POTENTIALS OF GUIDED WAVES IN AIRCRAFT CFRP COMPONENTS IN TERMS OF DAMAGE TOLERANCE AND SHM IMPLEMENTATION

by

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ABSTRACT

Carbon fibre reinforced polymer (CFRP) materials are a class of materials becoming possibly the most important in aeronautical structures today. Due to its relative novelty neither its damage mechanisms nor its potentials are far from being sufficiently understood. As a consequence CFRP when compared to metallic structures are still designed safe life. Damage could in CFRP structures be more efficiently monitored. Then damage tolerance potentials even in CFRP structures could be considered. Guided waves are a means on how a significant amount of CFRP structures could be monitored in principle since many of those structural components are flat plate like. Typical joints are lapped or tapered such as with structural repairs, which are structural elements of a specific criticality. This thesis will address the following aspects and questions related to CFRP plate structures:

1. What are guided waves?
2. Material parameters in a CFRP panel relevant for structural design to be obtained through non-destructive testing.
3. Limitations of guided waves with respect to a lap joint.
4. Monitoring concepts of a lap joint in terms of structural health monitoring (SHM).
5. What damages may be monitored with the SHM concept proposed?
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1. Glossary

1.1. Acronyms

- **BVID**: Barely Visible Impact Damage
- **CF**: Carbon Fibre
- **CFRP**: Carbon Fibre-Reinforced Polymer
- **DTD**: Damage tolerant design
- **FFT**: Fourier Transform of a signal in the time domain
- **GF**: Glass Fibre
- **GFRP**: Glass Fibre-Reinforced Polymer
- **LSS**: Laminar Stacking Sequence
- **NDI**: Non-Destructive Inspection
- **NDT**: Non-Destructive Testing
- **PZT**: piezoelectric lead zirconate titanate
- **SHM**: Structural Health Monitoring
- **S-N**: stress/life (diagram)
- **UD**: unidirectional
- **UT**: Ultrasound Test

1.2. Definitions

- **Acoustic impedance**: The opposition presented by the particles to be displaced by the sound.
- **Acoustic interface**: The boundary between two materials with different acoustic impedances.
- **Amplitude**: A measurement of the size of a wave. In ultrasonic testing, changes in signal amplitude may indicate defects inside a composite.
- **Anisotropy**: is the property of being directionally dependent, as opposed to isotropy, which implies identical properties in all directions.
- **Asymmetric Lamb wave mode**: flexural shear Lamb wave.
- **Attenuation**: Attenuation in ultrasound is the reduction in amplitude of the ultrasound beam as a function of distance through the imaging medium.
- **Bolted joints**: They consist of fasteners that capture and join other parts.
- **Bonded joints**: is an adhesively joint between two parts.
- **Compression stress**: The internal load that a part is subjected to when a force squeezes or pushes down on it.
Damage tolerant design: determine the life considering only the crack propagation, supposing cracks to already exist.

Delamination: The separation of the layers in a laminate. Laminate is a sheet of material that has been created by stacking thin layers, or plies, and bonding them together.

Dispersion curve: plot of the phase velocity or group velocity against the frequency-thickness product. Is needed to know where and when are propagating the waves and which types of modes are propagating.

Fatigue: Progressive structural damage to an object that is subjected to cumulative stress from repeated loads.

Flexural stress: The internal load that a part is subjected to when a force causes an object to bend perpendicular to the object's long axis.

Group velocity: is the velocity at which the variations in the shape of the amplitude of a wave (also called modulation or envelope) propagate in space.

Lamb waves: Are plate waves to make large-area NDT. These are propagated according to the interaction of the generated surface waves reflections of an ultrasonic beam on the faces of a plate.

Laminate: A sheet of material created by stacking thin layers, or plies, and bonding them together.

Phase velocity: is the velocity at which the phase of any wave with a specific frequency is propagated.

Reflection: is the change in direction of a wavefront at an interface between two different media so that the wavefront returns into the medium from which it originated.

Residual stress: Stress that remains in the composite after the force that originally caused the stress has been removed. Typically, residual stress shows up as deformation or warping in the composite.

Resolution: the ability of an ultrasonic system to produce simultaneous signals produced by different defects, which are close to each other, within the space of the ultrasonic beam.

Shear strength: The internal force that causes a material to slide against itself or its internal components.

Smart composites: Composites with sensors included inside that provide information about the condition of the structural component.

Strain energy release rate \( G \): is the energy dissipated during fracture per unit of newly created fracture surface area.
- **Structural Health Monitoring**: Integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of the structure to be recorded, analysed, localised and predicted in a way of non-destructive testing.

- **Symmetric Lamb wave mode**: compression longitudinal Lamb waves.

- **Tensile stress**: The internal load that a part is subjected to when pulled apart by an applied force.

- **Transmission coefficient**: describes the amplitude, intensity, or total power of a transmitted wave relative to an incident wave.

- **Ultrasounds**: is an oscillating sound pressure wave with a frequency greater than the upper limit of the human hearing range.
2. Introduction

2.1. Motivation

Aircrafts design and manufacture is a complex process in which designers consider several factors such as engine efficiency and weight of the aircraft. Fuel efficiency permits longer distances to travel and larger quantity of cargo. Traditional engineering materials have evolved to advanced metal alloys and advanced composite materials in order to meet weight reduction and engine efficiency. During the last years, composite technology has continuously and progressively been introduced as a consequence of successful experience accumulated. In Figure 2.1 the progressive introduction of composite materials can be seen:

![Figure 2.1. Evolution of composite application at Airbus [7]](image)

The extraordinary fatigue performance of composites has brought to their use in a wide variety of components that must withstand extreme cyclic loads for long times. Aircraft structures are designed to be a damage-tolerant able to sustain multiple localized damages up to a defined size with little influence on the global properties. That implies a component life control and it allows lighter-weight structures to be designed and in consequence higher stresses can be supported.

Structural Health Monitoring consists in the integration of sensing and also actuation devices to allow the damaging conditions of the structure to be recorded, analysed, localised and predicted in a way of non-destructive testing in order to have ‘Smart Composites’.
Through Lamb waves large areas and difficult to access parts in aircrafts can be rapidly examined by this method. However the potentials have to be seen in terms of the detectability of damages and results interpretation.

2.2. Scope and objectives of the thesis

The principal research goal is to determine the potentials of guided waves to detect damages in an aircraft CFRP element and determine a methodology in order to obtain an effective configuration for the SHM system in terms of:

- Sensitivity of guided waves to the damage selecting a wave mode and a frequency.
- Detection and quantification of a delamination size.
- Transducer configuration locating a concrete number of sensors.
- Influence of the bonded joints in the inspection.

The thesis is divided in eight chapters explaining different topics.
In chapter 1, a list of acronyms and general definitions are provided and in chapter 2 the motivation and the principal objectives of the project are presented.

In chapter 3, the principal concepts and properties of composites materials are explained and then in chapter 4 are talking about fatigue, fracture and damage propagation in a composite material. This knowledge helps not only to provide a fatigue life prediction also to design optimally the elements in terms of DTD. Although composites are designed to be damage tolerant, their properties (such as stiffness and strength) may change during the life of a component, prior to the failure. This study will be useful in terms of SHM to detect and size damage and predict remaining lifetime of a laminated composite component.

In chapter 5 an introduction to ultrasonic and Lamb waves is made. This knowledge make possible the further experimental study explained in chapter 6 that includes the characterisation of a CFRP plate by ultrasounds, the creation of the dispersion curves and the interpretation of data to detect flaws by Lamb waves.
Finally, in chapter 7 an environmental impact study is done.
3. Composite components in aircraft

3.1. Introduction to composites

A composite material is formed by the union of two or more different materials presenting some specific physical properties greater than those of the constituent materials.

In aeronautical engineering are required low-density materials that are strength and stiff and also resistant to impact, abrasion and corrosion. This is an unusual combination of properties in a single material, as usually the most resistant materials are relatively dense; moreover, an increase of resistance and rigidity generally results in decrease the impact strength. Through the development of composite materials can be combined different properties. These are expressed as specific properties that correspond to the property itself divided by the material density because it’s better to compare with other materials as metals. These have good physical properties but their density is very high.

Most of these materials are composed of a matrix that is continuous and enclose the other phase, called disperse phase.

This project will focus on composites formed of a polymer matrix reinforced with continuous fibres as a disperse phase because they are the more common in use in aircrafts.

In order to make the better selection of materials, as shown in Figure 3.1, the selection of a proper fibre (carbon, aramid, glass…) and matrix (epoxy, polyester…), then the fibre form (woven, unidirectional…) and finally the composite form (laminate, sandwich structure…) have to be considered.

![Figure 3.1. Material Selection](image_url)
3.1.1. Fibre material and fibre form

The mission of fibres is providing the composite material good stiffness and strength properties. The range of fibres is extensive and below in Figure 3.2 the comparison of different fibres in concrete properties and characteristics can be seen.

Glass fibre has a low density of \( \rho = 2.6 \text{ g/cm}^3 \) but higher than other fibres, moderate stiffness, good strength, low cost and has chemical and galvanic corrosion resistance.
There are several types of fiberglass:
- **E-Glass (Electrical Glass):** is made of borosilicate glass and is used for electrical applications because have high resistance to current flow.
- **S-Glass (Structural Glass):** is made of magnesia-alumina-silicate. It has higher strength.

GF is used in fairings and interiors.

**Carbon fibre** has a very low density ($\rho \approx 1.8 \text{ g/cm}^3$), good strength, very good stiffness (3 to 10 times GF), high cost and corrosion resistance. Depending on their properties can be: high modulus carbon, intermediate modulus carbon and high strength carbon. There is a considerably difference of cost between them.

CF is used in most load-carrying and structural applications. For example: floor beams, stabilizers, flight controls and primary fuselage and wing structure.

**Aramid fibre** called also Kevlar® has very low density ($\rho \approx 1.5 \text{ g/cm}^3$), good strength, moderate stiffness and excellent resistance to impact damage. The weakness in compression is the main disadvantage of these fibres.

The form of the fibre can be:
- **Unidirectional (Tape):** high strength and stiffness in the fibre direction and no strength across the fibres.
- **Woven (Fabric):** are characterized by better impact resistance, damage tolerance, high toughness, dimensional stability over a large range of temperature, subtle conformability and ease of manufacturing. But, the in-plane properties are compromised by the use of the reinforcement in fabric form. Strength and stiffness in two directions. The weave style can be varied according to crimp and driveability. Low crimp gives better mechanical performance because straighter fibres carry greater loads. A driveable fabric is easier to lay up over complex forms.

The more common weave styles are:
- Plain: Each warp fibre passes alternately under and over each weft fibre.
- Twill: One or more warp fibres alternately weave over and under two or more weft fibres in a regular repeated manner.
- Satin: are fundamentally twill weaves modified to produce fewer intersections of warp and weft.
3.1.2. Matrix material

The mission of the matrix is acting as a vehicle for transmitting forces between the fibres, keeping the fibres in their position and chosen orientation and avoiding the crack propagation from one fibre to another. The matrix also determines composites environmental resistance and maximum service temperature that has to be lower than its glass transition temperature. Matrix can be classified as thermosetting or thermoplastic resins.

Thermoplastic resins become fluid when heated and returns to its original solid state when cooled. These are used in moulding processes.

Thermosetting resins require a curing process to harden. Normally, the resin is mixed with a hardener or curing agents and then heat, pressure and time are applied to start the chemical reaction.

