Validation of Structural Health Monitoring Techniques in a Complex Composite Structure

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Abstract:

In recent years, aircraft parts manufacturing with composite materials is increasing. The possibility of applying Structural Health Monitoring (SHM) to this type of material is one of the most interesting techniques in Non-Destructive Inspection (NDI) nowadays. In addition, ultrasonic inspection and, particularly, Lamb waves, are a very useful tool, as it allows to analyze plate-like structures using Piezoelectric Transducers (PZT) to guide the wave. The generation, acquisition and processing of electric signals (which is interesting to perform it in an embedded electronic system), and the application of damage detection algorithms (in this case, it will be used delay-and-sum and RAPID algorithms, and a topological derivative approach), allow the assessment of the damage state of the structure without the information of the previous state (baseline). The sample to be analyzed is a complex multi-curved part of CFRP, in which 5 defects have been introduced artificially during the manufacturing process. The generation and acquisition of signals in various states of excitation (varying the amplitude of the signal) was carried out, obtaining significant values of difference between the signals of the same path (pitch-catch mode), in order to finally calculate the location of the damage.

Keywords: structural health monitoring, student challenge, lamb waves, composite, damage detection

1. Introduction

The use of composite materials for manufacturing aircraft structures is increasing significantly in recent years, to the extent that the percentage by weight of this type of material in certain commercial aircraft has exceeded 50\% [1][2]. Structural Health Monitoring (SHM) of aircraft components is a viable solution to assess the damage state of these kind of structures [3]. Non-Destructive Ultrasonic Testing and Inspection (NDT-I), and particularly Lamb waves based NDT [4], is one of the most promising techniques to perform the analysis of aeronautical structures, particularly plate-like components. However, composite materials present certain difficulties, such as anisotropy of mechanical properties or manufacturing irregularities, which make the inspection of the structure a great challenge [5][6]. In this study, the inspection of a complex geometry and small-size specimen, manufactured in CFRP, will be carried out using piezoelectric transducers (PZT) and Lamb guided waves principles. The problem of this study is the lack of knowledge of the position, size and nature of these defects. The signals acquired by these transducers will be processed in a computer, and then analyzed using various algorithms, including the Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) [7] and delay-and-sum (DAS) [8], as well as a prototype of an algorithm based on the sampling method [9], and its effectiveness was tested for synthetic data (generated with a computer by solving the wave’s dynamics equation in a homogeneous two-dimensional...
plate) in [10] for a wide variety of defect configurations. Finally, an estimation of the position of the damage will be obtained over an image of the structure.

This paper is consequence of the Student Challenge from the 11th International Symposium on NDT in aerospace.

2. Experimental Set-Up and Problem Statement

The specimen to be analyzed Fig. 1 is a multi-layer monolithic structure manufactured of Carbon Fiber Reinforced Polymer (CFRP), with a variable thickness, as well as a number of layers that vary locally.

![Fig. 1. CFRP specimen. The maximum dimensions are 295 mm x 140 mm x 30 mm.](image1)

A Keysight 33512B 20 MHz 2-channel signal generator has been used for signal generation, and an 8-channel platform based on the Texas Instruments AFE5808EVM at 40 MHz Fig. 2 was used for signal acquisition.

![Fig. 2. Experimental set-up. At the back, the power supplies and the signal generator. At left, the acquisition system. At right, the specimen with the PZT's stuck.](image2)

In addition, connected through cable to the signal generation and acquisition system, several piezoelectric transducers (PZT) CERAMTEC SONOX P502 have been bonded to the surface of the specimen, in order to generate Lamb waves and acquire the responses in a pitch-catch configuration Fig. 3.

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The positions of the transducers were selected randomly, due to the complex geometry of the sample. In order to simplify the analysis, the specimen is considered as a plane surface. Due to this, the lateral surface was not analyzed (some transducers were bonded to it, but the wave propagation was not appropriate). In addition, due to the availability of 8 acquisition channels, only 9 transducers were used (one transmitter, eight receivers). Their position is depicted in the section Results.

As stated above, the position, size and nature of the damages are unknown. Therefore, the approach to the solution will be made in successive attempts, modifying both the excitation and processing parameters.

In order to obtain a set of signals with a good number of them that allow a good analysis, Round-Robin tests (pitch-catch configuration) will be carried out.

3. Methods

In the absence of information on the condition without damage (pristine state), the difficulty of the problem increases substantially, because it is very complex to set the test parameters and an adequate process to find out the position of the damages. Therefore, the problem is divided into two factors: the damage index (DI) and the imaging algorithm.

