Active Health Monitoring of Aerospace Composite Structures by Embedded Piezoceramic Transducers

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To Ailsa

and

to my grandfather
Preface

The work reported in this Ph.D. thesis is a part of a long-term collaboration between the Swedish Defence Research Agency (FOI) and the Micromechanics and Electronics Institute of Northern France (IEMN). The thesis summarises the work carried out over the past 49 months. This work was financially supported by FOI and by the Research and Technology funds (FoT), under the administration of the Swedish Defence Materiel Administration (FMV).

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Stockholm, November 2001

Christophe Paget
Abstract

The objectives of the thesis work were to study the interaction between embedded piezoceramic transducers and composite structures as well as determine techniques to simplify the Lamb waves analysis. Firstly, this study considered the design of the embedded piezoceramic transducers. Secondly, the effect of the embedded transducer on the composite strength as well as the influence of the mechanically loaded composite on the characteristics of the embedded transducer were investigated. Finally, to simplify the analysis of such complex Lamb wave responses, two techniques were developed. They were based on the wavelet technique and a modelling technique, respectively.

The design of the embedded piezoceramic transducers was improved by reducing the stress concentrations in the composite as well as in all components constituting the piezoceramic transducer, that is, the piezoceramic element, interconnector and conductive adhesive. The numerical analysis showed that the thickness of the interconnector had no significant influence on the stress state of the piezoceramic transducer. It was also found that a compliant conductive adhesive reduced the stress concentration located at the edge of the piezoceramic element. The structural integrity of composites embedded with the improved piezoceramic transducer was investigated. The experiments, performed in tensile and compressive static loading, indicated that the strength of the composite was not significantly reduced by the embedded piezoceramic transducer. Further investigations were conducted to evaluate the performance of the improved piezoceramic transducer used as a Lamb wave generator embedded in composites subjected to mechanical loading. The tests were conducted in tensile and compressive static loading as well as fatigue loading. The study showed a large working range of the embedded piezoceramic transducer. A post processing technique based on the wavelets was further assessed in the detection of damage and in the damage size evaluation. A new wavelet basis was developed specially for processing the Lamb wave response. This method, focused on the wavelet coefficients from the decomposition Lamb wave response, showed promising results in evaluating the damage size. The wavelets offered a sensitive tool to detect small damage, compared to other detection methods, improving the damage detection capabilities. The other technique was devoted to the simplification of the generated Lamb waves by the use of multi-element transducers. The transducers were designed using both a normal-mode expansion and a FE-method. This technique allowed reducing the effect of a Lamb wave mode towards another. This technique was successfully implemented in a damage detection system in composites.

Keywords: Embedded piezoceramic, transducer, composite, structural integrity, health monitoring, damage detection, Lamb waves, wavelets, normal-mode expansion, FE-method
Dissertation

The Ph.D. thesis includes an introduction on embedded piezoceramic transducers used for damage detection in composite materials and the five following appended papers.


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Overview

In 1880, the brothers Jacques and Pierre Curie first discovered the piezoelectricity effect in a single crystal such as the Rochelle salt (sodium potassium tartrate tetrahydrate, KNaC₄O₆/4 H₂O) or lithium niobate (LiNbO₃). The origin of the piezoelectric effect is related to an asymmetry in the unit cell of the crystal and the resultant generation of electric dipoles due to mechanical distortion. However, it was not until 1946 that scientists discovered that barium titanate (BaTiO₃) ceramics could be made piezoelectric by application of an electric field. The polycrystalline ceramic materials have several advantages over single crystals, such as higher sensitivity and ease of fabrication into a variety of shapes and sizes. In contrast, single crystals must be cut along certain crystallographic directions, limiting the possible number of geometrical shapes. After the BaTiO₃ ceramics, scientists discovered a number of piezoceramics and in particularly the lead zirconate titanate (PZT) class in 1956. With its increased sensitivity and higher operating temperature, PZTs soon replaced BaTiO₃ and are still the most widely used piezoceramics. An important step was taken in 1958 by Bechmann and Fair [1]. They standardised the terminology and formulation of the linear equations of piezoelectric materials, as well as the methods to measure their elastic and electric properties. In the sixties, new varieties of piezoelectrics were developed based on both ceramics and polymers.

Piezoelectrics are available in different forms, such as film [2-4], powder [5,6], paint [7], multilayered [8,9] or single fibre [10,11]. They are available in several types, such as polyvinylidene fluoride, PVDF [2], lanthanide-modified piezoceramic, PLZT [5], or the popular class of the lead zirconate titanate piezoceramics [7,12-14]. This list is not complete, because the composition of the piezoelectric materials allows a large variety of piezoelectrics, and new piezoelectric classes are expected to be developed in the near future. The properties of piezoceramics have attracted a large group of industries such as the aerospace and automotive industries. Piezoelectrics have found applications in several different fields, such as noise suppression, vibration control or micro-positioning.

The focus in this Ph.D. thesis is on embedded piezoceramic transducers for damage detection in composites using a technique based on Lamb wave generation [15-18]. The thesis aims to give an overview of the piezoelectricity theory and embedded piezoceramic transducers as well as Lamb waves and damage detection techniques in composites. It also discusses the aspects of embedded piezoceramic transducers in composites, addressing the design of piezoceramic transducers [19] (Paper A), and the structural integrity of the composites with the transducers as Lamb wave generators [15] (Paper B). The report also deals with the characteristics of embedded piezoceramic transducers in mechanically loaded composites [16] (Paper C). A new processing technique for Lamb wave response is herein discussed based on the wavelets (Paper D). A modelling technique using both the normal-mode expansion and the FE-method is been investigated (Paper E) for the simplification of the Lamb wave generation.
1. State of the art of embedded transducers

The field of damage detection by piezoceramic transducers is still at the research level. Therefore, several research teams [16,20-26] developed customised piezoceramic transducers to best suit their applications, although a few companies offer ready-made piezoceramic transducers [27,28]. The choice of transducer materials [29] depends on a number of criteria discussed in this chapter.

