Spectral Analysis of the propagation of Lamb Waves on Fibre-Metal Laminated Plates to detect and evaluate different defects

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Abstract
Fibre Metal Laminates (FML) are composite materials that present aggregated characteristics of different materials, being widely applied in the aerospace industry due to their superior properties if compared to the alloys. However, aeronautical materials are invariably subjected to environmental action during in-service conditions. It is fundamental to detect damage onset and its evolution by using nondestructive techniques. The nondestructive inspection using Lamb waves becomes an important tool in the evaluation of materials due to the possibility of spreading over long distances. Nevertheless, to better evaluate the results it is necessary the use of digital signal processing. On the present work, the spectral analysis of the propagation of Lamb waves will be done on FML. Plate-like specimens with known defects will be utilized on the pitch-catch configuration and further the signals will be processed by computational software to detect and evaluate damages such as delamination and fibre fracture.

Keywords: Fibre Metal Laminates, Non Destructive Testing, Ultrasonic Lamb Wave, Digital Signal Processing.

1. Introduction
A fibre metal laminate is a hybrid material consisting of alternating layers of metal and pre-impregnated fibres reinforced polymers (PREPEG). FMLs were primarily developed for fatigue prone areas of modern civil aircraft. An example of this composite is a combination of aluminium and glass fibre reinforced epoxy, Figure 1. This material has better fatigue properties than traditional aluminium alloys. These properties enable them to be applied in fibre bridging, which impede crack propagation of the aluminium alloy layers under tensile cyclic loading, for instance.

![Figure 1. Illustration of a FML with three aluminium layers and two intermediate PREPEG layers with unidirectional fibres in 0- and 90° direction [1].](image)

In the traditional nondestructive evaluation ultrasonic techniques frequently used in metallic materials are not always adaptable to the composites due to their heterogeneous and anisotropic nature. In addition to, there is difficulty in the resolution of defects near the surface using ultrasonic techniques as pulse-echo in normal incidence on composite laminates of small thickness, where the reflections from the discontinuity are often found inside the
transmitted ultrasonic pulse length. That gives it a limit of minimum deep where a defect can be found with a transducer of low frequency. Improve this minimum deep limit using a high frequency transducer without an adequate methodology and without a signal processing, could be problematic for a laminated composite, because there could occur reflections caused by the interface between the many layers and the plates free boundaries, which could complicate the defects reflections view. And still, the area of investigation, using the conventional ultrasonic method, is limited to the area that the transducers ultrasonic beam covers [2]. This type of local testing consumes a lot of inspection time for large plate shaped structures for the transducers necessity of the entire area to be tested. Therefore, there is a necessity of testing technique development for detection of damage on FML in a quick and reliable way.

Between the many available ultrasonic techniques, guided Lamb waves in special, offers a method that could be convenient for the material composite testing, due to their propagation in small thickness and long range capability. The propagation depends on the material density and elastic properties, being affected by the wave frequency selection, ultrasonic beam incidence angle and material thickness [3].

When the Lamb waves find any kind of discontinuity on its way of propagation there is scattering and it should also generate other modes [4]. So, it is necessary to use the digital signal processing to change the domain. This change guarantees others characteristics that are implicitly bonded to every evaluated domain. For many signals, the frequency content is important and information more distinguishable is hided in the frequency components [5]. The temporal domain change to the frequency domain by the Fourier Transform (FT) permits a more concise evaluation and aggregates more characteristics to the evaluated signal.

On the present work, it will be done the spectral analysis of the propagation of Lamb waves on fibre metal laminated. Specimens in plate shape with different defects will be utilized for ultrasonic testing by immersion in the pitch-catch configuration and further the signals will be processed by computational software to detect and evaluate damages as delamination and fibre fracture.

2. Theory

2.1 Fibre Metal Laminated

The principal damage types which can reduce the mechanical resistance of the laminated composite are the fibre rupture, the displacement fibre/matrix and delamination [6]. The flaw mode operative depends, among others factors, of the loading conditions and the inner structure of the specific composite system.

