has three degrees of freedom (dof) per node, associated to the displacements u_x, u_y, u_z.

Figure 2 displays the dispersion curves, obtained using, as SAFE's input, the experimental results shown in Table 1; despite the quasi-isotropic layup, to quantify the anisotropy level, three different directions of Lamb wave propagation (0°,45°,90°) have been simulated, regarding the 0° aligned fibre. These curves highlight, true to form, the quasi-isotropic behaviour of the laminate, and an essential parameter for the SHM process: the so called cut-off frequency, which outlines the extension of the non-dispersive region, where only three fundamental Lamb wave modes exist (S_0, A_0 and SH_0) and whose dispersive behaviour is restrained (velocity is almost constant in this range). Figure 2 a) to c) show no substantial difference of the $f_{cut\text{-}off}$ parameter, whose value is about 380 kHz, since the quasi-isotropic stacking sequence attempts to minimise the anisotropy level of the laminate; this behaviour is highlighted in Figure 2 d) which shows the phase velocity polar diagram of the Lamb wave modes.

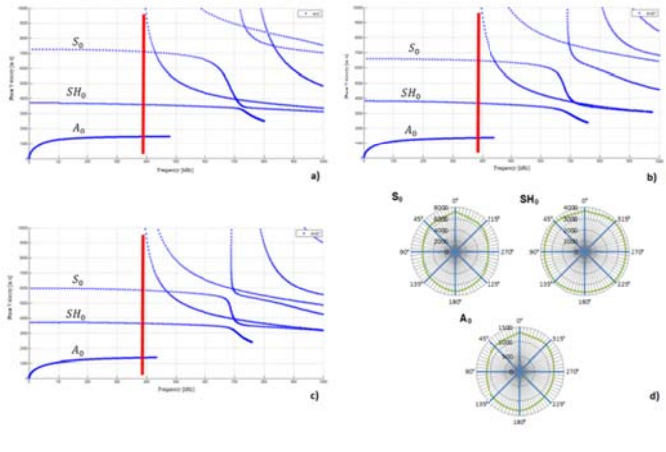

Figure 2: Dispersion curves from the SAFE approach in the quasi-isotropic laminate, a) 0° , b) 45°, c) 90° wave propagation referring the aligned 0° fibre; d) shows the phase velocity polar diagram at 200 kHz.

Figure 3: Detail of a surface mounted PZT transducer.

Having determined the cut-off frequency, the PZT ceramic that best suits the Lamb wave-based SHM process (on the base of its piezoelectric constant) has been chosen and has, consequently, enabled the design of the transducer: the actuating and receiving Lamb waves, the planar and thickness resonant frequency, and therefore the geometrical features, must be chosen in agreement with either the actuating (frequency below 380 kHz) and receiving phase (adequately far away from the resonant frequencies). The aforementioned properties of the PZT PIC255, used for the experimental activity, can be found at the PiCeramic website; moreover, Figure 3 closely outlines the chosen piezoelectric transducer.

4. A “Design Of Experiment” approach

The DOE approach essentially consists of a preliminary experimental stage and of a secondary stage dedicated to the design of an experimental plan and the analysis of the ensuing experimental results.

4.1 Preliminary stage

As Montgomery (2005) said: ‘’the success of an experimental research is founded, more than 90%, on an early stage of laboratory work’’. This requires initially a better understanding of the physical phenomenon, in a composite material, causing the Lamb wave propagation and, consequently, of the development of the best experimental setup and of the way of conducting the experiments; regarding the first aspect, Figure 4 displays the developed measurement and acquisition systems.

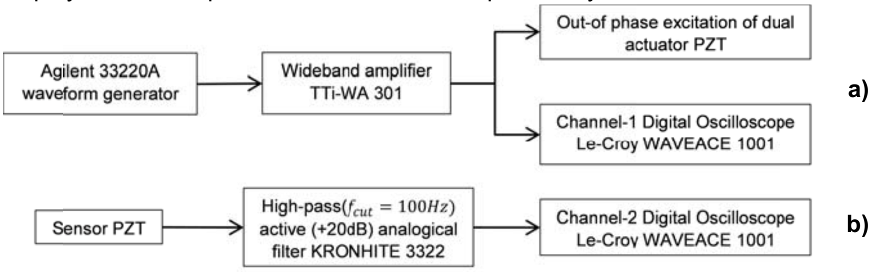

Figure 4: Detail of the measurement chain a) and of the acquisition system b).