Several manufacturing techniques have been developed, and these are discussed further. The transducers are embedded in the composite, therefore certain aspects need to be considered. These aspects concern the influence of both the transducer on the composite and the mechanical loading on the characteristics of the transducer, as mentioned further.

1.1. Choice of transducer constituents

The piezoceramic transducer, composed of a piezoceramic element and interconnectors, is embedded in the composite structure, therefore it has to withstand the composite curing temperature without significant degradations. The transducers must also have a minimal effect on the strength of the composite and be reliable during electrical and mechanical loading. It is moreover essential for the transducer to have a good bond to the composite. The characteristics of the piezoceramic transducer are further chosen to suit best the transducer applications.

1.1.1. Piezoceramic element

The piezoceramics offer a large selection of materials with different electromechanical properties. The common electromechanical properties are the coupling factor, piezoelectric charge constant, piezoelectric voltage constant, mechanical quality factor, dielectric loss and relative dielectric constant.

The coupling factor is defined as the ratio of the mechanical energy stored to an electrical energy applied, at a given frequency or frequency range. It also could be defined as the ratio of the electrical energy stored to the mechanical energy applied. The coupling factor characterises the coupling between the electrical and mechanical properties of the piezoceramic.

The piezoelectric constant, $d$, also called charge constant, is the ratio of the electric charge generated per unit area to an applied force. It can also be defined as the ratio of the strain developed by the applied electric field. Another piezoelectric constant exists, called the voltage constant, which is derived from the charge constant. The piezoelectric voltage constant, $g$, is the ratio of the strain developed to the charge applied or the electric field developed to the mechanical stress applied.

The mechanical quality factor is the ratio of the reactance to the resistance in the series equivalent circuit ($R_s, C_s$) identifying a piezoelectric resonator. The relative dielectric constant, also called relative permittivity, is defined as the ratio of the material dielectric constant, $\varepsilon$, to the free-space dielectric constant, $\varepsilon_0$ [21]. The dielectric loss, also known as loss tangent in the
literature [20], is defined as the ratio of the imaginary component of the complex dielectric to its real component.

However, the most important electromechanical properties for the purpose of this work are the coupling factor and the piezoelectric constants. A high coupling factor would give a greater sensitivity to the piezoceramic in converting the Lamb waves into an electrical signal.

A high piezoelectric charge constant is desirable for materials intended to generate ultrasonic waves such as Lamb waves, because for an applied electric field, or excitation signal, a large developed strain is necessary to propagate over a long distance.

Other non-electromechanical parameters also exist, that play a large role in the selection of the PZT, which are for the most important, the mechanical elastic constants, the Curie temperature and thermal coefficients of expansion.

The value of elastic constants needs to be as low as possible in order to reduce the local stress inside the PZT as well as in its vicinity [19]. The Curie temperature is the temperature at which the piezoceramic loses its piezoelectric properties. The Curie temperature has to be as high as possible to allow a large working temperature range and must be higher than the curing temperature of the composite laminate to prevent the loss of piezoelectric properties. Typically, the working temperature has to be 100°C lower than the Curie temperature. The thermal coefficients of expansion have to be similar to those of the composite to reduce also the stresses in the transducer and the composite.

Four main piezoceramic materials are commercially available; lead zirconate titanate, modified lead titanate, lead metaniobate and bismuth titanate. For transducers used in damage detection as well as sensitive detectors and actuators, the class of lead zirconate titanate (PZT) is considered to be a suitable material because of its high coupling factor, high charge constant, high Curie temperature, low mechanical quality factor and thermal coefficients [22] similar to those of composites.

The dimension of the embedded piezoceramic element has a direct influence on the way the PZT works, that is, the functioning characteristics of the PZT. Some PZT coefficients, such as the coupling factor, the relative dielectric constant or the mechanical quality factor [22], are dependent on the PZT dimensions. Moreover, the piezoceramic dimensions are chosen by analytical methods based on the properties of the wave propagation in the composite [30-33].

### 1.1.2. Interconnection

In the literature, several types of interconnectors were used with embedded piezoceramic elements; wires [12,25,34], coaxial cables [35,36], conductive plies [23] and strips [16,26]. The conductive part of wires is made of copper, silver or gold, in various forms, such as plain or multi-strands. Gold is however preferred for its high conductivity properties. The insulating coating of wires is mainly based on polymers. The polyimide, known as Kapton®, was found suitable as coating material because of its good bonding property to composites but also its good electrical insulation. The outer diameter of wires or coaxial cables might have an influence on the strength of the composite. Therefore, small diameter wires and coaxial cables are available
Coaxial cables are found with similar materials as for wires and moreover offer a good insulating to magnetic fields.

Another type of interconnector is the “conductive ply”. The reinforcement in the conductive ply is often carbon or aramid fibres and the matrix is usually epoxy in aircraft applications. In high temperature applications, thermoplastic matrices, such as polyetherimide (PEI) or polyetheretherketone (PEEK), may also be used. The utilisation of such an interconnector requires non-conductive plies, such as glass fibre reinforced matrix, to isolate the interconnectors from each other. Finally the interconnector strips are made of a conductive part, such as copper or gold, plated or bonded to an insulating film with the same material as for wires. The shape of the interconnector varies, depending on the user needs. As in the case of the other interconnectors, the strips are available with small thicknesses [41].

For embedded piezoceramic transducers, the interface between the piezoceramic element and interconnector needs to have a reliable electrical-conduction and bonding during service. This could be achieved in three different ways, by the use of solder [12,25,35,42], conductive adhesive [15,16,43,44] or co-cured conductive ply [23]. The co-cured conductive ply is an interconnector made of conductive ply that is cured at the same time as the laminate. The conductive adhesive is usually made of two components, the binder (often epoxy, for high temperature applications) and particles (often silver particles) to achieve the conductive part. The conductive adhesive is mainly used with strip interconnectors and solder with wires or coaxial cables.