![Figure 2. Lateral view cut of a FML 3/2 with delamination buckling and some secondary cracks](image)

Unlike the traditional composite materials, the FMLs are not susceptible to form large areas of inner damage when liable to impact. Inner damage, due to the impact on slow velocity, is the
most commonly found in composite structures and consist in cracks in the polymeric matrix, as well as delamination and fibre rupture, being, usually, visible for eyes. Between the many damage types, a delamination buckling (view figure 2) causes a significant loss of resistance of compression and hardness. The material can be sensitive to delamination buckling, which occurs when a partially delaminated panel is subjected to a compressive force [8].

2.2 Guided Lamb Waves

In Lamb waves, a large number of particle vibration modes is possible with specific energy quantities (specific modes), which depends substantially of some factors, as: pulse system, the ultrasonic beam incidence angle, transducer central frequency, the bandwidth frequency and others parameters described in [2, 3, 9]. Figure 3 shows the propagation modes most common: the symmetric and asymmetric modes. The complex movement of the particle is similar to the elliptical orbit to the surface.

Figure 3. (a) Propagation of Lamb waves in a plate of thickness d; (b) symmetric mode; (c) asymmetric mode.

The velocity guided Lamb waves is not only dependent on the material (like longitudinal, shear and surface waves) but also the thickness of the material and frequency. Dispersion curves are used to describe and predict the relationship between frequency, phase velocity and group velocity, incidence angle, mode and thickness [3]. These curves are originated from solutions that satisfy boundary conditions of the wave equation for a determined system and are described, as seen before, in terms of Lamé Constants. The solutions can be found numerically through a data set of constants related to the materials properties. Figure 4 shows Dispersion curves for an Aluminium plate with 0.5 mm thickness and immersed in water.

Figure 4. Dispersion curves for aluminium plate with 0.5 mm thickness immersed in water. The modes showed are symmetrical (S) and asymmetrical (A).
Through the analysis of the Lamb waves propagation modes dispersion curves in function of frequency-thickness, it was determined the frequency range of interest and the incidence angle to be applied on the practical experiments to ensure the less dispersive guided wave propagation mode only. Farias et al [10, 11] selected the propagation mode $S_0$ due to their non-dispersive characteristic on the 0.85 MHz-mm region to inspect the aluminium plates with defects on immersion testing. The researchers analyzed the simulated dispersion curve by Disperse Software® [12], evaluating the phase velocity variation, group velocity and attenuation of the fundamental propagation modes $A_0$ e $S_0$.

Rosali et al [13] conducted a study with fibre metal laminates specimens based on the change in group velocity of Lamb waves with frequency–thickness product as the determinant parameter for the detection of delamination. Two methods are applied: a surface contact method, which utilizes a wedge probe tuned to excite a single Lamb mode, and the embedded PZT method, which involves incorporating lead zirconate titanate (PZT) elements in the glass fibre reinforced resin matrix during the manufacture of the GLARE® aluminium specimens. It was found for all specimens laminates that as the delamination area increased the group velocity of propagating Lamb waves also increased, approaching but not exceeding the analytical group velocity of aluminium.

2.3 Digital Processing of Ultrasonic Signals

The ultrasonic inspection requires different signal processing steps in order to achieve proper efficiency. Considering the guided lamb waves and their multiple propagation modes, operations such as transformation to the frequency-domain, filtering, feature extraction and classification may be used in practical inspection equipments.

Analyses in the frequency domain are usually applied in ultrasonic inspection in order to reveal the fundamental characteristics of the acquired signals [5]. Decision support systems have also been proposed in the literature aiming at producing valuable information to help the inspector on the diagnosis. These systems usually comprise two different steps, feature extraction/selection (where valuable information are obtained from the available signals) and hypothesis testing (where the classification is performed) [14].

2.3.1. $k$-means Clustering

Clustering algorithms [15] are applied to arrange signals into groups with similar features. Among the most successful clustering algorithms one can mention k-means and SOM (self-organizing maps) [16]. K-means clustering consists on finding the centers of k clusters in a way that the mean distance (usually Euclidian distance is used) between the centers and the elements (signals) belonging to the cluster are minimized. In our particular problem, the aim is to organize the signatures from different material conditions (no defect, delamination, cracks etc.) into separated clusters [17].