- **Epoxy**: excellent mechanical properties, good environmental resistance and easy processing. The main disadvantages are brittleness and reduction of properties in moisture presence because the $T_g$ is reduced. Epoxy can be formulated to meet a wide range of processing.
- **Polyester and Phenolic**: Excellent fire resistance, good temperature resistance, rapid cure and economic processing. Used in secondary structures (interior components).
- **Bismalemides and Polymide**: Excellent resistance to high temperatures, good structural properties, good resistance to chemical agents, fire and radiation. These have a high cost and are used in elements working at high temperature.
Prepregs are pre-impregnated fibres. So consist in the combination of matrix and fibre reinforcement. These are available in unidirectional form and fabric form. The resin components in it have been mixed and the chemical reaction has started. Therefore, to avoid the further curing, it must be in a freezer. When the material is required is removed from the freezer and warmed. After that, prepreg is ready to laminate. Many prepreg materials are used in the aviation industry and mostly are impregnated with epoxy resin. Prepregs are commonly used because the resin content is controlled and its not depending on the operator managing and also, because it is easy to be processed, has a lower fabrication cost and the energy consumption is very low.

3.2. Applications of composites on aircraft

Fibre reinforced polymers are primary materials for aerospace structure applications. In Figure 3.4 the percentage of the materials used in an aircraft and where are each one used is shown.

As can be seen, composites materials are the most common material in an aircraft (50%). Carbon fibre dominates the aerospace composites market followed by glass fibre. CFRP is used in fuselage structure, wing upper surface, spoilers, vertical and horizontal stabilisers, trailing edge flaps and ailerons. Carbon fibre sandwich laminate is used in engine intake cover, rudder and elevators.
And GFRP is used in lateral fuselage, wing tips, wing upper surface and horizontal and vertical stabilisers\(^1\).

### 3.3. Principal composite materials properties

Previously to obtain the properties of a lamina a more precise definition of the parameters relating to the matrix and fibre contents should be establish.

A parameter of composite material definition is the volumetric content of the reinforcement of the lamina (\(V_f\)) and the volumetric content of the matrix (\(V_m\)). These are define like that:

\[
V_f = \frac{\text{fibres volume}}{\text{total volume}} \quad (3.1)
\]

\[
V_m = \frac{\text{matrix volume}}{\text{total volume}} \quad (3.2)
\]

\[
V_f + V_m = 1 \quad (3.3)
\]

The density of a lamina can be determined form the densities and volumetric percentages:

\[
\rho = \frac{M_f}{V} + \frac{M_m}{V} = \frac{\text{fibres volume}}{V} \rho_f + \frac{\text{matrix volume}}{V} \rho_m = V_f \rho_f + V_m \rho_m \quad (3.4)
\]

The laminates present an anisotropic behaviour so their properties are dependent on the orientation that is measured. Knowing that, it is necessary to determine properties foe engineering purposes as:

- Young's modulus in the fibre direction
- Young's modulus transverse to the fibres
- Shear modulus along the fibres
- Shear modulus in the plane transverse to the fibres
- Poisson's ratios

Material elastic properties are a measure of its stiffness. This information is necessary to determine the deformations that are produced by loads.

\(^1\) For more information about aircraft's parts see section A1.
Deformations are also produced by temperature changes and by absorption of moisture. A change of temperature produces thermal strains while moisture absorption produces swelling strains. The relevant physical parameters to quantify these are:
- Thermal expansion coefficients
- Swelling coefficients

In Appendix A.2 some Ashby diagrams where can be compared composites and other materials as metals, ceramics or polymers are shown. Looking at these, the conclusion is that metals and composites have similar good properties but the composites have very low density. That’s the main reason why composites materials are selected for aeronautical applications.

<table>
<thead>
<tr>
<th>Composites</th>
<th>Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical in compression</td>
<td>Critical in tension</td>
</tr>
<tr>
<td>Accidental damage</td>
<td>Fatigue damage</td>
</tr>
<tr>
<td>Failure defined by first ply failure</td>
<td>Failure defined by yielding</td>
</tr>
<tr>
<td>Variable stress across thickness</td>
<td>Constant stress across thickness</td>
</tr>
<tr>
<td>Anisotropic material</td>
<td>Isotropic material</td>
</tr>
</tbody>
</table>

*Table 3.1. Properties comparison between composites and metals [7]*

### 3.4. Composite lay up rules and different laminations

Composite materials are not isotropic in behaviour so properties are very depending on the orientation and position of fibres through the material. Due to it, proper selection of ply orientation in composites is necessary to provide a structurally efficient design.

To make a laminate analysis and to know the effect of laminates in coupling, this matrix system is solved.

\[
\begin{bmatrix}
N_i \\
M_i
\end{bmatrix} =
\begin{bmatrix}
A & B \\
B & D
\end{bmatrix}
\begin{bmatrix}
\epsilon_i \\
k_i
\end{bmatrix}
\]

\(3.5\) 

\([A]\): Membrane terms / in-plane stiffness matrix 
\([B]\): Coupled in plane / flexural stiffness matrix 
\([D]\): Bending terms / flexural stiffness matrix
There are some basic lay up rules that are commonly used in the laminar stacking sequence (LSS):

1) Symmetrical laminates to avoid coupling in plane curvature \([B]=0\). The plies have to be positioned at equal distance above and below the midplane.

2) Balanced laminates to avoid coupling bending-torsion. These, have equal numbers of \(+\theta^\circ\) and \(-\theta^\circ\) plies.

3) Should have at least four distinct ply angles (e.g., \(0^\circ, \pm\theta^\circ, 90^\circ\)) with a minimum of 10% of the plies oriented at each angle. Ply angles should be selected such that fibres are oriented with principal load axes.

4) In order to minimize the bend-twisting coupling \(+45^\circ\) and \(-45^\circ\) plies should be put together.

5) Quasi-isotropic lay-up simulates the properties of an isotropic material.
If a balanced and symmetric laminate is not possible due to other requirements, locate the asymmetric or imbalance as near to the laminate midplane as possible.

In order to react tension-compression loads are used a high percentage of $0^\circ/90^\circ$ plies and to react shear loads are used high percentage of $\pm45^\circ$ direction plies. So simple formulations can be used for estimate laminate mechanical from data of UD lamina and lay-up percentage:

$$E_x = E_{UD} \cdot (0,1 + 0,9 \cdot \%\, \text{plies at } 0^\circ)$$  \hspace{1cm} (3.6)

$$\sigma_x = \sigma_{UD} \cdot (0,1 + 0,9 \cdot \%\, \text{plies at } 0^\circ)$$  \hspace{1cm} (3.7)

$$G_{xy} = E_{UD} \cdot (0,028 + 0,234 \cdot \%\, \text{plies at } \pm45^\circ)$$  \hspace{1cm} (3.8)

3.5. Principal damages in aircraft structures and repairing

The principal damages are due to manufacture sources such as improper cure or processing, improper machining, mishandling, improper drilling, tool drops, contamination, improper sanding, misplacement of holes or details, inadequate tooling or a substandard material. Also can be in-service sources because of the environment or in-service loads.

Damage can occur at several scales and within the composite material and structural configuration. That is explained in more detail in section 4.

Fibre breakage is critical because structures are designed to fibres carrying most of the loads. The failure is limited to a near point of impact zone but some damages can lead to large areas of fibre damage.

On the other hand, matrix imperfections normally occur in the interface matrix-fibre or in the matrix parallel to the fibres. These are seldom critical to the structure but the material properties can be reduced such as interlaminar shear or compression strength.

3.5.1. Manufacture defects

The manufacturing technique selected depends partly upon the size and quality or the composite required.
During manufacturing processes, defects can be introduced into the material, although the size and frequency of occurrences of each type depends on the particular process cycle. A number of defect types have been identified including, in order of importance:

- **Porosity**: presence of small voids in the matrix caused by incorrect cure parameters such as duration, temperature, pressure or vacuum bleeding of resin. These affect mechanical parameters such as inter-laminar shear stress.
- **Inclusions**: may contaminate the matrix or act as a local stress concentration in the finished product. These can lead to delamination during the production process or later when the component is in service.
- **Incorrect fibre volume fraction**: resin starved or resin rich areas cause a reduced performance.
- **Ply misalignment**: produced as a result of mistakes made in lay-up of the component plies. This alters the overall stiffness and strength of the laminate and may cause bending during cure.
- **Wrinkles**
- **Cracks due to an incorrect cure cycle**: using the wrong temperature or heating rate can cause cracking.
- **Delamination**: are formed due to excessive interlaminar normal and shear stresses. The accumulation of intralaminar and interlaminar matrix failures depends strongly on LSS. It can be produced also by a bad-curing cycle as the laminate expands or contracts too quickly.

### 3.5.2. In-service defects

Composites can be degraded in service by a number of mechanisms and those of most importance will obviously depend upon the environment experienced and the sensitivity of the particular materials used. The principal defects, in order of importance, are:

- **Impact damage**: under impact most composite laminates do not show much external evidence of damage. This type of damage is called barely visible impact damage (BVID). Can cause delamination failure.
- **Delamination**: is formed on the interface between the layers in the laminate due to matrix cracks that grow into the interlaminar layers or due to low-energy impact. That is the most critical type of damage and will reduce the tensile performance.
3.5.3. Repairing

There are two types of structural defects in composite materials: bonded joints and bolted joints. The choice of the joining technique will depend on joint design region, joining process used, joint strength and stiffness, needing to disassemble and repair durability.

Bonded joints are capable of high structural efficiency and constitute a resource for structural weight saving because of the potential for stress concentrations elimination that cannot be achieved with mechanically fastened joints. These have a requirement for close dimensional tolerances in fabrication. Fatigue live of bonded construction tend to be good due to the flexibility of the adhesives and with a good design can retain a high level of residual strength after initial cracking.

![Figure 3.7. Solid Laminate Bonded Repair](image)

To make this repair, first has to be defined the damaged area to be repaired and after the damage part must be removed.

Then, has to be in account that repair mechanical properties have to be as close to original as possible. So the reinforcing material should be identical to the original composite and also the LSS.

This method has high tooling and process cost but is a good option to be used.

It’s important to know that water tends to create additional damage in repaired parts when cured unless all moisture is removed from the part. Normally, the repair material
is cured at temperatures above the boiling point of water, which can cause a disbond wherever trapped water resides.

**Bolted joints** can damage the composite due to the holes formation, add weight to the structure and are stress concentrators. But on the other hand, is easy to disassemble, its manufacture and inspection is simpler and is a simple joint configuration.

![Figure 3.8. Bolted repair](sensorprod.com)

### 3.5.4. Non-destructive Inspection of composites

NDT for fatigue damage is an essential requirement when composites are used in structural applications and also to avoid not predicted flaws.

The firstly inspection method for in-service inspections is the visual inspection. Resin rich and starved areas, wrinkles, impact damage by any cause, foreign matter, blisters, and disbonding are some of the flaws that can be detected with a visual inspection. This method can't find internal flaws in the composite so more sophisticated NDI techniques are needed to detect these types of defects.

So then, the most commonly method used for composite structures is ultrasonic inspection. In composite structures, the most normally defects are disbond or delamination in material plane, or porosity. The reason for favouring ultrasound inspection is that it is very sensitive to these types of common defects. It is also one of the few methods available for detecting porosity and it can detect most of the other defects at the same time.

For in-service inspection it is possible to improve the rate of scanning significantly by using phase-arrays of ultrasonic transducers or including several single transducers (senders and receivers) in various specific points of the element².

Summarizing, there are different NDT methods for detecting fatigue damage in composites. Each one have the ability to detect certain flaws but no single method is able to detect all the different fatigue damages modes. In Table 3.2 can be seen which are the detectable types of damages for each NDT method.