To achieve electrical contact with the piezoceramic element, two surfaces of the element are electroded. Besides the surfaces need to be fully electroded, that is, electroded over the whole piezoceramic area to insure a homogeneous piezoelectric effect in the piezoceramic element. Several electrode types are available, such as fired-on gold, vacuum-evaporated gold, electroless nickel, electroless copper, fired-on palladium, fired-on platinum, vacuum-evaporated platinum or air-drying silver paint. The vacuum-evaporated gold is frequently used for its good contact to the PZT element surface and its good electrical conductivity [21].

In aircraft, the magnetic field may not be negligible, especially with the increasing use of electrical apparatus in aircraft wings for example. Therefore the use of shielded interconnectors, such as coaxial cables, becomes necessary to insulate the electrical signals from any magnetic interference. Coaxial cables of small diameter are interesting as interconnectors for embedded piezoceramic transducer and also for structural strength reasons, as explained above. Vianco [35] developed a technique to attach a thin coaxial cable to a piezoceramic transducer. The cable that Vianco used was a commercial coaxial cable [39] with an outer cable diameter of 1.9mm. The centre conductor was composed of seven silver- and copper-plated steel strands. A Teflon insulator separated the shielding braid from the centre conductor. Smaller coaxial cable exists to an outer diameter of 0.5mm [36]. The corresponding working temperature range is from –73°C to 125°C. Such cables cannot be embedded in aeronautic composites because the curing temperature is too high (often 180°C).

1.2. Manufacturing techniques

Two configurations with embedded piezoceramic transducers are described in the literature. The technique concerns how to embed the PZT transducer in the composite. Some researchers have
chosen to cut the composite plies surrounding the embedded piezoceramic transducer, such as Elspass et al. [23], Hagood et al. [25], Moulin et al. [12], Mall and Hsu [45] or Warkentin and Crawley [46]. Other researchers directly embedded the PZT transducers avoiding cutting the fibres such as Bourasseau et al. [26], Paget and co-authors [15,16] (Papers B and C), Neary et al. [34] or Shen et al. [47].

![Piezoceramic element embedded in carbon-fibre reinforced thermoplastic composite](image1)

**Figure 1:** Piezoceramic element embedded in carbon-fibre reinforced thermoplastic composite [23]

Elspass et al. [23] manufactured a piezoceramic transducer to be embedded in carbon-fibre reinforced thermoplastic composites. The material in the interconnectors was the same as the composite. The two interconnectors were placed on each side of the piezoceramic element. The electrical insulation from the upper and lower interconnectors was achieved by two glass-fibre reinforced thermoplastics, as shown in Figure 1. Cutouts in the glass- and carbon-fibre reinforced thermoplastic were performed to allow electrical contact between the terminals and the embedded piezoceramic element. The manufacture of such a lay-up was complex.

![Piezoceramic element embedded in a glass/epoxy laminate](image2)

**Figure 2:** Piezoceramic element embedded in a glass/epoxy laminate [25]
Hagood et al. [25], similar to Elspass et al., used a cutout technique to embed piezoceramic transducers in glass-fibre reinforced polymer (GFRP) laminates. A cutout window had about the same dimension as the PZT element. Slits were also cut in the plies directly above and below the piezoceramic element to allow the interconnectors to be drawn out to the edges, as shown in Figure 2. The interconnectors were wires that were soldered to the faces of the piezoceramic element. Hagood also embedded the piezoceramic element in conducting material, such as carbon-fibre reinforced polymer (CFRP). To electrically insulate the piezoceramic transducer from the surrounding material, a polyimide layer was used to encapsulate both the piezoceramic element and the interconnectors, as shown in Figure 3.

Mall and Hsu [45] embedded piezoceramic transducers in CFRP-plies that were cut in a similar way to Hagood [25]. The piezoceramic transducer [27] consisted of the PZT element and wires. To link the PZT to the wires as well as electrically insulate the transducer from the composite, interconnector strips, probably made of copper bonded onto polyimide film, were placed on both sides of the PZT element. The two adjacent plies to the PZT were cutout to avoid local deformation of the laminate around the piezoceramic transducer. Moulin et al. [12] bonded a cylindrical shaped piezoceramic element in a hole drilled in the cured composite. Ordinary wires were soldered onto the faces of a piezoceramic element. The gap between the piezoceramic transducer and the hole in the composite was filled by epoxy. In this case, the requirements for temperature and bonding properties of the transducer, as well as the piezoceramic transducer dimensions, are less severe than for the PZT used by Hagood et al. and Elspass et al. In another interesting example, Warkentin and Crawley [46] embedded an electronic component in CFRP laminate. The electronic component had interconnectors made of polyimide encased wires. Three plies were cutout to contain the electronic component, and one ply was slotted to host the interconnector similarly to Hagood and co-authors.

![Figure 3: Insulation of the piezoceramic transducer [25]](image-url)
Bourasseau et al. [26] embedded a piezoceramic transducer without cutting the CFRP composite plies adjacent to the transducer. The transducer was made of a lithium niobate material and a pair of strip interconnectors. The lithium niobate was chosen for its high Curie temperature, $1100^\circ C$. The connection between the interconnector and the piezoceramic element was achieved by a silver/epoxy conductive adhesive. Paget and co-authors [15,16] (Papers B and C), further developed the technique of Bourasseau et al. Piezoceramic transducers made of soft lead zirconate titanate [22] were embedded in a CFRP laminate, as shown in Figure 4. Neary et al. [34] as well as Shen et al. [47] encapsulated PZT transducers in composites in a similar way as Bourasseau et al. as well as Paget and co-authors.