3. Methodology

3.1 Specimens

Four aluminium laminated and epoxy reinforced by carbon fibre, in the dimensions 300 mm x 300 mm x 1.34 mm, with two layers of pre-impregnated specimens were used. In order to verify the influence of the fibre direction, the specimens were made with parallel (CP₀) and
orthogonal (CP90) fibre, in the aluminium lamination direction. To make the specimens were used aluminium plates (dimensions: 300 mm x 300 mm x 0.5 mm; composition: Al-99.00%, Cu-0.05%, Fe/Si<1.00%, Mg<1.00%, Mn-0.05%, Ti-0.00%, Zn-0.10%, Cr-0.00%, others-0.00% to 0.15%), and prepreg carbon/epoxy fibre sheets (UD) Fibredux 920CX-TS-5-42®, with dimensions of 300 mm x 300 mm x 0.17 mm, made by Ciba-Geigy Corporation. On Table 1 are presented the specimens configurations. The fibre fracture was simulated by the cut and removal of the prepreg, and a delamination by adding the spray Teflon®. After stacking, the specimens were cured in an autoclave. The location of the inserted defects can be viewed in figure 5.

Table 1. Specimens configurations

<table>
<thead>
<tr>
<th>FML 2/1</th>
<th>DEFECT</th>
<th>PREPREG CONFIGURATION</th>
</tr>
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<tbody>
<tr>
<td>CP0_CF</td>
<td>Crack fibre</td>
<td>0º/0º</td>
</tr>
<tr>
<td>CP0_D</td>
<td>Delamination</td>
<td>0º/0º</td>
</tr>
<tr>
<td>CP90_CF</td>
<td>Crack fibre</td>
<td>90º/90º</td>
</tr>
<tr>
<td>CP90_D</td>
<td>Delamination</td>
<td>90º/90º</td>
</tr>
</tbody>
</table>

Figure 5. Dimensions and defects places on the specimens: (a) delamination; (b) fibre crack.

3.2 Experimental Setup

The transducer-receptor was positioned in line. The testing was done by using the pulse generator Olympus®, model 5077PR, with transducers Olympus Parametrics®, model V-303-SU, diameter 1/2” and central frequency of 0.9 MHz and bandwidth frequency of 0.51 MHz. The signals were collected in a digital oscilloscope Tektronix®, model TDS 2024B, the sampling frequency of 250 MHz with interface to a microcomputer to store the signals. The inspection of the plates was done in steps of 4 mm scanning a total of 84 mm on each specimen, enough distance to sweep the entire area with or without defects. Figure 6 shows the disposition of the equipment and sensors and the experimental scheme for the immersion testing on the pitch-catch configuration.

Figure 6. Experimental scheme: generation of Lamb waves using pitch-catch configuration.
3.3 Dispersion Curves

The dispersion curves were simulated using Disperse Software® [12] designed to calculate curves of multilayer structures. Through the analysis of the simulated dispersion curves of the phase velocity against frequency-thickness was determined the frequency and the incidence of angle beam to be used in the experimental work in order to generate only the fundamentals Lamb waves modes.

3.4 Signal Processing Scheme

The signal processing scheme consists on performing analysis in both time and frequency domains using computational software MATLAB®. Time-domain signals were plotted in order to allow a spatial visualization of the ultrasonic signals along the sweep of the specimens. The amplitude of the signals in the $S_0$ Lamb wave mode was evaluated for the no-defect, edges (or borders) and defect regions.

Aiming more information, the Fast Fourier Transform algorithm (FFT) was applied on the ultrasonic signals to obtain the signal in the frequency domain [5] and, that way it was able to see sensible differences of the spectral amplitude as well as the small displacements in different evaluated areas.

The classification was performed using the k-means algorithm fed from the frequency-domain coefficients. The purpose here is to detect the regions with and without defect. For this, three clusters were used (k=3) allowing the algorithm to better deal with the signals at the borders of the defects (which present characteristics of both classes, defect and no-defect).

4. Results and Discusions

4.1 Simulation Disperse Curves

In figure 7 are shown the simulated dispersive curves related to immersed testing for CP$_0$ and CP$_{90}$ specimens by Disperse Software®. $S_0$ mode was selected because it is less attenuating than $A_0$ mode in a frequency-thickness band less dispersive for the realization of the practical experiments. Like shown in figure 7, the incident angle more adequate for the ultrasonic sensors was 11.5° for CP$_0$ and 19° for CP$_{90}$ specimens.