Concerning the latter, a PZT wafer fixed onto a host structure generates simultaneously both symmetric and anti-symmetric modes, which superimpose and influence each other making the interpretation, of the diagnostic signal, a troublesome task. At present, most mode selection approaches are based on the rationale that a desired wave mode can be enhanced while other undesired modes minimised in the resultant signal, after mutual interaction of an array of appropriately placed PZT. Z. Su, L. Ye (2004) assert to be able to selectively activate a desired Lamb mode energising, in-phase (symmetric mode S_i) or out-phase (anti-symmetric mode A_i), a pair of PZT transducers symmetrically bonded on the upper and lower surfaces of a quasi-isotropic composite laminate. Actually, this approach seemed here to enhance a specific mode at a given frequency, but it wasn’t able to cancel wave modes completely. An alternative method, instead proposed here, turns out to be particularly efficacious at low frequency: actuating within [0;50] kHz, a pure A_0 mode is generated (see Figure 5a). The magnitude of such an A_0 mode can then be magnified, thereby improving the SNR, through the aforementioned mode tuning approach, as exemplified in Figure 5b. All these preliminary tests have been carried out on the quasi-isotropic circular laminate visible in Figure 6 and explained in detail in A. Gianneo (2012).

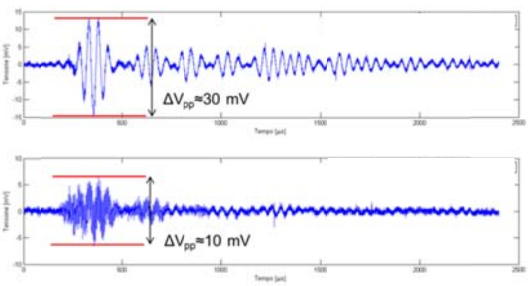

Figure 5: Effect of the PZT actuation strategy: the signal in response to a pair of PZT excited out of phase; b) signal in response to a single PZT excitation.

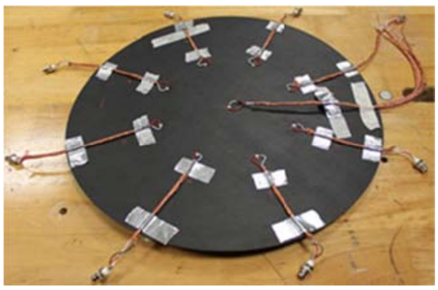

Figure 6: Quasi-isotropic circular laminate target of the preliminary experimental stage.

4.2 Design and analysis of experimental results

With the aim of studying the influence of the k factors on the SHM process of composite laminates, an experimental screening plane with a factorial design 2^k approach has been chosen, thus taking into account both the principal and interactional effects. The design factors, established amongst many others classified as constant and noise factors, are: the frequency of excitation set at 21, 36 kHz according to the

range [0;50] kHz, the position and the dimension of the delamination defects. The defect dimensions of 8 and 24 mm have been chosen on the basis of the SAFE's wavelength simulation at the excitation frequencies. They are located, via Teflon patches during the manufacturing process, between the first and second ply, and the sixteenth and seventeenth ply (respectively at a distance of 0.125 mm and 2 mm from the upper surface). Furthermore, as the experimental scatter can potentially hide the significance of the factors under investigation, the chosen levels are sufficiently spaced from one another to prevent such circumstances.
The designed plan has been conducted driving a pair PZT actuators out-of-phase, in agreement with a five cycle sinusoidal toneburst 30 V peak-peak modulated with a Hanning window. Two groups of time records (21 and 36 kHz) have been sampled, one for each of the two artificially defected composite panels, according to the measurement chain aforementioned in Figure 4a. The sampled data have been processed using the wavelet transform for denoising the signal (DWT, wavelet Daubechies 6th level) and extracting the feature of the diagnostic signal (CWT, wavelet Morlet) in response to the artificial defects.
Such a SHM process is able to identify defects as well a classic ultrasonic phased array B-Scan, as the good agreement between the two methods displayed in Figure 7 shows, but the SHM process is much more time efficient and demonstrates the presence of damage without any handling of the ultrasonic probe and briefly indicates its location in the laminate.

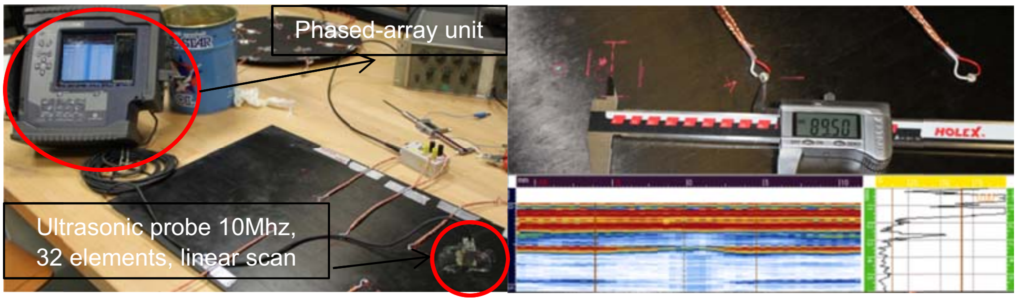

Figure 7: Comparison between results obtained from an ultrasonic phased-array B-scan (red dotted line) and a SHM process (asterisked circles) based on the TOF of CWT coefficients.