![Figure 4: Polyimide/copper interconnectors and PZT element embedded in CFRP [16]](image)

A research group of Stanford University [47-52] developed a commercial transducer called the Stanford Multi-Actuator Receiver Transduction layer (SMART Layer™) [53]. The SMART Layer™ was similar to the transducers used by Mall and Hsu. The transducer SMART Layer™ could be customised in variety of sizes, shapes and complexity, allowing its embedment in many composite structures, such as pressure vessels, pipes or wings, as shown in Figure 5. The PZT elements were the PKI-400, with a thickness of $254 \mu m$. The interconnector was made of copper layer bonded on a polyimide film. The interconnector was shaped to provide a perfect fit to be embedded in the composite. The conductive adhesive linking the PZT element to the interconnector was probably a silver/epoxy compound. The transducer could withstand over $200^\circ C$, required for embedment in aerospace composite structures.

![Figure 5: Piezoceramic transducer network for embedment in composite plates (left), pressure vessels (right) [53]](image)
1.3. Structural integrity

Embedded piezoceramic transducers cause changes in the microstructure that may have a significant influence on the stresses in the PZT transducer and the composite. Interlaminar stresses arise at, or near, the material interfaces. These may result in a reduction of the load carrying capability of the composite structure. Furthermore, interlaminar stresses may result in the premature failure of the interface between the piezoceramic transducer and the composite. Such a phenomenon may then decrease the working range of the embedded transducer, which is not allowed in aeronautics. Chow and Graves [54] showed that interlaminar stresses resulting from the embedment of a rectangular epoxy inclusion in CFRP were significantly increased. This study was not sufficient to conclude on the effect that embedded transducers might have on the integrity of smart structures. Vizzini and his co-workers [55-57] have developed a technique to decrease the interlaminar stress by distributing the discontinuity through the laminate thickness. This technique is referred to as interlacing the embedded transducer and is similar to ply drop-off technique. Vizzini showed for CFRP that interlacing results in as much as a 42% reduction in the maximum interlaminar tensile normal stress and a 22% reduction in the maximum interlaminar shear stress of the laminate. Furthermore, the critical location for initiation of the delamination can be shifted from the embedded piezoceramic transducer by selecting the proper interlacing technique, which may preserve the integrity of the embedded device even after the onset of delamination.

Several studies were focused on the strength reduction in composites due to embedded transducers. One early study by Warkentin and Crawley [46] investigated CFRP embedded with integrated silicon chip circuits. The ultimate strength was then reduced by 15%. Crawley and de Luis [58] showed that the ultimate strength of GFRP was reduced by 20% when the piezoceramic transducer was embedded in the composite.

Recently, Mall and Coleman [59] evaluated the effect of embedded PZT transducers on the tensile strength and fatigue life of quasi-isotropic CFRP. The transducer reduced the ultimate strength of the composite by 4% in tensile loading case. The embedded piezoceramic transducer did not significantly reduce the strength in fatigue at 0.2% strain with a stress ratio of 0.1.

In Paper B [15], a similar study was performed on cross-ply CPRP where the plies were not cut as in the study by Mall and Coleman. The reduction in terms of failure stress of the composite was similar to that of Mall and Coleman in tensile loading. In compression, the embedded transducer did not affect the strength.

1.4. Performance of loaded PZT

Mall and Hsu [45] carried out tests on the performance of embedded piezoceramic transducers in CFRP subjected to combined mechanical and electrical cyclic loading. The mechanical fatigue was performed up to 0.2% of strain with a stress ratio of 0.1. Simultaneously the electrical fatigue was performed by applying electric voltages ranging from 10V to 100V and –10V to –100V, which resulted in out-of-phase and in-phase electrically induced strain, respectively. The fatigue life was defined as a decrease of the PZT output signal of 30%. With a strain level of 0.1% in out-of-phase cycling condition, the fatigue life of the embedded piezoceramic transducer was not reached after a million cycles. For in-phase cycle condition, the functioning of the embedded piezoceramic transducer failed at about 850 000 cycles. At 0.17%
of strain, the fatigue life was reduced to 100 000 cycles for in-phase cycling loading, and was almost a million cycles in out-of-phase condition. At 0.2% of strain, the fatigue life decreased to 10 000 cycles in out-of-phase cycling condition. Mall and Coleman [59] also showed that the embedded piezoceramic transducer maintained a steady voltage output during cyclic loading at a strain limit of 0.15%.

Paget et al. [16] (Paper C) evaluated the performance of embedded piezoceramic transducers in carbon/epoxy composite materials, similarly to Mall and co-authors, except for the plies around the PZT that did not have a cutout. The specimens were mechanically loaded, in static tension and compression and in tension-compression fatigue loading. The results of static tests showed no decrease in the functioning of the embedded piezoceramic transducer until the final failure of the specimens. In mechanical fatigue tests, a significant decrease in the PZT function was obtained at a strain level of ± 0.2% between 50 000 and 100 000 cycles. At ± 0.3% of strain, the degradation of the function of the PZT occurred after similar number of cycles.

2. Damage detection using Lamb wave response

The Lamb waves are sensitive to damage in the composite, resulting in changes in the Lamb wave response. The interaction damage/Lamb-waves is complex and difficult to predict. Two different approaches were seen in the literature, concerning research on Lamb waves for damage detection. There are research groups that try to simplify the Lamb wave generation [12,14,32,60], and there are others that directly post-process the Lamb wave response without simplification in the Lamb wave generation [24,61,62]. To generate simple Lamb waves, researchers use wedged PZT, in order to create an incidence angle between the PZT and the composite plate, that allowed the generation of specific Lamb wave modes. In the case of this thesis, the piezoceramic transducers were embedded in the composites, which excluded the use of wedges with the transducers. Nevertheless, it is still possible to improve the generation of Lamb waves by means of PZT size optimisation or simplify them by using arrays of embedded transducer [32]. The latter has so far only been done on surface-bonded PZT transducers. However, the improvement in the generation of Lamb waves was outside the scope of this thesis. This section deals then with post processing techniques that are used to track information in the Lamb wave response on the damage [24,60,63-65].