---

² More details information of ultrasonic waves is given in section 5.
<table>
<thead>
<tr>
<th></th>
<th>Damage to laminates</th>
<th>Damage to sandwich composites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transverse matrix cracks</td>
<td>Delamination</td>
</tr>
<tr>
<td>Ultrasonics</td>
<td>Difficult</td>
<td>Yes</td>
</tr>
<tr>
<td>Acousto-ultrasonics</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Lamb waves</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Acoustography</td>
<td>Difficult</td>
<td>Yes</td>
</tr>
<tr>
<td>Acoustic emission</td>
<td>Difficult</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermo-acoustic emission</td>
<td>Difficult</td>
<td>Yes</td>
</tr>
<tr>
<td>X-ray radiography</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermography</td>
<td>Difficult</td>
<td>Yes</td>
</tr>
<tr>
<td>Vibrothermography</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Eddy currents</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Moiré interferometry</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3.2. Summary of capabilities of NDT methods for detecting fatigue damage in laminates and sandwich composites [12]
4. Fatigue, fracture and damage propagation

Fatigue is a form of failure that occurs in structures subjected to alternating stresses over time.

To design CFRP elements in aircraft as DTD is necessary to have a good knowledge how damage in a composite is propagating and how the fatigue is affecting. That could be damage tolerant because the constituents of composite materials may sustain multiple, distributed localized fractures with a little influence on the global properties that control the life of the component [12].

Fatigue damage in composites can take the form of delamination, matrix cracking, fibre failure, matrix crazing, fibre/matrix debonding and void growth or a combination of these defects.

A very important aspect to take into account is anisotropy of a composite material because properties are directionally dependent. This anisotropy influences in composites behaviour and also how is presented the fatigue degradation mechanism.

The stresses during a flight, change along the time and also vary in magnitude. An example of stress data in an aircraft is shown in Figure 4.1.

![Figure 4.1. Example of loads during a flight](image)

To get a simplified form of these loads the Rainflow cycle counting method is one of methods to be used⁴. This is principally used to count the cycles in a spectrum of different amplitudes and to form a fatigue damage spectrum that will be used in methods to calculate the degree of accumulated damage.

---

⁴ To know more about Rainflow cycle counting method see section B.
Using S-N curves, constant life diagrams, residual strength models, residual stiffness models, etc. permits interpretation of fatigue data and estimation of materials fatigue life.

4.1. Fracture and damage propagation

It is important for design purposes to not only know fatigue life, but also how performance is degraded during life by damage and how failure occurs.

Composites are fragile to failure in fibre direction and contrary, metals are ductile to failure. This difference can be seen in Figure 4.2, comparing the notch sensitivity between composites and metals.

Failure in metals is defined by the yield strength while in composites it is defined by first ply failure characterised by a fibre failure and not by matrix cracking.

In fatigue case, the mechanism that produces the failure does not look like the nucleation and propagation of a single defect as metals, but it is caused by a distribution of defects that increase with the number of cycles until the rupture of the whole laminate is produced.

Fracture of a composite caused by cyclic loads is a progressive process in which different laminate degradation mechanisms are appearing and combining. The appearance of small cracks in the matrix can result, depending on the characteristics of the laminate, in a propagation of these cracks until the rupture of fibres in adjacent areas and a local delamination between layers occur. The delamination, otherwise, can...
be also caused by foreign body impacts but especially occur when the interlaminar stresses are high. Delamination also grows where there is a high interlaminar shear stress. Therefore, these areas should be identified for fracture analysis.

When there is fracture of some fibres the loads have to be redistributed around local failures until a critical level of damage is reached. Resin will be important through its effect on resistance to matrix damage accumulation and local load transfer. The lamina will tolerate a limited number of fibre breaks before the entire ply fails. Once a ply has failed, its contribution to laminate strength and stress is conservatively reduced and it can trigger a catastrophic laminate failure. Otherwise, when subjected to a compressive strength the fibres are buckling and matrix may be splitting.

In Figure 4.3 the principal failure modes in composite materials are shown:

(a) Fibres failure
(b) Fibres buckling due to compressive stresses
(c) Debonding
(d) Matrix cracking
(e) Delamination

In Figure 4.4 a typical damage zone at a sharp crack obtained after fatigue testing can be seen but this will depend on the type and direction of the applied stresses and the type of the fibre, matrix, fibre interface, fibre geometry and specimen shape.
With metals a structure will not be affected by the initiation of a crack with regard to stiffness and residual strength during the largest fraction of the structure’s lifetime. However, the situation is completely different with composite materials. Any damage mechanisms lead to a loss of the stiffness of the composite.

To predict stiffness reduction as a function of the number of fatigue cycles, the origin and propagation of matrix cracks and delamination (that might be modelled as a single crack [12]) are characterized in terms of the strain energy release rate $G$. This is the energy dissipated during fracture per unit of a newly created fracture surface area. It is important for fracture mechanics because the energy that must be supplied to a crack tip for it to grow must be balanced by the amount of energy dissipated due to the formation of new surfaces. $G$ is independent of the LSS, lay-up and ply thickness and is a general parameter representative of composite materials. It is defined as:

$$G = -\frac{\partial (U - V)}{\partial A} \left[ \frac{J}{m^2} \right] \quad (4.1)$$

$U$: potential energy available for crack growth
$V$: work associated with any external forces acting
$A$: crack area

To predict the stiffness over fatigue cycles requires the characterization of the stiffness loss in the laminate and the prediction of matrix cracking and delamination as a consequence of fatigue cycling. This is shown in Figure 4.5.
Figure 4.5. Prediction of stiffness loss in composite laminates [12]

(a) Characterization of stiffness loss in laminate: to characterize delamination initiation a plot of $G$ vs. $\log N$ is generated. To characterize damage growth a relationship between $G$ and the rate of growth of delamination with fatigue cycles is required.

(b) Prediction of matrix cracking and delamination under fatigue cycling: Using the previous plot the increase in delamination size (a) with fatigue cycles can be predicted.

(c) Prediction of stiffness loss with fatigue cycles: The decrease of the stiffness (elastic modulus) or the increase in global strain with number of cycles can be then predicted.
This method can be used when one type of damage occurs in greater quantity or magnitude because the interaction of various damage modes can complicate the characterization of each type of them in terms of G. But usually it is used when delamination occur because it is the more critical mode of damage.

4.2. Fatigue life curve

Stress-cycle (S-N) curves of a material or structure are used to determine the maximum alternating stress a material can support for an infinite number of cycles without causing failure. This is useful to do an estimation of the fatigue life of the material that is being studied. But this does not proportionate any indication about the diminution of stiffness, damage mechanism, cracks presence or the change of the materials characteristics as a consequence of the degradation progress. To characterize the fatigue behaviour constant amplitude fatigue tests are performed at different load levels.

In Figure 4.7, S-N curves for different UD CFRP materials are shown.

As expected, the lower the stain level, the longer the fatigue life of the material. After 10 million fatigue-loading cycles the peak-applied strain is above 0,6% (6000µε). Composites materials allow higher loads than metals for the same number of cycles equivalent to many aircraft lifetimes at this strain level without failing.
4.3. Fatigue sensitivity

There are some factors that affect the fatigue behaviour of composites materials. Principally these are the ones that will affect the cracks or delamination formation and their propagation. As an example, some factors are commented below:

- **Fibres orientation**: Carbon fibres are not too sensitive to fatigue loading [12] which is the reason why CFRP has a fatigue strength comparatively superior to metals. But, usually composite materials are used in laminate form and the fibres are oriented in different orientations. By the increasing the number of off-axis oriented layers the static properties are decrease because there are fewer fibres that can support in the direction of the applied stresses. Figure 4.8 shows the effect that has this phenomenon in fatigue sensitivity. It can be seen that, for the same of cycles, when the number of different orientations increases, the peak applied strain decreases. So a multi-orientation compound would have a better fatigue performance.

![Figure 4.8. Effect of UD plies in fatigue sensitivity [12]](image)

- **Loads spectrum**: When carbon composites are subjected to repeated loading they are more sensitive to compressive loading than to tension. Under compression or shear loading, the sub laminates adjacent to the delamination or debonded
elements may buckle and cause a load redistribution mechanism that leads to structural failure.

In figure 4.9 different S-N curves depending on the stress ratio can be seen.

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]  (4.2)

R-values between \(-\infty < R < 0\) indicate a tension-compression stress (CT), a value of -1 indicates a symmetrically oscillating load. When R is between \(0 < R < 1\) it indicates only tension stress (TT). Values between \(+\infty > R > +1\) defined only compression stresses (CC). The limit value of R equal to +1 indicates stationary tension or compression.

![Figure 4.9. Composition of typical fatigue behaviour for tension and tension-compression loading [13]](image)

- **Matrix and fibre-matrix adherence:** fatigue properties are improved, as the resistance of the matrix to crack propagation or the fibre-matrix adherence are also improved by materials treatment or processing.

- **Environment and temperature:** the exposure of composite materials to water result, in most of the cases, in a plasticization of the matrix or the weakening of the interfacial bond. So in these cases, the fatigue resistance will be reduced. For elevated-temperature service, the resin softens and the fatigue resistance is reduced.

- **Impact damage:** As a consequence of the high stiffness and strength of the composites there is relative weakness under impact by foreign bodies. The compressive strength is affected for this type of damages so it will affect the
fatigue life of the composite too. But the influences of impact damage to predict residual fatigue life are not truly available.

4.4. Damage and fatigue life prediction

Fatigue prediction in composite materials today is complicated. Actually, no validated tool exists to predict damage propagation, fatigue life and residual strength in composites materials, however some tools allowing estimations to be done are explained below.

Mathematical relationships based on stiffness reduction can be developed, allowing residual strength degradation to be related to fatigue life.

\[
\sigma_{\text{min}} \leq \sigma \leq \sigma_{\text{max}}
\]

Figure 4.10. Representation of mean and alternating stress (materialsengineer.com)

The ratio of mean stress ($\sigma_m$) and alternating stress ($\sigma_{alt}$) is very significant in the behaviour of materials subjected to fatigue. Therefore some graphical representations have been developed to present this influence in an equivalent way.

One of the most common representations is the constant-life diagram in the plane $\sigma_m$-$\sigma_{alt}$ which relates mean stress with the alternating stress for a given number of cycles.

As shown in Figure 4.11, a boundary between failure and security for a certain lifetime of the material can be represented. This diagram is used usually for the design of parts. $S_{UT}$ along the horizontal axis represents the tensile strength limit and $S_a$ in vertical axis represents the fatigue limit.
Figure 4.11. Design application of the constant-life diagram in the $\sigma_m$-$\sigma_{alt}$ plane [13]

The model of Goodman can predict the fatigue response of a composite material, only requiring the tensile and compressive properties, through a normalised constant-life diagram according to the function below:

$$a = f (1 - m)^u (c + m)^v$$ (4.3)

$$a = \frac{\sigma_{alt}}{\sigma_t} = \frac{1}{2} \left( \frac{\sigma_{max} - \sigma_{min}}{\sigma_t} \right)$$ (4.4)

$$m = \frac{\sigma_m}{\sigma_t} = \frac{1}{2} \left( \frac{\sigma_{max} + \sigma_{min}}{\sigma_t} \right)$$ (4.5)

$$c = \frac{\sigma_c}{\sigma_t}$$ (4.6)

where $\sigma_{alt}$ is the alternating component of stress, $\sigma_m$ the mean stress, $\sigma_c$ the compressive stress and $\sigma_t$ the tensile stress.

