Material elastic waves test exploitation in benefit of composite structure health monitoring

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Abstract

Composite structures suffer from an unsatisfactory behavior to impact damage, which involves conservative designs, high maintenance and repair costs in order to prevent premature failures. These time-consuming operations can be optimized by SHM techniques. In the case study presented, a 48 PZT sensing network has been integrated within two similar composite panels, representative of real aeronautical structures and multi-functional skin concept, approximate size 600mm width and 1650mm length, with substrate made of carbon fiber and thermoset matrix, with two integrated hat stiffeners along the longitudinal direction, and transverse C metallic stiffeners. This sensors network may be used by both active and passive techniques. Passive monitoring consists in the continuous acquisition of high frequency signals during impacts tests on the structure, and thus detecting impact time and location. Active methods require that at least one PZT works as an actuator, thus generating elastic Lamb waves that propagate along the structure. Damage-wave interaction is studied, in such a way that damage detection and location should be possible. The test plan includes different sources of damages from an instrumented impact hammer till air shotgun scenario, taking into consideration BVID levels defined for each part. This paper deals with the analysis of waves traveling through the structure in benefit of event and damage characterization.

1 INTRODUCTION

Lately, special attention has been paid to Structural Health Monitoring for damage detection so as to avoid premature failure on aeronautical structures. More specifically, SHM could help to improve the philosophy from scheduled maintenance moving towards condition based maintenance, allowing lighter and optimized structures.

However, the widespread practical implementation of SHM is still some way away, mainly because the high levels of confidence required on aircraft structures **[1]**.

Meanwhile, non-destructive techniques based on Lamb waves propagation are taking advantage over other techniques such as ultrasonic inspection, because of the long distance that Lamb waves can travel along the structure. This approach allows to monitor a full structure using a sparse array of sensors with good accuracy and sensitivity over a long range.

Taking a small number of sensors as the main goal, PZT (Lead Zirconate Titanate) piezoelectric sensors are chosen, due to its outstanding characteristics to generate and measure elastic waves, and they are also particularly suitable for integration within an aircraft structure because of low weight and volume, high sensitivity, ease of integration, broad frequency response, low power consumption, low acoustic impedance and, last but not least, low cost.

One of the most severe requirements to be fulfilled on aircraft structures is impact tolerance, since on composite materials the load carrying capacity might be drastically reduced on damaged structures without any visual proof of damage existence. Barely Visible Impact Damages (known as BVID) may be present on composite structures due to design allowables. In case these damages grow, a reliable methodology for both detection and location in order to get the real-time condition of the structure might offer an advantage over traditional inspection.

Most common defects that usually appear after a low or mid-energy impact are basically delaminations and stiffener debonding, with mainly local effects. Currently, the SHM techniques for detecting and locating these types of defects with integrated sensors are based on the study of elastic guided waves that propagate along the structure. Both Time Of Arrival (TOA) and the amplitude response are the variables measured by piezolectric sensors after the elastic wave arrival. TOA is the time that it takes for the wave to reach the sensor since the event occurs, and it is crucial for triangulation purposes.

On one hand, the main difficulty lies on signal processing, with the target aimed at damage extension characterization and localization. On the other hand, anisotropy can become a challenge difficult to overcome, since most studies are carried on rectangular flat plates made from isotropic or quasi-isotropic material. There is much literature on calculation of Lamb waves on isotropic media. Lamb also developed a method to calculate dispersion waves in isotropic media, but composite materials requires a more sophisticated method that combines anisotropic media and layered media. Furthermore, most of these studies have been carried out on infinite or semi-infinite plates, without taking into account edge effect produced on stringers and stiffeners that cause the wave to be reflected, thus tangling the signal and making it difficult to be processed.

The structure of this paper is as follows: a brief description of the structures tested and the experimental setup are described in Section 2. The passive method with some results is presented in Section 3, whereas the active method is evaluated in Section 4, which is followed by the conclusions at Section 5.