2.1. The Lamb waves

In 1885, the English scientist Lord Rayleigh [66] demonstrated theoretically that waves can be propagated along the boundary of an elastic half-space and vacuum or sufficient rarefied medium (for example air). It was only in 1914 that Stoneley generalised the propagation of waves in two different solids. In 1917, Lamb [67] introduced a third solid defined as thin layer of finite thickness. This allowed the study of wave propagation in multilayered materials, such as in composites. The waves propagating in this multilayered material were then called Lamb waves. The Lamb waves refer to elastic waves propagating in a solid plate with free boundaries. The displacements of the Lamb waves occur both in the direction of the wave propagation and perpendicularly to the plane of the plate.
The Lamb waves consist of several waves $\gamma_i$ of same waveform $\gamma$ that propagate in laminates with different propagation velocities $v_i$ called group velocities. The waveform is often called mode. Each Lamb wave mode can propagate symmetrically or anti-symmetrically within the laminate, as shown in Figure 6. The amplitude of $\gamma_i$ depends on the composite used. No theories exist that can predict the amplitude of the Lamb waves. Figure 7 shows an example of multimode signal containing three modes. The time $t_i$ is the time of flight of the Lamb wave mode $\gamma_i$. In the present case, the Lamb wave generator and receiver are separated by a distance $d$. The response given in Figure 6 does not correspond to Lamb waves, because a Lamb wave response such as that shown in Figure 10 would be too complex for the educational purpose of this section. Indeed, a Lamb wave response would include not only the Lamb wave modes but also their reflections, that are nonexistent in the multimode response of Figure 6. Besides, it is possible that at the excitation frequency, some Lamb wave modes might be dispersives, meaning that their corresponding waveform may not be similar to the waveform of the excitation signal.

The group velocity $v_i$ of the mode $\gamma_i$ is given by:

$$v_i = \frac{d}{t_i}. \quad (1)$$

However, the number of waveforms, or modes, propagating in a laminate as well as their time of flight can be predicted by the dispersion curves [24,68]. Two types of dispersion curves are mostly used for Lamb wave technique, the phase velocity, $c$, and group velocity, $v$, as shown in Figures 8 and 9, respectively. The phase velocity corresponds to the ratio of the spatial component that is the wavenumber $\xi$ given in (10), to the temporal component that is the angular frequency $\omega = 2\pi f$, of a harmonic wave. The group velocity may be described as the “energy” velocity of the Lamb wave modes in relation to the laminate. The phase velocity curves are mainly used to determine whether or not the Lamb wave modes will be dispersive, and also to obtain the wavelength $\lambda$ of each Lamb wave mode generated in the laminate, using the following relationship:

$$\lambda = \frac{c}{f}, \quad (2)$$

where $f$ is the frequency spectrum of all Lamb wave modes generated in the laminate.

In order to find out if a Lamb wave mode is dispersive or not, the derivative of the phase velocity is used. If, at a given excitation frequency, the derivative of the phase velocity is zero, then the Lamb wave modes should be non-dispersive. Most of the time, non-dispersive Lamb waves are chosen, because their corresponding waveforms generally remain the same throughout the propagation. Moreover, the phase and group velocities of a non-dispersive wave are theoretically identical [69]. Indeed, both velocities are governed by the following equation:

$$\frac{1}{v} = \frac{1}{c} \left( 1 - f \cdot \frac{dc}{df} \right). \quad (3)$$

For a non-dispersive wave, $\frac{dc}{df} = 0$, and therefore (3) leads to $v = c$. 
The wavelength of each Lamb wave mode is directly related to the sensitivity of the Lamb waves in the detection of damage. In principal, a Lamb wave of wavelength $\lambda$ is able to interact with damage maybe in the order of or greater than $\lambda$.

The dispersion curves depend on the composite material and lay-up used. It is often that the dispersion curves are given as a function of the product $f \cdot h$ (frequency by half laminate thickness). Two examples of dispersion curves are given in Figures 8 and 9, for the stacking sequence of $[0_4/90_4/0_4/90_4/0_2]_S$ and the composite material HTA/6376C. In the figures, $S$ and $A$ stand for symmetric and anti-symmetric modes, respectively, and the subscript corresponds to the mode number.

The dispersion curves are important for characterising the active system that detects damage in the composite. The frequency spectrum of all Lamb wave modes is in principal equal to the frequency spectrum, $f$, of the excitation signal of the Lamb wave generator. In the example shown in Figure 9, the frequency of the excitation signal is 240kHz for a composite thickness of 4.83mm. Figure 9 therefore shows that the only Lamb wave modes that can exist in this composite would be the modes $A_0$, $S_0$ and $A_1$ with group velocities of 1.6km/s, 5.8km/s and
4km/s, respectively. Figure 8 further allows determining the wavelengths of those modes $A_0$, $S_0$ and $A_1$ that are about 6mm, 28mm and 41mm, respectively. In such an example, the mode $A_0$ would be able to detect damage of at least 6mm or larger, with the condition that its amplitude is large enough for the mode to be measured. Note that for higher frequencies, the wavelength of the mode $A_0$, for example, is smaller than 6mm. This would therefore allow the detection of damage smaller than 6mm. Unfortunately, the propagation distance of the Lamb wave modes tends to decrease with increasing frequency.

**Figure 8:** Phase velocity for the cross-ply laminate [0°/90°/0°/90°/0°]$_S$

**Figure 9:** Group velocity of Lamb waves propagating in the laminate [0°/90°/0°/90°/0°]$_S$
2.2. The amplitude-based method

The principle of the amplitude-based method is to compare the amplitude of the Lamb wave response before and after damage. Different features occur such as attenuation or amplification of the Lamb wave amplitude. This method can be used for all damage types.