$f$ controls the height of the curve and depends on the test material, $u$ is the slope of the contour in the tensile mean stress zone and $v$ the slope in the compressive mean stress zone. All those parameters are dependent on the log of life. Also, to create a life-diagram the stress ratios are compared.
An example of a normalized constant-life diagram for a quasi-isotropic CFRP laminate is shown in Figure 4.12.

![Normalized constant-life plots for a [(0₂±45)₂,90]₅ CFRP laminate](image)

Assuming that the right- and left-hand sides of Goodmann type diagrams are almost symmetric would simplify the predictions. The analysis could be done with the Palmgren-Miner rule as used with metallic materials saving regions of high tensile and compressive loading occurring at the same time. Exceptionally in these zones the two loads can be directly summed [12].

The Palmgren-Miner's rule is used to calculate fatigue life for elements that are subjected to loads that are not of constant magnitude. It determines the total accumulated damage ($D$) by calculating the linearized damage per load cycle at a constant stress level $S_i$ ($D_i$). To determine the number of cycles at the stress level $S_i$ ($n_i$) fatigue load spectrum is used. To know the number of cycles to failure corresponding to the stress level $S_i$, the S-N curve or the normalized constant-life curve is used. The procedure applied is shown in Figure 4.13.
As damage is assumed to accumulate linearly, failure is predicted to occur when
\[ \sum_{i=1}^{k} \frac{n_i}{N_i} \geq 1 \] (4.7)

At this point the fatigue life is achieved.

With this method the areas where damage accumulated can be identified and these will be the more important zones to be studied by SHM. The sensors will be positioned at these points to control the damage propagation.

4.5. Control of damage propagation

It is very important to develop a damage-growth-predictive methodology and fatigue-life prediction capability for composite materials if the advantages of these materials are to be exploited through designs at higher strains and stresses. Predicting damage growth is difficult, but fracture mechanism approaches are an option when growth is by the progression of a single delamination and like that could be controlled.

If delamination is predicted to initiate, then it must be determined how far it will grow under fatigue loads and if this amount of growth is critical leading to component failure. If the delamination grows in a stable manner, then the inspection intervals may be set up to ensure that the delamination has not grown beyond some expected extent.

First of all, a relationship between strain-energy release rate \( G \) and delamination length \( (a) \) for a given stress or strain is obtained. For an initial delamination length, a critical value of \( G \), \( G_c \), is determined. Then this is compared with the material’s delamination
data to give a number of cycles to initiate the delamination and a delamination growth rate ($da/dN$). For an incremental number of cycles, the increment in delamination length is determined. This procedure can be seen in Figure 4.14.

*Figure 4.14. The fracture mechanics to control the damage propagation [12]*

When a part has a delamination that exceeds a critical length the part must be repaired.

The designer has to set some aircraft maintenance checks frequent enough that parts are replaced while the crack is still in the 'slow crack growth' phase.
5. Ultrasonic waves

Ultrasound tests (UT) are extensively used as non-destructive testing technique in order to detect defects in a wide variety of structures and components during their fabrication or their service.

The sound generated above human audible level, which is typically 20 kHz, is called ultrasound.

![Figure 5.1. Acoustic spectrum (physics.stackexchange.com)](image)

Ultrasound can be reflected from surfaces such as very small defects inside certain materials.

The ability of an ultrasonic system for detecting small defects at given depth in a material agrees with the sensitivity. The larger the signal produced by the defects, the more sensitive is the system. Furthermore, the axial resolution is the ability of an ultrasonic system to produce simultaneous signals produced by different defects, which are closed to each other, within the space of the ultrasonic beam.

Besides, the opposition presented by the particles to be displaced by the sound is the acoustic impedance of a material. It is the product of the material density and velocity of sound propagation:

\[
Z = \rho \cdot c = \rho \cdot \lambda \cdot f \quad (5.1)
\]

There are different types of ultrasonic waves. In Table 5.1 there is a list of the applicability of ultrasonic waves types.
Table 5.1. Characteristics and application of waves (mty.itesm.mx)

<table>
<thead>
<tr>
<th>Type of wave</th>
<th>Gas</th>
<th>Liquid</th>
<th>Solid</th>
<th>Particle Movement</th>
<th>Application</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Compression and refraction along the propagation axis</td>
<td>Tests, measurements</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Transversal</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>Displacement of the particle perpendicular to the propagation axis</td>
<td>Tests, welding, resonance</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Surface (Rayleigh)</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>Ellipses are fast attenuated underneath the surface</td>
<td>Surface tests in difficult to access parts</td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Lamb</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>Ellipses, guided wave transmission</td>
<td>Plates and thin rods</td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

5.1. Lamb waves & Guided waves in general

Long-range ultrasound is based on generating plate waves or Lamb waves to make NDT for a large area. These, with frequencies in the kHz range, are propagated according to the interaction of the generated surface waves reflections (at a particularly angle of incidence) of an ultrasonic beam on the faces of a plate. The interlaminar stresses caused by Lamb waves make detection over the complete laminate thickness possible, which offers a potential way to diagnose the internal defects as well as the surface ones like matrix cracks and planar defects such as delamination.

Sensors are placed at various locations on the material and are used to receive Lamb waves signal.
Lamb waves offer an infinite number of guided wave modes divided in two general types:

- **Asymmetric mode**: flexural shear waves. For low frequencies is a pure bending mode. Going to higher frequencies, the effects of shear and rotatory inertia have to be taken into account. Defects at or close to the surface have a larger influence on the bending stiffness of the plate than anomalies in the center, and can therefore be more easily detected.

- **Symmetric mode**: compression longitudinal waves.

In both forms the movement of the particles through the surface is elliptic.

**Figure 5.2. Lamb waves modes [3]**

5.2. Generation and propagation of Lamb waves

Lamb waves are generated through piezoelectric effect by a transducer. Certain piezoelectric materials, those being the active elements of the transducer and subjected to particular efforts have electrical charges on their surface. Thereby, the generation of mechanical vibrations by the application of an electrical field is possible. To explain this effect, a quartz molecule (SiO$_2$) represented in figure 5.3 is considered as an example. The Si atom has four positive charges and the two atoms of O have four negative charges, so the molecule is neutral. But, when it’s subjected to a pressure in X-axis, atoms experience a displacement and take up new positions (in a non-Centro symmetric material). Is at this point when appears opposite charges producing a longitudinal effect. If the stress is applied in Y-axis changes the polarity of these causing a transversal effect.
In current SHM studies, the most frequently applied effective method is based on PZTs and active Lamb waves thank to its sensitivity for small size damages, such as cracks or delamination. A piezoelectric transducer can work as an emitter (electrical signals into mechanical signals) or as a receiver (mechanical signals into electrical signal).

It emits windowed signals because is needed a sign of voluntarily limited length. To change the signal to the frequency domain a Fourier transform (FFT) is used. A usual signal waveform and their frequency spectrum are shown in figure 5.4. In this specific case, the signal has a number of pulse cycles \( n \) of 3 and central frequency \( f_c \) of 5 MHz.

Lower frequencies provide greater energy and penetration in a material, while high frequencies provide reduced penetration but greater sensitivity to small discontinuities.
The emitted signal propagates having a bending or a compression movement depending on whether the wave mode is asymmetric or symmetric. In figure 5.5 a representation of these movements can be observed.

**Figure 5.5. Representation of Lamb waves generation and propagation (own source)**

Lamb waves propagate in a parallel direction to the surface through the material thickness. Their phase velocity \( c_p \) depends on density and elastic material properties of the material. Also is influenced by the frequency of the wave, the thickness of the plate and the incident angle of the initial wave. These waves form interference of multiple reflections and mode conversion of longitudinal and shear waves at free surfaces of the plate. It makes the analysis of the results more complex.

Figure 5.6 shows a simple SHM configuration where an emitted wave is generated by the actuator, this beam is propagating through the plate and finally the sensor receives the wave.

**Figure 5.6. SHM configuration (mdpi.com)**
5.2.1 Behaviour of Lamb waves in surface boundaries

The boundary between two materials with different acoustic impedances is called an acoustic interface. When the wave arrives at an interface, an amount of the energy is reflected and another amount is transmitted through the interface.

In Figure 5.7 is indicated the mode conversion from a longitudinal wave and from a shear wave. The sub index C is for longitudinal (compression) waves and S for shear waves. The incident wave and the reflected waves are propagating in media A and the transmitted waves are propagating in media B.

**Mode conversion from longitudinal wave**

\[
\sin i = \frac{v_{CA}}{v_{SA}} = \frac{\sin r_C}{v_{SB}} = \frac{\sin R_C}{v_{CB}}
\]

**Mode conversion from shear wave**

\[
\sin i = \frac{v_{CA}}{v_{SA}} = \frac{\sin r_S}{v_{SB}} = \frac{\sin R_S}{v_{CB}}
\]

*Figure 5.7. Different mode conversions of waves and the corresponded Snell’s Law [4]*

The Snell’s law gives the relationship between the angles of waves and their propagation velocity.

Can be observed that the incident and the same mode reflected wave have the same angle. That is like that because these waves are travelling in the same media; so also have the same velocities.

To calculate reflection and transmission coefficients 5.2 and 5.3 equations are used:

\[
\Gamma_r = \frac{z_2 - z_1}{z_2 + z_1} \quad (5.2)
\]

\[
\Gamma_t = \frac{2z_2}{z_2 + z_1} \quad (5.3)
\]

There are three cases in materials tests where the boundaries have a strong influence on the propagation of sound. These will result in more confusing signals:
The wave has to penetrate the edges of the object as it passes into the material and vice versa when it returns.

- Defects within the material are detected by the effect that the limits of the discontinuities have on the wave (reflection or transmission).
- Other limits of the material can influence the propagation due to reflections that create interference. For example, the lap joints of flaw reparation.

![Figure 5.8. Reflection and transmission on boundaries [4]](image)

5.2.2 Attenuation of Lamb waves in solids

Ultrasound is attenuated as it passes through a material. Assuming that there are no reflections from discontinuities, there are two causes of attenuation:

- **Dispersion**: is the result of the non-homogeneity of the materials, as these have boundary surfaces in which the acoustic impedance changes due to the variation of the density and acoustic velocity within materials.
- **Absorption**: is a direct conversion of ultrasonic energy into heat due to a breaking effect of the particles oscillation.

The amplitude of the wave decreases in an exponential way as represents the attenuation law:

\[
A = A_0 e^{-\alpha z} \quad (5.4)
\]

- **A**: attenuated amplitude
- **A_0**: unattenuated amplitude
- **\(\alpha\)**: attenuation coefficient [dB/m]
- **z**: length
The attenuation coefficient increases with the number of load cycles and augment rapidly when the laminate is almost at the end of its life [12]. That is shown in Figure 5.9. So the proportion of attenuation change for the same element can be a good indicator of residual fatigue life. Nevertheless, it does not provide information on the type and size of the fatigue damage.

![Figure 5.9. Effect of number of load cycles on the attenuation coefficient of a carbon/epoxy composite [12]](image)

The attenuation can suppose a problem for the inspection of very large components, because the longer the travelling way of a sound wave in the material, the higher the loss of amplitude.

### 5.3. Dispersion curves

Multiple modes of waves travel through the plate at different velocities that are function of the frequency. So these modes are dispersive.

\[
\lambda(freq) = \frac{c(freq)}{f} \tag{5.5}
\]

In Lamb waves a dispersion curve, where the phase velocity or group velocity are plotted against the frequency-thickness product, is needed to know where and when are propagating the waves, which types of modes are propagating and to interpret the results.
An example of dispersion curve is shown in figure 5.10. This is for aluminum and can be seen that as the frequency increases the number of wave modes generated increase too. Therefore, for high frequencies the analysis would be more complex and difficult.