2 EXPERIMENTAL SET-UP

2.1 Specimens geometry

The two panels tested during this work, made of carbon fiber and thermoset matrix, are similar in geometry, but differ on sensor lay-out and wiring scheme. Panel 1 was instrumented using 30 PZT, focusing on areas prone to impact damage, whereas for panel 2 48 PZT were bonded on an 8x6 matrix pattern (see **Figure 1**).

Regarding geometry, both are approximately 600mm width and 1650 mm length, and include two longitudinal hat stiffeners along the longest side, and two transverse metallic C stiffeners.

They are bolted to a metallic frame for shear load introduction through a test rig, and a series of impacts were given, detailed on the next sub-section.

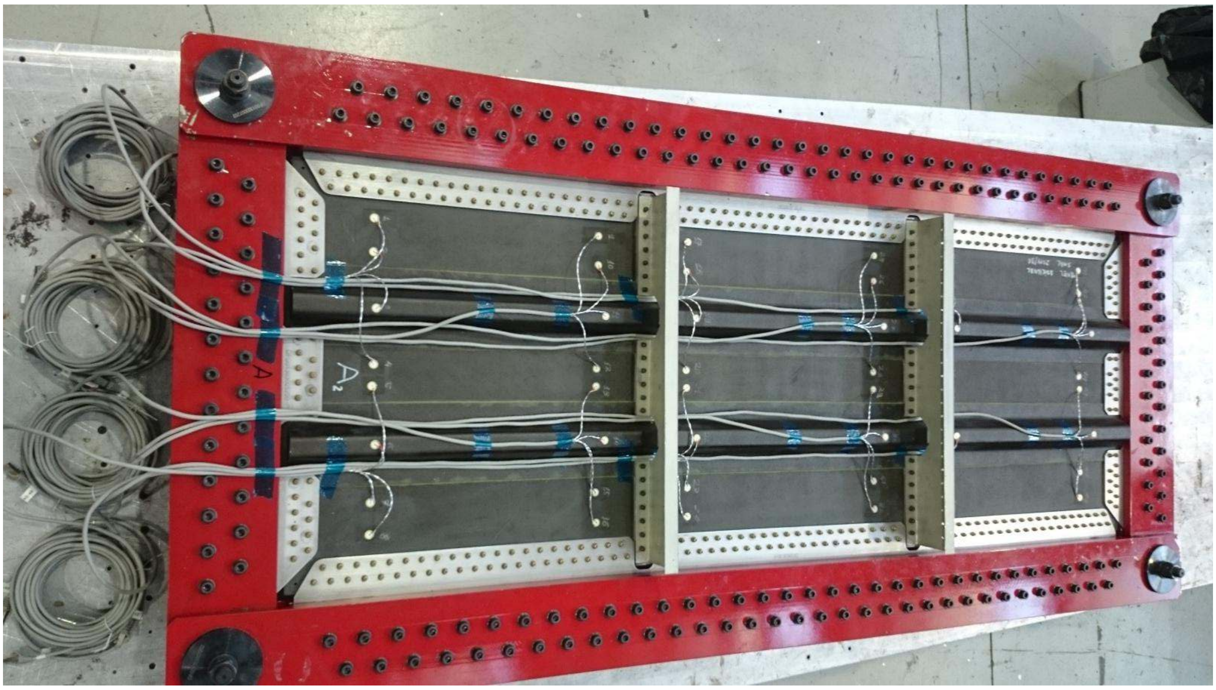

Figure 1: Sensor lay-out over the specimen, with the origin of coordinates system used for positioning.

2.2 Impacts schedule

The test plan started with 4 impacts given at different locations using a calibrated hammer with 3 different weights for each location. It was not expected to introduce any damage.

Then, 2 impact grids (R1 and R2) were sketched on two of the 9 bays of the panel. R1 consisted on a matrix of 3x10 impacts, and R2 had 3x5 points. In this case just one weight for the instrumented hammer was used.

After this, impacts at 5 and 10 Joules at other 4 locations were given by means of a gravity impactor.