![Graph showing Lamb wave response before and after impact damage](Image)

**Figure 10:** Comparison of Lamb wave response before and after impact damage. Emitter/receiver distant of 260mm and a damage size of 58mm by 38mm

An example of Lamb wave responses is given in Figure 10, showing that an impact damage of 12J, corresponding to a damage size of 58mm by 38mm, can be detected by the change in the amplitude of the Lamb wave response. The width of the composite plate was small (180mm), therefore both Lamb wave responses contained reflections from the plate borders along the width.

Guo and Cawley [70] tested this method with three different strategies using the changes in the S\(_0\) mode. They evaluated the S\(_0\) mode transmission, S\(_0\) mode conversion to A\(_0\), and the reflection of the S\(_0\) mode. The S\(_0\) mode transmission corresponded to the direct propagation of the S\(_0\) mode from the Lamb wave generator to the Lamb wave receiver. The S\(_0\) mode reflection corresponded to the Lamb wave mode S\(_0\) of a Lamb wave response that was reflected from a delamination. The interaction of Lamb waves with damage converted a S\(_0\)-mode to another, in this case A\(_0\). Guo and Cawley showed that the amplitude of the reflection of the S\(_0\)-mode from a delamination was strongly dependent on the position of the delamination through the thickness of the laminate. However, they demonstrated that using an amplitude-based method, they could detect a damage of 10mm to 20mm in diameter over a range of at least 500mm. Blanquet [24] related the damage size to the amplitude decrease of the Lamb wave mode S\(_0\). Neary et al. [34] showed the possibility with this method of detecting damage simulated by holes in composite panels from 1mm to 3.7mm in diameter.

The inconvenient of such method is that it is depending on the coupling agent between the PZT transducer and the composite plate. This coupling agent is often contact gel for surface-mounted transducers or adhesive for surface-bonded and embedded PZT transducers. In any case, the properties of the coupling agent may change throughout its lifetime, because of thickness
change in the gel layer or crack initiation and debonding in the adhesive. In many cases, this interaction between the amplitude of the Lamb wave response and the coupling agent is not wanted, and could be avoided by a time-based method discussed in a following section.

2.3. The frequency-based method

This technique uses the Fourier transform to analyse the Lamb wave response in the frequency domain [71]. A previous section discussed that the Lamb wave response collected by a Lamb wave receiver showed a change in amplitude. Instead of analysing the Lamb wave response using the amplitude in time scale, the idea here is simply to identify whether the damage induces amplitude losses of the Lamb wave response in the frequency domain. The FFT of the Lamb wave response before and after damage is further computed. As for amplitude-based method, both FFTs are compared to detect damage and evaluate its size. Blanquet [24] showed that this method was within acceptable limits in evaluating the size of a simulated damage. The simulated damage was a notch of various depths.

In the same way as the amplitude-based method, this frequency-based method is dependent on the coupling agent between the piezoceramic transducer and the composite plate.

2.4. The time-frequency based methods

The representation of a time-based signal can be done in a three-dimensional way. The first and second dimensions are the time and frequency domains, while the third dimension can be obtained using various transforms [72-74]. The overview focuses only on the two transforms that are the Fourier transforms or the wavelets.

2.4.1. The short-time Fourier transform

In order to introduce time-dependency in the Fourier transform, a simple solution consists in pre-windowing the signal \( x(t) \) around a particular time \( t \), calculating its Fourier transform, and doing that for each time instant \( t \). The resulting transform is called the short-time Fourier transform (STFT). The STFT computes the signal energy density as a function of the time and frequency. The signal energy is represented by the squared amplitude of the short-time Fourier transform of the signal. The representation of a signal in three-dimensions is called spectrogram. The signal energy of a discrete signal \( x[n] \) is given by the following equation:

\[
\text{SPEC}(n, \omega) = \left| \sum_{k=-\infty}^{\infty} x[k] \cdot w(k-n) \cdot e^{-jk\omega} \right|^2,
\]

where \( n \) is the discrete time, \( \omega \) the angular frequency and \( w(k-n) \) the weighted function, or sometime called window function, that selects a part of the signal being processed. The time-frequency resolution of the spectrogram is fixed, meaning that \( \Delta t \) and \( \Delta \omega \) are constants. Those constants are directly dependent on the window function, \( w(t) \), and are defined as:
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\[
\Delta t = \sqrt{\frac{\int t^2|w(t)|^2 \, dt}{\int |w(t)|^2 \, dt}}, \quad (5)
\]

\[
\Delta \omega = \sqrt{\frac{\int \omega^2|W(\omega)|^2 \, d\omega}{\int |W(\omega)|^2 \, d\omega}}. \quad (6)
\]

Figure 11: Example of spectrogram of generated Lamb waves in composites

The square modulus of window function, \( w(t) \), needs to be integrable, and \( W(\omega) \) is the Fourier transform of the window function. The time bandwidth product, \( \Delta t \Delta \omega \), must satisfy the following lower bound known as the uncertainty principle

\[
\Delta t \Delta \omega \geq \frac{1}{2}. \quad (7)
\]

An example of a spectrogram is given in Figure 11 for Lamb waves propagating in a cross-ply composite material.

The advantage of this method is that it requires only one measurement. On the other hand, the disadvantage is that the time-frequency resolution is fixed, and will then deal with the same resolution the low and high frequencies of the data. Therefore the low frequency data will have too high resolution, while for the high frequency data, it will not be enough.
2.4.2. The wavelets

The wavelets can be described in simple words as a more general and complex Fourier transform [75]. According to Fourier, a signal could always be decomposed into a sum of continuous sinusoidal signals, determining the Fourier coefficients. The Fourier coefficients may be defined here as coefficients of level 1, and the continuous sinusoidal waveform may be called a basis. The wavelets decompose a signal using a basis that is shorter in time than the Fourier sinusoidal waveform. Besides, the basis starts as well as ends at zero, such as Haar, Morlet, Gabor or Daubechies bases. The decomposition is performed in n-levels in the tree decomposition scheme, determining wavelet coefficients of levels 1 to \( n \). Thus, the wavelets may be a better adapted transform to decompose signals because of the basis that can be tailed to the processed signal. The wavelets are also very sensitive to signal changes as shown in paper D.