![Dispersion curves for Aluminum](image)

**Figure 5.10. Dispersion curves for Aluminium [3]**

In the figure above are shown two graphics, one compares the frequency*thickness (f*d) with the phase velocity (c_p) and the other one, the f*d with the group velocity (c_g):

- Phase velocity is the velocity at which the phase of any wave with a specific frequency is propagated. This is known through the dispersion relation. This relates the wavelength (λ) or wavenumber (k) of a wave to its angular frequency (ω).

\[
    c_p = \frac{\omega}{k} = \frac{\omega}{2\pi} \lambda
\]  

(5.6)

- Group velocity is the velocity at which the variations in the shape of the amplitude of a wave (also called modulation or envelope) propagate in space. The group velocity is defined as the ratio:

\[
    c_g = \frac{\partial \omega}{\partial k}
\]

(5.7)
Depending on the thickness of the plate, the adequate frequency is chosen. Normally, a low frequency is chosen because in those cases the excitation of unwanted modes is reduced, the response signal is more distinguishable and the time separating the emitted and received signals is higher ($c_p$ is lower in low-frequency modes), making any changes more visible.

But on the other hand, if the defect size that is inspected is very small the sensitivity has to be in account. So a higher frequency would be needed thereby increasing the complexity of the analysis by Lamb waves.
6. Experimental study

An experimental study is done to determine how the Lamb waves are propagating through a CFRP laminate plate.

First of all a plate is laminated with a usual configuration in CFRP aircrafts elements. But in this case the LSS is not specifically known. Therefore, would have to be considered whether the plate has a quasi-isotropic behaviour as expected or if on the other hand, the anisotropy has an influence.

Then, from the properties can be determined the dispersion curves. These allow us to study the propagation of the different modes of Lamb waves as a function of frequency and plate thickness.

Also, to know more about the propagation of Lamb waves and their potentials to detect damages a study in an aluminum plate is done. And are studied which are the best positions on the plate to place the sensors. This would provide more information of the propagating behaviour.

6.1. Characterisation of the specimen by ultrasonic waves

Individual lamina properties can be obtained from material qualification a data sheet but the laminate properties are approximated using classical laminate theory.

To characterize the laminate to test in a more exactly and proper way than an approximation ultrasonic waves can be used. This way is also good because it is a tool to determine the material properties without destructing the laminate.

Specifically the pulse-echo technique is used, in which the transmitter and the receiver are together in the same unit. Figure 6.1 shows a typical pulse-echo transmission and representation. The transducer sends a wave into the material, it reflects and returns onto the surface again.

The signal recorded is transmitted to the oscilloscope which represents an A-scan of the signal sent called main bang echo and the signal received called back-wall echo.
The LSS of the inspected lamina is unknown, so it has to be studied in different orientations to determine if has an anisotropic behaviour or not.

At ultrasonic frequencies an aqueous or organic coupling fluid for longitudinal waves or honey for transversal waves are required between the transducer and the composite to overcome the large difference in acoustic impedance between air and solids. With composite materials the testing range is significantly reduced because of the increased attenuation.

### 6.1.1. Set-up

- Tektronix 2445B Oscilloscope 150MHz as a display.
- Krautkrämer-Branson Usip 12 as a signal generator.
- Longitudinal wave transducer: contact technique, normal incident, 1,5 cm of diameter and 5MHz of center frequency.
- Transversal wave transducer: contact technique, normal incident, 1,5 cm of diameter and 2,25 MHz of center frequency.
- CFRP laminate plate 387 x 275 x 10 mm.
- Honey as couplant.
6.1.2. Test procedure

Two different probe heads are used to generate longitudinal and transversal waves. A specific frequency is applied to the transducer and then it is manually pressed to the samples.

To do the measurements a couplant is needed to maintain a stable contact to transmit and receive the waves correctly. In this test honey is used.

To determine the elastic properties the following parameters are needed:

- Material density value ($\rho$)

  The density is defined as:

  $\rho = \frac{M}{V} \left[\frac{kg}{m^3}\right]$ \hspace{1cm} (6.1)

  A scale for weighing is used to calculate the mass of the plate. The plate considered weighs 1566.43 g.

  And the dimensions of the plate are known (387 x 275 x 10 mm) so the volume can be calculated.
And with this information the density can be calculated as:

\[
\rho = \frac{1566.43 \cdot 10^{-3}}{387 \cdot 275 \cdot 10^{-9}} = 1471.86 \frac{kg}{m^3}
\]

- **Sample thickness (d)**
  
  Is measured with a sliding caliper and it is 10mm.

- **Time interval between two sound echoes (t)**
  
  This interval is the distance between the main bang and the first back-wall that corresponds to a wave run through twice the thickness of the plate as shown before in figure 6.3. These data are read from the oscilloscope screen where the x-axis is the time and y-axis is the amplitude of the wave. Working with the obtained wave is not easy as there is a strong attenuation in composites and only two wave peaks can be identified.

![Figure 6.3. Representation of the received wave (own source)](image)

The time could be calculated by two methods:

1) **Overlapping**: the main bang and the first back-wall are overlapped and the time between them can be calculated. This is made by the superposition of two oscilloscope channels containing the same wave. To use this method the resolution of the wave has to be clear. Only in this way the wave can be enlarged.
2) **Cursors**: this method is used when the definition of the wave is not so clear and it cannot be enlarged. As can be seen in figure 6.5, two vertical lines are represented and these are moved until are aligned with the main bang (A) and the first back-wall (B). The oscilloscope gives the time between these two points.

The measurement is made in different points (showed in figure 6.6) to have lower error and to provide a statistical distribution data. Moreover, the time interval has to be calculated for longitudinal and transversal waves that are generated with two different prove heads.
- **Longitudinal wave propagation velocity** \( c_L \)
  Is calculated dividing the thickness of the laminate into travel time of longitudinal waves.

\[
c_L = \frac{2d}{t_L}
\]  

(6.2)

- **Transversal wave propagation velocity** \( c_T \)
  Is calculated dividing the thickness of the laminate into travel time of transversal waves.

\[
c_T = \frac{2d}{t_T}
\]  

(6.3)

### 6.1.3. Results

In Table 6.1 are the measurements of the time intervals for longitudinal waves. These were measured in three different points. For further calculations the mean of all this intervals and the standard deviation are needed.
In Table 6.1, the time intervals by longitudinal waves (own source) are shown. In this case, are determined by two methods (overlapping and cursors) because the signal was not so clear, also is measured in two different points and in three directions.

Table 6.1. Time intervals by longitudinal waves (own source)

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_L (\mu s)</td>
<td>6,597</td>
<td>6,598</td>
<td>6,435</td>
</tr>
<tr>
<td></td>
<td>6,569</td>
<td>6,681</td>
<td>6,482</td>
</tr>
<tr>
<td></td>
<td>6,504</td>
<td>6,673</td>
<td>6,502</td>
</tr>
</tbody>
</table>

\[ t_{L\text{mean}} = 6,56011 \]
\[ \text{Std. dev} = 0,08552 \]

Table 6.2. Time intervals by shear waves (own source)

<table>
<thead>
<tr>
<th>Direction 1 (0°)</th>
<th>Overlapping</th>
<th>Cursors</th>
<th>Overlapping</th>
<th>Cursors</th>
<th>Overlapping</th>
<th>Cursors</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>11,145</td>
<td>10,757</td>
<td>11,500</td>
<td>11,430</td>
<td>10,880</td>
<td>10,810</td>
</tr>
<tr>
<td>P2</td>
<td>11,523</td>
<td>10,435</td>
<td>11,521</td>
<td>11,496</td>
<td>10,901</td>
<td>10,876</td>
</tr>
<tr>
<td>P3</td>
<td>10,860</td>
<td>10,479</td>
<td>11,530</td>
<td>11,430</td>
<td>10,910</td>
<td>10,810</td>
</tr>
</tbody>
</table>

\[ t_{T1\text{mean}} = 10,73675 \]
\[ t_{T2\text{mean}} = 11,51917 \]
\[ t_{T3\text{mean}} = 10,89917 \]

\[ t_{T\text{mean}} = 11,05170 \]
\[ \text{Std. dev} = 0,41291 \]

From the previous table can be concluded that the anisotropy in the plate have no influence because the values of the calculated intervals are very similar to each other.

Once the mean time intervals are determined the longitudinal and shear propagation velocities can be calculated by the equations below:

\[ c_L = \frac{2d}{t_{L\text{mean}}} = \frac{2 \cdot 10^{-6}}{6,56011} \cdot \frac{10^{-3}}{10^{-6}} = 3048,729 \frac{m}{s} \] (6.4)
\[ c_T = \frac{2d}{t_{T,\text{mean}}} = \frac{2 \cdot 10}{11,05170} \cdot 10^{-3} = 1809,676 \frac{m}{s} \] (6.5)

Can be seen that the shear waves travel in lower velocity than longitudinal waves.

Using the longitudinal and transversal velocities the different material properties are calculated. To do that is important to be aware of the unit conversions that should be done.

\[ 1 \cdot 10^{-9} GPa = Pa = \frac{N}{m^2} = \frac{kg \cdot m}{m^2 \cdot s^2} = \frac{kg}{m \cdot s^2} \]

So the elastic modulus, shear modulus and poison’s ratio is determined by:

- Elastic modulus:

\[ E = \rho v_T^2 \frac{4c_T^2 - 3c_L^2}{c_T^2 - c_L^2} = 1471,86 \cdot 1809,676^2 \cdot \frac{4 \cdot 1809,676^2 - 3 \cdot 3048,729^2}{1809,676^2 - 3048,729^2} = 11,838 \text{ GPa} \] (6.6)

- Shear Modulus:

\[ G = \rho c_T^2 = 1471,86 \cdot 1809,676^2 = 4,820 \text{ GPa} \] (6.7)

- Poisson’s ratio:

\[ \nu = \frac{2c_T^2 - c_L^2}{2c_T^2 - 2c_L^2} = \frac{2 \cdot 1809,676^2 - 3048,729^2}{2 \cdot 1809,676^2 - 2 \cdot 3048,729^2} = 0,228 \] (6.8)

- Lamé parameters:

\[ \lambda = G \cdot \frac{E - 2G}{3G - E} = 4,820 \cdot \frac{11,838 - 2 \cdot 4,820}{3 \cdot 4,820 - 11,828} = 4,041 \text{ GPa} \] (6.9)

\[ \mu = G = 4,820 \text{ GPa} \] (6.10)

6.1.4. Error Analysis

In experimentation the error that is produced during the data collection has to be always analysed.
This error can be produced due to the measuring instrument, the operator, the environmental factors or the geometric tolerances in the piece itself.

There are two ways to quantify the measurement error. Using absolute error or relative error.