An ANOVA analysis of the plan sampled data, reported in Table 2, points out, with a p-value of 10%, the frequency and the interaction of the position-dimension as the potential key factors influencing the SHM process.

Table 2: ANOVA report referring to the complete model

Term	p-value	R^2	$R^{2\text{-adj}}$
Constant	0.019	57.08%	19.53%
Frequency	0.100		
Position	0.533		
Dimension	0.408		
Frequency*Position	0.542		
Frequency*Dimension	0.462		
Position*Dimension	0.100		
Frequency*Position*Dimension	0.251		

As a result, a lowered model is considered, which only contains the factors previously highlighted. The resulting model fits the experimental evidence better since both the R^2_{adj} parameter rise and also the hypothesis about the residuals normality, the homogeneity of variance and the absence of any structure, as shown in Figure 8, enhance passing from the complete model to the lowered one.

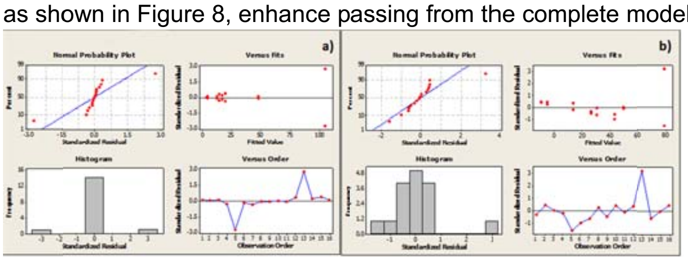

Figure 8: Check of the residuals hypothesis of 2^k factorial plan: normality, homogeneity of variance, absence of structure, independence from run-order; a) complete model, b) lowered model.

Therefore, the ANOVA gives the coefficients of a predicting model of a composite host structure to the delamination damage, the target of such an implemented SHM process, which can be arranged in the following equation:

$$Y = cost - 18.02 \cdot f_{act} - 17.99 \cdot d \cdot h \qquad (1)$$

where Y is the magnitude of response, f_{act} the frequency of the PZT actuation, *d* the dimension of the artificial defects and *h* their position in the laminate; the factors are coded, as usually by ANOVA, with a low and a high level so that i.e. 21 kHz is associated to -1 (low level) and 36 kHz to +1 (high level). According to (1) and the main effect and interaction plot of Figure 9, a higher chance of detecting delamination defects can be obtained by working at a low frequency (21 kHz), since the response is maximum. Therefore, the implemented SHM process gives the best indication in the combination of position-dimension factors respectively low (between the 16th and 17th ply of laminate) and high (24 mm); Such a SHM process has been able to provide a response in all other possible factor combinations.

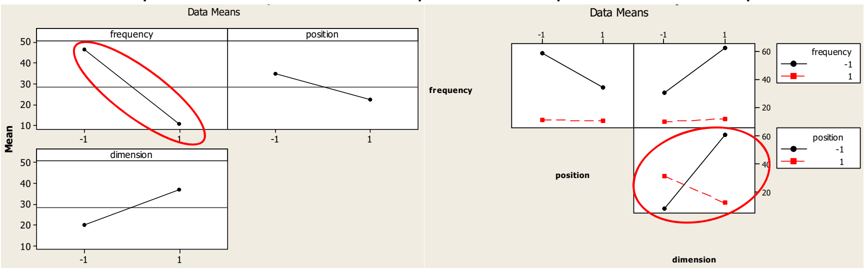

Figure 9: Main effects and interaction plot of the studied factors: frequency, dimension and position of delaminations.

5. Concluding remarks

A new way of Lamb wave mode tuning, actuating at a very low frequency [0;50] kHz, which is able to give back only the fundamental A_0 mode has been observed and characterised; this simplifies the interpretation of the diagnostic signal waves received from the PZT sensors, since only one mode propagates and interacts with the host structure. Moreover, the magnitude of the diagnostic signal as its ratio to noise using a pair of PZT actuators symmetrically bonded onto the upper and lower surfaces of the composite laminate can be enhanced. As a result, the performance and the potentially influencing factors on such a SHM process, referring to a quasi-isotropic composite laminate in a pulse-echo configuration of the PZT transducers has been studied. We can assert the ability of the detection of small delamination defects, from 8 to 24 mm size, wherever placed in the laminate, and highlight that the better detection performance are achievable working at 21 kHz and in the factor combination of high dimension combined with low position, or vice versa.

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