The wavelets are used for a broad range of purposes, such as signal de-noising, signal compression or time-frequency representation. Unlike the STFT for time-frequency representation, the wavelets provide a trade-off between time and frequency resolutions. This means that the wavelets have multiresolution capability. Indeed, the time resolution, \( \Delta t \), varies inversely with the frequency and the frequency resolution, \( \Delta \omega \), varies linearly with the frequency, instead of being constant at all times and frequencies as for STFT. More detail are given in the last chapter of the thesis. The time-frequency representation by wavelets is called scalogram. The signal energy is defined by the square of the wavelet transform.

Another way of using the wavelets is for de-noising signals, such as Lamb wave response, because it can identify information in signals with a large signal-to-noise ratio. This is possible by using special algorithms to find the best basis that decomposes a signal with the lowest number of wavelet coefficients. Staszewski and co-authors [76,77] used wavelets to enhance the damage detection by thresholding the wavelet coefficients during signal reconstruction. Urnes [78] also studies several bases of wavelet packets, to enhance the detection of low-amplitude signal hidden in background noise. Mallat [75] and Daubechies [79] defined several algorithms for signal improvement and compression.

It is feasible to extract a pattern from Lamb wave response carrying information on the damage [23]. By processing the Lamb wave response collected from a plate that has only one type of damage, a specific pattern can be therefore established. By applying this to other existing damage types in composite, it may be then possible to define a library of pattern corresponding to all types of damage. The wavelets, processing the Lamb wave response, produce coefficients, called wavelet coefficients that are related to the size of the damage [61]. A pattern recognition technique may be based on the wavelets and its principle is to train an identification system. This technique, part of the so-called neural network [80], is based on algorithms that are specific to each application. Staszewski and co-authors [81-83] used wavelets to classify damage types. Loe et al. [84] ranked the efficiency of several wavelet bases to classify damage. Saito and Coifman [85] applied the pattern recognition by wavelet packet to detect the presence of oil in soil. Patsias et al. [86] used neural network and Lamb wave techniques to monitor the health of a metal plate. Kinjo et al. [87] used pattern recognition of AE-signals from composites to classify different fracture modes, such as Mode I fibre breakage, Mode I matrix crack or Mode I and II debonding. Kinjo et al. showed that the Fourier phase correlation (FPC) was an attractive pattern recognition method with great possibilities of classifying fracture modes. Ohtsu and Ono
[88] used autoregression modelling in pattern recognition analysis. The method was successful in passive detection, where a receiving transducer detected impact damage including fibre breakage, splitting and slow growth of delaminations, crack face friction and rapid growth of delaminations. However, this pattern recognition can be applicable to active detection, using Lamb wave generators and receivers. Paget et al. [61] used wavelets to predict impact energy and damage size in cross-ply composites and extract a pattern for a damage in composites. The technique was based on the generation of Lamb waves and the wavelet coefficients. The wavelet basis, used in the study, was a new basis inspired from the excitation signal applied to the Lamb wave generator and had variable vanishing moment, as Daubechies [79]. Paget et al. further showed the great sensitivity of the technique in detecting damage of small sizes.

Neural networks proved their ability to locate damage and evaluate the damage size, in a study performed by Maseras-Gutierrez et al. [89]. They used damage features extracted by various pre-processing algorithms, and showed that the technique was relatively accurate.

### 2.5. The time-based method

For a given excitation frequency, composite stiffness and thickness, specific Lamb wave modes would be propagated in the structure. Damage in composite materials can be considered as equivalent to a local change in the composite thickness and stiffness. When the Lamb waves propagate through the area where these local changes occur, it is expected that the type of Lamb wave modes will be modified, so as to become reflection mode or mode conversion. Since each Lamb wave mode has a different group velocity, a change of mode leads to different times of flight of the corresponding wave. Therefore, the technique implies detecting and studying the changes, creations or losses of Lamb wave modes in the Lamb wave response based on the time scale. This method, called the time-based method, may also be used with the square or the absolute value of the amplitude of the Lamb wave response. The signal is further filtered or the signal envelope [32,90-92] is used to obtain the minima or maxima of the Lamb wave response.

The signal envelope [90-92], $\bar{x}(t)$, of a signal, $x(t)$, can be determined by

$$\bar{x}(t) = \sqrt{g_+ \cdot g_-} = \sqrt{x(t)^2 + H[x(t)]^2}, \quad (8)$$

where $g_+$ is the analytic signal given by $g_+ = x(t) + iH[x(t)]$ and $g_-$ is the complex conjugate of $g_+$. The analytic signal is a complex signal created by taking a real signal, $x(t)$, and then adding in, as imaginary part, its Hilbert transform, $H[x(t)]$, also called the quadrature filter. The analytic signal is also known as the pre-envelope of the real signal. The Hilbert transform of a signal, $x(t)$, is given by

$$H[x(t)] = \frac{1}{\pi \cdot t} \otimes x(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{\tau - t} \, d\tau. \quad (9)$$

where the Hilbert transform is defined as the convolution of the signal with $(\pi \cdot t)^{-1}$. In the frequency domain, the Hilbert transform performs a phase shift of $\pi/2$ radians according to the relationship $\hat{H}[\omega] = -i \cdot \text{sign}(\omega)$ [32], where $\hat{H}[\omega]$ is the Fourier transform of $H[x(t)]$. 