In addition, with the aim of simplify the geometry, it was considered as a plane surface, in order to facilitate the processing of the signals. However, this simplification can cause a loss of information, but it is the only way to make a good analysis using the available methods.

3.1. Damage index

The choice of an adequate DI is very important. Two types of values will be used in this study: those based on the formation of higher harmonics, and those based on differences in signals. For the first one, only the information of one test is necessary, and it is based on the appearance of superior harmonics when the signal crosses the defect [11]. In the second case, due to the absence of pristine state information, two tests will be carried out at different excitation amplitude (high amplitude and low). The appearance of any nonlinearity when normalizing the signals indicates the presence of damage [12].

3.1.1. Harmonic-based damage index

The appearance of higher order harmonics occurs when the elastic wave passes through a damage. In this study, the relative amplitudes of the second, third and fourth harmonics have been used. The Fast Fourier Transform (FFT) is performed to each signal, and then, the relative amplitudes of each harmonic with
respect to the main tone are compared. Fig. 4 depicts the frequency domain spectrum of two different signals. The main frequency and the higher harmonics amplitude is slightly different.

![Frequency Domain Spectrum](image)

*Fig. 4. Comparison between the frequency domain spectrum of two different signals. The higher order harmonic which has highest amplitude is the third one.*

With the values calculated using the FFT, the DI (1) is obtained:

$$DI_{XY} = \frac{A_n}{A_1^2}$$

(1)

Where:

- $A_1$: main tone of the signal’s amplitude.
- $A_n$: amplitude of the n harmonic.

For this study, the harmonic which had higher relative amplitude and, accordingly, was more appropriate for this analysis was the Third Harmonic Method (THM) [11].

3.1.2. Signal difference coefficient damage index

In order to carry out this analysis, two tests are necessary to compare the signal from the same path between transducers in two different states. The usual process is to compare the signals from the pristine state and from the damaged state but, since there is no information of the undamaged state, it is necessary to analyze signals from the same state.

To do this, the state variation is achieved by generating a signal at two different amplitudes (high and low). After normalizing the acquired signals, the non-linearity in the signal caused by the presence of a damage can be analyzed in two ways: with the Correlation Coefficient Method (CCM, sensitive to shift changes, calculating the standard Pearson’s coefficient between both signals) or the Scaling Subtraction Method (SSM, sensitive to amplitude changes, consists on normalize the signals and calculate the area between them) (2)(3). Fig. 5 depicts the difference in amplitude after the normalization.

$$SSM_{XY}(t) = X_H(t) - Y_L(t)$$

(2)
\[ DI_{XY} = \int_{0}^{T} SSM_{XY}(t) dt \] (3)

Fig. 5. Comparison between two acquired (normalized) signals at different excitation levels. Changes in amplitude are nonlinear between normalized high and low signals.

3.2. Imaging algorithm.

The image processing algorithm used was the Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID). It consists on assigning to each analysis point an elliptical geometrical value \[ \beta \], which is higher in the direct path between transducers Fig. 6 [13], and combine it with the DI value.

Fig. 6. Elliptical distribution of the RAPID algorithm.

The ellipse's size is controlled by the parameter \( \beta \), which for these analyses has been chosen as \( \beta = 1.01 \). The final equations for each analysis point are (4)(5)(6):

\[
E_{ij}(x_p, y_p) = \left[ \frac{\beta - RD_{ij}(x_p, y_p)}{\beta - 1} \right] \]

(4)

\[
R_{ij}(x_p, y_p) = \begin{cases} 
RD_{ij}(x_p, y_p) & \text{if } RD_{ij}(x_p, y_p) < \beta \\
0 & \text{if } RD_{ij}(x_p, y_p) \geq \beta 
\end{cases}
\]

(5)

\[
RD_{ij}(x_p, y_p) = \frac{\sqrt{(x_p - x_i)^2 + (y_p - y_i)^2} + \sqrt{(x_p - x_j)^2 + (y_p - y_j)^2}}{\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}}
\]

(6)
where:

- $E_{ij}$: is the value of the elliptical distribution in the point of analysis $P(x_p, y_p)$.
- $\beta$: is the value which limits the size of the ellipse, through the factor $R_{ij}$.
- $RD_{ij}$: is the ratio between the distance of the indirect path and direct path.