Once this series of impacts was finished, the structure is loaded at +120kN, and two different locations were impacted at 25J with a gun impactor. A similar situation was reproduced with the structure under compression load, at -120kN, for 2 additional locations.

This schedule is summarized on **Table 1**.

Impact	**Energy**	**Condition**	**Impactor**
D1 to D4	3 different weights	Unloaded, on ground	Hammer
R1 & R2	Small weight	Unloaded, on ground	Hammer
I1 to I4	5 & 10 J	Unloaded, on test rig	Gravity impactor
I1 & I3	25 J	Loaded, +120kN	Impact gun
I2 & I4	25J	Loaded, -120kN	Impact gun

Table 1: Test schedule for Panel 1.

3 PASSIVE METHOD

3.1 Theoretical background

Lamb waves can have an infinite number of both symmetric and antisymmetric modes, though for frequency-thickness product below 1 MHz·mm, (called the cut-off frequency of higher-order modes), only the fundamental modes S0 and A0 propagate **[2]**. In this low frequency range (i.e. when the wavelength is greater than the plate thickness) these modes are often called the “extensional mode” and the “flexural mode" respectively, terms that describe the nature of the motion and the elastic stiffnesses that govern the velocities of propagation.

At the tested panels, this product falls below mentioned cut-off frequency, which should simplify data post-processing.

Impact triangulation consists of an optimization of the Time of Arrival (TOA) of the guided waves for the measured signals together with theoretical Lamb waves dispersion velocity to obtain the most suitable impact time and impact position.

First of all, a classic triangulation based on minimizing the error of a cost function was studied. Taking into account that these tested aeronautical composite structures are anisotropic, this method needs the calculation of the dispersion curves, thus requiring to know material properties in order to get group velocity for S0 and A0 modes. **[3]**

The excited wave mode by impacts was assumed to be only the first antisymmetric mode A0. Symmetric mode S0 excitation is negligible and could not be distinguished from PZT noise. Therefore, theoretical group velocity is extracted from results of the A0 dispersion curve.

Another statistical approach was to train a neural network to fit data from tests to impact positions. This ANN training needs a great amount of impact data, therefore only grid results were candidate for using this triangulation method.

Input data for triangulation was the TOA of wave signals to PZT positions. TOA were treated so the first PZT to receive the signal had TOA zero.

3.2 Hardware configuration and software implementation

For measuring during impact events, a National Instruments data acquisition card has been used, with a maximum sampling rate of 2 MS/s for one channel, adequate for capturing high frequency phenomena occurring during an impact event. For each impact location, measurements are taken over clusters of 8 sensors at most, with a predefined lay-out depending on impact position, enough for damage location by means of triangulation.

Set-up includes a calibrated impact hammer from Brüel & Kjaer, with three different masses, a gravity impactor, an impact gun and an air cannon.

PZT data acquisition was started by means of an external analog trigger signal manually activated after which 2 seconds of data were recorded. This way, both the DAQ and the hammer signal were synchronized in time.

Developed LabView® software allows, after trigger activation, to start data acquisition for the preselected time period. These data are subsequently translated into MATLAB®, searching for wave arrival peaks to each sensor, with its corresponding amplitudes.

For post-processing the signal, several algorithms have been implemented, where analyses were mainly done in time domain, such as filters to clean undesirable low frequencies and transforms to get the absolute value of the signal with its envelope, which filters oscillatory components at high frequencies.

3.3 Results

A first approach using classical triangulation is shown at **Figure 2**. The method used to decide the best candidate for impact position was to calculate an error function for a grid of possible impact positions within the PZT positions. In addition, initial time of impact was another variable, as it is a priori unknown.