Jiang et al. [93] experimented an accurate technique for assessment of the location of damage in one-dimension. It consisted of taking the difference of the time response between the undamaged and damaged composite conditions. The technique was based on two transducers, a Lamb wave generator and a Lamb wave receiver. Using more Lamb wave generators/receivers, it is then possible to locate the damage in two-dimensions [94] with similar time-based method. Tracy et al. [95] demonstrated that the relationship between the damage size and the phase delay in the Lamb wave response is linear. Grondel used the envelope derivative of the Lamb wave response, the so-called time difference parameter (TDP) to detect changes in the Lamb waves propagating in riveted structures [62]. The derivative was used because it improved the sensitivity of the method. This technique was found suitable to complex Lamb wave response. It also allowed monitoring successfully complex structures, such as riveted aluminium strap joints during mechanical loading.

2.6. The wavenumber-frequency based method

This technique processes the energy spectrum density of a signal, \( x(t) \), as a function of the both the frequency and the wavenumber, as shown in an example in Figure 12. The wavenumber is inversely proportional to the wavelength, \( \lambda \), of a Lamb wave mode, or in other words the ratio of the angular frequency, \( \omega \), by the phase velocity, \( c \), of a Lamb wave mode. The wavenumber, \( \xi \), is defined as

\[
\xi = \frac{2\pi}{\lambda} = \frac{\omega}{c}.
\]  

(10)

The principal of this method is based on the measurement of the phase velocity and frequency spectrum. To obtain the phase velocity, several measurements need to be carried out at various distances \( y \) between the Lamb wave generator and Lamb wave receiver. Assume a Lamb wave response defined as follows:

\[
x(y, t) = \sum_{i=1}^{M} R_i \sin(\xi_i y - 2\pi f t_0),
\]  

(11)

where \( M \) is the number of Lamb-wave modes propagating in the plate, \( R_i \) is the amplitude of the \( i^{th} \)-mode, \( \xi_i \) is the wavenumber. The time \( t_0 \) represents the fixed time at which the measurements were taken and \( f \) is the working frequency.

The energy spectrum density (ESD) has by definition the ability to extract the wavenumber, \( \xi \), from the signal \( x \) [96]. The ESD is defined by the following equation:

\[
ESD(\xi) = \left| \int_{-\infty}^{\infty} x(y, t) w(y) e^{-j\xi y} dy \right|^2,
\]  

(12)

where \( \xi \) is again the normalised spatial frequency and \( w(y) \) is the weighted function. The weighted function could be Hanning, Hamming, Gaussian, rectangular windows or others. For the example of the rectangular window, the weighted function is equal to 1 for \( 0 \leq y < N \), where \( N \) is the specific number of points, and \( w(y) = 0 \) otherwise. The weighted function removes the
undesired parts in the Lamb wave response, corresponding to the reflections of the Lamb waves. It also improves the detection on the Lamb wave modes in the ESD.

Another method consists of representing the signal amplitude as a function of the wavenumber. This method was used by Alleyne and Cawley [97] in the case of metallic plates and by Grondel et al. [62] with composites. The idea is to shift the Lamb wave receiver along the plate by a given interval, and then apply the spatial Fourier transform on the set of Lamb wave responses. Grondel et al. further process the energy spectral density, and Alleyne and Cawley compute the Fourier transform in three-dimensions, that is, the Fourier transform in terms of the wavenumber and the temporal frequency.

Alleyne and Cawley [97] showed that the FFT modulus was satisfactory to quantify Lamb wave interactions with defects. They also showed that the sensitivity of individual modes of Lamb waves to particular notches is dependent on the frequency-thickness product, the mode type (symmetric or anti-symmetric), the mode order and the geometry of the notch.
Future work

In other to predict more accurately the failure modes, the failure criteria need to be improved and the non-linearities included in the analysis. Additional tests would be required to obtain the strength data of the transducer material that were not provided by the manufacturers.

Aircraft structures are assembled of mechanically joined sub-structures. Aluminium structures increasingly tend to be replaced by composites. It is then interesting to study the effect of joined composite structures on the damage detection.

Most of the investigations on the interaction between the embedded transducer and the composites were performed at room temperature and in dry conditions. It is therefore interesting to study the interaction between the composite and the transducer at high temperatures and in wet conditions.

In this thesis, the performance of the transducer embedded in composite and subjected to mechanical loading was studied. However, the transducer is an electromechanical device, and in that respect, the performance of the transducer needs to be evaluated under electrical fatigue loading.

The wavelets were seen sensitive to damage. However, more investigations are necessary to determine the sensitivity of the wavelets to other changes, such as temperature. It is also important to verify that the technique is reliable.

The study on the damage detection using wavelets and Lamb waves showed promising results. However, the Lamb wave response was complex, since it contained reflections from the plate edges. Therefore more study are required using a mode reflection technique that allows obtaining a Lamb wave response reflected essentially by damage.

The selective-mode technique achieved by multi-PZT transducers surface-bonded to the composite surface is expected to be evaluated with various composite lay-ups and damage types. It is important to investigate the benefits of such a technique with embedded multi-PZT transducers in the detection of damage.
Division of work between authors

**Paper A:** Paget performed the finite element analysis, the experimental investigation and wrote the paper. Jarlås and Levin supervised the work and contributed to the manuscript.

**Paper B:** The work was done by Paget, who also wrote the paper. Levin supervised the present investigation and checked the manuscript.

**Paper C:** Paget carried out the work and wrote the paper. Levin and Delebarre initiated the work and checked the manuscript.

**Paper D:** Paget has done both the theoretical and experimental studies as well as wrote the paper. Grondel and Levin supervised the work and checked the manuscript. Delebarre also checked the manuscript.

**Paper E:** Paget and Grondel carried out the experiments and wrote the manuscript. Grondel performed the theoretical study. Delebarre initiated the work and checked the manuscript along with Assaad and Levin.
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