Finally, by combining DI values using CCM or SSM, the sum of all signal contributions on the point to be analysed ($P(x_p, y_p)$) was calculated as follows (7):

$$P(x_p, y_p) = \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} DI_{ij} E_{ij}(x_p, y_p)$$  \hspace{1cm} (7)

### 3.3. Other tested methods.

In addition to the previous methods, another signal processing algorithm were tested. The obtained results from Delay-and-sum algorithm and topological derivative were unsatisfactory, due to the complex geometry of the specimen, the impossibility of calculate the distances between the points of analysis and, therefore, the impossibility to calculate the velocity of propagation of the wave.

Furthermore, a sampling method based algorithm was tested. This processing method for experimental ultrasound data is based on simple physical concepts and algebraic operations that allow to avoid the use of more complex algorithms based on wave equation resolution. The scope of this algorithm development is to provide a simple way to build a damage indicator function where the highest values pinpoint the location of damaged zones.

The method is strongly based on scattering phenomena (which is the interaction between the wave equation fronts and the defect border) that causes wave deflection. When testing the time-domain sampling algorithm proposed in [10] with the provided data, the method did not succeed in finding damage for the following reasons:

- The nature of the damage is a critical factor taking into account the maturity level of the algorithm. In [10], only penetrable defects were tested. Delamination and composite materials failures are out of the scope of the method, at least at its current state.
- The method is strongly based on the knowledge of the domain. If distances in the plate cannot be accurately calculated, the algorithm would not be able to provide a good damage indicator.
- The speed of the waves in the structure must be a known parameter. In composite materials, due to anisotropy, the speed value depends on the direction of propagation.

In Fig. 7 are depicted some examples of the obtained results.
Fig. 7. Obtained results from Delay-and-Sum algorithm (a) and from sampling method (b). The rounded points are the locations of the considered PZT.

4. Results

The characteristics of the excitation signals are 20 Vpp, 5 cycles and 250 kHz for high amplitude test, and 10 Vpp, 5 cycles and 250 kHz for low amplitude signals, as well as Hanning windowing for both experiments. Some acquired signals, after normalizing, are depicted in Fig. 8.

Fig. 8. Excitation (black) and acquired (red) normalized signals.
The images obtained from the proposed methods (CCM, SSM and THM, using RAPID imaging algorithm), are depicted in Fig. 9. A procedure to detect local maxima was used, consisting in get the local maxima of every area of 10x10 mm$^2$ of the surface.

Fig. 9. Results using SSM (a), CCM (b) and THM (c). Black stars are the obtained maximum for each analysis.
The previous images show the obtained points by the used methods. In Fig. 10 are depicted all the results together. Table 1 summarizes the obtained points.

![Fig. 10. Obtained damage points (6 zones). The selected PZT are surrounded by a red circle, and the damaged zones are framed by yellow rectangles.](image)

<table>
<thead>
<tr>
<th>Zone</th>
<th>SSM X [mm]</th>
<th>SSM Y [mm]</th>
<th>SSM DI</th>
<th>CCM X [mm]</th>
<th>CCM Y [mm]</th>
<th>CCM DI</th>
<th>THM X [mm]</th>
<th>THM Y [mm]</th>
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<tr>
<td>1</td>
<td>92.6</td>
<td>50.5</td>
<td>0.2</td>
<td>95.1</td>
<td>56.8</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
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<td>2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>131.5</td>
<td>85.6</td>
<td>0.5</td>
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<tr>
<td>3</td>
<td>170.4</td>
<td>49.4</td>
<td>0.7</td>
<td>167.9</td>
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<td>0.8</td>
<td>149.0</td>
<td>49.9</td>
<td>0.9</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>210.5</td>
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<td>0.5</td>
<td>211.8</td>
<td>67.2</td>
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<tr>
<td>5</td>
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<td>0.6</td>
<td>208.0</td>
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<td>1.0</td>
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<td>6</td>
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</table>

### 5. Conclusions

The difficulty of analyzing the specimen of this study comes from its very complex shape, which involves a lot of curves and perpendicular angles, the lack of information from the pristine (undamaged) state, and other important characteristics (velocity of propagation of Lamb waves, mechanical properties, etc.).

However, the main objective of this paper was to validate and test usual SHM methodologies on a complex geometry. The obtained results show some points with higher DI, which are summarized in Fig. 10 and Table 1. This points are over six zones on the surface.

The main problem was to set some criteria in order to decide which point was a real damage or not. In this case, all the points on an analysis area (10x10 mm²) which had the maximum DI were considered as a damage. Some points are obtained only from one method (zone 2), and another points from two methods (zones 1 and 4).
References