**Absolut Error**

It is the difference between the measured value and the exact value. Have the same units as the compared measure.

\[
G = \rho v_f^2 = \rho \left(\frac{2d}{t_f}\right)^2 = \rho \frac{4d^2}{t_f^2}
\]  

(6.11)

\[
\Delta G = \left[\frac{\partial G}{\partial d}\right] \Delta d + \left[\frac{\partial G}{\partial t}\right] \Delta t = \left[\frac{\partial G}{\partial d}\right] \left(\rho \frac{4d^2}{t_f^2}\right) \Delta d + \left[\frac{\partial G}{\partial t}\right] \left(\rho \frac{4d^2}{t_f^2}\right) \Delta t
\]

\[
= 0 + \left(-8 \cdot 1471,86 \cdot \frac{10^2}{11,05170^2}\right) 0,41291 \cdot 10^{-3} = \pm 0,36018 \text{ GPa}
\]  

(6.12)

**Relative error**

It is the quotient of the division between the absolute error and the exact value. If is multiplied by 100 is obtained the percentage (%) error.

\[
E_R = \frac{\Delta G}{G} \cdot 100 = \frac{0,36018}{4,820} \cdot 100 = 7,47\%
\]  

(6.13)

**6.2. Creation of dispersion curves**

The propagation speed or phase velocity of Lamb waves is a function of the frequency and layer thickness for a particular plate material.

In dispersion curve is given the plate mode phase velocity \(c_p\) as a function of the frequency-thickness product. Each curve represents a specific normal mode designated as \(A_0, S_0, A_1, S_1, \text{ etc.},\) where \(A_i\) means asymmetric and \(S_i\) symmetric modes, respectively.

The longitudinal and shear velocities and the thickness of the plate are needed to calculate the dispersion curves. As calculated before these are:

- \(c_T = 1809,676 \text{ m/s}\)
- \(c_L = 3048,729 \text{ m/s}\)
- \(d = 10\text{ mm}\)
- \(h = d/2 = 5\text{ mm}\)
Apart from these velocities, some other variables have to be defined:

- **Angular frequency:**
  \[ \omega = 2\pi f \]  
  (6.14)

- **Wavenumber:**
  \[ k = \frac{\omega}{c_p} \]  
  (6.15)

- **Variable p:**
  \[ p^2 = \left( \frac{\omega}{c_L} \right)^2 - k^2 \rightarrow p = \sqrt{\left( \frac{\omega}{c_L} \right)^2 - k^2} \]  
  (6.16)

- **Variable q:**
  \[ q^2 = \left( \frac{\omega}{c_T} \right)^2 - k^2 \rightarrow q = \sqrt{\left( \frac{\omega}{c_T} \right)^2 - k^2} \]  
  (6.17)

Then, some characteristic equations have to be solved to obtain the phase velocities of Lamb waves.

**Symmetric modes**

\[
\frac{\tan(qh)}{q} + \frac{4k^2 p \tan(ph)}{(q^2 - k^2)^2} = 0
\]  

(6.18)

**Asymmetric modes**

\[
q \tan(qh) + \frac{(q^2 - k^2)^2 \tan(ph)}{4k^2 p} = 0
\]  

(6.19)

Usually these equations present complex numbers due to negative square roots. To solve that, a modification in the equations is done. It is useful to consider different regions:

- **Region 1** when \( k > \frac{\omega}{c_T} \) and \( c_p < c_T \):
  \[
  \frac{\tan(q'h)}{\tan(p'h)} = \pm \left\{ \frac{4k^2 p q r}{(k^2 - q^2)^2} \right\}^{1/2}
  \]  
  (6.20)

- **Region 2** when \( \frac{\omega}{c_T} > k > \frac{\omega}{c_L} \) and \( c_T < c_p < c_L \):
  \[
  \frac{\tan(qh)}{\tan(p'h)} = \pm \left\{ \frac{4k^2 p q}{(k^2 - q^2)^2} \right\}^{1/2}
  \]  
  (6.21)
- **Region 3** when \( k < \frac{\omega}{c_L} \) and \( c_p > c_L \):

In this case complex numbers are not obtained. So the equation is not modified.

\[
\frac{\tan(qh)}{\tan(ph)} = \left\{ \frac{4k^2pq}{(q^2-k^2)^2} \right\}^{\pm 1}
\]  

(6.22)

If the equations are raised to +1 is a symmetric mode and if it is -1, is an asymmetric mode.

Also has to be considered that:

\[
p = ip' \quad q = iq' \quad p'^2 = -p^2 \quad q'^2 = -q^2
\]

The characteristic equations, in appearance, seem to be simple to calculate. But the dispersion equations can be solved only by numerical methods.

The procedure to obtain the dispersion curves is:

1. Choose a frequency-thickness product \((f \cdot d)_0\).  
2. Make an estimation of an initial phase velocity \((c_p)_0\).  
3. Evaluate the signs of the left-hand side of the characteristic equations (6.18) and (6.19) assuming that are different of zero.  
4. Choose another phase velocity \((c_p)_0 < (c_p)_I\) and recalculate the sign of (6.18) and (6.19).  
5. Repeat steps 3 and 4 until there is a change of the sign. So if a sign change occurs in a continuous function, there would be minimum one crossing through zero. In this interval a root exists. It is useful to have an iteration root-finding algorithm.  
6. Continue searching another roots for the same \(f \cdot d\) according to steps 2 and 5.  
7. After finding the roots, choose another \(f \cdot d\) product and repeat steps 2 through 7.

This method permits choosing the concrete required range of \(f \cdot d\) products.

With all this information, dispersion curves for the examined CFRP plate are calculated. To make all the procedure of roots search a MATLAB program is done. It could be seen in detail in Appendix C.3.

The result obtained is represented in Figure 6.7. For an interval of 3000 kHz-mm three symmetric mode curves and four asymmetric mode curves are observed. As the frequency increases so does the number of excited modes.
Usually lower frequencies are chosen because the analysis of the waves complexity is lower. So an enlarged image of the modes involved in common studies have been done.

Only the dispersion curves comparing the $f \cdot d$ product with the phase velocity has been made. To obtain these curves in relation to group velocities the same procedure is required.
6.3. Detection of flaws by Lamb waves study

Lamb wave velocity is very sensitive to a change to the stiffness of the material caused by damage. So a reduction of the velocity can be related to the accumulation of damage caused by fatigue.

This reduction can be detected by SHM that is a NDT for detection of damages in large-area structures. A wave is generated by one transducer and received by X sensors. One of the principal objectives in SHM is to maximize efficiency minimizing the number of sensors. So the best locations have to be thought. Usually, these will be implemented in the areas of most damage accumulation called hot spots or on locations likely to have accidental damage.

In this section, is studied how waves propagate in an aluminum plate for later be able to extrapolate the obtained results to a CFRP plate.

The aluminum plate have 600x112x1,4mm dimensions. There is one actuator located at (56,270) mm and six receivers of 8mm diameter in the plate distributed as shown in figure 6.9. The best location has to be determined by the comparison between different waves received by the sensors. To know much better the influence of damage in the received waves, four cases are studied:

A. Without any damage (reference plate)
B. With one hole (6 mm diameter)
C. With three holes (3 x 6 mm diameter)
D. With three holes and one crack
Flaws in the structural material can be detected by comparing the received signals with those from an undamaged reference plate.

Figure 6.9. Different studied cases (own source)
The actuator emits a five cycle windowed signal of a symmetric mode with a center frequency of 300 kHz. At this frequency, only the S₀ and A₀ mode are existing and reflected.

With a frequency of 300 kHz and a thickness of 1.4 mm, a relation \( f \cdot d = 0.42 \text{ MHz} \cdot \text{mm} \) is obtained. As can be seen in Figure 6.10, two different modes with different velocities could be generated.

![Graph showing modes and velocities](image)

*Figure 6.10. Selected modes and their velocities of the study (own source)*

However, signals can be quite confusing because when the damage is too small is so complicated to identify. Usually, the defect size should be larger than one half of the wavelength: \( a > \frac{1}{2} \lambda \).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (kHz)</th>
<th>Group velocity (m/\text{ms})</th>
<th>Wavelength (mm)</th>
<th>Minimum detectable length of damage (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₀</td>
<td>300 kHz</td>
<td>2.8</td>
<td>9.3</td>
<td>4.6</td>
</tr>
<tr>
<td>S₀</td>
<td></td>
<td>5.3</td>
<td>17.6</td>
<td>8.8</td>
</tr>
</tbody>
</table>

*Table 6.3. Minimum detectable length of damage for a f=300 kHz (own source)*
The detectable damage length in this study (f=300kHz) would be minimum 4.6 mm so the holes could be complicate to detect. In Table 6.3 this is calculated for each wave mode.

A representation of Lamb waves emission, propagation and reflection is shown in Figure 6.11. The received waves by the sensors will be a complete signal displayed which is a superposition of different reflected waves and different modes of waves. Concretely, the reflected waves due to the boundaries and the damages.

![Representation of emission, propagation and reflection of Lamb waves](sfb477.tu-braunschweig.de)

*Figure 6.11. Representation of emission, propagation and reflection of Lamb waves (sfb477.tu-braunschweig.de)*

When there is a defect, a conversion into a different wave mode is done and a different behaviour from the wave amplitude can be identified. For example, when only a single S0 mode passes through a flaw, minimum four modes will be generated, including two transmitted A0 and S0 modes, and two reflected A0 and S0 modes.

To compare the different waves, a data of the received waves obtained by simulation is used to display those by MATLAB⁴ where:

---

⁴ For more information about the implemented program to plot the waves see the section C.4.
In this study, for each sensor, cases with damages are compared with the undamaged case. This comparison is required to know the damage influence in the sensors for the correct placement selection. The amplitude peak to peak is the attribute to distinguish the different modes conditions. Principally, it is easy to distinguish a S0 from an A0 mode by the propagation velocity and wavelength.

First of all, the reference waves are compared to observe which modes are appearing and understand how the waves are propagating through the undamaged plate. These are represented In Figure 6.12.\(^5\)

---

5 In section C.4. the displayed waves are enlarged to see them in more detail.
Figure 6.12. Received waves for each sensor in the undamaged plate case (own source)

In most of the cases, the first wave is the emitted one and those that follow are some waves attributed to reflected signals returning from the boundaries of the specimen and passing under the sensor.

In receiver 1 and 3 an asymmetric mode is not apparently shown. That would happen because the propagation speed of S0 mode is higher than that of A0 mode and it would be expected that in a specified time domain, no A0 mode would be collected due
to its slow velocity. Also can be seen that in this two receivers the waves are similar. That is due to the symmetric position of them in relation to vertical axis.

On the other hand, for all other sensors a change in the asymmetric mode is observed. Those waves can be identified because have less energy when pass through the sensor so the amplitude is lower.

At first, seems that there is symmetry between sensor 4 and 5 but the received waves are very different. After watching more carefully, the distances from the vertical axis are a little different and the sensor 5 is 5mm further. Therefore, the result has to be different between these. Also, in both cases, after an interval of time there is a wave with higher amplitude. That could be caused because different reflected waves are overlapped.

After observing the reference wave, the comparison between received waves in the damage cases with the undamaged one can be done. These waves are showed in Figure 6.13 to 6.15. All the graphics represent time domain in x-axis (µs) and the amplitude in y-axis (mV).