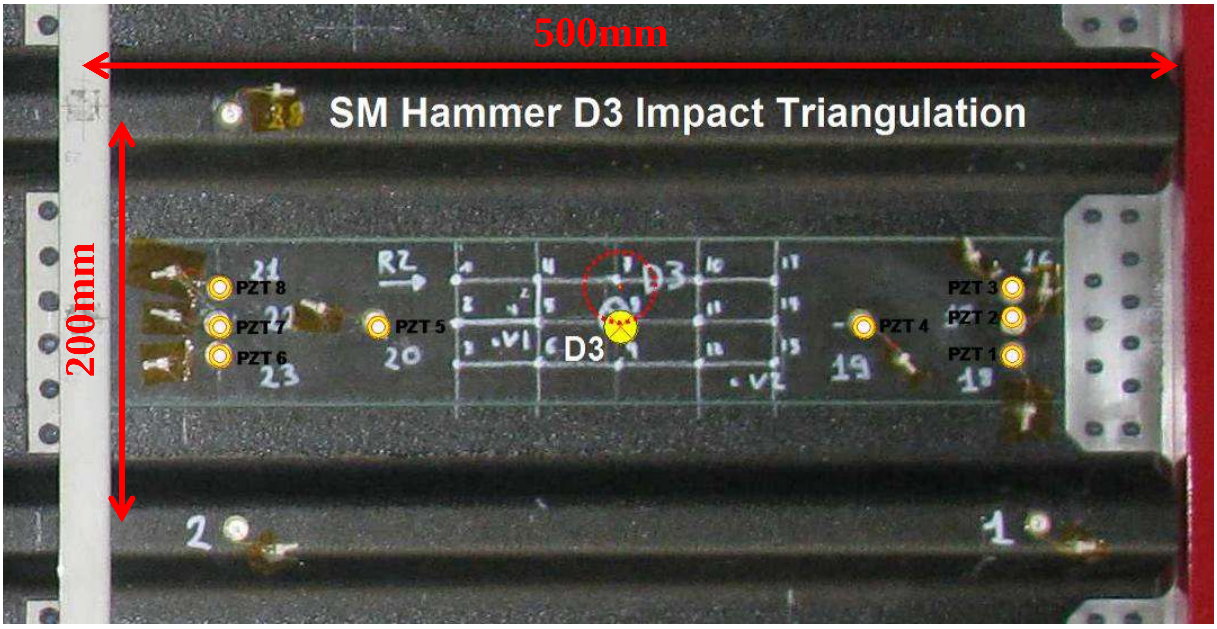

Figure 2: Results for classic triangulation at D3 position for small mass hammer impact.

For the sake of completeness and error improvement, an Artificial Neural Network statistical method is also considered.

As an example, results at one of the impact grids (R1) are shown below (**Figure 3**).

Triangulation error and ANN performance was checked with some test data (red dots) that was not used for the ANN training (blue dots).

PZT 5 showed poor results and was, therefore, discarded. Although PZT 1, 3 and 4 showed incoherent results for classic triangulation, ANN non-linear condition makes them effective for this kind of problems. Therefore, only PZT 5 was discarded.

Results show that, for impacts at a fair distance from PZT 8, impact position could be at large correctly triangulated. In addition, transversal coordinates could be triangulated. Note that estimated error is extracted from error derived from test data. This error is generally lower than the error obtained with classical triangulation.