It can be observed that on the simulation, the dispersive curves for the incident angles of the ultrasonic beam in function of frequency-thickness, figures 7(c) and 7(d), indicate a constant angle equal to 90° to $A_0$ mode. The software considers this value for all the specimens which modes have less phase velocity than the same mode on the material that compounds the medium in contact with the specimen, on the wave incident local. That occurs from Snell’s law, when the wave velocity in the medium where it propagates the incident wave is higher than the one in the medium where the wave is transmitted. In this case, $\sin \theta_i > 1$, being $\theta_i$ the incidence angle.
4.2 Signals on Time Domain

Like in Farias [18], the results obtained by the inspections on immersed testing showed clearly an increase of attenuation for the signals on time domain of the $S_0$ propagation mode in specimens with fibres perpendicular to the direction of the wave propagation, figures 8(b) and 8(d).
Considering the results for the test specimens CP₀-CF, CP₀₀-CF, figures 8(a) and 8(b), the decrease in amplitude of the signals at the defects border regions was due to the spreading of the ultrasonic signal. On the central region of the crack there was an increase on the signal amplitude, probably due to the wave propagation on the aluminium plate on the place where the fibers were taken off. On the test specimens CP₀-D and CP₀₀-D, figures 8(c) and 8(d), it is possible that on the fabrication process of the FML, the simulated delamination have been uncharacterized seeing that the amplitude of the signal almost does not vary on the zone of inspection.

4.3 Spectral Analysis

As a result of the Fast Fourier Transform algorithm applied to the acquired signals, it was observed that the frequency-domain information (i.e. peak frequency component amplitude) confirms the positions of the defects. In Figures 9 (a) and 9 (b), the peak frequency amplitudes (considering different inspections) decreases in amplitude in the border areas and present a peak at the center of the crack, it is important to note that the frequency amplitude presents similar behavior in all realized inspection. Besides, it is possible to see a great similarity between the results for the CP₀-CF and CP₀₀-CF. Considering the CP₀-D (see Figure 9 (c)), it was expected a great peak at the border areas and a decrease at the affected area. However, it was only detected the first border and then a behavior similar as a defected zone. The results for CP₀₀-D, 9 (d), were not satisfactory because they do not have a behavior similar to CP₀-D and cannot characterize the delamination zone. The specimens with delamination had different results between them and the probable causes were already discussed in the previous topic.

Figure 9. Peak frequency component amplitudes of the signals on the S₀ mode obtained in different inspections of the specimens (a) CP₀-CF, (b) CP₀₀-CF, (c) CP₀-D and (d) CP₀₀-D. The vertical arrows delimit the regions where the defects border can be found.
4.4 **K-means Clustering**

An automatic defect detection system was developed using the k-means algorithm. The inputs for the classifier were the frequency components obtained after the FFT. The k-means algorithm was initialized using three clusters (k=3) in order to accommodate signatures from no-defect, border and defect regions. The available signatures were equally split into training, validation and testing sets. Table 2 illustrates the obtained results (testing set). It can be observed that the defect regions were identified with high efficiency (> 98 %) for all cases. The system produces a significant error for the no defect regions (~ 17% for CP90-CF and CP0-D and ~ 10 % for CP0-CF), but as the aim is to provide a decision support information, this mistake can be corrected in further (more accurate) inspection procedures.

Considering that the frequency-domain analysis was not able to properly reveal the characteristics of the CP90-D (probably due to its internal structural problems), this specimen was not used here.

<table>
<thead>
<tr>
<th></th>
<th>CP0-CF</th>
<th>CP90-CF</th>
<th>CP0-D</th>
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<tbody>
<tr>
<td>ND</td>
<td>90.0 %</td>
<td>83.3 %</td>
<td>83.3 %</td>
</tr>
<tr>
<td>D</td>
<td>98.3 %</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
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</table>

**Table 2– Classification efficiencies obtained for three different specimens using the k-means algorithm.**

5. **Conclusions**

Fibre metal laminates (FML) are widely applied in the aerospace industry due to their particular mechanical characteristics. The ultrasonic inspection of FML usually requires the use of more sophisticated tools for signal analysis as the multi-layer structure can deteriorate the acoustic signal. This work presented both time and frequency domain analysis tools for the detection of defects in FML using Lamb wave ultrasound inspection. Through these techniques it was possible to properly identify the locations of the border and the defect regions. Additionally, an automatic decision support system based on the k-means algorithm was designed. The proposed discriminator was able to identify the defect regions with accuracy higher than 98 %.

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**References**