The maximum and mean of amplitude variance due to damage reflection in comparison with the reference wave will be the criteria to choose the best location for the sensor. So this will be the aspect that will be focused at the following figures and tables.
CASE A – CASE B

Figure 6.13. Comparison between one hole case and undamaged case waves for sensor 1 to 6 (own source)

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum</strong></td>
<td>5,981E-9</td>
<td>1,041E-8</td>
<td>6,062E-9</td>
<td>6,637E-9</td>
<td>9,225E-9</td>
<td>9,492E-9</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>1,485E-9</td>
<td>1,962E-9</td>
<td>1,497E-9</td>
<td>1,521E-9</td>
<td>2,202E-9</td>
<td>2,139E-9</td>
</tr>
</tbody>
</table>

Table 6.4. Comparison of the amplitude difference between receivers in cases A-B (own source)

In this A-B case, receiver 2 has the maximum amplitude difference and receiver 5 has the most variation of amplitude during all the interval of time. These are the most affected by the presence of a hole.
CASE A – CASE C

Figure 6.14. Comparison between three holes case and undamaged case waves for sensor 1 to 6 (own source)

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>1,106E-8</td>
<td>1,511E-8</td>
<td>1,113E-8</td>
<td>1,178E-8</td>
<td>1,280E-8</td>
<td>1,458E-8</td>
</tr>
<tr>
<td>Mean</td>
<td>2,679E-9</td>
<td>4,011E-9</td>
<td>2,674E-9</td>
<td>1,138E-9</td>
<td>2,551E-9</td>
<td>3,514E-9</td>
</tr>
</tbody>
</table>

Table 6.5. Comparison of the amplitude difference between receivers in cases A-C (own source)

In this A-C case, receiver 2 is the most affected by the presence of three holes. This has the maximum amplitude difference most variation of amplitude during all the interval of time.
Figure 6.15. Comparison between three holes with crack case and undamaged case waves for sensor 1 to 6 (own source)

Table 6.6. Comparison of the amplitude difference between receivers in cases A-D (own source)
In this final A-D case, receiver 3 has the maximum amplitude difference and receiver 2 has the most variation during all the interval of time. These are the most affected by the presence of three holes and a crack.

Based on the numerical simulations above, it can be seen that the interaction between different signal modes and reflection from the boundaries waves is very complex. With the previous graphics, is not easy to see what is happening exactly and due to it, choosing a concrete placement of the sensor is not so accurate. Even so, once the arrival time of a reflected wave from the delamination is determined, the difference between the arrival times of the incident and reflected waves can be used to detect the damage position if the distance between the emitter and the sensor is known.

If there would be damage close to the boundaries it gets complicated because the reflected signal of the damage can be completely overlapped with the reflections from the boundaries.

Overall, can be determined that sensor 2 has the higher influence by the presence of damage and therefore, this would be the selected receiver to make an SHM inspection in this case of study.

6.4. Inspection of a CFRP plate by Lamb waves

In homogeneous isotropic plates, Lamb modes can be grouped into symmetric and anti-symmetric modes. Due to the material isotropy, Lamb wave propagation behaviour is independent from the propagation direction. However, composite plates have anisotropic material properties. So it means that Lamb waves propagation behaviour depends on the propagation direction. For this reason, the complexity of Lamb wave propagation increases. The dispersion and high attenuation intensifies this difficulty.

Composite materials require more precise and efficient signal processing and feature extraction methods to identify damage information more accurately. That is due to the multiple interference sources and noise that is produced in the signals. So the resulting data for composite materials in terms of SHM could be more complicated to interpret than for other materials and other NDT techniques.

The implementation of SHM can be analyses as the aluminum case although in CFRP some important aspects have to be taken in account. The main aspects in the inspection, apart from the dispersion, would be:
• **Attenuation**

With composite materials, due of the increasing of attenuation with the frequency, the testing range is reduced.

As commented in previous sections, lower frequencies are usually selected for inspections by Lamb waves because there are few modes excited and an other cause is the reduction of attenuation in these frequencies.

![Figure 6.16. Involvement of attenuation in CFRP components over a specific frequency range](iopscience.iop.org)

Also, the attenuation is influenced by the damage appearance because the signal energy is reduced so there will be more attenuation in the waves propagation.

Attenuation could be determined by measuring the height of successive back-wall echoes and the space of time between them.

• **Anisotropy**

Due to anisotropic material properties in a composite plate, the phase velocity depends on the angle of propagation. A minimum of two modes requires to be considered which are the S0 and A0 modes. In figure 6.17 a diagram, which relation the influence of the orientation in the velocity, is shown.

In the case of the fundamental symmetric mode $S_0$ the curve seems to be perfectly circular. However, the fundamental asymmetric mode $A_0$ shows a strong dependency on orientation of propagation.
If the plate would have repairs part based in bolted joints the study would be a little different and more complex because there would be more reflection waves, in this case due to the repair, overlapping with the reflection waves produced by the boundaries.

For complex bonded joints, the use of higher order modes (A1 or S1) may be important for the detection of localized damage through the thickness. That would complicate a lot the analysis because there would be four modes of excitation and therefore more difficulty in the analysis of damages.

Each time that a repair is done, the reference wave would have to be determined again. It is necessary because comparisons with this reference should be made to determine if damage had initiated or not.

Finally, a good method to control the damage, in most of the cases delamination, could be to have a graphic like in Figure 6.18 representing the evolution of the ratio between the A0 and S0 mode amplitude. Previously, should be determined allowed damage size limit (by fatigue studies, see section 4) to facilitate the control. A dashed line represents the sill for detection of critical damage.
7. Environmental impact

The environmental impact assessment is a process on which the effects of certain projects on the physical and social environment are identified and evaluated. Environmental issues have an increasing concern to society and must be taken into account to preserve the environment.

The use of composites materials permits higher operating temperatures and as a result greater engine efficiency. Greater engine efficiency means better fuel consumption and less impact on the environment. Also, the low weight in aircraft using composites implies a reduction of fuel consumption.

An important issue also is the manufacture process of composite materials that could have an impact on the environment. The manufacture of carbon fibre involves high energy consume therefor high levels of contamination are generated. So it would useful and important the recycle or reuse of composites. But the problem is that, for example, epoxy/carbon composites are very difficult to recycle. It’s very complicated to separate fibres from matrix and usually they are burned. The smoke produced is highly contaminating and therefore environmental regulations can lead to prohibition of these processes.

On the other hand, to implement SHM different electronic components are used. Once their life ends have to be correctly recycled. If not, the waste generated could become a serious problem of environmental contamination and a risk to society due to their high level of toxic and contaminant elements.

Finally I would like to coment that we must be aware of the importance of preserving the environment. Therefore a sustainable use of energy sources and a properly recycling hav to be made.
8. Conclusion

Today a little implementation of SHM in aerospace industry is so little. It could be like that because the SHM potentials are not sufficiently quantified and also because aircraft operators are not aware of SHM potentials and are afraid of getting more sensors into aircraft. But, by SHM, structures could be made better available, lighter weight, more cost efficient and more reliable with sensors that become an integral part of the structure. With a reliable SHM system, a promising monitoring, maintenance and repair strategy can be planned.

From the measurement of the guided wave at a few points on the surface of the structure it is possible to detect defects in a large area with a fast method. In composite materials the most critical defect would be delamination and therefore the inspection method has to be design to detect this defect.

First of all, the selection of an inspection frequency should be done. It would have to be low in order to have less excited modes and less complexity in the waves analysis. This analysis is a little bit confusing because there could be different waves overlapping and it is difficult to determine the origin of each signal part. Concretely, for CFRP, anisotropy and high attenuation complicate the analysis. Therefore, a reference signal would be required to compare the waves in different intervals of inspection times. With this comparison, the detection and quantification of delamination can be determined. It would be significant to manage the complexity that the presence of so many modes can produce. Hence, one of the disadvantages of SHM is that only specialised operators could analyse it.

After, to receive these signals, the placement of different sensors has to be designed in order to have the clearest received signals with the lowest number of sensors.

Then, if delamination reaches its critical size (previously has to be determined by fatigue size prediction methods) the position of the damage has to be determined so that reparation could be made. Through measuring the propagation speed of a wave and the traveling time of a reflected wave from the delamination, their position can be identified.
Finally, for complex bonded joints, the use of higher order modes (A1 or S1) may be important for the detection of localized damage through the thickness. That would complicate a lot the analysis because there would be four modes of excitation and therefore more difficulty in the analysis of damages. Each time that a repair is done, the reference wave would have to be determined again or the signal difference due to bonded joint has to be identified in order to avoid this amplitude changes in the inspection.
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APPENDICES

A. Composite materials in aircraft parts

A.1. Aircraft General Vocabulary

In some parts of the project aircraft parts are commented. To clarify what these are and where are located can be seen Figure A.1.

A.2. Ashby diagram comparison

An Ashby plot is normally used for selecting which is the best material for a specific application. This is a scatter plot that displays two or more properties of many materials or classes of materials.

Materials families (composites, metals, polymers, etc.) are identified by larger coloured bubbles. The image is created using CES selector software.

In the following Ashby diagrams is shown a comparison between different materials and properties.
Potentials of guided waves in CFRP components in terms of DTD and SHM

Strength - Elongation

Strength - Cost

Strength – Maximum Service Temperature

Specific Stiffness – Specific Strength

Notes:
The chart shows the range of strength properties, but the range of the materials.
The strength axis has a linear scale.

Ceramics: that shows compressive strength, tensile strength, and 10% of compressive.
Other materials: strength in tension/compression.
Figure A.2. Ashby diagrams comparison (www-materials.eng.cam.ac.uk)
It can be seen that the composites and metals have good mechanical properties but composites have excellent specific properties due to their low density. So these materials are normally used in aerospace industry.

B. Rainflow cycle counting method

The Rainflow algorithm is the most popular method of counting to estimate fatigue life because it follows the hysteresis loop of the stress-strain curve. This method of counting was named Rainflow by its creators, M. and T. Endo Matsuishi because graphically looks like rainwater flowing down the roof of a pagoda.

The rules governing the rainflow method are:

1) Order the historical of loads so that the higher magnitude is the first peak and the last valley.
2) Beginning with the first peak or valley, allow rain to drip until a cycle is closed, as described in step 3; or until the rain stops, as described in step 4.
3) If is started at a peak, a cycle is closed when another peak is found whose value is greater or equal than the peak of start. This is shown with points 5-6-7.

Figure B.1. Rainflow cycle counting method (www.iberisa.com)
If is started at point 5, the rain falls to the point 6 and then drops straight to the point 7. In point 7 the rain stops because the magnitude of point 7 is higher than point 5. A cycle is shown in figure with short horizontal line that indicated where stops the rain.

4) If is started in a valley, a cycle is closed when there is an opposite valley with a valley less or equal than the starting valley. 2-3-4 points demonstrate this. Starting at point 2, the rain falls to the point 3 and then drips to point 4. It stops in front of point 4 because the magnitude of this valley is less than the valley 2.

5) The rain stops when is finding rain falling from one of the above roofs. The rain, running from point 3 to point 4, demonstrates this. It stops before arriving in point 4 due to rain falling from point 2. Vertical short line at the end of the line running from 3-4 indicates that the rain stands.

6) After closing a cycle, or after the rain is stopped for the first point, move to the second point and let the rain fall. Repeat this until each point is processed.

C. Ultrasonic waves

C1. Types of representations of ultrasonic waves

There are different types of representations of ultrasonic waves depending on the cutting plane or the point of view.
The **A-scan** presentation displays the amount of received ultrasonic energy as a function of time. The relative amount of received energy is plotted along the vertical axis and the elapsed time (which may be related to the sound energy travel time within the material) is displayed along the horizontal axis. Reflector depth can be determined by the position of the signal on the horizontal sweep.

The **B-scan** or **D-scan** presentation is a cross-sectional view of the test specimen. In these scans, the travel time of the sound energy is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis. From the B-scan, the depth of the reflector and its approximate linear dimensions in the scan direction can be determined.