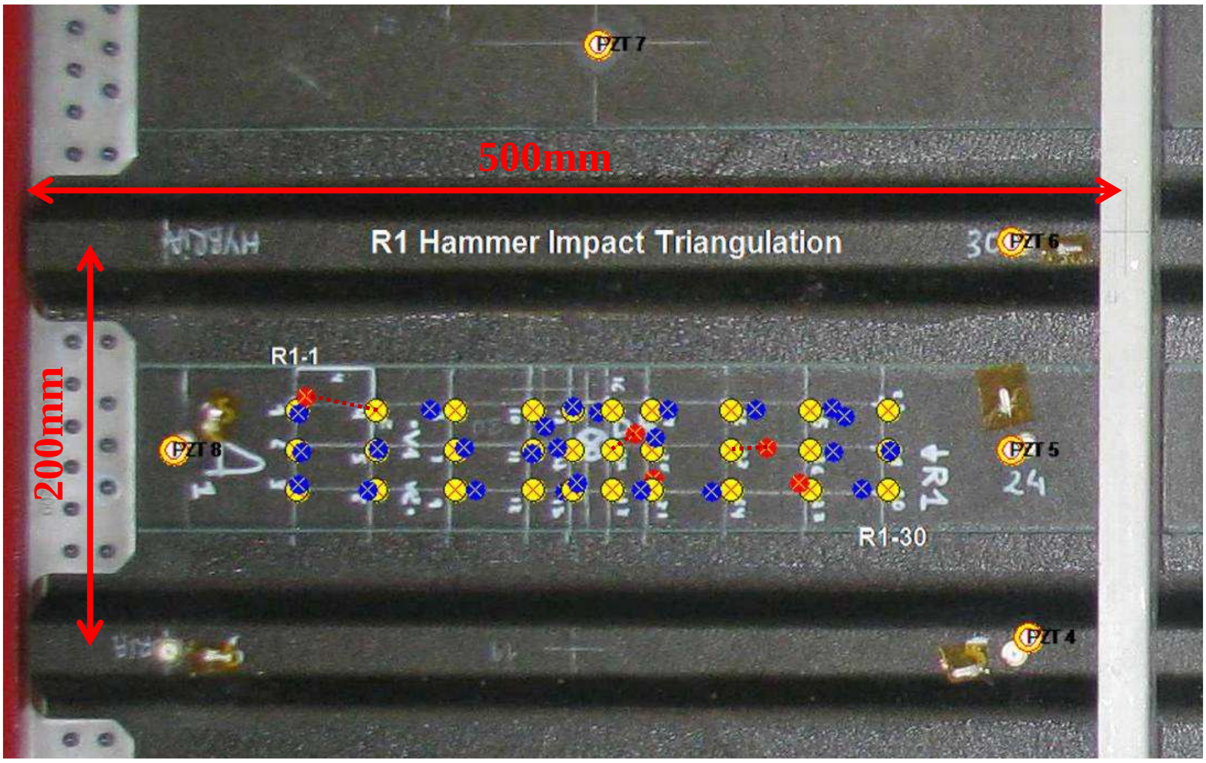

Figure 3: Results for ANN triangulation at R1 impact grid.

4 ACTIVE METHOD

4.1 Theoretical background

Via the active method, the structure is monitored through comparison between one measurement taken on operating condition against one reference or baseline. In order to do that, one PZT sensor must act as an actuator while the others are listening, on a pitch-catch configuration. So, main steps include taking a reference, producing damage, taking new data, and comparing between both data sets in order to estimate damage appearance, location and characterization.

The wave train sent travels through the structure, and it will be recorded by the elements acting as sensors. If any defect appeared along the path, the received signal would change compared to a healthy part reference. Since there are several sensors working, it is possible to estimate damage location by means of triangulation. Damage magnitude can also be approximated, even though not on a quantitative way, at least qualitatively. With that goal on mind, a Damage Index is defined for each path, and then a Damage Map can be plotted by surface interpolation amongst all that paths.

4.2 Hardware configuration and software implementation

The device used for this purpose is commercial equipment from Acellent®, being ScanGenie® the hardware, and ACESS® the software providing machine instructions.

With the hardware available at this laboratory, up to 10 PZTs can be connected. Paths to be interrogated can also be defined, and so do frequencies.

The signal sent is a burst5 type with a frequency swept from 50 kHz to 450 kHz, by hundreds **[4]**. This way, it will be possible to check which frequencies induce greater excitation on the structure, since these will be the ones providing most information. This is because Lamb waves are dispersive and its velocity is dependent on frequency-thickness product.

For visualization purposes, a MATLAB® algorithm has been developed to get a contour plot of the damage to get information about possible defects in quite a visual way.

4.3 Results

This system needs therefore a reference to be used as a baseline for next measurements. This reference must be taken before any impact, since this will be regarded as healthy condition. After each impact, the part has to be interrogated again.

Figure 4 displays one of this damage maps after a 25J impact while the structure was under traction load.

While real damage does not cover the whole represented area, this can be used as a first approximation damage location for a further inspection by means of other techniques (NDT, X-Ray, etc) able to characterize real damage size.