The **C-scan** presentation provides a plan-type view of the location and size of test specimen features. The plane of the image is parallel to the scan pattern of the transducer. C-scan is a powerful technique for showing the morphology and size of delaminations to a high degree of resolution. This method is able to determine the size of defects to within 0.4-0.7 mm for composites that are several millimetres thick, although the resolution deteriorates with thicker materials. C-scan ultrasonics is often used to generate a two-dimensional map of fatigue damage and this have the disadvantage of not providing information on the distribution of damage in the through-thickness direction. It is possible to combine B-scans with C-scans to generate a three-dimensional map of fatigue damage.
C2. Generation of Dispersion Curves with MATLAB

%Title: Dispersion curves
%Description: The aim of this program is to obtain the dispersion curves from the properties of a CFRP plate.

warning off %shut off warning on divide by zero

d = 0.01; % thickness m

% since the roots occur at very small decimal values, you need to decimate cp by about 0.01. Otherwise it will miss roots and then, the data values will shift.
cp = 1:1:100000; %range of possible cp values m/s
cl = 3048.72937; %cl of the composite plate
ct = 1809.67634; %ct of the composite plate
start_point = 0.1; % (f*d) - this is because .1 on dispersion curve is where it starts to get interesting
end_point = 1000000; %f*d
skip = 1000; %each iteration jump
start_frequency = start_point/d; %holding thickness constant find frequency to start

matt_index = 1; %Initialization

for f = start_frequency:skip:end_point
    w = 2*pi*f; %angular frequency
    matt_index = matt_index + 1; %Counter

    %% Solve Lamb's equation numerically equations are from J.Roses book, formatted to remove complex numbers
    h = d/2; % h term from Rose
    k2 = (w./cp).^2; %P squared term from Rose book
    p2 = ((w/cl).^2) - (k2); %P squared term from Rose book
    q2 = ((w/ct).^2) - (k2); %q squared term from rose
    q = (((w/ct).^2) - (k2)).^0.5;
    lamb = real((tan(q.*h)./q) + 4.*k2.*p.*tan(p.*h)./((q2 - k2).^2));
    lamb2 = real((q.*tan(q.*h))+ ((q2 - k2).^2).*tan(p.*h)/4.*k2.*p));

    %% Find zero crossings
    %There are two parts, part one finds symmetric roots, part two asymmetric
    %Part 1 - Symmetric Roots
    %Check if the absolute value is the same as numerical value
    %Hold negative numbers with index -1 and +1 for positive in an array of same index. There are also NaN, which are assigned the old value.
    change_sign_occured = []; %Initialization
numbersign = zeros(1,length(lamb)); %Initialization

findNaN = isnan(lamb);
for n = 1:length(lamb)
    if n > 1 %do not run the first loop
due to n-1 term giving error
    if abs(lamb(n))> lamb(n)
        numbersign(n) = -1 ; %flag for negative number
    end
    if abs(lamb(n)) == lamb(n)
        numbersign(n) = 1 ; %positive number
    end
    if findNaN(n) == 1 %if it is NaN then old number is assigned
        numbersign(n) = numbersign(n-1);
    end
    if numbersign(n) ~= numbersign(n-1) %check the last to see if equal
        change_sign_occured = [change_sign_occured, n];
    end
end

change_sign_occured2a(matt_index,1:size((change_sign_occured),2)) = change_sign_occured ;
fd(matt_index) = f*d;

%Part 2 - Asymmetric Roots
%I had to assign an initial change sign that was not + or - which automatically flips

change_sign_occured2 = []; %Initialization
numbersign2 = zeros(1,length(lamb2)); %Initialization

findNaN2 = isnan(lamb2);
for n = 1:length(lamb2)
    if n > 1 %do not run the first loop
due to n-1 term giving error
    if abs(lamb2(n)) > lamb2(n)
        numbersign2(n) = -1 ; %flag for negative number
    end
    if abs(lamb2(n)) == lamb2(n)
        numbersign2(n) = 1 ; %positive number
    end
    if findNaN2(n) == 1 %if it is NaN then old number is assigned
        numbersign2(n) = numbersign2(n-1);
    end
    if numbersign2(n) ~= numbersign2(n-1) %check the last to see if equal
        change_sign_occured2 = [change_sign_occured2, n];
    end
end
end

change_sign_occured2b(matt_index,1:size((change_sign_occured2),2)) = change_sign_occured2;
end

%%% Paste Arrays together and put into Excel

change_sign_occured2a(:,1)=transpose(fd); %replace bogus values in first column with f*d data
change_sign_occured3 = zeros(size(change_sign_occured2a),size(change_sign_occured2b)+size(change_sign_occured2a,2));
change_sign_occured3(1:size(change_sign_occured3,1),1:size(change_sign_occured2a,2)) = change_sign_occured2a;
change_sign_occured3(1:size(change_sign_occured3,1),1:size(change_sign_occured2a,2)+1:size(change_sign_occured3,2)) = change_sign_occured2b;
dlmwrite('matt.csv', change_sign_occured3, ','); %Creating file

C3. Creation of plots with MATLAB

MATLAB is used to plot the signals of the received waves by the different sensors. D1, D2, D3 and D4 are tables with the signals data information that are opened in MATLAB. These are proportionated by R.Sridaran. Then the following program is implemented to create the variables that will correspond to each sensor and case. From them the signals may be represented.

% a1...a6 contains signals for Receivers 1 to Receivers 6 for no holes case(D1)
% b1...b6 contains signals for Receivers 1 to Receivers 6 for one hole case(D2)
% c1 ..c6 contains signals for Receivers 1 to Receivers 6 for three holes case(D3);
% f1 ..f6 contains signals for Receivers 1 to Receivers 6 for three holes with crack case(D4);

temp=D1;
D1=D2;
D2=temp;
t1=D1;%noholes;
t2=D2;%onehole;
D1=50.*t1; % Amplifiying 50 factor for no holes case
D2=50.*t2; % Amplifiying 50 factor for one hole case
D3=S3_wod;%three holes
D4=S3;%threeholes_with crack;

%Case(D1)
a1=D1(:,2);
a2=D1(:,3);
a3=D1(:,4);
a4=D1(:,5);
a5=D1(:,6);
a6=D1(:,7);

%Case(D2)
b1=D2(:,2);
b2=D2(:,3);
b3=D2(:,4);
b4=D2(:,5);
b5=D2(:,6);
b6=D2(:,7);

%Case(D3)
c1=D3(:,2);
c2=D3(:,3);
c3=D3(:,4);
c4=D3(:,5);
c5=D3(:,6);
c6=D3(:,7);

%Case(D4)
f1=D4(:,2);
f2=D4(:,3);
f3=D4(:,4);
f4=D4(:,5);
f5=D4(:,6);
f6=D4(:,7);

%comparison of reference case A with one hole case B
figure;plot(a1,'b');hold on;plot(b1,'r');hold off;
figure;plot(a2,'b');hold on;plot(b2,'r');hold off;
figure;plot(a3,'b');hold on;plot(b3,'r');hold off;
figure;plot(a4,'b');hold on;plot(b4,'r');hold off;
figure;plot(a5,'b');hold on;plot(b5,'r');hold off;
figure;plot(a6,'b');hold on;plot(b6,'r');hold off;

%comparison of reference case A with three holes case C
figure;plot(a1,'b');hold on;plot(c1,'r');hold off;
figure;plot(a2,'b');hold on;plot(c2,'r');hold off;
figure;plot(a3,'b');hold on;plot(c3,'r');hold off;
figure;plot(a4,'b');hold on;plot(c4,'r');hold off;
figure;plot(a5,'b');hold on;plot(c5,'r');hold off;
figure;plot(a6,'b');hold on;plot(c6,'r');hold off;

%comparison of reference case A with three holes with crack case D
figure;plot(a1,'b');hold on;plot(f1,'r');hold off;
figure;plot(a2,'b');hold on;plot(f2,'r');hold off;
figure;plot(a3,'b');hold on;plot(f3,'r');hold off;
figure;plot(a4,'b');hold on;plot(f4,'r');hold off;
figure;plot(a5,'b');hold on;plot(f5,'r');hold off;
figure;plot(a6,'b');hold on;plot(f6,'r');hold off;

%follow the same procedure to plot the representations that are needed.
C4. Lamb waves plots to analyse aluminum plate’s flaws influence

In this Project a study of the detection of flaws by Lamb waves is done. Different waves are obtained and then compared between them.

The following figures are separated in different cases and different receivers to see in more detail each wave. X-axis is in time domain expressed in µs and Y-axis is the amplitude expressed in mV.

1. Case A: Undamaged plate (Reference waves)

![Figure C.2. Received wave by sensor 1 in undamaged case (own source)](image1)

![Figure C.3. Received wave by sensor 2 in undamaged case (own source)](image2)
Figure C.4. Received wave by sensor 3 in undamaged case (own source)

Figure C.5. Received wave by sensor 4 in undamaged case (own source)

Figure C.6. Received wave by sensor 5 in undamaged case (own source)
2. **Case B: One hole**

![Figure C.7](image1)

**Figure C.7.** Received wave by sensor 6 in undamaged case (own source)

![Figure C.8](image2)

**Figure C.8.** Received wave by sensor 1 in one hole case (own source)
Figure C.9. Received wave by sensor 2 in one hole case (own source)

Figure C.10. Received wave by sensor 3 in one hole case (own source)

Figure C.11. Received wave by sensor 4 in one hole case (own source)
3. Case C: Three holes

Figure C.12. Received wave by sensor 5 in one hole case (own source)

Figure C.13. Received wave by sensor 6 in one hole case (own source)

Figure C.14. Received wave by sensor 1 in three holes case (own source)
Figure C.15. Received wave by sensor 2 in three holes case (own source)

Figure C.16. Received wave by sensor 3 in three holes case (own source)

Figure C.17. Received wave by sensor 4 in three holes case (own source)
Figure C.18. Received wave by sensor 5 in three holes case (own source)

Figure C.19. Received wave by sensor 6 in three holes case (own source)

4. Case D: Three holes and crack

Figure C.20. Received wave by sensor 1 in three holes and crack case (own source)
Figures C.21, C.22, and C.23 show the received waves by sensors 2, 3, and 4, respectively, in a three-hole and crack case. The figures illustrate the potential of guided waves in CFRP components in terms of DTD and SHM.
Figure C.24. Received wave by sensor 5 in three holes and crack case (own source)

Figure C.25. Received wave by sensor 6 in three holes and crack case (own source)

5. Comparison between case A and B

Figure C.26. Received wave by sensor 1 in A and B cases (own source)
Potentials of guided waves in CFRP components in terms of DTD and SHM

Figure C.27. Received wave by sensor 2 in A and B cases (own source)

Figure C.28. Received wave by sensor 3 in A and B cases (own source)

Figure C.29. Received wave by sensor 4 in A and B cases (own source)
6. **Comparison between case A and C:**

Figure C.30. Received wave by sensor 5 in A and B cases (own source)

Figure C.31. Received wave by sensor 6 in A and B cases (own source)

Figure C.32. Received wave by sensor 1 in A and C cases (own source)
Figure C.33. Received wave by sensor 2 in A and C cases (own source)

Figure C.34. Received wave by sensor 3 in A and C cases (own source)

Figure C.35. Received wave by sensor 4 in A and C cases (own source)
Figure C.36. Received wave by sensor 5 in A and C cases (own source)

Figure C.37. Received wave by sensor 6 in A and C cases (own source)

7. **Comparison between case A and D:**

Figure C.38. Received wave by sensor 1 in A and D cases (own source)
Figure C.39. Received wave by sensor 2 in A and D cases (own source)

Figure C.40. Received wave by sensor 3 in A and D cases (own source)

Figure C.41. Received wave by sensor 4 in A and D cases (own source)
Figure C.42. Received wave by sensor 5 in A and D cases (own source)

Figure C.43. Received wave by sensor 6 in A and D cases (own source)