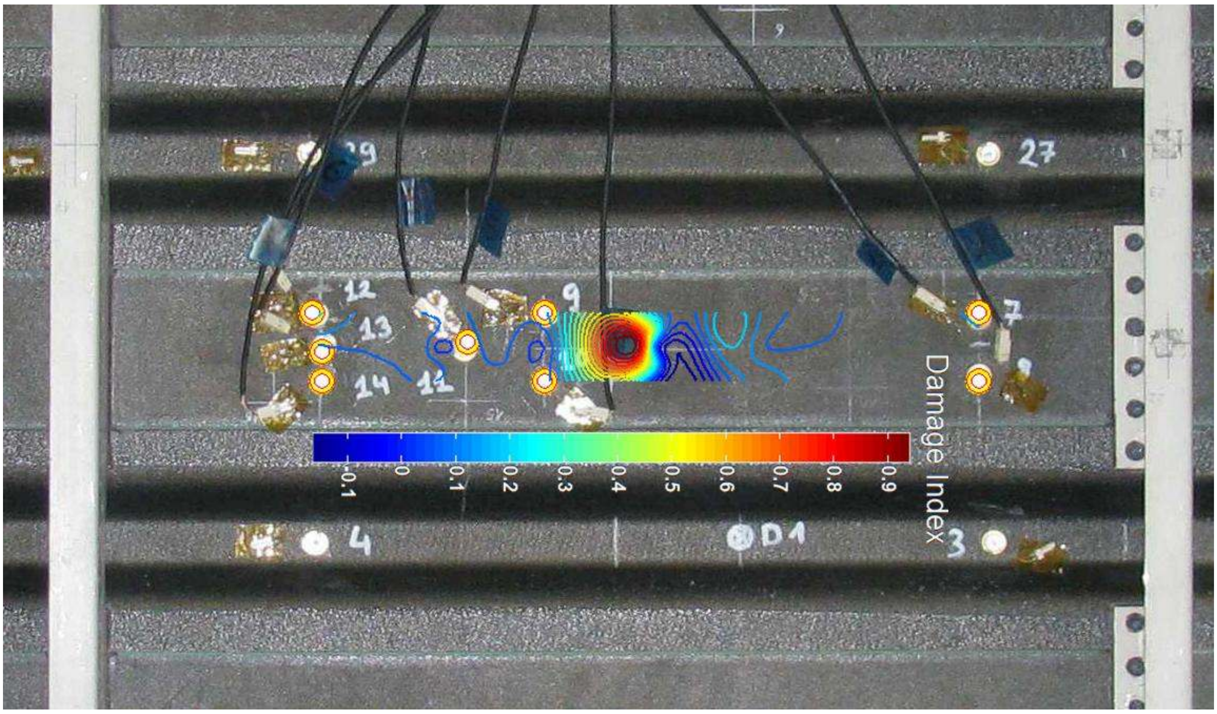

Figure 4: Damage map after 25J I1 impact.

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6 CONCLUSIONS

A methodology to detect impact events and damage location is the subject of the present paper. The scheme uses two approaches, one is based on a passive method, which just listens for events and locates them, and the other relies on an active method able to detect damage appearance.

Concerning the passive method, the advantage of the classical triangulation method is that an error measurement is provided. However, linear sum of errors has proven to give a non-conservative value of triangulation error. When the number of effective PZTs was above 4 (the minimum to obtain a measure of error), obviating the worst error provided a more accurate result. It is assumed that highest error is produced by accumulation of errors (in TOA calculation, velocity calculation, etc.)

ANN method provides a good statistical model for impact triangulation. Internally, ANNs learn to capture the physics of the problem with some training data without any further modeling. This statistical approach provides a much more straight-forward method to perform impact characterization.

Regarding the active approach, it is immediate to get visual information about damage appearance and its location, without attaining a full characterization of it.

However, damage indicators can be obtained in an easy, inexpensive and non-invasive way. That permits to keep advantageous operation conditions for as long as possible before premature failure takes place.

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